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MARMAPS

Replication guide of the Decision Support Framework for Designating Marine Protected Areas in the Black Sea

Contents

Introduction

Safeguarding biodiversity is essential for maintaining ecosystem health and resilience, which in turn supports long-term human well-being. Biodiversity underpins critical ecosystem services, including food provision, raw materials, pharmaceuticals, and livelihoods for millions worldwide. Despite covering the majority of the planet, marine ecosystems remain undervalued and inadequately protected. Recognizing this, the EU Biodiversity Strategy (2020) commits to conserving at least 30% of Europe's seas by 2030, with a minimum of 10% designated as strictly protected in areas of high ecological value. On a global scale, over 190 nations have endorsed the Kunming-Montreal Global Biodiversity Framework (2022), which targets the effective protection and management of 30% of terrestrial, freshwater, coastal, and marine areas by 2030. Within this context, the MARMAPS project focuses on the conservation of Black Sea ecosystems, advancing regional expertise in biodiversity planning and implementation. By developing a structured framework for identifying priority areas for marine protected areas (MPAs) and promoting stakeholder engagement in MPA governance, the project seeks to achieve long-term, sustainable conservation outcomes.

The Black Sea is, indeed, a unique ecosystem with global importance (Alpenidze et al., 2013). Bordered by Romania, Bulgaria, Russia, Ukraine, Georgia and Turkey, it holds substantial geopolitical and economic value (Avoyan et al., 2017). The basin is semi-enclosed, connected to the Sea of Azov through the Kerch Strait in the northeast and to the Mediterranean Sea via the Marmara Sea, with a unique hydrography that features a deep central region exceeding 2,000 m and an extensive northwestern continental shelf. Major rivers such as the Danube River, Dniester River, and Dnieper River significantly shape its hydrology, collecting water from a large part of Europe and creating an environment with both freshwater and oceanic characteristics (Bosneagu, 2022). It is characterized by anoxic conditions below depths of 130–180 meters (Coutto & Devlen, 2014), restricting aerobic life to its upper layers. Despite these challenging conditions, the Black Sea hosts remarkable biodiversity with research documenting around 3,774 multicellular species, including a range of algae, invertebrates, fish, and marine mammals (Bosneagu, 2022).

However, despite its ecological richness, the Black Sea faces extensive anthropogenic pressures and is considered one of the most degraded marine ecosystems globally. Since the second half of the 20th century, overfishing has driven substantial declines in fish populations, while pollution from agriculture, urban wastewater, and industrial activities has contributed to eutrophication and deteriorating water quality (Avoyan et al., 2017; Avoyan et al. 2022; Oguz & Velikova, 2010). The introduction of non-native species, extensive marine traffic, oil spills, and unsustainable development have further stressed the ecosystem, while climate change exacerbates the risks of coastal erosion, flooding, and habitat loss. Climate change adds to these threats by increasing the risks of coastal erosion, flooding, and habitat loss (Bosneagu, 2022; Serpetti et al., 2025). The cumulative effect of these pressures has led to widespread ecological degradation, highlighting the urgent need for coordinated, transboundary conservation measures to protect the Black Sea's biodiversity and maintain its viability (Güneroğlu et al., 2019).

Marine Protected Areas (MPAs) in the Black Sea are unevenly distributed across national jurisdictions, according to data from The World Database on Protected Areas. For example, Romania currently protects approximately 21% of its Exclusive Economic Zone (EEZ), the highest amongst the Black Sea countries, whereas, Bulgaria protects about 8.2% and Ukraine 9.1%. Georgia, Russia, and Turkey have notably lower protection levels, with 0.85%, 0.02%, and 0.04%

of their EEZs designated as MPAs respectively (WDPA, 2025). This fragmented and country-specific approach hinders the establishment of a coherent, transboundary network that could effectively support biodiversity conservation and ecosystem resilience at the regional scale.

A well-established methodological foundation already exists for setting conservation priorities in a structured way that balances ecological goals with socio-economic considerations (Margules & Pressey, 2000). Within the framework of Systematic Conservation Planning (SCP), conservation actions are guided by science-based, transparent decision-making processes that integrate multiple objectives and scenarios. This approach enables planners to strategically allocate limited resources, explicitly incorporate ecological, environmental, and socio-economic dimensions, and adapt to complex and changing contexts (Burbano Girón & Etter Rothlisberger, 2020; Kujala et al., 2013). According to Moilanen et al. (2009), SCP commonly involves six key stages: (1) collecting data on species and habitats of conservation concern, (2) setting biodiversity targets, (3) dividing the study region into discrete planning units, (4) quantifying biodiversity features within each unit, (5) calculating the cost value of each of these units, and (6) using decision-support tools to identify priority areas that promote biodiversity conservation, reduce fragmentation, and lower costs.

In the last twenty years, spatial prioritization tools have been created and extensively utilized in terrestrial and marine systems (Ribeiro & Atadeu, 2019), employing optimization algorithms to design efficient and cost-effective conservation networks. By integrating ecological and socio-economic data, these tools enable the evaluation of alternative planning scenarios and support transparent, data-driven decision-making that balances biodiversity with impacts on local communities and the economy (Ball et al., 2009; Hanson et al., 2025; Moilanen et al., 2009).

In this context, spatial prioritization provides a structured and science-based framework to guide conservation actions in the Black Sea. In line with the targets set by the European Union, different planning scenarios were designed to identify priority areas that would contribute to achieving these goals in the region. Furthermore, the analysis aims to ensure a more balanced and equitable distribution of MPAs by allocating the same percentage of protection within each EEZ, thereby promoting a more coherent and transboundary network. This approach supports more coordinated and cost-effective management and strengthens ecosystem-based management efforts in the region.

Step-by-Step Framework

Step 1. Structuring scenario framework to achieve conservation goals

During the project a full set of 60 scenarios for the Black Sea, which are grouped into four scenario families (Figure 1), were created in order to capture the widest possible range of conservation actions needed to protect the Black Sea ecosystem.

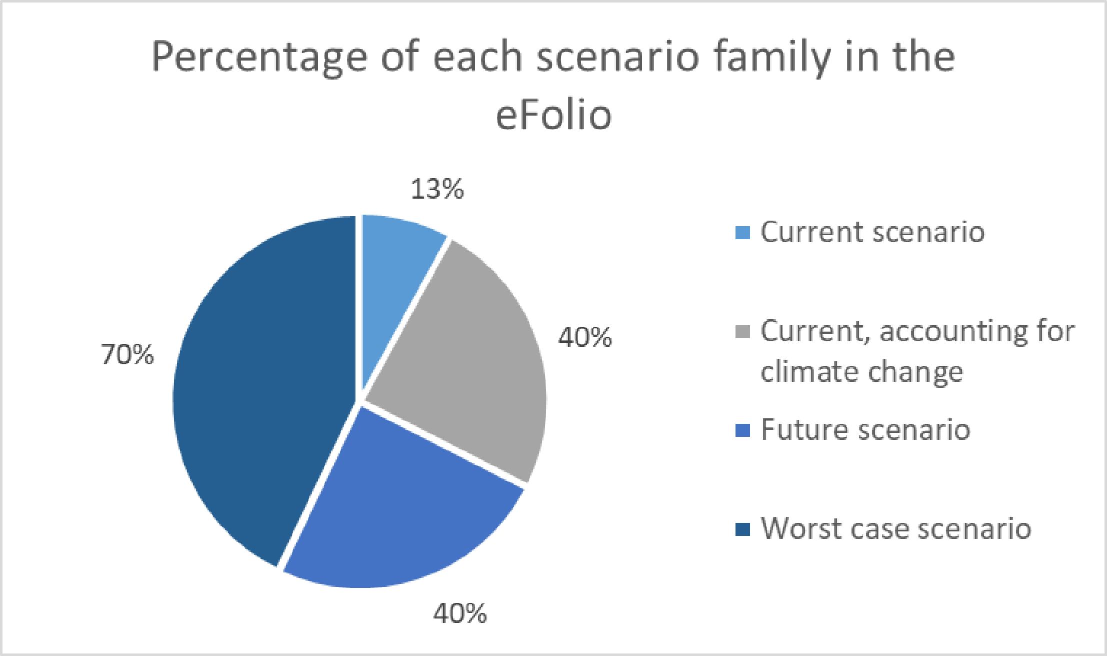

Figure 1. Proportion of scenario families represented in the full set of 60 scenarios. The pie chart illustrates the relative contribution of each scenario family to the eFolio.

a. <u>Current species distribution scenario (2 base scenarios, 8 variants total)</u>: It reflects the distribution of species under the current environmental conditions. This base scenario is implemented both with and without the socioeconomic costs stemming from blue economy activities.
b. <u>Current distribution of species under climate change scenarios (6 base scenarios, 24 variants total)</u>: This group of scenarios examines the impact of climate change on the current and near future species distributions in the Black Sea. It considers three climate change scenarios in two time frames (2050 and 2100), explored by the Intergovernmental Panel on Climate Change (IPCC), and known as Representative Concentration Pathways (RCPs):
    a. RCP2.6: strong mitigation, aiming to keep global warming below 2°C
    b. RCP4.5: moderate stabilization with average temperature between 2°C and 3°C above preindustrial level by the end of the century
    c. RCP8.5: high emissions, high warming
c. <u>Future distribution of species under climate change scenarios (6 base scenarios, 24 variants total)</u>: These scenarios explore the future distribution of marine biodiversity in the Black Sea under the climate change conditions described above in category 2.
d. <u>Severe climate change or worst-case scenario (1 base scenario, 4 variants total)</u>: This scenario explores conservation priorities for the Black Sea under a severe climate change future, combining multiple climate change components to identify areas likely to remain valuable for biodiversity even under extreme warming.

For each base scenario, four variants were generated by combining two factors: the inclusion or not of existing MPAs, and the application or omission of species weights. Species weights represent conservation priorities in the Black Sea, ensuring that the most vulnerable and regionally significant species receive greater emphasis in the prioritization process.

Step 2. Collection of data on biodiversity

2.1. Extract species from AquaMaps

Marine species distribution data were sourced from AquaMaps (Kaschner et al., 2019), which produces standardized range maps for marine taxa using ecological niche modeling. These models estimate the probability of species occurrence on a scale from 0 to 1 by combining known distribution records with environmental preference envelopes. For this study, we extracted all species whose predicted current native ranges intersect the Black Sea Large Marine Ecosystem (LME) and had at least one grid cell with a probability of occurrence value over 0.5, using the 0.5° (~55.5 km) native range grid resolution provided by AquaMaps. We also extracted the modelled native range maps of these species for the years 2050 and 2100 based on IPCC RCP2.6, RCP4.5 and RCP8.5 emissions scenarios.

2.2. Clean and refine species list

The initial dataset contained 383 species. We then refined this list by cross-referencing each species with information from FishBase (Froese & Pauly, 2025), SeaLifeBase (Palomares & Pauly, 2025), and relevant literature sources to exclude taxa not confirmed in the Black Sea. The final dataset consisted of 102 species.

2.3. Convert to desired analysis format

We applied a probability cutoff of 0.5, reclassifying values above this threshold as presence (1) and all others as absence (0). Binary presence/absence rasters were subsequently resampled to the target analysis resolution (0.25° (~27.8 km)) using nearest-neighbor interpolation to retain categorical values.

Step 3. Calculate Species Weights

Species weights were calculated to reflect their need for conservation priority in the Black Sea. Extinction risk was considered first, using IUCN Red List categories and regional assessments where available: Critically Endangered species received the highest score (=1.0), Endangered species a high score (=0.75), Vulnerable and Near Threatened species intermediate scores (=0.5), and Least Concern species lower scores (=0.25). Data Deficient or Not Evaluated species were assigned an intermediate weight (=0.5) following a precautionary principle. Endemism was also incorporated: species restricted to very small areas of the Black Sea received maximum weight, species endemic to the broader Black Sea region were scored moderately (=0.75), and species with wider distributions in the Mediterranean were assigned lower scores (=0.5). Additionally, species identified as priorities under the EU Habitats Directive (Council Directive 92/43/EEC) and those recognized as key species used for identifying Important Marine Mammal Areas (IMMAs) in the Black Sea were assigned the highest weight (=1.0). These weights were combined to produce a single value for each species reflecting both ecological vulnerability and regional conservation priorities.

Step 4. Collection of data on socio-economic variables and threats

4.1. Gather anthropogenic pressure datasets

To account for current human uses of the marine environment, we compiled a set of socioeconomic cost layers representing different types of pressures in the Black Sea. Anchorage locations, port locations, munition sites, offshore platforms, fishing effort, and marine traffic were used to incorporate this aspect into the analysis. Offshore platform, marine traffic and munition site data were obtained from the European Marine Observation and Data network (EMODnet), port location data were sourced from the World Port Index (NGA, 2023), while fishing effort and anchorage locations were accessed through the Global Fishing Watch platform (GFW; Global Fishing Watch, 2025).

4.2. Convert to desired analysis format

As all the above are point datasets, we overlaid each of them on the 0.25° grid, assigning each cell a value corresponding to the number of points falling within it, and converting these counts into raster format.

Fishing effort was calculated using vessel tracking data from the Automatic Identification System (AIS), as provided by the GFW platform. Data were classified by gear type, enabling the calculation of annual fishing hours for three main categories of fishing activity: purse seiners, trawlers, and small-scale fisheries using static gears. For each category, we calculated the mean annual fishing effort (hours/year) for the period 2015-2024 in each planning unit.

Marine traffic data were obtained from EMODnet, representing the average number of vessel routes per km2 per year between 2019 and 2024.

4.3. Standardize and weight pressures

The individual cost layers were then standardized to a common 0–1 scale and combined into a cumulative index using expert-based weighting, to account for the relative ecological impact of each pressure type on the Black Sea ecosystem.

Species were first grouped using three ecological traits: habitat zone (neritic or oceanic), ecological position (pelagic, demersal, or benthic), and mobility (mobile or sessile), based on information from FishBase and SeaLifeBase. This classification resulted in six ecological groups, such as “Neritic, Demersal, Mobile” or “Neritic, Pelagic, Mobile”. Experts were then asked to rate how strongly each human pressure affects each group, using a scale from 1 (negligible impact) to 5 (severe impact), according to what they considered ecologically relevant for the Black Sea.

These scores were analyzed using linear mixed-effects models (utilizing the lme4 R package, (Bates et al., 2015)), with respondents treated as random effects and species group and pressure as fixed effects, following the approach of Donlan et al. (2010). This modelling framework was selected because it accounts for non-independence among responses from the same expert, controlling for individual scoring tendencies and ensuring that the outputs reflect the underlying consensus rather than individual bias. The model outputs were then aggregated into combined estimates for each pressure, producing final weights that represent the cumulative intensity of human activities in each planning unit.

Step 5. Integrate climate change metrics and refugia

Climate change data were integrated into some of the scenarios to account for future shifts in environmental conditions and species distributions.

5.1. Identify refugia

The concept of refugia can be defined in terms of climatic stability and habitat stability, while distinguishing between the two is essential for conservation planning. Climate refugia are those areas experiencing relatively low levels of climate change, while habitat refugia are locations where suitable environmental conditions for particular species are expected to persist through time (Ashcroft, 2010). Recognizing this distinction, our analysis explicitly incorporated both dimensions.

Habitat refugia were delineated for each species by overlapping current and future modeled distributions, with the intersecting areas representing locations of persistent habitat suitability under changing climate conditions.

In parallel, climatic stability was evaluated using the climate change velocity metric, a distance-based metric that describes the rate and direction at which organisms would need to move to track their preferred climatic conditions, to identify areas where climatic conditions are expected to remain relatively stable or to shift more slowly through time. By integrating both definitions of refugia, the analysis aimed to identify locations that are projected to retain suitable habitats for species but also likely to experience reduced change, thereby increasing their potential to serve as long-term refuges under future conditions.

5.2. Compute additional climate change metrics

In addition, several climate change metrics were derived using the *climetrics* R package (Taheri et al., 2024), to capture different dimensions of climatic exposure and risk. Specifically, we calculated (i) changes in the probability of local climate extremes, representing the difference in the likelihood of extreme temperature events (above the 95th percentile) between 1990–2020 and 2070–2100; (ii) novel climate, quantifying the dissimilarity between present and future climate conditions using standardized Euclidean distance, with higher values indicating increasingly non-analog climates; and (iii) standardized local anomalies, representing the magnitude of local temperature change standardized by inter-annual variability during the baseline period.

Habitat refugia were integrated into the prioritization as binary rasters, where a value of 1 indicated overlapping areas (refugia) and 0 non-overlapping ones (non-refugia). Climate refugia were also incorporated as biodiversity features, and since the prioritization algorithm was designed to favor areas with low climate change velocity, the scale of the layer was normalized and then inverted, so that high values represent more stable areas. The remaining metrics were normalized, summed, and re-normalized into a cumulative cost layer, ensuring that areas with higher climatic instability were assigned lower priority.

Step 6. Prepare additional data

To account for the current conservation decisions and to explore potential conservation scenarios, we compiled all established Marine Protected Areas (MPAs) in the Black Sea (WDPA, 2025). All data were originally available in polygon format and were rasterized to match the 0.25° planning unit grid used in our analyses.

A Digital Elevation Model (DEM) raster is necessary for the prior3d R package to conduct a prioritization analysis. Therefore, a bathymetric map was obtained from the General Bathymetric Chart of the Oceans (GEBCO, 2025).

Step 7. Run three-dimensional spatial prioritization (*prior3D*)

Conservation priority areas in the context of the third dimension are identified in the following process, ensuring the protection of important areas for the Black Sea ecosystem at various depths and taking into account deep-sea areas, which are often underrepresented.

Our analysis was implemented using the prior3D R package (Doxa et al., 2025), which employs advanced algorithms to perform nested prioritization across depth layers. The goal of the algorithm is to identify planning units within the area of interest that maximize biodiversity representation within a predefined geographic extent, by solving a 2D optimization problem at the lowest depth layer, and the solution at each level informs the upper levels.

In this analysis three bathymetric zones were used, based on expert opinion: a) ≤30 m, b) 30–50 m, c) 50-120 m and d) >120 m. The threshold of 120m depth was selected to reflect the specific environmental characteristics of the Black Sea (Callieri et al., 2019). This constraint was also incorporated into the analysis through the data required by *prior3D*, which include -aside from species distributions in raster form- a species information table with the minimum and maximum depth ranges of each species and classifications as pelagic or benthic, here obtained from FishBase and SeaLifeBase. For species whose maximum depth was found to exceed 120 m, the depth limit was automatically adjusted to 120 m, ensuring that the algorithm considered only the viable depth zones of the Black Sea.

The above algorithm is applied iteratively for different target percentages of protected area, resulting in a binary solution (selection/non-selection) for each planning unit. Repeating this process across various total protection levels (0%, 10%, 20%, ..., 100%) produces a set of overlapping, nested solutions, called a selection frequency map. The more frequently a planning unit is selected, the more important it is considered for protection and inclusion in a stricter zoning regime. In this way, the importance of each planning unit can be evaluated and a prioritization index estimated.

Step 8. Perform connectivity analysis (*priorCON*)

Connectivity refers to the physical and functional linkages between protected areas, enabling the movement of organisms and the flow of genetic material. In ecosystems, maintaining connectivity supports healthy populations, reduces the risk of isolation, and enhances ecosystem resilience to environmental changes.

To incorporate connectivity into the analysis, we employed the *priorCON* R package (Adam et al., 2024), which enhances prioritization algorithms by identifying clusters of features that exhibit strong ecological linkages, using graph community detection methods. For this study we utilized an edge list previously generated from a high-resolution sea current dataset for the Black Sea (Nagkoulis et al., 2025). Connectivity was quantified using the PageRank algorithm, originally developed by Google to rank web pages, which estimates the relative importance of each planning unit based on the number and quality of connections directed to it (Brin & Page, 1998). The core assumption is that important nodes accumulate more connections and are connected to other important nodes.

Step 9. Final Prioritization analysis (prioritizr):

The final prioritization analysis was conducted using the prioritizr R package (paired with the algorithmic solver Gurobi (Gurobi Optimization, LLC, 2024)), a systematic conservation planning tool which uses mixed integer linear programming (MILP) techniques to provide a flexible interface for building and solving conservation planning problems (Billionnet, 2013; Rodrigues et al., 2000). For this exercise we chose to use the maximum utility objective function, which seeks to maximize the overall level of representation across a suite of conservation features, while keeping cost within a fixed budget (Hanson et al., 2025). We, also, incorporated the biodiversity features at twice their value (2*features) in order to reflect the true number of features (species) actually involved in producing the layer. In the scenarios where existing MPAs were forced in the solution and their coverage exceeded the 10% of the area, as is the case in Romania, we forced the algorithm to select planning units within the existing network of the country, so as to highlight the top-priority areas already assigned as protected.

In this framework, conservation features consist of the selection frequency map produced by *prior3D* based on the respective scenario's species distributions. Depending on the scenario, the PageRank connectivity map derived from *priorCON* is also included as a biodiversity feature, while the cost layer used consists of the cumulative socioeconomic or climate change pressure index calculated as mentioned above. A detailed overview of the inputs used and how they are inserted in the prioritization in each scenario is provided in the Appendix.

Each step of the framework (*prior3D, priorCON*, and *prioritizr*) was carried out independently within the Exclusive Economic Zone (EEZ) of each Black Sea country. This approach ensured that the algorithm was constrained to allocate an equal proportion of priority areas within every national jurisdiction. By doing so, potential biases that could arise if the analysis were conducted at the basin-wide scale without jurisdictional constraints are avoided, considering the algorithm might otherwise concentrate priority areas disproportionately in certain countries while leaving others underrepresented.

Results

The final output of the framework consists of a binary solution for each PU (1=Selected, 0=Not selected), for area targets of 10% and 30% and a map showcasing the frequency with which each PU was selected amongst all budget solutions.

Across the 60 spatial prioritization analysis developed in this study, we produced a comprehensive suite of outputs to enable comparison across planning scenarios. For each scenario, three rasters were generated: (i) the spatial prioritization solution meeting the 10% representation target, (ii) the corresponding solution for the 30% target, and (iii) the selection frequency map, which captures how consistently each planning unit was chosen across multiple algorithm runs, adding up to 180 rasters. In addition, two maps per scenario were created to facilitate interpretation, one depicting the combined 10 and 30% priority areas and another visualizing the spatial patterns of selection frequency, resulting in 120 maps total.

Given the volume of results, we showcase four representative scenarios that illustrate the diversity of spatial outcomes produced under different parameterizations of ecological features, cost layers, and constraints. The complete set of generated maps can be found in the Appendix, including detailed tables describing the data inputs and parameter settings for every scenario.

1. Current scenario, with socioeconomic costs, MPAs locked in and species weights used (Figure 2)

This run identifies conservation priority areas based purely on current species distributions in the Black Sea and areas where human activity might pose a challenge on conservation efforts, while ensuring existing Marine Protected Areas (MPAs) remain part of the solution and giving higher priority to species of greater conservation concern (Figure 2).

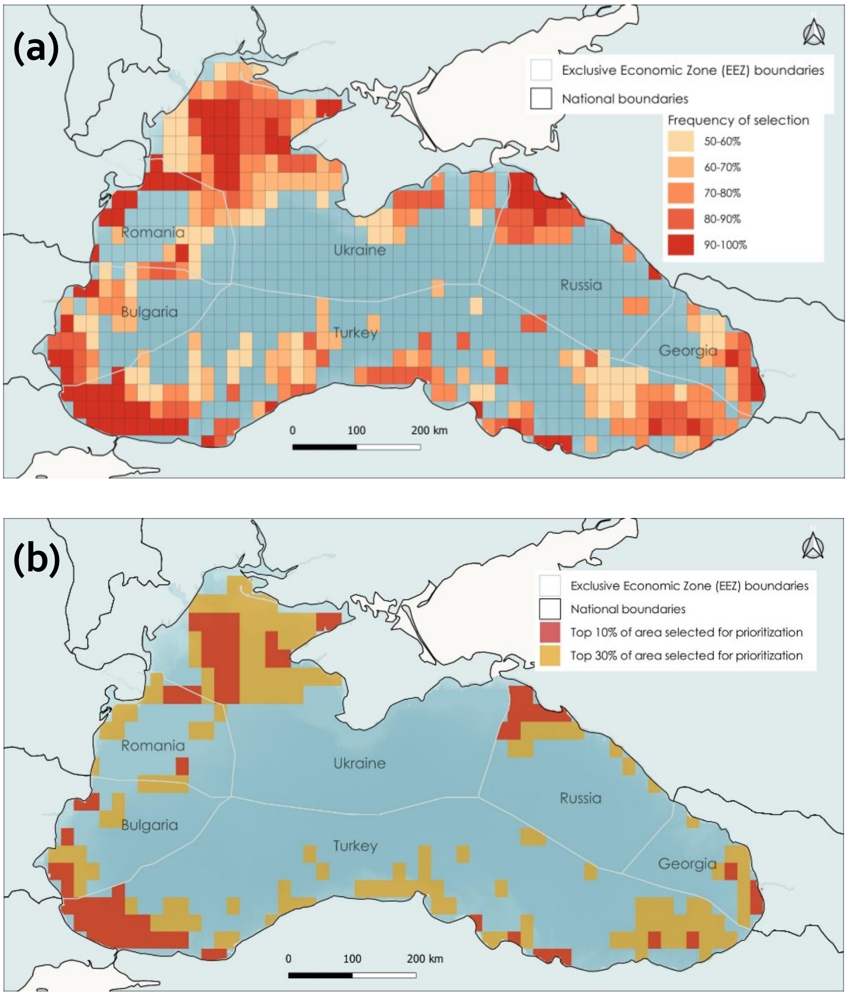

Figure 2: (a) Map showing the selection frequency of each planning unit across 11 budget scenarios (0%, 10%, 20%, ..., 100%) generated by the prioritizr algorithm. Values are grouped into classes, reflecting how consistently each planning unit is prioritized as conservation budgets increase. (b) Areas representing the top 10% (red) and 30% (yellow) of the study region identified as the highest priority for conservation by the prioritizr algorithm, aligned with the EU Biodiversity Strategy for 2030.

2. Current scenario accounting for climate change (RCP4.5 2100), with MPAs locked in and species weights used (Figure 3)

This run identifies conservation priority areas based on current and near future (Representative Concentration Pathway 4.5 – for the year 2100) species distributions in the Black Sea and areas where human activity might pose a challenge on conservation efforts, while ensuring existing Marine Protected Areas (MPAs) remain part of the solution and giving higher priority to species of greater conservation concern (Figure 3). The analysis is based on species distribution models projected under RCP 4.5, an intermediate scenario where CO_2 emissions peak around 2040 and then decline gradually. It involves moderate reductions in methane and sulphur dioxide emissions, along with some negative emissions measures like carbon absorption by forests. This pathway is projected to lead to a global temperature rise between 2 °C and 3 °C by 2100.

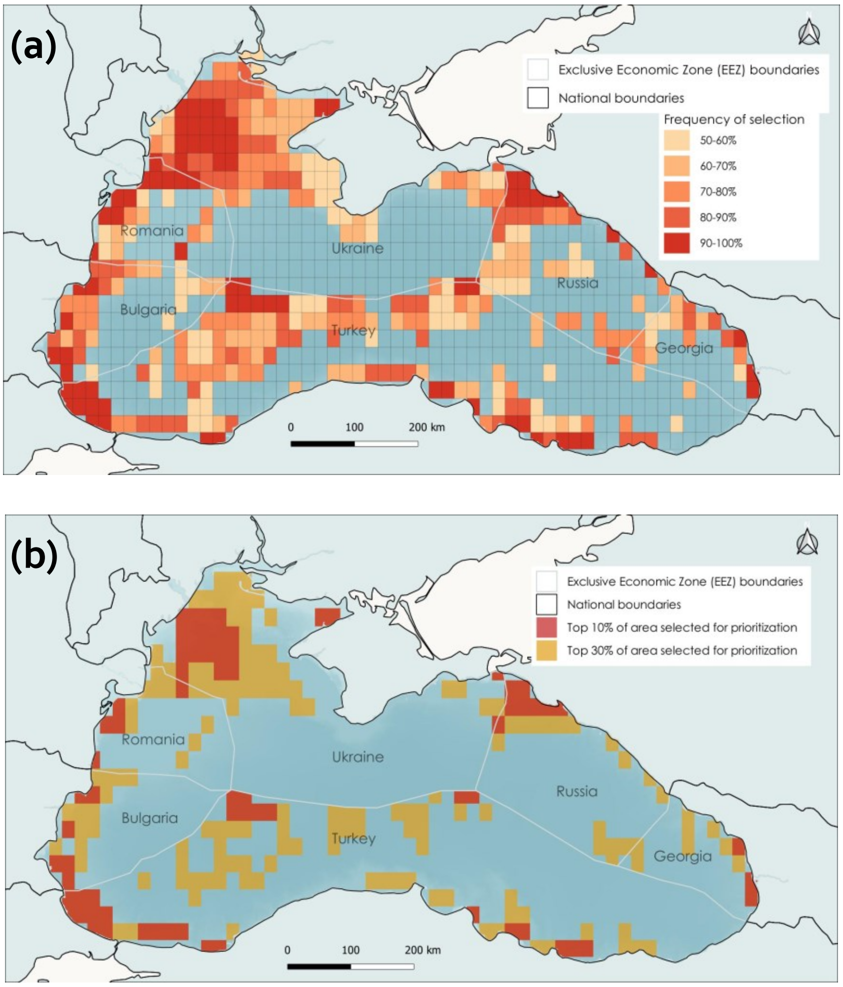

Figure 3: (a) Map showing the selection frequency of each planning unit across 11 budget scenarios (0%, 10%, 20%, ..., 100%) generated by the prioritizr algorithm. Values are grouped into classes, reflecting how consistently each planning unit is prioritized as conservation budgets increase. (b) Areas representing the top 10% (red) and 30% (yellow) of the study region identified as the highest priority for conservation by the prioritzr algorithm, aligned with the EU Biodiversity Strategy for 2030.

3. Future scenario (RCP4.5 2100), with MPAs locked in and species weights used (Figure 4)

This scenario explores the future distribution of marine biodiversity in the Black Sea under projected climate change by the year 2100, using Representative Concentration Pathway 4.5. It examines how conservation priorities might shift when accounting for changing species distributions due to climate change, while ensuring existing Marine Protected Areas (MPAs) remain part of the solution and giving higher priority to species of greater conservation concern (Figure 4).

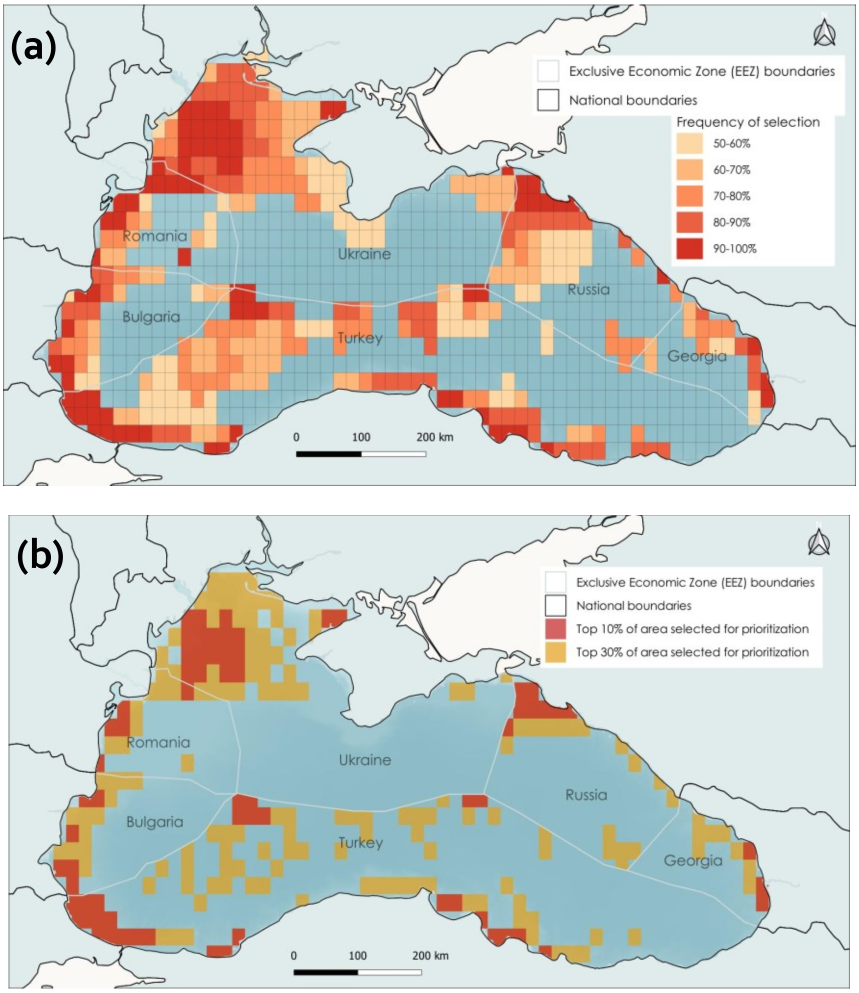

Figure 4: (a) Map showing the selection frequency of each planning unit across 11 budget scenarios (0%, 10%, 20%, ..., 100%) generated by the prioritizr algorithm. Values are grouped into classes, reflecting how consistently each planning unit is prioritized as conservation budgets increase. (b) Areas representing the top 10% (red) and 30% (yellow) of the study region identified as the highest priority for conservation by the prioritzr algorithm, aligned with the EU Biodiversity Strategy for 2030.

4. Worst case climate change scenario (RCP8.5 2100), with MPAs locked in and species weights used (Figure 5)

This scenario explores conservation priorities for the Black Sea under a severe climate change future (RCP8.5 - year 2100), combining multiple climate change components to identify areas likely to remain valuable for biodiversity even under extreme warming, while ensuring existing Marine Protected Areas (MPAs) remain part of the solution and giving higher priority to species of greater conservation concern (Figure 5). The analysis is based on species distribution models and environmental conditions projected under RCP 8.5, a high-emissions scenario where greenhouse gas emissions continue to increase throughout the century. This pathway assumes limited climate action and results in substantial warming and sea level rise by 2100, posing significant risks to ecosystems and human societies.

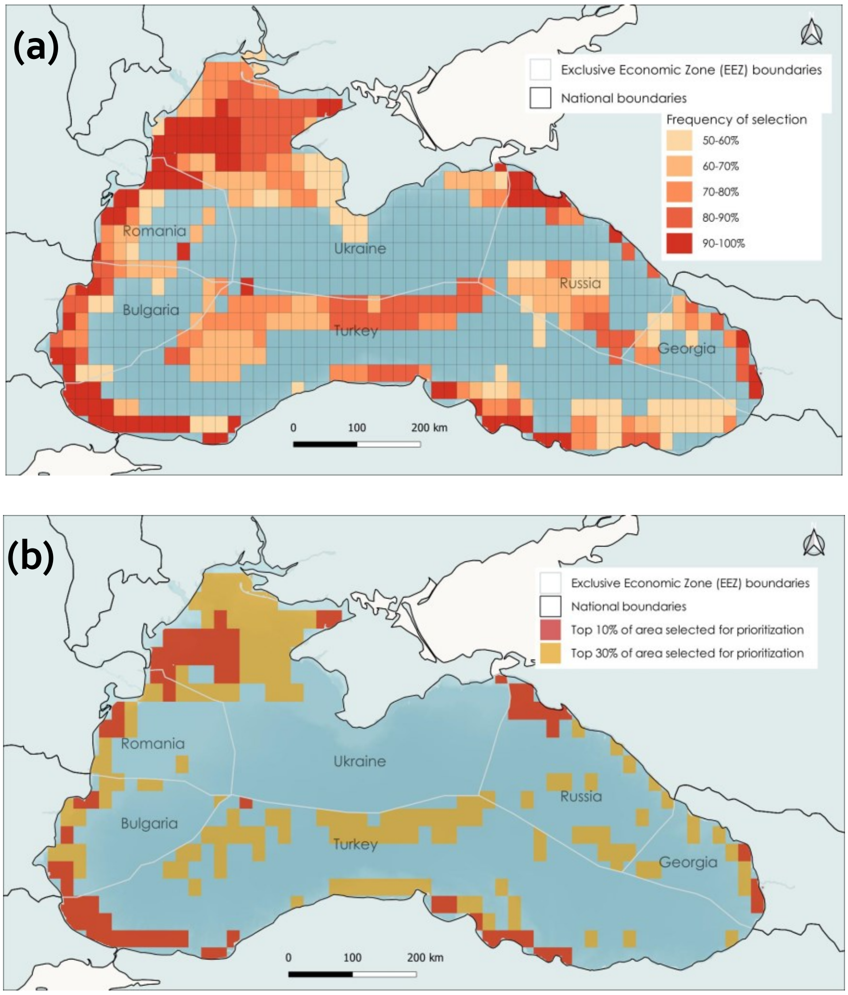

Figure 5: (a) Map showing the selection frequency of each planning unit across 11 budget scenarios (0%, 10%, 20%, ..., 100%) generated by the prioritizr algorithm. Values are grouped into classes, reflecting how consistently each planning unit is prioritized as conservation budgets increase. (b) Areas representing the top 10% (red) and 30% (yellow) of the study region identified as the highest priority for conservation by the prioritzr algorithm, aligned with the EU Biodiversity Strategy for 2030.

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