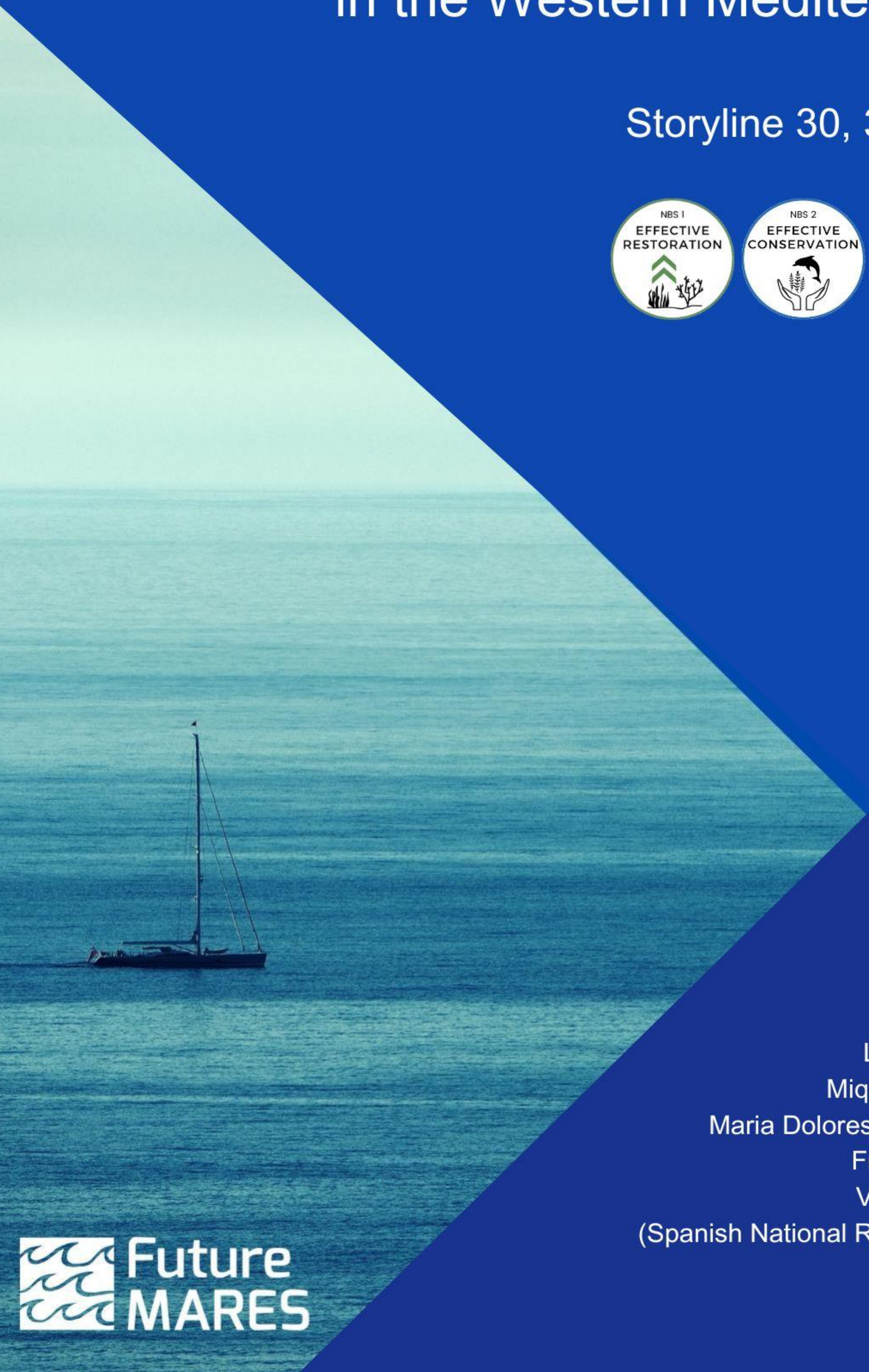
Management of Coastal to Offshore ecosystems and their services in the Western Mediterranean

Storyline 30, 31 & 33

NBS 1 EFFECTIVE RESTORATION

NBS 2 EFFECTIVE CONSERVATION

NIH NATURE-INCLUSIVE HARVESTING



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Future MARES

Introduction to FutureMARES

The EU Horizon project FutureMARES (2020-2024) was designed to develop science-based advice on viable actions and strategies to safeguard biodiversity and ecosystem functions to maximise natural capital and its delivery of services from marine and transitional ecosystems in a future climate. The program investigates effective habitat restoration, conservation strategies and sustainable harvesting at locations across a broad range of European and other marine and transitional systems. The restoration of habitat-forming species (plants or animals) and habitat conservation (e.g. marine protected areas, MPAs) represent two nature-based solutions (NBS) defined by the EU as "resource efficient actions inspired or supported by nature to simultaneously provide environmental, social and economic benefits that help to build resilience to change". A third action that will interact with these two NBS and have positive effects on marine biodiversity is nature-inclusive harvesting (NIH) such as the sustainable farming of plants and animals at the base of marine food webs and ecosystem-based management practices for traditional (artisanal) and commercial fisheries.

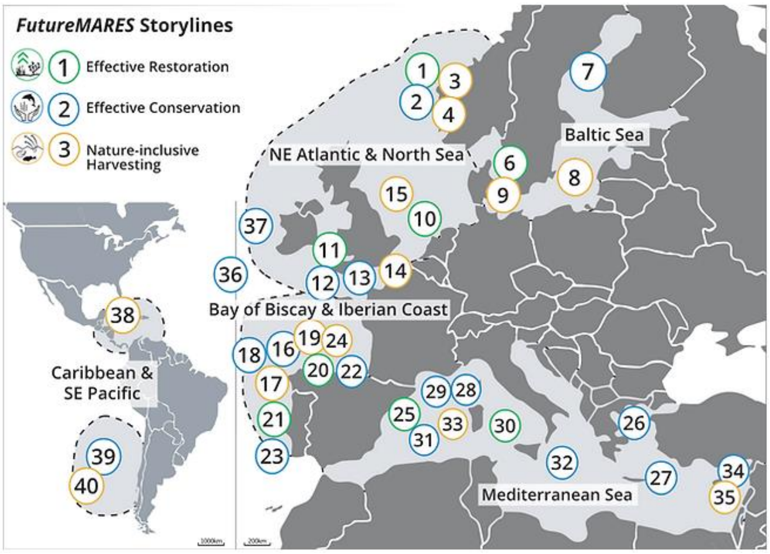

Figure 1: *Overview of FutureMARES Storylines*

FutureMARES was designed to:

- advance the state-of-the-art forecasting capability for species of high conservation value,
- explore new and less carbon intensive aquaculture production methods,
- perform modelling analyses geared towards informing the development of climate-smart marine spatial planning approaches, and
- provide an assessment of ecosystem services based on scenarios of climate change and the implementation of NBS and NIH.

This document provides a summary of activities conducted in FutureMARES in a specific area on specific NBS and/or NIH. The activities are multi-disciplinary and include marine ecology (analyses of historical time series and experiments performed in the field and laboratory), climate change projection modelling (future physical, biogeochemical and ecological changes), economic analyses and social-ecological risk assessments. Many of these components and analyses were co-developed with local and regional stakeholders through regular engagement activities. The work presented in this Storyline document represents activities conducted by a large number of FutureMARES project partners. Broader comparisons and syntheses (across regions and/or topics) are provided in the FutureMARES deliverable reports submitted to the European Commission (www.futuremares.eu).

Regional Storyline Context

The Western Mediterranean Sea basin (~ 846,000 km^2, 0-3600 m depth) includes the European Mediterranean coastlines belonging to Spain, France and Malta, as well as the portion of Italian coastlines along the Thyrrenian Sea and Strait of Sicily, and the coastlines of Morocco and Algeria. The basin includes five marginal seas: the Thyrrenian Sea, the Balearic Sea, the Sea of Sardinia, the Ligurian Sea and the Alboran Sea.

The region is relatively productive compared to the Eastern and Central parts of the Mediterranean Sea, especially the northwestern region and the continental shelves associated with large rivers and deltas (Rhone and Ebro Delta) and a counter-clock marine circulation (Bosc et al. 2004). It hosts important proportions of Mediterranean species and habitat diversity, and important percentages of endemic and at-risk species, including seabirds, marine turtles, marine mammals, chondrichthyans, finfish, invertebrates and primary producers (Coll et al. 2010).

The region is strategically positioned and is one of the principal maritime corridors in the world and the gateway to Africa for European countries. Goods transport represents close to 40% of the Mediterranean value. Marine harvests from fisheries (artisanal and industrial) and aquaculture are the second most important activity in terms of gross added value and employment. In addition, recreational and subsistence fishing are very important activities from an economic, social and cultural point of view. The region is also a traditional and consolidated tourist destination, in particular its northern rim (Katsanevakis et al. 2015).

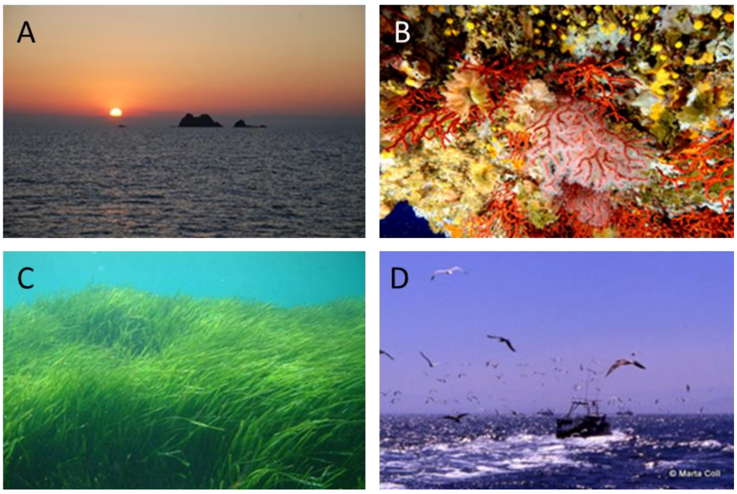

Figure 2*: Photos of emblematic marine ecosystems and habitats (a) Columbretes Islands (source: M. Coll), (b) Coralligenous assemblage (source: http://agricultura.gencat.cat), (c) Seagrass Posidonia oceanica meadow (source: M. Coll) and (d) Bottom trawl fishing vessel followed by seabirds. Credit: M. Coll.*

Human activities involve a number of environmental pressures causing high or very high impacts in marine and coastal ecosystems and resources. Maritime, but also land-based activities (industrial activities and a dense urbanised coastline), pose environmental pressures, including air and water pollution, waste generation and resource degradation and depletion (Coll et al. 2012, Micheli et al. 2013a, Katsanevakis et al. 2015). Overexploitation of fishing resources is among the most important pressures in the region, along with biodiversity and habitat loss. Climate change (CC) is posing increasing impacts to habitats and resources, and is expected to intensify more rapidly that the average global mean (Calvo et al. 2011, Marbà et al. 2015, Moatti and Thiébault 2018, Garrabou et al. 2019, Salat et al. 2019). Current conservation actions are not enough to halt resource degradation since marine protected areas (fully, highly, moderately or poorly protected) cover less than 1% of the region (Claudet et al. 2020a, Castro-Cadenas et al. Submitted). This highlights the need to implement spatial-temporal management measures resilient to CC, including the mandate for protection of Vulnerable Marine Ecosystems (VMEs) and Essential Fish Habitats (EFH) (Micheli et al. 2013b, Coll et al. 2015, Giménez et al. 2020).

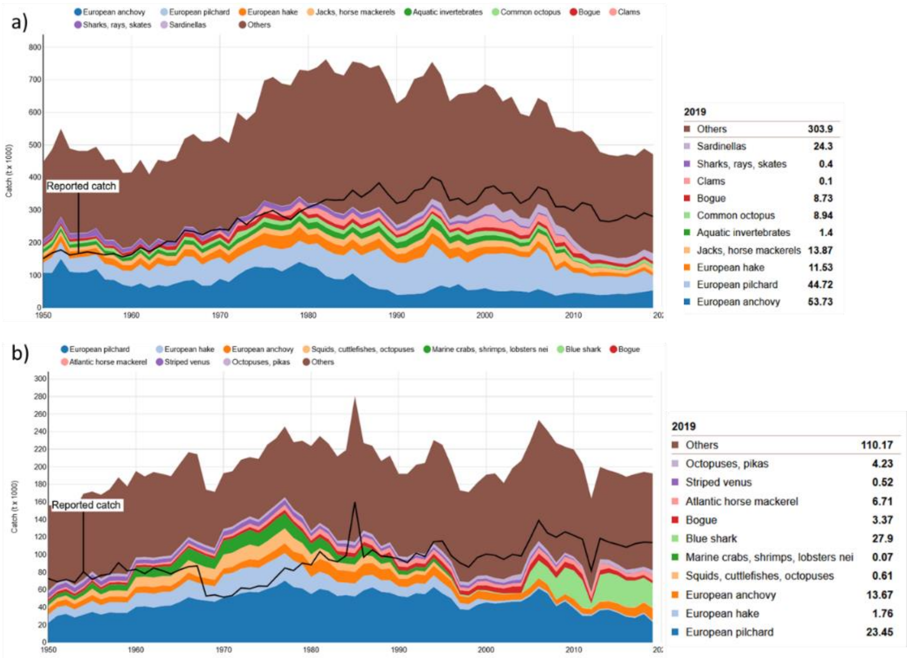

Figure 3: *(a) Fisheries catches from the Western Mediterranean Sea and (b) the Alboran Sea (source http://www.seaaroundus.org).*

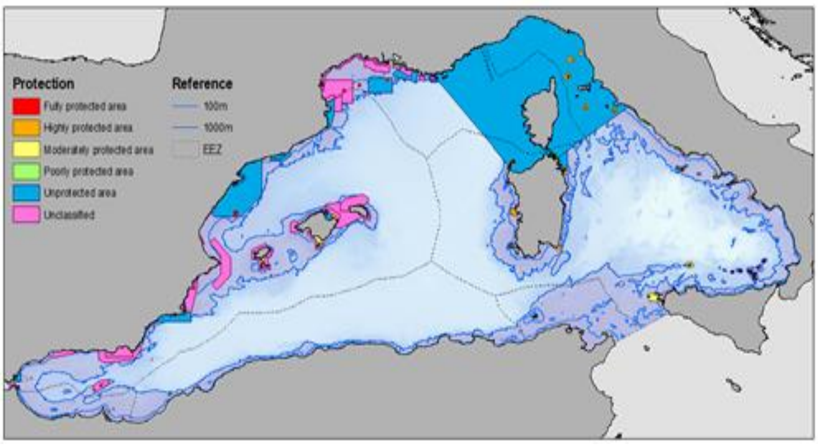

Figure 4: *MPAs, Gulf of Lions (GoL) no take zones, and FRA GoL and their classification (according to (Horta e Costa et al. 2016) (source M. Coll).*

Projected impacts of climate change

Climate change in the region is projected to intensify more rapidly than the average global mean and is already posing increasing impacts to habitats and resources. Available trends indicate increases in sea water temperature at different depths, declines in sea surface salinity related to declines in rainfall, river run-off and wind, a prolonged stratification period and more frequent and intense marine heat wave events (Calvo et al. 2011, Marbà et al. 2015, Moatti and Thiébault 2018, Garrabou et al. 2019, Salat et al. 2019, Kristiansen et al. 2024).

Several studies projected that, by increasing the vertical stability of the water column and by decreasing nutrient replenishment, seawater warming will cause changes in phytoplankton bloom phenology, biomass and community structure (Moullec et al. 2016). The sensitivity of Mediterranean biota to warming varies across taxonomic groups (Marbà et al. 2015). However, warming is already affecting the fitness of marine biota as observed by changes in the abundance, survival, reproduction, phenology and migration of species (Marbà et al. 2015).

The large effects of CC are already evident, for example, in: (1) a meridionalisation of taxa (including algal, invertebrate and vertebrate species) with the favourization of the more thermophilic species over the temperate ones (Sabatés et al. 2006) and changes in community structure (Veloy et al. 2022, Veloy et al. 2024); (2) mass mortality events of sessile invertebrates of the coralligenous communities (Garrabou et al. 2019{Garrabou, 2022 #7760)}; (3) increases in the small fraction of phytoplankton (Moullec et al. 2016); (4) proliferation of gelatinous carnivores, including jellyfish (Calvo et al. 2011); (5) a faster acidification of seawater with important impacts on many organisms, including bivalves and the coralligenous systems (Lacoue-Labarthe et al. 2016); and the socioecological system (Espasandin et al. 2024, Espasandin et al. Submitted).

The effects of CC on Mediterranean marine biota have synergistic effects with other anthropogenic impacts such as high exploitation (Piroddi et al. 2017, Ramírez et al. 2018, Ramírez et al. 2021, Coll et al. 2024a, Veloy et al. Submitted). These effects may ultimately have significant consequences for ecosystem productivity, biodiversity and functioning and hence for the overall goods and ecosystem services they provide, especially the production of living resources (Moullec et al. 2016, Piroddi et al. 2017, Coll et al. 2024a).

FutureMARES has made projections of physical and biogeochemical impacts of climate change in the region including three IPCC scenarios (SSP126, SSP 245 and SSP 585 (for background see Deliverable Report 2.2). Geographical Maps were extracted from the full dataset by averaging over the following periods, consistent with the periods considered in the IPCC AR6 WG1 report:

- present day: 1995-2014
- near future: 2021-2040
- mid future: 2041-2060
- far future: 2080-2099

Time-series plots were produced averaging over the area of interest for each storyline and show the ensemble mean in the full lines and the range of model responses in the shaded areas as represented by the 2.5 and 97.5 percentiles of the ensemble. Credit: Momme Butenschön, Euro-Mediterranean Center on Climate Change (Kristiansen and Butenschön 2022, Kristiansen et al. 2024).

Time series plots show important changes in temperature (both at 5 m depth, 0-150 m depth integrated and at seafloor) under the three SSP scenarios tested, which mostly project an increase with time, larger under SSP 585, followed by SSP 245 and SSP 126). In addition, important changes are being projected for Salinity, Oxygen, Chlorophyll and Phytoplankton Carbon. All these changes are spatially heterogenic, illustrating that within the Western Mediterranean Sea, changes will be different between sub-regions.

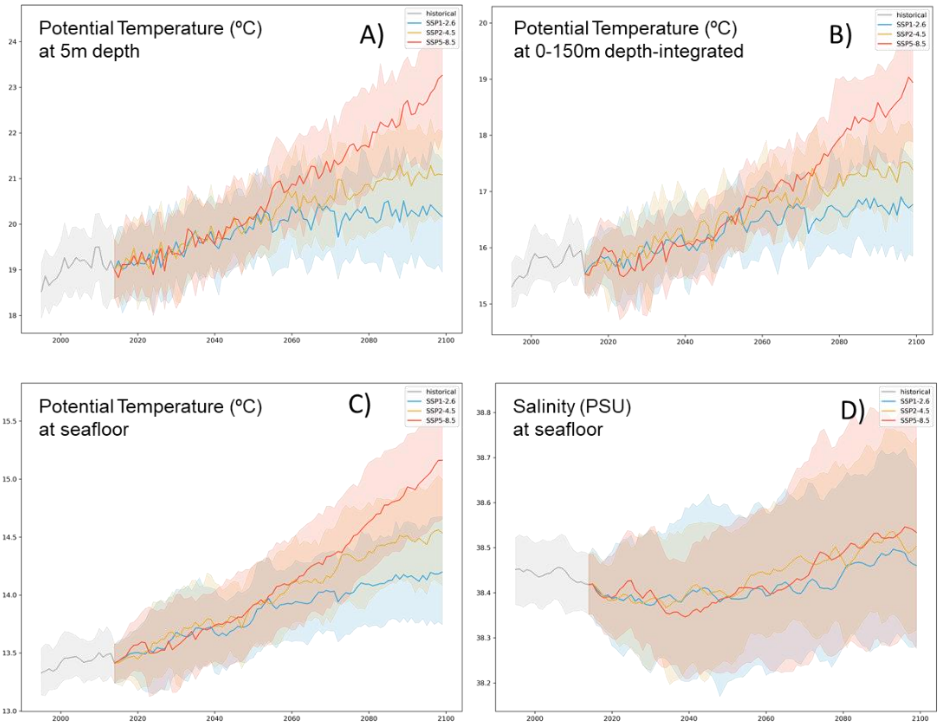

Figure 5: *Time series of climate projections for the Western Mediterranean Sea regarding Temperature and Salinity from FutureMares. The figures were produced using trend preserving statistical downscaling (Lange, 2019) of a multi-model ensemble Earth System Model historical simulations and future projections from the CMIP6 archive trained on reanalysis datasets from the Copernicus Marine Environment Monitoring Service (Kristiansen et al. 2024)..*

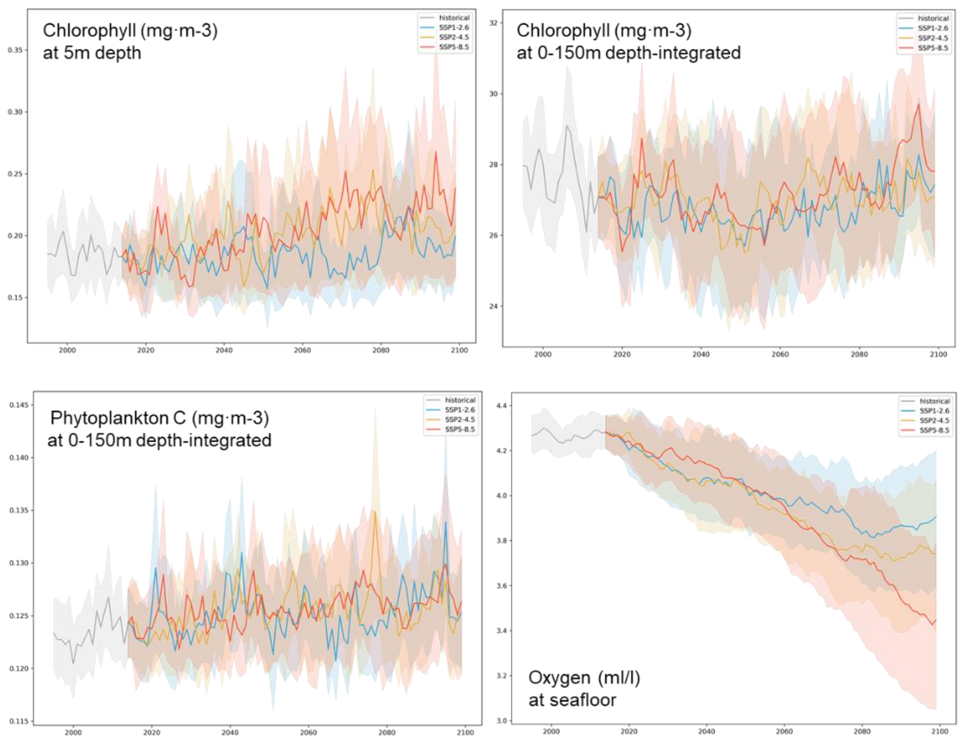

Figure 6: *Time series of climate projections for the Western Mediterranean Sea regarding Chlorophyll, Phytoplankton Carbon and Oxygen from FutureMares. The figures were produced using trend preserving*

statistical downscaling (Lange, 2019) of a multi-model ensemble Earth System Model historical simulations and future projections from the CMIP6 archive trained on reanalysis datasets from the Copernicus Marine Environment Monitoring Service (Kristiansen et al. 2024).

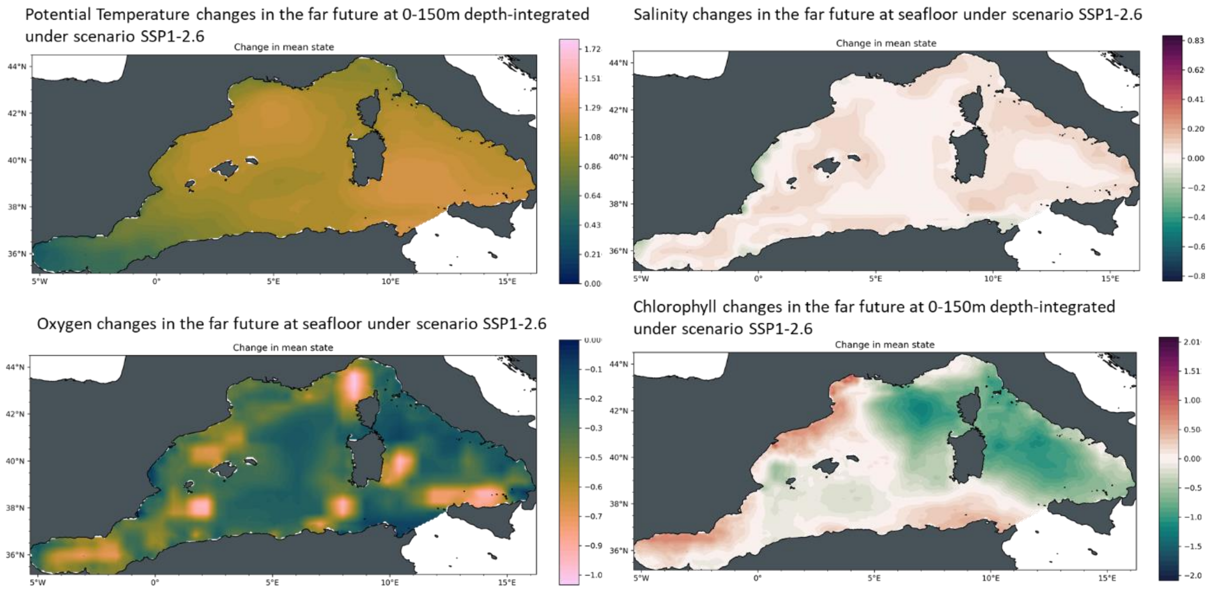

Figure 7: *Change in mean state of climate projections for the Western Mediterranean Sea regarding Temperature, Salinity, Oxygen and Chlorophyll under scenario SSP 1-2.6 from FutureMares. The figures were produced using trend preserving statistical downscaling (Lange, 2019) of a multi-model ensemble Earth System Model historical simulations and future projections from the CMIP6 archive trained on reanalysis datasets from the Copernicus Marine Environment Monitoring Service (Kristiansen et al. 2024).*

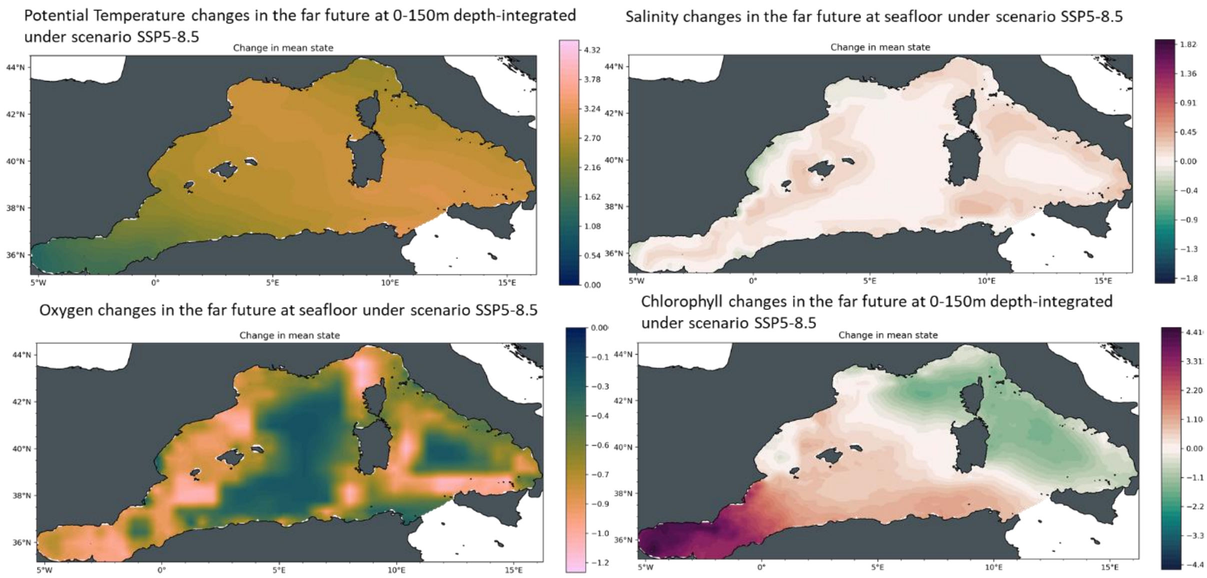

Figure 8: *Change in mean state of climate projections for the Western Mediterranean Sea regarding Temperature, Salinity, Oxygen and Chlorophyll under scenario SSP 5-8.5 from FutureMares. The figures were produced using trend preserving statistical downscaling (Lange, 2019) of a multi-model ensemble Earth System Model historical simulations and future projections from the CMIP6 archive trained on reanalysis datasets from the Copernicus Marine Environment Monitoring Service (Kristiansen et al. 2024).*

Scenarios describing future society and economy

FutureMARES developed three policy-relevant scenarios for NBS and NIH based on commonly used IPCC frameworks (for more details see hyperlink). These scenarios were regionalised based on stakeholder perspectives to guide activities such as model simulations and risk assessments.

(GS) Global Sustainability (SSP126) - Low challenges to mitigation and adaptation

The world shifts gradually but pervasively to a more sustainable path, emphasising inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, investments in educational and health accelerate lower birth and death rates, and the emphasis on economic growth shifts to an emphasis on human well-being.

(NE) National Enterprise (SSP385) - High challenges to mitigation and adaptation

A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to focus on domestic or regional issues. Policies shift over time to be oriented more on national and regional security. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development.

(WM) World Markets (SSP585) - High challenges to mitigation, low challenges to adaptation

The world increasingly believes in competitive markets, innovation and participatory societies to produce rapid technological progress and train and educate people for sustainable development. The push for economic and social development is coupled with exploiting abundant fossil fuel resources and adopting resource and energy intensive lifestyles around the world.

Figure 9: *The three, broad scenarios that were regionalised to guide activities in FutureMARES. © FutureMARES project*

At the present time, the current national policy is limited to few MPAs that have been established due to ad hoc value/aims. Overall, there has not been a proactive planning for Marine Conservation. Most existing MPAs are partially protected, with low protection efficiency, and of small size. The current national policy is limited to the application of the CFP in EU waters, and sub-national legislation in national interior waters, with little success due to low compliance. National legislation and regional agreements are applied in non-EU waters. There are several cultural activities that may conflict with marine conservation, including fishing (recreational, artisanal or industrial), recreation and tourism, diving, etc. Moreover, there are several cultural activities that may conflict with sustainable fishing, including recreational, artisan and/or industrial fishing as well as tourism and its impacts (pollution of waters, use of the coastal line and beaches, use of the maritime domain, increase of noise, ...).

In the future, the GS scenario areas in EU waters increase to reach 30% in 2030, with 10% fully protected and 20% highly protected. Areas outside EU waters may follow if financial cooperation is enhanced. Areas in EU waters reach MSY targets (CFP) and MSFD complementary targets in 10 years. Areas outside EU waters may follow if financial cooperation is enhanced. Most human marine activities improve, with the exception of highly impacting industrial fishing such as bottom trawling which is banned or highly reduced. Fishing activities reach sustainability. Other activities related to tourism reduce their impact and converge towards lower ecological footprints. On the other hand, in the NE scenario, areas in EU waters do not increase to reach global conservation targets and MPA remain similar size as today. Areas outside EU waters do not improve either. Areas in EU waters do not reach MSY targets (CFP) and MSFD complementary targets with further degradation with as CC intensifies in region. Substantial improvements are unlikely in areas outside EU waters. Some human marine activities improve, mostly related to recreational fishing, tourism and diving; however, negative activities persist, especially related to tourism. Thirdly, in the WM scenario, areas in EU waters increase to reach 10%-30% in 2030, but are mostly poorly or moderately protected. Areas outside EU waters may follow if financial cooperation is enhanced. Regarding MSY targets (CFP), this scenario plays out similarly to the NE scenario. It is likely that the amount of human marine activities increases and their negative environmental impacts worsen.

FutureMARES research needs

The research needs to be undertaken under FutureMares included obtaining a broader, more robust and integrated overview of CC impacts on the Western Mediterranean region. This entailed obtaining improved CC projection data and understanding of how CC will interact with multiple stressors to influence the productivity, biodiversity and ecosystem service provision of the western Mediterranean. For implementation of Nature-based Solutions, a better understanding of the potential impact of single and the synergistic effect of multiple solutions within a CC scenario context was needed. Such scenario testing needed to include plausible alternatives for future protection (MPAs and other measures – NBS2) and sustainable harvesting of seafood (NIH) compared with status quo (spatial, temporal and spatiotemporal).

There was a lack of understanding of how to consider habitat-forming species and their recovery (NBS1) within regional assessments. Furthermore, research was needed to assess ecological risks at the regional level and changes in ecosystem services under CC and different implementations of NBS. Moreover, research was needed to understand the adaptive capacity of the socio-ecological system with respect to CC and its impacts. Finally, this knowledge needed to be implemented to emergent but still incipient initiatives for climate-ready marine and maritime spatial planning.

FutureMARES research (T = Task – see program structure at futuremares.eu)

- **T1.1** Retrieve available environmental data to track observations of climate change, compilation of historical data series about vertebrates and invertebrates (abundance, biomass, catches), and calculation of the Community Thermal Index based on selected time series for the Western Mediterranean Basin (WMB);
- **T1.2** Compilation of published data about distribution, abundance and traits (including information on the thermal limits) of selected fish species characteristic of the WMB and their distribution in relation to depth, impacts of fishing pressure as well as their legal protection status in the region;
- **T1.3** Downscaling of FutureMares general scenarios to the Western Mediterranean ecological, political, social, economic, technological and legal context;
- **T2.3** Identification of environmental data needed for the regional model analyses;
- **T3.3** Contribution to the knowledge available about genetic adaptation of species to climate change;

- **T4.1** Compilation of GIS layers about distribution of habitat forming species, such as mael, coralligenous and *Posidonia oceanica* meadows distribution, in the WMB;
- **T4.2** Compilation of GIS layers about distribution of charismatic species, such as marine mammals, seabirds and turtles, in the WMB;
- **T4.3** Modelling the fisheries activity and plausible scenarios in the WMB using a marine ecosystem model of the region (4.4 model);
- **T4.4** Testing the effects of NBS 1 and 2 and NIH, and their interactions and synergies, under moderate and extreme CC projections. When modelling NBS2 we considered the ecological consequences of recovering habitat forming species (NBS1);
- **T5.1** Developing Climate Risk Assessment at functional group level for the WMS;
- **T5.3** Developing Climate Risk Assessment of the ecosystem services level of the WMS;
- **T6.1** Prioritization of management sites in the WMS in the face of climate change (identification of Bright Spots);
- **T6.2** Estimation of planning costs of managing sites in the WMS;
- **T7.1 & 7.2** Engagement with policy makers at national, regional or EU level, and international level (IPCC, IPBES, through FishMIP collaboration);
- **T8.1** Online presentations, synergies with other projects and initiatives (e.g., INTEMARES), and meetings with regional stakeholders in annual venues.

2. Research conducted

2.1 Ecological Knowledge

Several studies have been developed regarding ecological knowledge in the Western Mediterranean Sea within FutureMares (Sbragaglia et al. 2021, Ouled-Cheikh et al. 2022, Sbragaglia et al. 2022, Veloy et al. 2022, Antoniou et al. 2023, Sbragaglia et al. 2023, Chust et al. 2024, Espasandin et al. 2024, Veloy et al. 2024, Castro-Cadenas et al. Submitted, Espasandin et al. Submitted, Veloy et al. Submitted).

Below we highlight the contribution to the CTI analysis applied to the Western Mediterranean region (Chust et al. 2024, Espasandin et al. Submitted). In this analysis, we developed a contribution using commercial fisheries landings with a high spatial and temporal resolution.

- **Time series compiled and examined**

We used a long-term dataset (2000-2023; (ICATMAR 2023)) of commercial fishery landings to assess and quantify spatial-temporal changes in the catch and revenue composition in the Northwestern Mediterranean Sea and the underlying processes driving these changes. To do that, we analysed the weighted mean thermal affinity of the catch (Mean Temperature of the Catch, MTC) and revenue (Mean Temperature of Revenue, MTR) using a 23-year highly resolved time series from commercial fleets across the Catalan coast, including 22 different ports located all along the coast.

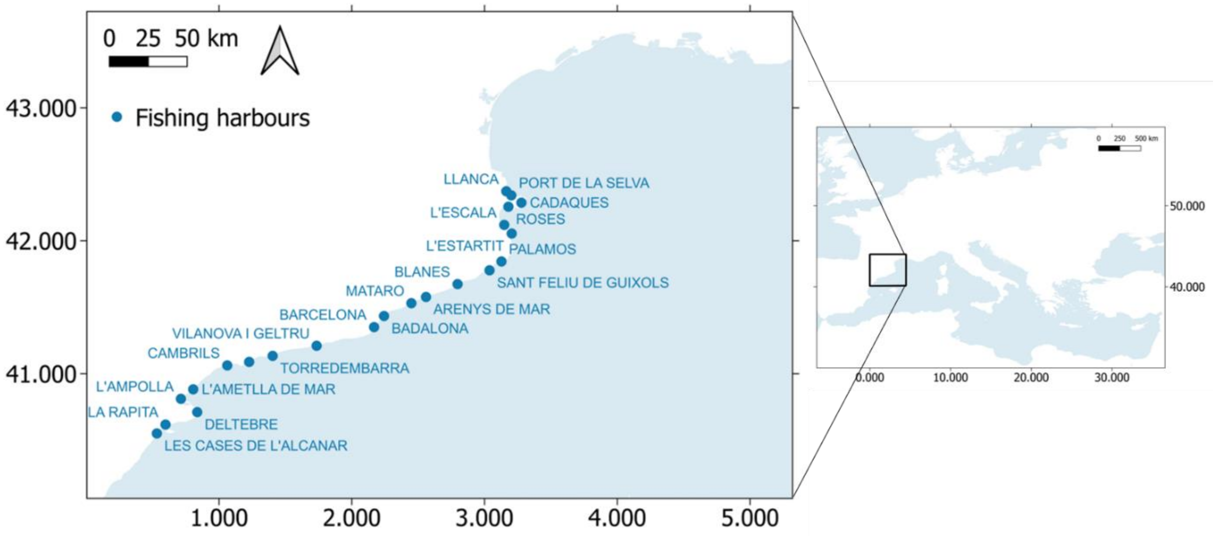

Figure 10: *Map of the study area with fishing harbours indicated (Espasandin et al. Submitted).*

Data was aggregated per fishing port to analyse the spatial variability. We considered the landings of the main fleets occurring in the area (i.e., purse seiners, bottom trawlers, small scale, surface long liners, and bottom longliners). We also aggregated the data by considering three different taxonomic groups (i.e., cephalopods, crustaceans, and fish). We performed the analysis by aggregating daily data into annual values.

- **Main results**

Our results indicated an overall increase of both the composition of the catch and the revenues for different taxonomic groups and fleets, with an increase in the contribution of warm-affinity species (i.e., tropicalization). Importantly, the decrease in the contribution of cold-affinity species to fishing catches (i.e., deborealization) emerged as a significant process as well, particularly influencing pelagic fisheries (i.e., purse-seiners and surface longliners) and some important commercial species (e.g., European hake *Merluccius merluccius*, European sardine *Sardina pilchardus*, Blue whiting *Micromesistius poutassou*, and Norway lobster *Nephrops norvegicus*). Even if the increase in both MTC and MTR was the most common result, the spatial dimension showed heterogenic trends and declines in some cases.

In summary, our study provided valuable information about changes in catch composition over time, which may have had important consequences for ecosystem functioning and structure in the Northwestern Mediterranean Sea. Moreover, we revealed that the effects of ocean warming may cascade through the entire social-ecological system, reflected by the changes in revenue composition over time. The correlation between catch and revenue change evidenced the adapting capacity or fragility of specific fishing fleets and pointed to management priorities in the region.

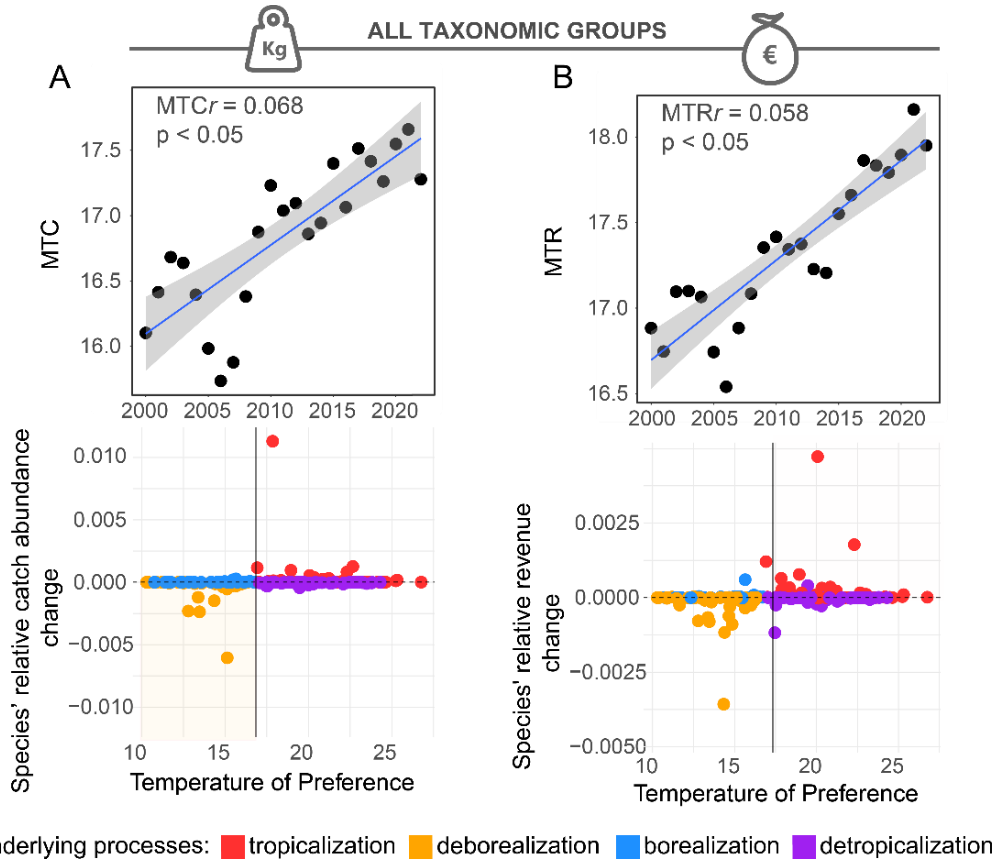

Figure 11: *Changes in the MTC and MTR with time and the underlying processes aggregating all the taxonomic groups, all the fleets, and all the fishing harbours. (A) Changes in MTC with time – upper panels – and the underlying processes – bottom panels. (B) Changes in MTR with time – upper panels – and the underlying processes – bottom panels. Significant linear regressions and 95% intervals are represented in blue lines and grey shadows for the period 2000-2022. The red and yellow squared shadows represent the dominant process contributing to the increase in MTC and MTR, tropicalization or deborealization in each case (Espasandin et al. Submitted).*

2.2 Projections of future biological effects

Several studies have been developed regarding projections of biological effects in the Western Mediterranean Sea (Heymans et al. 2020, Garcia et al. 2021, Piroddi et al. 2021, Steenbeek et al. 2021, Tittensor et al. 2021, Carmezim et al. 2022, Piroddi et al. 2022, de Mutsert et al. 2023, Ofir et al. 2023, Sánchez Zulueta et al. 2023, Sarzo et al. 2023, Coll et al. 2024a, Shin et al. 2024, Fuster-Alonso et al. Submitted). Specific results are also included in Deliverables 4.3 and 4.4 of FutureMares (Coll et al. 2024b, Shin et al. 2024).

We here highlight the contribution on the consequences of combinations of Nature-Based solutions under climate change scenarios (Coll et al. 2024b), which were presented in Deliverable 27 (4.4). In this analysis, two marine ecosystem models were used to investigate future effects of climate change and management interventions in the region.

- **Marine ecosystem models**

Ecospace models representing both the Western Mediterranean Sea, and the sub-region of the North-western Mediterranean Sea, were refined and used to model ecosystem change following regionally downscaled narratives based on the general scenarios. The models, previously calibrated and driven with standardized downscaled (ensemble average) environmental data, were used to run contrasting scenarios (SSP1-RCP2.6, SSP3-RCP8.5 & SSP5-RCP-8.5, including climate equivalent status quos). Implementations of management interventions under different Nature-Based Solutions (NBSs) and Nature-Inclusive Harvesting (NIH) options included protection, restoration and ecosystem-based management of fisheries, and considered regional contexts, current legislations and future developments of the legal frameworks.

For each scenario, the spatial-temporal impacts of climate change and human activities on key commercial and vulnerable species, spanning different trophic levels of the marine food web, were modelled. Ecological and economic indicators that integrated multiple species and fisheries were also included. Trade-offs between management strategies were investigated, contrasting change in whole-system diversity, ecosystem structure and service delivery, and their resilience to climate change.

- **Main results for the Western Mediterranean Sea**

In the Western Mediterranean, the modelling exercise of the three scenarios (GS, NE, and WM), along with their associated climate change scenarios (RCP2.6 and RCP8.5) resulted in distinct ecological and fisheries socioeconomic realities by the mid-term (2050) and long term (2100). The outcomes were influenced not only by varying environmental conditions but also by the critical impacts of different combinations of conservation, restoration, fisheries, and management measures on the final outcomes.

By 2100, GS scenarios showed an increase in fish biomass and a decrease in invertebrates' biomass, along with a clear increase in endemics B. Conversely, the RCP 8.5 scenarios showed an increase in invertebrates, and decrease in endemics biomass. Notably, commercial biomass in the GS increased over time, while capture decreased significantly. This trend was driven by the explicit assumption of a constant low fishing effort under the GS scenario.

At a more aggregated level, the primary distinctions among the analysed scenarios emerged in the indicators, Kempton's Q index, predatory biomass and Shannon diversity index. Clear increasing trends were evident in the GS scenario, while smaller changes were observed in the remaining scenarios. The WM scenario showed a decreasing trend in Kempton's Q, and Trophic Level (TL) indicators.

From a socioeconomic perspective, it was noteworthy that, under all RCP 2.6. scenarios, the total tonnage of catches decreases, and the stock composition of the harvest underwent notable changes. The changes were especially pronounced under the GS scenario, underscoring the necessity of adapting the socioeconomics of the fisheries in the area. Conversely, catches increased or remained stable under all RCP 8.5 scenarios, albeit with very significant differences. The NE and WM scenarios, in particular, indicated a significant increase in catches - except for European sardine and deep water rose shrimp –, while the RCP 8.5 status quo scenario did not show major differences with the current situation.

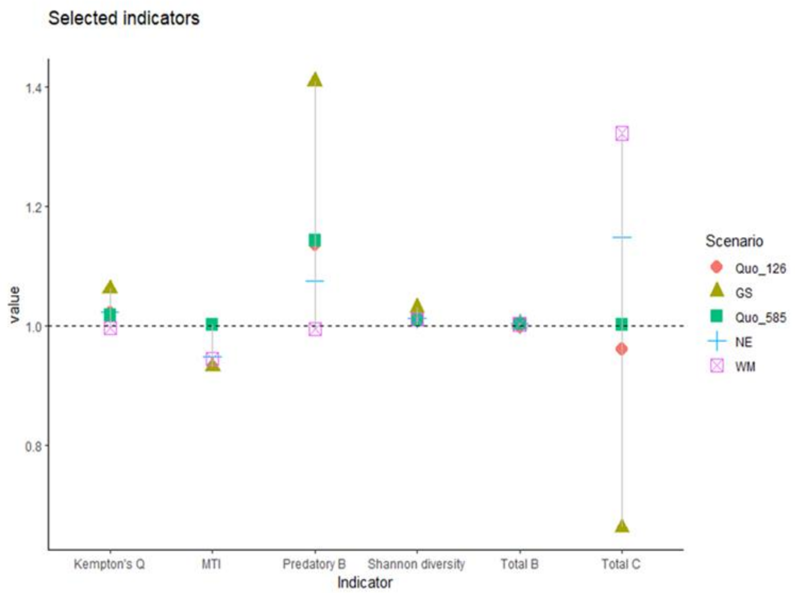

Figure 12: *Selected ecological indicators calculated for the different simulations run with the Western Mediterranean Sea model.*

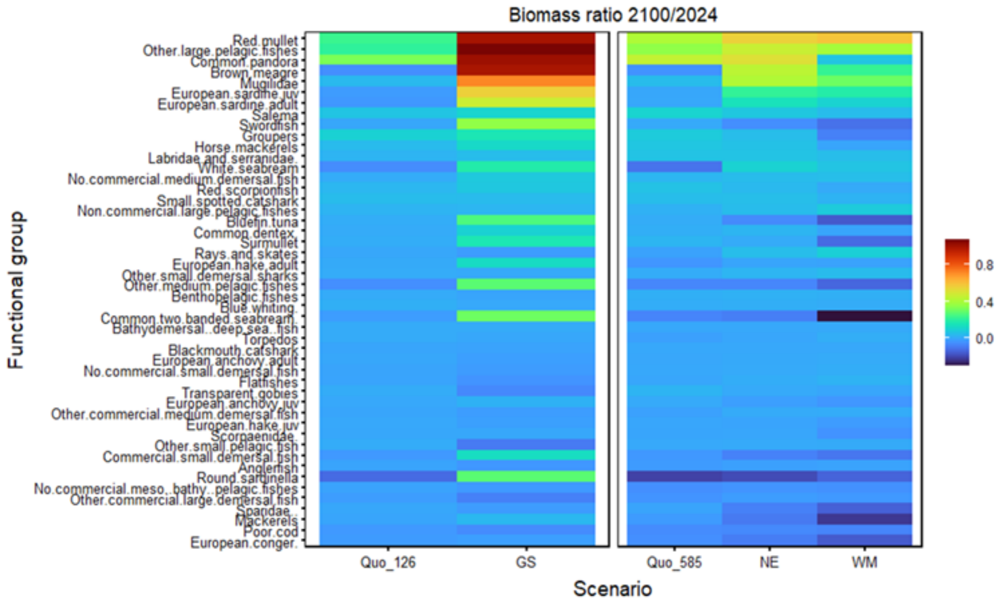

Figure 13: *Biomass ratio 2100/2024 (log10 transformed) of fish functional groups of the Western Mediterranean Sea model across all scenarios.*

- **Main results for the Northwestern Mediterranean Sea**

In the Northwestern Mediterranean, the modelling exercise of the three FutureMARES scenarios (GS, NE, and WM), along with their associated climate change scenarios (RCP2.6 and RCP8.5), also resulted in distinctly different ecological and fisheries socioeconomic outcomes in the mid-term (2050) and long term (2100). These changes were influenced not only by varying environmental conditions but also by the different combinations of conservation, restoration, and sustainable harvesting management measures.

As in the Western Mediterranean Sea, with the exception of Status Quo RCP2.6, it was important to note that while the overall biomass increases in all scenarios, there was significant change in the ecological structure of the system, including a substantial decrease in endemic species under the WM scenario. Only in the GS scenario did the biomass of endemic species increased by up to 60%. The highest increases in biomass were observed in mammals, birds, and reptiles (around 10% in all scenarios and 17% in GS), as well as in invertebrates (in the range of 5-12% with higher values in WM scenario).

At another level, changes in ecological indicators such as the Kempton's Q index and the Marine Trophic Index (MTI) were likely attributed to a rebuilding of low trophic level organisms in the community, given the increase in the TL of the community (TLco) under the GS scenario. The TLco with organisms higher than TL 4, and length indicators (such as Mean Length and Mean Lifespan of the fish community) were also larger under the GS scenario.

From a socioeconomic perspective, under all scenarios except GS, the total fisheries harvest was predicted to increase. This marks a significant shift from the declining trend observed in the last decades, and it was mostly driven by increases in primary production predicted to occur in the mid-21st century (in direct contrast to the North Sea) according to the ensemble projections used to drive this modelling exercise. These increases were particularly pronounced in the WM scenario (with an increase in harvested tonnages of more than 60%) and in the NE scenario (showing an increase of over 30%). All fleet segments were benefiting from this change. However, the recovery was uneven. Key commercial catches for purse seiners and mid-water trawlers were not expected to reach historical levels from 2000-2020, even by the end of the simulation in 2100. In contrast, increases in catch of demersal species appeared to be greater under all scenarios except GS, suggesting a benefit to bottom trawling, deep longline, and artisanal fleets in WM and NE. However, the recovery would be species- and spatially-heterogeneous, requiring fleets to adapt to the changing ecosystem with specific sub-regional strategies.

On the other hand, the simulations projected decreasing trends or stable catches in the GS scenario for most of the key commercial species (with the exception of the emblematic hake, which shows a small increase). An important and substantial decrease was projected in red shrimp, Norway lobster and mullet catches, which were key target species for the bottom trawling fleet. These declines were due to recovery of predators and increases in competition with from other organisms and highlighted a significant economic impact on bottom trawling activities in this scenario and suggested the need to adopt a fisheries socioeconomic transition plan for this fleet segment if a transition towards the GS scenario occurs. The situation was less acute for purse seiners and mid water trawlers, as anchovy catches declines could be compensated by sardine catches increases.

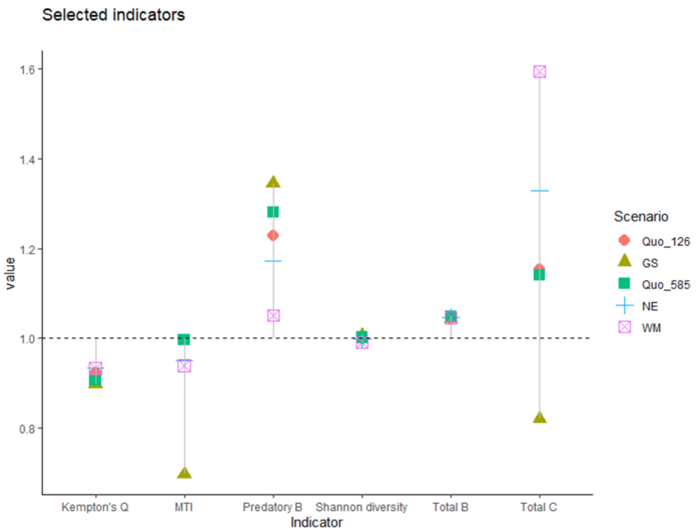

Figure 14: *Selected ecological indicators of the Northwestern Mediterranean Sea model.*

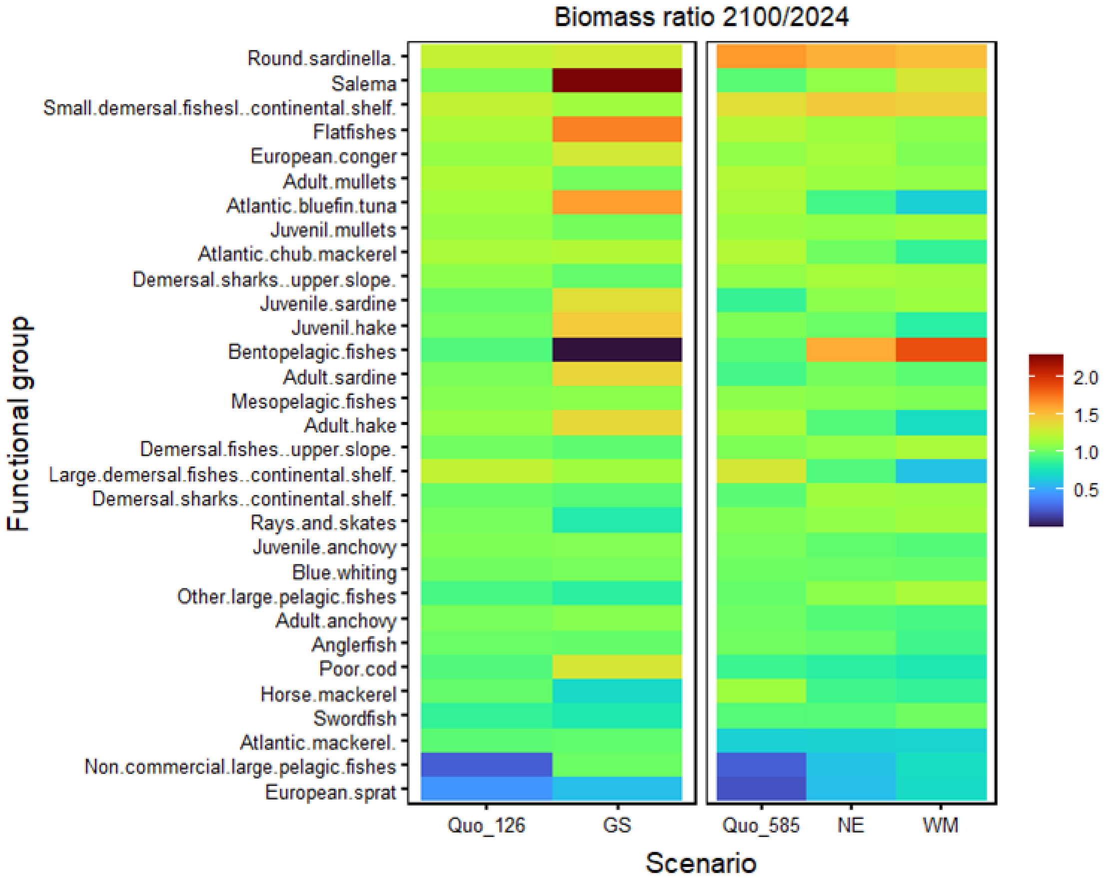

***Figure 15**: Fish functional groups biomass ration 2100/2024 of the Northwestern Mediterranean Sea model.*

- **Overall results**

Our findings may be relevant for international fisheries and conservation management organizations operating at the regional and sub-regional level, such as the General Fisheries Commission for the Mediterranean - RFMO or the EU, and for the ongoing discussions regarding the interplay between biodiversity conservation and restoration, on one hand, and sustainable fisheries, on another, in the region. They are also relevant at the National level, as spatial heterogeneities in biomass and catch emerged over time. In a context of future climate change, with heterogenic changes in primary production and temperature according to the ensemble projections from WP2 data, these different outcomes highlighted that distinct management interventions are crucial to protect ecological and socioeconomic status of the Western Mediterranean Sea in the future.

A key message from both the biological and socio-economic analysis is that regardless of the climate change scenario, marine management measures and global socioeconomic trends are pivotal in shaping the ecological system structure and the outcomes of marine resources in the study area.

3.1 Social-ecological vulnerability

Our storylines also contributed to the analyses of social-ecological and economic vulnerabilities (Garcia et al. 2023, Simons and and co-authors 2023, Queiros et al. 2024, Espasandin et al. In preparation).

Here we would like to highlight the contributions to the Climate Risk Assessments (CRAs) to the Western Mediterranean region (Espasandin et al. In preparation).

Climate Risk Assessments (CRAs)

We applied the ecological CRA (T5.1) and the social-ecological CRA (T5.3) approach in our area of study, following the Guidelines developed in the WP5 based on the conceptual framework proposed in the fifth assessment report (AR5) of the IPCC.

Regarding Task 5.1 about the ecological CRA, our main aim was to understand the risks for four different important commercial and conservation species (i.e., *Engraulis encrasicolus*, *Sardina pilchardus*, *Epinephelus marginatus*, and *Posidonia oceanica*) and the risk mitigation potential of Effective Conservation NBS and NIH. To do that, we conducted several workshops with Experts for the species in question collecting all the necessary information.

The risk results from the combination of three dimensions: (1) Hazard, (2) Exposure, and (3) Vulnerability. Specifically, we considered two climatic hazards (i.e., Temperature increase and Heatwaves) and two human hazards (i.e., Mortality increase of commercial and non-commercial species related to fisheries and Habitat destruction related to fisheries).

The CRA methodology can be empowered when used with spatial-explicit analysis, with the final output of mapping the risk to the mentioned hazards for the species in question. This approach allows the identification of areas with a higher potential for mitigation and adaptation across several scenarios and time slices, while also assessing the effectiveness of NBSs.

Regarding Task 5.3 about the social-ecological CRA, our main aim was to estimate the climate risk for the social-ecological systems present in our area of study. We identified relevant stakeholders in our area, intending to evaluate their risk under different scenarios and time slices. Specifically, the climate risk estimated in T5.1 was used as an indicator of Hazard in Task 5.3. Additionally, as in T5.1, the idea was to evaluate the mitigation risk potential of the Effective Conservation NBS and NIH but also to evaluate the potential drivers of NBS and NIH effectiveness.

- ### Main results and general conclusions

Regarding the **results of the ecological CRA** (T5.1), the overall risk across the difference scenarios was lower for *Posidonia oceanica* than the other three species evaluated. The pattern of risk change across scenarios was however similar across all taxa and for both the NBS of Effective Conservation and NIH, with generally lower risk in Global Sustainability (GS), and higher in National Enterprise (NE) and World Markets (WM).

The mitigation effects of the NBS of Effective Conservation seemed to be taxa dependent with more pronounced effects for anchovy and dusky grouper, the relative effects otherwise did not vary depending on the scenario and time-slices. The confidence was high for anchovy and sardine and medium for dusky grouper and seagrass. Overall, the NBS of Effective Conservation in the Western Mediterranean Sea had only positive effects on the overall risks (decrease) for all species evaluated and all scenarios and time-slices. The NBS effects were mostly because of the impacts on adaptive capacity.

The relative mitigation effects of NIH were similar across taxa and scenarios. The confidence was high for anchovy and sardine and medium for dusky grouper. Overall, NIH in the Western Mediterranean Sea had only positive effects on the overall risk (decrease) for all fish species evaluated and all scenarios and time-slices. The NBS relative effects were similar across taxa and scenarios and is mostly changing adaptive capacity.

Regarding the spatial-explicit assessment, we selected three case studies: Sardine under Nature-Inclusive Harvesting, Anchovy under Nature-Inclusive Harvesting, and Dusky grouper under Effective Conservation NBS. This analysis allows us to identify areas with higher and lower risk for each scenario and time slice. In general, we see that the risk level increases with time (i.e., higher in the long-term future) and it is also higher for the National Enterprise and World Markets scenarios. In particular, we see an area that maintains lower risk levels in all the scenarios for the mid-term future, the Alboran Sea. Detecting areas with higher and lower risk levels is useful to prioritize where to apply mitigation and adaptation management measures.

Regarding the **results of the social-ecological CRA** (T5.3), we had very few responses from the stakeholders. As a result, we were only able to examined the effect of the Effective Conservation NBS on one social group (i.e., artisanal fishers). In this case, we estimated the climate risk of the fish species: sardine, anchovy, and dusky grouper. We found that artisanal fishers developing their activity close to the conservation areas of the Western Mediterranean showed moderate to high levels of climate risk under the different scenarios evaluated. The overall level of risk of the fishers was mostly driven by an extreme exposure (probably due to a high specificity of target species) and low adaptive capacity (mostly driven by poor social and organizational characteristics).

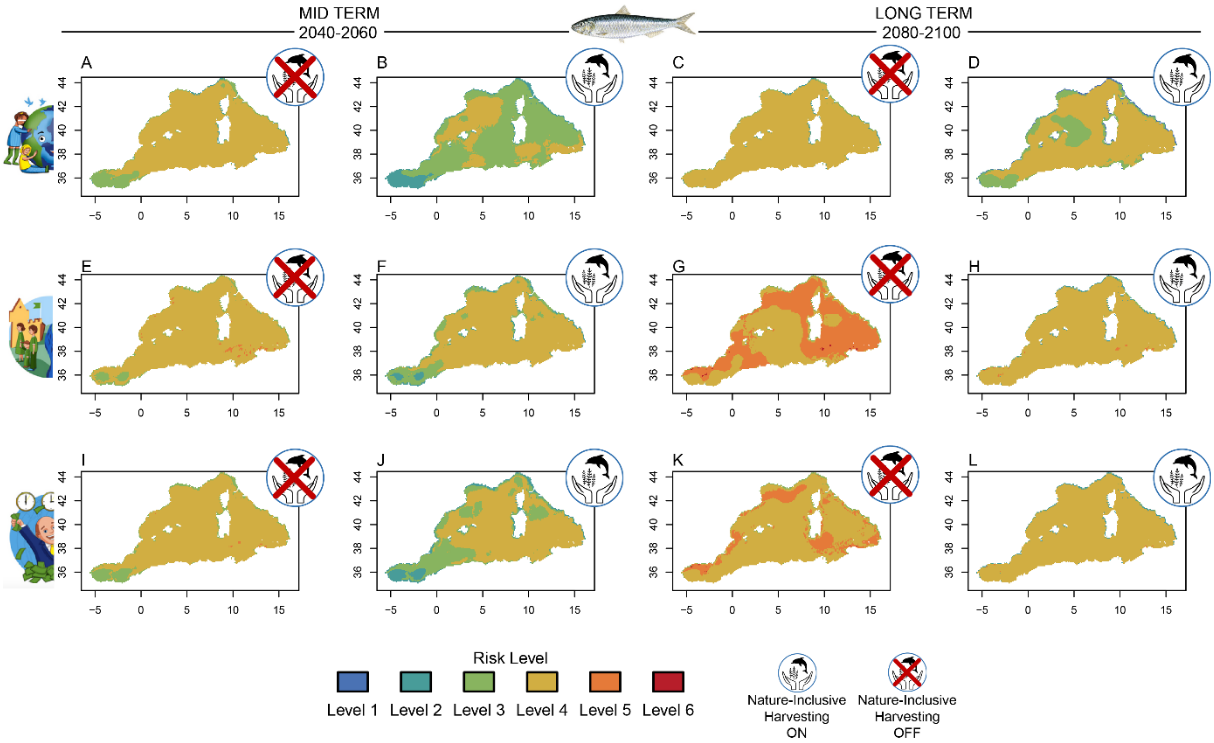

__Figure 16:__ Spatially explicit climate risk assessed for European sardine under the 3 different scenarios (i.e., Global Sustainability – A, B, C, and D -, National Enterprise – E, F, G, and H -, and World Markets – I, J, K, and L -), 2 time slices (i.e., mid-term future and long-term future) and considering the mitigation effects of Nature-Inclusive Harvesting (i.e., NBS OFF and NBS ON) (Espasandin et al. In preparation).

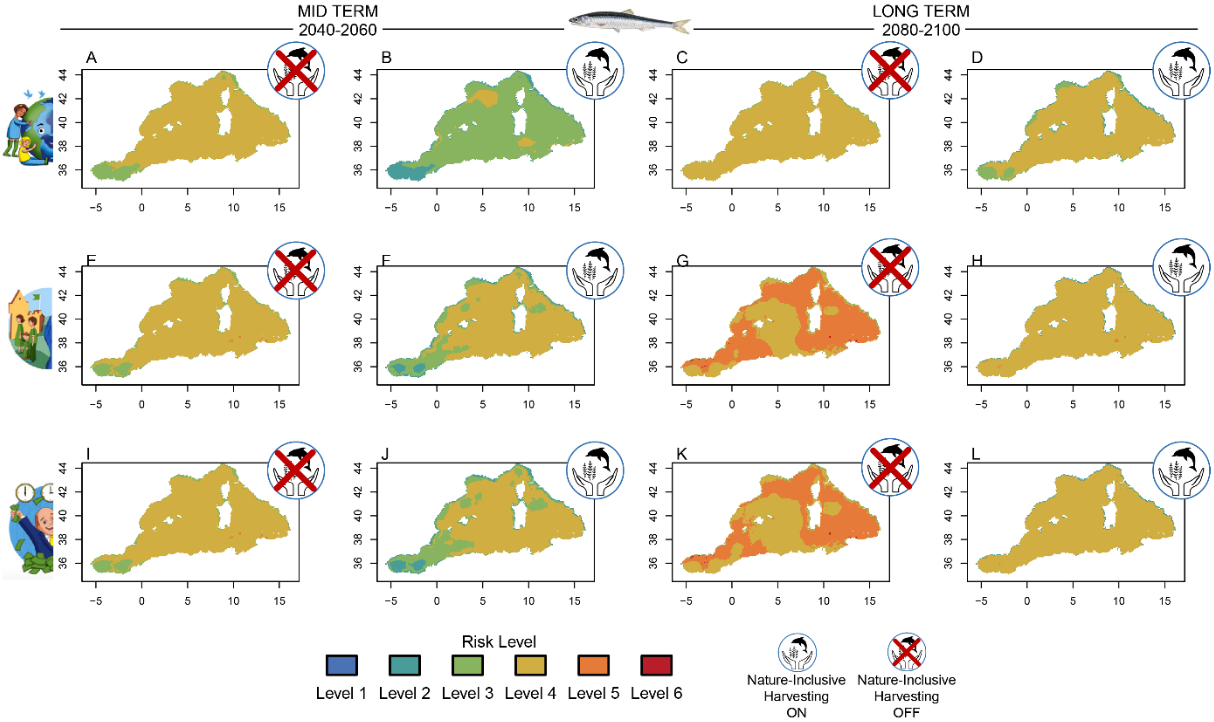

Figure 17: *Spatially explicit climate risk assessed for Anchovy under the 3 different scenarios (i.e., Global Sustainability – A, B, C, and D -, National Enterprise – E, F, G, and H -, and World Markets – I, J, K, and L -), 2 time slices (i.e., mid-term future and long-term future) and considering the mitigation effects of Nature-Inclusive Harvesting (i.e., OFF and ON) (Espasandin et al. In preparation).*

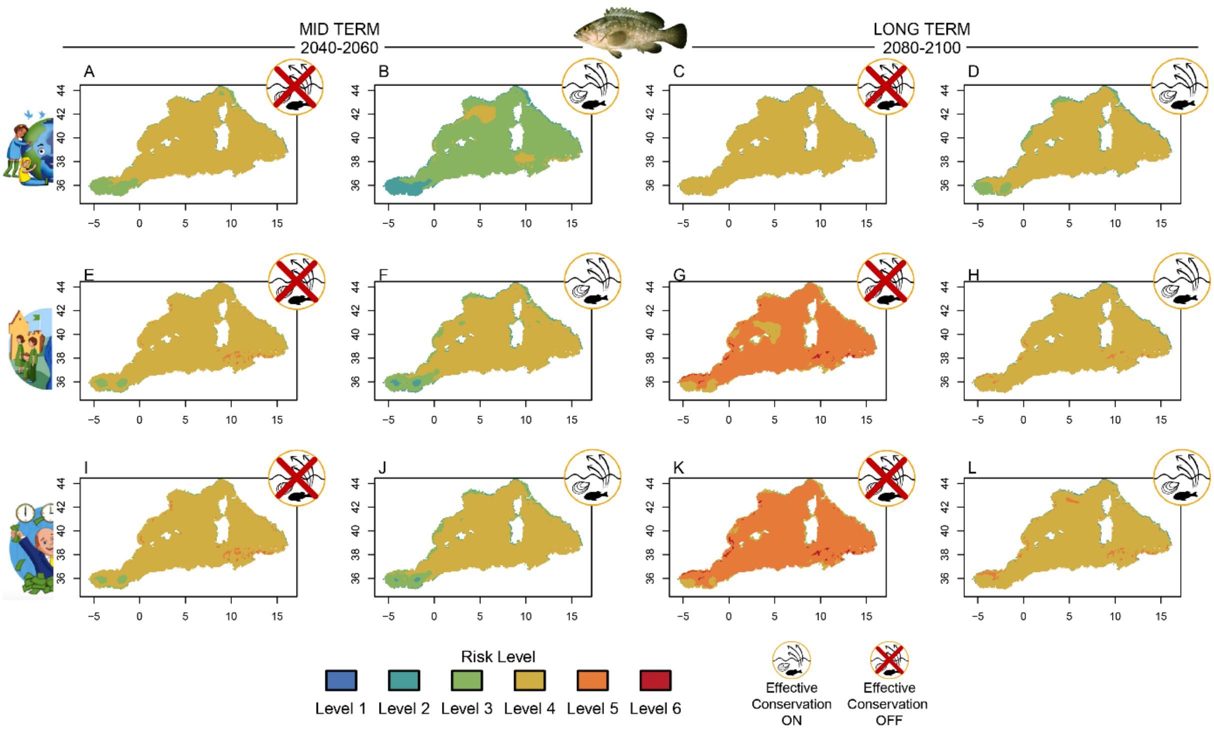

Figure 18: *Spatially explicit climate risk assessed for the Dusky grouper under the 3 different scenarios (i.e., Global Sustainability – A, B, C, and D -, National Enterprise – E, F, G, and H -, and World Markets – I, J, K, and L -), 2 time slices (i.e., mid-term future and long-term future) and considering the mitigation effects of Effective Conservation (i.e., OFF and ON) (Espasandin et al. In preparation).*

4.1 Testing NBS Implementation Scenarios

These storylines made a major contribution to test NBS under the work done for Deliverables 4.3 and 4.4 of FutureMares (Coll et al. 2024b, Shin et al. 2024).

Here we the downscaling of the global PESTLE FutureMares scenarios to the Western Mediterranean and Northwestern Mediterranean regions prior to the scenario testing in D4.4. This process is highlighted in step 2 of the workflow of scenarios, figure below.

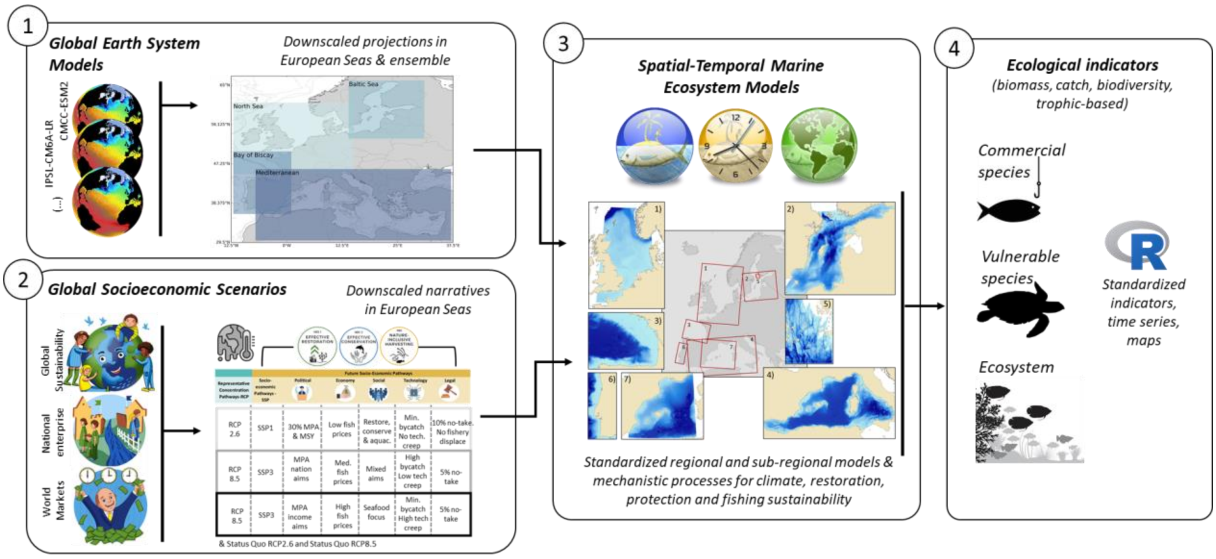

Figure 19: *Overall workflow of scenarios development under D4.4 (Coll et al. 2024b).*

- **Downscaled narratives and scenarios for the Western Mediterranean**

The process followed several steps that involved taking decisions according to the information available and stakeholders' positions in different topics. Below we summarize the decisions.

Site common features

Regarding MPA and Fisheries Closures (FC) we followed Claudet and coauthors (Claudet et al. 2020b). The baseline protected areas were classified according to a decreasing level of protection as: fully protected areas (FPA), highly protected areas (HPA), moderate protected areas (MPAs), poorly protected areas (PPAs), and Unprotected areas (UPA). In all scenarios the protected areas implemented from 2030 onwards were classified either as FPAs, where no fishing activities were allowed, or HPAs, where fishing activities are restricted for bottom trawlers, purse seiners and long liners. PPA and UPAs were treated as unprotected areas and were not applied to any fishing fleet.

In all scenarios, prices were set using 2020 EUMOFA Mediterranean first sales Mediterranean data (European Commission, 2023). For some species data were not available, in this case we have used North Western Mediterranean Waters prices (ICATMAR 2023).

Regarding fishing costs, in all scenarios we used Mediterranean average values obtained from the General Fisheries Commission for the Mediterranean (GFCM) reported on The State of Mediterranean and Black Sea Fisheries 2022 (FAO 2022).

Global Sustainability Scenario

Marine Protected Areas surface and location: 20% of each country's EEZ was covered with HPAs, and 10% FPAs. In Spain, France and Italy, where marine planning figures exist, their location was based on the already existing protected areas in combination with the priorities of marine spatial planning national processes (Ministère de la transition écologique et solidaire, 2022, Ministero delle infraestrutture e della mobilità sostenibili, 2022; (Esparza et al. 2021)), while in Morocco, Algeria and Tunisia, where no specific spatial national planning exist, prioritisation was based in current protection areas and expert identified priority areas (Coll et al. 2015, Gomei et al. 2021).

Table 1: *Marine Protected Areas national location criteria under the Global Sustainability scenario of the Western Mediterranean Sea (Coll et al. 2024b).*

CRITERIA	FPA	HPA
SPAIN	Current FPA & HPA and addition up to 10% based in national suggested extension of LIC/ZEC Natura 2000 areas, covering all geographical priority areas and prioritizing those with already MPAs or PPAs protection figures.	Current PPAs and addition up to 20% based in the remaining national suggested extension of LIC/ZEC Natura 2000 areas, and current existing MPAs and UPAs.
FRANCE	Current FPA, HPA, MPA & PPA and additional areas up to 10% that corresponds to Natura 2000 sites in Corsica areas prioritized in National Marine Spatial Planning strategy as conservation areas.	Up to 20% based in a proportional coverage of the areas prioritized in National Marine Spatial Planning strategy as conservation areas and Natura 2000.
ITALY	Current FPA, HPA, MPA & PPA and addition up to 10% based in current UPAs excluding the cetaceans Ligurian area.	Up to 20% based in a proportional coverage of all conservation priorities areas established in the draft of the National Marine Strategy Planning.
MOROCCO, ALGERIA AND TUNISIA	Current FPA, HPA, MPA, PPA & UPA and addition up to 10% based in IUCN consensus areas for protection, prioritizing non-coastal areas and geographical distribution all around the coast.	Up to 20% based in consensus areas non-classified as FPAs, prioritizing geographical equilibrium and non-coastal protection when needed.

Restoration: habitat restoration targets were set in (30%, 60% and 90%) of the current distribution of Posidonia oceanica and coralligenous communities (Giakoumi et al. 2013, Martin et al. 2014, EMODnet Bathymetry Consortium) for each of the EEZ following the targets per period. Habitat restoration targets were set to recover at least 30 % of the degraded area (within MPAs in NBS2) of each group of habitat types by 2030, at least 60 % by 2040, and at least 90 % by 2050.

Fishing effort: A linear reduction of fishing effort from 2024 to 2030 was applied up to achieve Fmsy in 2030. This required major changes from the current situation, since according to the GFCM 93% of the evaluated stocks in the Western Mediterranean Sea are currently overfished (FAO 2022). Fishing effort remained constant from 2030 to the end of the simulation.

Discards and bycatch: We applied a linear 90% reduction of discards in the period 2024-2030 starting from the current regional average of discards rates in the region, which is 14% (25.3% in trawlers, 3.1% in purse seiners and 9.9% artisanal fishers) (FAO 2022). Bycatch reduction was set up to 99% in the same period. Both elements remained constant from 2030 to the end of the simulation.

Fisheries closures: All existing non-fishing areas were maintained active during the simulated period, including those that started in 2021. New areas entered into force in 2030: all fisheries, except purse seiners, artisanal and recreational, were banned in waters up to 50 meters depth, expanding the current Mediterranean EU towed gears ban (Regulation (EC) No 1967/2006) and including all Western Mediterranean countries. Additionally, trawling was limited to the range 100-400m, expanding the current 1000 FRA applied in the Mediterranean Sea (Recommendation GFCM/29/2005) to 400 meters depth, using as a reference point the bathymetric depth reference used to implement specific measures to protect VMEs in the north-east Atlantic deep-sea regulation (Regulation (EU) 2016/2336). Finally, all Fisheries Restricted Areas currently discussed in the context of the GFCM (Ortega et al. 2023) were assumed to be implemented in 2030, and therefore were closed to bottom trawlers and long liners from 2030 to the end of the simulation.

National Enterprise Scenario

Marine Protected Areas surface and location: 5% of each country's EEZ was covered with FPAs, and 5% HPAs. See Table **2:** for specific details.

Table 2: *Marine Protected Areas national location criteria under the National Enterprise scenario (Coll et al. 2024b).*

CRITERIA	FPA	HPA
SPAIN	Current FPA & HPA and addition up to 10% based on national suggested extension of LIC/ZEC Natura 2000 areas, covering all geographical priority areas and prioritizing those with already MPAs or PPAs protection figures and small areas.	Addition up to 20% based on the remaining national suggested extension of LIC/ZEC Nature 2000 areas, covering all geographical priority areas and prioritizing small non-coastal areas.
FRANCE	Current FPA, HPA, MPA & PPA. In order to reduce up to 5% some PPAs have been excluded following national conservation priorities and forcing the creation of small protected areas.	Up to 5% based on the previously excluded PPAs Corsica areas that are prioritized in National Marine Spatial Planning strategy as conservation areas and that are already part of Natura 2000.
ITALY	Current FPA, HPA, MPA & PPA. In order to reduce up to 5% some MPAs and PPA have been excluded prioritizing the exclusion of transboundary areas and forcing the creation of small protection areas.	Up to 5% based on the previously excluded PPAs and in a proportional coverage of all conservation priorities areas established in the draft National Marine Strategy Planning forcing the creation of small protection areas and avoiding transboundary areas.
MOROCCO, ALGERIA AND TUNISIA	Current FPA, HPA, MPA, PPA & UPA. And addition up to 5% based on expert selected areas for protection, prioritizing simultaneous superposition with UPAs -when existing-, non-coastal areas,	Up to 5% based on previously eliminated expert selected areas. In the case of Morocco also UPAs was prioritized. In Algeria and Tunisia priority was non-coastal and non-transboundary areas, and small areas.

	geographical distribution all around the coast and creation of small areas.	

Restoration: There are no restoration measures implemented in this scenario.

Fishing effort: Increase according to technical creep of 0.44% annual from 2024 to 2100, which is half of the historical rate of technical creep (Damalas et al. 2014), due to the slowing down of innovation in the National Enterprise scenario.

Discards and bycatch: There are no discards and bycatch reductions in this scenario.

Fisheries closures: There are no new fishing closures, only the current fishing closures remained active.

World Market Scenario

Marine Protected Areas surface and location: 5% of each country's EEZ is covered with FPAs, and 5% HPAs. See Table **3:** for specific details.

Table 3: *Marine Protected Areas national location criteria under the World Market scenario (Coll et al. 2024b).*

Criteria	FPA	HPA
SPAIN	Current FPA & HPA and addition up to 5% based on the highest percentages of aggregated EFH for red shrimp, red and blue shrimp, and hake; prioritizing those areas with already existing national areas already designed to protect total or partially EFHs.	Addition up to 5% based on the remaining areas with highest percentages of aggregated EFH for red shrimp, red and blue shrimp, and hake.
FRANCE	Current FPA, HPA, MPA & PPA. In order to reduce up to 5% we eliminate those PPAs with lower percentages of aggregated EFH for red shrimp, red and blue shrimp, and hake, and prioritizing those included in national conservation areas.	Up to 5% based on the previously excluded PPAs, and in the areas with highest percentages of aggregated EFH for red shrimp, red and blue shrimp, and hake.
ITALY	Current FPA, HPA, MPA. In order to increase up to 5% we include those PPAs areas with higher percentages of aggregated EFH for red shrimp, red and blue shrimp, and hake.	Up to 5% based on the previously excluded PPAs, and in the areas with highest percentages of aggregated EFH for red shrimp, red and blue shrimp, and hake.
MOROCCO, ALGERIA AND TUNISIA	Tunisia: 5% is reached with current FPA, HPA, MPA, PPA & UPAs. Morocco: FPA, HPA, MPA, PPAs. To reduce up to 5% of protection, from PPAs we eliminate two from the centre to guarantee geographical distribution.	Up to 5% based on: Morocco: adding previously eliminated PPAs and one UPA cell with EFHs. Tunisia and Algeria: adding areas with higher percentages of aggregated EFH prioritizing those non-coastal and

	Algeria: current FPA, HPA, MPA, PPA and UPAs are included as FPAs. To reach 5%, we included also areas with higher percentages of aggregated EFH prioritizing those non-coastal and try to guarantee geographical distribution all around the coast.	transboundary areas, in the Algerian case also those in connection with FPAs.

Restoration: There are no restoration measures implemented in this scenario.

Fishing effort: Increase according to technical creep of 0.88% annual from 2024 to 2100, in coherence with (Damalas et al. 2014) values found in the Mediterranean Sea (Damalas et al. 2014).

Discards and bycatch: Linear 50% reduction of discards in the period 2024-2030 starting from the current discards rates. Bycatch reduction is set up to 99% in the same period. Both elements remain constant since 2030.

Fisheries closures: In Spain, Italy and France, 5% of the surface of each national EEZ was closed to bottom trawl and purse seiners to protect EFHs. The areas were allocated in the surfaces with higher percentages of aggregated Essential Fish Habitats (nurseries and spawning areas) for the most commercially valuable species in the region (red shrimp - *Aristaeomorpha foliacea*-, red and blue shrimp - *Aristeus antennatus* -, and hake - *Merluccius merluccius*). MEDISEH project data was used (Giannoulaki et al. 2013). Since no information was available on these species for Morocco, Algeria and Tunisia, the same selection criteria were used but based on all EFH species prioritized in the GFCM data collection framework (GFCM 2021); group 1 and group 2 species), complemented with species included in the European Union Multiannual management plan for demersal stocks in the western Mediterranean Sea (REGULATION (EU) 2019/1022). Only species for which geographic distribution data was freely available were included in the analyses following Ortega et al. (Ortega et al. 2023). When the proportion of EFH was the same in different areas we prioritise, those areas containing a figure of protection FPA or HPA, and are transnational.

Human drivers

The scenarios included changes in fishing effort according to previous descriptions and the placement of MPAs (both highly protected and fully protected) and fisheries closures according to the scenario and fishing fleets allowed in each MPA and FC.

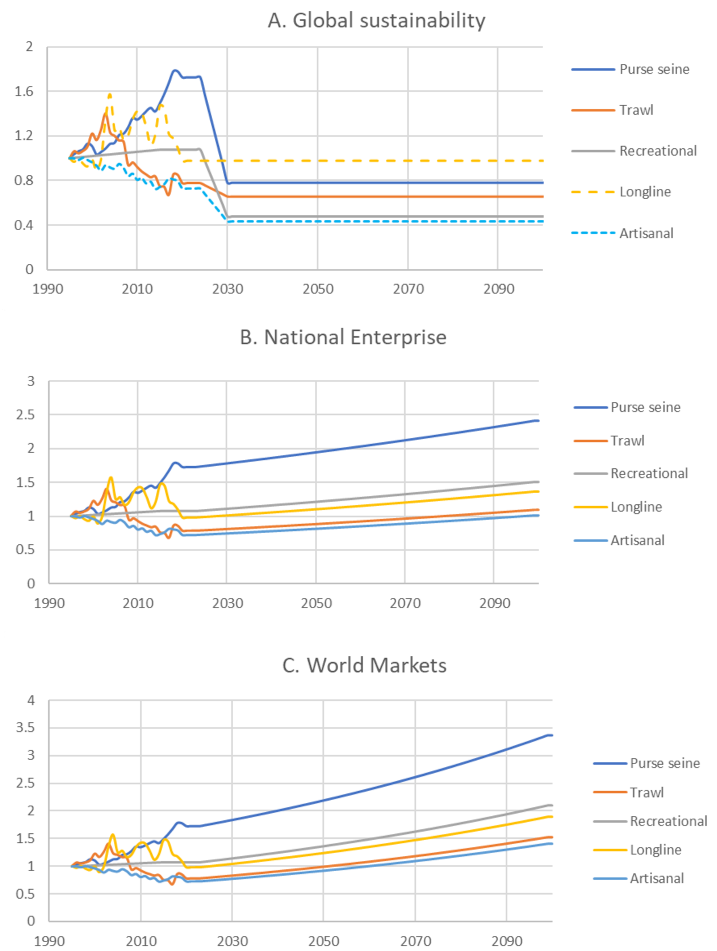

Figure 20: *Fishing effort changes of the fleets from the Western Mediterranean Sea model under the scenarios of FutureMARES: a) Status Quo; b) Global Sustainability, c) National Enterprise, and d) World Markets (Coll et al. 2024b).*

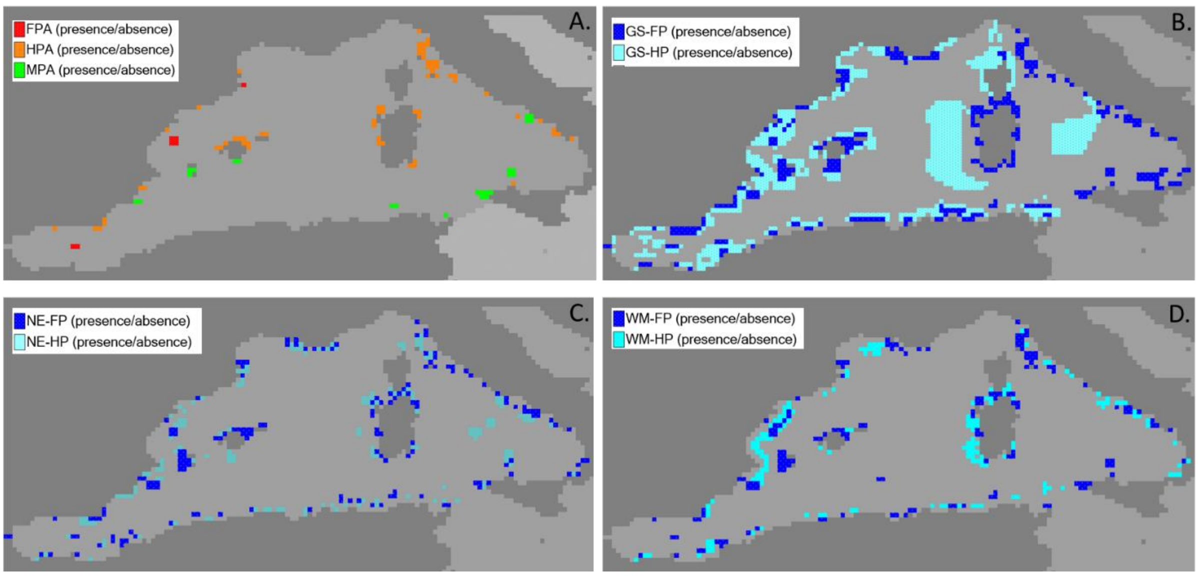

Figure 21: *Configurations of MPAs with Fully Protected Areas (FPAs) and Highly Protected Areas (HPAs) from the Western Mediterranean Sea model under the scenarios of FutureMARES: a) Status Quo; b) Global Sustainability, c) National Enterprise, and d) World Markets (Coll et al. 2024b).*

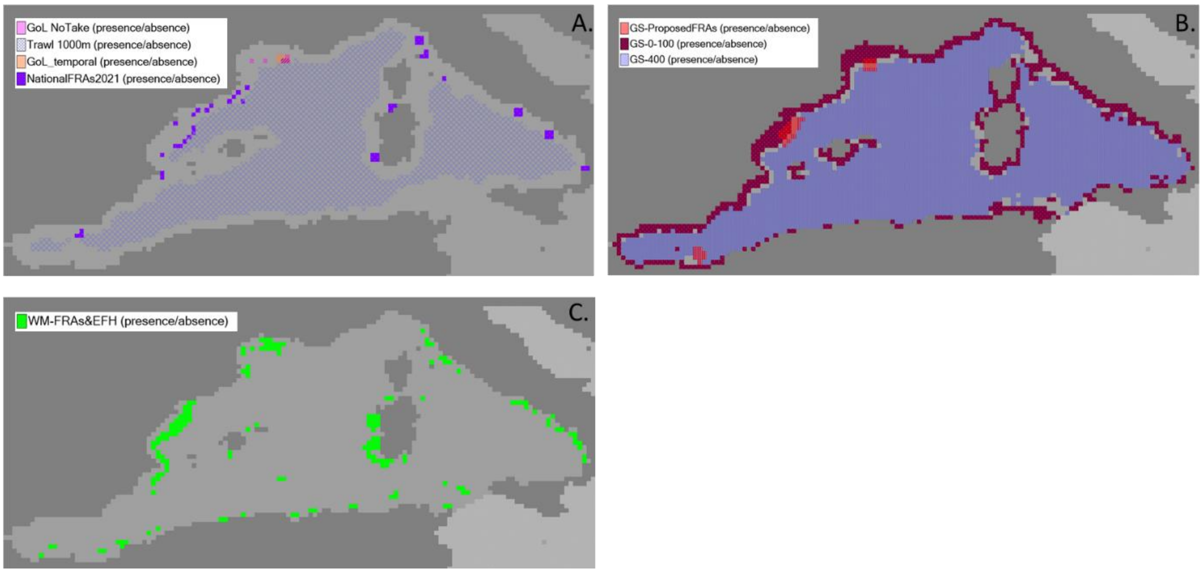

***Figure 22**: Configurations of Fisheries Closures from the Western Mediterranean Sea model under the scenarios of FutureMARES: a) Status Quo; b) Global Sustainability, c) World Markets. The National Enterprise scenario does not include additional FCs after the 2021 (Coll et al. 2024b).*

***Table 4**: Spatial management scenarios used to run the Western Mediterranean Sea model under the scenarios of FutureMARES: a) Status Quo; b) Global Sustainability, c) National Enterprise, and d) World Markets (Coll et al. 2024b).*

Scenarios		**Bottom trawling**	**Purse seine & mid-water trawling**	**Long liners**	**Artisanal fisheries**	**Recreational fisheries**
			Status Quo			
Initial	FPA	x	x	x	x	x
	HPA	x	x	x		
	MPA	x	x			
	Gulf of Lions No take	x				
	Trawl ban 1000 m	x				
2021	Gulf of Lions temporal (2021)	x		x		
	National FRAs (2021)	x		x		
			Global Sustainability			
Initial	FPA	x	x	x	x	x
	HPA	x	x	x		
	MPA	x	x			
	Gulf of Lions No take	x				

	Trawl ban 1000 m	x				
2021	Gulf of Lions temporal (2021)	x		x		
	National FRAs (2021)	x		x		
2030	FPA expansion (2030)	x	x	x	x	x
	HPA expansion (2030)	x	x	x		
	New FRAs implemented (2030)	x		x		
	Trawl ban 0-100 m (2030)	x				
	Trawl ban > 400 m (2030)	x				
National Enterprise						
Initial	FPA	x	x	x	x	x
	HPA	x	x	x		
	MPA	x	x			
	Gulf of Lions No take	x				
	Trawl ban 1000 m	x				
2021	Gulf of Lions temporal (2021)	x		x		
	National FRAs (2021)	x		x		
2030	FPA expansion (2030)	x	x	x	x	x
	HPA expansion (2030)	x	x	x		
World Markets						
Initial	FPA	x	x	x	x	x
	HPA	x	x	x		
	MPA	x	x			
	Gulf of Lions No take	x				
	Trawl ban 1000 m	x				
2021	Gulf of Lions temporal (2021)	x		x		
	National FRAs (2021)	x		x		
2030	FPA expansion (2030)	x	x	x	x	x

HPA expansion (2030)	x	x	x	
FRAs in EFH (2030)	x		x	

Results of scenarios using these downscaled narratives for the Western Mediterranean region, and a sub-regional analysis of the Northwestern Mediterranean region were presented with detail in Deliverable 4.4 (Coll et al. 2024b) and were used extensively in Deliverables 6.2 and 6.3 (Simons and and co-authors 2023, Queiros et al. 2024).

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