# Climate Change and European Fisheries and Aquaculture

CERES Project Synthesis Report

**'Climate change and European Fisheries and Aquaculture'**
**CERES Project Synthesis Report**

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This report summarises the research findings of the EU Horizon 2020 CERES (Climate change and European Aquatic Resources) project, executed between March 2016 and February 2020, and coordinated by the University of Hamburg.

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**List of species common names and their scientific equivalent**

| Common name | Genus species (or family) |
|---:|---|
| American lobster | *Homarus americanus* |
| Atlantic horse mackerel | *Tachurus tachurus* |
| Atlantic salmon | *Salmo salar* |
| Bighead carp | *Hypophthalmichthys nobilis* |
| Blue crab | *Callinectes sapidus* |
| Blue mussel | *Mytilus edulis* |
| Bluefin tuna | *Thunnus thynnus* |
| Bream | *Abramis brama* |
| Catfish | *Silurus spp.* |
| Common carp | *Cyprinus carpio* |
| Dolphinfish | *Coryphaena hippurus* |
| European anchovy | *Engraulis encrasiocolis* |
| European clam | *Ruditapes decussatus* |
| European sardine | *Sardina pilchardus* |
| European sea bass | *Dicentrarchus labrax* |
| Fivebeard rockling | *Ciliata mustela* |
| Gibel carp | *Carassius gibelio* |
| Goby | *Neogobius sp.* |
| Grass carp | *Ctenopharyngodon idella* |
| Gurnard | *Eutrigla gurnardus* |
| Haddock | *Melanogrammus aeglefinus* |
| Hake | *Merluccius merluccius* |
| Mackerels | *Trachurus spp.* |
| Mackerels | *Scombridae* |
| Meagre | *Argyrosomus regius* |
| Mediterranean mussel | *Mytilus galloprovincialis* |
| Mediterranean parrotfish | *Sparisoma cretense* |
| Mullet | *Mullus surmuletus, M. barbatus* |
| Pacific oyster | *Crassostrea gigas* |
| Peruvian anchovy | *Engraulis ringens* |
| Picarels | *Spicara sp.* |
| Pike-perch | *Sander lucioperca* |
| Plaice | *Pleuronectes platessa* |
| Pollack | *Pollachius pollachius, P. virens* |
| Rainbow trout | *Oncorhynchus mykiss* |
| Red mullet | *Mullus barbatus, M. surmuletus* |
| Roach | *Rutilus rutilus* |
| Round sardinella | *Sardinella aurita* |
| Saithe | *Pollachius virens* |
| Sea bream | *Sparus aurata* |
| Silver carp | *Hypophthalmichthys molitrix* |
| Sole | *Solea solea* |
| Sprat | *Sprattus sprattus* |
| Squid | *Loligo spp.* |
| Topmouth gudgeon | *Pseudorasbora parva* |
| Whiting | *Merlangius merlangus* |

## List of abbreviations

| | |
|---|---|
| **ABC** | Aquaculture Biosecurity and Carrying-capacity model |
| **BSAP** | Baltic Sea Action Plan |
| **CVA** | Climate Vulnerability Assessment |
| **DOC** | Dissolved Organic Carbon |
| **E-HYPE** | European application of the Hydrological Predictions for the Environment model |
| **EU** | European Union |
| **FARM** | Farm Aquaculture Resource Management model |
| **GDP** | Gross Domestic Product |
| **GHG** | Greenhouse Gas |
| **ICES** | International Council for the Exploration of the Seas |
| **IIASA** | International Institute for Applied Systems Analysis |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **MAGNET** | Modular Applied GeNeral Equilibrium Tool |
| **MEY** | Maximum Economic Yield |
| **MSY** | Maximum Sustainable Yield |
| **PP** | Primary Production |
| **NOAA** | National Oceanic and Atmospheric Administration |
| **NUTS** | Nomenclature of Territorial Units for Statistics |
| **PESTEL** | Political, Economic, Sociological, Technological, Environmental and Legal |
| **RCP** | Representative Concentration Pathway |
| **SRES** | Special Report on Emissions Scenarios |
| **SSP** | Shared Socioeconomic Pathways |
| **SST** | Sea Surface Temperature |
| **WG** | Working Group |

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# Introduction to the CERES project

Myron A. Peck

# Chapter 1: Introduction to the CERES project

Fish and shellfish harvested from capture fisheries and aquaculture play a critical role for global food security. The per capita supply of fish continues to increase driven largely by aquaculture (FAO 2018). The production of fish from European inland and marine waters in 2016 supported about 10% of global capture fisheries and 4% of global aquaculture (FAO 2018).

In these two Blue Growth sectors, Europe directly employs about 450,000 fishers and farmers but the economic and cultural importance is considerably larger as Europe is the largest single market for fish and fish products in the world (FAO 2018).

A primary goal of the EU is to sustainably grow the European aquaculture sector and effectively manage its fish stocks to promote self-sufficiency in the domestic supply of fish and shellfish (EC 2017).

Long-term management plans will need to consider the potential future impacts of climate change on these aquatic living resources and the human communities that depend on them.

During the most recent decade, unequivocal evidence for the impacts of climate change on aquatic habitats, such as ocean heating and acidification, deoxygenation, sea-level rise and changes in rainfall patterns has increased at an alarming rate (IPCC 2013, Breitburg et al. 2018).

Fish and shellfish resources in the sea and in inland waters have been profoundly impacted by climate change as evidenced by shifts in their distribution and/or productivity (Cheung et al. 2009, Comte et al. 2013, Jones et al. 2014, Pecl et al. 2017).

Moreover, mass mortality events of aquatic animals have been associated with unprecedented heatwaves documented in Europe and elsewhere (Frölicher et al. 2018).

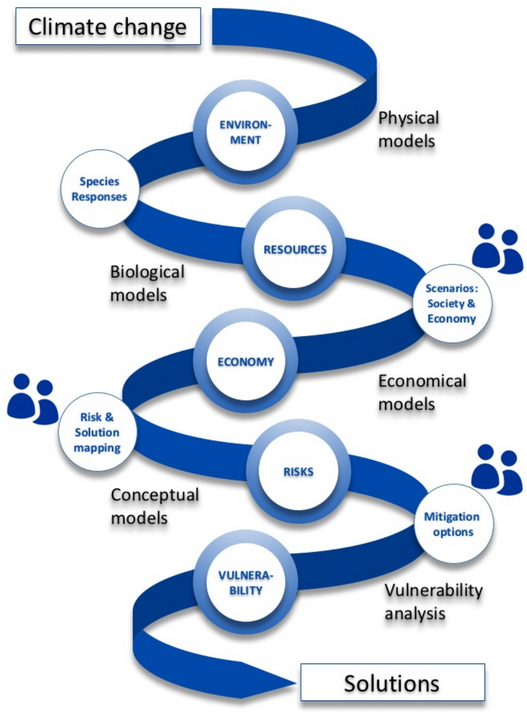

**Figure 1.1** CERES research areas.

The increased $CO_2$ in the atmosphere not only causes warming but is also causing the acidification of aquatic habitats (IPCC 2013) which can harm sensitive / early life stages of fish and can inhibit shell growth in bivalves (Feely et al. 2004).

These physical and biogeochemical impacts of climate change on aquatic habitats are exacerbated by other human-driven stressors such as land-based eutrophication of coastal waters, over-exploitation of fish stocks and freshwater diversion (Blanchard et al. 2010, Mora et al. 2013, Arthington et al. 2016).

The ecological and economic impacts of climate-driven warming and acidification and other stressors on fisheries and aquaculture are critical to estimate (e.g. Fernandes et al. 2017) if we hope to develop long-term management plans to safeguard aquatic food production.

Governments around the world have responded to the threats of climate change and other pressures by agreeing on ambitious future sustainability targets.

In 2015, the UN released its 17 Strategic Development Goals (SDGs) providing nations with a roadmap for cooperation to obtain specific global sustainability targets by 2030 (UN General Assembly 2015).

The targets directly related to climate change impacts on fisheries and aquaculture include SDG 2 ‘Zero Hunger’, SDG 13 ‘Climate Action’, SDG 14 ‘Life below Water’, and SDG 15 'Life on Land.' In 2016, the Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC) came into force, establishing clear goals for nations to limit greenhouse gas emissions in the coming decades.

In 2018, the European Commission announced its target for a climate neutral economy by 2050. At the same time as these policy initiatives have advanced, the IPCC has released updated reports on the impacts of climate change such as the Special Report on the Ocean and Cryosphere (SROC) in 2019 (Bindoff et al. 2019). Chapter 5 of SROC describes unprecedented warming, losses in sea ice, acidification, and reductions in oxygen content of the world’s oceans.

That report also highlights the projected consequences of remaining on the current, global $CO_2$ emissions trajectory and the projected benefits of reducing $CO_2$ emissions and atmospheric concentrations.

Against this backdrop of climate impacts and global and European policy developments, the CERES project (Climate change and European aquatic RESources) was funded under the EU Horizon 2020 programme from 2016 to 2020. CERES was designed to advance a cause-and-effect understanding of how climate change will influence European fish and shellfish resources and the economic activities depending on them (Fig. 1.1). More than 150 scientists from 26 partner institutions in 15 countries participated in this four-year project.

Partners included national research laboratories, universities as well as industry members from the aquaculture (five partners) and fisheries (two partners) sectors and additional stakeholders. Focusing on the most commercially valuable fish and shellfish, the project increased knowledge and developed tools needed for adaptation planning for European fisheries and aquaculture sectors in marine and inland waters to anticipated climate change.

The project identified not only risks but also opportunities as well as uncertainties of climate change impacts, information needed to enhance the resilience and support the development of sustainable management and governance systems in these Blue Growth sectors.

In support of goals outlined by the United Nations' SDGs and the European Union's Blue Growth and climate policies and to promote national climate adaptation planning, CERES was designed to:

1. Provide regionally relevant present day, mid- and end of-century, high resolution projections of key environmental variables for European marine and freshwater ecosystems
2. Integrate the resulting knowledge on changes in productivity, biology and ecology of wild and cultured animals (including key indirect / food web interactions), and 'scale up' to consequences for shellfish and fish populations, assemblages as well as their ecosystems and economic sectors
3. Utilise innovative risk-assessment methodologies that encompass drivers of change, threats to fishery and aquaculture resources, expert knowledge, barriers to adaptation and likely consequences if mitigation measures are not put in place
4. Anticipate responses and assist in the adaptation of aquatic food production industries to underlying biophysical changes, including developing new operating procedures, early warning methods, infrastructures, location choice, and markets
5. Create projections tools for the industry as well as policy makers to more effectively promote blue growth of aquaculture and fisheries in different regions
6. Consider market-level responses to changes (both positive and negative) in commodity availability as a result of climate change
7. Formulate viable autonomous adaptation strategies within the industries (bottom-up) and for policy (top-down) to circumvent/prevent perceived risks or to access future opportunities
8. Communicate these findings and tools to potential end-users and relevant stakeholders

To accomplish these eight goals, CERES integrated physical, social, ecological and economic analyses relevant to both European fisheries and aquaculture sectors (Fig. 1.1). The programme studied the most valuable species and groups and associated businesses across 'Storylines' highlighting sector- and region-specific research findings.

CERES developed 24 Storylines to capture the high diversity of European regions (from marine to freshwaters and from high to low latitudes) and commercially important species (from pelagic to demersal fisheries and from the culture of fish and shellfish (Fig. 1.2).

Whereas Storylines form separate, stand-alone products, the present report summarises CERES findings across Storylines to compare the potential severity of effects of climate change (from risks to potential opportunities) among European marine and freshwaters.

This synthesis report includes national-level comparisons of climate vulnerability for both sectors as well as analyses of the potential climate change impacts on the interaction between fisheries and aquaculture.

# CERES Storylines

| No. | Region | Species |
|---|---|---|
| 1 | **Northern Europe** | Rainbow trout |
| 2 | **Eastern Mediterranean** | Rainbow trout |
| 3 | **North-east Europe** | Carp |
| 4 | **South-east Europe** | Pike-perch |
| 5 | **North Sea** | Mussels |
| 6 | **North Sea** | Oysters |
| 7 | **Atlantic coast** | Mussels |
| 8 | **Atlantic coast** | Oysters and Clams |
| 9 | **Western Mediterranean** | Mussels |
| 10 | **North-east Atlantic** | Salmon |
| 11 | **Atlantic coast** | Meagre |
| 12 | **Western Mediterranean & Canary Islands** | Sea bass and Sea bream |
| 13 | **Eastern Mediterranean** | Sea bass and Sea bream |
| 14 | **Barents and North-West Sea** | Herring, Capelin and Cod |
| 15 | **Baltic Sea** | Herring, Sprat and Cod |
| 16 | **North Sea** | Herring |
| 17 | **North Sea** | Gadoids |
| 18 | **North-east Atlantic** | Mackerel |
| 19 | **North Sea and north-east Atlantic** | Flatfish |
| 20 | **North-west Mediterranean** | Dolphinfish |
| 21 | **Bay of Biscay** | Sardine and anchovy |
| 22 | **North-west Mediterranean** | Sardine and anchovy |
| 23 | **Aegean Sea and eastern Mediterranean** | Hake |
| 24 | **North-west Mediterranean** | Bluefin Tuna |

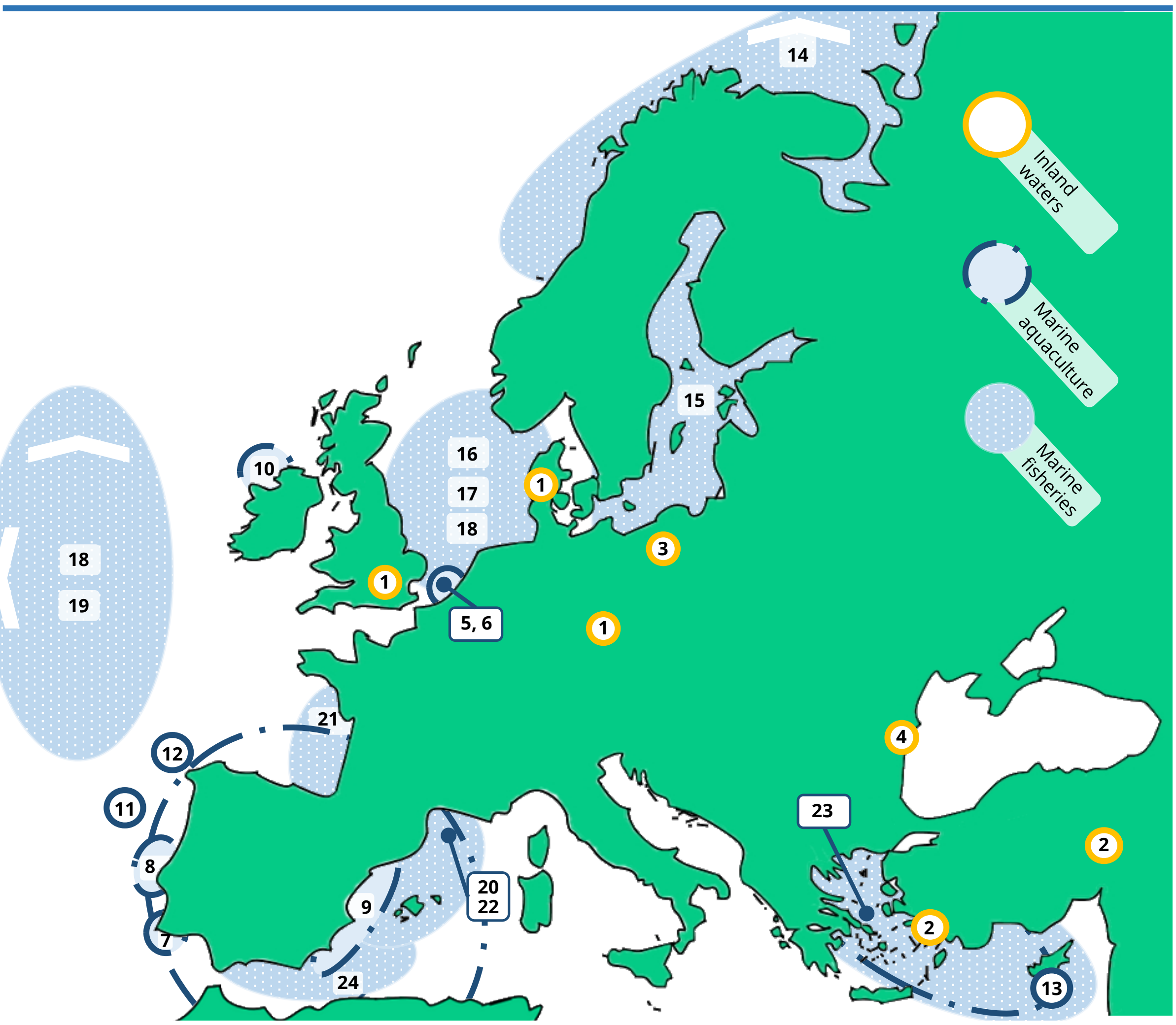


**Figure 1** Map indicating locations of CERES storylines

A key element of CERES was repeated engagement of stakeholders across the four years of this project to produce results most useful to the fisheries and aquaculture industry and to policymakers.

During the first year of the project, stakeholders were involved in regionalising scenarios, input that helped guide specific analyses performed during the project. Across each of the 24 Storylines, a qualitative mind-mapping exercise (Bow-tie analysis) allowed regional stakeholders to provide their perspectives on the climate-driven factors and processes of highest concern to their businesses along with potential measures for transformative adaptation.

Expert knowledge from stakeholders was also used to build quantitative Bayesian Belief Networks of the probabilities of negative or positive climate impacts given different future scenarios of change. Establishing and maintaining a dialogue with industry representatives and policy makers is essential in any research programme attempting to effectively address complex, social-ecological effects of climate change such as impacts on fish and shellfish and the human communities that depend on these resources.

The structure of this synthesis report maps onto the structure of the CERES research programme. After this brief introduction, the following five chapters are included:

Chapter 2 includes a broad summary of the physical and biogeochemical impacts of climate change expected for European marine and freshwater habitats. Future changes in key aspects of the quality of aquatic habitats for fish and shellfish are summarised including future changes in temperature, rainfall and pH as well as changes in primary production (at the base of the food web). Future changes were based on Representative Concentration Pathways (RCPs) developed by the IPCC to describe future concentrations of greenhouse gases.

CERES considered two pathways: RCP4.5 in which the concentrations of greenhouse gases increase until mid-century then remain stable, and RCP8.5 in which the concentration of greenhouse gases continue to increase through 2100. The level of global warming in RCP4.5 is close to the 2.0°C limit imposed by the 2018 COP Paris Agreement while RCP8.5 is a worst-case scenario leading to much larger global increases in temperature.

Chapter 3 describes the scenarios developed in CERES to allow future bioeconomic impacts of climate change on fish and shellfish to be evaluated. Four, contrasting scenarios were created using a PESTEL approach including Political, Economic, Social, Technological, Environmental and Legal developments. Future changes in the Environment are based on projections from the two RCPs described in Chapter 2 while those in the other PESTEL elements are based on the Shared Socio-economic Pathways (SSPs) developed by the IPCC and used in conjunction with the RCPs. Four CERES scenarios (Global Sustainability, National Enterprise, Local Stewardship and World Markets) were elaborated to determine how future bioeconomic impacts on fisheries or aquaculture activities across European regions.

Chapter 4 provides a summary of CERES results on the effects of climate change on European fisheries. This includes an appraisal of the current state of knowledge on direct and indirect effects of climate change on high-value targets of demersal and pelagic fisheries. Based on the results of a suite of state-of-the-art, single-species and food web models, projections of the impacts of climate change on the distribution and/or productivity of species are summarised across regions.

These results are used within economic models to explore the costs and potential benefits of climate change across 10 European fisheries. This chapter summarises the results of a Climate Risk Assessment conducted on the 421 distinct fishing fleets operating in European waters and discusses the outcome of Bow-tie analyses capturing the perceptions of stakeholders on adverse consequences and potential opportunities of climate change for the fisheries sector.

Chapter 5 considers the potential impacts of climate change on the European aquaculture sector. Analyses include the impact of both direct (e.g. warming on species growth) and indirect (e.g. projections of changes in the risks of disease pathogens) effects of climate change across various regions.

The direct effects are examined using physiological-based species models scaled to farm-level cultivation practices for key finfish (salmon, trout, carp, sea bass / sea bream) and shellfish (mussels, oysters) within and across various regions. These direct and indirect effects of climate change are then included in 'Typical Farm' models to assess bioeconomic impacts. The chapter summarises the results of a Climate Vulnerability Assessment for high-value European aquaculture targets across 22 nations and discusses the perceptions of stakeholders on the adverse consequences and opportunities for the aquaculture sector stemming from Bow-tie analyses.

Chapter 6 provides high-level recommendations based on the results of the CERES project for both European aquaculture and fisheries. Both bottom-up (industry based) and top-down (policy) recommendations are provided to help European fisheries and aquaculture sectors prepare for the likely future impacts of climate change.

This includes how climate change is expected to simultaneously influence both fisheries and aquaculture by, for example, impacting the global trade of fishmeal and fish oil used in aquaculture feeds. The combined, economic impacts to fisheries and aquaculture are compared across several nations to identify risks and potential benefits of climate change. Finally, recommendations are provided for future avenues of climate research.

The physical, biogeochemical, biological, economic and societal activities were assessed at different time scales including both historical research as well as mid-and late-century projections (Fig. 1.3).

More detailed information on the methods and results presented in each chapter of this synthesis report can be found on the CERES website (www.ceresproject.eu). The website contains information in various formats for different target audiences including reports submitted to the European Commission and articles published in peer-reviewed science journals.

Furthermore, reports for each of the 24 CERES Storylines are available to download.

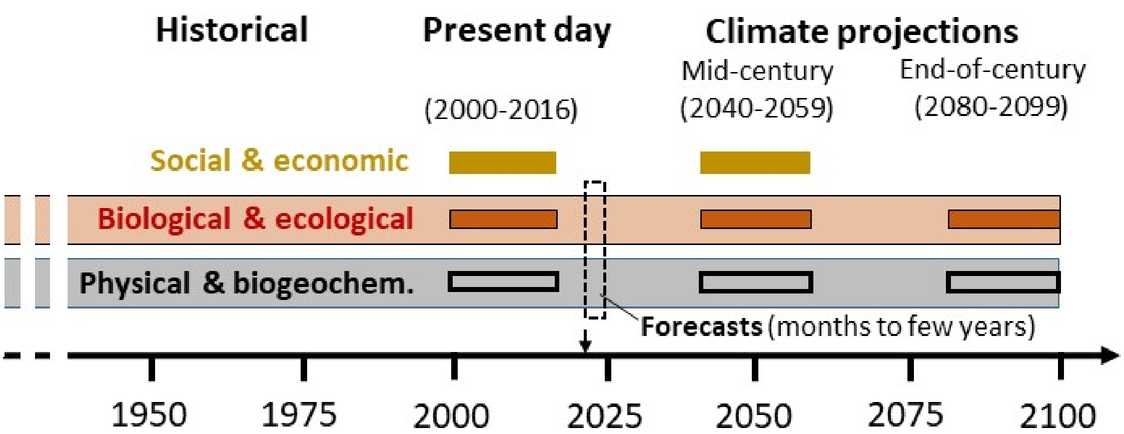


**Figure 1.3** Illustration of the various time scales in CERES.

2

# Projections of future environmental change

Susan Kay, Adam S. Kennerley, Mark R. Payne, Myron A. Peck

# Chapter 2: Projections of future environmental change

## 2.1 Introduction

The growth and productivity of local fish and shellfish resources and the broader geographic distribution of species is governed by physical, biogeochemical and biological factors (Fig. 2.1 and Table 2.1). Modelling climate change impacts for European basins requires climate change information at higher spatial resolution than that available from global climate models. It also requires using ecosystem models more suited to shelf seas, coastal systems and inland waters. The CERES project, therefore, used regional-scale model projections for all parts of Europe: this included the creation of a new, consistent set of projections for most European seas covering the entire 21st century. These projections demonstrate the effects of climate change on key physical and biogeochemical factors such as temperature, dissolved oxygen, pH, salinity and primary production.

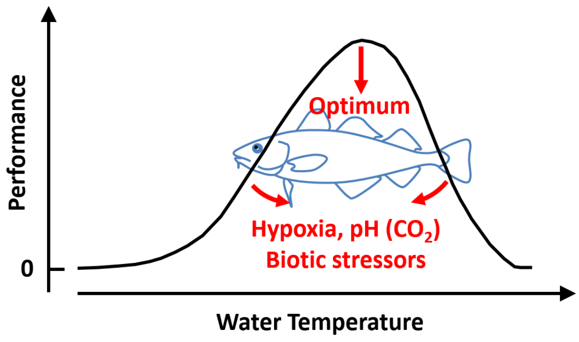


**Figure 2.1** Schematic illustrating the multiple ways by which changes in climate-driven factors can affect the performance fish and shellfish.

**Table 2.1** The effects of climate change-related factors on fish and shellfish.

| Factor | Effect(s) on fish and shellfish |
|---|---|
| Temperature | Key environmental factor controlling metabolic rates, appetite and growth capacity; species-specific optimal range |
| Dissolved Oxygen (DO) | Decreased DO concentration can reduce individual growth and biological carrying capacity, and very low levels (e.g. hypoxia) can cause mortality |
| pH | Increases in $CO_2$ decrease water pH with life-stage and species-specific consequences (e.g. reduced survival and growth of early life stages of some fish and shellfish, increased growth of aquatic plants) |
| Salinity | Increases (salinisation) or decreases (freshening) can cause shifts in rates of growth and/or survival; optimal and tolerable ranges are species-specific |
| Water Currents | Changes in wind strength and direction impact water circulation patterns influencing nutrient dynamics, primary production and the movement of planktonic organisms |
| Primary Productivity | Changes at the base of the aquatic food web will have important consequences for the availability of food for shellfish and other consumers |

The projections were created using models with a good track record in each region (POLCOMS-ERSEM for the North East Atlantic and Mediterranean Sea, RCO-SCOBI for the Baltic Sea, NORWECOM for the Norwegian and Barents Seas and EHYPE for river flows and nutrients).

For all but the high latitude region, projections were made based on two IPCC scenarios, RCP4.5 and RCP8.5, and spanned the entire 21st century. The Representative Concentration Pathways (RCPs) are used to describe a consistent set of greenhouse gas (GHG) concentration trajectories up to 2100 (Fig. 2.2a). They are each defined in terms of the radiative forcing in the year 2100 relative to pre-industrial conditions and direction of change (van Vuuren et al. 2011):

- In RCP8.5, GHG emissions rise over time reaching a radiative forcing higher than 8.5W $m^{-2}$ by 2100 and concentrations more than 1370 ppm in 2100;
- In RCP6.0, the total radiative forcing is stabilised at 6.0 W $m^{-2}$ shortly after 2100 corresponding to a stabilisation of GHG concentrations at around 850 ppm.
- In RCP4.5, the total radiative forcing rises only slowly after 2050 and is stabilised at 4.5 W $m^{-2}$ shortly after 2100. GHG concentrations stabilise around 650 ppm.
- In RCP2.6, low greenhouse gas concentration levels are reached. Its radiative forcing level peaks around 3 W $m^{-2}$ by mid-century and declines to 2.6 W $m^{-2}$ by 2100.

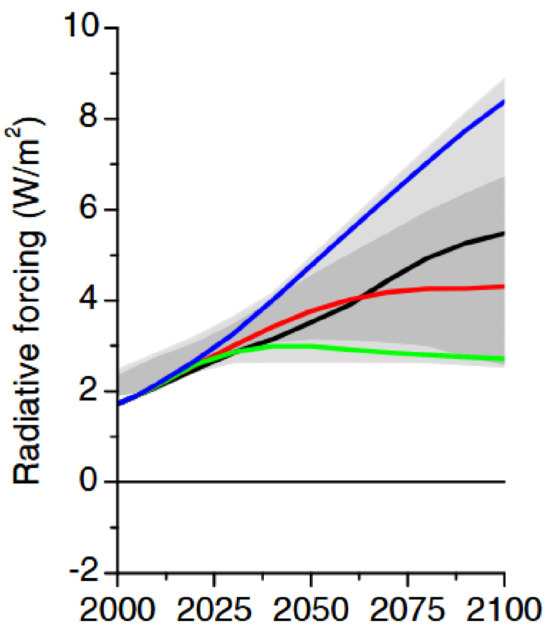


**Figure 2.2** Trends in radiative forcing of the Representative Concentration Pathways. The dark grey area shows the range covered by previous IPCC scenarios. From van Vuuren et al. (2011, their Figure 10a).

RCP4.5 is estimated to correspond to a global temperature rise of about 2°C above pre-industrial levels and RCP2.6 to a 1°C rise (IPCC 2013). RCP6.0 and RCP4.5 are similar until about 2070 and RCP2.6 represents only a small change from current conditions. Therefore RCP4.5 and RCP8.5 were used to give an indication of the envelope of climate response that is likely to occur in the system; they were combined with Shared Socio-Economic Pathways (SSPs) to create the four CERES scenarios discussed in Chapter 3.

Projections of change in the North East Atlantic, the Mediterranean Sea and the North Sea were created using a single global climate model, downscaled to a resolution of about 11 km using a regional model (CERES D1.3 2018). The global model was chosen as being reasonably representative of a range of global models in the European region. Sections 2.2 to 2.4 present some key points from these projections, including comparison with a range of other global model projections. Projections for the Baltic Sea used an ensemble of four global models, downscaled to 3.7 km for a range of river inputs as well as RCPs; results from these projections are given in section 2.5.

Modelling for the Norwegian and Barents Seas is presented in section 2.6. For this region, a global model was chosen which gives a good representation of Arctic conditions; it was downscaled to 10 km for the time period up to 2070. River discharge was modelled using an ensemble of global models; these projections are presented in section 2.7.

All of these regional projections were used as inputs for the fisheries and aquaculture models used in CERES, whose results are discussed in Chapters 4 and 5. For aquaculture further downscaling was carried out and the method is described in section 2.10.

## 2.2 Atlantic coast

Sea surface temperatures are projected to rise by about 2°C by the end of the century in the southern part of the Atlantic region under RCP8.5 and about 1°C under the lower-emissions RCP4.5 climate scenario (Fig. 2.3). Changes at higher latitudes are smaller, where there is less difference between the RCPs. Global model projections for the NE Atlantic vary considerably, and the increases projected by CERES modelling are in the low part of the range (Fig. 2.4); higher end-century temperatures are possible.

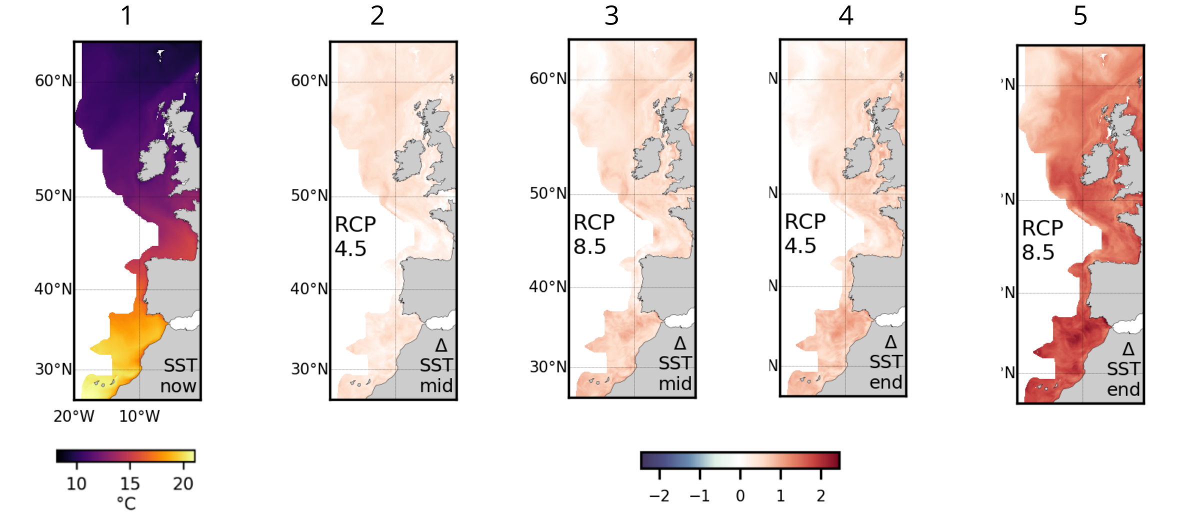


**Figure 2.3** Present day sea surface temperature for the Atlantic coastal region (1) and projected change at mid-century (2,3) and end century (4,5) for RCP4.5 and RCP8.5. Present day values are the median for 2000-2019, mid-century 2040-2059 and end century 2080-2099.

Projections also indicate a decrease in surface salinity by 0.3-0.5 psu and an increase in bottom water temperature of 1 to 2°C in coastal regions. Deep water in the north of the region may decrease in temperature, associated with changes in Atlantic circulation.

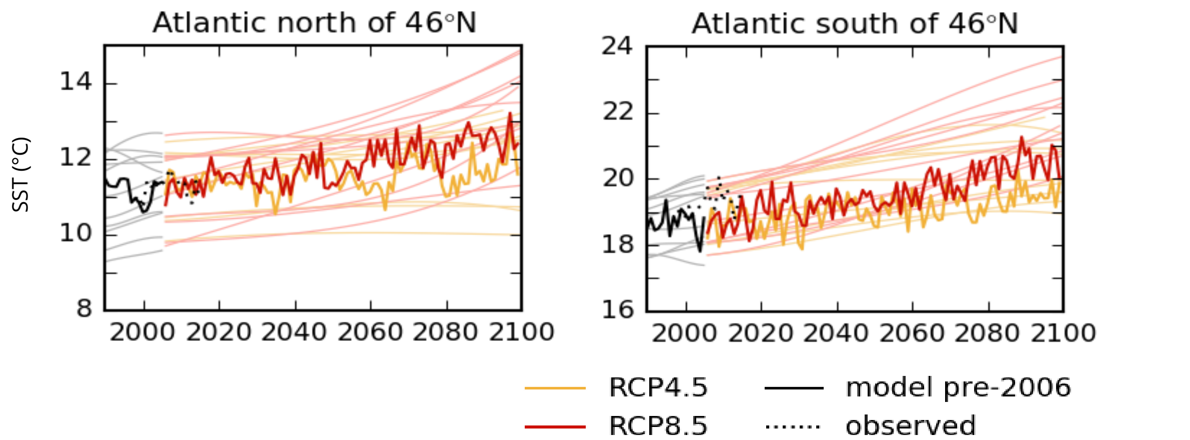


**Figure 2.4** Annual average sea surface temperature for the Atlantic coast, northern and southern regions. The fainter lines show values from global models, smoothed to show trend only. Observations are merged satellite and in situ measurements.

Primary production in the Atlantic coast region is projected to fall by about 10% over the 21st century, except for the Iberian Peninsula – here production is projected to rise in the first half of the century before falling back to present day values (Fig. 2.5).

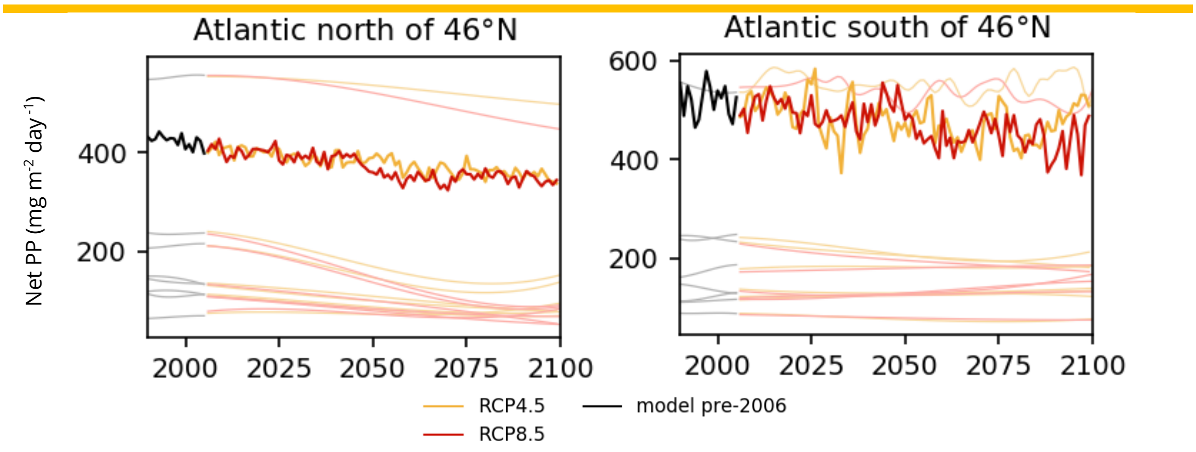


**Figure 2.5** Annual average net primary production (column total) for the Atlantic coast, northern and southern regions. The fainter lines show values from global models, smoothed to show trend only.

Global model projections for this region vary widely, but most agree on a decreasing trend (Fig. 2.6). The large changes in production seen at the western boundary of the model in Fig 2.6 are likely to be effects of the model boundary and should not be considered reliable.

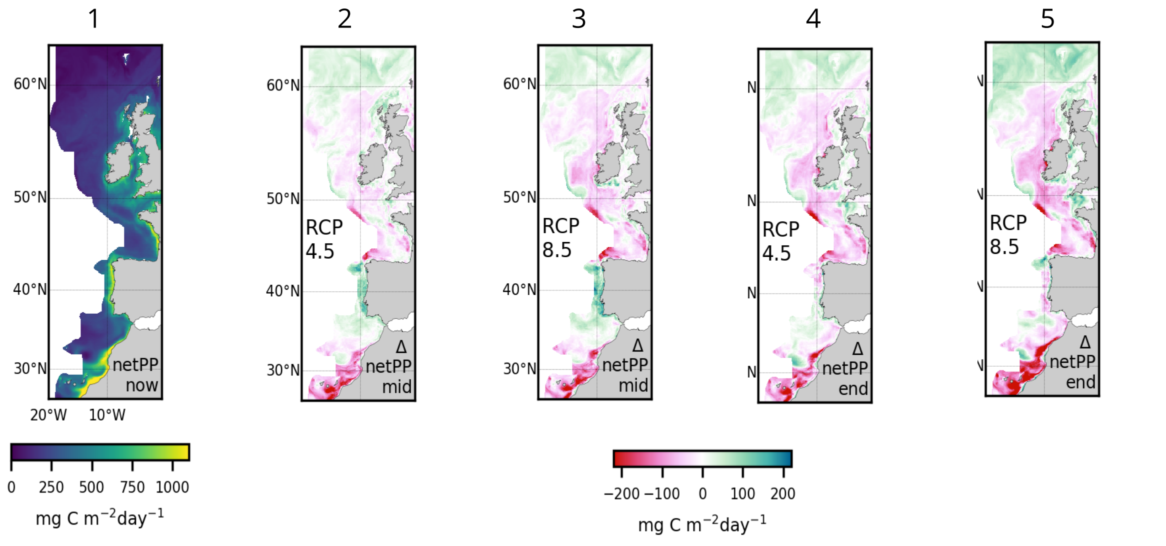


**Figure 2.6** Present day net primary production for the Atlantic coast (1) and projected change at mid-century (2,3) and end century (4,5) for RCP4.5 and RCP8.5. Present day values are the median for 2000-2019, mid-century 2040-2059 and end century 2080-2099.

## 2.3 Mediterranean Sea

Surfaces temperatures in the Mediterranean Sea are projected to rise by 3°C during the 21st century under RCP8.5, with an increase of about 1.5°C under RCP4.5 (Fig. 2.7). This is in line with the range projected by global models, though some project a larger increase (Fig. 2.7). Temperatures under the two RCPs are similar for the first few decades, but clear differences can be seen by mid-century (Fig. 2.8).

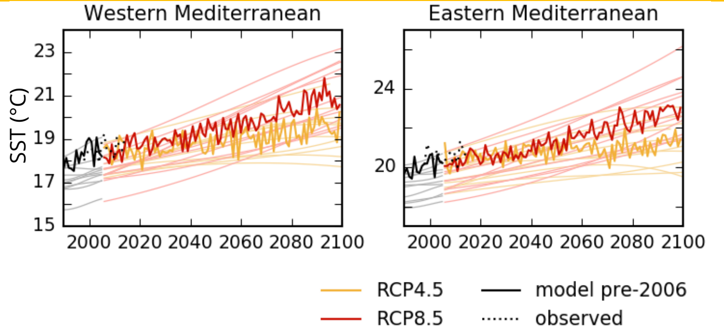


**Figure 2.7** Annual average sea surface temperature for the Western and Eastern Mediterranean Sea. The fainter lines show values from global models, smoothed to show trend only. Observed = merged satellite and in situ measurements.

Sea bottom water temperatures are projected to rise by a comparable amount as surface waters, giving a corresponding decrease in oxygen concentrations. Some freshening of surface waters is projected for the west, influenced by the Atlantic, but surface salinity could be as much as 0.5 psu higher by end century in the east.

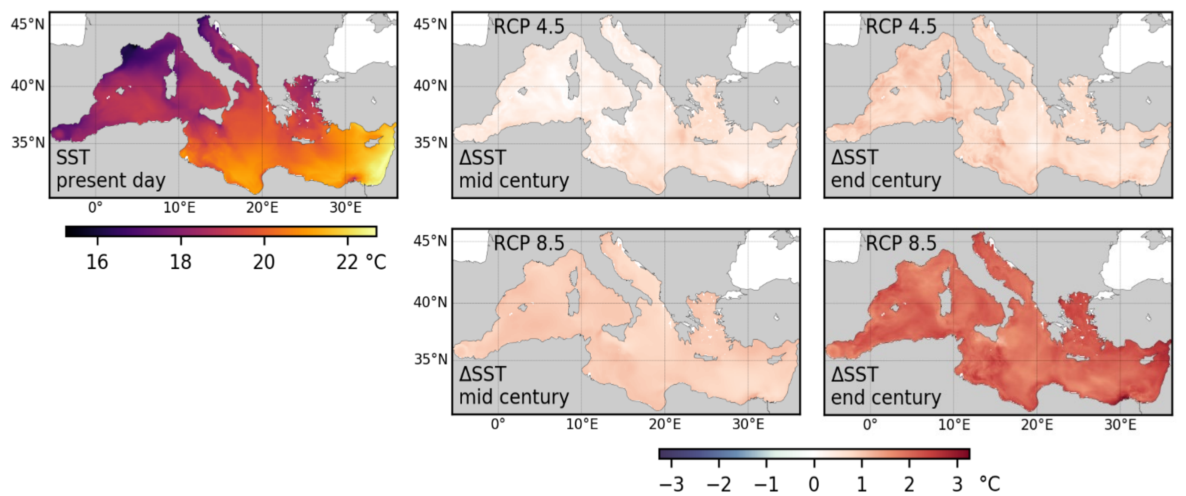


**Figure 2.8** Present day sea surface temperature for the Mediterranean Sea (left) and projected change at mid-century (centre) and end century (right) for RCP4.5 (top row) and RCP8.5 (bottom row). Present day values are the median for 2000-2019, mid-century 2040-2059 and end century 2080-2099.

Primary production is projected to rise in the western part of the Mediterranean Sea; production in the east also rises under RCP4.5 but is static under RCP8.5. Global models vary widely but show magnitudes of change in their trends (Fig. 2.9, Fig. 2.10).

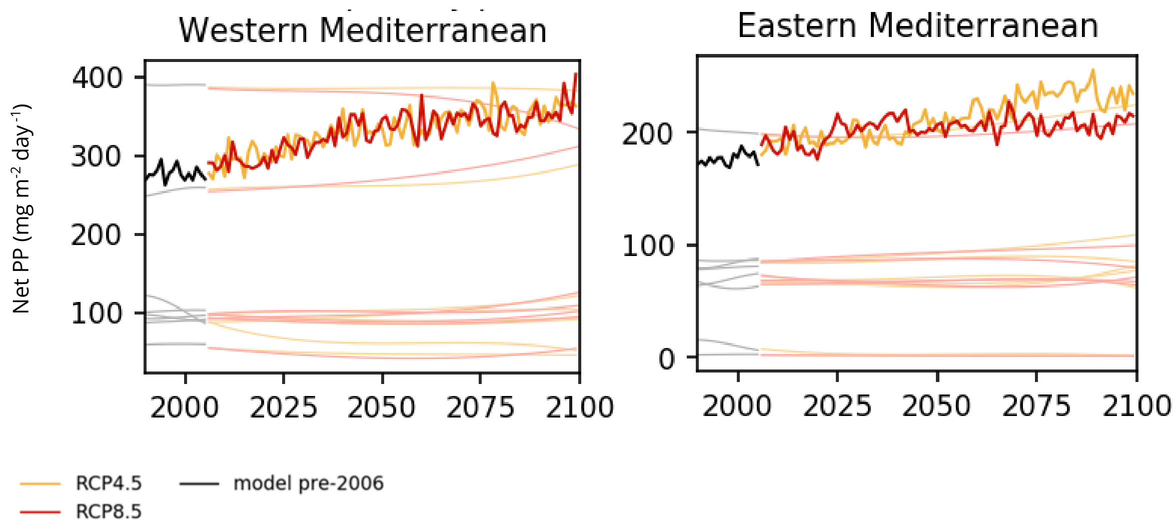


**Figure 2.9** Annual average net primary production (column total) for the Western and Eastern Mediterranean Sea. The fainter lines show values from global models, smoothed to show trend only.

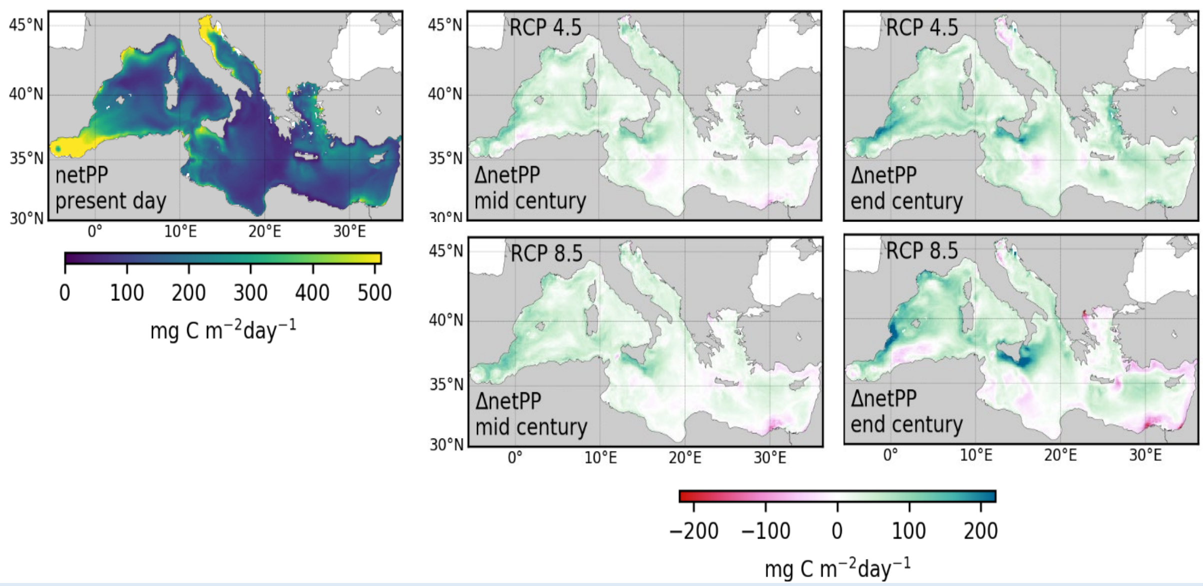


**Figure 2.10** Present day net primary production for the Mediterranean Sea (left) and projected change at mid-century (centre) and end century (right) for RCP4.5 (top row) and RCP8.5 (bottom row). Present day values are the median for 2000-2019, mid-century 2040-2059 and end century 2080-2099.

## 2.4 North Sea

The North Sea is projected to warm by about 2°C during the 21st century under RCP8.5 and about 1°C under RCP4.5 (Fig. 2.11), with comparable increases at the surface and bottom levels. These increases are in the range projected by global models, though some estimate a larger rise (Fig. 2.12a). A reduction of sea surface salinity of 0.5-0.7 psu is also projected.

Some global models project a much larger decrease in North Sea production compared to the regional model utilized in CERES (Figure. 2.12b), but global models are not optimised for shelf seas and so, in this case, the regional model is more likely to be reliable. The regional modeling performed in CERES shows reduced production in most of the North Sea (Fig. 2.12). Production is projected to increase near the Norwegian Trench, but this should be considered unreliable because changes in nutrients from the Baltic outflow were not included in the modeling.

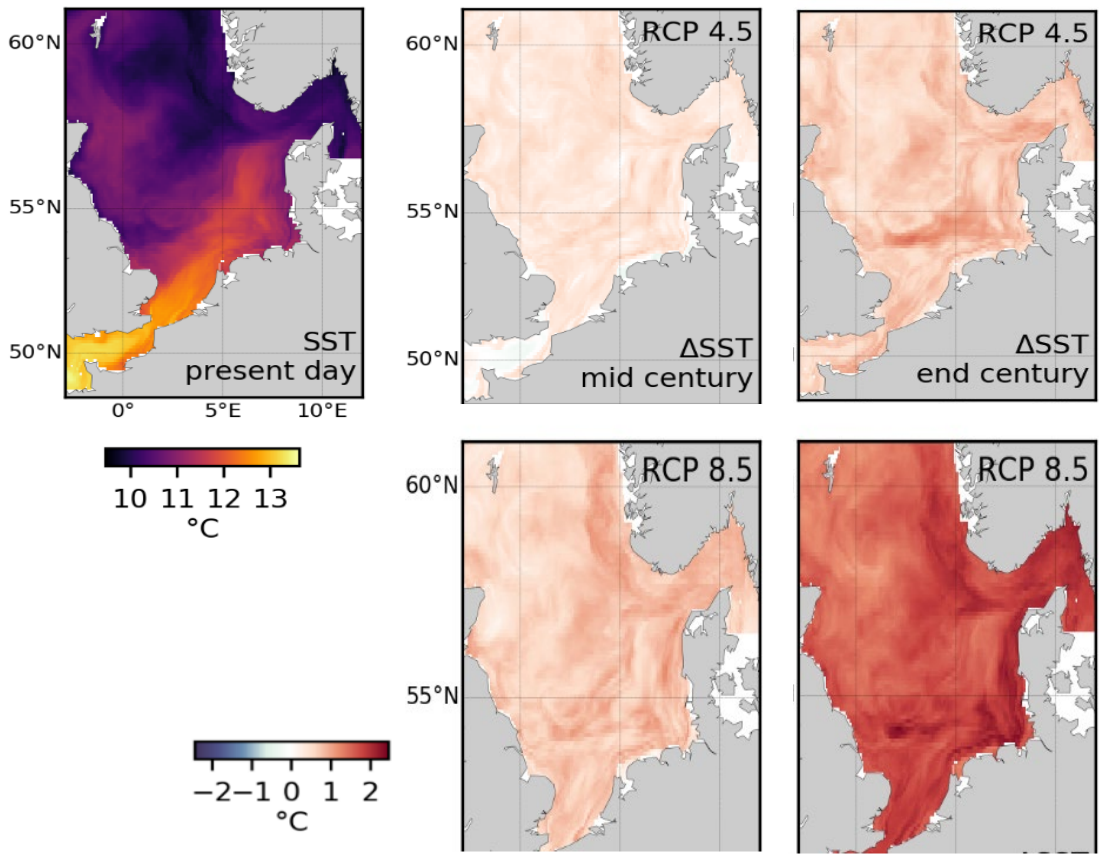


**Figure 2.11** Present day sea surface temperature for the North Sea (left) and projected change at mid-century (centre) and end century (right) for RCP4.5 (top row) and RCP8.5 (bottom row). Present day values are the median for 2000-2019, mid-century 2040-2059 and end century 2080-2099.

## 2.5 Baltic Sea

Projections of climate change impacts in the Baltic Sea were based on downscaled output from several global climate models as forcing for a regional ocean model (Saraiva et al. 2019a&b [internet]): the figures below show the average and range of values from this ensemble of simulations.

As well as climate change, the effect of changes in river nutrient inputs was tested by comparing model runs using inputs consistent with water quality improvements under the Baltic Sea Action Plan (BSAP) to those using a scenario of today's level (reference) and a scenario of deteriorating water quality (worst).

Temperatures are projected to rise by about 1°C in the first half of the century, with a further 2°C rise by the end of the century under RCP8.5, but only 0.5°C under RCP4.5 (Fig. 2.14).

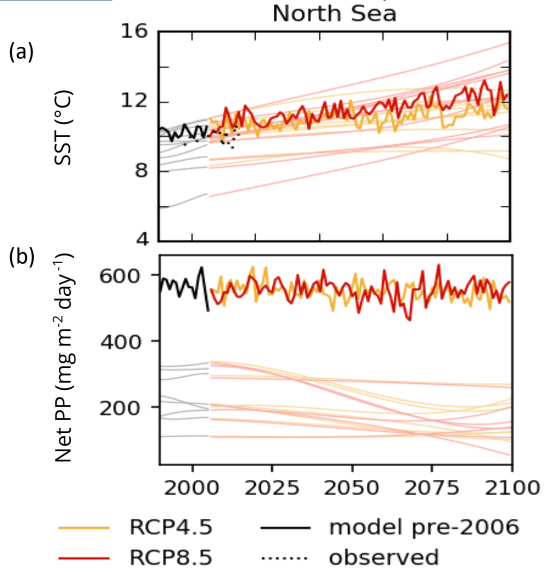


**Figure 2.12** Annual average (a) sea surface temperature and (b) net primary production (column total) for the North Sea. The fainter lines are from global models, smoothed to show trends. Observed = merged satellite and in situ measurements.

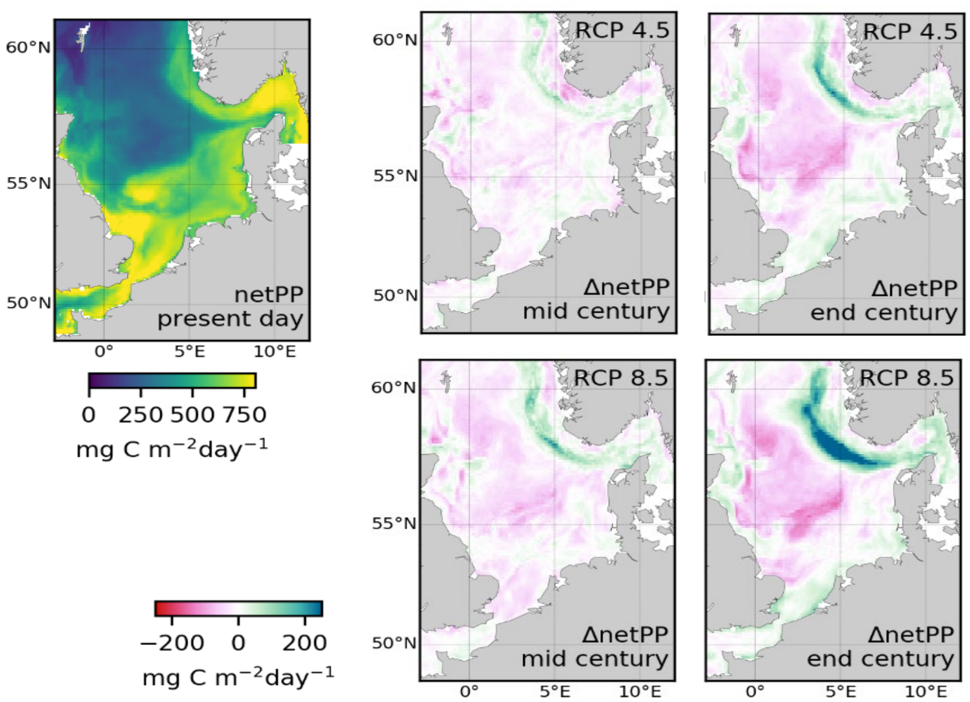


**Figure 2.13** Present day net primary production for the North Sea (left) and projected change at mid-century (centre) and end century (right) for RCP4.5 (top row) and RCP8.5 (bottom row). Present day values are the median for 2000-2019, mid-century 2040-2059 and end century 2080-2099.

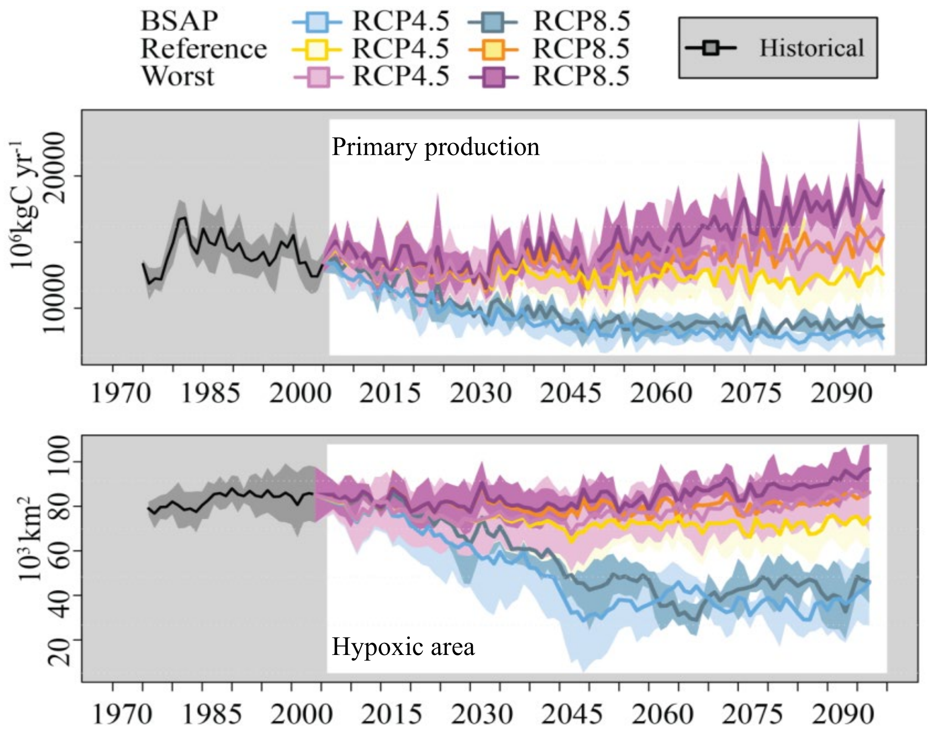


**Figure 2.14** Volume averaged primary production and hypoxic area in the Baltic Sea for 1975–2098 and their standard deviations among ensemble members. For all combinations of the two greenhouse gas concentration scenarios (RCP4.5 and 8.5) and the three nutrient load scenarios (BSAP, Reference and Worst Case) the ensemble mean and spread were calculated from four regionalised global climate simulations (from Saraiva et al. 2019b, their Figure 9).

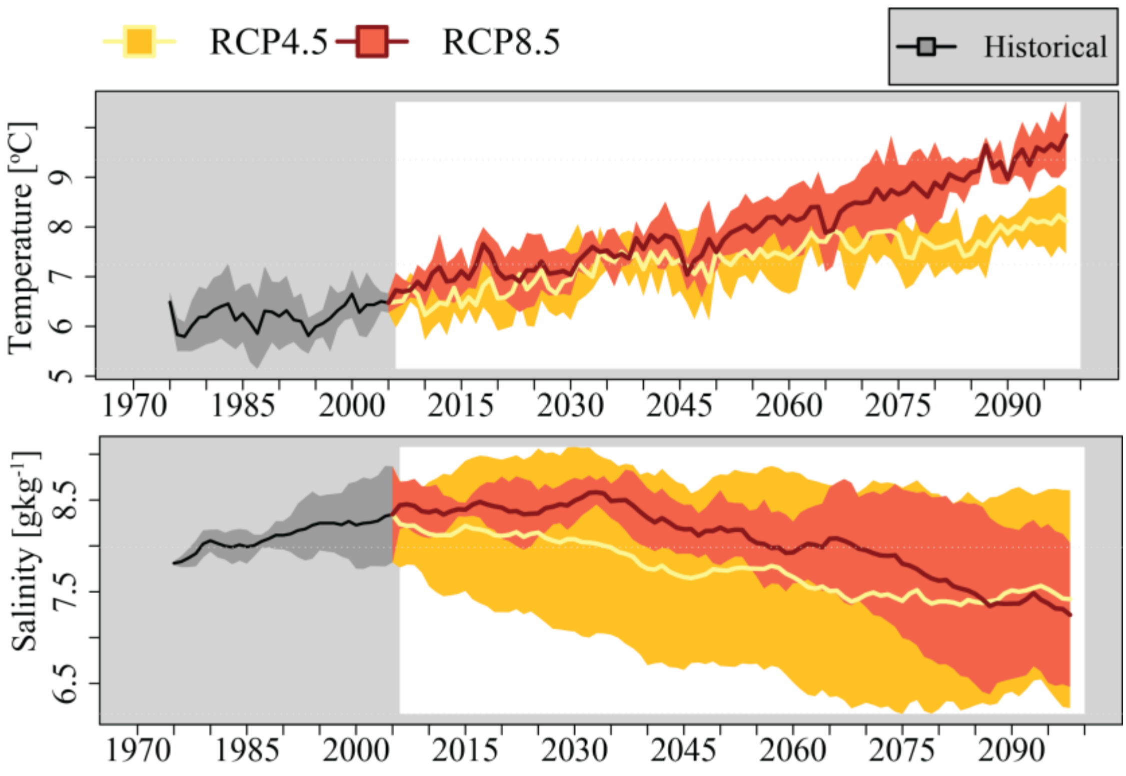


**Figure 2.15** Volume averaged temperature (in °C) and salinity (in g $kg^{-1}$) for the Baltic Sea for 1975–2098, RCP4.5 (orange) and RCP8.5 (red). The shaded areas denote the standard deviations among the ensemble members (see Saraiva et al. 2019b, their Figure 6).

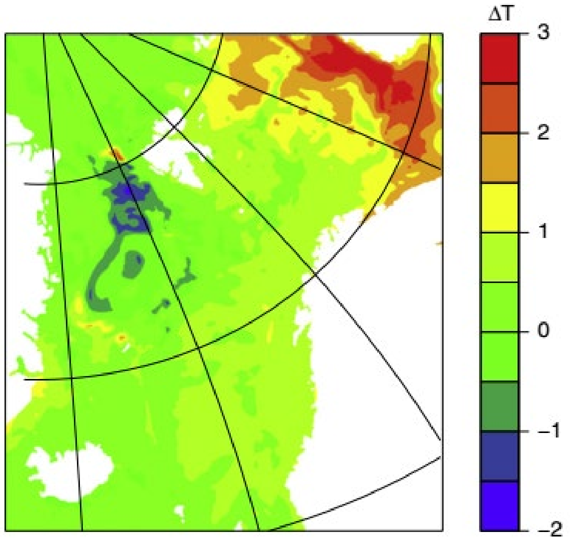


**Figure 2.16** Modeled change in sea surface temperature (°C) between 1998-2000 and 2063 to 2065 (from Skogen et al. 2014, their Figure 11).

Salinity is expected to fall under both RCPs, but the size of fall varies widely between models and so is uncertain.

Primary production in the Baltic Sea has declined in recent years and is projected to continue decreasing until about 2030 (Fig. 2.15). After 2030, future changes in primary production depend on river nutrient inputs. In the BSAP scenario production continues to fall and then stabilises around 2050. In the reference and worst-case scenarios production stabilises and, under RCP8.5, starts to rise again from mid-century.

For nutrient concentrations and other biogeochemical variables, the effects of river inputs are stronger than climate change. The Baltic Sea Action Plan (BSAP) scenario leads to an improvement in the health of the Baltic Sea, even under the high-emissions RCP8.5 scenario, with a reduced hypoxic area.

## 2.6 Norwegian and Barents Seas

Regional modelling for the Norwegian and Barents Seas has been carried out up to 2070 under RCP4.5 (Skogen et al. 2014 & 2018); CERES used information from global climate models to give equivalent extended projections to end of the century and for RCP8.5.

Sea surface temperatures are projected to rise by 0.5°C in the Norwegian Sea and 2.5°C in the Barents Sea by 2060 relative to present conditions, under the RCP4.5 (moderate) climate scenario and by 0.6°C and 3°C respectively by the end of the century (Fig. 2.18, overleaf). The corresponding increases for RCP8.5 are 1°C in the Norwegian Sea and 5.3°C in the Barents Sea. These are rather imprecise projections, but they agree well with global projections of the 5th Coupled Model Intercomparison Project (CMIP5) that suggest a 3°C increase in the Norwegian Sea and 4 to 5° C increase in the Barents Sea (Alexander et al. 2018).

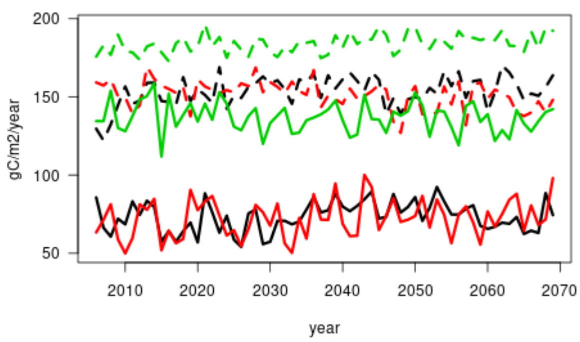


**Figure 2.17** Annual mean gross primary production for Barents Sea (black), Greenland Sea (red) and Norwegian Sea (green) under the RCP4.5 climate scenario. The dashed lines show projections from a regional model and the solid lines show a global model (from Figure 8 of Skogen et al. 2018).

Increased precipitation and melting sea ice will freshen the water but increased Atlantic Water inflow will tend to increase the salinity. Some climate models suggest a decrease in near surface salinity and, in combination with increasing temperatures, an increase in vertical density stratification. With the high heat content in the Barents Sea, sea ice will decrease and disappear altogether in the Barents Sea during summer under RCP8.5.

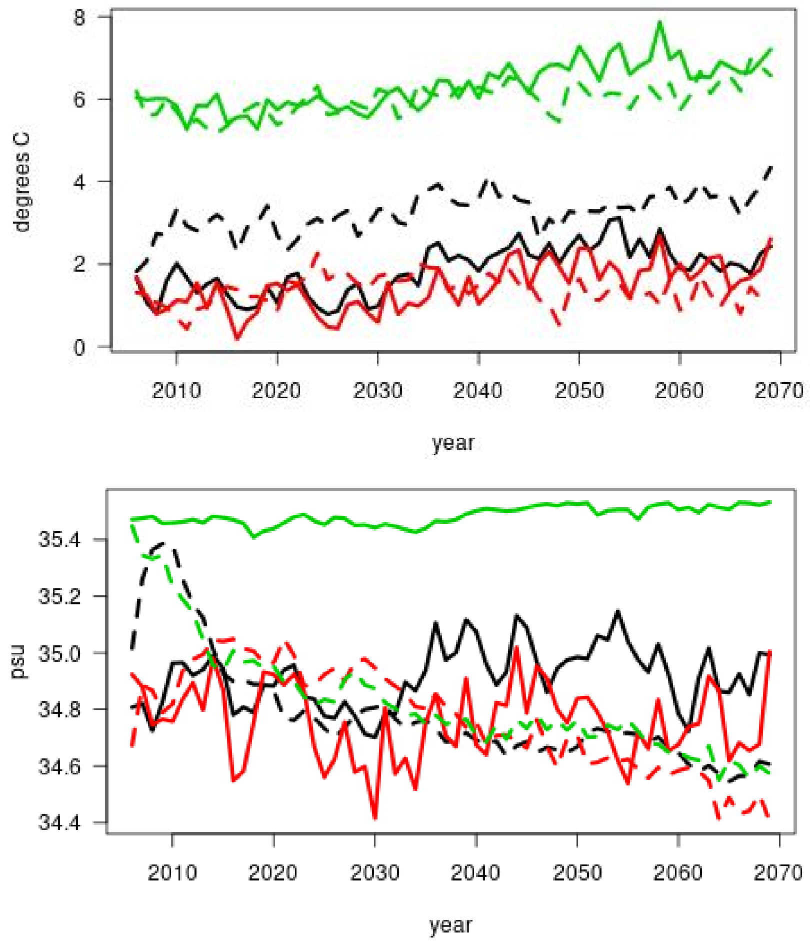


**Figure 2.18** Annual mean sea surface temperature (top) and salinity (bottom) for Barents Sea (black), Greenland Sea (red) and Norwegian Sea (green) under the RCP4.5 climate scenario. The dashed lines show projections from a regional model and the solid lines show a global model (from Figure 3 of Skogen et al. 2018).

Regional modelling shows no clear trend in gross primary production (Fig. 2.17); however modelling studies vary in the size and direction of any projected trend and future changes in primary production should be treated as uncertain. In areas that currently have seasonal ice cover, annual primary production is projected to increase and satellite imagery shows an increase over recent years (Filin et al. 2015). The pH is projected to decline by 0.1 to 0.2 pH units over the period to 2060 under RCP4.5.

## 2.7 Inland waters

Fig. 2.19 shows projected change in discharge for river basins across Europe. The projections were produced from an ensemble of global climate models, downscaled to Europe using several regional climate models, which were then used to drive the hydrological model E-HYPE (Donnelly 2016).

River discharge is projected to decrease in southern Europe and increase across the north, though there are local variations in a number of places. The magnitude of change intensifies through the century and is greater under RCP8.5 than under RCP4.5. Projected decreases by the 2080s are up to 25% under RCP4.5, up to 50% under RCP8.5. The biggest increases are projected for Norway and Sweden, with discharges 10-25% higher by the 2080s.

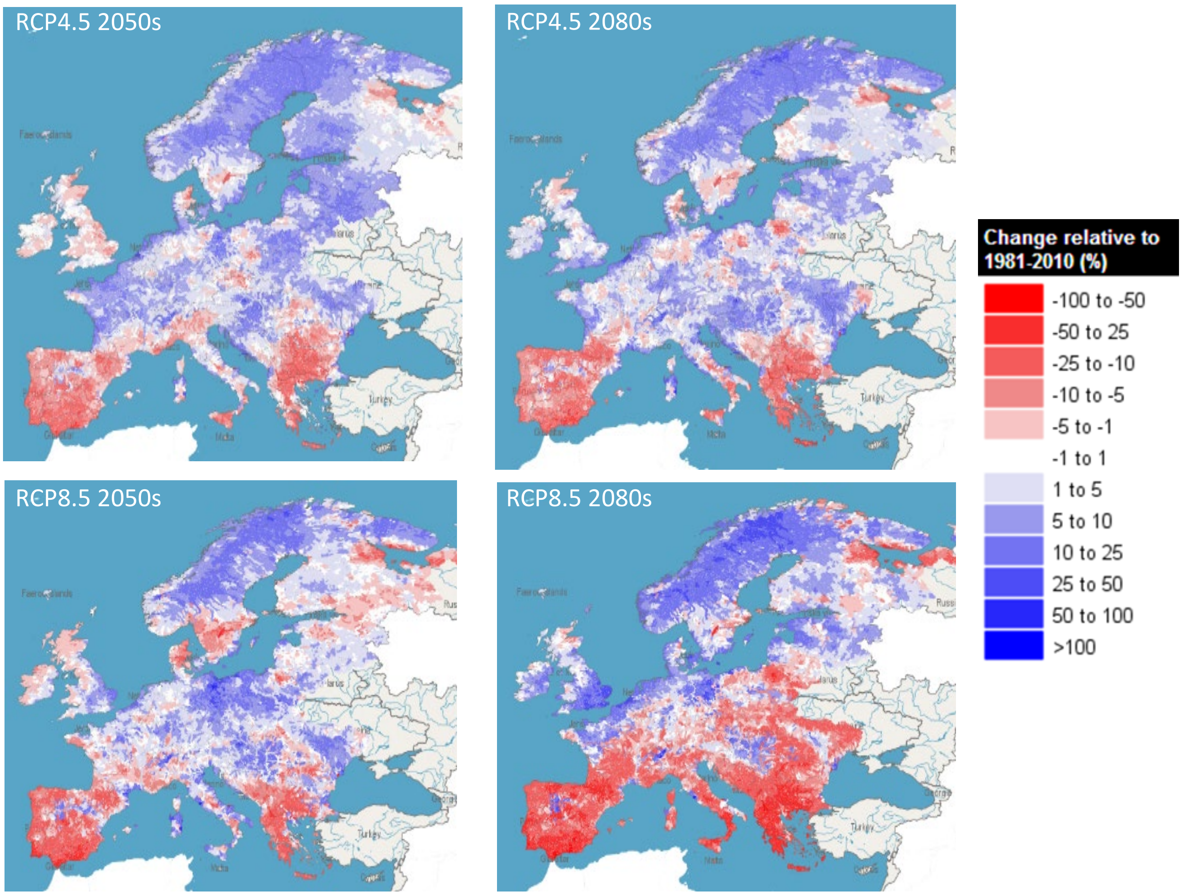


**Figure 2.19** Change in river discharge (%) projected using RCP4.5 (top) and RCP8.5 (bottom). The left-hand column shows changes from the present day to the 2050s, the right hand column shows change to the 2080s.

Modelling has also made it possible to investigate changes in the lowest and highest flow rates. Low stream flows are projected to increase in northern Europe but decrease in the south and in coastal areas throughout Europe. Flood flows decrease throughout the century under RCP4.5 but decrease and then increase under RCP8.5

In all cases, the ensemble range is wide, and the projections should be considered to have high uncertainty. Changes in riverine water temperature may be a significant stressor for aquatic life as climate change continues. A useful summary has been produced by the European Environment Agency (EEA 2016). Surface temperatures in major European rivers have increased by 1-3°C in the last 100 years and are expected to increase further this century.

Projections from a global model of river discharge and water temperature suggest a further warming of 1-3°C this century, with the biggest increases in southern and central Europe (van Vliet et al. 2013). Europe is projected to see some of the largest increases globally, with the warming tendency being exacerbated by reduced flows and an increase in seasonality.

Projected changes in air temperature give information about how inland water temperatures will change, and Fig. 2.20 shows surface air temperature from one regional model. The areas of highest projected temperature change are likely to be in southern Europe and Scandinavia. Comparison with the range of climate models suggests an uncertainty in the projected air temperature change of about 1°C, with the model shown having an average to low value.

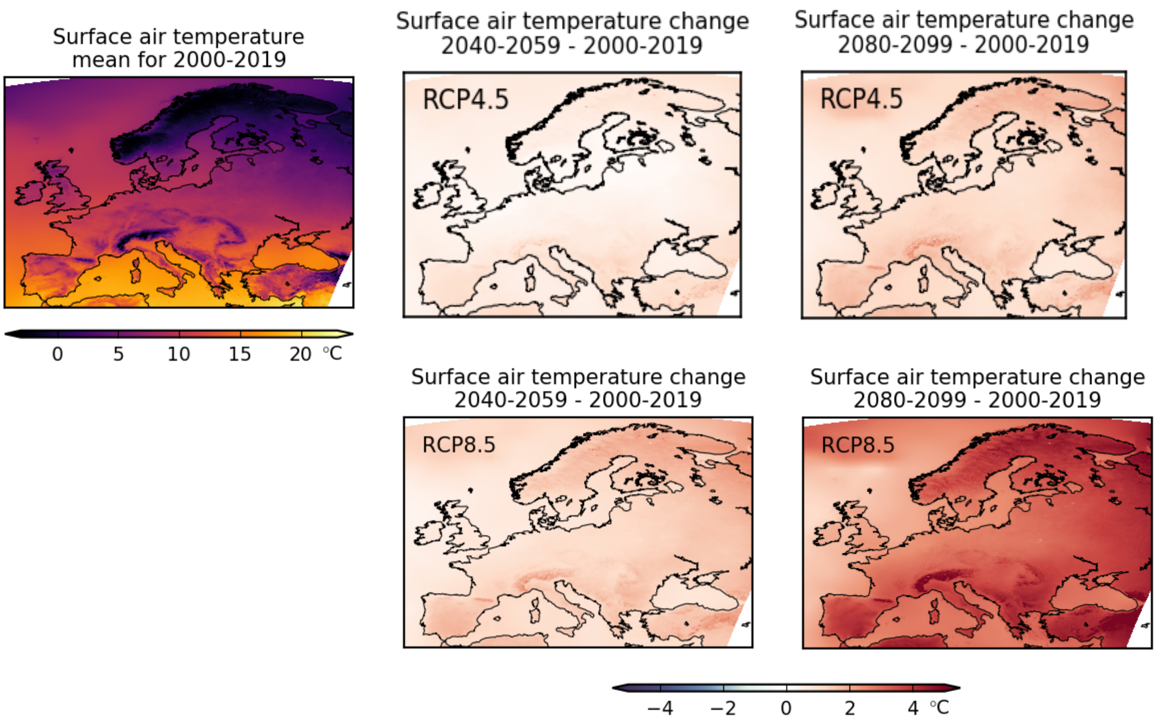


**Figure 2.20** Modelled surface air temperature for the present-day (left) and change in surface air temperature for mid-century (centre) and end century (right). The top row shows a RCP4.5 projection, the bottom row shows RCP8.5.

For modelling changes in temperature of inland waters, the modelled air temperatures were converted to freshwater temperatures using a regression method based on projected change in mean temperatures and in the annual minimum and maximum. This does not include local factors that can affect the relationship between air and water temperature at a particular site, but it gives a gives a good guide to expected change.

## 2.8 Comments on quality and uncertainty

For marine areas except the Baltic Sea, it was only possible to produce one regional climate model in the CERES project (three for the Baltic), so it is not possible to provide quantitative estimates of uncertainty. Comparison with the outputs of global climate models and other regional model outputs (Tinker et al 2016) gives some information about the range of possibilities within which are placed the CERES projections for the NE Atlantic and Mediterranean Sea are placed: see sections 2.2-2.4. Note that the global climate models are not able to resolve all the features and processes which are included in regional modelling, but they give a guide to the range of potential future outcomes.

The Baltic Sea projections in section 2.5 were created using an 11-member ensemble covering a range of greenhouse gas and river nutrient conditions, so the range of outputs from the ensemble gives an indication of uncertainty. For Arctic regions, the range of outputs from global models is particularly large. The downscaled projections in section 2.6 were created using a global model selected as giving the best performance in that region but other downscaled models are not currently available. For inland waters, the projections shown are the average from an ensemble of runs; the range from the ensemble is wide and so the projections should be considered to have high uncertainty (CERES D1.4 2017).

Global modelling indicates that one area of particularly high uncertainty, affecting European seas, is the future positioning of the Gulf Stream (IPCC 2013). If the Gulf Stream is at the lower latitude (southern) end of the projected range, cold Arctic waters can push further south and this restricts warming in North-west European Seas. A higher-latitude (more northerly) position of the Gulf Stream, however, would allow a greater increase in temperature. For this reason, a relatively wide range of temperatures is projected from different global models for the Atlantic coast of Europe (Fig. 2.3). The temperature increases projected by CERES modelling are moderate to low compared to the range of global model projections and larger increases should be considered possible.

The reliability of CERES modelling has been assessed by comparison with present-day observations and details can be found in the deliverable report (CERES D1.3 2018). Measurements of sea surface temperature for 1998-2015 are included in sections 2.2 to 2.4 of this chapter and CERES model outputs for this period are generally within the range of observations; analysis shows a strong correlation between observed and modelled sea surface temperature. The agreement is less good for biogeochemical variables such as chlorophyll and nitrate, but the model is still able to reproduce the observed patterns of seasonal change, giving some confidence in its use.

The Baltic model has been assessed using multiple time series of measurements in that region. It shows a good match to observed temperature and salinity and captures the main biogeochemical processes. The model used for the Norwegian and Barents Sea has a good match to observed temperature and to spatial patterns of salinity, though it slightly underestimates salinity. Outputs from the hydrological model used for inland waters have a good correlation with observed flows with errors of less than 30% in most cases (CERES D1.4 2017).

## 2.9 Changes in sea level and storminess

CERES used information on projected sea level rise and storminess from the IPCC Assessment Report 5 (IPCC 2013). Globally, mean sea level is projected to rise by 0.3-0.8 m by the end of the 21$^{st}$ century, perhaps more if the West Antarctic ice sheet collapses. Sea level rise in Europe is projected to be slightly higher than the global mean for the Atlantic and southern North Sea, slightly lower for the Mediterranean and up to 30% lower for regions at the highest latitudes.

Projections of changes in storminess have high uncertainty; there are some indications of an increase in extreme wind speeds in northern and central Europe, with medium confidence and a slight decrease in southern Europe (low confidence). An increase in extreme sea level events is projected around the UK and Ireland and, with less confidence, for the southern North Sea.

Rainfall is projected to increase in northern Europe, particularly in the winter, and decrease in southern Europe. Changes of the order 20% are projected in each case under RCP8.5, but the details have high uncertainty (IPCC 2013).

## 2.10 Downscaling to aquaculture farms

In Europe, most marine aquaculture takes place either in estuarine and fjordic systems or on the inner shelf. The CERES regional climate models have a 10 x 10 km (100 km$^2$) spatial resolution, which is too coarse to apply directly to aquaculture modelling of farms in embayment or coastal waters. For farm-scale biological modelling, observations at each study site were combined with information about trend and variability from the regional models to obtain present-day, mid-century and end-of-century responses to climate change under the RCP4.5 and RCP8.5 scenarios.

The steps followed were:

- Set a baseline of one year or more of measurements of the main environmental drivers;
- Fill gaps between observations by linear interpolation, scaling the dynamic range of the regional model at that location and time period, to create a consistent set of present-day conditions;
- Apply the same scaling method to the regional model future projections at that location to create a comparable future dataset;
- Select two years for mid-century and end-of-century models, for each species and climate scenario, to represent the extremes of possible conditions;
- For the fish species, warmer and colder years were selected for each location and time period, with the colder year having the lowest number of days below the 10th percentile of daily temperature and the warmer year the one with the highest number of days above the 90th percentile.
- For bivalve shellfish species, a single individual model was run for the full combination of scenarios and the years yielding highest and lowest harvestable biomass were selected;

The one-year sets of present and future conditions were repeated for each model to reproduce the distribution of possible outcomes within a twenty-year interval time-slice.

The FARM model (Ferreira et al. 2016), method was used to produce estimates of farm-relevant variables such as harvest weight and dissolved oxygen, enabling future estimates to be compared to the present-day under each RCP – examples are included in the CERES storylines for aquaculture species and summarised in Chapter 5 of this synthesis report. The effect of selecting extreme years means that the two RCPs can have different ranges for the present day, so comparison should be between time periods for each RCP rather than between RCPs. The plots are intended as qualitative guide; numerical values should be considered as approximate.

## 2.11 The potential for seasonal forecasting to support the fishing and aquaculture industries

Adapting to climate change poses many challenges for the fishing and aquaculture industries. The projections described in this chapter illustrate potential medium- and long-term change in the marine environment, but there is also a need for shorter-term forecasts to assist with adaptation. The skill of such forecasts, from a few weeks to a few years ahead, is increasing and these forecasts can provide information relevant to industry and policy makers (Payne 2017, Tommassi et al. 2017).

In some cases there is sufficient observational evidence available to link the distribution and productivity of a species to environmental conditions on these short time scales. This information can be used to build a spatial distribution or production model, which can then be linked to an environmental forecast. One example is forecasting of coral reef bleaching, where NOAA's Coral Reef Watch provides a bleaching outlook four months ahead, available online to reef managers worldwide.

Several examples exist where short-term forecasts have been utilised for fisheries. Seasonal forecasts of southern bluefin tuna in the Great Australian Bight are assisting an industry that was struggling with unexpected shifts in the range of this quota-managed species. Seasonal forecasts (online, updated weekly) of the start date of the lobster fishery in Maine, USA, allowed the industry, including fishers, packers and transporters, to anticipate the timing of the spring migration and be ready to respond quickly when landings increase; this could help them to avoid heavy losses due to an unusually early spring, as happened in 2012.

The aquaculture industry already uses forecasts a few days ahead to plan operations, for example to allow for changes in temperature or pH. Seasonal forecasts would enable strategic planning and investment, particularly in cases where climate change is making current methods less effective. For shellfish farming, forecasting of harmful algal blooms is currently limited to timescales of less than one month but there is potential to extend this. Since 2012, two-month forecasts of temperature and rainfall have been available to the prawn industry in Queensland, Australia. The delivery system was developed with farm managers to ensure that it is effective and useful.

Although these early examples are based in North America and Australia, there is evidence that the North Atlantic has good seasonal and even decadal predictability and so there is scope to develop similar services in Europe. To help identify where forecasts with useful skill could be most easily developed, three best practices have been suggested (Payne 2017):

- Where possible, apply mechanistic as opposed to empirical models;
- Use environmental forecasts with the most skill: forecasts of temperature are usually more accurate than those of plankton;
- Focus on cases where there is a close cause-and-effect link between the physical driver and the biological response.

Most importantly, however, such forecasts need to be driven by the needs of the user. From meteorology, it is well established that the value of a forecast is not determined by its skill from a scientific perspective, but by whether a stakeholder uses it to make decisions. Developing valuable forecasts to support climate adaptation therefore requires a fundamental change in the relationship between science and society.

Rather than being driven by scientific curiosity, a demand-driven approach is required, based on the needs of society. The best way to approach this is in the context of a close collaboration between scientists and decision makers, working in a co-design and co-production approach. Good forecasts that support climate adaptation occur where the needs of decision makers can be satisfied by an approach that is scientifically feasible (Payne 2017).

# 3

# Social and economic developments in Europe

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# Chapter 3: Social and economic developments in Europe

## 3.1 CERES scenarios

As climate scientists strive to provide improved advice within the context of a changing environment, it is essential to consider how societal development might at together with physical climate to impact aquatic ecosystems and aquatic activities and, hence, the goods and services provided to society.

Short-, medium-, and long-term developments in governance, social, technological and economic drivers may be just as important as climate in determining the status, abundance and distribution of habitats or species. Scenarios are imagined 'futures', they are not used alone as a forecast, but are applied in sets of alternatives. Scenarios are not necessarily 'visions' or 'plans', but they can help to guide strategy. They describe both optimistic and problematic futures.

This chapter of the CERES synthesis report summarises the scenarios designed by CERES, particularly focusing on fisheries and aquaculture. Four socio-political scenarios were developed, based partly on the IPCC SRES (Special Report on Emissions Scenarios) framework and partly on the newer system of Shared Socio-economic Pathways (SSPs).

A set of quantitative outputs was generated for each CERES scenario. Specifically, projections were developed for seafood demand in Europe, as well as future fuel and fish prices. These four prototype CERES scenarios were further articulated and explored through a series of stakeholder workshops. Participants were tasked to outline how they thought their sector might develop in each of the four, different future worlds and to describe how Political, Economic, Social, Technological, Environmental and Legal (PESTEL) factors might look in each case.

We argue that it would be beneficial if a similar, standardised 'scenario' framework was adopted in other programmes projecting bioeconomic impacts of climate change to facilitate cross-comparison and harmonise the communication of results.

**Shared Socioeconomic Pathways (SSPs)**

A basic outline of the four, prototype CERES scenarios (Fig. 3.1) was provided to scientists and stakeholders at the CERES 'kick-off' meeting in April 2016. These social-political prototypes were based on outputs from previous scenario-construction exercises (e.g. Pinnegar et al. 2006, Langmead et al. 2007, Groeneveld et al. 2018). Personal visions of how the future might unfold under each of the four scenarios were gathered (Figures 3.2 and 3.3). The resulting outputs were then 'mapped' against the Shared Socio-economic Pathways (SSPs) framework published in 2016 by the IPCC, to ensure that CERES outputs could be taken up in the next IPCC assessment scheduled for 2021.

The SSPs were designed by the IPCC to be used alongside the Representative Concentration Pathways (RCPs) to analyse feedbacks between climate change and socioeconomic factors such as world population growth, economic development and technological progress (O'Neill et al. 2014). The SSPs consist of two elements: a narrative scenario and a set of quantified measures of development. van Vuuren & Carter (2014) provided a useful methodology for mapping the SSPs against the previous generation of IPCC SRES socio-political scenarios.

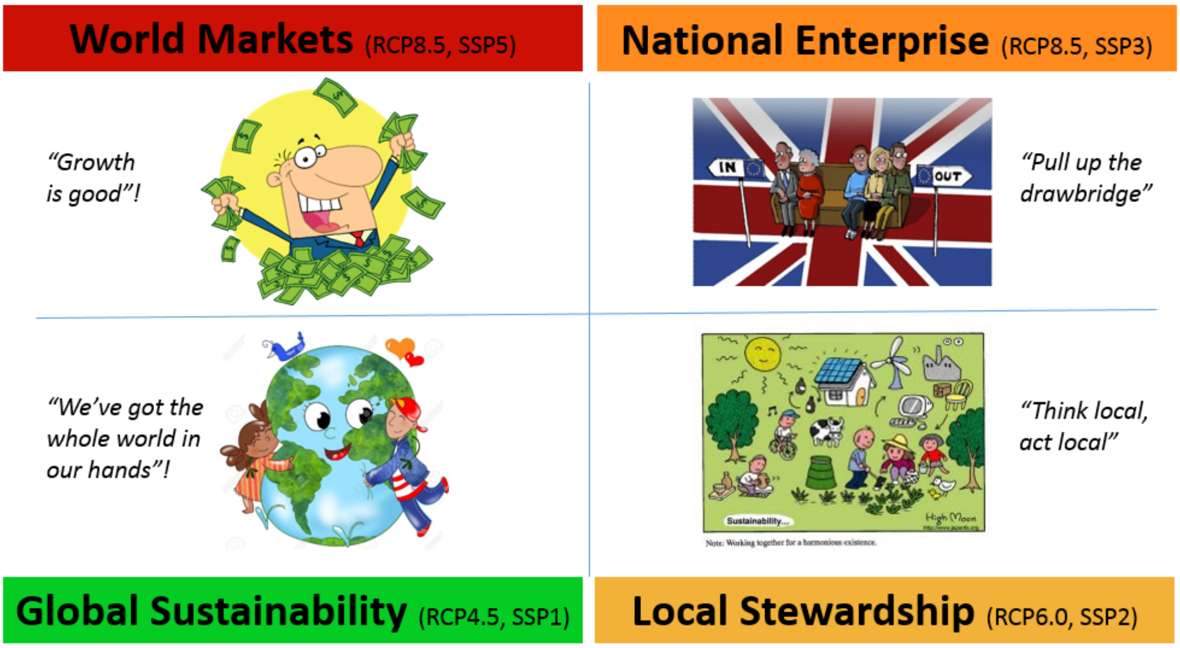


**Figure 3.1** The four CERES scenarios encapsulated in a single cartoon image and dramatic phrase. Note, no climate projections were made with RCP6.0 in CERES and, for Local Stewardship, RCP4.5 was assumed. RCP4.5 & RCP 6.0 are similar through 2070 (see Chapter 2).

A 'glossy report card' (CERES 2016) introduced the CERES socio-political scenarios to stakeholders early in the CERES project (month 6) allowing project partners to refer back to this common architecture for subsequent activities, irrespective of where they were working in Europe (from the Mediterranean Sea to the Barents Sea) or whether they were working on fisheries or aquaculture.

Additional quantitative analysis was carried out using recent outputs from the IIASA SSP community. These included research papers outlining the logic behind each of the five SSPs as well as a series of overview papers that talk about human demographics, GDP, urbanisation, land and energy use trajectories, etc. Information on individual European countries was extracted from the IIASA data portal.

The changing demand for fish and shellfish products within Europe is clearly influential in terms of governing how the fisheries and aquaculture industries will develop in the future. A considerable amount of previous modelling work provided regional predictions of per capita fish consumption (Failler et al. 2007, World Bank 2013).

Within CERES made use of these earlier scenario outputs and combined these with updated outputs based around the new SSPs. Seafood demand (Fig. 3.4) is driven by both world population size and the relative affluence of citizens.

**World Markets** (RCP8.5, SSP5)

- Fish obtained from the cheapest sources
- Decommissioning subsidies reduced
- Few legal and technical restrictions
- Only a few high-tech boats
- Sequentially depleted fish stocks
- More competition for resources globally
- Low taxes, strong private sector
- Europe outcompeted by Asia/China
- Use of cheap immigrant labour

**National Enterprise** (RCP8.5, SSP3)

- Maintaining national supply important
- Frequent 'cod wars'
- Decline in fish imports (import tariffs)
- Sport fisheries 'squeezed out'
- Higher fish prices and taxes
- Little new technology
- Food security more important than MPAs
- Individual Transferrable Quotas (ITQs)
- Increased disparity – rich and poor countries

**fisheries**

**Global Sustainability** (RCP4.5, SSP1)

- Fish from sustainable sources worldwide
- Equitable and ethical are important
- EU/international marine strategy
- Lower meat & fish consumption per capita
- Ecolabel certification schemes
- EIA required for new fisheries
- Traceability and quality standards
- Fisheries displaced by windfarms & MPAs
- Sustainable, low impact fishing gears

**Local Stewardship** (RCP6.0, SSP2)

- 'Bottom up' local/regional governance
- Self sufficiency viewed as important
- Large number of small/traditional vessels
- Improved opportunities for 'sport fisheries'
- Mosaic of different management measures
- Not worried about downstream impacts
- Equity and ownership are important
- Traceability standards important
- Individual Transferrable Quotas (ITQs)

**Figure 3.2** Draft socio-political scenarios elaborated for European fisheries by CERES partners and stakeholders.

**World Markets** (RCP8.5, SSP5)

- Huge expansion of offshore fish farming
- Luxury product vs anonymous fish protein
- *Pangasius* dominated aquaculture markets
- Extensive use of cheap immigrant labour
- Big businesses strive for value-for-money
- Frequent fish kills due to pathogens & jellyfish
- Global trading of aquaculture products
- Technology/automation important
- Low seafood prices, low energy prices

**National Enterprise** (RCP8.5, SSP3)

- High seafood prices, high energy prices
- Less technology, more labour
- Regional production with public subsidies
- Genetic engineering of aquaculture species
- Aquaculture to feed domestic tastes
- Some countries adopt new tech., others not
- Local certification and marketing schemes
- Food security dominates over environment

**aquaculture**

**Global Sustainability** (RCP4.5, SSP1)

- Tight regulation of inputs and outputs
- EIA required for new farms
- Traceability and quality standards
- Organic and fair-trade ecolabel schemes
- Technology transfer to poorer countries
- Carbon footprint considered
- Inland, closed systems more common
- Renewable energy powering most farms
- Expansion of offshore production

**Local Stewardship** (RCP6.0, SSP2)

- Local/regional governance –high autonomy
- Self sufficiency viewed as important
- Small scale, low-impact fish farming
- EIA required for all new farms
- Quality and traceability important
- Sale/marketing of locally produced products
- Greater variety of organisms farmed
- Strong incentives to recycle waste materials

**Figure 3.3** Draft socio-political scenarios elaborated for European aquaculture by CERES partners and stakeholders.

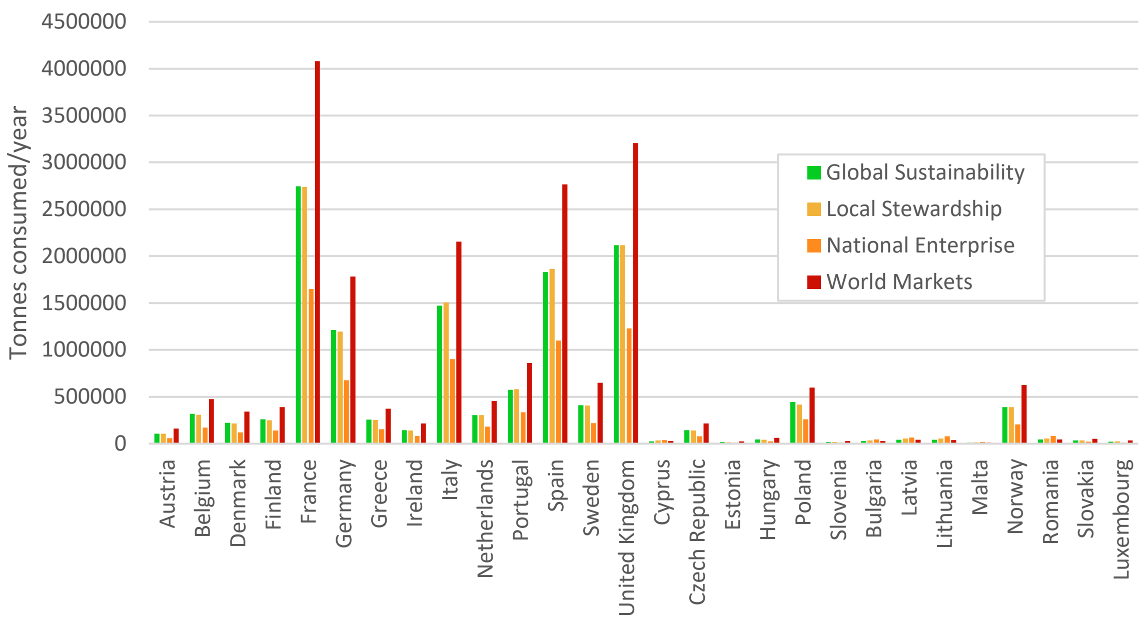


**Figure 3.4** Projections of total demand for seafood products (in tonnes/year) out to 2100 for each EUR-28 country and CERES Scenario.

### Fuel and Fish Prices

Fuel and fish prices are influenced by the global market and, for this reason, CERES used trends derived from the MAGNET model (Woltjer & Kuiper, 2014). MAGNET is a global general equilibrium model that is considered one of the best sources of projected prices up to 2050. The prices, provided in real terms and corrected for inflation (Fig. 3.5), are fairly similar among the scenarios. Annual change in rates ranged between +1.3 and +1.7% per year for fish and +2.6 and +2.9% per year for fuel prices. The simulation results are consistent with assumptions on future changes in GDP and population originally used by Riahi et al. (2017) to develop the SSPs as they result from the same EU project LUC4C *'Assessing the net climate forcing, and options for climate change mitigation and adaptation of land-use'* .

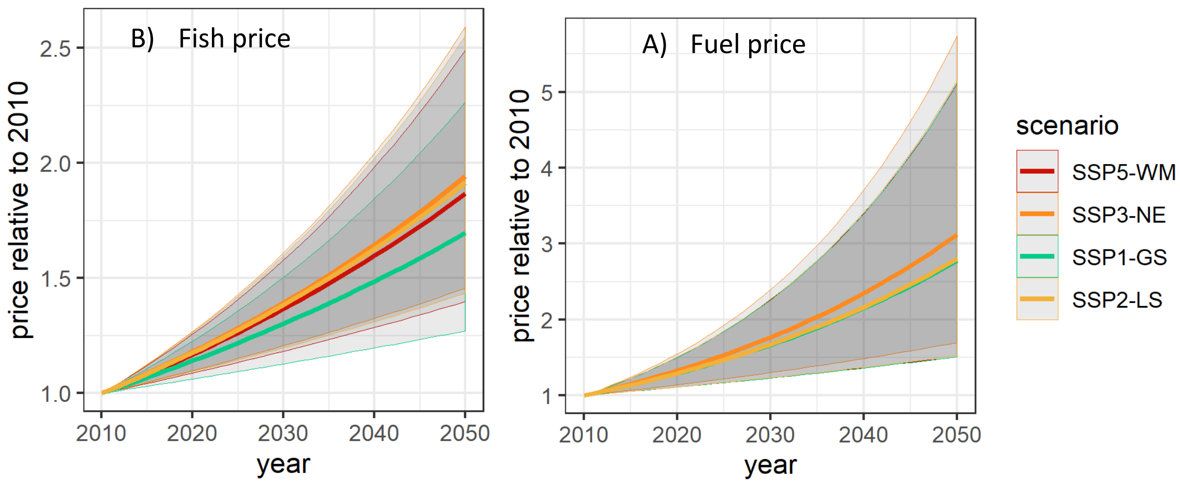


**Figure 3.5** Price trends relative to 2010 for the period 2010-2050 for the four CERES scenarios. The shaded areas correspond to the 95% confidence intervals.

## 3.2 Fisheries scenarios

For fisheries, a few aspects of the scenarios are of particular importance. In addition to the development of fuel and fish prices, governance and technological development have also been included in the CERES analyses. These were defined using (grey) literature, stakeholder consultation, legislation and expert knowledge.

### Different MSY targets to define the total level of catch

Fig. 3.6 shows fishery targets under each CERES scenario. In the World Markets scenario (WM: RCP8.5, SSP5), fisheries are expected to operate at the most efficient level from an economic perspective. The companies consolidate to the point of pseudo-monopoly and the fish stocks are exploited at the Maximum Economic Yield (MEY) or the level of exploitation that maximises the difference between revenue (proportional to the yield) and the cost of fishing (assumed proportional to the exploitation rate). The exploitation rate associated with MEY is typically estimated at 80% of the associated Maximum Sustainable Yield (MSY).

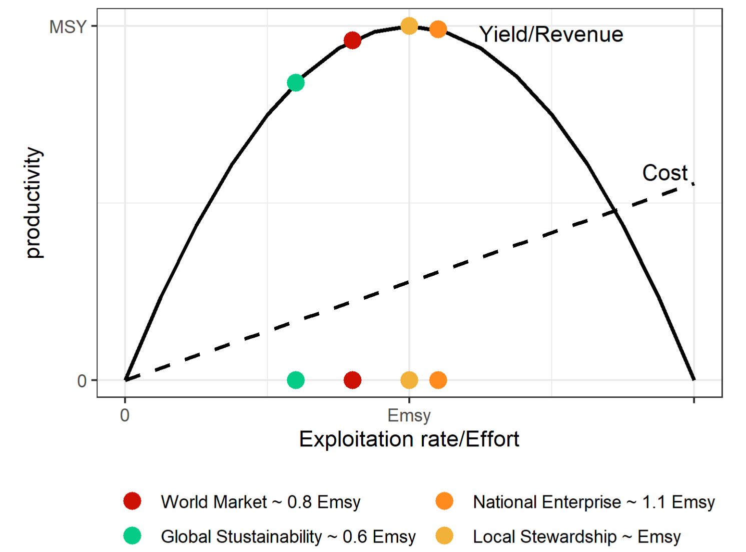


**Figure 3.6** Fishery targets under each CERES scenario, expressed in relation to the exploitation rate /effort leading to the Maximum Sustainable Yield (Emsy)

In the National Enterprise scenario (NE: RCP8.5, SSP3), conflicts between nations exploiting the same stocks are expected to arise. The lack of agreement on how to share Total Allowable Catch (TAC) among nations, as well as the added, local political will of maintaining the largest possible fleets that provide employment, leads to the over-shooting of the sustainable TAC and, in the long term, to the overexploitation of stocks at about 110% of the MSY.

In the Global Sustainability scenario (GS: RCP4.5, SSP1), priority is given to maintaining ecosystems and the whole ecosystem is therefore considered in fisheries management. This philosophy results in a limitation of catches from mixed fisheries not only by the 'choke'[2] effect of the least abundant commercial species but also because fishing gears also encounter vulnerable and endangered species. Exploitation levels associated with multispecies MSY are, therefore, reduced (60% of the MSY) to protect all species from overfishing. In the Local Stewardship scenario (LS: RCP6.0, SSP2), sustainability remains an important issue but the scope of regulation is limited to the local resources. Therefore, the exploitation level associated with the current MSY is the management target.

[2] Having to stop fishing for a species A for which one still has quotas because the quota of a species B, caught at the same time, is exhausted is called the 'choke' effect

### Marine spatial planning

Coastal areas are becoming increasingly busy with the development of human activities. These activities are already competing for space with the fishery. For example, the amount of area in the North Sea remaining for fisheries is expected to decline in the coming 30 years (Matthijsen et al. 2018). Depending on the scenario, the development of wind farms, marine protected areas or the closure of British waters to European fishing vessels in the event of a hard Brexit may lead to the closure of a large part of the traditional fishing grounds (see Fig. 3.7). Spatial areas closed to fishing due to various activities (e.g. MPAs, windfarms, oil and gas rigs) were included in the CERES scenarios drawing on Matthijsen et al. (2018). By comparing the future closures to the current situation, fishers' access to fishing ground is expected to be greatly reduced over the 2015-2050 period under all four future scenarios.

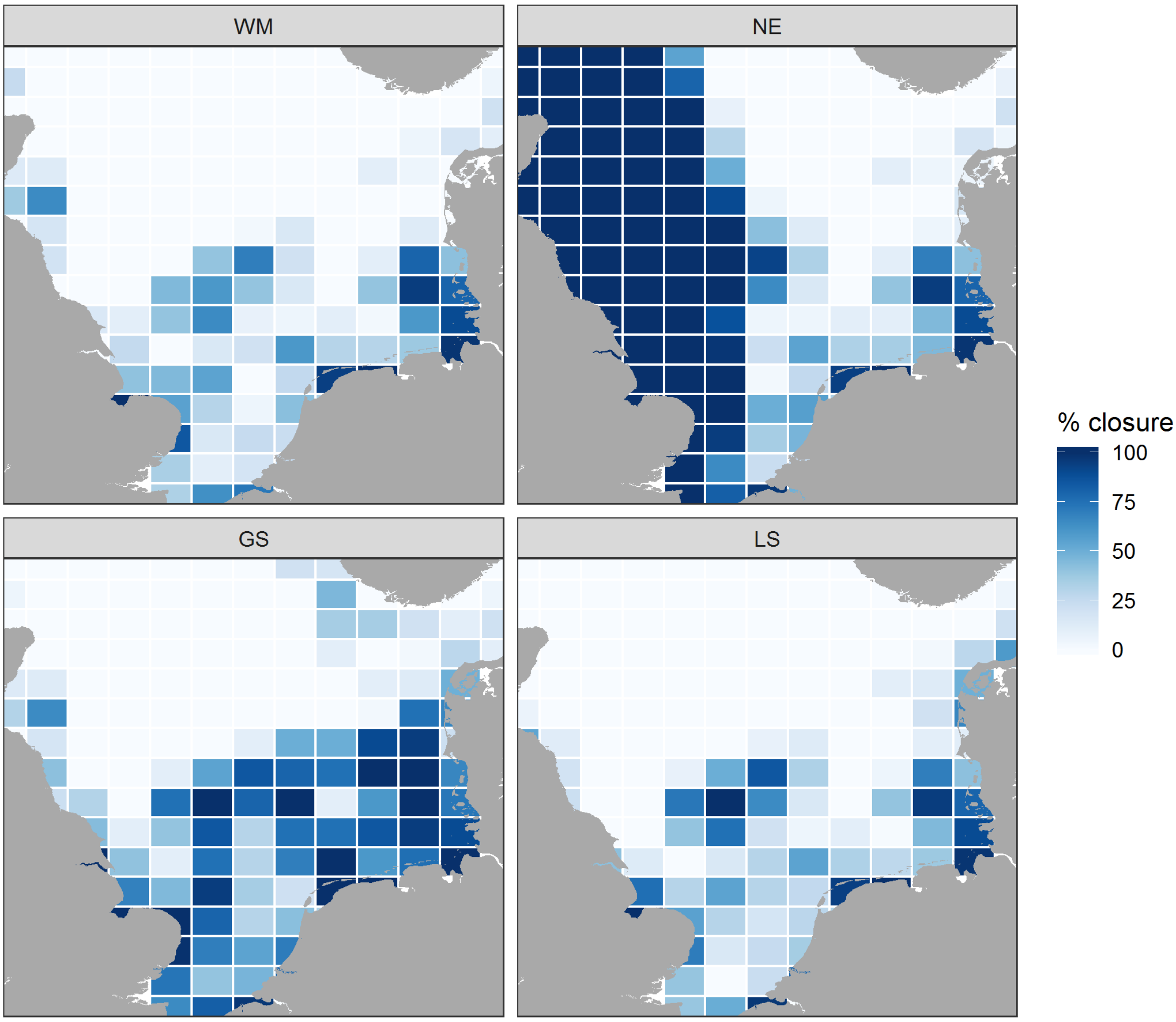


**Figure 3.7** Area closure scenarios in the 2050 North Sea for bottom contact gears operating from the EU mainland

### Distribution of fishing rights between national fleets

Changes in the distribution of fish stocks and changes in the access to fishing grounds previously described raise difficult questions on how the TAC or fishing effort should be shared amongst fishing fleets from different nations in the future. Countries and fleets that are party to the EU Common Fisheries Policy (CFP) are able to operate anywhere within EU Community waters but are subject to the principle of 'relative stability'. The 'relative stability' principle was first established in 1983 in order to avoid protracted fishery quota negotiations each year. The TACs are divided among Member States on the basis of their historic 'track record'. In each case the 'relative stability' allocation keys grant countries a fixed percentage of TACs (in perpetuity), and shares have remained constant over time.

The 'reference period' for relative stability arrangements was taken as 1973-1978 and it is known that the distribution of many (if not most) species and fisheries have changed during the intervening 40-yr period (e.g. see ICES 2017). For fisheries management and governance to be truly 'adaptive' to distribution shifts would require adaptive structures that allow access and allocations to be based on updated information that reflects current, and future prevailing conditions, and places less emphasis on an historical track record (Pinsky et al. 2018).

Economic aspects are expected to take precedence over a number of existing regulations in the World Markets (SSP5) scenario. Typically, TACs can be distributed by privatising all fishing rights, irrespective of country, using individual transferable authorisations. A new repartition of fishing rights occurs by buying and selling those authorisations across borders.

In the National Enterprise (SSP3) scenario, territoriality is very important and the share of fishing rights per nation reflects the distribution of fish in the national waters, i.e. the concept now known as 'zonal attachment'. This new allocation key is then strictly applied. In order to maintain a large national fleet (of small vessels), fishing rights are not transferable from one vessel to another.

As in the World Market scenario, fishing rights are transferable in the Global Sustainability (SSP1) scenario. The sustainability of the gears used, however, is taken into account. New quota can be purchased by participants that use gears that cause less damage. In this scenario, it is also possible for environmental NGOs to buy fishing rights that are subsequently not used in order to further decrease the fishing pressure.

In the Local Sustainability (SSP2) scenario, relative stability arrangements are revisited but remain important to ensure an equitable allocation of the fishing rights to local people. Those rights are transferable within a country and are linked to local fishing grounds.

**Technological changes**

Fuel is an important cost for fisheries operating with towed gears. While prices are expected to increase in all scenarios (see previous section), technological developments and particularly the fuel efficiency of engines partly compensates for the price increase.

This is especially true for the more global, collaborative scenarios (World Market and Global Sustainability) where the most efficient and sustainable techniques prevail, allowing all EU fisheries to reach the EU target of 75% decrease of $CO_2$ by 2050 (compared to the 2017 level). Fisheries only reach half of that EU reduction target through technology in other two scenarios (National Enterprise and Local Stewardship).

**Application of fisheries scenarios**

Within CERES, different bioeconomic models were applied in different regions and regions depending on data availability. For these and other practical reasons, not all elements of the four scenarios were applied across all CERES Storylines (see Chapter 1) as summarised in Table 3.1.

**Table 3.1** Summary of the application of CERES scenarios (WM = World Markets, NE = National Enterprise, GS = Global sustainability, LS = local stewardship) and their various component in the different CERES fisheries Storylines.

| Storyline | Scenario | Environment | Economic | Legal (Management) | Technological | Political/Social |
|---|---|---|---|---|---|---|
| **NoBo Atlantis** | WM | RCP4.5 | Fleets not explicitly modelled. Fish price scenarios used a posteriori on catch | $E_{MSY}$ 0.8 | Not applied | Same set of exploitation rates, but including 5 additional species, among these mesopelagic fish and mesozooplankton |
| | NE | RCP4.5 | | $E_{MSY}$ 1.1 | | |
| | GS | RCP4.5 | | $E_{MSY}$ 0.6 | | |
| | LS[1] | RCP4.5 | | $E_{MSY}$ | | |
| **Baltic Atlantis** | WM | RCP8.5 | Price scenarios as defined in sub-chapter 3.1 | Not applied | Technological scenarios as defined in section 1.2 | |
| | NE | RCP8.5 | | | | |
| | GS | RCP4.5 | | | | |
| | LS[1] | RCP4.5 | | | | |
| **NEA small pelagics** | WM | Herring recruitment failure specific to RCP4.5 and RCP8.5 | Price scenarios as defined in sub-chapter 3.1 | $E_{MSY}$ 0.8 | Technological scenarios as defined in section 3.2 | Current relative stability |
| | NE | | | $E_{MSY}$ 1.1 | | Change to the relative stability |
| | GS | | | $E_{MSY}$ 0.6 | | Current relative stability |
| | LS[1] | | | $E_{MSY}$ | | Change to the relative stability |
| **NS flatfish - SIMFISH** | WM | Using RCP4.5 and RCP8.5 spatial distributions for sole, plaice and brown shrimp | Price scenarios as defined in sub-chapter 3.1 | $E_{MSY}$ 0.8 | Technological scenarios as defined in section 3.2 | Area closure scenarios modified from Matthijsen et al. 2018 |
| | NE | | | $E_{MSY}$ 1.1 | | |
| | GS | | | $E_{MSY}$ 0.6 | | |
| | LS[1] | | | $E_{MSY}$ | | |
| **NS flatfish - RUM** | WM | Using RCP4.5 and RCP8.5 habitat suitability for sole and plaice distribution & productivity | Price scenarios as defined in sub-chapter 3.1 | Not applied | Not applied | |
| | NE | | | | | |
| | GS | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| | LS | | | | |
| **BoB small pelagics** | WM | Using RCP4.5 and RCP8.5 DEB-IBM output for anchovy | Price scenarios as defined in sub-chapter 3.1 | Current anchovy management plan is applied | Not applied |
| | NE | | | | |
| | GS | | | | |
| | LS | | | | |
| **West Med small pelagics** | WM | SSB/R relationship modulated by monthly SST, from WP1 regional projections W Med. | Price scenarios as defined in sub-chapter 3.1 | $E_{MSY}$ 0.8 | Technological scenarios as defined in section 3.2 |
| | NE | | | $E_{MSY}$ 1.1 | |
| | GS | | | $E_{MSY}$ 0.6 | |
| | LS | | | | |
| **Aegean demersals** | WM | Modified intrinsic growth rate (r) of the species, using CERES biological results for RCP4.5 and RCP8.5 | Price scenarios as defined in sub-chapter 3.1 | MEY[2] | Technological scenarios as defined in section 3.2 |
| | NE | | | Maximum landings[2] | |
| | GS | | | B>Bmsy[2] | |
| | LS[1] | | | PGY[2] | |

[1]little difference is expected between RCP4.5 and RCP6.0 before 2070. RCP4.5 is therefore used as a proxy.[2]effort restrictions are used rather than TAC

## 3.3 Aquaculture scenarios

The economic impact of climate change on European aquaculture production was analysed using a step-by-step process. In contrast to the Storyline-specific applications in fisheries, a single model was used across all aquaculture Storylines to assess various levels of biological and economic impacts of climate change.

The future economic situation of individual farms was assessed based on socio-political assumptions imbedded within the four CERES scenarios: World Markets (WM), National Enterprise (NE), Global Sustainability (GS) and Local Stewardship (LS) (see section 3.1).

Projections of global warming based on the RCP scenarios (see section 2.1) not only influenced the biological productivity of fish and shellfish within a farm (section 5.3) but also influenced the future abundance of fish stocks that are important inputs for the fishmeal and Fish Oil (FMFO) model.

Thus, the future profitability of typical finfish and model mussel farms resulted from future changes in both biological factors (feed conversion ratios and harvest weights) as well as future economic trends (prices of fishmeal/oil, fish, energy and crop feed ingredients). In addition, scenario-based assumptions on public payments and marketing were included (Fig. 3.8).

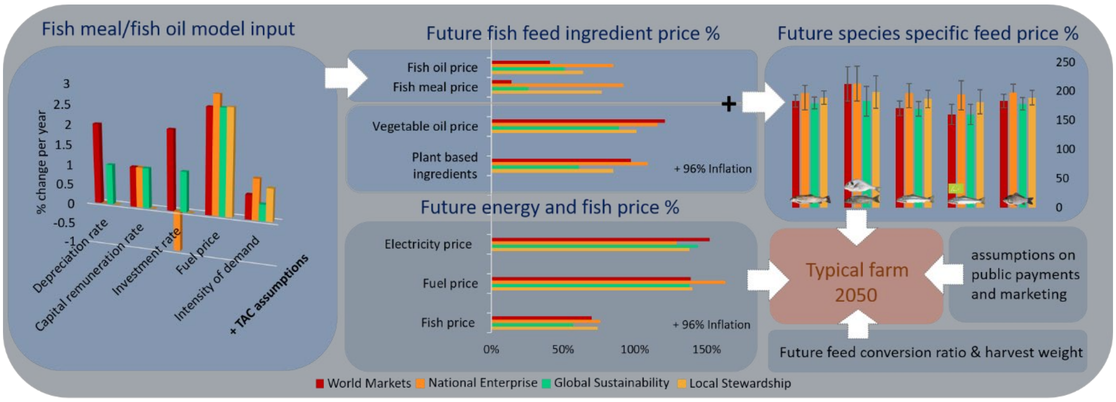


**Figure 3.8** Model inputs shaping future farm economics, displayed as percentage change by year for the fishmeal and oil model and for prices as percentage change until mid-century from present day (2016) values under the four CERES scenarios: World Markets (red), National Enterprise (orange), Global Sustainability (green) and Local Stewardship (yellow). The fishmeal and fish oil model inputs set the basis for future prices of these commodities and these, together with future price trends for plant-based ingredients, define future fish feed prices for the different species according to the respective feed composition and present price per kg (left to right: rainbow trout, carp, seabass/seabream, organic salmon, conventional salmon). Future development of energy and fish prices, feed conversion ratios and harvest weight as well as scenario-specific assumptions on public payments and marketing further influence the future profitability of farms. Remaining costs not covered within future price trends were calculated according to inflation development. TAC= total allowable catch.

Future fishmeal and fish oil prices were based on mid-century projections made with the FMFO model (Mullon et al. 2009) under each of the four CERES scenarios. This is a global-scale model that captures the geographically dispersed FMFO market.

The model includes fisheries (TAC and fuel price assumptions, see also 3.2), fishing fleets (defined by investment rates, depreciation rates and capital remuneration rates, see also 3.2) and transformation industries on the production side and the intensity and flexibility of demand on the consumption side (Fig. 3.8).

The future demand for fish is scenario-specific and linked to human population growth (KC & Lutz 2017) and to assumptions on the availability of substitutes for fishmeal and fish oil, which trace back to the technological development and trade opportunities under the four CERES scenarios (see 3.1). RCP-based projections of the latitudinal shift of FMFO target fish stocks are included and influence a number of variables such as the level of TACs.

The mid-century profitability of farms is also influenced by future developments in the prices of other fish feed ingredients, energy resources (fuel, electricity) and fish as product. These price trends were sourced from the general equilibrium MAGNET model (Woltjer & Kuiper 2014), which is globally oriented and based on the SSPs and the same assumptions of GDP and population growth underlying the four CERES scenarios (Doelman et al. 2018). For the future typical farms for finfish and model mussel farms, the overall nominal price development until mid-century (2050) was considered.

Energy and fish price projections were directly applied to the present cost and returns of typical fish farms and model mussel farms, which were estimated in high detail through interviews with focus groups together with expert participants from research and the business sector (fish) or based on expert knowledge and farm economic data (mussel). Future feed costs, being often the major costs within aquaculture fish production, were obtained in four different steps.

The current costs per kg fish feed were obtained from focus group meetings of farmers growing specific species in specific regions or countries. Fish feed composition assumptions were made for all target aquaculture species based on literature and verified by relevant stakeholders from the fish feed and farming industries. The current raw material costs for feed ingredients were obtained from different databases and commodity statistics reports and allocated to the respective amount of raw material in the different fish feeds defined within the previous step.

In the final step, future projections in the price of fish feed under the four CERES scenarios were applied to the allocated raw material costs. The remaining share of the present fish feed price, which is allocated to other factors than raw material costs, was adapted to future inflation development.

According to future FCR development, the total fish feed costs per farm was applied to the typical farm analysis. Any costs other than for feed, energy or the market returns itself were adapted according to inflation projections. The profitability of individual farms was also validated using a sensitivity analysis of historical price variation.

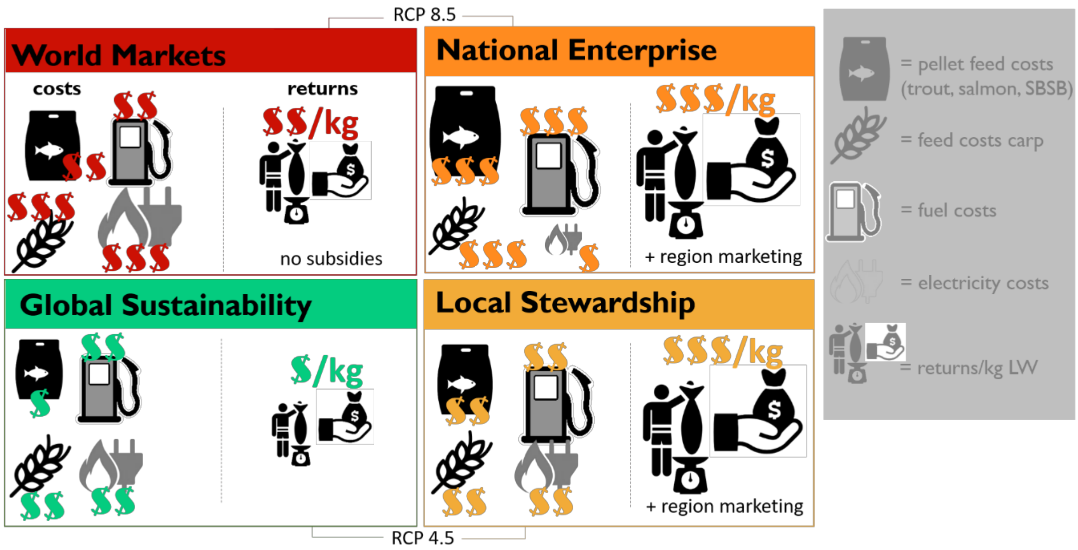


**Figure 3.9** Visualisation of future price developments applied to typical fish and model mussel farms under the four CERES scenarios. Icon size and number of $ signs correspond to future price development as displayed in Figure 3.8. SBSB= seabass and seabream.

A number of typical farms include public payments as additional returns and, when such payments were coherent within a scenario narrative, they were included in the economic analysis. The same is true for regional marketing. For example, the carp sector in Germany sees regional marketing to achieve higher prices than the current, non-labelled marketing under the two local scenarios (NE and LS).

When fish are locally sourced, future fish market price is generally higher and more promising for producers than under the two global scenarios (Fig. 3.9), which provides more market opportunities for e.g. 'Protected Geographic Indication (PGI)' fish products.

Although input costs mostly followed the same pattern across all four scenarios (Fig. 3.8), lower revenues tended to be achieved in the two global scenarios (WM and GS) compared to the two local scenarios (NE, LS) (see Chapter 5).

The future prices of pellet fish feed (trout, salmon, seabass and seabream) and carp feed follow different future trajectories since the latter only contains grains. The species-specific differences in the development of feed costs, the fact that mussel aquaculture does not require any feeding, and that cost structures are often dependent on production systems or the size of the national sector, all play a role in the projected differences in the future profitability of typical farms across the aquaculture sector in Europe.

4

# Risks and opportunities for the European fisheries sector

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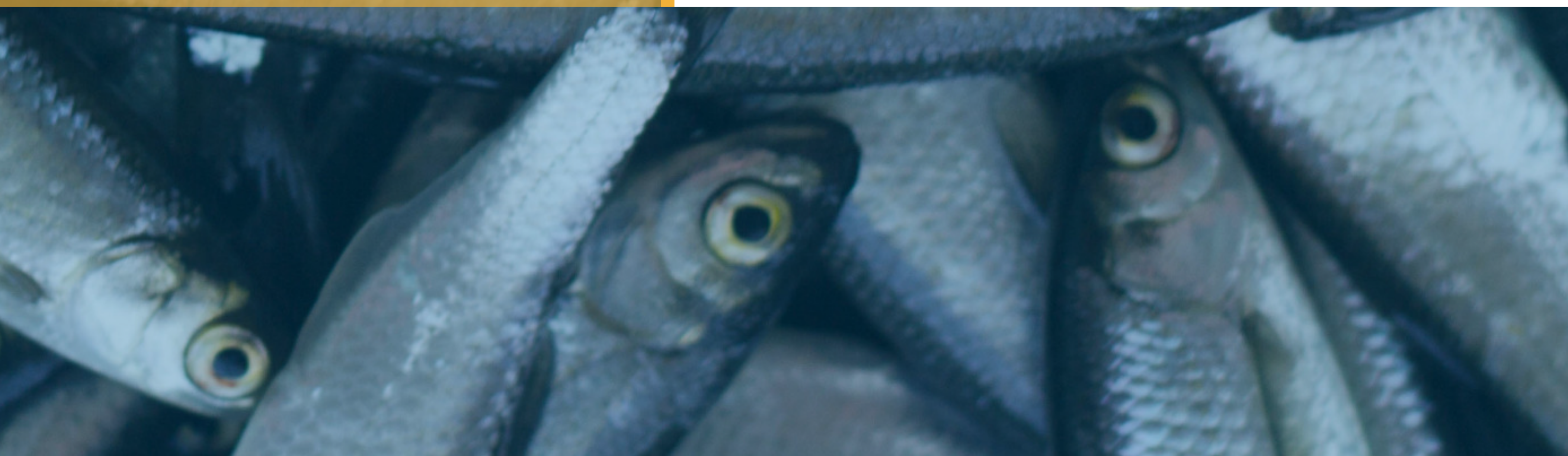


## 4.1. Introduction

Numerous initiatives at regional to global levels have tried to understand how climate change will affect fisheries. A recent FAO report (Barange et al. 2018) compiled the existing evidence on the impacts of CC on marine and freshwater fisheries. Decreased catch is expected globally, driven by decreased primary production and increased temperature (Lotze et al. 2019).

Among the recommendations from the FAO report, the need for coordinated initiatives that use common scenarios stands out (e.g. the Fish-MIP approach to compare ecological models, Tittensor et al. 2018) to gain robustness in future climate change projections. CERES improves and applies this common scenario approach across European regions (Chapter 3) to make biological (fish) and bioeconomic (fishery) projections in this chapter. This chapter also summarises the risks and vulnerability of European fisheries to climate change and proposes adaptation measures (Fig. 4.2.1).

Current knowledge compiled in that FAO report shows that marine fisheries in the Atlantic and Arctic contribute little to gross domestic product (GDP) but some regions/communities rely on fisheries for food security and cultural heritage (Peck & Pinnegar 2018). The latter is particularly true for inland fisheries, including recreational fisheries (Harrod et al. 2018) The projection of climate change and its impacts in these and other areas is uncertain but there is evidence for historical temperature-related poleward migration of some key fished species in marine systems (Cheung et al. 2010, Jones et al. 2013). These changes have caused conflicts between countries, although the effects are fishery-/region-specific (Vinagre et al. 2011, Fernandes et al. 2017).

Long-term changes in climate change-related geochemistry (mainly pH) are known for the European Atlantic/northern Seas, but its potential future effects are unclear, ranging from negative (Narita & Rehdanz 2017) to positive (Sswat et al. 2017). By contrast, species extirpation and altered fish community structure and functioning are expected in inland waters in catchments exposed to altered thermal and hydrological regimes (Logez & Pont 2013, Pont et al. 2015).

In southern European Seas, the review by FAO reported amplified effects of climate change on fisheries due to interacting effects of overfishing and invasive species, and due to the particular structure of some fisheries (multi-fleet, multi-species) (Hidalgo et al. 2018). For fisheries in the Mediterranean Sea, warming has been associated with Meridionalisation (occurrence of warm water species in more northern regions) and tropicalisation (expansion of non-native tropical species).

Projected reductions in river runoff and ocean productivity (with high East-West variability), coupled to increased temperatures and extreme events (for example marine heat waves, MHV) may have positive and negative impacts on fisheries (Lloret et al. 2015): small pelagic species (anchovy, sardine) are likely to decline, but the expected effects for demersal species and migration routes of large pelagic species are more uncertain.

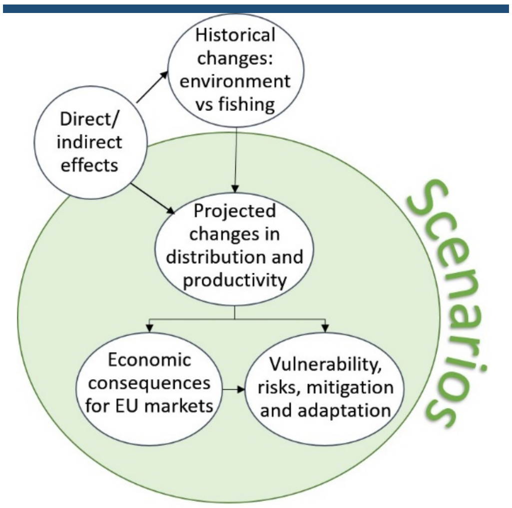



**Figure 4.1** CERES approach to analyse the potential effect of climate change on EU fisheries for a given scenario (green space, defined in Chapter 3)

European inland fisheries have relatively little capacity to buffer against changes in fish stock dynamics and, therefore, are more sensitive to climate-induced shifts in habitat suitability (particularly from extreme events related to climate change or climate variability) (Harrod et al. 2018). Inland fisheries are also subject to a variety of other human-based pressures that will interact with climate change to, in most cases, cause detrimental impacts to native species.

European inland fisheries are particularly prone to habitat degradation by dams and associated flow regulation, river channel engineering works, water abstraction for agriculture and potable supply and water quality problems, plus continuous expansion of the range of invasive non-native species (Cowx 2015). The challenge is to identify the risk and uncertainty associated with climate change, its effect on freshwater species and how this will consequently affect inland fisheries and the resilience of communities to respond to these changes (Paukert et al. 2017).

Current knowledge on how European fisheries may adapt to the effects of climate change (e.g. including capacity building within the fishing sector, policy measures, building resilience, developing alternative markets) is scarce, and adopted measures are sparse and unequally distributed cross regions. In this respect, it is important to first understand and quantify climate variability, and co-design, with the industry and policy makers, flexible and iterative adaptation tools that enable feedbacks and taking no-regret actions even in the face of uncertainty (Poulain et al. 2018). For inland fisheries, this will require engagement with the water resource sector to ensure adequate environmental flows are maintained to sustain inland fish populations.

To date, there has been no coordinated, cross-regional effort using a consistent set of drivers/scenarios to address the potential changes in distribution/productivity, profitability and vulnerability in the face of climate change for the European fisheries sector. This is the objective pursued by CERES in this chapter (Fig. 4.1.).

Section 4.2 summarises efforts by CERES to identify existing knowledge (and gaps in knowledge) on responses of fish to the direct and indirect effects of climate change (based on existing laboratory data, field studies and/or theoretical considerations). By identifying and filling some of these knowledge gaps, CERES improved biological models to project climate impacts (see section 4.4).

Section 4.3 explores the relative contribution of fishing or environment to observed historical trends in past evolution of European fish production and distribution, so that projection models could also absorb this information. In that section, available evidence for many high-value species has been complemented with an in-depth analysis of historical changes at the ecosystem level.

By combining the physical/biogeochemical projections (Chapter 2), biological responses and fishing pressure, section 4.4 describes how the productivity and distribution of European marine and freshwater fisheries (including indirect interactions/food webs) are projected to respond to the scenarios defined in Chapter 3. This sets the scene for exploring the potential economic consequences that changes in distribution and productivity may have in the four CERES scenarios in section 4.5. In section 4.6, a risk-assessment of fish (over 450 stocks), European fleets and fisheries-dependent communities is conducted.

Finally, section 4.7 summarises Bow-tie analyses of the threats and opportunities derived from climate change on all fisheries storylines, largely derived from stakeholder's perceptions. This information is expanded and complemented in Chapter 6, which offers details on proposed adaptation measures and the evaluation of the pros and cons of (not) taking a series of proposed actions.

Although it is inherently challenging and uncertain to predict the future effects of climate change in complex, natural systems (Planque 2016), it is, nonetheless, imperative to broadly identify potential threats to likelihoods that are yet to come and that will demand action. The work presented in this chapter, tightly coupled to Chapter 6, results from a joint effort between a broad spectrum of scientists and stakeholders to examine how future scenarios of climate change will likely impact on European fish and fisheries.

## 4.2. Direct and indirect effects of climate change and biological models

CERES revised, collated and produced new data to improve biological models used for the projections in section 4.3. In total, 642 independent datasets were analysed (CERES D2.1 2018), and biological models from 10 institutions across Europe were updated or developed with these data.

Direct and indirect effects on fisheries were revised. CERES concentrated on direct effects that could be drawn from experimental data (e.g. effects of temperature, pH, oxygen on fish/shellfish biology), and indirect effects on fisheries via modification of estuarine and freshwater systems due to climate change, and their effects on fisheries. Other indirect effects, such as those derived from trophic interactions, were only considered as part of complex models that included these dynamics (section 4.3).

**Direct effects: evidence from experiments**

An analysis of the current status of empirical knowledge on the direct effects of climate change on 25 high-value species targeted by European fisheries was conducted (Catalán et al. 2019). A gap analysis revealed considerable bias in the knowledge on potential effects of climate change on these species, including a lack of consideration of all life-stages, awith few studies examining the interaction of abiotic factors (e.g., temperature and pH taken together), or poor assessment of the potential for local adaptation of species (Fig. 4.2).

Existing data from laboratory studies indicate that projected warming will increase mean growth rates and elevate metabolic rates in fish. In addition, decreased levels of dissolved oxygen are expected to depress rates of growth and metabolism across coherent fisheries species groups (e.g., small pelagics), while expected declines in pH will reduce growth in most species groups.

The information that can be gleaned from laboratory-based analyses is influenced by the study design and key variables such as the life stage being investigated (Rijnsdorp et al. 2009, Pörtner & Peck 2010), or the season or the region in which the experiment was conducted (Ojaveer & Kalejs 2005, Crozier & Hutchins 2014). These CERES results call for further research efforts in Europe (and world-wide) to improve our capacity to make projections of the effects of climate change on marine and freshwater fishes.

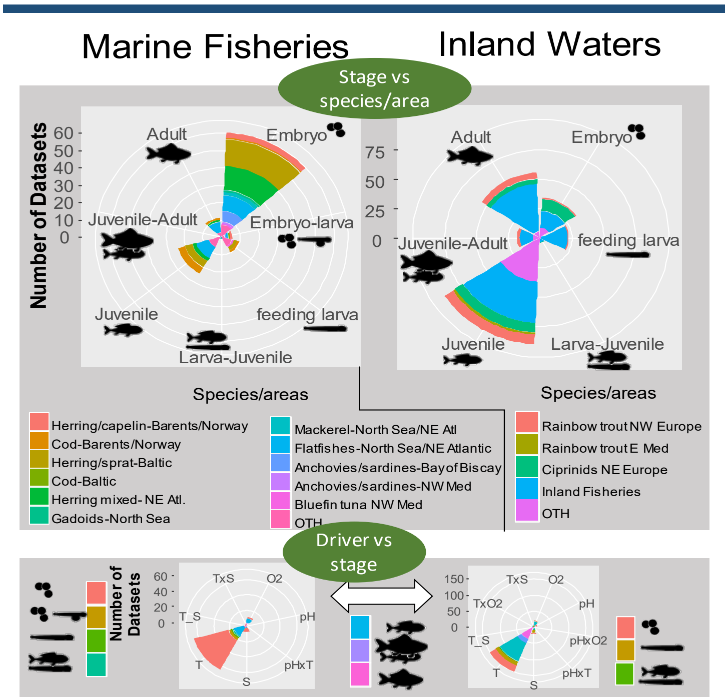



**Figure 4.2** EU research effort (number of datasets) in marine fisheries and inland waters, classified by combinations of life-stage vs species/area (top panel) or climate change-related driver vs life-stage (bottom). Modified from Catalán et al. (2019). Note the large bias in knowledge on potential direct effects on EU fisheries resources. T=temperature, O2= oxygen, S=salinity OTH=works on species of interest but in non-EU areas. Symbo 'X' denotes interactions, symbol'_' denotes concurrent measurement.

**Box 1: Indirect effects of climate change on marine fisheries, via effects on estuarine systems**

Estuaries play an important role in supporting marine fish stocks, as several marine species (e.g. sole, plaice, cod, whiting, herring, sea bass) rely on these habitats to provide food and protection for early life stages (juveniles) critical for enhanced survival and rapid growth. The connectivity of these nursery grounds with the adult fish populations at sea ensures the latter are replenished and maintained. Further, estuaries are important habitats for diadromous species migrating between the marine and freshwater environments to complete life histories. Therefore, any impact affecting estuarine systems, their biota and connectivity with marine habitats, including climate change, can have important, indirect effects on the productivity and viability of marine fish stocks and their fisheries. Figure 4.3 gives a graphical summary showing the life cycle of marine migrant fishes that use estuaries as nurseries and the pathways of indirect effects of climate change on the productivity of marine fish stocks. The main processes involved are in yellow while the direct and indirect effects in estuaries, the marine environment and on the connectivity between the two systems are in red, blue, and green, respectively).

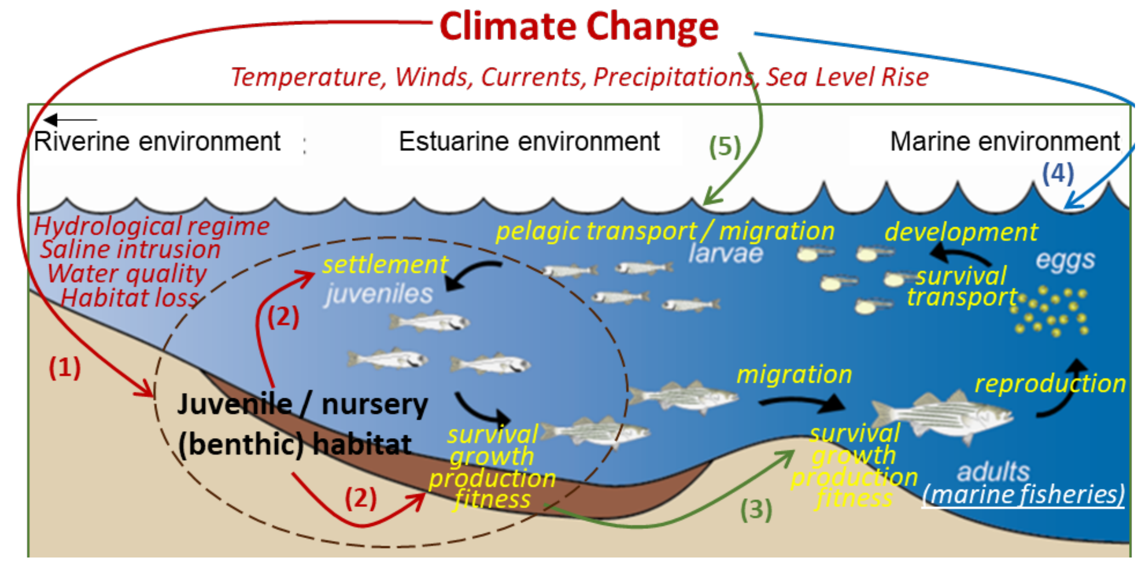



**Figure 4.3** The various pathways of climate impacts on fish using estuarine habitats

**(1)** Climate change effects on abiotic (physical, biogeochemical, geomorphological) conditions may affect fish habitat availability, quality and distribution.

**(2)** Abiotic changes have physiological and behavioural effects on fish depending on species-specific differences in tolerance and preferences, leading to changes in habitat use and functioning, at both the local scale (within an estuary) and the regional one (climate-induced latitudinal shifts, e.g. observed for pollack and five-bearded rockling along the UK coast (CERES D2.1 2018)).

**(3)** Changes in estuarine nursery function and in the growth and survival of individuals may affect the recruitment of juveniles back into the marine populations hence stock size and productivity.

**(4)** Climate change effects on the marine environment also directly affect marine fish populations (hence fisheries) and all processes involved.

**(5)** Climate change may affect larval transport into estuaries, and, combined with changes in (4), this may have feedback effects on estuarine nurseries.

Image from Anita Franco (Univ. Hull).

## 4.3. Historical changes: Attribution of climate versus fishing

To understand how past fluctuations in populations can be attributed to environmental effects, fishing pressure, or both, CERES investigated the longest available time-series of fish abundances or community structures in several European regions. Time-series were mathematically analysed to detect both effects of external drivers on fish production and distribution, and historical shifts in ecosystems.  No such analsysis was possible for inland fisheries where impacts of external human activities of fish stocks tend to override any climate change impacts (Harrod et al. 2018, Cowx et al. 2020).

**Effects on recruitment:** For the Atlantic bluefin tuna in the NW Mediterranean, coinciding regimes of temperature and recruitment were found (Table 4.1), which were mechanistically explained by the effect of temperature on the survival of eggs and larvae. The good match between the survival index and recruitment indices from standarised CPUE fisheries data also suggest environmentally driven recruitment (Reglero et al. 2018). However, the spawning stock biomass to recruitment relationship was not improved by including temperature directly. In the Bay of Biscay, anchovy spawning stock biomass was the only factor explaining the spawning distribution of this species, i.e. inferring density-dependence (Table 4.1, CERES D2.2 (2018)). In the Barents Sea, investigations on cod recruitment concluded that temperature alone could not explain variations in cod recruitment.

**Effects on spatial distribution:** Changing environmental conditions can lead to a marked shift in the geographical distribution of a species. Such a turnover, characterised by an increase of thermophilic species was observed in the North Sea, concurrent with the increase of winter temperatures (CERES D2.2 (2018), Table 4.1). At a species level, the migration patterns of plaice in the same area were found to follow variations in temperature, while a shift in the distribution to colder and deeper waters was observed for both juvenile and adult plaice (Table 4.1, CERES D2.2 (2018)). In waters surrounding the British Isles, poleward shifts were detected and found to be consistent with climate driven patterns only for pollack and fivebeard rockling, with no clear evidence for the rest of the stocks studied (Table 4.1, CERES D2.1 2018).

**Effects on landings and landings per unit effort:** In the Mediterranean, the Western Mediterranean Oscillation (WEMOi, Hidalgo et al. 2011, Martin et al. 2012, Gulev et al. 2013, Maynou et al. 2020) and sea air heat loss had positive and negative effects on the anchovy and sardine abundance of the Catalan Sea. In the Aegean Sea, increases in gross primary production were synchronised with increased catches of hake and red mullet landings.

**Effects at the community level:** Effects on marine species caused or triggered by environmental changes can go across all trophic levels causing the reorganisation of marine ecosystems, termed regime shifts. Evidence of ecosystem regime shifts were identified in Eastern Europe, in the Aegean Sea and Razim Lake (Table 4.1, CERES D2.2 (2018)), the latter a freshwater system in the Danube Delta. In both cases, 1985 was identified as the year of shift, with a second shift occurring in 1995. In the Aegean Sea, evidence was presented linking this shift to a corresponding shift in climatic conditions, while the Razim Lake the shift was thought to be driven primarily by eutrophication.

**Disentangling effects of fishing and CC:** in four out of 11 analyses, fishing appeared to be a major influence either on stock abundance (cod in the Barents Sea and anchovy in the Bay of Biscay), or size structure of the populations (plaice in the N. Sea, sardine and anchovy in the Catalan Sea). In the Barents Sea, high levels of fishing pressure most likely amplified and prolonged the collapse of the capelin stock.

The complex interaction between fishing, environmental and recruitment variability and trophic relations between cod, capelin and polar-cod stocks have shaped the historical production of the stocks including three collapses of capelin.

Fishing pressure was the crucial driver of anchovy stock collapse and subsequent recovery in the Bay of Biscay as opposed to environmental factors, causing changes in recruitment and natural mortality (Bueno-Pardo et al. 2019).

In the North Sea, a 100 year historical time series of plaice size structure was examined. The effects of fishing on the stock were clear, with an increase of the mean length during the two World Wars (when fishing stopped), another increase in the period 1960-1970 due to increased nutrient loadings from fertilisers (despite the intensification of the fishing activities), and the recent reduction of mean length because of intense fishing but also linked to climate cchange(Table 4.1, CERES D2.2 (2018)).

In the Catalan Sea, excessive removals of anchovy and sardine due to fishing led to both stocks composed of young age classes (basically, classes 0, 1+) with little resilience to adverse environmental conditions (Maynou et al. 2020).

The historical changes attribution of climate versus fishing can be summarised as follows:

- Significant correlations between species production and environmental variables were detected in many cases, but simple cause-and-effect relationships are rarely apparent. At a community/ecosystem level, evidence of ecosystem shifts in the mid-1980s has been observed in the Aegean Sea and Razim Lake (Danube delta) (CERES D2.2 (2018)).
- It seems that historically, fishing has been the major driver behind stock production patterns with climatic variability having a secondary role, that of triggering, amplifying or weakening the observed responses.
- Our capacity to build reliable projection models necessitates robust (long, continuous, data-rich) time series for the main European Seas and inland waters, yet these time-series are currently scarce and biased towards few areas.

**Table 4.1** Results from climate and fishing-related effects on European Aquatic Resources compiled in CERES, based on available long time series. Positive or negative effects are represented with (+) and (-) signs, respectively. Upper arrows denote poleward migration, whereas horizontal arrows denote no noticeable effect. Blanks are for no sufficient data to evaluate the status, whereas question marks (?) mean not investigated.

| | | | Temperature effects (potentially related to climate change) | | | | | Fishing effects on stocks | |
|---|---|---|---|---|---|---|---|---|---|
| **Region** | **Period** | **Species** | **Recruit-ment** | **Growth / size** | **Distribu-tion** | **Productivity /stock size** | **Regime shift? (decade)** | **Size/age truncation** | **Stock abun-dance** |
| Barents Sea | 1970-2018 |  Cod, herring, capelin | | | | + | √(80s) complex interactions | | - |
| Baltic Sea | 1950-2016 |  Cod, sprat, herring | ↔ | ↔ | ↔ | | | ? | ? |
| British Isles | 1960-2016 |  5 gadoids & 4 flatfish | | | ↑ most spp. | | | ? | ? |
| North Sea | 1902-2016 |  Plaice | | - | | | √(80s) | - | ? |
| North Sea | 1988-2017 |  Plaice | | | ↔ colder and deeper | | | ? | ? |
| North Sea | 1983-2013 | +150 species | | | ↑ Lusitanian spp. | | | ? | ? |
| Bay of Biscay | 2000-2017 |  Sardine & Anchovy | | -anchovy | | | | ? | -anchovy |
| Razim lake (Black Sea) | 1971-2015 |  Pike perch, perch, catfish, pike, gibel carp, common carp | ↔ | ↔ | ↔ | ↔ | ↔ | ? | ? |
| Aegean Sea (E. Mediterranean) | 1960-2016 |  Hake | | | | | √(80s) | ? | ? |
| Eastern Atlantic and Mediterranean | 1968-2011 |  Bluefin tuna | + some regimes | | | | | ? | ? |
| Catalan Sea (North-west Mediterranean) | 1974-2016 |  Sardine & Anchovy | | | | - | | - | |
| Western Mediterranean | 1954-2015 |  Dolphin fish | | | | | | ? | ? |

## 4.4. Future changes in distribution and productivity

The abundance and distribution of most components of food webs will be altered by climate change. This includes impacts on commercially important fish at mid- and upper trophic levels with direct effects on food supply from fisheries, effects which may differ between northern and southern European sea areas.

CERES used twelve state-of-the-art biological models CERES D2.3 (2019) to project the effect of two climate change scenarios (RCP8.5 and RCP4.5) on the distribution and abundance of key commercial species. The selection of the model to employ depended on the amount of knowledge available and the target species. In some cases, different models were used in the same region and on the same species, allowing agreement between models to be compared (Tables 4.2 and 4.3).

For knowledge-rich groups, mechanistic models were used while statistical (non-mechanistic) approaches were employed for groups and species with more sparse knowledge. A mechanistic model takes into account aspects of the life-history, ecology (e.g. habitat preference, migration) and physiology (e.g. growth and reproduction) to determine biomass and distribution of fish species in response to changes in the environment (e.g. temperature, competition with other species, food availability).

The statistical models use historical data to find relationships between environmental factors (e.g. temperature, primary production) and a species occurance (e.g. abundance of a key life cycle stage) or processes (e.g. larval survival, growth of adult, distribution); they then apply these relationships to climate change projections and see if any future modification of distribution range or productivity is anticipated compared with present conditions.

Where possible (depending on the model), the impact of management strategy was also considered (e.g. in a model used for over 50 species across Europe, Lotze et al. 2019). The impact of management is characterised by the MSY used within the model (see Chapter 3.2). This resulted in potentially three simulations for each RCP8.5 scenario with MSY 1.1 (National Enterprise); RCP8.5 with MSY 0.8 (Global Market); and RCP4.5 with MSY 0.6 (Global Sustainability). The correspondence between these scenarios and IPCC Shared Socioeconomic Pathways (SSPs) is provided in Chapter 3.

**Projections**

The main results of the projected changes in distribution and productivity under different scenarios are summarised below:

1. While there was not much difference between climate scenarios (when only taking into account the impact of climate change, without fishing) up to 2050, differences become more marked by 2100, with the trends observed under RCP4.5 being exacerbated under RCP8.5. (See Table 4.2). The model results highlight several ‘winners’ and ‘losers’ depending on the fish species as well as the region considered.

2. Temperature increases will cause an increase in the metabolic demands of fish, particularly when warming occurs in surface water layers, with limits on growth due to low oxygen levels. In some cases, the reduction in dissolved oxygen (deoxygenation) might be a more critical and important driver than rising temperature (Pauly 2019)

3. Trophic amplification of biomass loss (Kwiatkowski et al. 2019) was observed

4. Some model projections highlight the role of trophic interaction, as well as management measures (e.g. fishing pressure, trophic level on which the fishing is focused) and while the model projections provide a good guide as to what can be expected, outcomes may vary based on management measures adopted.

5. SST and primary production are not the only drivers and there are other factors to take into consideration. One of those is secondary production, i.e. zooplankton, which was shown to be a driver of the future population dynamics of anchovy in the Bay of Biscay and Norwegian spring spawning herring. Models in the Aegean have found that pH and benthic DOC are additional drivers that need to be considered beyond SST and primary production.

6. Importantly, the impact of climate change is consistent across models despite small discrepancies in the results that emerge based on whether/how food web interaction are included or how fishing pressure was applied across the CERES scenarios. Across all models, steps were taken to address knowledge gaps identified early in the project (e.g. by updating parameters values and other aspects, as specified in section 4.2).

7. Sub-regional and loca-scale processes and effects are crucial and challenging to capture. Thus, it is likely that changes in some sub-areas of broader regions will experience less or more pronounced impacts of climate change.

8. The projections included only species currently distributed within a region. This means that, although some areas and regions appear as being overall losers (e.g. North Sea, south part of the Northwest Atlantic) this was characterised in terms of losing temperate or cold water species. As poleward (or longitudinal in the Mediterranean) migrations happen, new species will move into the warming systems, and existing subtropical ones may increase their relevance (Portner et al. 2014, Garcia Molinos et al. 2016, Lloret et al. 2015, Tsikliras & Stergiou 2014). This is likely to affect the ecosystems with consequences that cannot as yet be fully included in model projections.

9. Localised changes species abundance and productivity proved difficult to detect in inland fisheries (e.g. Razim Lake, Romania) but, Europe-wide, the distribution of cold-water species such as Atlantic salmon has shifted polewards and populations of some species are being impacted by prolonged drought conditions, especially in Mediterranean countries (Harrod et al. 2018)

| RCP8.5 | | | | | | | | | RCP4.5 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Norwegian / Barents Sea | Baltic Sea | North Sea | Northeast Atlantic | Bay of Biscay | W. Mediterranean | Aegean | Razim Lake | | Norwegian / Barents sea | Baltic Sea | North Sea | Northeast Atlantic | Bay of Biscay | W. Mediterranean | Aegean | Razim Lake |
| | | | | | | | | SST | | | | | | | | |
| | | | | | | | | Primary production | | | | | | | | |
| | | | | | | | | Capelin | | | | | | | | |
| | | | | | | | | Norw. herring | | | | | | | | |
| | | | | | | | | Sprat | | | | | | | | |
| | | | | | | | | Cod | | | | | | | | |
| | | | | | | | | Saithe | | | | | | | | |
| | | | | | | | | Herring | | | | | | | | |
| | | | | | | | | Atl. Horse mackerel | | | | | | | | |
| | | | | | | | | Mackerel | | | | | | | | |
| | | | | | | | | Sardine | | | | | | | | |
| | | | | | | | | Plaice | | | | | | | | |
| | | | | | | | | Sole | | | | | | | | |
| | | | | | | | | Hake | | | | | | | | |
| | | | | | | | | Haddock | | | | | | | | |
| | | | | | | | | Anchovy (SDM) | | | | | | | | |
| | | | | | | | | Anchovy (DEB-IBM) | | | | | | | | |
| | | | | | | | | Sardinella | | | | | | | | |
| | | | | | | | | Dolphinfish | | | | | | | | |
| | | | | | | | | Bluefin tuna | | | | | | | | |
| | | | | | | | | Red mullet | | | | | | | | |
| | | | | | | | | Hake (landing) | | | | | | | | |
| | | | | | | | | Red mullet (landing) | | | | | | | | |
| | | | | | | | | Pike perch | | | | | | | | |
| | | | | | | | | Bream | | | | | | | | |
| | | | | | | | | Gibel carp | | | | | | | | |
| | | | | | | | | Roach | | | | | | | | |

**Table 4.2** Qualitative overview of changes in driver and fish responses to change by the middle of century under RCP8.5 (left) and RCP4.5 (right). SST: warming in °C, with the scale going from white (no warming) to dark red (+4°C). Primary production and fish abundance are expressed as a percentage change, with green being an increase and red a decrease. White indicates a lack of change. Grey indicates a lack of information.

**Confidence in projections**

Confidence in the projections was assessed using the same approach as developed by the IPCC. Models were scored on two metrics: Agreement and Evidence (see Table 4.3).

Agreement is evaluated as the agreement between models, when two or more models where used to project the same species in the same region. In the cases where only one model was used, the score was computed based on whether the model explored multiple scenarios and whether it is a state-of-the-art model in the area or a newly implemented model.

Evidence is scored based on the use of updated parameters for the model, and accounting for the availability of historical and present time data (see section 4.3) to validate the model.

**Table 4.3** IPCC scheme used to derive the confidence ratings

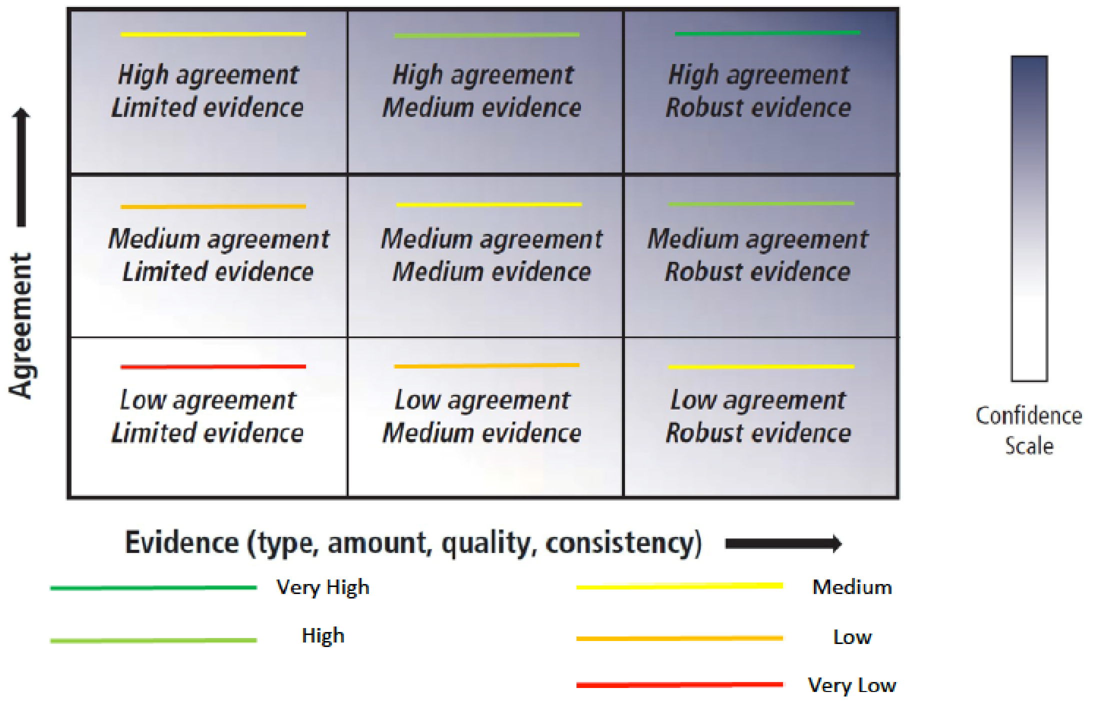



Table 4.4 presents the Confidence rating for the fish projections. Where different models were used in different areas without any overlap, multiple scores were calculated. In case the scores ended up being the same they are not provided separately. Most rating fall within the Medium confidence range, which only reflect cases where only one model was used or there was slight differences in the model outcomes due to differences in the model.

**Table 4.4** Confidence rating of the fish projections. (-) Very low; (*) Low; (**) Medium; (***) High; (****) Very high

| Fish species | Confidence rating |
|---|---|
| Capelin | ** |
| Norwegian herring | ** |
| Sprat | ** |
| Cod | ** (Norwegian and Barents Sea)<br>** (Baltic Sea)<br>*** (North Sea) |
| Saithe | ** |
| Herring | ** |
| Atlantic horse mackerel | ** |
| Mackerel | ** |
| Sardine | ** |
| Plaice | *** |
| Sole | ** |
| Hake | **<br>*** (Aegean) |
| Haddock | ** |
| Anchovy | ** |
| Sardinella | ** |
| Dolphinfish | **** |
| Bluefin tuna | ** |
| Red mullet | *** |
| Pike perch | * |
| Bream | * |
| Gibel carp | * |
| Roach | * |

## 4.5 Economic consequences for European fisheries

The economic effects of climate change on European fishing fleets will be manifested through climate-driven changes in the productivity and distribution of their main target fish species, and through the social, economic, political and legal context in which they operate. In CERES, the direct effects of climate change on the productivity and distribution of commercial species were combined with the four socio-political scenarios developed in the project (Chapter 3) to assess potential economic impacts to fisheries by mid-century (2050). Those scenarios were applied in bioeconomic models covering nine marine fisheries storylines geographically distributed from the Southern Arctic Ocean to the eastern Mediterranean Sea (see Table in Chapter 3.2).

### a How would the current fleets fare given the biological and socio-political scenarios?

The outputs from bioeconomic moddels concerning future economic performance (or catch opportunity in the Norwegian and Barents Sea) of the current European fleets did not offer clear patterns under the tested scenarios (Table 4.5). CERES model projections of European pelagic fisheries show a contrasting picture where some stocks (and the fleet catching them), like hake in the Aegean Sea, benefit in the CERES scenarios mid-century while others, such as the North Sea autumn spawning herring, decrease due to continuous reduced recruitment. Demersal fleets seem to maintain profitable performance in the mid-century with no clear pattern as to which scenario would be the most favorable in the longer term, largely because of projected fish price rises under all four scenarios examined.

**Table 4.5** Mid-century economic performances of the fishing fleets in the four CERES scenarios for pelagic and demersal fleets in different EU regions. * catch potential used as proxy for profitability in the Norwegian and Barents Sea

| Regions | Pelagics fleets | | | | Demersal fleets | | | |
|---|---|---|---|---|---|---|---|---|
| | World market | National enterprise | Global sustainability | Local Stewardship | World market | National enterprise | Global sustainability | Local Stewardship |
| Norwegian and Barents Sea* | | | | | | | | |
| Baltic Sea | | | | | | +/- | | |
| North Sea/ North East Atlantic | +/- | ++/-- | | ++/-- | | | | |
| Western Mediterranean Sea | | | | | | | | |
| Aegean Sea | | | | | | +/- | | |

Most negative | No effect | Most positive | No data

**Fishing fleets will adapt to changes in prices, technological development and management before changes in distribution and productivity of their target species affect them**

Projected changes in fish productivity due to climate change have been included in the bio-economic projections of most of CERES marine fisheries storylines. The simulated changes in fish distributions by mid-century appear limited in magnitude. As a result, the fishing fleets depending on those stocks can adapt their fishing effort without substantially affecting their profitability e.g. the North Sea demersal (flatfish) fishery.

Compared with other external factors, the impact of biological changes remains limited by mid-21$^{st}$ century (Table 4.6). Simulation results reveal that the evolution of fuel & fish prices are stronger drivers for profitability of fishing fleets. This is unsurprising as fleets are somewhat flexible in selecting fishing areas (to react to distribution changes), while fish & fuel prices must be accepted as they occur and adjustments may not be that easy (e.g. development of fuel saving fishing strategies or fuel saving technological improvements on board). The impacts of changes in prices seem stronger for the demersal fleets than for the pelagic ones. Increases in fuel prices have stronger reprecussions in the case of demersal fisheries as the gears are dragged on the bottom and fuel is usually the main operating cost for those fleets.

The change of management targets (legal) has an opposite impact depending on the current situation of the fishery. Increasing the exploitation rate leads to more catches in the Norwegian and Barents Sea (the costs are not included in this model), but has no to slightly negative impact on the economic performance of other fisheries.

Changes in target species would require a change in quota distribution between countries and/or fishing fleets, which in the current system of fishing rights per country is not an easy task. In the EU, the distribution of TACs in national quotas follows the principle of relative stability where each country receives a fixed percentage of the overall EU quota (note: in the Mediterranean Sea, very few stocks are managed with quotas). A change in stock distribution, and thus a change in availability of certain species compared with others (one species increases while another decreases) would require re-negotiating the internal quota distribution within the EU, but also between the EU and other countries in the Northeast Atlantic. In the Mediterranean, however, the situation is different as there is no quota system and countries regulate their fisheries mostly with limitations of fishing effort.

**Table 4.6** Relative effect of the different factors as defined in the CERES scenarios on the economic performance of the fisheries. P: climate drive productivity; D: climate driven spatial distribution; Fu: Fuel price; Fi: Fish prices; MSP: marine spatial planning

| | Region | Environment | Economic | | Legal[1] | Technological | Political |
|---|---|---|---|---|---|---|---|
| pelagic | Norwegian and Barents Sea | P | | | | | |
| | North Sea | P | Fu | Fi | | | |
| | North East Atlantic | P | Fu | Fi | | | |
| | Western Mediterranean Sea | PP | Fu | Fi | | | |
| demersal | Norwegian and Barents Sea | PP | Fu | Fi | | | |
| | Baltic Sea | P | | | | | |
| | North Sea | D | Fu | Fi | +/- | | MSP |
| | Aegean Sea | PD | Fu | Fi | | | |

[1]increase in exploitation rate

| Most negative | | | No effect | | | Most positive | No data |
|---|---|---|---|---|---|---|---|

**b) How will climate change impact the seafood market?**

At this point, it is not possible to predict with strong certainty what the direct impacts of changes in species distribution and negative/positive effects on stock sizes will have on the European seafood markets. There will be winners and losers, but the European market is also characterised by a high percentage of imported fish. Some aspects of the larger seafood market are discussed in the macro-economic modeling work presented in Chapter 6, including impacts of climate change on small pelagic fish and fishmeal and fish oil important for aquaculture in Europe. Decreased supply of small pelagic fish in other parts of the world such as the Peruvian anchovy could result in substantially higher prices for fishmeal and fish oil, which could markedly increase production costs for certain farmed species. Higher fish prices are predicted also because of higher demand for fish in the future, which may lead to substitution of fish with other sources of protein (e.g. poultry or vegetable proteins).

#### c) How to use CERES bio-economic fisheries projections?

No model can predict the exact future for any fishery but, using the scenarios defined in CERES, the models can provide the likely direction for the future development of the fisheries. The state-of-the-art models used here, all have assumptions and further work using the same scenarios would be useful to examine model structures and improve the robustness of estimations.

***Fishing fleets will adapt to their environment in unforeseeable ways***

Fishing fleets constantly have to adjust to environmental, economic and regulatory changes. While fisheries are traditional activities often involving families over several generations, fishers innovate by modifying their fishing practices, including their gears, target species and fishing grounds. Part of the fleet adaptation is captured by the technological advancement included in the scenarios. The bio-economic simulations were run for about 35 years until mid-century in CERES, which is shorter than bio-physical projections but many transformations of the current fishing industry will happen during this period and fishers would typically change their fishing vessels once or twiceduring this interval. The simulation results are an entry point for discussion with stakeholders about the possible future of their fishery.

## 4.6 Risk analysis of European marine fish, fishing fleets and fishery-dependent communities

Climate risk (vulnerability) analyses are broad-brushed but powerful tools that allow a systematic comparison of the consequences of climate change across a broad swath of society. While the tool lacks the resolution and fine detail of many of the other analyses performed in CERES, it has the advantage of being able to cover an extremely broad range of appliations that would be otherwise impractical to analyse in fine detail. The approach employed here is based on the IPCC's 'climate risk' framework, a successor to the more well-known 'vulnerability analysis', and divides risk into three components: hazard, exposure and vulnerability. The hazard dimension measures the strength and severity of climate change on the unit of interest – in this case, fish stocks in European waters. Exposure is an indicator how of how sensitive a community or fishing fleet is to changes in the fish stocks, for example, are there other fishing opportunities or does everything ride on one stock in one area? Vulnerability in this setting refers to the resilience of the socio-economic unit (either a fleet or a community) and its ability to mitigate the hazard via adaptation. While there are many examples of vulnerability and risk analyses at both the global and regional scale, such work has not been performed across Europe.

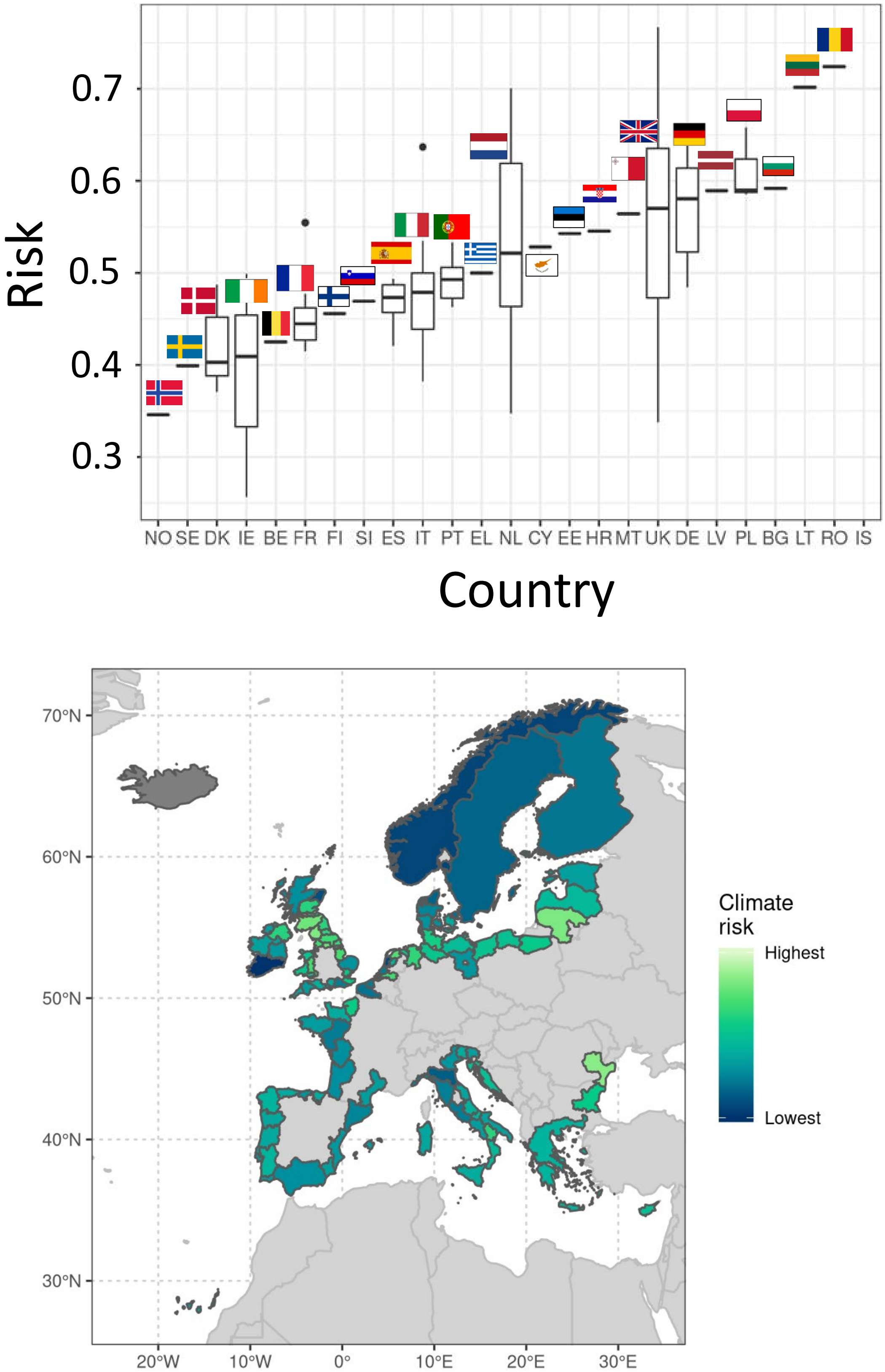



**Figure 4.4** Climate risk for coastal regions around Europe, showing the distribution of risk of the regions within a country (bottom panel) and the median value (top panel).

The CERES climate risk analysis considered two basic units of analysis: the fishing fleet and region. Both of these elements are exposed to the same hazard, namely climate-driven changes in the fish stocks that they are dependent on. We quantified this hazard based on the biological traits of the species, namely lifespan, habitat specificity and mobility. We also incorporated stock-specific metrics, by estimating the thermal-safety margin (distance between the upper thermal tolerance of the species and the local temperature) for each stock: this approach allows for a differentiation in the hazard between, for example, cod in the North Sea and in the Barents Sea. The stock-specific hazard was then integrated up to the fleet or regional level, weighted by local catch or landings data for each stock. Regional and fleet metrics for exposure were based on measures of the diversity of catch / landings: higher diversity gives a lower exposure. Regional metrics of vulnerability were based on socio-economic metrics such as per capita Gross Domestic Product (GDP): lower GDP decreases the adaptive capacity of nations to cope with the potential negative impacts of climate change. Fleet metrics of vulnerability were based on the profitability of the fleet: lower profitability makes for higher vulnerability.

The climate-related hazards for 140 marine fish and shellfish species (523 stocks) were estimated, covering more than 90% of the total commercial value of European fisheries. The analysis covered 26 European countries, including Norway, Iceland and Turkey: all countries had at least 75% of their fisheries covered by value. In total, 404 fleet segments from across the EU and 101 regions were also included in the analysis. While there is a wide diversity of risks, smaller vessels and dredgers tended to have the highest climate risk amongst fishing fleets. Regions with the highest climate risk included Romania and Bulgaria, those along the south coast of the Baltic, and southern Scotland/northern England (Fig. 4.4). Analyses were also been performed for each of the Storylines, allowing their individual risks to be set in the wider context of European fisheries. Similar analyses were carried out for 120 freshwater species and small-sized individuals with limited distribution ranges were found to be the most vulnerable (CERES D5.4 2020).

## 4.7 Adverse consequences and opportunities: Stakeholders perceptions

The following is a summary of the comments provided by stakeholders after participating in a mind-mapping exercise which then contributed to the 12 CERES fisheries Storylines. Comments apply to one or more Bow-tie diagrams and Storylines and are organised under general headings (see Cormier et al, 2019 for the rationale for Bow-tie analyses). It is emphasised that they indicate an expert judgement based on a large and varied experience amongst stakeholders. Different Bow-tie diagrams were completed by differing numbers of stakeholders and so there may be differing degrees of confidence in the conclusions. Summary examples are given below but the individual Bow-tie diagrams (Appendices 1-3 in CERES D5.1 (2020)) should be consulted to determine which individual comments relate to which Bow-tie diagram. These can then be cross-referred to the Storylines.

In general, the Bow-tie analysis identified more adverse consequences than opportunities for fisheries due to climate change. This may be the result of the industries being more concerned with short- to medium-term than long-term repercussions. In some Storylines, such as for the Mediterranean dolphinfish fishery, there were more opportunities identified than adverse consequences. It is noted, however, that for some Storylines (gadoids in the North Sea and mackerel in the NE Atlantic), the stakeholders did not identify any opportunities due to climate change.

**Adverse consequences**

**Biodiversity, ecosystems, foodwebs and ecology**: Reduced biodiversity caused by climate change may favour non-native species, changes to predator/prey relationships and a simplification of the food web. Continued expansion of the habitat of invasive tropical tuna species, for example, could change the ecosystem structure of the Mediterranean Sea. Warm temperatures can decrease energy-rich zooplankton while, at the same time, increasing the energy requirements of fish.

The food web structure may be strongly impacted through changed predation pressure on small/medium pelagic species; for example, increased predation pressure on plankton (e.g. copepods) gives a feedback-loop into mackerel food webs. Similarly, in the case of cod, capelin and herring, for example, as more Atlantic water enters the Barents Sea there will be an increase in biodiversity, although some Arctic species may disappear.

Increased predation pressure on target species coincides with climate-driven increases in the abundance of some species, such as bluefin tuna as a predator or mackerel migration to higher latitudes. There may be a change from the Arctic to the Boreal food web, a pelagic-dominated ecosystem leading, for example, to reduced catches of cod but improved conditions for herring. There may be changes from mesotrophic to eutrophic conditions with negative effects on system complexity and diversity and nursery and spawning areas may also need more protection.

In one example, fishing other species was not expected to reduce pressure on cod, capelin or herring, but if mackerel became very abundant it could reduce capelin and herring stocks in the Norwegian/Barents Sea through predation and indirectly lead to less cod.

In inland waters, the changes to food webs and pressure on other species through simplified food webs, the vulnerability of some species and the decrease in prey availability may increase the pressure on other species, such as pike-perch or common carp, or expansion of stocks of invasive species like bighead and silver carp or Prussian carp, and pest species like top-mouthed gudgeon.

**Company structure and practices** - Company size and portfolio may benefit under a slight temperature increase due to greater stocks of fish. Agriculture could expand at the expense of fishing leading to the migration of employees to other areas, the decreased number and size of fishers associations, and reduced company size. There will be a tendency towards fewer, larger, more efficient vessels and a concentration of larger companies (and increased monopolism) due to buy-outs of smaller companies (or their quotas) that cannot adapt. Migrating stocks could increase steaming time with economic consequences, but there was a mixed view by stakeholders of the changes to the accessibility of fishing grounds depending on species.

**Local culture, traditions, values and tourism** - Climate change may lead to decreased touristic appeal, reduced cultural heritage, weakened traditional (cultural) values and hence a decreased local welfare. This leads to impacts on local communities, values and fishing traditions with the loss of tourism to traditional fishing villages.

Traditions and values associated with fish species, however, will not necessarily change irrevocably unless the stocks are in danger of disappearance. As an example, as suggested for the Norwegian and Barents Sea fisheries, tourism will increase with warmer temperatures and losses in sea-ice that, in turn, could increase conflicts between tourist and fishing vessels. In a similar vein, the northerly shft in distribution of salmonids will make communities dependent on recreational sport fishing more vulnerable to loss of livelihoods, particularly in rural, isolated landscapes

**Employment** - Climate change will lead to decreased employment and casualisation of employment, possibly due to reduced catches. The pattern is mixed, however, since employment could increase in some cases (e.g. due to greater bluefin tuna abundance), or be reduced (e.g. due to migrations of stocks to high latitudes). There are also unpredictable employment effects due to multispecies fisheries.

As an example, there could be increased short- to medium-term employment due to increases in Barents Sea cod but decreased long-term employment as fishers would need to travel farther as stocks move to Russian waters and, for Norwegian fishers, more fish would be inaccessible. Fishers may end up selling elsewhere or relocating, leading to decreased jobs in the fishery sector that could lead to young people not entering the industry or going abroad for work.

**Industry structure and practices -** With climate change, fishing may move further offshore and there could be shorter fishing seasons. The general industry structure may improve in colder areas, but in already warm areas, such as the southern central Mediterranean, the industries may suffer. A large-scale fishery may no longer be viable and there could be a loss of certification and challenges in traceability.

Several of the Bow-tie stakeholders emphasised that there could be losses of family-owned businesses in favour of larger companies, co-operations or co-operatives (monopolisation). This could reduce the diversity of fisheries and markets. These above-mentioned structural changes to the industry would increase conflict between fishermen, fishing vessel owners, and authorities and ultimately the capture fisheries could be replaced with aquaculture.

**Markets** - The market and economic repercussions of climate change would lead to changed prices for fish in relation to both RCP4.5 and RCP8.5, to changes in consumer habits if new species enter the markets, and to cost increases. The change in fishing costs would reduce the market viability. Market sizes and regions might increase, as already observed in some regions (such as the N Atlantic for mackerel).

Decreases in market price are also possible through oversupply, especially if the size of stocks continues to increase (e.g. in the case of bluefin tuna). In the case of inland waters, monopolisation and higher prices, the decrease of regional wild freshwater fish markets and the increased aquaculture in the area would all have an adverse effect.

**Transboundary policy issues** – Climate change could increase exploitation and value of mackerel by northern Non-EU countries (Iceland, Greenland) leading to increased political pressure and the possibility of a 'mackerel war' as there is no agreement between Iceland and the EU, Faroe Islands and Norway. If more cod inhabit the Russian zone of the Barents Sea, then fisheries treaties between Norway and Russia will be required and there could be less quota for Norwegian fishers.

Political factors could exacerbate changes, such as 'Brexit' (the departure of the United Kingdom from the EU Common Fisheries Policy) could reduce access among EU fishing fleets to UK waters and vice versa, with major consequences for fleets and local economies. It will become difficult for individual fleets to follow fish across international boundaries, and quota allocation keys will need to be revisited on a regular basis to reflect the share of stocks currently residing in indigenous waters.

**Opportunities**

**Alternative areas, stocks and species -** Climate change may cause the industry to exploit other stocks (as well or instead of current stocks). In the Mediterranean, examples include targeting the round sardinella instead of sardine and anchovy (although round sardinella currently has a low market price) and Mediterranean parrotfish, jack mackerels, picarels and squid instead of hake.

There may be the potential expansion of tropical tuna into the Mediterranean that could be fished instead of bluefin tuna. In the Baltic, the invasive goby (*Neogobius*) could be targeted instead of cod, herring or sprat. A given fishery could target different species in different areas, for example, sardine, anchovy and sprat locally but other species further away.

The NE Atlantic flatfish fishery could exploit new or other species such as red mullet, gurnard and squid. In inland waters such as Lake Razim, catches could change to non-natives such as silver, big head and grass carp, away from pike-perch, or in Swedish lakes a shift towards fishing for cyprinids is being predicted to offset the potential decline in whitefish stocks. In the Norwegian and Barents Sea, instead of targeting cod, capelin and herring fisheries might switch to species migrating into the region such as mackerel and blue whiting may be targeted.

**Industry, Market and Employment Opportunities -** The changes in industry structure due to climate change may lead to increased employment due to increased abundance and access to a particular resource. There could be an increase in market price in the short-term and an increase in market size, regions and length of fishing seasons. As a short-term gain, there may be a positive increase in ex-vessel prices.

There could be an expansion of markets through increased globalisation and in exploiting new markets. Markets may respond positively to the changing stocks – for example, for cod in the Norwegian and Barents Sea, market prices should remain high due to high stock biomass and generally lower biomass of stocks in other parts of the North Atlantic.

**Local Culture, Traditions, Tourism and Values -** The realignment of the industry (and the changing climate) may reinforce traditional (cultural) values, including increased tourism to increase seafood consumption.

While there could be an erosion of cultural heritage based on fishing, it was emphasised by stakeholders that traditions evolve, and societal priorities change and thus change is not necessarily seen as negative. In inland waters, while there may be a decrease of tourism for recreational sport angling, there may also be an increased demand for fish due to more tourists.

5

# Risks and opportunities for the European aquaculture sector

Pauline Kamermans, Nick G.H. Taylor, Thomas K. Doyle, Joao Gomes Ferreira, Alhambra M. Cubillo, Cornelia Kreiß, Michael Elliott, Myron A. Peck

# Chapter 5: Climate change and the European aquaculture sector

## 5.1. Introduction

Recently, the FAO summarised evidence on the impacts of climate change on aquaculture (Barange et al. 2018). The main conclusion was that short-term climate change impacts on aquaculture arise from a mixture of direct (physical) and indirect (biological) factors and can include losses of production and infrastructure arising from extreme events such as floods, increased risks of diseases, parasites, and harmful algal blooms. Long-term impacts can include reduced availability of wild seed (for shellfish) as well as reduced precipitation leading to increasing competition for freshwater.

Climate-driven changes in temperature, precipitation, ocean acidification, incidence and extent of hypoxia and sea level rise, amongst others, are the direct (physical) factors expected to have long-term impacts in the aquaculture sector at multiple scales.

Options for adaptation and resilience building were offered, noting that interactions between aquaculture, fisheries and agriculture can either exacerbate the impacts or help create solutions for adaptation. In the CERES project, impacts of climate change for the European aquaculture sector, including risks and opportunities (both marine and freshwater) were evaluated using a coherent set of physical, economic and socio-political scenarios across regions.

Climate-driven physical stressors such as increased average temperature or heatwaves (extreme events), acidification and hypoxia can affect growth and survival of fish and shellfish and, hence, the productivity of farms. The productivity of farms can also be affected by climate-driven biological stressors such as diseases and blooms of harmful algae or jellyfish. Data on regional changes in climate-driven stressors such as temperature (both air and water), pH, salinity, oxygen, and chlorophyll a (generally considered a good proxy for food for bivalve shellfish) are presented in Chapter 2. Knowledge on the effects of climate change related stressors on the physiology of farmed fish and shellfish species is presented in section 5.2.

In order to predict the impacts of climate change on fish and shellfish, biological models need to be adapted to depict these factors (e.g. functional responses to changes in temperature). Results of the biological modelling that incorporate future changes in these stressors are presented in section 5.3. Furthermore, effects of increased host-pathogen interaction were modelled for some species and European regions. The modelled changes in production were used to calculate economic consequences for European aquatic food producers (farms) and markets (see Chapter 6) under the CERES scenarios. In addition, a vulnerability analysis is presented for the European region in section 5.4 for the different species across 22 nations. Finally, section 5.5 reports on the results of a stakeholder-driven mind-mapping analysis ('Bow-tie') identifying control and adaptation measures available for the aquaculture sector to climate change.

The following species were evaluated across a number of regions: northeast Atlantic - Atlantic salmon (Ireland and Norway), eastern Mediterranean - European sea bass / sea bream (Turkey), western Mediterranean - European sea bass (Spain), northeast Europe - common carp (Poland, Germany), eastern Europe - rainbow trout (UK, Turkey, Denmark, Germany), North Sea coast - blue mussel (Denmark and the Netherlands), North Sea coast - Pacific oyster (the Netherlands), southwest Europe (Atlantic) - Mediterranean mussel (Portugal), southwest Europe (Atlantic) – Pacific oyster and European clam (Portugal), western Mediterranean – Mediterranean mussel (Spain).

## 5.2. Direct and indirect effects on farmed fish and shellfish

### 5.2.1 Direct effects

As a first step in the CERES project, available data and knowledge on climate-driven environmental factors from previously published laboratory experiments conducted on selected aquaculture fish and shellfish species in marine and inland waters was compiled by Catalán et al. (2019). A gap analysis revealed the need for continued research quantifying how changes in interacting abiotic factors affect farmed fish and shellfish (Fig. 5.1). Second, experiments were conducted to fill gaps in knowledge concerning the effects of interacting factors on the growth, survival and productivity of specific fish and shellfish species (Table 5.1). Together, this gave an overview of parameters and values to be used in the biological projections of climate impacts presented in section 5.3.

**Effects of increased temperature and interactions with food availability**

A meta-analysis performed by Catalán et al. (2019) showed that warming was associated with a consistent (but not significant) increased somatic growth for fish and a significant increase in the growth of bivalves. Experiments conducted in CERES revealed that the Critical Thermal Maximum (CTmax) of European sea bass larvae was not affected by warming (Moyano et al. 2017).

CERES experiments also demonstrated that mortality rates of sea bream and sea bass were not significantly affected by temperature, pH or food restriction, and that warmer temperatures promoted increased growth and intake regardless of the food restriction. Experiments on mussels and oysters revealed that the effects of temperature depended on levels of feeding.

Higher optimal temperatures for growth of mussels and oysters were observed at higher food conditions and significantly lower feeding (clearance) rates were found at higher food conditions. CERES experiments with Mediterranean mussels tested a 3°C increase in temperature above ambient levels across all four seasons. The sensitivity of mussels to climate change depended on both the mussel condition and ambient temperature. A 3°C increase in spring temperatures inhibited mussel feeding by decreasing clearance rates and food absorption efficiency. That warming also degraded digestive glands indicating changes in the functionality of their immune system.

**Effect of decreases in pH and interactions with temperature**

At low pH (acidification), the mean growth rate of both freshwater fish and bivalves significantly declined, whereas the mortality of bivalves significantly increased (Catalán et al. 2019). In CERES, the stress response of Mediterranean mussels to acidification (pH 8.1, 7.7 and 7.3) was tested in different seasons. In summer, autumn and winter in increasingly acidic waters, mussels compensated for impairments to their immune system by gonadal degradation, a process that redirects energy from reproduction to immune defence to improve mussel health.

**Effect of deoxygenation and interactions with temperature and food availability**

Decreased dissolved oxygen concentration (DO) significantly decreased growth in freshwater fish and significantly reduced the metabolic rate in marine demersal fish (Catalán et al. 2019). CERES performed experiments exploring how decreased DO, temperature and feeding level interacted to affect mussels.

Low DO significantly reduced mussel growth and higher temperature significantly affected growth when DO was low. High temperature and low DO significantly reduced clearance rate and increased metabolic rate (oxygen consumption). In the high food treatment, reduced DO resulted in decreased growth rate. In the low food treatment there were no differences in growth among the different DO levels (see Fig 5.1).

**Effect of reduced salinity**

CERES studied the effect of salinity on the performance of European clam and oyster. Abrupt reductions in salinity caused high mortality in juveniles and adults of both species. Juveniles were particularly sensitive to low salinity and high temperature, suffering higher mortalities than adults.

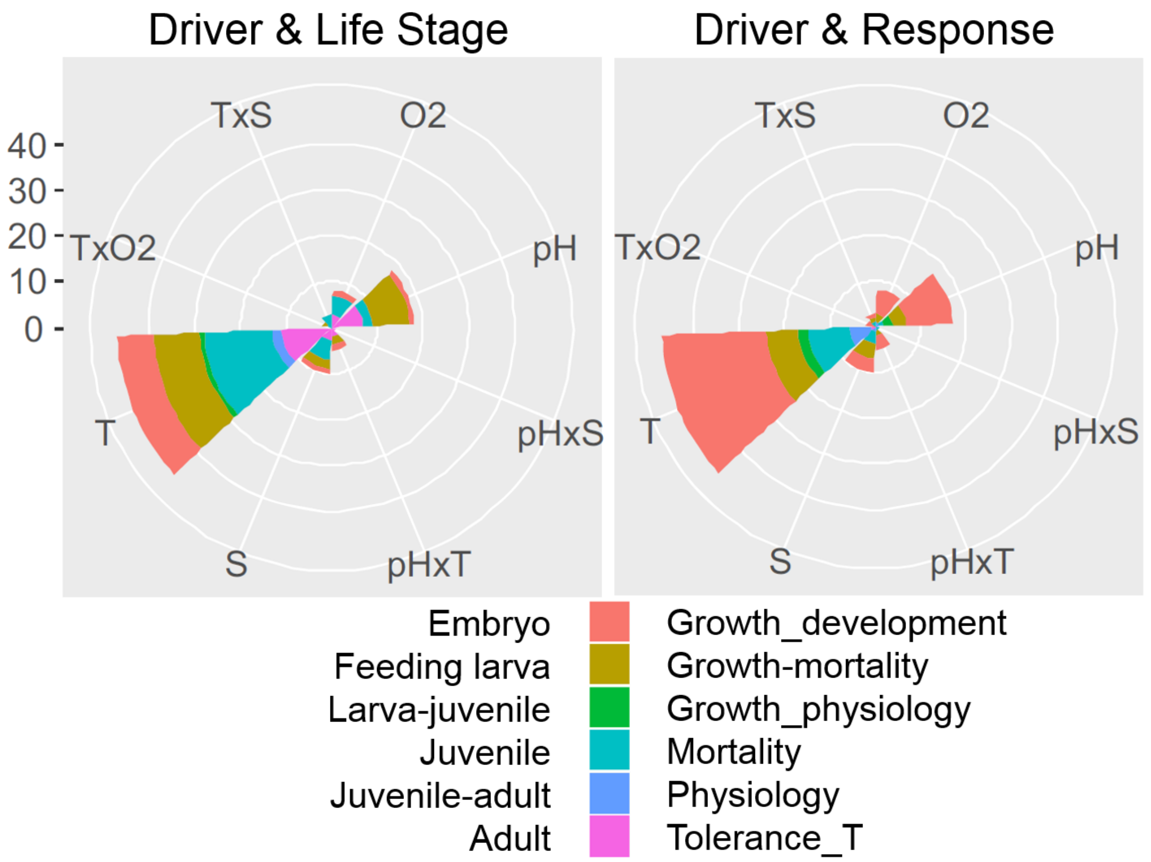



**Figure 5.1** Summary of published data sets (n = 120) examining the effect of abiotic drivers on key, European marine aquaculture species. In total, six life stages (left side) and six responses (right side) were studied. Drivers include: T, temperature effect; O2, deoxygenation effect; pH, acidification effect; S, different salinities. Some studies examined the combined effect of two drivers. From Catalán et al. (2019).

**Table 5.1** Experiments conducted during CERES on the direct effects of interacting factors, T = temperature, pH = acidification, O2 = oxygen, S = salinity.

| Species | Stressor | Response tested |
|---|---|---|
| sea bass | T, pH | thermal windows (temperature tolerance, survival) |
| sea bream | T, food | growth, feed conversion, survival, welfare, condition and quality |
| mussel & oysters | T, O2, food | growth, survival, clearance rate, oxygen consumption |
| oysters & clams | S, T | survival and behaviour |
| mussel & clams | T, pH | four seasonal experiments (growth, survival, filtration) |

### 5.2.2. Indirect effects

Climate change will not only have direct but also indirect effects on the growth and performance of aquaculture species from increases in the occurrence of diseases, harmful algal bloom species and jellyfish. CERES developed tools to make projections of the occurrence and risk posed by these indirect effects (see Box 2). For example, species distribution modelling was used to understand how harmful algal species may respond in the future to climate change, by considering environmental preferences and how these might shift in the long-term (Townhill et al. 2018).

CERES projections suggest that the habitat of most HAB species (defined by temperature, salinity, depth, and stratification) will shift north this century, with suitability increasing in the central and northern North Sea. An increase in occurrence here might lead to more frequent detrimental blooms if wind, irradiance and nutrient levels are also suitable. Prioritising monitoring in these susceptible areas could help in establishing early-warning systems for aquaculture and health protection schemes (Townhill et al. (2018).

Disease is a ubiquitous concern related to climate change across all aquaculture sectors (Jennings et al. 2016, stakeholder feedback). Katharios et al. (2019) summarised the importance of disease to aquaculture and provided useful insights on the key, farm-level concerns and tools required by the industry under present day conditions.

When integrated into a holistic, biosecurity plan, their recommendations of farm-level requirements can help regions and sectors best prepare for incursions of more resilient pathogens and allow adaptation to increased risks of disease posed by climate change.

Disease occurrence and impact is directly linked to water temperature. Water temperature determines the rate at which pathogens can proliferate and influences both the effectiveness of the immune response as well as the level of physiological stress in fish.

Disease affects profitability of farms through mortality, reduced growth, and increased costs associated with monitoring, and veterinary intervention. The implementation of statutory control measures against disease may require the culling of stock, can impact supply chains, restrict trade and limit market availability.

In many terrestrial host-pathogen systems disease impacts are assessed and predicted through the use of modelling. For aquatic systems, there is a lack of appropriate data to parameterise such epidemiological models and lifecycle characteristics displayed by aquaculture species are very diverse. Thus, alternative approaches to modelling diseases of aquaculture species were developed within this project.

A model was developed that used a dose-response function to predict pathogen transmission between organisms and production units, and for the first time this was integrated into an aquaculture production model (Aquaculture Biosecurity and Carrying-capacity: ABC, see Ferreira et al. 2016).

This allowed for the assessment of disease losses at the level of the production unit, farm, or farming area. Applying this tool for two key viral diseases demonstrated that the profile of seasonal temperatures is of critical importance in determining the duration and severity of a disease outbreak, but that the overall loss depends on the interaction between stock density and the time in the production cycle that the pathogen is introduced.

CERES developed methods to assess the risk of disease occurrence based on temperature profiles for present day and future (mid-century) projections under RCP4.5 and RCP8.5. Risk was based on the proportion of days in a year that areas would be in the permissive temperature window for disease expression.

This was predicted based on observed and projected Sea Surface Temperature (SST) for marine aquaculture, or by converting air and soil temperatures to water temperatures for inland aquaculture. Maps of present and future risks were produced for key diseases of the main European aquaculture species examined in CERES and clearly demonstrate how risk changes spatially and is influenced by the severity of future climate change (between RCP4.5 and RCP8.5) (CERES D3.2 2019).

These outputs allow improved targeting of surveillance and biosecurity measures and to pinpoint areas of low risk where future aquaculture production could be developed. For example, climate change is projected to cause large changes in the areas at risk of the occurrence of Spring Viraemia of Carp (SVC) across Poland (Fig. 5.2).

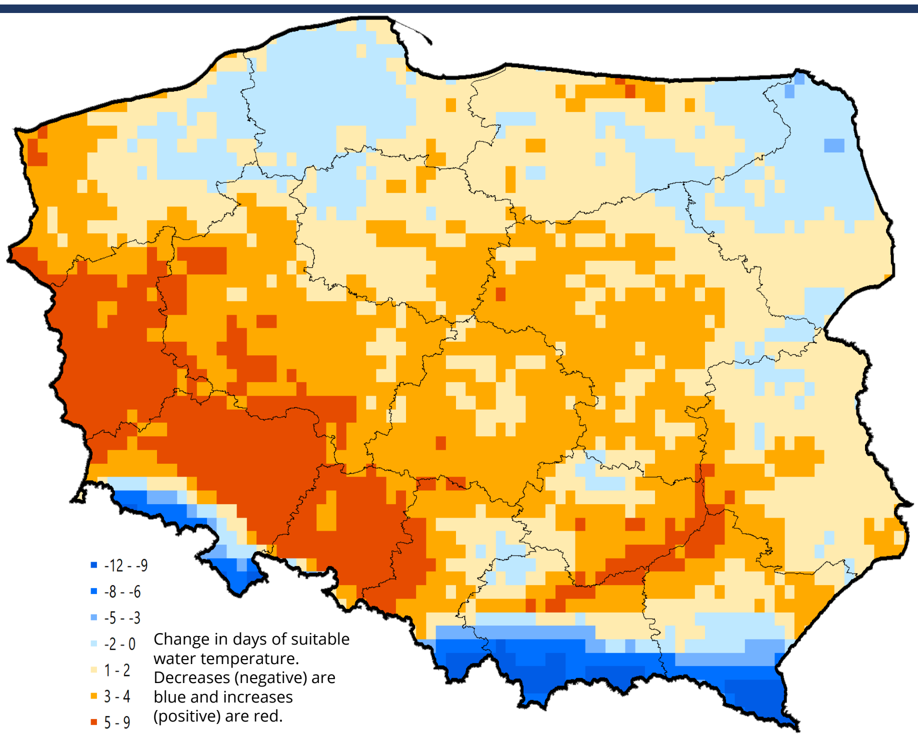



**Figure 5.2** Comparison of end-of-century (2080-2099) to present-day projections for change in the number of days when water temperatures are suitable for expression of Spring Viraemia of carp under RCP8.5. The colors represent decreases (negative - blue) and increases (positive-red) in the number of days.

**Box 2: Early warning of blooms of harmful algae and jellyfish**

Across Europe, blooms of harmful algae and jellyfish are known to be detrimental to marine fish and shellfish aquaculture (Baxter et al. 2011, Raine et al. 2010, Bosch-Belmar et al. 2016). One of the potential effects of climate change may be an increase in the frequency, intensity and distribution of these harmful blooms and a growing need exists to develop accurate short-term forecast models. Previous research has developed empirical models to successfully forecast HAB events in Bantry Bay in Ireland (McGillicuddy 2010, Raine et al. 2010). That model was based on the prime forcing variable wind direction which causes the transport of harmful algae into the bay from the neighbouring coastal shelf (Raine et al. 2010). Based on that model, CERES developed a predictive jellyfish model that successfully predicted a jellyfish bloom that occurred in 2009 based on available data on jellyfish, fish mortality and wind data (Fig. 2). Early warning of blooms of harmful algae and jellyfish is feasible when relevant datasets are available online and validation can be performed.

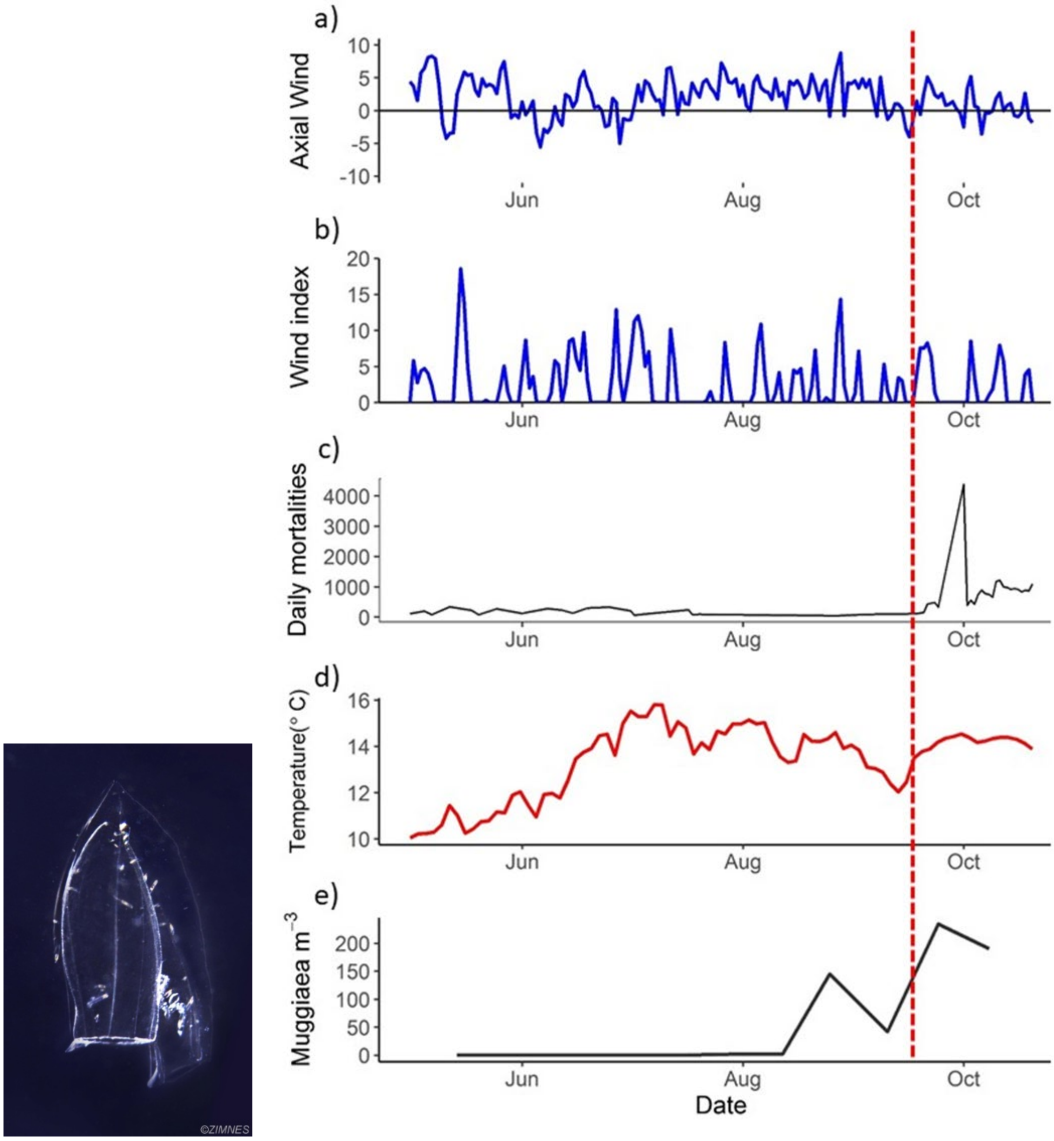



**Figure 5.3** Bantry Bay time series for the jellyfish bloom in 2009, with axial wind (a), wind index (b), daily mortalities of fish at salmon farm (c), temperature (d) and mean *Muggiaea atlantica* abundance (e). Vertical red dash line indicates exchange event predicted by flip-flop event in bay (negative axial wind component in (a) + wind index value approaching -10 m $s^{-1}$).

## 5.3. Future changes in the productivity of farmed fish and shellfish

This section addresses the projected changes in productivity due to: (i) direct effects of climate change on finfish and (bivalve) shellfish species of economic importance in Europe (Table 5.2); and (ii) indirect effects of climate change on Atlantic salmon, common carp, and Pacific oysters.

**Table 5.2** CERES species-location pairs, type of culture, and annual production (economic importance).

| Region | Species | Country | Annual production[3] (1000 tonnes $y^{-1}$) | Culture system |
|---|---|---|---|---|
| Northeast Atlantic | Atlantic salmon | Ireland (marine) | 18.3 to 1442.9 | Circular cages |
| Northeast Atlantic | Atlantic salmon | Norway (marine) | 1233.6 to 1442.9 | Circular cages |
| E. Mediterranean | Sea bass | Turkey (marine) | 100.0 to 179.0 | Circular cages |
| W. Mediterranean | Sea bream | Spain (marine) | 17.0 to 156.0 | Circular cages |
| Northeast Europe | Common carp | Poland (freshwater) | 17.2 to 69.7 | Earthen ponds |
| Eastern Europe | Rainbow trout | Turkey (freshwater) | 106.7 to 288.5 | Earthen ponds |
| North Sea coast | Blue mussel | Denmark (marine) | 2.4 to 110.4 | Longlines |
| North Sea coast | Blue mussel | Netherlands (marine | 44.0 to 110.4 | Bottom culture |
| North Sea coast | Pacific oyster | Netherlands (marine) | N.A. to 95.7 | Off-bottom trestles |
| Southwest Europe (Atlantic) | Mediterranean mussel | Portugal (marine, offshore) | N.A. to 334.2 | Longlines |

### 5.3.1. Direct effects on finfish aquaculture

Most of the marine finfish species were projected to have decreased growth performance by mid-century (2041- 2050) and end-of-century (2091-2100), although only salmon (Ireland) and sea bream productivity would be significantly negatively affected (Table 5.3). This is particularly clear in the end-of-century results. Sea bream is the marine fish most affected by temperature-related changes projected at mid- and end-of-century. By mid-century (2050), this species is predicted to need a significantly longer time to reach minimum commercial size. The other marine finfish consistently increased their productivity in the lower (RCP4.5) emission scenario. Projected, end-

[3] Country and European totals from Eurostat, sourced from https://longline.co.uk/meta

of-century salmon production appears to be more negatively impacted in Ireland than in Norway (Table 5.4).

For inland species, carp in Poland is projected to have lower production, particularly in the high-emission (RCP8.5) scenario, where future growth performance is much lower compared to present day. Out of all the modelled finfish, common carp is the species most negatively impacted by the direct effects of climate change by mid-century.

### 5.3.2. Direct effects on bivalve shellfish aquaculture

Mediterranean mussels cultivated in offshore longlines appear to be the least adversely affected by climate-driven projections of changes in temperature and food availability at both mid- (Table 5.3) and end-of-century (Table 5.4). The productivity of Mediterranean mussel aquaculture in Portugal was projected to remain similar or slightly improve compared to the present day situation.

**Table 5.3** Projected changes in productivity (prod) at mid-century (2050) across regions and species. Note: higher feed conversion ratio (FCR) indicates worse cultivation performance.

| Country | Species | Harvest weight | | Total Prod. | | Average Prod. | | FCR | |
|---|---|---|---|---|---|---|---|---|---|
| | | RCP4.5 | RCP8.5 | RCP4.5 | RCP8.5 | RCP4.5 | RCP8.5 | RCP4.5 | RCP8.5 |
| Ireland | Atlantic salmon | | | | | | | | |
| Norway | Atlantic salmon | | | | | | | | |
| Turkey | Sea bass | | | | | | | | |
| Spain | Sea bream | | | | | | | | |
| Poland | Commo n carp | | | | | | | | |
| Turkey | Rainbow trout | | | | | | | | |
| Denmark | Blue mussel | | | | | | | | |
| Netherlands | Blue mussel | | | | | | | | |
| Netherlands | Pacific oyster | | | | | | | | |
| Portugal | Med mussel | | | | | | | | |

Legend:

- much lower
- same average and range
- significantly greater
- significantly lower
- same average, wider range
- much greater
- lower average
- ≥ present day
- ≤ present day
- Higher average

Conversely, longline culture of blue mussel in Denmark and off-bottom culture of Pacific oyster in the Netherlands were projected to be most deleteriously impacted (in all production parameters) in both RCP4.5 and RCP8.5 scenarios by the end of the century (2100). At mid-century (2050), the bottom culture of blue mussel in the Netherlands was similar to present day but decreases in production were projected for 2100.

**Table 5.4** Projected end-of-century (2100) changes in the productivity (prod) of culture for different regions and species. Note: higher Food Conversion Ratio (FCR) indicates worse cultivation performance.

| Country | Species | Harvest weight | | Total Prod | | Average Prod | | FCR | |
|---|---|---|---|---|---|---|---|---|---|
| | | RCP4.5 | RCP8.5 | RCP4.5 | RCP8.5 | RCP4.5 | RCP8.5 | RCP4.5 | RCP8.5 |
| Ireland | Salmon | | | | | | | | |
| Norway | Salmon | | | | | | | | |
| Turkey | Sea bass | | | | | | | | |
| Spain | Sea bream | | | | | | | | |
| Poland | Carp | | | | | | | | |
| Turkey | Rainbow trout | | | | | | | | |
| Denmark | Blue mussels | | | | | | | | |
| Netherlands | Blue mussels | | | | | | | | |
| Netherlands | Pacific oysters | | | | | | | | |
| Portugal | Med mussels | | | | | | | | |

Legend:

- much lower
- significantly lower
- lower average
- ≤ present day
- same average and range
- same average, wider range
- ≥ present day
- Higher average
- significantly greater
- much greater

### 5.3.3. Indirect effects

CERES used the Aquaculture, Biosecurity, and Carrying Capacity (ABC) model to simulate indirect effects of climate change (incidence of disease) on the productivity of Atlantic salmon and Pacific oyster farms in Ireland and the Netherlands, respectively.

In both cases, the increase of seawater temperature as climate change progressed led to a greater number of days within the optimum temperature range for host-pathogen interaction: salmon infectious hematopoietic necrosis virus (IHNv, 8–15°C), and oyster herpes virus (OHv, 16–24°C) were tested, and hosts were exposed to the disease for 2, 13 and 26 days in the present, mid-century, and end-of-century time periods, respectively.

Fig. 5.3 shows the change in disease-related mortality when the window of host-pathogen overlap is more favourable. When feeding is needed in the aquaculture setting, this leads to higher (i.e. worse) FCR due to investment in feed which does not result in harvestable biomass. If a disease event occurs at a later stage in the culture, the FCR, and therefore the unrecovered costs, will increase.

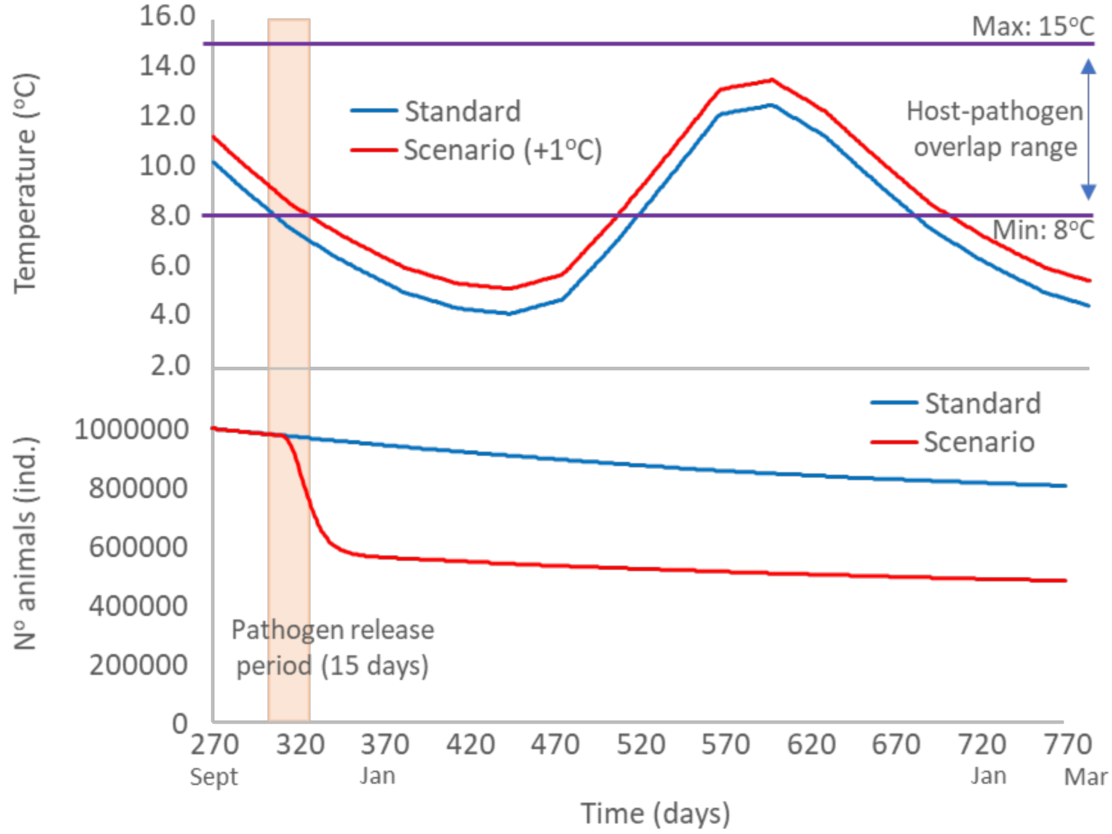


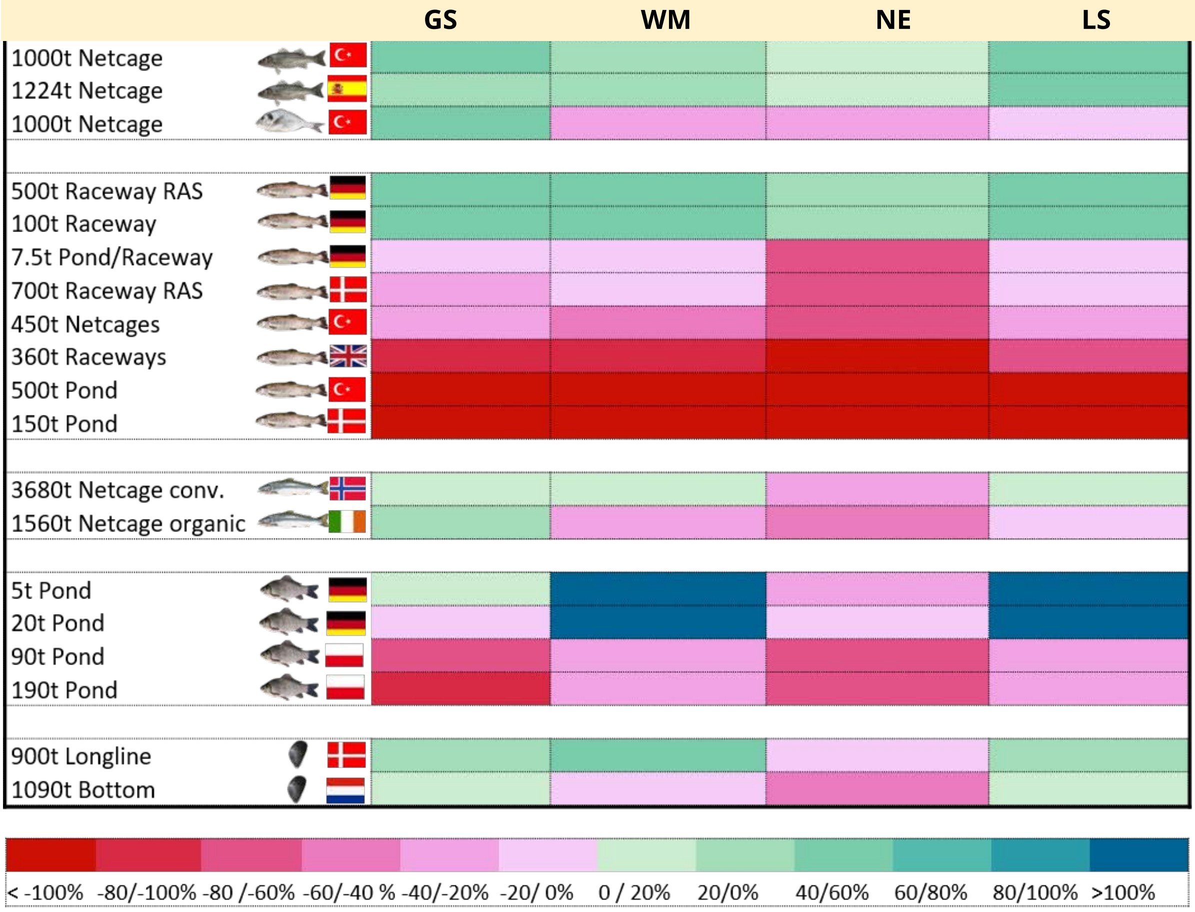

**Figure 5.3** Simulation of host-pathogen interactions (Atlantic salmon and IHNv) at a typical farm for (i) standard water temperature conditions; and (ii) a warming of 1°C.

## 5.4. Economic consequences for European aquatic food producers and markets

### 5.4.1. Economic consequences on individual farms under the CERES scenarios

In addition to impacts on environmental parameters such as water quality and temperature that might influence the fish and shellfish production itself, the aquaculture sector is also facing an uncertain future in terms of production costs and returns. Present- day costs and profitability for the key European aquaculture species rainbow trout, carp, Atlantic salmon, sea bass, sea bream and blue mussels farmed across a total of ten European countries were investigated to understand the opportunities and challenges associated with future trends in production costs and market returns. Based on species-specific feed cost developments, trends for future energy costs and market returns combined with assumptions on subsidies and marketing options. In the following section, potential winners and losers are discussed across the species and between countries under and  between the four CERES scenarios until mid-century (2050): World Markets (WM), National Enterprise (NE), Global Sustainability (GS) and Local Stewardship (LS).

**Table 5.5** Future change in profitability of typical farms analysed for future prices of fish feed, energy costs and fish price (returns) for the mid of century. WM= World Markets; NE= National Enterprise, GS= Global Sustainability, LS= Local Stewardship. Species from top to bottom: Seabass, Seabream, Rainbow Trout, Salmon (industrial and organic production), Carp, Mussel.




Considering mid-century price developments, WM is the most promising scenario; it bears the highest chance that the profitability of about half the farms examined could be increased in the future (Fig. 5.4). A similar picture emerges in the LS and NS scenarios. In contrast, almost 80% of the farm types were less profitable than today under the GS scenario (Fig. 5.4). In general, future profitability of fish farms is due to the combination of the market price for fish and feed costs. The relation between these two is least favourable in the GS scenario with comparably low fish prices due to scenario-specific assumptions of the key drivers of world food prices such as future change in population, income, international trade, agricultural expansion and technology (Popp et al. 2017) (see Chapter 3).

Farms projected to be non-profitable by 2050 under all four scenarios had a similar present-day profit margin of around 7%. A profit margin between 11- 31% was predicted to often lead to a decreased future profitability compared to today, however, depending on the scenario these farms still have a chance to survive. Farms with a present-day profit margin of >30% increased their future profits under all of the four scenarios. This pattern could be used as a first-order classification of future opportunities of other individual farms not included here or for profit margins for the overall aquaculture sector.

Although operating earnings were lowest under the GS (RCP4.5) scenario, there may be little additional costs associated with investments in infrastructure needed to counteract the effects of climate change (e.g. storminess, lower oxygen content of water). Such costs were not included in the modelling and are expected to be much higher in RCP8.5 scenarios (WM and NE). Conversely, changes (either negative or positive) in harvest weight and feed conversion ratio (FCR) induced by changes in water temperature will be stronger by 2100. When including future ranges of change in FCR and harvest weight within the economic analysis (see section 5.3), the picture changes quite substantially for some species-region combinations.

This is particularly the case for the two mussel farms where poor production years lead to further losses in profits and strong production years lead to higher profits under all fours scenarios. For the Irish salmon farm, the slight positive profitability trend under the WM scenario cannot be maintained in extreme warm years, and this pattern is also seen for the Turkish seabass production in cold years under the NE scenario. Net cage farming of trout in Turkey is no longer viable due to additional profit losses caused by decreased productivity in the GS scenario under extreme cold years. In contrast, extreme warm years experienced in the WM scenario increase profitability above present-day levels.

#### 5.4.2 Economic consequences on the whole sector and market under the CERES scenarios

Scaling up to the whole sector by including also the suitability of water bodies according to future temperature and pathogen occurrence caused little change in the trends discussed for individual farms in the preceding section. For carp farms in Germany and Poland, however, there was a strong influence of future changes in habitat suitability. Besides the direct and indirect effects of increased temperature, water availability and extreme weather events (not included in the analysis) might impact the future economic performance of those farms.

A ranking of the future profitability of individual farms allow patterns to emerge of winners and losers across species and production type/country. In general, sea bass and salmon farms are projected to be the most profitable in the future, whereas the other species, on average, suffer sharp declines in profitability. An exception is the German best-practice trout farms and German carp farms under NE and LS scenarios due to local marketing options.

The average change in country-specific profitability (weighted by present-day returns) provides a cross-species ranking of the typical farm and country pairs analysed in CERES. This is particularly interesting for those countries where more than one species was investigated (Fig. 5.5) including Germany, Turkey and Denmark. For Germany, the expected losses in future profit of smaller farms (trout and carp) are outweighed by the positive future expectations of the best practice trout farms within the country (Fig. 5.4 & 5.5).

A similar picture is shown for Turkey where the projected future profitability of sea bass and sea bream production is contrasted with losses projected for typical trout farms. A sector focus on these marine species could be beneficial, thereby, providing opportunities for other trout producing countries.

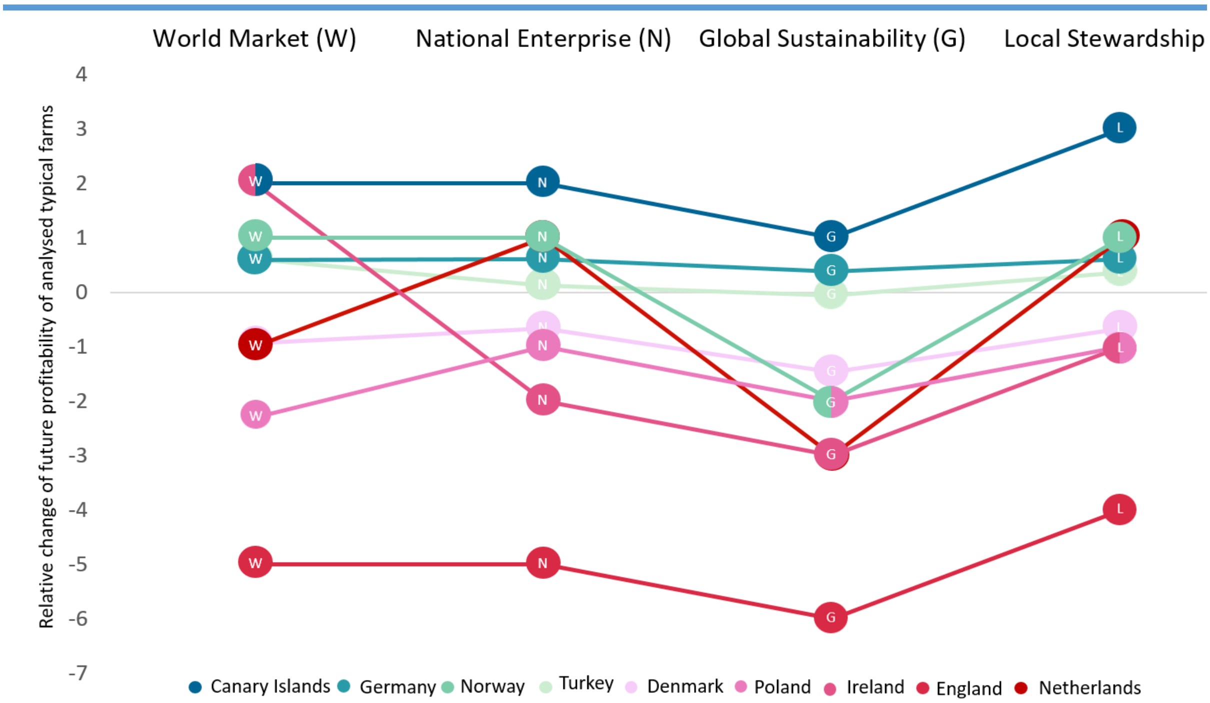



**Figure 5.5** Average change in future, relative profitability of typical farms analysed per country for future prices of fish feed, energy costs and fish price (returns) for 2050. Relative classification 3= +40 to +60%, 2= +20 to +40%, 1=0 to +20%;-1=-20 to 0%; -2=-40 to-20%; -3= -60 to -40%; -4= -80 to -60 %; -5= - 100 to -80 %; -6=<-100 % of present profitability. Canary Islands (n=1, seabass), Germany (n=5 trout & carp), Norway (n=1, salmon), Turkey (n= 4, seabass, seabream, trout), Denmark (n=3 trout, mussels), Poland (n=2, carp), Ireland (n=1, organic salmon), England (n=1, trout), Netherlands (n=1, mussels). For countries with more than one farm the average was weighted according to the present returns.

The overall pattern for Denmark demonstrates that future losses in profit projected for the typical Danish trout farms (Fig. 5.4) is only slightly countered by the more promising projections for typical mussel farms (Fig. 5.5).

The latter has lower value compared to the former. In the future, a sustainable profit margin within the Danish trout sector would, therefore, be important to take advantage of the comparably low temperature and precipitation impacts that are projected in 2050 for Danish freshwater bodies compared to other areas countries where trout farms were examined in CERES.

Future expansion of aquaculture production in general or for a specific species is obviously dependent on the availability of suitable areas and affordable inputs such as feed, the granting of licenses and the prevalent market demand.

## 5.5. Vulnerability of farmed fish and shellfish

A climate vulnerability assessment (CVA) was conducted on the European aquaculture sector using the FAO model of Vulnerability = Exposure + Sensitivity + Adaptive Capacity. Exposure was based on climate-driven warming projected in RCP4.5 and RCP8.5 for mid-century (2050). The CVA included the physiological attributes and farming methods of nine species (Atlantic salmon, sea bass, sea bream, trout, carp, blue mussel, Mediterranean mussel, oysters and clams) representing > 95% of the value for the European region. The assessment also used national-level economic data (employment and value by species and farm type) as well as the proportion of aquaculture value to GDP. Potential indirect effects of climate change (e.g. disease, harmful algal blooms, jellyfish) were not considered for two reasons. First, projected changes in these factors were not available across all European regions and, second, the CVA only applied common elements of climate exposure acting across both freshwater and marine habitats.

Based on the availability of these data, the vulnerability of 22 countries – the top producers in the EU28 as well as Norway and Turkey – could be ranked and relative values are shown (Fig. 5.6).

Based on the thermal windows of growth performance (lower and upper thresholds for optimal growth), climate-driven warming projected in RCP8.5 for 2050 caused little change in the suitability of culture conditions for most species in many regions. Differences in the vulnerability scores were most attributable to national-level differences in the prevailing farming technique (e.g. extensive versus semi-intensive or amounts of control of finfish versus shellfish culture) and national-level economic indicators.

Many countries growing freshwater fish such as trout and carp, were relatively vulnerable to climate change due the high number of small-scale farms within the sector (low adaptive capacity in terms of the ability to invest in technological innovation) and environmental control in extensive (pond) or semi-intensive (e.g. raceway) farms. Farming clams, mussels and oysters is inherently vulnerable due to the lack of control of the production cycle and the fact that most businesses are relatively small (translating to low adaptive capacity).

In this context, Spain had only intermediate vulnerability due to the mixture of species farmed while Portugal, where the aquaculture sector relies much more heavily on the culture of clams, had a higher vulnerability. Similarly, the aquaculture sector in The Netherlands is more focused on shellfish compared to that in Denmark and this is reflected in differences in relative vulnerability to climate change.

Countries were ranked with low vulnerability for different reasons. Countries either had large economies (GDP) and a relatively minor aquaculture sectors (e.g. Germany, Sweden) or had a relatively high dependence on aquaculture but larger, more technologically innovative firms (Norway). Some countries with low scores had a combination of those attributes plus a good mixture of species under cultivation (UK and Ireland).

Another factor contributing to national-level vulnerability ranks was the extent of implementation of national climate adaptation plans which varied widely among the 22 countries examined here.

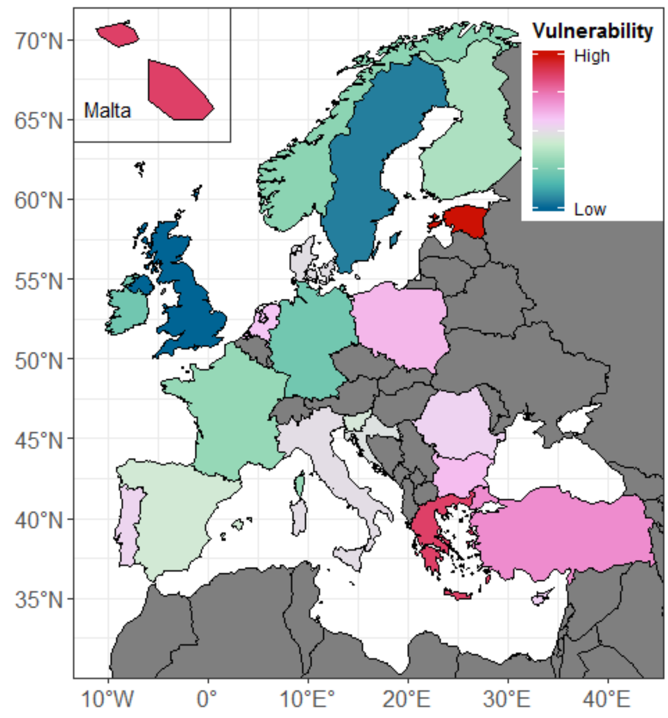



**Figure 5.6** Relative climate change vulnerability based on the attributes of species farmed (physiological tolerance, farming method) and national-level economic data.

## 5.6 Adverse consequences and opportunities for aquaculture: Stakeholder perceptions

The following is a summary of the comments provided by stakeholders within 13 Bow-tie analyses which then contributed to the 12 CERES aquaculture Storylines (Cormier et al., 2019 provides details of the rationale or Bow-tie analysis). Comments apply to one or more Storylines and are organised under general headings. Bow-tie analyses were completed by differing numbers of stakeholders with different levels of experience and so there may be differing degrees of confidence in the conclusions. Individual Bow-tie diagrams (see Appendices 1-3 in CERES D5.1 2020) should be consulted for the source of specific comments.

In general, the Bow-tie analyses identified more adverse consequences than opportunities for aquaculture due to climate change. This may be the result of the industries being more concerned with short- to medium-term rather than long-term repercussions. It is noted, even, that for some Storylines (e.g. - mussels in southern European waters), the stakeholders did not identify *any* opportunities due to climate change.

### 5.6.1 Adverse Consequences

**Biodiversity, ecosystems and ecology -** There is likely to be high pressure on wild and cultured species due to increased market demand for seafood. There will be a loss change of biodiversity and food web structure and only more resistant species can be cultured if there are notable environmental changes. There will be an increased pressure on other seafood species/cvulture systems as oyster culture becomes more difficult.

The focus will be on species (fish and shellfish) farmed that can tolerate higher temperatures and, since most of the production is expected in sea cages, the impact of escapees will be of concern. Industry expansion could be restricted due to carrying capacity issues related to food for birds, i.e. restrictions may be placed on using wild-caught fish such as sand eels to produce fish meal and fish oil for aquaculture. Jellyfish may become more prevalent which may cause problems for salmon culture and salmon losses may be indirectly increased as overfishing of wild stocks may result in increases in jellyfish. Within dam lakes in inland waters in some areas, ecosystem regime change will affect production and is likely to shorten the production period of rainbow trout.

**Company structure and practices -** There will be changes in general industry structure and at farm level, as well as changes in product growth and quality, production cycles may become shorter (less time in aquaculture facilities, less risk) and therefore the products may be marketed at a smaller size. There could be a consolidation of the sector with a move towards large farms and a reduction in small enterprises, with more profitable farms, and farms concentrating on more than one species (e.g. char). A movement of marine culture from near-shore to offshore sites is expected. The consolidation of existing companies will accelerate and equipment upgrades will be needed to continue farming but adapting gear or operations may increase costs. There could be greatly reduced employment due to pathogen infections and fluctuations in annual survival. Companies may need to hire climate change professionals for advice and marketing. National production will be affected, for example in the main culture areas such as in the Algarve, southern Portugal. Inland farms using groundwater as opposed to surface water may have an advantage following future climate changes.

**Employment** – There will be decreased employment due to farm closures or due to pathogen infections, the loss of coastal production areas, and annual fluctuations of recruitment (e.g. delivering spat in mussel cultures). There could be reduced employment due to a decrease in the number of companies and perhaps an increase in mechanisation or a switch to seasonal employment.

**Industry structure, practices and competition -** Climate change may bring a reduced profit margin and increased competition; there could be an effect on investment (if there is no financial protection) and an increase in stock insurance premiums (so the business may become non-viable). There could be increased global competition as larger firms acquire smaller farms, accelerating the trend toward global aquaculture monopolies as opposed to many, smaller farms. Competition will be reduced as industry moves to more multi-national companies, which may be better able to cope with smaller profit margins or absorb risk if individual sites fail. This move towards conglomerates would reduce the industry diversity and change the distribution of farms around the region. These structural changes in the industry will change the dynamics of aquatic food markets and any increased production costs will decrease profits. For rainbow trout in the Mediterranean region, production may be moved to higher altitudes thereby increasing costs. Elsewhere, there could also be increased cost for mussel seed purchase.

**Markets** – Climate change could greatly reduce market prices (especially if the quality diminishes) or the reduction in supply (and increased demand and operating costs) could give higher market prices and a long-term decrease in market size, e.g. for mussels and oysters. Market prices will change according to the supply and quality of mussels and other shellfish produced in warmer waters. Markets may only operate in the spring, thereby decreasing the supply. If the product is easily substitutable then the prices remain unchanged. For example, the trout market will probably reduce (as any impacts will outweigh benefits).

There will be changes in aquatic food market dynamics. In shellfish, for example, there are specific interrelationships between the Portuguese companies and French markets. There could, however, be reduced prices due to increases in imported seafood to offset reduced local production. Overall, the viability of the operations may decrease.

**Competition** – For shellfish, there may be more competition with other seafood products but within the industry less capacity for competition due to reduced supply of clams; for oysters, a decreased supply increases competition between producers. There could be increased pressure to compensate mussel production loss although for mussels, pressure on other species is not possible because the blue crab is becoming a dominant predator. In fish cage culture, there is likely to be an increased demand for wild-caught cleaner wrasse.

**Local culture and tourism -** There could be reduced ecotourism due to a reduced biodiversity in the region or tourism could have negative pressure on future farming. There may be an impact on local traditions and values and, for example, a loss of location identity. The long-standing tradition of artisanal clam culture, for example, depends on the productivity of specific locations and so the loss of the ability to culture clams in specific sites will cause families to change profession. There could be potential competition and conflicts with tourism in coastal areas. The successful 'Wild Atlantic Way' tourism initiative, for example, conflicts with the space needed for salmon farming. In addition, it could become more difficult to obtain permits for new farms if tourism becomes more successful because of warmer conditions.

**5.6.2 Opportunities**

**Alternative areas and species -** If the conditions become too stressful for species currently farmed, the industry will be open to experimenting with alternative species, more tolerant of the new conditions. Climate change would allow new farms to be located in the north and alternative species to be farmed, for example meagre. The Pacific oyster may decline relative to the European oyster, in the latter having a better growth rate at higher temperatures and a higher market value. For bivalves, for example, the emerging species may respond positively to future change but could exert higher pressure. In the sea bass/sea bream Bow-tie analysis stakeholders suggested that new species could be exploited and that there would be benefits in farming herbivorous and omnivorous fish species.

While, new species can be exploited, both by the wild and farmed sectors, knowledge is needed to culture/harvest new species such as clams, oysters and blue crab. In inland waters, new warm-water, disease resistant species may be cultured. In turn, the effects of commercial pressure on new species will require research but there may be public pressure for a decrease in terrestrial protein (e.g. beef) and an increase in salmon or shellfish production due to the lower carbon footprint for salmon protein.

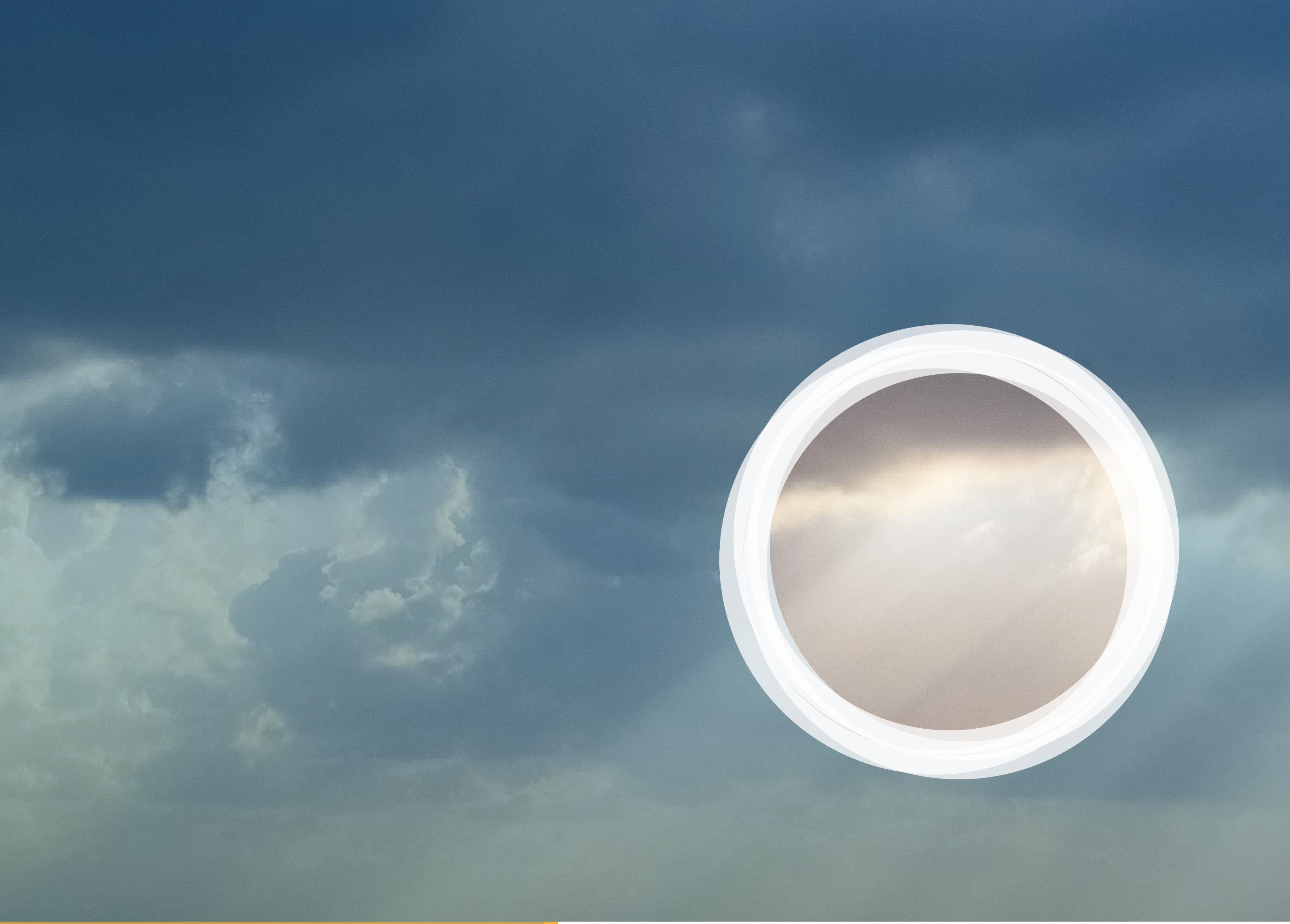
**Industry and company structure, practices, competition and employment -** Climate change may diversify production and employment with the move to farm new species and resistant species and could require different methods. Initial negative growth due to high economic investment would eventually pay dividends. The diversification of aquaculture products would increase customer choices and the reputation of the sector. For example, the increase of meagre farming will require commercialisation by processing into fillets or portions. There may be an increase in the number of farms but the industry will be dominated by large, vertically integrated companies operating cage systems and processing plants (again meagre is used as an example). In inland waters, there will be the increased possibility to move from cage culture to closed or semi-closed production. Increased employment could result due to risk management for adverse climate change effects and especially in new farms, RAS and cage farming technology areas, as well as seafood processing. For example, in the case of Atlantic salmon farming, organic farming methods would allow other areas to compete with Scotland and Norway,

**Markets -** There may be an increased market price, as in the case of oysters, due to lower production (a short-term benefit). Although the economics of new species being marketed are unknown, for example meagre, the income is expected to cover the demand in the Mediterranean region and, once processed, it can be exported to non-EU markets. There may even be higher prices due to decreased supply and production and more environmentally-friendly products. The sector would benefit from the increasing size of markets, possibly through greater offshore production.

If new areas are opened for production by government initiatives then aqproduction areas will grow. As an example, for clams there may be increased market prices and regions because they are a popular food. The industry changes may lead to a stability in markets as firms consolidate, and consumer choice may change with aquatic protein being regarded as more sustainable than terrestrial protein. There may also be changes due to the domestic market becoming smaller and consequently the product being increasingly exported.

**Biodiversity, ecology and food webs -** Despite the possible negative effects due to escapees, food web interactions and changes in dominance, if farms are moved offshore, escapees may have a lesser effect on coastal biodiversity.

**Culture, traditions, values and tourism -** Changes to all of these factors could have a positive effect on the future development of aquaculture and the economic benefits, for example for sea bass and sea bream in the Western Mediterranean. Tourism could create a positive economic future and there may be a positive impact on local tourism if aquaculture facilities are moved offshore. There may even be the increased promotion of alternative fish or shellfish to tourists.



6

# Climate change and European fisheries and aquaculture: solutions and future directions

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# Chapter 6: Climate change and European fisheries and aquaculture: Solutions and future directions

## 6.1 Introduction

Providing robust, science-based advice on how to sustainably manage and increase aquatic food production in a future climate is critical to global food security. In a review of the environmental impact of animal protein sourced from livestock, aquaculture and capture fisheries, Hilborn et al. (2018) highlighted the clear benefit (low environmental impact) of obtaining protein through fisheries on small pelagic fish and from the aquaculture of salmon and molluscs (shellfish) in particular. The benefits are accrued through relatively low utilisation of fuel and energy and by the fact that these animals have a relatively high conversion efficiency of feed. As shown in the CERES Scenarios and elsewhere, the burgeoning world population will place increasing demands on food production in the coming decades and sustainably-produced sources of protein such as fish and shellfish will become more and more important.

Switching dietary protein sources from terrestrial-based to aquatic-based (fish and shellfish) sources can help mitigate climate change. Hugh-Guldberg et al. (2019) estimate this potential mitigation to be between 0.34 and 0.94 $GtCO_2$ by 2030, and between 0.48 and 1.24 $GtCO_2$ by 2050. Finally, with better climate-ready management in place, effective mitigation of greenhouse gas emissions (e.g. from RCP8.5 to RCP4.5 as tested in CERES) is projected to increase the productivity of marine fish stocks (Gaines et al. 2018). Thus, there are strong links and feedbacks between climate change and both the production and consumption of fish and shellfish resources. Some of these links were investigated in-depth for the European region by CERES.

Through its four years of activity, CERES has contributed significant new knowledge on the projected physical, and biogeochemical impacts of climate change on European marine and freshwater habitats, The project has demonstrated how those impacts translate to biological effects on commercially important fish and shellfish, and the potential economic consequences to European fisheries and aquaculture. Not only 'losers' but also 'winners' and future opportunities for both of these Blue Growth sectors were identified. A common framework and diversity of fit-for-purpose methods and tools were used to make separate projections for each of the sectors. The results reveal not only potential risks and vulnerabilities but also pathways for climate adaptation or to minimise potential negative impacts across the 12 fisheries and 12 aquaculture Storylines in the future.

The potential physical and biogeochemical impacts of climate change on European waters is clearly illustrated in Chapter 2. Those projections highlight the diversity of habitats supporting valuable fisheries and farming activities from sub-polar, temperate and sub-tropical environments in marine and freshwater areas. A worst-case (RCP8.5) scenario portends warming across all regions and a stronger latitudinal gradient in rainfall from droughts in the Mediterranean to more rainfall across Scandinavia. If left unchecked, the next generation of fishers and fish farmers will need to make evermore ambitious business plans accounting for the effects of warming temperatures, sea level rise and increased frequency of extreme events such as gales and storms. Changes are less drastic in an intermediate (RCP4.5) scenario that assumes a strong commitment to reducing greenhouse gas emissions over the next 20 years. These different 'climate futures' stem from differences in the willingness and capacity to implement climate mitigation and adaptation strategies as borne out in the CERES 'PESTEL' scenarios presented in Chapter 3.

CERES used a consistent approach to project climate impacts on both fisheries (Chapter 4) and aquaculture (Chapter 5).

Despite some gaps in knowledge on how climate-driven physical and biological factors will interact to affect key fish and shellfish species, and biological communities, effective tools have been created based on first principles such as fundamental physiology, size-based theory and/ or species traits to examine climate impacts. These tools can identify species or populations that are susceptible to climate change. They can also project changes in the distribution and/or productivity (Koenigstein et al. 2016, Peck et al. 2018, Jarić et al. 2019).

Using a suite of state-of-the-art models, CERES demonstrates the consequences of scenarios of climate change to wild-capture fish and shellfish critical to European fisheries and aquaculture sectors. A consistent, scenario-based approach was used to project climate impacts on fisheries resources (22 species, >45 stocks across 8 European regions) and aquaculture resources (8 species across 8 regions with a total of 10 farms).

Scenario-based bioeconomic modelling was performed on a variety of fisheries (pelagic and demersal fleets across five regions) and aquaculture farms (six species across nine regions with a total of 19 typical farms). This biological and bio-economic modelling presented provides an unparalleled (seminal) opportunity to compare climate effects with these two sectors across different European regions.

These Storyline-specific results were complimented by broader, climate vulnerability assessments for fisheries (523 stocks across 23 nations) and aquaculture (nine key species across 22 countries) identifying nations, fleets and/or regions where climate adaptation efforts are most needed in the future.

This final chapter discusses economic analyses that demonstrates how the fisheries and aquaculture sectors are indelibly linked and summarises climate change projections of the combined impacts on both sectors. Next, solutions identified by and for each sector are summarised. Finally, future avenues of research are presented that will continue to advance our capacity to project the biological impacts of climate change on fish and shellfish and the downstream economic and societal consequences for human communities relying on these resources in European regions and elsewhere.

## 6.2 Combined effects of climate change on European fisheries and aquaculture

There are a considerable number of links between the fisheries and aquaculture sectors that must be considered when developing climate change adaptation and mitigation strategies for European aquatic food production. First, fisheries and aquaculture provide substitute goods (e.g. Mulazzani et al. 2019) defined as '…at least two products that could be used for the same purpose by the same consumers.' Fish that are grown or caught are readily absorbed by the market, both for the same species (e.g. European sea bass, sea bream), and for different species (e.g. cod and *Pangasius)*.

Thus, biological impacts of climate change have complex, inter-sectoral economic consequences requiring analyses that include both sectors. Second, fisheries products for secondary use, fishmeal and fish oil, are widely used as feed ingredients in both agriculture and aquaculture. As a result, fisheries management and the climate sensitivity of fished stocks are tightly coupled to the sustainability of farming of carnivor species such as salmon or sea bream. Part of the diet of farmed and wild-caught fish is derived from the same portion of the marine food chain (e.g. small pelagic fish) that is particularly sensitive to changes in climate-driven forcing as discussed later in this chapter.

Third, the responsible development of aquaculture (minimising environmental impact, mitigating pathogen risks, reducing fishmeal and fish oil in diets) has the potential to reduce the pressure on wild capture fisheries (as mentioned above).

Additionally, bivalve and seaweed cultivation may improve the marine environment through bioremediation of anthropogenic nutrient sources and act as potential nursery grounds for wild-swimming juvenile fish.

Despite the logical links and inter-dependencies between capture fisheries and aquaculture, these sectors are almost always separately considered in institutional arrangements, legislative instruments, and by policy makers. For example, the guidance document for the EU Marine Strategy Framework Directive (MSFD - 2008/56/EC) descriptor on 'Commercial Fish and Shellfish' does not consider aquaculture (EC 2019). Similarly, none of the twenty-seven National Aquaculture Plans submitted to the European Maritime and Fisheries Fund (EMFF) include fisheries in their analysis of growth projections (Lopes et al. 2017). However, it is of note that the forthcoming EMFF round for 2021-2025 has a particular focus on the effects of climate change on aquactulture and fisheries.

The separation of these sectors will invariably make it more challenging to implement measures to control and/or mitigate the effects of climate change on European aquatic food production.

CERES estimated the combined effect of climate change on fisheries and aquaculture, highlighting the importance of conducting analyses that consider both sectors. Both economic and social impacts were examined from three different spatial and economic perspectives (CERES D4.3 2020).

At the global level, CERES employed a bioeconomic model based on the supply and demand of commodities to examine future prices of fishmeal and fish oil under each of the four CERES scenarios.

This global model included scenario-specific assumptions on future environmental change (increased water temperatures), accessibility of fisheries, intensity of seafood consumption by a growing human population, and "demand flexibility" (availability of alternatives). For example, the model incorporated rates of latitudinal shift in small pelagic fishes projected for RCP4.5 (13 km decade$^{-1}$) and RCP8.5 (33 km decade$^{-1}$) (Jones & Cheung 2015, Jones et al. 2015, Weatherdon et al. 2016).

Among the scenarios, the highest prices for fishmeal (€2,282 tonne$^{-1}$) and fish oil (€1,921 tonne$^{-1}$) were obtained in National Enterprise (NE), followed by Local Stewardship (LS) (Fig. 6.1). The price structure was similar in the World Markets (WM) and Global Sustainability (GS) scenarios with GS producing the lowest and most stable (least variable) pricing of all four scenarios.

Under the GS scenario, fishmeal and fish oil prices reach a maximum of €1,269 and €1,306 tonne$^{-1}$, respectively (Fig. 6.1) in 2050. These projections are important as approximately 50% of European finfish aquaculture production currently relies on fishmeal and fish oil sourced from countries outside of the European region such as Peru and Chile.

Understanding the uncertainty of prices under alternative climate change scenarios provides useful information on the potential level of exposure of Europe's aquaculture farms to the effects of climate change on fisheries. This information can directly contribute to developing climate adaptation strategies for the sector such as variation in quotas for managing small pelagic fish, the use of fish trimmings and by-products, and exploring alternative ingredients such as soya, algae oil, and insect protein.

These direct effects of climate change on the price of fishmeal and fish oil can translate into much larger national economic impacts (additional 30 to 100% losses or gains) when supply-side industries are considered. CERES explored these national-level effects using an Input-Output model for five countries (Spain, the Netherlands, UK, Denmark and Germany). For the UK, reduced outputs of the fisheries and aquaculture sector under the WM scenario not only produces a loss of €117 million to the sector itself but also results in an additional loss of €110 million to the rest of the economy.

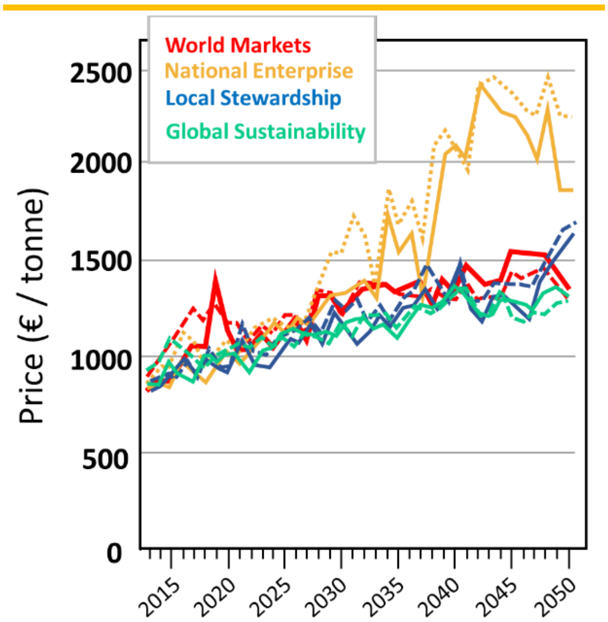


**Figure 6.1** Prices for fishmeal (dotted lines) and fish oil (solid lines) through 2050 across the four CERES scenarios.

In total, the UK economy would face a loss of €227 million. Although the magnitude of direct and indirect effects is country-specific (Fig. 6.2) due to differences in economic structures, the results highlight the importance of using not only sector-specific but also more holistic (economy-wide) approaches when considering the impacts of climate change. This information will be important for planning adaptation strategies across sectors (e.g. flexibility in links between sectors, diversifying operations).

Finally, the results of a multi-regional trade model highlight that management and co-operation between countries could lead to a much stronger and successful adaptation to climate change than when efforts are undertaken independently. An example of trade in small pelagic fish between Spain, the Netherlands and the UK provides initial insights into how different trade structures can promote self-sufficiency and food security but also generate vulnerability in a region. When strategies of cost-minimisation are used, trade patterns support co-operation and strengthen food security of countries by ensuring all or part of their domestic demand is satisfied from domestic production.

In contrast, attempts to maximise profits leads to increased risks for future food security. For example, under the profit maximisation model runs, the UK was found to be not only the sole recipient of aquatic commodities from Spain and the Netherlands but also their sole supplier. In this case, the exposure of Spain and the Netherlands to climate-driven changes in UK fisheries was elevated.

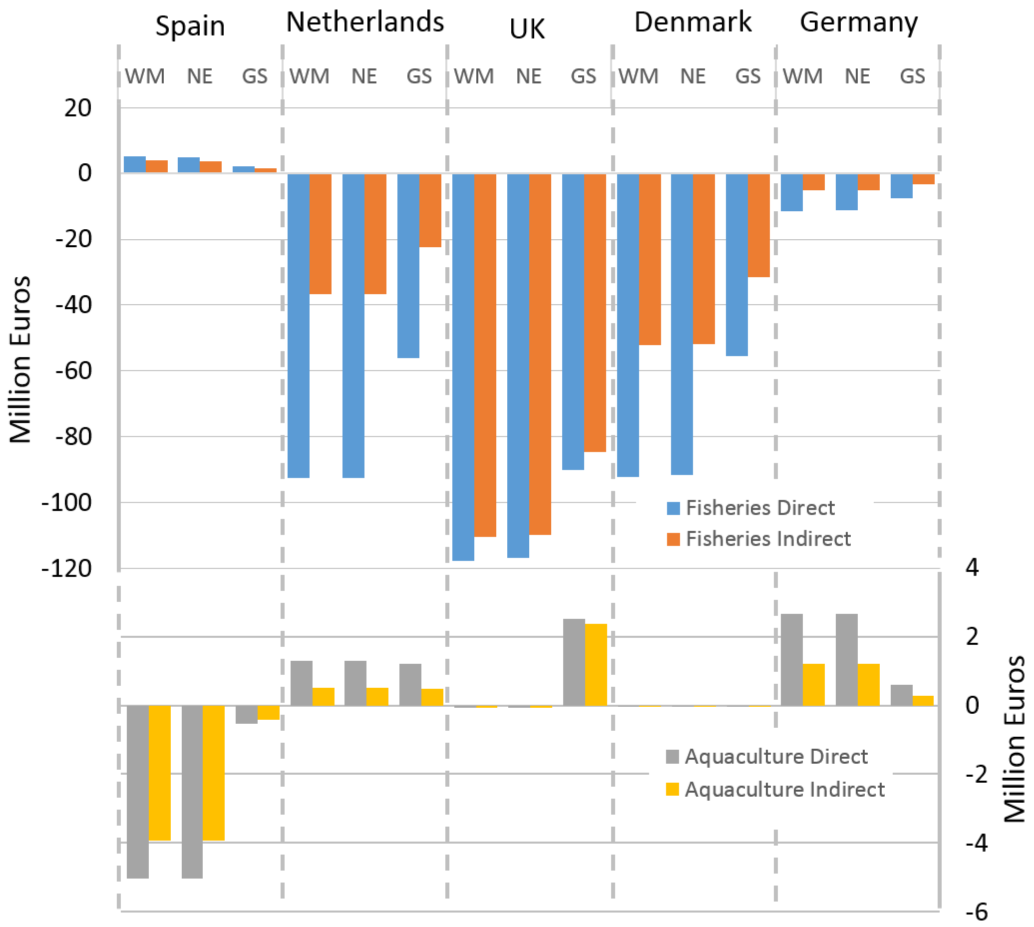


**Figure 6.2** Economic impacts due to climate-driven changes in small pelagic fisheries (top) and aquaculture (bottom) from both direct and indirect sources to the economies of Spain, the Netherlands, Denmark and Germany. In each case, the results from three CERES scenarios are shown.

## 6.3 Solutions for European fisheries and aquaculture

CERES used Bow-tie analyses (CERES D5.1 2020) as a mind-mapping exercise to engage stakeholders across the 12 Fisheries and 12 Aquaculture Storylines. These analyses identified both bottom-up (industry-based) and top-down (policy) measures for the prevention, mitigation, compensation and control of the causes and consequences of climate change. Note, mitigation refers to minimising impacts to industry as opposed to “climate mitigation” which is accepted to refer to implementing measures to reduce global atmospheric concentrations of $CO^2$ and other greenhouse gases.

These measures can be placed within seven categories: five categories in common to both fisheries and aquaculture and two additional categories specific for each sector. While prevention measures will stop adverse effects and other measures will minimise them, compensation may be of three types including: i) for users (fishermen or famers) to offset losses in earnings, 2) for habitat to replace that lost through climate change, and where the habitat may be used as a nursey or feeding area, and 3) for the resource to restock target species or apply enhanced breeding programmes (Elliott et al. 2016, CERES D5.1 2020).

The following solutions are measures ranked as the highest priority by stakeholders (see Fig. 6.3) although many Storylines had additional measures that were ranked of medium or low priority; it is noted that stakeholders for some of the Storylines did not rank their measures.

Those measures marked with an asterisk (*) occurred in many of the Storylines (between 4 and 7 of the fisheries or aquaculture Storylines) thus showing that some mitigation, compensation, prevention and control measures were widely applicable. It is of note that for fisheries the largest number of management control measures were listed in the Storyline for sardine and anchovy in the Bay of Biscay (#21) followed by that for mackerel in the northeast Atlantic (#18). Many of the Bow-tie analyses, especially for aquaculture, listed a considerable number of solutions. For example, the Storyline for Atlantic salmon (#10) had the most management control measures, which could be a result of using a large stakeholder workshop. In this regard, it is important to note that there were differing levels of expertise and numbers of stakeholders involved in identifying solutions which will affect the veracity of this synthesis.

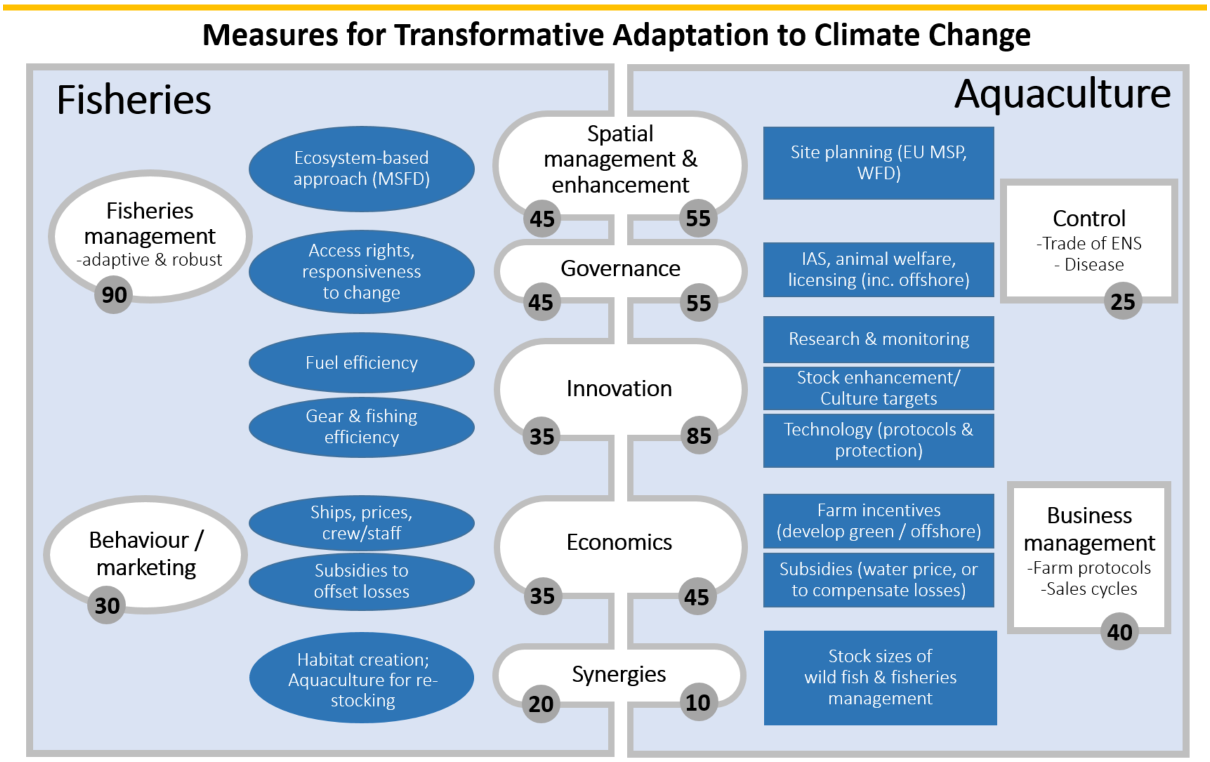


**Figure 6.3** Measures to promote transformative adaptation of the European fisheries and aquaculture sectors to climate change. The numbers indicate the percentage of Bow-tie analyses in which a measure was given high priority by stakeholders in the 12 Fisheries (left) or 12 Aquaculture (right) Storylines. Categories of measures were common (centre) or unique (edges) to sectors.

It is emphasised that governance is often the means of bringing about change and responding to adverse consequences or capitalising on opportunities. Governance is defined as the policies, politics, administration and legislation covering all tiers from local, national, European and international. While fishery-adopted and aquaculture-adopted management initiatives (bottom-up solutions) may prevent the worst consequences of climate change, governance instruments (top-down solutions) may be needed to give weight to force through (and gain acceptance of) the industry changes.

**Climate change solutions for fisheries**

**F1 Behaviour/ marketing:** This included, first, exploring and promoting alternative resources, species or stocks (including invasive thermophilic ones) in order to conserve target species (*). Second, and linked to this, was exploring alternative markets and consumers. Third, educating consumers on changing species, including ecolabelling to increase the acceptance of the consequences of climate change to favoured species.

**F2 Economics:** This included, first, investing in improving revenue income in the mid-term (via technology, security in price, staff recruitment and retention, and vessels). Second, this requires investing in reducing costs in the mid-term (technology, staff recruitment and retention, vessels). Investment (possibly including subsidies) will allow and/or promote alternative species, and government measures (possibly initially financial) are needed to diversify fleets.

**F3 Fisheries management:** this includes many measures such as adapting seasons to account for shifts in reproduction migrations or recruitment levels, to protect nursery and spawning grounds, and to modify catch quotas and markets. Better stock assessment methods are needed to provide more robust management measures for sustaining stocks and fisheries. Stakeholders also suggested the need to explore how quota could be better allocated or how the methods and accuracy of calculating FMSY could be improved to adhere to larger-scale management objectives. It was acknowledged that fishing quotas will not only control stocks but also market price (and employment).

Measures to help maintain the phenotypic diversity will optimise the adaptive capacity of fish populations in light of projected impacts of climate change. These changes could be enhanced by adopting an adaptive management regime including a pluri-annual management plan, quota swaps between species and years and regional stock quotas and/or season closures (*).

**F4 Governance:** Controls are needed on access rights for stocks and to protect quotas, especially for areas/species displaying rapid, climate-driven growth. The health of stocks would benefit from the adoption of new EU/international legislation to control climate change (e.g. limiting greenhouse gas emissions) and adopting adaptive legislation that can more rapidly react to unexpected positive or negative changes in stocks, thus allowing for innovation development. In particular, local legislation needs to be adopted and adapted to reduce fishing pressure and to allow for changes in the presence and/or distribution of the species (e.g., to open or close the fishery, to regulate a fishery targeting a new resource).

**F5 Spatial management and enhancement:** Fisheries need to be managed together with all other activities in marine and inland waters, hence needing spatial management especially that under the EU Maritime Spatial Planning Directive (EU 2014). To avoid the consequences of climate change, stakeholders proposed flexible spatial limits for management to improve habitats and productivity, including offsetting and No-take Zones. Legislation is required to protect essential spawning (*) and nursery (*) areas, including time-bounded closures and dynamic Marine Protected Areas. Finally, legislation is required to enforce ecoengineering such as the restocking of threatened and declining species.

**F6 Innovation:** Various innovations can reduce the environmental consequences and improve fishing techniques and technologies. These include reducing fossil fuel consumption (and $CO_2$ emissions) (*) and/or increasing alternative energy use for vessels and fish and shellfish processing. There could be technology and best practice transfer between fishery sectors and other industries and an increased efficiency and suitability in the canning industry. More selective and efficient fishing and gears (such as the promotion of intelligent FADs (fish aggregating devices) and locating devices such as hydroacoustics) will enable the industry to reduce effort and, hence, reduce costs and improve sustainability. Other measures such as producing less marine debris and using biodegradable materials in fisheries would also have wider environmental benefits.

**F7 Synergies:** Only two topics were mentioned by stakeholders for this category to counter the adverse consequences of climate change. First, ecoengineering and environmental management can improve habitat quality and environmental conditions. Second, the production of native species using aquaculture can be promoted to relieve pressure on traditional fishing targets (i.e. restocking or market substitution).

**Climate change solutions for aquaculture**

In comparison with fisheries, the solutions for aquaculture are more technology-orientated and there were several categories of various types of innovation. There is also both more control and more scope for control given that aquaculture is often a land-based activity or at least close to the shore compared to wild-capture fisheries. Also, in contrast to fisheries, there is more variation among the control measures, with only a few applicable to more than several aquaculture Storylines. The categories of prevention, mitigation, compensation and control measures are given below:

**A1 Business management*:*** The controls require an elaboration of localised plans for maintenance of existing culture facilities and larger investment in maintaining existing production capacities. Next, aquaculture should promote the culture and release of endangered native species (resyocking). Third, there should be a cost-efficient improvement to maintaining farm conditions and reducing production costs. Finally, there is the need over time for a change in culture techniques and the sale-cycle to adapt to climate change.

**A2 Control:** Mechanisms are needed to control the trade in marine species and both control and punish the trade of endangered native species. There needs to be an increased control for the introduction of exotic species, and a control programme for disease. Each of these will require governance (top-down policy) support via EU legislation and national regulations.

**A3 Economy:** As economic drivers and incentives, stakeholders suggested that government compensation payments would be needed to farms (e.g. to mitigate the cost of massive mortalities due to various causes including jellyfish blooms or invasive species) (*). It will require types of enhancing incentives and/or subsidies, including the ability to support and improve production technologies, especially the adaptation to new technologies (*). Given the recent technological developments, there would need to be economic incentives to develop offshore farms and upgrade the necessary technologies. There could also be incentives such as fiscal benefits for those who adopt 'green' (environmentally friendly) farming strategies. Finally, there would need to be economic measures to counteract employment loss and to make improvements for financial stability and the sustainability of farms such as a reduced cost for water usage.

**A4 Governance**: This includes adopting the new EU Invasive Alien Species Regulation (*EU Regulation* 1143/2014 on *Invasive Alien Species*) and adopting or passing the EU legislation needed for the adaptation for monitoring and support of aquaculture (this could be based on developments from the shellfish hygiene regulations now embedded in the EU Water Framework Directive but this only covers inland, transitional and coastal waters to 1nm). The movement offshore of aquaculture may be a necessary to overcome risks associated with climate change in shallow waters (e.g. warming, wave action from storms) and legislation at the European level would be required to build up large offshore management areas with common facilities.

The movement offshore would require adapting Maritime Spatial Planning in territorial waters. It would also require enactment of local legislation regarding controls on exotic (introduced) species and better animal welfare.

Movement offshore, however, requires bridging inshore and offshore controls (for example further harmonizing the European Water Framework, Marine Strategy Framework and Maritime Spatial Planning Directives). Local legislation for coastal and inland developments is needed to allow stakeholders to implement and to revamp aquaculture licences. Next, incentives for innovation can improve, promote and support production (including growing species better adapted to higher temperatures, early warning systems of environmental stressors, etc.).

**A5a) Innovation in research & monitoring:** Several research priorities were identified such as the development of prophylaxis to treat salmon if stung by jellyfish and the means of fighting new diseases. Genomic selection can help maintain the robustness of cultured species in a future climate. As increased preparedness for climate change symptoms, there is the need to monitor water quality to predict mass mortality, and for research into early warning systems for HABs, biofouling and jellyfish. Finally, technological advances in the development of new feeds will make the industry less sensitive to climate-driven shocks in the availability of feedstuffs from aquatic (e.g. fishmeal and fish oil) and terrestrial sources.

**A5b) Innovation in stock enhancement:** Measures are needed to capitalise on more climate-resilient species and to encourage production, selective breeding and enhancement of alternative targets, resources and spat better adapted to higher temperature (*). The development of alternative culture targets should include increased culture of herbivorous and omnivorous fish species and diversification into other stocks. The introduction of disease-resistant strains would also alleviate increased risks associated with climate change.

**A5c) Technological innovation:** Given the environmental conditions created in fish cages, with climate change additional oxygenation and better recirculation technologies (RAS) will be required which may provide scope for increasing production in drier areas and for adjusting the production cycle to water availability. Advances such as bubble curtains will lead to the protection from harmful plankton and jellyfish. The increased use of onshore RAS will enhance availability/reliability of the hatchery and fry stages.

Local concerns and constraints will encourage developers to cultivate in open water away from the coast, instead of warming bays, and to adapt the technologies/facilities for the site characteristics and new conditions under climate change (e.g. stronger storms) – hence there will be the need for flood/storm-approved equipment and measures.

Technologies are needed to make production more cost-efficient, to minimise escapees and to cope with changes in water quality of culture conditions. The creation of new and/or improved and better-monitored rearing systems and hatchery protocols will also allow farms to cope with climate change. Co-development and utilisation of established technologies from other offshore industries (e.g. oil, gas and offshore wind exploitation) will allow more rapid innovation of offshore farming techniques including robust mooring systems and submersible cages.

**A6) Spatial planning:** Common regulation is needed for aquaculture and all other marine and inland waters activities, for example under the EU Maritime Spatial Planning Directive (EU 2014) for marine areas and the Water Framework Directive coupled with land management for near coastal, estuarine and inland waters. Local legislation will be required as local or central governments strive to allow aquaculture at new, suitable locations and offshore to compensate for shifts in habitat quality due to climate change.

Habitat compensation will sometimes be required including habitat creation or biodiversity/ habitat offsetting such as increasing the area destined for bivalve seed collection and bivalve settlement structures.

Taken together these elements will require a well-designed and holistic ecosystem management system supported by research and surveillance. The latter will include the ability to used models to identify production areas with a low probability of climate change effects (e.g. climate refugia). This relies on appropriate technologies to allow the relocation of cage farms.

**A7) Synergies:** From an aquaculture perspective, the synergistic solutions with fisheries include the links to fishery management measures, the development of seasonal limits and control on quotas (*). These aspects are also dependent on the availability of resources.

## 6.4 Future research needs

Climate change is regarded by natural and social scientists as a 'wicked problem' and addressing its impacts on complex social-ecological systems such as aquatic living resources and the human communities that depend on them is challenging and requires an inter-disciplinary approach. Such an approach, integrating physical/biogeochemical, biological, economic and social analyses, was required to address the three expected impacts for the CERES research programme:

- Support fisheries management and aquaculture development by reducing uncertainties and risk, while optimising scientific advice, policy implementation and production planning
- Allow regulators, fisherman and aquaculture operators to anticipate, prepare and adapt to different scenarios driven by climate change, while minimising economic losses and social consequences
- Identify opportunities that might occur under the different scenarios and prepare to reap the potential benefits for the European fisheries, aquaculture and seafood sectors and consumers

In addressing each of these expected impacts, CERES identified gaps in knowledge that remain to be filled in future research programmes addressing climate change effects on the fisheries and/or aquaculture sectors. Advances in the following, inter-linked themes and topics will further strengthen the science-based advice contributing to bottom-up (industry led) and top-down (policy) solutions to minimise the risks and maximise the opportunities offered by climate change on fisheries and aquaculture not only in the European region but worldwide.

**1) Integrating climate research across disciplines:** It is inherently challenging to conduct inter-disciplinary science as most researchers receive formal training in only one discipline. To strengthen research on climate change impacts, inter-disciplinary degree programmes need to be championed bridging social-economic and physical-biological science (Kelly et al. 2019). This will make it easier to conduct research across disciplines. Climate research programmes in fisheries and aquaculture need more emphasis on embedding social scientists with knowledge on economic and biological impacts of climate change. Regional differences in available expertise (e.g. in southern versus northern Europe) need to be addressed since, although many EU research programmes working on fisheries and aquaculture are Europe-wide, activities are often conducted at local to regional scales and compared across regions (an approach also taken in CERES).

**2) Conducting climate change science with industry*:*** Historical barriers to conducting trans-disciplinary science (science that bridges academia and non-academic actors such as businesses) on potential climate impacts in both the aquaculture and fisheries sectors are disappearing. CERES benefitted from having seven industry partners making active contributions to the Storylines. Trans-disciplinary research with the fisheries and aquaculture sector is facilitated by the fact that: i) some businesses in both sectors have now created science advisor positions, and ii) many businesses (particularly in aquaculture) have a long tradition of working with national (government) laboratories or universities on research and development.

Additional bridges are needed, however, to conduct trans-disciplinary climate research, particularly with artisanal fishers and farmers. Those bridges are formed through long-term relationships and mutual trust (e.g. Mackinson & Wilson 2014). Future programs need to continue to create and reinforce these bridges. It is highly recommended that future programmes follow best practice guidelines to conducting trans-disciplinary climate research (e.g. Mauser et al. 2013).

**3) Engaging stakeholders**: Stakeholder engagement is critical for the success of projects designed to examine the social-ecological consequences of climate change. Future research programmes will benefit from embedding trained facilitators to conduct engagement activities with stakeholders in the aquaculture and/or fisheries sectors. A self-reflection exercise performed by CERES identified key lessons learned including: i) to tailor engagement activities to the local situation and/or pressing issue realizing that important differences may exist in viewpoints of stakeholders across different parts of each sector (e.g. from catch to plate or farm to fork) such that, even within a region, the most effective approach may differ, ii) face-to-face interviews are very time consuming but can provide the most clear insight on the situations and perceptions of stakeholders and are the most helpful in building trust, iii) the best engagement is a give-and-take process where stakeholders share viewpoints and, in return, scientists take these into account and provide project results in an appropriate format, and iv) complex scientific concepts must be broken down into understandable ideas and language before interacting with stakeholders.

**4) Capturing uncertainty in physical projections:** Global-scale projections of the physical and biogeochemical impacts of climate change (from GCMs) do not all agree and this is an important source of uncertainty to be captured and communicated in future programs. The most straightforward (and resource intensive) approach is to use the outputs from multiple GCMs to force a region-specific physical and biogeochemical model (or models). This approach was taken in one CERES region (the Baltic Sea) and was available for freshwater habitats (e.g. river flows). Biological projections, therefore, included this source of uncertainty. In other regions (Mediterranean Sea, northeast Atlantic and Barents Sea), however, CERES needed to take other steps to evaluate this source of uncertainty. Considerably more resources need to be committed in future programmes to create physical and biogeochemical ensemble projections from multiple global-scale models (see point 4). An example of this approach is the ACLIM project exploring the impacts of climate change on fish and fisheries in the Bering Sea (Hermann et al. 2019). Finally, applying low emission (RCPs1.9 and RCP2.6) together with worst-case (RCP8.5) scenarios will better illustrate the benefit of climate change mitigation on aquatic habitats, species and sectors.

**5) Spatial and temporal resolution of physical impacts:** Regarding the spatial resolution of models, CERES focused on regional climate change impacts most appropriate at the sub-basin scales (see Storylines). Advances are needed to create projections with higher spatial resolution to estimate climate impacts at sub-regional/local scales. This will allow future programmes to: i) identify climate hot spots and refuges (Popova et al. 2016, Ban et al. 2016), ii) assess small-scale processes such as disease transfer among aquaculture farms (Viljugrein et al. 2009), and iii) to better estimate physical impacts in near-shore, shallow waters – areas currently hosting the majority of some types of aquaculture farms. Models better linking upstream land-use change to the downstream biogeochemical consequences for coastal and offshore waters are needed. Finally, applying state-of-the-art physical models and statistical analyses will improve projections of the biological impacts of extreme events such as heatwaves (Hobday et al. 2018) and droughts.

**6) Direct biological effects of climate change on aquatic living resources:** A gap analysis identified research needs on how interacting factors affect various life stages of commercially important fish and shellfish (CERES D2.1 2018). In terms of the effects of physical factors (e.g. temperature, salinity, dissolved oxygen, pH) on vital rates (survival, growth, reproduction) of European species, not surprisingly, more is known for aquaculture compared to fisheries species. Gaps in knowledge (on effects on European species, some of the best-studied in the world, underscore the importance of continuing to conduct fundamental laboratory and field research on various species worldwide.Data collected by the aquaculture or fisheries industry can be an important, untapped source of knowledge.

**7) Indirect biological effects of climate change:** Several, indirect pathways of climate change impact were examined by CERES and some of these were included within projection tools. For fisheries, changes in predator-prey dynamics in future (novel) food webs will affect the productivity of fish stocks (see Chapter 4). For aquaculture, the future prevalence of disease will affect the productivity of aquaculture farms (see Chapter 5). Additional research can increase the robustness of how these indirect effects are included in models. For example, diet analyses of North Sea fishes conducted in the 1990's have only been partially updated (e.g. MARE/2012/02). Other potential indirect effects of climate change such as local / regional outbreaks of HABS and jellyfish may have important consequences to both fisheries and aquaculture. If blooms can be linked to physical or biogeochemical mechanisms, these indirect effects can be projected alongside direct effects. Such knowledge will also increase the robustness of early warning tools.

**8) Projecting bioeconomic impacts at mid- to late-century:** CERES devoted a considerable amount of effort to produce logical, consistent and contrasting future political, economic, social, technological, Environmental and legal (PESTEL) scenarios that build from those established by the IPCC (RCPs, SSPs) and that were regionalised for application to specific European fisheries and aquaculture activities (see Chapter 3). The results indicate that future changes in policy or economics (in particular fuel and fish prices) may be more important to the profitability of European fisheries and aquaculture than the direct, biological effects of climate change on fish and shellfish. Further work is needed to ground truth these CERES scenarios, particularly with regard to future technological developments by both sectors. Beyond CERES, climate programmes should endeavour to use similar scenarios to facilitate world-wide comparisons of regional projections of bioeconomic impacts of climate change (both within and beyond the fisheries and/or aquaculture sectors).

**9) Climate change risk and vulnerability of dependent human communities:** Recent efforts to examine climate change vulnerability or risk both within (CERES D5.3 2020) and outside (Peck & Pinnegar 2018) the CERES project underscore the need to more thoroughly incorporate aspects of dependent human communities. While CERES took a "top-down" approach using national or regional economic indicators to assess the sensitivity and adaptive capacity of fishing fleets and aquaculture activities, a bottom-up approach is needed which focuses on specific attributes of specific human communities to better estimate climate vulnerability and risk within regions, and to develop viable adaptation strategies. Colburn et al. (2016) provide a good example of this "bottom-up" approach to estimating the sensitivity and adaptive capacity of fishing communities.

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