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Spatial conservation priorities for marine megafaunal predators: Multi-taxon versus taxon-specific approaches

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Abstract

Marine megafaunal predators are globally threatened by anthropogenic stressors, but are key for ecosystem functioning. Their worsening conservation statuses indicate that current management is failing, requiring us to urgently reassess their conservation needs to ensure their survival. Their life histories, threats, and resource needs are diverse. Consequently, spatial conservation areas targeting all species will likely overlook such heterogeneity, contributing to the problem. Here, we model 42 marine megafaunal predator species distributions (marine mammals, elasmobranchs, teleost fishes) in the Mediterranean Sea using available biodiversity data to highlight diversity among species richness gradients for separate taxonomic groups. Secondly, we employ the Marxan spatial planning decision-making tool to identify priority conservation areas for the different taxonomic groups and quantify overlap with the current marine protected area (MPA) system. Different marine megafaunal predator taxonomic groups had heterogeneous distributions, resulting in drastically different spatial conservation priority areas. None of the marine megafaunal predators are sufficiently covered by Mediterranean MPAs (<30% coverage), with marine mammals being the least protected despite having the greatest designated MPA extent, highlighting disconnects between conservation goals and current management outcomes. To conserve marine megafaunal predators, taxon-specific ecological requirements and resulting spatial heterogeneity need to be accounted for in marine spatial planning.

KEYWORDS
cetaceans, conservation, fish, marine protected areas, Marxan, MPAs, sharks, spatial planning

This paper is targeted towards researchers and practitioners implementing marine spatial planning tools for the conservation of marine megafauna.

1 | INTRODUCTION

Marine megafaunal predators, composed of teleost fishes, mammals, and elasmobranchs (e.g., sharks and rays), are globally declining due to anthropogenic pressures including fishing, climate change, and habitat degradation (Avila et al., 2018; Dulvy et al., 2021). These species create millions of job opportunities through being heavily targeted commodities in multi-billion dollar industries, global fisheries, and eco-tourism (Cisneros-Montemayor et al., 2010; Juan-Jordá et al., 2011). In addition to economic impacts, their loss reduces important ecosystem functions such as top-down control, redistribution of nutrients, habitat engineering, and carbon sequestration (Hammerschlag et al., 2019). Marine megafaunal predators are typically either protected within marine protected areas (MPAs) planned across multiple species and habitats, or focused on popular taxa, that is, marine mammals (Notarbartolo di Sciara et al., 2016), but both approaches neglect the heterogeneous habitat requirements of predators stemming from their complex life histories, contributing to their ineffectiveness (Klein et al., 2015). Further, marine megafaunal predator home ranges typically exceed plausible sizes for MPAs, allowing exposure to threats outside MPA boundaries (Conners et al., 2022).

Marine megafaunal predators are some of the most globally threatened taxa, with over a third of marine mammals and elasmobranchs classified as threatened in IUCN Red List assessments, and targeted fisheries causing the loss of 90% biomass of large predatory fishes (Avila et al., 2018; Dulvy et al., 2021; Myers & Worm, 2003). Fishing is the largest threat to all marine megafaunal predators, with incidental bycatch in large-scale industrial fisheries most prevalent, although fisheries also present other threats such as resource exploitation, direct harvesting, and habitat destruction. Further, climate-induced habitat degradation and range shifts are increasingly prominent threats (Avila et al., 2018; Dulvy et al., 2021). The impacts of shipping traffic are well established for marine mammals, but less certain, although potentially significant, for sharks or teleost fishes (Schoeman et al., 2020). The loss of marine megafaunal predators from ecosystems causes trophic cascades and reduced resilience to climate change (Estes et al., 2016). Marine megafaunal predators also exhibit high cultural and economic significance, which can be both a benefit (i.e., high conservation interest) and a detriment (i.e., drives high demand) (Estes et al., 2016). Therefore, we urgently need to improve understanding of the conservation requirements for top marine megafaunal predators to prevent further declines.

Marine spatial planning (Directive 2014/89/EU) offers a coordinated and transparent approach to managing different stakeholders using the marine space, while minimizing impacts to the environment. Incorporating marine megafaunal predators into spatial planning is important to indicate ecologically significant areas, that is, with high productivity, species diversity or biomass of prey species (Augé et al., 2018). Incorporating multi-taxa approaches to identify priority areas has been advocated (Augé et al., 2018), but this oversimplifies the diverse habitat requirements of different taxonomic groups (Heupel et al., 2019). In contrast, predator-specific MPAs focus on narrower objectives, that is, protecting specific life stages such as breeding or feeding grounds, but this strategy will only be effective if the protected life history stages maximize population growth rates (Conners et al., 2022). Different marine megafaunal predator taxa have distinct spatial requirements, affecting their susceptibility and exposure to different threats (Avila et al., 2018). For example, divergent thermoregulatory strategies mean that marine mammals represent highest predator richness in temperate and polar waters, and in pelagic zones, while sharks and teleost fishes dominate tropical and coastal waters (Grady et al., 2019). At finer-scales, spatial partitioning between species is driven by mechanisms such as competitive exclusion and varying life history strategies (Heupel et al., 2019). Attempting to maximize conservation benefits for taxonomic groups offers a suitable balance between species-specific approaches, which will not afford protection to unstudied species, and broad (all taxa) biodiversity objectives that fail to account for taxon-specific requirements.

The Mediterranean Sea hosts a high diversity of marine megafaunal predators that are exposed to some of the highest human impacts globally (Coll et al., 2010). Consequently, the Mediterranean Sea is an extinction risk hotspot for elasmobranchs (Dulvy et al., 2021), and local extinctions of marine mammal and teleost fish populations have already occurred (Bearzi et al., 2008; MacKenzie et al., 2009). Only 6% of the Mediterranean Sea is covered by MPAs and, of these, 95% have no regulations in place, owing to most being coastal and coinciding with high vessel density areas resulting in stakeholder conflicts (Claudet et al., 2020). Transboundary marine spatial planning has been encouraged given the large number of relatively small countries bordering the Mediterranean Sea (Li & Jay, 2020), yet marine spatial planning for marine megafaunal predators has so far focused on single species or small spatial scales (Carlucci et al., 2021; Mazor et al., 2016). To ensure that spatial planning results in the best conservation benefits for marine megafaunal predators, it needs to be executed at scales relevant to the expansive spatial ranges of marine megafaunal predators (Conners et al., 2022; Estes et al., 2016).

In practice, conservation practitioners use all available biodiversity information for spatial planning prioritizations across taxa, and typically omit taxon-specific requirements. In this paper, we test whether taxa with different spatial ranges and habitat requirements need different conservation priority areas in the Mediterranean Sea. We firstly model the distributions of large teleost fishes, marine mammals and elasmobranchs. Second, we identify separate and joint reserve prioritization solutions for different taxa to test our expectation that each taxon requires specific conservation areas. Finally, we evaluate how different our reserve networks are compared to currently designated MPAs. We highlight discrepancies in the realized and required conservation efforts for marine megafaunal predators and develop recommendations to facilitate the implementation of improved management measures for each group.

2 | METHODS

2.1 | Species distribution modeling

We classified a marine megafaunal predator as having a total length ≥ 100 cm and a trophic level ≥ 4 based on FishBase (https://www.fishbase.se/) or SeaLifeBase (https://www.sealifebase.ca/) records (Boyse et al., 2023). Occurrence records for individual species were collated from different databases, including GBIF (https://www.gbif.org, June 2020, GBIF Occurrence Download https://doi.org/10.15468/dd.tqx2he), OBIS (https://obis.org/), EurOBIS (https://www.eurobis.org/), the Mediterranean Large Elasmobranchs Monitoring (Medlem) database, and Accobams (ACCOBAMS Survey Initiative, 2020; Mancusi et al., 2020). Species with <40 occurrences were excluded, as small sample sizes can impact model performance (Meynard et al., 2019), resulting in 42 marine megafaunal predator species, covering three taxonomic groups (20 teleost fishes, 9 marine mammals, 13 elasmobranchs), with sufficient data to model their distributions (Appendix S1). Seventy-five percent of these species are listed as threatened or data deficient by the IUCN Red List, including four critically endangered species: the Strait of Gibraltar subpopulation of killer whales (*Orcinus orca*), Mediterranean populations of blue sharks (*Prionace glauca*) and short-fin mako sharks (*Isurus oxyrinchus*), and the global population of oceanic whitetip sharks (*Carcharhinus longimanus*). We obtained data for bathymetry, sea surface temperature mean, sea surface temperature range, and chlorophyll *a* mean from Bio-ORACLE v2.0 covering the years 2000–2014, and bathymetric slope and distance from shore from Marspec in WGS84 projection and 0.83° × 0.83° resolution (Assis et al., 2018; Sbrocco & Barber, 2013). Prior to modeling, we spatially thinned occurrence records with a nearest neighbor distance of 10 km (Aiello-Lammens et al., 2015). We modeled species distributions using maximum entropy (MAXENT), multiple adaptive regression splices (MARS) and random forest (RF) algorithms with the SSDM R package (Phillips et al., 2006; Schmitt et al., 2017). We generated 10,000 background points for MAXENT. MARS and RF require pseudo-absence data, which we created randomly using the two-degree method, with 1000 points for MARS and an equal number of pseudo-absences as presence data for RF (Barbet-Massin et al., 2012). We made ensemble models across the different algorithms using weighted AUC scores, with an AUC threshold of 0.75, to reduce the biases inherent in any single modeling approach. We converted ensemble habitat suitability models for each species to presence-absence models using the sensitivity equals specificity threshold (Schmitt et al., 2017). Binary ensemble models were summed to produce stacked species distribution models to visualize patterns in species richness.

2.2 | Priority areas for marine megafaunal predators in the Mediterranean

We divided the Mediterranean Sea into planning units of 10 km × 10 km, in line with European Union guidelines on spatial planning (European Commission, 2007), resulting in 25,141 planning units in total, in the Lambert Azimuthal Equal Area projection (EPSG:3035). We assigned each planning unit an opportunity cost of displaced vessel traffic, represented by annual vessel density (hours per square kilometer) at a 1 km × 1 km resolution (European Marine Observation and Data Network, EMODnet; https://www.emodnet.eu/). These maps are derived from AIS data, mandatory for all vessels ≥15 m, and includes the following vessel types: fishing, service, dredging, sailing, pleasure craft, high-speed craft, tug/-towing, passenger, cargo, tanker and military/law enforcement (Falco et al., 2019). We averaged annual vessel density across the available 4 years (2017–2020) and summed the data to a 10 km × 10 km resolution (Appendix S4). Vessel density is a suitable surrogate for opportunity cost as this incorporates multiple sectors (e.g., fisheries, passenger and cargo transportation, offshore industries) which all represent important threats for marine megafaunal predators (Avila et al., 2018; Dulvy et al., 2021; Giménez et al., 2020).

We employed the spatial planning software Marxan to identify priority areas for conserving marine megafaunal predators across different taxonomic groups. Conservation actions within identified areas may include protected areas, maritime transport regulations, fisheries regulations, or by-catch reduction measures, depending on the specific needs of each taxonomic group. Marxan

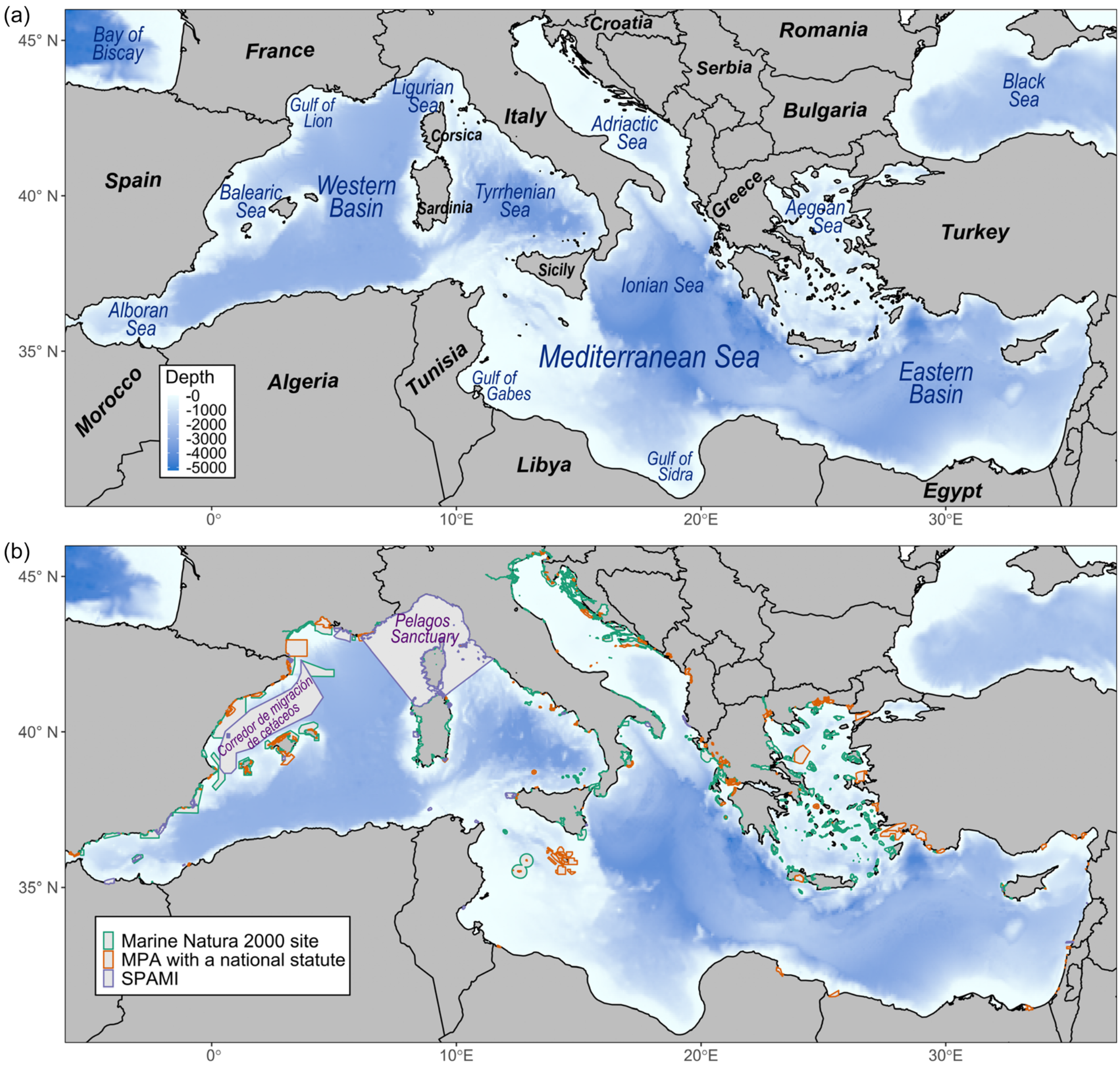

FIGURE 1 Bathymetric maps of the Mediterranean Sea showing (a) marine regions, and (b) designated marine protected areas (MPAs) including Marine Natura 2000 sites, MPAs with a national statute and specially protected areas of Mediterranean importance (SPAMIs).

provides near-optimal solutions to the minimum set problem where conservation features (i.e., species) are adequately represented for the least possible cost (Ball et al., 2009). Our conservation features consisted of individual marine megafaunal predator binary species distributions across the three different algorithms for 42 species. We set a target of 30% protection for each species, in line with the post-2020 Global Biodiversity Framework guidance to protect 30% of marine and coastal habitats by 2030 (CBD, 2021). While protecting 30% of each species distribution will not necessarily result in 30% of the total area receiving protection, this approach allows ecologically relevant areas to be conserved. We ran Marxan using the simulated annealing algorithm and a boundary length modifier of 0.01 after calibration. We performed 100 iterations for each of the conservation feature scenarios: (1) all marine megafaunal predator species, (2) teleost fishes, (3) marine mammals, and (4) elasmobranchs.

2.3 | Comparing conservation planning scenarios with different taxonomic information

We used both the selection frequency, that is, how many times each planning unit was selected in 100 iterations, and the 10 solutions with the lowest objective scores to compare conservation priority differences across marine megafaunal predator taxa. First, we quantified the overlap

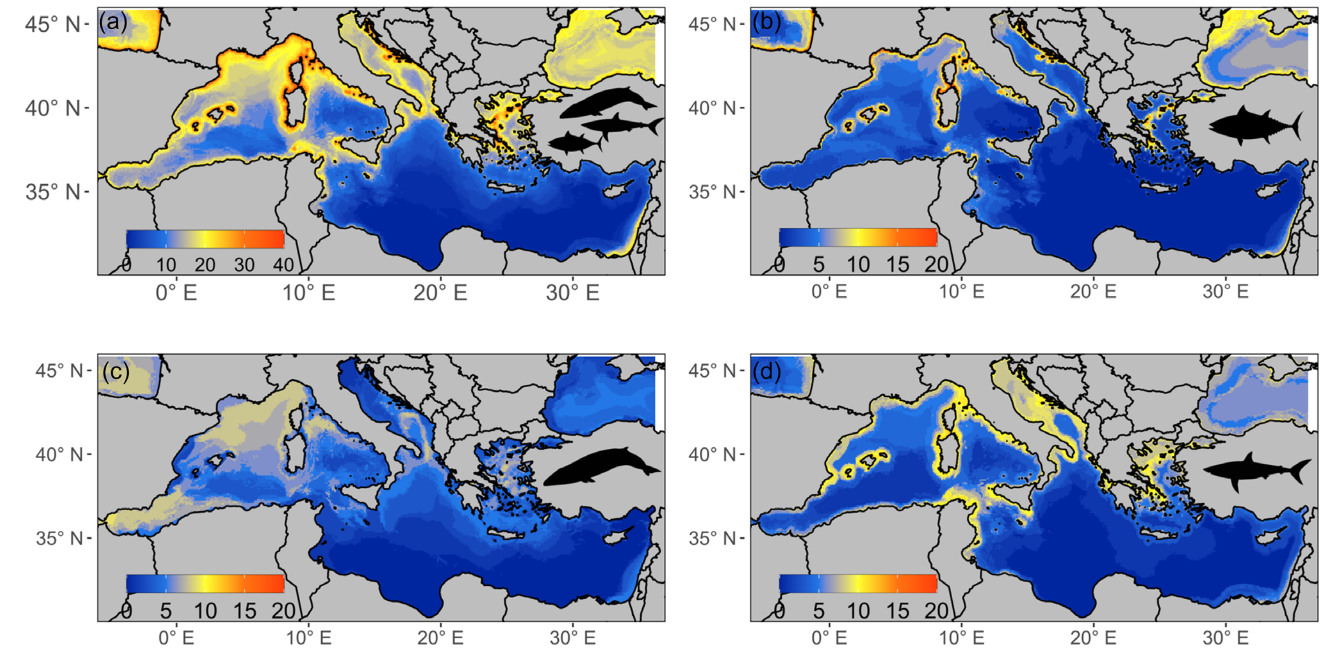

FIGURE 2 Maps of the Mediterranean Sea showing species richness from stacked species distribution models of (a) all taxa, (b) teleost fishes, (c) marine mammals, and (d) elasmobranchs.

between planning unit selection frequencies of different taxa with Cohen's Kappa coefficient (McHugh, 2012). The Kappa statistic requires categorical data, so we classified the selection frequencies into five groups: 0, <25, 26–50, 51–75, >75 (Ruiz-Frau et al., 2015). Second, we performed hierarchical clustering with Jaccard dissimilarities from the 10 best solutions across the conservation feature scenarios (Brumm et al., 2021). We also compared the average cost and number of planning units required across the different taxa.

The most current database for MPAs in the Mediterranean was downloaded from MAPAMED, including 1126 designated MPAs (MedPAN & SPA/RAC, 2022) (Figure 1b). We included MPAs with a national statute, Natura 2000 sites, and Specially Protected Areas of Mediterranean Importance (SPAMI) (MedPAN & SPA/RAC, 2022). We calculated the overlapping area between species distributions and MPAs and our 10 best spatial prioritization solutions to quantify which taxa are currently receiving the most protection, and differences among taxa-specific prioritization solutions.

3 | RESULTS

Different taxa of marine megafaunal predators have distinct distribution patterns (Figure 2). High species richness of elasmobranchs and teleost fishes is found along the coastlines of the north-western basin as well as the Balearic Islands, Corsica, and Sardinia. Elasmobranchs have wider distributions in the Adriatic Sea, Aegean Sea, and along the coastlines of Tunisia and Sicily, compared to teleosts. The highest species richness of marine mammals occurs in the Alboran Sea and between the Balearic Islands and Corsica/Sardinia. Overall, there is a clear decrease in species richness with distance from shore, with the highest species richness occurring in the north-western basin as well as the Adriatic and Aegean Seas. The marine megafaunal predator SSDM overpredicted species richness, with a high proportion of true presences predicted correctly (sensitivity $= 19.06 \pm 7.23$ SD) but a lower proportion of absences (based on pseudo-absences generated in this study) predicted correctly (specificity $= 0.54 \pm 0.17$ SD) (Appendix S2).

Conservation feature scenarios considering taxa separately resulted in vastly different spatial prioritization solutions (Figure 3). The Kappa statistic and hierarchical cluster analysis show highest similarity between selection frequencies for elasmobranchs and all taxa (Figure 4). Visually, elasmobranchs and all taxa scenarios share similar high selection frequency areas occurring along the coastlines of Tunisia and Egypt, the southern Alboran Sea, and the northern Aegean Sea. The Kappa statistic shows mammals and teleosts to have similar disagreement to the all taxa scenario, while cluster analysis reveals greatest dissimilarity between mammals and all taxa.

Including all taxa resulted in solutions with highest costs and greatest number of planning units (Appendix S3). Marine mammal prioritizations required

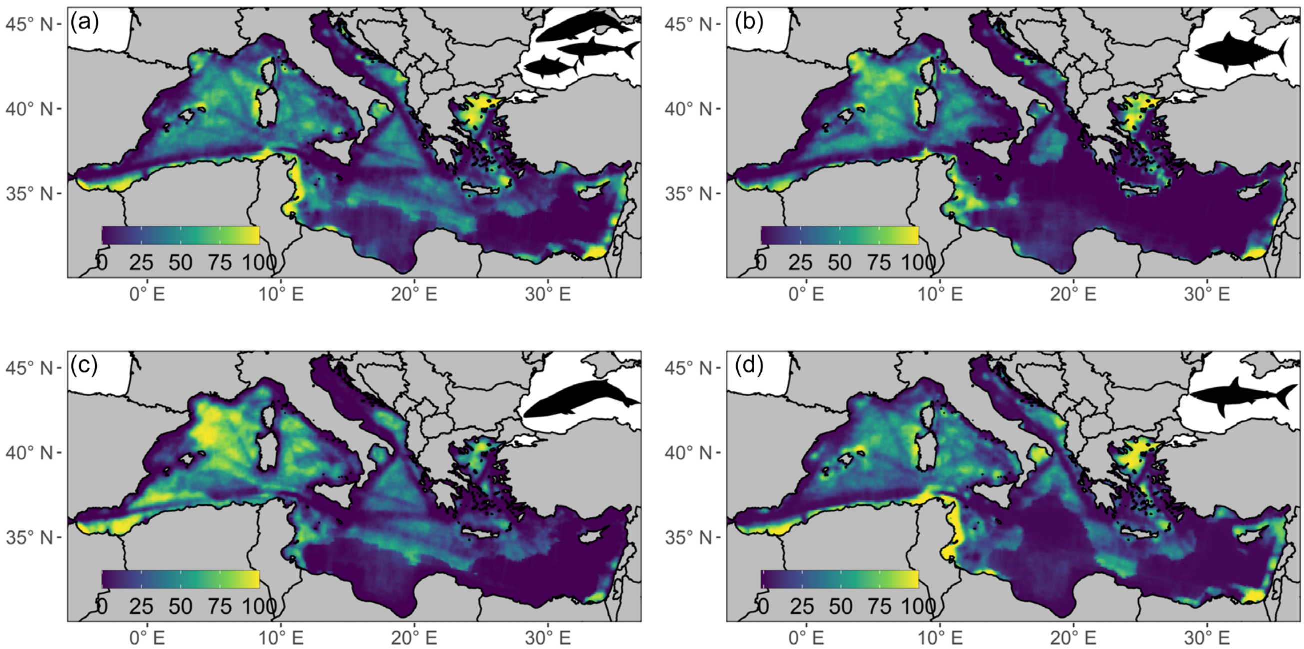

FIGURE 3 Maps of the Mediterranean Sea showing the selection frequency, that is, how many times each planning unit was selected in 100 iterations, from Marxan outputs for each of the taxa scenarios: (a) all species, (b) teleost fishes, (c) marine mammals, and (d) elasmobranchs.

the lowest costs (81,939 ± 2206) despite requiring the greatest number of planning units (5644 ± 178) while elasmobranchs have the greatest costs (104,217 ± 2043) despite needing a relatively similar number of planning units to mammals (5526 ± 180).

The Mediterranean MPA network does not fulfill the 30% coverage target for any of the marine megafaunal predator taxa distributions (Figure 5). Teleost fish distributions overlap most with the current MPA network (24.12% ±13.27 SD), while marine mammals (16.54% ±6.49) and elasmobranchs (18.58% ±10.81) share similar lower levels of protection. Overlap with the MPA network varied greatly for species within a taxonomic group, so the overall differences between groups were not significant (Kruskal–Wallis, $p > .05$). Scenarios including a single taxonomic group resulted in greatest overlap with species distributions from that group (Kruskal–Wallis, $p < .05$) (Appendix S5). Our spatial prioritization solution for marine mammals afforded the least co-protection to other taxa, with teleost fish distributions overlapping 18.42% ±11.08 and sharks 19.92% ±11.06.

4 | DISCUSSION

We discovered that existing MPA systems in the Mediterranean Sea only afford limited protection to marine megafaunal predators, with highly variable coverage within and between different taxonomic groups. We recommend implementing new and extending current MPAs in the northwestern basin, the Sicilian Channel, the Aegean Sea, and the Southeastern Levantine Sea to improve the conservation status of Mediterranean marine megafaunal predators. Marine megafaunal predator taxa require different conservation priority areas due to their specific habitat requirements and life histories, as indicated by their heterogeneous distributions. Focusing spatial planning on all species simultaneously, as is common practice, adequately captured the conservation needs of elasmobranchs but excluded sites that would gain the highest conservation benefits for marine mammals and teleost fishes. Hence, where spatial planning aims to capture all (i.e., as many as possible) taxa in conservation management areas, there is a risk of missing conservation needs of important taxa. We advocate that incorporating conservation objectives and actions specific to marine megafaunal taxonomic groups will better achieve effective conservation of taxa with contrasting or specialized life histories, and habitat needs that are especially vulnerable or challenging to protect with spatial measures.

We found a striking contrast between the coastal distributions of sharks and teleost fishes, with the offshore ranges of marine mammals, consistent with globally observed patterns in predator richness (Grady et al., 2019) (Figure 2). These differences may be exaggerated by greater data availability offshore for marine mammals from ferry-based visual surveys, while data for elasmobranchs and teleosts largely come from coastal

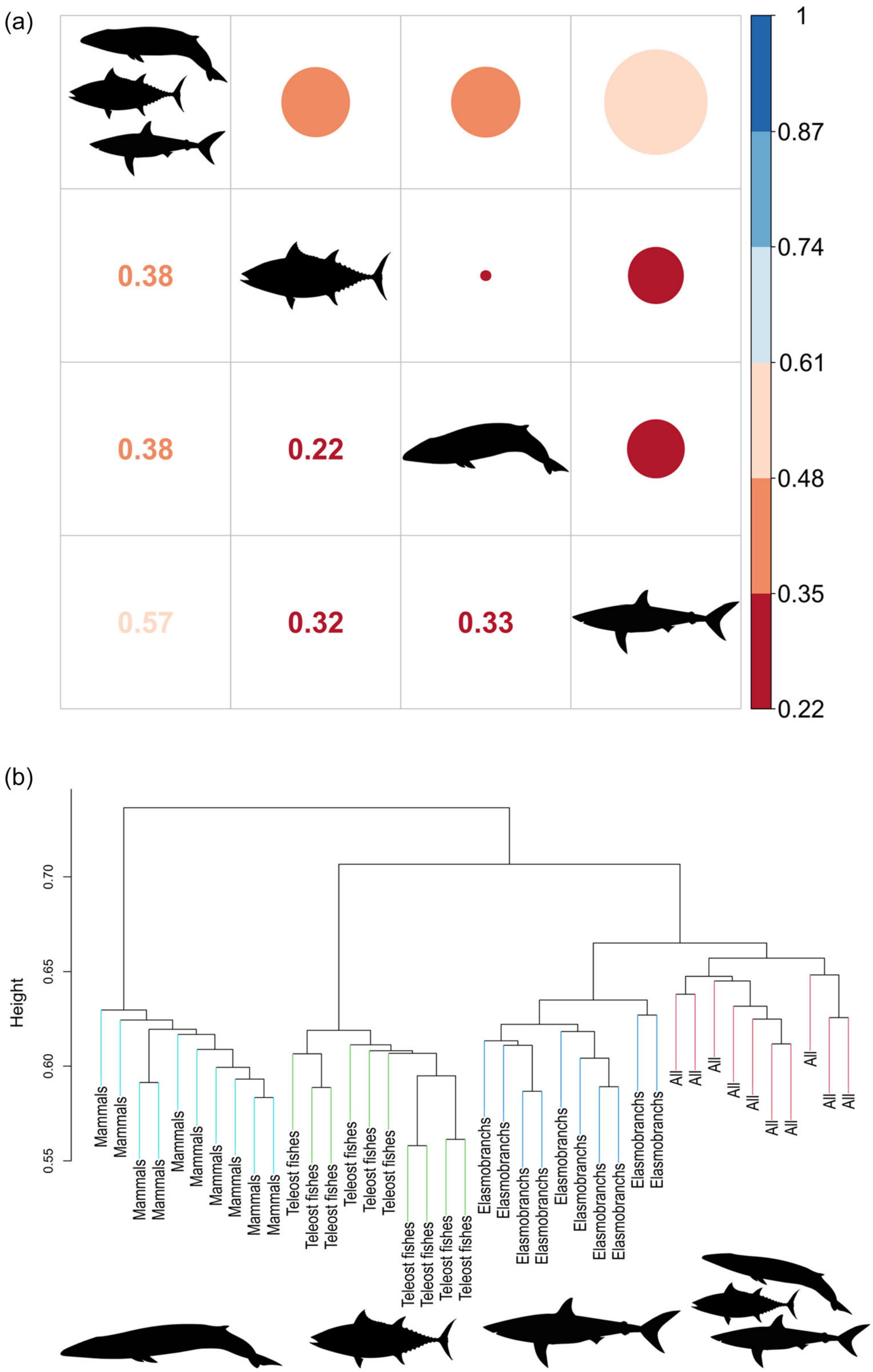

FIGURE 4 (a) Cohen's Kappa coefficient showing similarity between selection frequency classes across the different conservation feature scenarios (all taxa, teleost fish, elasmobranchs and marine mammals). Larger circles represent higher similarity between the selection frequency classes of the two conservation feature scenarios considered, that is, all taxa and elasmobranchs have the highest similarity in selection frequency classes. (b) Dendrogram displaying the average Jaccard distances between the 10 best solutions across the different taxa conservation feature scenarios.

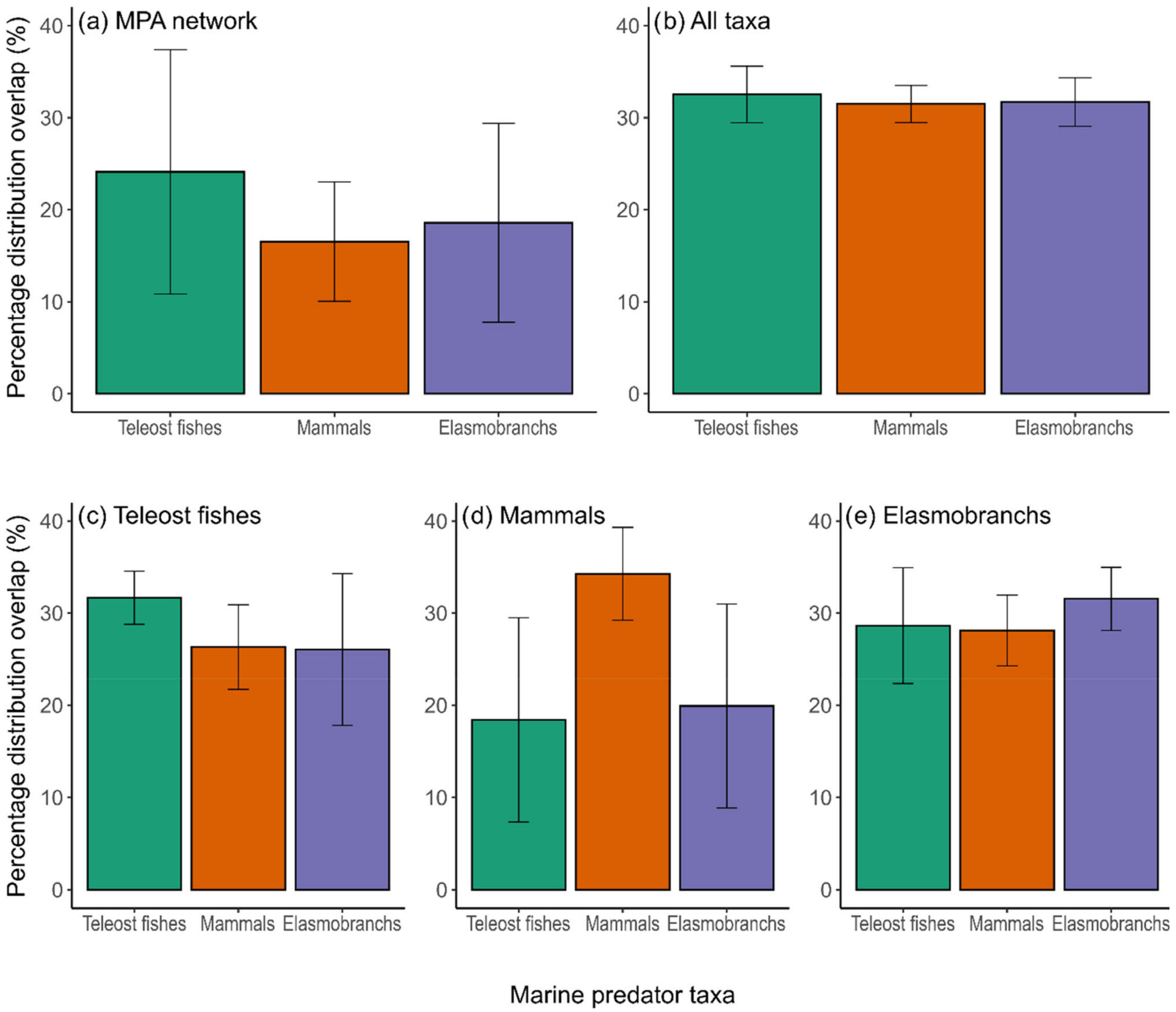

FIGURE 5 Average percentage distribution overlap of fish, mammal and elasmobranch taxa with (a) the current network of Mediterranean MPAs, or conservation feature scenarios with (b) all taxa, (c) teleost fishes, (d) mammals or (e) elasmobranchs. Standard error bars shown.

fisheries (Mancusi et al., 2020; Mannocci et al., 2018). We also found higher predator richness in the north-western basin, due to its proximity to the Strait of Gibraltar, which is an important migration corridor connecting the Mediterranean Sea with the Atlantic Ocean (Coll et al., 2010). This result may be inflated by higher observation effort in the north-western basin (Coll et al., 2010). Our SSDM was good at correctly predicting presences but had a high false positive rate, which could result in larger areas being protected than necessary (Appendix S3). Further, marine megafaunal predators are often migratory with seasonal breeding and foraging grounds (Lascelles et al., 2014), but we had inadequate data to consider seasonal variations in distributions for most species. Increasing research efforts to reduce biases in data, and thus ensuring the most effective conservation actions, should remain a priority. For example, incorporating seasonal distributions could allow for a dynamic MPA approach where management measures are implemented seasonally to correspond with marine megafaunal predator presence (Maxwell et al., 2020). However, spatial planning should be viewed as a continuous process whereby priority areas are designated based on the best available data, especially given the threatened statuses of Mediterranean marine megafaunal predators, and then iteratively updated and adapted as better data become available (Smith et al., 2009).

Contrasting distributions of marine megafaunal predator taxa translated into significant differences in the spatial arrangement of priority areas (Figure 3), highlighting that omitting any of these taxonomic groups from conservation planning will locate MPAs in the wrong areas. Prioritization solutions including all taxa and elasmobranchs were most similar, driven by elasmobranch species occupying species-poor habitats, or costlier areas which were avoided in the teleost fish or mammal solutions (Kujala et al., 2018). Including representative species across different taxa granted protection to rare species within the taxonomic groups considered. For example, currently recognized important habitats for critically endangered angel sharks were covered in the elasmobranch priority areas despite the species not being included in the current analysis (Giovos et al., 2022). Most importantly, encompassing all taxa simultaneously provided no information about which species or taxa were covered by which priority areas, making it difficult to implement targeted management measures. The requirement for taxa-specific conservation actions to be incorporated into spatial planning has been acknowledged through 'Important Marine Mammal Areas' (IMMAs) and 'Ecologically and Biologically Significant Marine Areas' (EBSAs) (Corrigan et al., 2014). However, obligations to act in response to IMMAs/EBSAs are unclear, and it is debatable how they will specifically contribute to area-based conservation (Corrigan et al., 2014). Specific objectives for separate taxa could necessitate less severe restrictions, that is, banning of fishing gear which affects the target taxon, instead of a complete fishing ban (Tixier et al., 2021). Future research could extend our analysis by incorporating different vulnerabilities of marine megafaunal predator taxonomic groups to particular threats and respective spatial planning scenarios as some threats may be more prevalent for certain taxa. For example, the time spent at the surface will impact the likelihood of vessel strikes posing a major threat to certain species (Schoeman et al., 2020).

Current Mediterranean MPAs failed to achieve the 30% coverage target for any of the marine megafaunal predator taxa (Figure 5). Teleost fish distributions overlapped most with Mediterranean MPAs (24% overlap), despite the two largest MPAs, 'the Pelagos Sanctuary for Marine Mammals' and 'Corredor de Migración de Cetaceos del Mediterraneo', being designated for cetaceans (MedPAN & SPA/RAC, 2022) (Figure 1b). Instead, marine mammal distributions overlapped the least with Mediterranean MPAs (16% overlap), showing misalignment between conservation objectives and outcomes. Our results underscore calls that existing MPAs be extended to include the area in between the Pelagos Sanctuary and 'Corredor de Migración de Cetaceos del Mediterraneo' to better encompass high biodiversity of marine mammals (Figure 3). This recommendation is endorsed by the Northwest Mediterranean Sea, Slope and Canyon System IMMA and the North-western Mediterranean Pelagic Ecosystems EBSA, both of which acknowledge the high levels of marine mammal biodiversity, including vulnerable Mediterranean fin whales and endangered sperm whales and Risso's dolphins, and important habitats for marine mammals, such as reproductive and feeding grounds. This area is also exposed to the highest rates of shipping traffic within the whole Mediterranean basin resulting in large whales being at increased risk of mortality from collisions with ships (David et al., 2022). This risk is heightened during the summer season when whales are concentrated in relatively small feeding areas, and when ship traffic is highest, so measures to reduce ship strikes such as enforcing speed restrictions would be beneficial (David et al., 2022; Sèbe et al., 2022).

The majority of MPAs in the Mediterranean Sea are within European Union waters (Claudet et al., 2020), but our prioritization solutions highlighted important areas for marine megafaunal predators in the southern and eastern Mediterranean Sea, that currently have limited or no protection. We show the importance of implementing a MPA covering the Tunisian coastline and Sicilian channel joining the western and eastern basin to protect important spawning grounds for commercially important, threatened bluefin tuna, swordfish and hake, and important elasmobranch nursery grounds (Di Lorenzo et al., 2018). In particular, the Gulf of Gabes, southern Tunisia, has high elasmobranch biodiversity, including 63 elasmobranch species, of which at least 52% are threatened and 20% are data deficient according to the IUCN Red List (Enajjar et al., 2015; Enajjar et al., 2022). Currently, unmanaged fisheries also operate in this area where elasmobranchs are caught in targeted fisheries and as bycatch (Saidi et al., 2016). Catch includes high rates of young life stages and pregnant females, which can result in rapid population depletions and threatens the long-term sustainability of the fisheries, with data already indicating population declines of the endangered sandbar shark (*Carcharhinus plumbeus*; Saidi et al., 2016, 2020). Increased data on elasmobranch landings and stock assessments are essential, along with the introduction of targeted fisheries management measures such as spatial or seasonal closures during important reproductive periods when sharks aggregate in nursery grounds (Saidi et al., 2019, 2020). It is important to consider that vessel density is likely underrepresented along the African coastline with AIS data, so these areas may be more costly to protect than suggested in our study (Paolo et al., 2024).

The North Aegean Sea and Southeastern Levantine Sea both include priority areas for all three taxonomic groups of marine predators, therefore potentially representing cost-effective areas to introduce management measures applicable to all three taxonomic groups (Figure 3). These areas are currently recognized by EBSA and IMMA designations (Appendix S7), highlighting further areas where increased management is warranted. In both the North Aegean Sea and Levantine Sea, data limitations on the status of marine mammal and elasmobranch populations needs addressing as this currently prevents accurate quantification of exploitation levels or conservation status assessments (Cucknell et al., 2016; Giovos et al., 2021; Spanier & Zviely, 2022). Interactions with fisheries have been documented for marine mammals and elasmobranchs in both areas, including evidence of bycatch and deliberate killings, potentially representing a significant threat to these species (Miliou et al., 2018). Since priority areas are not shared equally across countries, cross-country collaborations are required to support those with the highest burden, which will be challenging in the dynamic political environment of the Mediterranean (Mazor et al., 2013). However, this is the most cost-effective method to prioritize key habitats for marine megafaunal predators, and will improve the likelihood of successful compliance given that stakeholders and conservation features have been considered synergistically (Mazor et al., 2013).

Despite the rapid expansion in the global extent of MPAs, marine megafaunal predator distributions are not being sufficiently protected, contributing to increasing proportions of species beoming threatened. They are notoriously difficult to conserve through MPAs as their vast distributions cannot be encompassed completely, resulting in debate over which key habitats or life history stages should be prioritized in MPA systems. While we acknowledge the value of multi-species planning in enhancing efficiency and cost-effectiveness (Carwardine et al., 2009; Margules & Pressey, 2000), we recommend that such approaches specifically consider the unique characteristics of marine megafaunal predator taxonomic groups when co-designing conservation objectives with different stakeholders. Due to their heterogeneous distributions, divergent life history strategies, and distinct habitat use, as outlined by this study, these groups require focused attention or key priority areas may be excluded. We further suggest that highly vulnerable taxa be more explicitly explored or enhanced within multi-taxa planning frameworks. This could include re-prioritizing or adjusting the weighting of these taxa in decision support tools (e.g., Marxan, Zonation, and Priortizr) or providing additional taxon-specific mapped outputs and evidence to guide decision makers in the establishment of new protected areas, marine spatial planning, or ecosystem-based management.

AUTHOR CONTRIBUTIONS

M.B. and E.B. led the conceptualization and design of the study, with S.J.G. supporting this. E.B. performed the data analysis and wrote the first draft. All authors have developed, edited and approved the final manuscript for publication.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Marine predator species distribution models are available at https://doi.org/10.5061/dryad.280gb5ms5.

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REFERENCES

ACCOBAMS Survey Initiative. (2020). Thirteenth Meeting of the Accobams Scientific Committee. Technical Reports of the Mediterranean and Black Sea Surveys. Monaco.

Aiello-Lammens, M. E., Boria, R. A., Radosavljevic, A., Vilela, B., & Anderson, R. P. (2015). spThin: An R package for spatial thinning of species occurrence records for use in ecological niche models. *Ecography*, *38*(5), 541–545.

Assis, J., Tyberghein, L., Bosch, S., Verbruggen, H., Serrão, E. A., & De Clerck, O. (2018). Bio-ORACLE v2. 0: Extending marine data layers for bioclimatic modelling. *Global Ecology and Biogeography*, *27*(3), 277–284.

Augé, A. A., Dias, M. P., Lascelles, B., Baylis, A. M., Black, A., Boersma, P. D., Catry, P., Crofts, S., Galimberti, F., & Granadeiro, J. P. (2018). Framework for mapping key areas for marine megafauna to inform marine spatial planning: The Falkland Islands case study. *Marine Policy*, *92*, 61–72.

Avila, I. C., Kaschner, K., & Dormann, C. F. (2018). Current global risks to marine mammals: Taking stock of the threats. *Biological Conservation*, *221*, 44–58.

Ball, I. R., Possingham, H. P., & Watts, M. (2009). Marxan and relatives: Software for spatial conservation prioritisation. In *Spatial conservation prioritisation: Quantitative methods and computational tools* (pp. 185–195). Oxford Academic.

Barbet-Massin, M., Jiguet, F., Albert, C. H., & Thuiller, W. (2012). Selecting pseudo-absences for species distribution models: How, where and how many? *Methods in Ecology and Evolution*, *3*(2), 327–338.

Bearzi, G., Agazzi, S., Gonzalvo, J., Costa, M., Bonizzoni, S., Politi, E., Piroddi, C., & Reeves, R. R. (2008). Overfishing and the disappearance of short-beaked common dolphins from western Greece. *Endangered Species Research*, *5*(1), 1–12.

Boyse, E., Beger, M., Valsecchi, E., & Goodman, S. J. (2023). Sampling from commercial vessel routes can capture marine biodiversity distributions effectively. *Ecology and Evolution*, *13*(2), e9810.

Brumm, K. J., Hanks, R. D., Baldwin, R. F., & Peoples, B. K. (2021). Accounting for multiple dimensions of biodiversity to assess surrogate performance in a freshwater conservation prioritization. *Ecological Indicators*, *122*, 107320.

Carlucci, R., Manea, E., Ricci, P., Cipriano, G., Fanizza, C., Maglietta, R., & Gissi, E. (2021). Managing multiple pressures for cetaceans' conservation with an ecosystem-based marine spatial planning approach. *Journal of Environmental Management*, *287*, 112240.

Carwardine, J., Klein, C. J., Wilson, K. A., Pressey, R. L., & Possingham, H. P. (2009). Hitting the target and missing the point: Target-based conservation planning in context. *Conservation Letters*, *2*(1), 4–11.

CBD. (2021). First draft of the post-2020 global biodiversity framework.

Cisneros-Montemayor, A. M., Sumaila, U. R., Kaschner, K., & Pauly, D. (2010). The global potential for whale watching. *Marine Policy*, *34*(6), 1273–1278.

Claudet, J., Loiseau, C., Sostres, M., & Zupan, M. (2020). Underprotected marine protected areas in a global biodiversity hotspot. *One Earth*, *2*(4), 380–384.

Coll, M., Piroddi, C., Steenbeek, J., Kaschner, K., Ben Rais Lasram, F., Aguzzi, J., Ballesteros, E., Bianchi, C. N., Corbera, J., & Dailianis, T. (2010). The biodiversity of the Mediterranean Sea: Estimates, patterns, and threats. *PLoS One*, *5*(8), e11842.

Conners, M. G., Sisson, N. B., Agamboue, P. D., Atkinson, P. W., Baylis, A. M., Benson, S. R., Block, B. A., Bograd, S. J., Bordino, P., & Bowen, W. (2022). Mismatches in scale between highly mobile marine megafauna and marine protected areas. *Frontiers in Marine Science*, *9*, 897104.

Corrigan, C. M., Ardron, J. A., Comeros-Raynal, M. T., Hoyt, E., Notarbartolo Di Sciara, G., & Carpenter, K. E. (2014). Developing important marine mammal area criteria: Learning from ecologically or biologically significant areas and key biodiversity areas. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *24*(S2), 166–183.

Cucknell, A., Frantzis, A., Boisseau, O., Romagosa, M., Ryan, C., Tonay, A., Alexiadou, P., Öztürk, A., & Moscrop, A. (2016). Harbour porpoises in the Aegean Sea, eastern Mediterranean: The species' presence is confirmed. *Marine Biodiversity Records*, *9*, 1–13.

David, L., Arcangeli, A., Tepsich, P., Di-Meglio, N., Roul, M., Campana, I., Gregorietti, M., Moulins, A., Rosso, M., & Crosti, R. (2022). Computing ship strikes and near miss events of fin whales along the main ferry routes in the Pelagos sanctuary and adjacent west area, in summer. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *32*(3), 442–456.

Di Lorenzo, M., Sinerchia, M., & Colloca, F. (2018). The north sector of the strait of Sicily: A priority area for conservation in the Mediterranean Sea. *Hydrobiologia*, *821*, 235–253.

Dulvy, N. K., Pacoureau, N., Rigby, C. L., Pollom, R. A., Jabado, R. W., Ebert, D. A., Finucci, B., Pollock, C. M., Cheok, J., & Derrick, D. H. (2021). Overfishing drives over one-third of all sharks and rays toward a global extinction crisis. *Current Biology*, *31*(21), 4773–4787.e4778.

Enajjar, S., Saidi, B., & Bradai, M. N. (2015). The Gulf of Gabes (central Mediterranean Sea): A nursery area for sharks and batoids (Chondrichthyes: Elasmobranchii). *Cahiers de Biologie Marine*, *56*(2), 143–150.

Enajjar, S., Saidi, B., & Bradai, M. N. (2022). Elasmobranchs in Tunisia: Status, ecology, and biology. In *Sharks—Past, present and future*. IntechOpen.

Estes, J. A., Heithaus, M., McCauley, D. J., Rasher, D. B., & Worm, B. (2016). Megafaunal impacts on structure and function of ocean ecosystems. *Annual Review of Environment and Resources*, *41*, 83–116.

European Commission. (2007). Directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007 establishing an infrastructure for spatial information in the European Community (INSPIRE). *Official Journal of the European Union*, *50*, 1–14.

Falco, L., Pittito, A., Adnams, W., Earwaker, N., & Greidanus, H. (2019). Eu Vessel density map. Detailed method.

Giménez, J., Cardador, L., Mazor, T., Kark, S., Bellido, J. M., Coll, M., & Navarro, J. (2020). Marine protected areas for demersal elasmobranchs in highly exploited Mediterranean ecosystems. *Marine Environmental Research*, *160*, 105033.

Giovos, I., Katsada, D., Spyridopoulou, R. N. A., Poursanidis, D., Doxa, A., Katsanevakis, S., Kleitou, P., Oikonomou, V., Minasidis, V., & Ozturk, A. A. (2022). Strengthening angel shark conservation in the northeastern Mediterranean Sea. *Journal of Marine Science and Engineering*, *10*(2), 269.

Giovos, I., Spyridopoulou, R. A., Doumpas, N., Glaus, K., Kleitou, P., Kazlari, Z., Katsada, D., Loukovitis, D., Mantzouni, I., & Papapetrou, M. (2021). Approaching the "real" state of elasmobranch fisheries and trade: A case study from the Mediterranean. *Ocean & Coastal Management*, *211*, 105743.

Grady, J. M., Maitner, B. S., Winter, A. S., Kaschner, K., Tittensor, D. P., Record, S., Smith, F. A., Wilson, A. M., Dell, A. I., & Zarnetske, P. L. (2019). Metabolic asymmetry and the global diversity of marine predators. *Science*, *363*(6425), eaat4220.

Hammerschlag, N., Schmitz, O. J., Flecker, A. S., Lafferty, K. D., Sih, A., Atwood, T. B., Gallagher, A. J., Irschick, D. J., Skubel, R., & Cooke, S. J. (2019). Ecosystem function and services of aquatic predators in the Anthropocene. *Trends in Ecology & Evolution*, *34*(4), 369–383.

Heupel, M. R., Munroe, S. E., Lédée, E. J., Chin, A., & Simpfendorfer, C. A. (2019). Interspecific interactions, movement patterns and habitat use in a diverse coastal shark assemblage. *Marine Biology*, *166*(6), 1–17.

Juan-Jordá, M. J., Mosqueira, I., Cooper, A. B., Freire, J., & Dulvy, N. K. (2011). Global population trajectories of tunas and their relatives. *Proceedings of the National Academy of Sciences*, *108*(51), 20650–20655.

Klein, C. J., Brown, C. J., Halpern, B. S., Segan, D. B., McGowan, J., Beger, M., & Watson, J. E. (2015). Shortfalls in the global protected area network at representing marine biodiversity. *Scientific Reports*, *5*(1), 17539.

Kujala, H., Moilanen, A., & Gordon, A. (2018). Spatial characteristics of species distributions as drivers in conservation prioritization. *Methods in Ecology and Evolution*, *9*(4), 1121–1132.

Lascelles, B., Notarbartolo Di Sciara, G., Agardy, T., Cuttelod, A., Eckert, S., Glowka, L., Hoyt, E., Llewellyn, F., Louzao, M., & Ridoux, V. (2014). Migratory marine species: Their status, threats and conservation management needs. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *24*(S2), 111–127.

Li, S., & Jay, S. (2020). Transboundary marine spatial planning across Europe: Trends and priorities in nearly two decades of project work. *Marine Policy*, *118*, 104012.

MacKenzie, B. R., Mosegaard, H., & Rosenberg, A. A. (2009). Impending collapse of bluefin tuna in the northeast Atlantic and Mediterranean. *Conservation Letters*, *2*(1), 26–35.

Mancusi, C., Baino, R., Fortuna, C., De Sola, L. G., Morey, G., Bradai, M. N., Kallianotis, A., Soldo, A., Hemida, F., & Saad, A. A. (2020). MEDLEM database, a data collection on large elasmobranchs in the Mediterranean and Black seas.

Mannocci, L., Roberts, J. J., Halpin, P. N., Authier, M., Boisseau, O., Bradai, M. N., Cañadas, A., Chicote, C., David, L., & Di-Méglio, N. (2018). Assessing cetacean surveys throughout the Mediterranean Sea: A gap analysis in environmental space. *Scientific Reports*, *8*(1), 1–14.

Margules, C. R., & Pressey, R. L. (2000). Systematic conservation planning. *Nature*, *405*(6783), 243–253.

Maxwell, S. M., Gjerde, K. M., Conners, M. G., & Crowder, L. B. (2020). Mobile protected areas for biodiversity on the high seas. *Science*, *367*(6475), 252–254.

Mazor, T., Beger, M., McGowan, J., Possingham, H. P., & Kark, S. (2016). The value of migration information for conservation prioritization of sea turtles in the Mediterranean. *Global Ecology and Biogeography*, *25*(5), 540–552.

Mazor, T., Possingham, H. P., & Kark, S. (2013). Collaboration among countries in marine conservation can achieve substantial efficiencies. *Diversity and Distributions*, *19*(11), 1380–1393.

McHugh, M. L. (2012). Interrater reliability: The kappa statistic. *Biochemia Medica*, *22*(3), 276–282.

MedPAN, & SPA/RAC. (2022). Marine protected areas in the Mediterranean. https://www.mapamed.org/

Meynard, C. N., Leroy, B., & Kaplan, D. M. (2019). Testing methods in species distribution modelling using virtual species: What have we learnt and what are we missing? *Ecography*, *42*(12), 2021–2036.

Miliou, A., Bas, A. A., Pietroluongo, G., & Briand, F. (2018). Interactions between marine mammals and fisheries: Case studies from the Eastern Aegean and the Levantine Sea. Engaging marine scientists and fishers to share knowledge and perceptions—Early lessons, CIESM workshop monographs.

Myers, R. A., & Worm, B. (2003). Rapid worldwide depletion of predatory fish communities. *Nature*, *423*(6937), 280–283.

Notarbartolo di Sciara, G., Hoyt, E., Reeves, R., Ardron, J., Marsh, H., Vongraven, D., & Barr, B. (2016). Place-based approaches to marine mammal conservation. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *26*, 85–100.

Paolo, F. S., Kroodsma, D., Raynor, J., Hochberg, T., Davis, P., Cleary, J., Marsaglia, L., Orofino, S., Thomas, C., & Halpin, P. (2024). Satellite mapping reveals extensive industrial activity at sea. *Nature*, *625*(7993), 85–91.

Phillips, S. J., Anderson, R. P., & Schapire, R. E. (2006). Maximum entropy modeling of species geographic distributions. *Ecological Modelling*, *190*(3–4), 231–259.

Ruiz-Frau, A., Possingham, H. P., Edwards-Jones, G., Klein, C. J., Segan, D., & Kaiser, M. J. (2015). A multidisciplinary approach in the design of marine protected areas: Integration of science and stakeholder based methods. *Ocean & Coastal Management*, *103*, 86–93.

Saidi, B., Enajjar, S., & Bradai, M. (2016). Elasmobranch captures in shrimps trammel net fishery off the Gulf of Gabès (southern Tunisia, Mediterranean Sea). *Journal of Applied Ichthyology*, *32*(3), 421–426.

Saidi, B., Enajjar, S., Karaa, S., Echwikhi, K., Jribi, I., & Bradai, M. N. (2019). Shark pelagic longline fishery in the Gulf of Gabes: Inter-decadal inspection reveals management needs. *Mediterranean Marine Science*, *20*(3), 532–541.

Saidi, B., Karaa, S., Enajjar, S., & Bradaï, M. N. (2020). Effects of fishing practice changes on pelagic shark longline captures in the Gulf of Gabes, Tunisia. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *30*(1), 53–67.

Sbrocco, E. J., & Barber, P. H. (2013). MARSPEC: Ocean climate layers for marine spatial ecology: Ecological archives E094-086. *Ecology*, *94*(4), 979.

Schmitt, S., Pouteau, R., Justeau, D., de Boissieu, F., & Birnbaum, P. (2017). ssdm: An r package to predict distribution of species richness and composition based on stacked species distribution models. *Methods in Ecology and Evolution*, *8*(12), 1795–1803.

Schoeman, R. P., Patterson-Abrolat, C., & Plön, S. (2020). A global review of vessel collisions with marine animals. *Frontiers in Marine Science*, *7*, 292.

Sèbe, M., Kontovas, C. A., Pendleton, L., & Gourguet, S. (2022). Cost-effectiveness of measures to reduce ship strikes: A case study on protecting the Mediterranean fin whale. *Science of the Total Environment*, *827*, 154236.

Smith, R. J., Eastwood, P. D., Ota, Y., & Rogers, S. I. (2009). Developing best practice for using Marxan to locate marine protected areas in European waters. *ICES Journal of Marine Science*, *66*(1), 188–194.

Spanier, E., & Zviely, D. (2022). Key environmental impacts along the Mediterranean coast of Israel in the last 100 years. *Journal of Marine Science and Engineering*, *11*(1), 2.

Tixier, P., Lea, M. A., Hindell, M. A., Welsford, D., Mazé, C., Gourguet, S., & Arnould, J. P. (2021). When large marine predators feed on fisheries catches: Global patterns of the depredation conflict and directions for coexistence. *Fish and Fisheries*, *22*(1), 31–53.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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