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Governance pathways shape trophic recovery under climate change in the western Mediterranean Sea

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Research Article

Keywords: Ecopath with Ecosim, ecosystem-based fisheries management, food-web modelling, habitat restoration, marine protected areas, Shared Socioeconomic Pathways

Posted Date: October 30th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11543814/v1

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Additional Declarations: The authors declare no competing interests.

Abstract

Marine ecosystems are increasingly shaped by the interacting effects of climate change and human activities, yet the extent to which alternative socio-economic pathways can modify future ecological trajectories remains poorly understood. Here, we integrate climate projections with coherent socioecological scenarios to evaluate long-term ecosystem responses in the western Mediterranean Sea. Using a spatially explicit marine ecosystem model (Ecopath with Ecosim) representing 92 functional groups and five fishing fleets, we simulated ecosystem dynamics from 1995 to 2020 and projected changes to 2100 under contrasting pathways combining climate forcing, fisheries management, marine protection, and habitat restoration. Scenarios included a sustainability-oriented pathway (SSP1–RCP2.6; Global Sustainability), two high-emission pathways with contrasting governance (SSP3–RCP8.5; National Enterprise and SSP5–RCP8.5; World Markets), and associated status quo baselines. Socio-economic pathways substantially modified the ecological outcomes of climate change. Under Global Sustainability, reduced fishing pressure, expanded marine protection, discard mitigation, and habitat restoration promoted rapid rebuilding of commercial and predatory biomass, recovery of conservation-relevant species, and improved trophic structure within two decades, although fisheries catches declined. In contrast, high-emission pathways produced slower and more uneven responses. Despite sharing the same climate trajectory, National Enterprise and World Markets generated markedly different outcomes, highlighting the importance of governance priorities, technological development, and spatial management in shaping ecosystem futures within the same climate constraints. Responses were spatially heterogeneous across the basin, revealing uneven ecological benefits, vulnerabilities, and trade-offs among regions and functional groups. Our findings demonstrate that marine ecosystem trajectories are shaped by interactions between climate forcing and human activities and highlight the potential for management, conservation, and restoration to enhance ecosystem resilience under future climate change.

1. Introduction

Predicting how marine ecosystems will respond to the combined pressures of climate change and human activities remains a central challenge in global change ecology (Coll et al., 2020; Simeoni et al., 2023). A key unresolved question is the extent to which management strategies - including fisheries regulation, conservation, and restoration - can buffer climate impacts while protecting ecosystem structure, biodiversity, and the provision of ecosystem services (Free et al., 2019; IPBES, 2019). Addressing this challenge requires approaches that evaluate the ecological outcomes derived from different trajectories of environmental and human development.

Ecological modelling frameworks are increasingly used to explore future ecosystem responses under alternative future scenarios, providing a basis for anticipatory and adaptive management(IPBES, 2016, 2024). However, a critical limitation remains: projections are often based on inconsistent or weakly coupled assumptions regarding climate forcing and socio-economic change (M. A. Peck et al., 2026). There is growing recognition that credible future projections depend on the integration and downscaling of internally consistent socio-economic pathways with climate scenarios, ensuring coherence between external drivers and human responses (M. Peck et al., 2022; Schuwirth et al., 2019). Such integrated scenario frameworks are now central to global environmental assessments, including those developed by the IPCC (IPCC, 2022) and IPBES (IPBES, 2019). Yet, their application to marine ecosystems—particularly within mechanistic, multispecies and trophically resolved models—remains limited (Maury et al., 2025). As a result, we currently lack a process-based understanding of how alternative future scenarios influence marine food webs and, in turn, shape biodiversity, ecosystem functioning, and fisheries outcomes under climate change (Blanchard et al., 2024; Maury et al., 2017; Pinnegar et al., 2021). This gap constrains our ability to evaluate the effectiveness of management interventions in a rapidly changing ocean. In the present study, we address this gap by integrating future coherent scenarios with a mechanistic food-web modelling framework to assess the ecological consequences of alternative future socio-ecological scenarios.

We focus on the western Mediterranean Sea, a region that illustrates the interaction between intense human pressures and rapid environmental change. The Mediterranean is a global marine biodiversity hotspot, hosting approximately 7.5% of marine species within less than 0.8% of the global ocean surface (Bianchi & Morri, 2000; Coll et al., 2010), while simultaneously experiencing high fishing pressure, coastal development, maritime traffic, habitat degradation and pollution (FAO, 2025; Halpern et al., 2025; UNEP, 2024). In parallel, the region is warming faster than the global ocean average (Salat et al., 2019) and is increasingly affected by marine heatwaves, with cascading effects on ecosystem structure and functioning (Artana et al., 2026; Calvin et al., 2023). These interacting pressures make the region a natural laboratory for assessing ecosystem responses to coupled socio-economic and climatic change (Bethoux et al., 1999; Lejeusne et al., 2010),

Building on a previously developed spatial-temporal Ecopath with Ecosim (EwE) model, we implemented a set of regionally relevant, internally consistent scenarios that combine climate change trajectories with contrasting management approaches, including fisheries regulation, conservation, and restoration. We quantify the effects on key commercial species, key species for conservation, and overall ecosystem dynamics using indicators of biomass, fisheries yield, biodiversity, and trophic structure.

We hypothesize that the ecological trajectories of marine ecosystems depend not only on the magnitude of climate change, but also on its interaction with management strategies. Specifically, we test the following hypotheses:

(H1) Under low-emission scenarios, ambitious and coherent management strategies will promote rapid ecosystem recovery, leading to increases in biomass, biodiversity, and trophic complexity within decadal timescales, albeit with short-term trade-offs in fisheries yields.

(H2) Under high-emission scenarios, management interventions will remain effective, but their ecological benefits will be delayed, reduced in magnitude, and more uneven across trophic levels, resulting in slower recovery and shifts toward lower-trophic system states.

(H3) Alternative socio-economic pathways operating under similar climate conditions will produce markedly different ecological outcomes, reflecting the central role of decision-makers in shaping marine ecosystem futures.

(H4) Ecosystem responses will exhibit strong spatial and functional heterogeneity, leading to uneven distributions of socio-ecological benefits and trade-offs across regions, species groups, and sectors.

By explicitly testing these hypotheses, this study provides a process-based assessment of how climate change and socio-economic development can jointly shape marine ecosystem dynamics. By bridging and downscaling global scenario frameworks with mechanistic ecosystem dynamics, we test whether management choices can substantially alter ecological trajectories under global change.

2. Methods

2.1. Overview of the modelling framework

We evaluated the ecological consequences of alternative socio-economic and climate futures for the western Mediterranean Sea using a scenario-based, mechanistic modelling framework. The approach integrates climate forcing, socio-economic pathways, and spatially explicit marine management measures within a spatial-temporal dynamic food-web model. This allows us to explicitly link climate change and human responses to ecosystem structure, trophic dynamics, and fisheries outcomes under global change.

Five scenarios were implemented with the modelling approach: a baseline status quo for each climate scenario and three alternative socio-economic pathways derived from established global scenario frameworks (Peck et al., 2026), combining Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs). These scenarios differ in their assumptions about climate change intensity, political priorities, technological development, and environmental policy ambition, resulting in contrasting trajectories of fishing pressure and conservation effort (Fig. 1; Table 1).

2.2. Scenario design and management assumptions

We evaluated three global socio-economic pathways: Global Sustainability (SSP1–RCP2.6), National Enterprise (SSP3–RCP8.5), and World Markets (SSP5–RCP8.5). Each pathway was compared with its corresponding status quo baseline under the same climate scenario: Global Sustainability vs. Status Quo (RCP2.6) and National Enterprise and World Markets vs. Status Quo (RCP8.5) (M. A. Peck et al., 2026). This approach enabled us to isolate the effects of alternative management strategies from those driven by climate change, thereby assessing the influence of management under contrasting climate scenarios.

The scenarios represent contrasting worldviews and governance structures:

- Global Sustainability (GS) assumes strong international coordination, rapid decarbonisation, and high environmental ambition.
- National Enterprise (NE) prioritises national interests, with fragmented governance and limited environmental ambition.
- World Markets (WM) emphasises economic efficiency and global trade, with technology-driven fisheries expansion and limited ecological constraints.

Each scenario was downscaled to the regional context to internally define them consistently with meaningful marine management strategies, including:

- establishment and expansion of marine protected areas (fully and highly protected areas),
- habitat restoration targets,
- fisheries management measures (effort control, discard reduction, bycatch mitigation).

Management intensity and spatial design varied consistently with socio-economic assumptions and the regional context (Table 1; M. A. Peck et al., 2026). In GS, protection targets followed international biodiversity commitments and ecosystem connectivity principles, whereas NE and WM prioritised national or economic objectives, respectively, with reduced ecological integration.

The GS scenario assumes that 20% of each country's Exclusive Economic Zone (EEZ) is designated as Highly Protected Areas (HPAs), where activities such as bottom trawling, purse seining, and longlining are restricted. In addition, 10% of each EEZ is allocated as Fully Protected Areas (FPAs), where all fishing activities are prohibited. In the NE and WM scenarios, the extent of HPAs and FPAs is reduced to 5% of each EEZ. Regarding their spatial allocation, the NE scenario prioritizes non-coastal and non-transboundary areas, whereas the WM scenario designates protected areas to safeguard key commercial species and ensure their long-term viability.

With respect to habitat restoration, the NE and WM scenarios do not include restoration targets, whereas the GS scenario includes restoration objectives for *Posidonia Oceanica* meadows and coralligenous communities. These objectives aim to restore 30% of each habitat type by 2030, at least 60% by 2040, and at least 90% of their historical distribution by 2050.

In terms of fishing effort, the GS scenario assumes a linear reduction in fishing effort from 2024 to 2030, reaching FMSY levels by 2030, after which effort remains constant. In contrast, the NE scenario assumes an annual increase in fishing effort driven by technical creep of 0.44% from 2024 to 2100, whereas the WM scenario assumes a higher annual technical creep rate of 0.88% over the same period (European Court of Auditors, 2017; Piroddi et al., 2017).

Regarding discards, the NE scenario assumes no reduction in discard rates. The WM scenario assumes a linear 50% reduction in discards between 2024 and 2030 relative to current levels, whereas the GS scenario adopts a more ambitious target of a 90% reduction over the same period.

Finally, with respect to non-take areas, the NE scenario assumes status quo. The WM scenario stablishes that 5% of the surface of each national EEZ closed to bottom trawlers and purse seiners to protect Essential Fish Habitats (EFHs) while in GS scenario, a more ambitious protection effort is deployed, including a prohibition on fishing under 400 meters for trawlers (Table 1).

The geographical distribution of marine protected areas and fisheries closures are shown in Supplementary Figures S1 and S2.

Scenario comparisons should be interpreted as explorations of internally consistent futures rather than predictions. Structural uncertainty arises from assumptions about socio-economic development, management implementation, and ecological response functions, among others. Relative differences among scenarios provide robust insights into the interaction between climate change, human decision-making, and ecosystem dynamics.

Table 1
Management measures scenario characterization.

Global scenarios	RCPs	SSPs	MPA surface	MPA location	Restoration target	Fishing effort	Discards	Fisheries Closures
			NbS2		**NbS1**	**NIH**		
Global Sustainability	RCP2.6	SSP1	20% of each country's EEZ was designated as Highly Protected Areas (HPAs) with restrictions on activities such as bottom trawling, purse seining, and long-lining. Additionally, 10% of each EEZ was allocated as Fully Protected Areas (FPAs) prohibiting all fishing activities.	In Spain, France, and Italy, where marine spatial planning frameworks exist, new MPAs were designated based on existing protected areas in conjunction with national marine spatial planning priorities (Esparza Alaminos et al., 2021; Ministère de la transition écologique et solidaire, 2022; Ministero delle infraestrutture e della mobilità sostenibili, 2022). In contrast, in Morocco, Algeria, and Tunisia, where no formal national spatial planning frameworks exist, prioritization was based on existing protection areas and expert-identified priority areas(Coll et al., 2015; Gomei et al., 2021). Details at the National Level can be Found in (Coll, Christopher, et al., 2024). New areas entered into force in 2030.	Objectives were included on *Posidonia oceanica* meadows and coralligenous communities, aiming for recovery of 30% of each habitat type by 2030, at least 60% by 2040, and at least 90% of their historical distribution by 2050. Focus on Natura 2000 network.	Fishing effort was reduced linearly from 2024 to 2030 until reaching Fmsy by 2030, after which it was kept constant.	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 in average 14% (25.3% in trawlers, 3.1% in purse seiners and 9.9% artisanal fishers) (FAO, 2022b). Bycatch reduction was set up to 99% in the same period. Both elements remained constant from 2030 to the end of the simulation.	All existing no-take areas remained in place and new areas entered into force in 2030: the current Mediterranean EU towed gears ban (Regulation (EC) No 1967/2006) was expanded up to 50 meters depth and included all western Mediterranean countries. Additionally, the current 1000 FRA applied in the Mediterranean Sea (Recommendation GFCM/29/2005) was expanded to 400 meters depth for trawlers. Finally, all FRAs currently discussed in the context of GFCM (Ortega et al., 2023) were assumed to be implemented in 2030 and were, therefore, closed to bottom trawlers and longliners from 2030 to the end of the period projected.
National Enterprise	RCP8.5	SSP3	5% of each country's EEZ was designated as FPAs and 5% as HPAs	Non-coastal areas were prioritized when additional protection was required, while transboundary areas were excluded. New areas entered into force in 2030.	No restoration targets were included.	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	No discard reductions, or bycatch reduction goals were included.	No additional no-take areas were implemented.

Global scenarios	RCPs	SSPs	MPA surface	MPA location	Restoration target	Fishing effort	Discards	Fisheries Closures
			NbS2		NbS1	NIH		
						to the slowing down of innovation in the National Enterprise scenario.		
World Markets	RCP8.5	SSP5	5% of each country's EEZ was designated as FPAs and 5% as HPAs.	Protected areas were designated to safeguard key commercial species, ensuring their viability. Thus, priority is given to areas with the highest concentrations of Essential Fish Habitats (EFH) for deep-water red shrimps (*Aristeus antennatus* and *Aristaeomorpha foliacea*), and European hake (*Merluccius merluccius*). Details at the National Level can be Found in (Coll et al, 2024). New areas entered into force in 2030.	No habitat restoration measures were implemented in the WM.	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).	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.	In Spain, Italy, and France, 5% of the surface of each national EEZ was closed to bottom trawl and purse seiners to protect EFHs. When the proportion of EFH was the same in different areas, those areas with FPA or HPA, were transnational.

2.3. Ecosystem model baseline

We used a previously developed and calibrated spatial-temporal food-web model (Christensen, Coll, Piroddi, et al., 2014; Christensen et al., 2024; Christensen & Walters, 2004; Heymans et al., 2016) of the western Mediterranean Sea implemented with Ecopath with Ecosim (EwE v6.7). The EwE modelling framework consists of three linked components: the Ecopath module, which provides a mass-balanced representation of trophic flows under baseline conditions; the Ecosim module, which simulates temporal ecosystem dynamics driven by fishing mortality, trophic interactions, and environmental forcing; and the Ecospace module, which introduces spatiotemporal dynamics by simulating species movement, habitat suitability, and spatial fishing effort distribution across a gridded domain (Christensen, Coll, Steenbeek, et al., 2014; de Mutsert et al., 2024).

The Ecospace model of the western Mediterranean Sea represents 92 functional groups, including marine mammals, fish, invertebrates, primary producers, detritus, and five fisheries fleets (Artana et al., 2026; Coll, Christopher, et al., 2024). A list of the functional groups and their distribution along community indicators of the used model can be found in the Supplementary material, Table 1.

The model was fitted to historical observations for 1995–2020 and used to generate mid (2020–2050) and long-term (2020–20100) projections under climate and socio-economic scenarios. The model was calibrated using a stepwise fitting procedure (Ecosim Stepwise Fitting Procedure), optimising vulnerability parameters and environmental response functions (Scott et al., 2016), and the model performance was evaluated against historical time series of biomass and catches.

The relative contribution of fishing pressure, trophic interactions, and environmental forcing to observed dynamics was assessed following standard EwE diagnostic procedures (Corrales et al., 2017). The calibrated model successfully reproduces observed temporal trends in key functional groups and fisheries (Coll, Christopher, et al., 2024).

2.4. Environmental forcing and climate scenarios

We ran Ecospace for the historical period and generated projections for both the RCP4.5 and RCP8.5, using FutureMARES ensemble downscaled oceanic data (Kristiansen et al., 2024). The climate variables to drive the model included sea surface, 150 meters and bottom temperatures, biomass of dinoflagellates and diatoms, and net primary production.

To link species to environmental conditions in the Ecospace habitat foraging capacity model (Christensen, Coll, Steenbeek, et al., 2014) we used environmental responses obtained from AquaMaps model (Kaschner et al., 2019), which were adjusted with local data for pelagic species (Palomera et al., 2007). Functional groups were linked to environmental variables according to their main depth preferences (pelagic or demersal) and temperature sensitivities.

Additionally, for benthic and demersal species, the configuration of habitats was used to complement the environmental conditions based on EMODnet seabed substrate maps(Populus et al., 2017) and MEDISEH(Giannoulaki et al., 2013). Substrate types with similar ecological features were combined to reduce Ecospace model complexity, following previous applications (Artana et al., 2026; Coll, Christopher, et al., 2024).

2.5. Ecosystem indicators and analyses

The outputs of each contrasting scenario were analysed at three ecological levels:

- Functional group level indicators, including results in terms of biomass and catch from key commercial species (*anchovy -Engraulis encrasicolus-, sardine -Sardina pilchardus-, European hake -Merluccius merluccius-, and flatfishes*,), and key conservation species (bluefin tuna -*Thunnus thynnus*-, swordfish -*Xhipias gladius*-, pelagic sharks and groupers) ($t \cdot km^{-2} \cdot yr^{-1}$).
- Community level indicators: demersal, pelagic, fish, invertebrates, predatory and commercial biomass ($t \cdot km^{-2}$).
- Ecosystem level: trophic indices and ecosystem functioning metrics calculated using the EcoInd plugin (Coll & Steenbeek, 2017) such as Kempton's Q (Ainsworth & Pitcher, 2006), Marine Trophic Index (MTI) (Pauly and Watson 2005) and mean trophic level of the catch (TL) index evolution.

Functional group level indicators are presented as time series. Community- and ecosystem-level indicators are presented as percentage of changes (%) between the average values for 2019–2023 and 2096–2099. These indicators are reported both for the entire study area and by western Mediterranean geographical subareas (GSA), the management units used by the General Fisheries Commission for the Mediterranean (GFCM, 2009).

We also analysed the community- and ecosystem-level indicators across geographical sub-areas (GSAs) and future scenarios using principal component analysis (PCA) followed by k-means clustering. For each scenario, PCA was performed using the FactoMineR package (Husson et al., 2008) to reduce dimensionality, retaining enough principal components to explain at least 80% of the total variance. PCA scores were then used as input for k-means clustering. The optimal number of clusters (k = 2–6) was selected by maximising mean silhouette width based on Euclidean distances in PCA space, while requiring at least three points per cluster. Cluster membership was linked back to original variables to compute mean indicator values per cluster, enabling ecological interpretation. Finally, changes in cluster membership across scenarios were assessed by constructing transition matrices to evaluate the stability and shifts of GSA classifications under different future conditions.

3. Results

3.1. Functional groups evolution

Key commercial and conservation functional groups exhibited strongly contrasting trajectories across climate and socio-economic pathways (Fig. 2).

Under low-emission status quo conditions, most commercial functional groups remained comparatively stable throughout the simulation period. In contrast, key conservation functional groups displayed more divergent responses, with pelagic sharks declining while groupers progressively increased, suggesting heterogeneous responses to climate change among upper trophic level groups.

The GS scenario triggered a rapid and significant biomass recovery in several key commercial functional groups, particularly European hake and sardine, whose biomasses increased markedly by mid-century. These ecological gains were accompanied by substantial short-term reductions in catches across most fisheries, reflecting the transitional costs associated with strong exploitation control and ecosystem rebuilding (Fig. 2). The GS scenario also promoted pronounced recovery across all analysed conservation groups, especially swordfish, bluefin tuna, and pelagic sharks, whose biomass increased rapidly during the first decades following management implementation. Overall, these patterns indicate that under low-emission conditions, coordinated conservation, restoration, and fisheries management measures can substantially accelerate ecosystem recovery and trophic rebuilding (Fig. 2).

Under high-emission status quo conditions, the most pronounced commercial response was the progressive decline in European hake catches toward the end of the century. However, stronger ecological divergence emerged under the NE and WM pathways, where catches of anchovy, European hake, and flatfish increased, whereas sardine catches declined substantially, resulting in an increase in sardine biomass. These responses were consistently more pronounced under the WM scenario, reflecting the combined effects of intensified exploitation and stronger technological creep (Fig. 2).

Compared with low-emission pathways, ecological responses under high-emission scenarios (NE, and WM) were slower and more progressive, suggesting increased ecological inertia and delayed ecosystem recovery under intensified climatic forcing. Overall, conservation species generally exhibited negative long-term temporal trends under both NE and WM scenarios, although groupers showed localized biomass increases under NE conditions. The strongest declines consistently occurred under the WM pathway, indicating that market-driven exploitation trajectories may substantially constrain the recovery potential of upper trophic levels despite partial management interventions (Fig. 2).

3.2. Community and ecosystem level change

Community and ecosystem indicators revealed substantial divergence among contrasting future pathways, particularly between the sustainability-oriented GS scenario and high-emission pathways characterized by increasing exploitation pressure (Fig. 3). Similar patterns were observed for the midterm simulation (Supplementary Material Figure S3).

Under the GS scenario, the combined implementation of reduced fishing pressure, increased selectivity and discard mitigation, habitat restoration, and expanded protection resulted in substantial ecosystem rebuilding. Commercial biomass increased by 8%, total fish biomass by 10%, and predatory biomass by more than 40%, indicating strong recovery of upper trophic level organisms relative to the associated status quo scenario. Similar trends were observed under the low-emission status quo pathway, although recovery levels remained substantially lower, highlighting the central role of management measures in enhancing ecosystem resilience under moderate climate change (Fig. 3).

Despite the recovery of predatory biomass, the GS scenario was associated with declines in the marine trophic level of catches and MTI values by the end of the simulation period. These changes likely reflect the combined effects of exploitation restructuring, increased fisheries selectivity, and shifts in catch composition associated with sustainable fisheries management. Pelagic biomass showed slight increases under GS conditions but declined under the corresponding status quo scenario, whereas demersal biomass increased moderately in both pathways. Invertebrate biomass declined across all low-emission scenarios, consistent with increased predation pressure associated with fish and predators' biomass recovery (Fig. 3).

High-emission pathways had substantially weaker recovery dynamics. Although commercial and predatory biomass increased slightly under WM and NE conditions, these gains remained considerably below those observed under GS. In contrast, demersal biomass increased more strongly under high-emission scenarios than under low-emission conditions. The simultaneous increase in demersal, pelagic, and invertebrate biomass under NE and WM pathways suggests that climate-driven increases in lower trophic productivity may partially compensate for intensified exploitation pressure.

Biomass levels for commercial and demersal groups were lower under the NE scenario than under the WM scenario. This difference is consistent with the contrasting socio-economic assumptions underlying the two pathways, including fragmented governance and limited environmental ambition in NE, and the combination of technological intensification and targeted protection of commercially valuable habitats in WM.

3.3. Spatial analysis

Ecosystem responses exhibited pronounced spatial heterogeneity across the western Mediterranean Sea, revealing substantial regional differences in biomass recovery, trophic structure, and ecosystem functioning under all future scenarios (Fig. 4). Although several broad trends were shared across geographical sub-areas (GSAs), important regional contrasts emerged in the magnitude and direction of change in biomass and ecosystem indicators. These differences were particularly evident for the indicators of commercial, demersal, and invertebrate biomass under high-emission scenarios, as well as for predatory biomass under low-emission scenarios, indicating uneven distributions of ecological benefits and vulnerabilities across the basin (Fig. 4).

There was a persistent spatial structuring of ecosystem trajectories across scenarios, indicating that regional ecosystem dynamics remained strongly differentiated despite large-scale climatic and management forcing (PCA analyses, Fig. 5). Under all scenarios except GS, two stable GSA clusters consistently emerged. The first cluster grouped the Alboran Sea GSAs (GSA 1, 2, and 3), whereas the remaining Mediterranean GSAs formed a second cluster. Under the GS pathway, however, the clustering shifted toward a northwestern Mediterranean grouping composed of GSAs 1, 6, 7, and 8, suggesting that ambitious management and restoration measures can reorganize the regional ecosystem through similar patterns.

PCA further highlighted differences in ecosystem organization among future pathways. Under high-emission scenarios (NE, and WM), the first principal component, largely associated with biomass-related indicators, explained a greater proportion of total variance, resulting in stronger separation between regional ecosystem states. In these scenarios, the Alboran Sea consistently exhibited higher demersal, commercial, pelagic, and invertebrate biomass than the remaining GSAs, whereas other regions retained comparatively higher predatory biomass and trophic-level indicators. These patterns suggest a trade-off between biomass production and ecosystem integrity across the western Mediterranean basin under intensified climate and exploitation pressure.

4. Discussion

4.1. Socio-economic pathways mediate climate change impacts on marine ecosystems

Overall, our results show that marine ecosystem trajectories under climate change are strongly mediated by socio-economic pathways and associated management responses. Ecological outcomes differed not only because of differences in climate forcing, but also because of differences in governance priorities, fisheries exploitation patterns, and conservation measures. These findings support the emerging view that climate-resilient fisheries and marine management (Holsman et al., 2019) depend not only on adaptation to environmental change, but also on broader socio-economic choices that shape cumulative anthropogenic pressures and ecosystem recovery capacity.

The contrasting trajectories observed across scenarios demonstrate that governance can act as a first-order ecological driver. Under the Global Sustainability scenario, reduced fishing pressure, restoration, and expanded conservation measures generated increased commercial and predatory biomass in comparison with the equivalent status quo scenario. In addition, high-emission pathways characterized by fragmented governance or market-driven exploitation produced weaker and more uneven ecological responses. These differences illustrate how socio-economic assumptions propagate through ecological networks to alter ecosystem structure and functioning over decadal timescales.

More broadly, the study highlights the importance of integrating coherent socio-economic pathways into ecosystem-based management and marine spatial planning frameworks. Although global environmental assessments increasingly rely on SSP-RCP scenario approaches (IPBES, 2016, 2019; IPCC, 2022), such integrated frameworks remain uncommon in operational marine governance and ecosystem assessments. Our results suggest that incorporating socio-economic development trajectories into marine management evaluations could substantially improve the realism and policy relevance of long-term ecosystem projections (M. A. Peck et al., 2026).

4.2. Recovery under low-emission pathways: evidence for ecosystem resilience and trophic rebuilding

The GS scenario illustrates how the combined implementation of climate mitigation policies, biodiversity conservation targets, fisheries management reforms, and habitat restoration measures can substantially alter the ecological trajectory of the western Mediterranean Sea within a few decades. According to our simulations, the alignment of existing international climate commitments (UNFCC, 2015), biodiversity protection targets (CBD, 2022; European Commission, 2020), ecosystem restoration objectives (EC, 2024), and fisheries selectivity and discard reduction measures promoted under the Common Fisheries Policy (EC, 2013), generated clear improvements in ecosystem condition across multiple trophic levels. These results suggest that, even without new political objectives, coordinated and ambitious management targets considered under current policies can partially reverse the long-term marine biodiversity crisis affecting the Mediterranean Sea (UNEP/MAP-Plan Bleu, 2020), supporting progress towards Good Environmental Status, which we are currently far from achieving (Möller, 2025).

Nevertheless, the ecological stabilization observed under the GS pathway was associated with important short-term socio-economic costs, particularly through reductions in fisheries catches during the first decades of implementation. This highlights the existence of transition trade-offs between ecosystem rebuilding and short-term fisheries extraction, which are likely to generate resistance from the fishing sector and coastal communities if not accompanied by well-designed fisheries transition pathways (Costello et al., 2016). Such transition strategies may require combinations of economic compensation mechanisms, diversification of livelihoods, participatory governance approaches, and long-term adaptive management frameworks to facilitate social acceptance and equitable implementation of ecosystem-based management measures (Markard et al., 2020).

The medium-term ecological benefits associated with the GS scenario are particularly evident in the recovery of commercial and predatory biomass, as well as in key pelagic and demersal commercial species such as sardine and European hake. Both species are highly commercial and have historically experienced intense fishing pressure in the Mediterranean Sea, contributing to long-term biomass declines in sardine populations in the western Mediterranean Sea (Coll, Bellido, et al., 2024) and persistent overexploitation of European hake stocks (GFCM, 2022, 2025a). The ecological status of European hake has motivated major management initiatives, including the implementation of the EU multiannual plan for the fisheries exploiting demersal stocks in the western Mediterranean (EC, 2019), while sardine declines continue to raise concern across the basin despite the absence of equivalent large-scale recovery frameworks.

Importantly, both species European hake and sardine are also considered highly vulnerable to ongoing environmental changes associated with climate warming in the Mediterranean Sea (Espasandíin et al., 2025; Farahmand et al., 2023; Hidalgo et al., 2022). Against this background, the relatively rapid rebuilding observed under the GS scenario strongly indicates that integrated management approaches combining climate mitigation, fisheries regulation, conservation, and restoration can substantially enhance ecosystem resilience even in climate-sensitive systems and species. These findings suggest that the Mediterranean Sea retains significant recovery potential when cumulative anthropogenic pressures are simultaneously reduced (Cappelletto et al., 2021).

The GS scenario also predicted strong recoveries of predatory species together with a rebuilding of trophic structure, indicating broader improvements in ecosystem integrity beyond commercially targeted stocks. This result is particularly relevant in the Mediterranean context, where several high-trophic species are currently classified as threatened or endangered by the International Union for Conservation of Nature (IUCN) (UNEP, 2024). The recovery of upper trophic levels under the GS pathway therefore suggests that integrated ecosystem-based management may contribute not only to fisheries rebuilding, but also to wider biodiversity conservation objectives and restoration of ecological functioning, reinforcing the benefits of integrating processes across trophic levels and ecosystem components within a holistic framework.

4.3. Limits of management under high-emission futures

The differences observed between the NE and WMscenarios demonstrate that management choices are key even under severe climate change trajectories. Thus, differences in governance priorities, technological development, and fisheries exploitation patterns can substantially alter ecosystem structure. However, the results also indicate that ecological benefits under high-emission pathways are generally delayed, spatially uneven, and partially offset by the combined effects of intensified climatic forcing and increasing exploitation pressure.

Several management-related mechanisms contribute to the contrasting ecological responses observed between the NE and WM scenarios. In the case of MPAs, both scenarios implement similar protection targets in terms of total protected surface and nominal protection levels (Table 1) but differ substantially in their spatial design and management objectives. While the WM scenario prioritizes the protection of commercially valuable EFH, the NE scenario follows a less ecologically integrated spatial allocation approach. This led to differences regarding the ecological effectiveness of protection measures, even considering scenarios with comparable nominal conservation targets. These results are consistent with previous studies showing that MPA effectiveness depends not only on total protected area coverage, but also on their quality, including factors such as spatial connectivity, protection objectives, restriction levels, ecological representativeness, and enforcement capacity (Castro-Cadenas et al., 2026; Stephenson et al., 2025).

The scenarios also differ in the projected intensity of technological creep -with higher values in WM scenario, followed by NE-, a process that may strongly influence long-term exploitation dynamics (Table 1). Technological development directly affects fishing efficiency and can partially counteract nominal effort reductions through increases in catchability (Eigaard et al., 2014). Despite its importance, technological creep remains insufficiently quantified in many fisheries systems worldwide, generating substantial uncertainty regarding future exploitation trajectories (Palomares & Pauly, 2019; Scherrer & Galbraith, 2020). Similarly, the NE and WM scenarios differ in their assumptions regarding discard reduction. Discard rates remain comparatively high in several Mediterranean fisheries, particularly in bottom trawl fleets (FAO, 2025), and the current EU landing obligation has had a very limited effects in the Mediterranean Sea (Spedicato et al., 2022). Nevertheless, previous studies suggest that improvements in selectivity and discard mitigation can generate positive ecosystem responses with relatively limited economic costs if properly designed (Spedicato et al., 2022).

Finally, unlike the NE scenario, the WM scenario includes the implementation of Fisheries Restricted Areas (FRAs) designed to protect EFHs, reflecting a more ecosystem-oriented fisheries management approach. Such spatial fisheries management measures are likely to become increasingly relevant in the Mediterranean region, where several successful experiences have already demonstrated their ecological potential (Chiarini et al., 2022). Their benefits of spatial management measures have also been highlighted by previous ecosystem modelling studies (Keramidas et al., 2025; Vilas et al., 2021). In parallel, spatial protection measures are gaining increasing prominence within regional governance frameworks, particularly through the General Fisheries Commission for the Mediterranean 2030 Strategy and the development of future multiannual management plans (FAO, 2021).

4.4. Spatial heterogeneity reveals uneven ecosystem vulnerability and recovery potential

Our results indicate strong spatial heterogeneity in ecosystem responses to climate change and management interventions across the western Mediterranean Sea, as previously predicted (Artana et al., 2026). Ecological trajectories differed not only among scenarios and functional groups, but also among geographical sub-areas, highlighting that ecosystem vulnerability and recovery potential are unevenly distributed across the basin.

Multiple factors likely contribute to these heterogeneous responses, including the marked geographical, oceanographic, and ecological diversity of the western Mediterranean Sea (Coll et al., 2010; UNEP, 2024). Differences in productivity regimes, habitat composition,

hydrographic conditions, and historical ecosystem structure are all likely to influence the way climate forcing and management measures propagate through marine food webs (Lotze et al., 2019). In addition, regional differences in fishing intensity, fleet composition, and exploitation history may further shape ecosystem sensitivity and recovery dynamics (FAO, 2025; Ouled-Cheikh et al., 2022; Ramírez et al., 2018).

The Alboran Sea consistently exhibited a distinct ecological trajectory across most scenarios, suggesting that its ecosystem dynamics are partially decoupled from the rest of the western Mediterranean basin. This pattern is likely linked to its biogeographic position as a transition zone connected to the Atlantic Ocean, where water exchange through the Strait of Gibraltar strongly influences temperature regimes, nutrient availability, and primary productivity (Báez et al., 2021). These oceanographic characteristics may partially buffer the Alboran Sea against some climate-driven impacts while supporting food web dynamics that differ from those in other Mediterranean regions. Interestingly, under the GS scenario, the clustering structure shifted toward a northwestern Mediterranean grouping, suggesting that ambitious management and restoration measures can reorganize ecological similarity across regions. This result indicates that ecosystem-based management may not only alter local ecological conditions, but may also reshape large-scale spatial ecosystem organization by reducing some regional disparities while amplifying other regional differences.

The spatially uneven effectiveness of management measures also has important governance implications. Conservation and fisheries management policies frequently lead to uneven distributions of ecological benefits and socio-economic costs across regions and sectors (Gill et al., 2019; Nahuelhual et al., 2025; Ruano-Chamorro et al., 2023), creating potential tensions among stakeholders and management jurisdictions. In the Mediterranean context, where governance is largely coordinated through transnational basin-scale institutions such as the General Fisheries Commission for the Mediterranean, these spatial asymmetries may complicate the implementation of coordinated regional management measures that rely on multilateral consensus.

Finally, the observed divergence in community-level responses among regions and functional groups suggests that the interaction of climate change and management measures may simultaneously result in ecological “winners” and “losers” across spatial scales (Free et al., 2020; Thorpe et al., 2022). Such asymmetries could reinforce conflicting national or sectoral interests, potentially leading to governance conflicts between local, national, and basin-wide management priorities (Mendenhall et al., 2020; Pinsky et al., 2018). These findings highlight the importance of incorporating spatial heterogeneity and multi-scale governance dynamics into future ecosystem-based management and marine spatial planning frameworks under global change.

4.5. Limitations and uncertainties

As with any modelling exercise, this study is subject to several uncertainties and limitations. First, important spatial differences remain in data availability across the western Mediterranean basin where ecological and fisheries data are more limited, consistent and/or reliable in southern regions (GFCM, 2025b). These regional differences in data may influence the representation of ecosystem dynamics and exploitation patterns across geographical sub-areas.

Second, the modelling framework does not explicitly incorporate pollution, invasive species, acidification, and other anthropogenic pressures that are likely to influence cumulative ecosystem impacts under global change (Piet et al., 2023). The changes projected here are likely conservative estimates of ecosystem vulnerability, particularly over long-term projections extending to the end of the century.

Additional uncertainty arises from the socio-economic assumptions underlying future scenario development. Although the scenarios were constructed to ensure internal coherence between climate trajectories, governance pathways, and management measures, future socio-economic developments remain inherently uncertain. Similarly, the fishing dynamics represented in the model are based on externally forced effort trajectories and therefore do not fully account for adaptive behavioural or economic feedbacks within fisheries systems. For example, improvements in stock status and ecosystem condition under sustainable management pathways could potentially generate economic incentives that stimulate renewed increases in fishing pressure, a dynamic associated with rebound effects or the Jevons paradox (Alcott, 2005).

Despite these uncertainties, the relative contrasts observed among scenarios are robust and provide valuable insights into how alternative climate and socio-economic trajectories may shape future marine ecosystem dynamics. Consequently, the results should be interpreted not as predictions, but as internally consistent exercises that allow the exploration of plausible alternative futures under global change.

5. Conclusions

Our results highlight how the future of marine ecosystems in the western Mediterranean Sea will be shaped not only by the magnitude of climate change but also, to a critical extent, by the ambition of marine management strategies. By using coherent scenarios within a mechanistic food-web modelling framework, we show how policy and management choices are expected to substantially modify ecological trajectories, even under similar environmental external pressures.

Our results highlight that under low-emission pathways, comprehensive and well-coordinated management measures—combining conservation, restoration, and sustainable harvesting—can trigger rapid and significant ecosystem recovery. Improvements in biomass, biodiversity, and trophic structure can occur within a few decades, reinforcing the idea that marine ecosystems retain a strong capacity for recovery when pressures are reduced and habitats are restored. However, these gains often involve short-term trade-offs, particularly in reduced catches, emphasizing the need for adaptive governance and socio-economic transition support mechanisms.

Under high-emission scenarios, management remains important, although its effects are delayed and more uneven. Increased fishing pressure and limited conservation lead to declines in higher trophic levels and further shifts toward lower-trophic species. Importantly, our results indicate that climate change does not fully determine ecological outcomes, with management emerging as a key driver shaping future ecological outcomes.

This study also reveals pronounced spatial and functional heterogeneity in ecosystem responses, pointing out the potential distributional conflicts among regions and sectors. This unevenness poses challenges for transboundary governance frameworks and calls for stronger coordination, equitable benefit-sharing mechanisms, and improved marine spatial planning across the Mediterranean basin.

Overall, our findings support the use of integrated, scenario-based modelling as a powerful tool for exploring the long-term consequences of policy decisions under climate change. They also stress the importance of maintaining coherence between external drivers and management responses to enhance the credibility of scenario-based modelling exercises.

Declarations

Acknowledgements

Authors acknowledge funding from the EU Grant Agreement 869300 (FutureMares project) and EU GA 101059877 (GES4SEAS project). JS and MP acknowledge funding from EU Grant Agreement 101060072 (ACTNOW project). The authors acknowledge the institutional support of the “Severo Ochoa Centre of Excellence” accreditation grant CEX2024–001494-S funded by AEI 10.13039/501100011033. This research is also part of the Integrated Marine Ecosystem Assessments (iMARES) research group funded by Agència de Gestió d’Ajuts Universitaris i de Recerca (Generalitat de Catalunya) Grant no. 2021SGR00435.

Open Research statement

Key data are available in supplementary material. If any other data is considered to be needed by the reviewers it will be available if the paper is accepted for publication.

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Figures

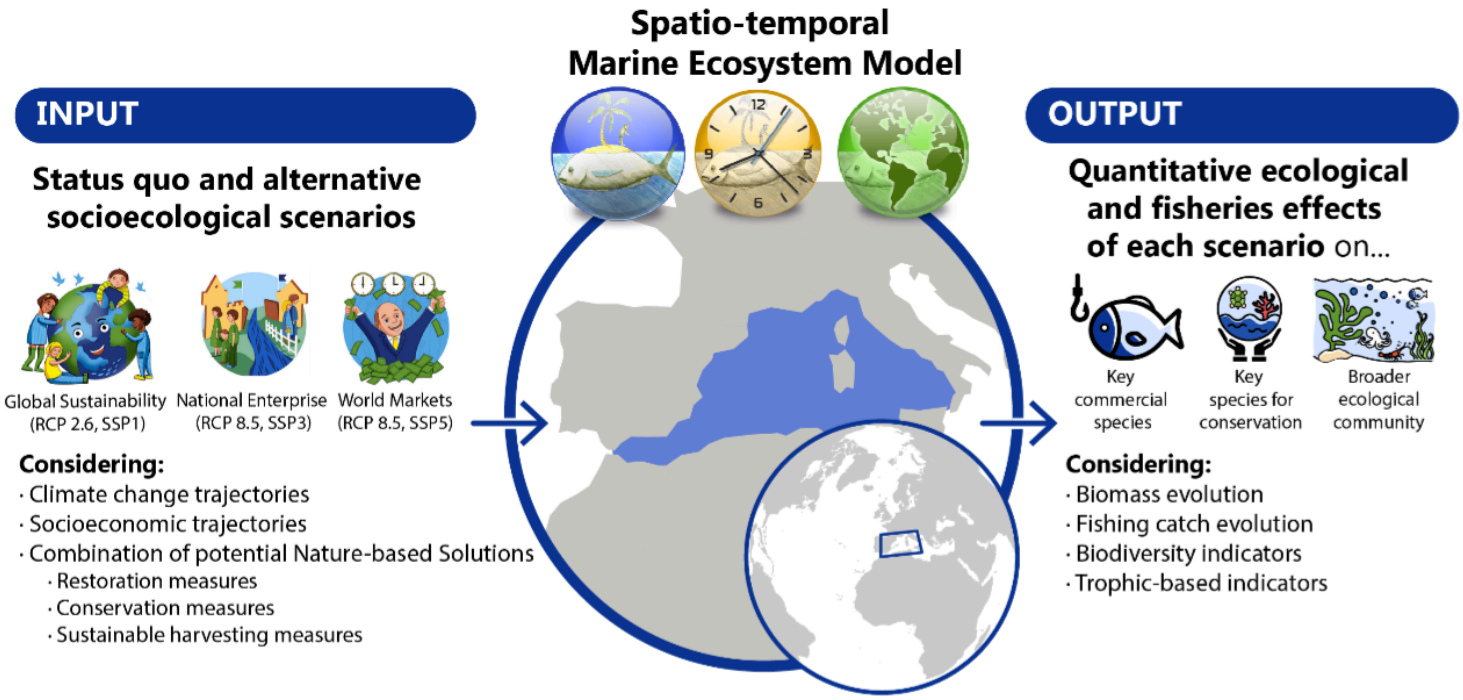


Figure 1

Conceptual framework and modelling workflow.

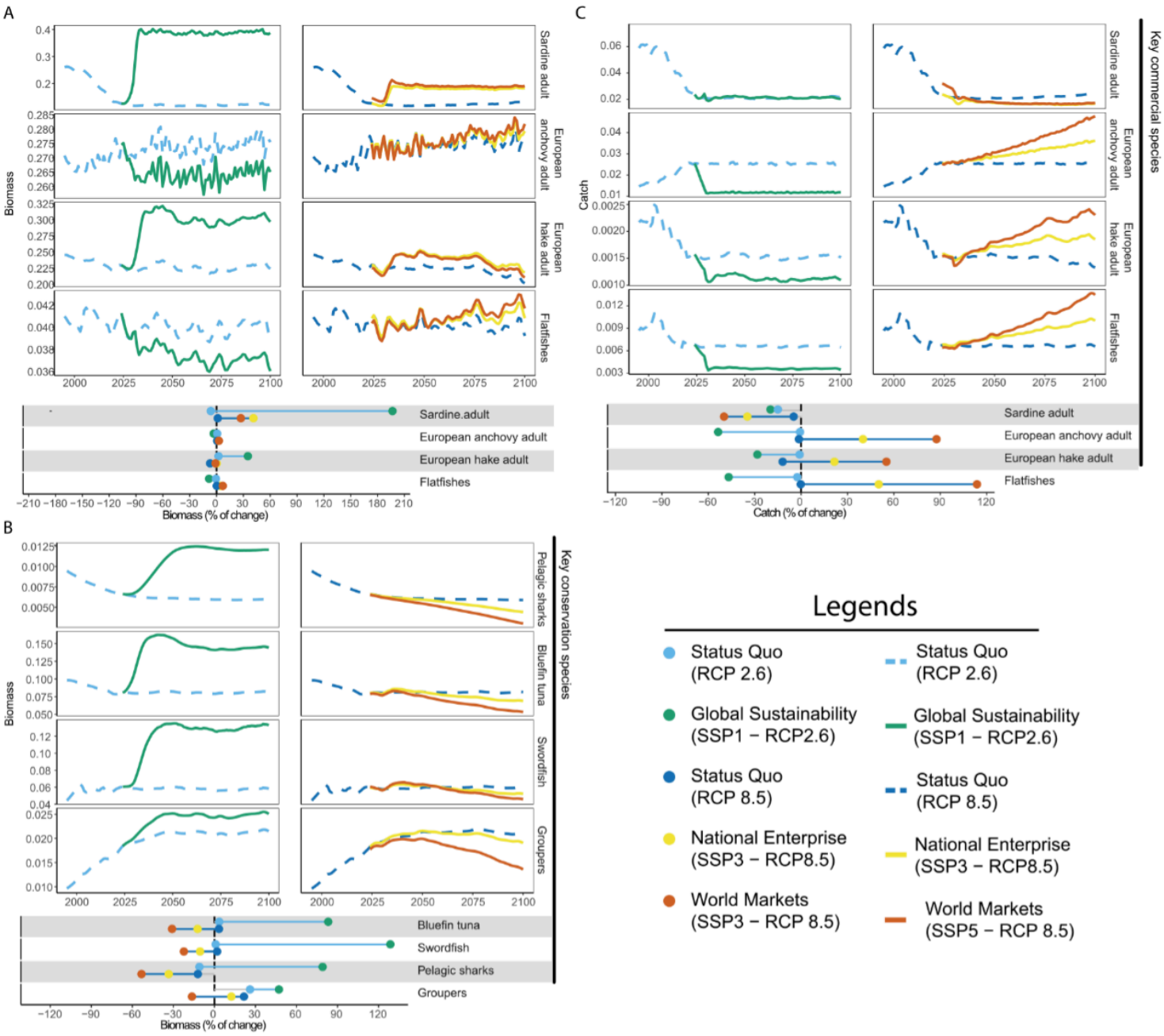


Figure 2

Key commercial and conservation functional groups temporal evolution for all the scenarios. A) Key commercial biomass, B) Key commercial catch, C) Key conservation species. Lollipops show the percentage of change (%) of each variable between 2019-2023 and 2096-2099 averages.

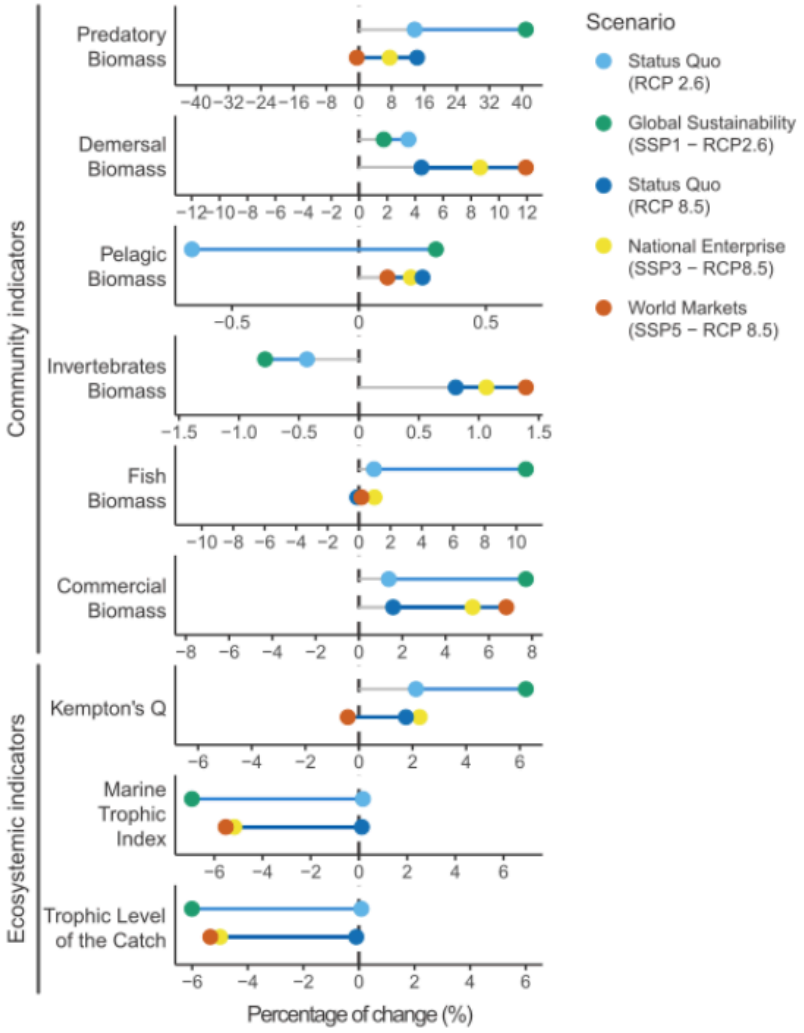


Figure 3

Projected changes (%) in community and ecosystem indicators calculated from the ratio of mean end-of-century (2096-2099) and the present day (2019-2023) values.

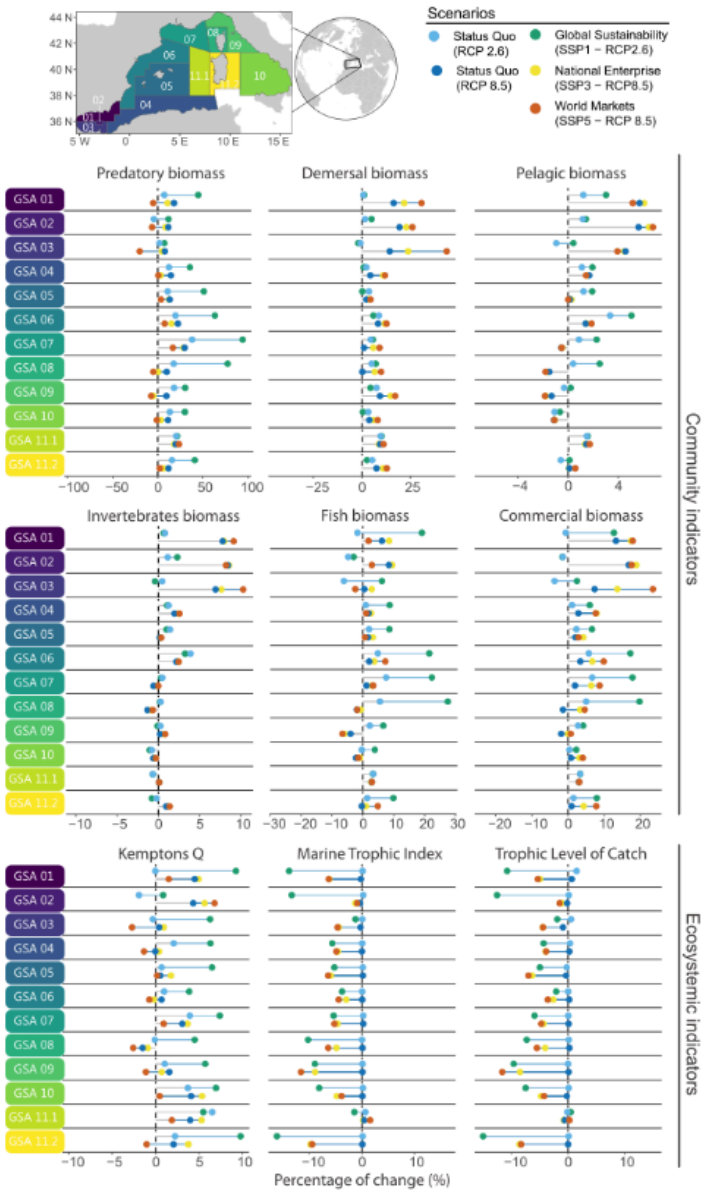


Figure 4

Spatial analysis of community and ecosystem indicators across 12 Geographical Sub-Areas (GSAs) of the western Mediterranean Sea. The x-axis shows the percentage change (%) between the average values for 2019–2023 and 2096–2099. The horizontal lines represent the differences between each management scenario and its corresponding status quo scenario.

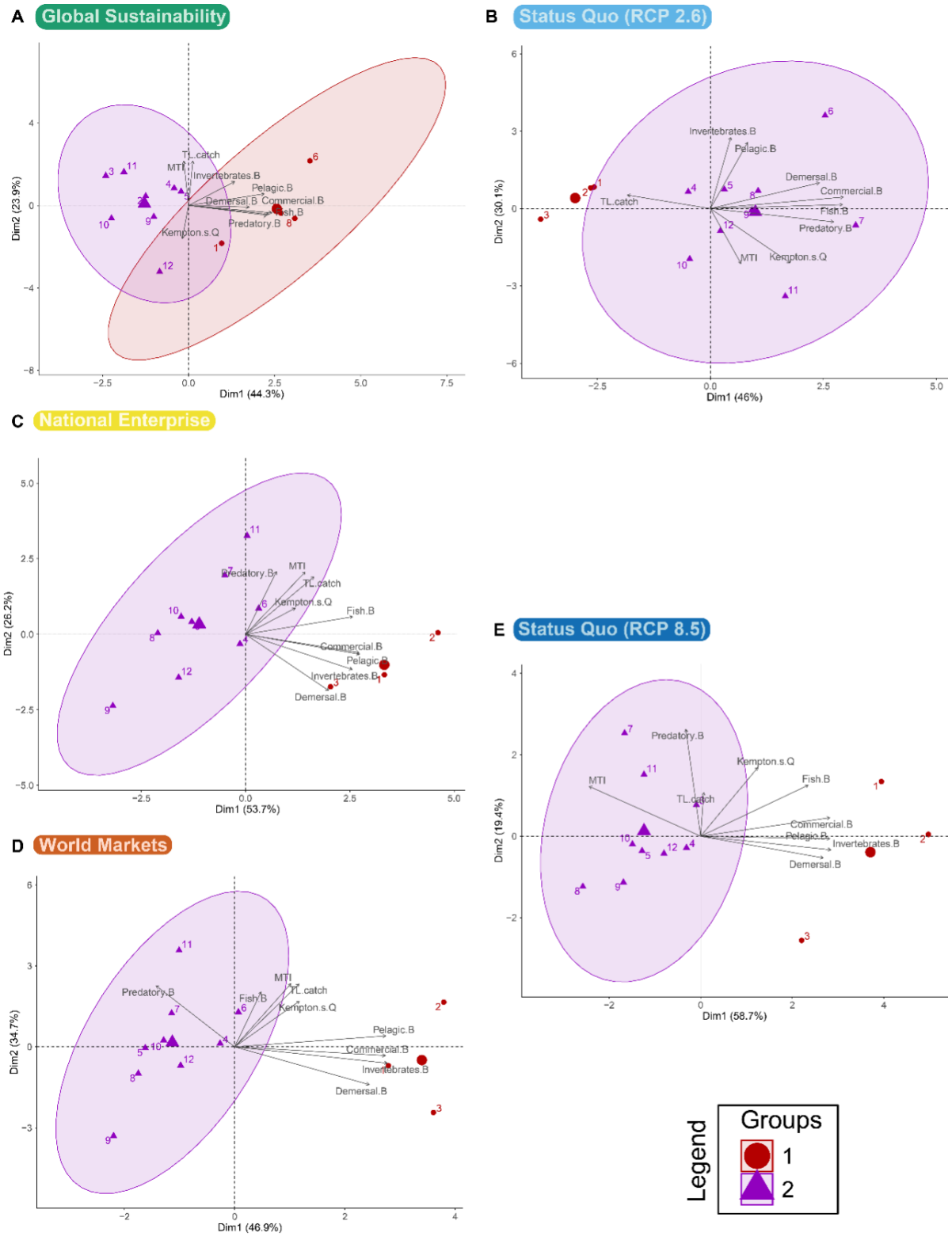


Figure 5

Principal Components Analysis (PCA), cluster analysis of community and ecosystem indicators (see Figure 4) by Geographical Sub-Area for all scenarios. Ellipse are shown only when more than 3 GSAs are found in the same cluster.

Supplementary Files

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- Supplementarymaterial.docx