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Project Deliverable Report *(D8.3: Synthesis Report: contribution of FutureMARES NBS to climate change adaptation in marine habitats in all Case Study Regions)*

Dissemination level: **Public**

Type of deliverable: Report

Due date: Project month 48 [31.08.2024]

Project Milestone(s) achieved:
MS31 Storylines comparison workshop at the project 3rd annual meeting (month 37)

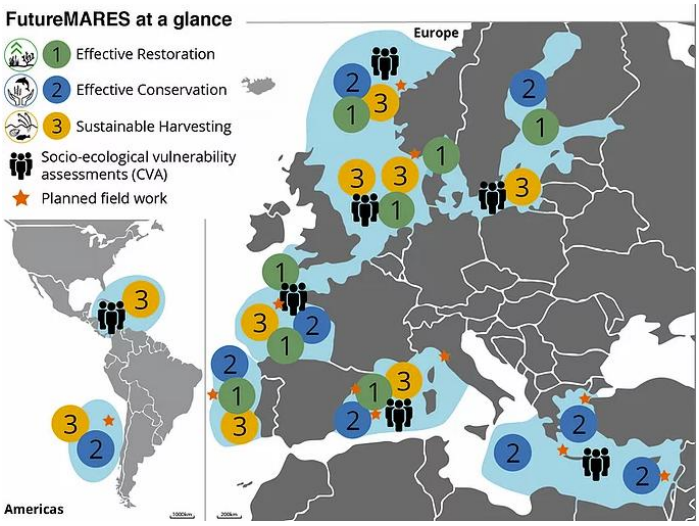
FutureMARES Project

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)

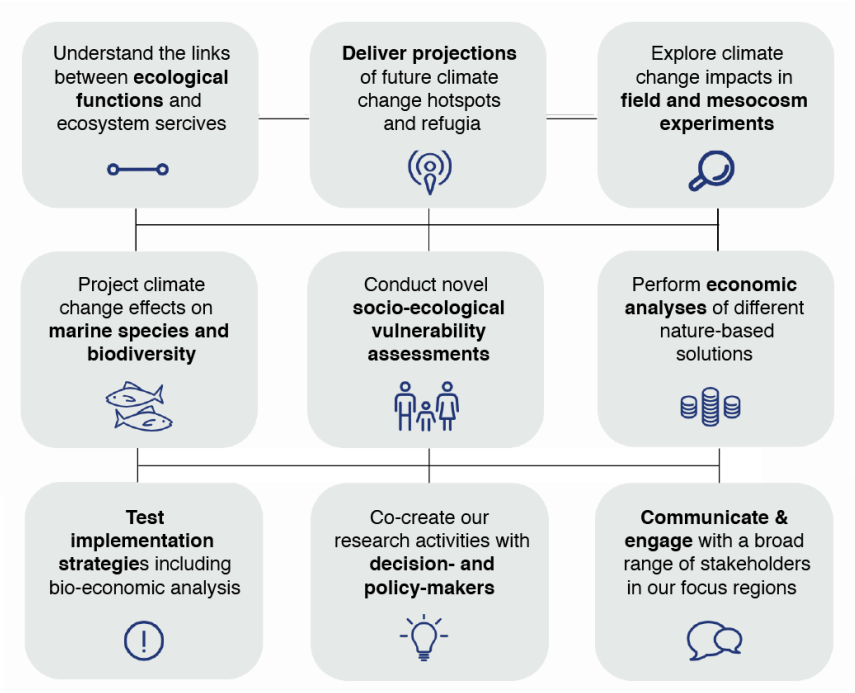
Effective Conservation (NBS2)

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:



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Contact:	Myron.peck@nioz.nl
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Involved partners

Project partner (affiliation)	First name	Last name	E-mail
NOTE - All project scientists in FutureMARES contributed to project synthesis.			
NIOZ	Myron	Peck	myron.peck@nioz.nl
NIOZ	Josefina	Cordera	josefina.cordera@nioz.nl
AU	Dorte	Krause-Jensen	dkj@ecos.au.dk
AZTI	Jose	Fernandes	jfernandes@azti.es
Cimar	Isabel	Sousa Pinto	isabel.sousa.pinto@gmail.com
Cimar	Joao	Rodrigues	joao.rodrigues@ciimar.up.pt
Cefas	Christopher	Lynam	chris.lynam@cefas. gov.uk
CMCC	Momme	Butenschön	momme.butenschon@cmcc.it
CSIC	Joaquim	Garrabou	garrabou@icm.csic.es
CSIC	Marta	Coll	marta.coll.work@gmail.com
Deltares	Luca	Van Duren	luca.vanduren@deltares.nl
IOLR	Gil	Rilov	rilovg@ocean.org.il
PML	Ana	Queiros	anqu@pml.ac.uk
PML	Sevrine	Sailley	sesa@pml.ac.uk
TI	Sarah	Simons	sarah.simons@thuenen.de
UHAM	Vera	Köpsel	vera.koepsel@uni-hamburg.de
UNIPI	Fabio	Bulleri	fabio.bulleri@unipi.it
UVIGO	Elena	Ojea	elenaojea@uvigo.es
UVIGO	Juan	Bueno Pardo	juan.bueno@uvigo.gal

Document history

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02	31.08.2024	V2.0 - Final version, including latest annexes, by Myron A. Peck
03	22.10.2024	V3.0 – Final version re-submitted, including final updates of annexes and DOI of publication, by Josefina Cordera and Myron Peck

FutureMARES receives funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869300 "Climate Change and Future Marine Ecosystem Services and Biodiversity"

Table of content

Executive summary

This report summarizes synthesis activities and products for the FutureMARES program. Synthesis activities started in earnest during the final 10 months of the project. This included three dedicated workshops and a series of online meetings. Project synthesis included three products: 1) Storyline Documents, 2) 5 Policy briefs and, 3) a 100+ page synthesis report. These products targeted regional audiences, policymakers and a wide variety of stakeholders, respectively. PDFs or hyperlinks are provided to all products.

Introduction

This report addresses FutureMARES Synthesis. The Synthesis products are provided as appendices (policy documents, synthesis report draft) or hyperlinks (Storyline documents).

Defining the Challenge

FutureMARES was an ambitious project with activities occurring in five broad regions, with three Case Studies (NBS1 – habitat restoration, NBS2 – conservation, NIH – nature-inclusive harvesting) being conducted at 39 demonstration sites termed “Storylines”. Multi-disciplinary activities occurred across 8 Workpackages, each with several Tasks. The role of project synthesis was to highlight the most important results and products stemming from the program at various scales (local, regional, cross-regional and global).

Approach

Workshops and writing meetings were convened with a selected group of WP and Task leaders to draft the synthesis report. Individual partner institutions were leading and drafting the Storyline Documents during the project. First versions contained introductory information only. Final Storyline documents contain all information on activities (particularly that reported within Deliverable Reports). Policy Briefs were authored by individual experts on specific topics. A graphic designer was hired for the final 8 months of the project to help produce high-quality synthesis materials.

Contribution to the project

The work synthesizes and presents all of the project’s activities in a manner appropriate to various target audiences.

Dissemination and Exploitation

Storyline documents are posted on the project website and will be distributed to relevant national authorities and scientists.

Policy documents are posted on the website and some have already been distributed to relevant stakeholders, particularly decision makers and policy officers at the European Commission and other umbrella projects (e.g. Biodiversa+, Network Nature), including

members of the IPCC (Intergovernmental Panel on Climate Change) and IPBES (Intergovernmental Platform on Biodiversity and Ecosystem Services).

The project synthesis report will be posted on the website and will be distributed to relevant stakeholders (in printed and electronic format), particularly policymakers, decision makers, coordinators of ongoing Horizon Europe projects, and national authorities. These products form the legacy of the FutureMARES project.

1. Section one – Storyline Documents

1.1. Hyperlinks to Storyline Documents

On the FutureMARES website (www.futuremares.eu), under the tab “ABOUT”, there is a list of 25 Storyline documents. Each document can be downloaded. Note, eight of the documents contain multiple Storylines for regional integration and comparison across the three FutureMARES case studies (NBS1, NBS2 and/or NIH).

FutureMARES Storylines

Storylines 1, 2, 3
Norwegian Coast, inter-relationships among kelp, sea urchins and cod

Storyline 4
Salmon at Hardangerfjord, Norway

Storyline 6
Restoration of eelgrass (Zostera marina) in the south-west Baltic Sea

Storyline 7
Conservation of coastal seaweeds, seagrasses, invertebrates and fish in the north-east Baltic Sea

Storyline 8
Basin scale management & MPAs in the Baltic Sea

Storyline 9
Sustainable mussel culture in the Limfjorden, SW Baltic Sea

Storyline 10
Restoration of oysters in Dutch coastal waters

Storyline 11
Saltmarsh, seagrass and kelp habitats in the North Devon UNESCO World Biosphere Reserve

Storylines 12, 13 & 14
Marine spatial planning (broad coverage)

Storyline 15
Seaweed, mussels, and oysters in the north-east Atlantic and North Sea

Storylines 16,17, 18 & 19
Diadromous species in the NE Atlantic Ocean, including transitional and upstream waters

Storylines 20, 22, 24
Nature-based Solutions in the Basque coast of Bay of Biscay: seagrass restoration, protected areas, and sustainable seafood harvesting

Storylines 21 & 23
Kelp forests & biodiversity in northern Portugal

Storyline 25
Restoration of seagrass (Posidonia oceanica) in the Balearic Islands (NW Mediterranean)

Storyline 26
Marine Protected Area network for Aegean biodiversity

Storyline 27
Karpathos & Saria MPAs: seagrasses and meadows, soft/rocky bottom

Storyline 28
Seagrass meadows and macroalgal forests in the MPA network of the Tuscan Archipelago

Storyline 29
Habitat-forming macroalgae / corals in the western Mediterranean Sea

Storylines 30, 31, 33
Conservation / Fisheries Sustainability in the Western Mediterranean from a regional perspective + synergies

Storyline 32
Basin-wide sea turtle conservation in the Mediterranean Sea

Storyline 34 & 35
Climate change and bioinvasion impacts on reef & canopy-forming macroalgae and shelf fisheries in SE Mediterranean Sea

Storyline 36
Biogeography and biodiversity change on coastal communities at continental scales

Storyline 37
Hotspots and refuges for European Seas under the pressures of warming, acidification and deoxygenation

Storyline 38
Sustainable Seafood Harvesting in the Belize EEZ

Storyline 39 & 40
Ecosystem approach for the Chilean island systems

Here is a list of hyperlinks to the Storyline Documents:

SL 1,2,3: Norwegian Coast, inter-relationships among kelp, sea urchins and cod.

SL 4: Salmon at Hardangerfjord, Norway.

SL 6: Restoration of eelgrass (*Zostera marina*) in the south-west Baltic Sea.

SL 7: Conservation of coastal seaweeds, seagrasses, invertebrates and fish in the north-east Baltic Sea.

SL 8: Basin scale management & MPAs in the Baltic Sea

SL 9: Sustainable mussel culture in the Limfjorden, SW Baltic Sea

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SL 20, 22 & 24: Nature-based Solutions in the Basque coast of Bay of Biscay: seagrass restoration, protected areas, and sustainable seafood harvesting

SL 21 & 23: Kelp forests & biodiversity in northern Portugal

SL 25: Restoration of seagrass (*Posidonia oceanica*) in the Balearic Islands (NW Mediterranean)

SL 26: Marine Protected Area network for Aegean biodiversity

SL 27: Karpathos & Saria MPAs: seagrasses and meadows, soft/rocky bottom

SL 28: Seagrass meadows and macroalgal forests in the MPA network of the Tuscan Archipelago

SL 29: Habitat-forming macroalgae / corals in the western Mediterranean Sea

SL 30, 31 & 33: Conservation / Fisheries Sustainability in the Western Mediterranean from a regional perspective + synergies

SL 32: Basin-wide sea turtle conservation in the Mediterranean Sea

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SL 36: Biogeography and biodiversity change on coastal communities at continental scales

SL 37: Hotspots and refuges for European Seas under the pressures of warming, acidification and deoxygenation

SL 38: Sustainable Seafood Harvesting in the Belize EEZ

SL 39 & 40: Ecosystem approach for the Chilean island systems

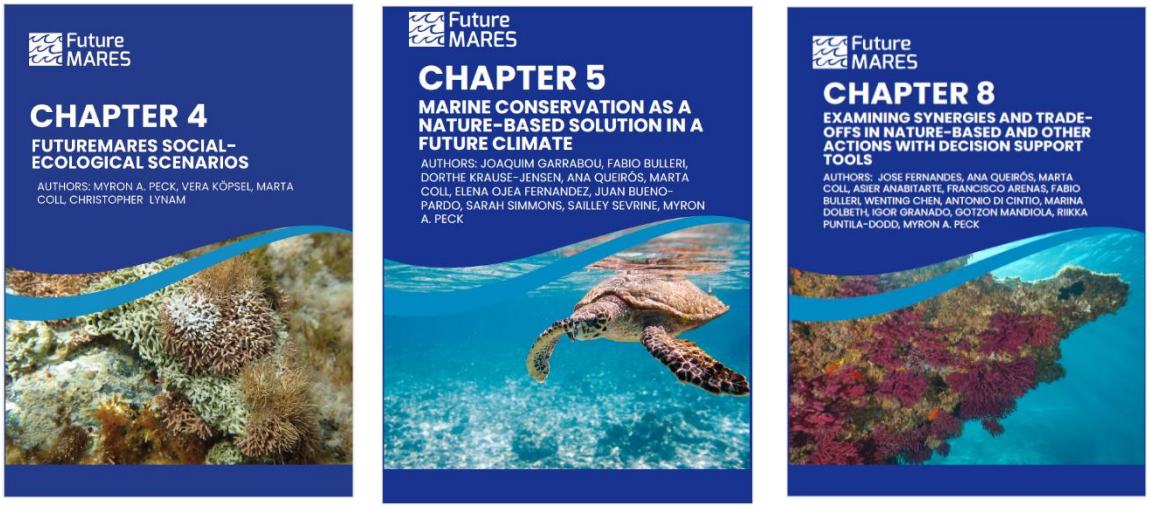
2. Section two – Synthesis Report

2.1. Synthesis Report

The Synthesis report is included as a separate PDF file.
DOI: 10.4121/eda95802-ce4e-4c34-93ad-c34ee59ec0da

A 1.5-day workshop was held in Thessaloniki, Greece directly after the 3rd annual meeting. All synthesis products were discussed. By the close of that meeting, all participants had agreed on chapter details, a timeline for writing and upcoming in-person meetings. A 2.5-day, in-person writing meeting took place in Driebergen, The Netherlands in early May. Additional work continued by correspondence and at the final meeting held on Texel in late June.

Some of the members of the synthesis writing group that met in Driebergen, The Netherlands from 7th to 9th May, 2024.

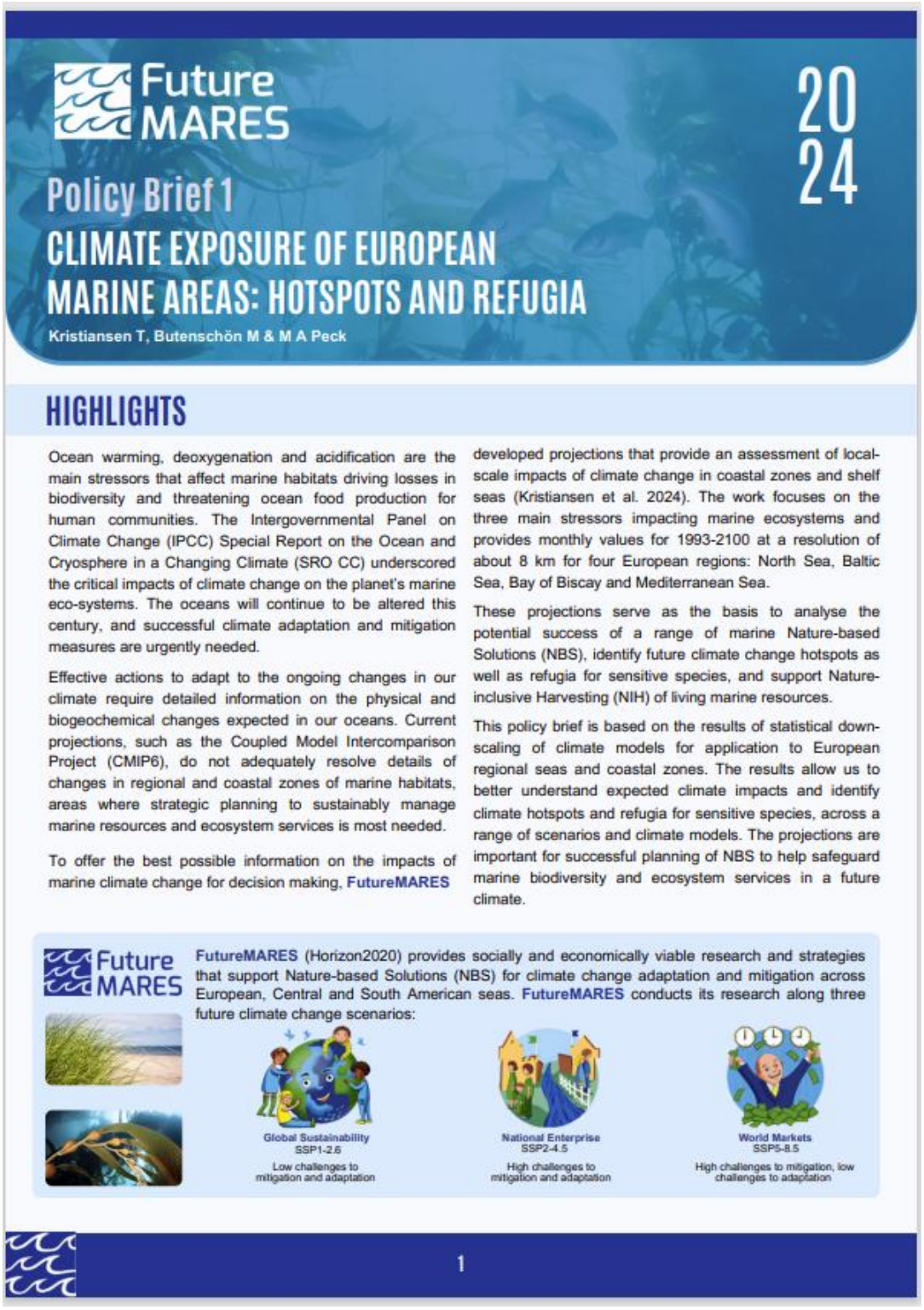


Examples of Chapter front pages.

3. Section three – Policy Briefs

3.1. Hyperlinks

Policy Brief 1: **Climate Exposure of European Marine Areas: Hotspots and Refugia.**



Future MARES

2024

Policy Brief 1

CLIMATE EXPOSURE OF EUROPEAN MARINE AREAS: HOTSPOTS AND REFUGIA

Kristiansen T, Butenschön M & M A Peck

HIGHLIGHTS

Ocean warming, deoxygenation and acidification are the main stressors that affect marine habitats driving losses in biodiversity and threatening ocean food production for human communities. The Intergovernmental Panel on Climate Change (IPCC) Special Report on the Ocean and Cryosphere in a Changing Climate (SRO CC) underscored the critical impacts of climate change on the planet's marine eco-systems. The oceans will continue to be altered this century, and successful climate adaptation and mitigation measures are urgently needed.

Effective actions to adapt to the ongoing changes in our climate require detailed information on the physical and biogeochemical changes expected in our oceans. Current projections, such as the Coupled Model Intercomparison Project (CMIP6), do not adequately resolve details of changes in regional and coastal zones of marine habitats, areas where strategic planning to sustainably manage marine resources and ecosystem services is most needed.

To offer the best possible information on the impacts of marine climate change for decision making, FutureMARES developed projections that provide an assessment of local-scale impacts of climate change in coastal zones and shelf seas (Kristiansen et al. 2024). The work focuses on the three main stressors impacting marine ecosystems and provides monthly values for 1993-2100 at a resolution of about 8 km for four European regions: North Sea, Baltic Sea, Bay of Biscay and Mediterranean Sea.

These projections serve as the basis to analyse the potential success of a range of marine Nature-based Solutions (NBS), identify future climate change hotspots as well as refugia for sensitive species, and support Nature-inclusive Harvesting (NIH) of living marine resources.

This policy brief is based on the results of statistical down-scaling of climate models for application to European regional seas and coastal zones. The results allow us to better understand expected climate impacts and identify climate hotspots and refugia for sensitive species, across a range of scenarios and climate models. The projections are important for successful planning of NBS to help safeguard marine biodiversity and ecosystem services in a future climate.

Future MARES

FutureMARES (Horizon2020) provides socially and economically viable research and strategies that support Nature-based Solutions (NBS) for climate change adaptation and mitigation across European, Central and South American seas. FutureMARES conducts its research along three future climate change scenarios:

Global Sustainability SSP1-2.6

Low challenges to mitigation and adaptation

National Enterprise SSP2-4.5

High challenges to mitigation and adaptation

World Markets SSP5-8.5

High challenges to mitigation, low challenges to adaptation

1

Policy Brief 2: **Marine Biodiversity: Climate Sensitivity and Resilience.**

Future MARES

2024

Policy Brief 2

MARINE BIODIVERSITY: CLIMATE SENSITIVITY AND RESILIENCE

Rilov G, Chust G & Peck M A

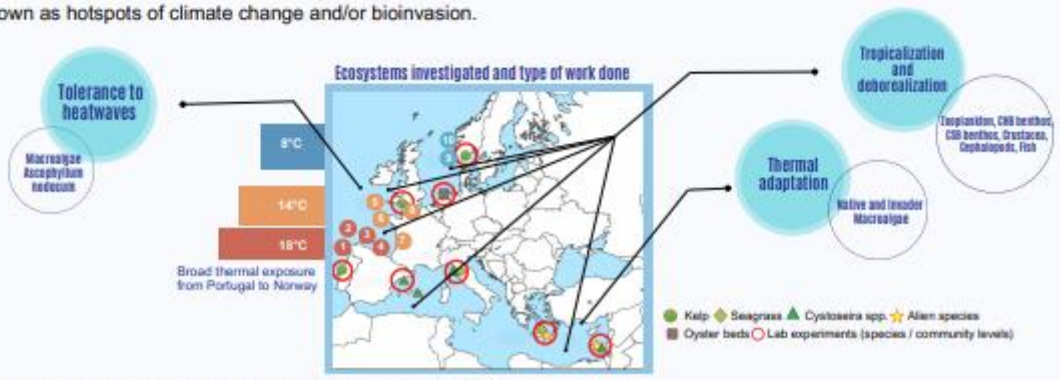
HIGHLIGHTS

Climate change poses a huge challenge to implementing effective Nature-based Solutions (NBS) - marine conservation and restoration - and Nature-inclusive Harvesting (NIH) for sustainable seafood harvesting. Local and regional shifts in the composition of marine species have occurred and can be particularly rapid in climate change hotspots* where sensitive species decline while warmer-water species thrive. The question is: what biodiversity do we preserve or restore in a future climate? This is more complex in areas also recognized as hotspots of bioinvasion where invaders from warmer waters will do better than native species in a future climate.

Marine communities altered by climate change and/or bioinvasion may not always represent degraded, or poorly-functioning systems. These altered systems may function similarly and provide similar services as the original, pristine communities, but homogenise regional diversity. Therefore, marine ecosystem health descriptors such as those used by the EU Marine Strategy Framework Directive (MSFD), may be improved by not only considering the richness of native species but also - or alternatively - the complementarity, functions and services offered by marine communities, especially in regions known as hotspots of climate change and/or bioinvasion.

Sensitivity to climate-driven stressors may differ within a species as local populations adapt to specific thermal conditions. In these cases, climate sensitivity is best defined by measurements made on local populations along latitudinal or thermal gradients. A correct sensitivity identification allows more reliable future climate-driven change estimations in species distribution. Moreover, differences in sensitivity can also be harnessed to increase the success of future restoration efforts by, for example, selectively using more climate-resilient populations of habitat-forming species.

This policy brief presents **FutureMARES** results from field and laboratory studies that increase our understanding of historical changes in marine biodiversity and our ability to predict future ecological impacts. **FutureMARES** aims to give solid science-based knowledge for better management of restoration and conservation targets (Rilov et al. 2019) and to improve EU directives on this matter, such as the MSFD as well as the Marine Spatial Planning (MSP) including Marine Protected Areas (MPAs) (Rilov et al. 2020).



*For a wider analysis of hotspots and refugia in future climate, see our Policy Brief 1

1

Policy Brief 3: **Nature-Based Solutions Decrease Climate Risks to Marine Habitats and Ecosystem Services.**

Future MARES

2024

Policy Brief 3

NATURE-BASED SOLUTIONS DECREASE CLIMATE RISKS TO MARINE HABITATS AND ECOSYSTEM SERVICES

Juan Bueno-Pardo,[1] Elena Ojea,[1] Myron A. Peck[2]
1 Future Oceans Lab, Centro de Investigación Mariña, Universidade de Vigo, Spain
2 Royal Netherlands Institute for Sea Research - NIOZ, Texel, Netherlands

HIGHLIGHTS

Nature-based solutions (NBS) are low-cost management tools inspired by the functioning of natural systems that can enhance our resilience to climate change by preserving or restoring the structural integrity of habitats.

The potential of NBS has raised the attention and there is an increasing demand from managers to understand their application, advantages and potential drawbacks. In this context, building consistent and comparable methods to gauge NBS effectiveness is an important step towards understanding and communicating the benefits of NBS.

FutureMARES evaluated more than 30 examples of the implementation of NBS (effective conservation and restoration), and Nature-inclusive Harvesting (NIH) using novel Climate Risk Assessment (CRA) methodology (Bueno- Pardo et al., 2024).

Based on expert opinion and environmental analysis, this method measures the amount of risk a NBS can reduce. The risk reduction due to NBS intervention provides an approximation of the NBS effectiveness from the perspective of different species, ecosystem services and social groups.

This policy brief provides a general overview of how risk is calculated considering NBS and introduces an online risk tool to perform the assessment. Examples of outputs from the **FutureMARES** project are provided to illustrate the effectiveness of marine NBS and/or NIH in reducing climate-driven risks to marine habitats and species.

Figure 1. Climate risk assessment framework adapted from the IPCC (2022) to measure the effectiveness of NBS. The NBS can potentially lower each dimension of risk (Hazards, Exposure and Vulnerability) for different components of the marine system (species, ecosystem services and social groups) under different future scenarios and timeframes.

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Policy Brief 4: **European Digital Marine Labs: Testing the role of NBS in Climate Change Mitigation and Sustainable Fisheries.**

Future MARES

Policy Brief 4

2024

EUROPEAN DIGITAL MARINE LABS: TESTING THE ROLE OF NBS IN CLIMATE CHANGE MITIGATION AND SUSTAINABLE FISHERIES

Marta Coll[1], Christopher Lynam[2], Xavi Corrales[3], Lucia Espasandin[1], Miquel Ortega[1], Riikka Puntila-Dodd[4], Dorota Szalaj[1], Maciej Tomczak[5], Jeroen Steenbeek[6], Myron A. Peck[7]

1 Spanish National Research Council - CSIC, Spain; 2 Centre of Environment Fisheries and Aquaculture Science - Cefas, UK; 3 Centro Tecnológico de Investigación Marina y Alimentaria - AZTI, Spain; 4 Finnish Environment Institute - SYKE, Finland; 5 Stockholms universitet, Sweden; 6 Ecopath International Initiative, Spain; 7 Royal Netherlands Institute for Sea Research - NIOZ, Texel, Netherlands.

HIGHLIGHTS

Digital marine laboratories are advanced research platforms that leverage digital technologies to study multiple aspects of marine ecosystems and cumulative impacts of human activities to assess "what-if" scenarios and inform management. These labs integrate computational tools, modelling frameworks, and data visualization techniques to develop digital experiments that simulate oceanographic and environmental processes, and the interactions between physical, chemical, biological, ecological and socioeconomic drivers.

FutureMARES used state-of-the-art digital laboratories for virtual experiments to investigate the effects of climate change and management interventions on human activities for three socio-political scenarios (Global Sustainability GS, National Enterprise NE and World Markets WM) for European regional seas. These experiments used an ecosystem-based perspective and combined Nature-based Solutions (NBS) with Nature-inclusive Harvesting (NIH).

In a context of future climate change, with expected further increases in temperature and changes in primary production, **these digital laboratories provide new tools to help management interventions to maintain and restore biodiversity and support productive, sustainable fisheries.**

This Policy Brief outlines the results of seven digital representations of European seas that take either a regional perspective (North Sea, Baltic Sea, Bay of Biscay and Western Mediterranean Sea), or a sub-regional perspective (Finnish Archipelago Sea, NW Mediterranean Sea, and the Portuguese Shelf).

Specifically, spatial-temporal marine ecosystem models, using the Ecopath with Ecosim and Ecospace framework, were refined and developed to explore impacts of contrasting climate projections with and without additional management interventions.

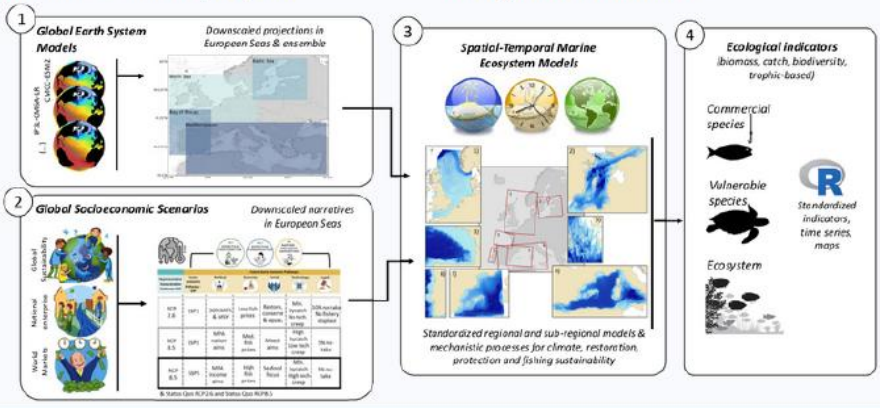


Figure 1. Workflow developed under FutureMARES to link global Earth System models, socioeconomic scenarios and marine ecosystem models to develop scenarios of NBS and NIH for each of 4 regional European Seas and 3 sub-regional areas.

1

Policy Brief 5: **Blue forest in a future climate**

Future MARES

Policy Brief 5

BLUE FORESTS IN A FUTURE CLIMATE

2024

Dorte Krause-Jensen[1], Ana Queirós[2], Fabio Bulleri[3], Elizabeth Talbot[2], Rob Wilson[2], Marta Coll[4], Ignacio Catalán[4], Jorge Terrados[4], Myron A. Peck[5]

1 Aarhus Universitet - AU, Denmark; 2 Plymouth Marine Laboratory Limited - PML, UK; 3 Universita di Pisa - UNIPI, Italy; 4 Spanish National Research Council - CSIC, Spain; 5 Royal Netherlands Institute for Sea Research - NIOZ, Texel, Netherlands.

HIGHLIGHTS

European blue forests - including saltmarshes, seagrass meadows and canopy-forming macroalgae - form fringes along the coastlines from the intertidal to the subtidal as deep as water clarity and other habitat conditions allow. **They support biodiversity, constitute a coastal nutrient filter and contribute to carbon uptake and storage** in the marine environment while also **protecting coastlines** against flooding and erosion and **buffering extreme temperatures and acidification.**

Blue forests have experienced **major declines** in distribution and associated provision of ecosystem services due to pressures such as eutrophication, physical damage caused by activities like coastal construction and trawling, as well as impaired top-down control from overfishing.

FutureMARES projected that **climate change**, including warming and heatwaves, will be **an increasingly challenging pressure interacting with other human activities** to alter the distribution and health of these habitat-forming species in Europe in the decades to come.

Our findings strongly suggest consideration of climate change effects on the distribution and health of blue forests to ensure that conservation and restoration efforts for these species remain sustainable. Beyond taking into account projections of climate change impacts, there is a need to reduce other pressures, such as eutrophication and physical damage. Hence, combined actions are crucial to avoid further losses and promote recovery of habitats and associated benefits, thereby offering nature-based contributions to address multiple challenges.

This policy brief presents FutureMARES' results linked to blue forests and the grounds of our recommendations.

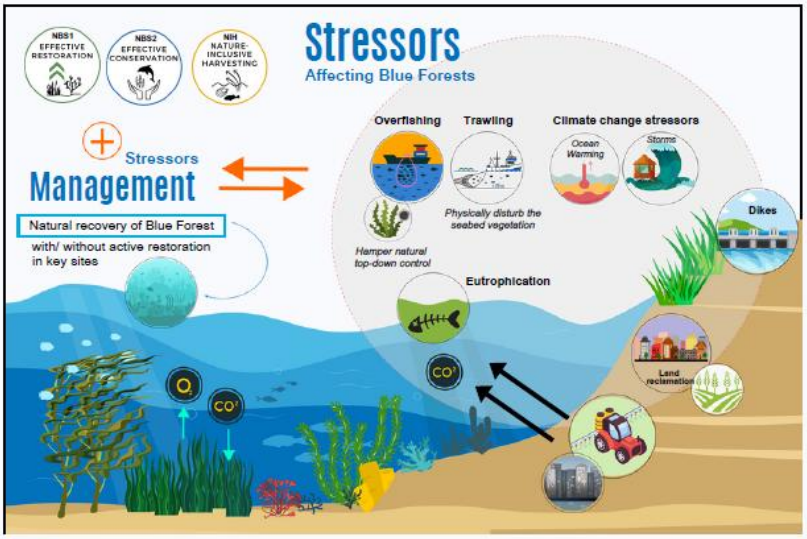


Figure 1. Principal pressures affecting Blue Forest and how nature-based contributions can help to avoid further losses.

1

Future MARES

THE FUTUREMARES EU PROJECT SYNTHESIS REPORT

Marine Nature-based Solutions and Sustainable Seafood Harvesting in a Future Climate

2020- 2024

"The FutureMARES EU Project Synthesis Report. Marine Nature-based Solutions and Sustainable Seafood Harvesting in a Future Climate".

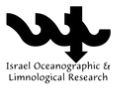
FutureMARES Coordinator	Myron A. Peck
FutureMARES Project Manager	Sanne Veenenbos

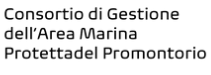
This report summarises the research findings of the EU Horizon 2020 FutureMARES (Climate Change and Future Marine Ecosystem Services and Biodiversity) project, executed between September 2020 and August 2024.
Coordinated by the Royal Netherlands Institute for Sea Research (NIOZ), part of the Stichting Nederlandse Wetenschappelijk Onderzoek Instituten - NWO-I

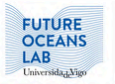
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869300. This publication reflects only the author's views and the European Union is not liable for any use that may be made of the information contained therein.

www.futuremares.eu

FutureMARES Consortium





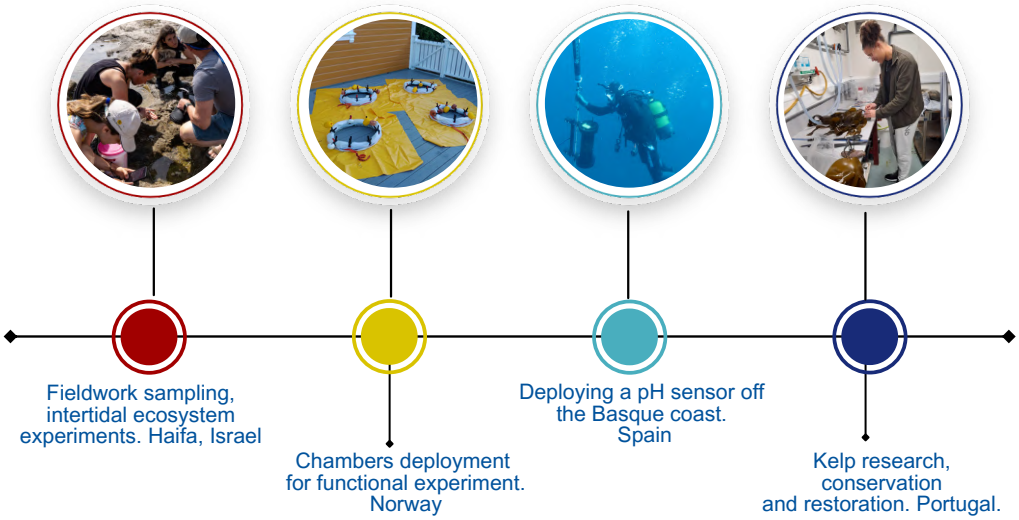


List of Abbreviations

BA	Bias Correction
BN	Bayesian Network
CBA	Cost-Benefit Analysis
CEA	Cost-Effectiveness Analysis
CC	Climate Change
CELAC	Community of Latin American and Caribbean States
CER	Cost-Effectiveness Ratio
CFP	EU Common Fisheries Policy
CICES	Common International Classification of Ecosystem Services
CM	Climate Model
CMIP6	Coupled Model Intercomparison Project Phase 6
COP	Conference of the Parties
CRA	Climate Risk Assessment
DAPSI(W)R(M)	Drivers, Activities, Pressures, State, Impacts (Welfare), Responses (Measures) framework
DEBs	Dynamic Energy Budget
DST	Decision Support Tool (or DSS - System)
EBMF	Ecosystem-Based Fisheries Management
EC	European Commission
ES	Ecosystem Service
ESM	Earth System Model
EEZ	Exclusive Economic Zone
EU	European Union
FMSY	Fishing Mortality at Maximum Sustainable Yield
GES	Good Environmental Status
GIS	Geographical Information System
GS	Global Sustainability (FutureMARES scenario)
ICES	International Council for the Exploration of the Sea
IPBES	Intergovernmental Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
MEO	Marine Estuarine Opportunistics
MPA	Marine Protected Area

List of Abbreviations

MSFD	EU Marine Strategy Framework Directive
MSP	Marine Spatial Planning
NBS	Nature-based Solutions
NE	National Enterprise (FutureMARES scenario)
NIH	Nature-inclusive Harvesting
OSPAR	Oslo and Paris Conventions
OWF	Offshore Wind Farm
RCP	Representative Concentration Pathway (IPCC scenario)
RSC	Royal Society of Chemistry
SD	Statistical Downscaling
SDMs	Species Distribution Models
SL	Storyline (a regional demonstration site in FutureMARES)
SSP	Shared Socio-economic Pathway (IPCC scenario)
TAC	Total Allowable Catch
UNFCCC	United Nations Framework Convention on Climate Change
WM	World Markets (FutureMARES scenario)



Some of the fieldworks performed along FutureMARES project.

Main Authors

NIOZ	Myron A.	Peck	Myron.peck@nioz.nl
NIOZ	Josefina	Cordera	josefina.cordera@nioz.nl
AU	Dorte	Krause-Jensen	dkj@ecos.au.dk
AZTI	Jose	Fernandes-Salvador	jfernandes@azti.es
Ciimar	Isabel	Sousa Pinto	isabel.sousa.pinto@gmail.com
Ciimar	Joao	Rodrigues	joao.rodrigues@ciimar.up.pt
Cefas	Christopher	Lynam	chris.lynam@cefas. gov.uk
CMCC	Momme	Butenschön	momme.butenschon@cmcc.it
CSIC	Joaquim	Garrabou	garrabou@icm.csic.es
CSIC	Marta	Coll	marta.coll.work@gmail.com
DELTARES	Luca	van Duren	luca.vanduren@deltares.nl
IOLR	Gil	Rilov	rilovg@ocean.org.il
PML	Ana	Queiros	anqu@pml.ac.uk
PML	Sevrine	Sailley	sesa@pml.ac.uk
TI	Sarah	Simmons	sarah.simons@thuenen.de
UHAM	Vera	Köpsel	vera.koepsel@uni-hamburg.de
UNIPI	Fabio	Bulleri	fabio.bulleri@unipi.it
UVIGO	Elena	Ojea	elenaojea@uvigo.gal
UVIGO	Juan	Bueno-Pardo	juan.bueno@uvigo.gal

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Future MARES

CHAPTER 1

INTRODUCTION: THE EU FUTUREMARES PROGRAM

AUTHORS: MYRON A. PECK

CO -AUTHORS: JOSE A. FERNANDEZ-SALVADOR, ARANTZA MURILLAS, VERA KÖPSEL

01 Introduction: The EU FutureMARES Program

Global assessment reports by the IPCC (2021) and IPBES (2019) provide irrefutable evidence for the global threats to our planet's climate and biodiversity. For more than a century, huge losses have occurred in the spatial extent of marine habitats supporting high biodiversity due to the impact of multiple anthropogenic pressures including eutrophication, other pollution, overfishing, trawling of the seafloor, coastal construction, deforestation of habitat-forming species, and climate change (Díaz et al. 2019, Duarte et al. 2020). The indelible link between the climate and biodiversity crises has been recognized and is increasingly reflected in international, EU and national policies. These crises are frequently seen as two interlinked components of a broader planetary crisis which needs to be addressed in an integrated manner (Pörtner et al. 2021). In the last three years, climate - and biodiversity - related issues have dominated the top (most likely) long-term risks identified in the annual Global Risks Report of the World Economic Forum including failure to mitigate climate change (CC), failure of CC adaptation, and biodiversity loss and ecosystem collapse (WEF 2023, 2024). Losses in healthy marine habitats are particularly acute in coastal areas which supporting 75% of the world's population and where ecosystem services for society have been estimated at > 27 trillion USD yr^{-1} (Costanza et al. 2014).

The EU Green Deal, its Biodiversity Strategy for 2030, and the EU Nature Restoration Law ratified in June 2024 represent a logical progression of increasing commitment by Europe toward implementing actions that halt the alarming loss of global biodiversity while, at the same time, increasing climate resilience. One of the key objectives of the European Union's H2020 work program was to help build societies resilient to the impacts of CC, including extreme events and natural disasters. The FutureMARES project ("Climate Change and Future Marine Ecosystem Services and Biodiversity") was funded by the EU H2020 call LC-CLA-06-2019 'Inter-relations between climate change, biodiversity and ecosystem services. The overarching goal of FutureMARES was to provide socially and economically viable actions and strategies for CC adaptation and mitigation to safeguard future biodiversity, and ecosystem functions, maximising natural capital and its delivery of services from marine and transitional ecosystems.

FutureMARES conducted the state-of-the-art science needed to provide targeted knowledge supporting the implementation and upscaling of Nature-based Solutions (NBS) in light of ongoing and future climate change. Building on the United Nations Environment Programme (UNEP 2022), the EU Commission defines NBS as "solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience". Europe is also the largest importer of seafood worldwide (FAO 2024) and, as part of its Farm to Fork strategy (EC 2020), the EU has placed emphasis on growing the Blue Economy and promoting more independence in food security, especially after lessons learned from the Covid-19 pandemic.

Addressing these policy goals and aspirations, FutureMARES was designed to study two types of marine NBS (habitat restoration, conservation strategies) as well as Nature-inclusive Harvesting (NIH) (Fig. 1.1).

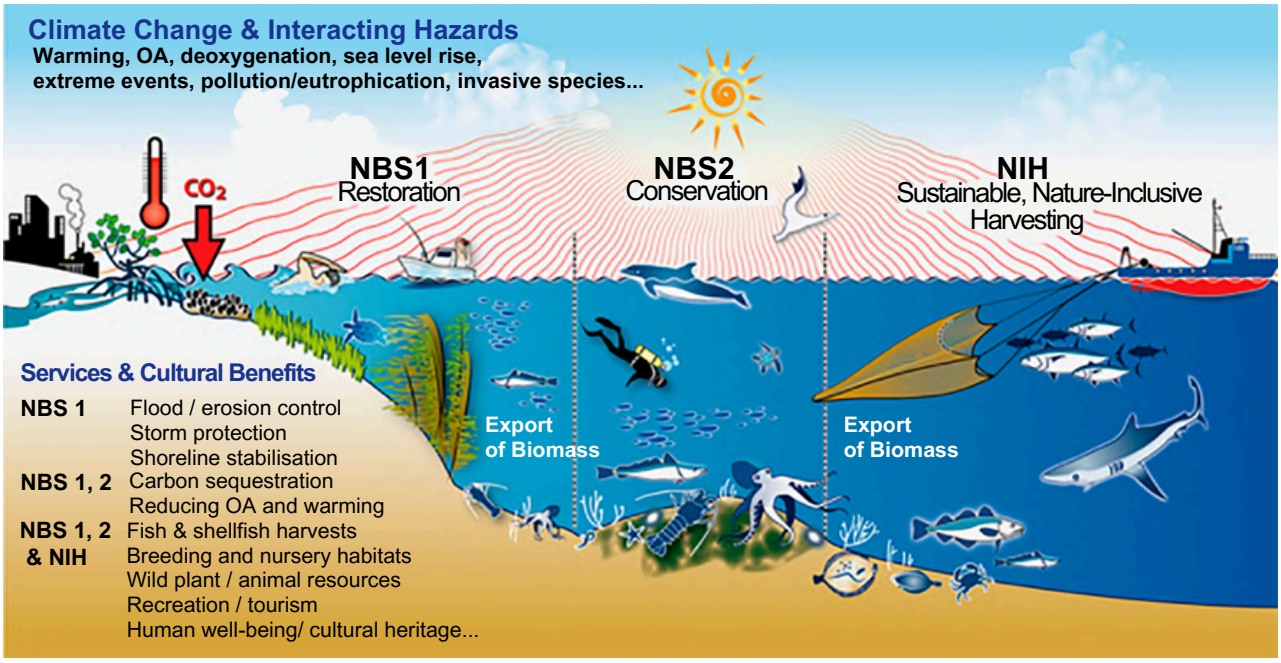

Figure 1.1, Interacting stressors and hazards, and Services and Cultural Benefits of the two Nature-based Solutions (NBS) and Nature-inclusive (Sustainable) Harvesting examined in the FutureMARES program.

(NBS1) Effective Restoration Strategies of habitat-forming species that can act as 'climate rescuers'. Targeted habitats include seagrasses, salt marshes, mangroves, kelp forests, coral reefs and shellfish reefs, which can buffer species from negative effects of warming and ocean acidification (Bulleri et al. 2018). These habitats are also key nursery areas supporting biodiversity (including commercially important species), provide natural refuges and feeding grounds, improve seawater quality, reduce coastal erosion and flood risk, function as carbon sinks (regulating climate), and sustain tourism and cultural activities.

(NBS2) Effective Conservation Strategies explicitly considering the range of impacts of CC and other hazards on habitat suitability for flora and fauna. Strategies explored include preserving the integrity of food webs and sustaining population connectivity across networks of climate refugia (where biogeochemical and physical conditions are stable or changing slowly (Ban et al. 2016)) over multiple spatial and temporal scales (i.e., from site-specific marine protected areas to conservation strategies for highly migratory charismatic megafauna).

(NIH) Sustainable, Nature-Inclusive Harvesting of seafood from fisheries and aquaculture that is flexible, adaptive, equitable, and managed on a whole-ecosystem basis. Ongoing impacts of CC require an ecosystem-based management and multispecies approach (Fu et al. 2018) that can adapt to shifts in the productivity, distribution and interactions of species (Peck & Pinnegar 2018), while continuing to provide social and economic benefits. High-level EU policy advisors have highlighted culture and capture at lower trophic levels as critical for sustainable seafood production (EU 2017).

Any solutions implemented to address the CC and biodiversity crises must also account for potential trade-offs among multiple users, different economic sectors and various types of ecosystem services.

Thus, the active restoration habitats (NBS1), the conservation and protection of marine habitats and ecosystems (NBS2), and sustainable Natural-inclusive Harvesting (NIH) are indelibly linked. Management interventions do not act in isolation but, rather, can exert synergetic, positive effects, or antagonistic, negative effects.

The goals and ambitions of FutureMARES were to (Fig. 1.2):

1. Advance knowledge on the historical impacts of CC on marine species based on their traits by analysing the best available, long-term field data, and performing new experiments to fill important gaps in knowledge on CC impacts on key species, their biogenic habitats, and ecological functions;
2. Deliver ensemble projections of the physical and biogeochemical impacts of CC, such as warming, decreases in dissolved oxygen content, and acidification, at appropriate spatiotemporal scales that reduce uncertainty and identify CC hotspots and refugia (Chapter 3);
3. Create social-ecological scenarios that build on existing IPCC frameworks to be able to perform regional projections of the consequences of implementing NBS and/or NIH to difference extents in different climate futures;
4. Advance a suite of state-of-the-art, mechanistic and spatially-explicit species and ecosystem models to deliver projections of the effects of CC on the distribution and productivity of important (keystone, structural, endangered) species and habitat characteristics important for planning climate-resilient conservation, habitat restoration or sustainable harvesting strategies;
5. Conduct novel, social-ecological risk assessments to rank the severity of the effects of CC in the presence and absence of NBS/NIH on various species / habitats, ecosystem services, and dependent human communities;
6. Perform bioeconomic analyses of implementation scenarios of NBS and NIH at real-world demonstration sites including the costs and benefits of habitat restoration, conservation strategies and sustainable harvesting;
7. Co-develop project research activities with decision- and policymakers and managers to help ensure impactful, transformative, science-based advice to contribute to CC adaptation and mitigation strategies (Box 1.1);
8. Engage and effectively communicate with a broad range of stakeholders involved in the stewardship of natural capital, biodiversity and ecosystem services in marine, transitional (and terrestrial) ecosystems.

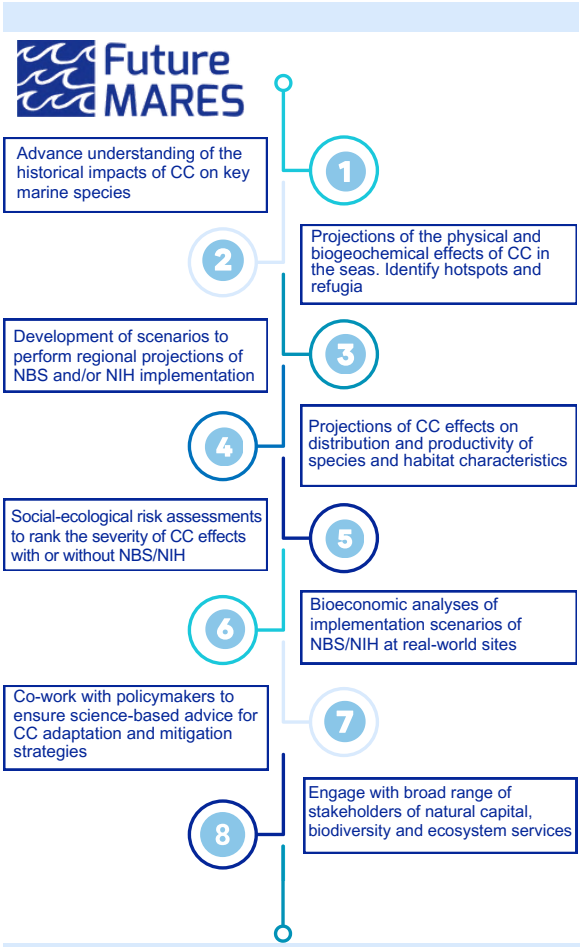

Figure 1.2, Actions and products of the EU FutureMARES program. Note, action point 7 occurred throughout the four years of the project.

BOX 1.1 Co-creating the FutureMARES program with stakeholders

A key element of FutureMARES was the exchange with a vast network of stakeholders from environmental management to scientists working on climate change adaptation planning (Fig. 1.3). Project partners cooperated with key stakeholders on national, regional and international levels to co-frame research activities and receive critical feedback from end-users on the design and usability of all products. This stakeholder network provided an invaluable vehicle for disseminating and increasing the impact and uptake of the results and products of FutureMARES.

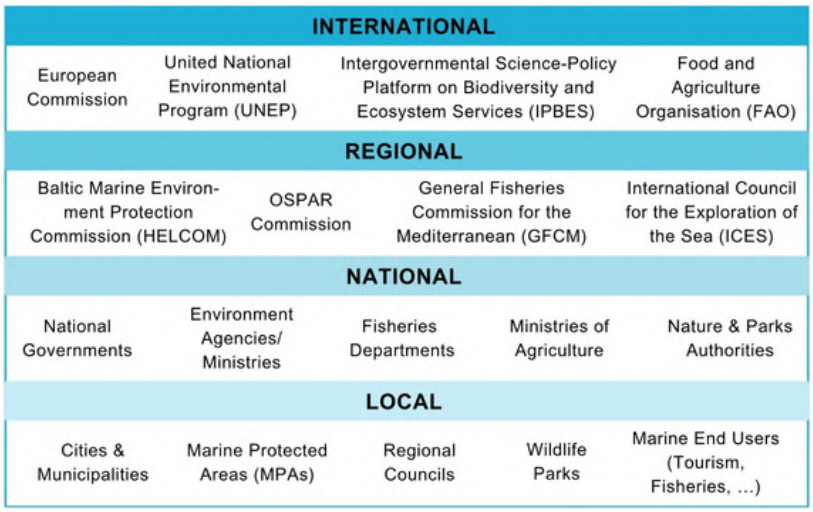

Figure 1.3, Timeline of Stakeholder Engagement in FutureMARES. (Deliverable Report 7.2)

To best tailor stakeholder engagement activities and project outputs to the specific needs of stakeholders across European and CELAC regions, FutureMARES partners conducted engagement activities with local stakeholders at the start, middle and toward the end of the 4-year project. These activities helped FutureMARES deliver information and results that can be exploited by these stakeholders in their daily work (e.g. by MPA managers to create CC adaptation plans) including the co-design of decision-support tools (see Chapter 8).

A novel element of the stakeholder engagement was the creation of a Platform for Knowledge Needs (Fig 1.4) that enabled decision makers to access the scientific and technical expertise within the project to address their knowledge needs on marine biodiversity and climate change. The Platform allowed for the co-creation of science-based solutions between decision makers and project experts, helping to bridge a common gap between science and policy, specifically a mismatch between the supply and demand of policy-relevant research. Within the Platform, FutureMARES worked with the Irish Wildlife Trust, as a member of Fair Seas, to identify where climate-resilient MPAs could be located in the Irish Exclusive Economic Zone to improve conservation efforts. That work was highlighted in the report, entitled A climate resilient path for Ireland's Marine Protected Area network (Queiros et al. 2024). FutureMARES also worked with the Norwegian Environment Agency to provide a climate risk assessment (see Box x) of emblematic species occurring at the North Atlantic Current and Evlanov Sea (NACES) basin MPA located in the high seas between Iceland and the Azores. FutureMARES recommends that future research programs use similar approaches and frameworks to create the actionable science needed to address the climate x biodiversity crises.

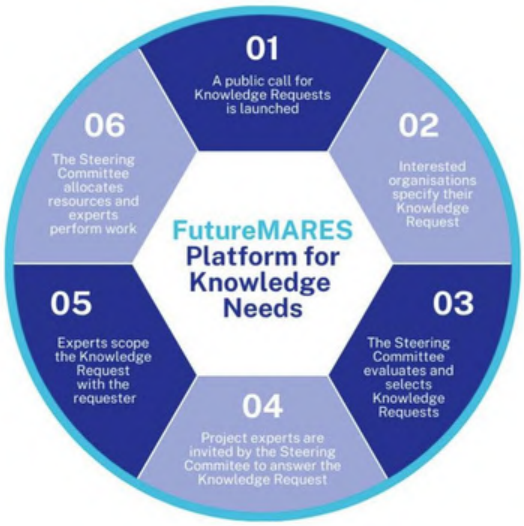

Figure 1.4, The six steps taken in the FutureMARES Platform for Knowledge Needs.

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These eight goals and ambitions demanded an interdisciplinary approach that combined various fields of research from the physical sciences, to sociology and economics.

Regional implementation in "Storylines"

FutureMARES explored marine habitat restoration, marine conservation and sustainable seafood harvesting within five regions. Locations of activities included sub-polar zones (NE Atlantic & North Sea, Baltic Sea), temperate zones (SE Pacific, Bay of Biscay, Iberian Coast, SE Pacific) and sub-tropical and tropical zones (Caribbean and Mediterranean Sea). This breadth in spatial coverage allowed the program to capture large differences in local contexts arising from not only ecological but also cultural differences.

The activities of the project were conducted within demonstration sites called “Storylines” (Fig. 1.5). Storylines differed markedly in spatial scale from specific field locations where habitat restoration was being monitored to basin-scale fisheries research within regional seas. The activities in each Storyline were tailored to fill existing knowledge gaps and the needs of policymakers and managers designing and implementing Nature-based Solutions and/or sustainable seafood harvesting.

Marine habitat restoration (NBS1) was explored in 8 Storylines. These Storylines targeted habitat-forming species: shallow-water seagrass meadows, kelp forests, coastal saltmarshes, and biogenic habitats from coral-forming animals, and reefs formed by bivalves (oysters).

Conservation measures (NBS2) were examined in 17 Storylines. This including climate-smart Marine Protected Area (MPA) networks covering different foundation and emblematic species within various habitats from marine to transitional waters and soft-hard to shallow-deep bottoms. Work also was performed on species of conservation concern such as marine turtles, diadromous fishes, and marine mammals.

Sustainable, Nature-inclusive Harvesting (NIH) practices were examined within 14 Storylines. This included work exploring synergies between nature-based solutions, particularly MPAs, and aquaculture or fisheries production to advance a more holistic, ecosystem-based approach to marine system management.

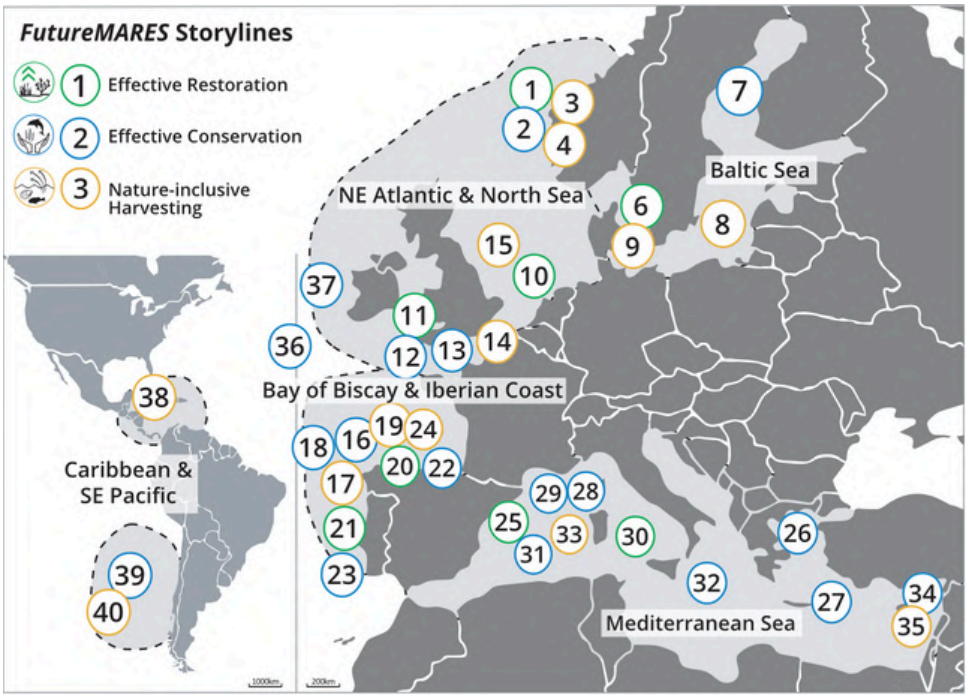

Figure 1.5, Demonstration sites "Storylines" where activities of the project were conducted.

BOX 1.2 Assessing the health of marine habitats: an ecosystem services indicator framework

The Common International Classification of Ecosystem Services (CICES) classifies ecosystem services (ES) into three overarching categories depending on whether the contributions to human wellbeing support: (i) the provisioning of material and energy needs, (ii) regulation and maintenance of the environment for nature and humans, and (iii) the non-material characteristics of ecosystems that affect the physical and mental states of people, that is their cultural significance.

An assessment framework of marine ES indicators to quantify the socio-ecological effectiveness of **Nature-based Solutions** (NBS) and **Nature-inclusive Harvesting** (NIH) under **climate-driven changes** was developed (Murillas- Maza et al. 2023). It creates a common understanding about the health status of ecosystems, their ES, and the impact of implementing restoration (NBS1), conservation (NBS2) & NIH to inform policymakers and the public. The interaction between the biodiversity indicators and the socioeconomic response, and pressure

Indicators per NBS/NIH and overlap

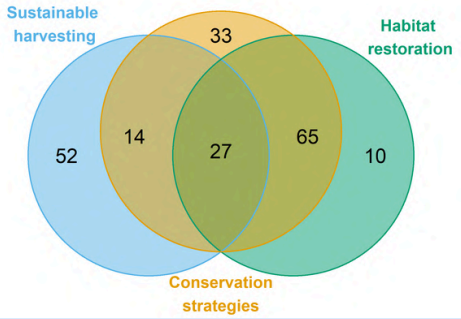

Fig 1.6, Number of indicators per Nature-based Solution and number of overlapping indicators in a Venn diagram. There were 201 distinct indicators. (Deliverable Report 1.5)

indicators was established using the ES cascade framework (Haines-Young & Potschin 2010, De Groot et. al. 2010) to summarize the link between ecological and biophysical structures and processes with the human well-being. This framework is combined with others such as the DAPSI(W)R(M) and the Standard National Account and the System of Environment Economic Accounting, which provide

evidence to value the contributions of ES to human well-being.

Literature review (LR). In total, 201 indicators were assessed (Fig. 1.6), and some can measure the effect of more than one NBS & NIH. Biodiversity & Environmental as well as Pressure indicators are the most numerous in the list, representing 34 % and 23 % of the total, respectively. Only the 12 % of the total belong to the economic dimension, mainly related to the output approach (business indicators) rather than demand-based indicators and, non-market-based ones, which are rarely adopted in the literature.

The analysis revealed several gaps and goals that need to be achieved to ensure that a holistic multidisciplinary ES assessments can be carried out. Trade-offs analysis between CC impacts and other broader biodiversity, social or economic impacts will be very limited unless those identified gaps will be fulfilling.

The use of the ES cascade model helped identify gaps where specific ES cannot be assessed across the entire model.

Application across 27 storylines. 70% of the LR identified indicators were also empirically verified. Few storylines provide an integrated and fully assessment of the NBS & NIH impacts in marine and coastal ES. The pattern is similar here for economic indicators which were less applied in the 27 European storylines and was worse for social indicators. This work provides the strengthened evidence-based framework of indicators needed to build resilience protecting the marine and coastal ES under climate change. A framework which reinforces not only the multidisciplinary nature of the evaluation of NBS & NIH impact on ES but also, the equilibrium between the key groups trying to overcome the current bias towards an assessment mainly based on harvest, habitats, and pressures knowledge.

Arantza Murillas & Jose A. Fernandes-Salvador

Outline of this Synthesis Report

This Synthesis Report includes nine chapters structured around the FutureMARES work program. After this brief introduction, the subsequent chapters describe the accomplishments of FutureMARES and highlight results that, in many cases, integrate across Storylines, regions and/or NBS and NIH.

Chapter 2 provides a summary of the historical time series revealing climate change impacts on marine taxa and communities. New measurements and analyses on habitat-forming species are discussed that allow to better understand climate sensitivity and, in some cases, the responses to multiple stressors. During the planning phase of FutureMARES, one of the biggest identified gaps in knowledge was on responses of plants and animals to increased frequency and intensity of marine heatwaves. A second gap in knowledge was quantitative comparisons of the ecological functions (such as carbon storage) of pristine, degraded, and restored benthic habitats. This chapter, therefore, examines historical changes and provides new measurements from field and laboratory experiments to overcome those gaps.

Chapter 3 discusses the results of statistically downscaling the physical and biogeochemical estimates from coarse-scale global climate model and earth system models to higher spatial resolutions, needed for performing ecological modelling. At the onset of the project, an important goal was to identify climate change hotspots, where rates of change were projected to be most rapid, and climate change refugia, where rates of change were minimal or zero. Identifying these different areas was deemed critical for planning successful interventions to boost marine biodiversity such as the location of MPA networks and/or areas of active habitat restoration.

These IPCC-based projections formed the backbone of ecological projections made for habitat-forming species, species of conservation concern, and for food webs and marine ecosystem modeling.

Chapter 4 briefly introduces the social-ecological scenarios developed in FutureMARES that were used for subsequent analyses and projections in the project. Broad scenario narratives for NBS1 (habitat restoration), NBS2 (conservation) and NIH were developed based on the IPCC Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs). These scenarios included Political, Economic, Societal, Technological, Legal and Environmental aspects needed to perform targeted projection modeling on NBS and NIH implementation. The three contrasting scenarios were used for climate risk assessments, Bayesian Network analysis, bioeconomic analyses, and in digital laboratories examining impacts to ecosystem functioning, services and indicators of Good Environmental Status.

The results of ecological and bioeconomic projections as well as the climate risk assessments performed by FutureMARES are discussed within and across its regional Storylines in **Chapters 5 to 8**. Specific chapters convey the results and messages on implementing habitat and species conservation (Chapter 5), active habitat restoration (Chapter 6) and Nature-inclusive/ sustainable Harvesting of seafood (Chapter 7). The results of analyses that cut across the two NBS and/or NIH to identify synergies and/or trade-offs are also discussed by providing examples from three decision support tools co-developed with end users and by analyzing ecosystem-based projections (Chapter 8).

The knowledge, tools, solutions, and activities produced under FutureMARES and presented in this synthesis report were aimed at informing and contributing to various stages of the policy cycle, including policy agenda setting, formation, implementation, monitoring and evaluation. The **final chapter** (Chapter 9) summarizes the accomplishments of FutureMARES to environmental policy. This includes the program's contribution to global, European and national policies.

Each chapter delivers concrete advice that will be useful to scientists, managers and decision-makers working at the climate x biodiversity interface and charged with implementing climate-ready NBS and NIH. Each chapter also includes one or more "Boxes" that dive more deeply into specific topics, methods or tools.

Much more detailed information can be found on the FutureMARES website (www.futuremares.eu). The website contains information in various formats for different target audiences including more than 20 reports submitted to the European Commission, five policy briefs, and around 100 peer-reviewed publications. Furthermore, reports for each of the FutureMARES Storylines are available to download (see Appendix 1).

Through its work, FutureMARES has improved the understanding of the inter-relations between climate change impacts, and how NBS and NIH implementation alone or in combination, can increase the adaptation and mitigation potential of marine habitats, and safeguard the delivery of ecosystem services. The interdisciplinary products and advice generated and shared within this synthesis report are the culmination of field monitoring and measurements, laboratory experiments, numerical modeling and expert interviews conducted by more than 200 scientists across 33 partner institutions located across 15 countries. FutureMARES is indebted to the hard work, dedication, and effective collaboration of all members of the project consortium.

Future MARES

CHAPTER 2

SENSITIVITY, FUNCTIONALITY, AND ADAPTIVE CAPACITY OF SPECIES AND HABITATS TO CLIMATE CHANGE

AUTHOR: GIL RILOV

02 Sensitivity, functionality, and adaptive capacity of species and habitats to climate change

Introduction

The unfolding climate crisis has rapidly changed ocean conditions, especially in climate change hotspots (See Chapter 3). In such areas, sensitive species exposed, for example to warming, can either adapt, move to more favorable areas (if they can), or die. Population decline is not necessarily immediate. For instance, ocean warming at the warm (trailing) edge of a species distribution will gradually reduce the performance (metabolic functions, growth, reproduction, etc.) of thermally sensitive species, which will affect the population viability followed by population decline and eventually collapse to extirpation (Bates et al. 2014). Decline can also be fast, such as the case of extreme events, like as marine heatwaves (MHWs), that can lead to mass mortalities (Garrabou et al. 2022), and MHWs accumulation. If they affect long-lived species such as corals, they can also lead to persistent local extinctions. Well-connected climate change hotspots can also experience the rapid colonization of more resilient species, either natives through range extension, or invasive non-natives arriving from other, warmer ecoregions with human aid, or both. These processes result in either deborealization or/and tropicalization of the local community (McLean et al. 2021).

The decline of sensitive native species and the colonization of new species in a specific site naturally leads to shifts in species composition (biodiversity) and possibly in ecosystem functions and services. Such shifts can pose a big challenge to marine conservation, restoration and sustainable harvesting because the species and communities we aim to preserve, or harvest, are changing in distribution and productivity in response to changes in ocean climate or weather. Thus far, this challenge has not been adequately addressed by planning and implementation of EU Directives such as the Marine Strategy Framework Directive (MSFD) and Habitats Directive, as well as Marine Spatial Planning (MSP), including the planning of MPAs (Rilov et al. 2020). To address this challenge, conservation targets and strategies need to be based on solid science from the fields of physiology, ecology, and genetics (Rilov et al. 2019) among others, and be adaptive to the shifting environmental conditions and policies (Rilov et al. 2020).

Gaps in knowledge exist, however, in ecological understanding on several key aspects - including trends, mechanisms, impacts and projections - that are relevant to understand the vulnerability or resilience of marine ecosystems to climate change. These gaps include: (1) detection and comparison of trends in biodiversity shifts that are based on long-term time series in different regions and taxonomic groups, (2) understanding the links between environmental conditions and species response traits, (3) physiologically testing the climate sensitivity of ecologically or economically key native species, (4) determining if key species show local thermal adaptation across their distributional range, (5) comparing how resilient would be native and invasive species to future change, and (6) evaluating what are the functional ramifications of current and future biodiversity change, and how would those changes affect potential ecosystem services.

FutureMARES was designed to fill some of these gaps in knowledge using (a) long-term biological and environmental datasets to detect biodiversity trends across regions and link them to climate shifts, and (b) both field and laboratory work conducted across Storylines from Norway in the north Atlantic to Israel in the southeastern Mediterranean to improve mechanistic understanding of how climate change may impact key species and communities. First, FutureMARES collated long-term biological time-series for benthic and pelagic species and ecosystems, collected by research laboratories and institutes across Europe. This unique, multidecadal dataset has facilitated the first European-scale analysis of changes in the Community Temperature Index (CTI) and allowed novel, trait-based analyses to be conducted. Second, climate-related knowledge gaps relevant to specific regions or habitats were addressed by new laboratory and fieldwork conducted on key species or communities within various Storylines. This included experiments predominately made on shallow benthic communities, where species sensitivity to one or several stressors was measured and ecosystem functions of relatively intact vs. altered or restored communities were compared. Ecological and genetic studies also examined the potential for adaptation to change, and the potential vulnerability of populations due to genetic isolation. This Chapter uses several examples from different Storylines to showcase the depth and breadth of the results on sensitivity, functionality, and adaptive capacity of species and habitats to climate change (Fig. 2.1).

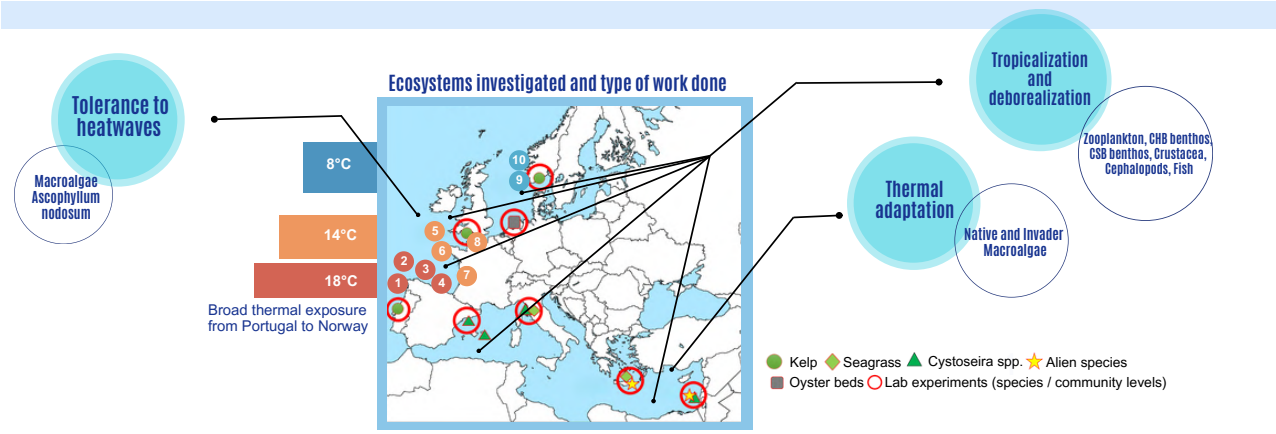

Figure 2.1, FutureMARES carried out field and laboratory studies that increase the understanding of historical changes in marine biodiversity and the ability to predict future ecological impacts. (Deliverable Report 3.1)

Research within FutureMARES

Long term trends in biodiversity change linked to ocean warming

FutureMARES has thoroughly documented historical changes in marine species and habitats that can be attributed to climate change (Chust et al. 2024). Environmental time series of up to four decades from 65 monitoring programmes, including historical data for 1,817 marine species (zooplankton, benthos, pelagic and demersal invertebrates, and fish) were analyzed by calculating the CTI. The CTI is a standardized indicator that provides quantitative information on community composition and its affinity for warm or cold waters. Across the entire range of organisms and habitats, results showed an average rate of increase in CTI of 0.23 ºC decade-1, meaning a consistent response of these various marine communities to ocean warming across European Seas. Over the past 40 years, the NE Atlantic Ocean has experienced a tropicalization of its communities, with an increase in the abundance of warmer-water species,

while the Mediterranean and Baltic Seas, where warming has been more rapid, have seen a marked decline in cold-water organisms (Fig. 2.2 & 2.3).

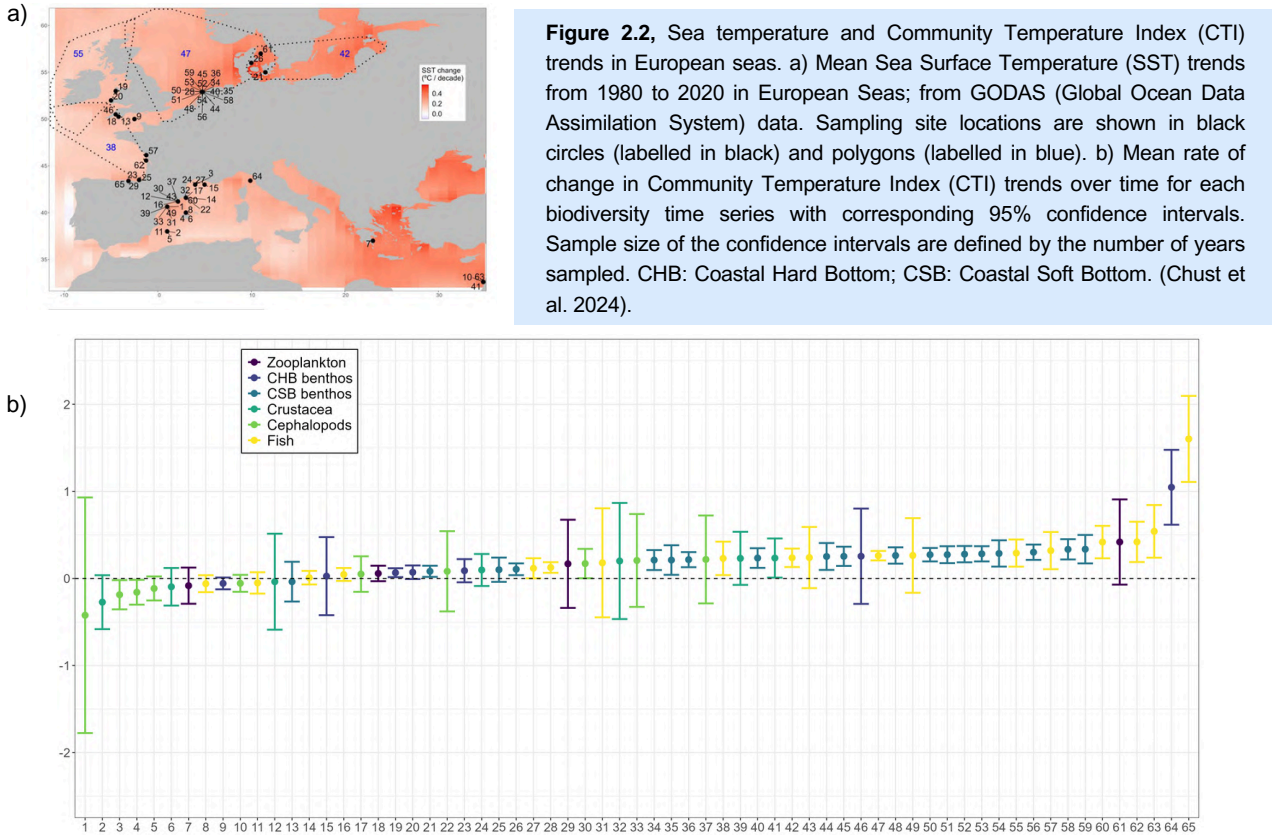

Figure 2.2, Sea temperature and Community Temperature Index (CTI) trends in European seas. a) Mean Sea Surface Temperature (SST) trends from 1980 to 2020 in European Seas; from GODAS (Global Ocean Data Assimilation System) data. Sampling site locations are shown in black circles (labelled in black) and polygons (labelled in blue). b) Mean rate of change in Community Temperature Index (CTI) trends over time for each biodiversity time series with corresponding 95% confidence intervals. Sample size of the confidence intervals are defined by the number of years sampled. CHB: Coastal Hard Bottom; CSB: Coastal Soft Bottom. (Chust et al. 2024).

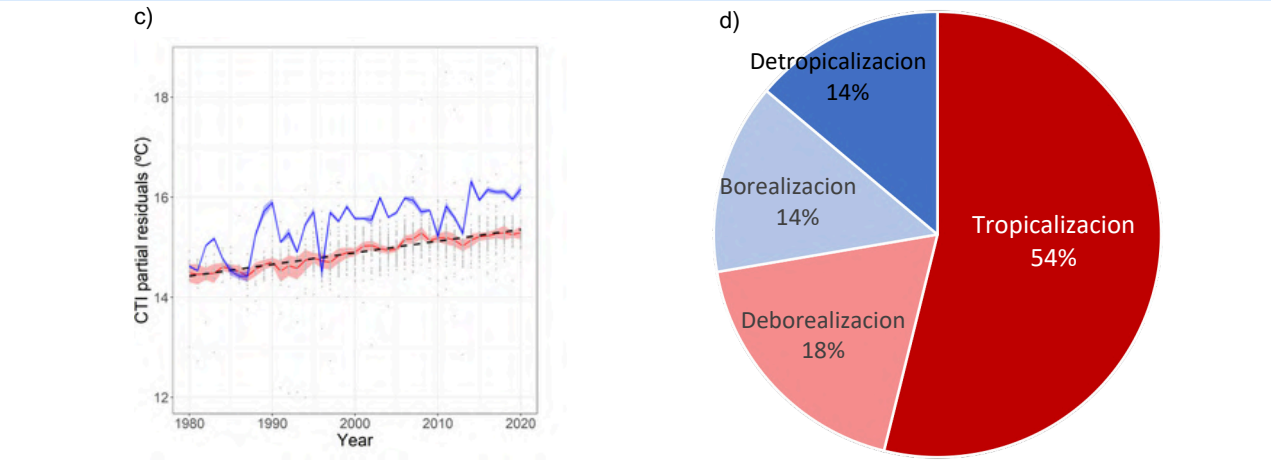

Figure 2.3, c) Partial residuals of CTI across time, calculated as CTI minus the random effect of sampling site of the mixed model with year as fixed effect and site as random effect. In blue, partial residuals of SST across time. Grey points: partial residuals. Black dotted line: fixed effect of the linear mixed model. In red and shaded pink: annual mean and confidence interval of CTI partial residuals. In blue: annual mean and confidence interval of SST partial residuals. d) Percentage of the prevailing underlying process ((de)tropicalization, and (de)borealization) over all biodiversity time series. (Chust et al. 2024).

One Mediterranean exception is the southeast corner of the Levant (Storyline 35) where tropicalization of shellfish was also strong (37%, vs. deborealization 34%) due to the invasion of dozens of tropical species through the Suez Canal, as was evident from trawl fishery data (Fig. 2.4). These CTI results, published in *Nature Communications*, warn of continued change in the biodiversity of European Seas and oceans as temperatures continue to increase.

These alarming trends have potential economic and social consequences and highlight the importance of NBS and NIH for climate adaptation and mitigation.

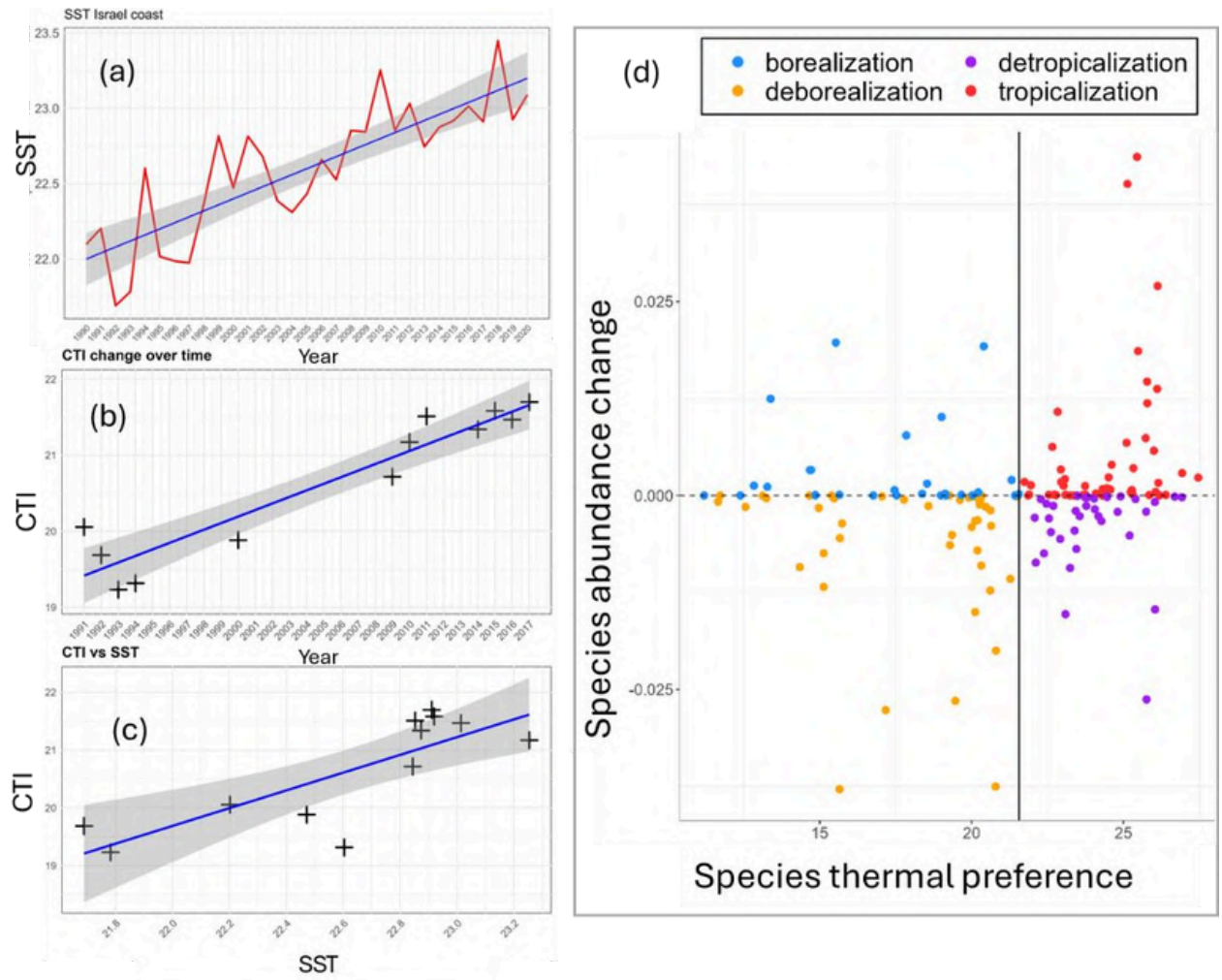

Figure 2.4, Community Temperature Index (CTI) and thermal affinity change based on fishery-independent trawl fishery data from the Israel coast between 1992-2022. (Chust et al. 2024). Annual mean sea surface temperature (SST) change (a), CTI change over the years (b), correlation between CTI and SST (c), and shifts in species abundances towards borealization, deborealization, detropicalization or tropicalization during that period (d). (Deliverable Report 1.3)

Links between biological traits and environmental conditions

A useful framework to foster a more mechanistic understanding of the underlying responses of species, habitats and communities to changes in their environment is the identification of species "key response traits". These traits serve to represent the performance of species in response to environmental variability and explain why a community is found in a specific habitat but not in another. To demonstrate this, FutureMARES conducted a statistical analysis of response traits and trait-environment relationships using available monitoring data across a broad range of marine organisms and ecosystems throughout European Seas.

In terms of traits, the majority of these field data exhibited pronounced structuring in space and time for characteristics and adaptations relating to lifespan (or longevity), age-(or size) at-maturation, growth, and body size. This was particularly evident for fish and benthic communities across a range of habitats and spatial scales in the Aegean Sea, as part of Storyline 26

(Fig. 2.5). Consequently, such life-history traits should be regarded as key response traits for these groups.

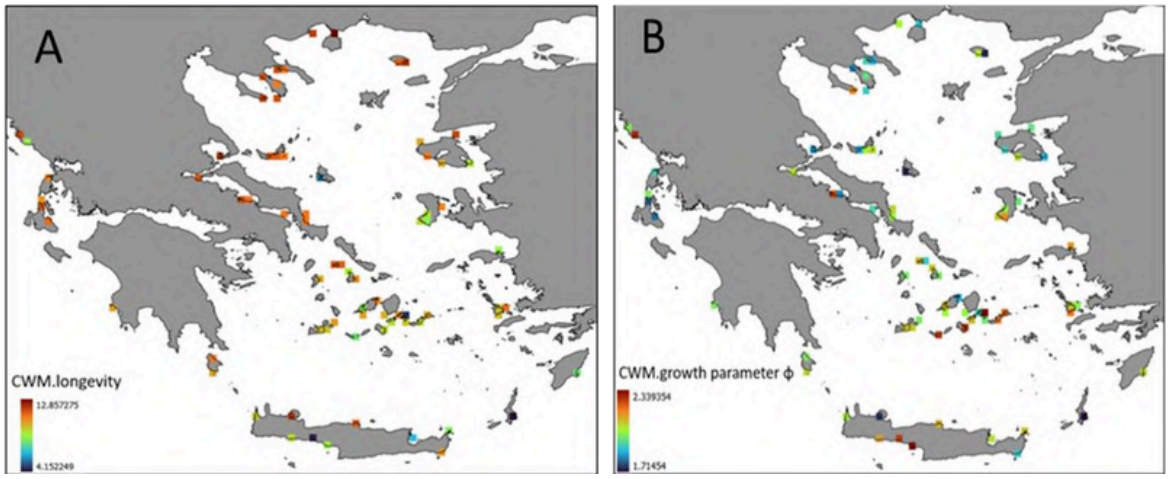

Figure 2.5, Example of key response traits identified in the analysis, including the mean longevity (A), and growth (B) of reef fish communities in the Aegean Sea. (Deliverable Report 1.4)

Similarly, studies on macroalgae communities in the Tuscan Archipelago (Storyline 28) demonstrated a pronounced spatial structuring of body size and complexity. Hence, traits associated with the vertical space and physical structure of rocky shore species might be considered as primary response traits for seaweed communities. Regarding the set of environmental conditions, the analysis identified temperature, or the degree of temperature seasonality, as a key determinant of the observed trait distributions (Fig. 2.6).

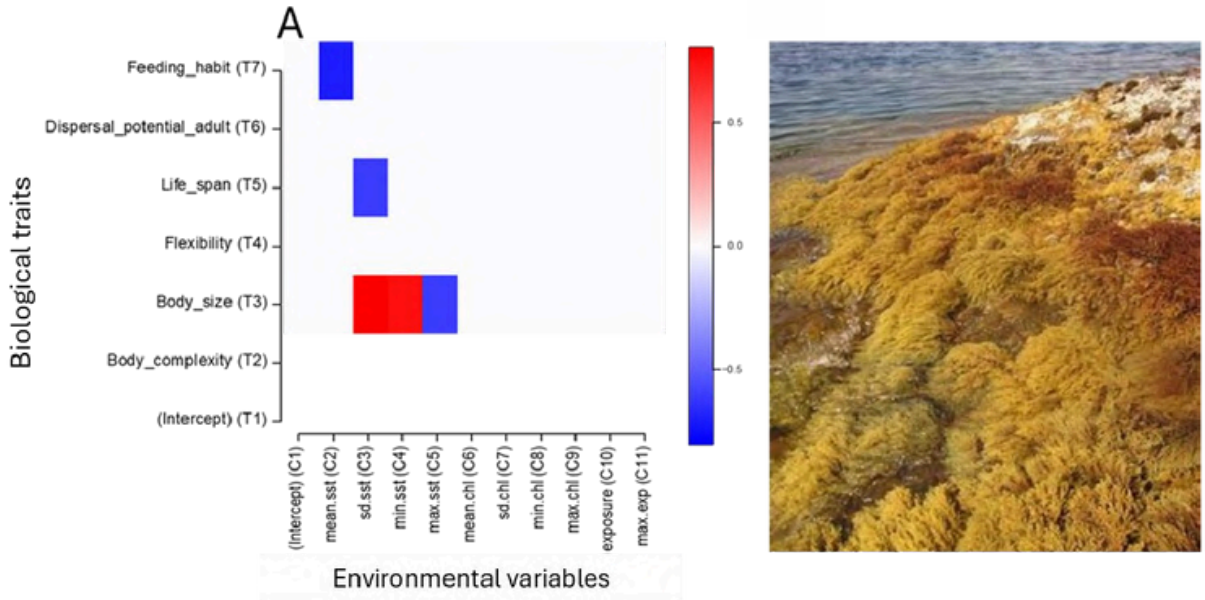

Figure 2.6, Example of trait-environment relationships (A) for benthic communities in the Tuscan Archipelago, illustrated by positive (red) and negative (blue) parameter values between traits and environmental conditions. (Deliverable Report 1.4)

However, local conditions were also identified as important determinants. Therefore, a combination of both large-scale climatic drivers, notably temperature, and more fine-scale

pressures, may jointly determine the trait composition and responses of marine organisms to environmental change. FutureMARES research revealed a general and continuous gradient from species with more opportunist traits associated with higher temperature environments, degree of seasonality and other forms of exposure, compared to species inhabiting colder, deeper, less seasonal and/or exposed environments. This is notable for fish communities. Fish species with generally faster growth, smaller size, and shorter lifespan predominated in warmer and more seasonal environments, whereas species with larger size, slower growth and longer lifespan tended to be found in more stable and, therefore, predictable environments. Similarly, seaweeds and macroalgae demonstrated a similar gradient from opportunistic species, characterized by more simple body forms, high dispersal potential (due to unattached position) and asexual reproduction, compared to species with higher structural complexity in terms of their body forms and vertical canopy.

Species sensitivity

FutureMARES conducted much work within multiple Storylines on species sensitivity to single or multiple climatic related or other local stressors (i.e., testing multi-stressor scenarios). Several examples in different environmental contexts are showcased here.

On the southeastern Mediterranean coast of **Israel** (Storylines 34, 35), where dozens of non-harvested native species have disappeared in the past few decades and hundreds of tropical invaders have become established (Rilov 2016, Rilov et al. 2018, Albano et al. 2021), thermal sensitivity and climate risk of key habitat- (canopy-) forming reef macroalgae vs. invasive counterparts that rapidly establish and spread, was assessed. Microcosm experiments indicated that the tropical non-native reef macrophytes, *Lobophora schneideri* from the Atlantic and *Galaxaura rugosa* from the Indopacific, had a much higher thermal optimum than two native, forest-forming, species, *Gongolaria rayssiae* and *Sargassum vulgare*. This indicates a much higher risk of the natives and much higher resilience of the invaders to warming (Fig. 2.7). Especially troubling was the high thermal sensitivity of *G. rayssiae*, which is endemic only to the Israeli and Lebanese coast (Mulas et al. 2020, Mulas et al. 2022).

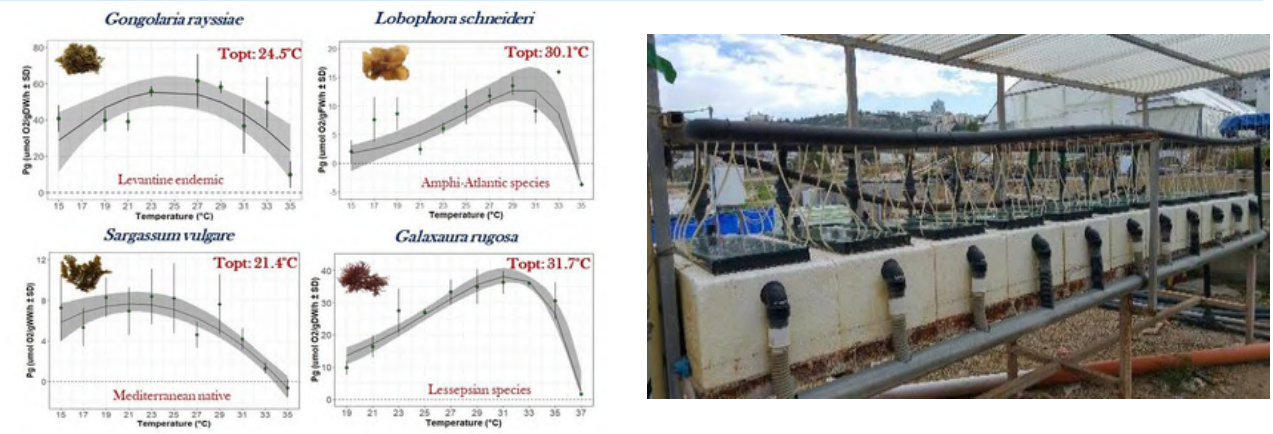

Figure 2.7, Thermal performance curves of native and invasive non-native species of reef seaweeds in the southeastern Mediterranean tested in the outdoor microcosm system of IOLR (bottom. Credit photo: Gil Rilov). (Deliverable Report 3.1).

The physiological data were used to make projections of habitat suitability on the Israeli coast under different ocean warming scenarios (see Chapter 6). Results suggest that survival of

native species is unlikely towards the end of the century (which would mean the global extinction to *G. rayssiae*) and that invaders that perform well through hotter and faster-warming summers are likely to persist. It is possible to speculate that the tropical aliens might maintain habitat with some metabolic functioning (carbon uptake) and partly compensate for the loss of the functional role played by the natives.

BOX 2.1 Metabolic rates incubations to assess benthic ecosystem functioning

FutureMARES performed a suite of field measurements to assess if and how altered benthic communities and original/pristine communities differ in their ecosystem functioning and Blue Carbon potential. The metabolic functioning of habitat-forming benthic species was measured both individually, i.e., *ex-situ* in the laboratory, and as part of the community they host or are part of, i.e., *in-situ*.

Metabolic functioning was assessed by measuring respiration and photosynthesis to assess oxygen production, carbon uptake. Calcification rate was assessed by measuring changes in pH, alkalinity, and dissolved inorganic carbon (DIC).

Measurements were done under light and dark conditions to calculate both net and gross production. In the field, metabolic incubations were done following the methodology described by Peleg et al. (2020) on i) kelp in Portugal and Norway within large plastic bags, ii) oyster reefs on mudflats in the Netherlands using full night incubations within chamber boxes, and iii) for macroalgae communities in the Mediterranean Sea within rigid plastic domes.

During incubations, water is circulated with a battery-operated pump, and amounts of water leakage assessed by injecting fluorescein dye and measuring its concentration at the start and end of measurements. Changes in oxygen and carbon concentrations were measured over the course of about an hour by sampling background levels in water outside the domes with syringes at time zero and then again from within the domes, at the end of the dark (t_1) and light (t_2) incubations. At the end of the second (light) incubation, all biomass was scraped and collected into plankton mesh bags and the biomass of all macrobenthic biodiversity components was measured in the laboratory. Net and gross photosynthesis rates were quantified from both oxygen and carbon data and carbon uptake rates (Blue Carbon potential) that can then be estimated per day or per year when measurements are repeated in several seasons.

These standard methods, when replicated in future monitoring programs, will provide much-needed estimates of Blue Carbon potential of different coastal marine habitats.

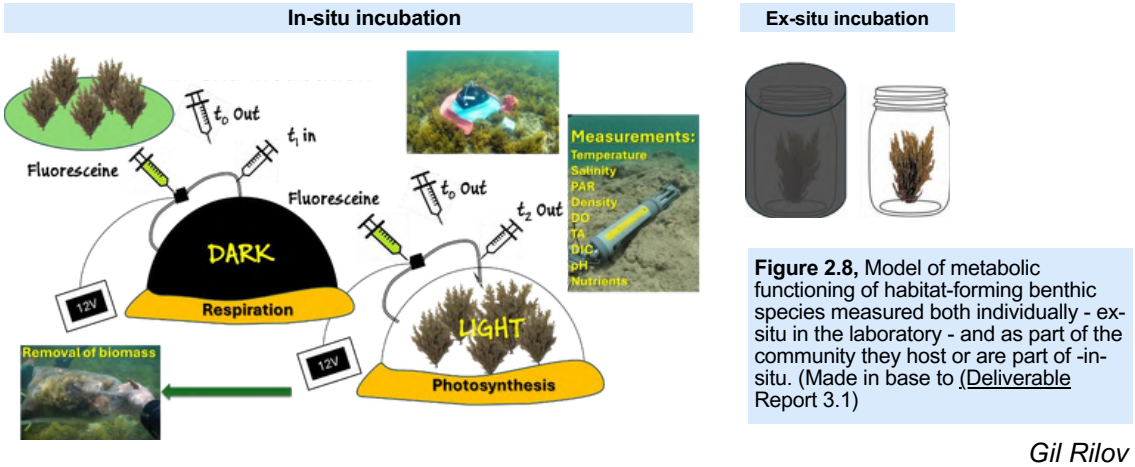

Figure 2.8, Model of metabolic functioning of habitat-forming benthic species measured both individually - ex-situ in the laboratory - and as part of the community they host or are part of -in-situ. (Made in base to (Deliverable Report 3.1)

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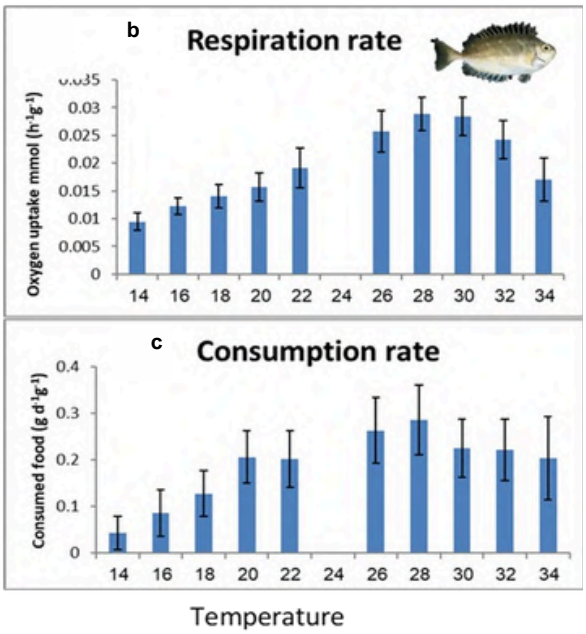
The region was also invaded by highly effective consumers, and experiments have shown that previously established (rabbitfish, *Siganus rivulatus*) and newly established (urchin, *Diadema setosum*) Red Sea species (Fig. 2.9) can maintain grazing pressure at temperatures 2°C higher than those presently observed during summer in coastal areas (~31.5°C, Fig. 2.10).

Figure 2.9, Newly established Urchin *Diadema setosum* and lionfish in Levantine reefs (photo: Guy Raanan).



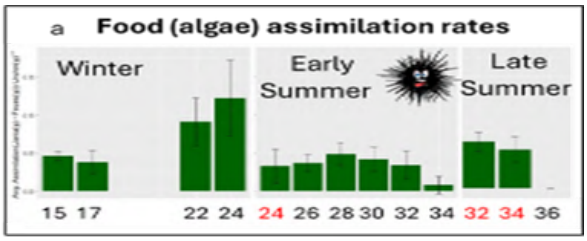


Figure 2.10, Thermal performance of invasive consumers under a range of temperatures. Performance of the invasive sea urchin *Diadema setosum* measured in three different seasons (a-left), and the invasive rabbitfish, *Siganus rivulatus* measured in winter and then summer (b,c- above), as tested in the indoor and outdoor mesocosm systems, respectively, in IOLR. Tested in the winter and overall rates are lower in early summer, perhaps at the pick. (Deliverable Report 3.1)

Rabbitfish performance is reduced above 30°C or 32°C. The urchin dies at 36°C while its peak feeding rates occur at temperatures around 24°C that now take place in the spring. Both of these invaders had strong grazing impacts on reef macroalgae in field and laboratory experiments (Fig. 2.11).

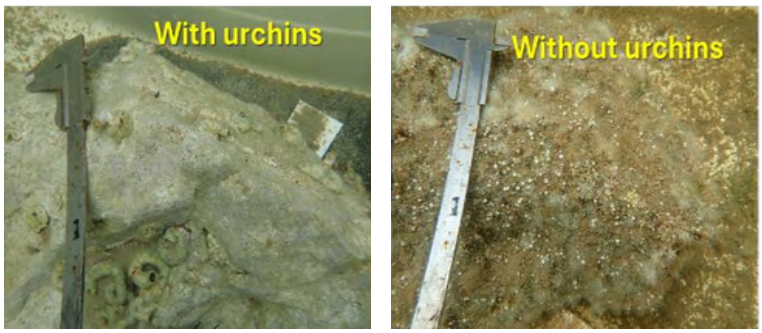


Figure 2.11, Boulders that were initially covered by turf after one month with or without the presence of urchin *Diadema setosum* in the outdoor mesocosm system. Urchins leave bare rock behind.

The northwestern Mediterranean coast of the Italian Tuscany Archipelago (Storyline 28) has experienced several massive marine heatwaves (MHWs) in the past two decades. Laboratory experiments demonstrated the complex effects of multiple drivers (heat stress and ocean acidification (OA)) on the seagrass *Posidonia oceanica* (Fig. 2.12).

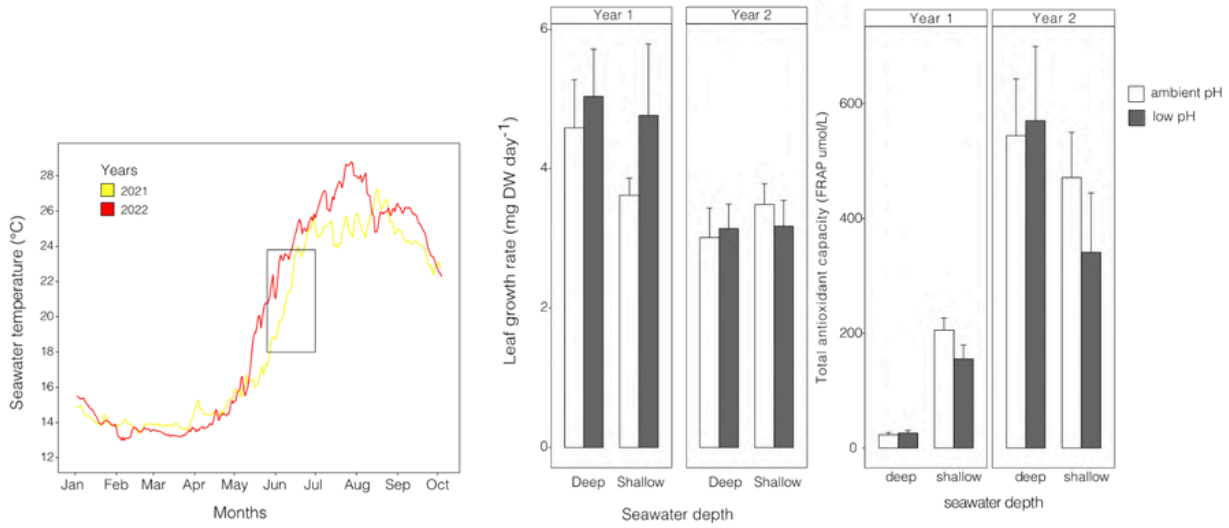


Figure 2.12, Response of *Posidonia oceanica* from deep and shallow depths to ocean acidification and marine heatwaves. Temperature profile in the study area in the two study years where research period is shown with the rectangle (left). Biological response: leaf growth area and antioxidant capacity indicating stress (right). (Deliverable Report 3.2)

Experiments conducted in a normal year (2021) and during a MHW year (2022) at 5 and 20-m depths, and ambient and low pH, indicated that the thermal stress due to the MHW overwhelmed any effects of OA on plant productivity. This suggests that the predicted intensification of extreme heat events will be a main driver of seagrass responses under future climate conditions (Ravaglioli et al. 2024). Under average temperature conditions unlikely to cause thermal stress, there was no effect of short-term elevation of CO2 on plant performance at both depths, indicating that *P. oceanica* is not limited by current seawater inorganic carbon concentrations, regardless of light availability. In contrast, OA exacerbated thermal stress, causing an increase and a decrease of plant lipid peroxidation and photosynthetic performance, respectively, with deep plants also showing signs of heat stress-induced damage (i.e., over-expression of heat shock proteins and activation of antioxidant system).

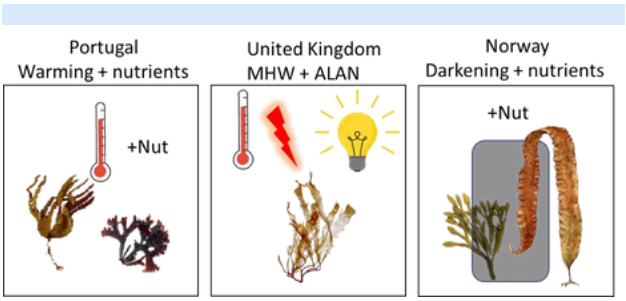


Figure 2.13, The multiple stressor experiments tested on Kelp in diverse locations and under different combinations of scenarios.
(Deliverable Report 3.1).

Threats to Northeast Atlantic rockweed and kelp forests were examined at several European locations. Specifically, the laboratory and outdoor mesocosm experiments from Portugal, Norway and the UK indicated the potential for additive and antagonistic effects of different combinations of drivers to macroalgae forest functioning and community structure (Fig. 2.13).

In **Portugal** (Storylines 21 & 23), there were complicated interactions between warming and nutrient levels (both influenced by changes in upwelling regime expected due to climate change) on two species of kelp as well as turf algae. In particular, for *Laminaria ochroleuca,* the reduction of growth, productivity, and photosynthetic functioning indicated a lower fitness when exposed to both stressors (high temperature/low nutrients – simulating a reduction in upwelling). These results are consistent with previous studies that suggested a decrease in eco-physiological performance with decreasing nutrient concentration and increasing temperature in *Laminaria* species and other canopy-forming seaweeds. Similarly, in **Norway** (Storylines 1-3), there were both additive and contradicting impacts of water darkening and nutrient additions (related to human-driven terrestrial inputs) at both the species and community levels. Specifically, the rockweed species *Fucus vesiculosus* and *F. serratus*, were both sensitive to coastal darkening and increased nutrient supply. Furthermore, the stressors reduced faunal abundance and species diversity of the community associated with *F. serratus*, through synergistic, negative impacts. The results indicate complex, not always intuitive, ecosystem responses that cannot be understood without conducting multi-stressor experiments. These experiments were possible because of the large-scale mesocosm facilities available to FutureMARES. Preliminary results from the incubation study on kelp indicate a negative impact of filamentous algae on the production rate of the kelp community. Hence, an increasing trend of coastal darkening and nutrient enrichment will further promote the presence of filamentous algae as demonstrated in the mesocosm experiments, thereby contributing to regime shifts towards a dominance of filamentous algae or fouled rockweed and kelps. In the UK experiments (Storylines 10 & 11), experiments have shown complex interactions between the impacts of artificial light at night (ALAN) and the exposure to a MHW, with some evidence that ALAN can counteract the negative effect of MHWs on growth and metabolic functioning of the kelp.

Potential for adaptation

Under the assumption that species have adapted to environmental conditions where they live, it has been increasingly shown that the same species in different climatic regions expresses adaptation to local conditions. This adaptation can stem from either a wide phenotypic plasticity or natural selection for adaptation, for example, to more extreme or varying local conditions. Within FutureMARES, it was tested whether the risk to thermal stress varied among populations of the same species across sites with different thermal histories and variability. On the **Italian** coast (Storyline 28), we tested the hypothesis that plants of the seagrass *Posidonia oceanica* from sites across the Tuscan Archipelago that were exposed to intense and frequent warming events in the last three decades would a) differ in physiological (i.e., photosynthetic efficiency, pigment and secondary metabolite content) and biochemical features (i.e., C/N ratio, alkaline phosphatases, lipid peroxidation and total antioxidant capacity), and b) would be more tolerant to a simulated future MHW compared to plants from sites that have not previously experience strong MHWs. The results (Fig. 2.14) suggested that plants belonging to populations from different sites across the Tuscan Archipelago and the mainland of Tuscany had differences in the physiological and biochemical properties of their leaf tissues. These differences suggest that local environmental and biological conditions may have selected locally adapted phenotypes that may or may not be related to MHWs. The connection to MHW exposure is not yet clear

because the simulated MHW in the laboratory caused no significant impacts on any of the populations (Fig. 2.14b).

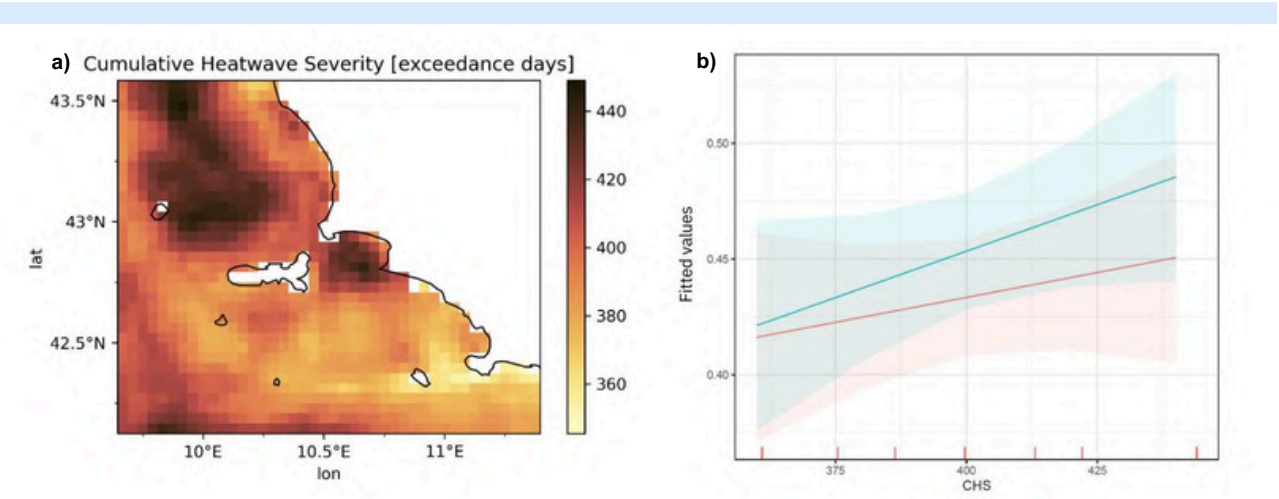


Figure 2.14, Maps of Cumulative Heatwaves Severity (CHS) in the Tuscan Archipelago (a) and the relationship between photosynthetic efficiency, expressed as effective quantum yield (fitted values with 95% CI) and CHS in leaves from *Posidonia* plants experimentally exposed to a MHW or maintained at ambient temperature at different study sites (b). (Deliverable Report 3.2)

The shallow reef canopy-forming brown algae *Ericaria crinita* was collected at different sites from the **East to the West Mediterranean Sea** (Storyline 29) and then exposed to temperatures ranging from 26-29°C for 80 days to examine if local thermal conditions affected the risk of algae to thermal stress. Exposure to long-term chronic warm temperatures affected the fitness and survival of the *E. crinita*, (Fig. 2.15) with sustained temperatures above 28°C causing considerable biomass losses (>40%). Populations dwelling in the warm range of the species distribution were more tolerant to the high temperatures than populations from colder thermal regimes.

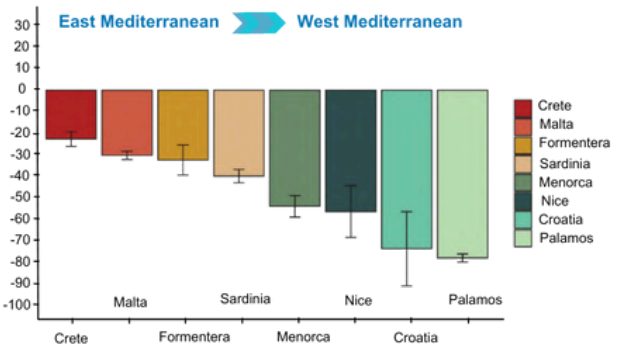


Figure 2.15, Biomass loss of different populations of *E. crinita* across the Mediterranean Sea under a warming experiment at 29°C after 80 days of exposure. Eastern populations had higher temperature tolerance than more western populations suggesting local adaptation to warm temperatures.

A population in Catalonia (NE Iberian Peninsula) for example, was already highly affected at 27°C, whereas the same level of damage occurred at 29°C for populations from warmer areas. This experiment, therefore, demonstrated local thermal adaptation, in accordance with the marked differences in thermal conditions that are found within *E. crinita* distribution range. It can be expected that future temperatures in the Mediterranean Sea, where mean summer temperatures can reach 31°C, might greatly affect shallow marine forests and strongly compromise the viability of many canopy-forming species similar to observations made on *G. rayssiae* along the Israeli coast.

On the **Atlantic coast** (Storylines 21 & 23), the local adaptation to thermal stress was tested with the intertidal canopy-forming brown algae *Ascophyllum nodosum*. An atmospheric (aerial) heatwave experiment was designed to simulate present and extreme future atmospheric conditions, making it a realistic representation of potential scenarios of climate change. **This was a pioneering investigation that examined the interplay between seawater temperature and atmospheric heatwaves.** The experimental design encompassed a gradient of atmospheric heatwave treatments which exerted significant impacts on the performance of *Ascophyllum* fronds. There was a clear latitudinal gradient in responses (Fig. 2.16), implying that local conditions likely have an impact on thermal sensitivity. Fronds collected from Northern European sites suffered stronger deleterious effects from the intense atmospheric heatwave treatments. However, it is worth highlighting that the influence of seawater temperature was also clearly discernible, indicating its synergistic role in shaping the ecophysiological response of this seaweed. The fronds in the treatments with colder water (14 ºC) exhibited poorer performance than those submerged at 20 ºC.

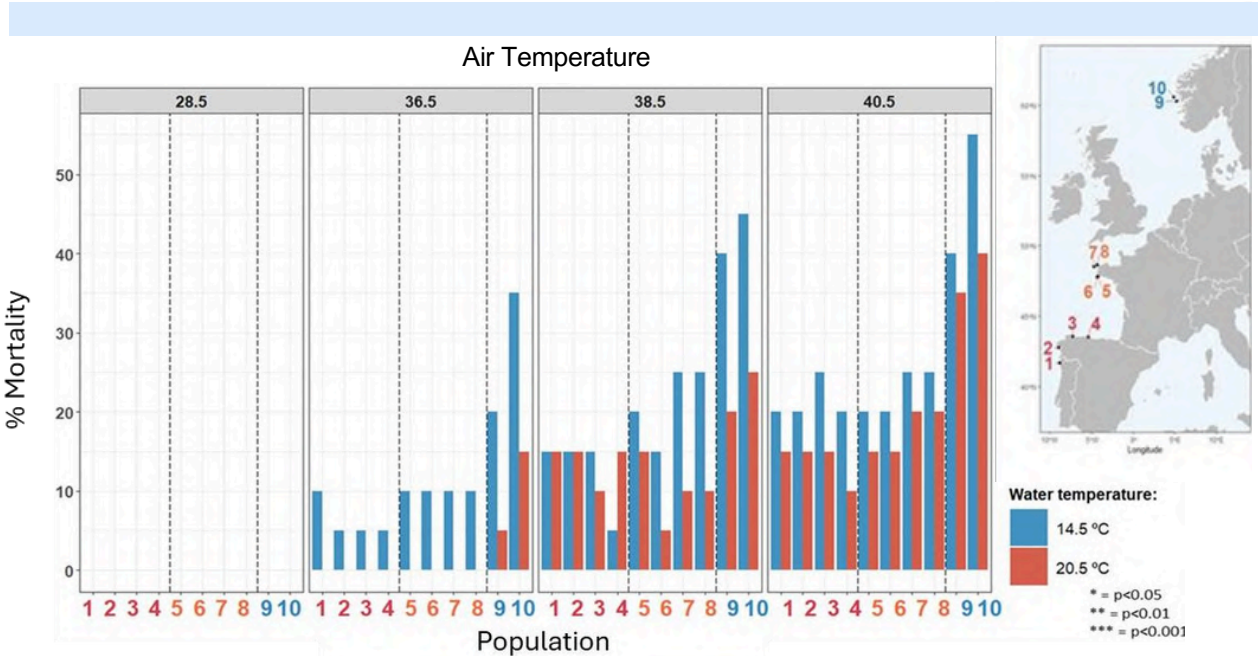


Figure 2.16, Observed mortality of *Ascophyllum nodosum* after 20 days of trial (n=10). Populations are numbered by growing latitude (1-Viana do Castelo, 2- Ria de Muros, 3- Ria da Foz, 4- Ria de Villaviciosa, 5- Landunvez, 6- Île-Tudy, 7-Penmarch, 8- Soulogan, 9- Espegrend and 10- Straumoyna). (Deliverable Report 3.2)

Population connectivity

FutureMARES tested the level of population connectivity on several key commercial and ecologically important species using population genetics and hydrodynamic modeling in the Mediterranean and the Northeast Atlantic. Results revealed that some commercial fish species in the Atlantic and the Mediterranean show low population differentiation and only at large regional scales (Fig. 2.17). This contrasts with some sessile invertebrates such as intertidal snails, that, although having pelagic larvae, have highly genetically-separated populations even at the levels of tens to hundreds of kilometers in the Mediterranean. Such low population connectivity may be detrimental if one of the isolated populations suffer a catastrophic events such as an extreme MHW, as rescue potential from distant populations is low.

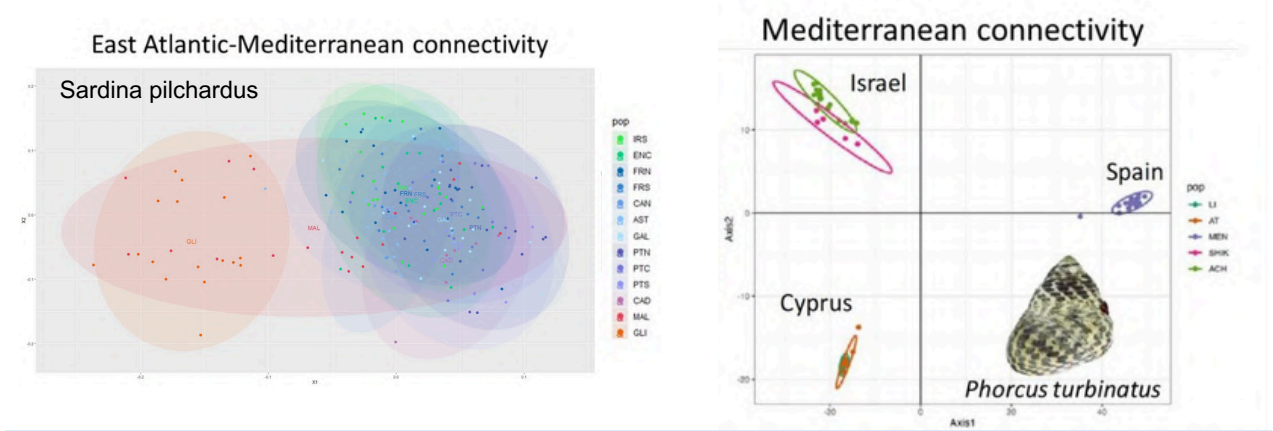


Figure 2.17, Two examples of different population connectivity patterns, the sardine with clear separation only between Atlantic and Mediterranean populations and high similarly among populations within regions (left panel), and the topshell snail, *Phorcus turbinatus*, with very high dissimilarity, even among populations within the southeast Levant – Israel and Cyprus (right panel). (Deliverable Report 1.4)

Functioning

Within FutureMARES, several Storylines compared the ecosystem functioning of intact and altered, invaded or restored benthic habitat-forming species, from kelp forests to oyster reefs using similar methodology with metabolic incubation chambers (Fig. 2.18). This synthesis report showcases part of this work by focusing on Mediterranean shallow reef macrophyte communities.

Figure 2.18, Incubation chambers testing metabolic functioning (oxygen consumption and production, carbon uptake and production, calcification rates) of different benthic communities in different regions.
(Deliverable Report 3.1)

Healthy shallow-water reefs around the Mediterranean are considered highly productive and ecologically diverse, and the presence of marine forests of *Fucales* brown algae, mainly of the genius *Cystoseira* sensu *lato*, are considered to be a clear sign of a healthy reef state (Sala et al. 2012, Bevilacqua et al. 2020, Bevilacqua et al. 2021). Today, shallow reefs in many parts of the Mediterranean Sea are rapidly being altered due to various local and global stressors, with both similar and different main drivers in the eastern and western basins. As a consequence, *Fucales* forests in many places are becoming rare. Instead of typical canopy forests, other communities dominate the substrate, and many different ecological states now exist on the reefs. It is, therefore, assumed that the ecological contribution and functioning of these altered community states are inferior to that of the *Fucales* forests. This assumption, however, has rarely been tested. FutureMARES tested the habitat and metabolic functioning of macroalgal-dominated communities on Mediterranean shallow reefs of different reef macrophyte states using very similar methods, i.e., incubation domes of the same dimensions and operational

procedures following those developed on the Israeli coast (Peleg et al. 2020) (see Box 2.1). Results provide evidence that some of those alternate reef states may not be that functionally inferior to the pristine *Fucales* forests.
This provides some hope for future persistence of some ecosystem services despite the rise of novel ecosystems (Fig. 2.19).

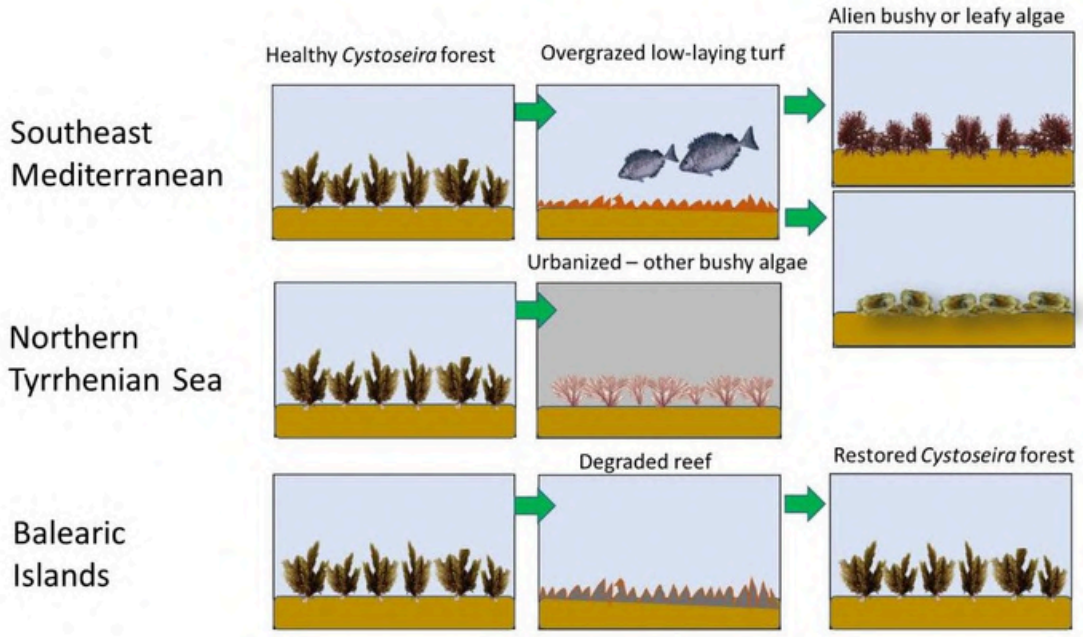


Figure 2.19, Different shifts in community state of macroalgal communities in shallow water reefs in the Mediterranean Sea in the different study regions. (Deliverable Report 3.1)

Nonetheless, restoration of *Cystoseira* forests should be attempted, as it evidently can work to restore functioning where the species was historically present and where local stressors are removed. Results from three areas of the Mediterranean are briefly summarized:

1) On **southeastern shallow reefs** most of the reefs today are mainly characterized by low-laying, overgrazed (by the invasive rabbitfish), turf barrens that are biologically poor and with low productivity. *Fucales* forests on the other hand are rare (Sala et al. 2011, Rilov et al. 2018) and they also have a very short growth season (Mulas et al. 2022). This work demonstrated, however, that meadows of alien bushy or leafy macroalgae that are becoming widespread in the region, are just as biologically diverse, productive and are found year-round. The thermal performance of these alien species indicates that they can better handle warming occurring at the present time and projected in the future. This provides hope that some of the ecosystem functioning may be maintained in the system. Some indication of higher cover of macroalgal meadows inside a well-functioning MPA (Rilov et al. 2018) suggests that protection might aid in the maintenance of higher primary productivity of the reef thus sustaining a more intact food web.

2) On **Northern Tyrrhenian Sea** reefs that are coastal and urbanized, *Fucales* are also rare, and reefs are now dominated by bushy and “turf” algae (mainly *Jania spp.*). These alternate communities, however, were also found to be as diverse and productive as healthy *Cystoseira*

forests occurring on more pristine reefs in Capraia Island, giving hope that, if restoration is not possible, those novel communities are good replacements, at least in terms of ecological functioning (habitat provisioning and carbon sinks).

3) On the **Balearic Islands reefs** where the *Cystoseira* forest have been destroyed in many areas, research demonstrated that long-term restoration efforts can indeed be successful. Ten years after a forest restoration was initiated, the area is almost equally diverse and productive as a healthy forest, and is much more functional than a nearby reef that is still degraded. This suggests that, if the driver of the forest destruction has been removed, there is a good chance for restoration, given that ocean warming will not affect the algae.

BOX 2.2 How to consider invasive species in conservation management – remove or protect?

Invasive non-native species are major drivers of biodiversity change globally, with often detrimental effects on native biodiversity and ecosystem functioning and services. Some alien species, however, could yield benefits, for example, by enhancing ecosystem functions, resilience, and service provisioning (Katsanevakis et al. 2014, van Rijn et al. 2020, Tsirintanis et al. 2022). This is specially the case in areas impacted by climate change where populations of newly introduced warmer-water species that play similar functional roles may compensate for the loss of populations of native species (Rilov et al. 2020).

The most influential types of invasive species are strong consumers such as lionfish in the Caribbean (Green et al. 2012) and, more recently, in the Mediterranean Sea (Kleitou et al. 2019), or herbivores such as rabbitfish in the Mediterranean (Vergés et al. 2014), as well as ecosystem engineers that reshape the environment with their bodies or activities (Rilov et al. 2023).

The dual impacts of biological invasions, both negative and positive, underscore the complexity of their roles in ecosystems

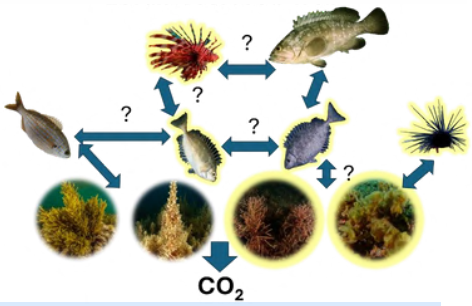


Figure 2.20, Southeast Mediterranean Sea shallow reef food web showing four main macroalgae primary producers (*Gongolaria rayssiae, Sargassum vulgare, Galaxaura rugosa, Lobophora schneideri*), four grazers (the fish *Sarpa salpa, Siganus luridus, S. rivulatus* and the sea urchin *Diadema setosum*), and two piscivores, the lionfish *Pterois miles* and a grouper. Invaders are highlighted in yellow.

(Guy-Haim et al. 2018) and highlight the need to consider them in conservation practices particularly within marine protected areas. Yet, in practice, alien species are largely ignored in conservation planning even if their impacts are recognized (Giakoumi et al. 2016, Mačić et al. 2018). The complex role of alien species prompts the need to reevaluate management and conservation strategies to encompass their multifaceted impacts on biodiversity and ecosystem functionality (Giakoumi et al. 2016).

Gil Rilov

Conclusions and policy recommendations

FutureMARES results demonstrate clearly that we need to incorporate climate and bioinvasions research into decision-making and policy because there is a need to be able to project, for

example, whether native species that we want to protect (or restore) are expected to exist in an area of interest under future conditions based on different climate scenarios. Strong biodiversity alterations of European marine habitats towards deborealization or tropicalization, or both, imply drastic shifts in community composition, which may be translated also to shifts in biological trait diversity, and from that to altered ecosystem functionality and ecosystem services. Taken together, our biological traits results highlight that climate change will favor more opportunistic, fast-growing species, while longer-lived, late maturing species with low fecundity are particularly sensitive and at risk. In addition to managing climate change, it is also of paramount importance to minimize exposure and impacts from other more local pressures, including overfishing, eutrophication, introduced species and habitat destruction and loss.

Complementing trait-based analyses, it is important to directly assess how new species (for example, non-native tropical ones) or altered whole communities in marine ecosystems are functioning (Fig. 2.21). Do they function similarly or differently from the original communities that are being altered? This will help to understand how these novel species or communities should be regarded in assessments of ecosystem health, for example. If new species or altered communities function similarly or provide similar services as the ones that are dwindling or will be locally, regionally or globally lost due to climate change, perhaps we need to consider them not as a problem but rather as a (nature-based) solution (Fig. 2.21). Such direct measurements of functions will also help determine what actions to take if these new species or novel communities occur in marine protected areas – should these populations be controlled or protected? FutureMARES recommendations are to simultaneously (1) promote targeted research to understand the functioning of novel communities under current and future climate conditions also within the context of other local and global stressors (a cumulative or multiple stressors approach like those done in a few cases within FutureMARES and with the new Horizon Europe project ACTNOW and GES4Seas), and (2) propose MSFD descriptors for Good Environmental Status that are more relevant to fast shifting communities because of climate change. This should also translate to more adaptive conservation and restoration measures that are relevant to the fact that biodiversity is shifting rapidly in climate and bioinvasion hotspots. The focus for conservation in such areas should also be on preserving ecosystem functions and services, even if they are provided by different (e.g., non-native) species, rather than focusing on preserving native species alone.

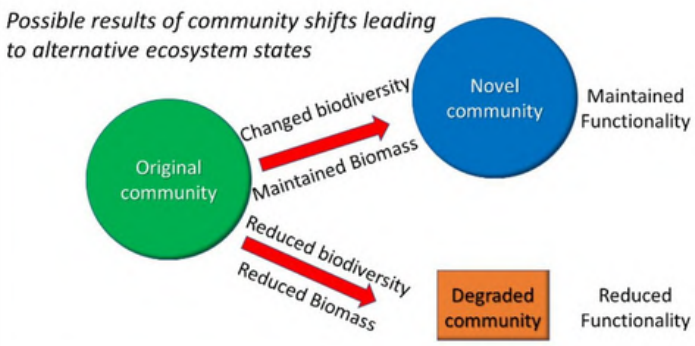


Figure 2.21, Schematic illustration of the different avenues of community change can take with regard to resulting ecosystem functionality.

Future MARES

CHAPTER 3

PROJECTIONS OF CLIMATIC STRESSORS IMPACTING MARINE HABITATS AND BIODIVERSITY

AUTHORS: MOMME BUTENSCHÖN, TROND KRISTIANSEN, MYRON A. PECK

03 Projections of climatic stressors impacting marine habitats and biodiversity

Introduction

Ocean warming, deoxygenation and acidification are the main stressors affecting marine habitats and their biodiversity that threaten important ecosystem services for human communities such as food production. The IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) (Bindoff et al. 2019) underscored the critical impacts of climate change on the planet's marine ecosystems.

Projections of the combined climate change-induced ecosystem stressors show how global-level changes in climate forcing and interacting regional hazards (e.g. eutrophication) cause local perturbations to environment characteristics (e.g., warming, acidification, deoxygenation, stratification, nutrient dynamics). These changes can have substantial consequences for the ecology and biodiversity of shelf seas and coastal habitats. Warming leads to geographical shifts in species distributions, the composition of ecological communities (Chust et al. 2024) and may induce habitat compression when combined with topographical barriers or other stressors. Warming also favors invasion and establishment of thermophilic alien species (see Chapter 2), induces metabolic stress, reduces body-size, alters reproductive patterns, and increases the risk of bacterial or viral infections in organisms, disrupting existing ecosystems. Ocean acidification strongly affects calcifying organisms that rely on calcium carbonate in their structural components and can significantly increase the metabolic energy demand for marine organisms via acid-base regulation. Deoxygenation leads to increasing areas of hypoxia, seriously limiting or damaging all organisms whose metabolism relies on oxygen. The combination of two or three of these stressors may have larger, synergistic effects on marine flora and fauna (Alter et al. 2024).

Global Climate Models and Earth System Models (GCMs and ESMs) are used as a primary means to understand how environmental conditions are expected to change in the future in response to a range of scenarios of change in atmospheric anthropogenic green-house gas concentrations. These models are complex tools that can simultaneously depict the physical, chemical, and biological processes of land, ocean, atmosphere, and cryosphere allowing researchers to explore the intricate relationships and dependences of these earth system components. An important part of the IPCC Assessment Reports (IPCC 2021) is the analysis of output from the Coupled Model Intercomparison Project (CMIP) which simulates future climate using the Shared Socioeconomic Pathways (SSP) narratives and Representative Concentration Pathways (RCPs) of future emissions. The CMIP models are global in scope and provide a wealth of invaluable, broad information at large spatial scales, illustrating the trajectory of change in the mean state of the Earth System and, importantly, the uncertainties in the model projections. In fact, an important characteristic of CMIP is the standardised sets of experiments (the so-called MIPS) based on well-defined protocols and supported and applied by a large international modelling community.

However, the relatively coarse-scale resolution of these CMIP models (most are 1x1-degree longitude-latitude in the ocean for the current generation of CMIP6 models) does not adequately resolve details of the regional oceanographic features (Stock et al. 2011) and coastal domains of marine habitats. Resolving these features and coastal areas is increasingly required for the strategic planning and management of marine resources and ecosystem services, as well as for the development of climate change adaptation and mitigation policies. Addressing these shortcomings clearly requires the downscaling of the global datasets to obtain information at adequate spatial resolutions that are consistent with the large-scale picture provided by the ESM and CM projections.

While a large number of individual dynamical downscaling products exist for regional ocean domains, these products lack the conceptual and standardised approach of the CMIP experiments or the Coordinated Regional Downscaling Experiment (CORDEX) available for regional atmospheric domains. Dynamic downscaled products also lack the broadness of the global datasets in terms of experiment realisations. This strongly limits the comparability of results among different systems and does not adequately quantify the uncertainties involved in the projections (Drenkard et al. 2021).

FutureMARES produced statistically downscaled datasets from global ESM and CM projections of selected key variables of marine habitat conditions.

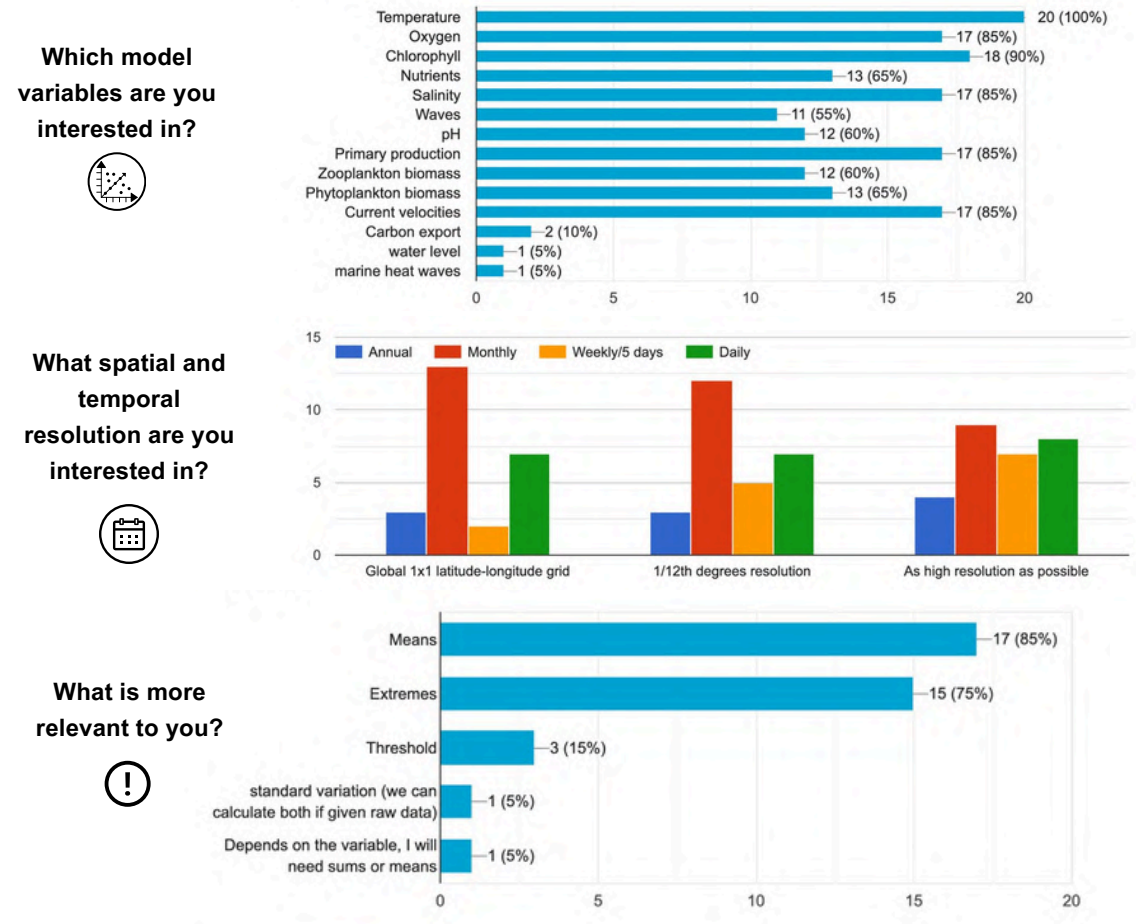


Figure 3.1, Outcomes from Storyline survey on data requirements to assess habitat conditions. (Deliverable Report 2.2)

The key variables emerged from the results of a survey conducted across researchers applying field work and biological models within the Storylines of the project (Fig. 3.1). The results of the survey helped tailor the information to best fit the needs of field ecologists, experimentalists and modelers. This included a subset of variables, depth layers and temporal resolutions. The results also helped identify, more broadly, the physical and biogeochemical attributes and spatial resolutions most relevant for taking into account climate change when implementing NBS or NIH as management actions (Kristiansen et al. 2024). Five indicators of marine habitat conditions were selected (temperature (°C), salinity, pH, dissolved oxygen (ml/l), and chlorophyll (kg/m^3)). These are provided as monthly means at three distinct depth levels (surface (5 m), sub-surface (25 m), and seafloor) for 1993–2100 under three different future scenarios (SSP1-2.6, SSP2-4.5, and SSP5-8.5) (Fig. 3.2). These SSP-RCP combinations also contributed the "environmental" aspect of the broader NBS and NIH scenarios developed and regionalized within FutureMARES (see Chapter 4).

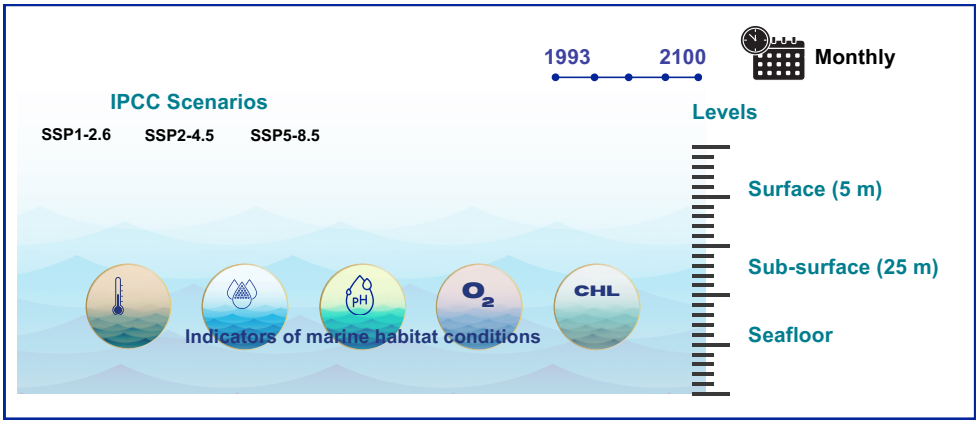


Figure 3.2, Key variables gathered in the survey for the statistically downscaled datasets.

Research within FutureMARES

Developing high-resolution projections

A statistical bias correction (BA) and downscaling (SD) were applied to the global CMIP6 projections for key variables of marine habitat conditions. The BA corrects systematic errors in the climate data to minimize the errors between observed and modelled values for a specific control period, while the SD allows us to establish an empirical relationship between historical, fine-scale data and large-scale climate variables, and applies this statistical connection to project future climate at smaller (local) scales. This approach produces a high-resolution climate dataset using a range of CMIP6 models and ensemble members (termed realizations) containing both the historical (1993-2020) and future projections (2021-2100) that captures the uncertainty across models. Box 3.1 provides technical details of the methods used to perform the bias correction and statistical downscaling.

The downscaling was performed for 3 to 7 CMIP6 models per variable per climate scenario (Fig. 3.3). Global climate models use global greenhouse gas concentrations emerging for the radiative forcing targets of the Representative Concentration Pathways—RCPs, under different

shared socioeconomic pathways (SSPs) up to 2100 according to the ScenarioMIP protocol (O'Neill et al. 2016). For the 6 Intergovernmental Panel on Climate Change (IPCC) report, five narratives provided alternative socio-economic developments for the world, including sustainable development (SSP1), regional rivalry (SSP3), regional inequality (SSP4), fossil-fueled development (SSP5), and middle-of-the-road development (SSP2). While, in principle, the two development streams of climate and socio-economic scenarios are independent, some combinations are more likely than others. This dataset focuses on the combinations SSP1-RCP2.6, SSP2-RCP4.5, and SSP5-RCP8.5 which are part of the ScenarioMIP Tier 1 simulations and available across various ESMs. The selection of CMIP6 models and variants was made based on the overall performance and skill of each model, and model availability across variables and scenarios.

The final product for users is the ensemble of these individual downscaled models. Within the datasets, the ensemble mean is provided along with standard deviations and 2.5, 50.0, and 97.5 percentiles, depicting the spread of the ensemble at each point in space and time in Gaussian and non-Gaussian metrics. The downscaled results were stored as compressed NetCDF4 files containing self-describing metadata of the downscaled variable and are freely available on Zenodo (links at the bottom of this chapter).

Model name	id	O2 SSP1-2.6, SSP2-4.5, SSP5-8.5			Temperature SSP1-2.6, SSP2-4.5, SSP5-8.5			Chlorophyll SSP1-2.6, SSP2-4.5, SSP5-8.5			pH SSP1-2.6, SSP2-4.5, SSP5-8.5			Salinity SSP1-2.6, SSP2-4.5, SSP5-8.5		
IPSL-CM6A-LR (Boucher et al., 2020)	r1i1p1f1 r3i1p1f1	x x	x x	x x	x x	x x	x x				x x	x x	x x	x x	x x	x x
MPI-ESM1-2-LR (Mauritsen et al., 2019)	r1i1p1f1 r2i1p1f1	x x	x x	x x	x x	x	x x	x x	x x	x x	x x	x x	x x	x x	x x	x x
GFDL-ESM4 (Dunne et al., 2020)	r1i1p1f1				x	x	x							x	x	x
CM CC-ESM2 (Lovato et al., 2022)	r1i1p1f1	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
CM CC-CM2-SR5 (Cherchi et al., 2018)	r1i1p1f1				x	x	x							x	x	x

Figure 3.3, Overview of the composition of the statistical downscaling ensemble. (Deliverable Report 2.2)

BOX 3.1 Bias correction and statistical downscaling of CMIP6 ensemble

This box provides technical details on the methods used to gain higher-resolution projections of climate-driven changes in temperature, salinity, dissolved oxygen and acidification across the regional seas examined within FutureMARES. This included bias correction and statistical downscaling of large-scale CMIP6 climate projections to the regional level conducted in three steps:

- Preparation of the GCM/ESM data to a standard grid.

The raw data from GCMs and ESMs can be represented on various global ocean grids. Some of these grids have higher resolution in one part of the world, e.g., around the equator, while others can have three poles to avoid the singularity in the ocean at 90° N. To be able to work consistently with these CMIP6 model outputs, we interpolated the data to a uniform cartesian grid of 0.5° × 0.5° longitude-latitude. We employed the Earth System Modelling Framework (ESMF) (Jones et al. 2021) to allow fast interpolation within a tested framework. To further simplify the conversion from the native to a uniform grid, the Python xesmf interface15 was used on the ESMF package. The xMIP package was used to pre-process the CMIP6 data (Busecke et al. 2023).

- Bias correction with respect to reference data.

The GCMs and ESMs within CMIP6 are designed to represent the probability distributions, variability, and observed trends in physical and biological variables and not to exactly replicate individual features in time and space such as reanalysis systems for the past or forecasting systems for the near future. For this reason, GCMs and ESMs are inherently biased from historical observations. To correct the offset in these global models, bias-correction was performed to constrain the large-scale climate signal to the observed values of the range and variability using detrended quantile mapping (DQM) transformations (Hempel et al. 2013, Cannon et al. 2015). The DQM removes biases across all quantiles, effectively aligning the data distribution of the modelled data to the observed values (Cannon et al. 2015). The DQM method was trained with the historical (1993–2020) GLORYS12V1 reanalysis (the observed values) and applied to the historical GCM/ESM data to calculate the transform function which was used to adjust the detrended quantiles for the future projections (2020–2100). Once the time series had been adjusted using the DQM methodology, the trend was added back to the time series (Lehner et al. 2021). This approach ensures that the trend from the GCMs and ESMs is preserved in the downscaled product. The bias correction was performed at the resolution of the interpolated GCM or ESM, which is 0.5° × 0.5° latitude-longitude. The global ocean physics of the GLORYS12V1 reanalysis at 1/12th degrees resolution have been thoroughly validated against observations (Lellouche et al. 2011, Drévillon et al. 2021). The GLORYS12V1 reanalysis assimilates available historical data (e.g., satellite, CTD, XBT, buoys) for 1993-01-01 to 2019-12-31 and represents state-of-the-art hydrodynamic modelling. GLORYS12V119 is developed by Mercator Ocean and is an operational service from the Copernicus Marine Service Centre (marine.copernicus.eu). Historical biogeochemical data for dissolved oxygen, chlorophyll, and pH were obtained from the Global Ocean Biogeochemistry hindcast (GOBH) from Mercator Ocean distributed via the Copernicus Marine Service. The GOBH model (Perruche et al. 2019) uses the PISCES model to represent biogeochemistry and physics from the FREEGLORYS2V4 model, which is a non-assimilative version of the GLORYS2V4 reanalysis model. The GOBH and FREEGLORYS2V4 models were run at a resolution of 1/4th degree. To directly align the downscaled physical and biogeochemical results, model data were interpolated →

(bilinearly) and extrapolated onto the physical model grid, allowing the final biological downscaled data to be at 1/12th degree resolution. As the bathymetry along the coastline of the biological model is coarser than the physical model, we extrapolated to the destination point by using the weighted average (inverse weighted distance method – Jones et al. 2014) of the eight nearest source points. The documentation for GOBH states that the model holds a global bias in pH of 0.02, making it slightly more acidic compared to observations. The model is able to reproduce observed surface and sub-surface oxygen concentrations including the oxygen minimum zones (Perruche et al. 2019). However, being a hindcast, as all dynamic ocean models, this dataset contains some biases with respect to the real world which will be inherited by the downscaled products developed by FutureMARES.

- Statistical downscaling of the bias corrected fields to high resolution.

The statistical downscaling (SD) allowed us to establish an empirical relationship between high-resolution historical and large-scale climate indicators and apply these statistics to produce local climate projections. The bias corrected fields at 0.5° × 0.5° longitude-latitude resolution were used as input to the DQM statistical downscaling algorithm together with the high-resolution GLORYS12V1 reanalysis to provide ESM sub-grid variability. This involved to:

(1) determine a scaling factor that allows the mean of the historical bias corrected CMIP6 projection to be equal to the mean of the historical GLORYS12V1/GOBH time series,
(2) remove the trend from both time series,
(3) calculate the adjustment factors between the quantiles of the two time series,
(4) apply the scaling factor to the future projections,
(5) match the quantiles of the detrended projections and apply the adjustment factor,
(6) add back the trend to the projections (Cannon et al 2015).

The GLORYS12V1 and GOBH models have 75 and 50 vertical depth levels, respectively, which were linearly interpolated if the bias correction and downscaling were performed at an intermediate depth level. Linear interpolation was also performed on the global climate model outputs as downscaling was done at individual, fixed depth levels (e.g., 5 m, 25 m). The exception was the bottom depth, where each grid point had a unique depth level, and the ESMs were interpolated to the GLORYS bathymetry.

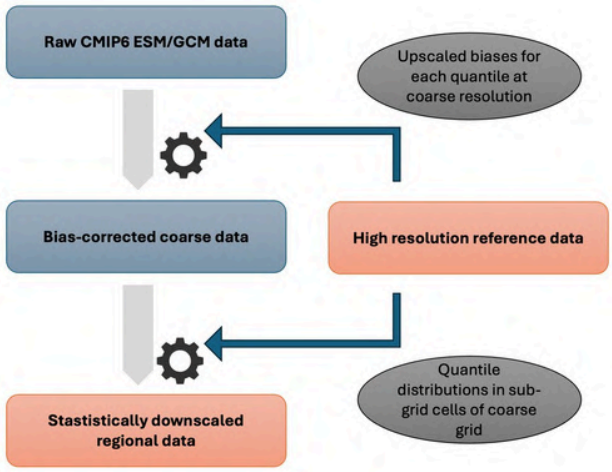


Figure 3.4, Downscaling workflow

Momme Butenschön

Projections by region with uncertainty analyses

This section illustrates the changes induced by anthropogenic greenhouse gas emissions in three key ecosystem pressures: warming (represented by the sub-surface temperature), acidification (represented by sub-surface pH) and deoxygenation (represented by bottom dissolved oxygen concentration). It should be noted that these changes are given with respect to present day conditions and not with respect to pre-industrial conditions which were used to define the goals of the Paris agreement.

The significance of the induced changes was further analysed by comparing them to three separate sources of uncertainties in these climate projections:

1. internal variability
2. model uncertainty
3. scenario uncertainty

The following subsections summarize the results of this analysis for each macro-region of the European Seas considered in FutureMARES.

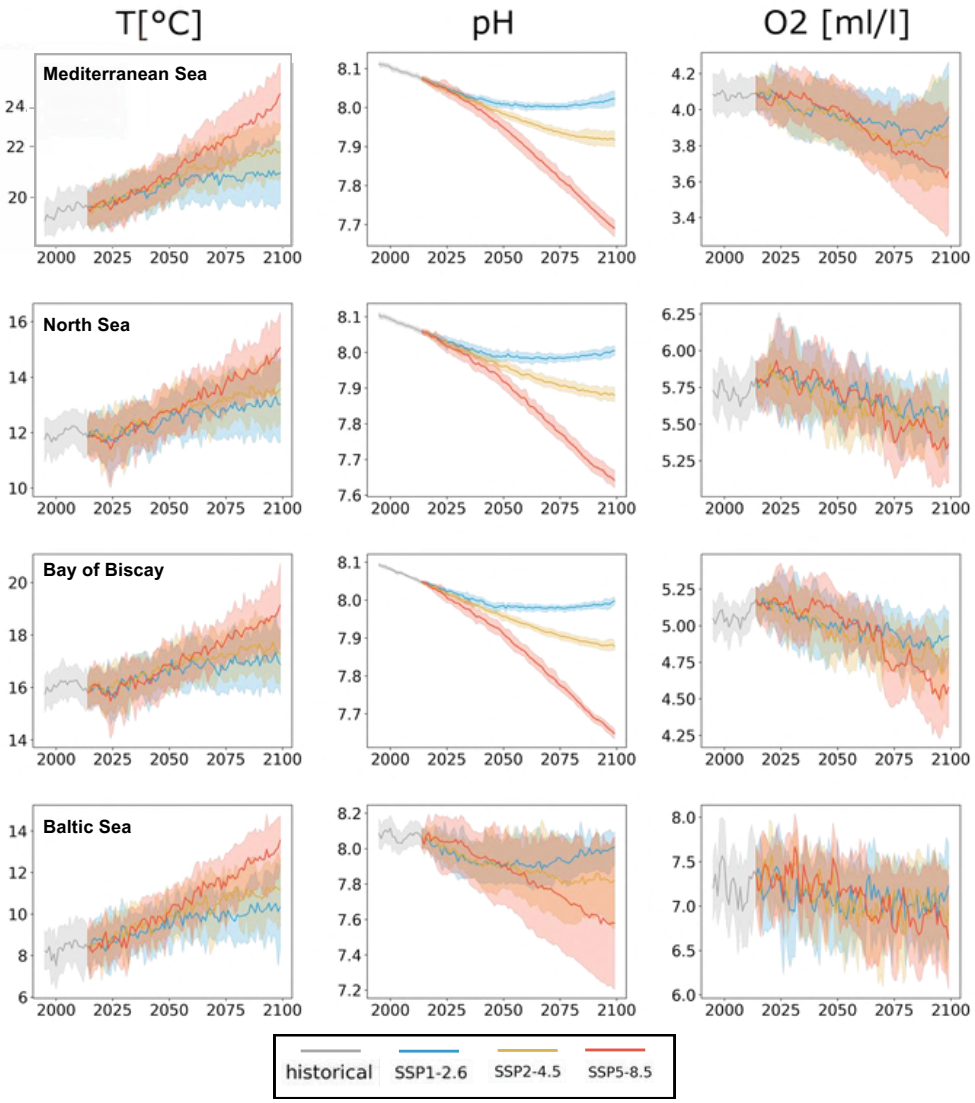


Figure 3.5, Basin-average trajectories of change in surface temperature (°C, left), surface pH (middle), and bottom oxygen (ml / l, right)) for three scenarios (SSP1-2.6: blue, SSP2-4.5: yellow, SSP5-8.5: red). Note, ranges in y-axes values differ among the four seas. (Deliverable Report 2.2)

Mediterranean Sea

In the Mediterranean Sea (Fig 3.5), the basin-average trajectories of change are qualitatively comparable to those observed for the global mean (IPCC 2022, Kwiatkowski et al. 2020). For the no-mitigation scenario SSP5-8.5, the mean surface temperature gradually increases to 5 °C higher than the present day. For the middle of the road scenario SSP2-4.5, the increase in temperature from present-day is lower, reaching approximately 2 °C. For the strongly mitigated scenario SSP1-2.6, the temperature initially increases and then stabilizes at about 1.5 °C of warming towards the middle of the century. The model spread is moderately high (2.5 to 3.0 °C), so the differences between the two scenarios producing weaker warming partially overlap. In contrast, for the high emissions scenario (SSP5-8.5) that produces stronger warming, the difference in temperature is greater than the uncertainty among models. Interannual variability is low compared to long-term changes. Regarding ocean acidification, in SSP5-8.5 a strong, gradual decrease in ocean pH occurs to about 0.4 units from present-day conditions, while the decline in SSP2-4.5 is less marked, and pH stabilizes by the end of the century in SSP2-4.5, after decreasing by 0.15 units. The SSP1-2.6 scenario suggests a slightly reversing trend, limiting the overall decrease in pH to less than 0.1 unit. Uncertainty for this pressure is inherently low, and differences in the changes among the scenarios are clear. For bottom oxygen concentration, uncertainty is higher relative to the changes observed among the three scenarios. For all three scenarios, oxygen decreases by approximately 0.5, 0.2, and 0.1 ml/l for SSP5-8.5, SSP2-4.5, and SSP1-2.6, respectively.

To give a clearer picture of the relative importance of the different sources of uncertainty and their role in different locations, maps of the changes of the three indicators for the ensemble average of scenario SSP2-4.5 as absolute values and relative to the uncertainties are provided (Fig. 3.6 & 3.7).

The increase in surface temperature is strongest in the Adriatic and Aegean Seas, with higher changes in the Eastern compared to the Western Basin of the Mediterranean Sea. Warming almost doubles from the middle to the end of the century with no major difference in the spatial distribution of change. Mid-century interannual variability and model uncertainty are of the order of the changes across the basin, while the differences between the scenarios are significantly lower than the changes induced. This situation reverses for long-term changes, which become more significant with respect to interannual variability. At the same time, the difference between the scenarios has become larger in relative terms and is comparable to the magnitude of the change.

For bottom dissolved oxygen, the situation is much less clear. While, on average, a decrease in bottom-water oxygen concentration is visible from the time series, some areas show an increase in oxygen for the ensemble mean (most evident in the Aegean Sea); interannual variability and particularly, model uncertainty is high in these areas. In contrast, areas with more severe decreases in oxygen emerge from interannual variability with changes slightly higher than the model uncertainty, although with some regional exceptions. Similarly, scenario differences are much larger and more important in areas of oxygen increase compared to areas of decrease. In the latter areas, differences among the scenarios were relatively small compared to the magnitude of the induced decrease in oxygen.

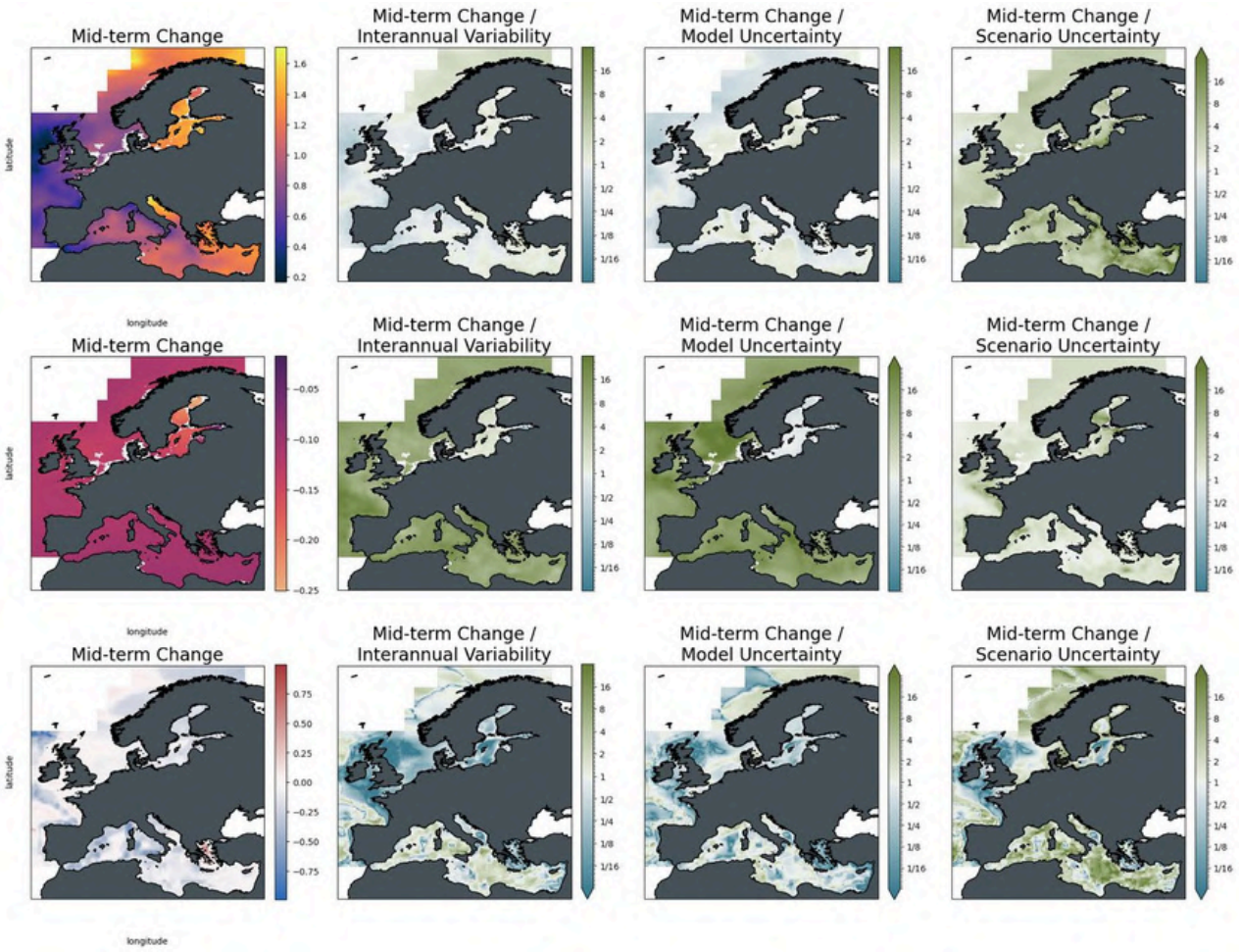


Figure 3.6, Significance of mid-term changes under SSP2-4.5, against three sources of uncertainty for three ecosystem indicators. From left to right: changes between mid-term conditions (2041-2060 mean) and present-day conditions (1995–2014); changes relative to internal variability; changes relative to model uncertainty; changes relative to scenario uncertainty. Top to bottom: Surface Temperature (K); surface pH; bottom dissolved oxygen (ml/l). (Deliverable Report 2.2)

North Sea

The basin-scale trajectories of projected change in mean physical and biogeochemical pressures of the wider North Sea area (Fig 3.5) is comparable to the Mediterranean Sea. Warming is, however, less accentuated in the North Sea compared to the Mediterranean Sea, with only a 3.0 °C increase projected at the end of the century for the no-mitigation scenario SSP5-8.5 and < 1.0 °C for the moderate and strong mitigation scenarios. Acidification as depicted in surface pH ranges from slightly less than 0.1 units (SSP1-2.6) to around 0.5 units of decrease (SPP5-8.5), while seafloor oxygen decreases by ~ 0.1–0.3 ml/l with interannual variability up to ~ 0.2 ml/l. Considering the spatial distribution of changes and uncertainties, warming is strongest towards the Eastern parts of the European shelf and comparatively weak towards the open Atlantic Ocean (Fig 3.6 and 3.7). On most of the continental shelf, however, these trends are comparatively weak with respect to interannual variability and model uncertainty (ratio is only slightly > 1). The differences among the scenarios are only of minor importance at mid-century (approximately 1/3 of the change signal across the basin) but eventually reach about the same order of magnitude as those induced by long-term changes.

Seafloor oxygen in the ensemble average only noticeably changes in the open ocean areas along the shelf break, where dissolved oxygen declines by up to 1 ml/l. These changes begin to emerge at mid-century but only become significant towards the end of the century. The difference in changes between greenhouse gas scenarios is minor, even towards the end of the century.

Bay of Biscay

In the area around the Bay of Biscay, the domain averages roughly followed the patterns observed in the two previous regions with strong continuous warming up to 3.0 °C by 2100 and acidification by 0.4 pH units for SSP5-8.5 (Fig 3.5). These changes are attenuated in the other two (moderate to strong mitigation) scenarios. For example, pH does not decrease but increases somewhat in the second half of the century for SSP1-2.6. Trends in acidification were strongly significant, while the warming trends emerged less clearly due to considerable model uncertainty (~ 1.5° to 3.5°), particularly for the two scenarios producing weaker changes. Deoxygenation shows considerable model (~ 0.4–0.5 ml/l) and interannual (up to 0.2 ml/l) variability. The trend in deoxygenation is minimal or absent for the strongest (SSP5-8.5) scenario through 2040, followed by a few years of strong interannual variability and a rapid decline that continues through the end of this century. There is a weaker, more continuous deoxygenation in the other two scenarios, similar to patterns in the North and Mediterranean Seas. Nonetheless, if the inter-annual variability is ignored, the trend is consistent among the three scenarios. The spatial distribution of these average patterns in the domain (Fig. 3.6 & 3.7) identifies the Northern coast of the Iberian Peninsula and the northern coast of Brittany as hotspots of surface warming, with the former particularly strong in the mid-term (up to 1°C) and the latter particularly strong in the long-term (almost 2°C). Relative to interannual variability and model uncertainty, however, this warming is only slightly emergent in the mid-term, while both interannual and model uncertainties are high in the deeper Atlantic waters. In the long-term, changes become significant with respect to interannual variability, while model uncertainty remains persistent through the end of the century. Consistent with patterns in the other regional seas, differences in scenario pathways in warming are small in the mid-term, while in the long-term, the different mitigation strategies will lead to differences in warming of the same order of magnitude as the change itself. Oxygen is expected to increase on the Celtic and Armorican shelfs although the three sources of uncertainty remain high for both mid and long term. In the deeper Atlantic waters, the coastal waters of northern Spain and the western coast of Portugal oxygen will decrease, and changes are significant with respect to interannual variability. For model and scenario uncertainty changes in oxygen are pre-dominantly significant with exceptions such as the inner coastal domain of Portugal which is dominated by upwelling and more complex oceanographic processes. Acidification trends are comparatively homogeneous across the domain, with somewhat stronger trends in the off-shelf areas of the North-Eastern Atlantic. This pattern is consistent between the two time slices; however, acidification is about 50% higher at the end of the century compared to the mid-century. The trends are strongly significant with respect to model uncertainty and interannual variability for both time slices. The difference between scenarios is of the same order of magnitude as the induced changes at mid-century, while at the end of the century, the mitigation pathways become increasingly important as the difference between scenarios reaches twice the magnitude of the change signal.

Baltic Sea

While the basin mean warming, acidification, and deoxygenation trends are also present in the Baltic Sea, their behavior and relation to uncertainty are substantially different in this coastal, semi-enclosed basin compared to the other regions. A fundamental difference is the large model uncertainty (up to 0.8 pH units) and increased interannual variability (up to 0.05 units) of surface pH with respect to the induced changes (0.1–0.5 pH units) (Fig. 3.5). In addition, the deoxygenation change (~ 0.2 ml/l) is much weaker, and interannual variability is much higher (up to 0.5 ml/l). In contrast, warming trends here (2–5 °C) are comparable to the other basins.

Looking at regional differences in these trends (Fig. 3.6 & 3.7), the ensemble average warming of the Baltic Sea for scenario SSP2-4.5 at mid-century is stronger in the Bothnian Sea and the Gulf of Riga and weaker at the margins of the Bothnian Bay and the Southern Baltic Proper. This pattern also persists at the end of the century, with the two warming hotspots spreading into the Northern Baltic Proper. Compared to interannual variability and model uncertainty, the trends only weakly emerge across the basin. Differences between scenarios are negligible at mid-century but reach the order of magnitude of the induced changes by 2100. For acidification, which is strongest in the Bothnian Bay, there is a clear distinction in the impact of interannual

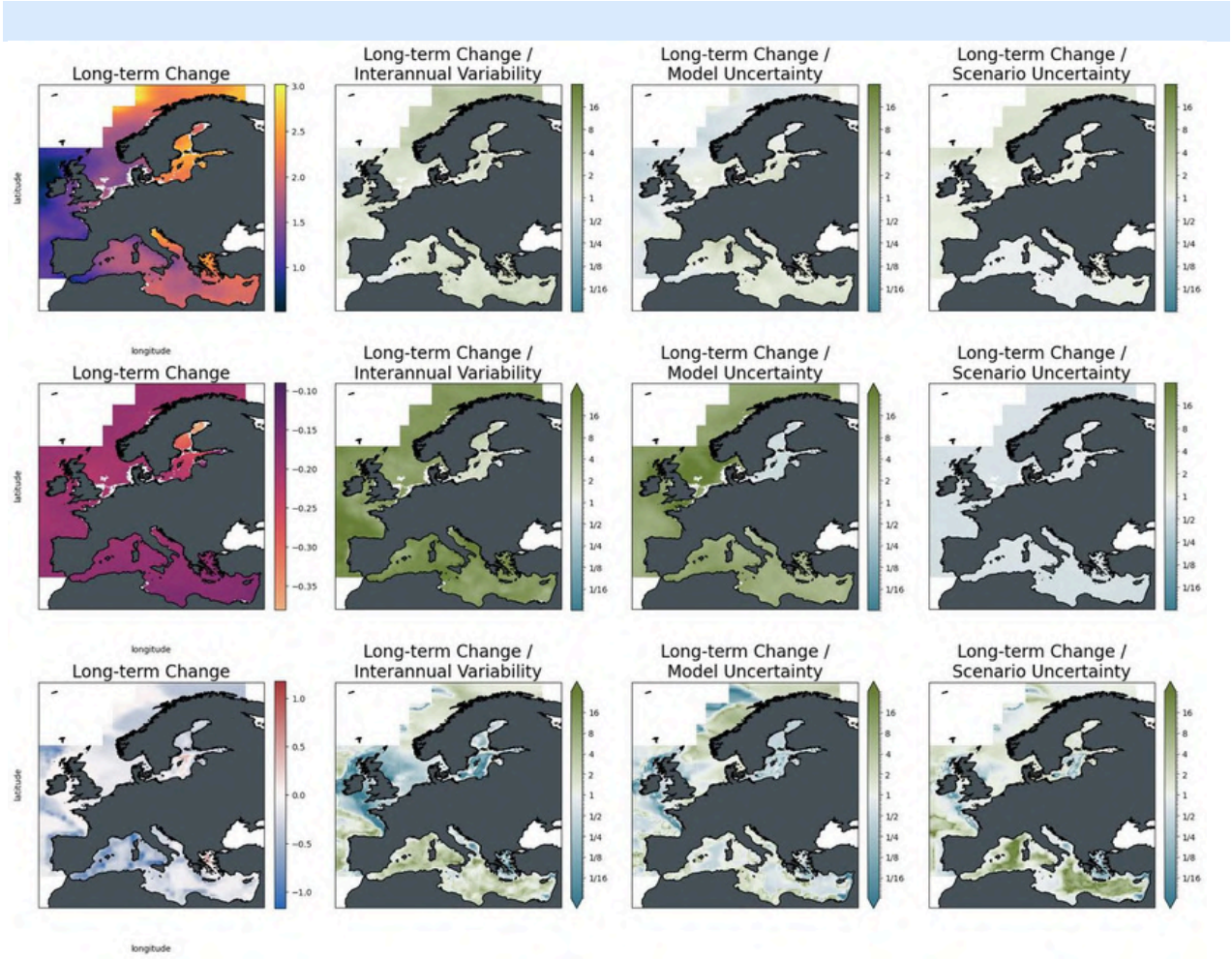


Figure 3.7, Significance of long-term changes under SSP2-4.5, against three sources of uncertainty for three ecosystem indicators. From left to right: changes between long-term conditions (2081-2100 mean) and present-day conditions (1995–2014); changes relative to internal variability; changes relative to model uncertainty; changes relative to scenario uncertainty. Top to bottom: Surface Temperature (Kelvin); surface pH; bottom dissolved oxygen (ml/l).
(Deliverable Report 2.2).

variability and model uncertainty on the mid-and long-term trends. While trends clearly emerge from interannual variability, model uncertainty is very high, visible already in the basin average time series that reaches more than twice the level of the trend.

The bottom oxygen concentration at mid-century reveals deoxygenation across the whole basin except for a small region of increase in oxygen north of the Gotland Basin that extends to the whole Gotland Basin by the end of the century. It should be noted, however, that these changes are comparatively uncertain with respect to interannual variability and model uncertainty across the entire Baltic Sea and are particularly uncertain for changes in dissolved oxygen concentrations. This area is also the only area in which scenario differences in oxygen trends are larger than the actual oxygen trend, making it an area of uncertain outcome in all aspects.

Generally, the Baltic area is subject to much higher uncertainties than the other regions and projections are error-prone with respect to observations (Kristiansen et al. 2024). Uncertainty and error are higher here for a number of reasons, ranging from insufficient resolution of the basin in the coarse-scale GCMs and ESMs, high sensitivity of the area to poorly constrained terrestrial inputs of nutrients and freshwater and other coastal processes, to high vulnerability to anthropogenic factors other than climate change that are not covered by the ESMs. For this reason, the projections for this area are to be taken with caution and the area is omitted from the subsequent multi-pressure analysis.

Multistressor exposure and mitigation potential

Projections of the combined climate change-induced ecosystem stressors show how global-level changes in climate forcing and interacting regional hazards (e.g. eutrophication) cause local perturbations to environment characteristics (e.g., warming, acidification, deoxygenation, stratification, nutrient dynamics). These changes can have substantial consequences for the ecology and biodiversity of shelf seas and coastal habitats.

Absolute thresholds for ecosystem stress, however, are difficult to establish because organisms have different sensitivity depending on, for example, adaptation to their local conditions as discussed in Chapter 2. Therefore, thresholds established for a specific location and species cannot be readily extrapolated to other contexts to derive a broader picture of hotspots and refuges of marine habitats under climate change despite the importance of hotspots and refugia for successful management of NBS under future conditions. To provide managers and policymakers a broader view, FutureMARES provides maps that express “climate stress” as the relative magnitude that future change exceeds local, natural variability.

The exposure of a given location to environmental stress is defined here by comparing its magnitude of change to the inherent variability of the system at that particular location. The underlying assumption of this definition is that most organisms in a given habitat and location will be sufficiently adapted and acclimated to cope with the natural variability. This definition is preferred here over the absolute definition of thresholds for two reasons:

1) to account for the plasticity and intra-specific (among population) differences in potential responses (tolerances) of organisms to stress at different locations due to adaptive capacity and acclimation (Sanford & Kelly 2011, Vargas et al. 2022);

2) to estimate the collective stress on a habitat at system level including all organisms that it contains.

The exposure indicator is hence defined as the change occurring over a given period in a specific location in relation to the range of natural variability:

$$E_{preassure} = \frac{change}{variabilty}$$

Change is defined here as the difference between the average of annual means of the ensemble medians for the future time slice (2041-2060 for mid-century, 2081-2100 for the far future) for a given scenario and the average of the annual means of the ensemble median for the end of the historical period (1995-2014). The range of natural variability is approximated here as the distance between the median and the 97.5th percentile of the detrended time series of monthly anomalies of the ensemble median for positive pressure variables warming and acidification and as the difference between the median and the 2.5th percentile for the negative pressure variable deoxygenation. In other words, exceedance of the stress thresholds of the 97.5th percentile and 2.5th percentile of natural variability is measured relative to their distance from the median.

The result is a non-dimensional stress exposure indicator for each ecosystem pressure.
For better comparison between different stresses, the indicator levels are further classified into categories of stress applying a logarithmic scale of base 2:

$$C_{preassure} = log_2 E_{preassure}$$

Yielding the following categorisation:

Category 1	$C1_{pressure}$	Change exceeds natural variability threshold
Category 2	$C2_{pressure}$	Change exceeds twice the natural variability threshold
Category 3	$C3_{pressure}$	Change exceeds four times the natural variability threshold
Category 4	$C4_{pressure}$	Change exceeds eight times the natural variability threshold

Following these definitions, exposure to warming is found to be higher in the Norwegian Sea and along the North African coast where stress levels reach more than twice and up to twice the natural variability respectively under unmitigated conditions. Warming exposure decreases significantly with mitigation to levels well below 1 under strongly mitigated conditions that don't emerge from model uncertainty for most of the domain.

Acidification levels are significant with respect to model uncertainty across the entire domain. Exposure is particularly high for this indicator (up to 32 times the natural variability and more under unmitigated conditions) as the natural variability is small compared to the climate change trends, as was already reported at the global scale (Henson et al. 2017). Exposure to acidification is stronger around the Iberian Peninsula, the Sicilian Strait, the Southern Adriatic and the Aegean Sea.

Deoxygenation appears stronger in various locations of the Mediterranean Sea, but the pattern for this indicator is very heterogeneous and uncertain for most of the domain across all scenarios, a reflection of the poorly constrained oxygen cycles found in the current generation of Earth System Models (Takano et al. 2023).

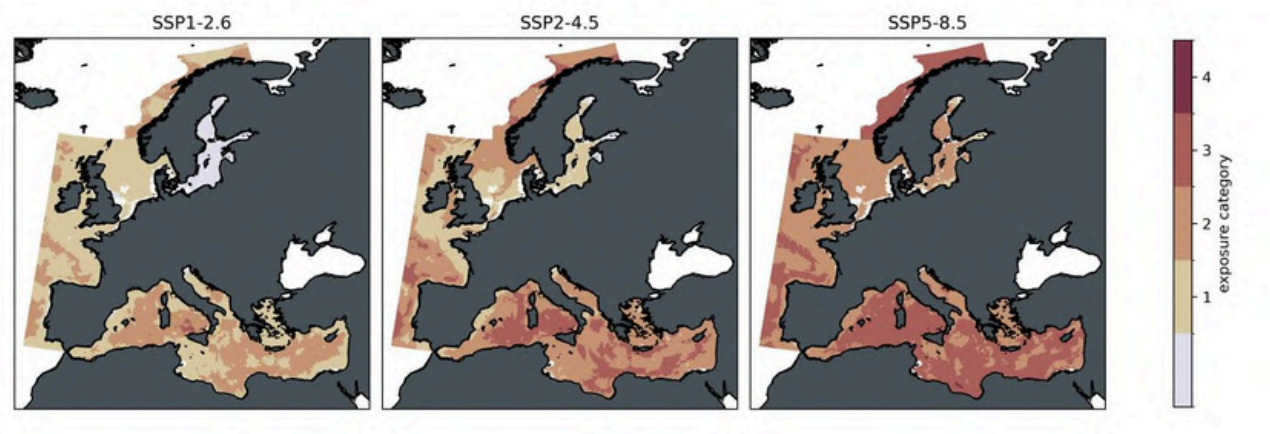


Figure 3.8, Exposure categories of combined ecosystem stress. (Deliverable Report 2.2).

To provide a comprehensive overview of hotspots and refugia of climate change induced ecosystem stress we compute the mean exposure to stress over the three indicators for warming and apply the exposure categories defined above yielding a map of exposure categories for each scenario (Fig. 3.8). Under unmitigated change the entire domain is subject to stress of at least category 2, virtually the whole Mediterranean and Norwegian Sea and part of the Northeast Atlantic reach at least category 3.

Exposure levels are gradually decreasing with mitigation levels applied, so that at SSP2-4.5 the maximum level reached, category 3, is much reduced, while for the strongly mitigated scenario only category 1 and category 2 are present.

Figure 3.9 shows the Mitigation Potential for each of the three ecosystem stressors. The highest potential is achieved for acidification where more than 50% of the stress occurring in unmitigated conditions can be avoided by the mitigation measures assumed in scenario SSP1-2.6. For warming and deoxygenation the mitigation potential reaches mostly levels of 30-40%, but for deoxygenation these results are much less certain due to comparatively high inter-model differences.

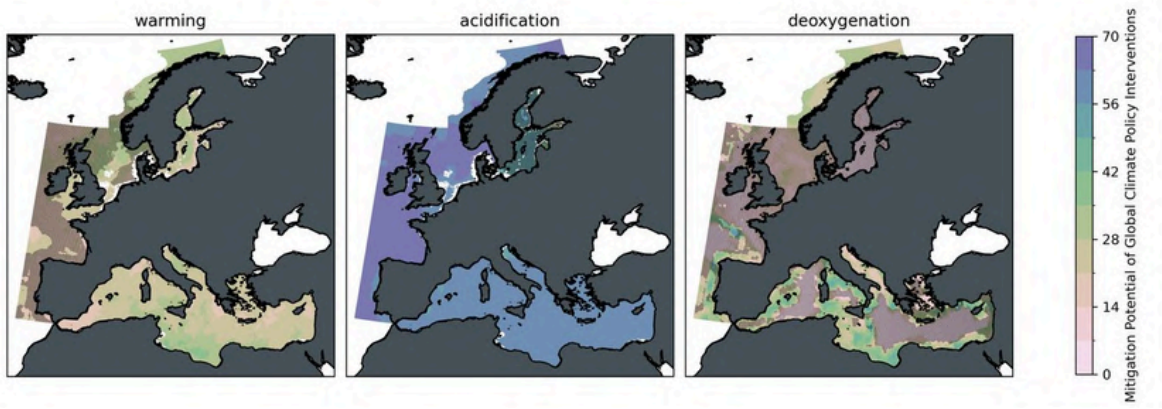


Figure 3.9, Mitigation potential for individual stressors of warming (left), acidification (middle) and deoxygenation (right). Shading indicates locations where model uncertainty exceeds mitigation potential. (Deliverable Report 2.2).

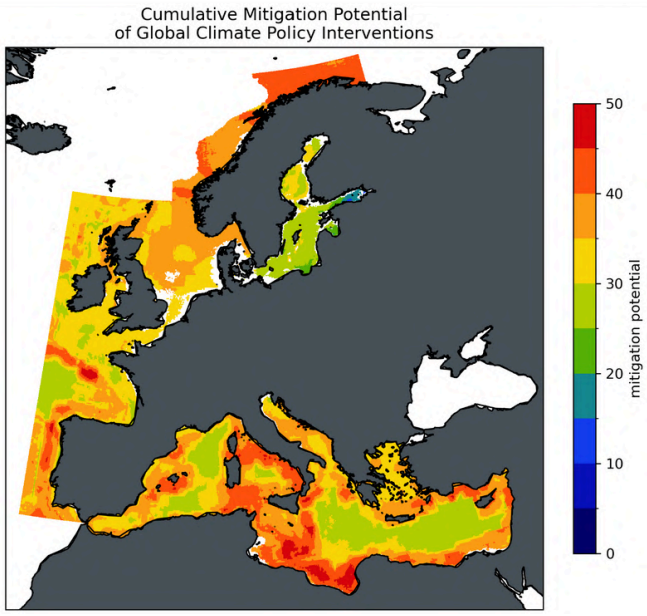


Figure 3.10, Cumulative mitigation potential for combined stressors. (warming, acidification, and deoxygenation). © Momme Butenschön, CMCC.

The cumulative Mitigation Potential for all three stressors combined is presented in Figure 3.10. This analysis suggests that mitigation efforts can lead to a marked reduction in stress exposure for at least 25% over the entire domain. At the same time, in no location does the mitigation potential exceeds 50%, even under intensive mitigation measures. The areas that benefit most (> 40% reduction) from mitigating greenhouse gas emissions are found in the central Mediterranean, Tyrrhenian Sea, Norwegian Sea, along the Eastern Mediterranean coast and along the shelf break, while the deeper open sea areas of Atlantic Ocean and Mediterranean Sea are less susceptible.

Links to statistically downscaled datasets on Zenodo:

North Sea: https://zenodo.org/doi/10.5281/zenodo.6523925

Mediterranean Sea: https://zenodo.org/doi/10.5281/zenodo.6523898

Bay of Biscay: https://zenodo.org/doi/10.5281/zenodo.6524141

Baltic Sea: https://zenodo.org/doi/10.5281/zenodo.6524110

Chilean Coast: https://zenodo.org/doi/10.5281/zenodo.6656120

Yucatan Peninsula: https://zenodo.org/doi/10.5281/zenodo.6524163

Future MARES

CHAPTER 4

FUTUREMARES SOCIAL-ECOLOGICAL SCENARIOS

AUTHORS: MYRON A. PECK, VERA KÖPSEL, MARTA COLL, CHRISTOPHER LYNAM

04 FutureMARES social-ecological scenarios

Introduction

Scenarios are imagined ‘futures’ that are not necessarily "visions" or "plans". Scenarios can help guide strategy and are created in sets of plausible and coherent alternatives. FutureMARES created a set of scenarios to help characterize how Nature-based Solutions (NBS) and Nature-inclusive (sustainable) Harvesting (NIH) might be implemented to safeguard ecosystem services under different social-ecological and climate change futures. These scenarios were inspired by the IPCC Special Report on Emissions Scenarios framework (Nakićenović et al. 2000) and were framed around three pairs of Shared Socio-economic Pathways (SSPs) (O’Neill et al. 2014) and Representative Concentration Pathways (RCPs). The SSPs describe future changes in society (population growth, gross domestic product, levels of international cooperation, etc.) that influence how easy it is for countries to implement actions for climate adaptation or climate mitigation and, by extension, biodiversity conservation and restoration, and Nature-inclusive Harvesting. The SSPs (social-economic, geo-political) and RCPs (amounts of global warming) were designed to be used together (van Vuuren et al. 2014) and, although not specifically matched, some SSP-RCP combinations are much more or much less likely.

The broad narratives for these scenarios were based on the socio-political scenarios developed under the EU Horizon 2020 project CERES (Peck et al. 2020, Pinnegar et al. 2021). FutureMARES used three of the four scenarios published by Pinnegar et al. (2021): World Markets (WM, SSP5-8.5), National Enterprise (NE, SSP3-8.5), and Global Sustainability (GS, SSP1-2.6). These scenarios differ in their focus on consumerism (WM, potentially NE) versus environmental (GS) goals, their local (NE) versus global (GS, WM) outlook, technological development, as well as on the severity of CO2 emissions and resultant physical and biogeochemical changes in marine waters. There is broad consensus on SSP-RCP combination applied in GS and WM, but not for the NE scenario. FutureMARES assumed high economic growth in the NE scenario to produce the amounts of warming in 2100 consistent with RCP8.5 (Riahi et al. 2017). The following provides the broad narratives for these scenarios.

Global Sustainability

SSP1-2.6: low challenges for climate adaptation and mitigation

The world shifts gradually but pervasively to a more sustainable path, emphasizing inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, investments in education and health accelerate lower birth and death rates, and the emphasis on economic growth shifts to an emphasis on human well-being. Societies increasingly commit to achieving sustainable development goals and this reduces inequality across and within countries. Consumption is oriented toward lower material growth, resource and energy intensity.

National Enterprise

SSP3-8.5: high challenges for mitigation and adaptation

A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to focus on domestic or regional issues. Policies shift over time to be oriented more on national and regional security. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development. Investments in education and technological development decline. Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time. Population growth is low in industrialized countries and high in developing ones. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions.

World Markets

SSP5-8.5: high challenges for mitigation, low challenges for adaptation

The world increasingly believes in competitive markets, innovation and participatory societies to produce rapid technological progress and train and educate people for sustainable development. Global markets become more integrated. Strong investments in health, education, and institutions are made to enhance human and social capital. The push for economic and social development is coupled with exploiting abundant fossil fuel resources and adopting resource and energy intensive lifestyles around the world. All these factors lead to rapid growth of the global economy, while global population peaks and declines in the 21st century. Local environmental problems such as air pollution are successfully managed. There is faith in the ability to effectively manage social and ecological systems, including by geo-engineering if necessary.

Developing scenario narratives for NBS and NIH

To apply each of these broad scenario narratives in quantitative economic or social-ecological projection modelling for NBS and NIH required that future changes be defined in a more holistic set of factors. To accomplish this, FutureMARES applied the 'PESTLE' framework (Aguilar 1967, Johnson & Scholes 2002) that describes how political, economic, social, technological, legal and environmental factors may cause risks and/or threats to specific plans or objectives. The PESTLE framework was previously used to create scenarios needed for projections of the bioeconomic consequences of climate change through 2050 on European fisheries and aquaculture (Pinnegar et al. 2020). For fisheries projections, future changes in fuel and fish prices and contrasting levels of fishing effort relative to Maximum Sustainable Yield (MSY) were defined (Hamon et al. 2021). For aquaculture projections, future changes in the prices of electricity and fish feed ingredients, and differences in the use of subsidies were defined (Kreiss et al. 2020).

The fisheries scenarios were further regionalized for application to specific communities such as economic profits of small-scale fleets targeting dolphinfish (*Coryphaena hippurus*) in the NW Mediterranean Sea (Rambo et al. 2022). The same three scenarios (WM, NE, GS) were regionalized by Chevallier et al. (submitted) for social-ecological projections of climate change impacts on local fisheries in two coastal communities, highlighting major differences in French fishers operating in the Mediterranean Sea versus Atlantic waters. The aquaculture scenarios were regionalized for economic assessments using the 'typical farms' approach (Chibanda et al. 2020). The PESTLE framework has also been previously applied to explore risks and threats to aspects of sustainability including the increased use of biofuels (Achinas et al. 2019) and the implementation of artificial floating islands as an NBS to improve water quality for communities in developing countries (Fonseca et al. 2022).

Based on the input of stakeholders and project partners, a "narrative matrix" was completed that included the three interventions (NBS1, NBS2, NIH), the three SSP-RCP scenarios, and the six "PESTLE" elements (Fig. 4.1, Fig. 4.2, Fig. 4.3). This matrix created the FutureMARES scenarios that were subsequently regionalized for application in different Storylines. These expanded, PESTLE narratives provided a consistent approach to conduct broad-scale analyses presented in Chapter 5, 6 and 7 of this report such as:

1. cross-regional comparisons of projections of the ecosystem-level impacts of scenario-specific differences in the implementation of NBS / NIH. In this case, comparisons were made among the W Mediterranean, Bay of Biscay, North Sea, Baltic Sea and the Portuguese shelf; using large-scale, spatially-explicit end-to-end models (Steenbeek et al. 2020, de Mutsert et al., 2023);
2. cross-regional comparison of social-ecological Climate Risk Assessment (CRAs) (Bueno-Pardo et al. 2024) exploring how NBS and NIH under climate change risk can influence mitigation or adaptation as well as the provision of ecosystem services;
3. comparisons of Cost-Effectiveness Analysis (CEA) or modified Cost-Benefit Analysis (CBA) of NBS and NIH in protecting or enhancing (provisioning, regulating and cultural) ecosystem services.

		Future Socio-Economic Pathways						
NBS 1	Representative Concentration Pathways - RCP	Socio-economic Pathways - SSP	Political	Economic	Social	Technological	Legal	Enviromental
Global Sustainability	Minimal warming [RCP2.6]	SSP1	Collaboration, Cross-border restoration activiites	Nature as non-profitable asset, Free access to natural environment	Social awareness, Restoration success is a priority	Innovations, Integrated restoration efforts	EU Restoration Law followed, Focus on Natura2000 sites	Mitigation to and adaptation of climate change
National Enterprise	Strong warming [RCP8.5]	SSP3	Poor linkages and limited efforts for joint restoration activities	Restoration of high-value species (food/job security, coastal protection)	Restoration in national waters is the priority	Little or no technological advancement	National targets will prevail for the restoration within MPAs	No mitigation or adaptation to climate change, MPA surface increase only 5%
Word Markets	Strong warming [RCP8.5]	SSP5	EU Green Deal, Transnational restoration efforts	Restoration of species with high economic value	Awareness for market valuable resources	Technological advances, better restoration methods	No restoration of habitat-forming species because the effort will be in fish habitats	Adaptation to climate change, No mitigation

Figure 4.1, PESTLE (political, economic, social, technological, legal and environmental) scenarios developed for NBS1 (habitat restoration). (Deliverable Reports 1.1 and 1.2)

NBS 2	Representative Concentration Pathways - RCP	Future Socio-Economic Pathways: Socio-economic Pathways - SSP	Political	Economic	Social	Technological	Legal	Enviromental
STATUS QUO								
Global Sustainability	Minimal warming [RCP2.6]	SSP1	Collaboration, MPA > 30%	Nature as non profitable asset, MPA free access	Social awareness, MPA effectiveness priority	Innovations, Integrated MPA management systems	International commitments	Mitigation to and adaptation of climate change
National Enterprise	Strong warming [RCP8.5]	SSP3	Independence, MPA according to national policy	Less financial supports to MPAs	Engagement, MPA effectiveness, Diversity	Little or no technological advancement	International commitments not universally upheld by all countries	Serious effects of climate change, MPAs local to mitigate the impact
Word Markets	Strong warming [RCP8.5]	SSP5	Focus on Economy, MPAs for Economic Growth	Nature as profitable asset, Entrance fees to MPAs	Awareness for market valuable resources	Technological advances, Better MPA management	No international commitments, Conflicts about MPAs	Serious effects of climate change, Mitigate impact on developed countries

Figure 4.2, PESTLE (political, economic, social, technological, legal and environmental) scenarios developed for NBS2 (habitat conservation). (Deliverable Reports 1.1 and 1.2).

NIH	Representative Concentration Pathways - RCP	Future Socio-Economic Pathways: Socio-economic Pathways - SSP	Political	Economic	Social	Technological	Legal	Enviromental
Global Sustainability	Minimal warming [RCP2.6]	SSP1	MPA 30% by 2030 with Max. Sustainable Yield	Low fish prices, No increase in fishing effort	Focus on restoration, conservation & aquaculture	Minimal bycatch, No creep	10% sea no-take, Avoid fisheries displacement	Mitigation to and adaptation of climate change
National Enterprise	Strong warming [RCP8.5]	SSP3	MPAs for national aims	Medium fish prices, Fishing effort increases with time	Mixed aims	High bycatch, Low tech creep (0.4% p.a.)	5% of sea no-take	No mitigation or adaptation to climate change
Word Markets	Strong warming [RCP8.5]	SSP5	New MPAs – commercial fish habitat	High fish prices, Fishing effort increases with time	Focus on seafood	Minimum by-catch, High tech creep (0.9% p.a.)	5% of sea no-take	Adaptation to climate change, No mitigation

Figure 4.3, PESTLE (political, economic, social, technological, legal and environmental) scenarios developed for NIH (Nature-inclusive Harvesting). (Deliverable Reports 1.1 and 1.2).

The IPBES (2016) categorized four types of scenarios: 1) Exploratory scenarios for raising awareness and setting agendas, 2) Target-seeking scenarios to design actions to meet specific targets or goals, 3) Intervention scenarios to forecast effects of alternative actions, and 4) Retrospective scenarios to evaluate how intended targets (e.g., increased fish stocks or biodiversity) of previous actions (e.g., MPA designation) compare with alternative actions or interventions. The scenario narratives developed in FutureMARES can be categorized as both type 1, exploring different levels of climate drivers (e.g., warming) or NBS / NIH strategies, and type 2 (target-seeking) to describe pathways of implementation of the EU Biodiversity Strategy. Obtaining the targets of that EU strategy were included in the broad narrative of the Global Sustainability scenario. For example, in terms of conservation, GS included protection of 30% of marine areas with 10% strict protection by 2030. In terms of restoration, the GS scenario aligns

with the aspirations of the newly ratified EU Nature Restoration Law which mandates that at least 20% of Europe's land and sea be restored by 2030 including 30% of habitats in poor condition by 2030 and 90% of those habitats by 2050.

Regionalising FutureMARES scenarios

Scenarios need to be tailored for regional contexts for many reasons. First, some regions examined in FutureMARES are outside the European Union and have their own national environmental / climate policies and objectives. Second, important drivers of ecological change vary regionally such as the magnitude of physical and biogeochemical impacts of climate change (a global-scale stressor) across among European Regional Seas and their transitional waters (Kristiansen et al. 2023, See Chapter 3). Finally, each region has a unique mixture of other, interacting stressors or key economic sectors.

In the Baltic Sea, for example, eutrophication has been a dominant stressor causing historical environmental change and scenarios developed under the auspices of HELCOM reflect this. For example, the BALTICAPP project used a participatory approach to create scenarios of plausible future trends in eutrophication, fisheries and marine traffic (Zandersen et al. 2019). At smaller, regional scales in the Baltic Sea, the Plan4Blue Interreg project (2016-2019) developed scenarios to examine the future development of blue economies in the Gulf of Finland and Archipelago Sea. In that northeastern region of the Baltic, four scenarios were used: "Unlimited growth", "Virtual Reality", "Sustainability above all" and "Sustainability dilemma" to test Maritime/Marine Spatial Planning (MSP) objectives that balance economic, social and environmental goals (Pöntynen & Erkkilä-Välimäki 2018). Bauer et al. (2019) also provide scenarios for future fisheries and ecological drivers in the Baltic Sea. FutureMARES, therefore, was able to rely on some of the information within scenarios created in these previous projects when running ecological projections for the Baltic Sea.

In the North Sea, the Netherlands Environmental Assessment Agency developed four scenarios of the MSP for the Dutch EEZ for 2030 and 2050 (PBL 2018). Three of those scenarios (Sustainable Together, Slow Change and Rapid Development) have common elements with FutureMARES scenarios (Global Sustainability, National Enterprise and World Markets). Those scenarios helped define trade-offs in the three ongoing transitions: renewable energy (particularly offshore wind), sustainable food production, and nature conservation. More recently, scenarios have been developed by Olsen et al. (2023) using Fuzzy Cognitive Mapping to facilitate stakeholder dialogue on future management strategies in the framework of Integrated Ecosystem Assessment and as a precursor to developing and testing SSPs. Qualitative maps were built for sub-regions of the North Sea and used to define scenarios to be compared in simulations using Ecopath with Ecosim (EwE), a quantitative ecosystem model employed in FutureMARES (Box 3.1). In that case, projections used scenarios for changes in fishing pressure (the only common driver among the models) and RCPs 4.5 and 8.5.

In the Western Mediterranean Sea, Marine Spatial Planning (MSP) scenarios for 2030 were developed as part of the MSPglobal Initiative (UNESCO-IOC 2021) to support an ecosystem-based approach to developing the blue economy. In that work, a "trend scenario" representing no new management interventions was compared to two, alternative marine spatial use

scenarios, a conservation-focused future and an integrated use scenario. The sectors of primary importance were included such as coastal and marine tourism, maritime transport, fisheries, oil and gas, windfarms and aquaculture. Those scenarios highlighted potential sub-regional (cross-border) conflicts for space to promote dialogue and the development of preferred MSP. Similar to the FutureMARES Glossy Card, that project's technical report included questions to help guide discussions at regional stakeholder workshops. Note, unlike FutureMARES, the scenarios did not consider climate change.

Regional differences

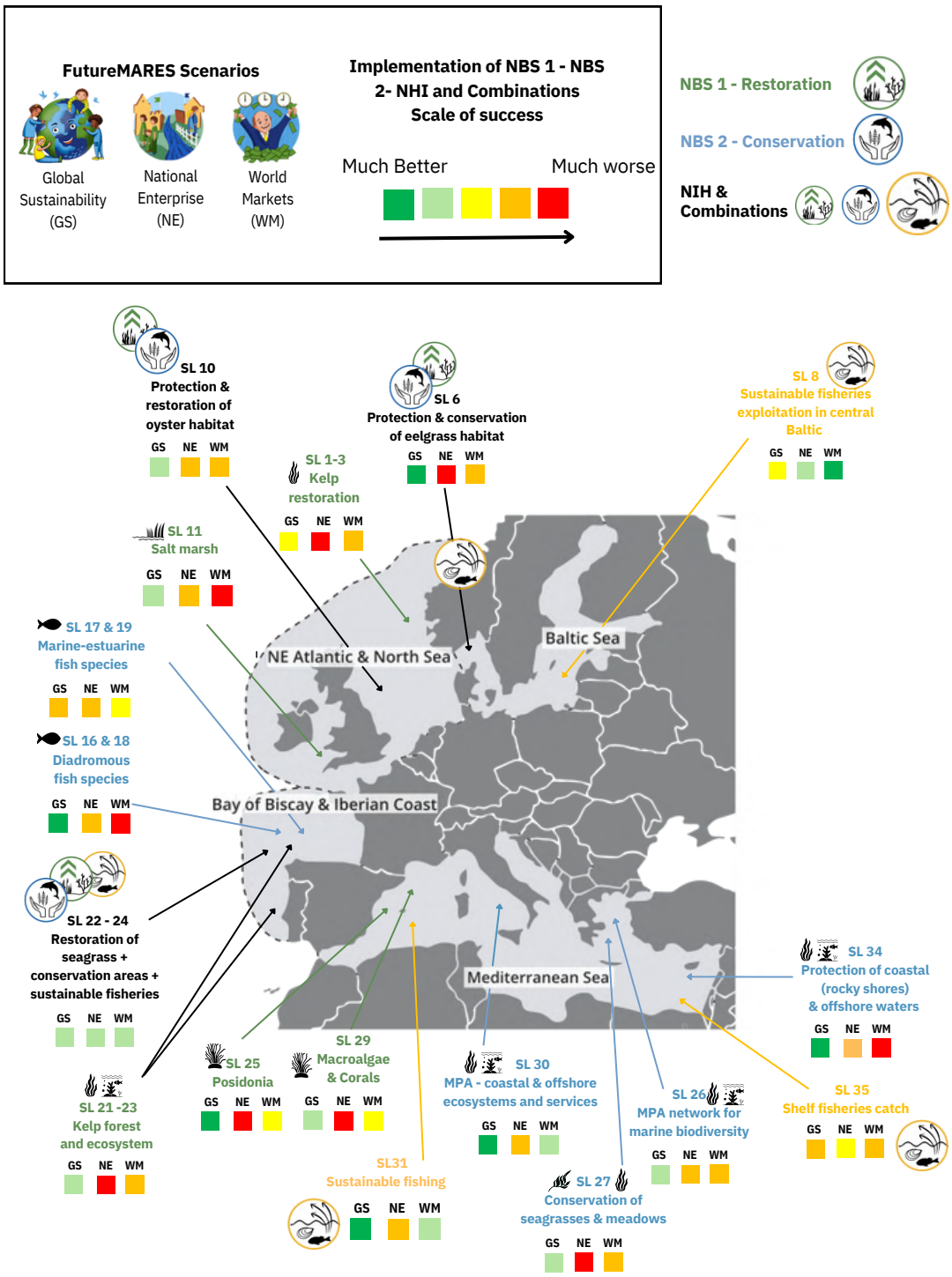


Figure 4.4, Regional differences in the ranking of the three FutureMARES scenarios in their effectiveness for implementing NBS and NIH.

Project partners and regional stakeholders ranked each of the three FutureMARES scenarios on a five-point scale in terms of the degree of effectiveness of local / regional implementation of policies related to NBS1 (restoration), NBS2 (conservation) and/or NIH (nature-inclusive / sustainable harvesting) (Fig 4.4). The results indicate not only strong differences in perspectives among the three scenarios, with GS recognized as the “best” scenario for NBS / NIH implementation but also regional differences in the ranking of the effectiveness of the WM and NE scenarios. This ranking also depended on the type of intervention. For sustainable harvesting and particularly for habitat restoration, perspectives were least optimistic with the NE scenario due to the lack of cooperation among nations. Often but not always, the WM scenario was considered more favorable for sustainable fisheries production but detrimental for biodiversity conservation and restoration.

BOX 4.1 Digital laboratories

Digital marine laboratories are advanced research platforms that depict physical (oceanographic), ecological (food webs) and human use (fisheries) attributes of marine systems to allow assessment of "what-if" scenarios. These labs integrate computational tools, modeling frameworks, and data visualization techniques to develop digital experiments that simulate oceanographic and environmental processes of marine ecosystems, and the impacts of changes in physical, chemical, biological factors as well as how humans exploit and manage these ecosystems (Fig. 4.5).

FutureMARES performed virtual experiments using 7 digital representations of European Seas at both regional (North Sea, Baltic Sea, Bay of Biscay and Western Mediterranean Sea), and sub-regional (Finnish Archipelago Sea, Northwestern Mediterranean Sea, and the Portuguese Shelf) levels. Spatial-temporal marine ecosystem models developed with Ecopath with Ecosim and Ecospace framework explored impacts of three, contrasting climate projections (see Chapter 3) and management interventions including status quo scenarios without additional management interventions. These interventions included combinations NBS and NIH within FutureMARES scenarios (see Chapter 4) including:

- the recovery of habitat-forming species (regionally chosen according to ecological and policy contexts, for example considering the recovery of *Posidonia oceanica* meadows in the Mediterranean Sea, native flat oyster Ostrea *edulis reefs* in the North Sea, or reductions in nutrient loading in the Baltic Sea);
- the protection of specific areas to achieve international targets (e.g., achieving 10% full protection and 20% high protection by 2030) and;
- the achievement of sustainable harvesting practices (e.g., reducing discards and bycatch, and achievement of fishing mortalities consistent with maximum sustainable yield F_{MSY}) (see Chapter 4).

Global Sustainability (GS) tested the effects of reaching EU & international legal regulations and targets for restoration of habitat-forming species (flat oysters, blue mussels, seagrass, corals), for protection (MSFD, HD, Biodiversity strategy, Green Deal) with priority for connectivity and climate-ready solutions, and for a full implement of EU fisheries directives (CFP, MSFD), RSC conventions, and EBFM principles. These included establishment of fisheries restricted areas, reductions in discarding and bycatch, and reduction of fishing effort to achieve values of fishing mortality below F_{MSY}.

National Enterprise (NE) tested the effects of prioritizing restoration of high-value species according to food security, job security or coastal protection within EU EEZ (according to national targets).

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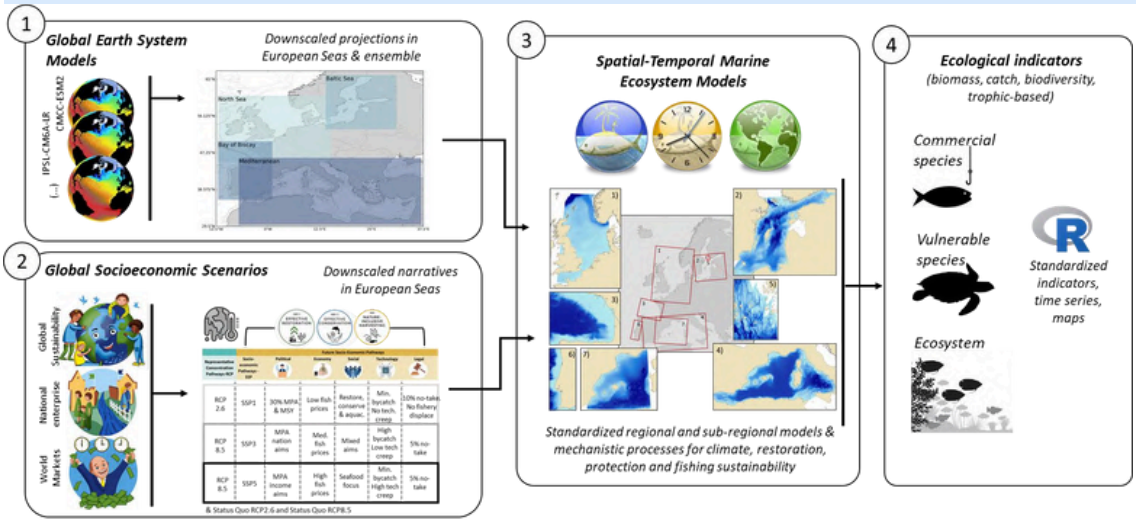


Figure 4.5, Workflow developed under FutureMARES to link global Earth System models, socioeconomic scenarios and marine ecosystem models to develop regional and sub-regional scenarios of NBS and NIH for 7 regions within European Seas.

Regarding protection actions, it included small MPAs with national interests and no connectivity and fishing was high (or very high) due to help from subsidies operating in national EEZ to ensure food security and maximum landed volumes.

World Markets (WM) tested the priority of restoring high-value (hake, cod, sole) commercial species with limited-scale interventions, establishing small MPAs with economic value and no connectivity, and increasing large-scale fisheries to achieve maximum landed values, while small-scale fisheries declined. NE and WM scenarios considered lower targets of discard reduction and bycatch, while the three contrasting scenarios also differed in terms of fishing and fuel costs. Finally, status quo scenarios simulated baseline conditions for management interventions.

Marta Coll & Christopher Lynam

Engagement methods used to regionalize scenarios

In the last decade, the number of projects using co-design and co-production by stakeholders has been growing, in part, due to the increasing urgency for science to produce societally relevant, actionable results. Best practice guides and handbooks now exist (e.g., Goudeseune et al. 2020) to help scientists involve potential end users (policymakers, businesses, practitioners) throughout the duration of scientific research. Much of the current “best practice” stems from work by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) including the Methodological Assessment on Scenarios and Models (IPBES 2016, Pichs-Madruga et al. 2016).

Worksteps for regionalizing the FutureMARES scenarios occurred in a five-step process (Fig. 4.6 & 4.7). To support this process, a number of products were created included creating 1) a scenario glossy card to describe the three broad, global scenarios (GS, NE, WM), 2) a template for a 90-minute, stakeholder workshop to introduce the scenarios with an option to use interactive software to collect stakeholder feedback, and 3) an online cuestionnaire to send to regional experts to gain information on three PESTLE elements: Political, Societal and Legal.

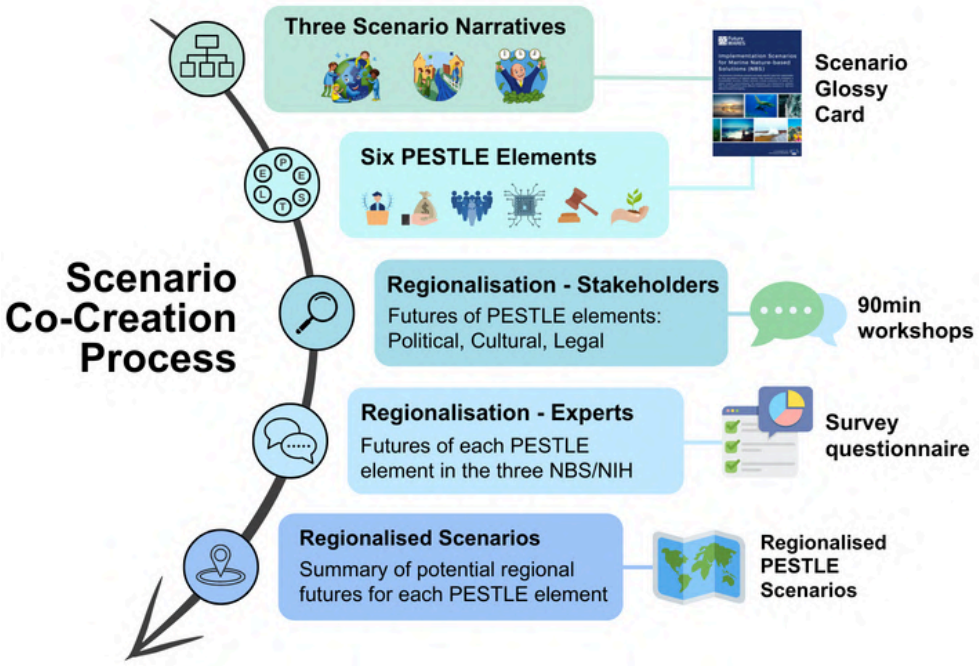


Figure 4.6, Work steps taken to create the three scenarios used by FutureMARES to assess the implementation of Nature-based Solutions and Nature-inclusive Harvesting. (Deliverable Reports 1.1).

The use of online materials was based on the recognition of challenges caused by the Covid-19 pandemic and recommended best practice for continuing stakeholder engagement in large EU projects during periods when national restrictions prohibited in-person meetings (Köpsel et al. 2021). Regionalization of elements of the PESTLE scenarios was also gained by "expert-based" engagement as part of climate risk assessments (see Box 5.1).

Figure 4.7, Partial output of an online exercise (Mural) to obtain feedback on elements of the three scenarios of future implementation of NBS (colors of sticky notes). Online engagement event held in October 2020 to exchange with high-level policymakers. (Deliverable Reports 8.1).

Future MARES

CHAPTER 5

MARINE CONSERVATION AS A NATURE-BASED SOLUTION IN A FUTURE CLIMATE

AUTHORS: JOAQUIM GARRABOU, FABIO BULLERI, ANA QUEIRÓS, MARTA COLL, ELENA OJEA, JUAN BUENO-PARDO, SARAH SIMMONS, SEVRINE SAILLEY , MYRON A. PECK

05 Marine conservation as a Nature-based Solution in a future climate

Introduction

Marine Protected Areas (MPAs) are a widely used area-based conservation tool intended to protect all components of biodiversity and promote healthy ecosystems that increase societal benefits in the form of ecosystems services (Fig. 5.1). MPAs are places in the ocean that receive some degree of protection to safeguard biodiversity from the threats associated with human activities such as fishing and habitat loss (Grorud-Colvert et al. 2021). The potential importance of designing effective networks of MPAs as Nature-based Solutions (NBS) to combat the combined biodiversity and climate crises has been highlighted and promoted during the last decade (Gattuso et al. 2019, Hoegh-Guldberg et al. 2019, 2023). As a result, the essential role of MPAs has been recognized by recent international (UN CBD Kunming-Montreal global biodiversity framework, Post SAPBIO 2020 Barcelona Convention) and European (EU Biodiversity Strategy) agreements including the establishment of MPAs to protect 30% of European ocean areas by 2030 with the strict protection of 10% of European waters.

The establishment of MPAs, especially "fully protected" MPAs where the impacts of human activities are absent can, in some cases, be used to address both climate change mitigation and adaptation (Roberts et al. 2017, Sala et al. 2021, Grorud-Colvert et al. 2021, Queiros et al. 2021, Arneth et al. 2023, Benedetti-Cecchi et al. 2024). MPAs can help promote climate change mitigation by protecting habitats such as kelp forests, seagrass meadows and the ocean floor, which support carbon sequestration. For example, the establishment of MPAs that limit bottom trawling has also been highlighted as a potential tool to limit the release of carbon trapped in the sediments, and consequent release of CO2 to the atmosphere, although more evidence is needed to understand this aspect of the marine carbon budgets (Hiddink et al. 2023, Atwood et al. 2024). MPAs, when effectively managed, may also help ensure the functioning of food webs that further promote the storage and transport of carbon from shallow to deep environments (Queiros et al. 2023).

Figure 5.1, Marine biodiversity within Mediterranean MPAs. Photo credit: top-mid: Joaquim Garrabou; bottom: Fabio Bulleri.

MPAs may help to promote climate change adaptation by enhancing ecological resilience where their management leads to the reduction and/or complete removal of local stressors from climate sensitive species before ecological thresholds or tipping points are reached. In this way, MPAs may improve the overall conservation status of populations, species and habitats (Simard et al. 2016, Roberts et al. 2017). Thus, providing species and habitats better conditions to resist and/or recover in the face of climate change stressors such as warming, marine heatwaves, sea level rise or ocean acidification. However, in the medium and long term, MPAs *as a de facto* measure to reduce other pressures on local biodiversity, cannot provide such benefits to local communities when climate change exceeds the tolerance range of local species to climate stressors (Queiros et al. accepted pending minor corrections). In those cases, dynamic ocean management is needed, whereby the boundaries of MPAs move over space and time to protect species and habitats as their own distribution is altered by climate change (Maxwell et al. 2015). Monitoring MPA effectiveness in promoting climate change adaptation must then be estimated within the context of the effects of climate-pressures on species and habitats used as site designation features (Doxa et al. 2022; Queiros et al. 2024). This aspect is explored in depth in Chapter 8.

Beyond their ecological benefits, MPAs can also be focal points of stakeholder engagement within complex socio-ecological systems. The consultation process with the main stakeholders operating around MPAs ensures a much more effective and efficient implementation of adaptation measures (Di Cintio et al. 2023), thus enhancing the effectiveness of MPAs as protective measures in a future climate. Moreover, MPAs, particularly in regions where they are main visitor attractors (e.g., the Mediterranean region), may play a major role in facilitating ocean literacy by informing the general public on the role of the ocean conservation in tackling the ongoing climate crisis (Simard et al. 2016). Raising awareness of our society on climate change both at local MPA and regional/global levels may largely contribute to accelerating the achievement societal transformations to reduce greenhouse gas emissions.

Currently, the proportion of European MPAs with strict (full and high) protection is extremely small; worldwide only 2,9% of MPAs have this type of designation (MPA Atlas). While the total European MPA's surface is just about 8%, very far from the 30% target by 2030. Therefore, the contribution of MPAs to climate change adaptation and mitigation is not being realized. Moreover, a great proportion of MPAs can be aptly termed "paper parks" since many of these areas lack management plans to safeguard marine biodiversity and even fewer MPAs include measures to adapt to climate change (Rilov et al. 2019, Claudet et al. 2020, Castro-Cadenas et al. submitted).

Research within FutureMARES

Critical need for climate-smart conservation planning and management

Ongoing national and international efforts are focused on the implementation of effective MPAs networks as a frontline for protecting biodiversity and for adaptation and mitigation to climate change. However, most MPAs and networks have been established without considering ongoing and future climate change impacts. In fact, climate change is already posing a threat to the effectiveness of MPAs as reported in studies examining the impacts of severe marine heatwaves (prolonged periods of anomalously warm ocean temperatures or shorter periods of extremely

warm temperatures) or long-term climate-driven changes in average temperature (Bruno et al. 2018, Hughes et al. 2018, Montero-Serra et al. 2019).

These studies showed that protection was not able to prevent the severe impacts of climate change in different habitats inside MPAs. Instead, MPAs support climate resilience by enhancing the recovery and the preservation of ecosystem functioning even though species and functional groups may be substantially altered. For instance, protection has been recently shown to sustain the stability of reef fish community under warming climates (Benedetti-Cecchi et al. 2024).
The effectiveness of MPAs can be improved by integrating climate-smart MPAs networks in conservation planning schemes at different scales. For planning these networks, areas with the greatest conservation potential, benefits and future resilience need to be identified and prioritised for protection. This requires enhancing our ability to assess the degree to which the current presence and functioning of species, habitats and ecosystems will be altered in different climate futures. Fine-scale, physical, biogeochemical or ecological projections is key to support tactical (operational) decisions at the local MPA level where the final implementation of conservation measures takes place (Pennino et al. 2020, Queiros et al. 2021).

Work performed in FutureMARES

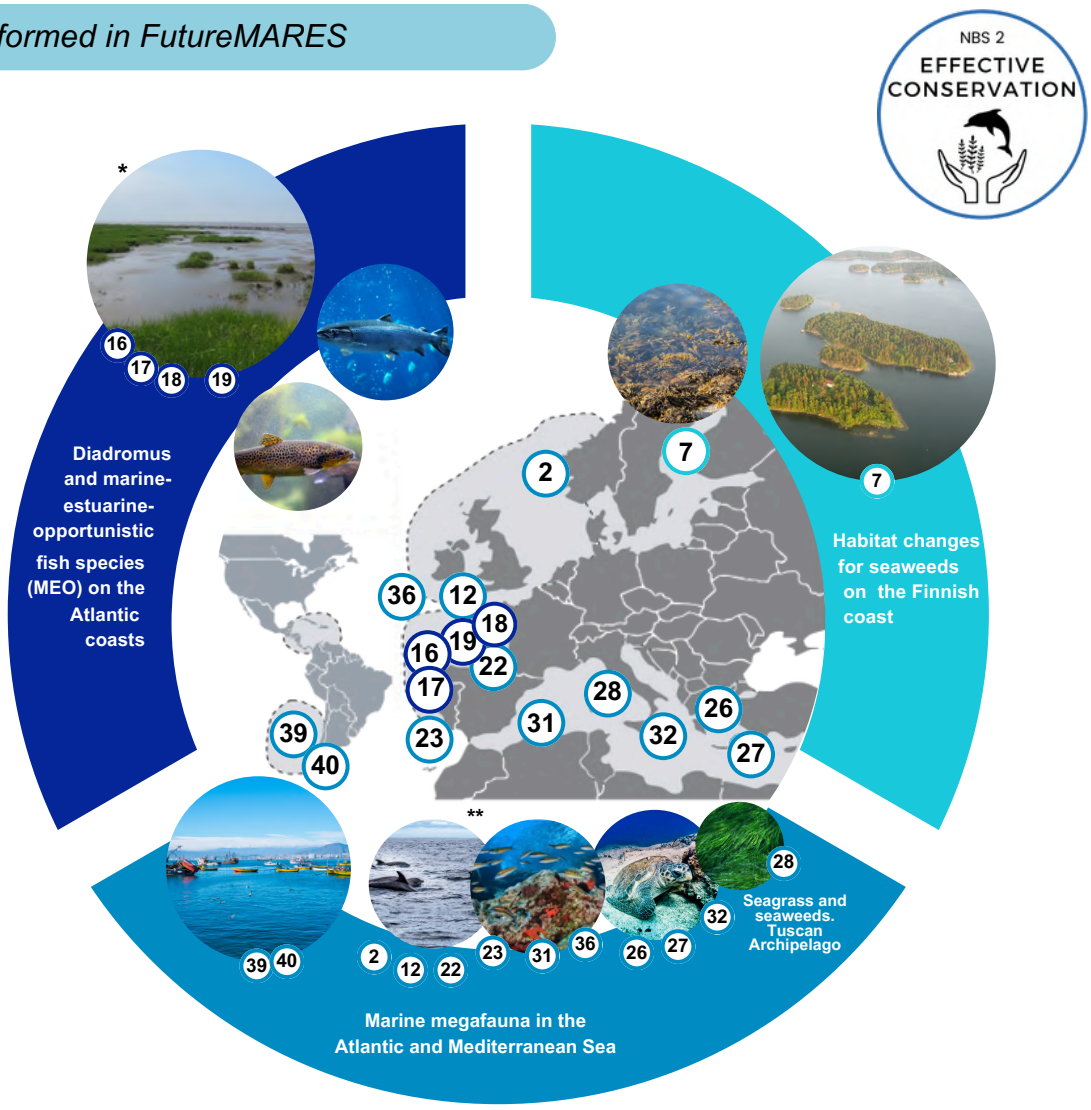


Figure 5.2, Location of the Storylines examining effective marine conservation in a future climate within the FutureMARES programme. Photo credit: *Gary Banta. **Joaquim Garrabou.

FutureMARES contributed to the implementation of climate-smart MPA networks (Chapter 8) and conservation measures across 17 Storylines (Fig 5.2). These different Storylines spanned the full geographical range of the project through European Seas and CELAC (Chile), from Norway and Finland, to the western and eastern Mediterranean Sea. They covered different foundation species such as kelp and seagrasses, as well as emblematic species such as turtles, marine mammals and fishes including habitats from marine to transitional waters with soft- to hard-bottom and shallow to deep bottoms.

The outcomes of the Storylines could allow to i) enhance MPA design and conservation measures exploring expected shifts in species and habitat distribution (using different modelling approaches), ii) assessing the risk of species and habitats in protected areas, and reductions in the ecosystem services they provide and iii) evaluating economic cost-benefit analysis projected under different climate change scenarios. In the next subsections, we showcase some of the main results obtained from the FutureMARES Storylines. Additional work in climate-smarting NBS, through the explicit identification of climate change refugia and bright spots for NBS programmes within Storylines are showcased in Chapter 8.

Accounting for expected distribution shifts in species and habitats

A growing number of studies is unveiling an acceleration of the impacts of the climate crisis. Different modelling approaches projecting climate change impacts on marine biodiversity further suggest that, during the next decades, numerous foundation and emblematic species will face an increasing risk of decline, with the majority of species subjected to shrinkage of their suitable habitats (Smith et al. 2024). The first step toward planning climate-smart MPA networks to support the conservation of marine biodiversity is to delineate the spatial distribution of at-risk species. This approach allows to estimate their vulnerability to current and future physico-chemical changes driven by climate change. The following examples from Storylines in FutureMARES help pinpoint some of the most critical aspects underpinning the planning of climate-smart MPAs.

1) Habitat changes for seaweeds in the Finnish coast (SL 7)

Fucus (bladderwrack, henceforth *Fucus*) is a perennial, brown macroalga typically occurring in the shallow, photic zone of the Baltic Sea. *Fucus* can be found on hard substrates, such as rocks or stones on the seafloor, where it forms dense underwater forests. These forests are essential habitats supporting juvenile fishes and invertebrates such as different gastropods, bivalves, amphipods and isopods (Rinne et al. 2022). *Fucus* also plays a vital role maintaining balance in the ecosystem by stabilizing the seafloor, reducing erosion, and contributing to nutrient cycling. The main environmental factors that limit the growth and distribution of *Fucus* are low salinity and eutrophication. The severe eutrophication status of the Baltic Sea has caused the disappearance of *Fucus* from several areas since the 1980s (Kangas et al. 1982), and the decline has continued since then due to light limitation at depth (Lappalainen et al. 2019; Rinne and Salovius-Laurén 2020). The relationship of *Fucus* to salinity and temperature is well studied, and the consensus is that the suitable area for *Fucus* will most likely shrink due

to declining salinity as temperatures exceed 26 °C (Takolander et al. 2017). The increasing occurrence of marine heatwaves combined with decreasing salinity will likely amplify climate-driven losses of *Fucus* forests.

FutureMARES projected changes in habitat suitability of *Fucus* under three scenarios available for the Baltic Sea. To do this, changes in key environmental variables were projected under (i) the SSP1-2.6 scenario, (ii) SSP2-4.5 scenario, and (iii) SSP5-8.5 scenario. According to the model projections, the most important areas for *Fucus* seem to reduce drastically, with large areas disappearing from the Bothnian Sea, northern Åland Island and eastern Gulf of Finland. There seems to be one potential area in the western archipelago of Gulf of Finland where changes are less dramatic and where conditions may become more favorable.

A further modelling effort focusing on marine food webs and using Ecopath with Ecosim and Ecospace in 7 regions and sub-regions of European seas explored the effects of MPAs, in combination to restoration and fishing sustainability actions, to overcome the effects of climate change (see Chapter 7). In the Archipelago Sea of Finland projections indicate that reaching conservation targets for MPAs and Nature-inclusive Harvesting can significantly mitigate future impacts of climate change with a clear trade-off between fisheries that depend on trawling compared to coastal “artisanal” fisheries. Under projected climate-driven warming and changes in primary production, management interventions such as an effective MPA network will be crucial to maintain biodiversity and support productive and sustainable fisheries in the Archipelago Sea.

2) Atlantic diadromous and marine-estuarine-opportunistic (MEO) fishes (SL 16-19)

Diadromous species perform their life cycle between ocean and rivers with mandatory migrations between the two domains (McDowall 1988), and marine-estuarine opportunist (MEO) use estuaries as nursery areas that offer suitable environmental conditions for rapid growth and predator refuge (Lefcheck et al. 2019). Beyond their ecological importance, more than 15 species such as shads (*Alosa alosa* and *A. fallax*), salmon (*Salmo salar*) and sea trout (*Salmo trutta*) support valuable commercial and recreational fisheries, with crucial interconnections between domains for their production (Castelnaud et al. 2011, Le Pape et al. 2003). The size of stocks of diadromous species has dramatically declined from historical levels (Limburg & Waldman 2009, Wilson & Veneranta 2019). Similar to many other NE Atlantic fish stocks, stocks of marine-estuarine opportunists have suffered from overexploitation but now show signs of recovery following improved management of EU fisheries (Zimmermann & Werner 2019).

Knowing the magnitude of the range-shift response of these functionally important species is crucial to provide advice for climate adaptation and the management of human activities within coastal and transitional waters. Increased water temperature, elevated salinity and sea level, and decreased precipitation and river flow are causing estuarine ecosystems to have more marine characteristics, particularly across southern Europe (Chaalali et al. 2013, Chevillot et al. 2016). These trends are predicted to intensify in the future (Hallett et al. 2017). In the marine domain, those changes translate into modifications in the spatial extent and dynamics of

river plumes, affecting the physical, chemical and biological properties of coastal ecosystems (Gamito et al. 2016). Chust et al. (2022) provide a synthesis of the multiple occurring climate trends in the Bay of Biscay with changes in temperature (warming), mixed layer depth (deepening), and sea level (rise) that could interact with the species' marine phase.

FutureMARES used physical and biogeochemical projections of climate change from three IPCC scenarios (SSP1-2.6, 2-4.5 and 5-8.5) to estimate changes in ranges and habitat suitability in the marine and coastal region covered by this Storyline (see Chapter 3). Various methods were used to assess the potential changes in species distribution at sea and connect changes in marine habitats with changes in continental habitats. The main conclusion for diadromous species (2 species) was that suitable habitats were mainly coastal and expected to experience minimal changes by mid-century, and these species may even benefit from new habitats at higher latitudes. Stocks of European flounder (*Platichthys flesus*), however, are likely to face greater challenges in the central part of the range of this species by the end of the century, as potential spawning grounds may be threatened (Navarro et al. 2023). For MEO, a visible north-westward shift was projected for all six species in the model domain. However, the northward expansion was greater for 'subtropical' than for 'sub-boreal' species due to faster gravity centroid displacement shifts and faster margins shifts (Janc et al. submitted).

Based on characteristics of marine habitat suitability for diadromous species, FutureMARES developed a concertation tool to managers and other stakeholders who might be interested in the topic of climate change impacts and land-sea continuum (Dambrine et al. 2023). This concertation tool (Fig. 5.3) takes the form of a decision tree comparing current population functionality with both continental and marine habitat suitability and does the same evaluation of

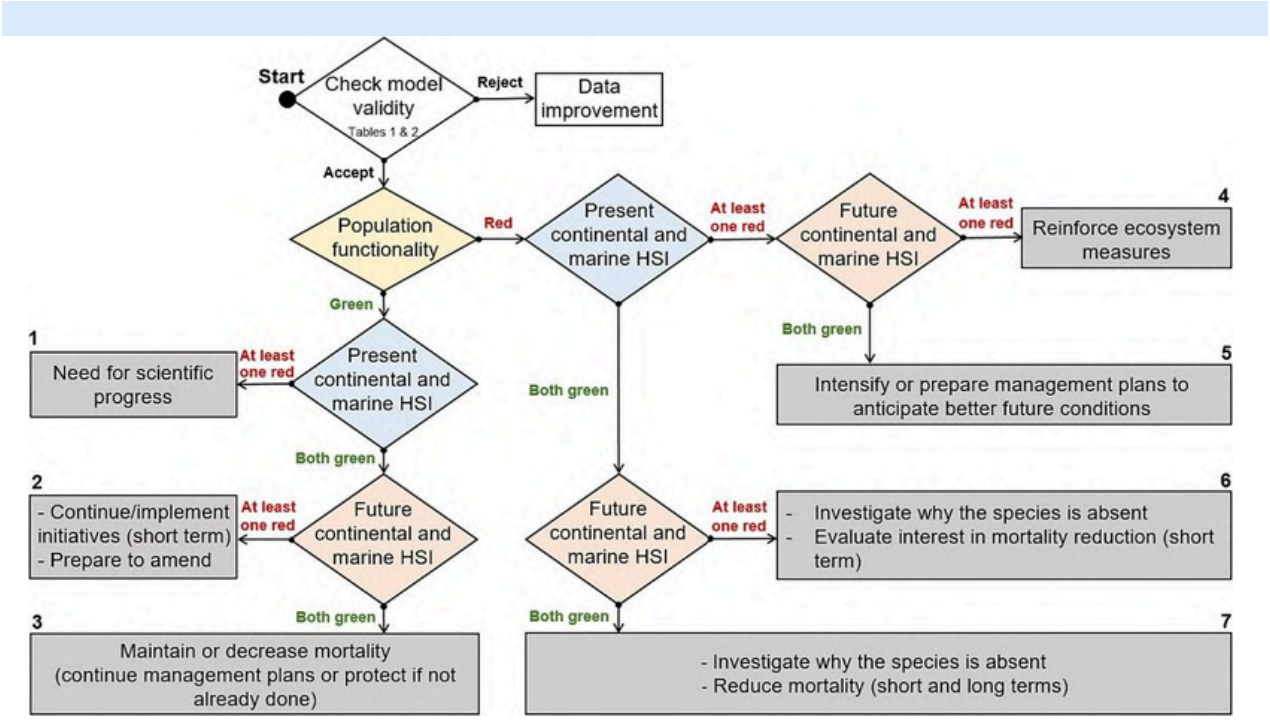


Figure 5.3, Decision tree linking the marine and continental life phases of diadromous species to provide options for management that integrate different environments used by the species during their lifecycle. Grey rectangles detail the proposed management guidance options while colored diamonds depict the decision variables used (Dambine et al. 2023).

habitat suitability coherency under future climatic conditions. Each branch of the tree leads to a management guidance to better integrate long-term issues and connectedness of suitable habitats into management practices.

3) Marine megafauna in the Atlantic and Mediterranean Sea SL 2, 12, 22, 23, 26, 27, 31, 32, 36, 39.

Marine megafauna includes large, charismatic species, such as marine mammals, sea turtles and seabirds which perform an important ecological role in the trophodynamic structure and function of ocean environments (Estes et al. 2016). These highly mobile organisms have been long considered as ecological indicators, often serving as keystone and flagship species. Indeed, recent evidence suggests that the recovery of large marine mammals, such as whales, could contribute to carbon dioxide removal, as these animals store in their bodies large quantities of carbon that can be then sequestered in the deep ocean via whale fall (Pearson et al. 2023). Charismatic marine megafauna occupies diverse habitats that often span large distances and, thus, these animals are exposed to several threats to population persistence (Pimiento et al. 2020, McCauley et al. 2015). Many representatives of marine megafauna are listed in the Bird Directive 2009/147/EC and the Habitat Directive 92/43/EEC (e.g., bottlenose dolphin *Tursiops truncatus*, fin whale *Balaenoptera physalus*, Cory's shearwater *Calonectris diomedea*), which aim to promote and maintain biological diversity through the conservation of natural habitats and biodiversity in the EU territory (Fig. 5.4).

Figure 5.4, Marine megafauna include large, charismatic species which perform an important ecological role in the trophodynamic structure and function of ocean environments.

Climate change not only has direct impacts on marine megafauna (e.g., changes in growth physiology, disease resistance, energy available for migration) but also indirect effects. The latter include spatiotemporal shifts in environmental conditions (e.g., sea currents, local productivity) that modify reproduction and feeding grounds, as well as migration routes and are particularly important to marine megafauna. Climate change can constrain existing migration corridors or previously unsuitable routes may become favorable (Robinson et al. 2009, Tulloch et al. 2019).

Many spatial distribution models use niche theory to establish statistical relationships between the environment and the distribution of plants or animals to predict present day and project future distribution. These models, however, do not take into account the impact of climate change on other variables, such as food availability or change in the animal metabolism and the effect on population dynamics (Rose et al. 2024).

To better inform conservation measures, FutureMARES developed a dynamic modelling framework for marine megafauna which combined elements of Species Distribution Models (SDMs), Dynamic Energy Budget models (DEBs) and population models (Fig. 5.5). The tool applied high-resolution, physical and biogeochemical projections (see Chapter 3) including primary production as well as other attributes of regional seas habitats such as depth. This is a marked advancement from previous distribution models that do not represent aspects of how habitat features impact vital rates (e.g., feeding, growth, maturity) of key species. This modeling framework was applied to two charismatic megafauna: loggerhead turtles (Caretta caretta) in the Mediterranean Sea and bottlenose dolphin (Tursiops truncatus) in the Eastern Atlantic (Bay of Biscay, and North and Celtic Seas).

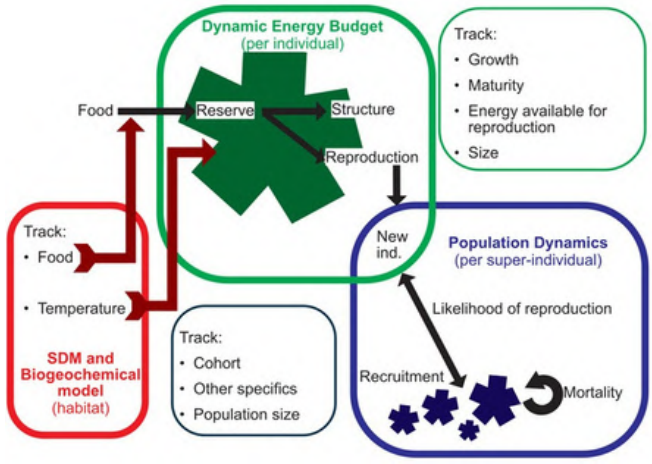


Figure 5.5, Schematic of the mechanistic model structure showing the three model components (SDM, DEB and Pop) and their interaction at specific stages. The square star shape represents a generic organism rather than a specific one, highlighting whether the model is at the individual or at the super individual/sub-population scale. (Deliverable Report 4.2)

The framework maintains a flexible structure so it can be adapted to other species of marine megafauna and can be used with the regional outputs from different climate models. For the loggerhead turtle, the model projected critical reductions in the amount of suitable habitat for juveniles (Fig. 5.6) which caused slower growth and delays in maturation and reproduction impacting the population dynamics (Fig. 5.7).

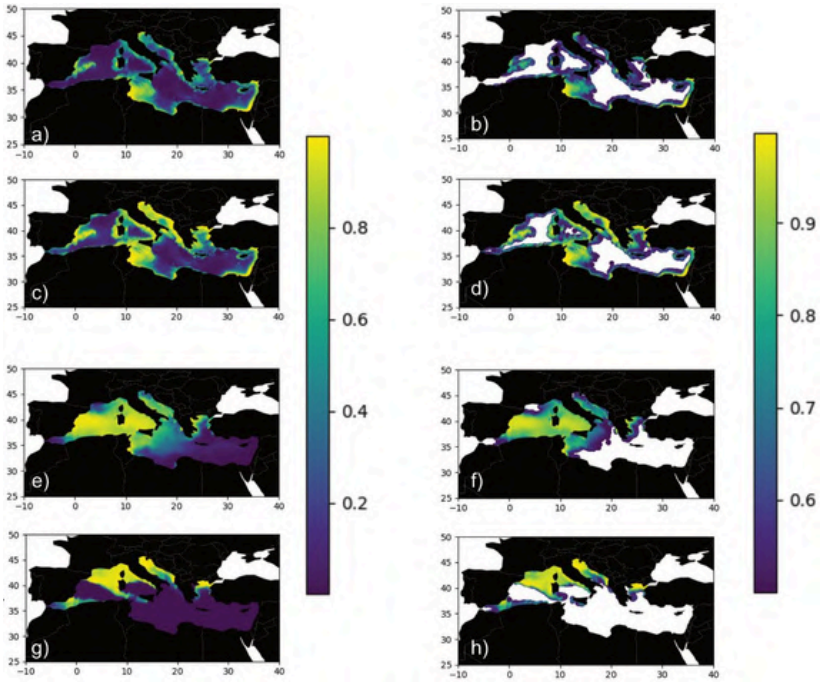


Figure 5.6, Distribution of suitable habitat as feeding grounds for loggerhead turtles in the Mediterranean Sea. The feeding grounds were mapped for both adult (plot a, b, c, and, d) and juveniles (plot e, f, g, and, h) for a present (plot a, b, e and f) and a future (plot c, d, g, and h) time slice. To highlight the change in suitability, some plots (left column: plot a, c, e, and g) contains the full Mediterranean Sea while others (right column: plot b, d, f, and h) only show areas with a habitat fit >= 0.5.

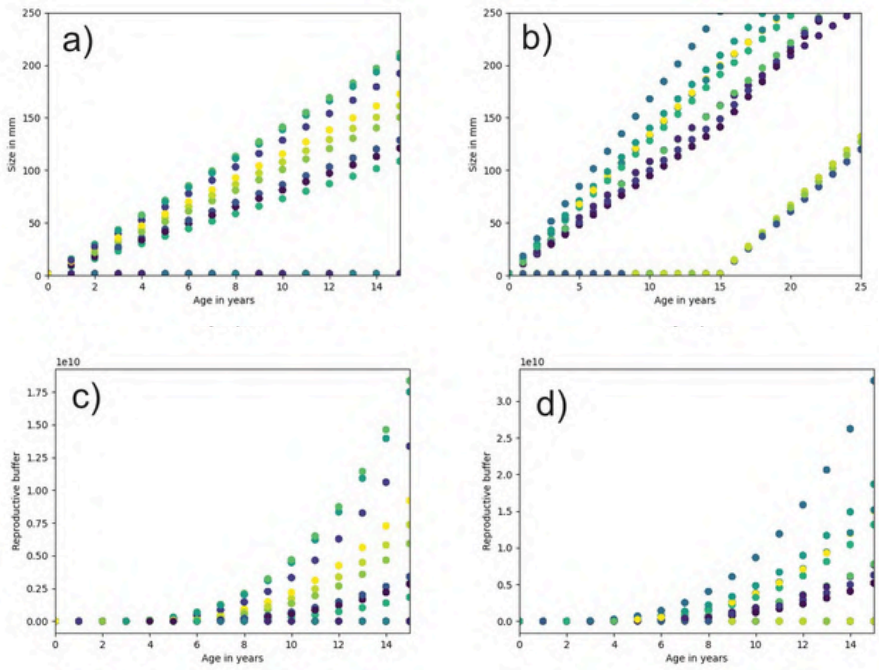


Figure 5.7, Potential impact of feeding grounds on growth (plot a and b) and maturation of juvenile loggerhead, expressed has the available energy for reproduction (plot c and d) in present (plot a and c) and future conditions (plot b and d). Different colors represent different feeding grounds.

This is important as conservation efforts for sea turtles tend to focus on nesting sites, but if the juveniles cannot survive to reproductive age or their maturation is affected by lack of proper feeding grounds, there will be serious impact on the populations despite the conservation effort. The bottlenose dolphin is more widely spread with a more flexible niche and its habitat was not projected to decline in a future climate but could even modestly increase in the regions covered by the model (Fig. 5.8). Bottlenose dolphins were not projected to have clear changes in their distribution and population dynamics suggesting low climate risks.

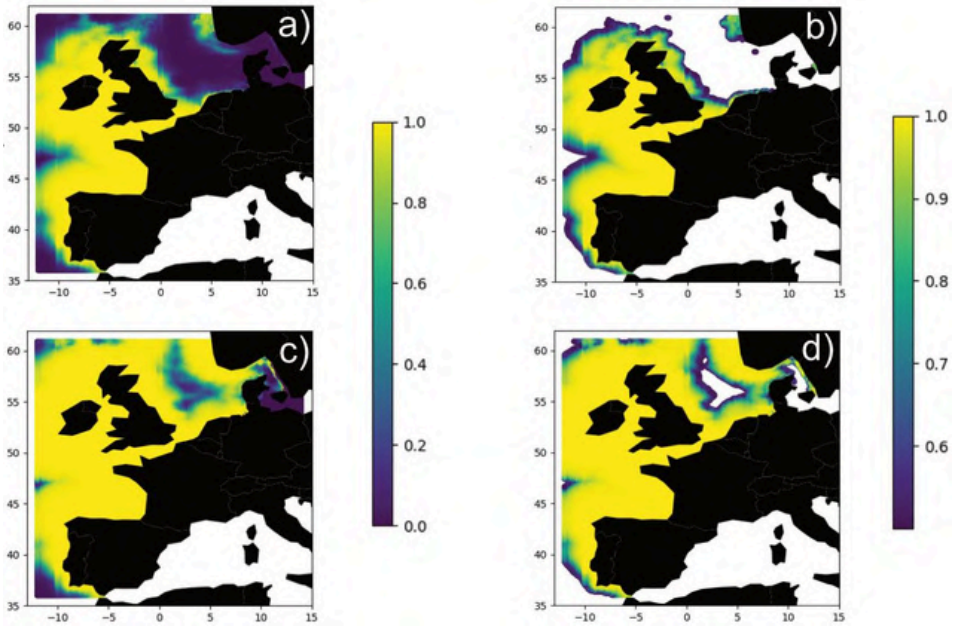


Figure 5.8, Distribution of suitable habitat for Bottlenose dolphins in the Northeast Atlantic. The habitat suitability was mapped for a present (plot a and b) and a future time slice (plot c and d).

One key question for MPAs as conservation tools to help mitigate and adapt marine systems to climate change is to what extent this NBS can be effective in reducing climate risks in those systems. This question was addressed by FutureMARES performing a climate risk analysis across 40 species, 15 Ecosystem Services, and 8 social groups covering all the project European regions. To do that, FutureMARES partners performed expert-based climate risk assessments (CRAs) comparing risks to species, Ecosystem Services and social groups when conservation is applied versus when it is not (see Box 5.1).

Interestingly, the conservation measures considered were capable of lowering the risk for all the species and ecosystem services analyzed, across the different regions investigated (Fig. 5.9). Nevertheless, the extent to which the risk lessened was variable and depended on different factors. The results imply that conservation measures can reduce climate risks at the ecological level, which favors the maturity and intricate structure of ecosystems, needed by the species that are more vulnerable to climate change. Moreover, these species were the ones with higher service value due to their scarcity or their pivotal role in sustaining the delivery of ecosystem functioning and services.

In general, the climate risk assessment indicates that conservation measures have deep structural effects on ecosystems, which alter the level of risks obtained. Conservation is found to be especially effective for species exposed to a higher risk, which are those more dependent on complex ecological interactions. Despite such promising effects of conservation, these results clearly show that conservation cannot completely offset the risks of climate change. Despite risk reductions being significant for species and ecosystem services, conservation alone is never able to completely reduce risk levels, indicating that strategies for climate change mitigation are crucial for maintaining current biodiversity and ecosystem services.

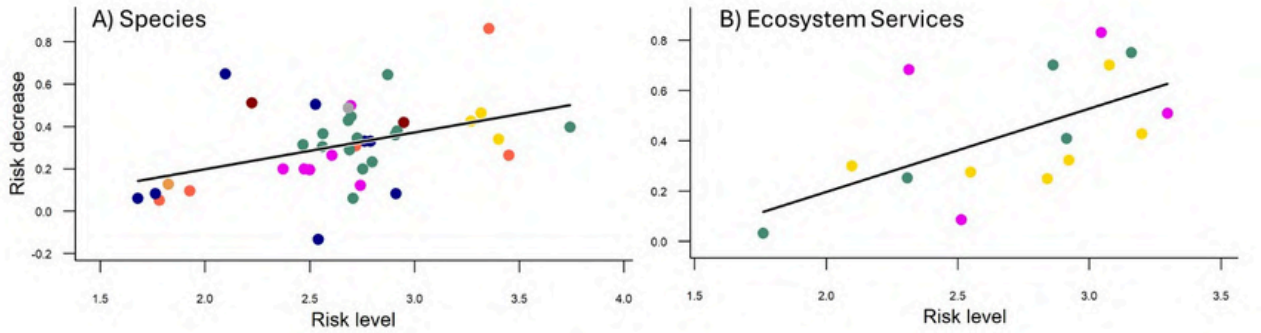


Figure 5.9, Relationship between the risk decrease due to the application of conservation and the risk estimates of species (A) and ecosystem services (B). Risk levels and decrease values are averages obtained across the different scenarios tested. (Deliverable Report 5.1)

The method developed also allowed us to explore the effects of different FutureMARES socio-ecological scenarios. The scenarios Global Sustainability (GS), National Enterprise (NE), and World Markets (WM) were considered over two different time slices: near-term future (2040 to 2059), and long-term future (2080 to 2099). In this regard, the amount of risk reduction for species across scenarios shows unclear patterns (Fig. 5.10). Although the effects of conservation under the GS

scenario are slightly higher than in the other two scenarios, conservation appears as an effective solution for reducing the risks of climate change even under the more severe climate emission scenarios (NS & WM). Hence, more local, well-managed conservation measures could be still effective by the end of the century. Finally, an evident higher average risk was observed for the species under the NE and WM scenarios, highlighting the urgency to curb emissions, especially in the Western and Eastern Mediterranean, where the differences of risk with the GS scenario are higher in the longer term.

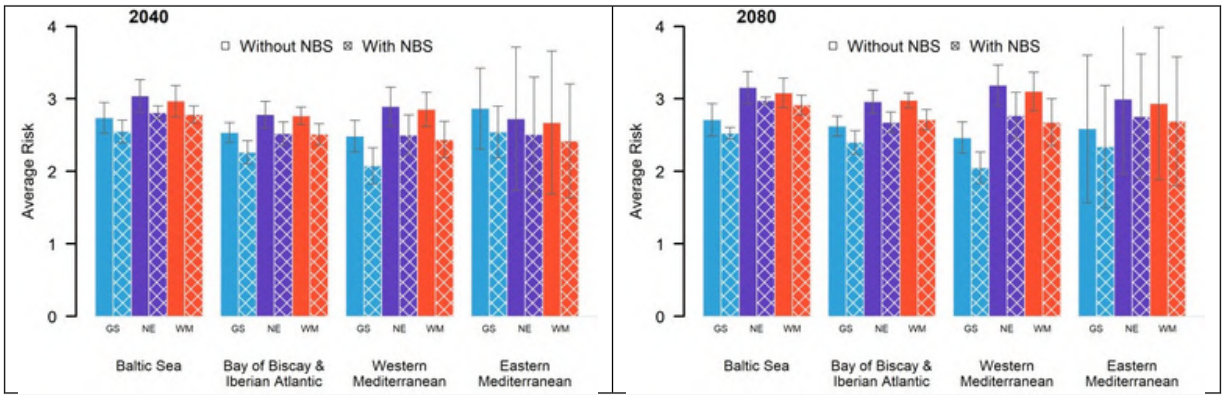


Figure 5.10, Average species risk estimated by FutureMARES storylines under three future PESTLE scenarios (GS: Global Sustainability; NE: National Enterprise; WM: World Markets) in the near future (2040) and in the long-term future (2080). Solid bars represent the risk of the species when conservation is not present, and the dashed bars represent species risk when conservation is applied. Gray lines represent the variance across the species analyzed.
(Deliverable Report 5.4)

BOX 5.1 An online tool for NBS Climate Risk Assessment

In FutureMARES, a Nature-based Solutions Climate-Risk Tool was developed to evaluate **the effectiveness of Nature-based Solutions (NBS) in reducing climate change risks.** Using Climate Risk Assessments that are fed both by expert elicitation and environmental data analysis (Bueno-Pardo et al. 2024), this method estimates the extent to which a species, ecosystem service, or social group is at risk due to climate change and other human activities causing environmental harm. The main objective of the tool is to illustrate to what extent a NBS is able to decrease climate change risks in the marine system.

Climate Risk Assessments (CRAs) are indicator-based tools that have gained increasing relevance in the last decade, particularly to identify the components of social-ecological systems that are at the most risk due to climate change impacts (Cinner et al. 2013, Ekstrom et al. 2015, Payne et al. 2021; Bueno-Pardo et al. 2021).

Nowadays, they are commonly used by scientists and decision-makers to prioritize conservation strategies and to design climate adaptation pathways.

As proposed by the IPCC (IPCC, 2014), CRAs should be constructed considering three dimensions of risk: hazard, exposure, and vulnerability, each of them assessed using a set of specific indicators. The score of these indicators can be calculated using data from models or, when data are scarce or the risk of systems needs to be estimated under future scenarios, expert interviews. The scores of each dimension, and the overall risk score are usually given in normalized ranges between 0 and 1, where 0 means very low risk, and 1 means extreme risk due to climate change.

The main contribution of this new tool is that the risk assessment starts by measuring the amount of climate risk to the marine system when the NBS is not applied ("**NBS OFF risk**"), to then compute the risk when the NBS is in place ("**NBS ON risk**"). Then, the difference of risk estimated between both situations is considered as a proxy for the effectiveness of the NBS (Equation 1, and Fig. 5.11).

Equation 1

$$\text{NBS effectiveness}_{\text{species i}} = \text{Risk NBS OFF}_{\text{species i}} - \text{Risk NBS ON}_{\text{species i}}$$

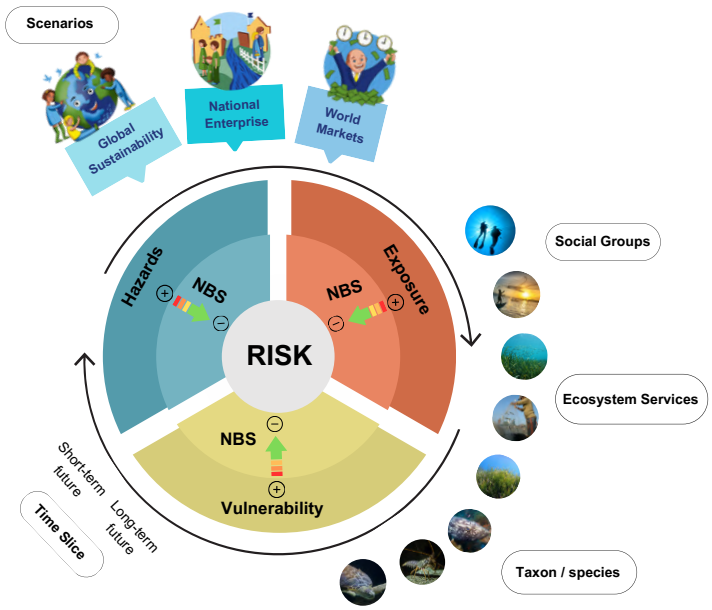


Figure 5.11, Climate risk assessment framework adapted from the IPCC (2022) to measure the effectiveness of NBS. The NBS can potentially lower each dimension of risk (Hazards, Exposure and Vulnerability) for different components of the marine system (species, ecosystem services and social groups) under different future scenarios and timeframes. (FutureMARES Policy Brief 3)

The NBS Climate Risk online Tool guides the user in a step-by-step process providing all the information and templates needed to conduct the analysis, explaining the conceptual framework and how the different future scenarios can be introduced. The tool can also read the templates previously completed by users and create summary figures to show the effectiveness of the NBS as a function of different scenarios (Fig. 5.12). Finally, the tool offers the possibility to explore some results obtained by the case studies of FutureMARES.

In that section, the user can choose the type of NBS, the unit of analysis (between some species and ecosystem services), and the dimension of risk to be evaluated (Fig. 5.13).

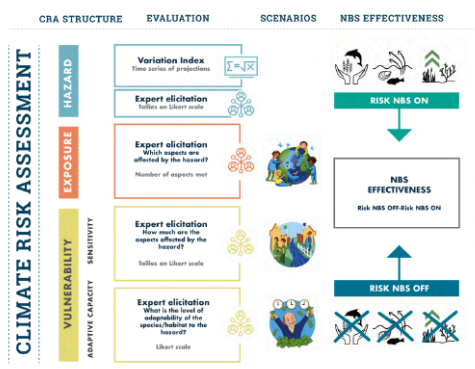


Figure 5.12, Approach used by the NBS climate risk tool, based on climate-risk assessments.

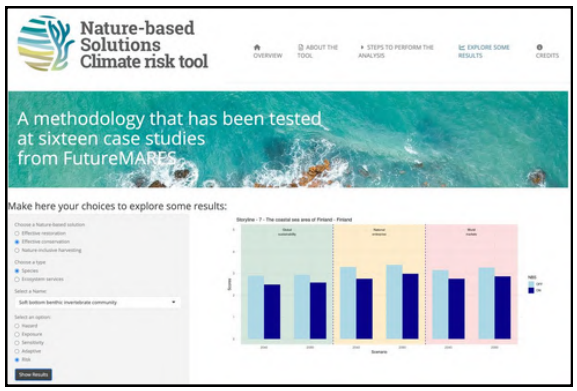


Figure 5.13, Overlook of the CRA tool, with sections in the top menu, and showcasing results on risks to benthic invertebrate communities in soft bottoms.

Juan Bueno-Pardo & Elena Ojea

Comprehensive assessments of the economic implications of marine conservation were conducted in two distinct regions, the Aegean Sea (SL 26) and the Western Mediterranean (SL 28), to ascertain the value of Ecosystem Services (ES) provided by key habitats, encompassing seagrass meadows, soft-bottom habitats, and rocky reefs. Additionally, the economic impact of implementing NBS2, particularly MPAs, was evaluated across the three FutureMARES scenarios: Global Sustainability, National Enterprise, and World Markets. The benefits derived from MPAs are multifaceted. First, MPAs enhance the conservation of critical habitats like seagrass meadows and macroalgal forests, thereby providing valuable ES such as nursery provisioning, carbon sequestration, and recreational activities. Second, MPAs stimulate economic growth through activities like diving, tourism, and sustainable resource utilization, significantly contributing to local economies and livelihoods. Third, MPAs function as indispensable tools in mitigating the impacts of climate change on marine ecosystems, fostering biodiversity preservation, and sustaining ES provision.

Conversely, the costs associated with MPAs need consideration. Expenses related to enforcement, monitoring, research, and stakeholder engagement accrue during the establishment and management of MPAs. Additionally, MPAs may impose restrictions on certain activities such as fishing or development, potentially resulting in short-term economic losses for stakeholders. In Storyline 26, the monetary values of numerous ES (values in $/ha/year) associated with three key habitats within the MPA (seagrass meadows, rocky reefs and soft bottoms) were estimated.

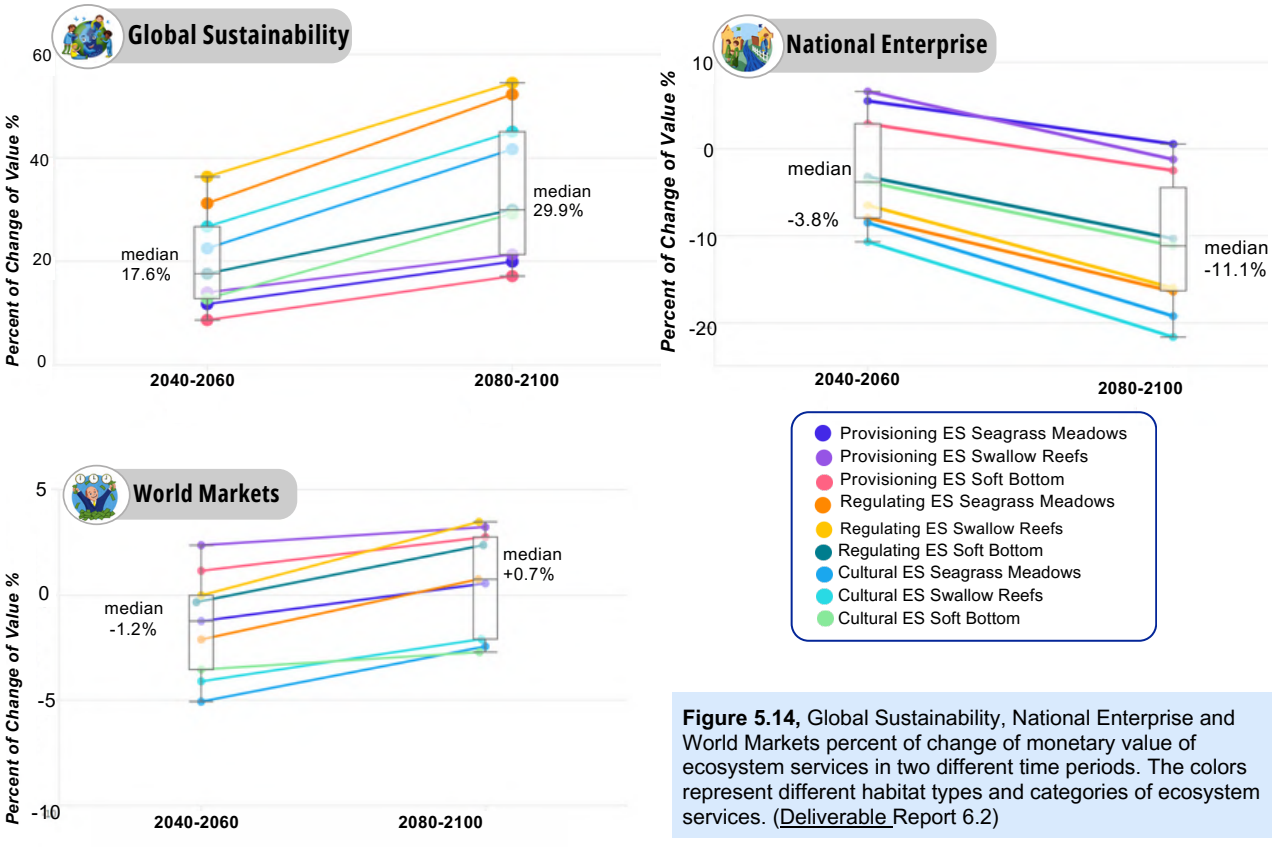


Figure 5.14, Global Sustainability, National Enterprise and World Markets percent of change of monetary value of ecosystem services in two different time periods. The colors represent different habitat types and categories of ecosystem services. (Deliverable Report 6.2)

This involved collecting data on recreational diving (travel cost and willingness to pay), creating a meta-analysis model for ES valuation provided by seagrass meadows, and conducting a systematic review with benefit transfer for reefs and soft bottoms. This research highlights the substantial impact of recreational diving – a significant ES - on coastal communities within the study area. Across all scenarios and temporal considerations, the establishment of MPAs in the Aegean Sea emerged as the most advantageous option among alternative management measures. Benefits peaked under the GS scenario, trailed by the WM and NE scenarios (Figure 5.14). Operational costs mirrored the trend of benefits, increasing with greater spatial coverage of protected areas. Unit costs per hectare were lower in scenarios with higher percentages of MPAs, such as GS (30% MPAs). Spatial distribution analysis indicated a surplus of benefits over costs (positive values) in most areas (Fig. 5.15). However, regions with soft bottom habitats near protected area hubs had negative values due to amplified costs and diminished benefits. Despite these setbacks, they did not prevent MPA creation, underscoring the importance of considering factors such as connectivity among MPAs when making decisions.

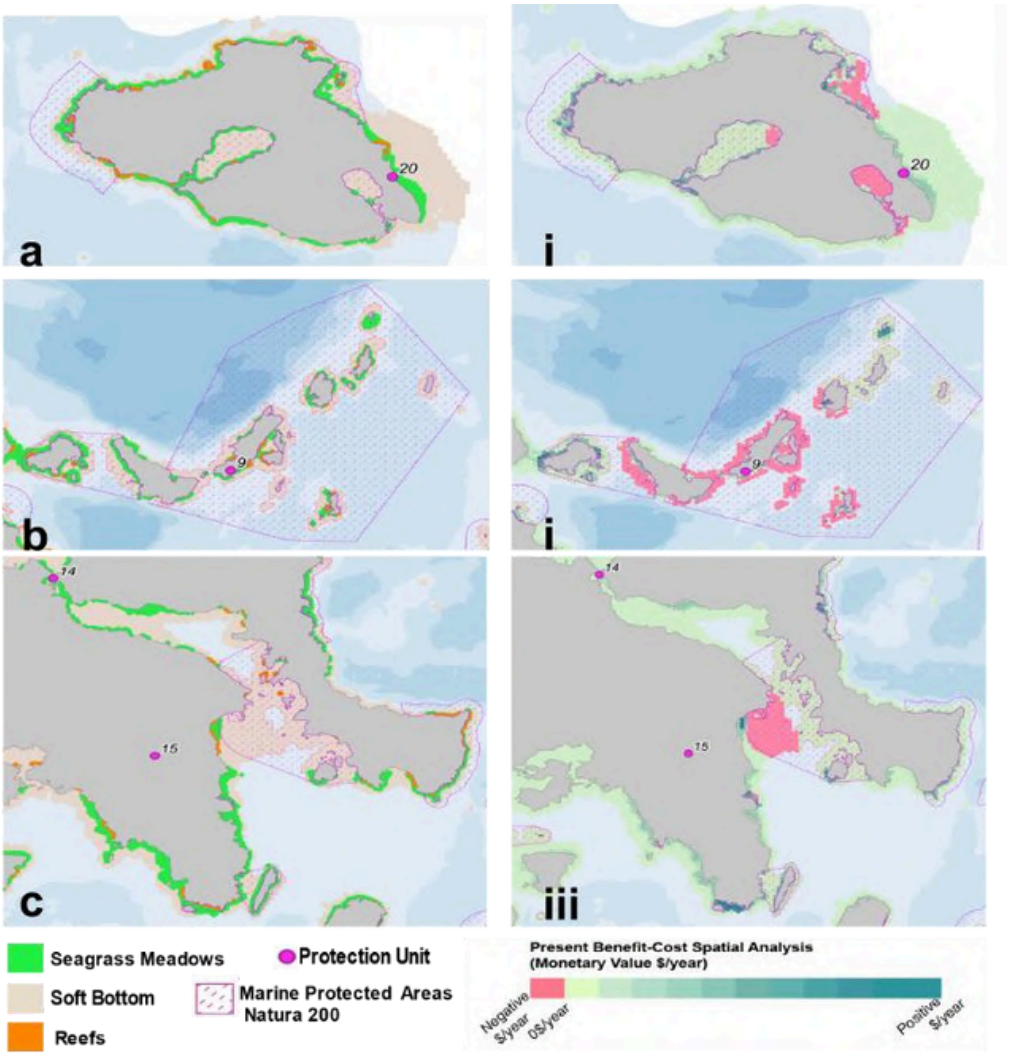


Figure 5.15, Figures a, b, c depict the spatial distribution of three habitats on the island of Lesbos (a), in the Sporades (b), and in Athens (c). Images i, ii, iii present the spatial cost-benefit analysis for the respective protected areas. The protected areas are indicated in dashed pink lines. In red areas where costs exceed benefits, while in green are the areas where the benefit surpasses the costs. (Deliverable Report 6.2)

The dispersion of induced effects across the 65 affected economic sectors was most extensive for coastal protection ES and generally larger for provisioning and regulating ES, while the lowest dispersion was associated with cultural ecosystem services (see Figure 5.16).

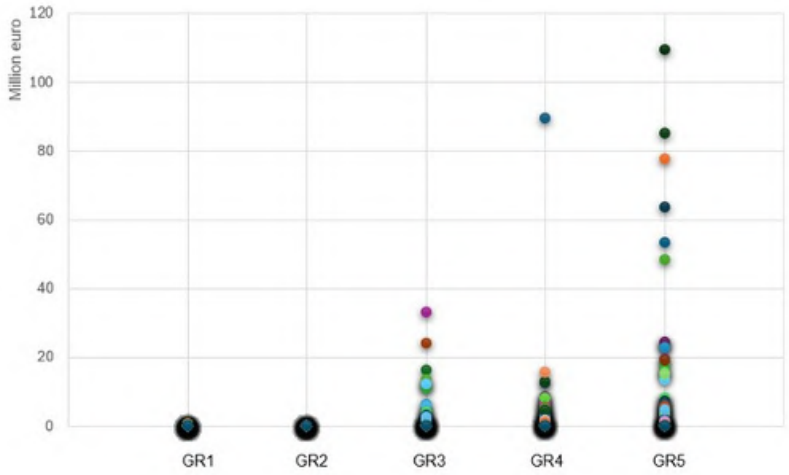


Figure 5.16, Dispersion over the 65 economic sectors of the induced effects per ES. GR1 Recreation and tourism, GR2 Cognitive values, GR3 Food provisioning, GR4 Water purification and GR5 Coastal protection. Source: own elaboration.

Climate change projections suggest a substantial decline in the capacity of marine ecosystems, particularly seagrasses and macroalgal forests, to deliver ES. Storyline 28 highlights the role of a MPA as a NBS to safeguard *P. oceanica* meadows and macroalgal forests within the Tuscan Archipelago National Park, Western Mediterranean Sea. Services assessed included nursery provisioning, carbon sequestration, and recreational diving activities for tourists and the local community. Results indicate that MPAs can effectively alleviate the adverse impacts of climate change, thereby preserving ecosystems and associated ES, ultimately benefiting humanity (Fig. 5.17).

Figure 5.17, Results in the Tuscan Archipelago National Park, Western Mediterranean Sea, indicate that MPAs as a NBS can effectively alleviate the adverse impacts of climate change, preserving ecosystems and associated ES to *P. oceanica* meadows and macroalgal forests. Services assessed included nursery provisioning, carbon sequestration, and recreational diving activities for tourists and the local community.

Although MPA establishment may not entirely counteract habitat degradation and the ensuing reduction in ES provision due to climate change, it can mitigate the loss of economic benefits. In the GS scenario, characterized by high mitigation of greenhouse gas emissions and sustainability pathways, the MPA was better able to offset some of the long-term economic losses in ES, such as carbon sequestration (Fig. 5.18), attributed to expanded conservation endeavors. This underscores the critical importance for conservation efforts to align with global initiatives aimed at decarbonization and reversing the trajectory of global warming to ensure the long-term sustainability of marine ecosystems.

Carbon sequestration →

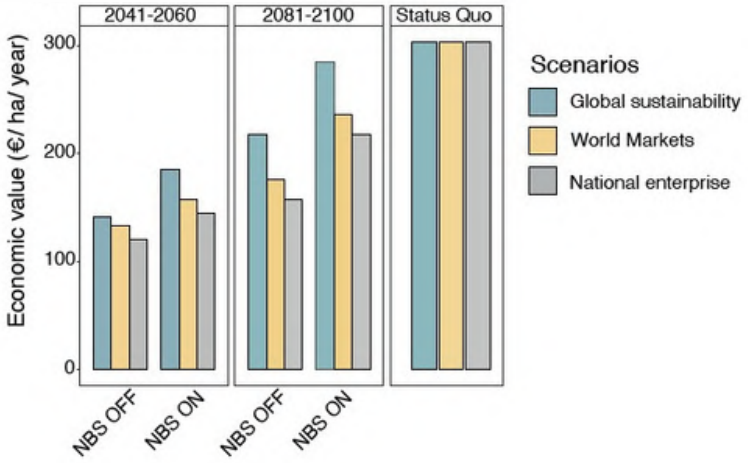


Figure 5.18, Mid- and long-term effects of conservation (NBS) on the economic value of carbon sequestration by seagrass meadows (€/ha/year) in the Tuscan Archipelago under different scenarios and in the status quo. (Deliverable Report 6.2)

Conclusions and policy recommendations

This chapter provides several examples of results that will help policy-makers and managers to integrate climate adaptation (and mitigation) into conservation efforts to better protect habitats and species in the future. The new tools will help making more robust projections of CC impacts. The following is a list of recommendations following from the results and products of FutureMARES on marine conservation as a NBS:

1) Conservation efforts such as the network design of MPAs need to include expected shifts in the distribution of species and habitats. Projections of the future distribution of species and habitats provided here are key for conservation actions.

2) MPA networks should take into account climate refugia and areas that will become more suitable for species and habitats under scenarios of CC. Connectivity is critical for sustaining the effectiveness of MPAs and enhancing climate resilience.

3) Conservation is more effective in reducing climate risk levels to species at most risk, leading to very promising targeted interventions.

4) Conservation measures always reduce the climate risks to species and ecosystem services, and this effect is consistent across future scenarios of CC.

5) MPAs reduce the risk of loss of species, habitats and ecosystem services, but they are not able to fully offset the negative economic impacts of CC. Evaluating the effect of MPAs within a larger context of various management interventions is necessary to assess realistic policy seascapes.

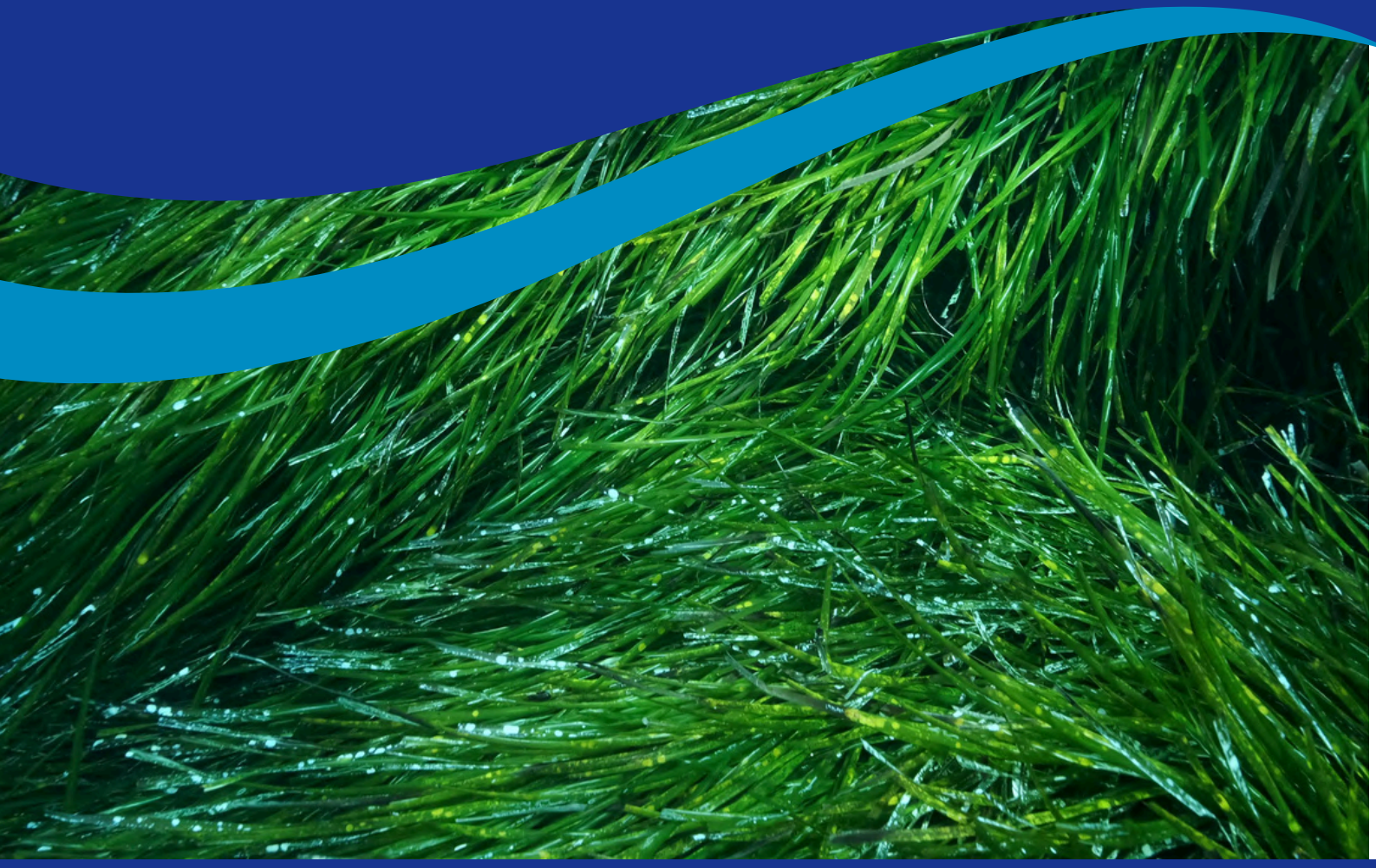
6) Conservation alone cannot completely offset CC impacts in scenarios that reflect current trajectories of increase in greenhouse gasses. Curbing carbon emissions is essential to increase the effectiveness of these and other conservation measures.

Future MARES

CHAPTER 6

MARINE HABITAT RESTORATION AS A NATURE-BASED SOLUTION IN A FUTURE CLIMATE

AUTHORS: FABIO BULLERI, DORTE KRAUSE-JENSEN, JUAN BUENO-PARDO, ELENA OJEA, LUCA VAN DUREN, SARAH SIMONS, ANA QUEIRÓS, LIZ TALBOT, MYRON A. PECK



06 Marine habitat restoration as a Nature-based Solution in a future climate

Introduction

Multiple stressors have caused major losses of coastal habitats and associated biodiversity and ecosystem functions over the past Century at European and global scales (Crain et al. 2008, Duarte et al. 2020). This has fostered attempts to restore declining populations of those species, the so-called foundation or ecosystem engineers (Jones et al. 1994, Ellison 2019, Duarte et al. 2020), that support biodiversity and provide a range of ecosystem services through the generation of habitat or the amelioration of physical conditions. Indeed, restoration is currently envisioned as a pillar to safeguard biodiversity and ambitious targets have been set by the European Nature Restoration Law, in June 2024, which aims to restore at least 20% of Europe's marine and terrestrial territory by 2030 and all endangered habitats by 2050. Restoration must be framed within the context of climate change which, interacting with regional and local stressors, is becoming an increasingly important driver of the geographical distribution of key coastal habitats (Gissi et al. 2021). Future habitat restoration should, therefore, integrate knowledge on the effects of climate change on marine ecosystems.

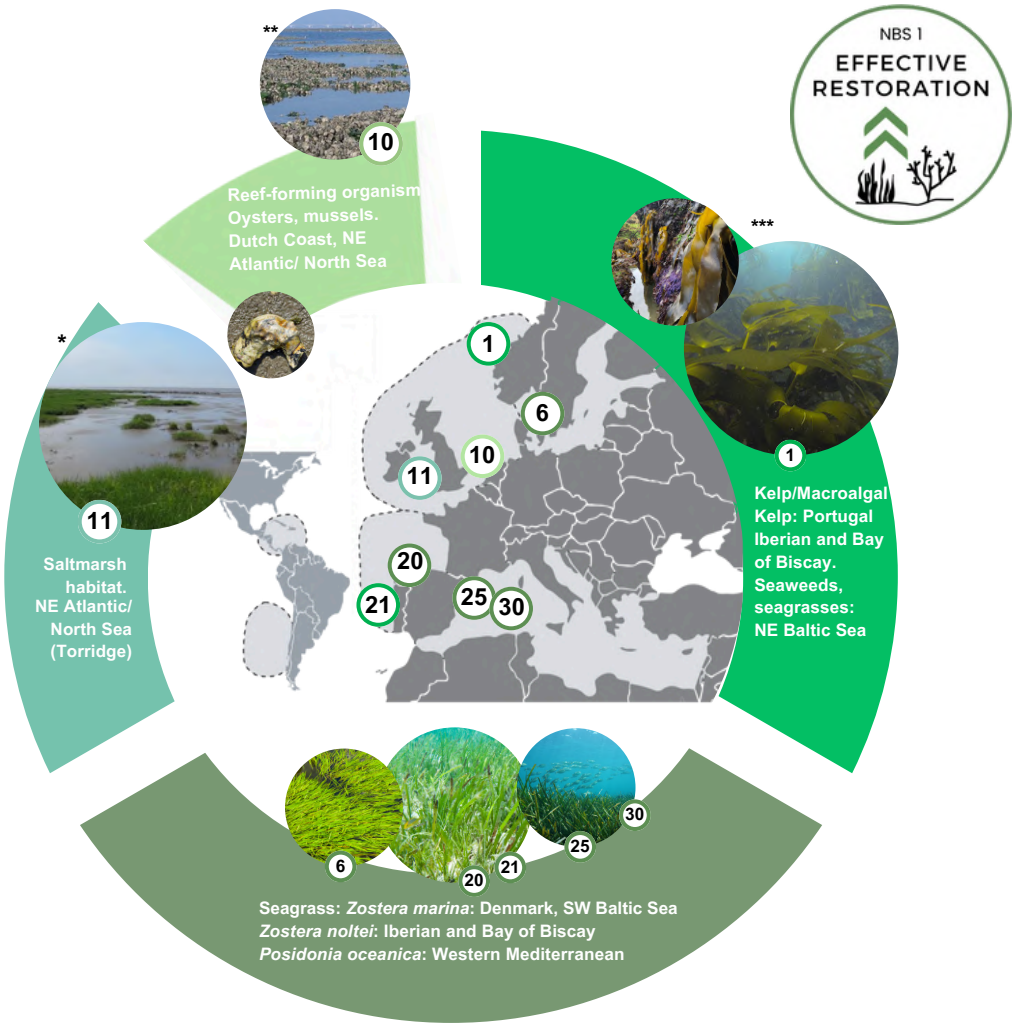


Figure 6.1, Overview of the FutureMARES Storylines related to restoration of habitat-forming species. Photo credit: *Gary Banta. **SL 10. ***SL 21-23.

FutureMARES explored the restoration of various coastal habitats in the face of climate change across European Seas via 8 key Storylines (SLs), each targeting one or two habitat types (Fig. 6.1), supplemented with information from related SLs. The target habitats were coastal vegetation including kelps and other macroalgae, seagrasses (*Zostera marina, Z. noltei and Posidonia oceanica*), saltmarshes, oysters, and corals. This chapter summarizes key findings to enhance the likelihood of restoration of habitats and associated ecological and socio-economic benefits in light of different scenarios of climate change. It is implied that this is about restoring lost habitats.

Research within FutureMARES

Planning restoration in a future climate

Planning climate-smart restoration requires (in addition to standard restoration guidelines) in-depth analyses of (1) the characteristics of the species to be restored (i.e., **what to restore**), (2) the identification of those sites at which restoration is more likely to be effective under different future climate scenarios (i.e., **where to restore**) and (3) **how to restore** (Fig. 6.2).

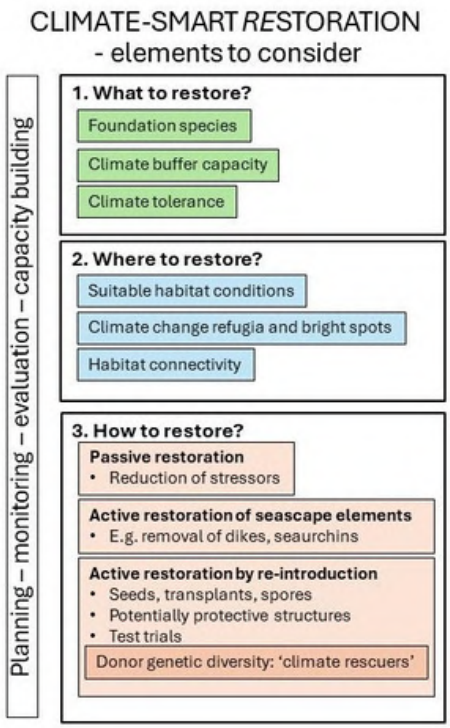


Figure 6.2, Key elements for enhancing the effectiveness of restoration under climate change scenarios.

What to restore

Foundation species

Species of restoration interest are typically the so-called "foundation species" having ecosystem-wide effects on biodiversity and other ecosystem functions through the formation of habitat (Halpern et al. 2007). There is compelling evidence that many communities are structured by networks of positive species interactions in which facilitation by foundation species is of primary importance (Altieri et al. 2007). Climate-smart restoration also requires that the target foundation species can tolerate adverse environmental conditions in a range of future mitigation and/or adaptation (Bulleri et al. 2018). In some cases, alternative foundation species may not differ from those they have replaced in terms of functioning, reducing the relevance of restoring the original species for sustaining ecosystem services.

Climate buffer capacity

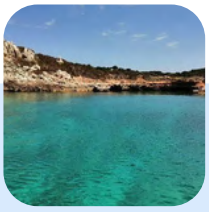
In addition to the existing knowledge on the role of many foundation species to support climate change mitigation and adaptation (Duarte et al. 2013), FutureMARES provided further evidence that some foundation species, including intertidal macroalgae (SL 36) and seagrasses (SL 28) (Fig. 6.3) have a high potential to buffer climate extremes. Studies on rocky intertidal biodiversity

(SL 36) documented that canopy-forming intertidal macroalgae can buffer extreme temperatures along climate gradients and, thereby, provide climate refugia below the canopies.

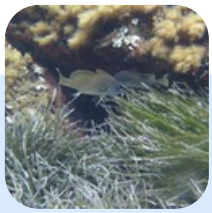
The microhabitats underneath macroalgae represent climate refugia similar to those offered by for instance, upwelling of cold waters or shading slopes. The amount of thermal buffering by macroalgae differed across the European coastline and with tidal level and orientation of the habitat. The temperature buffer effect of the canopy (relative to bare rock) reached 15°C and could explain regional and local patterns of intertidal biodiversity across the European coastlines. Hence, protection and restoration of these habitats would support climate adaptation by providing refuge against hostile climatic conditions during extreme warming events (i.e., atmospheric heatwaves). Likewise, studies on seagrass meadows (SL 28) demonstrated that, by regulating pH and seawater chemistry through photosynthesis and respiration, these meadows can provide daytime increases in pH offering refuge against ocean acidification for calcifying species, such as the larvae of sea urchins (Ravaglioli et al. 2024). These studies strengthen the argument that lost or declining foundation species with the capacity to support climate change adaptation and mitigation should have priority in restoration plans.

Climate tolerance

The species being restored should ideally be tolerant to future climate conditions to maintain its ecological function so that it can keep supporting biodiversity and the delivery of ecosystem services. FutureMARES found that the growth of the seagrass *Posidonia oceanica* is expected to be reduced when acidification is associated with seawater warming (SL 25, 28). This impact suggests that the functioning of the ecosystem could be impaired unless greenhouse gas emissions are curbed. The same is true for *Zostera marina* near its lower latitudinal distribution limit. Along the Portuguese coast (SL 21&23), common garden experiments exposing specimens of the fucoid *Ascophyllum nodosum* from sites spanning a broad latitudinal gradient to atmospheric heatwaves of different intensity reported a general decrease in primary productivity. Higher latitude populations experienced more negative impacts from the same levels of heatwave exposure compared to lower latitude populations (see Chapter 2). Including climate tolerance as a selection criterium for identifying habitat-forming plants or animals to be restored will increase the likelihood of restoration success over the mid- and long-term. Genetic diversity of donor populations is relevant to consider in this context as discussed later in this chapter.



The coast of the Island of Pianosa (Tuscan Archipelago)



Individuals of brown meagre in a *Posidonia oceanica* meadow of the Island of Pianosa (Tuscan Archipelago).

The intertidal canopy-forming alga E*ricaria amentacea* on the rocky coast of the Island.

Posidonia Oceanica

Figure 6.3, Tuscan Archipelago landscape and some of the species FutureMARES worked on. Credit photos: From the left: Fabio Bulleri, L. Benedetti-Cecchi, C. Mintrone

Where to restore

Suitable habitat conditions

Suitable growth conditions for the target species at the restoration site is an obvious, primary condition for successful restoration that, nevertheless, is often ignored. This involves controlling the factors causing the original habitat loss as well as considering climate change-related factors (see below).

Climate-driven changes in habitat suitability

The pace of climate warming varies at a hierarchy of spatial scales (Burrows et al. 2011). Thus, some areas are warming more rapidly than others. Areas characterized by less intense and rapid seawater warming and acidification (climate refugia, see Chapter 3) would enhance the success of restoration while attempts to re-establish lost or declining populations at sites predicted to undergo dramatic climate changes (i.e., hotspots of change) would have a higher risk of failure. Predicting the effect of warming also requires assessing how habitat suitability for the species to be restored will vary in time and space. FutureMARES employed novel modeling tools to generate key information on the future distribution of selected foundation species under alternative greenhouse gas emission scenarios and projections of climate-driven alterations in major oceanographic and atmospheric stressors.

Spatial modeling of the distribution and biomass of *Posidonia oceanica* under different climate change scenarios suggest major declines in the future (Fig. 6.4, SL 25, 28). The models do not consider potential adaptation to warming, which could make the effects less dramatic. Increased risk of heatwaves adds to the general negative effect of warming on the future distribution of Mediterranean seagrasses.

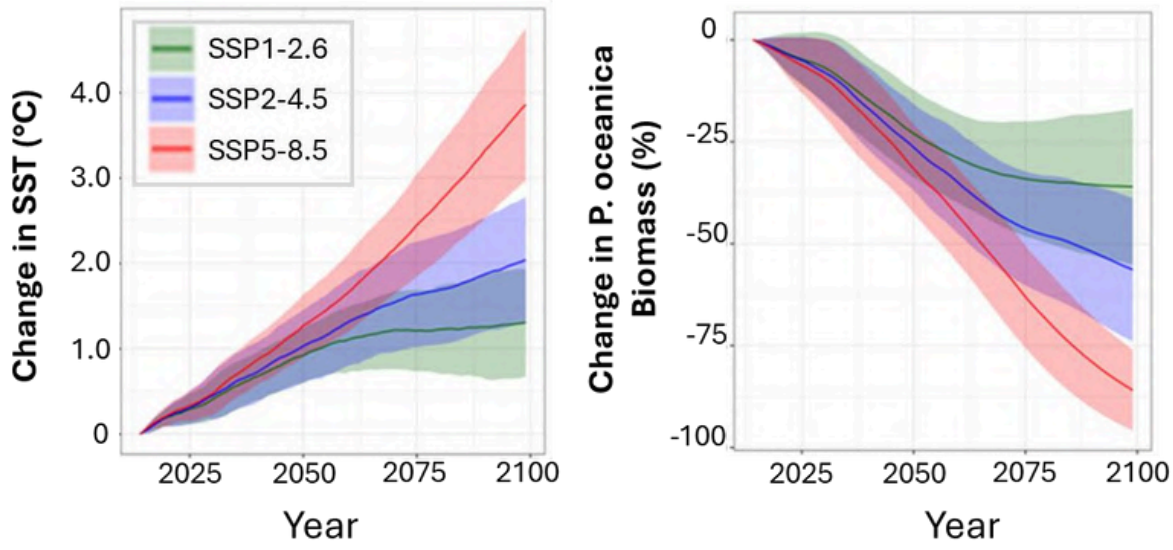


Figure 6.4, Projected changes since the period 1995-2014 in average sea surface temperature (left) and above-ground *Posidonia oceanica* biomass in the Balearic Islands under three climate change scenarios. Future impacts of climate change on seagrass in the Balearics were projected using a mechanistic seagrass model and an ensemble of 16 bias corrected global climate models. In each plot, the solid line represents the average change across the ensemble of 16 climate models, and the shaded area represents +/- one standard deviation of the multi-model spread. (Deliverable Report 4.1)

In FutureMARES, projections of physical and biogeochemical variables were combined with ecological knowledge on species responses to stressors, generating tools to identify sites most likely to serve as **climate refugia** as well as sites offering improved future conditions for growth, **"bright spots".** For example, new coastal conservation areas, where EU targets for the restoration of seagrass and coralligenous habitat-forming species are simulated (red over yellow, Fig. 6.5 bottom) become long-term climate change bright spots (improved habitat conditions (Queirós et al. 2021)) where they were previously climate change refugia (Fig. 6.5 top). This illustrates that restoration has the potential to improve food web resilience comparable to fisheries restrictions (yellow in open sea areas in the Balearic Sea).

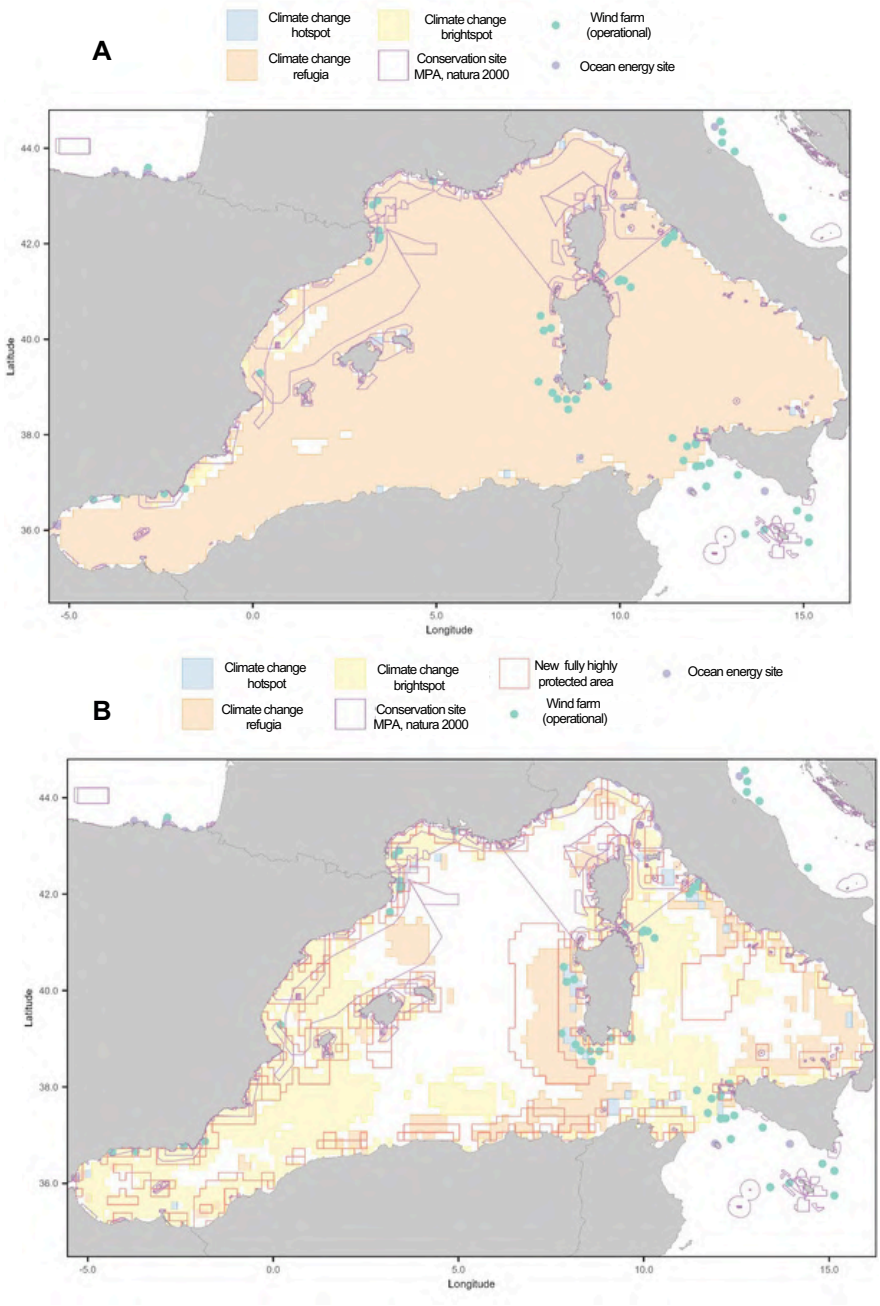


Figure 6.5, Long-term classification of the Western Mediterranean Sea ecosystem with regard to climate change sensitivity, between 2026-2069, (a) under the RCP 2.6 Status Quo scenario and (b) the Global Sustainability scenario (RCP2.6 and low barriers to climate change adaptation and mitigation). Reprinted with permission from Queiros et al. in prep, based on analysis of projections for the EwE regional Mediterranean Sea. (Model described in Deliverable Report 4.4).

Similar modeling of *Zostera marina* also projected future losses, especially near the southern distribution limit, although losses were much less pronounced than for *P. oceanica*. In the SW Baltic Sea, *Z. marina* has suffered major declines over the past century driven by multiple stressors, with eutrophication and bottom trawling confining populations to shallower waters where warming is emerging as additional stressor. Further limitation of eutrophication and trawling allowing eelgrass to recolonize deeper, cooler waters that may serve as climate refugia would, hence, support climate-smart restoration (Krause-Jensen et al. 2021, SL 6).

The upwelling zone of Northern Portugal hosts unique relict populations of tangle kelp (*Laminaria hyperborea*) at the lower latitudinal limit of the species (SL 21&23). Habitat suitability mapping (current and future) confirms the precarious persistence of *L. hyperborea* in this upwelling area and underscores the need to gain insights on future changes in mesoscale processes, such as upwelling, to make projections of the persistence of **climate refugia** for these populations.

Along the Norwegian coast, climate projections indicate that *L. hyperborea* is robust to changes and was projected to increase in spatial distribution under all climate scenarios in most areas except in southern Norway (SL 1-3). In southern Norway, tangle kelp ecosystems were projected to experience increasing pressure whilst increases in habitat suitability were projected for the far north. Green urchins (*Strongylocentrotus droebachiensis*), the key grazers of the kelp, were projected to experience reduced habitat suitability, particularly in summer, due to warming and reduced concentrations of dissolved oxygen (Fig. 6.6). After mid-century, ocean acidification is predicted to play an increasingly important role and, after 2070, a 90% reduction in habitat suitability is foreseen under the SSP5-8.5 scenario (WM). These projections support the development of smart management practices (e.g., fisheries management) and guide conservation, restoration and NIH (e.g., urchin and kelp harvesting).

Figure 6.6, Modeling projected future losses among different species driven by diverse stressors in the coming years.

H*abitat connectivity*

Connectivity and the lack thereof among restoration sites and natural populations is another relevant criterion for selecting restoration sites. FutureMARES explored this aspect for seagrass populations in the Baltic Sea and the Mediterranean Sea. While some populations recover naturally once conditions are suitable, restoration efforts are needed to assist recovery in areas where connectivity to natural populations implies that mother populations are lacking. To guide site selection for restoration efforts, FutureMARES developed a coupled biophysical model, involving the combination of hydrodynamic models and network analysis, to study eelgrass dispersal and connectivity in the Kattegat. The model identified hotspots of connectivity which, if restored, would also facilitate recolonization beyond the restoration site via natural spreading (Fig. 6.7). The model also identified poorly connected sites where restoration of mother populations should also be prioritised as those areas are unlikely to recolonize naturally (SL 6, Pastor et al. 2022).

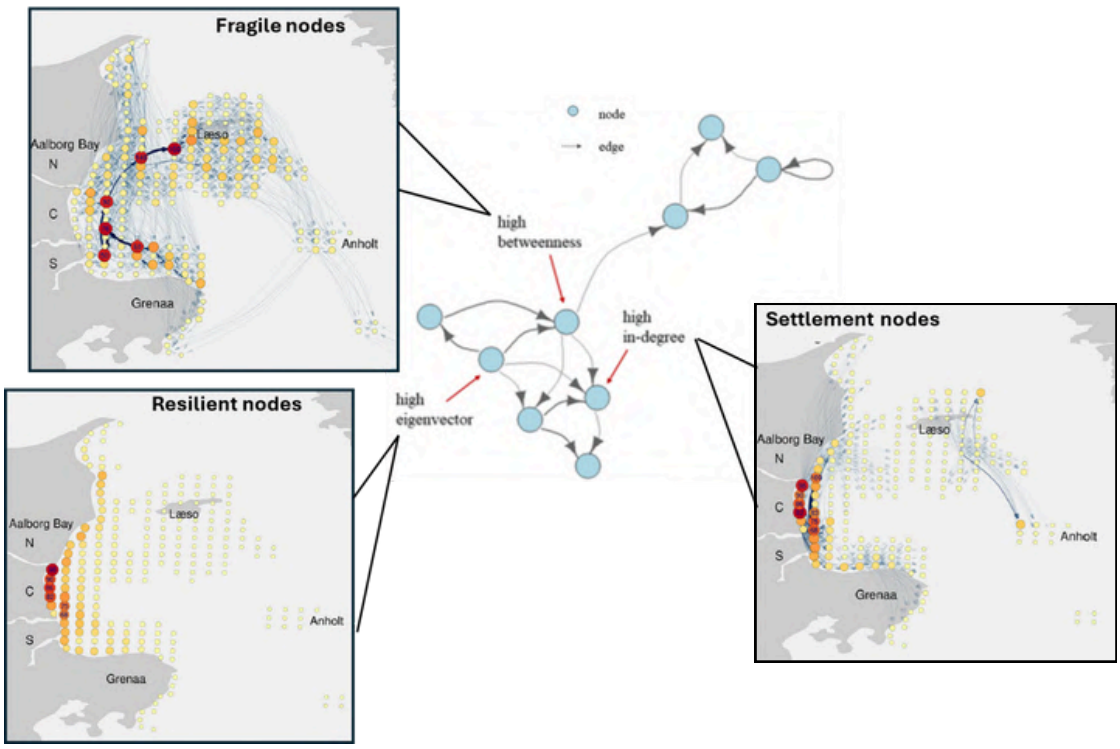


Figure 6.7, Coupled hydrodynamic and individual-based model and network analysis to describe connectivity of seagrass meadows. **Left panel**: A network consisting of a set of nodes (e.g., populations), and edges/connections linking them; arrows show the direction of the edges and arrow thickness reflect the strength of connection. Three so-called centrality measures are highlighted: "Weighted in-degree centrality" reflecting settlement nodes, "Betweenness centrality" reflecting fragile nodes and "Eigenvector centrality" reflecting resilient nodes. **Right panel**: Example of identified fragile nodes, settlement nodes and resilient nodes of eelgrass populations in the Kattegat, Denmark. (Based on Pastor et al. 2022)

How to restore

Passive restoration versus active restoration and reduction of stressors

Restoration involves first and foremost "passive"/general restoration of environmental/biotic conditions through the reduction of the stressors that caused the ecosystem loss. This part of the restoration is, hence, closely coupled to protection (See Chapter 5). While passive restoration can, to some extent, allow natural recolonization of lost habitats, active restoration of seascape elements may be required to initiate or increase the speed of restoration. Active restoration can involve restoring seascape elements to ensure the physical basis for the habitats to exist. For example, removal of drains/dikes to recreate natural hydrology is needed to restore coastal marshes that were lost due to land-reclamation. Likewise, if a boulder reef was destroyed by stone fishery, restoration requires transfer of new boulders. Also, if a kelp habitat is taken over by sea urchins, removal of those may be required to open the habitat for kelp recovery. Finally, another aspect of active restoration is the re-introduction of the target population of oyster, mussels or seagrasses where these have been lost over large areas and are not colonizing naturally or where there is a need to speed up natural recovery. In the case of seagrasses, re-introduction can be via seeds or transplants and can involve protective structures to increase the chance of survival of the transplants until they are sufficiently dense and well-established to protect themselves. In the case of macroalgae, reintroduction of kelp can be done, for instance, via so-called "green gravel" where algal spores are attached to gravel (SL 1). Active restoration is resource-demanding and requires some scale to increase the chances of success, which in any case is not guaranteed.

It is, therefore, particularly important that the restoration is carefully planned and follows the "climate-proofing" recommendations outlined above in addition to general guidelines on transplantation/seeding procedures, and that the process is closely documented, and thorough field monitoring occurs.

For active restoration of, for example, seagrasses, FutureMARES recommends conducting test restoration trials before going for large-scale restoration to make sure that local conditions support the restoration. In the Basque Country (Northern Spain), *Zostera noltei* has declined due to pollutants and other human activity. So that it only occurs in 3 out of 12 estuaries in the region (SL 20). Projections indicate that climate change may result in future coastal squeeze of these intertidal seagrasses due to rising sea level and land-infrastructure preventing land-ward migration, underlining the need to further reduce other stressors. Despite significant improvement in water quality, natural recolonisation did not occur, and FutureMARES, therefore, designed a restoration plan as a NBS to recover the vegetation and associated ecosystem services. The restoration plan includes feasibility and pre-project planning, project design with site selection and restoration trials followed by restoration and monitoring (Garmendia et al. 2023). In this region, the recommended active restoration method is by seeds rather than by transplants because this proved less resource demanding and had less impact on the mother populations. At higher latitudes in Danish coastal waters, eelgrass seeds are ripe in summer but do not germinate until the following spring and, because of this, transplantation of shoots has so far shown better success and is the recommended procedure (SL 6). This and other restoration procedures and follow-up monitoring are documented by Flindt et al. (2024) and embedded in national guidelines developed by the Center for Marine Restoration (https://www.danishmarinerestoration.com/) that FutureMARES collaborates with, and which also compiles experiences on restoration successes, failures and associated causes to develop a knowledge base.

Climate-tolerant donors for active restoration

In addition to variation in tolerance to adverse environmental conditions between species, tolerance may also vary within species because of different local climatic conditions that populations have experienced. The historical exposure to more intense and frequent climatic stressors can drive directional selection and can be expected to have increased the frequency of more resistant phenotypes within populations (Coleman & Wernberg 2020). Additional evidence on this work in FutureMARES was provided (Chapter 2).

A more resistant phenotypes was presented in FutureMARES (Chapter 2) for populations of *P. oceanica* in the Tuscan Archipelago, historically exposed to more frequent marine heatwaves and more resistant to warming (SL 28). A. *nodosum* also shows latitudinal variation in the response to heatwaves, implying that local conditions influence thermal sensitivity (SL 21&23). Fronds collected from Northern European sites suffered stronger deleterious effects in experiments mimicking heatwaves of different intensity.

Likewise, populations of the canopy-forming seaweed, *Ericaria crinita* (SL 29) from the warm range of the species distribution (e.g., from Crete and Malta) were more tolerant (suffered less biomass loss) to high temperatures than populations from the cold thermal regimes (Catalonia, See Chapter 2, Fig. 2.15). Projected future warming in the Mediterranean Sea, with mean

summer temperatures up to 31 °C may, therefore, compromise the viability of some but perhaps, not all of the populations of this canopy-forming species. These examples highlight the importance of choosing target species/populations which can maintain physiological functioning under changing conditions. The results suggest that individuals from more resistant populations should be given priority in conservation plans as well as in the selection of donor populations for active restoration, which would likely enhance the success of restoration under future climate scenarios.

Monitoring

Definition of the goals before the start of restoration activities is critical for assessing their effectiveness through subsequent monitoring. Monitoring should, as a minimum, address the distribution/abundance of restored foundation species. If the foundation species thrives, it is likely that the habitat also delivers associated ecosystem functions. When the goal of restoration is related directly to specific ecosystem functions and where resources allow, FutureMARES recommends that monitoring should also address ecosystem functioning in terms of associated biodiversity and process rates, like as primary production, nutrient uptake, or carbon sequestration capacity. In SL 29, primary productivity was compared between degraded, restored and natural subtidal forests formed by the brown macroalga *Gongolaria barbata*. Ten years after restoration, primary production of the restored site exceeded that of the degraded habitat and matched that of healthy and well-established natural habitats (Fig. 6.8). The net gain of primary production after restoration is expected to be transferred to higher trophic levels, thus benefiting associated invertebrates and fish. Evaluating the functioning of these important habitats in terms of productivity and recovery of the oxygen and carbon cycles gives a more holistic understanding of the restoration success than merely monitoring their distribution or abundance.

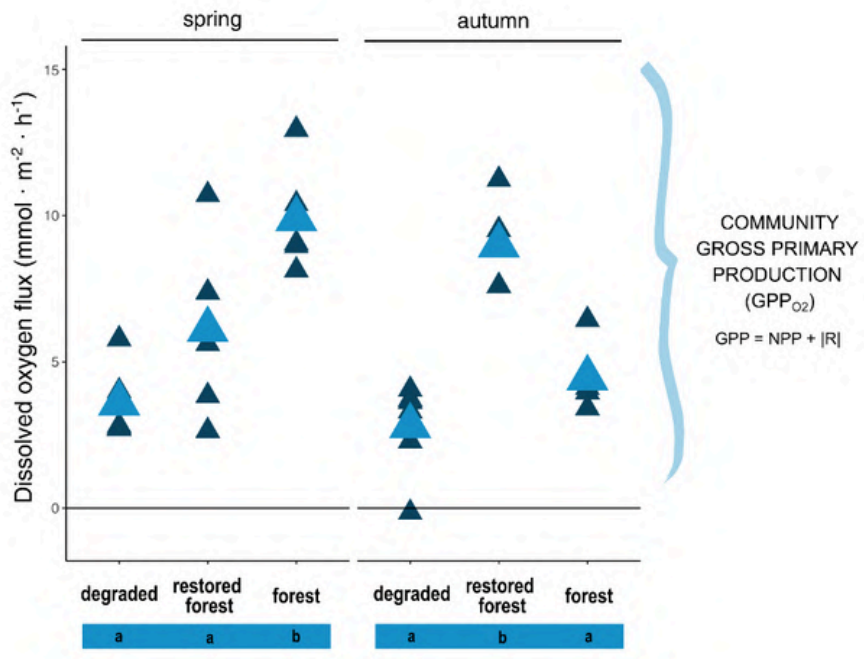


Figure 6.8, Community gross primary production (GPPO2) in the three studied sites (degraded, restored forest and forest) estimated via oxygen evolution in 1 h 30 min incubations in spring and autumn. Dissimilar letters under plots indicate significant differences (Bonferroni post-hoc pairwise test within 95% confidence intervals). (Deliverable Report 3.1)

Risks and benefits of implementing habitat restoration as NBS

Risk assessments are useful tools to understand how climate change threatens foundation species important for restoration (Wernberg et al. 2024). At the same time, such tools also allow to uncover the effectiveness of restoration as a NBS under different climate future scenarios. By comparing species and habitat risk levels with and without restoration measures (see Box 5.1) the benefits of implementing habitat restoration can be measured in terms of the effectiveness (or lack of effectiveness) to decrease risks to marine and coastal systems. In this project we quantitatively evaluated the effectiveness of restoration to lower the climate risk of 17 species and 5 ecosystem services across European waters, using an expert-based Climate Risk Assessment (CRA) approach (Bueno et al. 2024). Ecosystem services evaluated included biomass production, genetic material, climate regulation, and cultural services. Results from the analysis showed that the restoration measures explored could lower climate risks in all the species and ecosystem services included in the analysis. The average risk of the species (Fig. 6.10) and ecosystem services (Fig. 6.11) evaluated for different European regions and under different scenarios of climate change, ranged from moderate to high, generally between a level of 2 and 3 (the maximum risk is 4). The difference between the solid and the hashed bars represents the potential effectiveness of restoration (Fig. 6.10 & 6.11). Hence, the method makes it possible to explore the effectiveness of restoration for different regions and socio-ecological scenarios. In this case, we have considered the scenarios Global Sustainability (GS), National Enterprise (NE), and World Markets (WM) over two different time slices: 2040 to 2059, and 2080 to 2099 (Fig. 6.9).

Figure 6.9, Scenarios considered in the CRA

Marine and coastal restoration has the strongest effect in reducing climate risks to marine species and ecosystem services under the lowest emission scenario (GS, Fig. 6.10 & 6.11). For species risks, restoration is more effective in the long-term scenario (Fig. 6.10). Restoration was more effective in reducing the risks to biomass production and climate regulation (Deliverable Report 5.2), but a limited sample precludes this result from being broadly generalized. An apparent decrease in the effectiveness of habitat restoration was evident for the NE and WM scenarios in both time slices and was more marked in the NE Atlantic and North Sea region. These patterns (not observed in risk assessments for conservation – see Chapter 5) could indicate that restoration practices (NBS 1) depend more on the social, political, economic, and ecological contexts than conservation practices (NBS 2). Restoration measures are highly dependent on sustained economic resources for long-term monitoring, employment of personal, for materials, etc., which depend on the short-term local or regional political context. On the other hand, these results also align with the fact that restoration relies on species that are already impacted by climate change, and their ability to continue to recover in the future is strongly limited under the higher emission scenarios (Cooley et al. 2022, Wernberg et al. 2024).

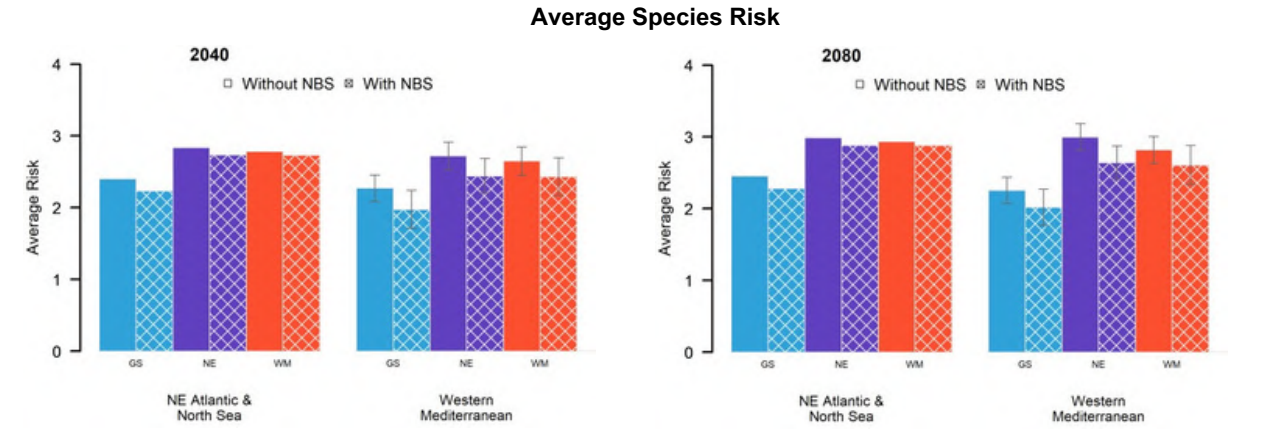


Figure 6.10, Average species risk estimated by FutureMARES storylines under three future PESTLE scenarios (GS: Global Sustainability; NE: National Enterprise; WM: World Markets) in the near future (2040) and in the long-term future (2080). Solid bars represent the risk of the species when restoration is not present and the hashed bars represent species risk when restoration is applied. Gray lines represent the variance across the species analyzed. (Deliverable Report 5.4)

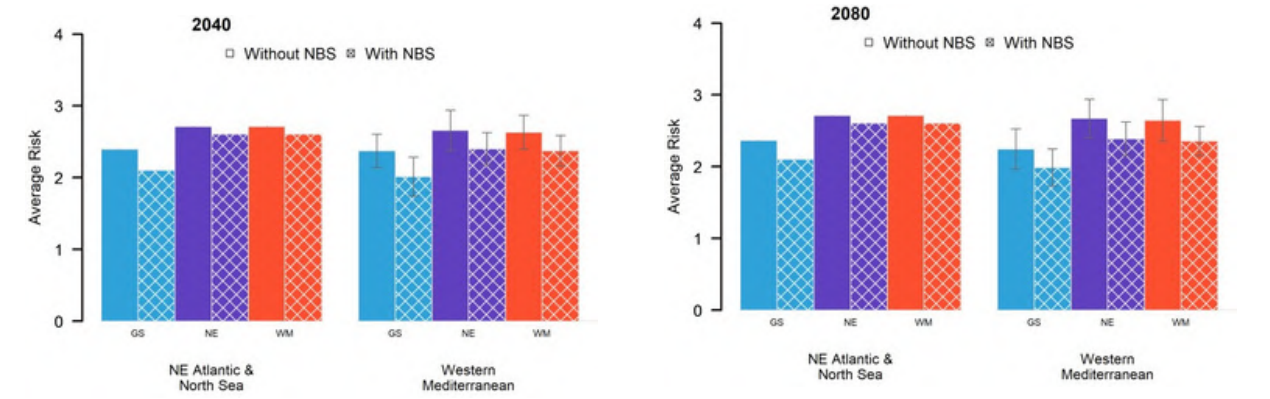


Figure 6.11, Average ecosystem services (ES) risk estimated by FutureMARES Storylines under three future PESTLE scenarios (GS: Global Sustainability; NE: National Enterprise; WM: World Markets) in the near future (2040) and in the long-term future (2080). Solid bars represent the risk of the ESs when restoration is not present and the dashed bars represent species risk when restoration is applied. Gray lines represent the variance across the ES analyzed. (Deliverable Report 5.4)

Economic implications of habitat restoration

Restoration efforts in marine environments have garnered increasing attention for their potential economic impacts as well as their ecological benefits. Restoration projects aim to rehabilitate degraded ecosystems, boosting their productivity and resilience while creating diverse ecosystem functions and economic opportunities. Two notable examples have been explored in an economic context by FutureMARES: oyster restoration in the North Sea and kelp forest restoration along the Northern Coast of Norway.

In the North Sea, oyster restoration plays a crucial role in revitalizing and protecting once-depleted populations of these ecologically and economically important bivalves (Fig. 6.12).

By restoring oyster beds, critical habitats are reclaimed, leading to the emergence of numerous associated benefits (Rijkswaterstaat & Deltares 2013). Oyster reefs should be protected and restored as they provide essential Ecosystem Services such as water filtration, shoreline protection, and habitat provision for various marine species. Economically, the restoration of oyster populations can potentially stimulate local fisheries, enhance tourism through activities like oyster farm tours, and bolster coastal economies through increased seafood sales.

Figure 6.12, Artificial oyster reef located near de Oesterdam. Trapped sediment and elevation difference can be seen comparing the level behind and in front of the oyster reef. (Source: Luca van Duren)

In the late 1800s and early 1900s, oyster reefs covered about 25000 km2 (Olsen 1883, Pogoda et al. 2019). These reefs have largely disappeared due to disease and overfishing. Given their former importance as biogenic habitat, numerous restoration efforts are underway in various North Sea countries, including the Netherlands. Some regions of the Dutch North Sea, however, are inherently unsuitable for oyster reef formation due to highly dynamic seabed formations (Herman & Van Rees 2022). The more stable and suitable areas are within seasonally stratified areas of the North Sea, which are likely to experience limited food transport to oysters on the seabed and consequently, limited oyster growth (Stechele et al. 2023). The restoration potential in the southern North Sea was investigated using a combination of statistical habitat suitability and Dynamic Energy Budget (DEB) growth models nested within ecosystem models. Oyster growth simulations were conducted in areas not exposed to fishing (either in fisheries exclusion zones, MPAs, or within wind farms) and with high habitat suitability. The best oyster growth occurred in the dynamic southern part of the North Sea, where suitable habitat is limited. The optimal locations were found in the fisheries exclusion zones at the Frisian Front and around some wind farms in the German Bight. These areas have the necessary combination of no bottom trawling, stable seabed conditions, and adequate food supply to support oyster growth and reproduction. Historical literature suggests that the large oyster reefs once reported in the area still known as the “Oyster Grounds”, likely consisted primarily of large amounts of dead oyster shells with only occasional living specimens. In the former ‘Oyster Grounds’, projected growth was so restricted that the carrying capacity for oysters would be insufficient for rapid recolonization. Although oysters are physiologically adapted to survive in areas with low and intermittent food supply, the carrying capacity for oyster assemblages in these areas was projected to be too limited to sustain large populations. Climate change (particularly under extreme scenarios) is expected to exacerbate stratification and further limit the carrying capacity for oysters.

The comparison of cost proxies between man-made solutions (MMS) and oyster reef restoration highlights the financial advantages of natural approaches to increasing coastal protection and water quality. The economic analysis demonstrated superior cost-effectiveness of oyster reefs in

improving flood water management and water quality. By using a standardized unit of measurement, the costs of different options were compared in a transparent way, as the comparison focused on achieving the same outcome (e.g., cost per percentage change in wave height) rather than same effort (e.g., cost per kilometer of breakwater and oyster reef). Notably, oyster reefs were deemed more cost-effective than MMS for water quality over the long term, despite higher initial investment costs, because mature, established reefs can provide denitrification benefits at almost zero cost. This analysis underscores that the high initial costs of oyster reef investments are offset by the ongoing benefits, significantly reducing annual expenses compared to technical solutions. It should be noted that oyster reefs are not constructed solely for filtration purposes and, therefore, the estimated cost of denitrification for the oyster reef has a much lower value.

Furthermore, applying different discount rates (2% for social and 17% for private) did not alter the outcome of the cost-effectiveness analysis. For both ES, the cost effectiveness ratio of the Net Present Value (NPV) - the difference between the present value of cash inflows and outflows - was estimated. This ratio remained lower for the NBS than for the MMS regardless of the FutureMARES scenario (Global Sustainability, National Enterprise, and World Markets) in which the NBS was applied (Fig. 6.13) The methodology, assuming linear effects, likely underestimated the total value provided by oyster reefs, as current assessment methods do not fully capture their combined benefits.

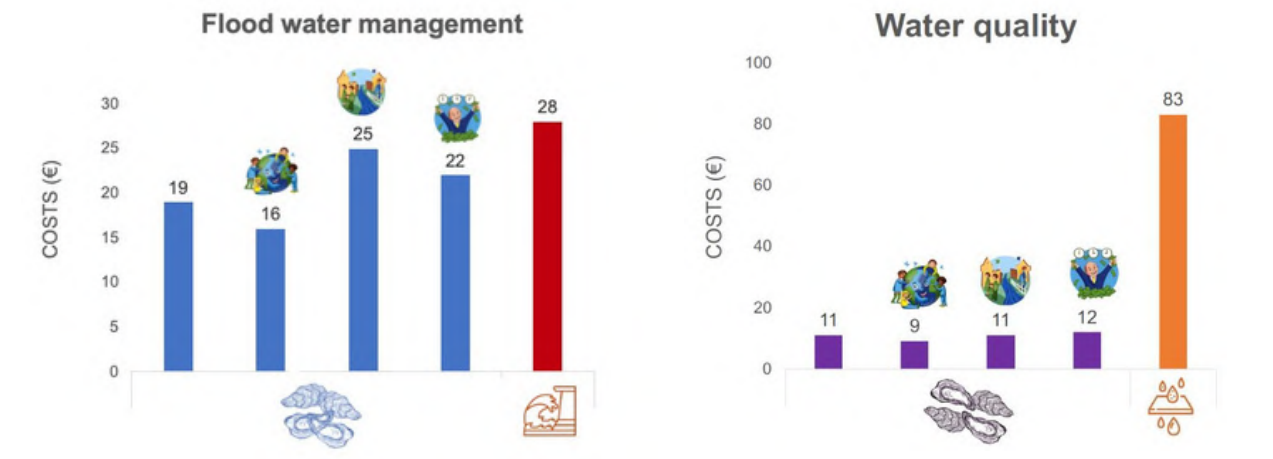


Figure 6.13, Cost-effectiveness ratios of NBS (restored oyster reefs, blue and purple bars) and MMS (breakwater constructions– red bar or industrial filtration systems – orange bar) for Improved Flood Management and Improved Water Quality in the Oosterschelde, under three FutureMARES scenarios (GS, NE, and WM) with a discount rate of 2%. Lower costs indicate higher cost-effectiveness. Average scenario effects for Improved Flood management consider a change in effectiveness of oyster reef in wave dissipation capacity to 0.66, 0.43 and 0.49 for GS, NE and WM scenarios, respectively. Average scenario effects for Water Quality consider a change in effectiveness of the oyster reef in total denitrification capacity of 3324, 2649 and 2363 kg for GS, NE and WM scenarios, respectively. (based on Deliverable Report 6.2)

Similarly, restoration along Norway's northern coast aims to restore degraded kelp forest habitats, which are vital components of marine ecosystems in cold-water regions (Chen et al. 2019). Since the 1970s, these kelp forests have suffered severe degradation, primarily due to overgrazing by the green sea urchin (Norderhaug & Christie 2009, Rinde et al. 2014). Kelp forests support sustainable fisheries and ecotourism ventures such as diving and wildlife watching, and contribute to carbon offset initiatives, thereby generating income and supporting local economies. FutureMARES explored the most cost-effective strategies for reducing the sea urchin population, thereby facilitating the restoration of kelp forests (Fig. 6.14).

This assessment provides crucial insights into the financial aspects of various restoration techniques and serves as an essential guide for strategic investment in these vital marine ecosystems.

Figure 6.14,Urchin barrens in the northern Norway and healthy kelp habitats after recovery (Photo source: Norwegian Institute for Water Research)

The results indicate that future restoration efforts and their associated costs will likely be shaped by various factors, including the scale of restoration needed, investment and operational costs, advances in restoration technologies, community involvement, and funding availability, especially under the changing conditions assumed to occur in the World Markets scenario (Fig. 6.15).

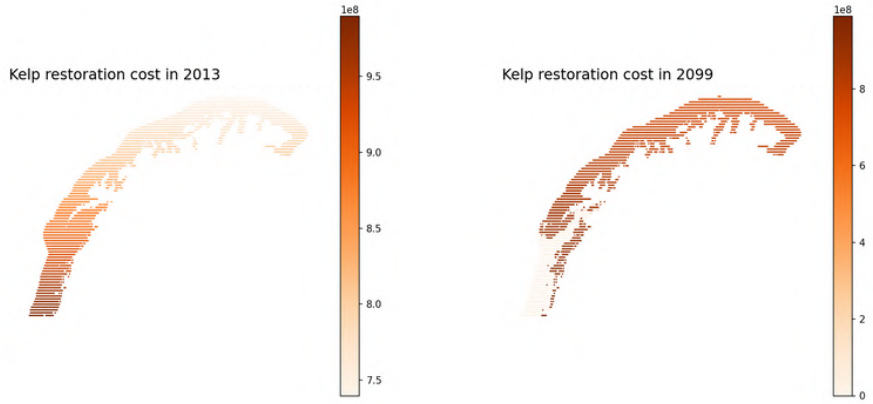


Figure 6.15, Projection for restoration cost distribution across the northern coast of Norway for World Markets scenario SSP5-8.5 in year 2013 in comparison to year 2099. (Deliverable Report 6.2)

Finally, scaling restoration initiatives is crucial for several reasons. Large-scale restoration can significantly enhance biodiversity, improve water quality, stabilize ecosystems, and contribute to the climate resilience of ecosystems. Small-scale initiatives often only impact local areas, whereas scaling up can create interconnected habitats that are more robust and sustainable. Although initial costs are high, larger-scale restoration projects can be more cost-effective in the long run. Additionally, large-scale projects often require a substantial workforce, including project managers, scientists, technicians, and laborers. This can support regional economies, particularly in rural and coastal areas where economic opportunities may be limited, by creating jobs, supporting local industries such as tourism and fisheries, and attracting further investment.

By enhancing ecosystem services such as water purification or biodiversity, restoration projects help ensure the long-term viability of economies that depend on these services. Although the scaling of restoration is essential, it presents a variety of challenges that can affect success and sustainability. Addressing these challenges requires careful planning, adequate resources, and broad stakeholder engagement. Restoration projects often require substantial upfront investment and ongoing maintenance costs.

Finding long-term funding sources that ensure sustainability beyond initial grants or funding cycles can be difficult. Each ecosystem is unique, and large-scale restoration requires a deep understanding of local ecological conditions. Projects must be based on sound ecological principles and detailed environmental assessments. Techniques that work well on a small scale may not be effective or feasible at a larger scale. This can include biological, physical, and chemical processes involved in restoration. Scaling up requires adaptation and sometimes significant modification of these techniques. Misjudging these conditions can lead to ineffective, costly or even harmful interventions.

BOX 6.1 Ecosystem services valuation for Nature-based Solutions assessment

Incorporating both valued and non-valued Ecosystem Services (ES) is crucial for understanding the full potential benefits of NBS and NIH. FutureMARES explored valued ES such as water quality, flood management, biodiversity, and carbon sequestration, as well as the less quantifiable but essential non-valued ES such as cultural and recreational benefits. Non-valued ES are challenging to quantify because of their intangibility, subjective valuation, and lack of direct market prices, requiring interdisciplinary valuation methods.

The findings of FutureMARES highlight a significant underestimation of indirect and induced economic impacts, especially in sectors such as recreation and tourism within MPAs. This work emphasizes the need for comprehensive assessments that encompass all ES for informed decision-making and sustainable policy development.

FutureMARES critically appraised two methods commonly used in the bioeconomic assessment of ES, Cost-Benefit Analysis (CBA) and Cost-Effectiveness Analysis (CEA) (Fig. 6.16).

Method	Cost-Benefit Analysis	Cost-Effectiveness Analysis
	A comprehensive framework for evaluating NBS by comparing the total costs of implementation with the total benefits accrued over time.	Focuses on assessing the efficiency of NBS by comparing the costs of achieving specific environmental out-comes among different interventions.
Pros +	Provides a holistic view of the economic feasibility of NBS allows decision-makers to quantify both monetary and non-monetary benefits, such as improved ES and enhanced resilience to climate change.	Provides insights into cost-effectiveness of various NBS or other non-NBS options, helping decision-makers identify the most efficient strategies for achieving desired environmental goals within budget constraints.
Cons −	May require detailed data on costs and benefits, which may not be readily available or easily quantifiable, especially in diverse ecological and socio-economic contexts.	Effectiveness depends on availability of data on costs and outcomes, which may vary across different case studies and regions, and over time - given that technological developments could reduce costs of alternatives in the future.
Changes over time	For both methods, using discount rates is crucial for comparing costs and benefits in the future, and for assessing the present value of future outcomes. Selecting appropriate discount rates can be challenging, as different regions and stakeholders may have divergent preferences and perspectives on equity and societal discounting. Moreover, discount rates may vary depending on factors such as inflation rates, interest rates, and risk preferences. Sensitivity analyses are needed.	

Figure 6.16, Methods used in the bioeconomic assessment of Ecosystem Services.

Given the diverse nature of Storylines within FutureMARES and the variability in ecological, socio-economic, and institutional contexts, there exists no standardized methodology for evaluating the economic impact of NBS. Instead, decision-makers need to tailor their approach by taking into account local conditions, stakeholder preferences, and data availability. By using interdisciplinary approaches adapted to the specific intervention, decision-makers can better capture the multidimensional benefits and costs of NBS and make informed choices about resource allocation and investment priorities. In conclusion, while CBAs, CEAs, and the use of discount rates are valuable tools for assessing the potential economic impact of a NBS, their application should be context-specific and flexible to accommodate the complexities and uncertainties inherent in taking these actions. By adopting a tailored approach and considering a range of methodological options, s can enhance the robustness and validity of economic evaluations to increase social acceptance (buy-in) for more effective strategies in both the development of policies and their implementation and sustainable management.

Sarah Simmons

Conclusions and policy recommendations

The key findings and recommendations regarding climate-ready restoration strategies are summarized below and in Figure 6.2.

1) The success of habitat restoration depends on a thorough analysis of which species should be restored (what), the identification of sites characterized by suitable physical and biological conditions (where) and of the most promising procedures for restoration (how).

2) Foundation species forming habitat and tolerant to increasingly adverse climatic conditions should be considered as a priority for restoration.

3) Transparent monitoring plans, fully developed ahead of interventions, are necessary to follow and document the degree of success and potentially adjust the interventions.

4) Passive restoration (i.e., MPAs and the recovery of suitable physical and biological conditions after removing stressors) should be first explored before proceeding with active restoration activities.

5) Beyond the target species, restoration is very likely to enhance populations of associated species and the ecosystem services they generate. The strength of these effects depends on CC emission scenarios and socio-political pathways.

6) Despite foundation species being already exposed to significant impacts from CC, restoration interventions can reduce the risks in marine species and ecosystem services, especially under lower emission scenarios.

7) Restoration will produce economic benefits over a long-term, despite requiring, in some cases, a higher initial investment.

Future MARES

CHAPTER 7

PLANNING SUSTAINABLE HARVESTING IN A FUTURE CLIMATE

AUTHORS: CHRISTOPHER LYNAM, LUCA VAN DUREN, ELENA OJEA, JUAN BUENO-PARDO, ERIK SULANKE, SARAH SIMMONS, JOSE A. FERNANDES-SALVADOR, ARANTZA MURILLAS, MARTA COLL, ANA QUEIROS, RICHARD BELLERBY, YUNNE SHIN, GUILLEM CHUST, MYRON A. PECK

07 Planning sustainable harvesting in a future climate

Introduction

About 17% of the world's protein consumption has marine origins and it is expected that this may increase in future, particularly so given the limited possibilities of land-based expansion (Costello et al. 2020). In the 1970s, over 95% of seafood production (tonnage) was from wild capture fisheries (FAO 2022). Aquaculture, including algae cultivation, has overtaken wild fisheries as the greatest proportion of production since 2012. Once excluding algae from the total tonnages produced in 2020, 49% of production arose from aquaculture and 51% was from capture fisheries (FAO 2022). In 2022, wild capture fisheries production of aquatic animals was estimated to be 49% of the total with aquaculture reaching 51% and greater than fisheries production for the first time (FAO 2024). Notably, the first sale value of the global production from capture fisheries (157 billion USD) was estimated to be substantially less than that from aquaculture (296 billion USD).

Aquaculture can derive their food resources either directly from the environment ("extractive aquaculture") or indirectly from external sources ("fed aquaculture"). Examples of the first are shellfish and seaweed, while examples of the second are fish farms, that are fed with fish food that can originate from other marine areas or from land (Rawson et al. 2002). Extractive offshore aquaculture is seen as an important development to contribute to food security, without the negative impacts on marine systems that, for instance, fish farming entails (Buck et al. 2017). However, extractive aquaculture in enclosed systems can also overexploit the environment and potentially breach the carrying capacity of marine ecosystems. Businesses that depend on extractive aquaculture in enclosed systems are thus likely to be affected by climate change. Furthermore, cultivated shellfish eat the same food as valuable natural shellfish beds. If offshore extractive aquaculture is rolled out on a large scale in the future, we will need to balance the needs for food production with the needs for healthy ecosystems along with the prospect of large-scale shellfish reef restoration.

Research within FutureMARES

FutureMARES performed analyses within 16 Storylines (SLs) examining sustainable seafood harvesting (Fig. 7.1). These included both the extractive culture of shellfish and seaweed in the North and Baltic Sea as well as different scales and types of fisheries from small cooperatives (Chile and Belize) to large-scale industrial fleets active in European regional seas. FutureMARES made projections of the impact of climate change on marine ecosystems (Deliverables Reports 4.3, 4.4, 6.2) for wild capture fisheries (SL 12-15, 24, 31, 33 & 38) as well as for offshore and nearshore aquaculture (including blue mussel *Mytilus edulis* and native flat oyster *Ostrea edulis* in the North Sea (SL9 & SL15), and salmon *Salmo salar* in Norwegian waters, (SL4).

Overfishing has had severe impacts on marine ecosystems, from the overexploitation of stocks and seabed damage to wider impacts on dependent species of conservation concern (including

in the North Sea SL12-15, Bay of Biscay and Basque coast SL 24 and Mediterranean Sea SL 31 and 33). Furthermore, unsustainable aquaculture practices can lead to detrimental impacts including additional pathways for the spread of disease and non-native species and increases in biotoxins in the environment alongside chemical and bacteria pollution. In Europe, improved fisheries policies and better implementation has resulted in fewer stocks being overfished. Moreover, compliance with national regulations for aquaculture has minimized environmental impacts of harvesting for shellfish (mussels and oysters) and finfish (especially salmon). Nevertheless, in some places, the direct impacts of fisheries on fish stocks, as well as impacts on non-target species and the marine habitat are considered unsustainable.

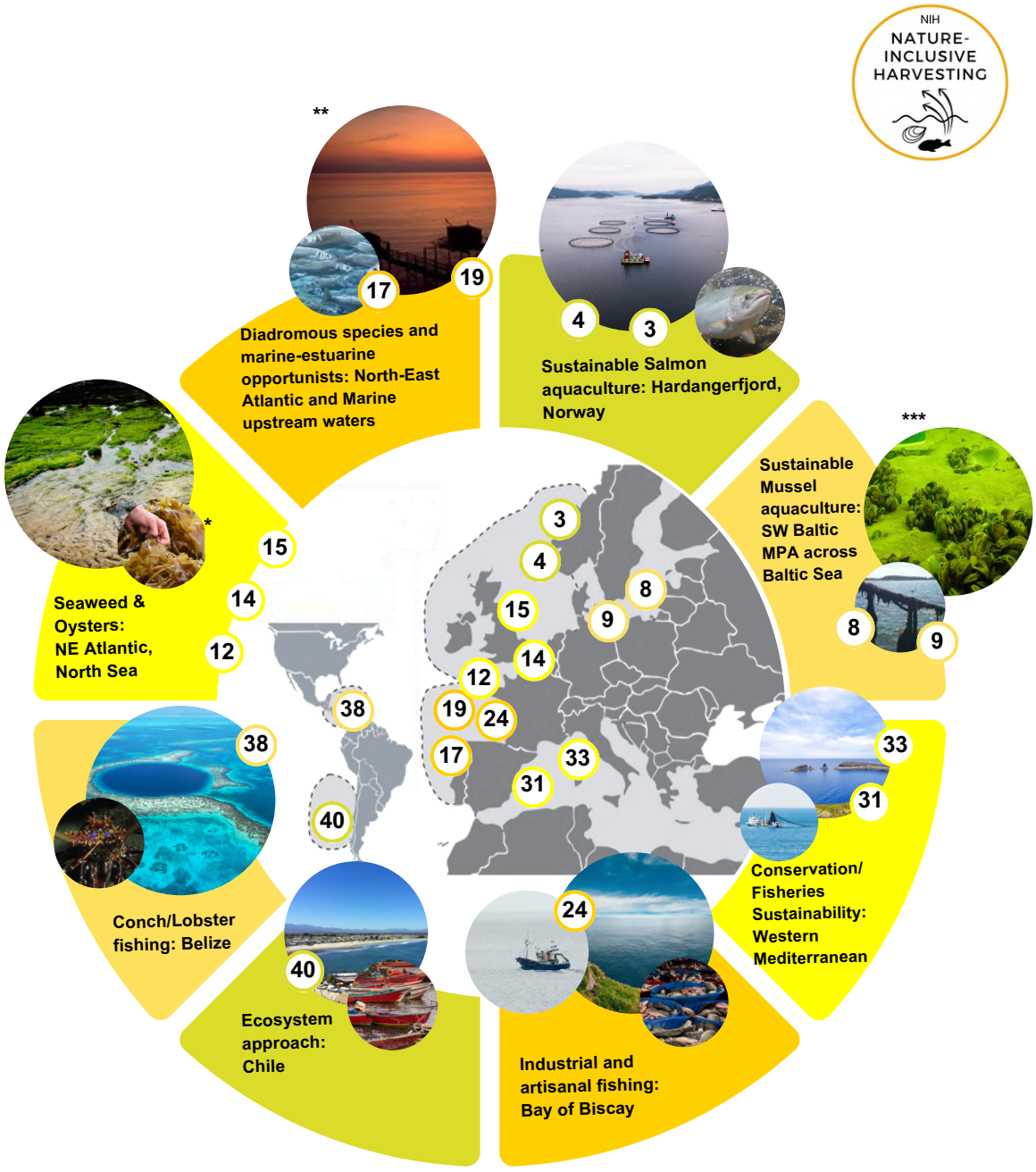


Figure 7.1, Location of the Storylines examining Nature-inclusive (sustainable) Harvesting within the FutureMARES programme. Photo credit: Luca van Duren. SL 10. **Irstea/Cemagref. SL 16-18. *** Jens Larsen and Marie Maar SL 9

Climate change is adding extra pressure on marine systems so what were sustainable fishing yields and practices in the past may no longer be sustainable in the future (SL4, 9, 12-15, 24, 31 and 33). An example of NBS to climate change (including Marine Protected Areas) in practice is the implementation in Belize through a rights-based access system for small-scale fisheries following the ban on trawling in 2011. Today fishing activities in Belize support ~15,000 people and there is a pilot managed access area scheme to support sustainable fisheries that is being scaled up nationwide (SL38). In the North Sea (SL12-15), the provision of fish protein is only a relatively small fraction of protein in the typical diet of the region (FAO 2022), but it remains an important source of sustainably produced food and FutureMARES model projections demonstrate how this can be supported by the implementation of NBS. In the Mediterranean Sea, the poor condition of many commercially exploited fish stocks is compromising fish production into the future so clear management interventions are required to achieve sustainable yields that can cope with climate change impacts (SL 31, 33).

Sustainable aquaculture

Seaweed production and mussel farming were investigated in the Danish Limfjord system and future wind farm areas in the Dutch EEZ (Deliverable Report 4.3). For seaweed cultivated in the surface water layers of the North Sea, model simulations projected decreased yields due to global warming in some regions for sugar kelp *(Saccharina latissima*). However, in some of the future scenarios, increases in available offshore nutrients compensated for this effect. The projected yields are lower for mussel cultivation under more severe climate scenarios, although local increases do occur due to increased nutrient runoff. For some wind farm areas, attention needs to be paid to local stocking densities and the presence of upstream extractive aquaculture farms. Mussel farms appear to be more susceptible to reaching local production carrying capacity. This effect is more pronounced with more extreme climate scenarios.

There is limited effect on yields from co-locating of cultivating mussels and seaweed, but the combination may heighten the impact on ecological carrying capacity with consequences for other ecosystem components. Results of model simulations within FutureMARES suggest that, when mussel farms and restored oyster beds are in direct competition with each other, the oysters are better able to cope with reduced food availability (Deliverable Report 4.4). This is consistent with their physiology, which has evolved to be adapted to low and very intermittent food conditions. This is something to consider in future marine spatial planning.

Climate-driven increases in temperature were not projected to pose a risk to hanging mussel cultures. In the Limfjord, a 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.

Model simulations projected short-term increases in yields for mussels due to climate change, as the rate of algal growth also increased at higher temperatures. In less 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 cases, decreased concentrations of dissolved oxygen that reduced mussel biomass in all scenarios. In RCP8.5 specifically, benthic mussels suffered from hypoxia, whereas suspended mussel cultures maintained a high harvest potential.

The current mussel fishery varies from 30 to 8 Kt FW per year and this yield has tended to decline over time. 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 would have marked impacts on the fishing quota, making it less economically attractive. Given the expected changes in climate impact, 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.

The available habitat for Atlantic salmon (*Salmo salar)* in Norwegian coastal waters and fjords will become constricted in present-day areas of activity following climate change. Although, new regions to the north will become more favorable (SL 4). In spite salmon will be able to operate in deeper waters, away from the inhospitable surface ocean, the projected changes in ocean conditions (namely water temperature and oxygen concentrations) to enable passage and feeding may impact on salmon behavior and population success. Therefore, salmon farming will be constricted by climate change, demanding that the fish be kept at greater depths and also modifying the threshold for oxygen demand, in an ocean with diminishing oxygen concentrations, related to stocking densities, size of market-ready adults and feeding operations.

Figure 7.2, FutureMARES projected climate change impacts on kelp, mussels, salmon and other cultivated species. Credit left photo Jens Larsen.

Sustainable fisheries harvests

The four large ecosystems studied within FutureMARES (North Sea, Baltic Sea, Bay of Biscay, Mediterranean Sea) have been heavily exploited historically by marine fisheries, leading to depletion of several commercial species. Fishing effort remains high in the Mediterranean Sea but has been greatly reduced for the North Sea. Current fishing management and conservation plans comprise a mosaic of measures, such as regulation of fishing effort, setting quotas, marine spatial management with ambitious plans such as extending no-take and highly protected areas (up to 10% of sea areas), as well as implementing spatial restrictions to fishing such as the GFCM Fisheries Restricted Areas in the Mediterranean. Details regarding the implementation of these management targets are currently pending, as they are under discussion at both national and supra-national levels.

The effects of fishing at Maximum Sustainable Yield (MSY) under climate change were investigated for multiple regions and with multiple ecosystem models (Deliverable Report 4.3). Changes in the Bay of Biscay were investigated using two models: Ecopath with Ecosim (EwE, SL24) and a Size-Structured Dynamic Bioclimatic Envelope Model (SS-DBEM, SL24). The North Sea was studied using the eco-evolutionary version of the Object-oriented Simulator of Marine Ecosystems model (OSMOSE, SL15) and EwE (SL12-14).

In the Mediterranean Sea (SL33) with a focus on spatial protections, both OSMOSE and EwE were used. Scenarios of Marine Protected Areas (MPAs) and Nature Inclusive Harvesting were tested using the digital labs approach (Box 4.1) in the Bay of Biscay, North Sea and Mediterranean Sea with EwE along with comparative simulations for the Portuguese coast, north-western Mediterranean Sea and Baltic Sea including the Finnish Archipelago Sea and demonstrate change in species considered important for conservation and for commercial fisheries (Fig. 7.3). In all of these models, predator-prey interactions within the food web can lead to increases in prey species when predatory fish stocks are overexploited or decreases in prey species when predatory fish stocks increase to high biomass. However, the food web effects of overexploitation or of a release of the predatory stock from fishing pressure is dependent on the ecosystem studied and the expected impact of climate change on the ecosystem.

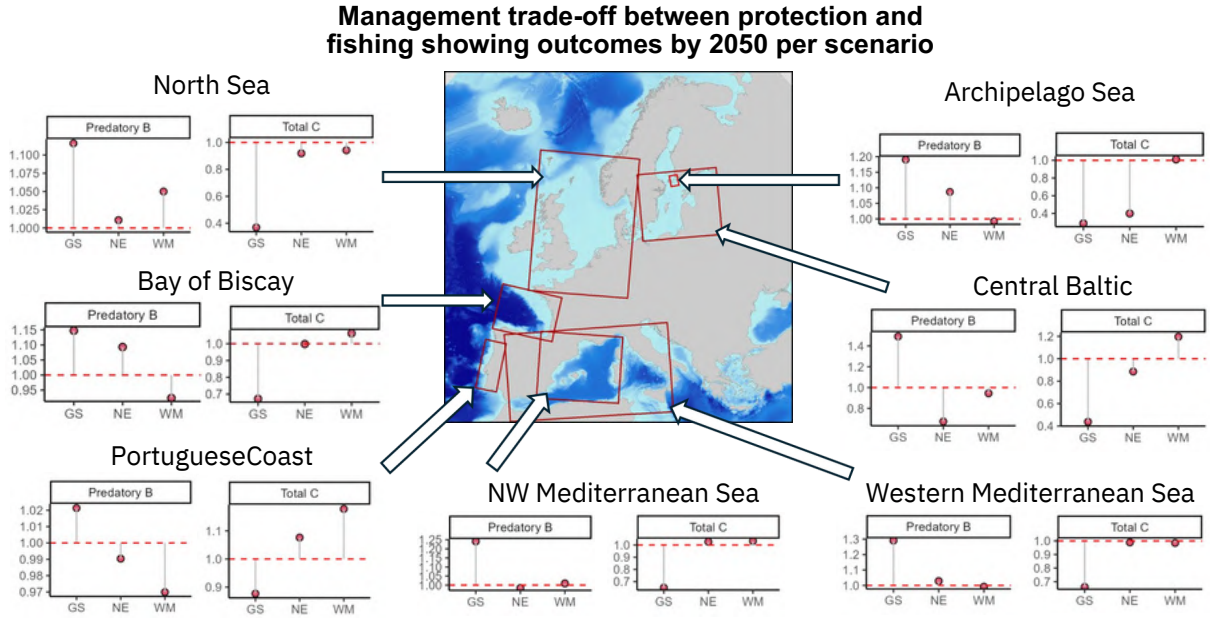


Figure 7.3, Projected changes by 2050 due to management (NIH) and Nature Based Solutions (NBS2-protection in each scenario with NBS1-restoration in GS only) on total biomass of predators (Predatory B) and total catch of all commercially fished species (Total C) by scenario scaled to climate only simulations (status-quo without additional management), modelled with Marine Ecosystem Models (see Chapter 4, Box 4.1 Digital Laboratories and Deliverable Report 4.4).

Specific investigations in relation to fisheries are described in Deliverable Report 4.3 (SLs 14, 15, 24, 31, 33). In the Bay of Biscay, the biomass of monkfish (*Lophius piscatorius*) increased following a reduction in fishing pressure to meet MSY targets, while hake (*Merluccius merluccius*) biomass increased due to a larger prey availability. In contrast, the model predicted declines in the biomass of blue whiting (*Micromesistius poutassou*) and megrim (*Lepidorhombus whiffiagonis*), mainly due to the increase of predators (monkfish and hake). Projections of climate change demonstrated many detrimental effects of ocean warming, with modelled impacts becoming greater as temperature increased and impacting pelagic groups greater than demersal groups.

When fishing and climate impacts were combined, detrimental effects could be exacerbated. Highly exploited species such as albacore tuna (*Thunnus alalunga*) was predicted to decline in all scenarios of fishing pressure (including F_{MSY}), which confirms the importance of management measures to effectively rebuild stocks for such species whether climate change is having an

impact or not. Tuna fisheries were further investigated for the Basque Country (SL 24) using SS-DBEM which also projected general declines (Erauskin-Extramiana et al., 2023): specifically in the Global Sustainability scenario, albacore declined 5-10% in biomass, while in the other scenarios the projected biomass decreased between 10 to 20%. In contrast, the biomass of bluefin tuna (*Thunnus thynnus*) was generally stable (or only slightly declined) in the Global Sustainability scenario. Decreases in body size were also reported not only in tuna species, but also in European anchovy (Taboada et al. 2023, see Box 7.1), which is also impacting the communities (Chust et al. 2024).

Nature-inclusive Harvesting goes beyond fishing at sustainable levels for target fish stocks. Fisheries management measures that lead to a reduction in the bycatch and/or discarding of unwanted catch can be particularly important when long-lived sensitive species are impacted either directly or indirectly through fisheries impacts on their prey. The impact on European regional seas of bycatch was modelled alongside reductions in fishing effort to meet targets for MSY and to avoid the displacement of fisheries from protected areas. Reducing these pressures in a climate context was found to lead to improvements in the environmental status of marine ecosystem (see Chapter 8 and Deliverable Report 4.4).

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 MSY of fish stocks, specifically for saithe (*Pollachius virens*) in the North Sea, reducing negative impacts of climate change. Incorporating ecosystem information into fisheries management represents one of the main challenges in the conservation and management of marine ecosystems and is an important, practical step towards Ecosystem-based Management (FAO 2008, NOAA 2016, Howell et al. 2021).

Results from ecosystem modeling conducted in the North Sea, Baltic Sea, Mediterranean Sea and Bay of Biscay indicated that future outcomes for specific fisheries depended strongly on the status of the ecosystem, on the fisheries activities projected to occur in the areas, and on future changes in environmental conditions. In some cases, higher catches were projected to occur under NE or WM scenarios, despite depletions of commercial and conservation important species. However, in other cases, higher catches were projected under the GS scenario. Overall, however, the status quo scenarios tended to project lower catches than historical levels. Our results also showed heterogenic changes in space for biomasses and catches, which are due to heterogenic changes in environmental and ecological conditions, but also in fisheries activities and management actions. The spatially-explicit results highlighted that distinct management interventions will be crucial to inform future ecological and socioeconomic status of European marine ecosystems. In a context of future climate change conditions, with expected increases in temperature and changes in primary production, the outcome highlighted that distinct management interventions are crucial to maintain biodiversity and support productive, sustainable fisheries into the future. The implications of these results hold significant importance for the proactive management of European Regional Seas under the climate change context.

BOX 7.1 Climate-driven changes in fish body size

In marine fish, changes in temperature and food availability or fluctuations in abundance, including those due to size-selective fishing, provide compelling mechanisms to explain changes in body size. Two studies in FutureMARES analized trends in sizes of pelagic fishes. In the first study, Taboada et al. (2023) reported a decline in the average body size of European anchovy, (*Engraulis encrasicolus*) in the Bay of Biscay. (Fig. 7.4)

Shrinking was evident in all age classes, from juveniles to adults. Trends in adult weight were nonlinear but, during the last two decades, rates of decline accelerated to up to 25% decade−1. There was a strong association between higher anchovy abundance and reduced juvenile size. In adults, the effect of density dependence was less clear and increasing temperature was the best predictor of declining body size.

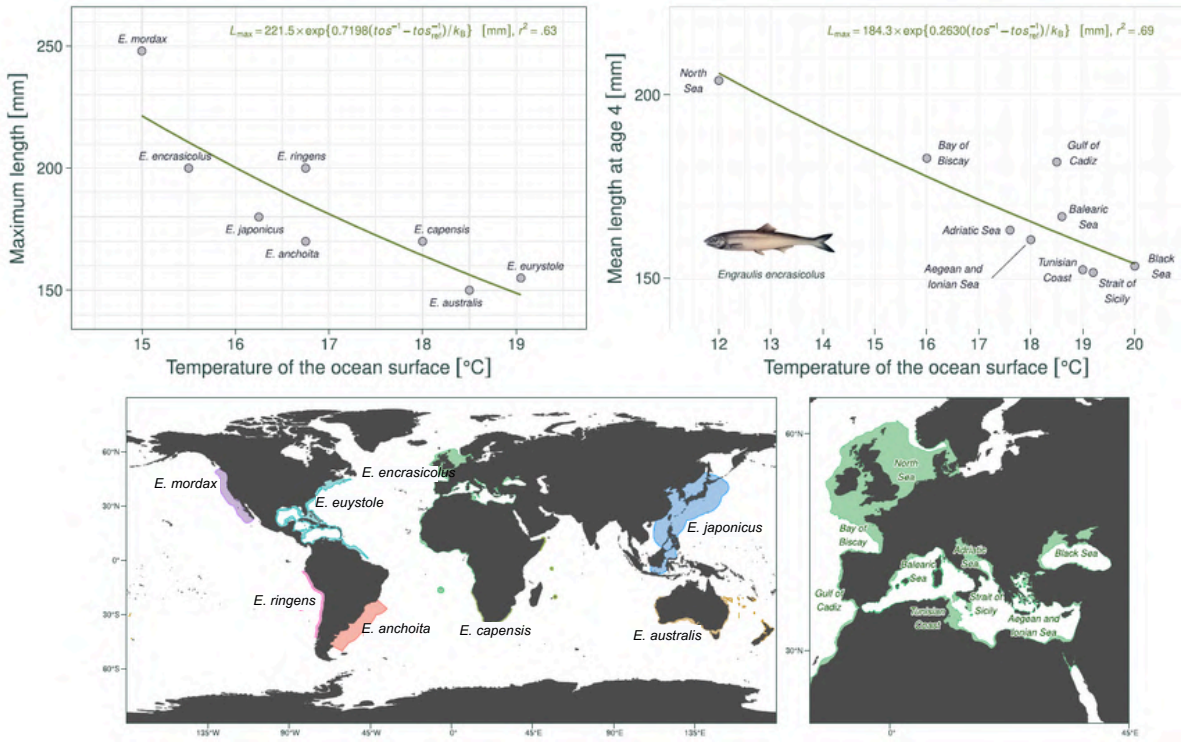


Figure 7.4, Ecogeographical patterns in the variation of anchovy body size with temperature (Taboada et al 2023). Top left: the maximum length of anchovies decreases with temperature. Top right: the mean body size of age 4 individuals from European anchovy also decreases with temperature. Maps: the global map at the bottom left shows the distribution of the species. The detail map on the bottom right shows the approximate location of each of the European populations.

In the second study, a mechanistic model was applied to evaluate the effects of scenarios of climate change and fishing on the body size and productivity of seven tuna species and swordfish (*Xiphias gladius*) (Fig. 7.4). These globally distributed and commercially exploited species are divided into 30 stocks for management purposes. Based on projections from two Earth System Models (IPSL and MEDUSA), Erauskin-Extramiana et al. (2023) reported that these high trophic level species will be more impacted by climate change than by fishing pressure under the assumption that their stocks are maintained near MSY levels. However, no-fishing scenarios projected much higher biomass. The overall productivity of the target species will decrease by 36% and only the Pacific bluefin showed a slight increase in the future.

Four tuna species (*Atlantic bluefin, Thunnus thynnus*), southern bluefin (*T. maccoyii*), bigeye (*T. obesus*), and albacore (*T. alalunga*) and swordfish were projected to decrease in biomass and size at different rates.

These species represent almost a third of the landings in the Atlantic Ocean and 10% in the Pacific Ocean with bluefins the highest-valued tuna species. On average, the body size is expected to decrease up to 15% by 2050.

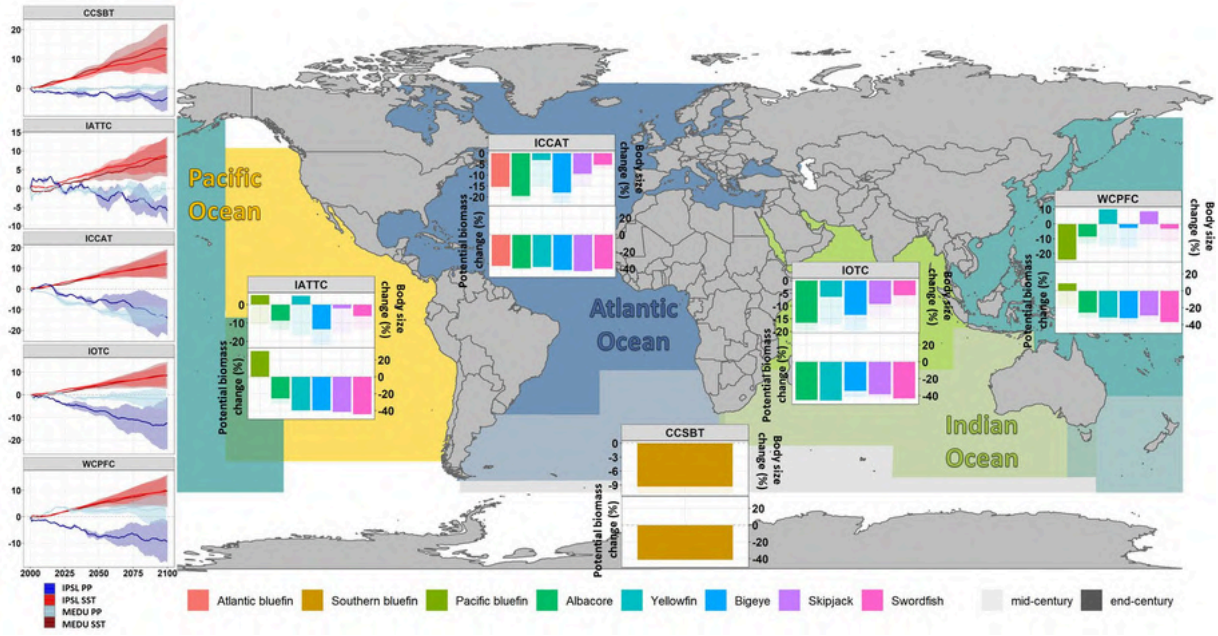


Figure 7.5, Averaged body size ratio (the biomass divided by the abundance, upper box) and biomass (lower box) change (y-axis) in percentage (%) related to the reference period (2000–2010) in bars (x-axis) across scenarios for each RFMO in the world map for main commercial tuna species and swordfish (Erauskin-Extramiana et al. 2023). 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.

Guillem Chust & Jose A. Fernandes-Salvador

Risks and benefits of implementation of Nature-Inclusive Harvesting (NIH)

Sustainable harvesting practices can be useful at lowering the climate risk of species, habitats, ecosystem services or social groups. For instance, ecosystem-based management measures such as the establishment of quotas can help stocks to recover, thus ensuring the existence of traditional fisheries in scenarios where the synergy between climate change and overexploitation could force them to collapse. The degree at which NBS or NIH succeed to lower climate risk to marine systems can be seen as a proxy of their effectiveness. FutureMARES evaluated the risk lowering capacity of NIH for 17 commercial fish and one bivalve across Europe. The method applied relies on climate risk assessments (CRA) that are conducted when NIH is applied vs when it is not (see Box 5.1, and Deliverable Report 5.4).

The analysis collected and interrogated data from 4 different ecoregions in Europe. Interestingly, NIH could lower the climate risk of all the species analyzed, albeit the magnitude of risk reduction varied significantly across species, regions and scenarios (Fig. 7.6).

In particular, the amount of risk lowered due to sustainable harvesting practices was very low for the bivalve species analyzed in the Baltic Sea (*in situ* aquaculture of mussels), but relatively high for the sharks evaluated in Israel (Eastern Mediterranean). In the Western Mediterranean, where small pelagics such as sardine or anchovy were evaluated, the amount of risk lowered was found to be very high, pointing to a clear beneficial effect of NIH on these stocks.

The method also allowed to explore the effect of different socio-ecological scenarios on the effectiveness of NIH. Scenarios considered include Global Sustainability (GS), National Enterprise (NE), and World Markets (WM) over two different time slices: 2040 to 2059, and 2080 to 2099. In this regard, an apparent drop in the effectiveness of NIH is expected both for the NE and WM scenarios in both time slices, specially noticeable in the Eastern Mediterranean Sea (note that the difference between the solid and stripped bars are larger in Fig. 7.6 for the Eastern Mediterranean).

This pattern could be driven by two forces. First, the limited capacity of sustainable harvesting to reduce climate risks in species that are highly impacted (and thus bearing higher risks), that we would expect under the higher emission scenarios.

Second is the socio-political and ecological context linked to future scenarios NE and WM, that can limit NIH effectiveness due to the limitations to sustainable harvesting in regulations and as an incentive for the fishing industry in those futures. Hence, scenarios of higher emissions, with exacerbated globalization and/or exploitation of national natural resources, could lead fishers to increase exploitation levels while climate change effects exacerbate. In such scenario, NIH might see its effectiveness lowered due both lowered quality and accessibility of the stocks, and increased social pressure.

There was no relationship between the level of risk of the species evaluated and the amount of risk lowered thanks to the application of NIH, meaning that NIH could potentially benefit organisms across the entire range of risks evaluated. This is because NIH entails benefits for the functioning of the entire ecosystem through the management of key species.

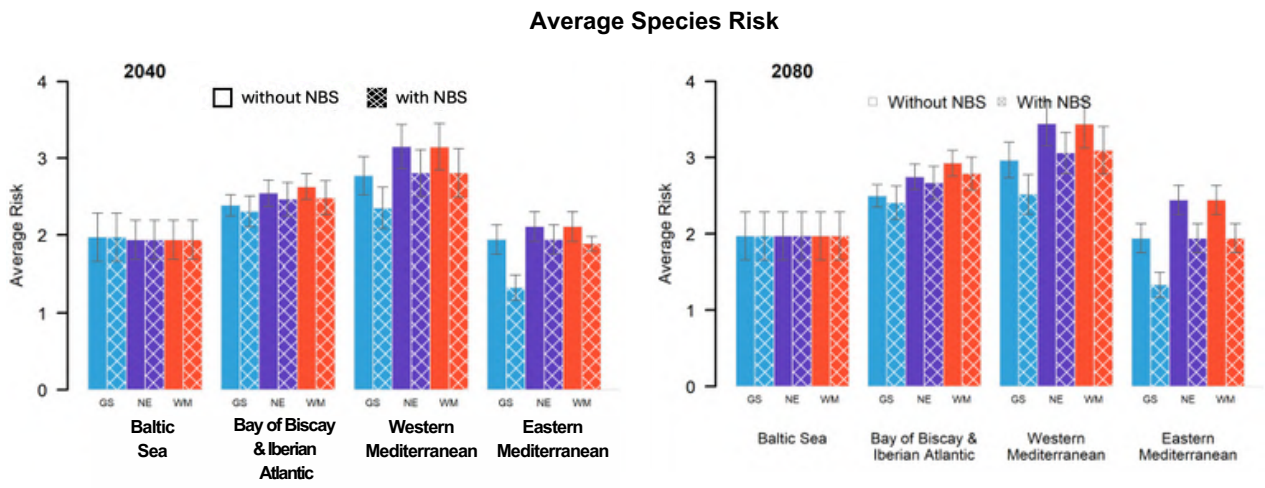


Figure 7.6, Average risk estimates for species considering three PESTLE scenarios (GS: global sustainability; NE: national enterprise; WM: world markets), and two time slices: 2040 (left), and 2080 (right). (Deliverable Report 5.4).

Nature-inclusive Harvesting frequently occurs alongside NBS due to their synergistic relationship. By integrating NIH into NBS interventions, stakeholders can promote both environmental conservation and sustainable livelihoods. This strategic alignment also enhances the resilience of ecosystems and communities to environmental changes, fosters stakeholder engagement, and supports policy objectives related to biodiversity conservation and socio-economic development. Overall, the integration of NIH with NBS reflects a holistic approach to environmental management that recognizes the interconnectedness of ecosystems and human well-being, ultimately contributing to more resilient and sustainable societies.

The economic implications of NIH initiatives are multifaceted (Deliverable Report 6.2). Not only do NIH initiatives contribute to the sustainable development of fisheries (including small-scale fisheries) and food security, but NIH initiatives also contribute to many non-tangible benefits, such as Cultural Ecosystem Services (CES). CES can be quantified by the bequest value of the service, that is the importance people place on preserving for future generations the cultural aspects of small-scale fisheries. The cultural aspects can include the non-material benefits people get from observing the natural capital (including fish species, sea view and in general, coastal area view) together with the port landscapes where the small vessels are located, the use of traditional gears, or the large number of additional events related to this activity across Europe coastal areas (a valuation of these is provided by Storyline 24 covering small-scale fisheries in the Bay of Biscay). The evaluation of ecosystem services is also applicable to other resources beyond coastal fish and fisheries. For instance, mesopelagic fish stocks provide regulating services, including carbon sequestration, for which a monetary valuation has been estimated (Prellezo et al. 2024).

Significant willingness to pay (WTP per household over a long period between 5 and 10 years) to protect CES is documented for small-scale fisheries in the Bay of Biscay (Storyline 24), using a non-market-based valuation as a proxy of the CES Economic value attributed to small-scale fisheries. So, a full valuation of the impact of actions to support NIH should consider both provisioning and CES valuation. FutureMARES identified indicators (ecological indicators but also social and economic indicators) to assess the full range of potential ecosystem services (Murillas et. al. 2023).

Such a ‘full valuation’ assessment represents a direct estimation of the effects of NIH. However, NIH initiatives also produce relevant indirect economic impacts on coastal economies (through the coastal and other terrestrial economic sectors and activities related or connected) that are usually missing in assessments of services. A general Input-Output model analysis (that serves as a quantitative economic framework for understanding the interdependencies between different sectors of a national economy or between regional economies) revealed significant indirect impacts across various economic sectors (more than 40 economic activities in the Basque region), with recreational and cultural activities being greatly affected due to the nature of the cultural ecosystem services assessed (Fig. 7.7). The Input – Output model categorized these impacts into three types: direct impacts within the economy, indirect impacts from the consumption of intermediate goods, and induced impacts from the re-spending of incomes by industry employees and suppliers.

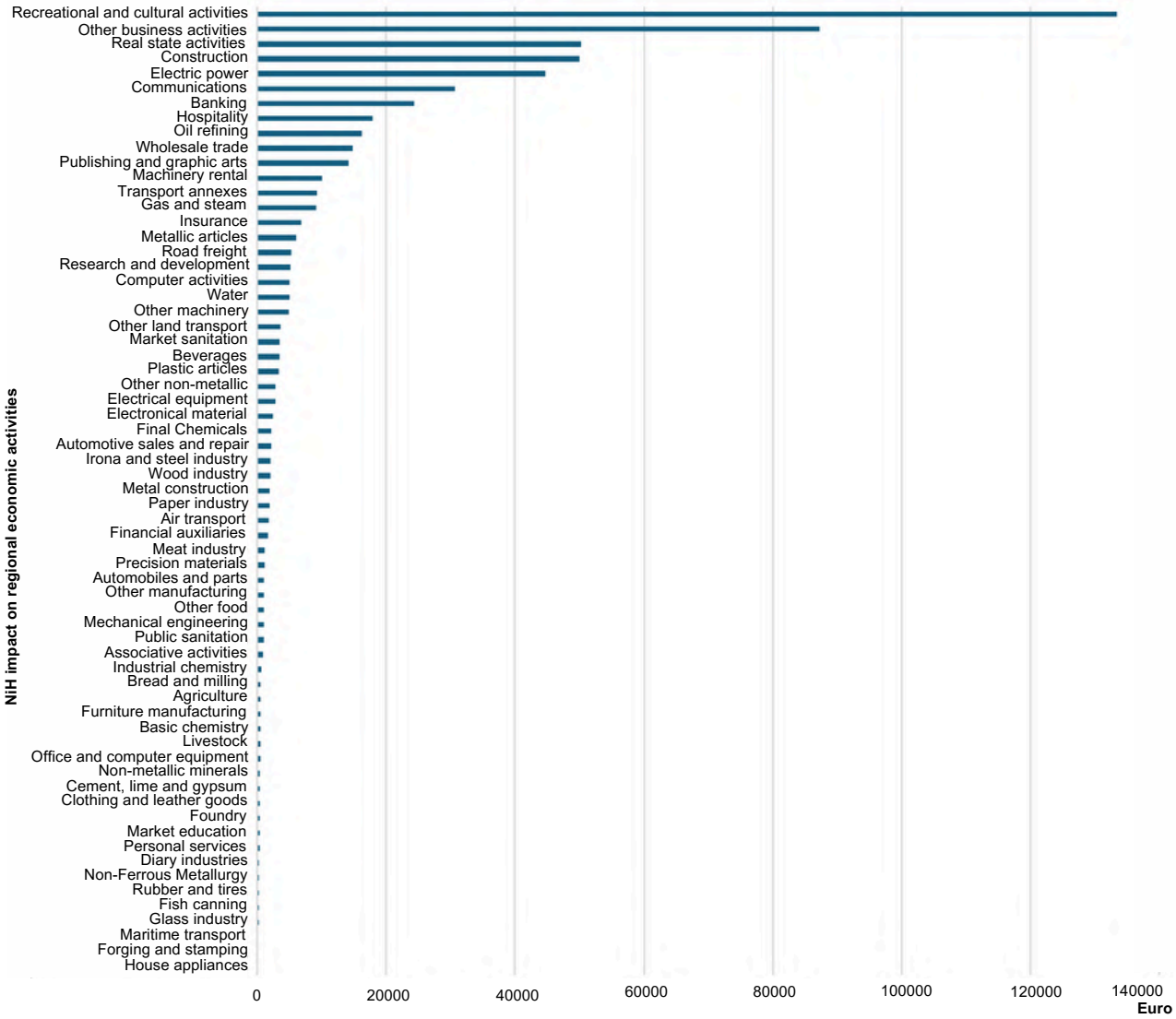


Figure 7.7, Nature Inclusive Harvesting in the Bay of Biscay: indirect effects (euro) on coastal economies across economic sectors from very high impacted to no impacted sectors because of the direct NIH estimated CES value (euro) (b). (Deliverable Report 6.2)

The dispersion for each category of CES considered, from 'immovable tangible heritage' to other social practices is shown in Figure 7.8. Dispersion means the number of economic activities and sectors impacted when adopting NIH initiatives, which have an important impact in terms of the monetary valuation of the CES associated to the small-scale fisheries. Although the 'immovable tangible CES' has the lowest impact on activities in relative terms, each CES is important enough and therefore, not only food provisioning but also all CES should be considered in a full valuation assessment across economic sectors of the regional economy.

In general, previous results emphasize the importance of a comprehensive valuation approach, which considers broader CES values beyond traditional fish food provisioning (Murillas-Maza 2024). Such an approach provides policymakers with science-based evidence on the economic benefits of NIH initiatives. Overall, the economic implications of NIH initiatives underscore the significant contributions actions can make to deliver sustainable economic development and the preservation of cultural and natural resources.

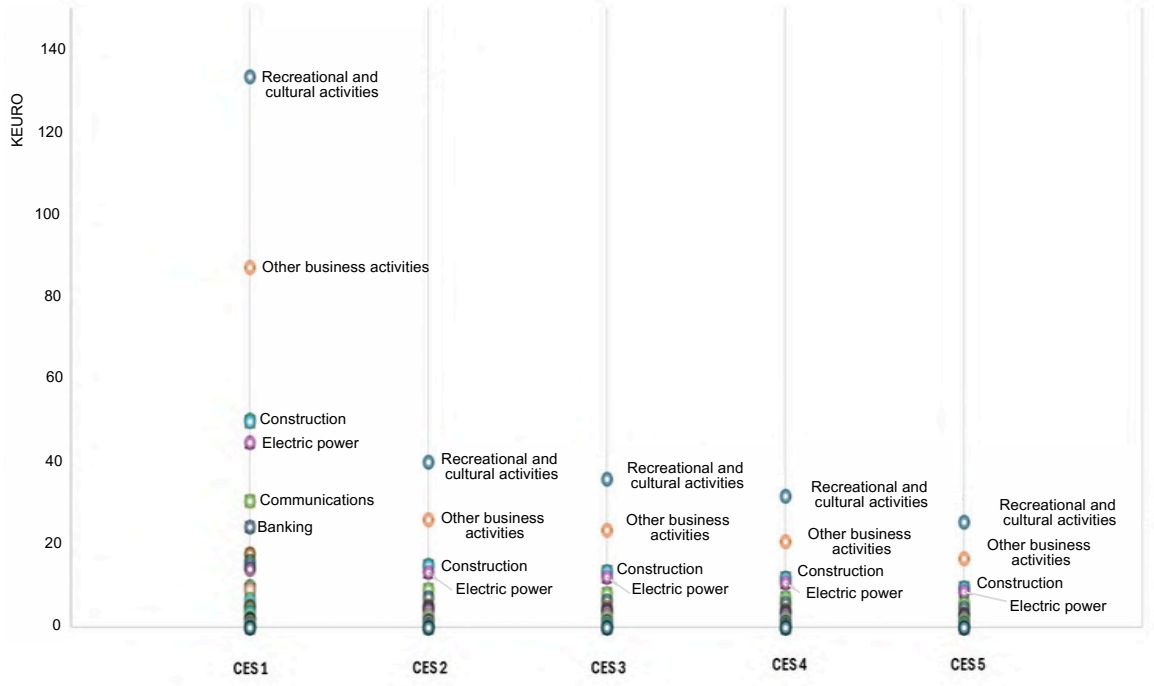


Figure 7.8, Dispersion across economic sectors of the induced effects per Cultural Ecosystem Services (CES) in the Bay of Biscay Storyline 24. CES1= All ES, CES2 = Nature and port landscape, CES3 = Gastronomy and food, CES4 = Social Practice, Ritual and festive events and, CES5 = Immovable tangible cultural heritage. (Deliverable Report 6.2).

For tactical management (short- to medium-term advice) and economic assessment of fisheries, multi-stock fisheries models can complement current advice from single-stock models and provide more detailed information on fishing fleet behavior than ecosystem models. For example, a spatially explicit bio-economic simulation and optimization model FishRent was applied for the North Sea (Deliverable Report 6.2). The model included five modules: a management module including FMSY and Total Allowable Catches, a biological module including stock-recruitment relationships, an interface module linking stocks to fleets, an economic module, and an investment module. It was used to investigate changes in the North Sea stocks of Atlantic cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*) and saithe, and three commercial fishing fleets (UK, Germany and Norway). Fuel prices, fish prices, fuel efficiency, and exploitation rates were altered in the scenarios reflecting the Shared-Socio-economic Pathways and available of fishing opportunities given spatial squeeze through the implementation of MPAs and restrictions at offshore wind farms (OWF). No fishing was allowed at OWFs in the Global Sustainability scenario, whereas fishing was allowed in 50% of OWF areas in the World Markets and National Enterprise scenarios.

Results indicated that addressing environmental pressures in the North Sea, particularly in demersal fisheries affected by climate change, spatial regulations, and economic factors, requires sustainable management and international cooperation. Fisheries are affected by spatial regulations leading to increased operation costs (Simons et al. 2015).

In particular, the demersal fisheries are important to the North Sea as they make a significant contribution to the overall fishing revenues (STECF 2023). However, this sector faces reduced fishing opportunities due to climate-induced stock shifts and increased competition for space with other interest groups. In SL12-14, Marine Protected Areas (MPAs) in combination with NIH

were projected to stabilize fisheries profits. However, profit trajectories varied among fleets and scenarios. While notable increases were projected in some scenarios for the German fleet, the Norwegian fleet was projected to experience dips in the 2030s across all scenarios, yet profits increased afterwards. The UK fleet displays high variability, underscoring the need to consider regional specifics in fisheries management (Fig. 7.9). Spatial dynamics of effort concentration and change in fishing strategies further highlight the intricate interplay between economic pressures, environmental factors, and regulatory frameworks in managing fisheries.

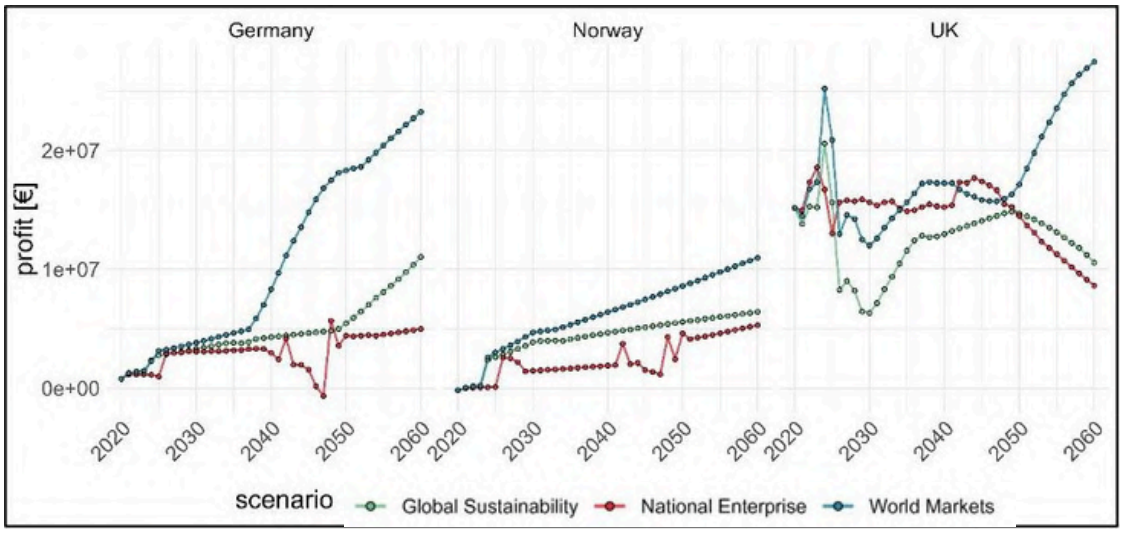


Figure 7.9, Profitability timeline of the respective fleet in the FishRent model under the three scenarios, with combined EMP and MSP effects. Net profits are depicted in €; the colors of the dots and lines indicate the applied scenario. The plot title indicates the modelled fleet. (Deliverable Report 6.2).

In all scenarios, total profits by the fishing fleets combined exhibit a consistent increase to 2040, with an increasing trend overall. However, in the World Markets scenario total profits more than tripled, initially due to the rapid increase in the German fleet between 2040 and 2050, followed by a later rapid increase in the UK fleet post 2050. In contrast, National Enterprise had the most modest rise in profits in the long term, specifically due to a long-term decrease in the UK fleet. Omitting spatial management measures reduced the variability of annual profits, while scenarios including only spatial management but no socioeconomic or harvest control projections showed little difference from the baseline scenario. This highlights the dependence of fleets on price dynamics and fisheries regulations. Furthermore, it is an indication that increased protection and offshore industry will lead to effort shifts rather than fishing ground losses. Over time and in each scenario, the model demonstrated a gradual redistribution of fishing effort north-eastward in areas of the North Sea with high catchabilities of the target species (cod, haddock, saithe) and short steaming distances to the fleet segments' home ports. For the UK fleet specifically, landings over time are shown to become more dominated by haddock in each scenario, as this species had high catchabilities in proximity to the fleet's operational port.

Decreases in spawning stock biomass of cod and haddock were most pronounced in the National Enterprise scenario. However, decreases in haddock were apparent in all three scenarios after a rapid increase in the first decade simulated. The cod stock reached a critical

near-collapse situation by 2050 (Fig. 7.10). However, in Global Sustainability, each of the three species was found to increase in biomass by 2050 and the scenario proved the best for each species.

For saithe, however, there was a strong modelled increase in biomass in the National Enterprise scenario post 2055 to the greatest levels simulated across the three scenarios. Yet, this development was not attributable to sustainable harvesting strategies but rather to economic pressures, as harvesting of this stock became unprofitable for a part of the modelled fleets due to increasing steaming costs.

Overall, the model suggested possible synergies between conservation measures (MPAs) and NIH. For instance, in Global Sustainability, the three fleets studied are profitable in the future; the stocks are in healthy states and protection goals are met.

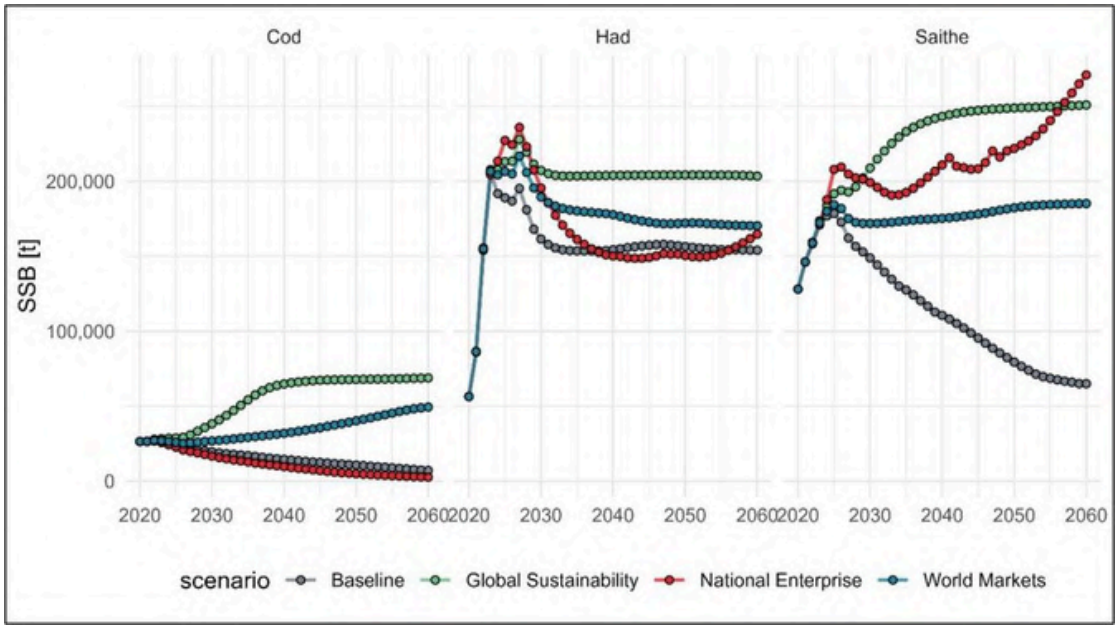


Figure 7.10, Timeline of the spawning stock biomass of the three modelled species in the FishRent model, given in tons. The colors of the dots and lines indicate the scenarios. (Deliverable Report 6.2).

Conclusions and policy recommendations

1) NIH strategies decreased the climate risk of all the species analyzed, although the magnitude of risk reduction significantly varied across species and regions. Overall, risk levels were most greatly reduced in the Global Sustainability scenario characterized by lower greenhouse gas emissions.

2) Marine ecosystem modelling in FutureMARES projected clear benefits of sustainable management interventions but showed different outcomes to their climate-change analogues. Results depended on regional features and the historical development of fisheries. These modelling tools enable identifying synergies and trade-offs resulting from combinations of

habitat restoration, conservation, and sustainable fishing interventions. In general, conservation measures were more effective in the Global Sustainability scenario (SSP1-2.6) in which climate changes followed a lower emissions projection and fishing efforts were reduced.

3) There remains a high level of uncertainty about how the efficiency of these measures will be modified by climate change, and to what extent the adaptive capacity of ecosystems to climate change can be improved through the reduction of human impacts while maintaining seafood production. Further work is needed to explore the sensitivity of the new spatio-temporal ecosystem models developed by FutureMARES to projections of climate change including uncertainty analyses.

4) The multi-stock multi-fleet fishery model (FishRent) suggested possible synergies between conservation (MPAs) and NIH in the North Sea. For instance, in the GS scenario, fleets were profitable in the future, the stocks are in healthy states; protection goals are met. The provision of fish protein, even though it comprises a relatively small fraction of protein in the typical diet of the region (FAO 2022), is a central ecosystem service of fisheries and the model projections (both FishRent and EwE) demonstrate how this is not precluded but rather supported by the implementation of NBS.

5) Greater emphasis on cultivation at sea rather than wild catch (fisheries) is expected in the future in many systems. In the North Sea, plans for extensive, 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) have the potential to exceed levels of ecological carrying capacity or production carrying capacity. This aspect requires further evaluation including bioeconomic assessment.

6) Strong responses of physical water properties and water quality to climate change was projected for the Danish Limfjord system that partly counteracted the planned nutrient reductions from land. Larger nutrient reductions in the coming Water Plans would be needed to reach a good ecological status under the influence of climate change. So, work is needed to assess what measures need to be taken to safeguard the ecological status. Bottom-cultivation of mussels in this area is not climate proof, and it has a much more negative impact on the environment compared to hanging cultures. In the coming decades, switching from bottom-based to pelagic cultures will benefit both the industry as well as the environment.

7) For the North Sea, the levels of upscaling of mariculture applied within scenarios were well below current industry targets. Policy measures will need to limit the upscaling of the industry to 'acceptable levels of impact'. Defining what is 'acceptable' and how this is put into legislation should be addressed as soon as possible. The Marine Strategy Framework Directive offers some guidance for this, although the background for the nutrient, chlorophyll and primary production targets has its background in eutrophication policies (OSPAR 2023). Limits for extraction of resources (nutrients and chlorophyll) are not well defined. Also, in an open, well connected international water body, it will be challenging to establish appropriate and effective legislation. Nevertheless, despite expected increases in food production from aquaculture, fish harvested from the sea are likely to remain part of the food production system in future.

Future MARES

CHAPTER 8

EXAMINING SYNERGIES AND TRADE-OFFS IN NATURE-BASED SOLUTIONS AND OTHER ACTIONS WITH DECISION SUPPORT TOOLS

AUTHORS: JOSE A. FERNANDES-SALVADOR, ANA QUEIRÓS, MARTA COLL, ASIER ANABITARTE, FRANCISCO ARENAS, FABIO BULLERI, WENTING CHEN, ANTONIO DI CINTIO, MARINA DOLBETH, IGOR GRANADO, GOTZON MANDIOLA, RIIKKA PUNTILA-DODD, MYRON A. PECK

08 Examining synergies and trade-offs in Nature-based Solutions and other actions with decision support tools

Introduction

Socio-ecological systems are complex and interconnected, and actions taken to address one aspect of ecosystem health or management may have unintended consequences or impacts on other components. Trade-offs can arise between different species within an ecosystem, between different objectives (such as conservation and exploitation objectives), within or between economic sectors (such as between different fishing fleets or sectors such as fishing and tourism) or between short-term benefits and long-term sustainability. Trade-offs can also occur between ecosystem services, such as balancing the provisioning of food resources with the maintenance of habitat quality or cultural values. Acknowledging, understanding and quantifying these trade-offs is essential for making informed decisions in marine management and conservation, as they help identify the most effective strategies that minimize negative impacts while maximizing overall benefits. FutureMARES was designed to explore the synergies and potential trade-offs among marine habitat restoration, marine conservation actions such as MPAs, and sustainable seafood harvesting. There are myriad other sectors and activities that compete for space and resources in marine and transitional waters and tools are needed to inform end-users charged with the stewardship of marine natural capital.

Decision-support tools (DSTs) synthesize complex information to assist environmental managers in taking decision and planning actions / interventions. DSTs can be defined very broadly to include any tool that condenses complex information into an understandable format to be applied in decision-making (Sullivan 2004) including: i) quantitative assessment tools, ii) model-based management tools, or iii) operational systems linked to databases. Within the Baltic Sea, for example, 42 DSTs were identified and evaluated by Nygård et al. (2020). Building on existing frameworks, FutureMARES advanced the operational use of three DSTs: 1) spatially-explicit ecosystem modeling (Fu et al. 2018, Steenbeek et al. 2020, de Mutsert et al. 2023), 2) climate-smart marine spatial planning using the Bright Spots Framework (Queirós et al. 2021), and 3) Bayesian network analysis (Uusitalo et al. 2022). These tools integrated new ecological knowledge and projections produced by FutureMARES and knowledge from stakeholders and end users to explore how Nature-based Solutions and sustainable seafood harvesting practices could be used as interventions to combat the biodiversity x climate crises. This chapter provides examples of each of these three DSTs and the main findings within several Storylines.

Research within FutureMARES

Ecosystem effects of Nature-based Solutions

Spatially-explicit ecosystem models were used to run contrasting climate and management scenarios. Implementations of management interventions under different Nature-based Solutions (NBSs) and Nature-inclusive Harvesting (NIH) options included protection, restoration

and ecosystem-based management of fisheries, and considered stakeholders contrasting views, regional contexts, current legislations and future developments of the legal frameworks. For each scenario, the spatial-temporal impacts of climate change and human activities on key commercial and vulnerable species, spanning different trophic levels of the marine food web, were assessed. Important scenario-specific changes were projected in ecosystem structure and functioning, with food web impacts such as trophic cascades and changes in species diversity due to lower rates of predation. In this context, several trade-offs and synergies relevant to fisheries were identified. For example, Baltic Sea cod (*Gadus morhua*) was projected to increase in the GS scenario but catches of cod and herring (*Clupea harengus*) decreased and sprat (*Sprattus sprattus*) biomass and catches increased in the NE and WM scenarios. In the Western Mediterranean, increases in fish biomass and decreases in invertebrate biomass were projected in the GS scenario associated with food web effects. In the Northwestern Mediterranean, an important and substantial decrease was projected in red shrimp (*Aristeus antennatus*), Norway lobster (*Nephrops norvegicus*) and mullet (*Mullus spp*) catches under GS (Fig 8.1).

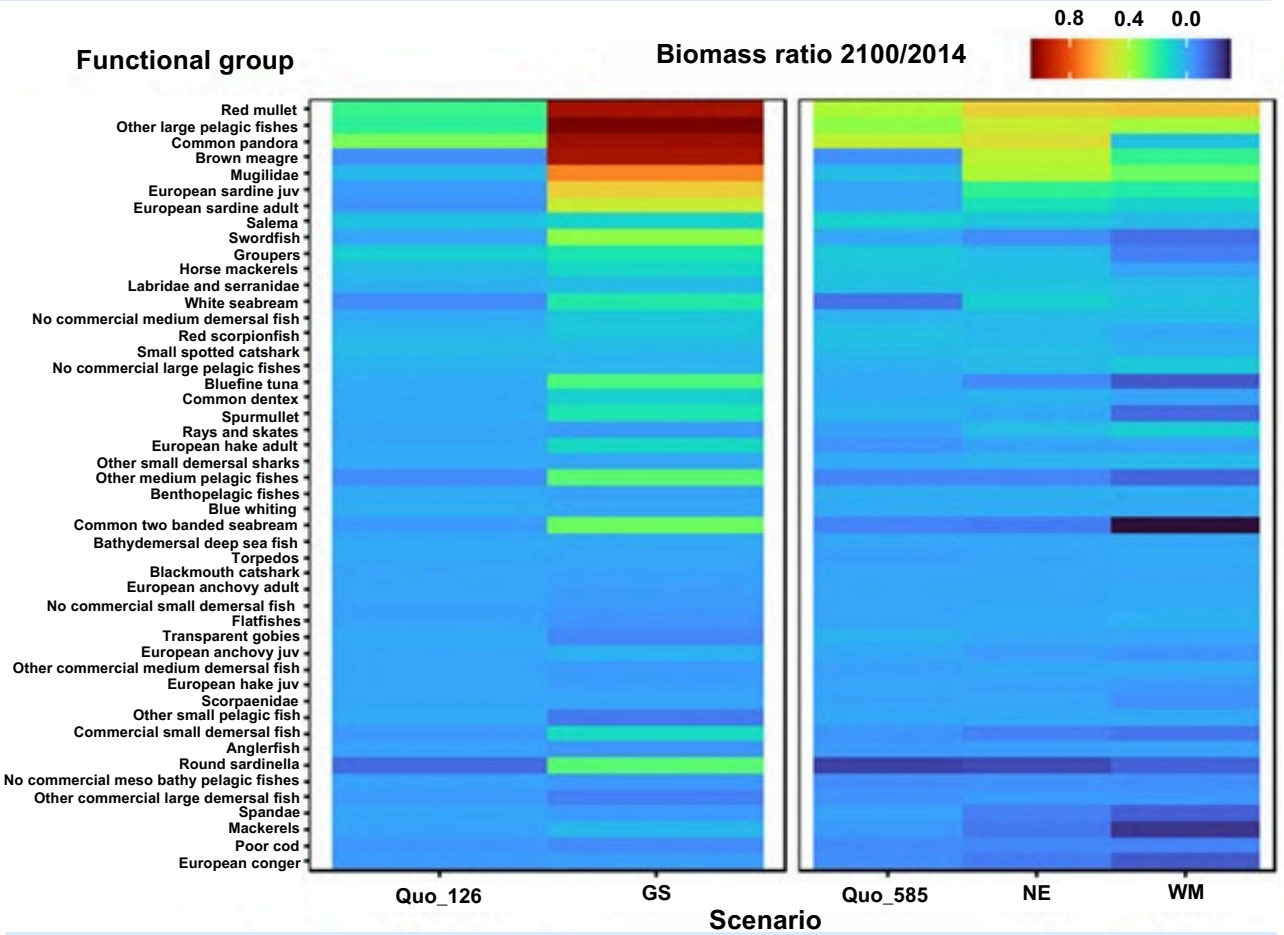


Figure 8.1, Changes projected by marine ecosystem models between contrasting scenarios of FutureMARES. The image shows the overall changes of biomass ratio projected for different fish groups included in the NW Western Mediterranean Sea model between 2100 in comparison to 2024 and identifies clear winners and losers among scenarios. Detailed results are available in Coll et al., 2024 (Deliverable Report 4.4.).

These declines, due to recovery of predators and increases in competition with other organisms, highlighted a potential significant economic impact on bottom trawling fleets activity. In the North Sea, losses of biomass of key commercial species threatened by climate change (i.e., cod, sprat, and herring) could be mediated by the provision of refugia through MPAs in the GS

scenario, but not in higher emissions scenarios where losses in unprotected areas were much larger. A key trade-off in the GS scenario was the reduction in catch of commercial species in order to protect conservation species (marine mammals, seabirds and large sharks). The resultant increase in predatory species, in combination with the impact of CC, caused higher predation pressure on species at low trophic levels in the food web (such as Norway pout, blue whiting and Norway lobster).

Ecological indicators of Good Environmental Status that integrated multiple species and fisheries were calculated from model outputs (Fig. 8.2) and integrated biomass-based, trophic-based and catch-based indicators. This illustrates the richness in model output (beyond that for single species) available to end users from these spatially-explicit ecosystem models.

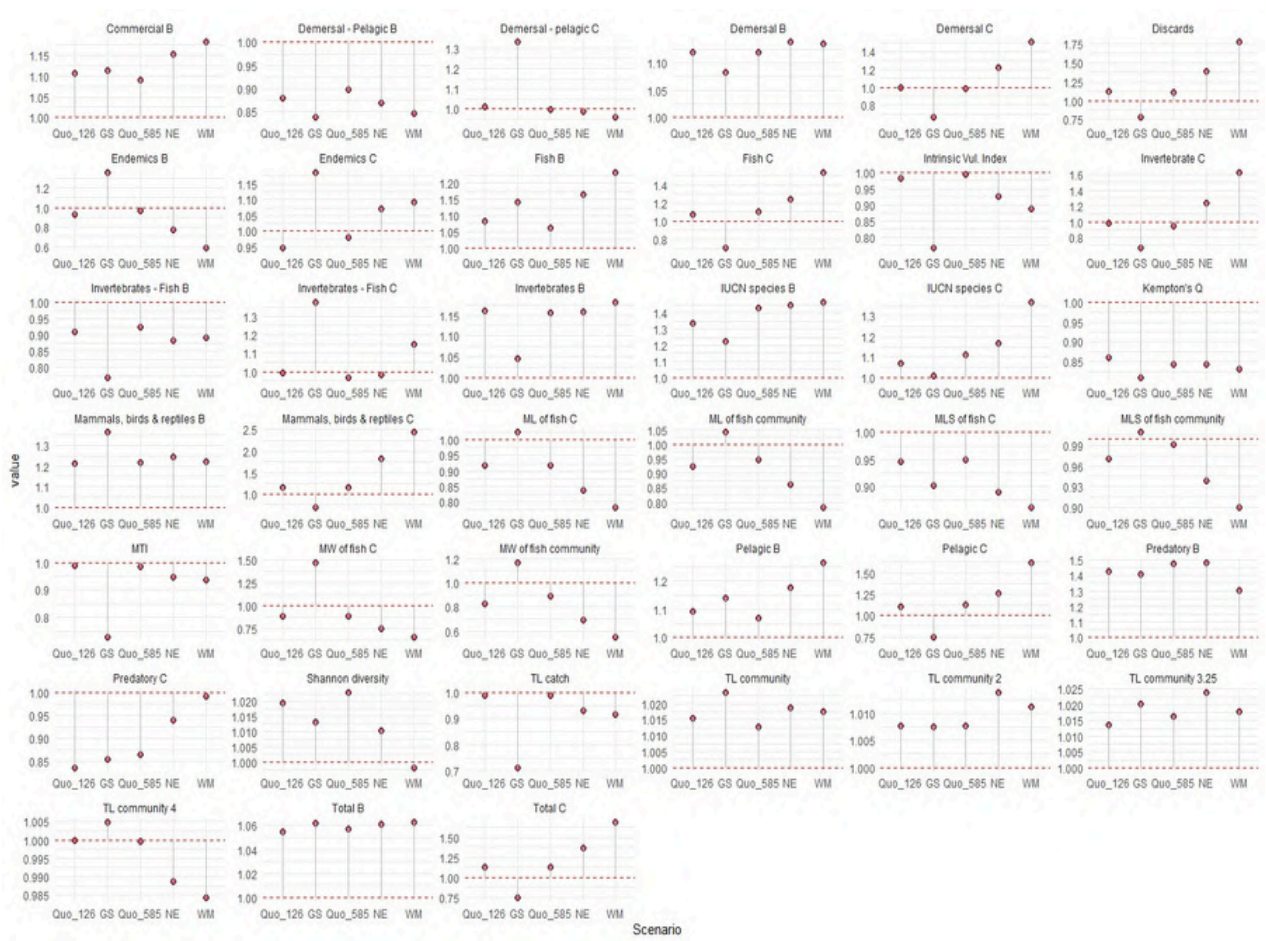


Figure 8.2, Ecological indicators showing change between 2100 and the reference period 2020 for the NW Mediterranean Sea and scenarios (the 3 FutureMARES scenarios GS=Global Sustainability, NE=National Enterprise, WM=World Markets) plus two relevant Status-Quo scenarios using RCP2.6 (also used in GS) or RCP8.5 climate projections (also used within NE and WM) without the implementation of management. Detailed results are available in Coll et al., 2024 (Deliverable Report 4.4.).

Results suggested that NBS (e.g., restoration of habitat forming species and protection of key areas, nutrient loading reduction, and reaching conservation targets regarding MPAs - 30%), together with NIH actions (e.g., reduction of fishing effort, discards and bycatch) may play a vital role in mitigating the impact of climate change in the future. A clear positive, scenario-specific result was that the Shannon diversity index (calculated between 2100 and the reference period 2020) was highest in the GS Scenario and also when contrasted to the relevant status-quo

scenario (no management change) at the same, low greenhouse gas emission scenario (RCP2.6). This was evident from model runs conducted in the North Sea (SL 12-14), Bay of Biscay (SL 20, 22, 24), Portuguese Coast (SL 21 & 23), NW Mediterranean (SL 25) and Western Mediterranean Sea (SL 30, 31, 33). Beyond increases in Shannon diversity, several other positive outcomes were projected in the GS (low emissions) scenario. These positive outcomes include the rebuilding of Atlantic cod stocks as well as other commercially important fish species in the Baltic (SL 8) and the North Sea (SL14), the recovery of habitat forming species such as corals, mussels and kelp in the Bay of Biscay, the Baltic Sea, the Portuguese shelf and the Western Mediterranean, or the rebuilding of Mediterranean seagrass, small pelagic fish and predators in the Mediterranean Sea. Furthermore, indicators of ecosystem degradation, such as the increase of gelatinous zooplankton and of cyanobacteria, were predicted to stabilize or decline under GS conditions. Under the National Enterprise and World Markets scenarios, declines of several commercial and conservation important species were projected. These declines were associated with important changes in ecosystem structure and functioning, and the occurrence of ecological changes in the food web, with trophic cascades and predation release effects in a diversity of species.

Climate-smart Marine Spatial Planning and NBS: Bright Spots Framework

It is widely accepted that, to be effective in a changing ocean, protected areas, restoration programmes and harvesting activities (e.g., wild capture fisheries and aquaculture) need to be planned and managed to consider climate-driven shifts in species and habitat distributions (Gaines et al. 2010). Recent peer-reviewed research has highlighted how the sensitivity of European waters to these and other climate change driven pressures varies over space and time, and this, in turn, depends on the magnitude of increased future greenhouse gas emissions we come to experience (Queirós et al. 2021).

Spatially-explicit numerical modelling tools developed in FutureMARES and presented in the previous section, allow for the simulation of the potential impacts of climate change on the coastal and marine environment, its species and habitats, over space and time, in parallel to other human impacts such as fishing mortality. Climate-signal detection, in turn, can help objectively understand the strength of those potential changes relative to the natural dynamics of these ecosystems (Hawkins & Sutton 2012). This approach, focused on detecting the time of emergence of a climate signal (when a system attribute, for instance temperature, is driven by climate beyond that range and into a new state – see Chapter 3) is broadly used by the IPCC to help understand how different areas of the ocean vary in sensitivity to climate change (IPCC 2019). When applied at the ecosystem level, this approach can also be used to help inform on marine spatial planning, by helping establish where human interventions (those focused on conservation, as well as those focused on resource harvesting) may be less affected by climate change (i.e. climate change refugia and bright spots) as well as where they will be most affected (i.e. climate change hotspots) (Queirós et al. 2021). That evidence can, in turn, be used to help design climate-smart conservation strategies and the spatial management of fisheries and aquaculture. That is, MPA, restoration and harvesting spatial strategies that take into account the ecosystem components, species, and habitats that these activities depend on, may be

changing (and indeed, re-distributing) under climate change (Queiros et al. 2023).
Using climate-signal detection, analyses were conducted to inform on how NBS explored within the FutureMARES Storylines could become climate-smart, i.e., by taking into account how climate change will affect ecosystems underpinning those specific interventions (i.e, conservation and restoration actions). The work addresses two research questions:
1) Will the current spatial distribution of NBS explored within the FutureMARES Storylines be effective in the coming decades, given the projected effects of climate change in the underpinning species and habitats?;
2) What other areas could be used within those regions to support those NBS, to improve the resilience of those regions and activities to climate change?

To answer these two research questions and provide specific advice for management, the framework developed by Queiros et al. (2021, 2023, i.e. the Bright Spots Framework, Fig 8.3) was applied for ecosystem level climate-signal detection through spatial meta-analysis of ocean modelling time-series, including physical-biogeochemical modelling, species distribution modelling, and food web modelling. The framework is a co-developed approach, and involves working with the end-user of the evidence (typically a government agency, an NGO, a marine industry body). The framework is highly flexible, and can be used in a variety of contexts, covering a range of geographical scales, end-user applications, and ecological complexity (Fig. 8.3).

First, end-users are engaged to define the specific question to be addressed around a specific policy instrument or marine activity sector for which climate-smart evidence is required (e.g., MPA siting, the effectiveness of a given restoration programme into the future, potential conflicts with the fishing or renewable sector, MSP).

The framework was applied by FutureMARES across 13 Storylines including those in the Western Mediterranean (SL 30, 31, 33), North Sea (SL12, 13, 14), the Portuguese coast (SL 21&23), for migratory estuarine opportunistic fish in the North Atlantic (SL 16, 17) and fish assemblages dependent on vegetated habitats in the Balearic Islands (SL 25), the Tuscan Archipelago (SL 28) and Finnish Archipelago Sea (SL 7 as well as within the Call for Knowledge Needs). In the latter, Fair Seas (an NGO coalition in Ireland) sought specifically to determine whether proposed areas for the expansion of the Irish MPA Network are climate-resilient (Queiros et al. 2024, Fig. 8.3). End-user engagement captured further information on the key species and habitats, marine activity sectors, and the temporal and spatial scales of most interest. This information drove the selection of modelling dataset (Fig. 8.3 step 1) and GIS data on specific marine activity sectors (Fig. 8.3 step 2, e.g., fishing effort distribution, MPA network, spatial data on renewable energy licenses), and helped define the most useful format in which to provide the climate-smart advice (Fig 8.3 step 3; e.g., maps, summary for policy makers, technical reports, infographics, GIS data). The latter is greatly shaped by the profile of the end-user and their previous experience accessing and using climate change evidence, as well as their specific application/policy mechanisms.

A second example of how the Bright Spots Framework was applied in FutureMARES comes from SL 25 examining local-scale restoration of seagrass and associated fish communities (Fig. 8.4, analysing food web modelling datasets described in Coll et al all. 2024).

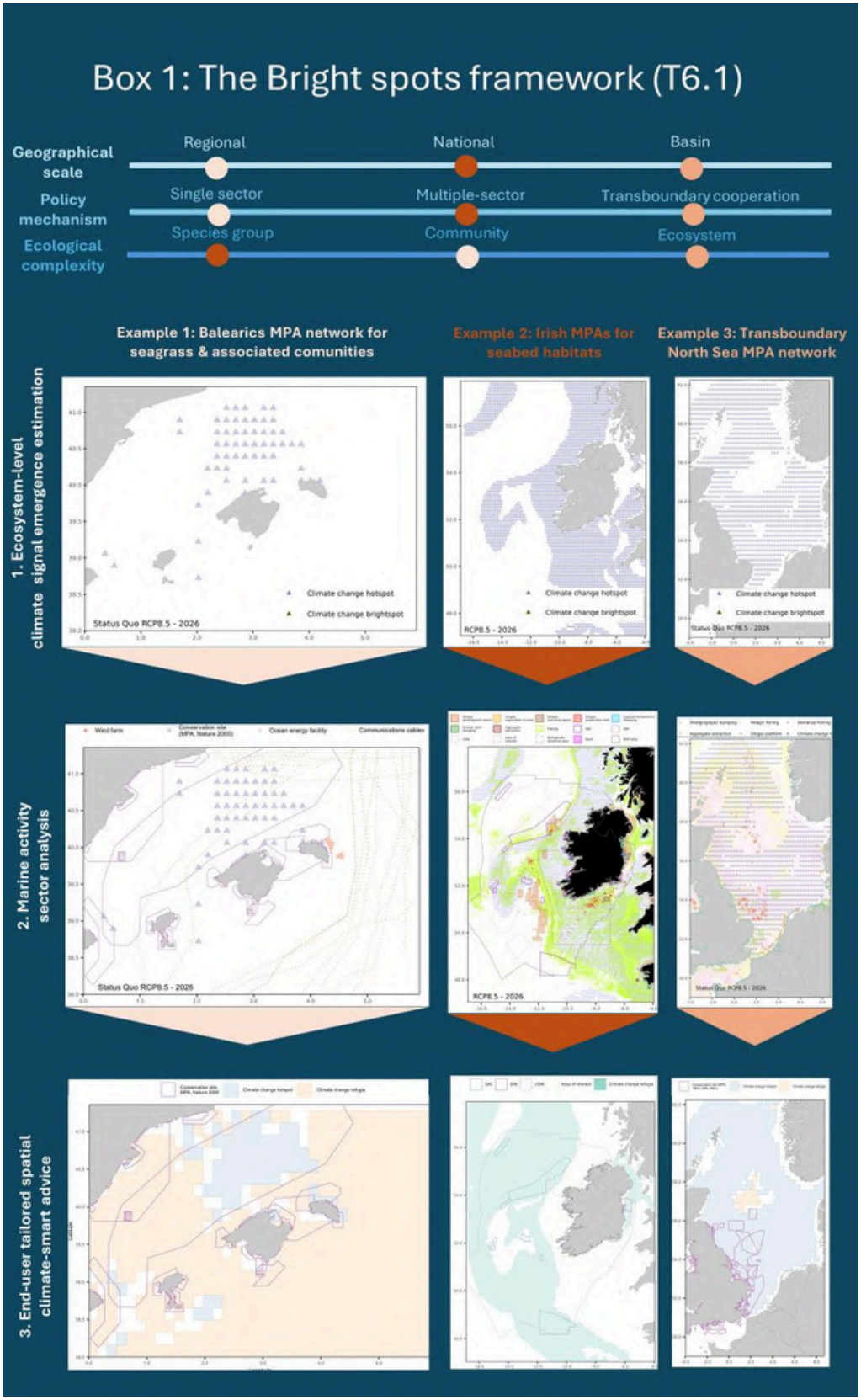


Figure 8.3, Workflow steps of the Bright Spots Framework, highlighting how climate-smart advice provided by the project to end-users (step 2) summarizes complex, ecosystem-level climate change modeling evidence (step 1). Step 2 is used as the basis of recommendations made on how climate change refugia identified (step 3) could be used to support climate change adaptation of marine life and associated marine activity sectors. Three examples are used: left - Balearic Islands (SL 25), middle – Ireland (Call for Knowledge), right – North Sea (SL12,13,14).

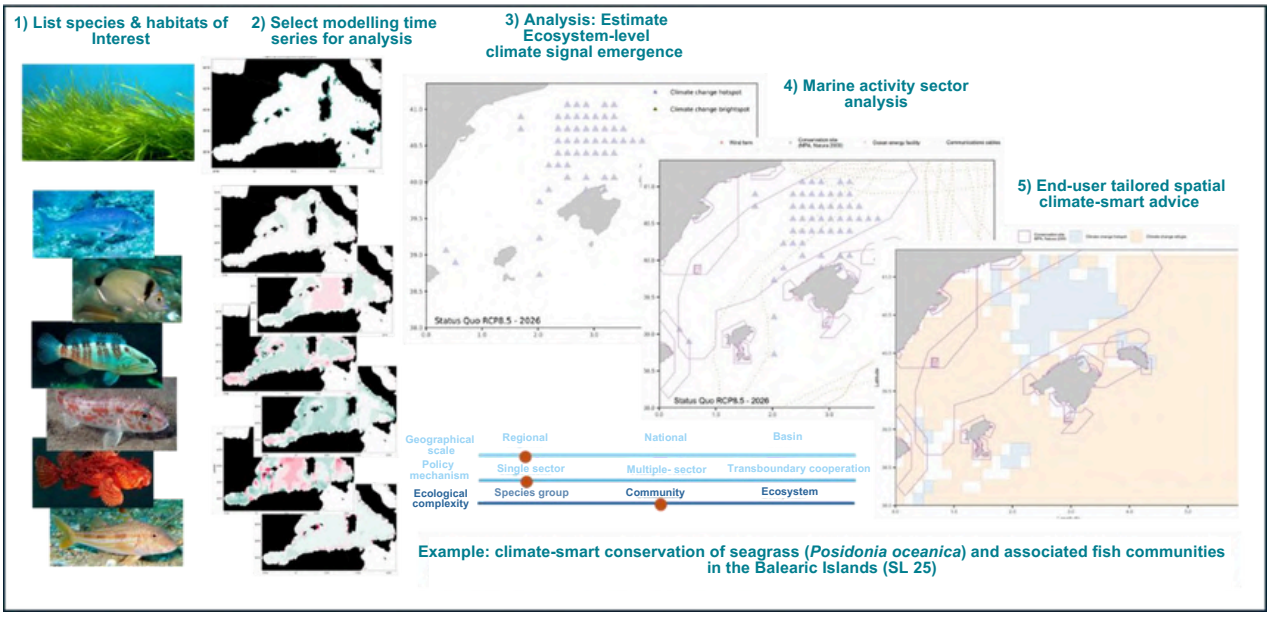


Figure 8.4, Spatial meta-analysis of T4.4 Ecosim with Ecopath projections for the Balearic Islands (SL25), focused on the conservation of seagrass habitats, and associated fish communities. a) Status quo (no management intervention) under RCP2.6; c) Status quo under RCP8.5. Purple triangles indicate the emergence of the climate signal, with the year (bottom left corner of plots) indicating the first year of a twenty year period when the signal emerges, relative to the reference period (2006-2025). Golden triangles indicate the location of bright spots. White background areas indicate climate change refugia, where the whole ecosystem remains within the boundary of present-day (2006-2025) variability.

Interactive Bayesian Network

Models based on probability theory, such as Bayesian Network (BN) classifiers, are especially useful for understanding and decision making in highly uncertain domains such as marine social-ecological systems (Fernandes et al. 2010, Trifonova et al. 2015, Coccoli et al. 2018). Interpretation of and knowledge extraction from BNs is aided by graphical representation and, thus, DST based on BNs can visualize trade-offs between contrasting scenarios, and for NBS policies and planning. Several SLs illustrate how BN's can be used in planning marine conservation and restoration, and to explore ecosystem services trade-offs under FutureMARES scenarios. The workflow to produce a BN starts with the co-definition of a conceptual model (Fig. 8.5), which is then trained using discretized data and validated with 10-fold stratified cross-validation. In some SLs, the BN was based on a literature review or the BN was not spatially explicit. One DST was created for SL 28 to examine the likelihood of MPA success within the Tuscan Archipelago as

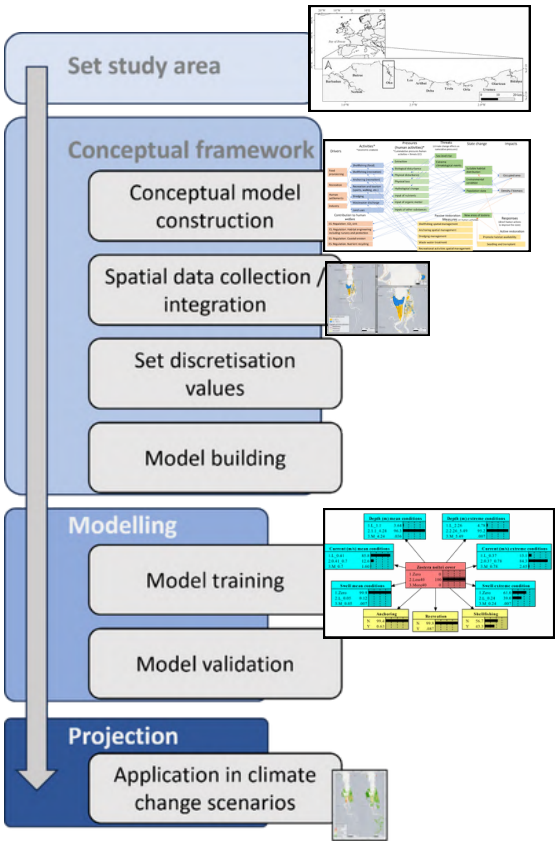


Figure 8.5, Workflow from Bayesian Belief Network (BNN) conceptual framework and modelling to predictions of climate change scenarios (Mandiola et al., submitted).

influenced by different FutureMARES scenarios (di Cintio et al. 2023, di Cintio et al., submitted) (Fig. 8.6). Success is defined as the effectiveness of achieving the ecological and socioeconomic goals for which they have been established. Hence, identifying the factors that contribute to increasing MPA effectiveness is pivotal to inform their planning and management. SL 28 included the impact of different socioeconomic factors (e.g., stakeholder involvement, increased communication and enforcement) on MPA effectiveness. Results highlight that the highest MPA effectiveness is achieved under the Global Sustainability scenario, while the lowest effectiveness occurred under the National Enterprise scenario.

A second non-spatial example illustrates trade-offs between scenarios which do and do not implement NBS or NIH. Prellezo et al. (2024) produced a network highlighting trade-offs of ecosystem services (provisioning, regulating and cultural) in the Bay of Biscay (SL 20, 22, 24) among the FutureMARES scenarios (Fig. 8.7). The Global Sustainability scenario, which corresponds to the implementation of NBS 1 (habitat restoration), NBS 2 (conservation such as marine protected areas) and NIH under maximum sustainable yield (MSY) had a higher chance of good economic value from regulating services. In contrast, World Markets and National Enterprise show a higher likelihood of achieving higher economic values of provisioning and cultural services.

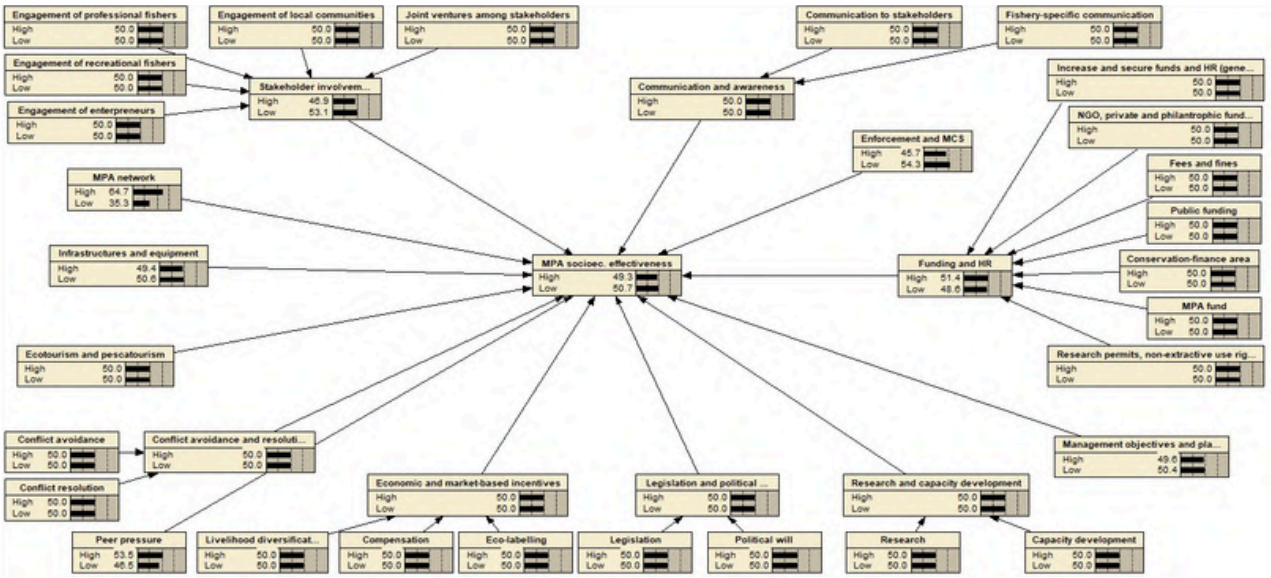


Figure 8.6, Example of DSTs based on BNs for trade-offs evaluations when implementing NBSs and NIH. MPAs success evaluation (di Cinto et al., submitted). (Deliverable Report 6.4).

A final example of a trade-off on the societal effects of different scenarios of NIH and other management interventions (e.g., nutrient loading control and climate change) was from the northern Baltic Sea (Uusitalo et al. 2023). This approach combined outputs from a spatially-explicit ecosystem model and a BN DST. Optimal strategies are searched by simulating different scenarios and finding the measures that produce the best environmental/ecological status. An ecosystem model (Ecopath with Ecosim) was used to simulate the ecosystem responses to management and climate scenarios, and the results are valuated based on a stakeholder questionnaire. In the questionnaire, the stakeholders reported the value they attribute to different ecosystem states and services.

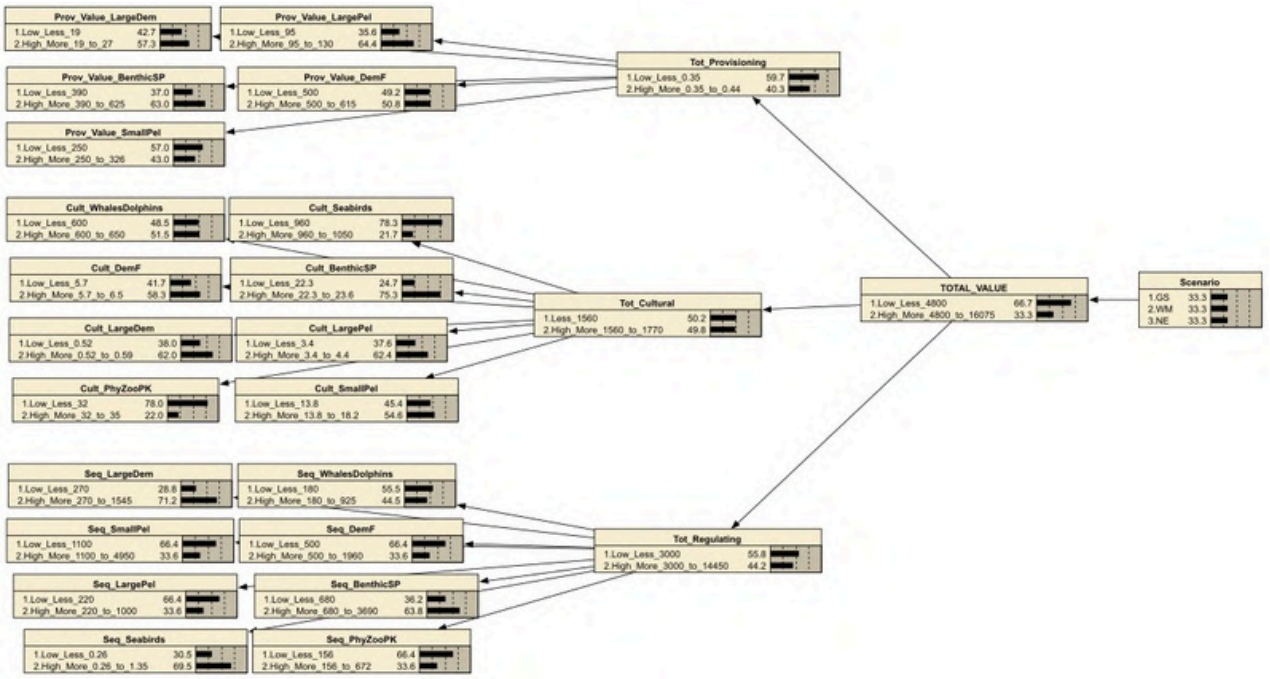


Figure 8.7, Examples of DSTs based on BNs for trade-offs evaluations when implementing NBSs and NIH. Ecosystem Services trade-offs with NIH and conservation measures (based on Prellezo et al. 2024). (Deliverable Report 6.4).

The ecosystem responses and the stakeholder values were combined in a Bayesian DST to illustrate which management options bring the highest benefits to stakeholders, and whether different stakeholder groups benefit from different management choices (Fig. 8.8). The largest differences are observed in recreational values. In this SL, the scenario with moderate climate changes and strict fisheries and nutrient loading management (resembles the Global Sustainability Scenario) brought the highest benefits to all stakeholders.

Two spatially-explicit examples focused on *Zostera noltei* restoration of Basque (SL 20) and Portuguese estuaries (Fig. 8.9), and on kelps in marine waters off Norway (SL1-3) and Portugal (SL 21). All the conceptual models followed the DAPSI(W)R(M) framework (Elliott et al. 2017), and were integrated using a Geographical Information System (GIS). *Zostera noltei* coverage distribution in the Oka estuary (Basque Country) was projected under different climate change scenarios (Mandiola et al. submitted) to plan conservation and restoration actions (Fig. 8.9).

The model with high performance (89.1%) illustrates the structure of the *Z. noltei* system and accounts for environmental factors, human activities, climate change effects, restoration actions and the ecosystem services provided by seagrass. Depth is the main environmental variable conditioning *Z. noltei* coverage distribution. In the Global Sustainability scenario it was projected that 15% of *Z. noltei* area will be lost, while 60.5% will be maintained, and 95.2% of the potential colonization area will be gained.

For the high emission scenarios, 6.8% of *Z. noltei* area will be lost, 61.4% will maintain the coverage, and a gain of area for potential colonization 241.3% is foreseen. However, this species colonization is very slow and can be limited by human activities.

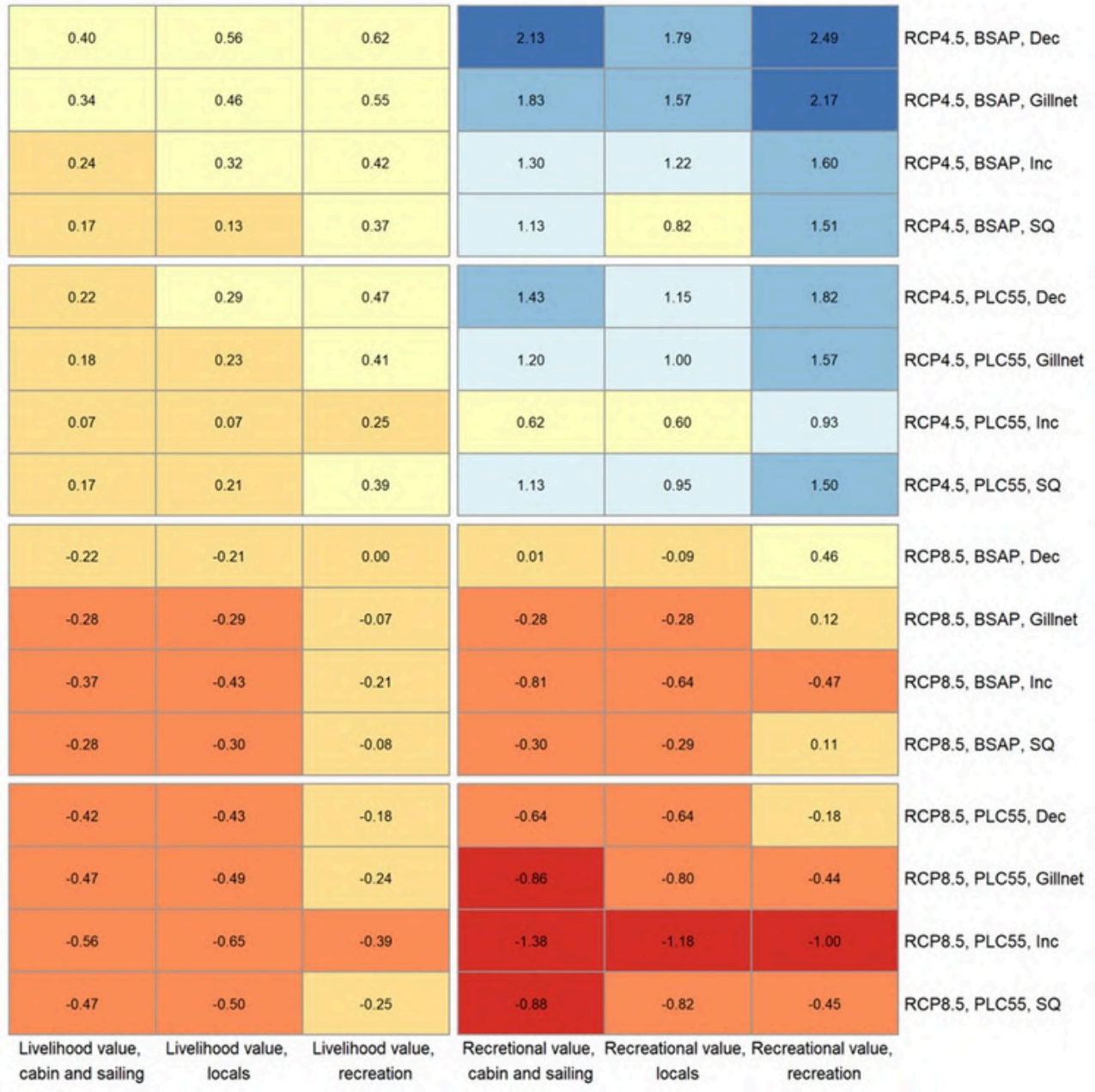


Figure 8.8, The main results shown as heatmaps of the ecosystem responses and the stakeholder values combined in a Bayesian decision support tool. (Deliverable Report 6.4).

In Ria de Aveiro coastal lagoon (Fig. 8.9), *Z. noltei* population extended up to 800 ha, but declined to less than 125 ha by the mid-2000s. This was due to habitat fragmentation caused by changes in hydrodynamics associated with harbour and shipping channel maintenance (Sousa et al. 2019), with additional pressure from shellfish fisheries, bait digging, and urbanization. There are currently around 250 ha of *Z. noltei* meadows, whose recovery might be due to water quality improvements and natural adaptation to the historical hydrological interventions (Sousa et al. 2019). A two-square-kilometer area is still historically one of the most mercury-contaminated in Europe (Oliveira et al. 2023). Therefore, active restoration of seagrass is being used as a NBS to promote the natural attenuation of pollutants (Oliveira et al. 2023) while supporting local biodiversity and productivity.

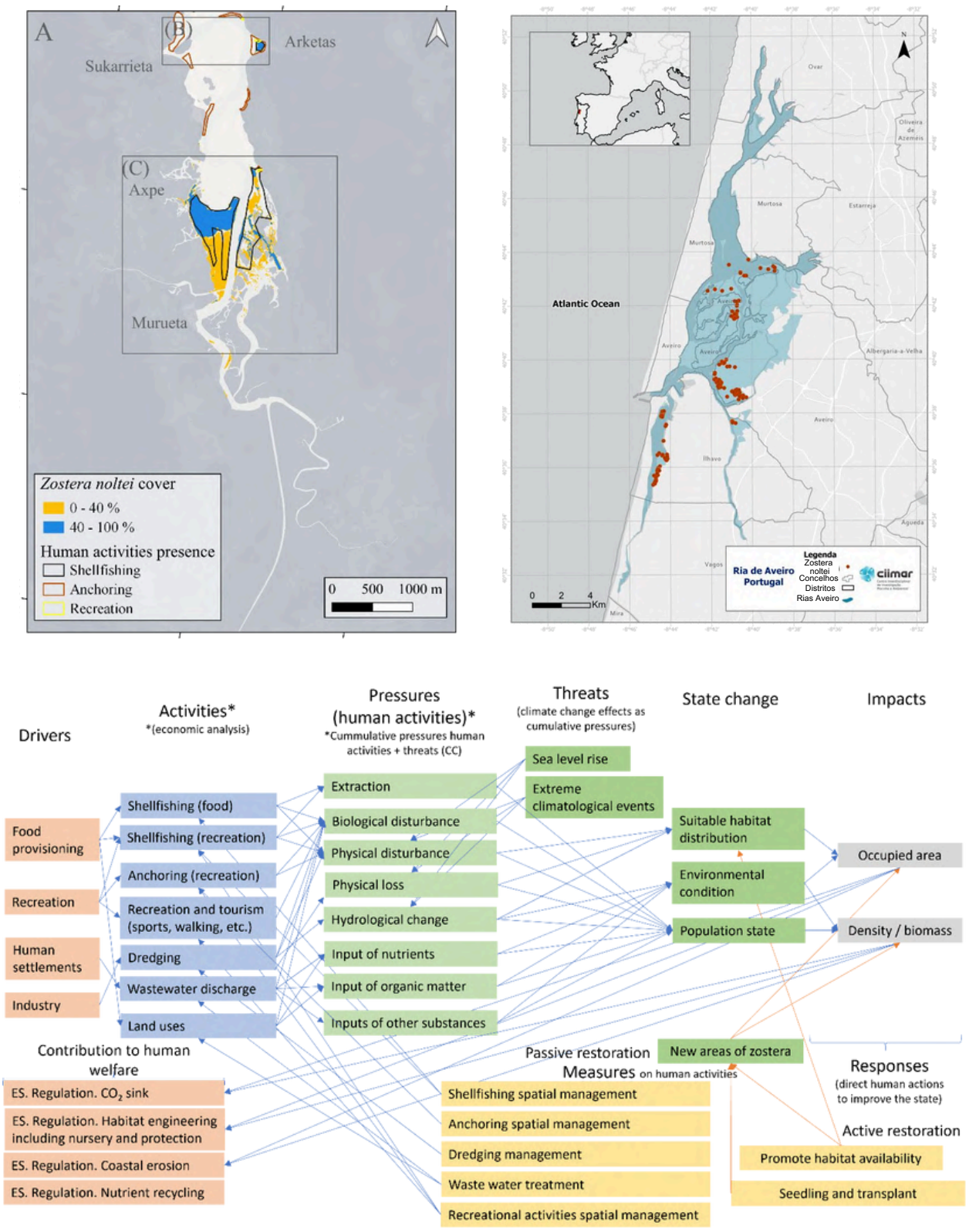


Figure 8.9, *Z. noltei estuary* (top) in Basque (left) and coastal lagoon in Portugal (right) regions. Conceptual model of *Z. noltei* structure system (bottom) created by expert consultation adopting DAPSI(W)R(M) framework in Basque estuaries (Mandiola et al., submitted).

The suitable colonisation area for seagrass depends on tidal exposure, amplitude and prism, elevation, sediment properties, and the condition of the plant itself (Sousa et al. 2019).

More recently, invasive species have also become a local factor influencing seagrass colonisation. The interplay of these multiple variables, which may be affected by sea level rise in the medium term and extreme weather events (e.g., floods, droughts and heat waves) determine the areas suitable for seagrass conservation, colonisation and restoration as depicted in the BN DST produced for this SL.

Atlantic kelp forests have declined, mainly due to climate change, overfishing, pollution and local stress factors (Fig. 8.10). MPAs are an important tool for habitat conservation but their effectiveness in protecting kelp forests from the influence of climate change is uncertain. Conversely, efforts to actively restore kelp habitats rely primarily on trial-and-error methods. There is an urgent need for research to establish appropriate spatial scales for sustainable kelp forest restoration. This is crucial for prioritising and scaling up restoration efforts, for which a BN approach is a valuable tool. In Northern Norway (SLs 1-3), kelp forests have severely degraded since the 1970´s mainly due to of sea urchin population explosion and their increased grazing. In southern Norway, fluctuations between sugar kelp and opportunistic filamentous algae occur and invasive seaweeds are frequently observed. Kelp ecosystems are anticipated to be directly sensitive to warming, ocean acidification, and nutrient enrichment (from agriculture and aquaculture) which produces coastal darkening and eutrophication. Temperature and oxygen levels will affect the metabolism of the species and hence their growth. Overfishing (e.g., wolffish, *Anarhichas lupus*) has been regarded as a potential reason for urchin overpopulation and hence kelp degradation. Restoration activities in Northern Norway focuses on the sea urchin harvesting and kelp transplanting. Reintroductions of urchin predators such as wolffish or regulating the harvesting of predators such as cancer crabs (*Cancer pagurus*) or king crabs (*Lithodes maja*) are also important restoration experiments which are included in the BN DST (Fig. 8.11).

Another example of a BN DST is from SLs 21&23 on large kelp forests in northern Portugal. These kelp populations occur at the lower edge of their latitudinal range, are particularly vulnerable. These kelp forests extend about 90 km from the border with Spain to Gaia, near Porto (Fig. 8.12 & Fig. 8.12b).

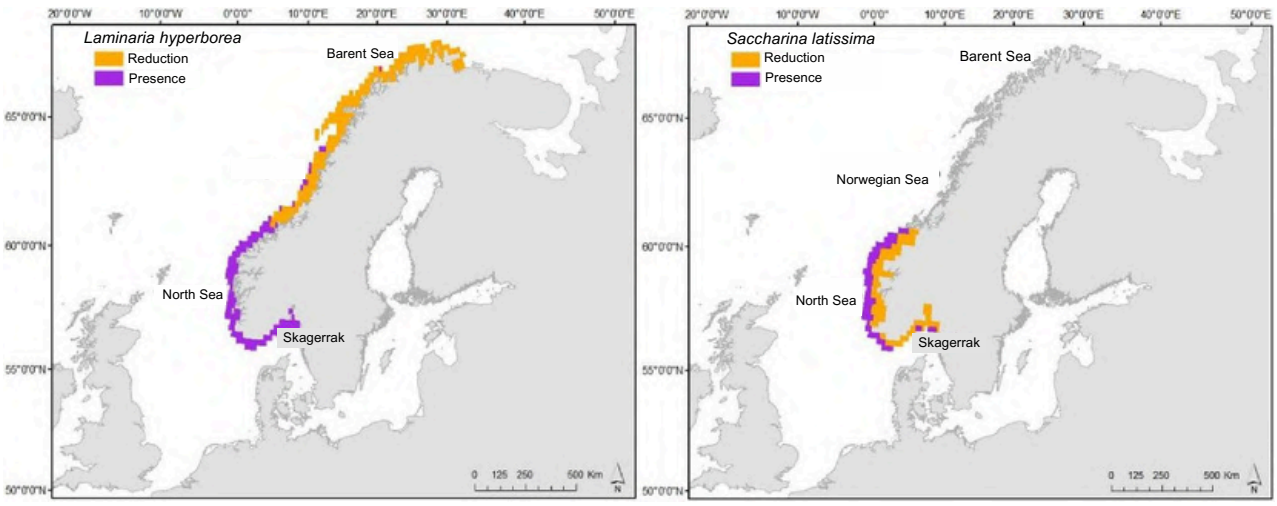


Figure 8.10, The current extent of two major kelp species in Norway (Chen et al., 2020). (Deliverable Report 6.4)

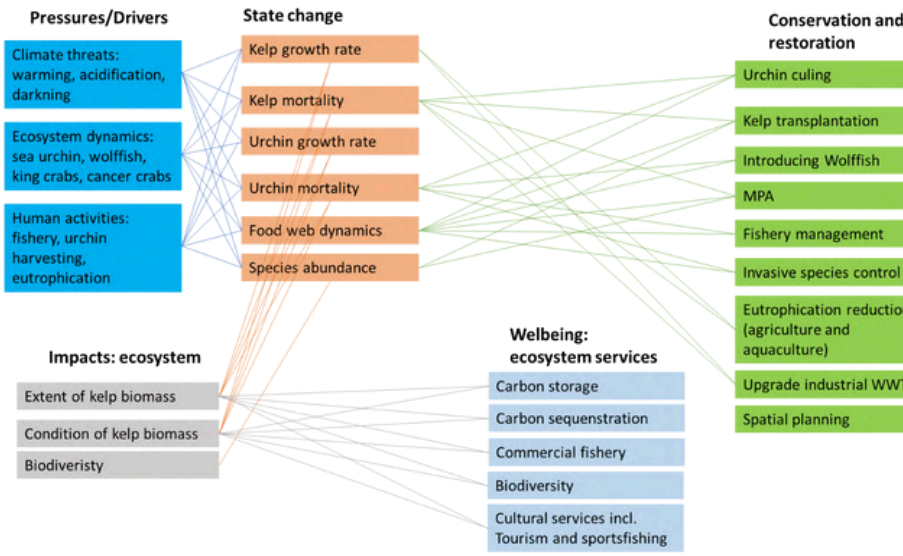


Figure 8.11, The conceptual model and a proof of concept of the Bayesian network considering carbon storage, of kelp ecosystems services in Norway. (Deliverable Report 6.4)

These forests cover nearly 6,000 hectares and are primarily dominated by the annual species *Saccorhiza polyschides*. However, the boreal perennial species *Laminaria hyperborea* also occupies around 2,000 hectares.

The upwelling driven by northwesterly winds is key in maintaining these cold-affinity species at relatively low latitudes, as it creates a "boreal refugium" that brings cold, nutrient-rich seawater to the coast in summer. Nevertheless, the extent of these cold-water species in this area has declined by 60% over the last decade, and there is growing evidence that the distribution of marine species in this area is shifting (de Azevedo et al. 2023).

A conceptual model for SL 21&23 includes potential threats and pressures, state changes and impacts, and also how the management options could influence these state changes. The decline in the extent of subtidal marine forests is likely a consequence of the direct (warming, heatwaves) and indirect (decreased nutrients) effects of climate change with reduction in upwelling being a main driver (de Azevedo et al. 2023). Implementing new climate-resilient NBS, including restoration and protection actions, is crucial for supporting sustainable kelp forests in their distributional edges.

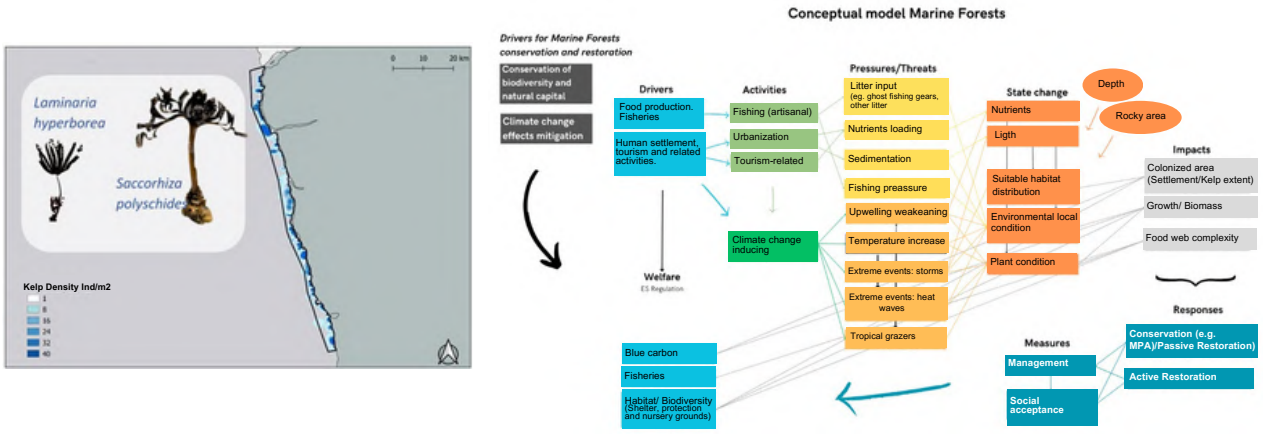


Figure 8.12, Actual map of kelp forests in Northern Portugal (SL 21 & 23) and conceptual model. (Deliverable Report 6.4).

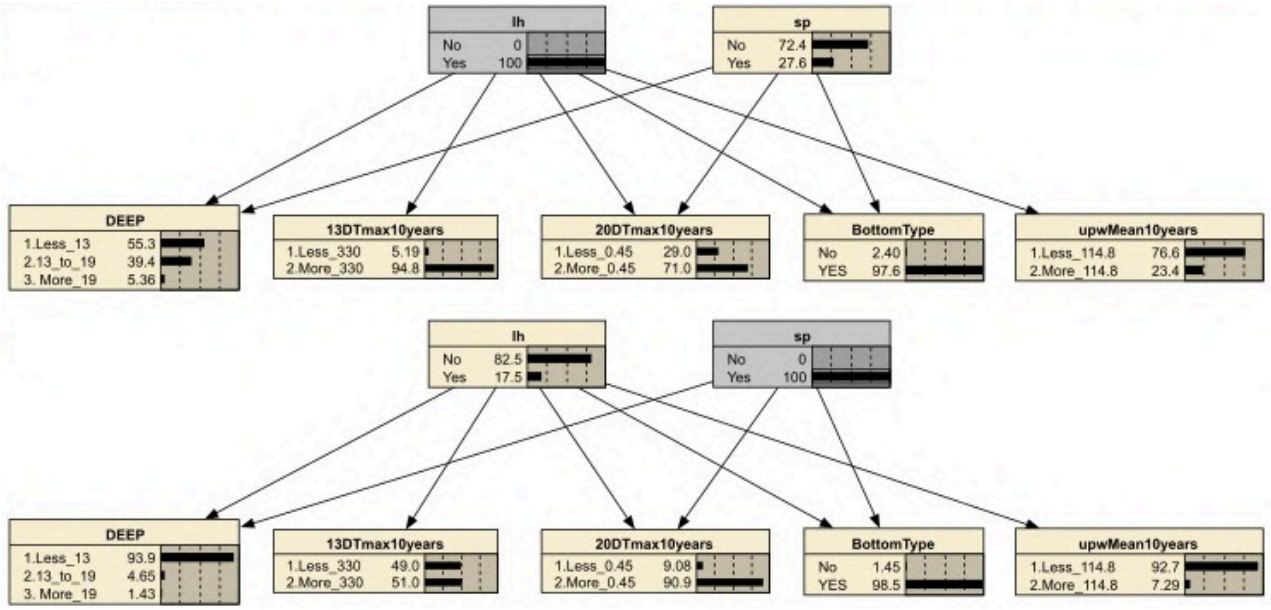


Figure 8.12b, Proof of concept of a Bayesian network tool with available data of kelp forests in Northern Portugal (SL 21 & 23). (Deliverable Report 6.4).

Trade-offs among marine restoration, marine conservation and sustainable harvesting

Although DSTs have helped advance social-ecological system understanding and identify potential climate-smart designs (or constraints) on effective marine restoration, marine conservation and sustainable harvesting practices, the integration both the ecological and economic trade-offs is sparse. Several trade-offs with implementing NBS and NIH have been identified through economic analyses of ecosystem services. These assessments highlight the ecological benefit and the economic implications of such practices (Box 6.1).

For example, while NBS could significantly enhance biodiversity and provide vital ecosystem services such as water filtration and flood protection, these long-term ecological benefits may conflict with immediate economic interests. Implementing NBS and NIH in fisheries exemplifies these trade-offs between short-term economic gains and long-term sustainability and health of marine ecosystems. Specific fisheries fleets, particularly industrial fleets as opposed to artisanal fleets, may suffer from the restrictions imposed by MPAs or habitat restoration activities in the short-term, leading to reduced catches and economic downturns. These measures might initially strain some industries, causing short-term economic losses and potential disruptions to livelihoods dependent on fishing from affected fleet segments.

However, these short-term challenges are often outweighed by the long-term benefits. By enhancing the health and resilience of marine ecosystems, NBS and NIH can contribute to the recovery of fish stocks, which in turn supports increased Gross Value Added (GVA) and sustainable employment opportunities over time. The restoration of habitats and the protection of critical nursery grounds within MPAs can lead to more robust fish populations, which can eventually result in higher and more sustainable yields.

Moreover, while the initial introduction of NBS and NIH may cause an increase in fish prices due to a temporary reduction in supply, the resulting improvements in marine ecosystem services-such as better water quality and habitat provisioning- can lead to more stable or even improved economic returns over time. These ecological improvements also contribute to the overall resilience of the marine environment, making it better equipped to withstand and recover from environmental stressors, including climate change. As a result, the fisheries sector, and the broader economy, can benefit from more sustainable and predictable outcomes, reducing the vulnerability to market fluctuations and environmental shocks.

Bioeconomic assessments (Chapter 7) indicate that while the fisheries sector may encounter initial economic difficulties due to sustainability-driven restrictions on harvesting practices, the broader benefits of implementing NBS extend far beyond fisheries alone.

Enhanced marine ecosystem health, a direct outcome of NBS, positively impacts various sectors such as tourism, recreation, and real estate. Healthier marine environments significantly boost tourism and recreation activities such as snorkeling, scuba diving, eco-tourism and recreational fishing and boating. These activities prosper in ecologically rich and biodiverse environments, attracting more visitors and enhancing the local economy. These effects are also evident in the real estate market, where properties near pristine coastlines and well-preserved natural areas see increased value due to their desirable locations. This uptick in property values benefits not only homeowners but also commercial enterprises such as beachfront hotels, resorts, and restaurants, which benefit from increased tourism and improved natural aesthetics.

Furthermore, sectors involved in environmental monitoring, ecosystem restoration, conservation, and management activities can expand and grow as NBS and NIH become more prevalent, leading to job creation and new business opportunities. As these practices become more prevalent, there is a growing demand for professionals and businesses specializing in these areas. This growth not only creates new job opportunities but also fosters innovation and investment in sustainable technologies and practices (Fig. 8.13).

Figure 8.13, Benefit of enhancing marine ecosystem health by NBS. Sectors such as tourism, recreation, and real estate are positively impacted. Furthermore, as NBS and NIH become more prevalent, they could lead to job creation, new business opportunities and fosters innovation and investment in sustainable technologies and practices.

However, the transition to NBS and NIH might also initially lead to shifts in employment likely to more specialized, potentially resulting in job losses in traditional sectors as these new practices take hold. This highlights the need of explicitly recognizing and addressing the trade-offs involved, where the disruption of established job markets must be balanced against the emergence of new employment opportunities in sectors aligned with sustainable practices.

To navigate these changes effectively creating DSTs is important as they offer a holistic view of both the ecological and socioeconomic impacts of NBS and NIH across various marine sectors. Such tools might be capable of assessing the risks and benefits in the context of future climate scenarios, thereby enabling informed decision-making that supports a balanced and sustainable approach to marine management. These DSTs would help policymakers and stakeholders anticipate and manage the transition, ensuring that the long-term benefits of NBS and NIH are realized without disproportionate short-term costs to vulnerable industries and communities.

Conclusions and policy recommendations

1) Decision-support Tools (DTSs) advanced in FutureMARES can illustrate climate-smart marine spatial planning, ecological trade-offs of management actions as well as actions to balance those trade-offs given policy objectives and management goals.

2) The three DSTs advanced in FutureMARES depict clear trade-offs among different degrees of implementation of habitat restoration, habitat conservation (particularly MPA networks) and sustainable harvesting practices and those trade-offs are indelibly linked to differences in the magnitude of climate change (e.g. ecological benefits from SSP1-2.6) and area specificities.

3) The outputs of DSTs can be effectively connected. Here, results from spatially-explicit ecosystem modeling informed both the Bright Spots Framework and Bayesian Network Analysis.

4) Some DSTs, particularly Bayesian Networks, can effectively incorporate uncertainty in the results of potential management actions. Some DSTs and their results can be “data hungry” and uncertainty will be reduced in situations where high-quality data on social-ecological systems are available.

5) Multi-disciplinary skill is needed to co-develop DSTs with end users and long-term mechanisms are needed to maintain these teams (e.g. experts in ecology, socioeconomics and computer science). Targeted educational programs and/or research funding including follow-up projects will help ensure the continued advancement of these state-of-the-art tools.

6) Coupling bioeconomic analyses with ecological analyses and risk assessments within DSTs would advance the science-based advice co-developed with decision makers.

7) Procedures are needed to establish the use of DST as one more evidence in policy advice and decision processes.

Future MARES

CHAPTER 9

THE LEGACY OF THE FUTUREMARES PROJECT – FROM KNOWLEDGE AND PRODUCTS TO POLICIES

AUTHORS: MYRON A. PECK & ISABEL SOUSA PINTO

09 The legacy of the FutureMARES project – from knowledge and products to policies

Introduction

The world is not on course to meet the UNFCCC Paris Agreement commitment to limit warming to well below 2°C, preferably 1.5°C or to put nature on a path to recovery by 2030 so that by 2050 “biodiversity is valued, conserved, restored and wisely used, maintaining ecosystem services, sustaining a healthy planet, and delivering benefits essential for all people” as is the goal of the Convention on Biological Diversity. Urgent and knowledge-based action is, therefore, required to bring about rapid and wide-ranging changes to reduce biodiversity loss and allow for the recovery of natural ecosystems as well as for reducing emissions and help people and nature adapt to, and withstand the impacts of, climate change. Climate and biodiversity crises are very interconnected and start to be seen as two interlinked components of a broader planetary crisis which needs to be addressed in an integrated manner (Pörtner et al. 2021, IPBES 2021).

FutureMARES was designed to bolster the implementation of Nature-based Solutions (NBS) to better conserve and actively restore the health of marine ecosystems and their commercially and culturally important natural capital. FutureMARES has demonstrated how NBS can work hand-in-hand with nature-inclusive (sustainable) harvesting (NIH) of marine resources to safeguard a host of ecosystem services. The project’s 33 partner institutions have cooperated with regional stakeholders in 39 Storylines across Europe and elsewhere to provide science-based advice for regional and local CC adaptation and mitigation actions through the implementation of NBS and NIH. FutureMARES took a six-step (Fig. 9.1) approach to provide the science-based advice and tools needed for successful, long-term rebuilding of biodiversity using NBS and NIH in marine, coastal and transitional waters.

Step 1: Document the unprecedented changes in marine biodiversity

FutureMARES has thoroughly documented historical changes in marine species and habitats that can be attributed to CC. As an example (see Chapter 2). ecological time series of up to four decades from 65 monitoring programmes, including historical data for 1,817 marine species (zooplankton, benthos, pelagic and demersal invertebrates and fish) were analyzed by calculating the Community Temperature Index (CTI) to provide quantitative information on community composition and its affinity for warm or cold waters. Over the past 40 years, the NE Atlantic Ocean has experienced a tropicalization of its communities, with an increase in the abundance of warmer-water species, while the Mediterranean and Baltic Seas, where warming has been more rapid, have seen a marked decline in cold-water organisms. That work, published in Nature Communications (Chust et al. 2024), warns of continued changes in the biodiversity of European seas and oceans when temperatures continue to increase. These alarming trends have potential economic and social consequences and highlight the importance of NBS for climate adaptation and mitigation.

Step 2: Improve projections of future climate-driven changes

To offer the best possible information for decision making, FutureMARES developed climate

projections of local-scale impacts of CC in coastal zones and shelf seas along with valuable information on their uncertainty. The datasets deliver monthly changes for 1993 to 2100 in five ocean indicators (temperature, salinity, pH, oxygen and chlorophyll) at different depths at a resolution of about 8 km for four European regions: North Sea, Baltic Sea, Bay of Biscay and Mediterranean Sea and two overseas territories (waters off of the coast of Chile and the Yucatan Peninsula). Published in Scientific Reports (Kristiansen et al. 2024), these projections identify the compound pressures of warming, acidification and deoxygenation on European regional seas and identify future CC hotspots as well as refugia for sensitive species (see Chapter 3).

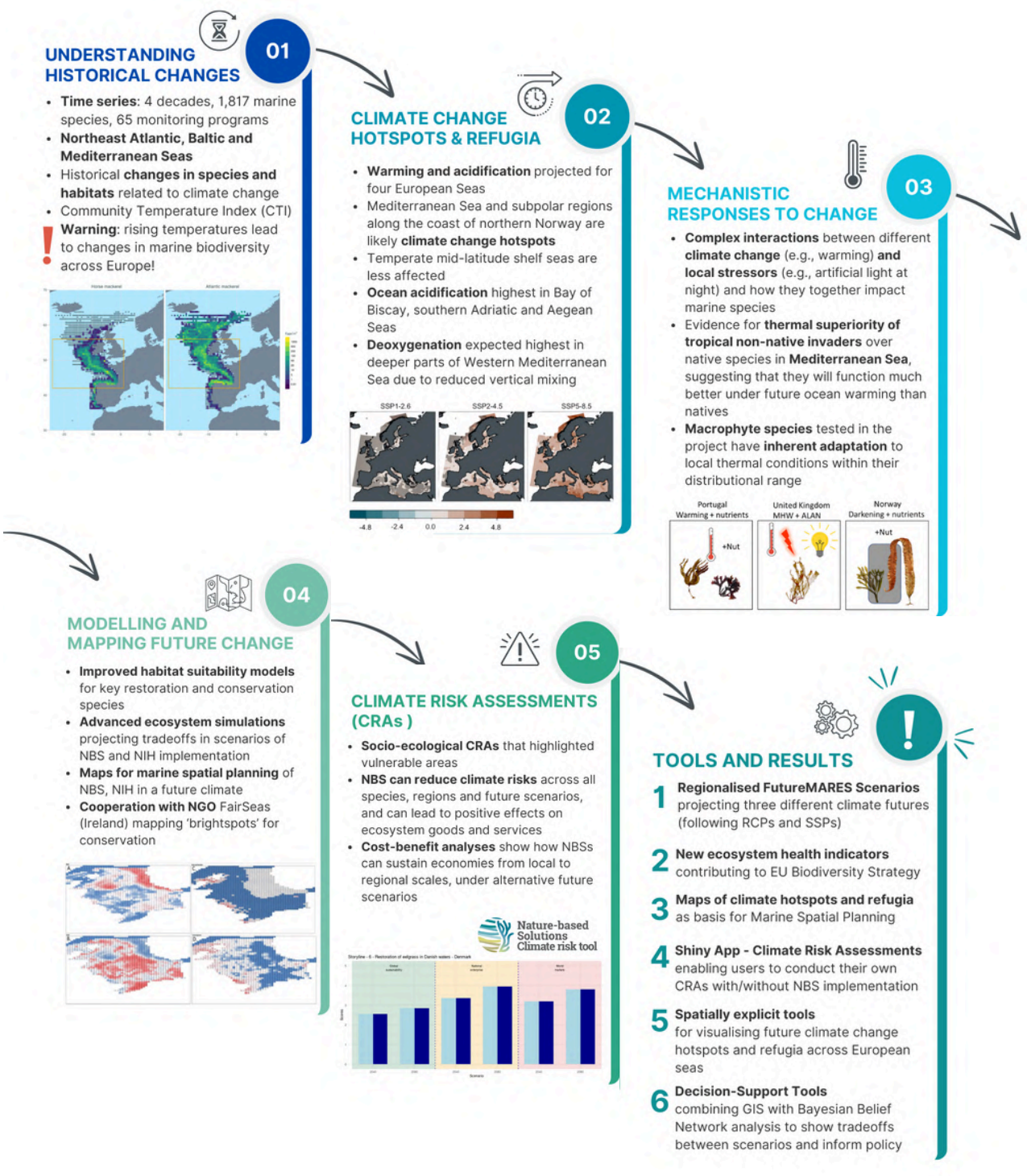


Figure 9.1, Six-step process taken by the EU FutureMARES Project.

While changes in pressures were variable both within and among regional seas, the projections underscore how policy interventions that decrease greenhouse gas concentrations can substantially reduce unwanted physical and biogeochemical impacts that continue to alter and degrade coastal and marine biodiversity and natural capital. These projections of physical and biogeochemical changes, when combined with socio-ecological scenarios (Chapter 4), allowed FutureMARES to estimate the potential success of a range of marine NBS and supports NIH of living marine resources.

Step 3: Create new knowledge on mechanistic responses to change

FutureMARES performed field and laboratory experiments to advance knowledge on the sensitivity of key habitat-forming species to climate-driven and other stressors. In the Mediterranean Sea, results provide evidence for the thermal superiority of tropical non-native invaders over native species, suggesting bio-invaders will perform much better under future ocean warming than natives. Results also show that alien-dominated, altered but rich, or restored macrophyte communities on shallow reefs can function similarly or superiorly to the original communities providing some hope that even highly altered communities may continue to provide functions and services important to the health of the ecosystem after the loss of native/original species.

FutureMARES showcased the response of habitat-forming species to interacting global (e.g., climate-driven warming) and local (e.g., artificial light at night) stressors, and how additive impacts cannot always be assumed. Experiments revealed population differences in climate sensitivity in habitat-formers with inherent adaptation to local thermal conditions. This may suggest some hope for acclimation or for selection towards more resilient genotypes if change is not extreme. These population differences have implications for the robustness of species distribution models, the selection of sites for marine protection, and the climate resilience of habitat restoration.

Step 4: Improve models and mapping of future change

The new knowledge on climate sensitivity and new projections of physical and chemical change allowed FutureMARES to create maps of the future distribution and productivity of key species and habitats (e.g., see Chapters 5-8). These maps help build the strong science foundation needed for planning networks of Marine Protected Areas (MPAs). A cooperation with the NGO FairSeas resulted in the mapping of climate change hotspots and refugia in Irish waters, and thus contributes to meeting Ireland's commitment within the EU 2030 Biodiversity Strategy (Queirós et al. 2024).

FutureMARES also advanced and applied marine ecosystem models to demonstrate how effective restoration of habitats can improve outcomes for associated species (Chapter 6) and how effective MPAs (Chapter 5) can provide climate refugia, and how more stringent protection (now planned for 10% of MPAs) combined with NIH (reduction in bycatch rates and fishing effort) can lead to the recovery of key commercial and conservation species (Chapter 7). The results of FutureMARES suggest that NBS together with NIH actions may play a vital role in climate adaptation and mitigation and to safeguarding marine biodiversity.

Step 5: Assessing climate risk with and without NBS and NIH

FutureMARES performed socio-ecological climate risk assessments (CRAs) that highlighted vulnerable areas such as the eastern Mediterranean and demonstrated how risks to species, ecosystem services, and social groups increase without NBS. The work revealed how NBS can reduce climate risks across all species, regions and future scenarios, and can lead to positive effects on ecosystem goods and services. The analysis also revealed that NBS can be less effective under IPCC scenarios with high greenhouse gas emissions. Cost-benefit analyses show how NBSs can sustain economies from local to regional scales, under alternative future scenarios. FutureMARES produced an CRA App guiding users on how to conduct their own CRAs.

Step 6: *Providing science-based tools to support policy implementation*

FutureMARES has also developed spatially explicit tools that display not only areas where CC is most likely to drive ecosystems towards a new state (CC hotspots) but also areas offering opportunities, such as the range expansion of species to foster sustainable growth (CC bright spots) across European regional seas (see Chapter 8). Additional decision support tools (DSTs) combining GIS with Bayesian network analysis were designed and used to visualize trade-offs between scenarios of climate x NBS / NIH implementation. These DSTs inform users about interactions among different ecosystem components and human activities to assess ecosystem services. Beyond advancing fundamental knowledge on the effects of CC on marine populations, species, communities and ecosystems, FutureMARES (co-)created products (e.g., regionalized scenarios, new ecosystem health indicators, maps of climate change hotspots and refugia, the CRA Shiny App, spatially explicit digital labs) including three different types of DSTs (see Chapter 8) to support the implementation of EU and international policies.

European policies supported by FutureMARES

The EU launched research programs to develop the knowledge needed to support its policies, its “Green Deal”, that included a Biodiversity Strategy for 2030, a “Farm to Fork” Strategy to increase food produced in Europe in a sustainable way, and new legislation such as the Nature Restoration Law ratified in June 2024. These programs included a strong investment in research to support the design of the integrated policies and actions needed to halt the loss of biodiversity while fighting and adapting to climate change. FutureMARES was designed to inform socially and economically viable options for the integration of biodiversity and climate objectives in policies and in the management of the marine and coastal environments so they benefit nature and people. This was done by evaluating the potential of NBS and NIH at local, regional, national and trans-national levels. The knowledge, tools, solutions, and activities produced under FutureMARES were designed to inform and contribute to various stages of the policy cycle, including policy agenda setting, policy formation, policy implementation, monitoring and evaluation.

To support the implementation of the EU 2030 Biodiversity Strategy, that has ambitious targets for having 30% of marine and coastal ecosystem under protection by 2030, including 10% of marine area under strict protection, and to shape and support implementation of the Nature Restoration Law, FutureMARES developed knowledge and tools at different scales that can be used both for European and National/regional scales.

Detailed maps were produced showing the distribution of the main climate-induced stressors, i.e., warming, acidification, and deoxygenation, across European Seas. These maps provide valuable insights for local adaptation policies, supporting marine spatial planning and implementing ecosystem-based management strategies. The high-resolution data sets (see Chapter 3) will be an asset to ongoing research programs identifying climate-smart interventions to preserve and restore biodiversity within European regional seas. FutureMARES identified areas projected to have very high (climate change hotspots) and very low (climate change refugia) levels of environmental stressors to inform decisions on where to establish new sites for conservation (e.g., MPAs), habitat restoration, and the effective management of existing sites to better safeguard vulnerable and resilient species and habitats.

FutureMARES demonstrated the value of designing effective networks of MPAs as an NBS to combat the combined biodiversity and climate crises and, thereby, has contributed to the implementation of climate-smart MPA networks (Chapter 8) and other conservation measures across the full geographical range of the European Seas and Chile and covering different foundation species such as kelp and seagrasses, as well as emblematic species such as turtles, marine mammals and fishes (Chapter 5). State-of-the-art species distribution models developed or advanced in FutureMARES on foundation species as well as charismatic megafauna provide projections of climate-driven shifts to aid in climate-smart conservation and restoration actions (see Chapter 5 to 8).

Regarding Marine Restoration, and in direct contribution to the implementation of the EU Nature Restoration Law, FutureMARES focused on habitat-forming (foundation) species, including reef-forming organisms (e.g., oysters and mussels), kelp/macroalgae, seagrass and saltmarsh habitats and developed a series of general recommendations for effective restoration. Effective restoration requires an iterative process, involving planning, monitoring, evaluation, and adjustment (see Chapter 6) and this should be considered when developing the National Restoration Plans.

FutureMARES also produced knowledge to support important considerations such as: a) what to restore: e.g., *focus* on foundation species that have a climate buffering capacity (canopy-formers) and climate tolerance; b) where to restore: areas with suitable habitat conditions that can be sustained in the future. Research on how to restore, including ‘passive restoration’ entailing the reduction of stressors that stimulates natural recolonization, ‘active restoration’ of seascape elements (e.g., removal of dikes and sea urchins); and ‘active restoration’ by re-introduction of species (e.g., seed, transplants, spores). Results also highlight the importance of identifying ‘climate rescuers’: populations that are especially suited for tolerating higher temperatures due to their historical exposure to and persistence within warmer waters (e.g., caused by marine heatwaves). The project also showcased that restored habitats should be connected and hotspots of connectivity should be protected. Seagrass connectivity models developed in FutureMARES allow to guide the choice of restoration sites (Chapter 6).

Support for decisions on application of NBS and NIH were developed in FutureMARES (Chapter 8). To evaluate the effectiveness of NBS and NIH, FutureMARES developed a novel methodology that allows for the comparison of climate risks estimated when an NBS or NIH is applied and when it is not applied, by using both expert elicitation processes and projections

from physical models, taking advantage of much of the knowledge that is being produced. This methodology was tested at the NACES High Seas MPA as requested by the Norwegian Environment Agency through the Call for Knowledge Needs promoted by FutureMARES. This NBS Climate Risk Assessment Tool could be accessible from EU portals and other platforms for its broader use.

The indicators framework developed in FutureMARES enables the selection of biodiversity, climate change, socio-economic, and policy-relevant indicators suitable to evaluate NBS. FutureMARES also developed a new indicator based on the Community Temperature Index (CTI), which considers species composition and abundance response to temperature. This and other climate and biodiversity indicators should be included in Eurostat and corresponding national and regional official statistical organizations. This research also points to the need to include new socio-economic indicators considering climate change (market and non-market based) to the System of Environmental Economic Accounting (SEEA) (Chapter 8).

Ecosystem Services valuation research for assessing cost-benefits or cost effectiveness of some NBS were performed including a comparison with man-made solutions. Establishment and expansion of MPAs can use spatial cost-benefit analysis to identify and prioritize regions for MPA expansion. Emphasis should be placed on areas where ecological benefits and connectivity between MPAs outweigh management costs, ensuring sustainable and economically viable conservation efforts. Integrating sustainable tourism practices into MPA management plans can ensure that the economic benefits of tourism are maximized while minimizing environmental impacts. Policymakers can use cost-benefit results to prioritize investments in NBS, demonstrating their long-term economic viability and environmental benefits. This research reinforced the detailed scenario analyses performed in FutureMARES that provides valuable insights for developing regional adaptation plans that incorporate NBS, tailored to specific local conditions and challenges. This supports adaptive management strategies in response to climate change.

FutureMARES results could show that when ecosystem service benefits are not included in cost-benefit analysis, there are risks of substantial underestimation of benefits, that can be as high as a 50% underestimation of benefits provided by NBS. This underscores the importance of including these benefits in cost-benefit analysis and advice, even though some methods on the social aspects of ecosystem services still need to be refined.

Other important contributions from FutureMARES can be made on the guidelines on Natura 2000 (EU Habitats Directive) specially on climate adaptation, as these guidelines are currently being updated by the EU Directorate-General.

FutureMARES can contribute to the ongoing revision of the Marine Strategy Framework Directive (MSFD) by proposing new indicators (Chapter 2), providing evidence that nutrient and chlorophyll can be an over-extracted resource (and not only a problem) leading to losses in the carrying capacity and health of some regional seas (Chapter 7).

The “From Farm to Fork” policy aims at moving Europe toward sustainable food production, including increasing food coming from the ocean. FutureMARES supports this policy by

developing knowledge and tools to inform fisheries and aquaculture management practices, to improve the health and profitability of commercial fish stocks and of existing and future aquaculture productions under climate change scenarios.

Digital marine labs were used as experiments to investigate the effects of socio-political scenarios with combined NBS and NIH, and results demonstrate that proactive, sustainable management of European Regional Seas can make a clear difference. Ecological benefits from reducing greenhouse gas emissions and promoting sustainable fisheries management within five heavily exploited regional seas (Baltic Sea, North Sea, Bay of Biscay and the Western Mediterranean) were projected to be dramatic, including the rebuilding of stocks of commercially important fish and increases in biodiversity.

Greater emphasis on cultivation at sea rather than wild catch (fisheries) is expected in the future in many systems, including extractive aquaculture (mussels, oysters, seaweeds) that may have the potential to exceed levels of ecological carrying capacity or production carrying capacity.

Through the advancement of science-based advice by project partners, FutureMARES can directly benefit decision makers and environmental managers across many European nations (Fig. 9.2).

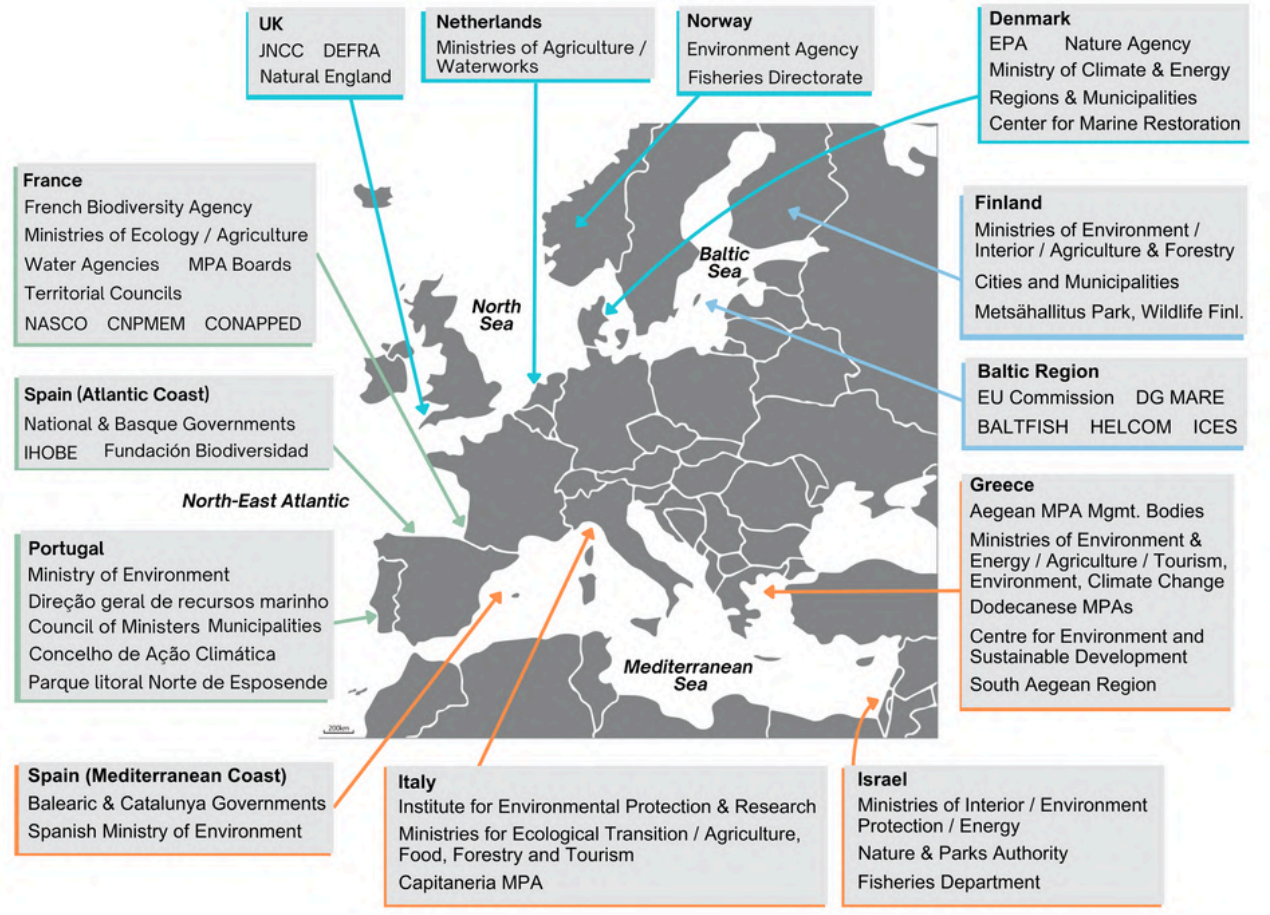


Figure 9.2, National-level institutions that can benefit from the science-based advice on marine NBS and NIH.

Global policies supported by FutureMARES

At the global level, FutureMARES was designed to deliver products to contribute to the goals of several conventions. This includes:

i) The Convention on Biological Diversity (CBD) and it recently approved Kunming-Montreal Global Biodiversity Framework (GBF) that aims at putting nature on a path to recovery by 2030 so that "biodiversity is valued, conserved, restored and wisely used…." by 2050. Here the essential role of MPAs has been recognized and targets of 30% of ocean under protection were agreed. So the work from FutureMARES on climate-ready area-based management tools (ABMTs), specifically on where MPAs should be located to help ensure their effectiveness now and in the future, safeguarding climate refugia and providing stepping stones to maintain and enhance connectivity are a key contribution to the implementation of this Convention and its GBF.

ii) The Ramsar Convention that aims at the conservation and wise use of wetlands and their resources and asks Parties to manage marine wetlands to increase their resilience to CC while maintaining and enhancing their contributions to climate mitigation and adaptation. The research produced by FutureMARES can support the decision on how and where to restore and conserve wetlands such as seagrass beds and estuaries.

iii) The interlinkages between climate change and biodiversity loss have also recently been recognized by the UN Framework Convention on Climate Change (UNFCCC) in the broader context of achieving the UN Sustainable Development Goals. The importance of protecting and restoring nature, including marine and coastal ecosystems, to achieve the goals of the Paris Agreement, was recognised. Most of the research from FutureMARES was focused on this goal.

iv) Regarding the 2030 Agenda for Sustainable Development (UN SDGs), FutureMARES inputs can inform actions for achieving several targets specially under SDG14 – Life under Water, specifically Target 14.2 which seeks the protection, sustainable use, and restoration of marine and coastal ecosystems with the research highlighted before including key tools for the implementation of Marine Spatial Planning, with methods to derive informative spatial indicators and plan MPAs and activities as fisheries and aquaculture that are climate resilient. FutureMARES research and tools also support SDG13 – Climate action particularly Target 13.1 which seeks to strengthen the resilience and adaptive capacity of countries to climate change and natural hazards, but also indirectly to other targets. Broader use of the Climate Risk Tool produced in FutureMARES will foster comparative assessments of climate risks and actions to build climate resilience.

v) FutureMARES also contributed to the aims of the UN Decades (2021-2030) of Ocean Sciences for Sustainable Development and Ecosystem Restoration, that recognizes the role of NBS to halt biodiversity loss, restore habitat functioning and rebuild natural capital to support the delivery of ecosystem services. Furthermore, knowledge produced can be fed into future Assessments as the Global Ocean Assessment, IPBES Global and Spatial Planning and Ecological Connectivity Assessments, and IPCC reports, indirectly helping to inform policies and support decisions.

Future Perspectives

This synthesis report has highlighted the accomplishments of the FutureMARES program over the course of its 4 years (2020 to 2024). Chapters specifically dealing with conservation (Chapter 5), active restoration (Chapter 6) and nature-inclusive (sustainable) harvesting (Chapter 7) provide lists of recommendations not only for effective policy implementation to support the conserving and restoring marine biodiversity and natural capital but also for future research needed to fill remaining gaps in knowledge to better understand the trade-offs and rapidly upscale the three Case Studies (NBS1, NBS2 and NIH).

The results of analyses conducted in these three FutureMARES Case Studies clearly indicate the pressing need to curb greenhouse gas emissions. This is borne out from the ecological and long-term economic benefits projected within the Global Sustainability scenario (SSP1-2.9) compared to scenarios (National Enterprise, World Markets) in which the rate of increase in greenhouse gas concentrations in the atmosphere remains at levels observed in the last two decades (e.g., RCP 8.5). The FutureMARES consortium hopes that marine climate and conservation scientists, decision makers, policymakers and other stakeholders utilize the products of this EU program to take actions to address the climate x biodiversity crisis in marine, coastal and transitional waters not only in Europe but in locations around the globe.

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Future MARES

APPENDIX

FURTHER READING – FUTUREMARES STORYLINE DOCUMENTS

Further reading – FutureMARES Storyline documents

Storylines 1, 2, 3 Norwegian Coast, inter-relationships among kelp, sea urchins and cod.

Storyline 4 Salmon at Hardangerfjord, Norway.

Storyline 6 Restoration of eelgrass (*Zostera marina*) in the south-west Baltic Sea.

Storyline 7 Conservation of coastal seaweeds, seagrasses, invertebrates and fish in the north-east Baltic Sea.

Storyline 8 Basin scale management & MPAs in the Baltic Sea

Storyline 9 Sustainable mussel culture in the Limfjorden, SW Baltic Sea

Storyline 10 Restoration of oysters in Dutch coastal waters

Storyline 11 Saltmarsh, seagrass and kelp habitats in the North Devon UNESCO World Biosphere Reserve

Storylines 12, 13 & 14 Marine spatial planning (broad coverage)

Storyline 15 Seaweed, mussels, and oysters in the north-east Atlantic and North Sea

Storylines 16,17, 18 & 19 Diadromous species in the NE Atlantic Ocean, including transitional and upstream waters

Storylines 20, 22, 24 Nature-based Solutions in the Basque coast of Bay of Biscay: seagrass restoration, protected areas, and sustainable seafood harvesting

Storylines 21 & 23 Kelp forests & biodiversity in northern Portugal

Storyline 25 Restoration of seagrass (*Posidonia oceanica*) in the Balearic Islands (NW Mediterranean)

Storyline 26 Marine Protected Area network for Aegean biodiversity

Storyline 27 Karpathos & Saria MPAs: seagrasses and meadows, soft/rocky bottom

Storyline 28 Seagrass meadows and macroalgal forests in the MPA network of the Tuscan Archipelago

Storyline 29 Habitat-forming macroalgae / corals in the western Mediterranean Sea

Storylines 30, 31, 33 Conservation / Fisheries Sustainability in the Western Mediterranean from a regional perspective + synergies

Storyline 32 Basin-wide sea turtle conservation in the Mediterranean Sea

Storyline 34 & 35 Climate change and bioinvasion impacts on reef & canopy-forming macroalgae and shelf fisheries in SE Mediterranean Sea

Storyline 36 Biogeography and biodiversity change on coastal communities at continental scales

Storyline 37 Hotspots and refuges for European Seas under the pressures of warming, acidification and deoxygenation

Storyline 38 Sustainable Seafood Harvesting in the Belize EEZ

Storyline 39 & 40 Ecosystem approach for the Chilean island systems

FutureMARES 2024

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