

Updated distribution mapping of *Posidonia oceanica* meadows, coralligenous assemblages and marine caves in the Mediterranean Sea: implications for conservation and restoration

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Abstract

Marine habitats in the Mediterranean Sea play a vital role in supporting biodiversity, ecosystem functioning and services, and climate resilience. However, they are facing escalating threats from anthropogenic pressures. This study, coordinated and financially supported by the Specially Protected Areas Regional Activity Centre (SPA/RAC) under the Barcelona Convention, presents an updated, harmonized assessment of the distribution and protection status of three iconic benthic habitats: *Posidonia oceanica* meadows, coralligenous assemblages, and marine caves. A standardized methodology was applied to compile, review, harmonize, and aggregate fine-scale data from regional databases, National Focal Points (NFPs), expert networks, and online repositories. *Posidonia oceanica* meadows were mapped over 22,379 km² across 15 Mediterranean countries, with 95% within territorial waters and 37% in Marine Protected Areas (MPAs). Coralligenous assemblages and maërl beds covered 2,889.5 km² in 13 countries, in line with previous modelling estimates, with 67.1% located within MPAs, particularly in the central and western regions. Approximately 3,000 marine caves were identified across 15 countries, representing the first country-level spatial inventory of this habitat. Nearly 69% of known caves are located in MPAs, although lacking specific conservation measures. Despite significant progress, notable limitations remain. Data quality and availability are uneven across regions, and inconsistencies in classification, spatial resolution, and ecological descriptors – especially for coralligenous assemblages and marine cave typologies – limit detailed habitat representation. This study highlights persistent knowledge gaps in parts of North Africa, the Eastern Mediterranean, and non-EU coastal states, and provides a robust baseline for conservation planning and supports regional monitoring efforts under the Barcelona Convention. Future priorities include addressing data gaps, standardizing classification systems, prioritizing sites for conservation and restoration to strengthen marine habitat protection and recovery and enhance the ecological effectiveness of MPAs.

Keywords: Marine habitats; Spatial inventory; Marine Protected Areas (MPAs); Data harmonization; Habitat conservation.

Introduction

Human activities – notably the exploitation of living resources, land- and sea-based pollution, and coastal development – are driving the degradation of global marine biodiversity (IPBES, 2019; WWF, 2020; Keith *et al.*, 2022). In response, international conservation targets set for 2020 called for the protection of at least 10% of ma-

rine areas of particular importance for biodiversity and ecosystem services through networks of Marine Protected Areas (MPAs) (CBD, 2010). However, most countries failed to meet this goal, with only 8.13% of the global ocean under protection by mid-2022 (UNEP-WCMC & IUCN, 2024). The post-2020 biodiversity framework modified the goal calling for at least 30% of the global ocean to be protected by 2030, introducing the possibility

of also considering Other Effective area-based Conservation Measures (OECMs), a tool formally defined by a decision made in 2018 (CBD, 2022), thereby demanding a concerted effort to identify, map, and effectively conserve ecologically valuable marine areas. In addition, at European level, in 2020, the European Union (EU) adopted the EU Biodiversity Strategy for 2030. Beyond aligning with the global target of protecting 30% of the world's seas, the Strategy also commits to the strict protection of 10% of European marine areas. Complementing this framework, the Nature Restoration Regulation (NRR) establishes a target to restore at least 30% of degraded marine habitats and species to good ecological condition by 2030 (EU, 2024). To meet these ambitious NRR objectives, EU Member States are required to address substantial knowledge gaps regarding the distribution and condition of marine habitats within their national restoration plans, which are to be submitted in 2026. Member States are also required to develop and apply appropriate approaches and criteria for prioritizing marine areas for conservation and restoration.

The term habitat refers to “a recognizable space which can be distinguished by its abiotic (i.e., physical) characteristics and associated biological assemblages, assessed at particular spatial and temporal scales” (Fraschetti *et al.*, 2011). Accurate, high-resolution, and standardized habitat maps are essential for understanding the spatial and temporal distribution of habitats, their associated biodiversity, ecological condition, and underlying physical characteristics (Cogan *et al.*, 2009; Frascchetti *et al.*, 2024; Radicioli *et al.*, 2025). Such maps are also fundamental for designing ecologically coherent MPA networks, guiding habitat restoration, and achieving global conservation targets (Gerovasileiou *et al.*, 2019; Montefalcone *et al.*, 2021; Frascchetti *et al.*, 2021). Moreover, habitat distribution data are also critical for ecosystem-based marine spatial planning and the sustainable governance of marine resources (Levin *et al.*, 2014; Strong *et al.*, 2019).

Marine habitat mapping employs a wide range of methods across spatial scales and resolutions, from broad-scale satellite remote sensing of ocean surface features to medium-scale acoustic seabed surveys, and fine-scale video and photographic transects (Cogan *et al.*, 2009; Frascchetti *et al.*, 2024; Radicioli *et al.*, 2025). However, direct biodiversity surveys are resource-intensive and time-consuming (Levin *et al.*, 2014). In data-poor regions, environmental predictors such as bathymetry and substrate type are often used to model habitat and species distributions in a cost-effective manner (Katsanevakis *et al.*, 2017). These models are typically validated through *in situ* sampling to ensure the accuracy of habitat extent and condition assessments (Strong *et al.*, 2019). While modelled outputs currently represent the best available evidence for the potential distribution of many marine species and habitats, there remains a pressing need to enhance the accuracy, transferability, and repeatability of these models.

Habitat mapping is typically based on structured classification schemes, which strongly influence both mapping outputs and their interpretation (Gerovasileiou *et al.*,

2019; Montefalcone *et al.*, 2021). A variety of classification systems have been developed to support regional conservation and management objectives. In Europe, widely used schemes include Natura 2000 (EEC, 1992), the European Nature Information System (EUNIS) (EUNIS marine habitat classification review 2022 – European Environment Agency: https://www.eea.europa.eu/en/datahub/datahubitem-view/ce3e4bf4-e929-404a-88c7-37f2c614fd1d/folder_contents), OSPAR (OSPAR, 2008), and HELCOM (HELCOM, 2013). As regards the Mediterranean Sea, a marine benthic habitat classification was developed in the late 1990s, within the Barcelona Convention framework, initially covering 183 habitat types (UNEP/MED, 1998). This framework was recently revised to enhance ecological consistency and interoperability with schemes such as EUNIS. The updated version now includes 394 habitat types at its most detailed hierarchical level (SPA/RAC–UN Environment/MAP, 2019a), providing a stronger basis for marine management and conservation planning (Montefalcone *et al.*, 2021).

The Mediterranean Sea, recognized as a global biodiversity hotspot, supports approximately 11% of all marine species within less than 1% of the world's ocean surface (Bianchi & Morri, 2000), with nearly 20% of these species being endemic (Coll *et al.*, 2010). Despite its ecological significance, this semi-enclosed basin is under severe pressure from cumulative human impacts and other pressures – including coastal development, overfishing, pollution, eutrophication, climate change, and biological invasions – all contributing to the widespread degradation of marine habitats (Claudet & Frascchetti, 2010; Coll *et al.*, 2012; Micheli *et al.*, 2013; Dailianis *et al.*, 2018). Nevertheless, current conservation efforts and management initiatives remain inadequate to effectively address these threats (Rodríguez-Rodríguez *et al.*, 2015), with the overall situation showing little improvement compared to a decade ago.

The EUSeaMap online viewer of the European Marine Observation and Data Network (EMODnet) is a key source of broad-scale seabed habitat maps for Europe and the Mediterranean Sea. However, existing habitat maps are largely based on habitat distribution models. Consequently, their accuracy and spatial resolution at finer scales remain limited, particularly in the Southern and Eastern Mediterranean (Gerovasileiou *et al.*, 2019).

Producing accurate marine habitat maps in the Mediterranean is essential to guide informed action; however, it is particularly challenging due to the region's environmental, socio-economic, cultural, and political complexity (Mazor *et al.*, 2013). Key inventory gaps were identified over a decade ago (Fraschetti *et al.*, 2011), including the absence of a comprehensive reference list of habitats and species at basin scale (UNEP/MAP-SPA/RAC, 2006). Persistent challenges include data scarcity (particularly in North African waters) and limited information on ecologically important habitats such as hard substrates, deep-sea environments, and pelagic systems. Other limitations include inconsistent classification criteria, lack of historical mapping, geographic biases, and poor representation across ecoregions (Fraschetti *et al.*,

2011; Giakoumi *et al.*, 2013; Gerovasileiou *et al.*, 2019). These are compounded by limited regional cooperation, restricted data accessibility, variable data quality, and jurisdictional fragmentation (Levin *et al.*, 2014).

The objective of this study is to contribute to filling these gaps, focusing on three iconic types of Mediterranean marine habitats of high ecological importance, which have been recognized as priority habitats under the EU Habitats Directive and the Barcelona Convention (92/43/EEC; UNEP/MAP-SPA/RAC, 2016, 2019, 2021), specifically *Posidonia oceanica* meadows, coralligenous assemblages, and marine caves. These habitats are also included in the Updated Reference List of Marine Habitat Types for the Selection of Sites to be added to the National Inventories of Natural Sites of Conservation Interest in the Mediterranean (SPA/RAC–UN Environment/MAP, 2019b).

Posidonia oceanica meadows serve as critical nursery habitats and provide a wide range of ecosystem services, including food provision, carbon sequestration, sediment stabilization, and shoreline protection (Sanz-Lázaro *et al.*, 2012; Vassallo *et al.*, 2013; Campagne *et al.*, 2015). Coralligenous formations, rhodolith or maërl beds and their assemblages – primarily composed of encrusting red algae – typically develop at depths ranging from 20 to 120 m, in dim-light conditions and are one of the most diverse and productive marine habitats in the Mediterranean basin, supporting ecological functions as well as provisioning services (Ballesteros, 2006; Giakoumi *et al.*, 2013; Thierry de Ville d’Avray *et al.*, 2019; Cinar *et al.*, 2020).

Marine caves – defined as cavities entirely or partially occupied by seawater, accessible to humans, and exhibiting substantial horizontal and volumetric development – are widely distributed along Mediterranean rocky coasts and the seabed (Gerovasileiou & Bianchi, 2021). They host unique, highly diverse biological communities and function as refuges, providing habitat and resources for species of both ecological and economic significance (Gerovasileiou & Voultsiadou, 2012; Ouerghi *et al.*, 2019; Digenis *et al.*, 2025).

Recently, *P. oceanica* meadows, coralligenous and maërl beds, as well as specific invertebrate assemblages occurring in Mediterranean marine caves (i.e., facies dominated by *Corallium rubrum* and *Leptosammia pruvoti*), have been included in Annex II of the EU NRR. This annex identifies species and habitat types whose restoration is considered a priority at EU level, requiring Member States to implement targeted restoration measures aimed at improving habitat extent, structure, and ecological functioning.

While considerable efforts have been made over the past decade to map the above-mentioned marine habitats (e.g., Giakoumi *et al.*, 2013; Martin *et al.*, 2014; Telesca *et al.*, 2015; Sini *et al.*, 2017; Ingrosso *et al.*, 2018; Traganos *et al.*, 2022; Illa-López *et al.*, 2023; Radicioli *et al.*, 2025) our understanding of their distribution and conservation status remains largely incomplete (e.g., uneven data coverage across ecoregions, lack of data from deeper or offshore areas). There is an urgent and growing

need to systematize existing knowledge on the distribution of marine habitats, in order to meet both global and EU biodiversity targets and to guide future mapping, conservation, and restoration efforts effectively. This study aims to update and produce spatially accurate distribution maps for these iconic Mediterranean habitats. The resulting data are provided as supplementary material accompanying the online article and will also be made publicly available by SPA/RAC through the Mediterranean Biodiversity Platform (<https://mbp.medchm.net/en>), providing a baseline for achieving global and regional conservation targets, supporting implementation of the EU NRR, and informing strategic marine spatial planning and restoration initiatives across the Mediterranean basin.

Materials and Methods

Compilation of habitat distribution data

To build a comprehensive and up-to-date database for the selected key marine habitats, a stepwise data collection approach was adopted, drawing on four primary sources:

1. *Regional Activity Centre for Specially Protected Areas (SPA/RAC) datasets*: All available digital data on habitat distribution from SPA/RAC (provided in both GIS and PDF formats) were compiled (Annex 1 in Supplementary File 1). A standardized Data Review Form (Annex 2 in Supplementary File 1) was developed to support the inventory, comprising 8 items and 24 fields, structured to describe and assess each dataset. The form followed the logical sequence of the review process, from initial dataset identification to final evaluation.
2. *Publicly available online data sources*: To complement SPA/RAC datasets, additional habitat data were retrieved from key online repositories, namely EMODnet (European Marine Observation and Data Network), OBIS (Ocean Biodiversity Information System) and its European node (EurOBIS), and UNEP-WCMC (United Nations Environment Programme – World Conservation Monitoring Centre).
3. *Contributions from habitat experts*: Marine habitat experts (e.g., scientists and potential data holders) forming part of our scientific networks were contacted and requested to share relevant datasets and metadata. To facilitate this task, an Introductory Letter (Annex 3 in Supplementary File 1) outlining the study’s objectives was sent via email, along with a simplified Data Collection Template (Annex 4 in Supplementary File 1).
4. *National Focal Points (NFPs)*: SPA/RAC engaged the NFPs of all Mediterranean coastal countries (signatories of the Barcelona Convention) by providing a standardized Introductory Letter and Data Collection Template. This coordinated effort aimed to encourage the submission of country-specific data and enhance the comprehensiveness and geographic coverage of the final dataset. In cases where the data gathered

from the above-mentioned sources were characterized by coarse spatial resolution (e.g., large grid sizes), potentially leading to overestimation of habitat cover (e.g., for *P. oceanica*), it was agreed, in consultation with SPA/RAC, to include the data provided by the NFPs, while acknowledging variability in data accuracy across countries.

Data review and quality assessment for habitat inventory

All retrieved datasets underwent standardized quality assessment using the Data Review Form (Annex 2 in Supplementary File 1), which provided the structural basis for the habitat data inventory. Each dataset was evaluated across three main dimensions:

- Technical quality: Including data format, spatial resolution, geolocation accuracy, and completeness.
- Ecological validity: Verified in consultation with habitat experts to ensure ecological relevance and reliability.
- Spatial and temporal coverage: Considering geographic extent and the timeframe of data acquisition.

The compatibility of each dataset with the *Updated Classification of Benthic Habitat Types for the Mediterranean Region* (SPA/RAC–UN Environment/MAP, 2019a) was also assessed, along with its potential contribution to the Integrated Monitoring and Assessment Programme (IMAP). Based on this review, datasets were categorized as:

- High quality: suitable for direct use in habitat mapping, meeting all technical, ecological, and classification standards;
- Moderate quality: used as ancillary data to improve mapping accuracy or fill spatial gaps;
- Low quality: limited utility due to insufficient resolution, poor accuracy, or weak relevance, though in some cases used for validation or supplementary support in data-poor areas.

All major limitations identified during the review were documented and considered in the final evaluation. The list of datasets used for the aggregation and production of habitat distribution maps is provided in Annex 5 in Supplementary File 1.

Data harmonization and aggregation

To ensure consistency across the heterogeneous datasets collected, a comprehensive data harmonization process was deemed necessary. The datasets varied widely in terms of format, spatial scale, resolution, and habitat classification schemes, as they originated from different sources, methodologies, and jurisdictions. The goal of harmonization was to generate a unified, structured dataset (vector data) in which each spatial unit (polygon) contained standardized and complete attribute information. All GIS operations were performed using the ArcGIS Desktop 10 application (ESRI, 2011). The harmonization

process involved the following:

- *Standardization of attribute fields*: A common data structure was established across all input datasets. Key fields included a general habitat classification (i.e., *P. oceanica*, coralligenous assemblages, or marine caves), specific habitat nomenclature (if available), reference source, data provider, year, spatial scale, geographic coverage, and certainty level;
- *Classification system alignment*: All habitat data were harmonized with the *Updated Classification of Benthic Habitat Types for the Mediterranean Region* (SPA/RAC–UN Environment/MAP, 2019a). Where other classification systems were used, expert judgement and crosswalks were applied to assign equivalent categories in the reference system;
- *Spatial aggregation*: Harmonized datasets were aggregated through a spatial union of input data. This process included a detailed review of the geographic coverage by country and the resolution of overlapping datasets (vector layers). For most countries, data aggregation involved straightforward merging due to the limited number of data sources. In data-rich countries (e.g., France, Greece, Italy, and Spain), where multiple national, subnational, and local datasets were available, a prioritization process was applied based on spatial resolution and ecological detail. The most comprehensive and high-resolution datasets were used as primary sources. Complementary datasets were integrated to fill evident spatial gaps only or refine habitat definitions, while maintaining the geometry of the most recent and accurate source.

Following aggregation, the attribute tables of the resulting spatial layers were reorganized to ensure clarity and consistency. Field names were standardized, and a logical structure was adopted to facilitate interpretation and future data use. The final output consisted of three habitat-specific GIS layers, one each for *P. oceanica* meadows, coralligenous assemblages, and marine caves, covering the entire Mediterranean Sea. For *P. oceanica* meadows and coralligenous assemblages, an additional mapping coverage layer was developed to indicate areas that have been surveyed. This enabled more accurate interpretation of apparent absences in the final distribution maps by distinguishing between confirmed absence and areas outside existing mapping coverage. Due to limited spatial data and fewer detailed mapping initiatives, this distinction could not be made for marine caves, and ‘No data’ areas cannot be interpreted as true absences for this habitat. All spatial data are provided in shapefile format as supplementary material accompanying the online article (Supplementary files 2-5).

Map production

The final step of the data aggregation process involved the production of habitat distribution maps for the Mediterranean region, covering 21 coastal countries. These maps were generated using the standardized mapping template provided by SPA/RAC to ensure consistency

in format, symbology, and cartographic representation. Maps were produced for each of the three target habitats (*P. oceanica* meadows, coralligenous assemblages, and marine caves), as defined by the harmonized dataset. The resulting spatial products depict the geographic extent and distribution of these habitats across the basin. For marine caves hosting sensitive species, geographic coordinates were slightly shifted (ca. 500 m to 1 km) to introduce a degree of spatial uncertainty, in order to address conservation and site protection considerations. Depending on the scale of the maps, especially those covering the entire Mediterranean, the boundaries of the habitat vector layers were slightly oversized for ease of visualization. However, in some cases, this could give a false impression i.e., overestimation of the surface area of these habitats in certain regions. In addition to spatial representation, basic descriptive statistics were computed for each habitat, both at country level and for the entire Mediterranean Sea. These statistics include total area (in km²) and percentage cover within national territorial waters and MPAs (including both national MPAs and Natura 2000 sites), classified as ‘Adopted’, ‘Inscribed’, or ‘Designated’ according to the February 2024 release of the Protected Planet database (UNEP-WCMC & IUCN, 2024).

Results and Discussion

Posidonia oceanica meadows

A total of 22,379 km² of *P. oceanica* meadows have been mapped across 15 Mediterranean countries (Fig. 1). Of this area, 95% lies within national territorial waters, and 35.9% in MPAs. No data were available for Bosnia and Herzegovina, Egypt, Lebanon, Morocco, or Syria (Table 1). Based on data availability and completeness, data quality was classified as ‘high’ for eight countries (Albania, Croatia, Cyprus, France, Greece, Italy, Spain, and Tunisia), ‘moderate’ for two (Libya and Monaco), and ‘low’ for the remainder (Table 1).

This study represents a substantial improvement in the understanding of *P. oceanica* distribution compared to previous assessments (Giakoumi *et al.*, 2013; Telesca *et al.*, 2015). The latter study reported a total coverage of approximately 1,224,707 ha (~12,247 km²), with extensive data gaps along more than 21,000 km of coastline. Compared to Telesca *et al.* (2015), this study nearly doubles the total area mapped and fills key spatial gaps. Increases in mapped area were observed in six countries (Algeria, Croatia, Greece, Italy, Tunisia, and Türkiye), with the most substantial gains in Greece (+ 600%, from

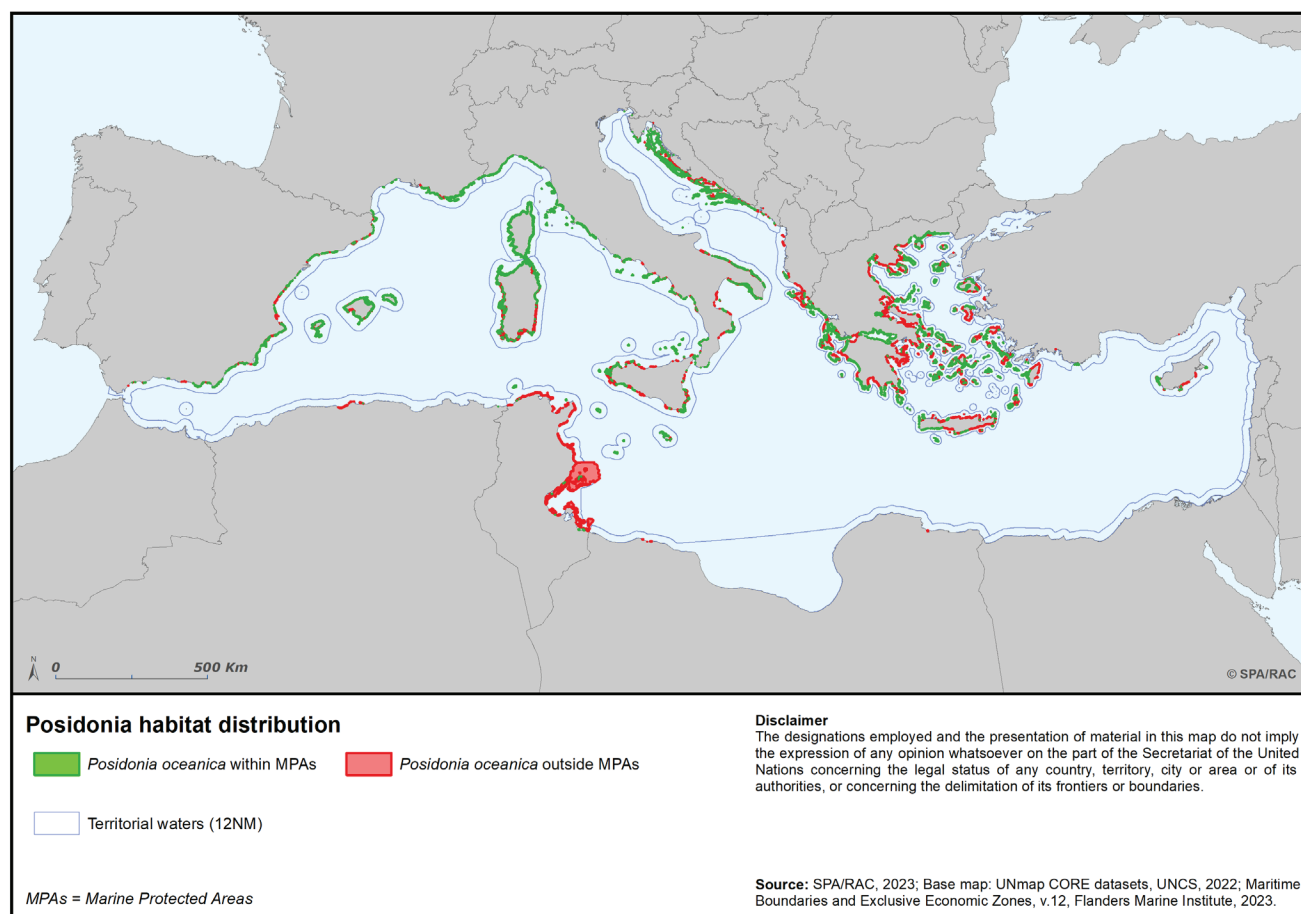


Fig. 1: Updated and standardized distribution of *Posidonia oceanica* meadows across the Mediterranean Sea, showing their extent inside and outside MPAs. The boundaries of habitat layers were oversized for ease of visualization.

Table 1. Updated distribution of *Posidonia oceanica* meadows across Mediterranean countries, including coverage in MPAs and certainty classifications based on data quality and availability.

Country	<i>Posidonia oceanica</i> habitats	<i>Posidonia oceanica</i> habitats within territorial waters*		<i>Posidonia oceanica</i> habitats inside MPAs		Certainty (based on data quality and availability)**
	Area (km ²)	Area (km ²)	%	Area (km ²)	%	
Albania	45	45	100	3	7.3	High
Algeria	44	44	100	0	0	Low
Bosnia and Herzegovina	-	-	-	-	-	No data
Croatia	446	446	100	287	64.3	High
Cyprus	78	78	100	46	59.1	High
Egypt	-	-	-	-	-	No data
France	786	786	100	765	97.4	High
Greece	3,264	3,233	99	1,703	52.2	High
Israel	-	-	-	-	-	No habitat
Italy	7,137	7,137	100	4,119	57.7	High
Lebanon	-	-	-	-	-	No data
Libya	8	8	100	-	-	Moderate
Malta	55	55	100	53	96.3	Low
Monaco	0.1	0.1	100	0.1	100	Moderate
Montenegro	0.2	0.2	100	0.2	45.7	Low
Morocco	-	-	-	-	-	No data
Slovenia	0.01	0.01	100	0.01	72.8	Low
Spain	1,210	1,210	100	1,020	84.3	High
Syria	-	-	-	-	-	No data
Tunisia	9,299	8,205	88.2	44	0.5	High
Türkiye	7	7	100	-	-	Low
Total Mediterranean	22,379	21,255	95	8,040	35.9	Moderate

* Habitats located outside national territorial waters correspond to extensive shallow shelves and/or offshore banks.

** Data quality classifications are based on feedback from NFPs. High (green): Reliable data with good spatial coverage and resolution. Moderate (yellow): Data are generally reliable but may have some limitations as regards coverage or resolution. Low (red): Data may be less reliable due to limited spatial coverage, low resolution, or other constraints.

449 to 3,264 km²) and Croatia (+ 97%). Notably, this study also provides the first mapping data for Montenegro (0.2 km²). In contrast, reduced coverage was reported for seven countries (Albania, Cyprus, France, Libya, Malta, Slovenia, and Spain), with decreases ranging from - 6% (i.e., for Malta, from 58.6 km² to 55 km²) to - 88% (i.e., for Slovenia, from 0.09 km² to 0.01 km²).

These differences may reflect improved mapping accuracy from recent national and regional initiatives (e.g., the “Posidonia Atlas” in Spain), actual changes in meadow extent, or both. In countries such as Albania, France, Malta, and Spain, where decreased areas were reported, historical declines had already been documented. For others with increased coverage, such as Algeria, Croatia, Greece, and Türkiye, due to the lack of historical data, it is not possible to confirm whether the increases reflect genuine expansion or improved mapping.

Recent efforts using remote sensing, such as those by Traganos *et al.* (2022), highlight the potential for basin-wide mapping, though often limited by insufficient

in situ validation. By integrating multiple data sources – especially through the contribution of NFPs – our study achieves higher spatial resolution and ecological accuracy. Only datasets classified as highly reliable, or validated through rigorous review or NFPs, were incorporated in the final maps. Consequently, some datasets, such as certain records from Türkiye, were excluded in order to maintain data consistency and comparability across countries, and avoid potential overestimates associated with coarse-resolution or low-certainty data.

Marked differences remain between countries as regards both mapped extent and confidence levels. Tunisia (9,299 km²), Italy (7,137 km²), and Greece (3,264 km²) account for the majority of mapped meadows, whereas Algeria (44 km²), Libya (8 km²), and Montenegro (0.2 km²) show limited coverage (Table 1). These disparities reflect both natural variation and uneven survey effort, methodological differences (e.g., acoustic, remote sensing, and *in situ* methods), and different timeframes and spatial resolutions, as also noted by Giakoumi *et al.*

(2013) and Telesca *et al.* (2015).

Levels of inclusion of *P. oceanica* in national MPAs vary considerably. France, Malta, and Spain report a high proportion of mapped meadows included in MPAs (97.4%, 96.3%, and 84.3%, respectively), whereas in Tunisia less than 1% of *P. oceanica* meadows are located in MPAs.

Overall, this study provides the most comprehensive and harmonized assessment of *P. oceanica* distribution to date, offering a solid baseline for conservation evaluation and restoration planning. Notably, the finding that nearly 36% of mapped meadows fall within MPAs reflects progress toward conservation goals, though effectiveness ultimately depends on the implementation of site-specific conservation objectives and consequent management measures.

Beyond site-based protection, *P. oceanica* meadows in EU Mediterranean waters also benefit from non-site-specific legal measures. In particular, Council Regulation (EC) No 1967/2006 prohibits bottom trawling at depths shallower than 50 m (or within 1.5 nautical miles from the coast where the 50 m isobath lies closer), irrespective of MPA designation, thereby potentially reducing direct physical impacts on shallow seagrass meadows, depending on the level of enforcement and the presence of equivalent national or regional regulations in non-EU countries.

Given the ecological importance of *P. oceanica*, enhancing monitoring efforts, expanding coverage into less-studied areas, and improving data harmonization remain key priorities. Despite significant progress, data gaps persist. For example, although *P. oceanica* has been reported in Egypt (e.g., Fouda, 2021), no spatial data are currently available. Similarly, no updated information is available for Morocco. Nevertheless, in some areas of the South-eastern Levantine Basin, the absence of *P. oceanica* does not appear to result from data deficiencies, but rather from habitat unsuitability; previous studies confirmed the absence of *P. oceanica* in Israel and Syria (Giakoumi *et al.*, 2013; Telesca *et al.*, 2015).

Targeted efforts are urgently needed to improve mapping and monitoring in these understudied areas, for a complete and accurate picture of *P. oceanica* distribution across the Mediterranean.

Coralligenous assemblages

A total of 2,889.5 km² of coralligenous assemblages and maërl beds has been mapped across 13 Mediterranean countries (Fig. 2), with the vast majority (92.1%) located within territorial waters and 67.1% in MPAs (Table 2). No data were available for Bosnia and Herzegovina, Cyprus, Egypt, Libya, Monaco, Morocco, Syria, or Türkiye

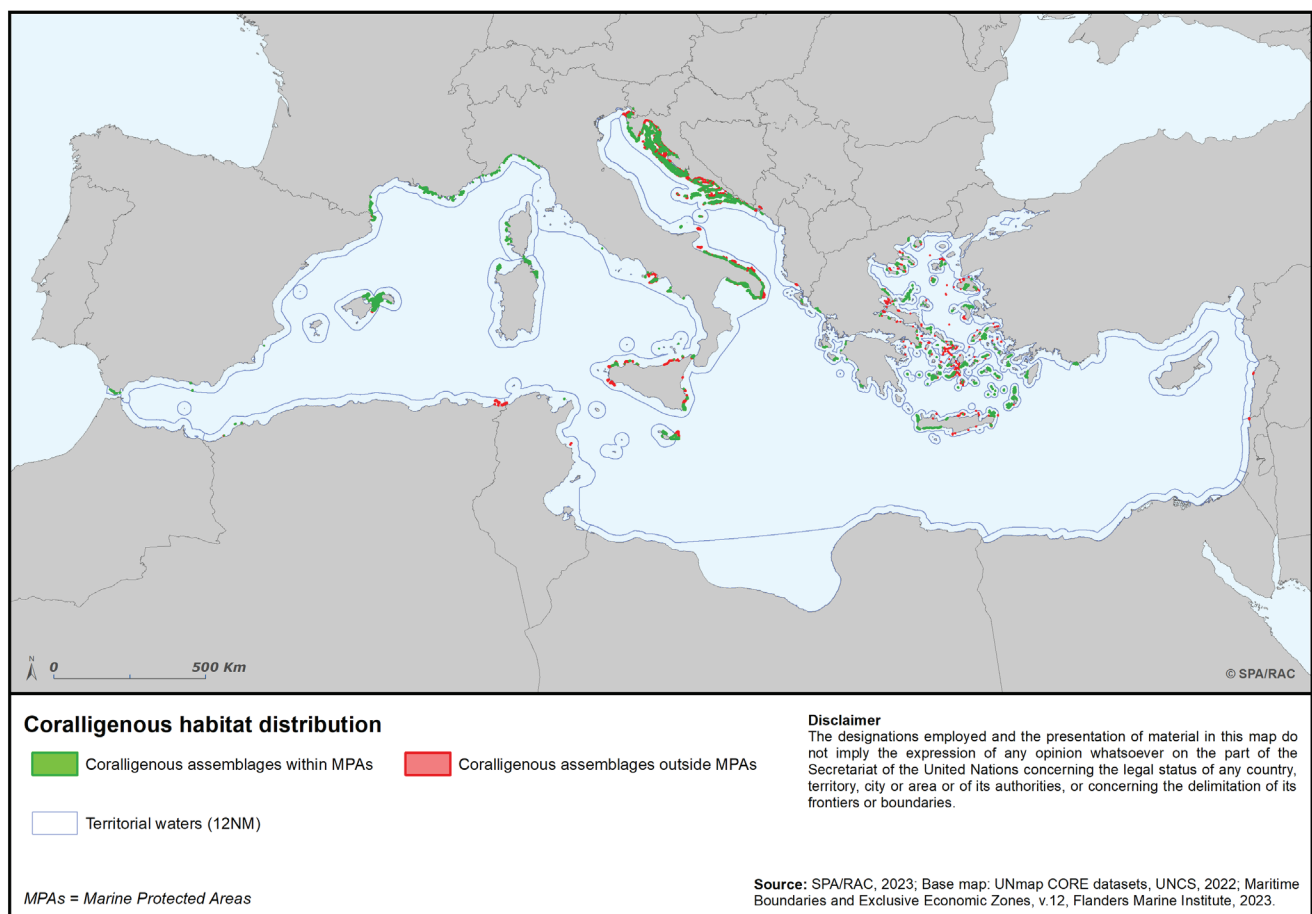


Fig. 2: Updated and standardized distribution of coralligenous assemblages and maërl beds across the Mediterranean Sea, showing their extent inside and outside MPAs. The boundaries of habitat layers were oversized for ease of visualization.

Table 2. Updated distribution of coralligenous assemblages and maërl beds across Mediterranean countries, including coverage in MPAs and certainty classifications based on data quality and availability.

Country	Coralligenous assemblages	Coralligenous assemblages within territorial waters*		Coralligenous assemblages inside MPAs		Certainty (based on data quality and availability)**
	Area (km ²)	Area (km ²)	%	Area (km ²)	%	
Albania	0.1	0.06	100	-	-	Low
Algeria	50.7	50.7	100	0.33	0.6	Low
Bosnia and Herzegovina	-	-	-	-	-	No data
Croatia	406.2	406.2	100	263.5	64.9	High
Cyprus	-	-	-	-	-	No data
Egypt	-	-	-	-	-	No data
France	40.0	40.0	100	39.98	99.8	High
Greece	79.1	77.5	98	72	91	Moderate
Israel	1.2	1.2	100	-	-	Low
Italy	833.0	833.0	100	513.1	61.6	High
Lebanon	0.3	0.3	100	-	-	Low
Libya	-	-	-	-	-	No data
Malta	458.3	230.88	50.4	278.95	60.9	Low
Monaco	-	-	-	-	-	No data
Montenegro	0.5	0.5	100	0.4	69.9	Low
Morocco	-	-	-	-	-	No data
Slovenia	267.4	267.4	100	31.5	11.8	Low
Spain	741.6	741.6	100	738.4	99.6	Moderate
Syria	-	-	-	-	-	No data
Tunisia	11.1	11.1	100	0.1	0.7	Low
Türkiye	-	-	-	-	-	No data
Total Mediterranean	2,889.5	2,660.5	92.1	1,938.2	67.1	Moderate

* Habitats located outside national territorial waters correspond to extensive shallow shelves and/or offshore banks.

** Data quality classifications are based on feedback from NFPs. High (green): Reliable data with good spatial coverage and resolution. Moderate (yellow): Data are generally reliable but may have some limitations as regards coverage or resolution. Low (red): Data may be less reliable due to limited spatial coverage, low resolution, or other constraints.

(Table 2). Based on data availability and completeness, data quality was classified as high for three countries (Croatia, France, and Italy), moderate for two (Greece and Spain), and low for the remainder (Table 2). The total mapped area reported in this study does not differ significantly from the estimates of Martin *et al.* (2014), who predicted 2,763.4 km² of coralligenous outcrops and 1,654.5 km² of maërl beds using predictive modelling. Discrepancies likely reflect differences between validated occurrence data and modelled distributions, as well as the exclusion of records not verified as highly reliable through the review process or by NFPs, and therefore omitted from the final maps.

Coralligenous formations are inherently complex, both morphologically and ecologically. They host diverse biological communities and exhibit significant small-scale heterogeneity, yet are often grouped under the broad term “coralligenous” (e.g., Ballesteros, 2006). While this generalization has been necessary, it limits our ability

to capture the fine-scale ecological variability of these habitats. Furthermore, the lack of standardized classification systems and consistent reporting protocols across datasets remains a major barrier to more accurate habitat characterization.

The currently mapped distribution is concentrated primarily in the Central and Western Mediterranean, with notable coverage in the Adriatic Sea. The vast majority of records (92.1%) fall within territorial waters, with Croatia, France, and Italy contributing high-quality and comprehensive datasets – similar to those available for *P. oceanica* meadows. In contrast, many countries in North Africa and the Eastern Mediterranean remain under-represented. These discrepancies likely reflect differences in research effort, survey intensity, and technological capacity rather than a true absence of coralligenous habitats. Notably, this study has expanded spatial coverage for previously data-poor countries such as Slovenia and Lebanon (Martin *et al.*, 2014). Nevertheless, data remain

unavailable for eight Mediterranean countries (Table 2), and significant baseline information gaps persist across the region.

The high proportion (67.1%) of coralligenous assemblages in MPAs is particularly noteworthy, given increasing pressure exerted by bottom trawling, abrasion caused by nets and longlines, and biological invasions (Piazzi *et al.*, 2012; Ingrosso *et al.*, 2018; Ferrigno *et al.*, 2018). However, the level of integration of coralligenous assemblages within national MPA networks varies considerably. France and Spain report nearly complete inclusion of mapped assemblages in MPAs (99.8% and 99.6%, respectively), whereas much lower percentages are observed in Slovenia (11.8%), Tunisia (0.7%), and Algeria (0.6%). It should be noted that the high levels of inclusion reported for some countries may partly reflect sampling bias, given that MPAs are typically more intensively surveyed due to their conservation status.

Nonetheless, these findings provide encouraging evidence of progress toward regional conservation targets and underline the importance of expanding mapping and monitoring efforts, particularly in under-surveyed regions. Recent studies indicate that MPAs in the Western Mediterranean can contribute positively to the conservation of coralligenous habitats, with many sites maintaining good to high ecological status (Fraschetti *et al.*, 2022). However, such conservation outcomes are often

limited in spatial extent, reinforcing the need for more coordinated, basin-wide strategies to ensure long-term protection and resilience of these vulnerable ecosystems.

Marine caves

A total of 2,926 marine caves were reported across 15 Mediterranean countries, with no data available for six countries: Bosnia and Herzegovina, Egypt, Libya, Monaco, Slovenia, and Syria (Fig. 3). The largest numbers of marine caves were recorded within the territorial waters of Italy (1,009), Greece (624), Croatia (541), Türkiye (270), France (158), and Spain (124). All remaining countries reported fewer than 100 caves each.

Based on feedback from NFPs, data quality – in terms of availability and completeness – was classified as high for seven countries (Croatia, Cyprus, France, Greece, Italy, Spain, and Türkiye), moderate for the rest, and low for Malta. Overall, 68.8% of the reported marine caves are located in MPAs (Table 3). All reported caves in Albania, Malta, and Morocco are located in MPAs. In most other countries, over half of the marine caves are located in MPAs, whereas the lowest proportions were found in Israel (33.3%), Lebanon (6.3%), Tunisia (4.2%), and Türkiye (0.4%).

This study represents the first systematic assessment

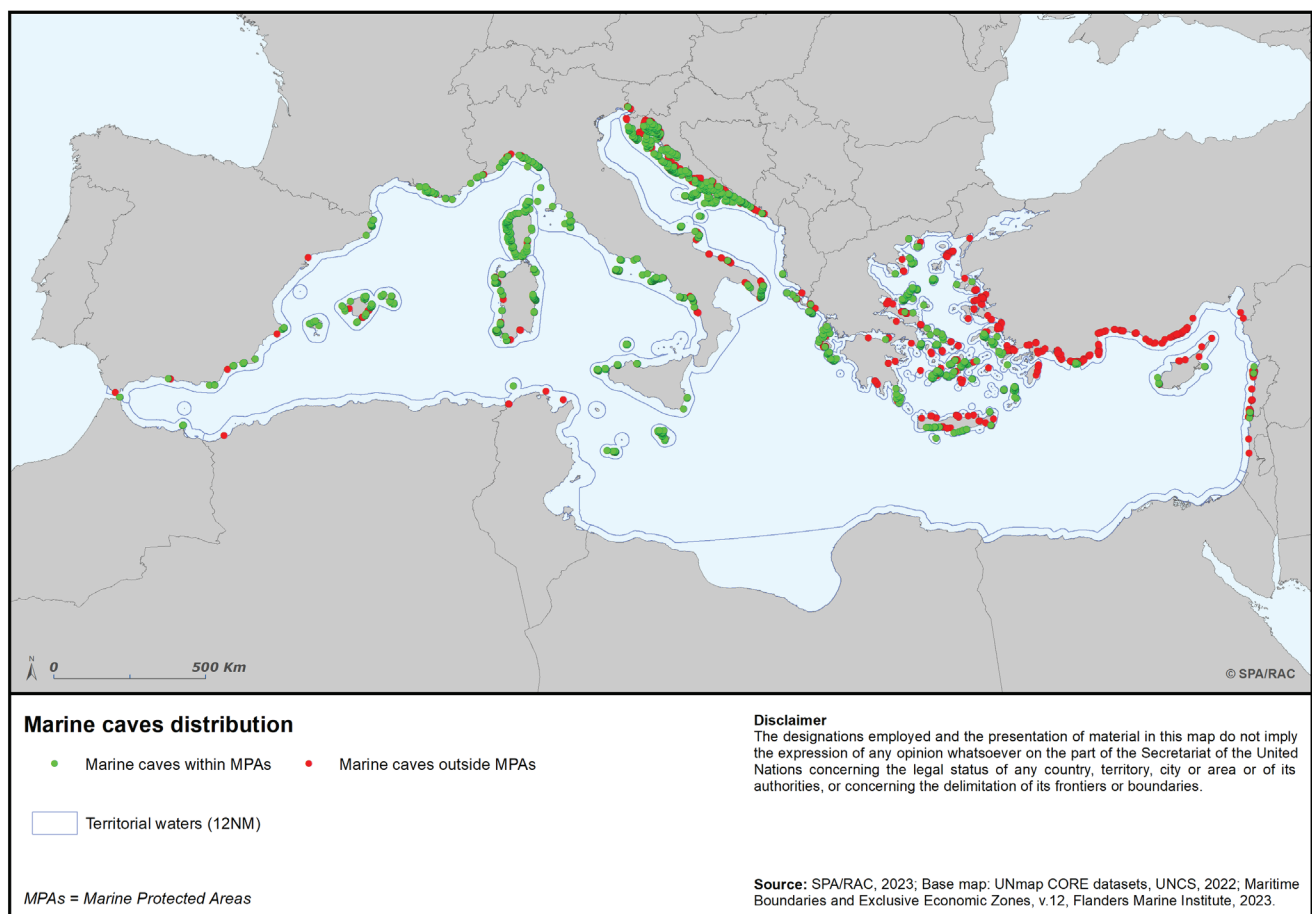


Fig. 3: Updated and standardized distribution of marine caves across the Mediterranean Sea, showing their presence inside and outside MPAs. Points represent cave locations but are not representative of size or surface area.

Table 3. Updated distribution of marine caves across Mediterranean countries, including presence in MPAs and certainty classifications based on data quality and availability.

Country	Marine caves		Marine caves within territorial waters*		Marine caves inside MPAs		Certainty (based on data quality and availability)**
	Number	Number	%	Number	%		
Albania	4	4	100	4	100	Moderate	
Algeria	1	1	100	-	-	Moderate	
Bosnia and Herzegovina	-	-	-	-	-	No data	
Croatia	541	541	100	391	72.3	High	
Cyprus	17	17	100	10	58.8	High	
Egypt	-	-	-	-	-	No data	
France	158	158	100	146	92.4	High	
Greece	633	624	98.6	455	71.9	High	
Israel	3	3	100	1	33.3	Moderate	
Italy	1,009	1,009	100	844	83.6	High	
Lebanon	95	95	100	6	6.3	Moderate	
Libya	-	-	-	-	-	No data	
Malta	33	33	100	33	100	Low	
Monaco	-	-	-	-	-	No data	
Montenegro	7	7	100	4	57.1	Moderate	
Morocco	5	5	100	5	100	Moderate	
Slovenia	-	-	-	-	-	No data	
Spain	124	124	100	106	85.5	High	
Syria	-	-	-	-	-	No data	
Tunisia	24	24	100	1	4.2	Moderate	
Türkiye	272	270	99.3	1	0.4	High	
Total Mediterranean	2,926	2,915	99.6	2,007	68.6	Moderate	

* Marine caves occurring outside national territorial waters are either located close to reference boundary limits or influenced by spatial or positional uncertainties in the underlying datasets.

** Data quality classifications are based on feedback from NFPs. High (green): Reliable data with good spatial coverage and resolution. Moderate (yellow): Data are generally reliable but may have some limitations as regards coverage or resolution. Low (red): Data may be less reliable due to limited spatial coverage, low resolution, or other constraints.

of marine cave distribution at national level across the Mediterranean, expanding on earlier basin-wide analyses (e.g., Giakoumi *et al.*, 2013; Gerovasileiou & Bianchi, 2021). Unlike previous studies that presented data by ecoregion, this effort leveraged direct communication with NFPs, allowing for finer geographic resolution. The absence of data from six countries may reflect either a genuine absence of marine caves – especially in areas with soft substrates, such as Slovenia – or data gaps due to limited research, as in Libya, where caves are likely present in the Cyrenaica region (Giakoumi *et al.*, 2013). The low number of caves reported from North African countries (24 in Tunisia, 5 in Morocco, and 1 in Algeria) raises questions about whether these figures reflect true scarcity or a lack of field surveys and habitat mapping. In contrast, the high number of records from Northern Mediterranean countries likely reflects both higher research intensity and the prevalence of suitable rocky coastlines,

especially around peninsulas and islands in Italy, Greece, and Croatia (Gerovasileiou & Bianchi, 2021). Nevertheless, even in these relatively well-studied countries, the actual number of marine caves is certainly underestimated due to the geomorphological complexity of the coastline, the abundance of rocky islets, and the current survey bias toward shallow, semi-submerged caves, which are more easily detected (Giakoumi *et al.*, 2013; Sini *et al.*, 2017).

Like other hard-substrate habitats (e.g., rocky reefs), marine caves are defined by complex morphologies including blind-ended and tunnel-shaped formations, which can be semi- or fully submerged. These structures create steep environmental gradients that support highly structured biological communities and facies (Gerovasileiou & Bianchi, 2021, and references therein). However, such morphological and ecological data were generally unavailable in most records. Inconsistencies in habitat typol-

ogy, as well as variability in coordinate accuracy, further limit data comparability across datasets.

Although Abdulla *et al.* (2008) reported the presence of marine caves in 33 Mediterranean MPAs, the actual number of caves in MPAs was previously unknown. The present estimate (68.6%) is a promising advancement. The notably low percentage of marine caves in the MPAs of non-EU Eastern and Southern Mediterranean countries emphasizes both the importance of EU policy tools such as the Natura 2000 network and the urgent need for increased conservation efforts and investment in under-represented regions.

Concluding remarks and future research directions

Our results point to progress in two main areas: (1) a substantial improvement in spatial knowledge for three iconic and priority Mediterranean marine habitats; and (2) evidence suggesting that these habitats appear to be largely included within the boundaries of MPAs.

While the strong representation of *P. oceanica* in MPAs is expected – given its long-standing protection under the EU Habitats Directive – the high inclusion rates of coralligenous assemblages and marine caves are more surprising and encouraging. Nevertheless, this pattern may partly reflect sampling bias, as MPAs are often better surveyed due to their legal status and research prioritization. Despite this, many MPAs, in particular those included in the Natura 2000 network, still lack targeted management measures. However, our findings indicate progress towards recognition of these habitats and integration in formal conservation frameworks.

Adopting a Systematic Conservation Planning (SCP) approach could further strengthen the current framework, given that the existing configuration of protected habitats does not necessarily ensure an ecologically representative, well-connected, or equitably governed network (Giakoumi *et al.*, 2025). In addition, most habitat maps do not include robust information on ecological condition, degradation status, or recovery potential; instead, they primarily depict the presence or extent of a habitat type rather than its health or functional integrity – an essential variable for prioritising conservation and restoration actions (Dailianis *et al.*, 2018; Gerovasileiou *et al.*, 2019).

A key challenge emerging from this assessment is the discrepancy between national habitat reports and harmonized regional estimates. These differences likely stem from variations in mapping methodologies, spatial resolution, and survey coverage. For this study, only high-confidence datasets (i.e., validated through review or confirmed by NFPs) were included in the final inventory. While this ensures comparability across countries, it may exclude locally relevant data lacking formal validation. Consequently, the results should be treated with caution due to potential biases and underlying methodological differences.

Habitat maps are often based on coarse-resolution datasets or predictive modelling approaches which, although valuable for regional overviews, frequently lack

the spatial accuracy required for effective restoration planning at local scale. Addressing these gaps requires stronger integration of local and national monitoring programs, alongside broader adoption of standardized, region-wide methodologies for habitat mapping and reporting. Improved methodological consistency will enhance data completeness, reduce uncertainty, and support more effective conservation planning and policy development across the Mediterranean.

Persistent heterogeneity in habitat classification systems, inconsistencies in data reporting, and variable coordinate precision – particularly for coralligenous and marine cave data – continue to limit fine-scale ecological interpretation. The absence of standardized typologies for sub-habitat features (e.g., distinct coralligenous communities or differences between semi-submerged and submerged caves) constrains the ecological resolution of maps. Data coverage also remains uneven, with major gaps in North Africa, the Eastern Mediterranean, and non-EU coastal states, thus highlighting the need for broader and more systematic surveying.

A further issue consists in the limited integration between unpublished data, maps presented in scientific literature, and those available through online portals (Gerovasileiou *et al.*, 2019). This fragmentation restricts the effective use of existing information in conservation planning and can lead to duplicated effort, inconsistent mapping standards, and gaps in spatial coverage. A recent ICES workshop on predictive habitat modelling showed that, despite the increasing number of marine habitat maps, their application in management remains limited, largely due to slow adoption of open data practices, uncertainties about map reliability, and persisting data deficiencies (ICES, 2021).

The use of Habitat Suitability Models (HSMs) and species distribution models (SDMs) provides a complementary approach when validated maps are unavailable. These models are increasingly applied in the development of national marine restoration plans under the EU NRR, offering estimates of habitat distribution, potential extent, and priority areas for intervention. Additionally, modelling approaches are valuable for projecting future changes under climate change scenarios, identifying potential habitat losses, range shifts, or refugia, and supporting proactive conservation and restoration strategies when empirical data are limited (Smith *et al.*, 2023; Georges *et al.*, 2024; Millot *et al.*, 2024). Although modelled outputs currently represent the best available evidence for the potential distribution of many marine species and habitats – particularly non-biogenic habitats and species that cannot be directly detected through remote sensing – greater efforts are needed to improve the accuracy, transferability, and repeatability of these models.

In conclusion, this study underscores the central importance of robust, standardized, and spatially explicit data for effective conservation and restoration of Mediterranean marine habitats. Such data are essential for fulfilling reporting obligations under international conventions and for implementing the IMAP framework. Based on our findings, key priorities for advancing marine hab-

itat conservation and management in the Mediterranean include:

- Filling regional data gaps, particularly in under-surveyed and non-EU regions;
- Adopting standardized habitat classification schemes to enhance cross-country comparability;
- Improving reporting accuracy and implementing systematic habitat condition assessments; and
- Strengthening the ecological representativeness and management effectiveness of MPAs to ensure that critical habitats are both recognized and actively protected.

Continued investment in regional collaboration, open data sharing, expert engagement, and harmonized monitoring protocols will be vital for securing the long-term sustainability of these ecologically and socioeconomically valuable marine habitats.

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Supplementary Data

The following supplementary information is available online for the article:

Supplementary File 1:

- Annex 1: Initial habitat data provided by SPA/RAC.
- Annex 2: Data Review Form.
- Annex 3: Introductory letter template.
- Annex 4: Data Collection Template.
- Annex 5: Input data used for the aggregation process and the final maps.

Supplementary File 2: Distribution of *Posidonia oceanica* in the Mediterranean Sea based on the information aggregated in this study.

Supplementary File 3: Distribution of coralligenous assemblages and maërl beds in the Mediterranean Sea based on the information aggregated in this study.

Supplementary File 4: Distribution of marine caves in the Mediterranean Sea based on the information aggregated in this study.

Supplementary File 5: Total mapping coverage of the aggregated datasets, representing areas with available information at the time of analysis. Areas outside this layer indicate lack of data, where the presence or absence of *Posidonia oceanica*, coralligenous assemblages, or marine caves is unknown.