

<https://doi.org/10.1038/s44183-024-00068-4>

Up to 80% of threatened and commercial species across European marine protected areas face novel climates under high emission scenario

Check for updates

Milica Predragovic¹ ✉, Jorge Assis^{1,2}, U. Rashid Sumaila³, Jorge M. S. Gonçalves¹, Christopher Cvitanovic^{4,5} & Bárbara Horta e Costa¹

Marine protected areas (MPAs) are a critical tool for safeguarding marine species and habitats for the future, though the effects of projected climate change raise concerns about their long-term success. Assessing the degree to which MPAs may be exposed to future novel climatic conditions is, therefore, crucial for informing conservation and management actions aimed at ensuring a resilient and thriving ocean in the years to come. Here, we evaluate the future exposure of 398 threatened and commercially important species to novel and extremely novel climatic conditions within European MPAs. We estimated climate novelty through multivariate analyses considering biologically meaningful distribution drivers of temperature, oxygen, pH, and primary productivity from present-day to the end of the 21st-century conditions under contrasting shared socioeconomic pathways (SSP) scenarios—low emission scenario (SSP1–1.9) and high emission scenario (SSP5–8.5). Our findings suggest that, under SSP1–1.9, ~6.5% of species and 0.5% of European MPAs will be at risk due to future novel conditions. In contrast, under SSP5–8.5, 87% of MPAs and 80% of species are projected to be at risk. Notably, up to 100% of species currently located in the MPAs of enclosed and semi-enclosed seas like the Baltic Sea and the Black Sea are projected to be exposed to novel or even extremely novel conditions. Virtually all species in most of those regions will be at risk, suggesting that even new MPAs might not be able to adequately protect them. Comparatively, the Norwegian Sea, North-East Atlantic, and western parts of the Mediterranean and North Seas are expected to be less impacted even under the high emission scenario. Overall, our study advances the understanding of the potential impacts of future climate change scenarios on threatened and commercially important marine species in European MPAs and reinforces the urgent need to meet the Paris Agreement. Our results suggest that existing approaches to marine governance in Europe may be insufficient for ensuring the success of MPAs in light of future impacts and that novel anticipatory forms of governance are needed.

Climate change, driven by anthropogenic greenhouse gas emissions, poses a significant threat to the health and stability of marine ecosystems worldwide^{1–4}. Observed environmental changes are already affecting the behavior, physiology, and geographical distributions of marine organisms, forcing species to migrate poleward in pursuit of suitable habitats^{5–7}. These

range shifts, which may result in local extinctions and altered community structure⁸, are particularly concerning for species already listed as threatened by the International Union for the Conservation of Nature (IUCN) Red List, as well as for species impacted by fishing pressure, or a combination of both. Importantly, future climate change projections under higher

¹Centre of Marine Sciences, CCMAR, University of Algarve, Campus de Gambelas, Faro, Portugal. ²Faculty of Bioscience and Aquaculture, Nord University, Bodø, Norway. ³Institute for the Oceans and Fisheries and the School of Public Policy and Global Affairs, University of British Columbia, Vancouver, Canada. ⁴School of Business, University of New South Wales Canberra, ACT, Australia. ⁵Centre for Marine Science and Innovation, University of New South Wales, Sydney, NSW, Australia. ✉e-mail: mpredragovic@ualg.pt

greenhouse gas emissions, e.g., the Shared Socioeconomic Pathway (SSP) 5–8.5, consistently show significant changes in ocean temperature, pH, oxygen levels, and productivity, further jeopardizing the survival and adaptability of marine organisms^{9,10}. These projected changes in marine ecosystems also have the potential to erode the natural capital underpinning societal well-being and prosperity in the future, threatening planetary boundaries^{11,12}.

Marine protected areas (MPAs) are established worldwide to support and safeguard biodiversity and ecosystems via the maintenance of essential ecological processes^{13,14}. Although MPAs provide benefits for climate change mitigation through, for example, fostering ecosystem resilience and enhancing carbon sequestration^{15,16}, they are not universally designed to withstand the impacts of climate change¹⁷. The designation of MPAs typically disregards the risk of future climate change¹⁸ (but see ref. 19) despite an increasing body of evidence demonstrating their vulnerability to climate change^{20,21}. MPAs are more likely to successfully protect species and habitats when serving as climatic refugia, i.e., providing stable and suitable climatic conditions for the long term²². On the other hand, regions exposed to novel climatic conditions (novel to that region and species) might not provide the required conditions for local species to prevail²³. As species may adapt to shifting climatic conditions by modifying their distribution patterns²⁴, this can lead to movements beyond the boundaries of existing MPAs, casting doubt on the ability of MPAs to cope with future climatic changes²⁵.

European seas, particularly enclosed or semi-enclosed seas such as the Baltic Sea and Black Sea, are experiencing some of the most rapid temperature increases globally²⁶. They are also the regions with the highest concentration of MPAs in the world^{27,28}. Previous efforts to estimate the potential effects of climate change on European MPAs have considered simplistic indicators like climate velocity changes as proxies for species' exposure to novel climatic conditions^{25,29,30}. Such approaches, however, have two main limitations that might have precluded conclusions regarding climate change effects, namely, (i) they have focused on sea surface temperature, overlooking biologically meaningful environmental variables like oxygen levels, pH, and primary productivity, which also influence species distribution³¹ and (ii) considered solely climatic conditions changes, disregarding species-specific niches. To address these limitations, alternative approaches have been proposed, notably climate novelty analyses, which have been previously used for terrestrial protected areas^{32,33}, and present a promising avenue for studying climate change impacts on marine ecosystems.

In this study, for the first time, we conduct a multivariate climate novelty analysis to understand to what extent species within MPAs are exposed to future novel climates, hereafter also referred to as at-risk species and MPAs. We focus on European MPAs and their threatened (IUCN Red List) and/or commercially important species, as these groups are typically the main targeted species of MPAs' objectives and respective conservation measures. We determine future climate novelty of target species within and beyond MPAs based on temperature, oxygen, pH, and primary productivity, and information on species distribution ranges. The analysis spans from the current climate conditions to end-of-century projections under two contrasting SSP scenarios (the low carbon emission SSP1–1.9 and the high emission scenario SSP5–8.5). Our approach provides novel and comprehensive insights into the potential impacts of climate change on threatened and/or commercial marine species and the vulnerability of European MPAs. Identifying at-risk species, i.e., exposed to future novel climates across their range, allows for the development or adjustment of management strategies and interventions within MPAs, increasing their overall efficiency and efficacy. This information is timely as we move into the era of the Kunming-Montreal Global Biodiversity Framework, a pivotal conservation initiative targeting the protection of 30% of the world's oceans by 2030 and the concurrent mitigation of and adaptation to climate change.

Results

The exposure of 398 threatened and/or commercial species within 1890 MPAs to novel ($2 < \sigma < 4$) and extremely novel ($\sigma > 4$) climates varied

significantly depending on the emission scenario considered. Under the low emission scenario (SSP1–1.9), all European sea regions maintain an average and median sigma dissimilarity (σ) below 2 (Fig. 1), with 0.5% of MPAs projected to harbor at least one at-risk species (i.e., experiencing novel or extremely novel future climate conditions). Likewise, only 6.5% of species are projected to be at risk in at least one of their resident MPAs. In contrast, under the high emission scenario (SSP5–8.5), 87.2% of MPAs and 80.7% of species are expected to be at risk. Specifically, 79.0% of MPAs are projected to contain at least one species exposed to novel conditions, and 63.2% exposed to extremely novel conditions. In parallel, 75.6% of species are anticipated to be exposed to novel conditions and 67.6% to extremely novel conditions within at least one MPA. Considering climate novelty across species ranges (SSP5–8.5), the Baltic and Black Seas are projected to face novel climates (average $\sigma = 2.82$ and 3.6, respectively), while the Mediterranean, North Sea, North-East Atlantic, and Norwegian Sea are projected to be less impacted (average $\sigma = 1.0, 1.3, 0.4,$ and 0.3, respectively). However, under the SSP5–8.5, we identified numerous species–MPA combinations across the six regions with novel (26,863 in total) and extremely novel climate (10,071 in total, Fig. 1, orange and red dots).

The proportion of threatened and/or commercial species projected to be at risk within each MPA across European sea regions is close to zero under the SSP1–1.9 (Fig. 2). Under the SSP5–8.5, several regions emerge as hotspots where a substantial proportion of species are projected to be at risk in many MPAs. Specifically, in the Baltic Sea, more than half of the analyzed (439 out of 662) MPAs contain more than 50% of species at risk, with 380 MPAs showing 100% at-risk species (Fig. 2, S1, panel d). In the Black Sea, all 26 MPAs contain more than 20% of species at risk; within these, 20 MPAs have over 70% at-risk species (Fig. S1, panel f). In the North Sea, more than one-third of the MPAs (99 out of 288) contain between 50% and 100% of species at risk, primarily in eastern regions along the coasts of Denmark, Germany, the Netherlands, and southern Norway (Fig. S1, panel b). Lastly, in the Mediterranean, 92 out of 376 MPAs contain between 20% and 50% of species at risk, mainly located in southern Italy, Malta, Albania, Greece, and Cyprus. However, the most impacted MPAs in the Mediterranean, with up to 100% at-risk species, are those in the northern Adriatic Sea, along the coast of Italy (Fig. 2, S1, panel e). In contrast, in regions like the Norwegian Sea, North-East Atlantic, western parts of the North Sea and the Mediterranean, most MPAs have <10% of species expected to be at risk, even in the high emissions scenario (Fig. 2, S1, panel a–c and e).

Across the six regions, the proportion of threatened and/or commercial species exposed to similar climates ($\sigma < 2$) under the SSP1–1.9 (Fig. 3, left panel) is 80–100% for all regions. Under the SSP5–8.5, the North-East Atlantic, Norwegian Sea, and western parts of the North Sea and the Mediterranean display very high percentages of species (80–100%) exposed to similar climates (Fig. 3, right panel). On the other hand, the regions previously identified with most at-risk MPAs, are projected to have very low percentages of species (0–5%) exposed to similar climates. The region with the lowest number of species with similar climates is the Baltic Sea (0–5%), specifically the southern half, followed by the Black Sea (0–20% in most parts). Eastern coastal areas of the North Sea and Mediterranean Sea are projected to maintain 20–40% of species with similar climatic conditions (Fig. 3, right panel).

Under the SSP5–8.5, the vast majority of species within MPAs and across groups are projected to be at risk, i.e., 223 out of 276 commercial species, 14 out of 22 IUCN species, and 36 out of 100 species that are both IUCN and commercial species. Many of the IUCN-listed species projected to be at risk fall into the near-threatened category ($n = 21$), followed by vulnerable ($n = 15$), critically endangered ($n = 7$), and endangered species ($n = 3$). These species predominantly belong to the Chondrichthyes (cartilaginous fishes including sharks, rays, and skates, $n = 25/46$) followed by Actinopterygii (ray-finned fishes, $n = 17/46$) classes. The Black Sea emerges as the most impacted region, with all IUCN-listed species (14 in total) anticipated to be at risk (Fig. 4). The Baltic Sea is also highly affected, with

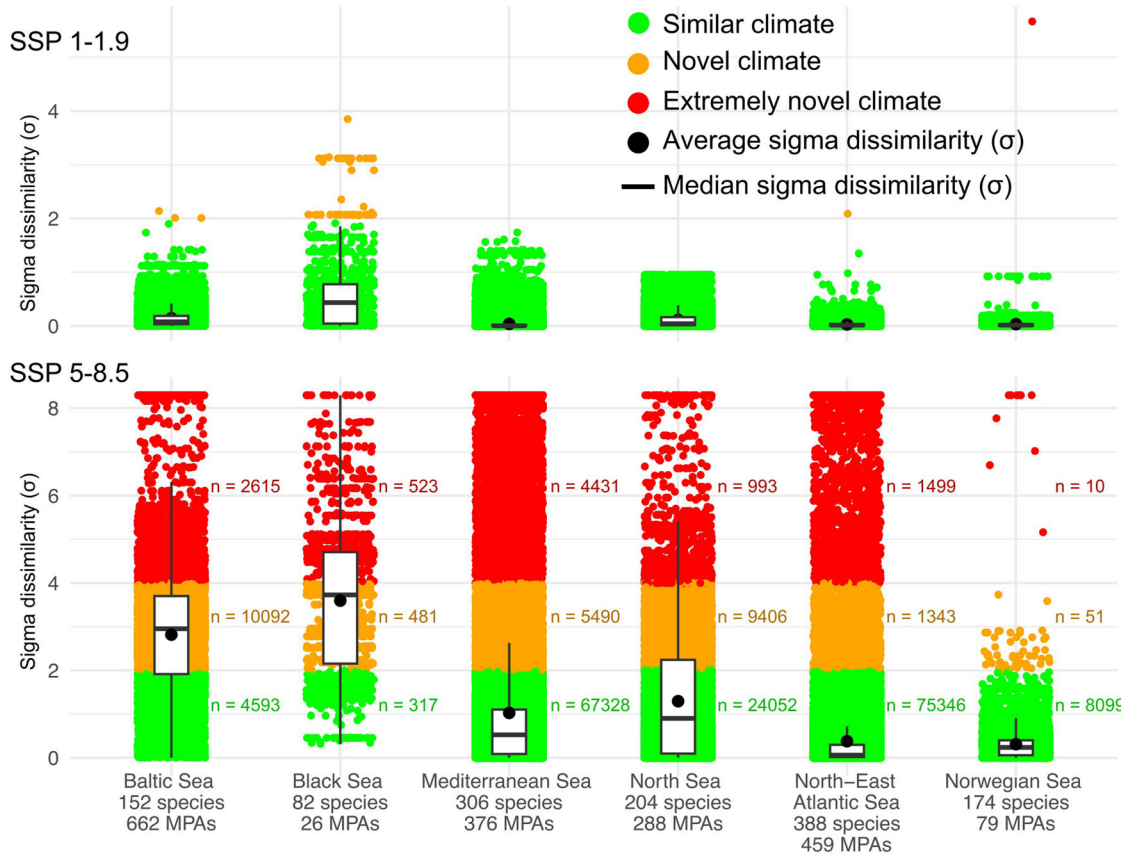


Fig. 1 | Box plot (showing the interquartile range (IQR) with median (center line), whiskers up to 1.5× IQR, black points for average value, no outliers displayed), and jitter plot illustrating the distribution of sigma dissimilarity (σ) values in six European sea regions under SSP1-1.9 (upper panel) and SSP5-8.5 (lower panel). The points represent σ for each threatened and/or commercial species and MPA

combination within regions. Green points indicate similar climate conditions ($\sigma < 2$), orange—novel climate ($2 < \sigma < 4$), and red—extremely novel climate ($\sigma > 4$). The numbers in the SSP5-8.5 scenario indicate the total number of species-MPA combinations in each category.

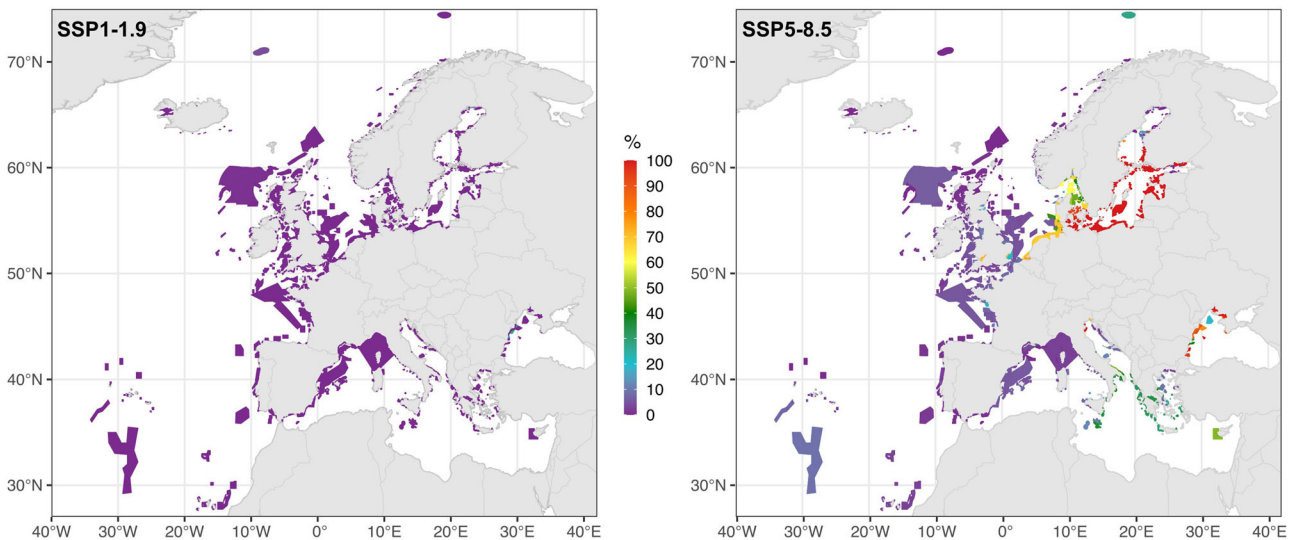


Fig. 2 | Percentage of threatened and/or commercial species projected to be at risk ($\sigma > 2$) in the future. Results are shown for each marine protected area under SSP1-1.9 (left panel) and SSP5-8.5 (right panel). Zoomed version of SSP5-8.5 for each region is in Fig. S1 (Supplementary Material).

26/37 IUCN-listed species projected to be at risk. In contrast, a lower proportion of IUCN species are predicted to be at risk in the Mediterranean (9/79), North Sea (7/70), and North-East Atlantic (10/118). Interestingly, none of the IUCN-listed species in the Norwegian Sea are expected to be at risk under the high-emission scenario. Furthermore, 36 highly commercial

species (out of 55 highly commercial species in total), predominantly Actinopterygii, are projected to be at risk under the SSP5-8.5 (Fig. 4). In the Black Sea, almost all (12/13) highly commercial species will be at risk. This is followed by the Baltic Sea, where 29/35 highly commercial species are projected to be at risk. In other regions, this proportion is smaller: 7/39 in the

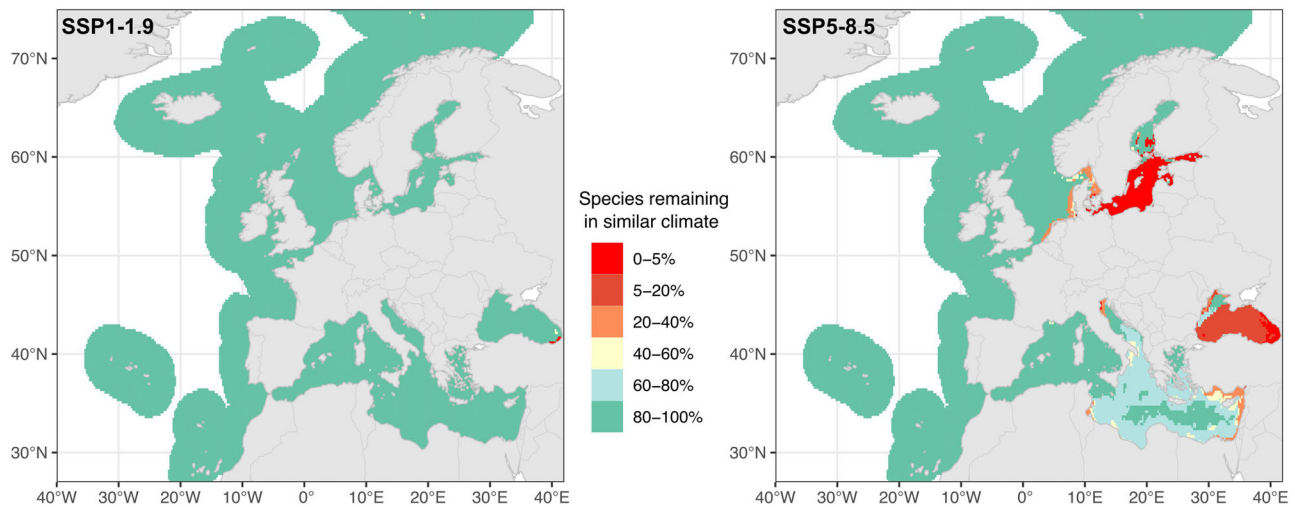


Fig. 3 | Percentage of threatened and/or commercial species projected to remain in similar climates ($\sigma < 2$) in the future. Results are shown for each European sea region under SSP1–1.9 (left panel) and SSP5–8.5 (right panel) scenarios.

Mediterranean, 4/42 in the North Sea, 2/52 in the North-East Atlantic, and 2/37 in the Norwegian Sea (Fig. 4).

Many species have distribution ranges within MPAs spanning two or more of the six regions (Fig. 4). In most of these cases, under the SSP5–8.5, species are projected to maintain similar climatic conditions in at least one MPA. On the contrary, species with narrow distribution ranges (occurring only in one region) are projected to experience more drastic climate change effects. For instance, in the Black Sea, the critically endangered Fringebarbel sturgeon (*Acipenser nudiventris*) and the highly commercial Black and Caspian Sea sprat (*Clupeonella cultriventris*), fall into this category. Similarly, in the Mediterranean Sea, the critically endangered Maltese ray (*Leucoraja melitensis*) is projected to be at risk in all the MPAs. Moreover, in the North-East Atlantic, we identified six species, all exclusive to that region, that will be at risk within the existing MPAs. These include two types of skates (*Raja maderensis* and *Raja straeleni*), a shark species (*Ginglymostoma cirratum*), two sea snails (*Phymorhynchus ovatus* and *Peltoispira smaragdina*), and a ray-finned fish (*Brachydeuterus auritus*), the latter of which is also a highly commercial species (Fig. 4).

Discussion

This study evaluated the exposure of threatened (IUCN Red List) and/or commercially fished species within European MPAs to end-of-the-century climatic conditions. Overall, our results show that the exposure of species largely depends on the emission scenario considered, underscoring the significance of greenhouse gas mitigation strategies and compliance with the Paris Agreement³⁴. Under SSP1–1.9 (low emission scenario), most MPAs and their resident species are projected to experience similar climatic conditions to the ones they currently experience. This increases the likelihood of preserving existing ecological functions and biodiversity in these areas²². In contrast, under SSP5–8.5 (high emission scenario), more than 80% of the species and MPAs are expected to face novel or extremely novel conditions (i.e., be at risk) within their MPAs. This can impact the resilience and adaptability of marine species and reduce the overall efficacy of MPAs in achieving their conservation objectives.

Within the high-emission scenario, we show variability in exposure to novel conditions across regions. The highest proportion of at-risk species are predominantly located in regions and MPAs of enclosed and semi-enclosed seas, such as the Baltic Sea (more than half MPAs with 100% of at-risk species), the Black Sea (77% of MPAs with 70% of species at risk), and eastern parts of the North Sea and Mediterranean Sea (more than one-third of MPAs with 50–100% at-risk species and one-fourth of MPAs with 20–50% of species at risk, respectively). Even though our results show that species in MPAs of the western Mediterranean Sea will be less impacted,

several MPAs with up to 100% at-risk species emerge in the north Adriatic Sea along the Italian coast. All these regions, with their unique biogeographic complexities, face additional human-induced stressors^{35–37}. In response to the multi-layered pressures, numerous MPAs have been designated under directives such as Natura 2000 and through regional cooperation efforts like the Baltic Marine Environment Protection Commission—Helsinki Commission (HELCOM) for the Baltic Sea, and the Bucharest Convention for the Black Sea. Despite such conservation efforts, future climate novelty will likely hinder the effective protection of threatened and commercial species currently residing in these regions. Further, locally adapted species with reduced genetic variation and relative isolation in these regions are still especially vulnerable to environmental shifts as they have limited movement options³⁸. With these geographical constraints, these species are particularly at risk of potential extinction if unable to adapt in situ⁷. Thus, for these regions and for the outlook of marine species and ecosystems in general, a global reduction of greenhouse gas emissions is imperative to ensure long-term effectiveness of MPAs for local marine populations.

We also revealed the areas where studied species are expected to experience stable climate conditions, even under the high emission scenario. Specifically in the North-East Atlantic, Norwegian Sea, western parts of the North and Mediterranean Seas, and northernmost parts of the Baltic Sea. Identifying and preserving climatically stable areas, which can serve as refugia or essential migration corridors for species adapting to climate change, is key for evolving conservation strategies into climate-smart MPAs³⁹. However, even in these regions where most of the species will remain in similar climates, we have identified some key species that will be exposed to novel and extremely novel climates. Moreover, despite the anticipated climatic stability in these regions, species residing there are still under pressure from human activities, even within MPA borders. Currently, most European MPAs lack strong protection and are minimally regulated or even unregulated, allowing destructive activities^{40–42}. For instance, significant portions of European MPAs are known to be trawled, leading to considerable declines in species abundance⁴⁰. It has been shown that only fully or highly protected MPAs can significantly decrease human impacts on biodiversity, resulting in positive ecological outcomes^{43–45}, including resilience to climate change^{16,46}. This underscores the complexity of ensuring effective protection and highlights the need for comprehensive approaches that address both climate stability and other pressures.

Throughout all regions, more than half of the species projected to be at risk in their MPAs under the high emission scenario belonged to Chondrichthyes (i.e., sharks, rays, and skates). Most of these are also of commercial value or were until they were listed as threatened by the IUCN Red

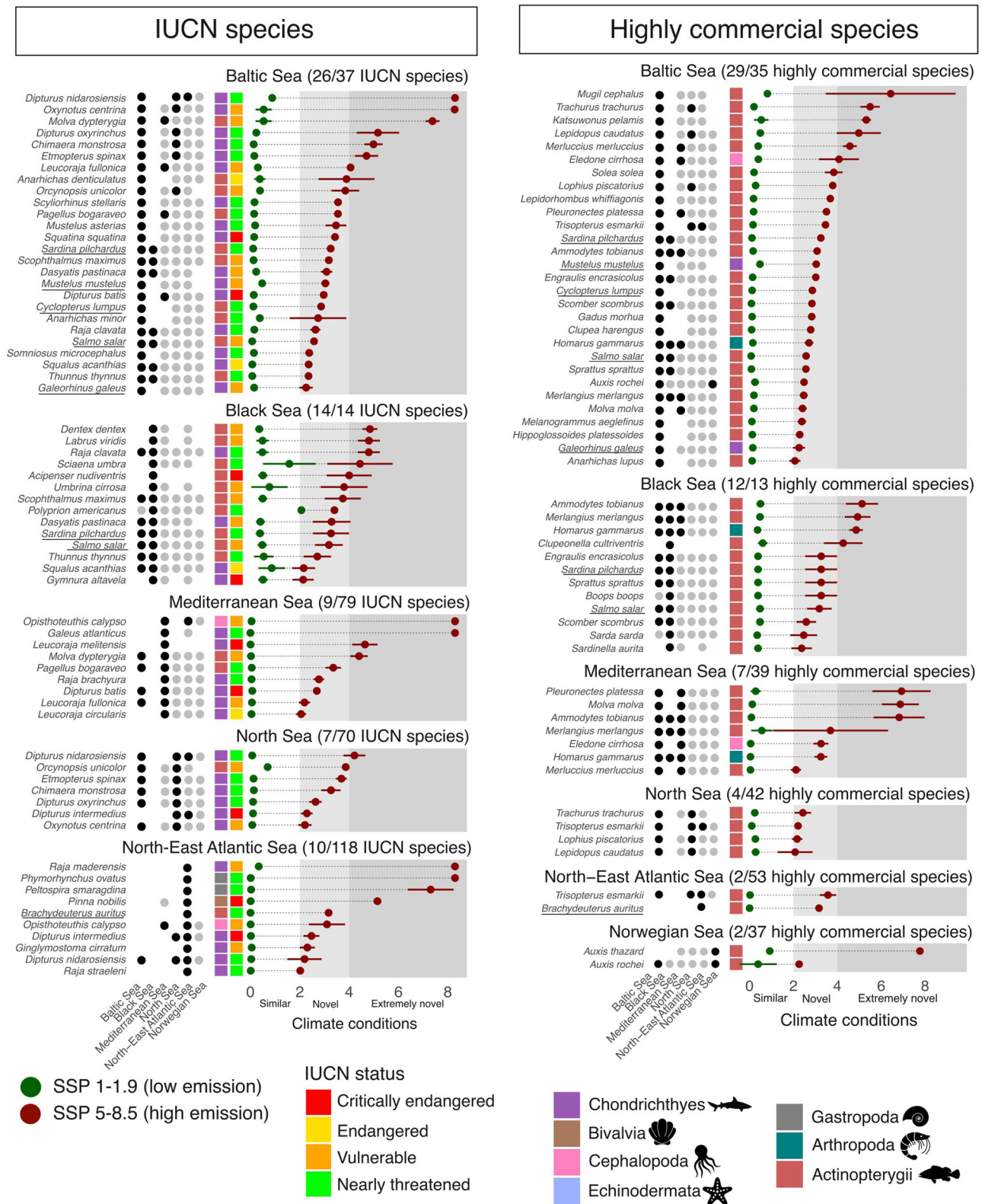


Fig. 4 | Species average sigma dissimilarity (σ) by region, including a 95% confidence interval, as an indicator of species exposure to projected climates in European marine protected areas (MPAs) under SSP1-1.9 (green dot) and SSP5-8.5 (red dot) scenarios. Projected climate categories (x-axis) are similar ($\sigma < 2$), novel ($2 < \sigma < 4$), and extremely novel climates ($\sigma > 4$). Only species with an average $\sigma > 2$ (at-risk species) within MPAs in the SSP5-8.5 scenario are displayed: the IUCN Red List (left panel) and highly commercial species (right

panel). The underlined species are those occurring both in the left and the right panel (both listed in the IUCN Red List and as highly commercial). The dot plot on the left of each panel is showing the other regions where species also occur within MPAs with black dots indicating $\sigma > 2$ (at risk) and gray $\sigma < 2$ (not at risk) under the SSP5-8.5. Full list of species projected to be at risk in each of the regions is in Fig. S2 (Supplementary material).

List. These species play a crucial role in the maintenance and regulation of marine ecosystems, often acting as apex or key mesopredators⁴⁷. Their potential exposure to novel climates may have cascading impacts on marine food web⁴⁸. This could affect overall ecosystem stability and services, even in regions where a relatively low percentage of species are exposed to novel climates in the future. Some of these species, for example, different species of skate, have small home ranges and high site fidelity, particularly during critical life stages such as spawning and feeding seasons^{49–51}. This can limit their ability to occupy new areas, given that species dispersion largely depends on adult movements. In our analyses, we found several skate species projected to be at risk across MPAs under the high-emission scenario. This includes the endemic Madeiran skate, *Raja maderensis*, and the Spotted skate, *R. straeleni*, with its current range around the Canary Islands and along the African coast⁵². When coupled with their slow life-history traits (e.g., slow growth, late maturation, low fecundity, and prolonged gestation periods), this could significantly elevate the risk of local extinctions for these species⁵³. Contrastingly, sharks generally have larger home ranges, making their conservation within MPAs a challenging task for different reasons⁵⁴. Many shark species undertake extensive migrations for feeding or breeding, often crossing hundreds or even thousands of kilometers⁵⁵. Some of these shark species, including *Galeorhinus galeus*, *Somniosus microcephalus*, and *Squalus acanthias* are projected to be at risk in some of their distribution ranges. Even though these wide-ranging species typically face different environmental conditions along their migratory pathways, significant changes may potentially disrupt sharks' traditional routes or habitats⁵⁶. Our findings showing regions with both generally low number of species exposed to novel climates and key species facing novel and extremely novel climates, stress the need to identify priority species for conservation. This step will inform and refine future conservation strategies, ensuring targeted protection efforts where they are most needed.

We provide a basis for planning future climate-smart MPAs by highlighting both at-risk and not-at-risk species, MPAs, and regions under future climatic changes. This allows targeted protection across the full range of climate change impacts, serving as a crucial component of forward-thinking management strategies³⁹. The observed differences in exposure to novel and extremely novel climates across regions and species emphasize the need for species-specific and region-specific climate change research¹⁰, a topic that has been notably understudied for many marine species in Europe³⁷. Moreover, our results have important implications for MPA governance in Europe, including that existing business-as-usual governance arrangements are not sufficient. Research effort in relation to marine governance has increased significantly in the past decade^{58,59,60}, but it has focused largely on responding to environmental change. While such reactive approaches to governance may facilitate incremental improvement, they are unlikely to deliver the shifts that are needed to ensure MPA effectiveness considering the findings presented here. Delivering transformation at the scale needed to safeguard marine futures for societal well-being requires proactive governance approaches where decision-makers can implement forward-looking interventions in the present in anticipation of future environmental change. Despite the plethora of technical work in relation to marine future thinking (e.g. foresighting future scenarios⁶¹), understanding how to transform marine governance arrangements in Europe remains critical. This transformation is necessary to become more forward-looking so decision-makers can understand and proactively develop actions to set pathways for ocean and human health⁶².

While we offer valuable insight regarding the exposure of threatened and/or commercial species to future climate change, we acknowledge several limitations of this approach. By assessing the dissimilarity between current and future climate conditions, we obtain species' novel climates and, hence proxies of their future risk that are limited by current knowledge and environmental projections. Although we focused on a multivariate approach with four variables affecting species distribution, there are other unconsidered environmental variables, such as salinity⁶³. This concern is applicable to other disregarded pressures⁶⁴, such as overfishing⁶⁵, pollution, or habitat damage known to affect species health⁶⁶. It is also worth noting

that the IUCN classification system, while valuable, may not be suitable for some organisms⁶⁷. As this study focused on evaluating the future exposure to climate change of a subset of species currently present in European MPAs, we did not account for species that might migrate into or out of the MPAs due to climate-induced range shifts. The arrival of new species may lead to substantial alterations in community compositions⁶⁸, potentially disrupting established predator–prey relationships and intensifying competition for resources^{6,69}. However, the functional overlap between new species arriving and current threatened native species can aid in the preservation of the ecosystem's overall functionality⁷⁰. Additionally, extending climate exposure analysis to include species beyond our target group would enable a more thorough assessment of the climate change on European MPAs and Seas. We recommend that future studies include all these aspects to offer a more comprehensive understanding of climate change effects, not only on individual species but also on the overall ecological dynamics within MPAs. Finally, while we provide insights into regions projected to maintain similar climates (e.g., western Mediterranean), we recognize that considerations of climate change are just one of many factors essential for optimizing MPA functionality^{71,72}.

Conclusion

Our findings underscore a concerning prevalence of threatened and commercial species and MPAs at risk under the high-emission scenario (SSP5–8.5). This highlights the imperative to pivot towards a low-emissions scenario. Concurrently, enhancing protective and proactive measures within existing MPAs and instituting adaptive management practices will significantly bolster the resilience of species and habitats facing multifaceted threats, notably related to climate change. Timely dissemination of this information is crucial, especially as we transition into the era of the recently ratified Kunming-Montreal Global Biodiversity Framework and the European Biodiversity Strategy. These frameworks delineate ambitious conservation objectives for 2030 and stress the nexus between climate change and MPA efficacy. In light of our study's revelations, there exists a critical opportunity to expand the roster of species safeguarded under the Habitats Directive and Regional Sea Conventions (OSPAR, HELCOM, Barcelona, and Bucharest). This expansion should encompass all identified threatened and commercially significant species susceptible to future climate alterations. Updating this list will facilitate strategic augmentation of the MPA network in the coming years. Furthermore, planners of MPAs might need to contemplate safeguarding species that perform similar ecological functions yet demonstrate greater resilience to impending climate shifts. Nonetheless, our research underscores the indispensable value of adhering to the Paris Agreement to reduce global greenhouse gas emissions. This adherence is crucial to ensure the enduring effectiveness of European MPAs in safeguarding numerous threatened and commercially valuable species amidst the challenges posed by climate change, in addition to being pivotal for the survival of life on Earth and global civilization.

Methods

European marine protected areas

The analysis focused on MPAs located within European exclusive economic zones (EEZ), including EU member countries, the United Kingdom, Norway, and Iceland. Polygons representing the spatial distribution of MPAs in European seas were acquired from the World Database on Protected Areas (WDPA)⁷³. To avoid overestimating the total protected area, overlapping polygons were spatially dissolved. This process resulted in 1890 polygons, which we will refer to as marine protected areas (MPAs) throughout the remainder of this study. MPAs were assigned to one of the six sea regions: Norwegian Sea, North Sea, Baltic Sea, North-East Atlantic Sea, Black Sea, or Mediterranean Sea (Fig. S1).

Species selection and their distribution maps

We assembled a list of commercial species and corresponding catch data per EEZ from the Sea Around Us database (<https://www.seaaroundus.org/>). Only species designated as minor commercial, commercial, or highly

commercial based on FishBase⁵² status were incorporated into our study. This list was augmented with species categorized as critically endangered, endangered, vulnerable, or nearly threatened on the European Red List (IUCN 2010 European Red List, accessed June 2022). Where a species' status was absent from The European Red List, we referred to the Global IUCN Red List, which was applicable to 40 species. This resulted in a final list of 398 species (Table S1) composed of 276 commercial species, 100 species with both commercial and conservation statuses, and 22 species that only held a conservation status. Among species with an IUCN status, 19 were critically endangered, 29 endangered, 36 vulnerable, 38 nearly threatened, and 34 data deficient. The taxonomic classes breakdown of all species was: 232 Actinopterygii (58.29%), 103 Chondrichthyes (25.88%), 24 Arthropoda (6.03%), 18 Bivalvia (4.52%), 10 Cephalopoda (2.51%), 6 Gastropoda (1.5%), 3 Echinodermata (0.75%), 1 Petromyzonti (0.25%), 1 Thecostraca (0.25%). Distribution range maps for all species were obtained from IUCN and Aquamaps⁷⁴.

Climate data

Climate variables at the global scale and with a spatial resolution of 0.25° were produced with the Bio-ORACLE computational pipelines⁷⁵. The timeframes examined were the contemporary baseline period (2010–2020) and the end-of-century period (2090–2100) under two Shared Socioeconomic Pathways (SSP) scenarios of future climate change: the SSP1–1.9, a low-emission “sustainability” scenario in line with the expectations of the Paris Agreement, and the SSP5–8.5 scenario, representing the “fossil-fueled development” associated with the highest carbon emissions and mitigation challenges. The variables chosen were maximum temperature, average dissolved oxygen, pH, and primary productivity (PP). Data for the baseline period was sourced from Copernicus Marine Service, while the SSP scenarios data was derived from an ensemble⁷⁵ of several general atmosphere-ocean circulation models (ACCESS-ESM1-5, CanESM5, CESM2-WACCM, CNRM-ESM2-1, GFDL-ESM4, GISS-E2-1-G, IPSL-CM6A-LR, MIROC-ES2L, MPI-ESM1-2-LR, MRI-ESM2-0, UKESM1-0-LL) provided by the Coupled Model Intercomparison Project's 6th iteration (CMIP).

Climate novelty analysis

Our climate novelty analysis is based on the sigma dissimilarity (σ) methodology described by Mahony et al.⁷⁶, which uses a modified multivariate standardized Euclidean distance (SED) metric^{77,78}. The modifications include converting SED to Mahalanobis distances and interpreting climate distances as percentiles of the chi distribution. This approach was selected because the application of Mahalanobis distance rescales variables in relation to local intra-annual climate variation (ICV) and reduces variance inflation due to correlations. The chi distribution interpretation accommodates the dimensionality effect, facilitating comparisons between analyses utilizing varying numbers of input variables^{79,80}.

This approach enabled quantifying climate novelty between end-of-century climate conditions (2090–2100) and their nearest present-day climatic counterparts (2010–2020). To calculate sigma dissimilarity for each species, we converted the variables of the baseline and projected periods into anomaly z-scores by subtracting the baseline data (2010–2020) mean ICV at each cell level and subsequently dividing by the baseline data ICV standard deviation⁸¹. Then, a principal component analysis (PCA) was carried out on the standardized baseline data, retaining the components that accounted for 99% or more of data variability. This PCA was employed to transform both standardized baseline and projected data. Next, the Mahalanobis distances between each ocean cell of the transformed projected climate data and its nearest equivalent from the transformed baseline climate data pool within the species of interest's range map were calculated⁸⁰. This process linked the multivariate climate distance of target locations to the species' climatic niche, with the closest similar climate reflecting global baseline data ocean cells with a similar climate to the projected climate at target locations. Finally, sigma dissimilarity, a statistical measure of deviation from baseline climates, was calculated by translating Mahalanobis distances using the chi

distribution. We modified Mahony et al.⁷⁶ and categorized $\sigma < 2$ as similar climate conditions, $2 < \sigma < 4$ novel climates (the 95th percentile of the baseline climate), and $\sigma > 4$ as extremely novel climate (the 99.99th percentile of the baseline climate). Sigma dissimilarity was calculated for all target species in this study, both within each European MPA and within the borders of each six sea regions (without MPA borders). Species and MPAs with $\sigma > 2$ are considered at risk in this study, and species and MPAs with $\sigma < 2$ are considered not at risk.

Data availability

Climate data and R code used to estimate exposure of threatened and commercial species to future novel conditions are openly available at: <https://doi.org/10.6084/m9.figshare.24794508>.

Received: 14 December 2023; Accepted: 20 May 2024;

Published online: 14 June 2024

References

1. Hoegh-Guldberg, O. & Bruno, J. F. The impact of climate change on the world's marine ecosystems. *Science* **328**, 1523–1528 (2010).
2. He, Q. & Silliman, B. R. Climate Change, Human Impacts, and Coastal Ecosystems in the Anthropocene. *Curr. Biol.* **29**, R1021–R1035 (2019).
3. Doney, S. C. et al. Climate change impacts on marine ecosystems. *Annu. Rev. Mar. Sci.* **4**, 11–37 (2012).
4. Sumaila, U. R., Cheung, W. W. L., Lam, V. W. Y., Pauly, D. & Herrick, S. Climate change impacts on the biophysics and economics of world fisheries. *Nat. Clim. Change* **1**, 449–456 (2011).
5. Poloczanska, E. S. et al. Global imprint of climate change on marine life. *Nat. Clim. Chang.* **3**, 919–925 (2013).
6. Pecl, G. T. et al. Biodiversity redistribution under climate change: impacts on ecosystems and human well-being. *Science* **355**, <https://doi.org/10.1126/science.aai9214> (2017).
7. Cheung, W. W. L. et al. Projecting global marine biodiversity impacts under climate change scenarios. *Fish Fish.* **10**, 235–251 (2009).
8. Parmesan, C., Yohe, G. & Andrus, J. E. A Globally Coherent Fingerprint of Climate Change Impacts across Natural Systems www.nature.com/nature (2003).
9. Bruno, J. F. et al. Climate change threatens the world's marine protected areas. *Nat. Clim. Chang.* **8**, 499–503 (2018).
10. Boyce, D. G. et al. A climate risk index for marine life. *Nat. Clim. Chang.* <https://doi.org/10.1038/s41558-022-01437-y> (2022).
11. Nash, K. L. et al. Planetary boundaries for a blue planet. *Nat. Ecol. Evol.* **1**, 1625–1634 (2017).
12. Lam, V. W. Y. et al. Climate change, tropical fisheries and prospects for sustainable development. *Nat. Rev. Earth Environ.* **1**, 440–454 (2020).
13. Edgar, G. J. et al. Global conservation outcomes depend on marine protected areas with five key features. *Nature* **506**, 216–220 (2014).
14. Cheng, B. S., Altieri, A. H., Torchin, M. E. & Ruiz, G. M. Can marine reserves restore lost ecosystem functioning? A global synthesis. *Ecology* **100**, e02617 (2019).
15. Roberts, C. M. et al. Marine reserves can mitigate and promote adaptation to climate change. *Proc. Natl Acad. Sci. USA* **114**, 6167–6175 (2017).
16. Jacquemont, J., Blasiak, R., Le Cam, C., Le Gouellec, M. & Claudet, J. Ocean conservation boosts climate change mitigation and adaptation. *One Earth* **5**, 1126–1138 (2022).
17. Wilson, K. L., Tittensor, D. P., Worm, B. & Lotze, H. K. Incorporating climate change adaptation into marine protected area planning. *Global Change Biol.* **26**, 3251–3267 (2020).
18. O'Regan, S. M., Archer, S. K., Friesen, S. K. & Hunter, K. L. A global assessment of climate change adaptation in marine protected area management plans. *Front. Mar. Sci.* **8**, 1–16 (2021).
19. Lopazanski, C. et al. Principles for climate resilience are prevalent in marine protected area management plans. *Conserv. Lett.* **16**, e12972 (2023).

20. Weinert, M., Mathis, M., Kröncke, I., Pohlmann, T. & Reiss, H. Climate change effects on marine protected areas: projected decline of benthic species in the North Sea. *Mar. Environ. Res.* **163**, 105230 (2021).
21. Andreollo, M., Mouillot, D., Somot, S., Thuiller, W. & Manel, S. Additive effects of climate change on connectivity between marine protected areas and larval supply to fished areas. *Divers. Distrib.* **21**, 139–150 (2015).
22. Keppel, G. et al. Refugia: identifying and understanding safe havens for biodiversity under climate change. *Global Ecol. Biogeogr.* **21**, 393–404 (2012).
23. Pinsky, M. L., Eikeset, A. M., McCauley, D. J., Payne, J. L. & Sunday, J. M. Greater vulnerability to warming of marine versus terrestrial ectotherms. *Nature* **569**, 108–111 (2019).
24. Bates, A. E. et al. Defining and observing stages of climate-mediated range shifts in marine systems. *Global Environ. Change* **26**, 27–38 (2014).
25. Brito-Morales, I. et al. Climate velocity can inform conservation in a warming world. *Trends Ecol. Evol.* **33**, 441–457 (2018).
26. Belkin, I. M. Rapid warming of large marine ecosystems. *Prog. Oceanogr.* **81**, 207–213 (2009).
27. Kriegl, M., Elias Ilosvay, X. E., von Dorrien, C. & Oesterwind, D. Marine protected areas: at the crossroads of nature conservation and fisheries management. *Front. Mar. Sci.* **8**, 676264 (2021).
28. Amengual, J. & Alvarez-Berastegui, D. A critical evaluation of the Aichi Biodiversity Target 11 and the Mediterranean MPA network, two years ahead of its deadline. *Biol. Conserv.* **225**, 187–196 (2018).
29. Kyprioti, A., Almpnidou, V., Chatzimontor, A., Katsanevakis, S. & Mazaris, A. D. Is the current Mediterranean network of marine protected areas resilient to climate change? *Sci. Total Environ.* **792**, 148397 (2021).
30. Arafah-Dalmai, N. et al. Incorporating climate velocity into the design of climate-smart networks of marine protected areas. *Methods Ecol. Evol.* **12**, 1969–1983 (2021).
31. McHenry, J., Welch, H., Lester, S. E. & Saba, V. Projecting marine species range shifts from only temperature can mask climate vulnerability. *Glob. Chang. Biol.* **25**, 4208–4221 (2019).
32. Holsinger, L. et al. Climate change likely to reshape vegetation in North America's largest protected areas. *Conserv. Sci. Pract.* **1**, e50 (2019).
33. Hoffmann, S., Irl, S. D. H. & Beierkuhnlein, C. Predicted climate shifts within terrestrial protected areas worldwide. *Nat. Commun.* **10**, 4787 (2019).
34. Rashid Sumaila, U. et al. *Benefits of the Paris Agreement to Ocean Life, Economies, and People* <https://www.science.org> (2019).
35. Bat, L., Öztekin, A., Şahin, F., Arıcı, E. & Özsandıkcı, U. *An Overview of the Black Sea Pollution in Turkey* Vol. 1 (MedFAR, 2018).
36. Gascuel, D. et al. Fishing impact and environmental status in European seas: a diagnosis from stock assessments and ecosystem indicators. *Fish Fish.* **17**, 31–55 (2016).
37. Micheli, F. et al. Cumulative human impacts on Mediterranean and Black Sea marine ecosystems: assessing current pressures and opportunities. *PLoS ONE* **8**, e79889 (2013).
38. Johannesson, K., Smolarz, K., Grahn, M. & André, C. The future of baltic sea populations: local extinction or evolutionary rescue? *Ambio* **40**, 179–190 (2011).
39. Tittensor, D. P. et al. *Integrating Climate Adaptation and Biodiversity Conservation in the Global Ocean* <http://advances.sciencemag.org/> (2019).
40. Dureau, M., Boerder, K., Burnett, K. A., Froese, R. & Worm, B. Elevated trawling inside protected areas undermines conservation outcomes in a global fishing hot spot. *Science* **362**, <https://www.science.org> (2018).
41. Claudet, J., Loiseau, C., Sostres, M. & Zupan, M. Underprotected Marine protected areas in a global biodiversity hotspot. *One Earth* **2**, 380–384 (2020).
42. Roessger, J., Claudet, J. & Horta e Costa, B. Turning the tide on protection illusions: the underprotected MPAs of the 'OSPAR Regional Sea Convention'. *Mar. Policy* **142**, 105109 (2022).
43. Lester, S. E. et al. Biological effects within no-take marine reserves: a global synthesis. *Mar. Ecol. Prog. Ser.* **384**, 33–46 (2009).
44. Zupan, M. et al. How good is your marine protected area at curbing threats? *Biol. Conserv.* **221**, 237–245 (2018).
45. Turnbull, J. W., Johnston, E. L. & Clark, G. F. Evaluating the social and ecological effectiveness of partially protected marine areas. *Conserv. Biol.* **35**, 921–932 (2021).
46. Benedetti-Cecchi, L. et al. Marine protected areas promote stability of reef fish communities under climate warming. *Nat. Commun.* **15**, 1822 (2024).
47. Ferretti, F., Worm, B., Britten, G. L., Heithaus, M. R. & Lotze, H. K. Patterns and ecosystem consequences of shark declines in the ocean. *Ecol. Lett.* **13**, 1055–1071 (2010).
48. Heithaus, M. R., Frid, A., Wirsing, A. J. & Worm, B. Predicting ecological consequences of marine top predator declines. *Trends Ecol. Evol.* **23**, 202–210 (2008).
49. Neat, F. et al. Site fidelity, survival and conservation options for the threatened flapper skate (*Dipturus cf. intermedia*). *Aquat. Conserv.* **25**, 6–20 (2015).
50. Hunter, E., Buckley, A. A., Stewart, C. & Metcalfe, J. D. Migratory behaviour of the thornback ray, *Raja clavata*, in the southern North Sea. *J. Mar. Biol. Assoc. UK* **85**, 1095–1105 (2005).
51. Sousa, I., Baeyaert, J., Gonçalves, J. M. S. & Erzini, K. Preliminary insights into the spatial ecology and movement patterns of a regionally critically endangered skate (*Rostroraja alba*) associated with a marine protected area. *Mar. Freshw. Behav. Physiol.* **52**, 283–299 (2019).
52. Froese, R. & Pauly, D. FishBase. www.fishbase.org (2010).
53. Marshall, D. J., Burgess, S. C. & Connallon, T. Global change, life-history complexity and the potential for evolutionary rescue. *Evol. Appl.* **9**, 1189–1201 (2016).
54. Heupel, M. R. et al. Conservation challenges of sharks with continental scale migrations. *Front. Mar. Sci.* **2**, 12 (2015).
55. Block, B. A. et al. Tracking apex marine predator movements in a dynamic ocean. *Nature* **475**, 86–90 (2011).
56. Birkmanis, C. A., Freer, J. J., Simmons, L. W., Partridge, J. C. & Sequeira, A. M. M. Future distribution of suitable habitat for pelagic sharks in Australia under climate change models. *Front. Mar. Sci.* **7**, 570 (2020).
57. Predragovic, M. et al. A systematic literature review of climate change research on Europe's threatened commercial fish species. *Ocean Coast. Manag.* **242**, 106719 (2023).
58. Cvitanovic, C., Hobday, A. J., McDonald, J., Van Putten, E. I. & Nash, K. L. Governing fisheries through the critical decade: the role and utility of polycentric systems. *Rev. Fish Biol. Fish.* **28**, 1–18 (2018).
59. Di Franco, A. et al. Improving marine protected area governance through collaboration and co-production. *J. Environ. Manag.* **269**, 110757 (2020).
60. Stephenson, R. L. et al. The Quilt of Sustainable Ocean Governance: patterns for Practitioners. *Front. Mar. Sci.* **8**, <https://doi.org/10.3389/fmars.2021.630547> (2021).
61. Kelly, R. et al. Foresighting future oceans: considerations and opportunities. *Mar. Policy* **140**, 105021 (2022).
62. Nash, K. L. et al. Oceans and Society: feedbacks between ocean and human health. *Rev. Fish Biol. Fish.* **32**, 161–187 (2022).
63. Jonsson, P. R. et al. High climate velocity and population fragmentation may constrain climate-driven range shift of the key habitat former *Fucus vesiculosus*. *Divers. Distrib.* **24**, 892–905 (2018).
64. Beckerman, A. P. The context dependency of multiple stressor effects on biodiversity: a commentary on Kefford et al. (2022). *Global Change Biol.* **29**, 563–565 (2023).
65. Sumaila, U. R. & Tai, T. C. End overfishing and increase the resilience of the ocean to climate change. *Front. Mar. Sci.* **7**, <https://doi.org/10.3389/fmars.2020.00523> (2020).

66. Hassell, K., Barrett, L. & Dempster, T. Impacts of human-induced pollution on wild fish welfare. *The Welfare of Fish*. 487–507 https://doi.org/10.1007/978-3-030-41675-1_20 (2020).
67. Brodie, J. et al. Red List for British seaweeds: evaluating the IUCN methodology for non-standard marine organisms. *Biodivers. Conserv.* **32**, 3825–3843 (2023).
68. Katsanevakis, S., Rilov, G. & Edelist, D. Impacts of marine invasive alien species on European fisheries and aquaculture—plague or boon. In *CIESM Monograph SO* (ed Briand F) *Engaging Marine Scientists and Fishers to Share Knowledge and Perceptions—Early Lessons*. CIESM Publisher, Monaco and Paris, pp. 125–132, 218 pp.
69. Dimitriadis, C., Fournari-konstantinidou, I., Sourbès, L., Koutsoubas, D. & Katsanevakis, S. Long term interactions of native and invasive species in a marine protected area suggest complex cascading effects challenging conservation outcomes. *Diversity (Basel)* **13**, 1–13 (2021).
70. Leuzinger, S. & Rewald, B. The who or the how? Species vs. ecosystem function priorities in conservation ecology. *Front. Plant Sci.* **12**, 758413 (2021).
71. Cochrane, K., Greboval, D., Sissenwine, M., Sanders, J. & Charles, A. Expert Workshop on Marine Protected Areas and Fisheries Management: Review of Issues and Considerations. *Fisheries Report No. 825. Rome, FAO*. pp 332 (2007).
72. Smith, J. & Metaxas, A. A decision tree that can address connectivity in the design of Marine Protected Area Networks (MPAn). *Mar. Policy* **88**, 269–278 (2018).
73. UNEP-WCMC and IUCN. *Protected Planet: the World Database on Protected Areas (WDPA)* (UNEP-WCMC and IUCN, Cambridge, UK, 2022).
74. Kaschner, K. et al. *AquaMaps: Predicted Range Maps for Aquatic Species* <https://www.aquamaps.org>. (2019).
75. Assis, J. et al. Bio-ORACLE v3.0. Pushing marine data layers to the CMIP6 Earth System Models of climate change research. *Global Ecol. Biogeogr.* <https://doi.org/10.1111/geb.13813> (2024).
76. Mahony, C. R., Cannon, A. J., Wang, T. & Aitken, S. N. A closer look at novel climates: new methods and insights at continental to landscape scales. *Glob. Chang. Biol.* **23**, 3934–3955 (2017).
77. Williams, J. W. & Jackson, S. T. Novel climates, no-analog communities, and ecological surprises. *Front. Ecol. Environ.* **5**, 475–482 (2007).
78. Veloz, S. et al. Identifying climatic analogs for Wisconsin under 21st-century climate-change scenarios. *Clim. Change* **112**, 1037–1058 (2012).
79. King, A. D. Identifying historical climate changes in Australia through spatial analogs. *Environ. Res. Lett.* **18**, 044018 (2023).
80. Lotterhos, K. E., Láruson, Á. J. & Jiang, L. Q. Novel and disappearing climates in the global surface ocean from 1800 to 2100. *Sci. Rep.* **11**, 15535 (2021).
81. Wilks, D. *Statistical Methods in the Atmospheric Sciences*, *International Geophysics Series*, 2nd edn, Vol. 91 (Academic Press, Amsterdam, Boston, 2006).
- CT0038). B.H.C. also acknowledges the support from Biodiversa+ MOVE: Movescapes, connectivity hotspots and eco-evolutionary dynamics: protecting the functional role of predatory coastal fishes (<https://doi.org/10.54499/DivProtect/0009/2021>) and EU HORIZON MARHAB: Improving marine habitat status by considering ecosystem dynamics (CL6-2023-Biodiv 2024-2027) projects. J.A. received support from Horizon Europe Framework Program through project MPAEurope (HORIZON-CL6-2021-BIODIV-01-12) and from FCT—Foundation for Science and Technology, I.P. (Portugal) through project PTDC/BIA-CBI/6515/2020 (<https://doi.org/10.54499/PTDC/BIA-CBI/6515/2020>) and the Individual Call to Scientific Employment Stimulus 2022.00861.CEECIND/CP1729/CT0003 (<https://doi.org/10.54499/2022.00861.CEECIND/CP1729/CT0003>). This study received Portuguese national funds from FCT—Foundation for Science and Technology to CCMAR through projects UIDB/04326/2020 (<https://doi.org/10.54499/UIDB/04326/2020>), UIDP/04326/2020 (<https://doi.org/10.54499/UIDP/04326/2020>) and LA/P/0101/2020 (<https://doi.org/10.54499/LA/P/0101/2020>). We thank Lily G.C. Genevier for help with R code troubleshooting and Matthew D. Tietbohl for writing support and insightful comments.

Author contributions

B.H.C., M.P., and J.A. conceived the idea of the study and defined the methodology with the contribution of all authors. J.A. and M.P. conducted all analyses. M.P. wrote the main manuscript text and prepared all the figures. B.H.C. provided supervision and writing. All authors reviewed and edited the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s44183-024-00068-4>.

Correspondence and requests for materials should be addressed to Milica Predragovic.

Reprints and permissions information is available at <http://www.nature.com/reprints>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

© The Author(s) 2024

Acknowledgements

The project that gave rise to these results received the support of a fellowship (LCF/BQ/DI21/11860039) from “la Caixa” Foundation (ID 100010434) to M.P. B.H.C. was supported by national funds through FCT—Foundation for Science and Technology, I.P. (Portugal), in agreement with the University of Algarve, in the scope of Norma Transitória with the research contract DL57/2016/CP1361/CT0038 (<https://doi.org/10.54499/DL57/2016/CP1361/>