Climate Change and
Future Marine
Ecosystem Services
and Biodiversity

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Project Deliverable Report 4.3
Projections of the impacts of scenarios of climate change and nature-inclusive harvesting policies on fisheries and aquaculture species

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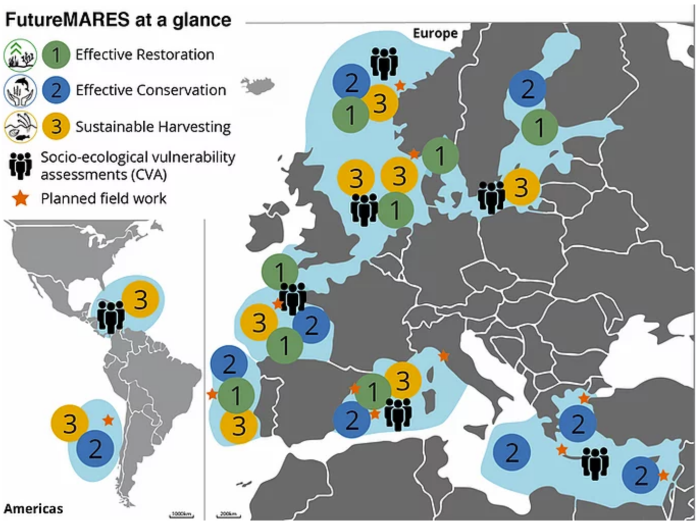
FutureMARES Project

FutureMARES - Climate Change and Future Marine Ecosystem Services and Biodiversity is an EU-funded research project examining the relations between climate change, marine biodiversity and ecosystem services. Our activities are designed around two Nature-based Solutions (NBS) and Nature-inclusive Harvesting (NIH):

Effective Restoration (NBS1)

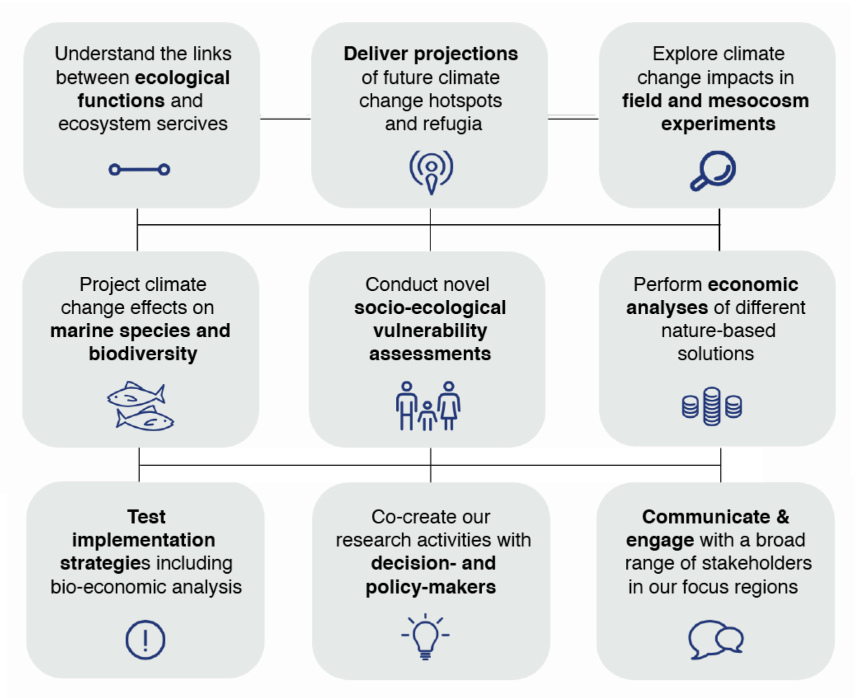
Effective Conservation (NBS2)

Nature-inclusive (sustainable) Harvesting (NIH)



We are conducting our research and cooperating with marine organisations and the public in Case Study Regions across Europe and Central and South America. Our goal is to provide science-based policy advice on how best to use NBS and NIH to protect future biodiversity and ecosystem services in a future climate.

FutureMARES provides socially and economically viable actions and strategies in support of nature-based solutions for climate change adaptation and mitigation. We develop these solutions to safeguard future biodiversity and ecosystem functions to maximise natural capital and its delivery of services from marine and transitional ecosystems. To achieve this, the objectives of *FutureMARES* defined following goals:



Understand the links between **ecological functions** and ecosystem sercives

Deliver projections of future climate change hotspots and refugia

Explore climate change impacts in **field and mesocosm experiments**

Project climate change effects on **marine species and biodiversity**

Conduct novel **socio-ecological vulnerability assessments**

Perform **economic analyses** of different nature-based solutions

Test implementation strategies including bio-economic analysis

Co-create our research activities with **decision- and policy-makers**

Communicate & engage with a broad range of stakeholders in our focus regions

Deliverable data	
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Lead beneficiary:	IRD, Deltares
Responsible author:	Yunne Shin (IRD), Luca Van Duren (Deltares)
Contact:	yunne-jai.shin@ird.fr, luca.vanduren@deltares.nl
Co-authors:	**IRD:** Yunne Shin, Alaia Morell, Cléa Abello, Adrien Chevallier; **Deltares:** Luca Van Duren, Lauriane Vilmin, Sonia Heye, Lisa Schneider, Tammo Zijlker, Firmijn Zijl, Yeyeong Chung; **CSIC:** Marta Coll, **CEFAS:** Christopher Lynam; **AUD:** Marie Maar; **AZTI:** Maite Erauskin-Extramiana, Jose A. Fernandes-Salvador; **PML:** Ana Queiros; **WUR:** Pauline Kamermans
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Involved partners

Project partner (affiliation)	First name	Last name	E-mail
IRD	Yunne	Shin	yunne-jai.shin@ird.fr
Deltares	Luca	Van Duren	Luca.vanDuren@deltares.nl
CSIC	Marta	Coll	marta.coll@icm.csic.es
CEFAS	Chris	Lynam	Chris.Lynam@cefas.co.uk
AUD	Marie	Maar	mam@ecos.au.dk
AZTI	Jose	Fernandes	jfernandes@azti.es
PML	Ana	Queiros	anqu@pml.ac.uk
WUR	Pauline	Kamermans	pauline.kamermans@wur.nl

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Table of content

List of symbols, abbreviations and a glossary

Bioen-Ev	Bioenergetics-Evolutionary
CC	Climate change
CFP	EU Common Fisheries Policy
DEB	Dynamic Energy Budget (model)
DFLOW-FM	D-Flow Flexible Mesh model suite
DoA	Description of Action, a part of the project Grant Agreement describing the project work plan
EC	European Commission
EC GA	European Commission Grant Agreement – a contract between the European Commission and FutureMARES consortium
ERGOM	Ecological Regional Ocean Model
EwE	Ecopath with Ecosim
FCM	Fuzzy cognitive map
FRAs	Fishing Restriction Areas
GA	Grant Agreement
MEMs	Marine Ecosystem Models
NBS	Nature-based Solutions
NIH	Nature-inclusive Harvesting
OA	Ocean Acidification
OSMOSE	Object-oriented Simulator of Marine Ecosystems
RCP	Representative Concentration Pathway
SL	Storylines
SS-DBEM	Size-spectrum Dynamic Bioclimate Envelope Model
SSP	Shared Socioeconomic Pathway
Tn.x	Task – a sub-component of a work package where “n” is a number of the work package and “x” is a number of the task within this work package
WP	Work Package

Executive summary

This report summarizes the results of model simulations examining the impacts of climate change scenarios on sustainable harvesting by traditional fisheries and from the culture of plants and animals at the base of the food web (Nature-inclusive Harvesting - NIH). Research is presented for seven FutureMARES Storylines (#9, 10, 14, 15, 24, 31, and 33). Planned activities on NIH in Storylines 17 and 19 (transitional waters) are reported elsewhere (Task 2.3 report). The work is based on projection scenarios developed in FutureMARES using the IPCC framework of Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs), specifically, SSP1-2.6, SSP2-4.5 and SSP5-8.5, including contrasts in fisheries management actions and aquaculture upscaling.

Simulations were performed for marine socio-ecosystems in the North Sea, Baltic Sea, Bay of Biscay, and Mediterranean Sea. Historically, these ecosystems have been heavily exploited and degraded by a variety of human activities including climate change. Current fisheries management strategies towards sustainable exploitation involve various measures, including fishing regulation, quotas, and spatial management such as no-take and marine protected areas. However, the effectiveness of these measures in the face of climate change remains uncertain. Similarly, current plans for upscaling the aquaculture of lower trophic level species such as seaweeds and shellfish from in enclosed bays to offshore areas in some European regional seas will require science-based advice on acceptable levels in a future climate, particularly due to concerns of ecological carrying capacity.

Model simulations for aquaculture indicated clear, scenario-specific impacts of climate change on the yield of mussel farms depending on the methods of cultivation. Bottom cultures of mussels were projected to be very susceptible to detrimental impacts of climate change due to increases in the duration and strength of stratification, making some areas susceptible to hypoxia. On the other hand, the productivity of hanging mussel cultures in the open North Sea areas as well as in coastal bays may increase, but increases in coastal areas was often associated with changes in run-off and nutrient loading as opposed to increases in temperature. Hanging cultures are much less susceptible to changes in stratification as they are, by definition, located in the upper water layers with direct access to primary production and well oxygenated waters. For seaweed, future cultivation yields depend on the combined effect of increasing temperatures and changes in nutrient loads. In the RCP8.5 scenario, 16% reductions in seaweed production were projected in the North Sea while slight increases in yields were projected at the end of the century in the most sustainable scenario (RCP 2.6). Hence, the expected combined impact of climate change and socio-economic pathways not geared towards global sustainability are expected to be negative on cultivation of these species.

Model simulations using cumulative impact scenarios of fishing and climate change suggested that ocean warming can limit the positive effects of sustainable fishing strategies. For example, sardine populations in the Bay of Biscay were projected to decline, while hake and anglerfish recoveries will be less significant. In contrast, bluefin tuna and anchovy were expected to thrive due to increased food availability and reduced competition. Climate change mitigation efforts may benefit demersal fish in the North Sea and the Mediterranean Sea. Increases in demersal fish, however, could negatively impact small pelagic fish, which may require even greater reductions in fishing effort to offset decreases in stock biomass. Overall, the work undertaken in T4.3 highlights that both winners and losers will emerge when considering the combined effects of climate change and fishing.

To explore management strategies in response to climate change, a variety of advanced marine ecosystem models (MEMs) were employed, including EwE, Ecospace, SS-DBEM,

Osmose, Bioen-Ev-Osmose, and FCMs. These models provide insights into trophic interactions, climate change impacts, and fishing effects on the dynamics of fish stocks. They are considered valuable tools for strategic, medium- to long-term fisheries management. These tools also provide valuable projections for the future development of aquaculture in areas where there currently is none. They provide clear indications of impacts from aquaculture on the marine system (e.g. impacts on primary production, the basis of the foodweb) and they can indicate when stocking levels exceed the carrying capacity either at local or at broader (regional or ecosystem) scales.

Involving stakeholders is crucial for ecosystem-based management. Scenarios used for aquaculture projections were co-developed with stakeholders. For fisheries in two FutureMARES regions, Fuzzy Cognitive Maps (FCMs) were used to engage stakeholders on the current and future status of marine ecosystems. FCMs offer a comprehensive representation of marine socio-ecosystems, including various human activities such as shipping, renewable energy, and oil and gas. They provide a broader understanding of socio-ecological systems and allow for the projection of diverse scenarios.

The report also highlights the importance of adaptive capacity of harvested species. On the one hand, it is important to take into account the ability of fish life history traits to evolve in response to climate change and fisheries. Fisheries- and climate-induced evolution can impact growth, maturation, and fecundity of fish. Evolutionary changes in fish populations may modify fishing reference points, necessitating adaptive strategies. On the other hand, the fisheries sector itself can adapt to environmental changes by increasing the value of products, reducing fuel consumption, and optimizing fishing routes. Modern fisheries are heavily reliant on fossil fuels, making fuel efficiency a priority. Additionally, rebuilding stocks and reducing over-capacity are essential for improving the long-term performance and environmental sustainability of the industry.

1. Introduction

FutureMARES Work Package 4 was designed to advance the ability to deliver mechanistic projections for changing species & ecosystems in European waters. As part of this ambition, Task 4.3 was envisaged to deliver a step change in current understanding of **how climate change will influence strategies for nature-inclusive (sustainable) harvesting** (NBS3) in marine waters. The workplan focused on both integrated production systems (such as Integrated Multi-Trophic Aquaculture) and wild capture fisheries. The task was, thus, geared towards informing on the susceptibility and resilience of these sectors to climate change, with the purpose of informing the development of climate adaptive policy. The workplan initially combined:

> *Objective 1)* the delivery of new, mechanistic capability to advance the skill of projections for these sectors with updated, state-of-the art tools.
>
> *Objective 2)* new ensemble analysis of hundreds of runs from legacy simulations for exploited species in European Seas (CERES) and globally (FishMIP) uniquely available to this consortium.

This report focuses primarily on the delivery of Objective 1 (Table I, below). As the programme developed, the analyses described in Objective 2 have been carried out as part of the workplan of Task 6.1 and ensures that FutureMARES continues to build on the legacy of past programmes. Work on transitional species initially designed for this Task (4.3) has been delivered by IRSTEA as part of Task 2.3, this allows a more consistent partitioning of different modeling techniques and involved research groups across the work programme. These strategic changes to the original T4.3 workplan, thus, focused task resources on the delivery of new, more refined predictive capability for wild capture fisheries and integrated aquaculture production systems in European regional seas.

As part of Objective 1, delivery has: i) assessed the harvest potential of lower trophic level species important to IMTA (seaweed and mussels; kelp, sea urchins and cod), generating habitat suitability maps useful for shellfish and seaweed farming (NBS3) as well as restoration programmes (NBS1) (Delft3D FM modelling suite and FlexEM); ii) foodweb modeling of North Sea, Mediterranean and Bay of Biscay ecosystems (EwE, SS-DBEM and Osmose), including novel simulations of species plasticity and genetic adaptive capacity to climate change and fishing (Bioen-Ev-Osmose); iii) new simulations of range expansion of thermophilic species that influence the resilience of wild-capture fisheries (SS-DBEM); and Fuzzy Cognitive Maps of the North Sea and the Mediterranean Sea socio-ecosystems. As the project evolved, Fuzzy Coginitive Maps emerged as useful tools to provide an integrated understanding of the dynamics of fisheries socio-ecological systems and allow for the projection of diverse scenarios. Hence, FCMs have been developed in the North Sea (storyline 14) and as part of the western Mediterranean Sea (storyline 31) with fruitful stakeholder engagement processes in both regions that allowed to downscale the global shared socio-economic pathways to local realities.

1.1. Defining the Challenge

In marine systems climate change can have many effects. Temperature is clearly a major driver for species distribution, but it will also affect patterns of freshwater run-off, as well as stratification patterns. Hence also indirectly, nutrient loads and patters of nutrient distributions in marine systems can be affected and hence temporal and spatial patterns of primary production, determining the system’s carrying capacity for low trophic, extractive aquaculture as well as fisheries. These changes will interact with changes in human exploitation of marine environments. We are already seeing a major change in food provisioning, shifting from wild harvest (fishing) to more cultivation (aquaculture). There is also worldwide more emphasis on sustainable fisheries policies. This deliverable explores the intricate interlinkage of environmental change and human use, using state-of-the-art numerical models. The aim is to assess how marine management could best anticipate and deal with expected future changes.

To address the report's objective, a combination of ecosystem models was applied to the different study areas. Table 1 (below) provides more details on each ecosystem model re-developed in this task of FutureMARES. Simulation methods and results of these models are presented in subsequent sections of this report. Set-ups of these models and simulated scenarios are detailed in Chapter 1.

Table 1: Ecosystem models developed for/applied in Task 4.3

Storyline	**Ecosystem**	**Model**	**Main features (dynamic, spatial, species-based, size-structured)**	**Model output (biomass, abundance, P/A...)**	**Target species**	**Contact person**
9	SW Baltic Sea, Limfjorden	FlexSem-ERGOM-DEB	Dynamic, spatial, biogeochemistry, species	Biomass, harvest, ecosystem effects	Blue mussels *Mytilus edulis*	Marie Maar
10-15	North Sea	Delft3D FM	Dynamic, spatial, biogeochemistry, species, nutrients	Biomass, harvest, ecosystem effects	*Saccharina latissima, Mytilus edulis*, 4 species groups of phytoplankton, each with 3 ecotypes	Lauriane Vilmin Luca van Duren
14	North Sea	EwE	Dynamic, (spatial), species-based, functional groups based	Biomass, Catch, Mortalities,Trophic Level	Many fish and other FGs	Christopher Lynam
14	North Sea	FCM	Static, nodes and links relating management objectives, human activities, pressures, species, physical environment	Fisheries catch, biomass of main species groups	Many fish and other FGs	Christopher Lynam
15	North Sea	Bioen-ev-Osmose	Dynamic, spatial, species-based, size-structured, trait-based, bioenergetics, evolutionary	{Biomass, abundance, Catch, Trophic Level, diets, metabolic rates} by size/species/age	A total of 16 species	Alaia Morell, Yunne Shin
24	Bay of Biscay	SS-DBEM	Dynamic, spatial, species-based	Biomass, Catch, Mortalities, ecophysiology, size spectrum, competition between species	Tuna, billfishes and main trophic competitors	Maite Erauskin-Extramiana, Jose A. Fernandes-Salvador

24	Bay of Biscay	EwE	Dynamic, (spatial), species-based, functional groups based	Biomass, Catch, Mortalities,Trophic Level	Many fish and other FGs	Xabier Corrales, Amate, Andonegi
31	Mediterranean Basin	OSMOSE	Dynamic, spatial, species-based, size-structured, trait-based	{Biomass, abundance, Catch, Trophic Level, diets} by size/species/age	About 100 fish and invertebrate species	Yunne Shin, Cléa Abello, Fabien Moullec
30-31,33	Western Mediterranean	Ecospace	Western Mediterranean & NW Mediterranean	Biomass, Catch, Mortalities, distributions, Trophic Levels, ecological indicators	Many fish and other FGs	Marta Coll
33	Western Mediterranean	FCM	Static, nodes and links relating drivers (governance, economy, social, technology, environment) and species/ecosystem status	All the previous variables/concepts	Many fish and other FGs	Adrien Chevallier, Yunne Shin

1.2. Contribution to the project

The overarching goal of FutureMARES is to gain insight into the sensitivity of species to climate change and offer nature-based solutions and sustainable harvest management options to increase climate robustness Task 4.3 focusses specifically on aquaculture and fisheries, using state-of-of-the-art numerical models and model combinations.

Table 2 summarizes the contribution of this work to the different FutureMARES storylines.

Table 2: Summary map of modelling undertaken in T4.3, and FutureMARES storylines (numbered as "#"), regions, and lead partner contributing.

	Storyline / Regions	#	NBS	Lead
NE Atlantic & North Sea	Marine spatial planning (broad coverage)	*14*	3	CEFAS
	Nature-Inclusive Harvesting (NIS)	*14*	3	IRD
	Seaweed, mussels, oysters	*15*	3	Deltares
Baltic Sea	SW mussel culture	*9*	3	AUD
Iberian & Bay of Biscay	Nature-Inclusive Harvesting	*24*	3	AZTI
Mediterranean Sea		*31*	2	CSIC

	Basin-wide: coastal to offshore ecosystems, habitat-forming, spatial management measures. Joint NBS-NIH	*31*	2	IRD
		33	3	CSIC
		33	3	IRD

1.3. Dissemination and Exploitation

Projections emerging from this task are used in FutureMARES Tasks 4.4, 6.1, 6.2 and 6.3.

Many of the individual studies are already published in scientific peer-reviewed journals, several other ones will follow. Inputs to the model set-ups from stakeholders were obtained via dedicated workshops (e.g. workshops with mussel farmers in the Netherlands and Denmark, with fisheries organizations in the french western Mediterranean sea). The results will be shared with stakeholders in similar workshops, either at general stakeholder platforms such as the North Sea Community of Practice, or in dedicated workshops with specific aquaculture or fisheries sectors. Furthermore, we are aiming to provide a webinar on this topic at EFARO[1], the European Fisheries and Aquaculture Research Organisation, which organises regular online and live meetings for the fisheries and aquaculture community and is well attended by representatives of different sectors as well as DG-MARE and other policy makers. In France, the positive feedbacks from the series of interviews and WS with fishers and fisheries representatives led by IRD have been materialized in a new joint project between IRD and non-academic stakeholders that has just been selected for funding for 4 years by France Filière Pêches (FFP).

We strive to ensure that the engagement work has tangible impacts for the stakeholders themselves, by providing new options for the futures, and helping to prioritize the actions needed to increase their adaptive capacities in the face of global changes.

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[1] https://efaro.eu/

2. Methods: ecosystem models and simulated scenarios

2.1. Delft3D FM model for the North Sea

The work was generated to specifically inform on the development of aquaculture and Integrated Multi-Trophic Aquaculture (IMTA) in the North Sea.

Model configuration

Hydrodynamics, water quality processes, shellfish growth and seaweed dynamics were computed using the D-Flow Flexible Mesh (D-Flow FM) component from the Delft 3D Flexible Mesh Suite (Zijl et al. 2018, Zijl et al. 2020). Water quality processes are simulated with the D-Water Quality module, fully integrated within D-Flow FM (i.e. tightly coupled hydrodynamics and water quality). The scenarios are run using a version of the 3D Dutch Continental Shelf Model – Flexible Mesh (3D DCSM-FM) which has been developed and validated using data from the Dutch national monitoring programme (MWTL) and other available sources. (Zijl et al. 2021) and that has been adapted for the simulation of future global change scenarios.

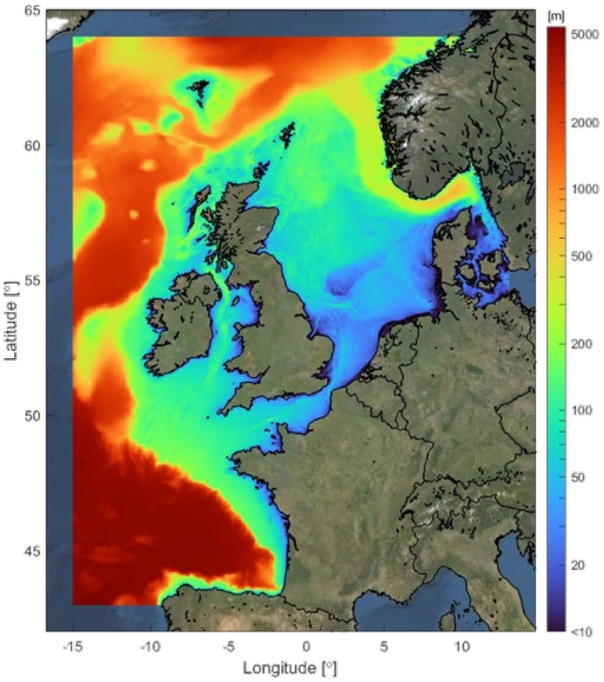


Figure 1: Domain and bathymetry (based on EMODnet data) of the 3D DCSM-FM model.

The Dutch Continental Shelf Model covers the Northwest European Continental Shelf, including the North Sea and adjacent shallow seas, such as the Wadden Sea (Figure 2). Here we used a coarse grid version of 3D DCSM-FM, with a horizontal resolution of about 4 by 4 nautical miles over the entire domain. The water column was divided into a fixed number of 20 layers up to depths of 100m (sigma-layers). In areas over 100m deep, the deeper part of the water column was further divided into a maximum of 30 additional layers at fixed depths (z-layers). The water quality module simulated the cycles of major nutrients (nitrogen, phosphorus and silica, herein noted N, P and Si), organic carbon (C) and dissolved oxygen (O2). Simulated state variables are listed in Table 1 and processes comprised are shown in Figure 3:

- Phytoplankton photosynthesis and associated uptake of nutrients and O2 production that depend on the light climate;
- Vertical attenuation of photosynthetically active solar radiation;
- Phytoplankton respiration and mortality resulting in the release of nutrients and the consumption of O2; - Mineralization of organic matter in the water column and in the sediment and associated O2 consumption;

- Dissolution of biogenic silica in the water column and in the sediment;
- Settling of organic matter and phytoplankton and burial of detrital organic matter;
- Nitrification;
- Denitrification in the water column and in the sediment;
- Atmospheric deposition of NH4 and NO3;
- Oxygen re-aeration at the water surface;
- Seaweed carbon and nutrient uptake and growth dynamics;
- Carbon uptake, nutrient recycling and growth dynamics of shellfish, using Dynamic Energy Budget modelling (blue mussel population in the Wadden Sea, Ensis population elsewhere along the coast, blue mussel individuals in mussel farming scenarios)

The seaweed module and its parameterization to simulate sugar kelp in the Dutch North Sea have been fully described in Vilmin and van Duren (2021).

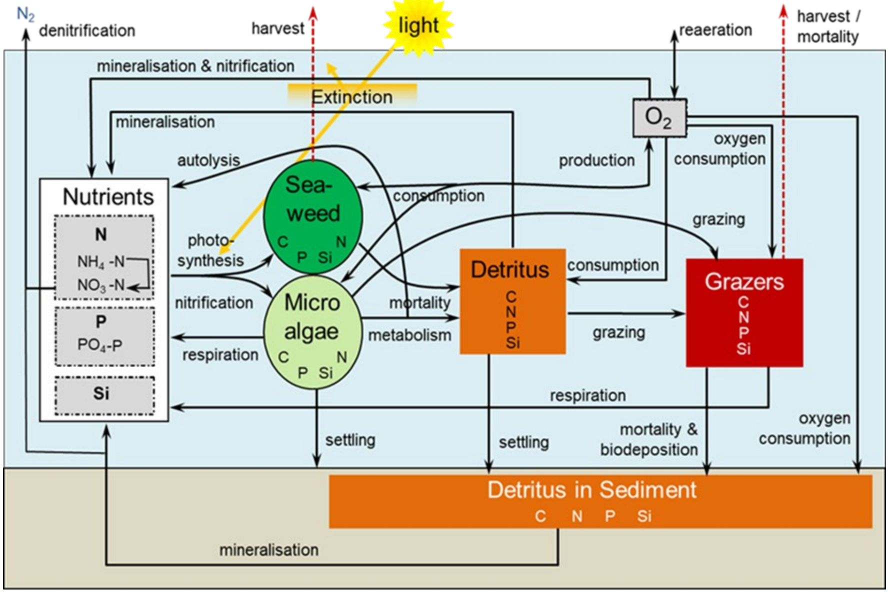


Figure 2: Scheme of simulated variables and processes.

Table 3: 3D DCSM-FM state variables and conversion factors used to translate CMCC-ESM2 variables to model forcings (e.g. initial conditions, offshore boundaries)

D-Water Quality state variable [unit]	Description	Active*	CMCC-ESM2 variable [unit]	Conversion factor	Reference
Water level [m]			zos [m]	1	
Salinity [‰]		x	so [‰]	1	
Temperature [ºC]		x	thetao [ºC]	1	
Ux [m/s]	Eastward current velocity		uo [m/s]	1	
Uy [m/s]	Northward current velocity		vo [m/s]	1	
OXY [g/m3]	Dissolved oxygen	x	o2 [mol/m3]	32	
NH4 [gN/m3]	Ammonium	x	nh4 [mol/m3]	14	
NO3 [gN/m3]	Nitrate	x	no3 [mol/m3]	14	
PO4 [gP/m3]	Phosphate	x	po4 [mol/m3]	30.97	
Si [gSi/m3]	Silica	x	si [mol/m3]	28.08	
POC1 [gC/m3]	Detrital Particulate Organic Carbon	x	pon [mol/m3]	12*(106/16)	
PON1 [gN/m3]	Detrital Particulate Organic Nitrogen	x	pon [mol/m3]	14	
POP1 [gP/m3]	Detrital Particulate Organic Phosphorus	x	pop [mol/m3]	30.97	
Opal [gSi/m3]	Biogenic silica	x	pon [mol/m3]	28.08*(106/16) *0.5*0.5*0.13	[1-4]
DOC [gC/m3]	Dissolved Organic Carbon	x	pon [mol/m3]	12*(106/16) *(91.8/8.2)	[1,5]
DON [gN/m3]	Dissolved Organic Nitrogen	x	pon [mol/m3]	14*(106/16) *(91.8/8.2)*(19/225)	[1,5-6]

DOP [gP/m3]	Dissolved Organic Phosphorus	x	pon [mol/m3]	30.97*(106/16)*(91.8/8.2)*(1/225)	[1,5-6]
DIAT_X, DINO_X, FLAG_X, Phae_X (X [E, N, P]) [gC/m^3]	Diatoms, dinoflagellates, flagellates and *Phaeocystis* (energy-, nitrogen- and phosphorus-limited)	x	-	-	
MALS [gDW/m2], MALC [gC/m2], MALN [gN/m2], MALP [gP/m2]	Macroalgae structural biomass and internal C, N and P reserves		-	-	
Mussel_V, Mussel_E, Mussel_R [gC/m^2]	Mussel structural biomass, energy reserves and gonadal biomass		-	-	
Ensis_V, Ensis_E, Ensis_R [gC/m^2]	*Ensis* structural biomass, energy reserves and gonadal biomass		-	-	

[*] Active substances are those transported by advection and dispersion processes

[1] Using the molar Redfield C:N:P ratio 106:16:1 for particulate organic matter (Redfield, 1934)

[2] Assuming a particulate organic carbon to phytoplankton ratio of 2

[3] Assuming that half of the phytoplankton carbon biomass is constituted by diatoms

[4] Using the C:Si ratio for diatoms from Brzezinski (1985)

[5] Assuming 91.8% of offshore organic matter is dissolved (estimate for waters of the shelf currents from Agatova et al. 2008)

[6] Using a molar C:N:P ratio of 225:19:1 (global average export stoichiometry of semi-labile dissolved organic matter below 100m estimated by Letscher et al. 2015)

Scenarios

Climate scenarios, definition and application

Simulations were carried out for a historical year (2010) and for 3 future years: 2030, 2050, 2100. Calculations were performed from September to September, to match cultivation cycles. This means the “2010” run actually covered the period from September 2009 to September 2010. The future years were simulated for 2 different combinations of Representative Concentration Pathways (RCPs) and Shared Socio-Economic Pathways (SS Ps):

- SSP1-2.6: Global Sustainability scenario i.e. low challenges to mitigation and adaptation,
- SSP5-8.5: World Markets scenario i.e. high challenges to mitigation and low challenges to adaptation.

The model was forced using CMCC-ESM2 outputs from the CMIP6 database (Lovato et al. 2022) for all scenarios because the FutureMARES North Sea products (Task 2.2) covered too small a domain and not all of the required variables. CMCC-ESM2 outputs were used to define initial conditions (of spin-up) and offshore boundaries for all 3D DCSM-FM state variables, some of them requiring conversion (see Table 1 for factors use and assumptions). Furthermore, atmospheric conditions were forced using CMCC-ESM2 outputs for wind, temperature, humidity, air pressure, cloud cover, solar radiation, precipitation and evaporation. Nitrogen atmospheric deposition was forced using the input4MIP data produced by NCAR for CMIP6 (Hegglin et al. 2016).

Seven of the largest Dutch river inflows were described using daily discharges, temperature and nutrient concentrations from Pätsch and Lenhart (2019). Water discharge, temperature and concentrations of active water quality constituents in all other freshwater inputs were represented with monthly means of E-HYPE model outputs from the Swedish meteorological institute (SMHI), adjusted with country correction factors to be consistent with national measured total N and P loads (JMP Eunosat report). Methodology to derive 3D DCSM-FM variables from EHYPE outputs was provided in Zijl et al. (2021) and van Kessel et al. (2022).

For future scenarios, average percent changes of discharge, temperature, nitrogen and phosphorus from the SWICCA project (Service for Water Indicators in Climate Change

Adaptation, https://climate.copernicus.eu/water-indicators-climate-change-adaptation), estimated for RCP2.6 and RCP8.5, were applied to future river inputs.

All simulations were spun-up for 1 year and 9 months. For example, the "2010" run used a spin-up from 1st of January 2008 to 1st of September 2009.

Cultivation / harvesting scenarios

Large-scale seaweed cultivation scenario

Currently there is no significant offshore aquaculture in the Netherlands, but there are plans to expand this over the coming years. All scenarios are, therefore, hypothetical and not based on existing plans. In the Netherlands, any future offshore aquaculture is going to be co-located in wind farms. Hence all sites were in areas that are either already designated for offshore wind or are designated as search areas (Figure 3).

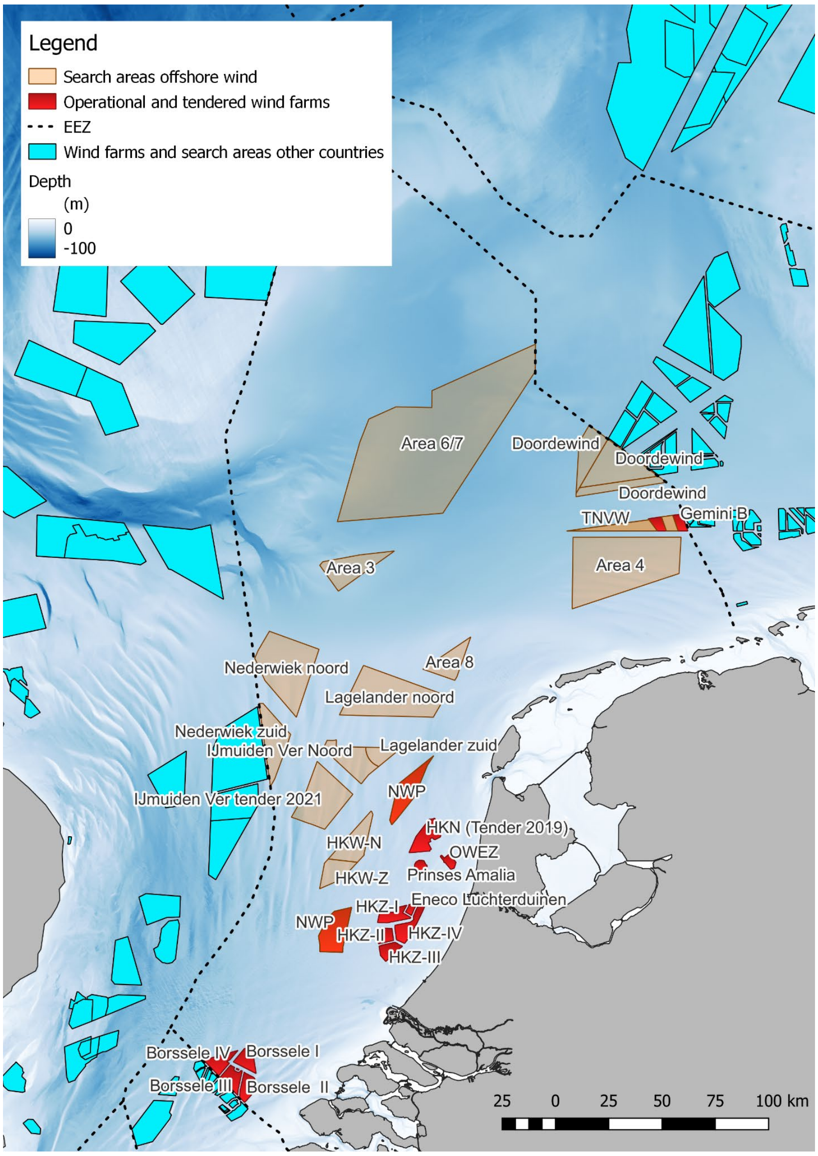


Figure 3: Wind farms and search areas for offshore wind in the Dutch EEZ

In these scenarios, we simulated the effects of sugar kelp cultivation over 145 km2 in the Dutch North Sea. This was the maximum area of seaweed cultivation for which 5% of the inflowing total nitrogen would be consumed (Van Duren et al. 2019). For wind farms Borssele and Hollandse Kust Zuid the area potentially allocated for marine aquaculture is already known (Vlak 2022, Gebiedspaspoort Borssele:

https://www.noordzeeloket.nl/publish/pages/188385/handreiking-gebiedspaspoort-borssele.pdf). In our simulations, half of this designated area was assigned to seaweed to make the rest of the area available for e.g. mussel aquaculture.

The left-over area of the 145 km2 was then divided across the offshore wind farms that were determined as being most suitable for seaweed aquaculture according to Steenbergen et al (2023), from order of suitability (table in seaweed results section). Old wind farms that are not possible for multi-use were left out (e.g. Eneco Luchterduinen, Prinses Amaliawindpark) due to the fact that the turbines are close together and multiuse was not taken into account in the tender phase. Bolman et al (2018) determined that in new OWF areas approximately 25% of the area will be made available to marine aquaculture. To ensure even distribution between seaweed and mussel aquaculture, 12.5 % of each suitable OWF area will be used for seaweed aquaculture until the 145 km2 target value is reached. The summary of cultivation locations and allocated space for seaweed cultivation in the simulations is provided in Table 2.

For a seaweed cultivation cycle lasting one year or slightly less, we initialize the seaweed scenario runs, using a spin-up without seaweed. After spin-up, seaweed biomass is initialized following (Vilmin & van Duren 2021) in which the initial seaweed biomass was calibrated to reach about 1 kgDW/m2 at the end of a cultivation cycle (here in the Borssele I OWF in the 2010 historical state situation).

Table 4: Location and size of allocated space for seaweed and mussel cultivation in the simulated scenarios

OWF area	**Total surface (km2)**	**Seaweed**		**Mussels**	
		Cultivated area (km2)	**% cultivated/total area**	**Cultivated area (km2)**	**% cultivated/total area**
Borssele I	65.53	3.18	4.9	3.18	4.9
Borssele III	71.25	11.77	16.5	11.77	16.5
Borssele IV	72.75	4.23	5.8	4.23	5.8
HKZ I	66.20	8.37	12.6	8.37	12.6
HKZ II	46.58	6.52	14.0	6.52	14.0
HKZ IV	89.93	4.47	5.0	4.47	5.0
HKN tender 2019	127.48	15.93	12.5		
HKWN	206.61	25.83	12.5	25.83	12.5
HKWZ	134.99	16.87	12.5	16.87	12.5
IJmuiden Ver tender 2021	459.83	47.83	10.4		
IJmuiden Ver N	245.32			30.67	12.5
Nederwiek- Z	272.04			33.09	12.2
	Total	145	**Total**	145	

Large-scale mussel cultivation scenario

For this scenario, the commercially viable upscaling of mussel cultivation within OWFs will be tested. The commercially viable area of mussel aquaculture must be at least 98 ha or 0.98 km^2 (van den Burg, Kamermans, Poelman, Soma, & Dalton, 2017). As this scenario was already tested in IMPAQT and shown to have no visible effects on the ecology of the North Sea, two other scenario runs were conducted.

In this scenario, the area of mussels was constrained to 145 km2 to investigate the effects of upscaling mussel cultivation to a similar cultivation area as our seaweed scenario. The 145 km^2 will be taken from the most suitable areas for mussel aquaculture estimated by Steenbergen et al. (2023). As for seaweed, mussel cultivation is placed in half of the space available for mariculture in OWFs where this space has already been allocated and in 12.5 % of all OWF that were determined to be suitable for mussel aquaculture (Steenbergen et al. 2023) (see Table 2 for locations and allocated space).

To fit as much as possible with reality, we assumed mussel cultivation cycles to last from May to September two years later. For example, the “2010” run was from May 2008 to September 2010. Therefore, we introduced mussels in the model from May of the 1st year of spin-up for all mussel cultivation scenario runs. Initial mussel biomass was calibrated to reach a target yield of 179200 kg of fresh weight per hectare at the end of the cultivation cycle, i.e. ~1 kgDW/m2 (using the model’s conversion factor parameter of 0.056 gDW/gFW). This target yield was calculated assuming a harvest of 7 kg/m of substrate (personal communication Pauline Kamermans) for a set-up similar to the one described in Van den Burg et al. (2017) (with 25600 m of substrate per hectare). Calibration was carried out to reach the target yield in the Borssele I OWF for 2010 conditions (data not shown).

Large-scale seaweed and mussel cultivation scenario

In this scenario, the effects of a combination of seaweed and mussel cultivation in OWFs were investigated. In this scenario seaweed and mussel cultivation are simulated in the same way as described in the last paragraphs and over the same cultivation areas (Table 2).

2.2. The FlexSem model for the Danish Limfjord, SW Baltic Sea. Impacts of climate change on benthic mussels and suspended mussel culture

The work described below was generated to inform specifically on the development of aquaculture in Danish coastal waters.

Model configuration

The Limfjorden is a micro-tidal, shallow estuary with a mean depth of 4.8 m, which consists of several smaller basins connected by narrow straits (Figure 4B). It is located in the northern part of Denmark with connections to the saline North Sea (west) and the brackish Kattegat (east) (Figure 4A). Accordingly, a salinity gradient ranges from 32-34 g kg^{-1} in the west to 19-24 g kg^{-1}in the east (Figure 4B). Further, the high supply of fresh water from rivers reduces the salinity, especially in the inner basins with salinities of 15-20 g kg^{-1}. The main current direction is from west to east modified by the wind direction and a weak tidal signal (Schourup-Kristensen et al. 2021). The Limfjorden is eutrophic with seasonal hypoxia in the inner basins and high-standing stock of blue mussels. The system receives a high nutrient load from the catchment dominated by agriculture and is in a poor ecological condition according to the EU Water Framework Directive. Mussel dredging is currently the most crucial fishery since the finfish fishery collapsed in the 1990ies. However, mussel fishery shows a decreasing trend in harvests over time due to reduction in stock biomass (Figure 5). Harvesting from commercial farms, on the other hand, recently increased due to higher technological expertise and profit. However, the number of farm licenses should be increased to support further development.

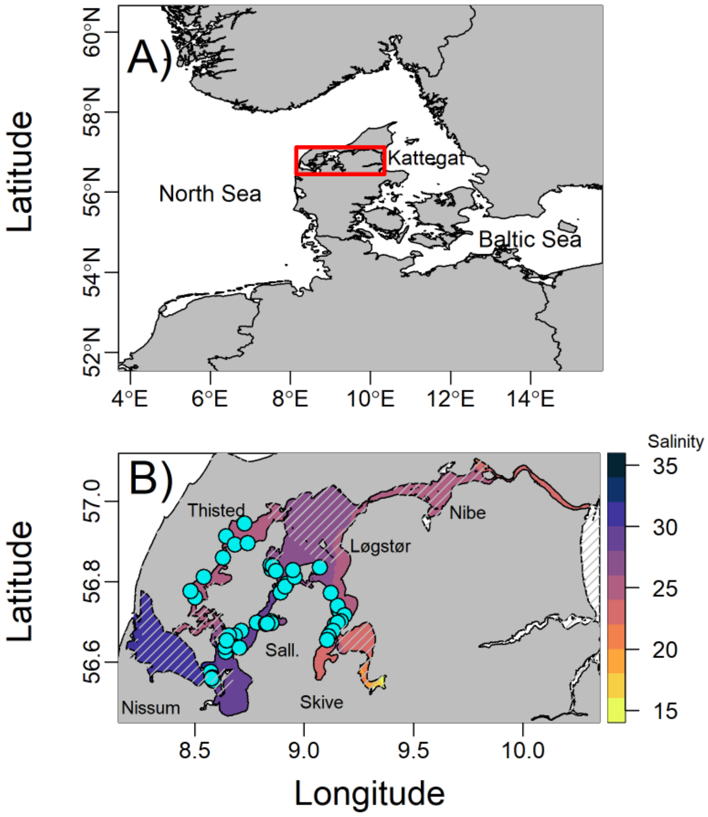


Figure 4: Map showing A) the location of the Limfjorden (red box) and B) surface salinity (color bar), mussel farms (cyan points), and names of the main basins; Nissum Broad (Nissum), Sallingsund (Sall.), Thisted Broad (Thisted), Løgstør Broad (Løgstør), Skive Fjord (Skive), and Nibe Broad (Nibe). Grey hatched lines are the Natura 2000 areas where mussel farming is not allowed.

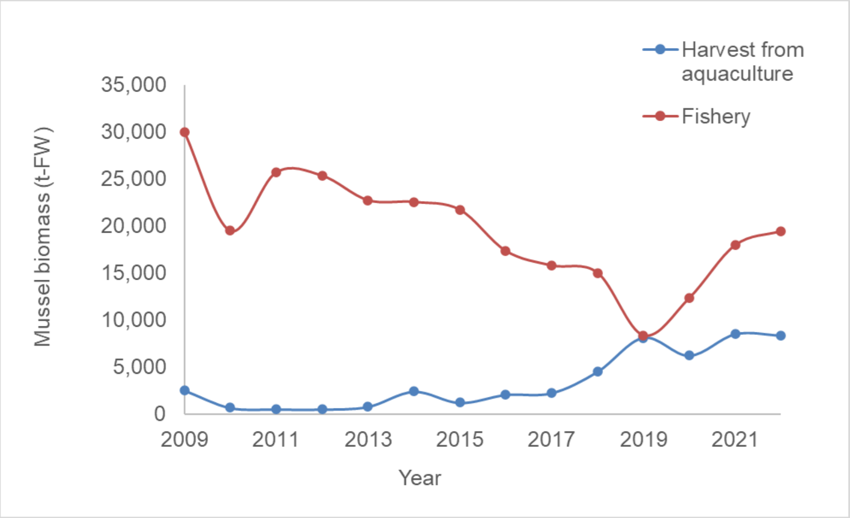


Figure 5: Mussel harvest from aquaculture and mussel landings from fishery in the Limfjord area (Data from the Fishery Agency).

We applied the FlexSem model framework for setting up a 3D coupled hydrodynamic - biogeochemical-sediment model for the Limfjord (Larsen et al. 2020). The model framework was previously applied to study the impacts of intensified mussel farming (Maar et al. 2023), mussel transplantation to mitigate hypoxia (Maar et al. 2021), dispersal of mussel larvae (Pastor et al. 2021), and drivers of hypoxia (Schourup-Kristensen et al. 2023) in the Limfjord. The model used an unstructured mesh with 6686 elements with a total area of 1502 km^2. The area of the elements varied from 20,368 m^2 (length= 143 m) to 314,297 m^2 (length= 1773 m) with an average of 224,579 m^2 (length =474 m). The vertical resolution was 1.5 m in the flexible surface layer followed by nine 1 m depth layers, and three 5 m layers, with a maximum water depth of 30 m. The hydrodynamic model solved the Navier-Stoke equations for velocities and the advection-diffusion equations for the transport of tracers (e.g., heat, salinity, nutrients). The turbulent part of the hydrodynamic solution was modeled by a *k*-epsilon model in the vertical and a Smagorinsky model in the horizontal. A surface radiation model was added to the setup, which calculated the heat transfer through the ocean surface and modified the water temperature by calculating the short-wave radiation, the long wave radiation, the sensible heat flux, and the latent heat flux. The latter three are surface layer effects, whereas the short-wave radiation penetrates the surface and attenuates throughout the upper water column (Larsen et al. 2020). The addition of a surface radiation model enables running scenarios to model water temperature under predicted future meteorological forcing SSP1-2.6. The physical model was described and validated in a previous study showing a good performance (Schourup-Kristensen et al. 2021).

The pelagic biogeochemical model in FlexSem was two-way coupled to a sediment biogeochemical model and a Dynamic Energy Budget (DEB)-population model (Maar et al. 2023). The pelagic model simulated the cycling of nitrogen (N) and phosphorous (P) using Redfield ratios. The 11 state variables described concentrations of inorganic nutrients (NO_3, NH_4, PO_4), PO_4 adsorbed by metals in particles ($PO_{4\text{-metal}}$), three functional groups of phytoplankton (diatoms, flagellates, picoplankton), micro- and mesozooplankton, detritus, and oxygen. The model considered the processes of nutrient uptake, growth, grazing, respiration, recycling, mortality, and settling of detritus and diatoms. Chl *a* concentrations were used as a proxy for phytoplankton biomass using a conversion factor of 2 mg Chl *a* $(\text{mmol-N})^{-1}$. The sediment model comprised an unconsolidated layer (Redfield ratios) exposed to resuspension, a consolidated layer with variable CNP-ratios, settled diatoms and mussel pellets, pore-water inorganic nutrients (NO_3, NH_4, PO_4, and $PO_{4\text{-metal}}$), deposit feeders, microphytobenthos, and oxygen. The DEB model described mussel growth as a function of temperature, salinity, and food levels and was previously parameterized and validated for the Baltic Sea (Buer et al. 2020). The DEB model was coupled with the population model describing the abundance of mussels in the farms over time which was set to decrease exponentially over time due to self-thinning.

Scenarios

The reference scenario (REF) used historical (2009 to 2018) atmospheric forcing, open boundary conditions (OBC), and river run-off and NP load data (Table 2.3.1). There were 14 active commercial mussel farms with a density of 35 mussels per farm-m^{-3} representing the mean production during this period (Maar et al. 2023). Daily OBC of salinity and temperature and hourly OBC of water level and velocities were obtained from the HIROMB-BOOS-HIRLAM model for the 10-year reference period 2009 to 2018. Monthly OBC of nutrients, Chl *a* (distributed in the three phytoplankton groups), and oxygen were obtained from monitoring data near the boundaries (www.odaforalle.dk). OBC of zooplankton were extracted from a station within the Limfjord, whereas detritus and $PO_{4\text{-metal}}$ were set to a constant value of 0.5 mmol m^{-3} due to missing observations. More details about model initialization, parameterization, configuration, and validation for the Limfjord set-up can be found in Maar et al. (2023a). Run-off and nutrient loads (diffuse and point sources) were obtained from the SWAT catchment model with 79 sources with daily resolution.

The three future climate change scenarios (SSP1-2.6, SSP2-4.5, and SSP5-8.5), are named after the shared socioeconomic pathway and the level of radiative forcing in the year 2100 they represent relative to pre-industrial conditions (2.6, 4.5, and 8.5 W m^2, respectively). The choice of these three FutureMARES scenarios allows for a representation of the range of potential future responses to climate change corresponding roughly to strongly mitigated, middle of the road, and unmitigated system responses, respectively (Pinnegar et al. 2021). SSP1-2.6 is broadly consistent with the maximum atmospheric CO_2 concentration required under the Paris Climate Agreement, which sets the ambition to “substantially reduce global greenhouse gas emissions to limit the global temperature increase in this century to 2°C while pursuing efforts to limit the increase even further to 1.5°C”. Greenhouse gas emissions are intermediate in SSP2-4.5 while they continue to increase throughout the 2100 century in SSP5-8.5 (Pinnegar et al. 2021). The scenarios were conducted for the time-slices 2051-2060 and 2090-2099. Each 10-year time-slice used a spin-up of 10 years (same forcing period as the scenario) to reach semi-steady state conditions for water column and sediment.

In the SSP1-2.6 and SSP2-4.5 scenarios, land-based nutrient load reductions are expected to be implemented according to the Danish Water Plans (36% reduction of current N-load, no P reduction required). In the SSP5-8.5 scenario, it was assumed that the National Water Plans were not implemented due to the growth of the agriculture sector with little concern for the environmental impacts (Table 3). Mussel culture was assumed to be intensified to meet the global market’s demand for protein food with a low carbon footprint in all scenarios after consultation with stakeholders in the EU FutureMARES project. The number of commercial mussel farms was set to 52 (density of 70 mussels m^{-3}, production cycle from July to June next year) aimed for food production corresponding to the maximum number of farms in a previous carrying capacity study (Maar et al. 2023).

Table 5: Overview of localized model scenarios with atmospheric forcing, time-slices, number and type of mussel farms, reduction of nutrient loads as % of the REF, and scenario description.

Scenario	Time-slice Years	Mussel farms	N-load reduction	Description
REF	2009-2018	14 commercial farms	-	Reference period
SSP1-2.6	2051-2060 2090-2099	52 commercial farms	36%	Global Sustainability, best case with strongly mitigated responses
SSP2-4.5	2051-2060 2090-2099	52 commercial farms	36%	Local Stewardship, middle of the road
SSP5-8.5	2051-2060 2090-2099	52 commercial farms	0%	World Markets, worst case with unmitigated system responses

Applied forcing data in the scenarios

Atmospheric boundary conditions to force the model simulations were taken from the EC-Earth CMIP6 simulations for the historical and future periods. The single model approach was chosen over an ensemble approach to preserve extremes (e.g. storms, heatwaves) and physical consistency of the dynamics and the particular model was chosen due to reduced bias over the region of interest.

In the climate change scenarios, OBC of water level, velocities, nutrients, zooplankton, and detritus were reused from the REF because they were not stored as output by the regional climate model projections. An ensemble of Ocean statistical downscaling was conducted on a range of CMIP6 models for the North Sea region, resulting in monthly averaged values for OBC for the period 1993-2100 (Kristiansen & Butenschön 2023). The statistical downscaling provided OBC for salinity, temperature, Chl *a*, and oxygen at 5 m, 25 m, and bottom depth levels for scenarios SSP1-2.6, SSP2-4.5, and SSP5-8.5.

The river runoff for the reference period and the future scenario periods is simulated with the SWAT model. The SWAT set up and calibration is the same as in (Molina-Navarro et al. 2017), using 17 and 12 monitoring stations for the calibration of discharge and nutrients, respectively. The reference (baseline) period is 2009 – 2018, with a 9-year spin-up period 2000 – 2008. The climate data is the observed daily values from the Danish Meteorological Institute, precipitation (10km grid), min. and max. temperature, wind speed, relative humidity (20 km grid), solar radiation (20 km grid). The precipitation is corrected for gauge under catch. The future scenarios are run as “delta change” scenarios, where the mean monthly difference between the climate model precipitation and temperature for the reference period and the future periods are forced upon the observed climate time series. Precipitation is changed as a percent change and temperature with the absolute change relative to the reference period. Wind speed, solar radiation and relative humidity were not changed for the future scenarios. All scenario runs include the 9 years spin-up period.

Forcing patterns in the scenarios

Overall, the SSP5-8.5 scenario showed the strongest changes in forcing data for the last time-slice 2090-2099, whereas SSP1-2.6 and SSP2-4.5 showed weaker and more similar changes (Figure 6). Air temperature increased (Figure 6A) and wind speed decreased in all scenarios (Figure 6C). Precipitation and run-off increased up to 20-25% in SSP5-8.5 by the end of the century (Figure 6B, D). TN load decreased considerably in SSP1-2.6 and SSP2-4.5 due to the implementation of the Water Plans, whereas SSP5-8.5 showed little change. TP followed the run-off patterns with highest increases in SSP5-8.5 for each time-slice (Figure 6F). OBC showed a gradual increase in seawater temperature, a gradual decrease in salinity, and oxygen, but no change in Chl *a* concentration over time (data not shown).

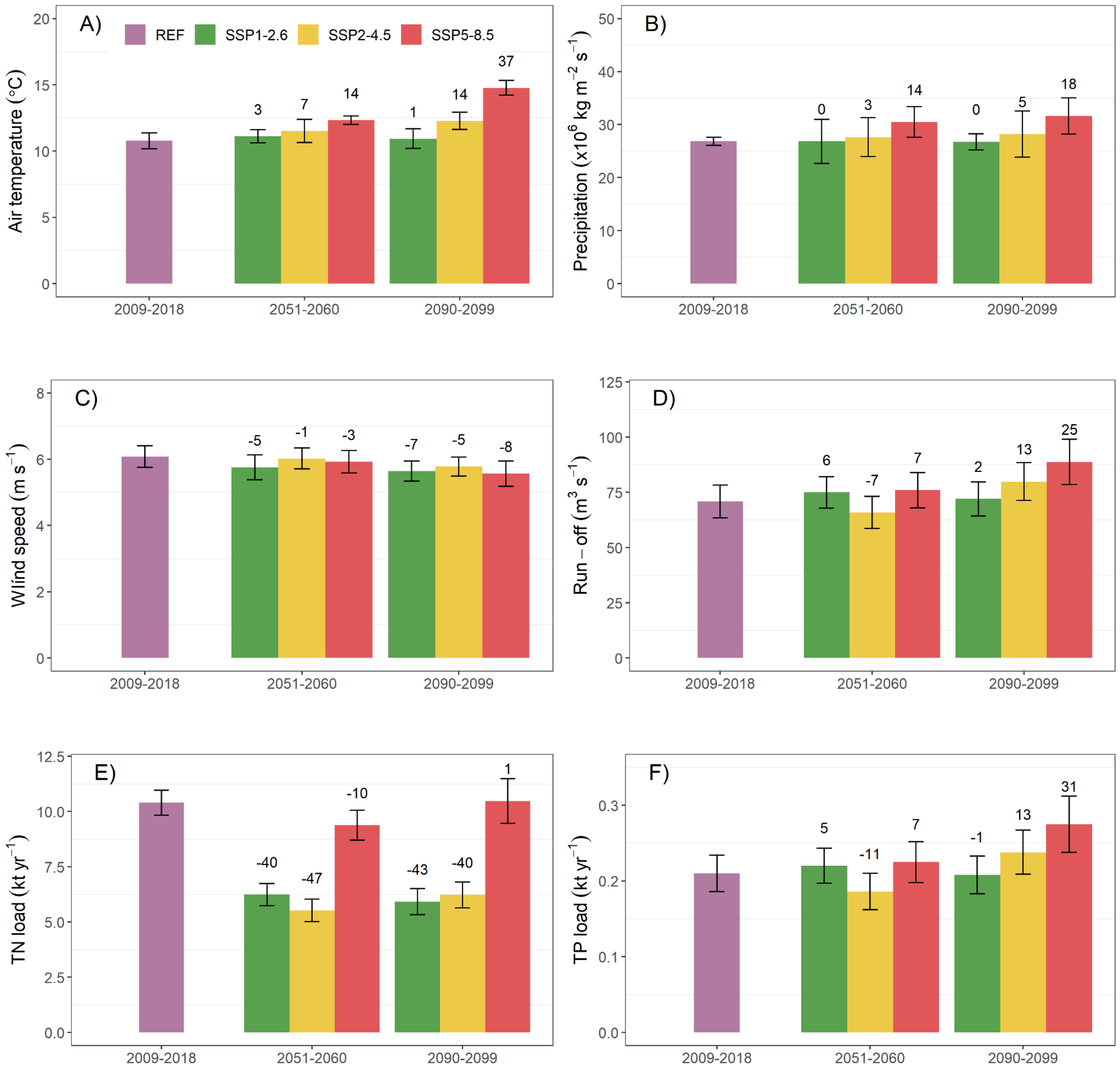


Figure 6: Forcing data showing annual means (±SD) for each period of A) air temperature, B) precipitation, C) summer wind speed, D) run-off, E) TN river load, and F) TP river load. Values above the columns are the percentage differences from the reference period 2009-2018.

2.3. EwE model: Bay of Biscay

The work described below was generated to inform specifically on the development of fisheries and conservation in the Bay of Biscay.

Model configuration

The Ecopath with Ecosim (EwW) model of the Bay of Biscay (BoB thereafter) encompasses the area from Brest (Brittany, France) to Cabo de Finisterre (Galicia, Spain), including the continental shelf and upper slope, between 0 and 1000 m depth (Figure 7). The model covers an area of 120.433 km2 and includes the ICES divisions 8abc (Figure 7). Ecological and fishery features of the area were used to establish the bathymetric and latitudinal limits. The BoB model represents the mean ecosystem functioning over the 2000-2003 period, which is the first period for which more reliable and available data exist, particularly in terms of catch statistics.

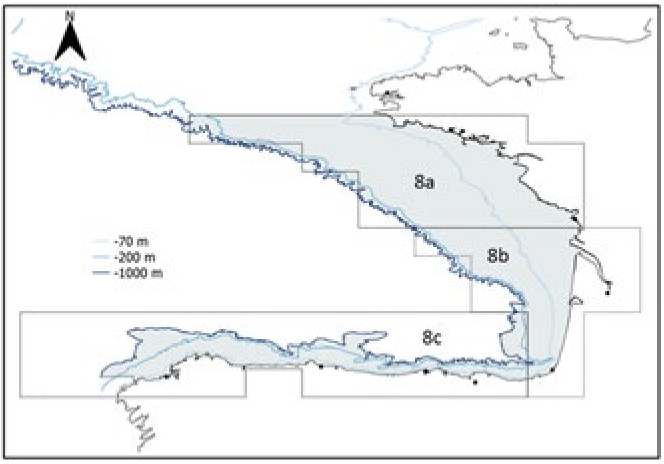


Figure 7: The study area located in the Bay of Biscay, showing the modelled area in grey, the ICES areas 8a, b, c), and selected depth contours.

The model includes 52 functional groups ranging from primary producers to top predators. Specifically, main target species were modeled separately such as bluefin tuna (*Thunnus thynnus*), albacore (*T. alalunga*), mackerel (*Scomber* spp.), horse mackerel (Trachurus spp.), sardine (*Sardina pilchardus*), anchovy (*Engraulis encrasicolus*), anglerfish (*Lophius* spp.), sea bass (*Dicentrarchus labrax*), hake (*Merluccius merluccius*), megrim (*Lepidorhombus* spp.), common sole (*Solea solea*), mullets (*Mullus spp.*) and Norway lobster (*Nephrops norvegicus*). Hake was split into two age groups (i.e., multi-stanza groups) (large hake, i.e., ≥ 27 cm of total length and small hake < 27 cm) attending fisheries and ecological reasons.

The model comprises 13 fishing fleets from Spain and France. For an extensive description of the BoB Ecopath model, species composition of the functional groups and its input data see Corrales, Preciado et al. (2022).

The food web model was fitted to available time series of data from 2003 to 2019 using the time dynamic module of EwE Ecosim considering the impact of fishing, temperature, and primary production (PP). Specifically, time series of fishing effort, fishing mortalities for those species with available stock assessment, sea surface temperature (5m depth - SST), sea bottom temperature (SBT) and PP were used to drive the model while time series of biomass and catches were used to calibrate the model.

The environmental response functions (f(〖Env〗 function,t)") that link the species or functional groups dynamics with the environmental drivers were obtained using shape-constrained generalized additive models (SC-GAMs) (Citores et al. 2020), except for albacore, for which data from AQUAMAPS (www.aquamaps.org) was used. SC-GAMs build species distribution models under the ecological niche theory framework (Soberón and Nakamura 2009) where response curves are unimodal and concave with respect to environmental gradients (Citores et al. 2020).

Scenarios

The temporal dynamic module Ecosim of the BoB was used to evaluate the effect of plausible future scenarios for major stressors in the area (Table 4). All scenarios were run for 80 years, from 2019 to 2099.

Table 6: List of all the scenarios simulated and the combinations between fishing and climate change conditions. Baseline – Scn. 1; Climate change – Scn. 2, 3, 4; Fishing – Scn. 5, 6, 7; Cumulative – Scn. 8,9,10,11. PP: relative primary production.

Scenario (Scn.)	Name	Fishing	Temperature and PP
1	Baseline	Kept at 2019 level	Kept at 2019 level
2	RCP-2.6	Kept at 2019 level	Follows RCP-2.6
3	RCP-4.5	Kept at 2019 level	Follows RCP-4.5
4	RCP-8.5	Kept at 2019 level	Follows RCP-8.5
5	F_{MSY}	At F_{MSY}	Kept at 2019 level
6	F_{MSY}-20%	F_{MSY}-20%	Kept at 2019 level
7	F_{MSY}+20%	F_{MSY}+20%	Kept at 2019 level
8	RCP-4.5 + F_{MSY}	F_{MSY}	Follows RCP-4.5
9	RCP-4.5 + F_{MSY}-20%	F_{MSY}-20%	Follows RCP-4.5
10	RCP-8.5 + F_{MSY}	F_{MSY}	Follows RCP-8.5
11	RCP-8.5 + F_{MSY}-20%	F_{MSY}-20%	Follows RCP-8.5

The original configuration of the Ecosim model was used as the baseline simulation (Scn. 1). Second, the impact of climate change was assessed by using the outputs from the ensemble projections of CMIP6 data on the Bay of Biscay through the FutureMARES project (Task 2.2). Specifically, SST, SBT and PP projections for the study area under three scenarios of greenhouse emissions (RCP-2.6 (Scn. 2), RCP-4.5 (Scn. 3), and RCP-8.5 (Scn. 4)) were included (Figure 8). Third, alternative scenarios of fishing were evaluated. In Scn. 5 the impact of fishing at the advised F_{MSY} for the functional groups with available stock assessment (Table 4) was assessed. In addition, two other scenarios were defined based on Hansen *et al.*, 2019; 20% decrease in the F_{MSY} (Scn. 6) and 20% increase in the F_{MSY} (Scn. 7). Finally, the combined impact of different stressors (climate change and fishing) was assessed through four scenarios (Scn. 8-11).

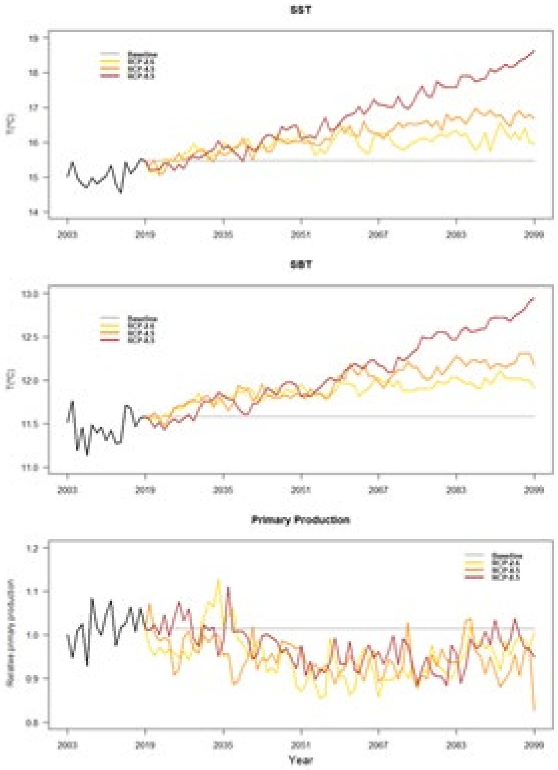


Figure 8: Historical (black line) and projections of each variable under the three IPCC climate change scenarios. SST: sea-surface temperature; SBT: sea-bottom temperature. Primary production values are represented by their relative value compared to the value of 2003. Values are annual averages downscaled at the study area.

2.4. EwE model: the North-western Mediterranean

The work described below was generated to inform specifically on the development of fisheries and conservation in the Mediterranean Sea.

Model configuration

Under Tasks 4.3 and 4.4, the North-western Mediterranean EwE model has been updated, based on a previous Ecopath model representing the North-western Mediterranean Sea in 2000 and covering most of the continental shelf and slope of the Spanish and French areas of GSA06 and 07 of the Western Mediterranean, representing 45,547 km^2, and including depths from 0 to 1000 m (Figure 9) (Corrales et al. 2015). We adapted the available model and developed the temporal and spatial-temporal model representing the same area, from 2000 to 2020 (Coll et al. submitted).

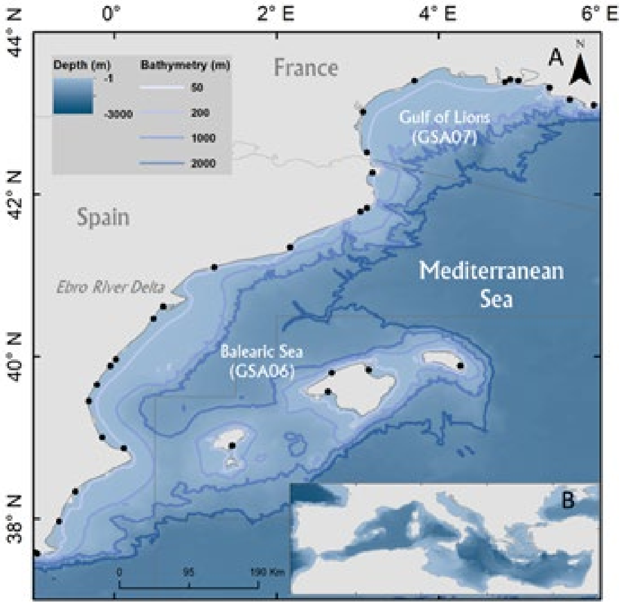


Figure 9: The North-western Mediterranean Sea region with the depth contours and main fishing harbors identified.

To develop the temporal dynamic model, we collected available time series of biomass of the main demersal and pelagic fish and invertebrate species, and fishing effort, landings and prices from the EU Data Fisheries Collection (DFC), the Spanish and Catalan Government and research institution. We obtained fishing mortality, standing stock biomasses and landings from state-of-the-art stock assessments available for anchovy, sardine, hake, red mullets, swordfish and Bluefin tuna for the Mediterranean Sea and ecosystem models at regional scale. All this temporal data was used to fit the updated model from 2000 to 2020: fishing effort and fishing mortality were used to drive the fishing fleets of Spain and France separately, and biomass time series and catches were used to calibrate the model, following previous studies in the Mediterranean Sea and best practices of EwE (Mackinson et al. 2009, Coll et al. 2013, Heymans et al. 2016, Corrales et al. 2017, Piroddi et al. 2017). We used the Stepwise Fitting Procedure (Scott et al. 2016) to automate the model fitting, which allowed us to estimate vulnerabilities, the primary production anomaly Vs, and minimize the SS. When the best statistical fit was obtained, we assessed its ecological suitability and we used it to estimate the individual contributions of trophic interactions, environmental change and fishing to the overall fit following previous procedures (Corrales et al. 2017).

The spatial-temporal Ecospace model for the study area was developed establishing a basemap with a spatial resolution of 1/12° (9.257 km x 9.257 km). Habitat substrate types were obtained from EMODNET, and were reclassified into 7 spatial habitat maps. Different functional groups were then associated with habitats according to their ecology.

Scenarios

Maps of time-varying environmental spatial-temporal variables were included to drive historical dynamics from 2000 to 2020 (Figure 10). These maps were extracted from the GETM-MedERGOM model (Macias et al., 2014), using historical hindcasts from 2000 to 2016, and forecasts for 2017 to 2020 for two contrasting emission scenarios RCP4.5 or RCP8.5. We selected environmental variables that mostly affect European anchovy and European sardine dynamics (Fernández Corredor et al., 2021): Sea Surface Temperature (SST, calculated as the top 150 m integrated temperature, ºC), Sea Bottom Temperature (SBT, ºC), Sea Surface Salinity (SSS, calculated as the top 150 m integrated salinity, PSU) and Net Primary Production (mmolN/m2/year). The spatial-temporal framework was used to drive the environmental layers dynamically from 2000 to 2020 (Steenbeek et al., 2013).

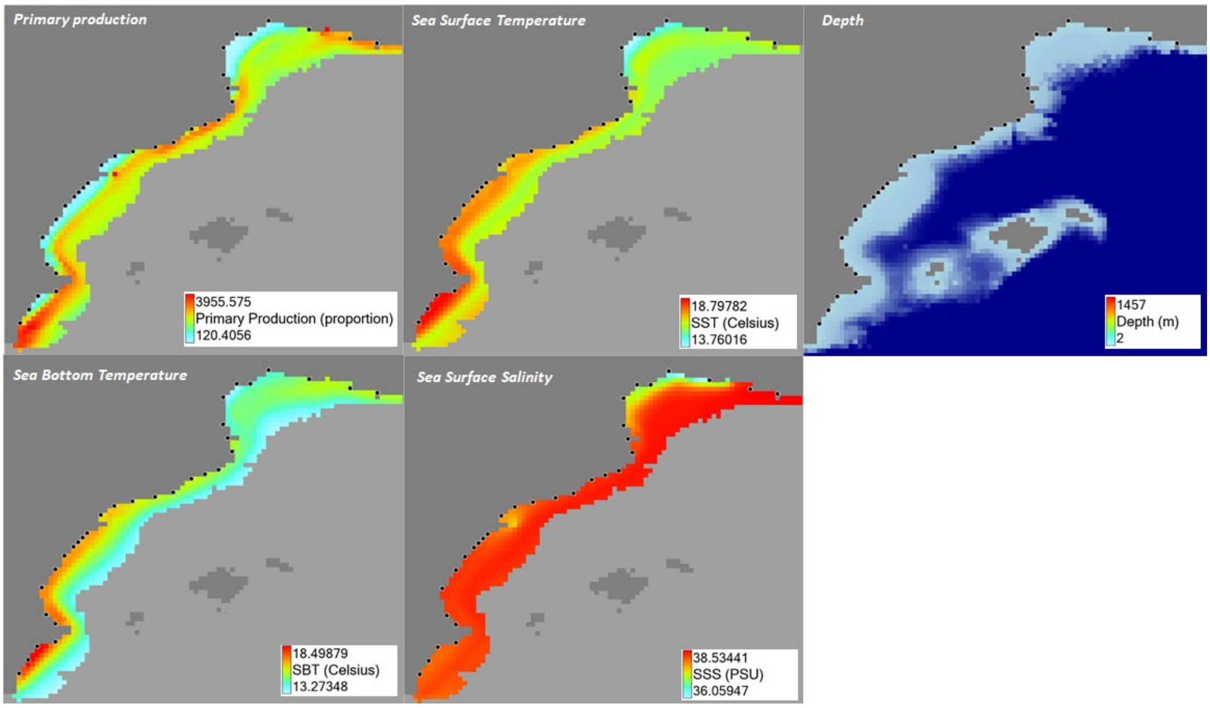


Figure 10: Initial conditions (2000) of the environmental layers used for the spatial-temporal North-western food-web model. Black dots indicate fishing harbours in the study area.

The environmental envelopes used to parameterize the functional responses in the Ecospace model, linking the environmental drivers with species groups, were obtained from AquaMaps (Kaschner et al., 2016), and were adjusted with local data and analyses (Palomera et al. 2007, Pennino et al. 2020b) when necessary. The other functional groups were linked to environmental variables according to their main depth preferences (pelagic or demersal) and sensitivity to environmental parameters.

We incorporated the base dispersal rate parameter into the model using values of 3, 30 and 300 km/year according to species movement and swimming capabilities following best practices (de Mutsert et al. 2023, Heymans et al. 2016; Martell et al. 2005), while keeping the dispersal in “bad habitat” and relative vulnerability to predation in “bad habitat” as default. To parameterize the gravity model to distribute fishing effort, we set prices for target species in the catch using mean available prices from the Catalan government for the study period 2000-2020 (ICATMAR, 2020). The value of bycatch species were set to 0 $/kg. We also included a cost layer to fishing using the distance to ports as an inverse relationship to the cost of fishing. Fleets from Spain were not allowed to fish in France and fleets from France were not permitted to fish in Spain. This was achieved by setting restricted areas to specific fleets in the spatial layers.

We identified the main drivers of historical change by quantifying the partial contributions of each main driver (trophic interactions, environmental change and fishing) to the global fit of the model, following previous analyses (Corrales et al. 2017, Serpetti et al. 2017). We quantified the contribution to the reduction of the sum of squares, and investigated their role in approximating historical dynamics of key species with biomass and catch information. In Ecospace, we developed spatial-temporal simulations using all fishing and environmental drivers of change, and we compared these results to driving the model with fishing and without fishing and under two scenarios of climate change (RCP4.5 and RCP8.5). Using temporal trends, we analysed changes in species biomass and catches between 2000 and 2020 and ratios of final/initial biomass (or catch) for all pelagic and demersal groups. The non-parametric Spearman rank correlation was used to test significant changes in predicted time series. For key pelagic species, we also investigated changes in the spatial distribution of biomass and catches comparing the distribution in 2000 with that in 2020, with the aim of identifying areas where species are expanding or shrinking. Spatial-temporal trends were also analysed as ratios of final/initial biomass (or catch) using projected spatial distributions.

A publication explaining the details of this study has been recently submitted (Coll et al., submitted).

2.5. EwE model: the Western Mediterranean

Current conservation actions are numerous and include a mosaic of no-take areas, highly, moderately and poorly protected areas, Natura 2000 sites, and spatial restrictions to fishing such as GFCM Fisheries Restricted Areas (Claudet et al. 2020, Micheli et al. 2013). However, they are mostly represented by small areas with low/medium level of enforcement (Claudet et al. 2020). The 2020 targets to reach 10% of protection were not reached and there are currently new targets being proposed to protect 30% by 2030. However, the historical contribution of historical and current spatial management to remediate cumulative impacts has not been assessed at the regional scale. The aim of this study is to assess the past contributions of existent spatial measures to overcome the cumulative effects of fishing and climate at the regional Western Mediterranean Sea scale, in order to inform about future additions to the existing measures.

Model configuration

Under Tasks 4.3 and 4.4, we modified a previously published EwE model representing the study area in 1995 (Coll et al., 2019), and we incorporated updated ecological and fisheries information to develop the temporal and spatial-temporal modules of the EwE approach (Christensen et al., 2014; Walters et al., 1997; Walters et al., 1999). Specifically, we (1) quantified the historical change of ecosystem components and contribution of various drivers of change (climate and fisheries), (2) investigated the historical contribution of spatial management measures existing in the region, and (3) assessed the potential contributions of these managed areas if their level of protection would have been different (counterfactual simulation). We investigated the importance of increasing effectiveness (or level of protection) as well as increasing the area coverage through different management measures, following Arneth et al. (2023), as the outcomes of protected areas depend not only on the size but also on the effectiveness of the protection.

The regional model representing the Western Mediterranean Sea covered a total area of 846,002 km2 with depth ranges including coastal to deep-sea areas (0-3600 m depth, Figure 11). The model included both European and non-European waters (of Spain, France, Italy, Malta, Morocco and Algeria) with the aim to create a comprehensive representation of the Western Mediterranean sub-basin, and five marginal seas: the Tyrrhenian Sea, the Balearic Sea, the Sea of Sardinia, the Ligurian Sea and the Alboran Sea.

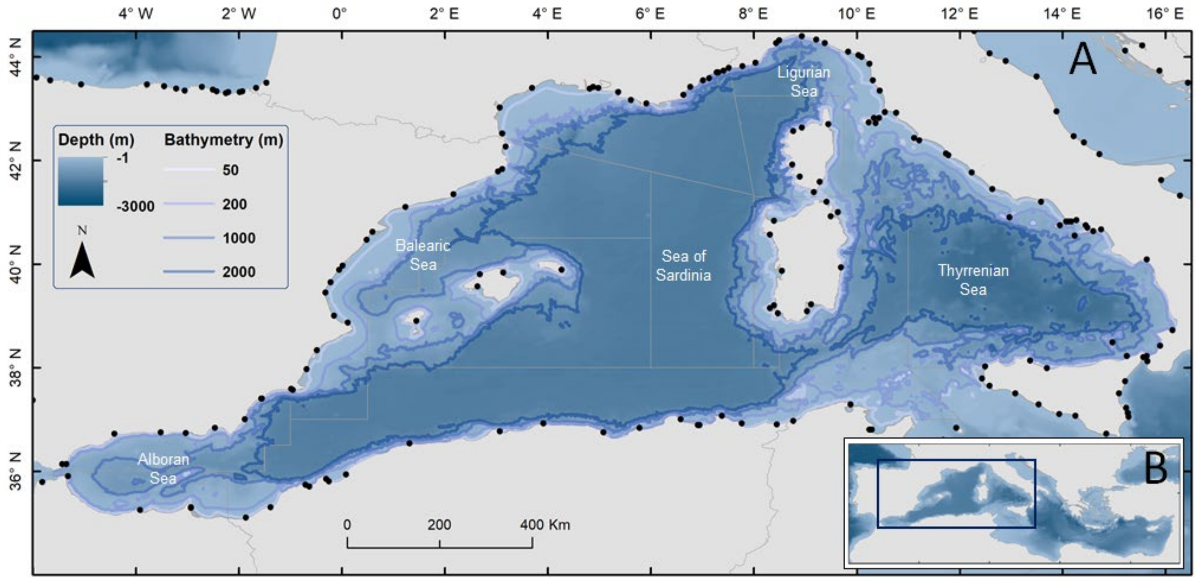


Figure 11: Map of the study area with main regions (GSAs), fishing harbours and bathymetric ranges indicated; (B) Location of study area in Mediterranean Sea.

The baseline food web model of the Western Mediterranean Sea contained 92 functional groups and represented the mid-1990s. The model included both commercial and non-commercial species and special emphasis was put on commercial species relevant for large scale fisheries, and small scale (artisanal) and recreational fisheries. The model considered coastal and off-shore areas, and the pelagic compartment was also explicitly represented to design and analyze meaningful scenarios of fisheries management and ecosystem sustainability together.

The model was driven with historical fishing effort and climate hindcasting (1995-2016) and forecasting (2017-2022) projections under two representative concentration pathway scenarios (RCP4.5 and 8.5) using the biogeochemical GETM-MedERGOM model (Macias et al. 2014). Climate variables include temperature, salinity and primary production. We used the Stepwise Fitting Procedure (Scott et al., 2016) of Ecosim to automate the model-fitting and to estimate vulnerabilities, and primary production anomalies. When the best statistical fit was obtained, we assessed its ecological suitability and we used it to estimate the individual contributions of trophic interactions, environmental change and fishing to the overall fit (Corrales et al. 2017).

Afterwards, we developed the spatial-temporal modelling approach using Ecospace. The spatial-temporal model for the study area was developed establishing a basemap with a spatial resolution of 1/6° (18.5 km x 18.5 km). Bathymetry data were obtained from EMODnet. Spatial distributions of seabed habitats were defined for eight types of substrate, reclassified from EMODnet seabed substrate maps and MEDISEH (Giannoulaki et al. 2013), combining substrate types with similar ecological features to reduce Ecospace model complexity. Data for a range of environmental parameters were obtained from the GETM/MedERGOM model (Macias et al. 2014) using historical hindcasts from 2000 to 2016, and forecasts for 2017 to 2020. Data was provided for a hindcast period from 1990 to 2016, and for emission scenarios rcp45 and rcp85 for the years 2017 to 2020. We selected the following environmental variables to drive the model: Sea Surface Temperature (SST, ºC), Sea Bottom Temperature (SBT, ºC), Sea Water Temperature calculated as the top 150 m depth (S150T, ºC), Biomass of Dinoflagellates (mmolN/m^2) Biomass of Diatoms (mmolN/m2), and Net Primary Production (mmolN/m2/year) (Figure 12).

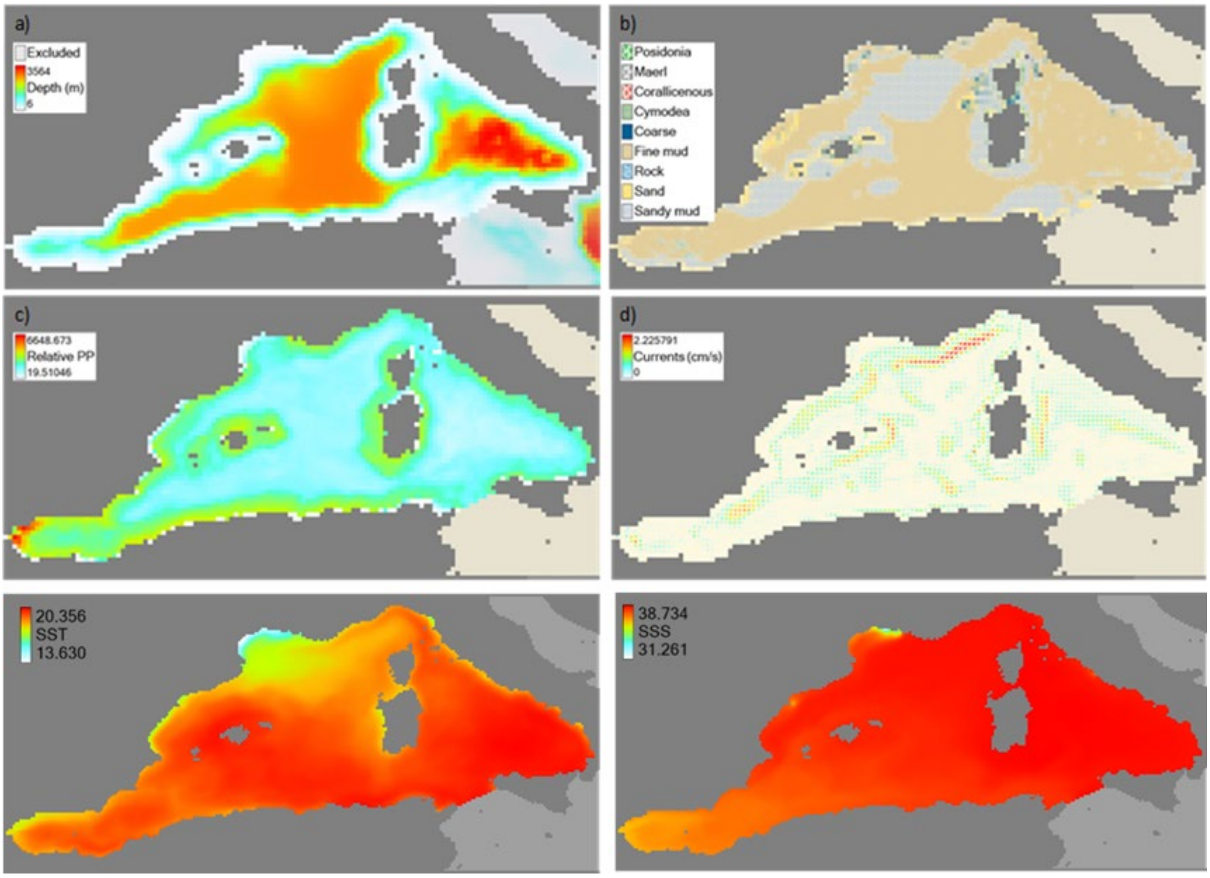


Figure 12: Initial conditions of some of the Ecospace environmental driver data for the Western Mediterranean Model.

The spatial-temporal framework was used to drive the environmental layers dynamically from 1995 to 2022 (Steenbeek et al. 2013). Annual averaged current data derived from GETM/MedERGOM for the top 150m of the water column were also applied.

Species preferences for environmental conditions in the habitat foraging capacity model were configured with environmental responses obtained from AquaMaps model (Kaschner, Kesner-Reyes et al. 2016) and 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 sensitivity to environmental parameters. For key functional groups, environmental response curves were aggregated from the functional responses of composing species. Additionally, for benthic and demersal species, the configuration of habitats was used to complement the environmental conditions (Coll et al. 2016, Coll, Pennino et al. 2019). We incorporated the base dispersal rate parameter into the model using values of 3, 30 and 300 km/year according to species movement and swimming capabilities following best practices (de Mutsert et al. 2023, Heymans et al. 2016, Martell et al. 2005), while keeping the dispersal in “bad habitat” and relative vulnerability to predation in “bad habitat” as default. To parameterize the gravity model to distribute fishing effort, we set relative price differences for target and bycatch species in the catch using two different prices: 10 €/t·km-2 when species were targeted by the fishing fleet segment, and 1 €/t·km-2 for bycatch species. We also included a cost layer to fishing using the distance to ports as an inverse relationship to the cost of fishing.

Scenarios

To assess the impact of historical spatial management measures, we run combinations of scenarios with and without historical spatial measures under different climate trajectories considering historical fishing dynamics (Table 5 and Figure 13). In total we run 5 scenarios under two different climate conditions. Existing MPAs and associated metadata were obtained from online databases and integrated into the Ecospace by MPA Class following a pre-established system classifying MPAs into Fully Protected Areas (FPA), Highly Protected Areas (HPAs), Moderately Protected Areas (MPAs), Poorly Protected Areas (PPAs) and Unprotected Areas (UPAs) (Horta e Costa et al., 2016). We collected the most up-to-date maps for additional proposals of protected areas such as Natura 2000 sites, added demersal trawl limit zones for 50 m depth and included the 1000m limit to bottom trawling.

All management scenarios were ran from 1995 to 2016 with historical fishing effort, and from 2017 to 2022 with fishing effort maintained at 2016 levels. Changes in fisheries management were applied to the entire model run since 1995, and considered the activity of the five fishing fleet segments: bottom trawling, purse seine and mid-water trawling, long liners, artisanal fisheries and recreational fisheries (Table 5).

Results were analyzed by looking at changes in biomass and catch indicators by species and functional groups, and using aggregated indicators (consumers, commercial, predators, fish, elasmobranchs, invertebrates, pelagic, demersal biomass & catch). We also compared biomass final / biomass initial between scenarios, looking at the historical contribution (S0 & S1) and counterfactual scenarios (S0-S1 & S2-S4). Finally, we analyzed the projected fishing effort and its potential displacement.

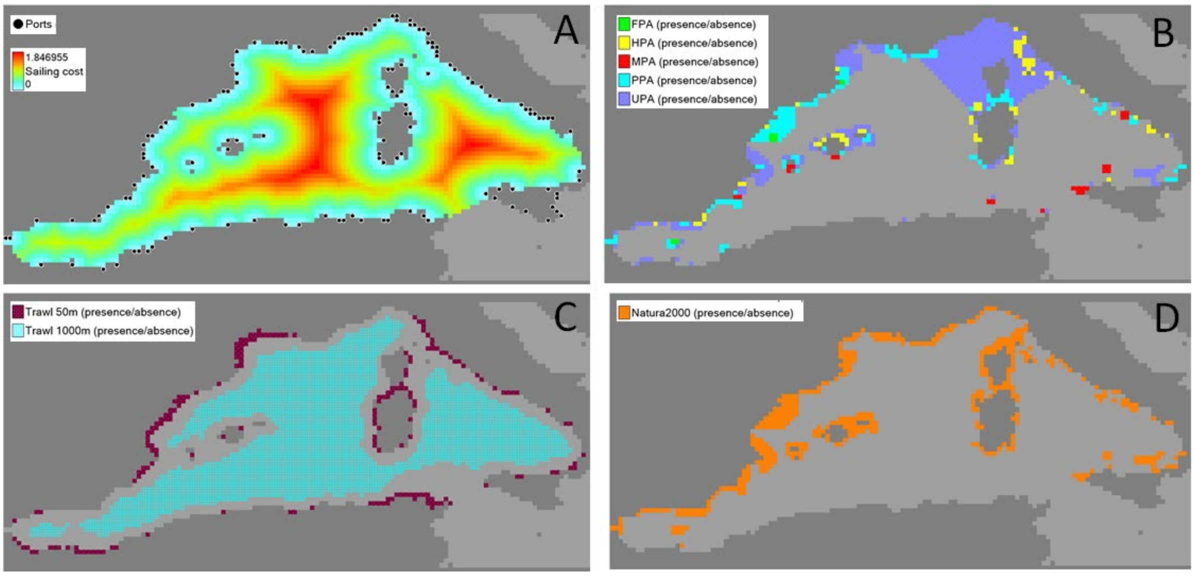
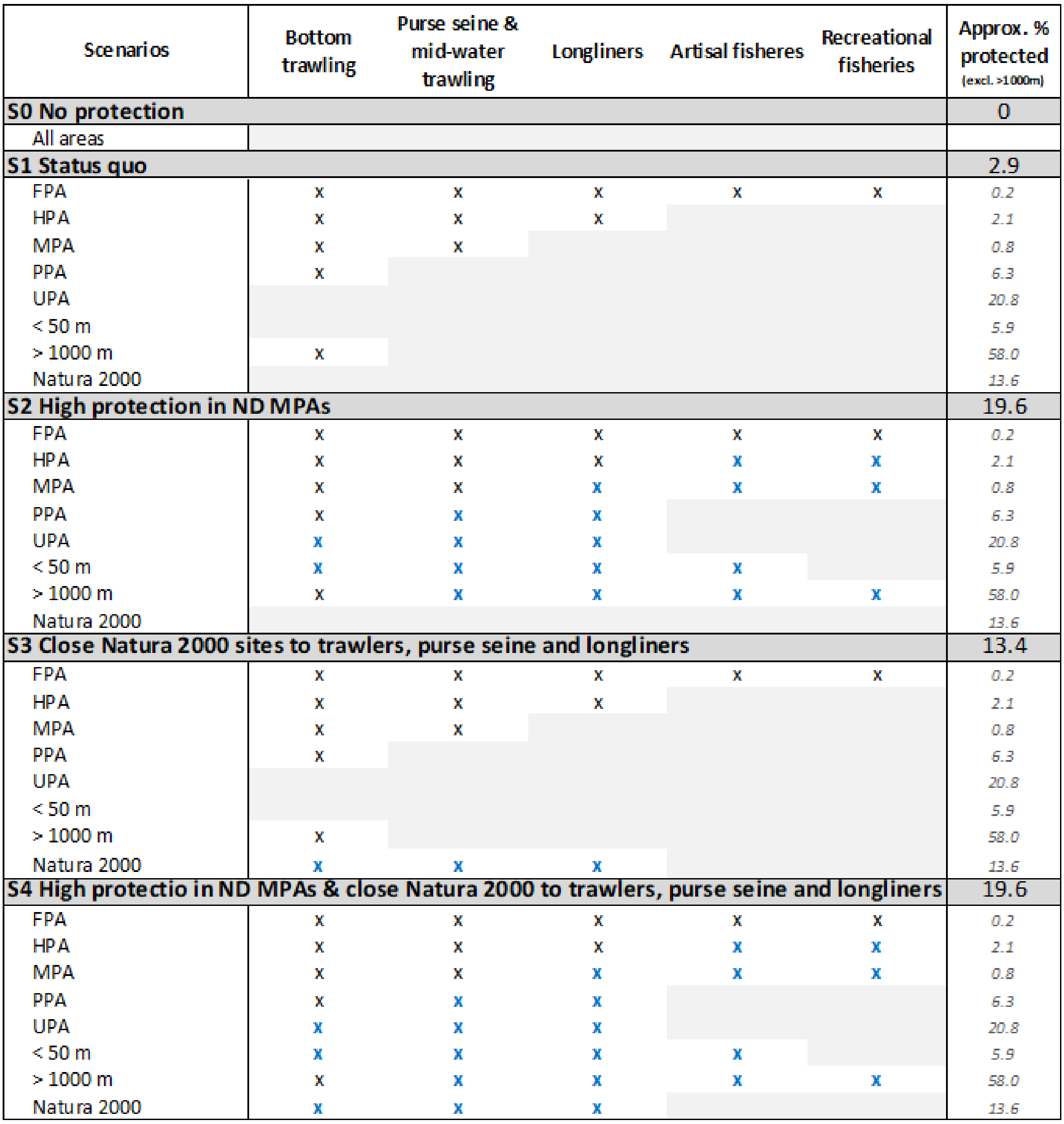


Figure 13: Initial conditions Ecospace management: A) Cost layer for fishing activities proportional to the depth and to distance from harbours, B) MPAs in the study area, classified by their efficiency level (Fully, Highly, Moderately, Poorly or Unprotected), C) depth above 50 m and below 1000 m depth, and D) Natura 2000 sites.

Table 7: Spatial management scenarios used to assess their historical contributions in the Western Mediterranean Sea and the application of each scenario to each fishing fleet segment.



Scenarios	Bottom trawling	Purse seine & mid-water trawling	Longliners	Artisal fisheres	Recreational fisheries	Approx. % protected (excl. >1000m)
S0 No protection						0
All areas						
S1 Status quo						2.9
FPA	x	x	x	x	x	*0.2*
HPA	x	x	x			*2.1*
MPA	x	x				*0.8*
PPA	x					*6.3*
UPA						*20.8*
< 50 m						*5.9*
> 1000 m	x					*58.0*
Natura 2000						*13.6*
S2 High protection in ND MPAs						19.6
FPA	x	x	x	x	x	*0.2*
HPA	x	x	x	x	x	*2.1*
MPA	x	x	x	x	x	*0.8*
PPA	x	x	x			*6.3*
UPA	x	x	x			*20.8*
< 50 m	x	x	x	x		*5.9*
> 1000 m	x	x	x	x	x	*58.0*
Natura 2000						*13.6*
S3 Close Natura 2000 sites to trawlers, purse seine and longliners						13.4
FPA	x	x	x	x	x	*0.2*
HPA	x	x	x			*2.1*
MPA	x	x				*0.8*
PPA	x					*6.3*
UPA						*20.8*
< 50 m						*5.9*
> 1000 m	x					*58.0*
Natura 2000	x	x	x			*13.6*
S4 High protectio in ND MPAs & close Natura 2000 to trawlers, purse seine and longliners						19.6
FPA	x	x	x	x	x	*0.2*
HPA	x	x	x	x	x	*2.1*
MPA	x	x	x	x	x	*0.8*
PPA	x	x	x			*6.3*
UPA	x	x	x			*20.8*
< 50 m	x	x	x	x		*5.9*
> 1000 m	x	x	x	x	x	*58.0*
Natura 2000	x	x	x			*13.6*

A publication explaining the details of this study is being prepared for publication (Coll et al., in preparation).

2.6. OSMOSE model: whole Mediterranean Sea

The work described below was generated to inform specifically on the development of fisheries and conservation in the Mediterranean Sea.

Model configuration

The end-to-end OSMOSE-MED model (Moullec et al., 2019, Figure 14) results from the coupling of three different models:

(1) A regional atmosphere-ocean coupled climate models, CNRM-RCSM4 (Sevault et al. 2014), driven one-way by atmosphere and ocean lateral boundary conditions extracted from the general circulation model CNRM-CM5 (Voldoire et al. 2013);

(2) A regional biogeochemical model, Eco3M-S (Auger et al. 2011), which represents at high-resolution carbon, nitrogen, phosphorus and silica cycles to simulate the dynamics of seven key planktonic functional types (phyto- and zooplankton) of the Mediterranean Sea;

(3) A multi-species age and size-structured stochastic model, OSMOSE (Moullec, Velez, et al., 2019), which simulates at high spatio-temporal resolution (regular grid of 6229 cells of 20 x 20 km^2; 15-day time step) the life cycle of 100 marine species (85 fish, 5 cephalopods and 10 crustaceans), accounting for about 95% of total declared catches in the Mediterranean Sea. For this study, three amphihaline fish species (i.e., *Alosa alosa, Alosa fallax,* and *Anguilla anguilla*) were removed from the original version of the model because their complex life cycle characterized by movements between fresh-water and salt-water has not been modeled as being influenced by climate change.

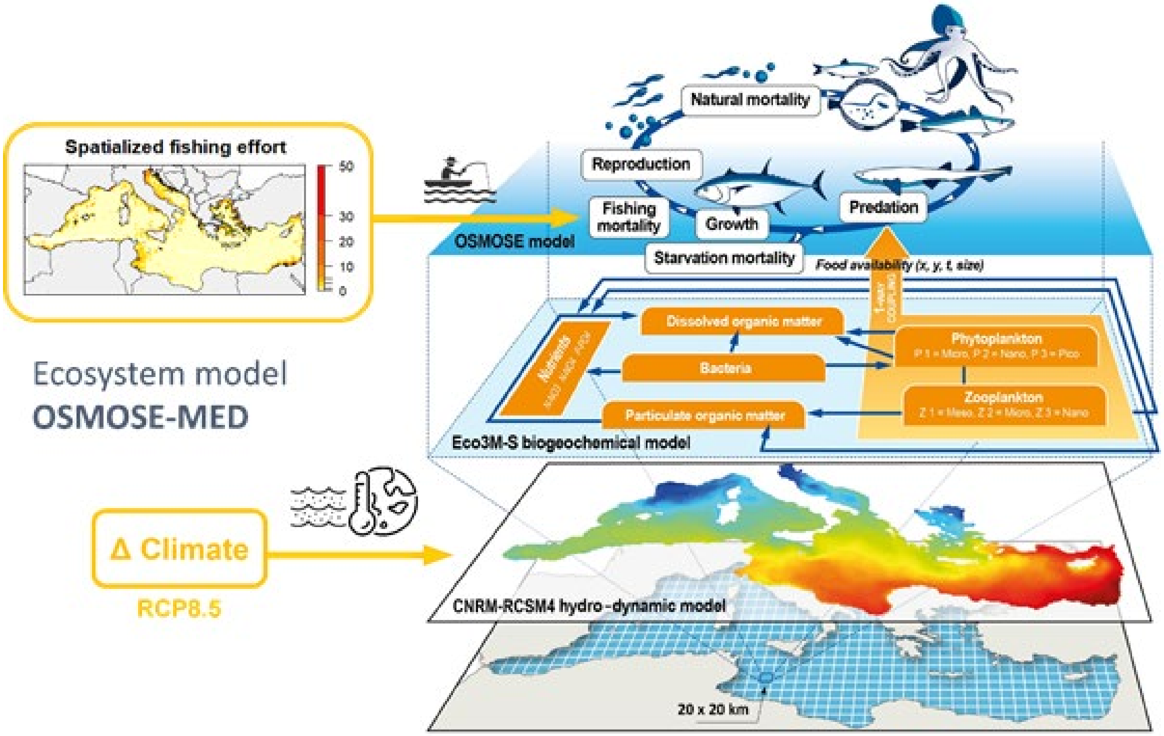


Figure 14: Conceptual representation of the OSMOSE-MED modelling chain (adapted from Moullec et al., 2019)

We used OSMOSE-MED to project the ecological and fisheries effects of the expansion of different Mediterranean MPA networks under climate change scenarios.

In order to correctly assess the changes in fish catches and biomass after the establishment of no-take marine reserves, we spatialized fishing effort in our model. We used Synthetic Aperture Radar (SAR) satellite imagery to spatialize fishing effort, to allow accounting for small vessels activity (with ca. 83% of small-scale vessels under 12 m in the Mediterranean sea, FAO 2020) . Not critically affected by weather conditions (e.g., cloud coverage) and day-night cycles, SAR satellites provide high-resolution images which allow the detection of ships above 10 m in length and therefore appear as a suitable solution to detect vessel position in real-time (Santamaria et al., 2017). We acquired 14,707 Ground Range Detected High-Resolution (i.e., 10 meters per pixel) images from Sentinel-1A and Sentinel-1B, the SAR satellite constellation of the European Union's Copernicus program for Earth Observation (Copernicus, 2022) covering the extent of the entire Mediterranean basin during the period 1 January – 31 December 2019.

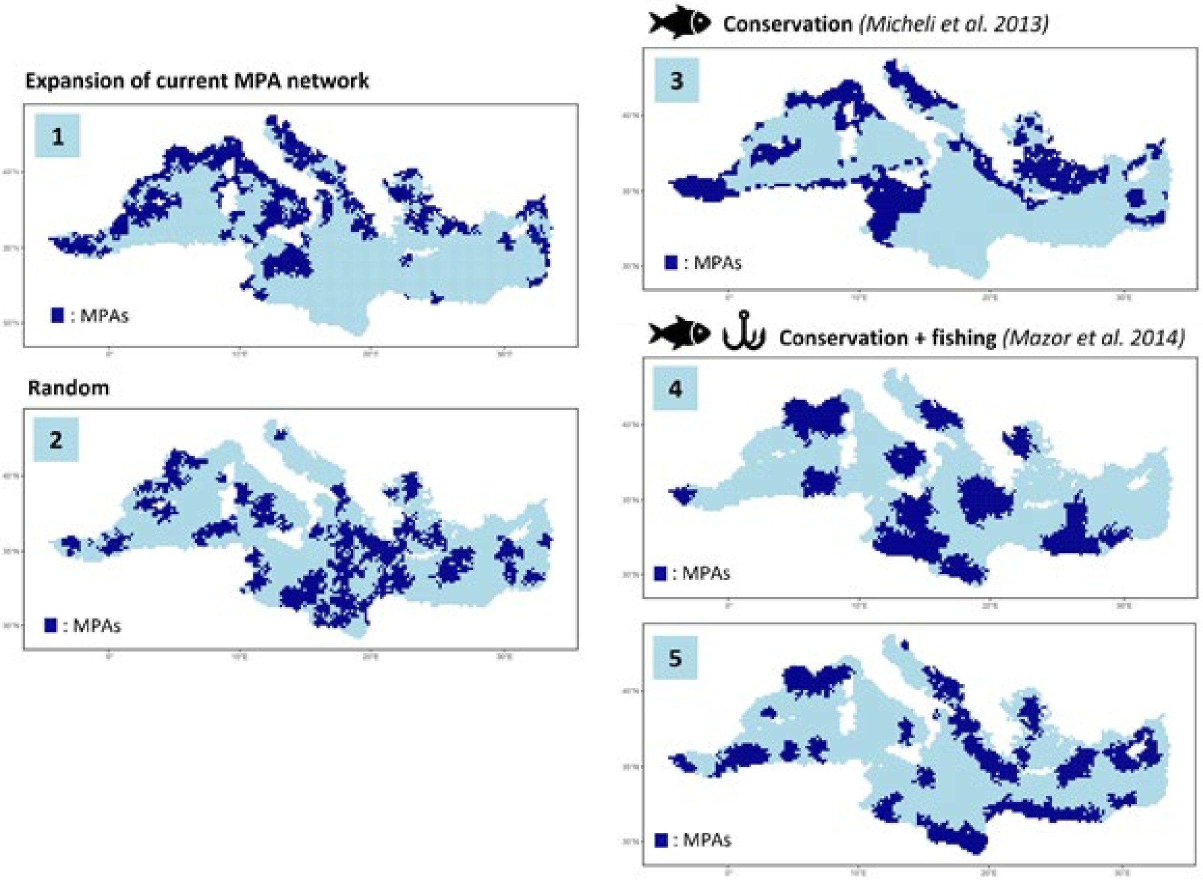
Ships were detected using the Search for Unidentified Maritime Objects (SUMO) algorithm developed by the European Joint Research Center (European Commission. Joint Research Centre., 2017). SUMO is a pixel-based Constant False Alarm Rate detector, which uses several detection thresholds to differentiate vessels from sea clutter (Greidanus et al. 2017). SUMO computes a reliability factor to distinguish between likely real targets and likely false alarms. To minimize the number of false positives, we followed the methodology developed by Pita et al. (2022) and deleted all false alarms and images with 95% more detections than the average image. In a conservative approach, detections in major transport shipping corridors provided by the dataset of Halpern et al. (2015) at 1 km^2 resolution, were also omitted, since we considered fishing vessels would only represent a small fraction of overall detections in such areas. Likewise, we deleted all detections found within a 10-meter buffer from offshore installations provided by Emodnet human activities platform (https://www.emodnet-humanactivities.eu).

In addition, we removed images highly affected by radio frequency interferences (RFI), a known important source of false detections (Santamaria et al. 2017). We then filtered vessels by size to remove abnormal sizes of fishing vessels above 60 meters, which corresponds to the maximum size of fishing fleets in the Mediterranean Sea according to fishing effort data from Global Fishing Watch (GFW), which uses AIS and two convolutional neural networks (CNN) to identify vessel characteristics and detect AIS positions indicative of fishing activity (Kroodsma et al. 2018).

Finally, we noticed that the revisit period of each satellite is not uniform throughout the Mediterranean Sea, with some areas being imaged more frequently due to overlaps in adjacent swaths, inducing a bias in the number of detections. To minimize this bias, we computed a correction factor of the number of detections per OSMOSE-MED grid cell (20 x 20 km^2) according to the number of times each cell was imaged from January 1st to January 12th 2019. A twelve-day time period was chosen since Sentinel-1 satellites have a 12 day repeat cycle.

Scenarios

We designed 5 different MPA network configurations, which we expanded up to 30% of the Mediterranean's surface in 24 steps (Figure 15). For simplification purposes, no distinction was made between levels of MPA protection and all MPAs were simulated as “no-take” areas (i.e., with no fishing allowed).



Expansion of current MPA network

Random

Conservation *(Micheli et al. 2013)*

Conservation + fishing *(Mazor et al. 2014)*

Figure 15: Tested MPA network configurations based on: [1) – the expansion of the current highly protected MPA network in the Mediterranean Sea. (2) – the random placement of MPAs across the Mediterranean basin (we averaged the outputs from 10 random scenarios for the analysis). (3) – top priority areas identified for conservation purposes only in (Micheli et al., 2013). (4 & 5) – areas selected in Mazor et al. (2014) which maximize conservation benefits and minimize fishing costs using either data from the GFCM-FAO (4) or from the Sea Around Us Project (5). Each MPA configuration was tested for 24 coverage percentages of the Mediterranean Sea between 0 and 30%. Above, only the 30% MPA network is shown.

When setting up a reserve, we assumed that fishermen were likely to report within 30km of their original fishing grounds. Given the resolution of our model grid (20 x20 km^2), this was equivalent to reallocating the fishing effort that was inside the MPA on the first row of cells on the MPA border, commonly called “fishing-the-line”. To maintain the spatial distribution of the fishing effort, we computed this redistribution by MPA cluster.

To drive species spatial distribution, OSMOSE takes into account presence/absence maps which are generated based on environmental data (temperature and salinity) using a niche modeling approach (see Moullec et al. (2019) for details). For projecting future species geographical distribution, we used a delta method: anomalies between the historical simulated period (1970–2005) and the future projected period (2070-2100, RCP8.5 scenario from the IPCC AR5) were calculated and applied to current forcings of temperature and salinity climatologies to create future environmental conditions. The same delta approach was followed for the biogeochemistry forcing extracted from Eco3M-S to project future plankton biomasses (see Moullec et al. (2019) for details).

The model was run for 200 years for each set of parameters. MPAs were implemented at year 110, once the model reached a steady state. Each simulation was replicated 30 times to account for the stochasticity of the model. We launched 24 sets of simulations for each MPA network scenario for the 24 MPA size steps up to a 30% coverage of the Mediterranean Sea and one simulation without MPAs (reference state). The 30 replicates and the last 60 years of each set of simulations were averaged for the analysis. All simulations were performed on DATARMOR, the French Research Institute of Marine Exploitation (IFREMER) high-performance computing facility at the “Pôle de Calcul et de Données Marines”.

2.7. Ev-OSMOSE model: the North Sea

The work described below was generated to inform specifically on the development of fisheries and conservation in the North Sea.

Model configuration

In T4.3, we investigate the impact of evolution and climate change on the sustainable fishing of a North Sea species under the RCP8.5 climate change scenario using the Ev-OSMOSE applied to the North Sea ecosystem (Morell et al. 2023).

Ev-OSMOSE is a modeling tool developed to study fish eco-evolutionary dynamics in response to multiple pressures such as fishing, predation or climate change. The theoretical aspects of the model have been extensively described in Morell et al. (2023a, b) and are therefore just summarized here.

The Ev-OSMOSE model represents the eco-evolutionary dynamics of fish communities in marine ecosystems. It is an individual-based, spatially-explicit multispecies model accounting for trophic interactions. The main characteristics of the model are opportunistic predation based on body length and spatial co-occurrence of predators and prey, the mechanistic description of individuals’ life-history traits emerging from genetics and bioenergetics, the consideration of inter-individual phenotypic variability due to both genotypic variability and plastic response to spatiotemporal variations in biotic and abiotic factors. The aim of the model is to explore the functioning and the eco-evolutionary dynamics of marine trophic webs, notably in response to perturbations such as fishing or climate change. The consequences of perturbations can be tracked from the individual genotype to the phenotype, to the population and to the community scale. The Ev-OSMOSE model extends the existing OSMOSE model by (i) explicitly accounting for the dependence of life-history traits on bioenergetics that, in turn, are determined by individual’s genotype, (ii) describing intra- and inter-specific genetic and phenotypic variability.

The Ev-OSMOSE model has been applied to the North Sea (NS) ecosystem by explicitly modelling the life cycle of 15 interacting fish species, referred to as high trophic level (HTL) species. The regional coupled physical-biogeochemical POLCOMS-ERSEM model provides input data on low trophic level (LTL) biomasses, temperature, and oxygen (Butenschön et al. 2016). The study area comprises the North Sea (except the Norwegian trench, i.e., restricted to depth shallower than 200m) and the Eastern English Channel, covering an area of 570 000 km².

A complete description of the North Sea configuration (i.e., the application of the Ev-OSMOSE model to the NS ecosystem referred to as Ev-OSMOSE-NS hereafter), its parameterization and its calibration is available in Morell et al. (2023a,b) and summarized in Figure 1. The configuration covers the NS ecosystem with a regular grid of 0.25° x 0.5° cells for a total of 632 cells and has a temporal resolution of 15 days. It is parameterized and calibrated to represent a steady-state of the NS ecosystem corresponding to the average fisheries landings (ICES database) (ICES, 2019a), biomass (for assessed species) (ICES, 2016, 2018a, 2018b, 2018c, 2019b) and length-at-age of the HTL species over the period 2010-2019. The 15 HTL species modeled in Ev-OSMOSE-NS were: 15 teleost fish species including 5 small pelagics, 7 demersal species and 3 flatfish species (Figure 16).

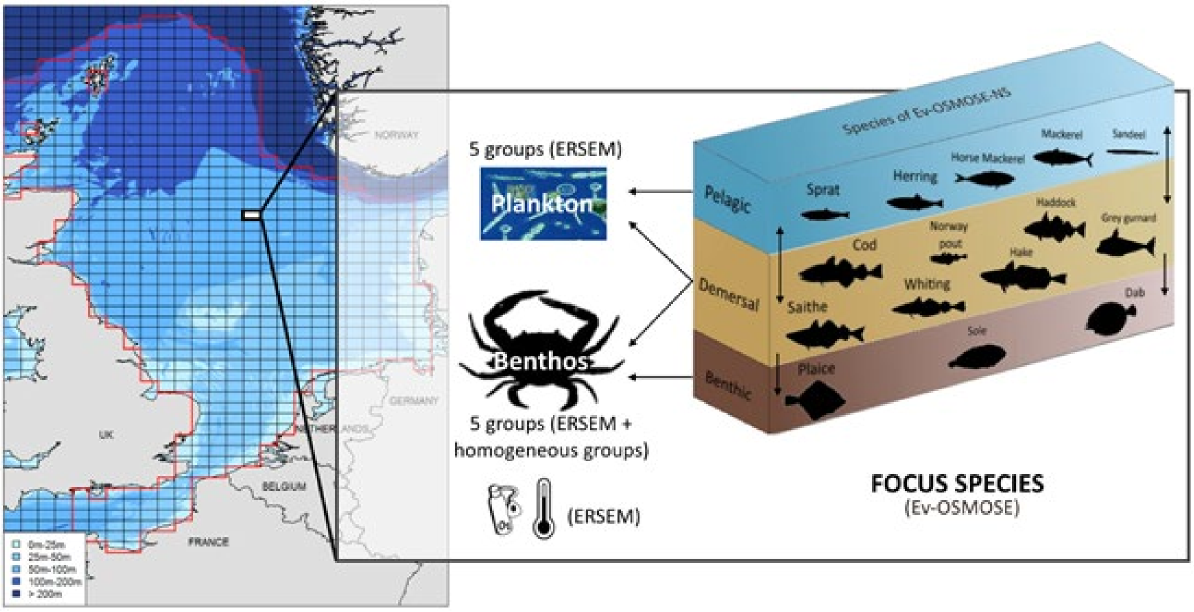


Figure 16: Representation of the Ev-OSMOSE-NS model applied to the North Sea and the Eastern Channel. Fifteen focus species are explicitly modeled. Outputs from the coupled POLCOMS-ERSEM model force Ev-OSMOSE-NS: temperature, oxygen, and the biomass of 8 LTL plankton and benthic groups. Two homogeneous benthic groups are added to model large benthic prey.

In this study, the physical and biochemical components of the ecosystem are modeled using the marine ecosystem model, ERSEM v15.06 (European Regional Seas Ecosystem Model), coupled to the regional ocean circulation models, POLCOMS (the Proudman Oceanographic Laboratory Coastal Ocean Modelling System) (Butenschön et al. 2016). The CMIP5 global climate model (MPI-ESM-LR) was used to provide atmospheric forcing and open ocean boundary conditions. The atmospheric conditions came from a regional, dynamically downscaled model, the open ocean conditions from the original global model. The outputs from POLCOMS-ERSEM have a spatial resolution of 0.1°x0.1° and a monthly temporal resolution. The two models were coupled unidirectionally by using the POLCOMS-ERSEM outputs as inputs to the HTL Ev-OSMOSE-NS. To obtain the spatial resolution of 0.25°x0.5° and the temporal resolution of 15 days used in Ev-OSMOSE-NS, the POLCOMS-ERSEM outputs were linearly interpolated in time and their spatial resolution was degraded.

The Ev-OSMOSE-NS model was forced with LTL species biomass, temperature and dissolved oxygen saturation for an average year over the period 2010-2019 to initialize the model. At each time step and in each cell, the biomass of 2 phytoplankton, 3 zooplankton and 3 benthos groups from POLCOMS-ERSEM and 2 homogeneous benthos groups (large and very large benthos) was provided as potential LTL prey for the HTL species. Biomass was vertically integrated for the plankton groups while benthic groups were found only at the bottom. Likewise, vertically integrated average temperature and dissolved oxygen saturation were used to force pelagic and demersal HTL species bioenergetics while bottom values were used for benthic HTL species.

Scenarios

The Ev-OSMOSE-NS model was used to project changes in yield at different level of fishing mortality in the historical period (climatology of the period 2010-2019) and at the end of the century (2090-2099 period using the average year 2095) under the IPCC high emission

RCP8.5 scenario. Simulations were run over 90 years. The yield value was averaged on the 10 last years of the simulations. Each climatic scenario for each fishing exploitation value was run twice: once without evolution and once with evolution. The evolution was activated after 70 years of simulation.

The activation of evolution in Ev-OSMOSE-NS enables the mendelian transmission of genes from parents to offspring so that the distribution of the life-history traits' genotypic and phenotypic values can change across cohorts within the species.

In order to account for the stochastic nature of Ev-OSMOSE, which is mostly related to movement, mortality, and genetic drift, we ran 28 replicates of each scenario.

Reference points (F_{msy} and the yield at F_{msy}) were estimated for the saithe, a species with cold water preference and that has faced an important fisheries-induced evolution in the North Sea (Marty, Rochet, Ernande 2014).

2.8. Fuzzy Cognitive Map: the Gulf of Lions

The work described below was generated to inform specifically on the development of fisheries in the Gulf of Lion.

Model configuration

We aimed to model projections of the consequences of climate change and contrasted socio-political orientations for the French fisheries of the Gulf of Lion, from the perspective of a long-term pathways towards sustainable fisheries. Our approach consisted of a regional downscaling of global scenarios combining IPCC Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs) for the 2050-2100 horizon. To co-construct policy-relevant downscaled scenarios, we engaged with fisheries managers, policy makers, scientific experts, and NGOs. We co-constructed four contrasted scenario storylines by mobilizing their knowledge, views and perceptions through an interdisciplinary framework implemented in a suite of participatory workshops (Figure 17, further details on the co-construction process of the local scenarios in Chevallier et al. in prep).

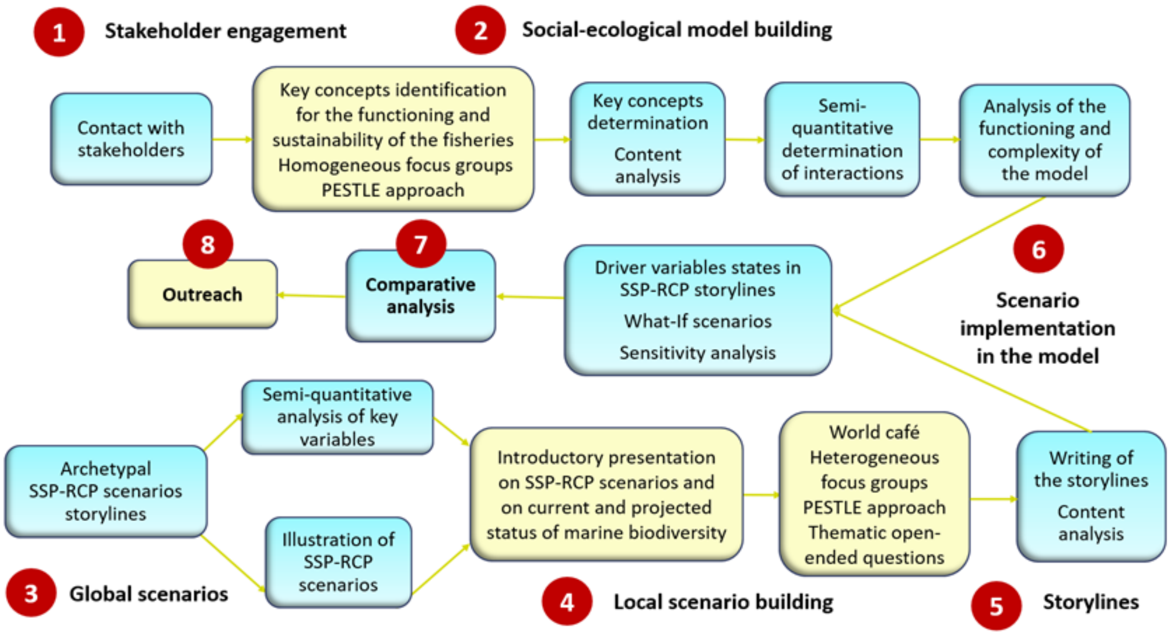


Figure 17: Protocol for the co-construction and modeling of SSP-RCP scenarios in the Gulf of Lion. Preparatory and analysis activities are in turquoise blue while participatory activities are in yellow.

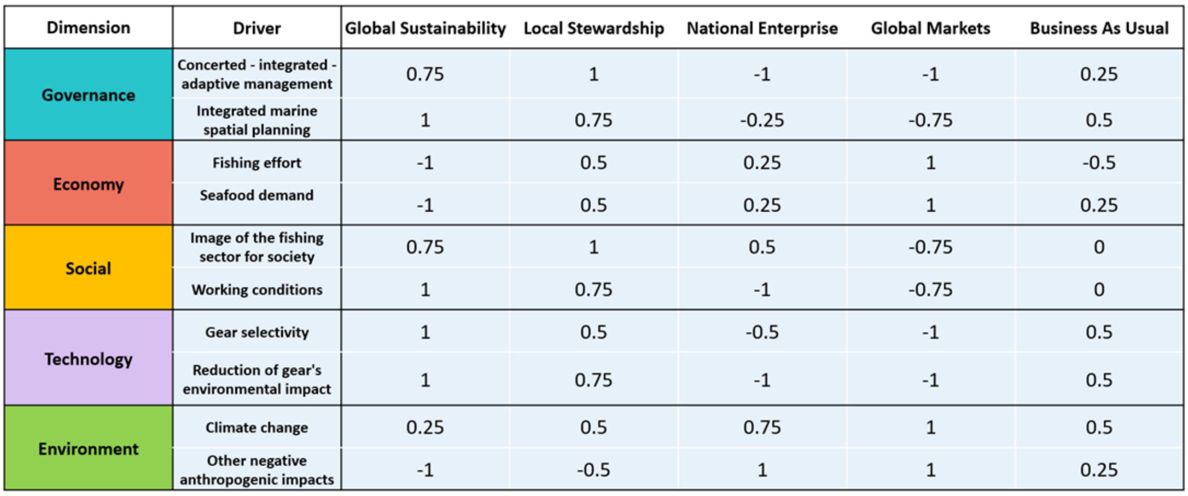
To model the Gulf of Lion fisheries social-ecological system (SES), from the perspective of assessing its sustainability status, we determined key concepts for its functioning and sustainability during an additional series of seven homogeneous focus groups with stakeholders. We interviewed 24 participants from the following organizations: three fish producer organizations, a regional fisheries committee, the national fisheries committee, a regional scientific team, and a local NGO focused on sustainable fishing. Using a PESTEL analysis, considering political, economic, social, technological, environmental, and legal dimensions, we asked stakeholders to identify individually, and then through a joint discussion, the concepts that promote or hinder sustainable fishing in the Gulf of Lion. We then compiled and standardized all the concepts identified by the stakeholders through a thematic analysis and obtained 71 key concepts for the functioning and sustainability of the Gulf of Lion fisheries.

Based on these focus groups, we constructed a fuzzy cognitive map (FCM) of the fisheries SES, i.e., a directed graph whose nodes explicitly represent the set of concepts from our study system, and whose links represent for each pair of concepts a causal relationship (Kosko 1986).

Scenarios

We then implemented our four co-constructed scenarios in the FCM. Indeed, by feeding the FCM with a vector of value changes, for a subset of key concepts, the FCM converges to an equilibrium point by iteratively applying a calculation rule and a threshold transfer function. In our case, we identified all the functioning and sustainability concepts mentioned in the four scenario storylines. We then selected a subset of key concepts as drivers of the four scenarios and determined the value changes that characterize the state of our scenarios compared to the current state. To do this, we considered the two concepts most frequently mentioned within the set of scenario storylines as being the main drivers for achieving these scenarios for each of the following dimensions: governance, economy, social, technology and environment (Table 6). Through a content analysis of the scenario storylines, we were able to assign a positive, zero or negative value to the change in these concepts for each scenario, compared to the current situation. Based on our expert knowledge, we also defined a "business-as-usual" scenario that follows current socio-political trends. We used the modified Kosko calculation rule and the sigmoid transfer function until our FCM converged (Dikopoulou et al. 2018, version 1.1 of FCMapper R package), then compiled the changes in values of all concepts for each scenario.

Table 8: Driver settings for scenario implementation. The values of the projected changes in relation to the current period are distributed from -1 to 1, depending on whether they are positive or negative, and according to the following Likert scale, in absolute values: 0 no change, 0.25 weak, 0.5 moderate, 0.75 strong, 1 very strong.



Dimension	Driver	Global Sustainability	Local Stewardship	National Enterprise	Global Markets	Business As Usual
Governance	Concerted - integrated - adaptive management	0.75	1	-1	-1	0.25
	Integrated marine spatial planning	1	0.75	-0.25	-0.75	0.5
Economy	Fishing effort	-1	0.5	0.25	1	-0.5
	Seafood demand	-1	0.5	0.25	1	0.25
Social	Image of the fishing sector for society	0.75	1	0.5	-0.75	0
	Working conditions	1	0.75	-1	-0.75	0
Technology	Gear selectivity	1	0.5	-0.5	-1	0.5
	Reduction of gear's environmental impact	1	0.75	-1	-1	0.5
Environment	Climate change	0.25	0.5	0.75	1	0.5
	Other negative anthropogenic impacts	-1	-0.5	1	1	0.25

For each scenario, we assessed the impacts of climate change and socio-economic mutations on marine ecosystems and fishing communities. We also conducted a sensitivity analysis to observe how key concepts related to marine ecosystem health and fisheries socioeconomic conditions respond to variations in the various drivers selected in our model, over their entire range.

These results were analyzed from the perspective of achieving sustainable fishing scenarios in the Gulf of Lions. To do this, we referred to the sustainability targets defined in the EU Biodiversity Strategy 2030 (EC 2020), a core part of the European Green Deal (EC 2019), and which in the case of marine ecosystem and fisheries is underpinned by EU's Common Fisheries Policy, the Marine Strategy Framework Directive, the Birds and Habitats Directives, and the European Maritime and Fisheries Fund orientations. We reviewed this document to determine the model concepts that correspond to sustainability targets (Appendices 1-2). We assigned a sustainability score for each scenario by considering all the values of the changes modelled for these concepts.

2.9. EwE model: the North Sea

The work described below was generated to inform specifically on the development of fisheries and conservation in the North Sea.

Model configuration

Fuzzy Cognitive Maps (FCMs) are signed directed graphs showing the directional interaction between nodes (components of the modelled system), on a 'fuzzy' scale (Olesen et al. 2022). Stakeholder workshops developed a range of scenarios including those linked to fisheries management, in order to evaluate the wider effects on the ecosystem, and climate change scenarios (ICES 2020). To evaluate the performance of the FCM models the same scenarios were run (by FutureMARES) using the Ecopath with Ecosim (EwE) model that had been approved by ICES (2016) through the "key-run" procedure. Future scenarios for the North Sea based on the EwE model were run with either increased or decreased fishing effort and were compared with similar scenarios based on FCM modelling for the southern North Sea, Skagerrak and Norwegian Trench subdivisions (see Olsen et al. (2023) for further details).

The EwE model of the North Sea was calibrated previously following quality control in accordance with guidance from ICES (2016). The model includes 69 functional groups from phytoplankton and benthic groups at the base of the food web up to predatory sharks and seabirds. In addition to modelling the predatory mortality between groups the impact of 11 fishing fleets that represent the major international fleets operating in the North Sea was considered, with functional groups and fishing fleets interconnected through 1521 links (ICES 2016). For top predators a number of functional groups include more than one species. The toothed whale group is composed of three species: harbour porpoise (*Phocoena phocoena*), white-beaked dolphin (*Lagenorhynchus albirostris*) and Atlantic white-sided dolphin (*Lagenorhynchus acutus*) but, this group is dominated by the abundant harbour porpoise. The baleen whale group is based on data for minke whale (*Balaenoptera acutorostrata*). The seals group includes both harbour seal *Phoca vitulina* and grey seal *Halichoerus grypus*. Seabirds are grouped into either 'surface-feeding seabirds' (includes species whose diet includes a significant fraction of fish (and other fauna) discarded from fisheries, e.g., gulls (*Larus* spp), kittiwakes (*Rissa* spp), terns (*Lari* spp)) and 'diving seabirds' e.g., northern gannet (*Morus bassanus*), common guillemot (*Uria aalge*) or razorbill (*Alca torda*)). The 'Large piscivorous sharks' group generally represents tope (*Galeorhinus galeus*). Juvenile stages of five species only are included in multi-stanza: cod, haddock, whiting, saithe, and herring.

The North-Sea Ecopath component represents biomass flows among biota groups within the food web and to fisheries in the initial model year, 1991. Ecosim was then calibrated to represent the temporal development of the food-web from 1991 to 2013. Changes in primary production (PP) and a temperature index (Atlantic Multidecadal Oscillation, AMO) were applied as forcing functions in the model calibration period (ICES 2016). Change in consumption rates over time of adult cod, whiting, saithe, and starry rays are also driven by an inverse relationship with AMO, while mackerel were fitted with a positive relationship. In contrast, consumption rates of juvenile groups (cod, haddock, whiting, saithe, and herring) are driven by recruitment indices that decrease during the calibration period. Fishing mortality in the model is driven directly by time series of fishing mortality estimated for assessed stocks (1991-2013). For other non-assessed species fishing mortality is driven over time by time series of fishing effort combined with catch and effort during the base year (1991).

Scenarios

Simple RCP4.5 and RCP8.5 scenarios were developed to make projections using the EwE model based on decadal averages of temperature (both sea surface and bottom) and net PP to 2100 downloaded for the North Sea from the U.S. National Oceanic and Atmospheric Administration's Climate Change Web portal (https://www.esrl.noaa.gov/psd/ipcc/ocn/ accessed 03 April 2020). Based on the CMIP ensemble average of models ("ENSMN"), simple linear decreases were generated and used as input time-series for Ecosim: RCP4.5 assumed an increase in AMO of 8.5% and a decrease in PP of 5% by 2199 relative to the end year of the calibration period (2013), while the RCP8.5 scenario assumed an increase in AMO of 23.2% and a decrease in PP of 8%. These environmental variables limit the production at the base of the food web and lead to decreases in the consumption rate of adult cod, whiting, saithe, and starry rays and thus an increase in natural mortality of these groups. Relative consumption rates of mackerel and juvenile cod, herring, saithe, and whiting were projected forward at the low levels reached at the end of the calibration period.

The North Sea EwE model was run for the period 2020 – 2100 under recent fishing pressure levels (2013 values) and IPCC RCP4.5 climate scenario as a base case. Furthermore, using the RCP 4.5 climate scenario, fishing effort by bottom trawling was increased by either +25% or decreased by 50% or 100% of the base effort. A worst case scenario was also run with RCP 8.5 and fishing effort increased by 75%.

2.10. SS-DBEM model: the Bay of Biscay

The work described below was generated to inform specifically on the development of fisheries in the Bay of Biscay.

Model configuration

A multi-species ecosystem model (hereafter called SS-DBEM; Fernandes et al., 2013) which integrates a species based model (DBEM, Dynamic Bioclimatic Envelope Model) (Cheung et al., 2008a; Cheung et al., 2011; Cheung et al., 2008b; Cheung et al., 2009) with the size-spectrum approach (SS) (Jennings and Collingridge, 2015; Jennings et al., 2008) was used in this study. This approach includes a large number of mechanisms and ecological processes such as population growth, movement, and dispersal of adults and larvae, as well as the ecophysiological effects of temperature, oxygen, and pH on body size, growth, mortality, and reproduction (Cheung et al., 2013). The SS-DBEM model (Figure 18, Table 7) provides spatially (at a 0.5x0.5º resolution) and temporally (yearly) resolved predictions of changes in species' size, abundance and biomass (Cheung et al. 2008a, Cheung et al. 2011, Cheung et al. 2008b, Cheung et al. 2009, Cheung et al. 2012) with consideration of competition (Fernandes et al. 2013). The competition algorithm describes the resource allocation between different species co-occurring in a spatial unit (thereafter cell) by comparing the flux of energy (in biomass) that can be supported (estimated with the SS model) with the energy demanded by the species predicted to inhabit that cell (estimated with the DBEM model) (Fernandes et al. 2013) (see Figure 18). In addition, the environmental conditions are considered in the mechanisms and since there are different environmental conditions that are provided by the biogeochemical models, species responses are also different spatially.

Table 9: Summary of mechanisms (with main equations and parameters) considered in SS-DBEM. For further details, check the associated references.

Mechanism	Equation	Parameters
Growth=anabolims-catabolism (Pauly, 2010; Cheung *et al.*, 2011)	$G = Hw^{a} - kW$ $H = g[O_2] * e^{-j1/T}$ $k = h[H^{+}] * e^{-j2/T}$	k= catabolism coefficient W=body weight α=anabolism exponent (0.5 to 0.95) W∞=asymptotic weight
Length-weight	$W = a * L^{b}$	W = weight L = length
Size-spectrum production (Fernandes *et al.*, 2013; Jennings *et al.*, 2008)	$P = \exp(25.22 - E/kT) * W^{0.76}$	E = activation energy of metabolism T = temperature in Kelvin (°C + 273) k = Boltzmann's constant
Intrinsic population growth rate (Hilborn & Walters, 1992)	$G = r * A * (1 - (A/KC))$	r = intrinsic rate of population increase KC = population carrying capacity A = the relative abundance
Larval recruitment (O'Connor et al., 2007; Cheung et al., 2008)	$\ln(PLD) = B_0 - 1368 * \left(ln\left({}^{T}/_{Tc}\right)\right) - 0.283 * \cdot \left(ln\left({}^{T}/_{Tc}\right)\right)^2$	PLD = pelagic larvae duration T = surface temperature Tc = 15 C DM is the developmental type of larvae (0 lecithotrophic, 1 planktotrophic) N = number of cells where species occur
Larval dispersal (Cheung et al., 2008; Hundsdorfer & Verwer, 2003)	$\frac{\partial Lav}{\partial t} = \frac{\partial}{\partial x}\left(D \frac{\partial Lav}{\partial x}\right) + \frac{\partial}{\partial y}\left(D \frac{\partial Lav}{\partial y}\right) - \frac{\partial}{\partial x}(u * Lav) - \frac{\partial}{\partial y}(v * N) - \lambda * Lav$	D = diffusion parameter LAV = larvae recruitment (u, v) = velocity parameters
Adult movement	cm/hr	cm = centimetre hr = hour
Natural mortality	M=-0.4851-0.0824+log(W∞) +0.6757+log(K)+0.4687*log(T)	W∞ = asymptotic weight T = average water temperature in the animal's range K = von Bertalanffy growth parameter
Fishing mortality at MSY	FMSY= 0.4*MSY	M=natural mortality

An initial distribution map with the probabilities of occurrences is needed in the SS-DBEM for each modeled species. Those initial distributions have been developed individually and acquired from Erauskin-Extramiana et al. (2019) for tuna and swordfish target species. These distributions were estimated from the historical catch and effort information of the Japanese pelagic longline fleet with a combination of a presence/absence analysis and a Gaussian error distribution estimated using Generalized Additive Models (for further details see Erauskin-Extramiana et al. (2019)). Initial distribution for the Pacific bluefin was obtained from the Sea Around Us Project (SAUP, www.seaaroundus.org) following the methodology from Close et al. (2006). Based on this initial distribution, DBEM linked the species probability of occurrence with the environmental variables included in the model (sea surface and bottom temperature, coastal upwelling, salinity, sea-ice extent, depth and habitat types) (Cheung et al. 2011, Fernandes et al. 2013) obtaining the preference range of environmental conditions for each species. Then, the model estimates changes in growth and their life history traits in response to changes in temperature and oxygen concentration based on algorithms derived from growth and metabolic functions and empirical equations (Cheung et al., 2011; Cheung et al. 2012). Using this information, the model predicts the size-frequency distribution for each species by grid cell using a size-structured 'per recruit' model. In the last stage, the model estimates the abundance and biomass within a cell based on the carrying capacity of a cell (given by the SS component of the model), density-dependent population growth, larval dispersal and adult migration (Cheung et al., 2011; Cheung et al., 2008c).

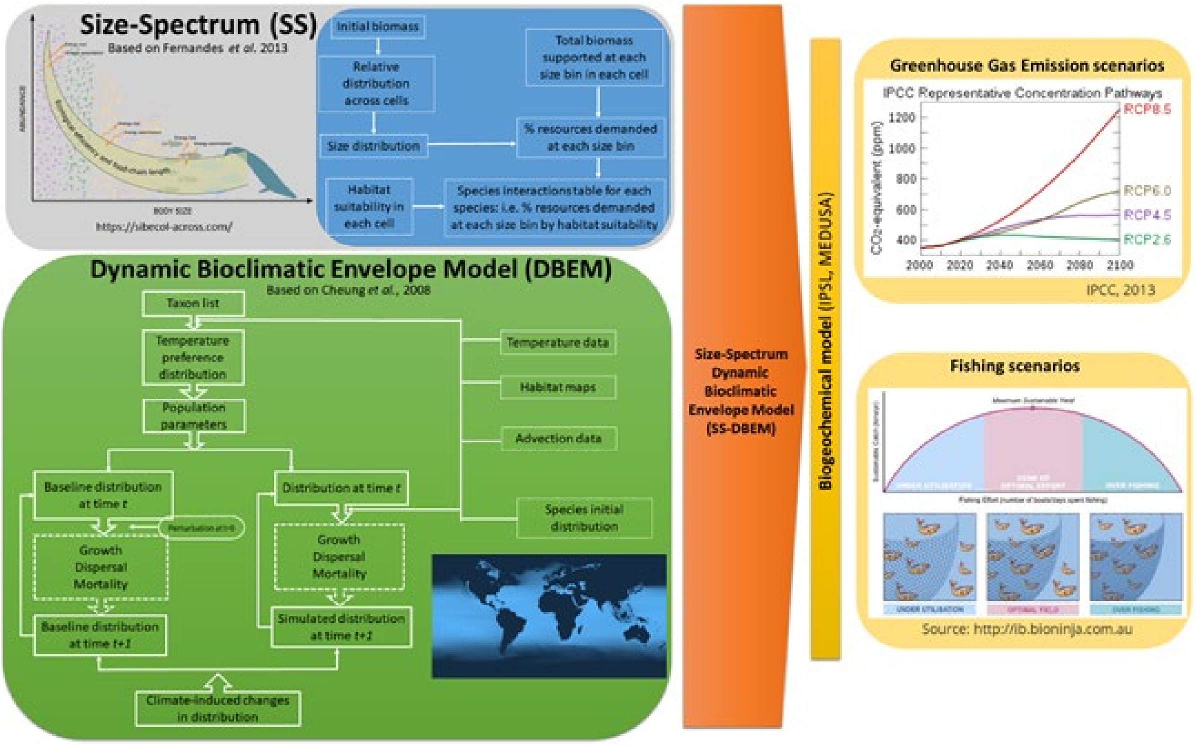


Figure 18: Schematic diagram of the SS-DBEM structure, defining the parameters used and the workflow of the model. Mechanisms included in each model are described, as well as the climatic and fishing scenarios. Based on Queirós et al. (2015), Fernandes et al. (2013) and Cheung et al. (2011).

Scenarios

Given the very high and long computation requirements of SS-DBEM model (global model and full species distribution) as well as limited resources of AZTI for modeling in WP4 (more focus on WP1 and WP6), biogeochemical projections already available from FISH-MIP were used and constrained the climatic scenarios to be run. Climate change is formulated from projections of Greenhouse Gas emissions (different Representative Concentration Pathways, RCPs), and fishing scenarios which were defined as different levels of compliance with fishing mortality at the Maximum Sustainable Yield (FMSY). The two climate scenarios that represent high-, and low- range greenhouse gas emissions are (i) the mitigation scenario with 421 parts in a million (ppm) (RCP2.6) and (ii) the high emission scenario (936 ppm)(RCP8.5) by the year 2100. The fishing effort scenarios were defined in consultation with scientists participating in all tuna RFMOs worldwide (Erauskin-Extramiana et al., 2023). The following levels were considered in the modeling: 0 (no fishing), 0.8, 1.0, 1.2 and 1.5 times the fishing mortality at Maximum Sustainable Yield (FMSY) (thereinafter 0 FMSY, 0.8FMSY, 1.0FMSY, 1.2FMSY, and 1.5FMSY). This modeling was done in collaboration with other European projects (Mission Atlantic and SusTunTech). For this report, the model projections selected considered FutureMARES scenarios as World Markets (RCP 8.5 and 1.0 times MSY), National Enterprise (RCP 8.5 and 1.2 times MSY) and Global Sustainability (RCP 2.6 and 0.8 times MSY).

3. Results on sustainable aquaculture of low trophic level species under CC

3.1. North Sea

In the rest of the report our simulations are named according to the socio-economic scenario (HIST, SSP126, SSP585), period (2010, 2030, 2050, 2100), and simulated aquaculture setup (None, Sw, M or SwM). For example: the historical scenario run without aquaculture will be called HIST_2010. The SSP1/RCP2.6 scenario run for 2050 with both seaweed and mussel aquaculture will be called SSP126_2050_SwM. Runs with seaweed aquaculture for 2100 are not yet available. As a consequence, in total, results of 24 runs are analysed.

Maps presented in this subsection show average nutrient concentrations (dissolved inorganic nitrogen and phosphorus, noted DIN and DIP herein) over the winter (December-February) or average surface temperature, temperature stratification (difference between near-surface and bottom water temperature) and chlorophyll-a (noted chlorophyll-a) concentrations (proxy for phytoplankton biomass) over the growing season (March-September). Winter mean inorganic nutrients can explain a large part of observed spatial variability in growing season mean chlorophyll-a concentrations (Blauw et al. 2018). Measured data plotted on historical state maps are extracted from the NWDM database (https://wstolte.github.io/nwdm/), and averaged over winters/growing seasons of the period September 2009-September 2014. This allows for assessing the performance of the model in reproducing seasonal patterns of these key ecosystem-functioning variables for the near past.

Historical state

The model reproduces well the spatial and temporal variabilities of salinity (not shown) and temperature (Figure 7). A more in-depth analysis of model outputs (data not shown) at Dutch national monitoring stations (MWTL) reveals that lowest winter temperatures however tend to be overestimated by the model for the year 2010. Model results of temperature stratification show that in near-shore regions in the Southern North Sea and Dogger Bank, the water column is relatively well mixed in the growing season, while the Northern North Sea is clearly stratified with average differences between near-surface and bottom temperatures of ~5ºC.

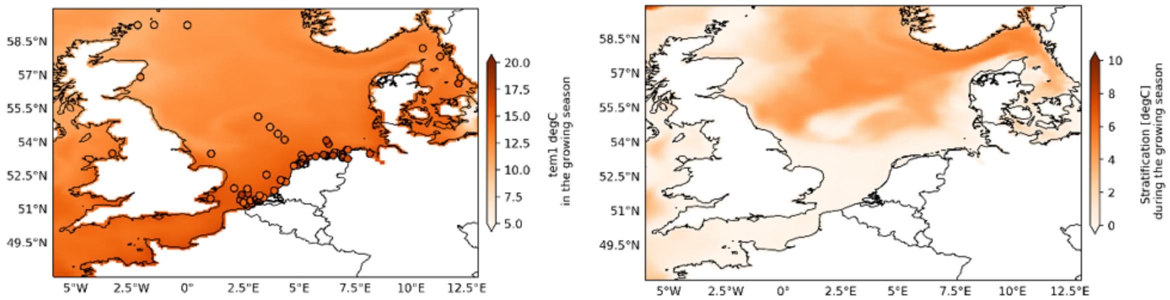


Figure 19: Left panel: simulated (background) and measured (dots) average growing season temperature in ºC. Right panel : simulated average growing season temperature stratification in ºC.

The model captures the spatial variability of winter concentrations of DIN and DIP, with a strong gradient from the coastal region towards offshore (Figure 8). Comparison at MWTL stations show that seasonal variability of DIN and DIP concentrations are well reproduced, with the period of depletion matching observations (data not shown). Winter concentrations of DIP are, however, slightly underestimated at some stations.

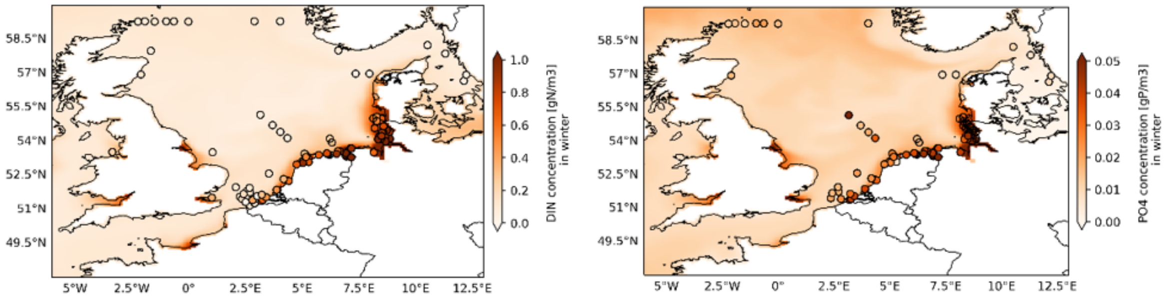


Figure 20: Simulated (background) and measured (dots) average near-surface winter DIN (left panel) and DIP (right) concentrations

Spatial gradients of chlorophyll-a concentrations during the growing season are well reproduced by the model (Figure 9). Comparison to MWTL measurements show that simulated chlorophyll-a peaks occur at the right time, when the bloom was captured by measurements (data not shown). Average yearly phytoplankton primary production is generally higher in shallow areas that are not too turbid, reaching values of ~1 gC/m^2/day.

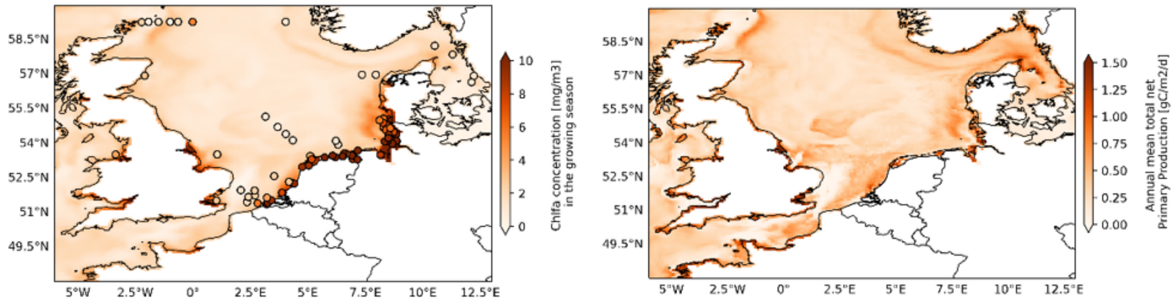


Figure 21: Left panel: simulated (background) and measured (dots) average near-surface growing season chlorophyll-a. Right panel: simulated yearly average primary production (integrated over the entire water column in gC/m^2/day).

Changes in environmental variables due to climate change

According to model results, near-surface sea water temperature is lower in 2030 than in our reference 2010 run (Figure 10). This is due to interannual variability in the CMCC-ESM2 data, 2030 being an exceptionally cold year compared to other years between 2020 and 2040 . To investigate pure climate change effects, it is therefore better to look at results from 2050 and 2100 runs. Temperatures are increasing sharply at the end of the century and reach differences with the 2010 situation of about +2ºC and +4ºC by the end of the century for scenarios SSP1/RCP2.6 and SSP5/RCP8.5, respectively (Figure 10). The strong increase in near-surface temperatures by the end of the century, lead to sharp increase in temperature stratification for already stratified areas. It also seems that currently weakly stratified areas (e.g. area mid-way the Dogger Bank and the Dutch coast) will become more strongly stratified in the growing season with increases in stratification of almost 4ºC for the least sustainable scenario (Figure 11).

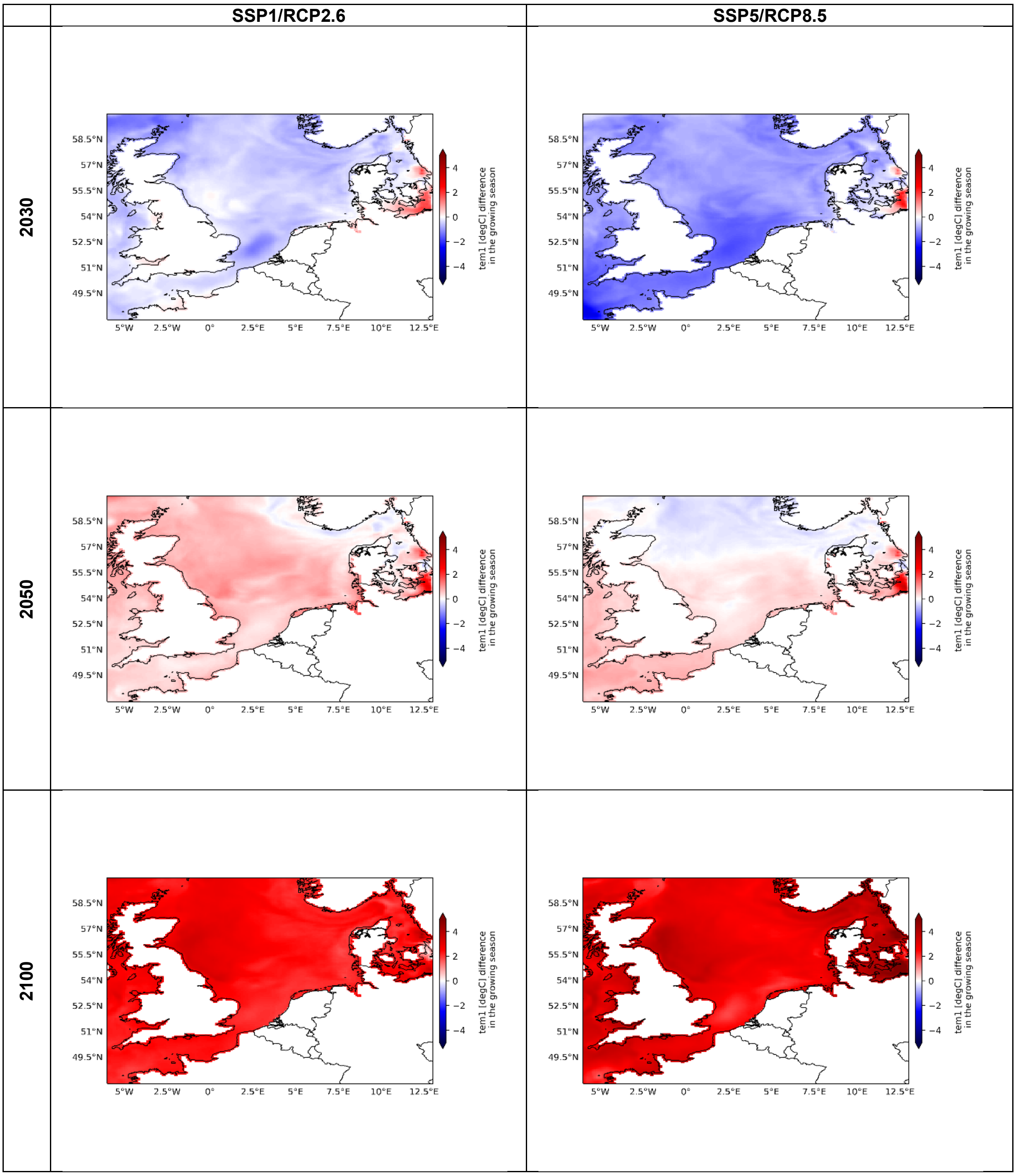


Figure 22: Simulated differences in growing season mean surface temperature between future scenarios without aquaculture and the historical scenario (HIST_2010)

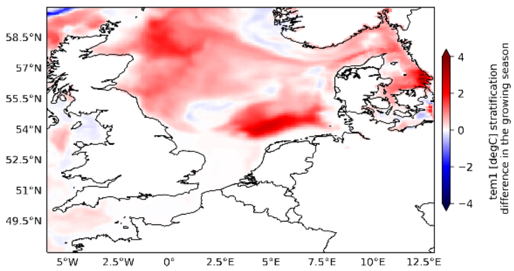
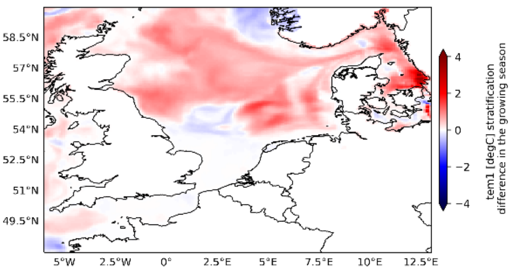
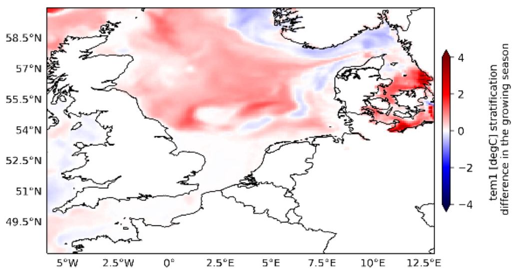
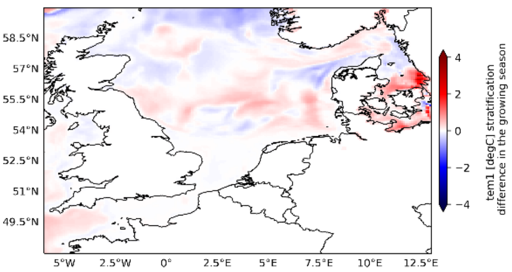
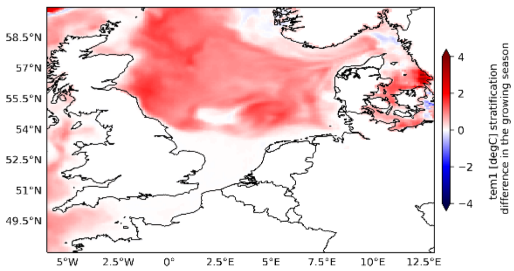
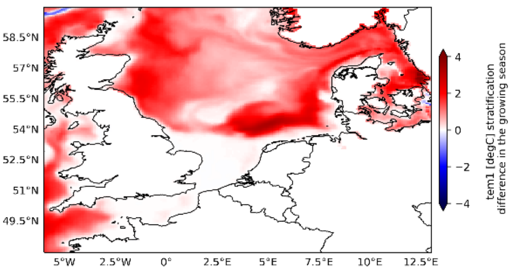
	SSP1/RCP2.6	**SSP5/RCP8.5**
2030		
2050		
2100		

Figure 23: Simulated differences in growing season mean temperature stratification between future scenarios without aquaculture and the historical scenario (HIST_2010)

Near-surface winter DIN and DIP concentrations clearly decrease in future scenarios in offshore regions (Figure 12 and Figure 13). That is consistent with global results from the CMCC-ESM2 model (Lovato et al. 2022). DIN and DIP inputs from the Baltic however increase and near-shore concentrations increase likely due to higher loads from river inputs. The sharpest increase in coastal nutrients in the model occurs in 2050 for the scenario SSP5/RCP8.5. Coastal nutrient concentrations then decrease slightly again due, likely due to decreases in freshwater discharges. Spatial patterns in future changes of chlorophyll-a concentrations and phytoplankton primary production can clearly be related to those in winter nutrients (Figure 14 and Figure 15), with clear decreases compared to the historical state in offshore regions and increases in coastal areas.

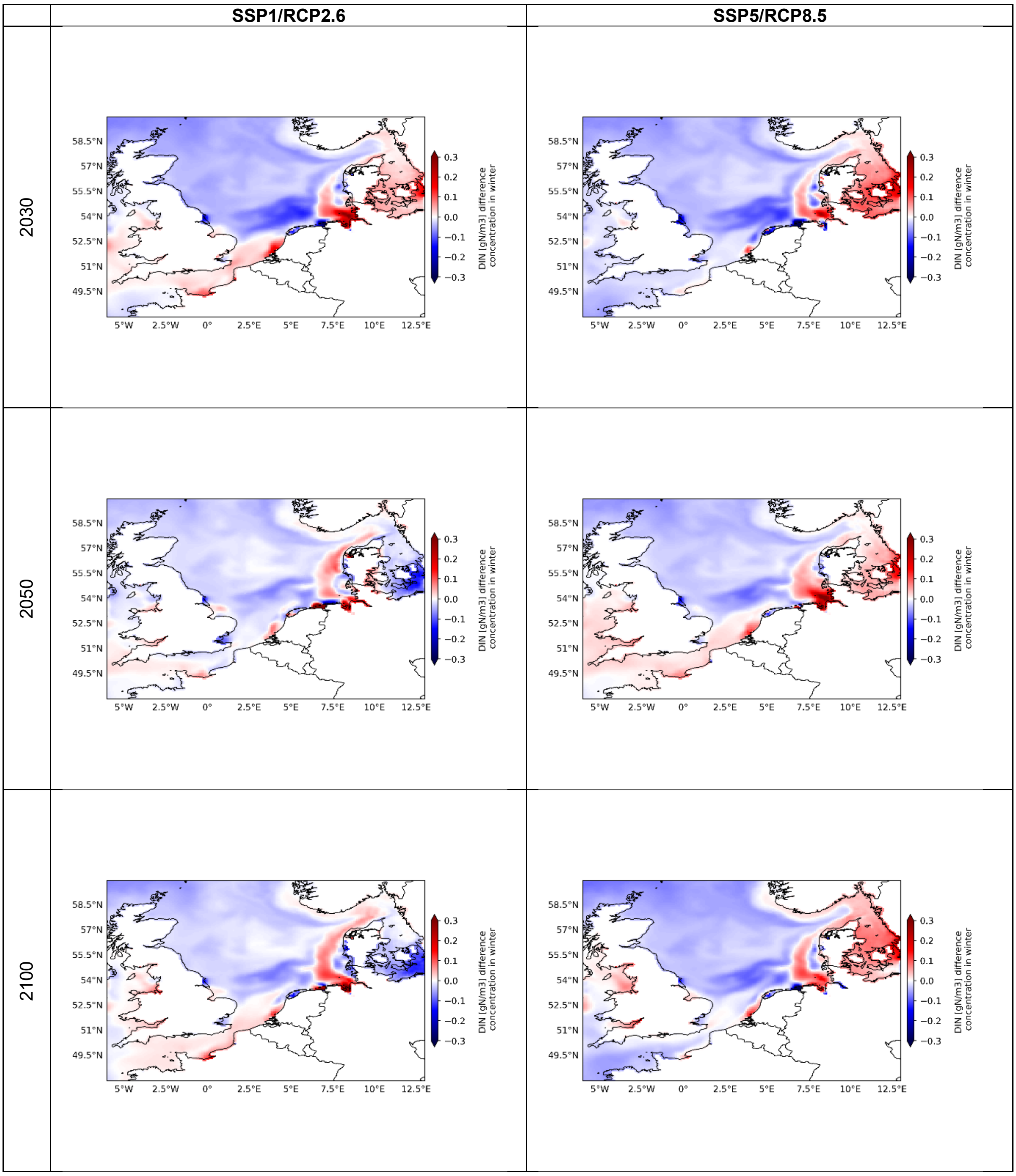


Figure 24: Simulated differences in winter mean near-surface DIN concentrations between future scenarios without aquaculture and the historical scenario (HIST_2010).

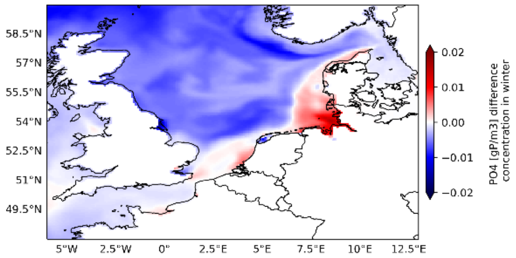
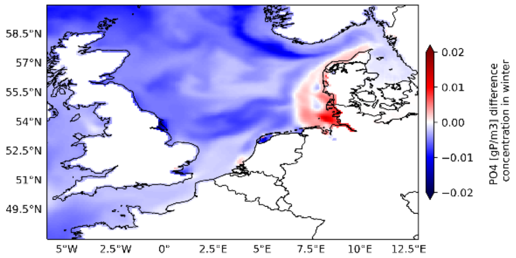
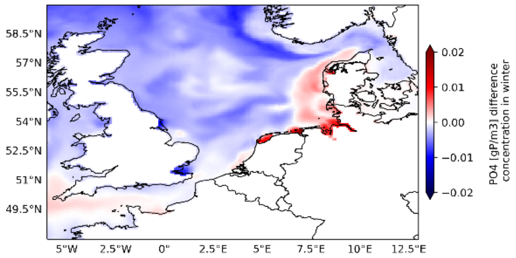
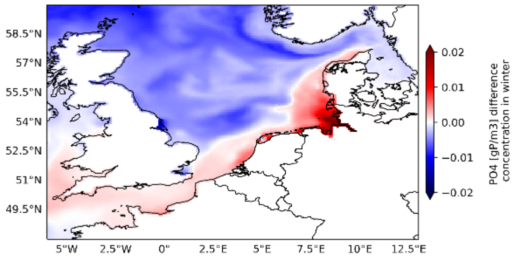
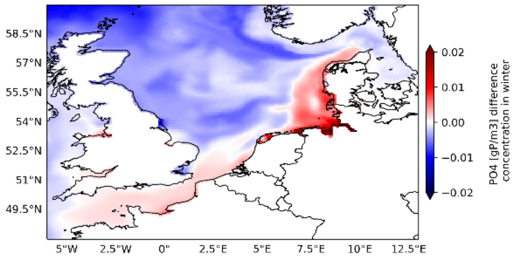
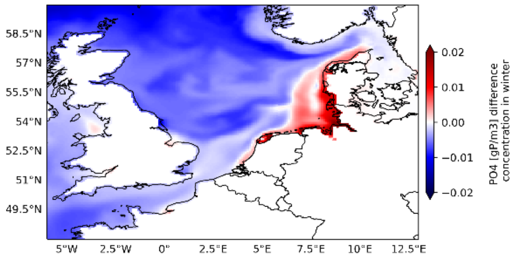
	SSP1/RCP2.6	**SSP5/RCP8.5**
2030		
2050		
2100		

Figure 25: Simulated differences in winter mean near-surface DIP concentrations between future scenarios without aquaculture and the historical scenario (HIST_2010).

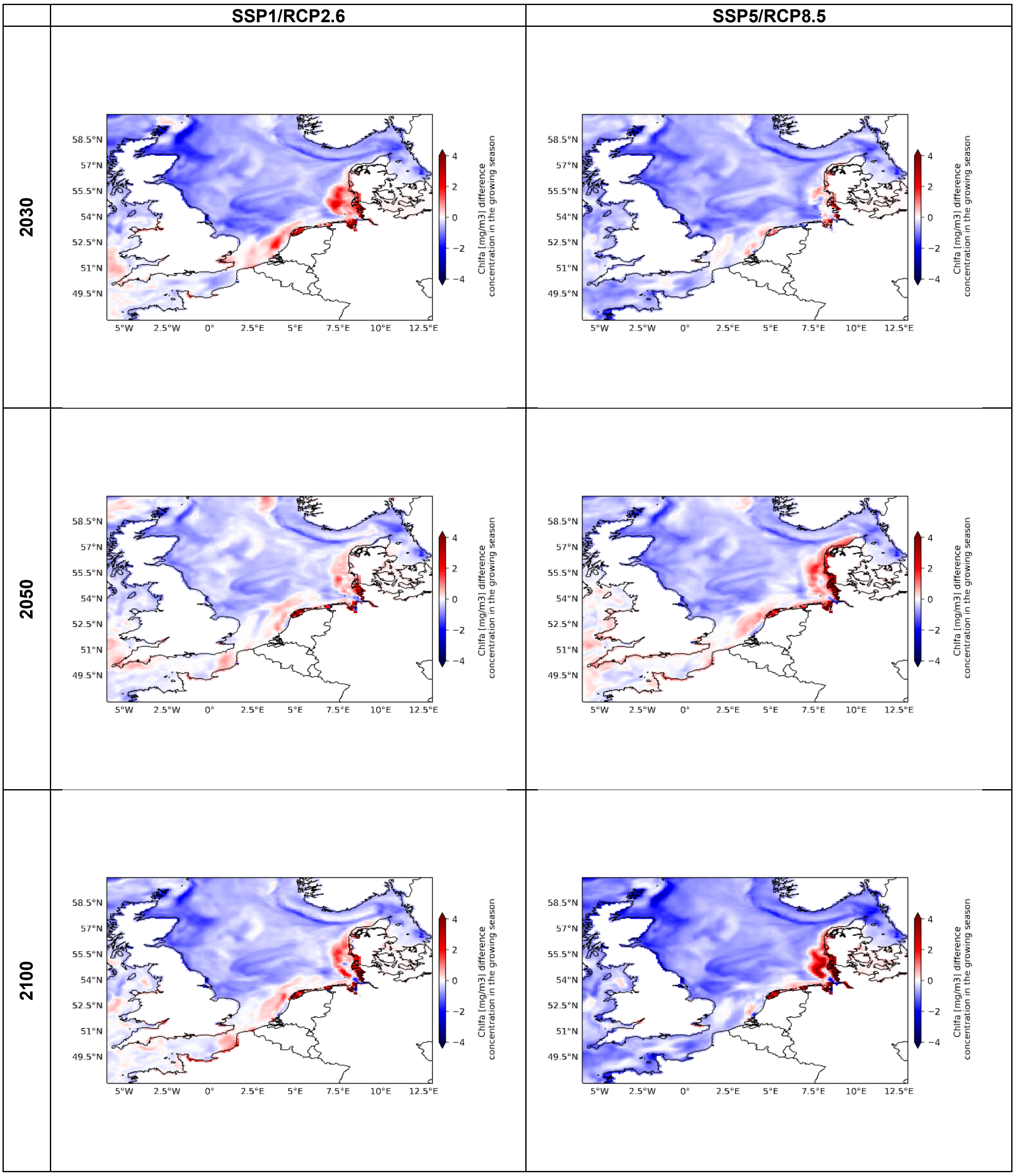


Figure 26: Simulated differences in growing season mean near-surface chlorophyll-a concentrations between future scenarios without aquaculture and the historical scenario (HIST_2010).

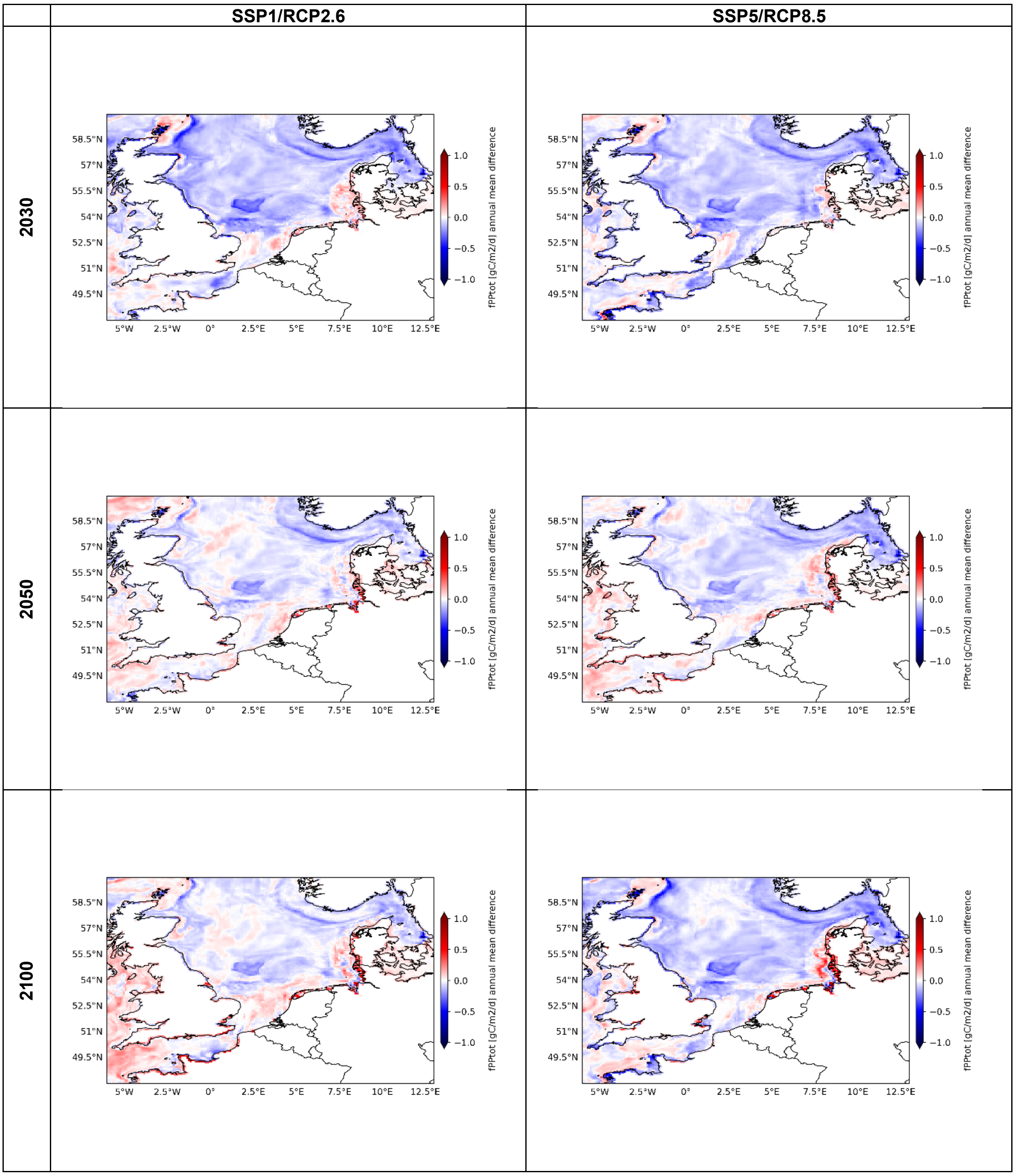


Figure 27: Simulated differences in growing season mean primary production between future scenarios without aquaculture and the historical scenario (HIST_2010).

Seaweed and mussel production capacity under climate change

According to the model results, seaweed cultivation yields close to the 1 kgDW/m^2 target can be achieved in all considered offshore wind farm areas in the historical state (yields of 833-940 gDW/m2 reached, see Table 4). Predicted yields decrease in future scenarios due to the decrease in offshore winter nutrients, except for the 2050 SSP5/RCP8.5 scenario for which nutrient concentrations increase further off the coast, in areas where Dutch OWFs suitable for aquaculture are located. Results from 2100 runs predict a slight increase in seaweed production yields for SSP126, the most sustainable scenario (2-10% compared to HIST). In this scenario, near-surface winter nutrients are higher along the Dutch coast than in the historical state. In the SSP585 scenario, temperatures simulated in 2100 are significantly higher and offshore nutrients in the Dutch EEZ are lower. As a consequence, simulated seaweed yields are 2-16% lower than in the historical state, with the largest differences occurring in the Borssele areas.

Results also show that production yields of seaweed are generally not significantly altered by the nearby cultivation of mussels at a similar scale. Yields are slightly increased when co-cultivated with mussels in the Hollandse-Kust Zuid offshore wind farm areas. This is most likely due to an accelerated nutrient re-mineralization due to the presence of mussels.

Table 10: Achieved yield of seaweed production (g/m^2 of dry weight)

OWF area	Seaweed cultivation only							Seaweed + mussel cultivation						
	HIST_2010	SSP126_2030	SSP126_2050	SSP126_2100	SSP585_2030	SSP585_2050	SSP585_2100	HIST_2010	SSP126_2030	SSP126_2050	SSP126_2100	SSP585_2030	SSP585_2050	SSP585_2100
Borssele I	920	828	859	938	871	973	793	912	828	853	934	872	972	793
Borssele III	919	841	872	937	883	981	783	915	842	866	935	884	981	783
Borssele IV	938	847	879	941	887	1002	808	935	848	876	938	888	990	807
HKZ I	860	738	747	922	807	888	882	882	753	760	937	827	909	897
HKZ II	871	743	757	929	806	892	883	887	755	766	937	824	909	895
HKZ IV	837	724	736	903	794	871	875	855	736	746	917	810	886	888
HKN tender 2019	853	752	746	942	804	890	919	860	757	747	949	815	897	917
HKWN	833	802	766	899	809	887	866	846	809	764	908	813	885	866
HKWZ	842	809	783	909	822	905	869	854	813	779	912	824	902	869
IJmuiden Ver tender 2021	940	840	860	960	904	1011	898	939	838	859	958	903	1007	897

Results from mussel cultivation scenarios show that, for a same seeding density, final cultivation yields are much more variable from one farm to another than seaweed yields (Table 5). Highest yields are achieved in the Hollandse Kust Zuid areas, where yields >1 kg/m^2 are reached (and up to 5 kg/m^2 in HKZ IV). These farms are the most near-shore and are located in the Rhine region of freshwater influence, receiving high nutrient loads and exerting higher primary production than at the other farm locations. The model outputs also show that the final cultivation yield is sensitive to the cultivation density. Indeed, in neighboring farms, with similar physical and biogeochemical conditions, final yields are significantly higher, where the ratio of farmed area per total OWF area is smallest, meaning that mussel density introduced in the model is the lowest. For example, in Borssele I, where only 4.9% of the wind farm area is covered with mussel cultivation, final cultivation yield is 25% higher than in Borssele III, where mussel cultivation covers 16.5% of the area. The highest yields are achieved for future scenarios SSP1/RCP2.6 in 2100 and SSP5/RCP8.5 in 2050. These two future scenarios show similar spatial patterns in increases in chlorophyll-a concentrations in near-shore areas and a bit further off the coast (including areas where farms are located in the model).

Combination of large-scale mussel farming with large-scale seaweed farming does not significantly alter mussel production yields.

Table 11: Achieved yield of mussel production (g/m^2 of dry weight)

OWF area	Mussel cultivation only							Seaweed + mussel cultivation						
	HIST_2010	SSP126_2030	SSP126_2050	SSP126_2100	SSP585_2030	SSP585_2050	SSP585_2100	HIST_2010	SSP126_2030	SSP126_2050	SSP126_2100	SSP585_2030	SSP585_2050	SSP585_2100
Borssele I	632	850	613	758	505	835	429	623	817	595	712	499	800	412
Borssele III	504	641	474	555	397	614	328	492	619	462	533	390	587	315

Borssele IV	556	713	514	623	428	692	346	539	681	497	590	419	653	329
HKZ I	1206	1317	1354	1222	1322	1465	1172	1156	1253	1310	1144	1266	1393	1123
HKZ II	1873	2264	2086	1772	2091	2155	1626	1821	2213	2037	1727	2043	2105	1574
HKZ IV	5679	4852	5487	4645	5338	5176	4590	5551	4701	5380	4539	5196	5059	4474
HKWN	405	703	422	513	359	571	386	376	637	385	431	337	529	335
HKWZ	427	736	435	576	388	639	425	407	692	408	510	371	605	390
IJmuiden Ver N	314	286	304	348	228	362	224	305	268	294	316	228	343	198
Nederwiek Z	579	206	352	403	236	348	233	579	206	352	403	237	349	234

Effects of large-scale seaweed and mussel production on environmental variables

Here we plot and analyse the differences in simulated winter DIN and DIP and growing season chlorophyll-a with and without aquaculture for the historical run and scenarios SSP1/RCP2.6 and SSP5/RCP8.5 for the year 2050. The year 2050 that was chosen, runs with seaweed are available for that year and mussel cultivation show clearly different patterns between the 2 future scenarios (with more suitable conditions for the least sustainable scenario due to increased chlorophyll-*a* concentrations further offshore along the Dutch coast).

Model results shows that seaweed cultivation over 145 km^2 within OWFs lead to clear decreases in winter nutrient concentrations not only in the vicinity of the wind farms but also far downstream (Figure 16). This is consistent with results from the ProSeaweed project (Vilmin and Van Duren, 2021). Decreases in nutrient concentrations seem sharper in the future. This could be made possible by higher nutrient concentrations along the coastline, meaning that the seaweed can store more nutrients over the winter. The nutrient uptake from the seaweed leads to a decrease in phytoplankton biomass during the growing season that is visible in the vicinity of the farms but also downstream along the German and Danish coasts.

According to the model, mussel cultivation leads to a sharp decrease in chlorophyll-*a* in the vicinity of the farms (Figure 17). Unlike seaweed farming the effect on chlorophyll-a is visible less far downstream, since it is not due to the reduction of nutrients in flowing water, but the grazing by mussels directly in the farms. Mussel farming also leads to an increase of DIN and DIP concentrations along the Dutch coast, probably due to increased re-mineralization of nutrients. This is less visible in future scenarios.

The combination of large-scale seaweed and mussel aquaculture leads to sharp decreases in chlorophyll-a in the growing season, due to the direct grazing from mussels and reduction in nutrients (uptaken by seaweed over the winter) (Figure 18). The decrease in chlorophyll-a is still visible downstream along the German coast, probably due to the reduction of available DIN and DIP, consumed further upstream by the seaweed. In the farms further offshore winter DIN and DIP indeed decrease due to consumption by the seaweed, while near the coast nutrients increase. These spatial patterns in DIN and DIP effects are sharper in the future scenarios.

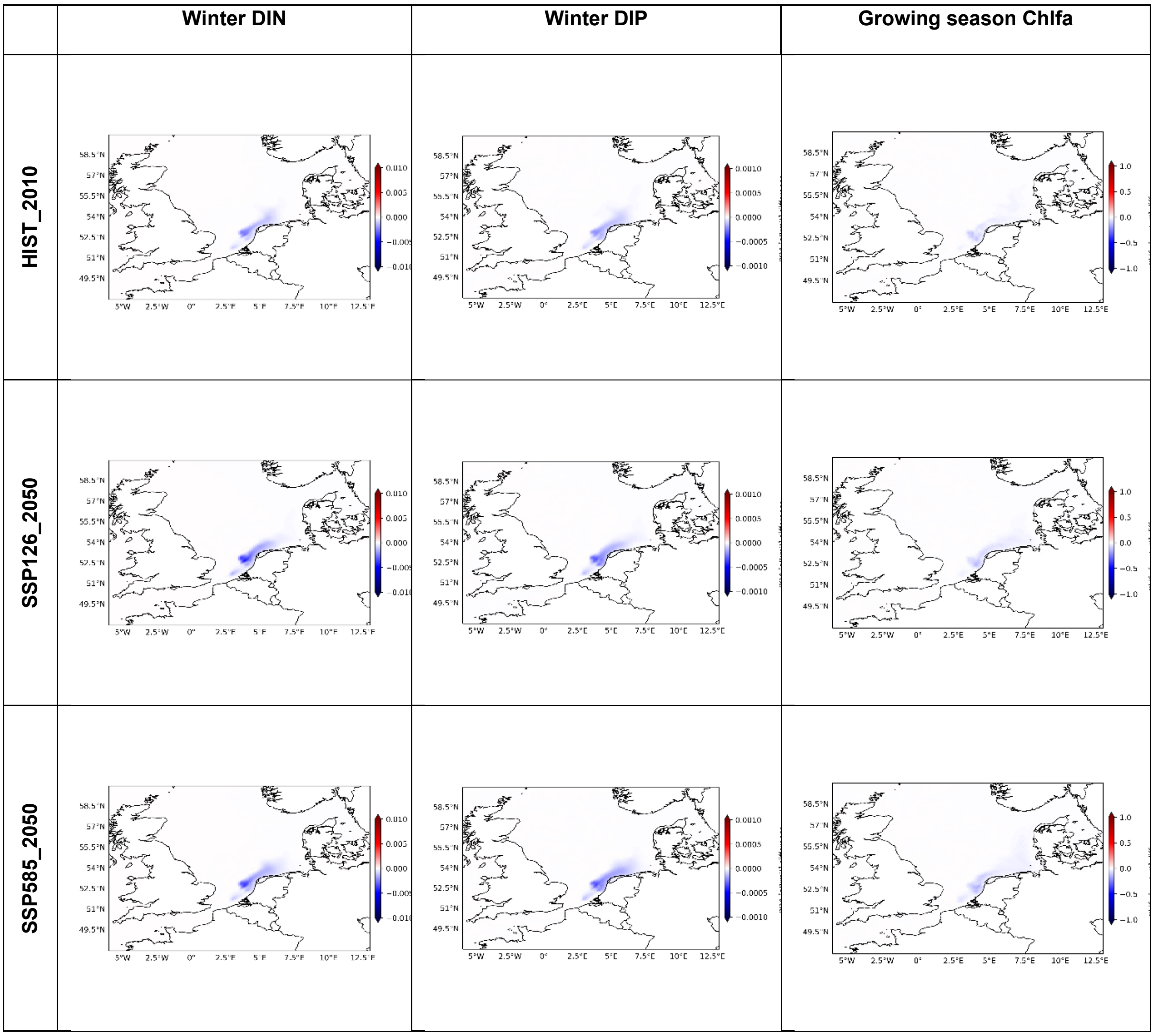


Figure 28: Difference between simulated winter DIN and DIP concentrations and growing season chlorophyll-a concentrations for scenarios HIST_2010, SSP126_2050 and SSP585_2050 with and without seaweed cultivation.

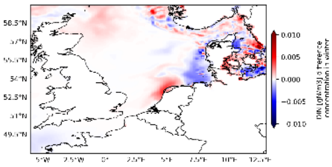
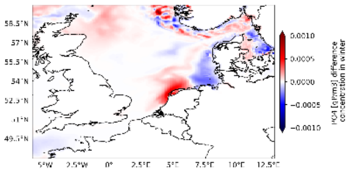
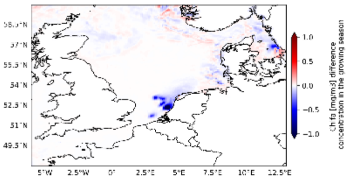
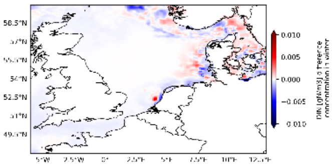
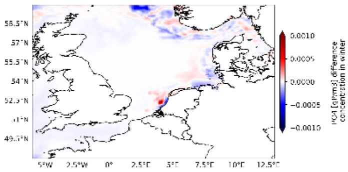
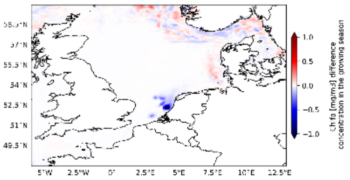
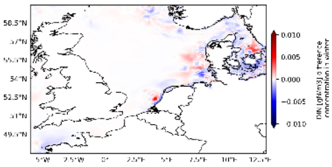
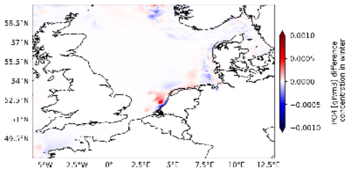
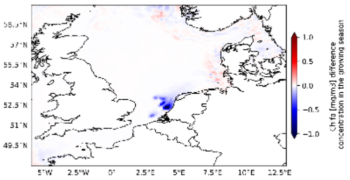
	Winter DIN	**Winter DIP**	**Growing season Chlfa**
HIST_2010			
SSP126_2050			
SSP585_2050			

Figure 29: Difference between simulated winter DIN and DIP concentrations and growing season chlorophyll-a concentrations for scenarios HIST_2010, SSP126_2050 and SSP585_2050 with and without mussel cultivation.

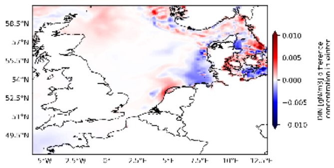
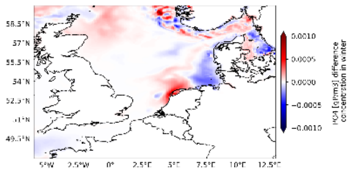
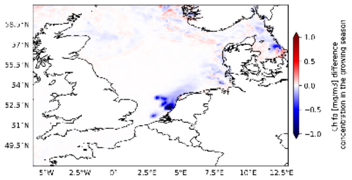
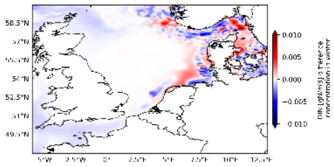
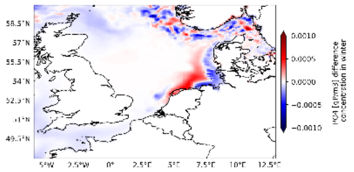
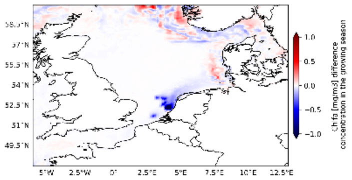
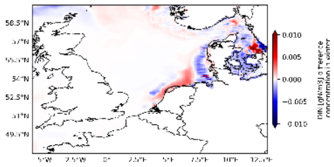
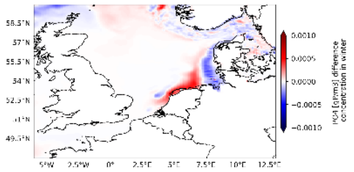
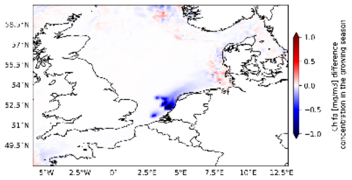
	Winter DIN	**Winter DIP**	**Growing season Chlfa**
HIST_2010			
SSP126_2050			
SSP585_2050			

Figure 30: Difference between simulated winter DIN and DIP concentrations and growing season chlorophyll-a concentrations for scenarios HIST_2010, SSP126_2050 and SSP585_2050 with and without a combination of seaweed and mussel cultivation.

3.2. FlexSem model for the Limfjord, SW Baltic Sea. Impacts of climate change on benthic mussels and suspended mussel culture

Changes in environmental variables

Physical variables showed the strongest responses to future conditions in the SSP5-8.5 scenario for the second time-slice (2090-2099) in agreement with forcing data (Figure 19A-C). The SSP1-2.6 and SSP2-4.5 scenarios showed in general similar and lower responses than SSP5-8.5 for the two time-slices. Sea surface salinity decreased by 0.5 to 2.2 g kg^{-1} corresponding to 2-8% change (Figure 19A), whereas sea surface summer temperature increased gradually over time and across scenarios with 1 to 5°C (5-27%) (Figure 19B). Salinity decreased slightly more in the inner parts of the estuary (Figure 20A) due to increased run-off, whereas the temperature increase was more homogenously distributed (Figure 20B). Water column stratification (PEA) did not change much in the first time-slice but increased in the second time-slice mostly in SSP5-8.5 (Figure 19C). Highest changes of PEA were found in the inner basins towards Skive and in the eastern Channel towards the Kattegat (Figure 20C).

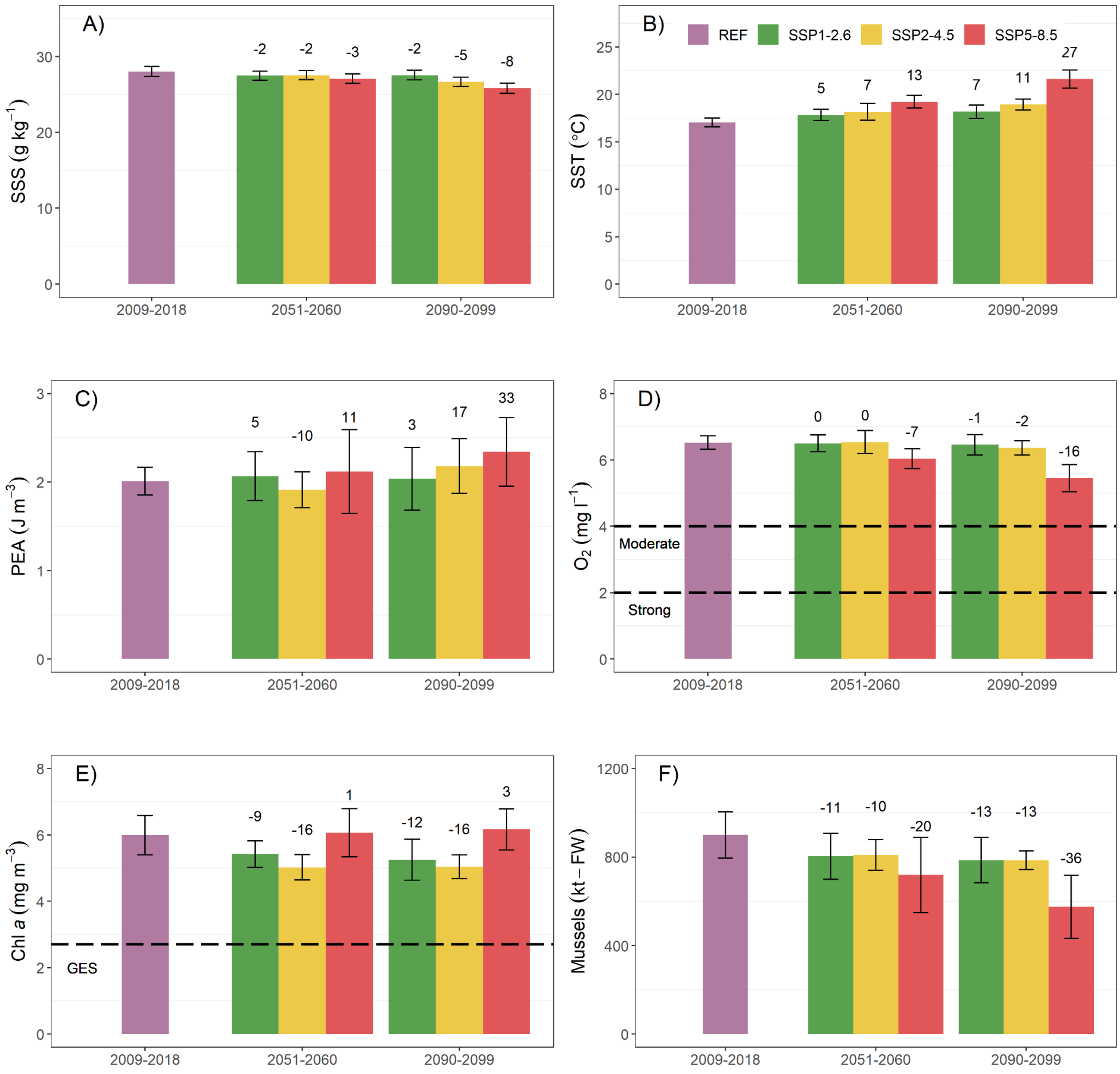


Figure 31: Summer (June to September) means (±SD) of A) sea surface salinity (SSS), B) sea surface temperature (SST), C) stratification index (PEA), D) bottom oxygen, E) surface Chl a concentration, and F) benthic mussel biomass for the reference period (2009-2018) and the three scenarios for the two time-slices 2051-2060 and 2090-2099. The values above the columns are the percentage deviations from the reference period. The horizontal dashed lines indicate the thresholds for D) moderate and strong hypoxia, and E) a good ecological status (GES).

Bottom oxygen conditions became worse over time in the SSP5-8.5 scenario with no changes in the other scenarios on average for the Limfjord (Figure 19D). The oxygen levels were on monthly average not below the critical thresholds for moderate and strong hypoxia due to the episodic mixing events on the scale of hours and days, but hypoxia did occur on many occasions. Oxygen concentrations increased slightly in the inner parts of the estuary in SSP1-2.6 and SSP2-4.5 (Figure 21A-B), whereas oxygen decreased all over the Limfjord in SSP5-8.5 (Figure 21C). Chl a concentrations decreased up to 16% in the scenarios SSP1-2.6 and SSP2-4.5 in contrast to SSP5-8.5 showing a small increase (Figure 19E). The average Chl a concentrations were never below the threshold for a good ecological status of the Limfjord. Spatially, Chl a concentrations decreased mostly in the Skive and Sallingsund areas in SSP1-2.6 and SSP2-4.5 (Figure 21D-E), whereas the pattern was more complex for SSP5-8.5 with some local increases e.g., in Nibe (Figure 21F). Benthic mussel biomass decreased in all scenarios, most severely in SSP5-8.5, (Figure 19F) and in all areas of the Limfjord (Figure 21G-I).

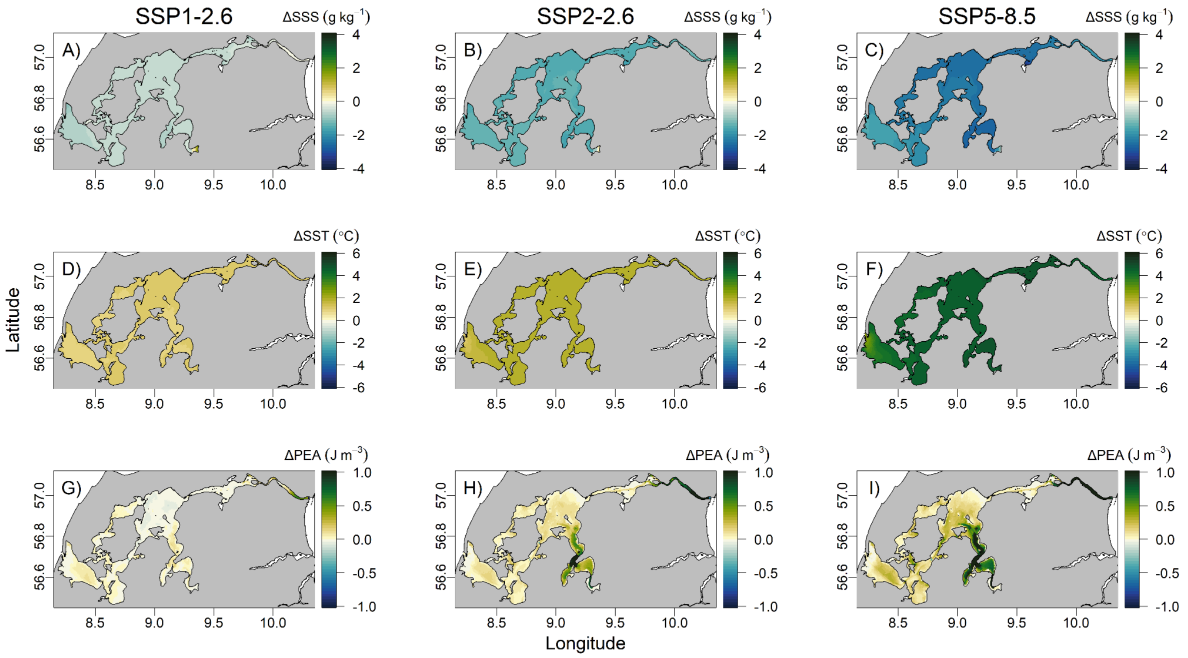


Figure 32: Spatial plots showing the difference of physical variables between the three scenarios (years 2090-2099) and the reference (years 2009-2018) for the summer period. A-C) surface salinity, D-F) surface temperature, and G-I) stratification index for the scenarios

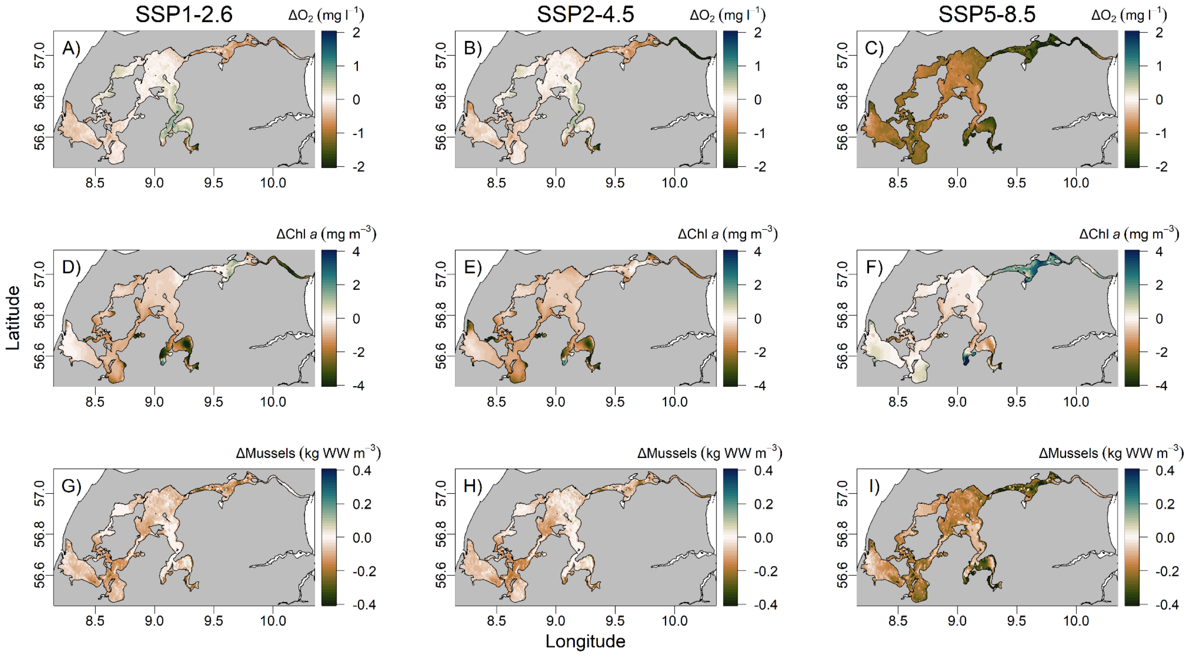


Figure 33: Spatial plots showing the difference of ecosystem variables between the three scenarios (years 2090-2099) and the reference (years 2009-2018) for the summer period bottom. A-C) oxygen, D-F) surface Chl a concentrations, and G-I) benthic mussel biomass for the scenarios

Suspended mussel culture

Suspended mussel culture harvest potential increased in all scenarios and time-slices compared to the reference, although slightly higher in SSP5-8.5, due to the higher number of mussel farms (Figure 22A). Mussel shell length at harvest time decreased less than 4% in all scenarios and time-slices, mostly in SSP1-2.6 and SSP2-4.5 scenarios (Figure 22B).

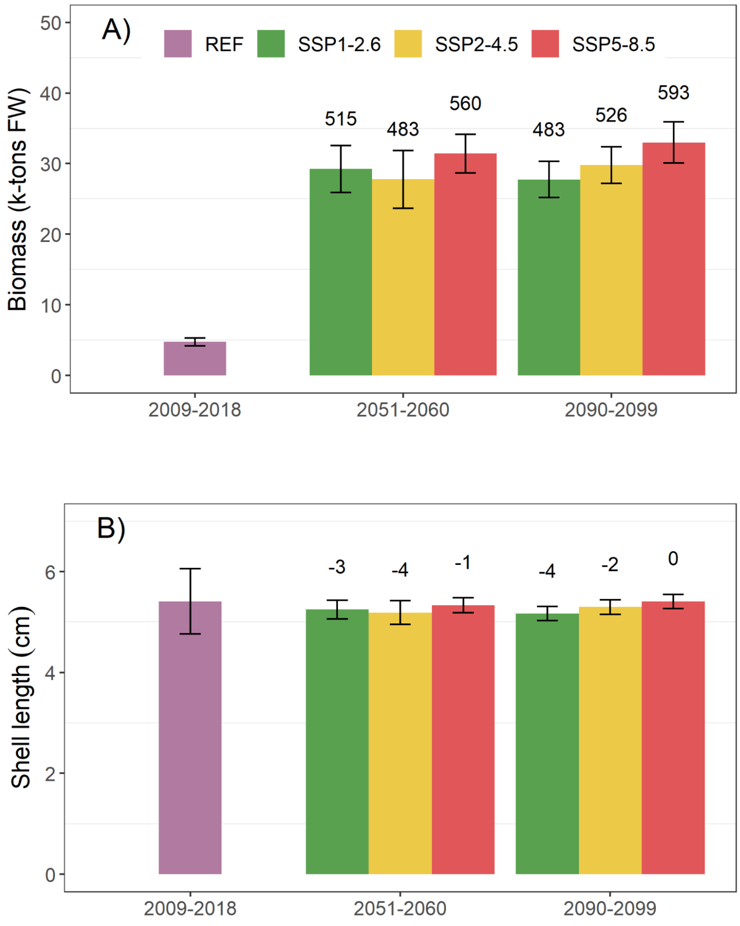


Figure 34: Annual means (±SD) of A) mussel harvest from suspended farms and B) mussel shell length in the scenarios indicated with percentage changes from the reference period 2009-2018. The values above the columns are the percentage deviations from the reference period.

4. Results on sustainable fishing under CC

4.1. Scenarios with changing fishing mortality

Fishing at MSY under climate change: Bay of Biscay (EwE)

Under the scenarios of climate change (Scn. 2, 3 and 4) the model predicted different responses of the functional groups. The model showed a significant biomass increase for anchovy due to a reduction of predators and competitors and more favorable thermal conditions. Blue whiting and megrim also increased mainly due to the decrease of its predators (e.g., horse mackerel and anglerfish, respectively). In contrast, anglerfish, hake, and sardine, decreased in all three scenarios mainly due to unfavorable thermal conditions. In fact, sardine was predicted to be almost depleted in the more pessimistic scenario.

Under the scenario of fishing at F_{MSY} and at F_{MSY}-20% (Scn. 5 and 6) pelagic and demersal species presented different responses. In the pelagic compartment, sardine and anchovy biomasses increased due to the reduction of predators (e.g., albacore) and in the case of sardine, also due to a reduction in its fishing pressure. Regarding demersal species, the model predicted various responses. For example, anglerfish biomass increased due to a reduction in the fishing pressure, and hake biomass increased due to a larger prey availability. On the other hand, the model predicted declines in the biomass of blue whiting and megrim, mainly due to the increase of predators (e.g., anglerfish and hake). Under the scenario of fishing at F_{MSY}+20% (Scn. 7) pelagic species showed similar trends as in the two previous scenarios due to less predation (e.g., albacore). In the demersal compartment, anglerfish and sea bass increased by having a greater availability of prey (e.g., anchovy) and less predation by hake. In contrast, megrim decreased due to the higher fishing mortality.

Under the cumulative scenario which assessed the combined effect of an intermediate climate change scenario in addition to fishing at F_{MSY} (Scn. 8) the model projected decreases in almost all pelagic groups. For example, biomass of albacore and sardine were predicted to decrease (Figure 35b,c). This is due to intense fishing pressure (e.g., albacore) and unfavourable thermal conditions. On the other hand, bluefin tuna and anchovy increased (Figure 35a,d), both benefiting from the decline of a competitor and predator, respectively (i.e., albacore). Regarding demersal species, the biomass of blue whiting and megrim decreased (Figure 35f,h) mainly due to the increase of predator biomass. On the contrary, anglerfish, hake (Figure 35g) and common sole increased. Under the intermediate climate change scenario plus a reduction of 20% in the F_{MSY} (Scn. 9) similar trends as in the previous scenario were observed. However, some trends were exacerbated (e.g., the biomass increase of bluefin tuna, hake and anglerfish was higher and the decline of seabass was higher) while others were reduced (e.g., the decline of albacore was lower, and the increase of anchovy was lower). For the cumulative scenarios where climate change followed the most pessimistic projections together with fishing mortality at F_{MSY} and 20% below F_{MSY} (Scn. 10 and 11) similar trends as in Scn. 8 and 9 were observed. For example, biomass of albacore (Figure 35b), mackerel, horse mackerel and sardine (Figure 35c) were predicted to decrease while biomass of bluefin tuna, anchovy and anglerfish were predicted to increase (Figure 35a,d,e). However, several trends were exacerbated. For example, horse mackerel is predicted to collapse in both scenarios and sardine is predicted to nearly collapse while the biomass of anchovy is predicted to increase (Figure 35c,d). Hake biomass was predicted to decline in the F_{MSY} scenario (Scn. 10), while it increased in the F_{MSY}-20% scenario (Scn. 11). This caused a biomass increase for blue whiting and megrim in the two scenarios (Figure 35f,h).

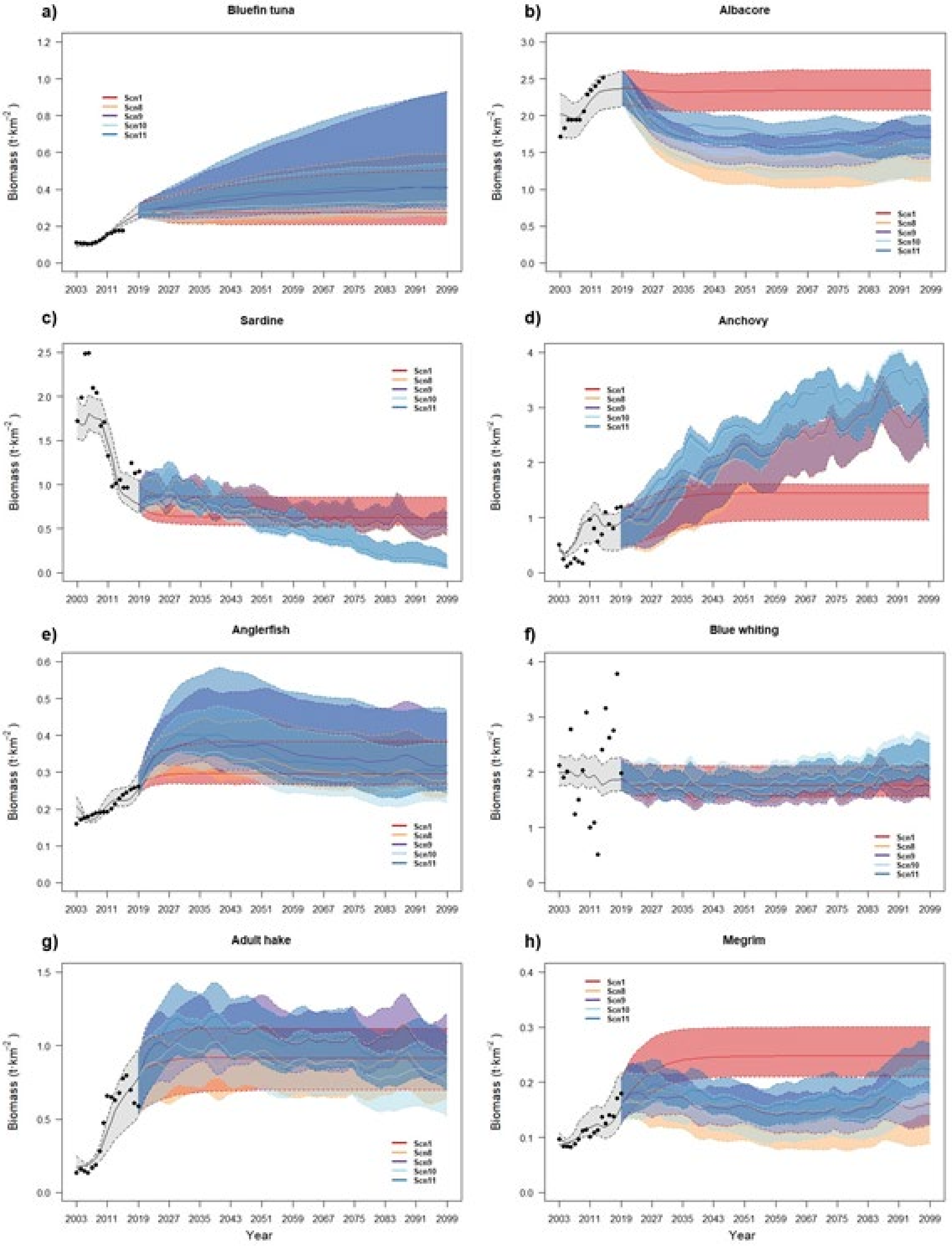


Figure 35: Comparison between the predicted (solid lines) and observed (dots) time series of biomass (t·km-2), and projections for (a) bluefin tuna, (b) albacore, (c) sardine, (d) anchovy, (e) anglerfish (f) blue whiting, (g) adult hake, and (h) megrim under different scenarios of combined stress by climate change and fishing for the Bay of Biscay (BoB) ecosystem model in the period 2003–2099. Black line represents historical model predictions and coloured lines represent different scenarios. Shadows represent the 5% and 95% percentiles obtained using the Monte Carlo routine.

Projections of climate change showed important effects of environmental drivers. Specifically, the scenarios showed many detrimental effects of ocean warming, with impacts becoming greater as temperature increased. Results suggested that changes in pelagic species or functional groups were greater than in the demersal ones. This is mainly because temperature has greater variations in the surface than in the bottom (Borja *et al.*, 2019). For example, sardine was predicted to almost collapse in the worst scenario. Several analyses have already indicated an important role of temperature in the dynamics of sardine in Atlantic-Iberian waters (Garrido *et al.*, 2017; Szalaj *et al.*, 2021). On the contrary, anchovy biomass would benefit from reduced competition for prey and more favourable thermal conditions. In addition, important changes in the demersal domain were also predicted due to unfavourable thermal conditions, with a decrease in the biomass of major predators such as anglerfish and hake.

The Bay of Biscay is part of the subtropical/boreal transition subprovince of the biogeographic Lusitanian province (OSPAR, 2000). Therefore, the fauna in the area is a mix of species with boreal and subtropical origin and where many species reach the southern or northern limit of their distribution in the Bay of Biscay. Therefore, this ecosystem is highly sensitive to environmental variations (mainly temperature). In fact, several analyses have indicated that ocean warming is affecting demersal and pelagic fish communities by the expansion of warm affinity species and the decline of cold affinity species, leading to a tropicalization and meridionalization of the area (Poulard and Blanchard, 2005; Baudron et al. 2020; Punzón et al. 2020, Chust et al. 2022). These fish distribution shifts may have implications for EU fisheries management as TAC allocations were devised in 1970 (Baudron et al. 2020). For example, TAC of hake in the North Sea represents only 3% in the northern stock, as landings in 1970s were almost negligible while actually the 34% of the entire stock is allocated in the region, which led to a large rate of discards (Baudron et al. 2020). In addition, these distribution shifts are expected to be amplified within the global change context and may include the arrival of southern non-indigenous species (NIS) in the Bay of Biscay (Le Marchand et al. 2020, Schickele et al. 2021) which could cause important effects on the structure and functioning of the ecosystem (Le Marchand et al. 2022).

In contrast, when fishing pressure was reduced, results highlighted a potential restoration of several exploited species. However, results indicated possible “winners” and “losers” and showed that there are species with different responses (in magnitude and direction) in the different scenarios of fishing reduction. Fishing at F_{MSY}-20% (Scn. 6) suggested larger recoveries of bluefin tuna, small pelagic fishes, anglerfish, and hake, while fishing at F_{MSY}+20% showed smaller recoveries of some predators (e.g., anglerfish, hake) or even declines (e.g., bluefin tuna), which allowed to increase some of their prey (e.g., medium pelagic fishes and sea bass). However, albacore was predicted to decline in all scenarios of fishing due to the application of a higher fishing pressure (although F_{MSY}), leading to less predation pressure in all scenarios as albacore is an important migratory predator in the Bay of Biscay (Nikolic *et al.*, 2017; Chust *et al.*, 2019). Therefore, results highlighted the benefits of fishing reductions, as indicated in other analyses (e.g., Froese et al. 2018, Travers-Trolet et al. 2020), and may confirm the potential of management measures promoted by ICES and ICCAT to effectively rebuild stocks without considering the impact of climate change.

Fishing at MSY under climate change: Bay of Biscay (SS-DBEM)

Tuna fishing is of high relevance for Basque Country not only because of the artisanal and industrial fleets, but all the global supply chain characteristics of the Basque industry and science. This worldwide relevance can be summarized in: 50 tuna purse seiner vessels, 25 inshore vessels, world-renowned canning sector, 10% of the world’s tropical tuna catches, over 6,000 direct and indirect jobs, presence in global management bodies, large capital goods technology companies, shipbuilders who are specialized in constructing tuna freezer ships, 95% of the design, engineering and construction of the tuna vessels are made in Basque Country. Therefore, in this work we look at projections at the scale of the Bay of Biscay (BoB) and worldwide. The SS-DBEM (Fernandes et al. 2013, Fernandes et al. 2020) was used in this study to estimate the combined impact of climate change and fishing pressure on the main 7 commercial tuna species and swordfish due to their high commercial value and landings volume. The selected target species are albacore (*Thunnus alalunga*), Atlantic (*Thunnus thynnus*), Pacific (*Thunnus orientalis*) and Southern (*Thunnus maccoyii*) bluefin tunas, yellowfin (*Thunnus albacares*), bigeye (*Thunnus obesus*), skipjack (*Katsuwonus pelamis*) and swordfish (*Xiphias gladius*). We consider the trophic interactions of tunas with 11 species of non-commercial top predators (e.g. other billfish species…) for model improvement purposes as direct competitors for prey resources. Tuna Basque fleets operating in the BoB target mainly albacore and bluefin tuna with pole and line gears with trips of a few days up to a week (Granado et al. 2021).

Figure 36 shows the projected trends in the biomass of albacore and bluefin tuna in the BoB. In general, both species are predicted to maintain their current biomass or decline by up to 15-20% by the middle or end of the century. The only positive trends are projected for albacore using the biogeochemical model Medusa under high emissions scenarios. However, these results are not consistent with those obtained by using the IPSL biogeochemical model under the same scenarios. Under Global Sustainability, albacore would have a 5-10% reduction in biomass while bluefin tuna would be closer to no change or a reduction of around 5%. However, other scenarios projected biomass decreases in the range of 10 to 20% for both species.

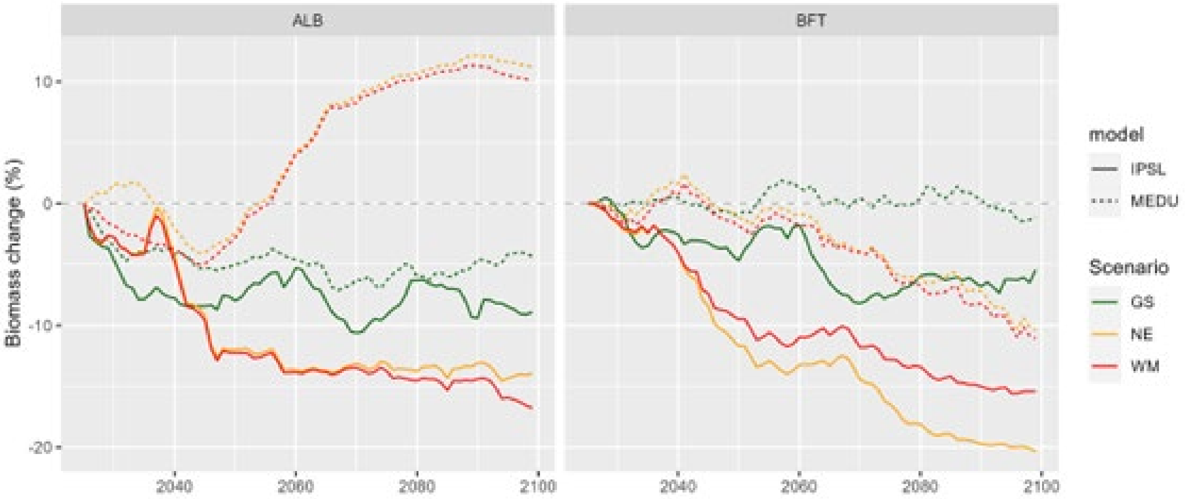


Figure 36: Relative change of biomass for the two main species fished in the Bay of Biscay by Basque fleets (ALB, albacore; and BFT, bluefin tuna). IPSL and MEDUsa are two different biogeochemical models. Colours represent the three FutureMARES scenarios: GS, Global Sustainability; NE, National Enterprise; and, WM, World Markets.

Looking at ICES subareas, coastal areas (Figure 37, areas ab and c) appear moderately impacted by climate change with biomass changes around 5% across scenarios (excluding outliers). However, these are small areas that do not concentrate most of the catches. The more offshore areas show the same general patterns as at the regional scale (Figure 36 with all the areas aggregated).

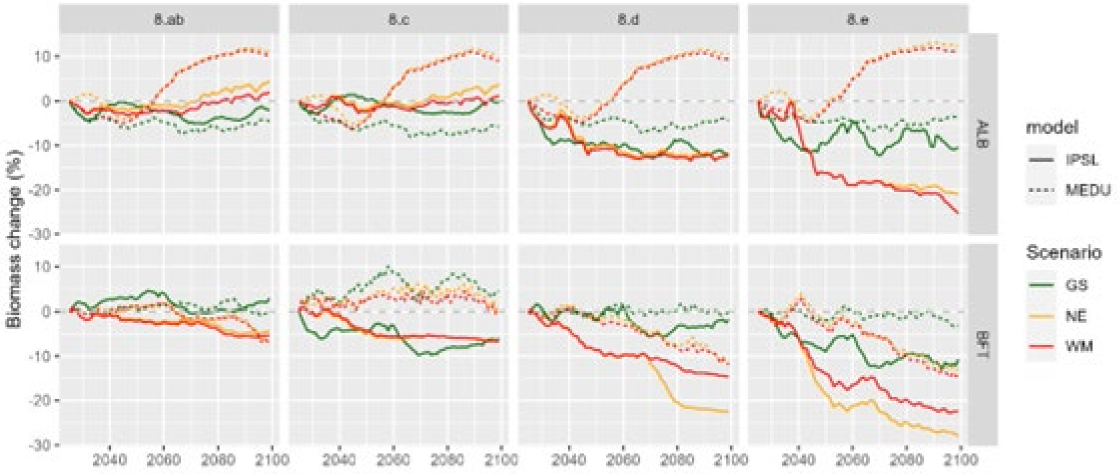


Figure 37: Relative change of biomass for the two main species fished in the ICES subareas of the Bay of Biscay (ICES area 8) by Basque fleets (ALB, albacore; and BFT, bluefin tuna). IPSL and MEDUsa are two different biogeochemical models that force the SS-DBEM model. Colours represent the three FutureMARES scenarios: GS, Global Sustainability; NE, National Enterprise; and, WM, World Markets.

Despite these direct impacts, the Basque tuna fishing and associated industry depends on global trends summarized in Figure 38 (Fig. 5 in Erauskin-Extramiana et al. 2023). The results suggest that high trophic level species will be more impacted by climate change than by fishing pressure under the assumption that they remain nearby their MSY levels. The overall productivity of the target species will decrease by 36%. Five species; Atlantic and Southern bluefins, swordfish, bigeye and albacore are estimated to decrease in biomass and size at different rates. These species represent almost a third of the landings in the Atlantic Ocean, with bluefin tuna being the most valuable species. On average, the body size is expected to decrease by 15% by 2050. Fish price and demand are partially driven by body size and, therefore, revenues can be reduced even in stocks with an increase in productivity. The fishing industry can adapt to the changing climate by increasing the value of fish through sustainability certifications and reducing fuel consumption and time at sea with higher digitalization. Reducing fuel consumption would also be an additional mitigation measure to climate change since it would reduce CO2 emissions.

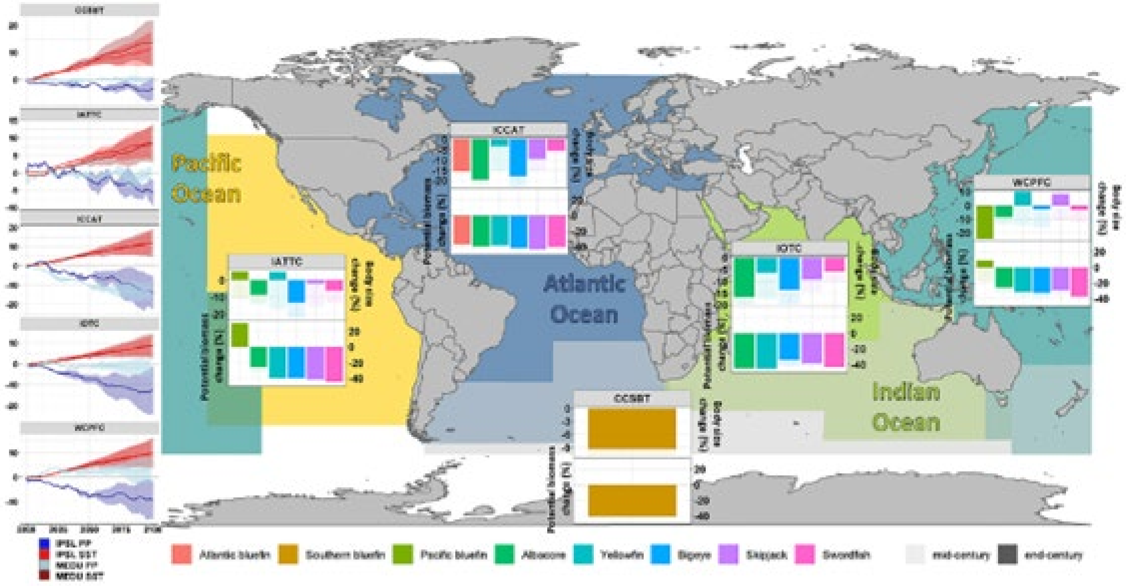


Figure 38: Averaged body size ratio (the biomass divided by the abundance, upper box) and biomass (lower box) change (y-axis) in percentage (%) related to the reference period (2000-2010) in bars (x-axis) across scenarios for each RFMO in the world map for main commercial tuna species and swordfish. RFMOs are ICCAT in the Atlantic, IATTC and WCPFC in the Pacific, IOTC in the Indian Ocean and CCSBT across three oceans but mainly placed in the Indian. The left column plots represent the rate of change (in %) of the temperature (in red) and primary production (in blue) for the two biogeochemical models by RFMO.

Our results are aligned with other studies which projected a decrease in the biomass and catch potential of high trophic level species under climate change (Cheung et al. 2009, Fu et al. 2019, Lotze et al. 2019, Petrik et al. 2020, Sumaila et al. 2011). Other studies also projected a high decrease of the large pelagic functional group (13.9% ±0.7% for TL>4) although this group is related with the highest degree of projection uncertainty (Petrik et al. 2020). Projected biomasses are also higher with lower fishing pressure in all of the species which may help increasing species resilience to climate change (Cheung et al. 2017, Fernandes et al. 2016; Travers et al. 2010). In this study, an average decrease in main commercial tuna species size of 15% has been projected by 2050, which is supported by other studies where the reduction in body size or change in the size-length frequency driven by fishing and climate change has also been reported (Baudron et al. 2014, Bianchi et al. 2000; Dulvy et al. 2004, Erauskin-Extramiana et al. 2017, Genner et al. 2010, Queirós et al. 2018, Sáenz-Arroyo et al. 2005). Physiological and evolutionary mechanisms could produce these life-history patterns of decrease in body size, increase in the proportion of small-sized species, young age classes and earlier maturation (Audzijonyte et al. 2016, Daufresne et al. 2009, Lindmark et al. 2022).

Fishing at MSY under climate change with evolution: North Sea (Ev-Osmose)

The bioenergetic and evolutionary model Ev-OSMOSE was run in the North Sea. In the scenarios with current climate conditions and without evolution, the relationship between yield and the fishing mortality F is dome-shaped (Figure 39, blue curve). For the scenario with evolution (green curve), the shape is a plateau in the historical period reaching yields that are slightly higher than without evolution. Under climate change, we obtain a similar pattern with the yield to F curve being dome-shaped without evolution and reaching a plateau with evolution, but with much lower yield values than without climate change.

With or without climate change, the F_{msy} is higher with a higher associated yield with evolution (Figure 39). Without evolution, the yield and the F_{msy} decrease with climate change. The $F_{collapse}$ is 0.97 year^{-1} in the historical period and 0.83 year^{-1} under climate change, whereas the $F_{collapse}$ is above 1.4 year^{-1} in scenarios with evolution.

In scenarios without evolution, the variability between replicates is low compared to scenarios with evolution (Figure 39). In scenarios with evolution, we even observe F values where the yield can collapse in some replicates or be maintained in others. The yield collapses more frequently with climate change. We hypothesize that the evolutionary responses of life history traits can increase the probability of regime shifts.

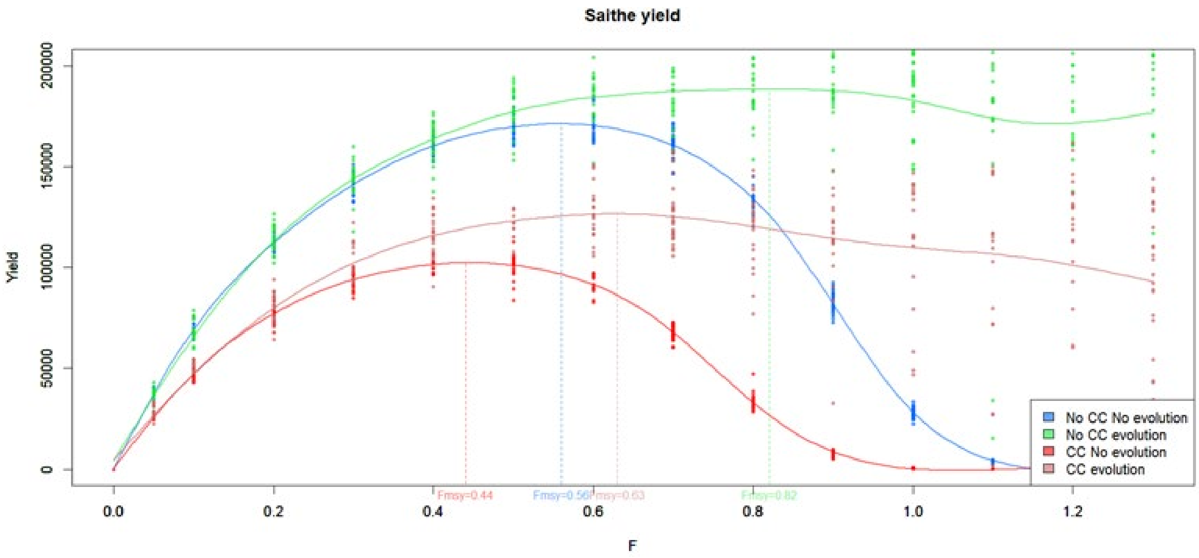


Figure 39: Change of the yield with fishing mortality rate for saithe under historical conditions without evolution (blue curve) and with evolution (green curve), and under climate change RCP8.5 scenario without (red curve) and with evolution (pink curve). Each dot per F value is the simulated yield of one run of Ev-OSMOSE. There are 28 replicated runs per F value. The line is adjusted with a loess function. The dashed lines indicate FMSY values for the four scenarios.

Our study reveals the change of F_{msy} and of the maximum sustainable yield for saithe accounting for evolution and climate change. A previous study has shown the risk associated with the decrease of MSY under climate change (Travers-Trolet et al. 2020). Our study takes a step forward by investigating the importance of evolutionary processes in correctly estimating fishery reference points.

The main difference between scenarios with and without evolution is the value of $F_{collapse}$. The collapse of the yield is rapidly reached without evolution whereas it is not observed in the range of F tested. This highlights the potential higher resistance of the saithe population to high exploitation rates. Future simulations will include higher F values to estimate $F_{collapse}$ in scenarios with evolution.

In addition, the higher F_{msy} values obtained with evolution suggest that evolution might dampen both fishing and climate change impacts on saithe, providing higher resistance of the population to high exploitation rates and a higher productivity through the evolution of life history traits. However, as fish life history traits evolve, fishing strategies would likely change as well, with for example different size selectivities. The absence of such co-evolution could explain why the yield levels off with evolution, and do not decrease much with $F>F_{msy}$.

As described for most species in Travers-Trolet et al. (2020), especially cold-water species such as saithe, we observe a decrease in both F_{msy} and yield under climate change. A next step would be to complete our result with all other species in the model, especially warm-water species. Furthermore, saithe is a species with an accelerated life cycle in response to fishing. The life cycle can be slowed down by dome-shaped fishing selectivity, which can also change the reference points.

This first study of the combined effects of fisheries-induced evolution and climate change on fishing reference points in a trophic web opens the field for including evolution into fisheries management studies. The evolution of life history traits has a major impact on population productivity and sustainable exploitation levels. In order to achieve sustainable and ecosystem-based fisheries management, we need to improve our understanding of the key biological processes that influence fisheries yield and stock productivity. In light of our results, it is important to consider the evolutionary responses of life history traits in order to correctly assess the MSY.

Combined fishing and climate change scenarios in the North Sea (EwE)

In all RCP4.5 scenarios (even without bottom trawling), the EwE simulates a decline in pelagic fish, marine mammals and diving seabirds (Figure 40). This indicates that fishing effort by other metiers (especially pelagic trawl) should be reduced (relative to 2013 levels) to lead to ecologically sustainable levels.

Under the RCP8.5 climate scenario with high fishing effort (bottom trawling +75% above 2013 levels) no group overall will increase in the long-term. Initial increases by surface-feeding seabirds (like kittiwakes) and seals arise due to reduced predation pressure on sandeels by fish, but these gains are reversed by 2100 as primary production declines. If the increase in bottom trawl fishing effort is lowered to 50% above 2013 levels and climate follows the RCP4.5 pathway, then decreases in the demersal fish are comparable but pelagic fish decline much less. Sustained increases in demersal fish and seals are possible with reductions in bottom trawling to <50% of 2013 levels.

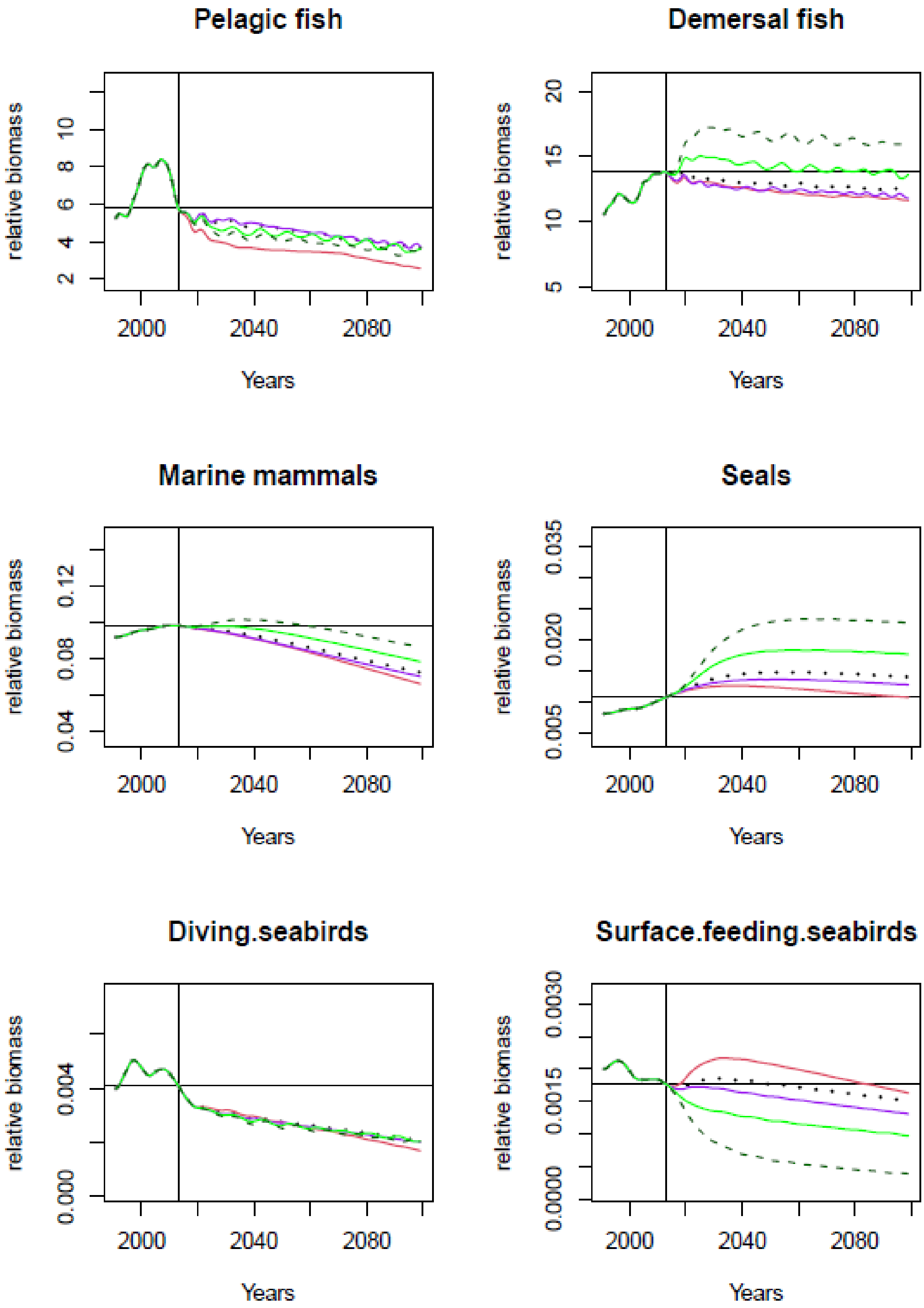


Figure 40: Relative biomass trajectories for key functional groups from the North Sea EwE under each scenario. The base case (under 2013 fishing pressure levels and RCP4.5) is shown by dotted black line. The worst case scenario with RCP8.5 and fishing effort increased by 75% is shown by the solid red line. The other RCP4.5 scenarios with fishing effort increased by 25%, decreased by 50% or decreased by 100% are shown by solid purple lines, solid green lines and dashed dark green lines respectively. The horizontal black line gives the relative biomass at the start of the forecast in 2013 and the vertical line intercepts the x-axis at 2013.

Model results were compared between EwE and FCM based on the responses of individual model components. For each EwE scenario the normalized deviation of each model component from the baseline was used as the metric to measure scenario effect. To allow comparison with the FCM models components of the EwE model were aggregated to match the FCM model components, with the unweighted average of the normalized deviations being used as the response for the aggregated EwE groups. To extract quantitative measures of the response of the mental models (MM) to the various scenarios the QPRESS press-perturbation method was employed (Olsen et al., 2023).

Southern North Sea FCM vs North Sea EwE
For the decrease in fisheries, only the biological components responded in the same direction for both model types (EwE and FCM) and both fishing effort scenarios in EwE (50% and 100%). While benthos and catch showed opposite responses. For the increased fishing scenarios (25% and 75%) none of the components showed corresponding directional response between the MM and EwE scenarios

Skagerrak FCM vs North Sea EwE
For the decreased fisheries scenarios, there was a correspondence in the direction of response for 47% and 44% of the components of the FCM compared to the two EwE scenarios (−100% and −50% fisheries), while for the increased fisheries scenarios (+25% and +75%), the correspondence in directional response was 31% and 38%, respectively.

Norwegian Trench FCM vs North Sea EwE
The absolute level of responses of the components to the scenarios were lower than for the Skagerrak model (except one—hake under the EwE “−100% fisheries” scenario). For the Norwegian Trench, the mental model and EwE scenarios showed the same directional response for 58% of the components in the EwE −100% decreased fisheries scenario and 45% for the EwE −50% scenario. For the increased fisheries scenarios, coherence in directional response was lower: 17% for the EwE +25% and 18% for the EwE +75% scenarios.

Discussion
Our comparison across subregions of the North Sea have shown that positive correspondence between mental model and EwE scenarios varied between 0%–33% for the southern North Sea, to 58% for the Norwegian Trench, with the Skagerrak falling between these two sets of values. The level of hierarchy of the FCM models seemed not to have any effect on the degree of correspondence between the two model type scenarios. For all regions, the scenarios featuring a decrease in fishing mortality showed the highest degree of correspondence between the qualitative and quantitative model. For qualitative models like FCM and quantitative models like EwE to share a role in the management and advisory process, it is essential to agree *a priori* on what are acceptable levels of correspondence between models.

Combined fishing and climate change scenarios in the North-western Mediterranean (EwE)

The best fit of the temporal model was achieved when trophic interactions, fishing and the environmental anomaly were included in the model configuration. The final fitting reduced the sum of squares (SS) by 47.9%. Individually, the environmental anomaly improved the baseline SS by 8.4%, while trophic interactions improved the baseline SS by 5.7%. Considering both the environment anomaly and trophic interactions improved the baseline SS by 25.6%. Fisheries and trophic interactions contributed to explain 33.7% of the variability, while fisheries alone or fisheries and the environment combined without ecological interactions did not improve the baseline model configuration.

The fitting of the model showed good agreement between predicted and observed biomass data when looking at available datasets for pelagic species (Figure 41). Overall, the model showed declines in 14 groups and increases or no changes in 8 groups.

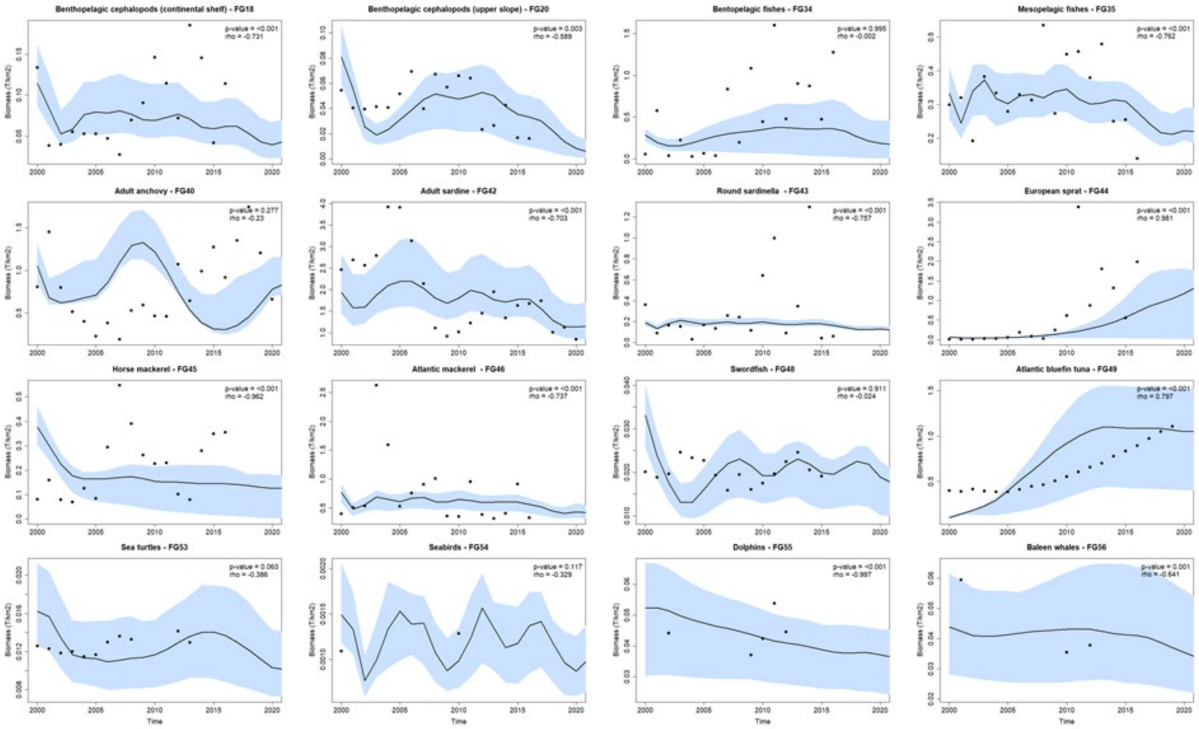


Figure 41: Temporal trends of biomass (t·km2) of key pelagic functional groups of the GSA06 and GSA07 food-web model from 2000 to 2020. Observations (dots), predicted trends (black line) and 95% confidence intervals (blue) are shown. The Spearman rank correlation coefficient between the predicted indicator and time and the p-value is indicated.

The model predicted important spatial-temporal changes in the biomass of pelagic organisms (Figure 42). European anchovy and European sardine (fg39-42) showed changes following a latitudinal gradient, with declines in 2020 compared to 2000 in the northern and central part of the study area, and increases in the southern part and deeper areas (Figure 42a-d). Round sardinella (fg.43) also showed general declines, although its distribution remained wide spread from north to south and biomass increased with depths (Figure 42e). On the contrary, European sprat (fg.44) showed increases in specific areas, especially near river mouths and in the southern and deeper areas (Figure 42f). Other pelagic organisms showed heterogeneous spatial-temporal trajectories of change, with increases of horse mackerel (fg45) and swordfish (fg48), especially in northern areas and bluefin tuna (fg49) in southern and central areas, as well as declines of Atlantic mackerel groups (fg46&47) and blue sharks (fg52).

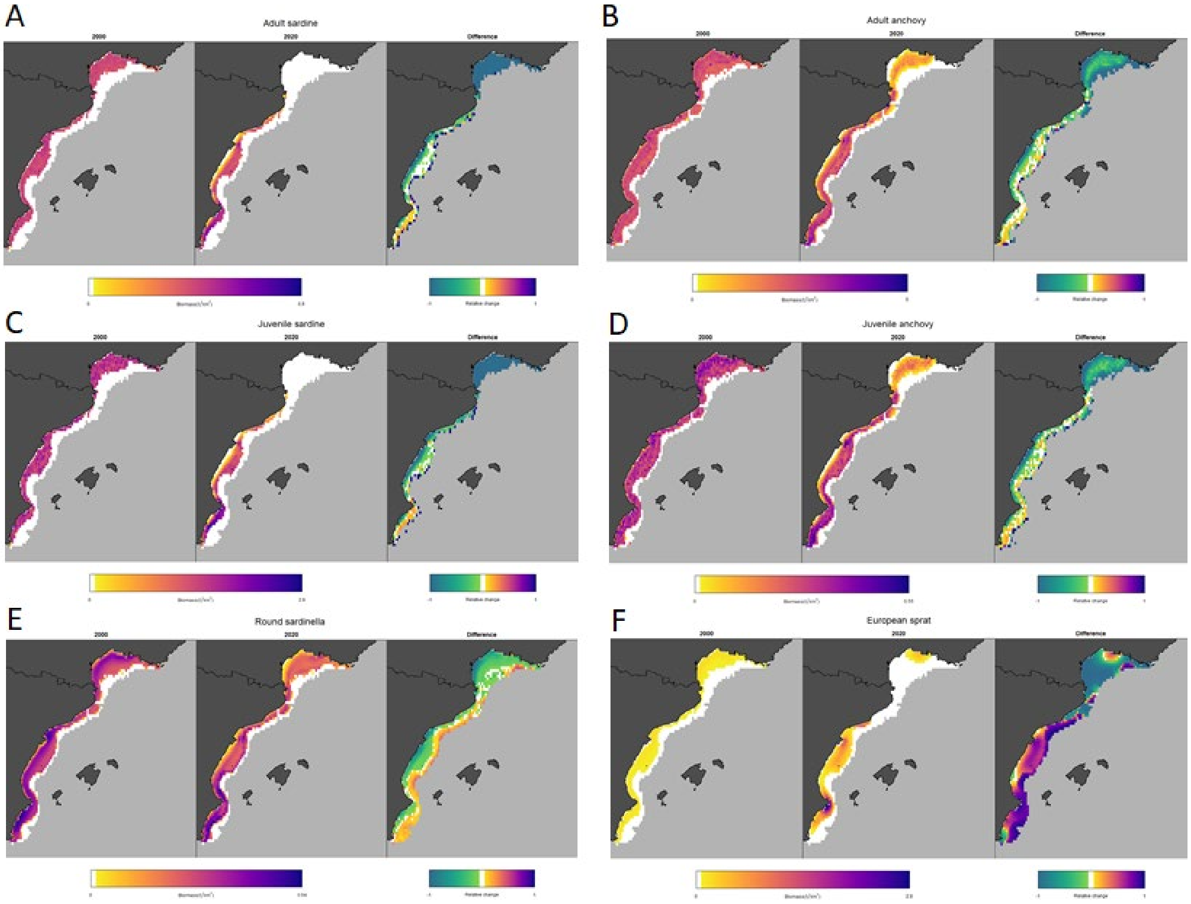


Figure 42: Changes in distributions of small pelagic fish species of the GSA06 and GSA07 food-web model between 2000 and 2020. Maps show predicted biomass in 2000, 2020 and the relative change between both (RCP4.5).

Overall, pelagic organisms showed spatial-temporal biomass declines both under RCP4.5 and RCP8.5 for 13 groups, slightly larger under the RCP8.5, and increases in 8 groups, slightly larger under the RCP4.5 (Figure 43a). The directions of change were mostly congruent between the temporal and spatial-temporal model.

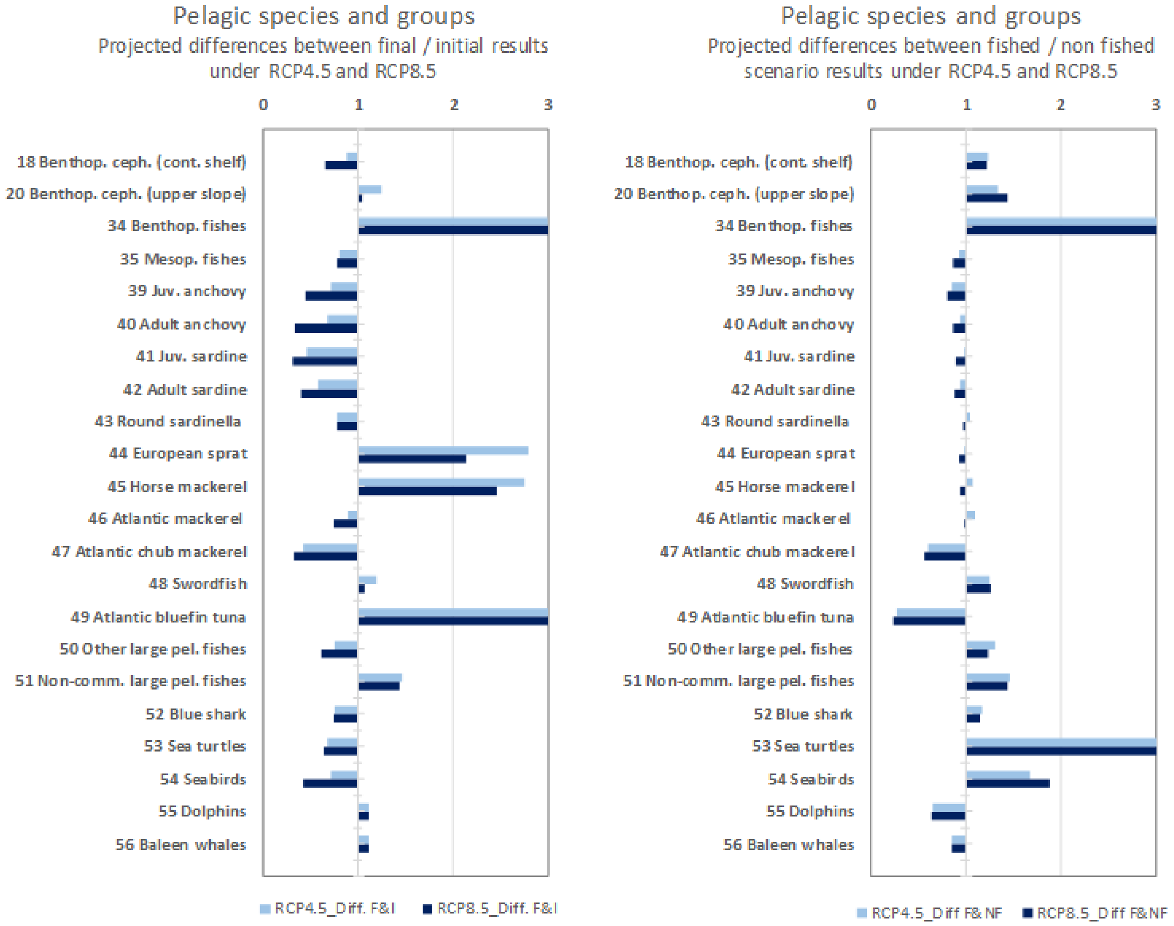


Figure 43: Changes in biomass of pelagic fish species and groups (2020/2000). Projected differences between (A) final / initial results under RCP4.5 and RCP8.5 and (B) fished / non-fished scenario under RCP4.5 and RCP8.5. Groups 34 and 49 present larger results that are not visualized.

The contribution of fishing to shaping the spatial-temporal dynamics of functional groups was especially relevant for benthopelagic fishes (fg34), marine turtles (fg53) and seabirds (54), followed by benthopelagic cephalopods (fg18&20), other large pelagic fish (fg50) and non-commercial large pelagic fish (fg51), which were projected to have been positively impacted under a fished scenario in comparison with a non-fished one. The groups negatively affected by a fished scenarios were bluefin tuna (fg49), Atlantic chub mackerel (fg47), dolphins (fg55), and baleen whales (fg56), followed by mesopelagic fishes (fg35) and European anchovy and European sardine (fg39-42) (Figure 43b).

Demersal organisms showed spatial-temporal biomass declines both under RCP4.5 and RCP8.5 for 14 groups, slightly larger under RCP8.5, and increases in 10 groups, slightly larger under RCP4.5. The contribution of fishing shaping the spatial-temporal dynamics was also evident for several groups.

The fitting of the model showed good agreements between predicted and observed catch data with benthopelagic cephalopods in the upper slope (fg20), adult European sardine (fg42), round sardinella (fg43), swordfish (fg48), bluefin tuna (fg49), other large pelagic fish (fg50), and blue sharks (fg52). The model performed worse at predicting catch trends of benthopelagic cephalopods of the continental shelf (fg18), adult European anchovy and sardine (fg40&42), horse mackerel and Atlantic mackerel (fg45&46). Overall, the model predicted catch declines in 12 pelagic groups and increases or no changes in 6. Similar results were obtained with the catch of demersal organisms.

The model predicted important spatial-temporal changes in pelagic organisms' catches (Figure 44). Adult European anchovy and European sardine (fg40&42) showed widespread changes following a latitudinal gradient, similar to those of biomasses, with declines in 2020 compared to 2000 (Figure 44a-b). Round sardinella (fg.43) also showed declines but with increases in deeper areas, while European sprat (fg.44), showed concentrations in specific areas of the northern region (Figure 44c-d). Overall, the pelagic organisms showed spatial-temporal catch declines both under RCP4.5 and RCP8.5 in 12 groups, slightly larger under RCP8.5, and increases in 4 groups, slightly larger under RCP4.5. The directions of change were mostly congruent between the temporal and spatial-temporal model, with some exceptions, the most important being benthopelagic fishes (fg34), European sprat (fg44) and non-commercial large pelagic fishes (fg51).

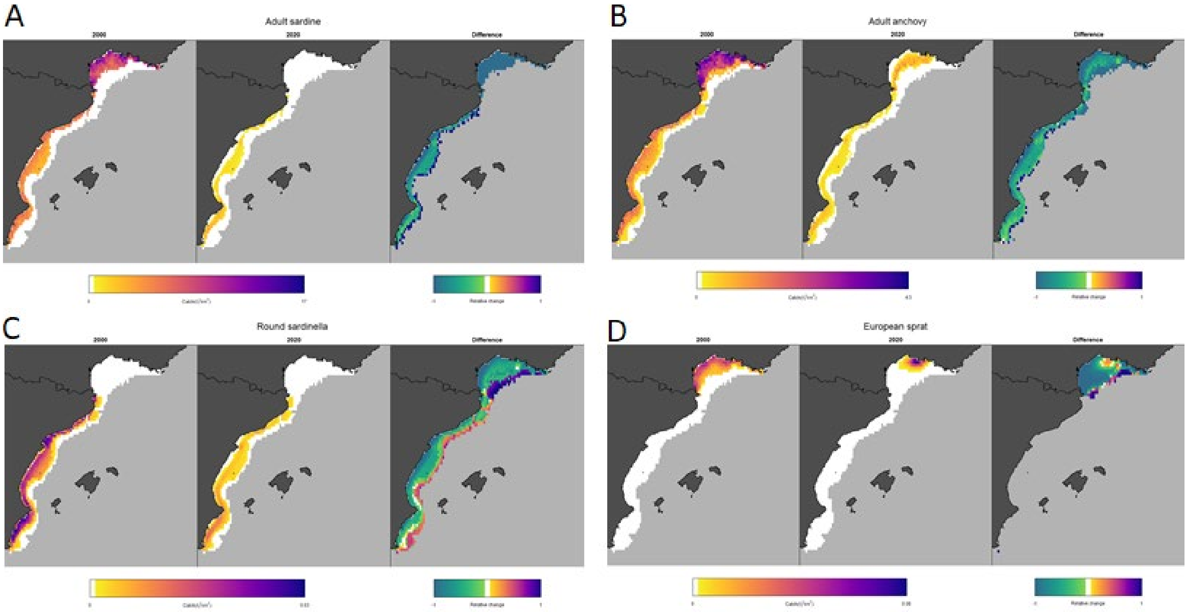


Figure 44: Changes in distributions of pelagic fish species (catch) of the GSA06 and GSA07 food-web model between 2000 and 2020. Maps show predicted biomass in 2000, 2020 and the relative change between both (RCP4.5).

A publication explaining the details of this study has been recently submitted (Coll et al., submitted, "Retrospective analysis of the pelagic ecosystem of the Western Mediterranean Sea: drivers, changes and effects." Science of The Total Environment.).

4.2. Scenarios with changing spatial management

Western Mediterranean (EwE)

The model fitting procedure for the regional model representing the whole Western Mediterranean Sea model showed that the best fitting was reached when considering the fishery, the trophic interactions and the environment. The fitting of the model showed good agreement between predicted and observed biomass data when looking at available datasets for key species (Figure 45).

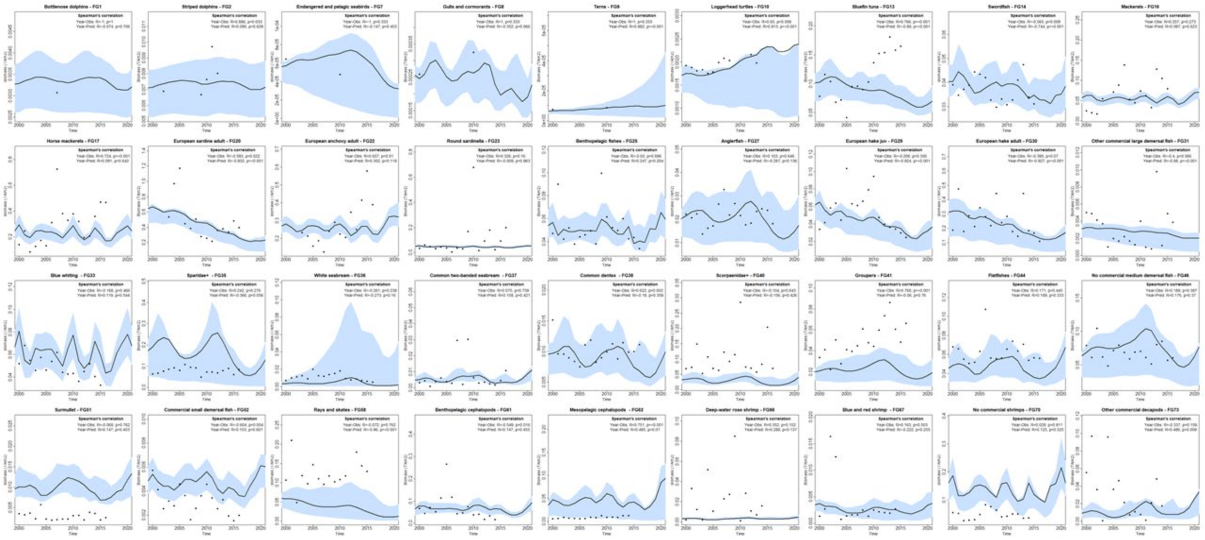


Figure 45: Temporal trends of biomass (t·km2) of key functional groups of the Western Mediterranean Sea from 1995 to 2020. Observations (dots), predicted trends (black line) and 95% confidence intervals (blue) are shown.

The spatial-temporal biomass changes of functional groups between 1995 and 2022 showed overall declines of pelagic groups, and some increases in demersal and invertebrate groups (Figure 46). Results showed small changes in biomass between S0 and S1, evidencing small effects of historical spatial management in the Western Mediterranean Sea. The groups that benefited the most were identified as European sardine (adults and juv.), groupers, and deep-sea water shrimps. Results from the counterfactual scenarios, on the contrary, showed changes in several groups, which were mostly moderate. Some changes included declines of various invertebrate groups, while highly commercial species such as European hake, did not show important benefits.

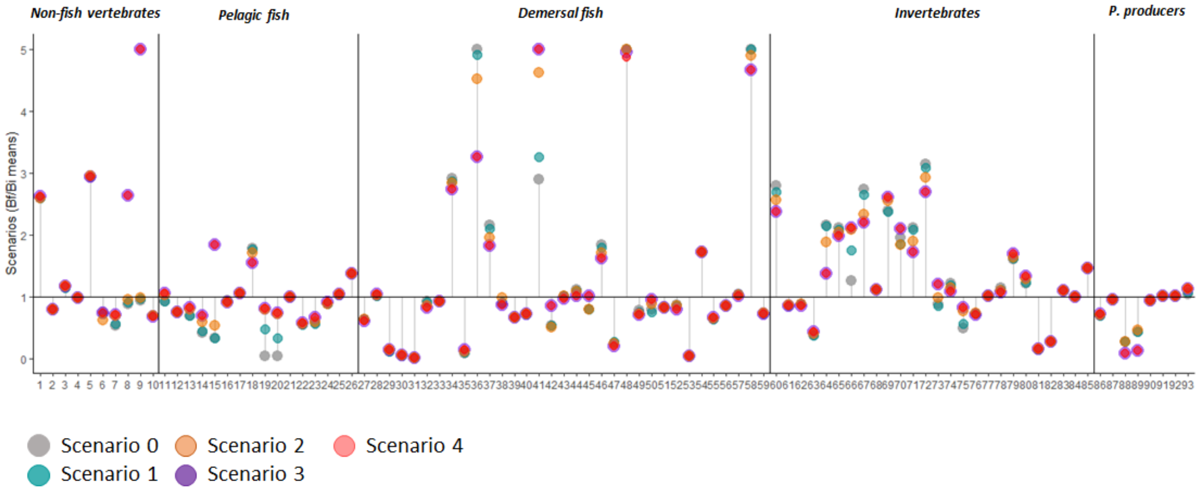


Figure 46: Spatial-temporal biomass change (Bf/Bi) of functional groups of the Western Mediterranean Sea model in 2022 compared to 1995, by scenario under RCP 4.5.

The analysis of specific distributional changes of key commercial species showed contrasting results. European sardine, for example, showed historical benefits from the spatial management in place, and would have benefited importantly from a more effective historical protection (Figure 47a-c). On the contrary, European hake did not show significant benefits from historical spatial management, and counterfactual scenarios showed still not clear benefits (Figure 47-f).

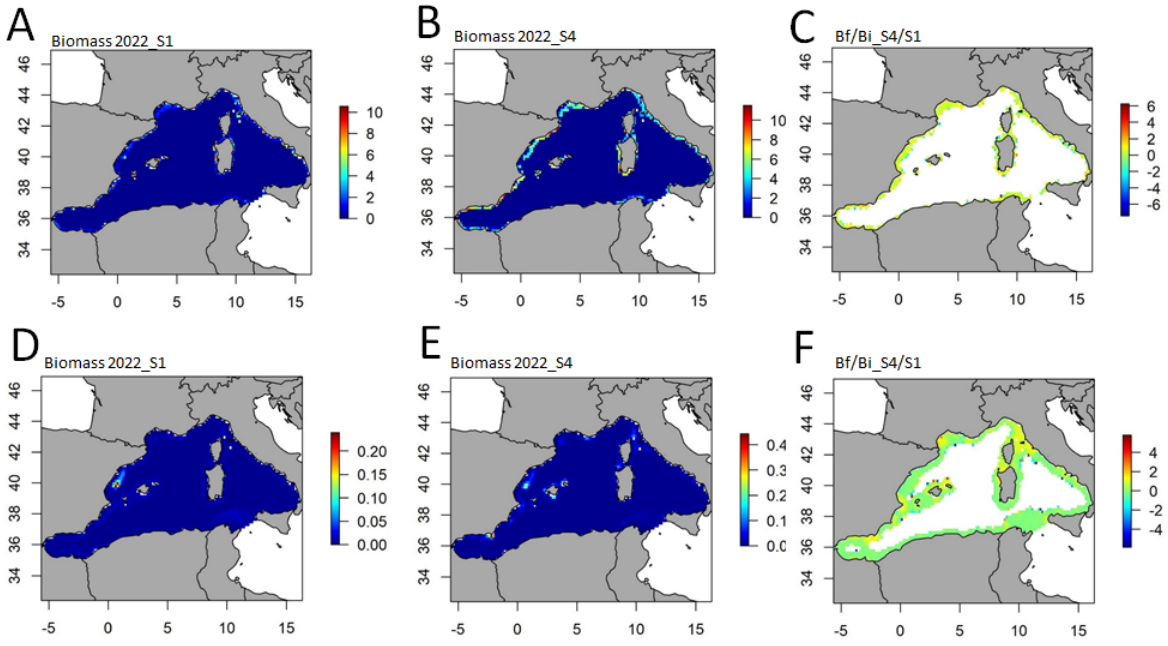


Figure 47: Changes in distributions of key species (a-c: European sardine, d-f: European hake) of the Western Mediterranean model between 1995 and 2022 under different scenarios of spatial management measures (S1 and S4). Maps show predicted biomass in 2000, 2022 and the relative change between both (under RCP4.5).

When analyzing biomass-based aggregated ecological indicators, we did not find any significant difference between scenarios S0 and S1 (Figure 48), with the exception of predators biomass, which showed a slight increase in S1 with respect to S0 (Figure 48c). Significant differences were clear between S1 and counterfactual scenarios for all indicators analysed, with the exception of fish biomass under S2 (Figure 48b). Overall, under counterfactual scenarios results showed larger commercial biomass, fish biomass and predators biomass, and lower values of invertebrate biomass. When analyzing catch-based aggregated ecological indicators, similarly to biomass results, we did not find changes between scenarios S0 and S1, with the exception of predators biomass and fish biomass, which showed slight increases in S1 with respect to S0. Significant differences were clear between S1 and counterfactual scenarios for all indicators analysed. Overall, under counterfactual scenarios, results showed larger commercial catch, fish biomass, demersal catch, consumers catch, pelagic catch, and predators catch, and lower values of invertebrate catches and elasmobranches catch.

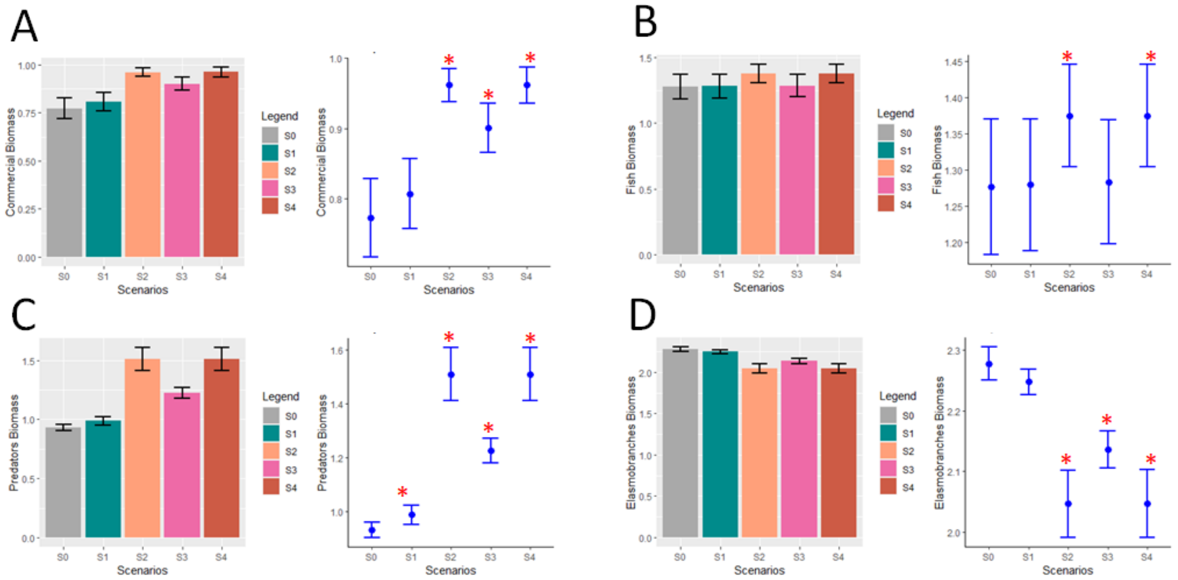


Figure 48: Spatial-temporal change (Bf/Bi) of aggregated indicators of the Western Mediterranean Sea model in 2022 compared to 1995, by scenario, under RCP 4.5.

A publication explaining the details of this study is being prepared for publication (Coll et al., in preparation).

MPA scenarios under CC in the Mediterranean Sea (OSMOSE)

Projected changes in biomass

At the Mediterranean scale, under the RCP8.5 emission scenario, total biomass is projected to increase by 18.5% even without MPAs (Figure 49). Such an increase in high-trophic level biomass can be explained by the Eco3M-S projections, which predict an overall increase of phytoplankton biomass, in particular of pico- and nano- phytoplankton by 28% and 13%, respectively (Moullec, Barrier, et al., 2019). With the implementation of MPAs, this overall gain of biomass is accentuated, with an increase of up to 25.9% in the case of the MPA scenario where areas were selected according to conservation criteria exclusively. The extra gain of biomass due to MPAs under present conditions is of the same magnitude as the one observed for the 2070-2100 period, suggesting that MPAs can remain effective despite changing environmental conditions.

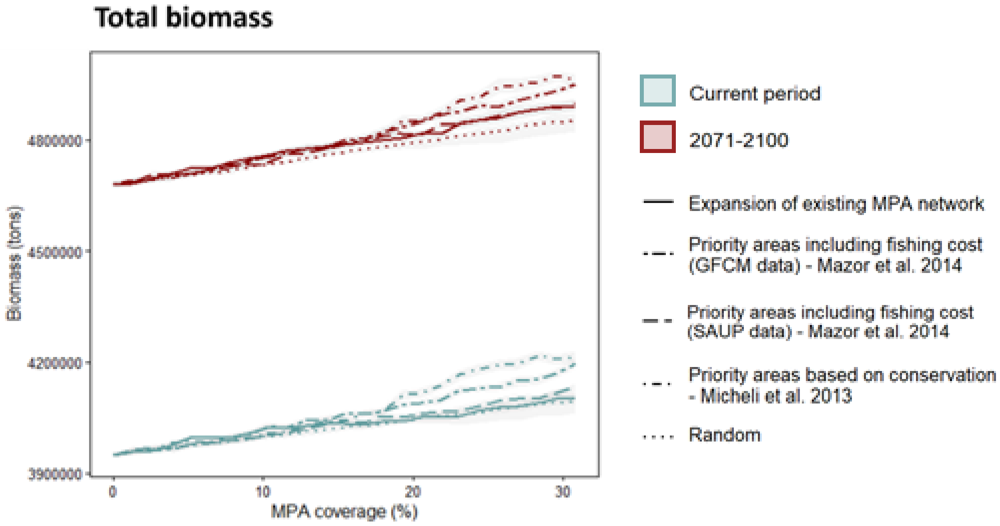


Figure 49: Total biomass in tons in the current period (2006-2013) and projected by the end of the century (2071-2100) under the RCP8.5 emission scenario. The average (dotted line) and minimum and maximum (grey envelope) of the 5 random scenarios is represented for the random MPA scenario. For the other scenarios, 95% confidence intervals were computed between the 30 replicates.

However, as was shown by Moullec et al. (2019), this biomass increase masks strong inter-species contrasts (Figure 50). In particular, the biomass of large demersal species is projected to decrease by 46.5% under the RCP8.5 scenario by the end of century, whereas mid-trophic level species (i.e., small pelagic, crustaceans, cephalopods) are projected to increase by 24%, 5% and 6%, respectively. Despite their higher trophic level, large pelagic species are also overall predicted to be favored by climate change (17.1% increase). In particular, species of high commercial value such as bluefin tuna *(Thunnus thynnus)*, mahi-mahi *(Coryphaena hippurus),* bonito *(Sarda sarda)* and swordfish *(Xiphias gladius)* are expected to increase by 26%, 14%, 61% and 23%, respectively.

“Loser” species of climate change are mostly large species, relatively high in the food chain and, for the most, belonging to the demersal group. Among them, some are of high commercial value, such as hake *(Merluccius merluccius),* common seabream *(Pagrus pagrus)*, blue and red shrimp *(Aristeus antennatus)* and the European squid *(Loligo vulgaris),* which are expected to decrease by 69%, 12%, 4% and 4%, respectively. Three other species are expected to be on the brink of extinction with a reduction of 99.9% of their biomass.

However, our results show that implementing strict protection measures could mitigate the projected effects of climate change. This is particularly true for large demersal species, for which the overall biomass loss could even be compensated for with a fully protected MPA network covering about 20% of the Mediterranean Sea (Figure 50). Although this scenario seems highly implausible in terms of political governance and socio-economic activities, our projections show that the benefits of MPAs could already be detected from low coverage levels, even well below the EU Biodiversity Strategy target of 10% of fully protected areas by 2030. If a 10% fully protected MPA network were to be implemented by the end of the century, the biomass of high commercial value species, such as hake would increase between 5 and 319% depending on the MPA network configuration in comparison to a scenario without any protection measures. It would also help prevent an almost total disappearance of some species from the Mediterranean Sea, like blue whiting *(Micromesistius poutassou)*, the biomass of which would be reduced by 95% instead of by 99.9%.

Still, MPAs do not appear to be beneficial for all species groups: the biomass of high trophic level species (i.e., large pelagic and large demersal species) is predicted to increase with the implementation of protection measures, while that of mid-trophic level species (i.e., small pelagic species, crustaceans and cephalopods) is predicted to decline with MPAs. As our model projects a gain of biomass for mid-trophic level species in the RCP8.5 scenario, their decline due to MPAs could be mitigated or even fully compensated for depending on the size of the MPA network. For cephalopods and crustaceans, even if the 10% protection target was to be reached at the scale of the Mediterranean, some MPA scenarios would still allow to maintain their biomass at current levels.

The variability observed between the different MPA network configurations highlights the importance of thinking strategically about network design at the scale of the Mediterranean basin and according to the desired objectives. In fact, no configuration performs equally well for every group of species. For instance, the scenario resulting from the expansion of current MPA locations provides the highest mitigation of large demersal biomass loss, as MPAs are located in large demersal biomass rich areas, and appears to be much more efficient in this sense than the random MPA scenario. In general, we observe that the three MPA network configurations based on conservation criteria alone perform better in protecting high-trophic level species, since among the criteria used for site selection, the distribution of demersal and large pelagic species was most frequently considered, but perform worse in protecting mid-trophic level species. We observe the opposite trend concerning the random MPA network configuration. This aligns with expectations that as high-trophic level species become more abundant due to fishing release, predation pressure on mid-trophic level species will increase.

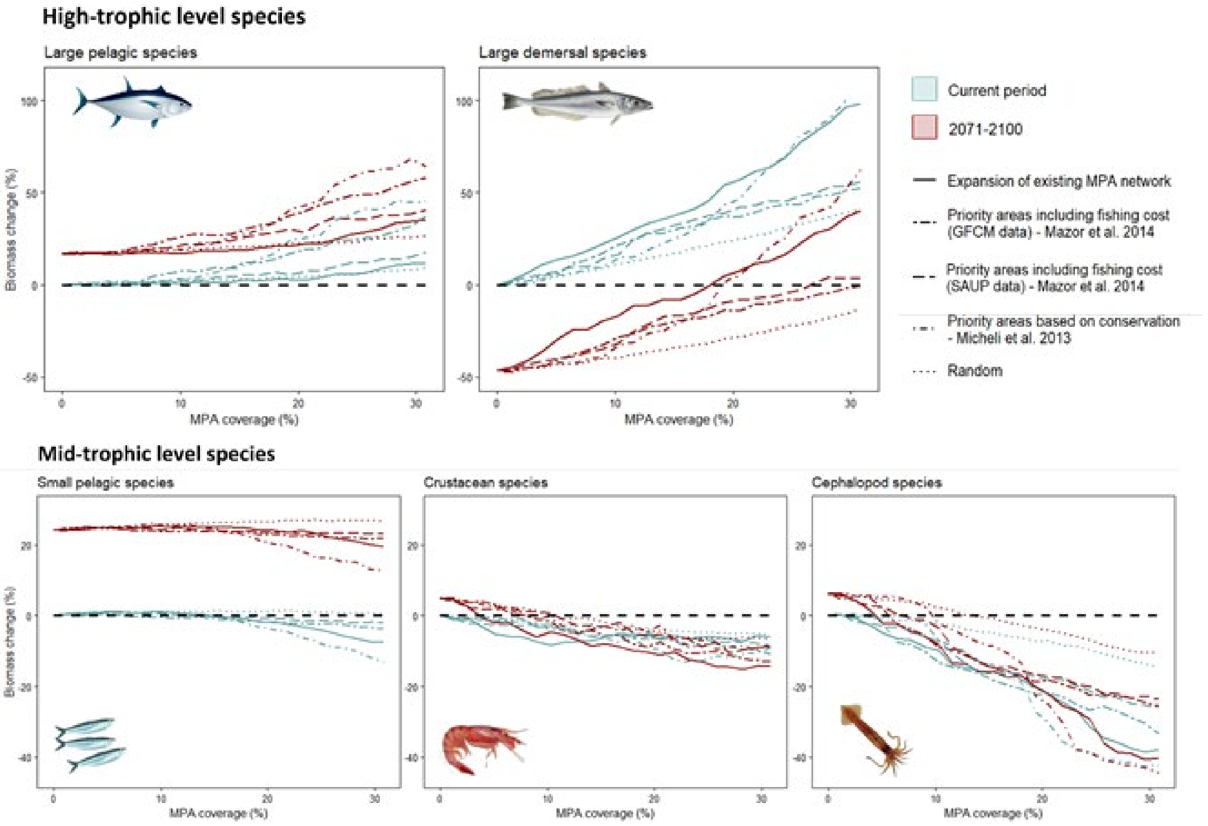


Figure 50: Changes in biomass relative to the current period (2006-2013) without MPAs by groups of species.

Projected changes in size structure

Fish sizes are also predicted to decrease with climate change in the Mediterranean Sea. The Large Fish Indicator (LFI), defined in the Mediterranean Sea as the ratio between the biomass of species over 20 cm and the total biomass of the community (Edelist et al., 2014), is projected to decrease by 7% by the end of the century under the RCP8.5 emission scenario. Our results show that implementing no-take MPAs allows fish sizes to increase both inside and outside reserves, benefiting both conservation and fisheries (Figure 51). Even if the increase in LFI is more pronounced inside reserves, the increase outside reserves is far from negligible: the LFI projected by the end of the century can approach that of today with an MPA network covering about 20% of the Mediterranean Sea. With a 10% no-take MPA network, the overall increase is predicted to be between 0.7 and 5.6% depending on the MPA network configuration. We also highlight that the MPA scenarios suggested by previous scientific studies (in dashed lines, Figure 51) outperform both the random scenario and the extension of the current MPA network.

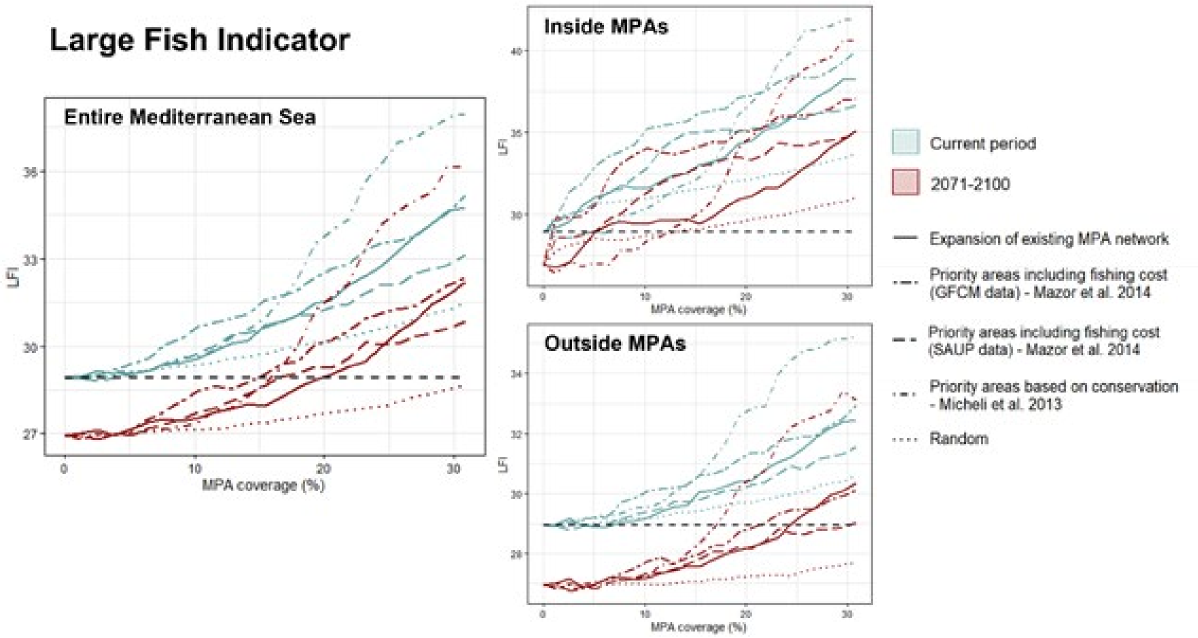


Figure 51: Large Fish Index (i.e., the proportion of fish which exceed 20 cm in length) in the current period (2006-2013) and by the end of the century (2071-2100) under RCP8.5, in relation to the extent of MPA network coverage. Five MPA scenarios were simulated.

Projected changes in catch

Total catch is projected to increase by 10% by 2071-2100 in the Mediterranean Sea under RCP8.5 (Figure 52). However, this increase will be mostly localized in the eastern part of the Mediterranean basin (Figure 53), in line with the increase in biomass, mainly due to a bulk increase in exotic thermophilic species such as the red-eye round herring *(Etrumeus teres)* and the lizardfish *(Saurida undosquamis)*. As was shown by Moullec et al. (2019), eastern basin fisheries will experience tropicalization of catch, whereas western basin fisheries, a substantial decline in catch.

In addition to meeting conservation objectives, the expansion of MPAs in the Mediterranean Sea must also take into account the impact on fisheries. Our scenarios show that MPAs will reduce catches, regardless of the MPA network configuration (Figure 52). However, the scenario that extends the current MPA network stands out from the others as the one that has the most significant impact on fisheries, causing an 8% reduction in catch compared to 3% for the least impactful scenario at a 10% coverage relative to the no MPAs scenario (Figure 52, Table 10). Our results also underline that the negative impact of the random MPA scenario is of the same magnitude as that of the scenarios based on previous scientific studies. We explain this by the fact that the areas protected in the random scenario are generally further offshore, particularly between Libya, Italy and Greece (Figure 15), where fishing effort is much lower. The best scenarios from a fisheries perspective are the two which included a fishing cost metric as a criterion for the selection of MPA location. At the scale of the Mediterranean Sea, implementing this scenario with a 10% coverage will not allow to compensate for catch loss in the Western Mediterranean basin, even if some areas, like the Algerian coast, the Alboran Sea or the southern Adriatic Sea, might benefit from protection as catch will increase greatly between MPAs (Figure 53).

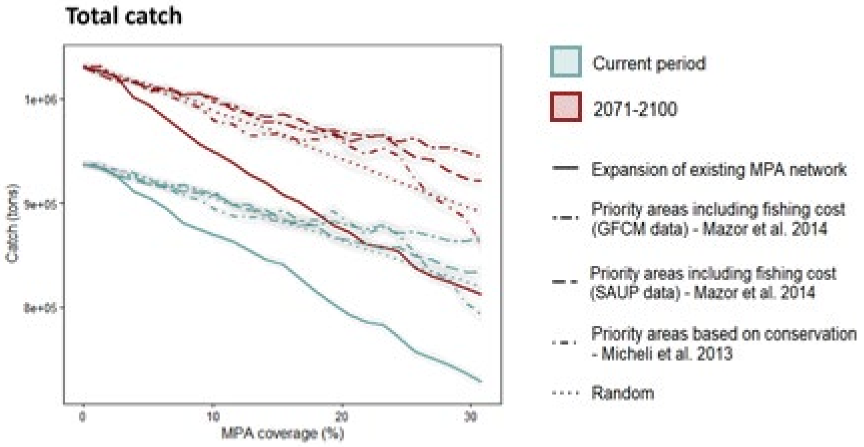
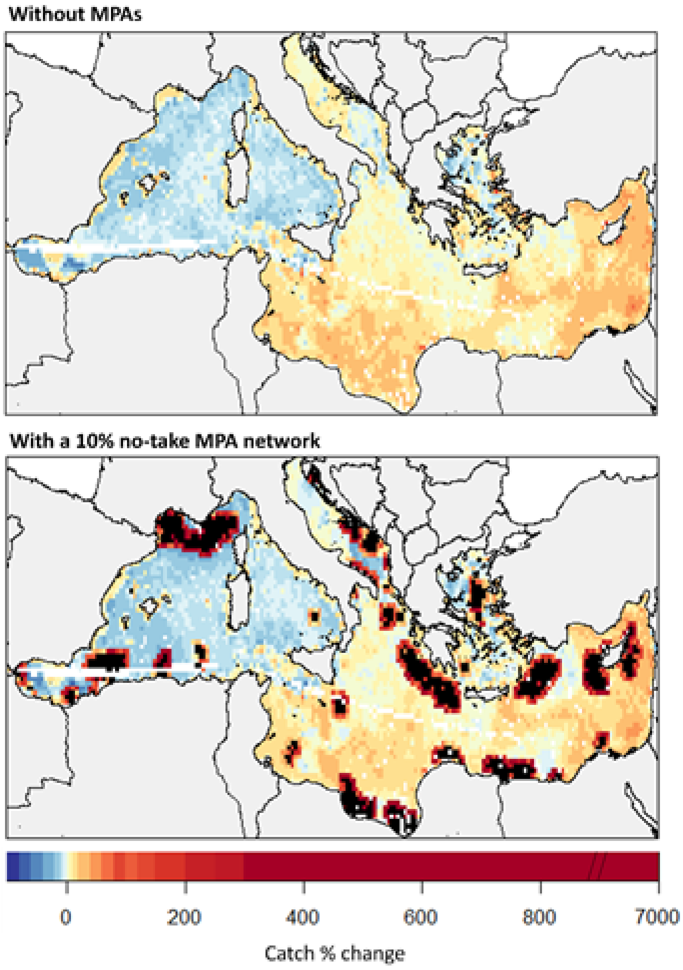


Figure 52: Total catch in tons in the current period (2006-2013) and projected by the end of the century (2071-2100) under the RCP8.5 emission scenario. The average (dotted line) and minimum and maximum (grey envelope) of the 5 random scenarios is represented for the random MPA scenario. For the other scenarios, 95% confidence intervals were computed between the 30 replicates.



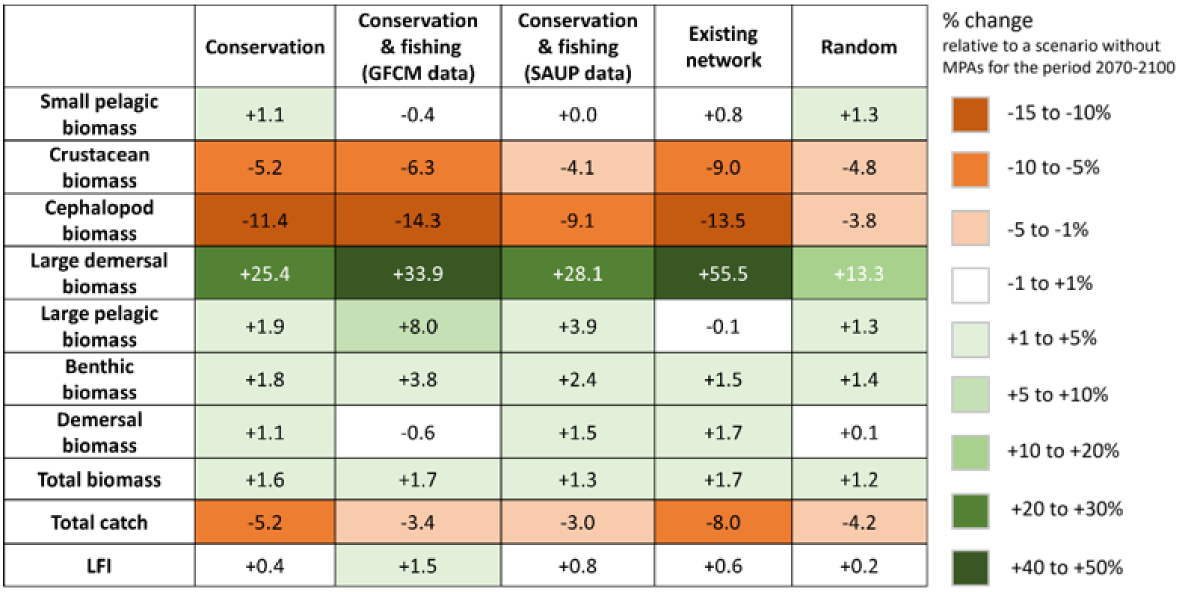
Without MPAs

With a 10% no-take MPA network

Figure 53: Above: Projected relative change in total catch between 2006-2013 and 2071-2100 before implementing MPAs; Below: Projected relative change in total catch between 2006-2013 without MPAs and 2071-2100 with a 10% no-take MPA network according to the best MPA scenario from a fisheries perspective, based (i.e., scenario based on both conservation and fishing criteria using data from the Sea Around Us Project from (Mazor et al., 2014). Areas in black correspond to no-take areas.

Table 12: Comparison between the 5 MPA network scenarios tested.

Conservation corresponds to the scenario from Micheli et al. (2013) based on conservation criteria only. Conservation & fishing scenarios are taken from Mazor et al. (2014) based on both conservation and fishing cost criteria. Existing network is the result of expanding the current MPA network. Random is the result of the average of 5 scenarios where MPAs were placed randomly across the Mediterranean basin. The values in the table correspond to the projected changes in biomass, catch and LFI in 2071-2100 under RCP8.5, with a 10% MPA network relative to a future scenario without MPAs.



	Conservation	Conservation & fishing (GFCM data)	Conservation & fishing (SAUP data)	Existing network	Random
Small pelagic biomass	+1.1	-0.4	+0.0	+0.8	+1.3
Crustacean biomass	-5.2	-6.3	-4.1	-9.0	-4.8
Cephalopod biomass	-11.4	-14.3	-9.1	-13.5	-3.8
Large demersal biomass	+25.4	+33.9	+28.1	+55.5	+13.3
Large pelagic biomass	+1.9	+8.0	+3.9	-0.1	+1.3
Benthic biomass	+1.8	+3.8	+2.4	+1.5	+1.4
Demersal biomass	+1.1	-0.6	+1.5	+1.7	+0.1
Total biomass	+1.6	+1.7	+1.3	+1.7	+1.2
Total catch	-5.2	-3.4	-3.0	-8.0	-4.2
LFI	+0.4	+1.5	+0.8	+0.6	+0.2

% change
relative to a scenario without MPAs for the period 2070-2100

-15 to -10%
-10 to -5%
-5 to -1%
-1 to +1%
+1 to +5%
+5 to +10%
+10 to +20%
+20 to +30%
+40 to +50%

Our results show that the projected negative impacts of climate change under the high emissions scenario RCP8.5 on Mediterranean marine ecosystems, in particular the substantial decrease in the biomass of large demersal species and in species size, could be mitigated by MPAs. We were able to show that even the implementation of a relatively small MPA network (less than 10% coverage) could already lead to significant changes in 2071-2100 compared to the absence of management measures, provided that the MPAs established have a high and enforced level of protection.

Our scenarios projected a decrease in catch with MPAs, regardless of the configuration of the MPA network. However, we stress that not all Mediterranean countries will be affected by this, as total catch is projected to increase with climate change in some areas of the Mediterranean, particularly in the Eastern basin. Furthermore, the reduction in catches in areas that become MPAs will be partly offset by the increase in biomass generated by the MPA, especially at the edge of the MPA.

Finally, the variability observed between the different MPA network configurations tested highlights the importance of thinking strategically about the design of the network at the Mediterranean scale in terms of location, size and shape and according to the desired objectives. In order to better cope with the negative effects of climate change, the best MPA scenarios were those designed with both conservation and fisheries criteria (Table 10). These were the ones that better preserved large demersal species and fish sizes, while having the least impact on fisheries. We therefore emphasize the importance of estimating, where possible, the combined effects of no-take MPAs on conservation and fisheries when expanding existing MPAs or designating new ones.

4.3. Multi-driver scenarios

Sustainable fishing under CC in the Gulf of Lion, Mediterranean Sea (FCM)

The 24 stakeholders interviewed by the IRD team identified 71 key concepts for the functioning and sustainability of the Gulf of Lion fisheries. This allowed to build a fuzzy cognitive map describing the causal relationships between the concepts (Figure 54). A negative, zero or positive weight, ranging from -1 to 1, describes the strength of each causal relationship. For example, a positive weight Wij between two concepts Ci and Cj means that if the value of Ci increases (or respectively decreases), the value of Cj will increase (respectively decreases). Weights can be attributed by relying on experts' domain knowledge or using stakeholders' knowledge, views, and perceptions. Here, we rely on the authors' expert knowledge to interconnect pair by pair the 71 key concepts identified by the stakeholders for the SES functioning and sustainability. We attributed to non-zero weights, whether positive or negative, absolute values of 0.75 for strong causal relationships, or 0.25 for weak causal relationships. Overall, over 16 percent of all causal relationships had non-zero weights.

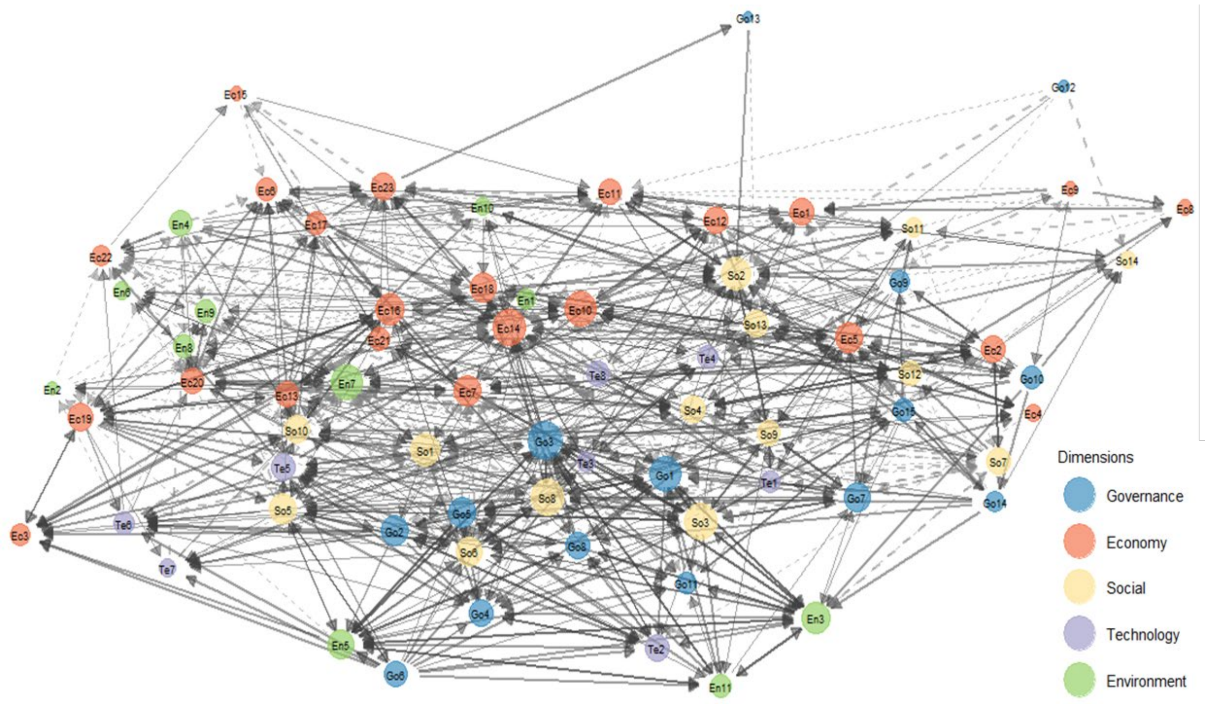
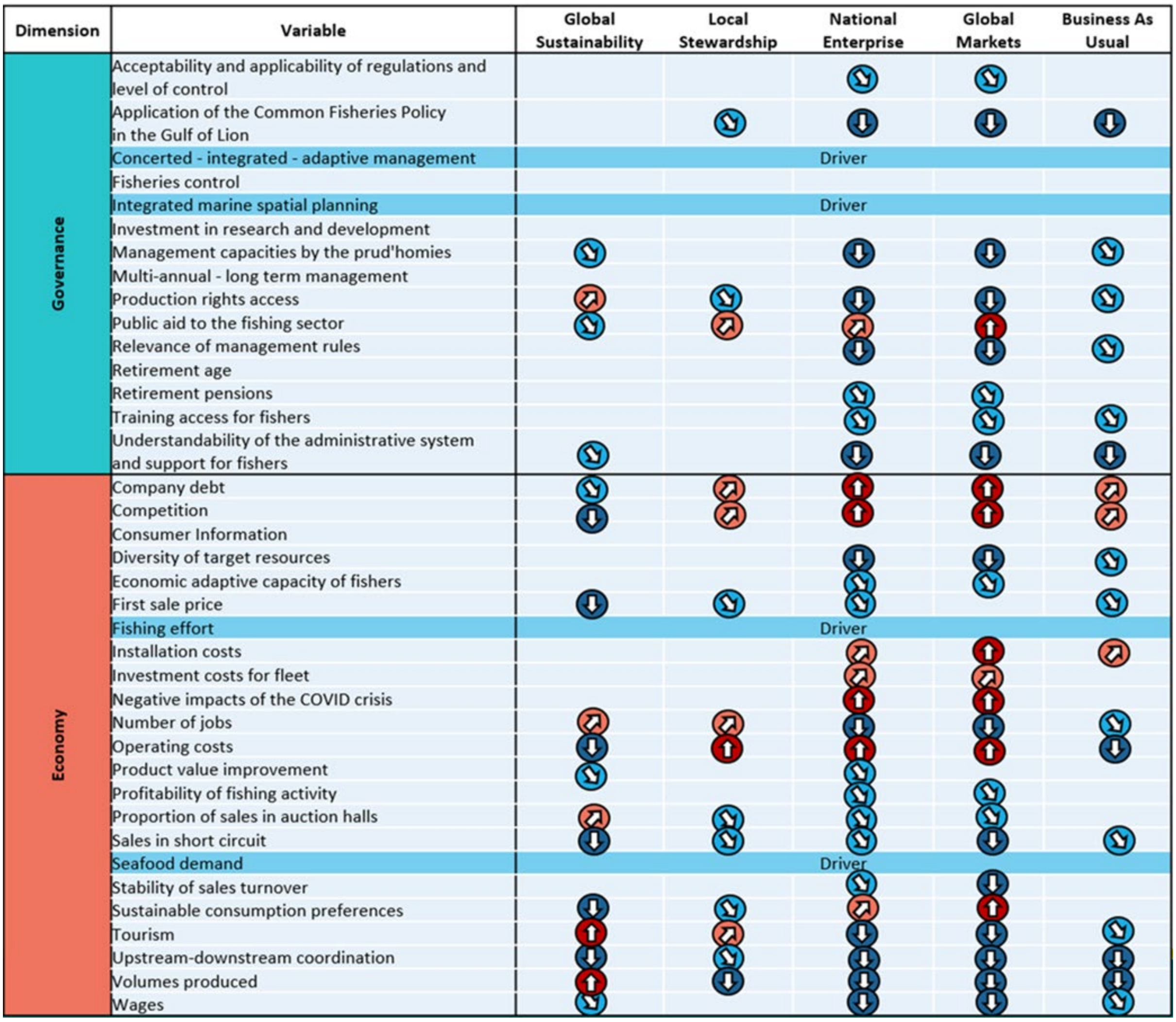


Figure 54: Fuzzy cognitive map of the social-ecological system of the Gulf of Lion fisheries. The meaning of the alphanumeric codes for the key concepts is shown in Appendix 1. The circle corresponding to each concept is proportional in size to the concept centrality within the social-ecological system, i.e., the sum of its absolute values of incoming and outgoing interconnections. Interaction arrows hatched in light gray are negative, those in solid dark gray are positive. Thin lines indicate weak interactions (0.25) while thick lines indicate strong interactions (0.75).

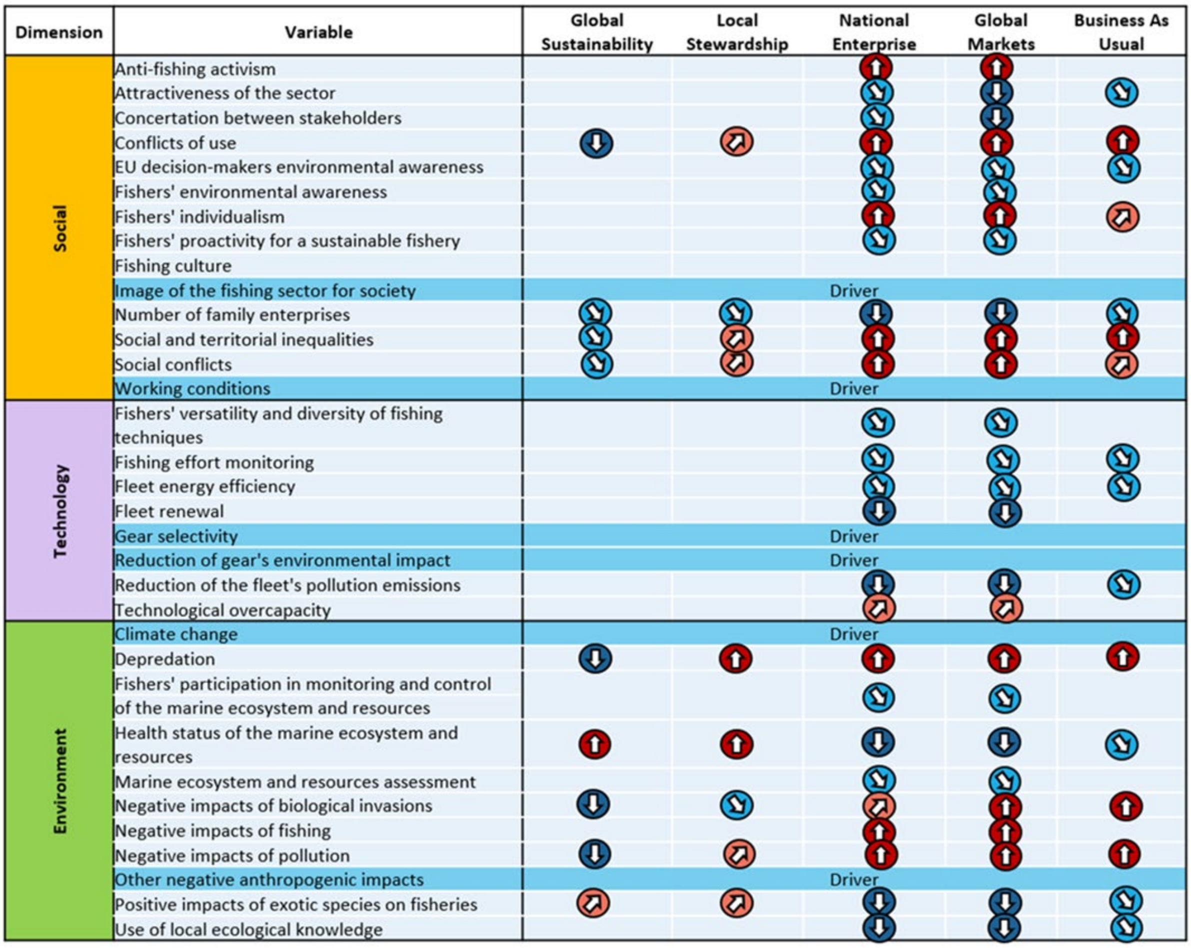
The implementation of the five scenarios in our FCM, i.e., varying the values of the 10 drivers selected from the 71 SES key concepts, resulted in significant changes for 90 percent of the other key concepts (Table 11). Overall, the trends observed for the key concepts of the five dimensions were consistent with our scenario storylines (Chevallier et al. in prep.). This indicates that our model, built using data from focus groups with stakeholders along with our expert opinions, and our scenario implementation based on storylines constructed during stakeholder workshops, accurately reflect stakeholder knowledge, views, and perceptions of the Gulf of Lion fisheries SES, in its current and projected forms.

Table 13: Modeled changes in key concept values according to each implemented scenario. The arrows represent the following significant changes: red for a moderate to strong increase, orange for a weak to moderate increase, light blue for

a weak to moderate decrease and dark blue for a moderate to strong decrease. We considered third quartiles of absolute effect size as threshold values.



Dimension	Variable	Global Sustainability	Local Stewardship	National Enterprise	Global Markets	Business As Usual
Governance	Acceptability and applicability of regulations and level of control			↘	↘	
	Application of the Common Fisheries Policy in the Gulf of Lion		↘	⬇	⬇	⬇
	Concerted - integrated - adaptive management			Driver		
	Fisheries control					
	Integrated marine spatial planning			Driver		
	Investment in research and development					
	Management capacities by the prud'homies	↘		⬇	⬇	↘
	Multi-annual - long term management					
	Production rights access	↗	↘	⬇	⬇	↘
	Public aid to the fishing sector	↘	↗	↗	⬆	
	Relevance of management rules			⬇	⬇	↘
	Retirement age					
	Retirement pensions			↘	↘	
	Training access for fishers			↘	↘	↘
	Understandability of the administrative system and support for fishers	↘		⬇	⬇	⬇
Economy	Company debt	↘	↗	⬆	⬆	↗
	Competition	⬇	↗	⬆	⬆	↗
	Consumer Information					
	Diversity of target resources			⬇	⬇	↘
	Economic adaptive capacity of fishers			↘	↘	
	First sale price	⬇	↘	↘		↘
	Fishing effort			Driver		
	Installation costs			↗	⬆	↗
	Investment costs for fleet			↗	↗	
	Negative impacts of the COVID crisis			⬆	⬆	
	Number of jobs	↗	↗	⬇	⬇	↘
	Operating costs	⬇	⬆	⬆	⬆	⬇
	Product value improvement	↘		↘		
	Profitability of fishing activity			↘	↘	
	Proportion of sales in auction halls	↗	↘	↘	↘	
	Sales in short circuit	⬇	↘	↘	⬇	↘
	Seafood demand			Driver		
	Stability of sales turnover			↘	⬇	
	Sustainable consumption preferences	⬇	↘	↗	⬆	
	Tourism	⬆	↗	⬇	⬇	↘
	Upstream-downstream coordination	⬇	↘	⬇	⬇	⬇
	Volumes produced	⬆	⬇	⬇	⬇	⬇
	Wages	↘		⬇	⬇	↘



Dimension	Variable	Global Sustainability	Local Stewardship	National Enterprise	Global Markets	Business As Usual
Social	Anti-fishing activism			↑	↑	
	Attractiveness of the sector			↘	↓	↘
	Concertation between stakeholders			↘	↓	
	Conflicts of use	↓	↗	↑	↑	↑
	EU decision-makers environmental awareness			↘	↘	↘
	Fishers' environmental awareness			↘	↘	
	Fishers' individualism			↑	↑	↗
	Fishers' proactivity for a sustainable fishery			↘	↘	
	Fishing culture					
	Image of the fishing sector for society	Driver				
	Number of family enterprises	↘	↘	↓	↓	↘
	Social and territorial inequalities	↘	↗	↑	↑	↑
	Social conflicts	↘	↗	↑	↑	↗
	Working conditions	Driver				
Technology	Fishers' versatility and diversity of fishing techniques			↘	↘	
	Fishing effort monitoring			↘	↘	↘
	Fleet energy efficiency			↘	↘	↘
	Fleet renewal			↓	↓	
	Gear selectivity	Driver				
	Reduction of gear's environmental impact	Driver				
	Reduction of the fleet's pollution emissions			↓	↓	↘
	Technological overcapacity			↗	↗	
Environment	Climate change	Driver				
	Depredation	↓	↑	↑	↑	↑
	Fishers' participation in monitoring and control of the marine ecosystem and resources			↘	↘	
	Health status of the marine ecosystem and resources	↑	↑	↓	↓	↘
	Marine ecosystem and resources assessment			↘	↘	
	Negative impacts of biological invasions	↓	↘	↗	↑	↑
	Negative impacts of fishing			↑	↑	
	Negative impacts of pollution	↓	↗	↑	↑	↑
	Other negative anthropogenic impacts	Driver				
	Positive impacts of exotic species on fisheries	↗	↗	↓	↓	↘
	Use of local ecological knowledge			↓	↓	↘

For 31 percent of our concepts, we can establish a direct correspondence with the sustainability targets of the EU Biodiversity Strategy 2030 (Appendix 2), according to our synthesis of this document Appendix 1). Among these 22 concepts, there is only one economic concept and none for the social dimension. This highlights a lack of consideration given to fishers' socio-economic conditions within the Strategy. It should also be noted that for two concepts, despite thematic similarity, it was not possible to determine a direct correspondence. This is the case for public aid to the sector, where it is not possible to determine within our model, which is too generalist, for which purposes this aid is intended. This is also the case for climate change, where although the European Strategy mentions the interlinkages between climate change and the biodiversity crisis, there is no concept in our model, nor indeed in the Strategy, that mentions a climate change mitigation process, except for the aim of using renewable energies, which is already present in another concept.

We assigned a sustainability score to each scenario based on the values of the changes modeled for the concepts associated with sustainability objectives (Table 12). 23 percent of these concepts are considered as drivers in our model and their change values were determined from the storylines of the scenarios co-constructed with stakeholders. We also assigned a second sustainability score based on the drivers' change values. Based on these sustainability scores, the Global Sustainability and Local Stewardship scenarios can be considered sustainable, while the National Enterprise and Global Markets scenarios are considered unsustainable. Although the Business As Usual scenario is considered to be sustainable, with a low positive score, at the level of driver parameterization, it obtains a negative score for the non-driver concepts.

Table 14: Score of the value of changes in concepts corresponding to sustainability targets. Absolute values of 0.5 and 1 were assigned for weak and strong changes respectively, based on the results presented in table 2. For the four concepts relating to negative impacts, the sign of the values was reversed to consider them as sustainability indicators. The values of the driver changes, highlighted in pale blue, were kept as parameterized in Table 1. The total sustainability scores for drivers and non-drivers correspond to the total sums of the individual scores determined for each concept.

Concept	**Scenario**				
	Global sustainability	Local stewardship	National Enterprise	Global markets	Business As Usual
Acceptability and applicability of regulations and level of control			-0.5	-0.5	
Application of the Common Fisheries Policy in the Gulf of Lion		-0.5	-1	-1	-1
Concerted - integrated - adaptive management	0.75	1	-1	-1	0.25
Fisheries control					
Integrated marine spatial planning	1	0.75	-0.25	-0.75	0.25
Investment in research and development					
Relevance of management rules			-1	-1	-0.5
Training access for fishers			-0.5	-0.5	-0.5
Understandability of the administrative system and support for fishers	-0.5		-1	-1	-1
Consumer Information					
Fishing effort monitoring			-0.5	-0.5	-0.5
Fleet energy efficiency			-0.5	-0.5	-0.5
Gear selectivity	1	0.5	-0.5	-1	0.5
Reduction of gear's environmental impact	1	0.75	-1	-1	0.5
Reduction of the fleet's pollution emissions			-1	-1	-0.5
Fishers' participation in monitoring and control			-0.5	-0.5	
Health status of the marine ecosystem and resources	1	1	-1	-1	-0.5

Marine ecosystem and resources assessment			-0.5	-0.5	
Negative impacts of biological invasions	1	0.5	-0.5	-1	-1
Negative impacts of fishing			-1	-1	
Negative impacts of pollution	1	-0.5	-1	-1	-1
Other negative anthropogenic impacts	1	0.5	-1	-1	-0.25
Driver score	**4.75**	**3.5**	**-3.75**	**-4.75**	**1.25**
Non-driver score	**2.5**	**0.5**	**-10.5**	**-11**	**-7**

Regarding the reliability of the projections provided by our model, it should be stated that this innovative methodology, which has proved to be functional for the case of the Gulf of Lion fisheries, still needs to be tested for other case studies before being generalized. At this stage, we can already conclude that our results are consistent with the storylines co-constructed in the workshop with a representative panel of SES stakeholders, and that it is possible to classify these scenarios according to sustainability indicators. However, these results should not be interpreted as quantitative projections. The sensitivity analysis presented in Figure 55 showed that the change values of the concepts modeled were highly sensitive to variations in the change values of the concepts used as drivers. This should be emphasized in conjunction with the high level of uncertainty concerning the value of change determined for each of the drivers. However, these results, considered as semi-quantitative projections, can be considered reliable due to the monotony of the trends observed in Figure 55, obtained using the sigmoid function as a transfer function. This function is indeed robust to changes in the values of the drivers used (Tsadiras 2008).

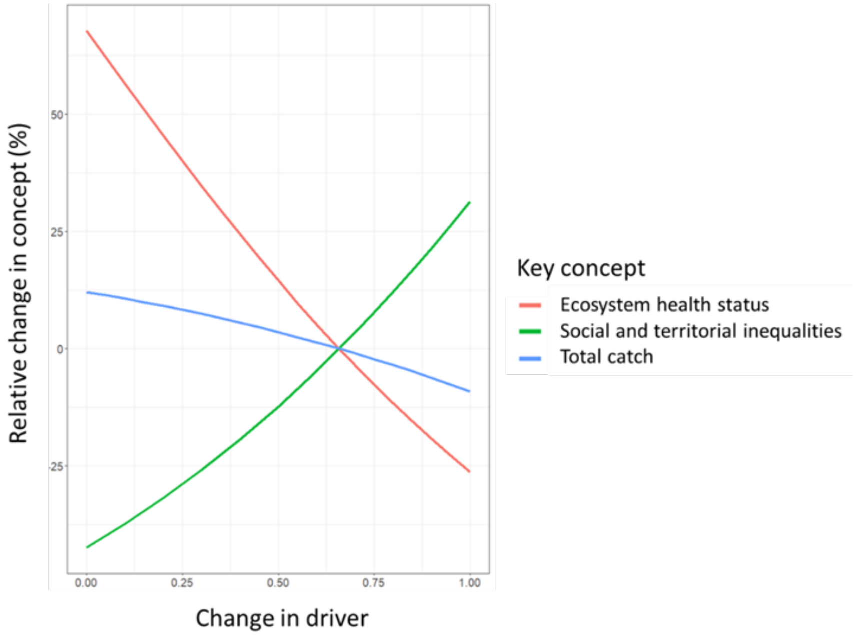


Figure 55: Sensitivity analysis of several key concepts to climate change. In this case, the driver varies between 0 and 1 in steps of 0.05, from no climate change (0) to RCP8.5 scenario (1).

In the social-ecological system of the Gulf of Lion fisheries, we have co-constructed and modeled different scenarios for society, fisheries, and the marine ecosystem through participatory research with a representative panel of stakeholders. Based on the IPCC SSP-RCP narratives, the downscaled scenarios take into account the local characteristics of the fisheries, as well as the knowledge, representations and perceptions of the stakeholders involved.

We found that two of the five scenarios were sustainable, in line with the sustainability targets defined in the EU's Biodiversity Strategy 2030:

- the Global Sustainability scenario (SSP1-2.6), focused on societal well-being and environmental protection, and promoted by strong international cooperation.

- the Local Stewardship scenario (SSP2-4.5), focused on local issues and the development of solutions at local level, and characterized by a wide diversity of livelihoods and socio-environmental conditions.

The three other modeled scenarios appeared to be unsustainable:

- the Global Markets scenario (SSP5-8.5), which features intensified globalization in terms of resource, goods and people flows, and whose energy model is based on the extraction of fossil fuels.

- the National Enterprise scenario (SSP3-7.0), in which each country relies almost exclusively on its own resources, as it withdraws from free-trade agreements and closes its borders.

- the Business As Usual scenario, in line with current trends in French society, and at the interface between the other four scenarios.

Therefore, our results indicate that several sustainable societal trajectories are possible and non-exclusive, at the interface between spheres of international, national, and local governance. To adopt a sustainable trajectory, we need to find practical solutions to establish a model of governance focused on societal well-being, sustainable lifestyles, environmental protection, and virtuous market regulation. To succeed, this model of governance should be based on international cooperation, stakeholder engagement and community empowerment at the local level. Our results are yet another call to action, to break out of the current inertial trajectory, to definitively rule out the most catastrophic scenarios, and to implement transformative change.

5. Conclusions and perspectives

We know that the marine socio-ecosystems studied here (North Sea, Baltic Sea, Bay of Biscay, Mediterranean sea) have been heavily exploited historically, leading to depletion of several commercial species, especially in the Mediterranean Sea, which has also become a hotspot of climate change. Current fishing management and conservation plans comprise a mosaic of measures, e.g., regulation of fishing effort, setting quotas, marine spatial management with ambitious plans such as extending no-take and highly protected areas up to 10%, as well as implementing spatial restrictions to fishing such as the GFCM Fisheries Restricted Areas in the Mediterranean (Claudet et al. 2020; Micheli et al. 2013). Details regarding the implementation of these management targets are currently pending, as they are under discussion at both national and supranational levels. There remains a high level of uncertainty about how the efficiency of these measures will be modified by climate change, and whether sustainable fishing practices helps adapting to climate change.

In addition to changes in fisheries and fisheries policies, for many systems we expect a switch from wild catch (fisheries) to cultivation at sea. In the open North Sea, the expected developments are likely to be extractive aquaculture, i.e. types of aquaculture that take their resources from the marine environment (as opposed to 'fed' aquaculture where food from outside the system is added). Plans for such forms of aquaculture (or mariculture) are extensive and the potential for some to exceed levels of ecological carrying capacity or even production carrying capacity is important to evaluate.

We explored many of these options in this deliverable report, using a variety of modelling approaches, exploring future scenarios as well as the assessment of historical contributions of past and current spatial management to mitigate the cumulative impacts of fishing, aquaculture and climate change.

5.1. Under climate change, there will be winners but also losers even when reaching sustainable fishing targets

Task 4.3 of FutureMARES endeavored to drive forward the ability to project climate driven changes in marine harvesting systems in European waters, which could be then used to inform the development of nature based solutions for these systems (WP6). The work presented in this report delivers on this aim.

Climate impacts on aquaculture

In this report, model simulations projected short-term increases in yields for mussels due to climate change, as the rate of algal growth also increased with higher temperatures. In low dynamic enclosed areas such as the Danish Limfjord, however, increased stratification can have very detrimental effects on bottom mussel cultures. Benthic mussels were projected to experience a lower food supply in all scenarios and, in some case, decreased concentrations of disolved oxygen that reduced mussel biomass in all scenarios. The current mussel fishery varies from 30 to 8 Kt FW per year and this yield has tended to decline over time (Figure 5). The fishery is highly regulated and monitored to avoid overfishing of the population and unacceptable cumulative effects on other ecosystem components (Nielsen et al. 2021). A further decrease of the standing stock by 10 to 36% would have marked impacts on the fishing quota making it less economically attractive.

Hanging cultures were projected to profit from climate change in the Limfjord. Intensified mussel farming was beneficial in all scenarios yielding a much higher harvest without decreasing the mussel shell length by more than 4% compared to the present situation. Shell length is important for the mussel farmers because the market generally demands a shell length >4.5 cm (Buer et al. 2020). For a full year production cycle, the shell lengths were >5 cm in all scenarios, and harvest could occur earlier and expand the market supply period. Mussel spat recruitment in the mussel farms was assumed to be the same in all scenarios and time-slices, despite a decrease in the benthic mussel population.

In the open North Sea, similar to the Limfjord model scenarios, mussel cultivation in many cases benefited from increased temperatures. Simulated cultivation yields were highest in the Hollandse Kust Zuid offshore wind area, which is in the Rhine region of freshwater influence with higher rates of primary production compared to other potential cultivation areas. Final cultivation yields were not proportional to initial seeding biomass: in the model, mussels grew better in areas with lower cultivation density. It has to be noted that there is currently no offshore mussel cultivation on the North Sea. The first experiments with cultivation in a wind farm have just started (https://www.oosinternational.com/oos-group-introduces-the-semi-submersible-mussel-farm-smf/), so there are few, well-validated DEB parameters for mussels for the North Sea. However, these simulations are immediately useful to the industry, as they can give guidance on maximum stocking densities.

Increases in temperature will eventually reduce achieved cultivation yields of kelp. However, in some of the future scenarios, increases in available offshore nutrients compensate for this effect. Kelp being a typical cold-water species, and its current parametrization in the model being based on Norwegian strains and conditions (Broch and Slagstad 2012), it would be valuable for future studies to acertain, through physiological laboratory experiments, if the current parametrization represents kelp behavior in warmer climates. This would lead to more accurate estimates of the net effect of combined changes in nutrient loads and global warming.

A recent particle tracking study indicated that mussel populations in the Limfjord were highly connected across basins (Pastor et al. 2021). Only extreme changes in the pelagic larvae duration or severe hypoxia causing mass mortality of mussels would change the overall dispersal patterns and potentially reduce the connection to the Skive area (Pastor et al. 2023). Furthermore, previous studies have shown that spat recruitment mainly is limited by substrate availability and predation, and not by larvae density in Danish waters (Riisgaard et al. 2015). It has to be noted that in neither of these models (the North Sea model and the Limfjord model) effects such as acidification are taken into account, which may interfere with shell formation and larval growth (Talmage and Gobler 2010).

Climate impacts on Fisheries

Under cumulative impact scenarios of climate change and fishing, ocean warming can impair, or at least limit, the beneficial effects of sustainable fisheries management. For instance, in the Bay of Biscay (using SS-DBEM model), sardine was predicted to largely decline while the recoveries of hake and anglerfish were predicted to have lower magnitude. On the other hand, bluefin tuna and anchovy were predicted to achieve their maximum biomass, mainly due to the increase in food (e.g., anchovy) and the reduction of competition (e.g., albacore and sardine), respectively. Reducing fishing effort appeared to benefit demersal fish in the North Sea under climate change (EwE model) and in the Mediterranean Sea (Osmose model), but with subsequent negative impacts on the biomass of small pelagic fish stocks. Simulations suggest that small pelagic target species would need stronger reductions in fishing effort, compared to large demersal species, to mitigate negative climate change impacts. In summary, all projections based on different models indicated both winners and losers under combined climate change and fishing scenarios, highlighting the importance of using models that explicitly include trophic interactions, climate change and fishing impacts on fish stock dynamics, to identify the most vulnerable species, and devise appropriate fishing management measures for achieving sustainable exploitation of multiple species within an ecosystem context. This report provides key evidence that will help environmental managers develop such strategies.

5.2. Using a variety of ecosystem models is necessary

The aquaculture models used within FutureMARES were relatively similar for mussels; both using a Dynamic Energy Budget (DEB). DEB is a well-established approach to model how organisms deal with energy. Online coupling with ecosystem models allows also to incorporate the feedback that shellfish have on the environment in terms of quick remineralisation of nutrients captured in phytoplankton. This is essential, in order to gain insight on interactions between grazers and interactions between e.g. grazers and primary producers that are not eaten by these grazers, such as seaweed. These mechanistic models, however, lack, the ability to assess the impact of aquaculture on habitat formation and biodiversity. Fundamentally different models (e.g. data driven habitat models) are needed to assess such impacts. These have not been explored within FutureMARES.

To explore future management strategies for fisheries in response to climate change, we relied on a variety of state-of-the-art marine ecosystem models (MEMs), including EwE, Ecospace, SS-DBEM, Osmose, Bioen-Ev-Osmose, FCM. These models are in an advanced development stage, whether in terms of resolved spatial dynamics (Ecospace, Osmose, SSDEM), inclusion of multiple drivers and options through FCMs, or explicit consideration of eco-evolutionary dynamics (Ev-Osmose), thus addressing a gap highlighted in the IPBES global assessment (IPBES 2019 – Chapter 4).

Ecosystem models are considered to be useful in a strategic management context (medium- to long-term advice) (FAO 2008, Howell et al. 2021). In addition, they can be valuable tools in providing input data for single-species stock assessment models (Howell et al. 2021). Ev-Osmose projections showed for example that fish evolution can change the maximum sustainable yield of North Sea saithe (mitigating climate change impacts), and the corresponding fishing mortality target. Ecosystem models have been recently used to adjust reference fishing mortality rates in the Irish Sea (Bentley et al. 2021), to estimate ecological reference points (Chagaris et al. 2020) and to estimate natural mortality rates (Plagányi et al. 2022). Incorporating ecosystem information into fisheries management represents one of the main challenges in the conservation and management of marine ecosystems and represents a practical step towards Ecosystem-based Management (FAO 2008, NOAA 2016, Howell et al. 2021). As next steps, running sensitivity and uncertainty analyses (Lujan et al. accepted), and ensemble model simulations (see T4.4 and WP6 deliverables) will help increase the credibility and usefulness of ecosystem models for the implementation of the Ecosystem-based Management for nature-inclusive harvesting (NBS3) in European regional seas.

5.3. FCMs allow to integrate stakeholder views, knowledge and values

Ecosystem-based management requires stakeholders to be involved to scope key processes, pressures, and impact in relation to sustainability and management objectives. The ICES Working Group on Integrated Assessments of the North Sea (ICES 2020) developed decision support tools using Fuzzy Cognitive Maps (FCMs) (as implemented by Mental Models www.mentalmodeler.org) with stakeholders to evaluate the status of marine ecosystems under varying impacts.

Quantitative ecosystem models are typically designed with a strong focus on the natural, ecological system and fisheries, with other human activities often lacking. By contrast, the sub-regional FCMs usually include several human activities (e.g., shipping, renewable energy, oil and gas) which provides the potential to evaluate a more extensive range of human activities, thus being more aligned with the public's concern for the human dimension of socio-ecological systems. FCMs can also be relatively easily expanded and revised to incorporate new activities. Therefore, FCMs offer a comprehensive representation of marine socio-ecosystems, allowing for the projection of a more varied set of scenarios compared to quantitative ecosystem models which require lengthy development and validation processes to explore new human activities. However, the performance of qualitative models versus quantitative models cannot fully be compared as they have very different structures, while there are also fundamental differences in how the different modelling approaches can be validated and verified.

5.4. Species and harvesting methods evolve

Future changes in aquaculture

In the mechanistic models for aquaculture, validated and calibrated parameter settings were used for the cultivated species. Climate-driven increases in temperature were not projected to pose a risk to hanging mussel cultures. In the Limfjord, benthic mussels were projected to suffer from limited food supply and also, in RCP8.5, from hypoxia, whereas the suspended mussel culture maintained a high harvest potential in all three scenarios. Hence, it is likely that there will be a shift from mussel fishery to suspended mussel culture provided there will be enough farming licenses issued and the spat recruitment continues to be sufficient. Previous studies have shown that system responses to climate change are more variable in coastal systems than for open waters due to the more complex geomorphology and influence of freshwater sources (Filgueira et al. 2016, Idzelytė et al. 2023). Hence, localized model set-ups and scenarios are needed for coastal ecosystems to achieve more realistic climate change projections with higher relevance for the local community. The results of the model scenarios can be used to inform managers, mussel farmers, fishermen, and the local population on potential future changes in bivalve harvesting and ecosystem health and to develop more robust climate adaptation and mitigation plans.

For seaweed, which is in the North Sea cultivated in the surface water layers, model simulations projected decreased yields due to global warming in some regions for *Saccharina latissima*. Parameters such as rates of nutrient uptake and temperature tolerance, were based on this species cultivated in Norway (Broch and Slagstad 2012) and in the Netherlands (Lubsch and Timmermans 2019). Large differences in nutrient uptake kinetics have already been reported for this seaweed in Norwegian versus Dutch waters (Broch and Slagstad 2012, Lubsch and Timmermans 2019). Moreover, evidence for temperature ecotypes of seaweed exist that are adapted to certain ranges in climate (King et al. 2019). Therefore, choosing specific ecotypes to cultivate is a likely climate adaptation strategy. However, there may be distinct limits to the performance of different ecotypes, particularly with kelp species.

In the Limfjord, the numerical ecosystem model was used to make projections of the impact of different scenarios of climate change and nutrient reductions on physical properties, water quality and associated consequences for the benthic and cultured mussels in a shallow estuary. The system showed strong responses of physical water properties and water quality to climate change that partly counteracted the planned nutrient reductions from land. Hence, higher nutrient reductions in the coming Water Plans would be needed to reach a good ecological status under the influence of climate change. The North Sea, being a much larger and better buffered system shows less extreme responses. However, particularly with respect to seaweed, this type of mariculture was projected to have large spatial scale impacts on the nutrient balance and on primary production by phytoplankton, with effects far beyond the perimeter of a farm. The levels of upscaling in scenarios were well below the industry targets. It is clear that there is a need for policy measures limiting the upscaling of the industry to 'acceptable levels of impact'. What is 'acceptable' and how this is put into legislation should be addressed as soon as possible.

Future changes in fish and fisheries

So far, MEMs for fisheries management have focused on the projection of interspecific biodiversity under climate change and management scenarios, but the evolution of intra-specific diversity has rarely been examined. However, fish populations may adapt to climatic and fishing pressures through evolutionary changes that result in changes in their life history that either mitigate (evolutionary rescue) or worsen (evolutionary trap) the consequences of these two pressures (Bradshaw 2006, Darimont et al. 2009, Parmesan 2006). Fisheries-induced evolution (FIE) may lead to faster life histories, i.e, faster growth, earlier maturation and higher fecundity in some instances (Heino et al. 2015). Climate-induced evolution (CIE) is expected to have a similar impact on life history traits (Waples and Audzijonyte 2016, Queiros et al. 2018). In contrast, fisheries-induced plasticity alters life history mostly by relaxing trophic competition or decreasing prey availability, resulting in a slower or faster life history. Climate-induced plasticity alters life history by modifying physiology, resulting in smaller body size and reduced fecundity as conditions worsen. These changes in life history traits could modify fishing reference points. Here, we reported new key evidence on how evolution could dampen climate change effects on North Sea saithe, but this is clearly a preliminary work (Morell et al. in prep.) that needs to be consolidated, and generalized to other exploited species and ecosystems.

Not only can fish populations but also the fisheries sector can adapt to changes in the environment. Adaptation tools need to be proposed and evaluated (Poulain et al. 2018). For example, the fishing industry can adapt by : (i) inducing reductions of captures through increasing the value of their products (increase revenue through sustainable certifications), (ii) reducing fuel use (reduce costs) and (iii) reducing the time at sea with higher digitalization and route optimizations. Modern fisheries heavily depend on fossil fuels (Pauly et al. 2003) and the price increases are likely to continue pushing the fishing industry to improve fuel efficiency to remain profitable (Daw et al. 2009). In addition, the performance of the fishing fleets has decreased, mainly due to declines in coastal fish stocks (Watson and Pauly 2001, Pauly et al. 2003) and the increasing effort needed by fleets to search for target species (Tyedmers et al. 2005, Parker et al. 2018). Like other sectors of the economy, fisheries would be required to mitigate their carbon footprint. Strategies to improve the short- and long-term performance of the industry and to decrease fuel consumption should include behavioral (i.e. reducing vessel speed while steaming and using more selective fishing times and locations Abernethy et al. (2010)), technological and managerial efforts (Parker et al. 2018). Route optimization methods offer an opportunity to the fisheries industry to enhance their economic and ecological sustainability by reducing costs and environmental impacts (Granado et al. 2021), i.e. a win-win for industry and the environment (Pauly et al. 2003, Granado et al. 2021). However, the most effective improvement to fisheries energy performance will result from rebuilding stocks where they are depressed and reducing over-capacity (Parker and Tyedmers 2015). Although few modelling studies have evaluated fish and fisheries adaptation, this lack of information is no reason to delay taking action to mitigate and adapt the fisheries sector to future potential changes (Sumaila 2019). Broader framing of fisheries management under climate change within international policy development for sustainability should thus lead to better outcomes for target species and the human communities that depend on them.

6. Appendices

6.1. Appendix 1. Review of the sustainability targets of The EU Biodiversity Strategy 2030 for marine ecosystems and fisheries

1) Achieving good environmental status of marine ecosystems and fishing resources, with a focus on:

- Nature protection and restoration based on area-based conservation-management measures.

- Reducing the most significant impacts of sea uses covering all maritime sectors and activities.

In the case of the fishing sector, a particular focus is on limiting the use of bottom-contacting fishing gear, illegal practices and by-catch.

- Promoting equity and justice to support the transition to more selective and less damaging fishing techniques.

- Maintaining or reducing fishing mortality at or under Maximum Sustainable Yield (MSY) levels.

- Raising monitoring and scientific advice for management decisions. data collection on all previous points needs to be stepped up.

2) A new government framework:

- Adaptive governance through monitoring, review, progress assessment, and potential corrective actions.

- Concerted management through supporting administrative capacity building, transparency, stakeholder dialogue, and participatory governance at different levels.

- The full implementation and enforcement of the EU environmental legislation.

- The application of an ecosystem-based management approach.

3) The need for more sustainable renewable energy.

4) Reducing pollution, including flows of nutrients such as nitrogen and phosphorus.

5) Limiting the introduction and establishment of alien species.

6) Promoting sustainability through investments, pricing, taxation and incentives:

- Support of biodiversity-friendly investments through EU funding.

- Ensuring that the financial system contributes to mitigating existing and future risks to biodiversity and better reflects how biodiversity loss affects companies' profitability and long-term prospects.

- Promoting tax systems and pricing that reflect environmental costs, including biodiversity loss.

- To incentivize and eliminate barriers for the take-up of nature-based solutions.

7) New business strategies that:

- Address human rights and environmental duty of care and due diligence across economic value chains.
- Ensure that stakeholder interests are fully aligned with the objectives set out in these strategies.

8) Improving knowledge, education, and skills:

- Investing in research, innovation, and knowledge exchange.
- To integrate biodiversity and ecosystems into the education system and professional training.

- Measuring the environmental footprint of products and organizations on the environment, including through life-cycle approaches and natural capital accounting.

6.2. Appendix 2. List of the key concepts for the functioning and sustainability of the Gulf of Lion fisheries

Key concepts were determined for each of the following dimensions through a series of stakeholder homogeneous focus groups. The correspondences of the key concepts with targets of the EU Biodiversity Strategy 2030 (Appendix 1) are highlighted in green.

Alphanumeric code	Dimension	Key concept
Go1	Governance	Acceptability and applicability of regulations and level of control
Go2	Governance	Application of the Common Fisheries Policy in the Gulf of Lion
Go3	Governance	Concerted - integrated - adaptive management
Go4	Governance	Fisheries control
Go5	Governance	Integrated marine spatial planning
Go6	Governance	Investment in research and development
Go7	Governance	Management capacities by the prud'homies
Go8	Governance	Multi-annual - long term management
Go9	Governance	Production rights access
Go10	Governance	Public aid to the fishing sector
Go11	Governance	Relevance of management rules
Go12	Governance	Retirement age
Go13	Governance	Retirement pensions
Go14	Governance	Training access for fishers
Go15	Governance	Understandability of the administrative system and support for fishers
Ec1	Economy	Company debt
Ec2	Economy	Competition
Ec3	Economy	Consumer Information
Ec4	Economy	Diversity of target resources
Ec5	Economy	Economic adaptive capacity of fishers
Ec6	Economy	First sale price
Ec7	Economy	Fishing effort
Ec8	Economy	Installation costs
Ec9	Economy	Investment costs for fleet
Ec10	Economy	Negative impacts of the COVID crisis
Ec11	Economy	Number of jobs
Ec12	Economy	Operating costs
Ec13	Economy	Product value improvement
Ec14	Economy	Profitability of fishing activity
Ec15	Economy	Proportion of sales in auction halls

Ec16	Economy	Sales in short circuit
Ec17	Economy	Seafood demand
Ec18	Economy	Stability of sales turnover
Ec19	Economy	Sustainable consumption preferences
Ec20	Economy	Tourism
Ec21	Economy	Upstream-downstream coordination
Ec22	Economy	Volumes produced
Ec23	Economy	Wages
So1	Social	Anti-fishing activism
So2	Social	Attractiveness of the sector
So3	Social	Concertation between stakeholders
So4	Social	Conflicts of use
So5	Social	EU decision-makers environmental awareness
So6	Social	Fishers' environmental awareness
So7	Social	Fishers' individualism
So8	Social	Fishers' proactivity for a sustainable fishery
So9	Social	Fishing culture
So10	Social	Image of the fishing sector for society
So11	Social	Number of family enterprises
So12	Social	Social and territorial inequalities
So13	Social	Social conflicts
So14	Social	Working conditions
Te1	Technology	Fishers' versatility and diversity of fishing techniques
Te2	Technology	Fishing effort monitoring
Te3	Technology	Fleet energy efficiency
Te4	Technology	Fleet renewal
Te5	Technology	Gear selectivity
Te6	Technology	Reduction of gear's environmental impact
Te7	Technology	Reduction of the fleet's pollution emissions
Te8	Technology	Technological overcapacity
En1	Environment	Climate change
En2	Environment	Depredation
En3	Environment	Fishers' participation in monitoring and control of the marine ecosystem and resources
En4	Environment	Health status of the marine ecosystem and resources
En5	Environment	Marine ecosystem and resources assessment
En6	Environment	Negative impacts of biological invasions
En7	Environment	Negative impacts of fishing
En8	Environment	Negative impacts of pollution

En9	Environment	Other negative anthropogenic impacts
En10	Environment	Positive impacts of exotic species on fisheries
En11	Environment	Use of local ecological knowledge

7. Indexes

7.1. Index of figures

7.2. Index of tables

7.3. References

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