Climate change and the Common Fisheries Policy: adaptation and building resilience to the effects of climate change on fisheries and reducing emissions of greenhouse gases from fishing

– EASME/EMFF/2020/3.2.6 - Lot1/SC07

– EASME/EMFF/2020/3.2.6 - Lot2/SC08

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Annexes

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Annex 1 DEFINING PLAUSIBLE, ECOSYSTEM-COHERENT SHOCK SCENARIOS: BALTIC SEA CASE STUDY

Synthesis of the literature reviews on the key climatic and environmental drivers of fish stocks

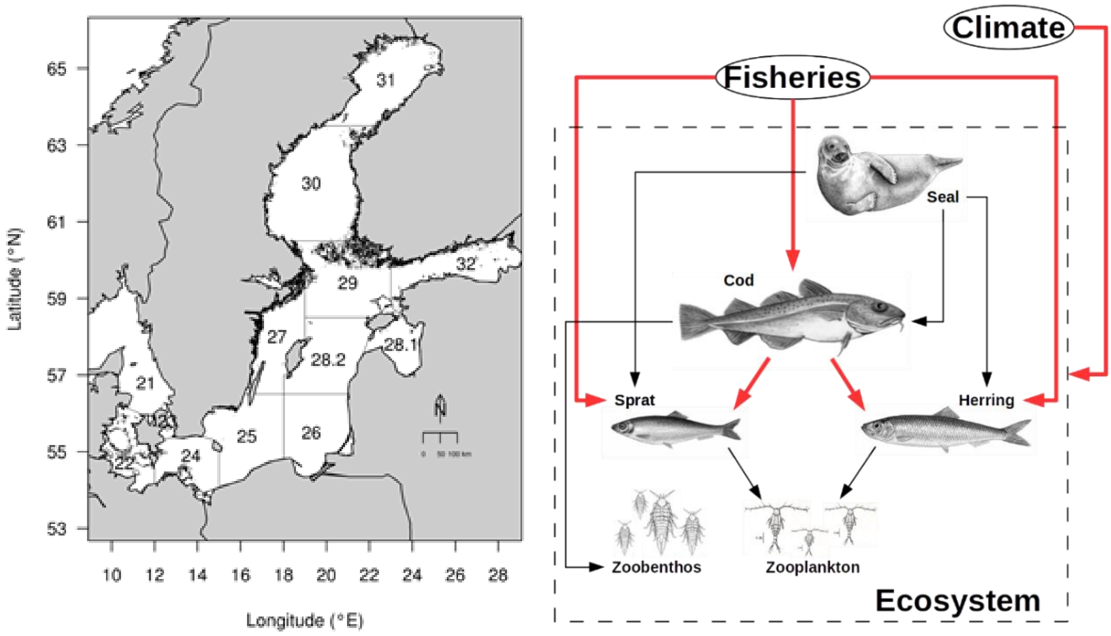

Figure 1 (Right) Map of the Baltic Sea with the ICES Subdivisions. (Left) Schematic representation of the central Baltic Sea foodweb including the fisheries. Main interactions are represented by arrows, in red those included in the resource scenarios (modified from ICES 2019).

Eastern Baltic Cod

Recruitment

Crucial factors for successful fertilization, development of eggs and larvae of Baltic cod are salinity (Pliksh s et al., 1993, Nissling 1994, Nissling and Westin 1997, Wieland and Jarre-Teichmann 1997, Hüssy 2011, Plikshs et al., 2015) > 11 PSU (MacKenzie et al., 2007), oxygen (Nissling 1994, Wieland et al. 1994, Rak et al., 2020) concentrations > 2mL /L (MacKenzie et al., 2007) and temperature (Köster et al., 2020), determined by the inflows from the North Sea (Hinrichsen et al., 2007). Detrimental hydrographic conditions reduced the reproductive success of cod in the Gdansk Deep and the Gotland Basin during the 1980s (Köster et al., 2005), and cod migrate from eastern areas into the Bornholm Basin for spawning (Horbowy 2016, Köster et al., 2001).

Eutrophication and climate change reduce cod reproductive habitats (Wåhlström et al., 2020). Hypoxia caused the shrinkage of recruitment and biomass due to the loss of cod spawning sites (MacKenzie et al., 2000).

Growth

Environmental changes influenced the decline in growth rates of young cod (ICES 2015, Orio et al., 2017, Hüssy et al., 2018, Mion et al., 2020, Neuenfeldt et al., 2020) and impact on maturation (Vainikka 2009), shift in the timing of spawning is observed (Wieland et al., 2000). The condition of cod is influenced by hypoxia (Teschner et al., 2010, Plambech et al., 2013, Casini et al., 2016, Limburg and Casini 2019, Brander 2020), density and food limitation (Eero et al., 2012, Casini et al., 2016, Niiranen et al., 2019, Karlson et al., 2020), prey quality (Carstensen et al., 2014) and genetic factors (McQueen et al., 2020).

The low condition of cod may lead to a significant increase in natural mortality (Dutil and Lambert 2000). High natural mortality is caused by the ecosystem drivers e.g., oxygen conditions (Neuenfeldt et al., 2020), spatial distribution of prey species and abundance of marine mammals (Eero et al., 2020), presence of liver nematodes (Horbowy et al., 2016, Ryberg et al., 2020), predation on cod eggs by clupeids (MacKenzie et al., 2007), cannibalism (Heikinheimo 2011), predation by seals (Casini et al., 2016).

Table 1 Possible variables in analyses (time series used in previous models):

Parameter	Time series used in analyses	Model	Reference
Recruitment			
Reproductive volume and oxygen content	1966-1973 and 1966-2013 (May until 1991 then August)	RV	Köster et al., 2005; MacKenzie et al., 2007; Köster et al., 2017
Temperature, salinity, oxygen concentration	Second quarter 1966-1989 – third quarter 1990-1999	Coupled bio/physical model	Köster et al., 2005; MacKenzie et al., 2007; Köster et al., 2017
spawning stock biomass	1966-2013 (beginning of the year)	Source (ICES 2013) SAM assessment model	Koster et al., 2017
average deep-water salinity	Second quarter 1966-1989 – third quarter 1990-1999	Coupled bio/physical model	Koster et al., 2005
Growth			
hypoxic areas	1976-2014	Swedish Meteorological and Hydrological Institute (SMHI) estimates	Casini et al., 2016
prey (herring and sprat) density	1976-2014	Baltic International Acoustic Survey (BIAS) estimates – GAMs model	Casini et al., 2016
Natural mortality			
predation on cod eggs by clupeids	1990-1999 and 2004-2008 (May and August)	Neumann et al. (2014)	MacKenzie et al., 2007; Köster et al., 2017
cannibalism			Heikinheimo 2011; Köster et al., 2017
cod stock size	1974-2004	SGMAB key run results (ICES 2005)	Heikinheimo 2011
grey seals stock size	1976-2014 (Swedish Museum of Natural History)	GAMs model	Casini et al., 2016

occurrence of anisakid nematodes in the liver	2011-2014	Fulton's condition factor	Horbowy et al., 2016

Central Baltic Herring

- ***Recruitment***

Among environmental variables that significantly contribute to the fish recruitment success can be mentioned sea surface temperature (SST), wind stress and salinity (Margonski et al., 2010, Pecuchet et al., 2015, Bartolino et al., 2014). These parameters have been used in several Stock-Recruits model types based on SSB (Pecuchet et al., 2015, Margonski et al., 2010, Bartolino et al., 2014).

Other parameters considered are zooplankton abundance or P. elongatus anomalies (Dippner et al., 2001, Pecuchet et al., 2015) as well as spawner quality (Cardinale et al., 2009). Optimal herring egg and yolk-suc-larvae survival and hutch occurs in temperature 7 to 13ºC (Peck et al., 2012).

Additionally, local and site-specific physical changes such as light conditions, wave exposure, temperature conditions affect aquatic vegetation such as seagrass population (Staehr et al., 2019), and their depth distribution (Moll et al., 2018) on which herring attaches its adhesive eggs (Aneer, 1989, 1987; Kanstinger et al., 2018; Rajasilta et al., 2006).

- ***Growth***

Herring growth and condition seems to be dependent on the competition with sprat stock (Casini et al., 2011, Rönkkönen et al., 2004, Smoliński 2019, Casini et al., 2006). Other considered factors are temperature, salinity, food availability (zooplankton abundance) and density dependence on the total Clupeid abundance (Cardinale et al., 2009, Möllmann et al., 2004, Casini et al., 2011, Casini et al., 2006).

- ***Natural mortality***

Natural mortality of herring is dependent on predator stock, for example, on cod (Heikinheimo 2011, ICES 2020). Additionally, the abundance of grey seals might be considered regarding the last decade substantial increase in the grey seal population in the Baltic (Gårdmark et al., 2012).

- ***Short-term climatic anomaly (theoretically):***

Recruitment failure - Baltic herring spawn in the coastal areas and lay eggs on substrate. Therefore, spawning site quality is an important prerequisite for successful spawning. Any anthropogenic influence or discharges of harmful substances during the spawning period (like oil spills) may lead to recruitment failure or even 100% loss of spawned eggs locally in a given area or seabed. Additionally, a substantial spawning disturbance could arise from storm events as demonstrated by Moll et al. (2017) for example leading to a total egg loss of 29% in one single spawning bed during a storm event within the spawning season.

Table 2 Possible variables in analyses (time series used in previous models):

Parameter	Time series used in analyses	Model	Reference
Recruitment			
SST in August	1974(?)-2009	Environmentally sensitive -R	Bartolino et al., 2014

		relationship based on the GAM	
SST in August	1975–2005	Additive modeling	Margonski et al., 2010, Cardinale et al., 2009)
SSB sprat	1974-2010	GAM models	Pecuchet et al., 2015
SSB herring			Margonski et al., 2010; Bartolino et al., 2014
Zooplankton, extracted from ERGOM* (mean of March-September	1974-2010	GAM models	Pecuchet et al., 2015
Windstress, extracted from ERGOM* (mean of March-September	1974-2010	GAM models	Pecuchet et al., 2015
Salinity, extracted from ERGOM* (mean of March-September	1974-2010	GAM models	Pecuchet et al., 2015
Zooplankton (P. elongatus)	1966-1984	Statistical downscaling model; anomalies correlation	? Northern Baltic: Dippner et al., 2001
Weight at age 3+	1974-2005	GAM model	Cardinale et al., 2009
Baltic sea Index (BSI)	1974-2005	GAM model	Cardinale et al., 2009
Pseudocalanus acuspes biomass	1974-2005	GAM model	Cardinale et al., 2009
Growth			
Herring abundance	1976-2008	GAM model	Casini et al., 2011; Rönkkönen et al., 2004; Smoliński, 2019; Casini et al., 2006
Clupeidae abundance	1986-2004	General Linear Model (GLM) model	Casini et al., 2006
Temperature 0–100 m (0–80 m in SD 25)	1978-2008	GAM model	Casini et al., 2011
Zooplankton abundance	1977-1999		Möllmann et al., 2004
Salinity (0–100 m (0–80 m in SD 25)	1978-2008	GAM model	Casini et al., 2011
Sprat abundance	1978-2008	GAM model	Casini et al., 2011
Natural mortality			
Cod biomass	1994-2004	Dynamic CHS model	Heikinheimo, 2011
Seal abundance	1980-2010	SAM model (ICES 2009)	Analysis for Bothnian sea: Gårdmark et al., 2012

* ERGOM: Ecological ReGional Ocean Model; Neumann, 2000

Baltic Sprat

- ***Recruitment***

Analyses of recruitment dependence on abiotic environmental conditions has revealed that sprat recruitment is depending on the Baltic ice cover index, NAO index and water temperature. High temperatures directly support sprat recruitment with increased egg survival, and indirectly with warm water zooplankton (e.g., Acartia) availability on larval survival (MacKenzie and Köster 2004, MacKenzie et al., 2007, Margonski et al., 2010, Bauman et al., 2006). The optimal temperature requirements for successful egg hatching obtained during laboratory experiments are between 3.4 - 14.7ºC (Petereit et al., 2008).

- ***Growth***

Sprat growth and body condition is linked to density-dependent competition (intra-specific competition) (Mollmann et al., 2005, Casini et al., 2011). Additionally, the total abundance of Clupeids may be considered because of the food coemption as limiting the sprat growth/condition (Cardinale et al., 2002)

- ***Natural mortality***

Natural mortality of sprat is dependent on predator stock e.g., cod (Heikinheimo, 2011; ICES, 2020). Additionally, cannibalism on eggs was found to be an important source of sprat egg mortality, but in the Bornholm Basin only. However, cannibalism could have a high seasonal and annual variation (Köster and Möllmann 2000, MacKenzie et al., 2007).

Sprat could respond to climate change. The periods of high abundance of sprat coincide with a rich freshwater discharge, relatively high winter temperature and low water salinity limiting the stock of its main predator— cod (Ojaveer and Kaleijs 2010). Thus, a shift in the spatial distribution of cod along with favorable recruitment conditions (temperature regime) recently toward Northern Baltic may lead to overall spatial changes in sprat distribution (ICES, 2019, Casini et al., 2014).

- ***Short-term climatic anomaly (theoretically)***

Recruitment effect: Several exceptional cold winters has led to successful reproduction in the southern Baltic only.

Table 3 Possible variables in analyses (time series used in previous models):

Parameter	Time series used in analyses	Model	Reference*
Recruitment			
Area of ice coverage	1973-2005	Regression	MacKenzie et al., 2007;
NAO index January February	1973-2005	Regression	MacKenzie et al., 2007
May water temperature at 45–65m Bornholm Basin	1973-2005	Regression	MacKenzie et al., 2007
Sea Surface Temperature (SST) July -August or August	1975–2005	Additive modeling	Margonski et al., 2010, Bauman et al., 2006
Growth			
Sprat SSB	1976-2008	Principal Component Analysis (PCA) – GAMs model	Mollmann et al., 2005, Casini et al., 2011
Clupeidae abundance	1986-2000	MSVPA – non-linear regression analysis	Cardinale et al., 2002
Natural mortality			
Cod biomass	1994-2004	Dynamic CHS model	Heikinheimo 2011

* see table T1.1_matrix_BalticSea.xlsx for more details

Projected changes in the Baltic Sea environment

The Baltic Sea is a shallow, semi-enclosed brackish sea suffering like many other coastal seas from the combined effect of climate change and eutrophication caused by human impact. The effects of climate change are tightly discussed in the context of nutrient load abatement strategies.

The combined impact of changing nutrient loads from land and changing climate during the 21st century is at the centre of intense research. A coupled physical-biogeochemical circulation model (RCO-SCOBI, Meier et al., 2003, Eilola et al., 2009, Almroth-Rosell et al., 2011) is available from the Swedish Meteorological and Hydrological Institute (SMHI). Environmental products for the historical and projection period used as input in this study are both derived from the RCO-SCOBI:

- Historical period - Baltic Sea reanalysis products (BALTICSEA_ REANALYSIS_PHY_003_011 and BALTICSEA_REANALYSIS_BIO_003_012) use RCO-SCOBI for a biogeochemical re-analysis of observations. High resolution (3.9 x 3.9 km, 56 depth layers) environmental fields are available for the period 1993-2019 from Copernicus Marine Environment Monitoring Service (accessed on May 2021).
- Projection period - downscaled projections from global climate models (GCM) to the Baltic Sea region are provided with a high-resolution (3.7 km horizontal and 3 m vertical resolution) by the SMHI. RCO-SCOBI is calibrated on a hindcast period and projections are carried out for two greenhouse gas concentration scenarios (based on IPCC Representative Concentration Pathways RCP4.5 (mild warming) and RCP8.5 (intense warming)) forced by three driving global climate models to account for uncertainties (Saraiva et al., 2019a,b). Climate scenarios provided by the RCO-SCOBI are combined with two alternative nutrient load scenarios corresponding to the Baltic Sea Action Plan (BSAP), and a reference case (only climate change effect) producing four environmental scenarios for each of the three climate models (12 projections in total used in this study) (Table 4).

Table 4 Projections used in Baltic study

GCM	Climate scenario	Nutrient scenario	Type
MPI-ESM-LR	RCP4.5	BSAP	*
MPI-ESM-LR	RCP4.5	Ref	
MPI-ESM-LR	RCP8.5	BSAP	
MPI-ESM-LR	RCP8.5	Ref	**
EC-EARTH	RCP4.5	BSAP	*
EC-EARTH	RCP4.5	Ref	
EC-EARTH	RCP8.5	BSAP	
EC-EARTH	RCP8.5	Ref	**
HadGEM2-ES	RCP4.5	BSAP	*
HadGEM2-ES	RCP4.5	Ref	
HadGEM2-ES	RCP8.5	BSAP	
HadGEM2-ES	RCP8.5	Ref	**

* most likely scenario; ** worst case scenario

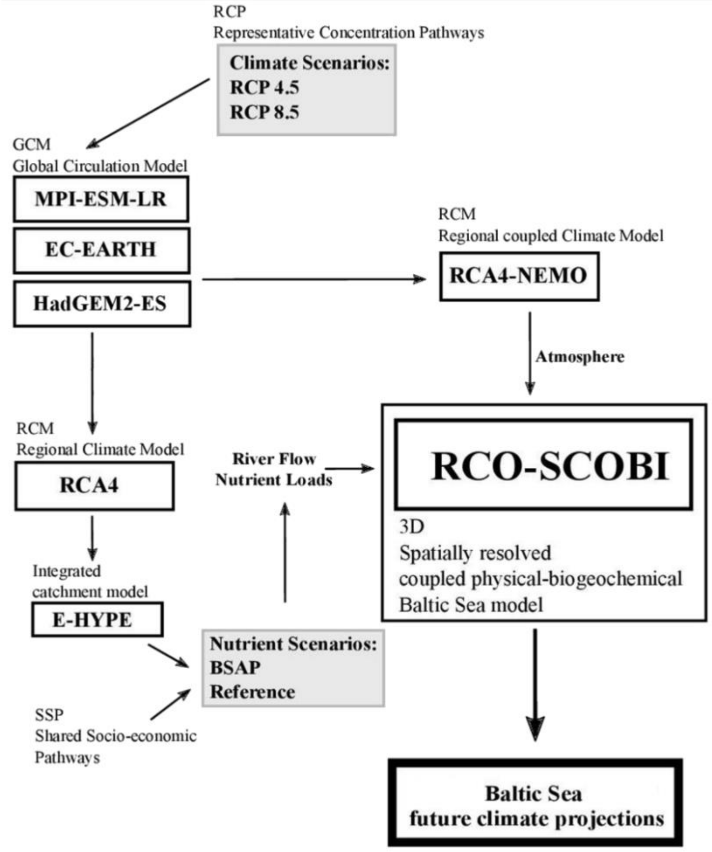

Figure 2 Conceptual diagram of the modelling framework providing hydrographic projections for the Baltic Sea (modified from Saraiva et al., 2019a).

The ongoing nutrient load reductions since the 1980s resulted in reduced eutrophication compared to the reference period. Projections from the RCO-SCOBI show that the impact of a warming climate may amplify the effects of eutrophication on a long time scale (end of the 21st century) but limitedly in the time horizon of the next two decades (Figure 2). However, nutrient supply, in particular phosphorus, controls the long-term response of eutrophication and biogeochemical fluxes in the Baltic and within the range of plausible climate scenarios the effects of changes in the nutrient loads appear to have a dominant effect on the occurrence of hypoxia in the deep waters (Saraiva et al., 2019a,b). Hypoxia areas could directly affect the cod reproductive volume.

In the projection, this reproductive volume for cod shows similar levels between the RCP 4.5 and RCP 8.5 warming scenarios until 2040 but pronounced differences with the nutrient loads already in the first decade of the projections (Figure 3).

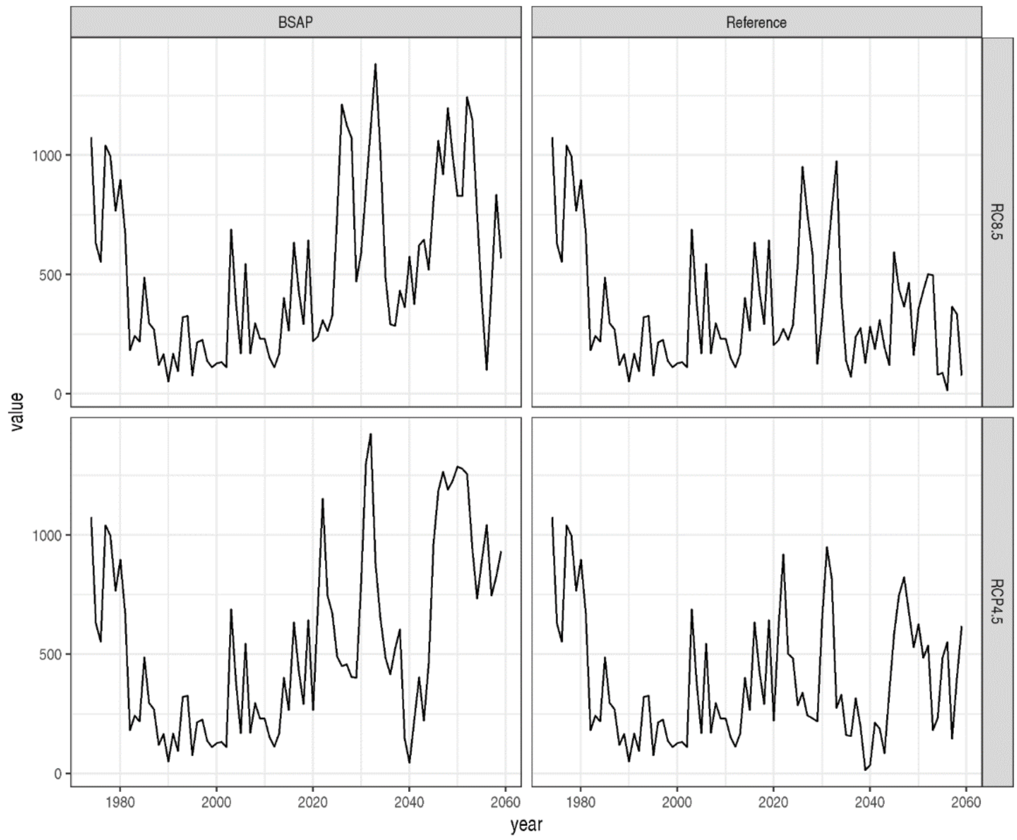

Figure 3 Cod reproductive volume calculated from the main cod spawning areas (Bornholm Basin SD25, Gdansk Deep SD26, Gotland Basin SD28.2). The projection period starts in 2020 and shows projections from one of the GCM model for the RCP 4.5 and RCP 8.5 and for the BSAP and Reference nutrient load scenarios.

Higher atmospheric temperatures lead to an earlier snow melt causing larger river runoff during winter. Projections on river runoff are highly uncertain. On average river runoff is expected to increase by about 1% in RCP4.5 and by 15% in RCP8.5. Due to the increased runoff volume, the marine water salinity will decrease on average by about 0.4 and 1.2 in RCP 4.5 and RCP 8.5, respectively. However, no pronounced differences are visible by 2030 compared to the historical period (Saraiva et al., 2019a,b) (Figure 4).

The climate model simulation results suggest that water temperature will increase with time due to an increase in air temperature projected by the driving GCM. Baltic Sea average changes in sea surface temperature (SST) between future (2069–2098) and historical (1976–2005) conditions in RCP 4.5 and RCP8.5 scenarios amount to about 1 and 2C°, respectively, with a more pronounced warming in the Northern part of the Baltic Sea (Saraiva et al., 2019a,b) (Figure 5).

While absolute values of changes in temperature and salinity vary between the two climate scenarios, the main pattern of the average profiles of temperature and salinity does not change significantly, and a strong water column stratification will still be one of the main characteristics of the Baltic Sea.

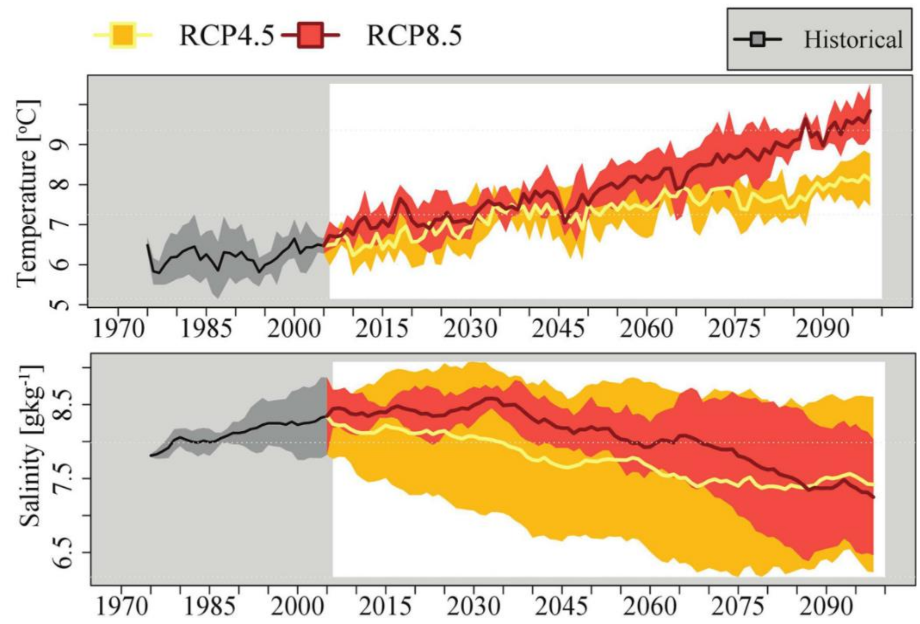

Figure 4 Ensemble mean volume averaged temperature (in ºC) and salinity (in g kg-1) as a function of time for 1975–2098 in the two climate scenarios, RCP 4.5 (orange) and RCP 8.5 (red). The coloured shaded areas denote the standard deviations among the ensemble members (from Saraiva et al., 2019a).

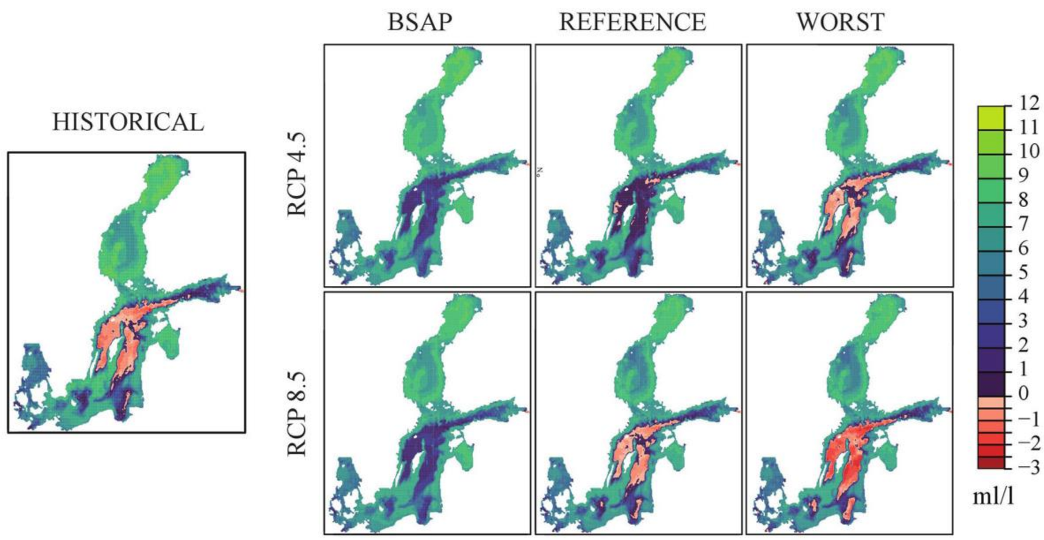

Figure 5 Historical (1976–2005) and projected future (2069–2098) ensemble mean summer bottom oxygen concentrations (in mL L-1) in three nutrient load (BSAP, Reference and Worst Case) and two greenhouse gas concentration scenarios (RCP 4.5 and 8.5). Hydrogen sulfide concentrations are represented by negative oxygen concentrations (1 mL H2S L-1 = -2 mL O2 L-1). (from Saraiva et al., 2019a).

Assumptions for future changes in fish stock dynamics and scenarios

Fish stock projections are forced by:

- Environmental sensitive stock-recruitment relationships are used for population dynamics models integrating forcing drivers to biology (e.g., GADGET, Atlantis). Selection of the environmental driver(s) specific for each stock is derived from the literature review in section 1 and Bossier et al. (2021). For the GADGET model, the relationship is parametrized based on historical SSB and recruitment pairs output from the Gadget model. In Atlantis, the Beverton-Holt relationship is used, which is sensitive to hydrographic parameters. The environmental variables derived from the RCO-SCOBI re-analysis of the Baltic Sea data is used for forcing in both GADGET and Atlantis. Projections of the same environmental variables are derived from the downscaled General Circulation Models (GCMs) also based on the RCO-SCOBI.
- Recent maturity, growth and conditions are used to reflect implicitly the most recent effects of environment and fishery exploitation on the biology of the stocks (Table 5).
- Cod predation on the clupeids which emerges from the predator-prey stocks dynamics and relationships built into the models.
- Similar fishery exploitation levels and fishing gear selectivity patterns.
- Change in the spatial distribution of the species and the underlying degree of overlap between predators (cod) and preys (sprat and herring), and with the geographical operational range of exploiting fishing fleets (relevant for spatially explicit models such as DISPLACE).

Table 5 Assumptions for long-term changes in fish stocks linked to climate/nutrient scenarios compared to the baseline.

Stock	Biological function	change	Magnitude of the change		Model implementation
			Most likely scenario	Worst case scenario	
cod	Recruitment	Effect of reproductive volume (RV) defined by levels of salinity and oxygen on recruitment success. S-R hockey-stick with deviations linked to RV	RV from the main spawning areas of the stock (SD25,26,28.2) linked to RCP4.5 and BSAP nutrient scenarios	RV from the main spawning areas of the stock (SD25,26,28.2) linked to RCP8.5 and reference nutrient scenarios	GADGET
	Recruitment	Effect of temperature change on recruitment success. Thresholds in temperature, salinity and oxygen	RCP 4.5 with reference nutrient scenario (Different nutrient scenarios, BSAP, reference and worst case with 2 nutrient sources, E-HYPE and PLC 7 are used in Bossier et al., 2021)	RCP 8.5 with reference nutrient scenario (Different nutrient scenarios, BSAP, reference and worst case with 2 nutrient sources, E-HYPE and PLC 7 are used in Bossier et al., 2021)	Atlantis
	Recruitment	Reproductive volume (RV) expected to contract and affect the habitat suitability for more likely lower recruitments	Decreased recruitments	Decreased recruitments	DISPLACE
	Growth/Condition	Not explicit climate effect but growth at its record low in recent years. von Bertalanffy parameters from the	Same all scenarios		GADGET

		last year of the model (k=0.210682 and Linf=54.3636). Length-weight (W=αLβ) with α= 3.0169 and β = 8.54e-06 for the last period.			
	Growth/Condition	Productivity change for faster growth and lower asymptotic body size	Slightly faster growth parameter (i.e., in Von Bertalanffy Growth Function (VBGF), Lower Length Infinity (Linf), higher K) lowering weight at age	Faster growth parameter (i.e., in VBGF, Lower Linf, higher K) lowering weight at age	DISPLACE
	Maturity	No explicit climate effect but maturity at length followed a long-term decrease. L50 assumed to remain low as in the recent period. Maturity ogive from the last four years of the model (L50 = 21 cm)	Same all scenarios		GADGET
Herring	Recruitment	Effect of sea-surface temperature in August (SST8) on recruitment success. S-R hockey-stick with deviations linked to SST8	SST8 over the entire distribution of the stock (SD25-29, excl. GoR) linked to RCP4.5. Nutrient scenario not relevant	SST8 over the entire distribution of the stock (SD25-29, excl. GoR) linked to RCP8.5. Nutrient scenario not relevant	GADGET
	Recruitment	Productivity change to more likely lower recruitments	Decreased recruitments	Decreased recruitments	DISPLACE
	Growth/Condition	Not explicit climate effect but weight-at-age remained low since mid 1990s and it is assumed to stay as such in the projections. Implemented in the model via length-weight (W=αLβ) with β = 5.43e-06 for the last period.	Same all scenarios		GADGET
	Growth/Condition	Productivity change for faster growth and lower asymptotic body size	Slightly faster growth parameter (i.e., in VBGF, Lower Linf, higher K) lowering weight at age	Faster growth parameter (i.e., in VBGF, Lower Linf, higher K) lowering weight at age	DISPLACE
	Predation	Dynamic cod predation	Emergent from each scenario		GADGET
Sprat	Recruitment	Effect of sea-surface temperature in July-August (SST78) on recruitment success. S-R hockey-stick with deviations linked to SST8	SST78 in the core of the distribution (SD25-29) linked to RCP4.5. Nutrient scenario not relevant	SST78 in the core of the distribution (SD25-29) linked to RCP8.5. Nutrient scenario not relevant	GADGET
	Recruitment	Productivity change to higher recruitments more likely (positive effect	Enhanced recruitments	Enhanced recruitments	DISPLACE

		of warmer water column temperature on sprat)			
	Growth/Condition	Not explicit climate effect but weight-at-age remained low since mid 1990s and it is assumed to stay as such in the projections. Implemented in the model via length-weight (W=αLβ) with β = 8.999465e-06 for the last period.	Same all scenarios		GADGET
	Growth/Condition	Warmer temperature leads to faster growth and earlier maturity	slightly faster growth parameter (i.e., in VBGF, Lower Linf, higher K) lowering weight at age	faster growth (i.e., in VBGF, Lower Linf, higher K) lowering weight at age	DISPLACE
	Predation	Dynamic cod predation	Emergent from each scenario		GADGET, DISPLACE
Cod, Herring and Sprat	Spatial distribution change	Range contraction	Imposed contraction of the baseline geographical extent of the stocks by 10%		DISPLACE
	Growth, condition, consumption, mortality, recruitment	Explicit climate change effects from changes in temperature, salinity, fluxes and riverine nutrient input	RCP 4.5	RCP 8.5	Atlantis

The use of coherent environmental scenarios via a coupled physical-biogeochemical model makes it difficult to generate extreme events (i.e., heatwave) coherent with the rest of the bio-physical system in a predefined moment in time. Quantitative definitions of marine heatwaves have been proposed (i.e., Hobday et al., 2016) and systems for categorization of their intensities (Hobday et al., 2018). However, an increasing number of regional studies is showing that the biological impact of marine heatwaves is highly context-dependent. Difficulties also exist in defining and characterizing extreme climatic events, and no standard for calculating a heatwave could be found. Moreover, the impact of extreme climate events on biological processes driving fish stock dynamics in the Baltic remains poorly understood. For this reason, we used coherent environmental scenarios to drive long-term changes in the stocks (i.e., recruitment), while the effects of a short-term shock are simplified in this study by simulating recruitment events at the limits of the distribution of recruitments observed (i.e., recruitment failure), well beyond what would be predicted by the S-R relationship (Table 6).

Possible heatwaves in 2015 and 2018 will potentially be explored and extracted from Copernicus data to indicate orders of magnitude of heatwaves.

Table 6 Assumptions for short-term shock compared to the baseline.

Stock	Biological function	Scenario most likely	Scenario worst case	rationale	Model implementation
cod	Recruitment	In line with assumptions on the long-term effect of climate. Recruitment predicted by the S-R relationship with deviations influenced by	Like in the most likely scenario but replacing the recruitment in the first year of the forecast (2020) with the lowest	Failure in recruitment comparable with the lowest observed independently of the stock size.	GADGET

		the reproductive volume (RV) defined by levels of salinity and oxygen. RV is calculated during the spawning period which is assumed to persist in the Summer.	recruitment observed in the time series.		
	Recruitment	RCP 4.5	RCP 8.5	Manually induced recruitment shock of cod of x percent. The magnitude is dependent on output from ongoing analyses on this.	Atlantis
	Recruitment	RCP 4.5	RCP 8.5	Potential heatwave induced shock on cod. Analyses are ongoing on this.	Atlantis
herring	Recruitment	In line with assumptions on the long-term effect of climate. Recruitment predicted by the S-R relationship with deviations influenced by the sea-surface temperature in August as assumed for the long-term effect of climate	Like in the most likely scenario but replacing the recruitment in the first year of the forecast (2020) with the lowest recruitment observed in the time series.	Failure in recruitment comparable with the lowest observed independently of the stock size.	GADGET
sprat	Recruitment	In line with assumptions on the long-term effect of climate. Recruitment predicted by the S-R relationship with deviations influenced by the sea-surface temperature in July-August as assumed for the long-term effect of climate	Like in the most likely scenario but replacing the recruitment in the first year of the forecast (2020) with the lowest recruitment observed in the time series.	Failure in recruitment comparable with the lowest observed independently of the stock size.	GADGET
Cod	Massive mortality event	Massive mortality event at the start of the simulation. This may be caused by the combined effects of warmer temperature and water oxygen content.	Like in the most likely scenario	A plausible short-term shock induced by climate change could result from the mortality affecting fish and other demersal animals. This may be caused by the combined effects of warmer temperature and water oxygen content. Marine populations are susceptible to low oxygen events that may increase in frequency and severity with the anticipated warming waters. Increased temperature increases metabolism for animals such as fish which require more oxygen consumed, and more detritus that trigger the microbial loop creating hypoxia areas for demersal fish and invertebrates, even more, when the stratification in the water column is increased. Even if fish can escape the unsuitable areas, benthos invertebrate species that are preyed on by fish will not survive, making fish possibly starving from the reduced resource or affecting the growth and reproduction.	DISPLACE
Herring and Sprat	Massive mortality event	Massive mortality event at the start of the simulation. This may be caused by a change in the primary production.		In the pelagic system, the primary productivity (phytoplankton) may also reduce drastically by reduced mixing of water layers or short-term events. These episodes may induce high mortality anomalies to	DISPLACE

				heavily environmentally-driven recruits such as those of pelagic species.	
	Recruitment	RCP 4.5	RCP 8.5	Manually induced recruitment shock herring or sprat of x percent	Atlantis

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Annex 2 : DEFINING PLAUSIBLE, ECOSYSTEM-COHERENT SHOCK SCENARIOS: NORTH SEA CASE STUDY

Synthesis of the literature reviews on the key climatic and environmental drivers of fish stocks

North Sea cod

Environmental effects on cod populations have been studied across all life history stages, but most have focused on the effect on early life stages before recruitment to fishing, stemming from the dramatic decrease in survival rates (i.e., recruitment per spawning stock biomass) observed over time. These changes have been most often linked to long-term climate change, such as increased temperatures in the North Sea.

The mechanism of the impact is not clear, however. There is less support for a direct adverse physiological response to increased temperatures. Temperatures may instead positively influence several aspects related to recruitment, including decreased development time in eggs, increased growth rates in larvae, and faster oocyte development in mature females.

Several possible indirect adverse effects have also been postulated, including higher predation rates on eggs, timing mismatches between spawning and suitable planktonic prey, and a general long-term northward shift in the habitat and abundance of suitable large-sized zooplankton species, such as Calanus finmarchicus.

Links between short-term interannual variability on recruitment processes are even less conclusive. However, several studies have shown that variability in sea currents and strength of inflowing Atlantic waters likely impact the transport and retention processes of eggs and larvae to important nursery areas. Currents are likely to influence the degree of exchange among sub-populations. For the larger fish (post-recruitment), a northward shift in the spatial distribution has been observed over recent decades. This spatial shift could be driven by increasing temperatures in the southern North Sea. Again, the mechanism for the shift is not clear, as it could be due to direct effect affecting cod outside its thermal optima, or indirectly whenever degrading the requirements for their prey.

North Sea whiting

Compared to other gadoid stocks like cod and haddock, whiting is reported to benefit from increasing temperatures. Spatial distribution was related to spatial patterns detected for SST, yet changing during the year. During winter and spring, the abundance of whiting was higher within the path of the Atlantic current than in the surrounding areas in the northern North Sea. The longitudinal distribution might change in the future for whiting, and Hadley SST and the Atlantic multidecadal Oscillation (AMO) index were identified to be significant predictors for westward shifts in distribution. Besides this, Whiting recruitment showed a statistically significant positive relationship to temperature.

Compared to the larvae of cod, whiting larvae were found to be opportunistic feeders, while cod is thought to be highly dependent on the copepod Calanus finmarchicus. This gives whiting larvae more predation opportunities, independent from a change in the composition of prey species. Furthermore, literature reports a phenomenon, where 0-group whiting was found to protect themselves from predators by hiding under the umbrellas of jellyfish. Since a positive relationship between the North Atlantic Oscillation and the occurrence of jellyfish was detected as well, an increase in temperatures is likely to increase the protection from predation.

North Sea herring

There is a wealth of literature linking climate variables to the potential impact on widely distributed herring stocks. The link with temperature can be variable and is often stock specific. For example, a positive relationship between high temperatures and good recruitment has been observed for the Norwegian Spring Spawning herring stock (Bogstad et al., 2013; Fiksen and Slotte 2002). In contrast, increased temperature could have changed plankton community, decreasing North Sea herring larval survival (Payne et al., 2009). This was suggested to be a driver of the recruitment regime shift observed around the 2000s. Recruitment was also shown to be correlated with the Atlantic multidecadal oscillation (Gröger, Kruse, and Rohlf 2010).

The link between climate change and biological parameters is more tenuous. Brunel and Dickey-Collas (2010) tested the change of van Bertalanffy parameters as a response to climate change across a range of herring stocks. It was found that temperature correlated negatively with Linf and positively with k. , meaning that the adult body length is reduced but reached earlier in adult life. Clausen et al. (2018) identified a negative of climate change on both recruitment and growth (using Calanus finmarchicus abundance as proxy). Hunter et al. (2019) showed significant relationship in specific areas at specific ages for herring for both growth and maturation (Lp50).

North Sea haddock

The haddock stock in the North Sea shows no apparent relationship to temperature. According to ICES reports, recruitment patterns are marked by exceptionally strong cohorts with lower recruitment in the following years.. Yet, what causes these high numbers is not completely understood. According to literature, recruitment of haddock shows opposite or lagged correlation patterns with sea surface temperature (SST) and no obvious link to the North Atlantic oscillation. Nevertheless, the egg survival may have its optimum at 7°C, with increasing temperatures likely to accelerate egg development. For the mature haddock, the optimal spawning temperature may coincide with egg survival at 7°C. Overall, the stock is driven to a large extent by outstanding year classes (spikes) that sustain the fishery over many years. The spikes tend to become smaller over time. In the last decades, abundance decreased in areas IVb and IVc, while it stayed constant in the northern part of the North Sea.

The growth of haddock larvae could be largest in medium temperature ranges, with a maximum at 8°C. Studies have shown that higher temperatures reduce the time haddock spend in different developmental stages, inducing earlier sex maturation. Therefore, young haddock reach sex maturation at a smaller body size. Generally, haddock is reported to benefit from bottom temperatures greater than 6°C in deeper areas with higher salinities. During the summer months of quarter three, especially age 0 haddock were located in temperatures less than 11°C mainly in the northern North Sea.

North Sea saithe

According to literature, North Sea saithe has so far not been directly influenced by temperature changes, and also its spatial distribution has not changed within the North Sea. Neither for recruitment nor for growth direct temperature effects have been observed. However, indirect effects have been described to play an important role. Changes in currents, large scale patterns as the northern annual mode, the composition and timing of phyto- and zooplankton blooms (especially Calanus finmarchicus as food for larvae) had likely a negative influence on recruitment over time.

If the effect of environmental conditions and their change could not be linked so far to any effect on the stocks, the stock has experienced some changes in recent years. According to ICES, recruitment is on a decreasing trend with the lowest levels in the past 10 years (after 2010). Growth of North Sea saithe may be influenced by density-dependent effects and competition with the northern hake stock. Both species prey on Norway pout as an important item. According to ICES, mean weight at age has decreased for ages 6+ between the late 90ies and 2010, but the trend has stopped and has reversed in recent years. Weights-at-age for ages 3–5 have been relatively stable, with some variation over the last decade.

Nephrops in the North Sea

For Nephrops, literature about temperature effects is relatively sparse. Within the North Sea, ICES divided the Nephrops stock into management units depending on their preferred habitat mud patches. Temperature alone was not reported to be significant for the development of the Nephrops stock. Nevertheless, the effects of ocean acidification affecting Nephrops could be more pronounced at higher temperatures, which could increase the risk for diseases that can infest Nephrops. However, these results were found for ocean acidification levels that are predicted to occur in 2100. Furthermore, it has been reported that egg development stops over winter for Nephrops. Hence, increasing temperatures may negatively affect the development time.

Anglerfish (ANF) in the North Sea

Both species, L. piscatorius and L. budegassa occur in the North Sea and west of Scotland and are assessed as one stock. L. piscatorius is currently clearly the dominant species in the North Sea as it is more associated with northern areas. However, in most recent years a small but significant increase of L. budegassa was observed in the North Sea area. For L. piscatorius, the trends in the probability of occurrence show significant increasing trends in the North Sea (northern parts) from the early 70s to the early 90s when this increase stabilized. More recent stock size indicators still show a strong increasing trend between 2010 and 2017 and a decline afterwards.

For the southern part of the North Sea and the English Channel predictions show a decreasing abundance of L. picatorius in IPCC 4.5 and 8.5 scenarios. However, in the southern part of the North Sea not much anglerfish is currently caught compared to the northern parts. Available literature points towards a general northward shift of anglerfish. Also, in the North Sea anglerfish moved into deeper water, however, also seasonal migrations seem to play a more prominent role making conclusions about spatial shifts within the North Sea uncertain. Overall, anglerfish has a relatively narrow temperature tolerance, but the optimum temperature is higher than for boreal species like herring, cod and haddock.

North Sea plaice

Recruitment of various stocks of plaice, including the North Sea stock, is negatively correlated to temperature (Fox et al., 2000). For the North Sea stock, year-class strength is mainly determined by the survival during pelagic (egg and larvae) stages (van der Veer et al., 2000) and both egg mortality and larval survival until settlement on nursery grounds is linked to temperature in the spawning season (December to march, van der Land, 1991, van der Veer and Witte, 1999; van der Veer et al., 2000). In addition, in extremely cold years, cold induced mortality of predators on the nursery ground led to high survival of the 0 group and exceptional year classes (van derVeer 2000). Such extremely cold temperatures however caused a high mortality for the older individuals (Woodhead, 1964b, 1964c).

The higher body growth in the 60s and 70s and its reduction in the 80s was related to changes in the nutrient discharge in marine waters (Rijnsdorp and van Leeuwen, 1996, Rijnsdorp et al., 2004). Temperature positively affects the body growth of early settled young plaice, but negatively at a later stage during the summer (too warm), and its effect is not clear for the older fish (Teal et al., 2008, van Keeken et al., 2007). Body growth in the recent year has been density-dependent limited as there is an inverse relationship between population density and body growth (vdSleen et al., 2018). Sex maturation is also linked to growth rate and temperature (Rijnsdorp, 1993a).

A shift in the depth distribution of young plaice was reported for the 1990s, whereas a shift to deeper waters of larger plaice (20 – 39 cm) was already apparent before the 1980s (van Keeken et al., 2007). This change in spatial distribution allowed the plaice to follow the ambient temperature that keeps within tolerance range while the North Sea ecosystem temperature increased (van Hal et al., 2016). North Sea coastal areas have become warmer and therefore allows for faster young plaice growth, but with higher energy demands (van der Veer et al., 2011). This increase in energy demands was coupled with a decreased benthic productivity (Tulp et al., 2008) which reinforced the need for plaice individuals to relocate.

North Sea sole

No relationship between adult growth and temperature has been reported. On the contrary, for the smaller individuals, earlier spawning may result larvae encountering too low temperature, which reduces larvae survival before the settlement on the nursery grounds (van de Wolfshaar et al., 2021).

Animal body length after its first summer of growth showed an increasing trend in survey data (Teal et al., 2008). larger body length likely results from both an increase in the growth rate at higher water temperatures and a longer growth period (Teal et al., 2008). The onset of sexual maturity is positively influenced by the growth rate during the juvenile phase (Mollet et al., 2007) and, thus, will also be influenced by temperature. In cold winters, there is higher mortality and sole aggregate in deeper-warmers pits.

Sole distribution has on average shifted to the south North Sea, due to higher winter temperature making the habitat more suitable for sole (Engelhard et al., 2011). However, in recent years, the northern limit of distribution in the North Sea has expanded northwards (Brunel and Verkempynck, 2018)

North Sea sprat

Very little research on the relationship between sprat productivity (i.e.,recruitment or growth) has been published. Sprat is short-lived and a substantial proportion of a cohort contribute to spawning within the first year of life (ICES 2018a).. Sprat recruitment showed no relationship with temperature, but a positive relationship with salinity in Oct-Dec was reported by Akimova et al. (2016). Besides this, sprat larvae might flourish in relatively high salinities, as indicated by a recent un-published larval study, showing a spatial correlation between larval abundance and salinity (EMFF-BEBRIS 2021). However, it is not conclusive yet to what extent the link to salinity is direct (i.e.,physiological) or whether salinity is merely an indicator of something else.

Historically, there is some indication that growth and recruitment success (recruitment per spawner biomass, R/S) was on average lower after the mid-1990s than before, indicating a shift for lower productivity (Clausen et al., 2018). However, in the early 1980s productivity was also relatively low, suggesting a temporary peak in productivity (rather than a regime shift) in the late 1980s when the spawner biomass was also low (i.e.,density dependent regulation). Recently, a significant relationship between growth of the younger age-classes and stock size has been shown, further supporting of the presence of a density dependence effect in this stock (Lindegren et al., 2021

Projected changes in the North Sea environment

An international team of 200 climate scientists in different research areas from all countries around the North Sea has recently published a North Sea Region Climate Change Assessment (NOSCCA). This report looked at past changes in the North Sea linked to climate change, and at projections for the next century (Quante and Colijn, 2016[1]). A chapter is dedicated to the projected changes in the North Sea physical environment and lower trophic levels[2]. A comparison of the different projections from a range of studies conducted with different regional models is presented. Coherent findings from the climate change impact studies reviewed in this chapter include overall increases in sea level and ocean temperature, a freshening of the North Sea, an intensification of the ocean acidification and a decrease in primary production. However, the study also points out the variability in the projections across models, regarding the amplitude and spatial pattern of the projected changes in sea level, temperature, salinity and primary production. The report also notes that the large natural variability in the North Sea climate (both interannual variations and multi-decadal climate modes) could have played a prominent role in the projections, in addition to climate change impacts. Especially until 2030, the expected changes are minor and inter-annual variability finally plays a larger role than overall trends.

In the present study, projections of the North Sea environment are only used for illustrative purpose. Due to the poor resolution of the linkages between fish stocks and environmental drivers, no attempt is made to use oceanographic models in background to link to the modelling of future dynamics of fish stocks quantitatively. Instead, in most cases, physical environmental models are used to qualify the more likely direction (increase/decrease), the amplitude and, if available, the spatial heterogeneity of future changes in a set of relevant variables. These will be used as a basis to formulate empirical scenarios for the biology of the fish-stocks.

To illustrate these future changes in the North Sea environments, the results from projections of physical and biogeochemical parameters done within the Horizon 2020 funded project CERES[3] are presented below.

- ***SST and primary production***

The projections available from the CERES project indicate an increase in the North Sea water temperature by 2°C by 2100 for the climate change scenario RCP 8.5 and by 1°C under the scenario RCP 4.5.

1 Quante, M.; Colijn, F. (Ed.) (2016). North Sea region climate change assessment. Regional Climate Studies. Springer: Switzerland. ISBN 978-3-319-39743-6. xlv, 528 pp.
2 https://link.springer.com/content/pdf/10.1007%2F978-3-319-39745-0_6.pdf
3 https://ceresproject.eu/

For the present project, the projection period (2020 to 2030) is roughly 1/8 of the projection period in Figure 1a. This would mean an increase of 0.125°C and 0.25°C for the scenarios RCP 4.45 and RCP 8.5 respectively for the simulations in the present study.

Projections also indicate a decrease in the primary production in the North Sea (Figure 1b) with a more marked reduction in the northern regions. In the coastal areas, especially along the eastern part of the North Sea, projections foresee a slight increase in the primary production, due to an increase in river run-off and an increase in nutrient availability in the marine waters for the primary producers. Overall, until 2030 predictions suggest a somewhat higher variability than the situation between 2000 and 2020, but the overall trend is not evident (Figure 1b).

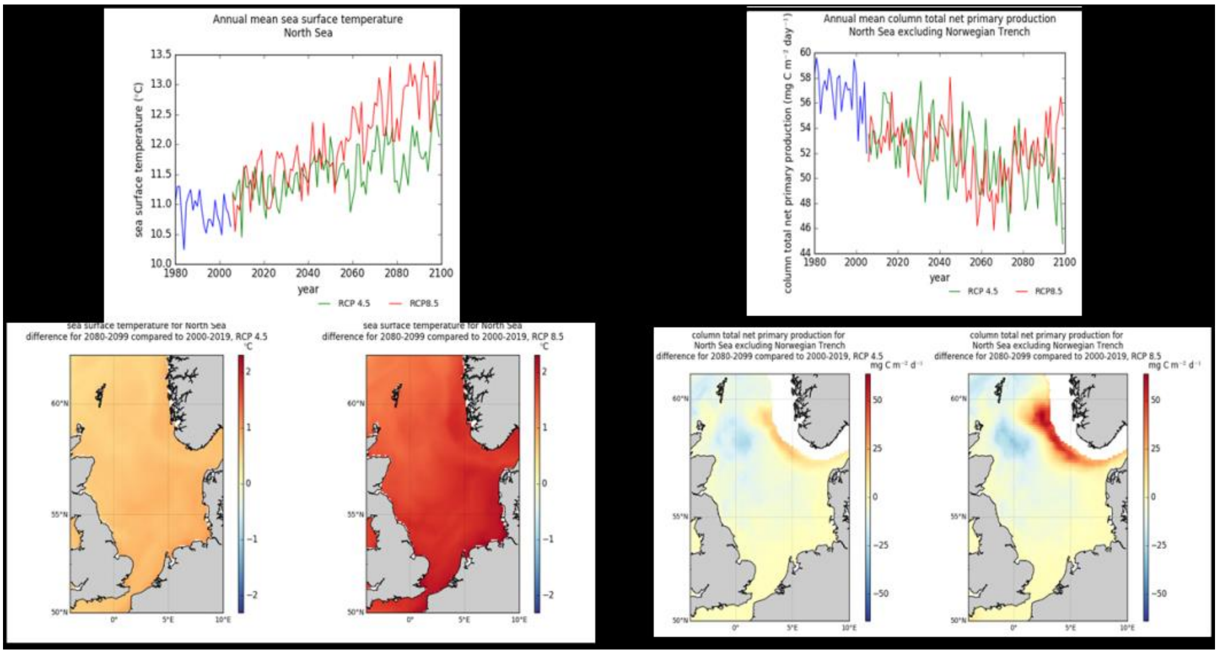

Figure 6 Trend for the average North Sea a) temperature, b) primary production (mgC/m2/day) and their comparison between present and future temperature under both RCP 4.5 and 8.5. (source : CERES project[4])

- ***storminess***

Regional climate models do not indicate an increase in the frequency of storms, but regional models are quite uncertain. Storms are projected to have more northerly tracks, but the uncertainty is also high. However, it is expected that storms could be of higher intensity, and bring more precipitation in the North Sea catchment area.

Assumption for future changes in fish stocks

Table 7 List of assumptions for long-term effects on fish stocks induced by a changing climate

Stock	Biological function	change	Magnitude of the change	
			Most likely scenario	Worst case scenario

[4] https://ceresproject.eu/wp-content/uploads/2020/02/19-Flatfish-in-the-North-Sea-and-north-east-Atlantic_revised.pdf

plaice	Recruitment	Decrease in recruitment as higher temperature is associated with higher mortality for early life stages recruitment-temperature correlation published in 2000 was revisited with new data and remains significant	based on a Beverton and Hold stock-recruitment model with temperature as covariate (GLM model). Future recruitment driven with RCP4.5	based on a Beverton and Hold stock-recruitment model with temperature as covariate (GLM model). Future recruitment driven with RCP8.5
	Distribution	All size-ranges continue to move northwards and to deep areas (for adults) to avoid areas that have become too warm		
sole	Growth	Faster growth for young fish due to Longer growing season and higher growth rate. A 1C° increase in temperature leads to a 0.58 cm increase in the body length at the end of the first year, no effect on growth in older ages.	The resulting changes in weight at age over the next 10 years for a temperature increase corresponding to RCP 4.5 are minimal (0.08 cm over 2020-2030) and are negligible, compared to recent interannual variations. Therefore these changes in growth are not implemented	Cf. most likely scenario
	maturation	Earlier maturation due to faster growth at young ages	Not implemented since changes in growth are judge negligible based on published correlations	Cf. most likely scenario
	Distribution	Centre of gravity moves southwards as habitat improves with the less frequent cold winters range expands to the north (habitat becomes suitable)		
Saithe	Recruitment	No direct temperature effect, but effects of sea currents. Recruitment has shown an overall decreasing trend over time with the lowest levels in the past 10 years.	Environmentally-mediated stock recruitment relationship (EMSRR) linked to patterns in currents and salinity. Future recruitment driven with RCP4.5. EMSRR developed during Pandora.	Environmentally-mediated stock recruitment relationship (EMSRR) linked to pattern in currents. Future recruitment driven with RCP8.5. EMSRR developed during Pandora

	Growth/ Mean weight at age	No direct temperature effects, but density dependent growth rates and competition with hake. Mean weight at age showed a decreasing trend for ages 6 and older between the late 90ies and 2010, but the trend has stopped and has been reversed in recent years. Ages 3-5 stable over time.	Mean weight at age stays at the levels observed in the last 10 years as the northern hake stock seems to stabilize at high level and the saithe stock will likely stay in the next 10 years at levels observed in recent years given its current low productivity.	As worst-case scenario mean weight at age for ages 6+ is scaled downwards to low levels observed between 2000 and 2010 by assuming further increasing competition with hake and associated stronger density dependent effects.
Anglerfish	Productivity	Overall, anglerfish has a relatively narrow temperature tolerance but the optimum temperature is higher than for boreal species like herring, cod and haddock. For the southern part of the North Sea (and English Channel) predictions show a decreasing abundance of L. piscatorius in IPCC 4.5 and 8.5 scenarios. However, most of the stock is already now concentrated in the northern part Overall, biomass in the North Sea showed an increasing trend until the 90ies when this trend leveled off. In recent years again an increasing trend is observed with some decline in the last two years. Lophius budegassa that is more associated to southern areas increased in the North Sea in recent years, but still on a low level.	Given that the optimum temperature for anglerfish is higher than for boreal species like herring, cod or haddock and , the most likely scenario for the next 10 years is that in general the current situation prevails in the northern part of the North Sea where most of the anglerfish stock is concentrated already now.	Given that the optimum temperature for anglerfish is higher than for boreal species like herring, cod or haddock, the worst-case scenario for the next 10 years is that that a minor decrease in productivity (-5%) occurs.
Whiting	Recruitment	Increase in recruitment with higher temperatures. Opportunistic predator in larval and juvenile stage (does not much depend on certain prey like cod larvae).	Environmentally-mediated stock recruitment relationship (EMSRR) linked to temperature. Future recruitment driven with RCP4.5. EMSRR developed during Pandora	
Haddock	Recruitment	Stock driven by recruitment spikes. Unclear mechanisms behind these spikes. In general, lower recruitment levels and spikes became lower after 2000.	Recruitment dynamics (frequency of spikes and recruitment level) stay as observed after 2000	See under shock scenarios

Herring	Recruitment	Relationship between surface temperature and recruitment (negatively correlated)	Implement a Ricker formulation with surface temperature as covariate.	
	Growth	Relationship between growth rate and temperature (negatively correlated).	Implement projection with von bertalanffy parameters indexed on surface temperature.	
	Spatial distribution	Decrease in abundance in areas IVb and IVc while remaining constant in the northern part of the North Sea	Indirectly taken into account in recruitment scenarios and low catchability for fleets and metiers mainly operating in the southern part of the North Sea.	Indirectly taken into account in recruitment scenarios and lower catchability (-10%) for fleets and metiers mainly operating in the southern part of the North Sea.
Cod	Recruitment	Clear relationship between temperature and decreased recruitment although likely not a direct physiological effect. Recruitment at low level since 1998 despite some recovery in the northern part of the North Sea. Cod in the southern part of the North Sea depleted.	Environmentally-mediated stock recruitment relationship (EMSRR) linked to temperature. Future recruitment driven with RCP4.5. EMSRR developed during Pandora	Environmentally-mediated stock recruitment relationship (EMSRR) linked to temperature. Future recruitment driven with RCP8.5. EMSRR developed during Pandora
	Spatial distribution	Northward shift of cod in the North Sea	Indirectly taken into account in recruitment scenarios and low catchability for fleets and metiers mainly operating in the southern part of the North Sea.	Indirectly taken into account in recruitment scenarios and lower catchability (-10%) for fleets and metiers mainly operating in the southern part of the North Sea.
	Maturity	Strong increase in maturity at age especially for age 2 cod. May be related to temperature but also because of low population size or fisheries induced evolution	Use maturity ogive representing the most recent 10-year period.	Use maturity ogive representing the most recent 10-year period.
North Sea sprat	Recruitment	The published correlation between recruitment and salinity Akimova et al. (2016) was revised, using more recent data (see details in the report). The correlation was no longer significant wih the addition of 3 new years of data.	Since the publish recruitment-salinity correlation was found not to be robust, no long-term climate effect	Cf. most likely scenario.

			was imposed on recruitment.	

Table 8 List of assumptions for climate-induced short-term shock on fish stocks

Stock	Biological function	Scenario most likely	Scenario worst case	rational
NS saithe	Recruitment	Low recruitment (ca. 56% of the predicted recruitment) for the first year of the forecast	Low recruitment (ca. 56% of the predicted recruitment) for the first two years of the forecast	The low recruitment shock is based on the distribution of relative deviations (i.e.,obs/pred) to that predicted by an 11-year running mean. The distribution of these annual deviations was used to define a negative anomaly occurring at a probability of the 5% (i.e.,quantile).
NS whiting	Recruitment	Low recruitment (ca. 66% of the predicted recruitment) for the first year of the forecast	Low recruitment (ca. 66% of the predicted recruitment) for the first two years of the forecast	Same as for NS saithe
NS haddock	Recruitment	Recruitment dynamics (frequency of spikes and recruitment level) stay as observed after 2000	No recruitment spike in the next 10 years	The stock is driven by sporadic recruitment spikes. Their frequency determines largely the dynamic in the stock and the fishery. The spikes can be seen as shocks for mixed fisheries creating potential choke situations. Worst case for yield in the haddock fishery, however, would be no recruitment spike in the next 10 years.
NS cod	Recruitment	Low recruitment (ca. 47% of the predicted recruitment) for the first year of the forecast	Low recruitment (ca. 47% of the predicted recruitment) for the first two years of the forecast	Same as for NS saithe
NS sprat	Recruitment	Low recruitment (lowest observed in the current assessment) will be imposed in the first	Low recruitment (lowest observed in the current assessment) will be imposed in the first	It´s the lowest ever observed and since we don´t know what caused it, we don´t know if it

		year of the simulations.	two years of the simulations.	could happen again.
NS plaice	Recruitment	Low recruitment (ca. 55% of the predicted recruitment) for the first year of the forecast	Low recruitment (ca. 55% of the predicted recruitment) for the first and second year of the forecast	Same as for NS saithe
NS sole	Recruitment	Low recruitment (ca. 27% of the predicted recruitment) for the first year of the forecast	Low recruitment (ca. 27% of the predicted recruitment) for the first and second year of the forecast	Same as for NS saithe
All stocks combined (only for the Ecopath model)	consumption rates	Heatwave in the first year of the simulation	Heatwave in the first 2 years of the simulation	The effect of the heatwave will be implemented as environmental driver that is linked to the environmental response curves of the functional groups (i.e.,consumption rate, see above).

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Annex 3 : DEFINING PLAUSIBLE, ECOSYSTEM-COHERENT SHOCK SCENARIOS: BLACK SEA CASE STUDY

Synthesis of the literature review on the key climatic and environmental drivers of fish stocks

Sprat

Black Sea sprat is one of the most abundant species in the sea with importance for the commercial fisheries as well as a food for predatory fish and cetaceans. Sprat is distributed in the whole Black Sea with maximum abundance in the north-western part and shelf waters. The Black Sea sprat is cold-water fish of Atlantic origin and in the summer stays under the seasonal thermocline forming dense aggregations near the bottom during the day and rising in upper layers during the night. It reproduces during the whole year with a maximum between November and March. Sprat spawning can be associated with winter divergence and the winter and spring plankton blooms (Daskalov 1999). Eggs and larvae are mostly found offshore in the subsurface layer 10-50m: in relatively stable water masses due to the permanent pycnocline.

Daskalov (1999) used generalized additive modelling (GAM) in exploring non-linear relationships between sprat different environmental variables (SST, SLP, wind, run-off). Sprat spawns in the open sea and its recruitment appeared to be less dependent on the parental stock biomass and is negatively related to SST and river discharge. It also showed positive relationships with the wind stress. The linear growth and maturation of sprat has been reported to be positively related to SST (Daskalov 1995), but sprat fat content is thought to be negatively related to SST (Shulman et al., 2011).

Anchovy

Black Sea anchovy is distributed in the whole Black Sea. In October-November it migrates to the wintering grounds along the Anatolian and Caucasian coasts in southern Black Sea. In these areas it forms dense wintering concentrations in November-March which are subject to commercial fishing. In spring and summer, the Black Sea anchovy occupies its usual spawning and feeding habitats across the sea with some preference to the shelf areas and the north-western part of the sea. The Black Sea anchovy is a warm-water species of Mediterranean origin and spawns during the summer, which is also the main feeding and growth season. The main feature characterizing the summer habitat is the strong stratification of the water due to the seasonal thermocline and reinforced in coastal and shelf waters by the river plumes. Anchovy was found to spawn mainly in the surface layer of these warm and stratified areas. Eggs and larvae are retained in the coastal layer stabilized in depth by the thermocline and protected from the offshore by thermo-haline fronts. A large convergence zone is formed on the northwestern and the western shelf (the main anchovy spawning area) due to the river Danube inflow, which favours fish offspring retention.

Sharp reductions in anchovy biomass and catch in the early 1990s have been described as a stock collapse (Daskalov 2011). The fishing effort and fishing mortality also dropped subsequently because of decreasing profitability of fishing. During the collapse phase the -size/age structure of the catch shifted toward a predominance of small, immature individuals and precocious maturation of young-of-the year fish was observed (Mikhailov and Prodanov 2002). Anchovy competes for food with the invasive ctenophore Mnemiopsis leidyi (Daskalov et al., 2017) and this competition probably further affects the anchovy population growth.

Panov and Spiridonova (1998) have found that anchovy abundance and aggregating behaviour depend on hydroclimate and used some climate indices like SST at Batumi and atmospheric circulation to draw relationships with the anchovy stock. Daskalov (1999) used generalized additive modeling (GAM) in exploring non-linear relationships in four fish species (sprat, anchovy, horse mackerel and whiting) and different environmental variables (SST, SLP, wind, run-off). Anchovy reproduction seemed to be related to the coastal habitat and favoured by stratification induced by river run-off and higher SST. The relationships with the wind stress were dome shaped with an inflection point that appears at nearly 4.8 m/s, where the slope changes from positive to negative. In a later study Daskalov (2003) explored the effect of various environmental and anthropogenic factors and found a significant positive correlation between anchovy abundance and increased phosphate level in the 1980s.

Probably the strongest environmental effect on anchovy stock the recent times was due to the invasive ctenophore M. leidyi. The initial outbreak of M. leidyi was reported in 1988-89. It appears that the catastrophic reduction of the Black Sea anchovy stock in the late 1980s was due to the combined action of two factors: the excessive fishing and M. leidyi outburst (Grishin et al., 2007). The total loss from the anchovy catch over the years 1989-1992 due to M. leidyi outbreak can be roughly estimated at about 1 million tons causing estimated losses of US$16.8 million (Knowler 2005). Damage by M. leidyi to the anchovy population is most likely done through food competition, as unusually low levels of the summer food zooplankton have been observed in the top 50m layer in the early 1990s (Grishin et al., 2007). Anchovy larvae could be also affected by predation by M. leidyi. Anchovy has a crucial role in the Black Sea pelagic food web as a prey of many predators such as bonito, blue fish, horse mackerel, dolphins, between the others. Anchovy is also an important consumer of zooplankton, especially when the stock is large and, as such, acts as a predator of zooplankton and competitor of other planktivores (Daskalov et al., 2007)

Most authors report positive relation of anchovy recruitment, growth (also fat content), and migratory pattern to SST, related to its preference for warm water habitats and zooplankton food related to such conditions (Daskalov 1999, Shulman et al., 2011, Guraslan et al., 2014, Daskalov et al., 2017, Guraslan et al., 2017). On the other hand, the formation of dense schools favouring successful purse seine fishing take place in rather specific temperature conditions, where water warming may disturb school formation and make anchovy distribution unsuitable for fishing (Gucu et al., 2017). Warmer conditions on the northern Black Sea shelf may disturb annual migration process (to southern Black Sea for over-wintering) by keeping the anchovy schools to over-winter in the northern areas (Gucu et al., 2017).

Mediterranean horse mackerel

The horse mackerel is migratory species distributed in the whole Black Sea. In spring, it migrates to the north for reproduction and feeding. In summer, the horse mackerel is distributed preferably in the shelf waters above the seasonal thermocline. In the autumn it migrates towards the withering grounds along the Anatolian and Caucasian coasts. The horse mackerel reproduces in the summer, which is also the main feeding and growth season. It spawns in the upper layers, mainly in the open part of the sea as well as near the coast. Eggs and larvae are often found in areas with a low productivity and higher salinity. Daskalov (1999, 2003) has found that horse mackerel recruitment negatively related to SST which interpreted as an effect of upwelling for increasing the productivity of plankton.

A strong negative correlation with surface temperature (SST) was found. It may appear surprising for a warm-water summer spawning species to correlate negatively with SST. Such relationships have been also found however in other studies (Mikhayluk, 1985, Simonov et al., 1992). The effect of the wind stress was significant and generally positive. These results indicate that horse mackerel recruitment has been more abundant in years with increased physical forcing and enrichment, probably related to the spawning distribution widespread over areas of low productivity.

Whiting

In the Black Sea, whiting is one of the most abundant demersal species. Whiting is a cold-water fish of Atlantic origin. It does not undertake distant migrations and spawns mainly in the cold season within the whole habitat area. It produces pelagic juveniles, which about inhabits the upper water layer. The mature whiting is distributed along the shelf, dense commercial concentrations are formed by 1-3 year old fishes in the water up to 150 m depth, most often in depth 60-120 m (Shlyakhov, Charova, 2003).

Daskalov (1999, 2003) has found that whiting recruitment is positively related to SST and river run-off.

Other fishes

Sprat, anchovy, whiting, horse mackerel, Black Sea shad (Alosa kessleri), and turbot have been found to correlate to various hydroclimatic, biological (plankton, benthos) and anthropogenic (hypoxia, eutrophication) factors (Daskalov et al., 2003). Turbot/dogfish are reported to be positively/negatively related to SST (Prodanov et al., 1997). Small pelagic biomass (sprat, anchovy, horse mackerel) were inversely related to pelagic predators (Daskalov, 2002) and gelatinous planktivores (Daskalov et al., 2007).

Regime changes in the Black Sea

Ecosystem regime shifts cascading down from top-predators to primary producers were registered in the Black Sea during the 1970s and 1990s (Daskalov et al., 2007). The first shift followed the depletion of top predators from the 1950-1970, after which the ecosystem stabilized at low abundance of top predators, high abundance of planktivorous fish, low zooplankton biomass and high phytoplankton biomasses during the 1970s and 1980s. The second shift was associated with the collapse of planktivorous fish and outburst of the invasive M. leidyi, which resulted in a second system-wide trophic cascade, with similar alternating effects on zoo- and phytoplankton, and on water chemistry.

Daskalov and colleagues (Daskalov et al., 2017) further investigated causal pathways linking external (hydroclimate, overfishing) and internal (foodweb interactions) drivers provoking regime shifts, and revealed mechanisms of hierarchical incorporation of environmental factors leading to particular responses of fish stocks, jellies and plankton. The hydroclimatic signal (e.g., changes in temperature and run-off) is conveyed through the foodweb via changes in productivity at all levels, to planktivorous fish. Fluctuating fish abundance is found to induce a lagged response in jelly-plankton trough exploitative competition. This effect further cascades down to phytoplankton and influences water quality. Deprived of the stabilising role of apex predators, the hierarchical ecosystem organisation is susceptible to both environmental and anthropogenic stresses, and increased fishing makes fish stock collapses highly probable.

The signs of the correlations between environment and fish stocks (recruitment or biomass) seem to shift with major changes in top-down control e.g., correlation between sprat recruitment/biomass and SST have been reported as negative (Daskalov 1999) until 1990, but changed to positive since (Daskalov et al., 2017). Ultimately these correlations depend upon the hierarchical structure of the food web and dominance top-down or bottom-up control in particular period (Daskalov et al., 2017). With that respect, changes due to introduction of invasive ctenophores M. leidyi and Beroe ovata on the top of the planktivorous food web, need to be taken into consideration.

Climate change projections in the Black Sea ecosystem

Black Sea environment projections

Most of the published projections of the Black Sea physical environment are based (e.g., Cannaby et al., 2015) on IPCC AR4. Sakalli and Başusta (2018) estimated linear trends in SST from the hindcast period (1982-2014), which they projected into the future and compared with SST trends from climate models' simulations (Figure 7).

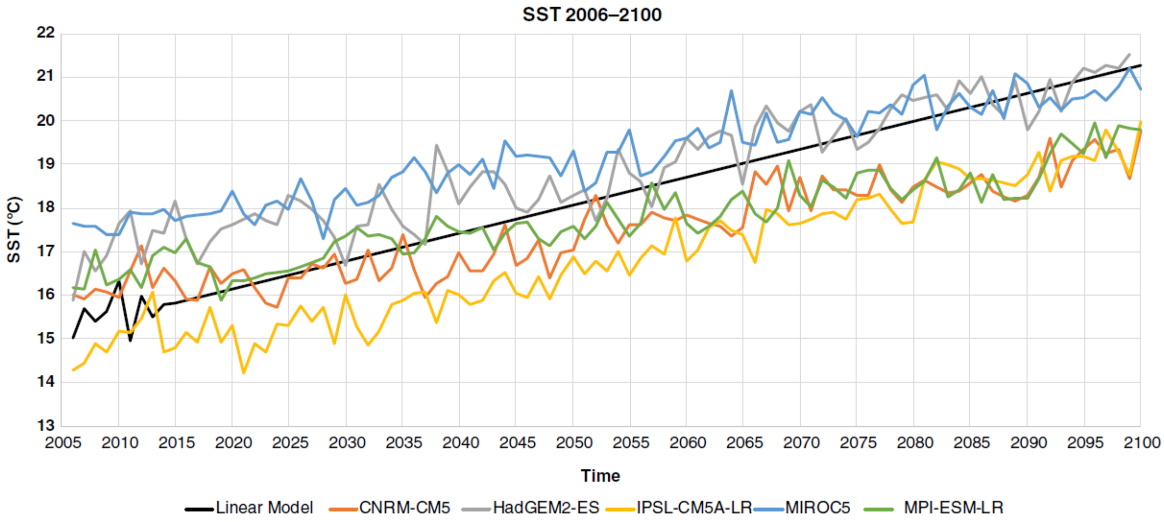

FIGURE 10 Modelled sea surface temperature for the Black Sea by five general circulation models (GCM) considering the representative concentration pathway 8.5 (RCP8.5) and by in this study defined linear model [Colour figure can be viewed at wileyonlinelibrary.com]

Figure 7 Sakalli and Başusta (2018) linear trend in SST compared to RCP 8.5 projections from different climate models in the Black Sea

Low trophic levels (primary production, phyto-and zooplankton biomass) projections

Low trophic levels (primary production, phyto-and zooplankton biomass) projections were obtained using coupled hydrodynamic-plankton models forced with IPCC AR4 climate simulation scenario A1B (Chust et al., 2014, Cannaby et al., 2015) (Figure 8). Consistent with other similar studies (e.g., Kwiatkowski et al., 2018), Chust and colleagues have reported amplification or attenuation of zooplankton biomass compared to the phytoplankton biomass in different areas of the Black Sea (Chust et al., 2014). The decrease in zooplankton biomass/ phytoplankton biomass on average in the Black Sea until 2100 is about 10% (Chust et al., 2014).

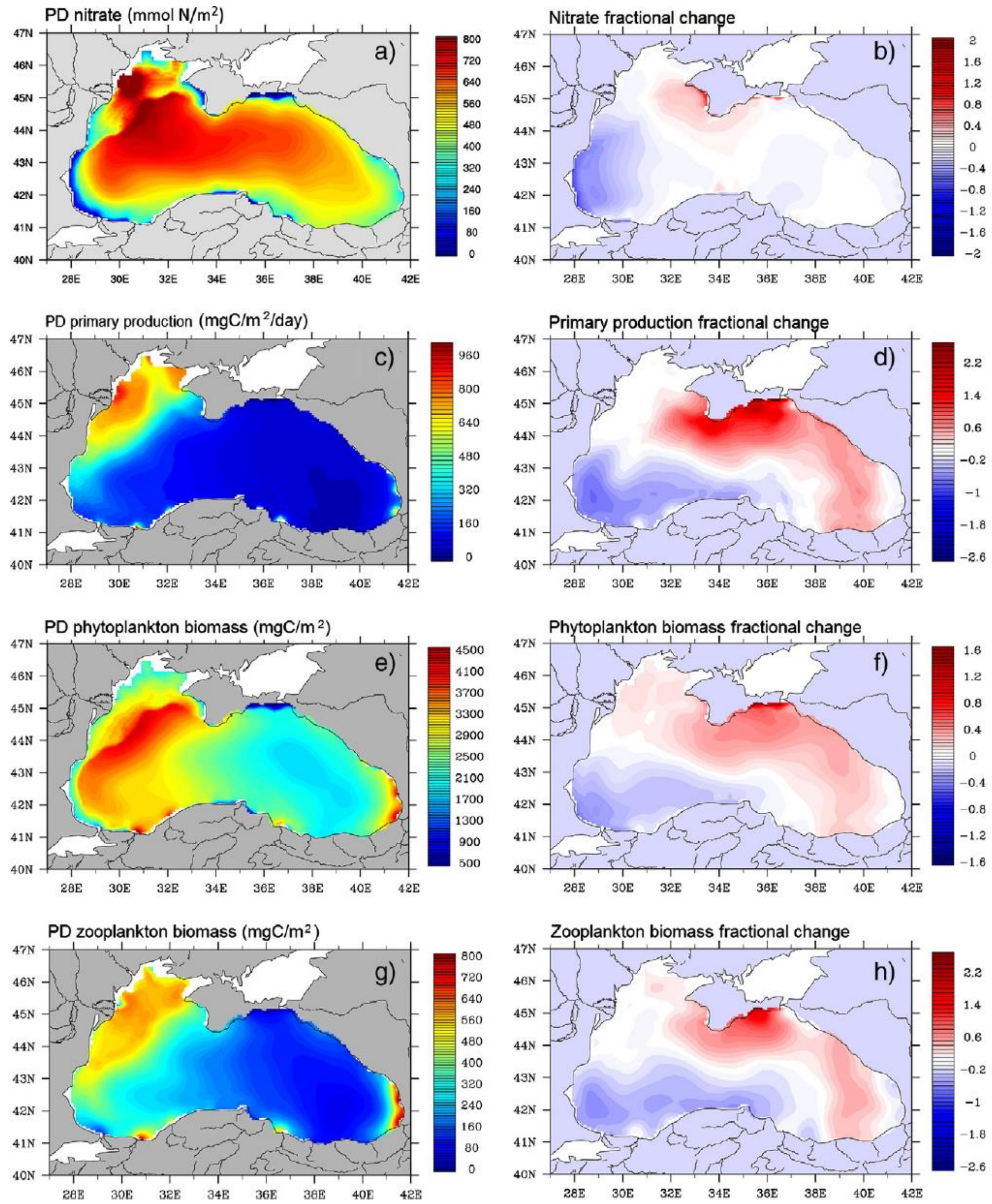

Fig. 12. PD mean concentration and fractional change [(A1B / PD) − 1] in depth integrated (a and b) nitrate concentration, (c and d) net primary production, (e and f) phytoplankton biomass, and (g and h) zooplankton biomass.

Figure 8 Low trophic levels (primary production, phyto-and zooplankton biomass) projections in the Black Sea (Cannaby et al., 2015)

Fish stock projections

Salihoglu and colleagues have forced an Ecopath with Ecosim (EwE) model with outputs from their coupled hydrodynamic-plankton model of Black Sea (BIMS) forced with IPCC AR4 climate simulation scenario A1B (Salihoglu et al., 2017) to project climate conditions 2015 to 2020 (at fishing mortality kept at F current in 2014), and their effect on fish stocks. The trends in the stocks are predicted to change in parallel with the changes in primary and secondary production (bottom-up effect).

Scenarios

Climate change

Most of the references indicate that environmental changes influence fish stocks in the Black Sea via changes in food production and trophic relationships. As the only available simulation framework is EwE, the main scenarios are built around simulated changes in primary production, and fishing mortality using the Black Sea EwE model. The change of primary production and phytoplankton biomass are extrapolated using the coefficients obtained in coupled models of Chust et al. (2014) and Cannaby et al. (2015) applied to SST projections from CMIPS 6 (RCPs 4.5 and 8.5[5]). Additional simulations can be run with altered production or biomass of the main commercial fish species, as well as with invasive ctenophores (*Mnemiopsis leidyi* and *Beroe ovata*), which might be affected by the climate change.

As effects of environmental variables and in particular SST seem to have been changing in recent years compared to historical data, a simple univariate regression analysis of recent SST vs total fish biomass data (1986-2016, Table 9) has been done. The regression coefficients would then be used to predict fish biomass from SST projections from CMIPS 6 (RCPs 4.5 and 8.5[6]). Statistically significant negative correlations are found between some fish biomasses and related fishing mortality coefficients when univariate regression analyses are run. Those biomasses are corrected for the effects of fishing (Table 10). Then regressions of corrected biomasses and SST are run to yield coefficient to be used in forward simulations.

Table 9 Results from univariate regression analyses of SST (predictor) to fish stocks (log transformed total biomass, dependent variable). Stocks marked in bold letters show statistically significant correlations with SST.

	Intercept	slope	r2	t	p	Data points
M. leidyi	**21.44**	**-1.56**	**0.38**	**-3.58**	**0.0018**	**23**
B. ovata	-10.53	0.28	0.3	1.73	0.1270	9
Sprat	**-7.76**	**0.36**	**0.41**	**4.47**	**0.0001**	**31**
Anchovy*	**-3.59**	**0.15**	**0.20**	**2.67**	**0.0123**	**31**
Horse mackerel*	-6.00	0.10	0.02	0.80	0.4289	28
Whiting*	-3.97	-0.03	0.01	-0.53	0.6004	31
Turbot	-6.99	-0.02	0.00	-0.33	0.7415	31
Dogfish	**19.91**	**-1.71**	**0.72**	**-8.59**	**0.0000**	**31**
Red mullet*	-6.33	-0.01	0.00	-0.07	0.9409	27
Bonito	-6.36	0.06	0.11	1.88	0.0701	31
Bluefish	**-2.47**	**-0.21**	**0.26**	**-3.15**	**0.0038**	**31**

* Stock biomass is corrected for effects of fishing

[5] https://cds.climate.copernicus.eu/cdsapp#!/dataset/10.24381/cds.d7eaec3d?tab=form
[6] https://cds.climate.copernicus.eu/cdsapp#!/dataset/10.24381/cds.d7eaec3d?tab=form

Table 10 Results from univariate regression analyses of fishing mortality (predictor) to total fish stock biomasses (dependent variable). Stocks in bold show statistically significant correlations

	Intercept	slope	r2	t	p	Data points
Sprat	-2.31	0.46	0.00	0.31	0.7624	31
Anchovy	-0.79	-2.23	0.25	-3.07	0.0046	31
Horse mackerel	-3.35	-2.27	0.29	-3.24	0.0033	28
Whiting	-3.57	-3.15	0.19	-2.65	0.0130	31
Turbot	-7.18	-0.18	0.02	-0.85	0.4004	31
Dogfish	-6.56	0.66	0.00	0.13	0.8981	31
Red mullet	-5.84	-1.36	0.32	-3.47	0.0019	27
Bonito	-5.49	0.22	0.07	1.50	0.1457	31
Bluefish	-5.77	0.08	0.00	0.16	0.8762	31

Shock effects: thermal wave

Short term (monthly) effect of temperature rise. Daily SST data-bases will be explored to search for frequency and amplitude of such events. An alternative value of thermal shock could also be the maximum SST predicted by RCP 8.5 in 2100. Effects on fish and producers are assumed the same as for the gradual change (though they might not be such in reality). Only the negative effects of increased SST will be simulated.

Fishing

All assessed Black Sea stocks except sprat are subject to overfishing (STECF 2017). In the simulations, fishing will be set at Fmsy and Fmsy lower.

Resilience

The resilience of the fish stocks will be assessed in terms of the size of the change in biomass of the main exploited stock and the time of occurrence of the biomass minimum of the stock affected by thermal shock (resistance). Recovery will be assessed by the time of recovery to the size of biomass prior to the shock (recovery time).

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Annex 4 : DEFINING PLAUSIBLE, ECOSYSTEM-COHERENT SHOCK SCENARIOS: CELTIC/IRISH SEA CASE STUDY

The Irish Sea case study uses an Ecopath with Ecosim (EwE) model of the Irish Sea to simulate the impacts of environmental shocks and climate forecasts on the systems resource (cod, whiting, haddock, plaice, sole, Nephrops) and ecological resilience.

The Irish Sea EwE model is a food web model originally designed to focus on the species of commercial importance within an ecosystem context as part of the ICES workshop on an ecosystem approach to fishery management for the Irish Sea (WKIrish; ICES 2015). The model includes Irish Sea fishing fleets which are defined by gear type and fishers' knowledge which was used to parameterize species interactions (Bentley et al., 2019a) and historic fishing effort trajectories (Bentley et al., 2019b). The model has been used to develop new approaches for indicator analysis (Bentley et al., 2019c), identify the environmental drivers underpinning commercial stock trends (Bentley et al., 2020), and provide a case-study for the use of ecosystem information to enhance single-stock catch advice (Bentley et al., 2021). The model has been approved as a key run by ICES and thus serves as a quality assured source for scientific input to ICES advice products (ICES 2019).

The Irish Sea EwE model will be used to deliver on aspects of Task 1 in relation to climate impacts on resilience and mitigation. Below are overviews of how the model will be used to simulate 1.1 Resource resilience and 1.2 Ecological resilience.

Resource resilience:

- The Irish Sea EwE model will be used to simulate species-level responses to short- and long-term climate driven stressors. Commercial species of interest include cod, whiting, haddock, plaice, sole, herring and Nephrops.
- EwE can account for climate uncertainty and alternate species-specific functional responses to temperature change. The list of scenarios to be tested are presented in Table 11.
- Resource resilience will be defined by the ability for fish stocks to remain above biomass limits and thresholds at which productivity is impaired (e.g., Blim, Bpa, Btrigger), and rebuild, in a timely manner, to levels that correspond to management targets.
- To measure the resilience of current management frameworks, a reference scenario will be defined without shocks, to define the state that the system is expected to return to after a shock. The reference scenario will be run with "perfect" management, i.e.,for F=FMSY based on FMSY as defined in the most recent single species advice.
- Biomass and catch performance metrics will be used to measure the impacts of long-term climate change and climate shocks on resource resilience (Table 12).
- Performance metrics from EwE will be compared to those derived from single species advice.

Ecological resilience:

- The Irish Sea EwE model will be used to simulate the biomass dynamics and trophic interactions across the Irish Sea food web, ranging from primary and secondary producers to endangered threatened and protected species such as sharks, seabirds, and marine mammals.
- The Irish Sea EwE model will be used to produce a suite of biodiversity indicators (Table 12) and simulate indicator performance under long-term climate change and climate shocks (Table 11).

- Scenario testing will be used to identify how best to maintain biodiverse ecosystems under fishing and climate scenarios.

Table 11 Baseline, long-term, and shock scenarios simulated using the Irish Sea ecosystem model

Scenario	Category	Name	Simulation end	Description
1	Baseline	Irish Sea under constant temperature	2030	Model simulated to 2030 under constant temperature from 2021.
2	Baseline	Irish Sea under RCP 4.5	2030	Model simulated until 2030 under SST trajectory from RCP 4.5. Temperature changes impact ecosystem through functional responses
3	Baseline	Irish Sea under RCP 8.5	2030	Model simulated until 2030 under SST trajectory from RCP 8.5. Temperature changes impact ecosystem through functional responses
4	Long-term	Irish Sea under constant temperature	2100	Model simulated to 2100 under constant temperature from 2021.
5	Long-term	Irish Sea under RCP 4.5 (long-term)	2100	Model simulated until 2100 under SST trajectory from RCP 4.5. Temperature changes impact ecosystem through functional responses
6	Long-term	Irish Sea under RCP 8.5 (long-term)	2100	Model simulated until 2100 under SST trajectory from RCP 8.5. Temperature changes impact ecosystem through functional responses
7	Shock	Cod recruitment decline	2030	Stock recruitment is reduced across a spectrum of values. This scenario has two runs: in the first run recruitment is reduced in 2021; in the second run recruitment is reduced in 2021 and 2022.
8	Shock	Whiting recruitment decline	2030	Stock recruitment is reduced across a spectrum of values. This scenario has two runs: in the first run recruitment is reduced in 2021; in the second run recruitment is reduced in 2021 and 2022.
9	Shock	Plaice recruitment decline	2030	Stock recruitment is reduced across a spectrum of values. This scenario has two runs: in the first run recruitment is reduced in 2021; in the second run recruitment is reduced in 2021 and 2022.
10	Shock	Haddock recruitment decline	2030	Stock recruitment is reduced across a spectrum of values. This scenario has two runs: in the first run recruitment is reduced in 2021; in the second run recruitment is reduced in 2021 and 2022.
11	Shock	Heatwave	2030	Temperature is increased across a spectrum of values and linked to species functional responses. This scenario has two runs: in the first run the temperature shock occurs in 2021; in the second

				run the temperature shock occurs in 2021 and 2022
12	Shock	Low productivity	2030	Primary productivity is reduced across a spectrum of values and linked to phytoplankton productivity. This scenario has two runs: in the first run the production shock occurs in 2021; in the second run the production shock occurs in 2021 and 2022
13	Shock	High productivity	2030	Primary productivity is increased across a spectrum of values and linked to phytoplankton productivity. This scenario has two runs: in the first run the production shock occurs in 2021; in the second run the production shock occurs in 2021 and 2022
14	Shock	Fishing effort increase	2030	Fishing effort is increased for each fleet across a spectrum of values. This scenario has two runs: in the first run the fishing shock occurs in 2021; in the second run the fishing shock occurs in 2021 and 2022

Table 12 Resource and ecological resilience performance metrics

Metric	Category	Name	Description
1	Resource resilience	Biomass	Time series of commercial stock biomass with comparisons relative to reference points
2	Resource resilience	Catch	Time series of commercial stock catches
3	Ecological resilience	Demersal-pelagic ratio	Bdemersals/Bpelagics
4	Ecological resilience	Kempton's Q	Biodiversity metric that expresses the biomass species diversity of functional groups in an ecosystem; $Q = S/\left[2log\left(\frac{R_2}{R_1}\right)\right]$
5	Ecological resilience	Mean trophic level of catch	NA
6	Ecological resilience	Mean trophic level of community	NA
Resistance			
Amplitude			Comparison between the indicator minimum level after the shock and its estimated initial level
Responsiveness			Number of years between the shock and the minimum level reached by the indicator
Risk			Probability of the indicator falling below a reference level

Resilience	
Recovery time	Number of years before the indicator reaches the level it would have had under the lack of a shock

Model set-up for environmental scenarios

The Ecosim component of the Irish Sea EwE model simulates the ecosystem from 1973 to 2017. The model has been calibrated against biomass and catch time series and is driven by multiple fishing and environmental drivers. Fishing fleet effort is driven by trends of fishing effort taken both from scientific data and fishers' knowledge. The recruitment trends of cod and whiting are driven by sea surface temperature and the natural mortality of large zooplankton (>2mm) is driven by the NAOw.

To access the impacts of long-term climate change, Ecosim will be projected forward under future temperature projections for two IPCC scenarios: RCP 4.5 and RCP 8.5 (Figure 9). These sea surface temperature (SST) forecasts for the Irish Sea were simulated using available IPCC model sets (42 models for RCP 4.5; 39 models for RCP 8.5). Data were extracted from http://climexp.knmi.nl/plot_atlas_form.py.

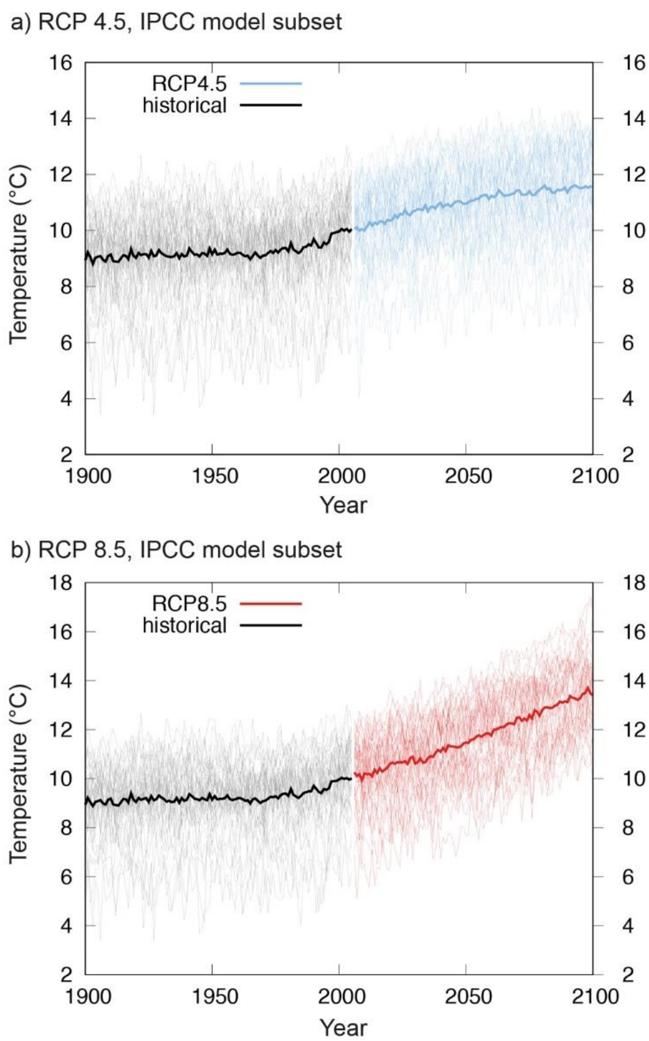

Figure 9 Irish Sea Surface Temperature (SST) forecasts under (a) RCP 4.5 and (b) RCP 8.5. Data were extracted from the IPCC model subset available at http://climexp.knmi.nl/plot_atlas_form.py

Temperature preference ranges were implemented to link environmental responses of functional groups in Ecosim to changes in temperature (see Bentley et al., 2017). Temperature tolerance ranges for functional groups were extracted from aquamaps (https://www.aquamaps.org/) (Figure 10). For multi-species functional groups, temperature tolerance ranges were weighted by the biomass each species contributed to the overall group. Tolerance ranges were entered as a trapezoid functions. Temperature functional responses impact the consumption rates of predators:

$$Q_{ij} = \frac{a_{ij} \times v_{ij} \times B_i \times P_j \times T_i \times T_j \times M_{ij}/D_j}{v_{ij} + v_{ij} \times T_i \times M_{ij} + a_{ij} \times M_{ij} \times P_i \times T_j/D_j} \times f\left(Env_{function}, t\right) \qquad (1)$$

where a_{ij} is the effective search rate for predator $j$feeding on a prey$i$, $v_{ij}$is vulnerability expressing the rate with which prey $i$move between being vulnerable and not-vulnerable, $B_i$is prey biomass, $P_j$is predator abundance, $T_i$represents prey relative feeding time, $T_j$is predator relative feeding time, $M_{ij}$is mediation forcing effects, and $D_j$represents handling time as a limit to consumption rate (Christensen et al., 2005, Ahrens et al., 2012). $f\left(Env_{function}, t\right)$ is the environmental response function that restricts the size of the foraging arena to account for external environmental drivers which change over time, such as temperature, salinity or ocean acidity.

The functional response imposes a multiplier on the consumption equation which can range from zero to one. Between a groups preferred minimum and preferred maximum temperature, consumption is multiplied by one, therefore temperature has no effect on consumption. As temperature moves away from a group's preferred range the multiplier moves towards zero, therefore reducing the consumption rate. At a group's upper and lower tolerance levels the multiplier is equal to zero and groups are unable to ingest energy and thus die.

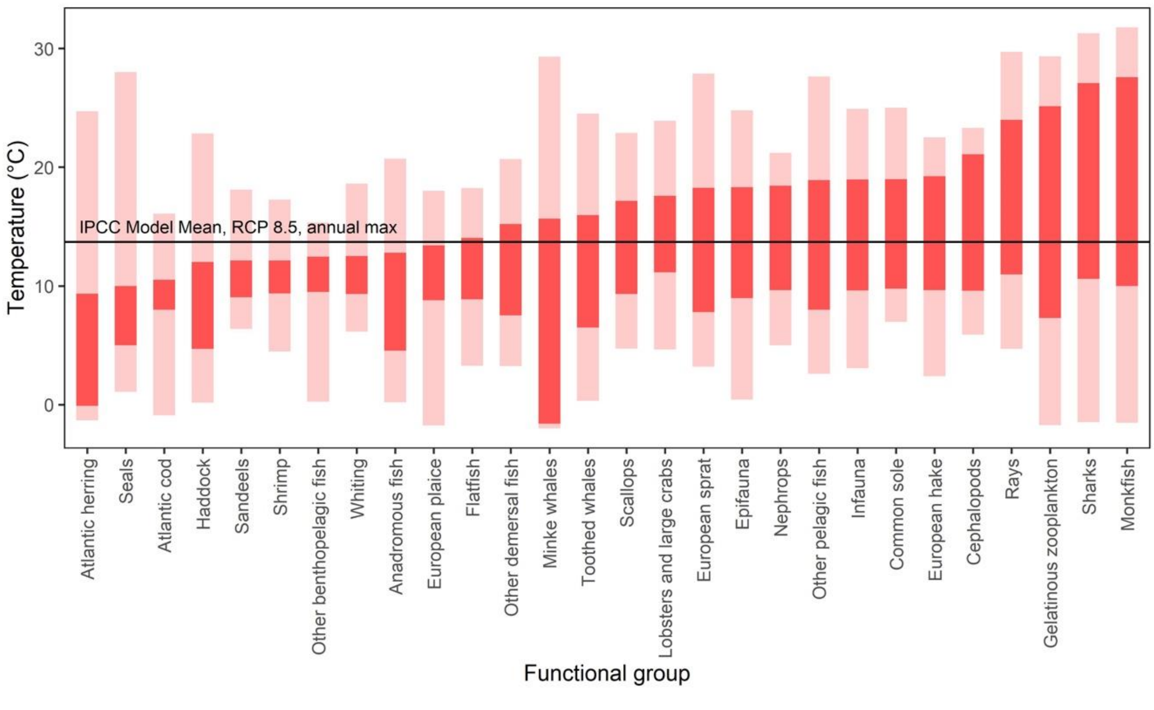

Figure 10 Temperature tolerance ranges for functional groups in the Irish Sea Ecosim model.

NB. Dark red areas reflect functional groups 'preferable range', within which temperature will not diminish group consumption rates. Faded red areas represent the extremes of each groups tolerance ranges, where consumption rates are negatively impacted in a linear fashion until consumption is equal to 0 at the minimum and maximum points of the tolerance range.

Using Multi-Sim to simulate shock scenarios

As opposed to running a single shock simulation, shocks will be simulated across a continuum to identify resource and ecological tipping points. For example, rather than running one heatwave scenario where the temperature has been increased by 2°C in 2021, multiple parallel simulations will be run where temperature is incrementally increased by 0.01°C in 2021. This would produce 200 simulations allowing us to identify at which point in the incremental shock increase do we find resilience is reduced (e.g., stocks fall below biomass limits or recovery time is detrimentally impacted). Multi-Sim is a plug-in for EwE, which allows testing a range of environmental forcing functions and collect the Ecosim results (Steenbeeket al., 2016).

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Annex 5 : DEFINING PLAUSIBLE, ECOSYSTEM-COHERENT SHOCK SCENARIOS: AEGEAN SEA CASE STUDY

We conducted a systematic literature review on the current knowledge about the linkages between the different components of European anchovy and sardine stock productivity and stock distribution in the Mediterranean (in particular in the Aegean Sea) with exogenous (environmental/climate) and endogenous factors, and the role of climate change as a driver of past changes. The literature review was conducted by surveying Scopus using the following two combinations of search criteria, the first aiming to identify relevant literature on the linkages between environment and stock biology, and the second aiming to identify literature on the role of climate change as a driver of past changes in anchovy and sardine stocks, and the effect of past short-term extreme events:

Search criteria 1: (TITLE-ABS-KEY ("Mediterranean Sea") AND TITLE-ABS-KEY (anchovy OR sardine OR "Sardina pilchardus" OR "Engraulis encrasicolus") AND TITLE-ABS-KEY (recruitment OR "larval survival" OR growth OR maturation OR "natural mortality" OR habitat OR "spatial distribution") AND TITLE-ABS-KEY ("environmental factor" OR "environmental effect" OR temperature OR plankton OR turbulence OR oxygen OR salinity OR transport OR "river runoff" OR eutrophication OR predation))

Search criteria 2: (TITLE-ABS-KEY (*"Mediterranean Sea"*) AND TITLE-ABS-KEY (*anchovy* OR *sardine* OR *"Sardina pilchardus"* OR *"Engraulis encrasicolus"*) AND TITLE-ABS-KEY (*trend* OR *regime* OR *"temporal shift"* OR *response* OR *anomaly* OR *failure* OR *decline*) AND TITLE-ABS-KEY (*recruitment* OR *productivity* OR *biomass* OR *abundance* OR *"fish stocks"* OR *"fishing opportunities"*) AND TITLE-ABS-KEY (*"climate change"* OR *"climate induced"* OR *"climate driven"* OR *"global warming"* OR *"sea warming"* OR *heatwave* OR *storms* OR *drivers* OR *extreme*))

From the first and second search criteria 95 and 13 documents came up respectively. In total, after removing duplicates, the combined two search criteria resulted in 100 documents. There was an initial screening of these results based on the title and abstract using the following criteria: (1) check that the content of the research corresponds to the keyword used (i.e., that the paper corresponds to the search criteria), and (2) check that the paper draws clear conclusions regarding the (existence or absence of the) relationship tested. After screening the titles/abstracts, 40 documents were kept for the review. At a following step, seven papers that were known to us but did not come up through the systematic search in Scopus were manually added. Furthermore, the reports of a number of research projects (RECLAIM, CERES, CLIMEFISH, PANDORA, futureMARES) and grey literature reports (ICES Report of the Working Group on Fish Distribution Shifts (WKFISHDISH), Rijnsdorp et al., 2010) that focused on the effect of climate change on fish stocks in the European waters were searched for additional information. Only a CERES report included related information for Mediterranean sardine and anchovy, and was also included in the review (for brevity Table 13 is provided at the end of this section).

Main findings

According to the review by Peck et al. (2021), the dynamics of small pelagics are largely defined by bottom-up factors. Specifically, short-term bottom-up processes impacting the dynamics of small pelagics in the Mediterranean include changes in riverine inputs, advection and eddies, salinity, temperature, and prey quantity and quality (Figure 1); changes in the strength of bottom-up control are associated with climate variability and climate change (e.g., Martín et al., 2011).

Large-scale climatic variability has been shown to affect small pelagic fish in the Mediterranean Sea (Stergiou et al., 2016; van Beveren et al., 2016; CERES 2018; Tsikliras et al., 2019), including the anchovy/sardine complex in the Greek Seas (Katara et al., 2011). Climate fluctuations and large climatic phenomena, such as the AMO (Atlantic Multidecadal Oscillation) and WeMO (Western Mediterranean Oscillation) have been linked to the landings of small pelagics in the Mediterranean (Stergiou et al., 2016 and references therein). Increase of sea temperature above an optimum has been reported to have a negative effect on individual growth; this optimum temperature for European anchovy larval growth has been identified at around 22 to 24oC (Peck et al., 2013), at 24.5oC for anchovy juveniles in the North Aegean Sea (Schismenou et al., 2014), and at 24oC for sardine juveniles in the North Aegean Sea (Schismenou et al., 2016) (Figure 11). Sea Surface Temperature (SST) has been also reported as a significant link between atmospheric and biological variability either because higher temperatures seem to be favouring sardine growth or because lower temperatures, characteristic of productivity-enhancing oceanic features, exert a positive influence on both species (Katara et al., 2011). Time-lagged effects show that environmental impacts on small pelagic fish are mainly felt through recruitment or growth with the subsequent effects this may have on population dynamics (Katara et al., 2011). However, even though Alheit et al. (2014) detected that during warm AMO the western Mediterranean anchovy landings tend to decrease, they argue that it is not primarily the temperature which drives the dynamics of the small pelagic fish populations and that climatic indices seem to be proxies for complex processes in the coupled atmosphere–ocean system. Adding to this, Saraux et al. (2019) explored several mechanisms that may have affected the observed shift in the late 2000s in the biomass and fish mean weight of anchovy and sardine in the Gulf of Lion and found that a dietary shift pre- and post-2008 and modelled mesozooplankton abundance was directly linked to fish condition. Temperature has a significant effect on anchovy growth, enhancing the growth of the youngest age classes but with a reduced effect on the growth in older individuals (Basilone et al., 2017).

Climate variability impacts the productivity and quality of fish habitats influencing the composition of plankton communities and the abundance of key plankton prey (Molinero et al., 2005); in a study examining several Mediterranean stocks, anchovy and sardine annual body condition and maximum size were strongly related to mean annual Eke (Eddy kinetic energy; measuring turbulence in cm2s-2) and chl-a respectively, instead of annual mean temperature, suggesting that their populations are affected through bottom-up control (Brosset et al., 2017). Queiros et al. (2019) experimentally showed that the reduced size of zooplankton (linked to higher temperatures in the western Mediterranean) can induce reduced growth and body condition in sardines. Maynou et al. (2014, 2020) attributed the reduction of egg and larvae of anchovy in the NW Mediterranean Sea to the increased stratification due to higher temperature regimes and the reduction of nutrients linked to the reduction of river runoff - both mechanisms decreased primary productivity and thus the abundance and quality of zooplanktonic prey. Reduced river runoff (Po river) and reduced wind-induced mixing have been related to reduced recruitment and the collapse of the anchovy stock in the Adriatic Sea in 1987 (Santojanni et al., 2006). The variability of larval growth and nutritional condition of sardine has been linked to the variability in abundance and composition of phyto- and zoo-planktonic communities driven by the variability of nutrients due to temporal changes in hydrological conditions (upwelling intensity) (Mercado et al., 2007; Vargas-Yáñez et al., 2020) . Patti et al. (2020) highlighted the importance of changes in surface circulation patterns as they control retention/dispersal processes of anchovy larval stages and largely define recruitment success and yearly biomass. Hydrological and regional atmospheric conditions may affect the distribution of nutrients and thus primary productivity, consequently affecting the productivity of small pelagics (Quattrocchi and Maynou 2017). Sardine is considered a more migratory species than anchovy and its more patchy distribution could be interpreted as a higher tendency to move in different coastal sectors searching for appropriate-sized food, leading such species to explore different environmental regimes (Bonanno et al., 2016).

In the Aegean Sea, model simulations revealed that mesozooplankton concentration is a key factor affecting the somatic condition of both anchovy and sardine (Gkanasos et al., 2019). The two species exhibit different spawning seasons and strategies. As anchovy spawns from spring to autumn and sardine from autumn to spring, and in the model anchovy is set to spawn when SST is above 15°C while sardine spawns only if SST <16°C (Gkanasos et al., 2019 and references therein), different effects may be observed depending on the seasonal patterns in mesozooplankton production. An increase in SST combined with decreased precipitation and river runoff may increase stratification and reduce productivity of the North Aegean waters, which may cause the substantial decline of the anchovy stock, as concluded through the combination of a POM-ERSEM Lower Trophic Model coupled to an anchovy full life cycle Individual Based Model (Triantafyllou et al., 2019). Further to the stratification, as the consumption by anchovy maximizes at an optimum temperature, whereas the respiration increases continuously with temperature, increased temperature alone results in a decrease of net fish somatic growth and associated egg production, while the increased energy needed to meet maintenance costs at warmer temperatures leads the early life stages to experience higher starvation mortalities (Triantafyllou et al., 2019). Furthermore, a substantial expansion of the suitable habitat of the invasive ctenophore *Mnemiopsis leidyi* in the North Aegean Sea is predicted due to climate change (Stergiou et al., 2016). This invasive species had caused the collapse of small pelagic stocks in the Black Sea in the 1980s and early 1990s (Katsanevakis et al., 2014). On the other hand, an end-to-end model (including a high-resolution regional climate model, a regional biogeochemistry model and a food web model OSMOSE) predicted a climate change driven increase of small sized (and a decrease or lower increase of large sized) phyto- and zooplankton groups at the Mediterranean level; consequently, the increased primary and secondary production benefits small pelagic species, the biomass of which is predicted to increase especially in the Eastern basin, including the Aegean Sea (Moullec e al. 2019).

Such strong contrasts in the projections, and the fact that the biomass of small pelagics is largely driven by primary productivity, suggests to consider abrupt changes in primary productivity (independent of the abiotic drivers) as the main driver of our ‘shock scenarios’ in the anchovy and sardine case study in the Aegean Sea. In addition, the predicted increase of the abundance of the invasive ctenophore *M. leidyi* and other jellyfish suggests to also consider the substantial increase of the ‘jellyfish trophic group’ as another shock scenario affecting small pelagics in the Aegean Sea.

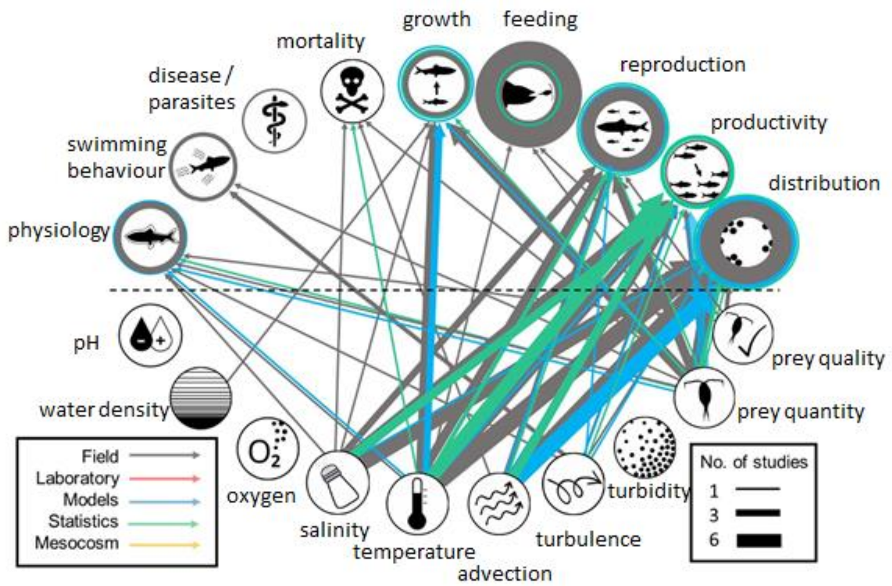

Figure 11 Papers published between 2001-2006 and 2011-2016 on European anchovy in the Mediterranean Sea.

NB. Ten categories of potential drivers are included below the dotted line, and nine categories of potential responses at individual or population level are included above the dotted line. The thickness of lines represents the number of studies and the color the type of studies. Adapted from Peck et al. (2021).

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Table 13 Summary of Aegean marine fish stocks, drivers, effects and impacts

Fish stock/fishery	Possible drivers	Possible effects	Possible impacts	Reference	Comments
Mediterranean anchovy	Physical mechanisms promoting (i) nutrient enrichment, (ii) concentration of larval food distributions, and (iii) local retention of eggs and larvae	Areas of the sea in which the three elements exist in mutually supportive configurations are sometimes referred to by the term 'ocean triads'	Favourable reproductive habitats	Agostini and Bakun, 2002	The paper refers to 5 subbasin scale 'ocean triads', in the Aegean Sea, the Gulf of Lions and nearby Catalan Coast, the Alboran Sea, the Straits of Sicily/Tunisian Coast, and the Adriatic Sea.
Mediterranean Sardine	Influence of environmental factors on juvenile sardines growth	Increased food abundance, resulting from coastal upwelling events, and calm sea weather conditions in the inshore bays (nursery areas) induced by northern and western winds enhance larval survival	Enhanced larval survival	Alemany et al., 2006	The paper refers to the West Mediterranean (Alboran Sea)
Mediterranean Sardine	Influence of environmental factors on juvenile sardines growth	Stormy conditions in coastal areas induced by Levantine winds modify spatial and temporal availability of food to fish larvae and thus negatively influence their feeding and growth	Reduced larval survival	Alemany et al., 2006	The paper refers to the West Mediterranean (Alboran Sea)
Mediterranean anchovy	warm AMO	changes in ocean circulation patterns and advection of water masses	anchovy landings tend to decrease	Alheit et al., 2014	The paper refers to the West Mediterranean
Mediterranean anchovy	Temperature increase	Water temperature was confirmed to be a determinant factor for anchovy growth at the species level positively affecting the length at age-1.	Temperature has a significant effect on anchovy growth. Global warming would be expected to enhance the growth of the youngest age classes but with a	Basilone et al., 2017	The paper refers to the Tyrrhenian Sea and the Strait of Sicily (Central Mediterranean)

			reduced effect on the growth in older individuals.		
Mediterranean anchovy	Sea surface temperature and chlorophyll-a concentration	A clear effect of environmental conditions, particularly of sea surface temperature and chlorophyll-a concentration, on the growth histories of juveniles of anchovy	Fishes born closer to the peak of the breeding season probably benefit from more favourable conditions for growth (such as temperature, food availability or photoperiod), than individuals born out of the reproduction peak	Basilone et al., 2018	The paper refers to the strait of Sicily (Central Mediterranean)
Mediterranean anchovy	Changes in hydrological conditions (upwelling)	Upwelling is associated with the enrichment of the upper layers linked to nutrient inputs from deeper waters	Environmental factors, particularly those associated with upwelling strength and zooplankton abundance, promoted anchovy growth and reproduction, whereas potential competitive factors associated with packing density were consistent drivers dampening it.	Basilone et al., 2020	The paper refers to the strait of Sicily (Central Mediterranean)
Mediterranean anchovy and sardine	Temperature increase	Climate change may be altering the composition and distribution of plankton species, as well as their importance in the food web, with higher temperatures favouring the smallest components of the plankton, thus strengthening microbial loop activity.	Variability in larval growth and nutritional condition	Biton-Porsmoguer et al., 2020	The paper refers to the West Mediterranean (northern Catalan Sea).

Mediterranean anchovy and sardine	The importance of riverine input in enhancing the productivity of some coastal areas	River runoff influences both the spawning and the survival rate of the early anchovy stages (mainly in spring-summer), which depend on food availability at the surface; food availability should be related to the nutrient content of surface water, which in late spring and summer depends on river runoff.	Enrichment, as a result of river runoff, positively influenced the habitat suitability of both anchovy and sardine.	Bonanno et al., 2016	The paper refers to the Tyrrhenian Sea (Central Mediterranean)
Mediterranean anchovy	Increase in mean annual Eke (Eddy kinetic energy)	No clear possible effect is derived; as anchovy is associated with eddies and local upwellings, the positive effect could be either due to suitable habitat expansion or increased prey	Positive effect on body condition and maximum size	Brosset et al., 2017	Results from several areas in the Mediterranean.
Mediterranean Sardine	Increase in annual mean chl-a	Increase in prey	Positive effect on body condition and maximum size	Brosset et al., 2017	Results from several areas in the Mediterranean
Mediterranean Sardine	Environmental factors affecting growth and condition of pilchard (surface temperature at 5 m (T5, °C), water stability index (Brunt-Väissälä, B-V, cycles h−1) and microzooplankton (T-N, ind. m−3),	A suite of favorable conditions could be broadly defined by T5 values < 19°C, B-V values < 0.8 cycles h−1 and mean N or T-N > 4500 ind.m−3 or > 5500 ind. m−3. Areas characterising the unfavorable environment, where condition was lower, would exhibit T5 values > 19°C, values of B-V ranging 0.81 to 1.7 cycles h−1 and potential food abundance below the aforementioned values.	Higher or Lower growth and condition	Catalan et al., 2006	The paper refers to the northwestern Mediterranean
Mediterranean anchovy	Temperature increase	European anchovy larvae in colder areas present faster growth rates in conditions characterised by a richer feeding environment	Increasing temperature trends in this area might not necessarily have a positive effect on anchovy populations	Catalan et al., 2010	The paper refers to the Aegean Sea (NE Mediterranean)

Mediterranean sardine	negative phase of the WeMOI, increasing water temperature or salinity	(not mentioned)	negative effects on small pelagics fisheries productivity	CERES 2018	The report refers to the West Mediterranean
Mediterranean anchovy	negative phase of the WeMOI, increasing water temperature or salinity	(not mentioned)	negative effects on small pelagics fisheries productivity	CERES 2018	The report refers to the West Mediterranean
Mediterranean anchovy and sardine	Temperature and salinity	Both fishing and environmentaldrivers, in addition to food web interactions, are necessary to pre-dict marine species distributions	Temperature and salinity had more modest impacts as factors conditioning the spatial and tem-poral distribution of hake, anchovy and sardine in the study area	Coll et al., 2016	The paper refers to the northwestern Mediterranean
Mediterranean anchovy and sardine	Temperature and salinity	Both fishing and environmentaldrivers, in addition to food web interactions, are necessary to pre-dict marine species distributions	Temperature and salinity had more modest impacts as factors conditioning the spatial and tem-poral distribution of hake, anchovy and sardine in the study area	Coll et al., 2016	The paper refers to the northwestern Mediterranean
Mediterranean anchovy and sardine	Sea surface temperature (SST) increase	Increase in SST that had either a positive impact on round sardinella or on gelatinous zooplankton abundance was the pressure that alone provided the most plausible insights into observed changes	A combination of various pressures, including an increase in SST, an increase of exploitation and changes to zooplankton also delivered results matching current observations	Coll et al., 2019	The paper refers to the northwestern Mediterranean
Mediterranean anchovy and sardine	Sea surface temperature (SST) increase	Increase in SST that had either a positive impact on round sardinella or on gelatinous zooplankton abundance was the pressure that alone provided the most plausible insights into observed changes	A combination of various pressures, including an increase in SST, an increase of exploitation and changes to zooplankton also delivered results matching current observations	Coll et al., 2019	The paper refers to the northwestern Mediterranean

Mediterranean anchovy	Changing hydro-meteorological conditions and food availability	River discharge enhances stratification and dominates the distribution and production of phytoplankton and zooplankton	There was no evidence for lower larval survival in areas, less influenced by the immediate river outflow plume, as a simple direct relationship between enhanced water column stability, improved feeding conditions and larval survival was not supported. A simple mechanistic relationship between wind speed and larval survival is not necessarily expected due to other non-linear interactions, such as predator/prey contact rates	Coombs et al., 2003	The paper refers to the northern Adriatic Sea (Central Mediterranean)
Mediterranean anchovy and sardine	Temperature	Cooler SST can be indicative of nutrient enrichment processes such as wind mixing, upwelling and river run-off, associated with fish favourable conditions.	Colder winters increasing primary production by the beginning of spring would result in higher anchovy landings the following year due to a better adult feeding and therefore an increasing in spawning intensity.	Fernández Corredor et al., 2021	Mediterranean Sea (review)
Mediterranean anchovy	Temperature	Temperature has a positive relationship with anchovy eggs. This is in accordance with the spawning season of anchovy, that begins with the increase of temperatures at mid/late spring and extends throughout the summer presence, abundance and growth. The effect of temperature is positive between 20 and 24 ◦C, but becames negative quickly at higher temperatures for both eggs and larvae. Regional differences for the effect of temperature are reported, with positive effects in the Gulf of Lions (García et al., 1998) and negative effects in the Spanish coast (García et al., 1998; Maynou et al., 2014).	Increasing temperatures lead to a more rapid egg development, but also to higher mortality rates. On adult anchovy presence and abundance and therefore, on catches, has found to be negative all over the Mediterranean basin.	Fernández Corredor et al., 2021	Mediterranean Sea (review)

Mediterranean sardine	Temperature	Sea temperature seems to affect the size attained at the end of the first year of life and has been found positive linear correlated with anchovy length at age-1 (Bacha et al., 2010; Basilone et al., 2017) and condition factor (Basilone et al., 2006).Cooler SST can be indicative of nutrient enrichment processes such as wind mixing, upwelling and river run-off, associated with fish favourable conditions.	For juveniles, daily growth was found to have a dome-shaped relationship with SST by Schismenou et al. (2016), with young sardine increasing their growth rates while rising temperatures up to an optimum temperature beyond which the growth is impaired. On adult sardine presence and abundance and therefore, on catches, has found to be negative all over the Mediterranean basin.	Fernández Corredor et al., 2021	Mediterranean Sea (review)
Mediterranean sardine	Temperature	Temperature settles the thermal limits of reproduction providing a physiological switch for the onset and the cessation of reproduction. However, within these limits the 'decision' of a female to remain or leave the spawning population, could be synergistically affected by other factors such as food availability. This switch-like role of temperature is further supported by its positive relationship with the prevalence of atresia which indicates that fecundity is down-regulated when habitat conditions tend to surpass the upper thermal limits of reproduction.	Indication of direct energy flow from phytoplankton filter-feeding to gonadal development and egg production, implying that besides capitalized energy sardine also uses current income for supporting reproduction.	Ganias, 2019	The paper refers to Greece (Eastern Mediterranean)

Mediterranean anchovy and sardine	Seasonal variability of the water column temperature and mesozooplankton concentration	Shifting the timing of the fishery ban affects the biomass of both species. Suitable timing (i.e., leading to the increase in average biomass) differs between anchovy (spring) and sardine (autumn). In both species, the most favorable closure period is the period of (and around) peak recruitment, as evidenced by the decline of mean fish weight in the population.	When protecting the recruiting fish prior and/or during the initial phase of their first spawning period population biomass is positively affected, clearly owing to the increased annual population fecundity. Due to the numerical dominance of recruit spawners in the population (>70% in both species), allowing a higher number of them to spawn results in the increase of egg production and the subsequent increase of population biomass.	Gkanasos et al., 2019	The paper refers to the North Aegean Sea (Eastern Mediterranean)
Mediterranean anchovy	Warmer temperature	Distribution in European waters spans from the Mediterranean Sea to the North Sea, and is expected to expand further north with global warming. An increase in temperature and food availability results in an increase in the instantaneous growth rate and maximum body size, respectively. When environmental conditions become severe, temperature may also limit the maximum size reached by anchovy at age 3−4, and food may limit growth rate over the full life cycle.	Averaging environmental forcing at the regional scale has the effect of smoothing the environment perceived by the fish; so does the use of a climatological forcing, which tends to increase the duration of the productive season and decrease its intensity. Survival under environmental seasonality and bioenergetics tradeoffs is far from a linear response. Besides, genetic adaptation is a constant background process that calls for parameter adjustment in model extrapolation across regions or across temporal regimes.	Huret et al., 2019	The paper refers to Eastern Mediterranean (North Aegean Sea), the Bay of Biscay and the North Sea
Mediterranean anchovy	Low SST	Increased ecosystem productivity	Time-lagged increase in landings	Katara et al., 2011	The paper refers to the Greek Seas
Mediterranean sardine	Low SST	Increased ecosystem productivity	Time-lagged increase in landings	Katara et al., 2011	The paper refers to the Greek Seas

Mediterranean anchovy and sardine	Influence of river runoff and wind mixing	River flow and wind were selected because they are known to enhance fertilization and local planktonic production, thus being crucial for the survival of fish larvae.	In the long term, landings of anchovy declined while those of sardine increased. The time lags obtained in the relationships stress the importance of river runoff and wind mixing for the early stages of anchovy and sardine, respectively, and their impact on recruitment.	Lloret et al., 2004	The paper refers to Ebre (Ebro) River delta (north-western Mediterranean)
Mediterranean anchovy	Incoming jet of Atlantic waters, which modulate the hydrographic features of the basin	The model predicts a substantial increase in horizontal water velocity and a negligible change in the associated biological production.	Reductions in anchovy stock, catches and revenues.	Macías et al., 2014	The paper refers to the Alboran Sea (SW Mediterranean)
Mediterranean anchovy and sardine	Climate fluctuations taking the Western Mediterranean Oscillation index (WeMOi) as an indicator of climate variability like sea surface temperature (SST) and river runoff	Link between climate fluctuations and sardine and anchovy production. Positive WeMOi values were significantly correlated with low SST, high river runoff and high LPUE, that is, with better-than-average recruitment of sardine and anchovy. Conversely, negative WeMOi values were associated with high SST, low river runoff and low LPUE. Negative WeMOi phases (such as that at the end of the analyzed period), environmental conditions are unfavourable for the overall biological productivity.	Decrease in survival, growth, condition and reproduction of sardine and anchovy during their life cycle.	Martín et al., 2012	The paper refers to the north-western Mediterranean
Mediterranean anchovy	Warmer temperature	Stronger stratification causing decreased primary productivity and zooplanktonic prey	Reduced spawning and recruitment	Maynou et al., 2014	the paper referes to the NW Mediterranean
Mediterranean anchovy	Warmer temperature	Stronger stratification causing decreased primary productivity and zooplanktonic prey	Reduced spawning and recruitment	Maynou et al., 2020	the paper referes to the NW Mediterranean

Mediterranean anchovy	Reduced river runoff (measured as increased salinity)	Decrease of nutrients and thus of primary productivity and zooplanktonic prey	Reduced spawning and recruitment	Maynou et al., 2020	the paper referes to the NW Mediterranean, a correlation between Rhone and Ebro rivers' discharge and anchovy recruitment has been documented
Mediterranean sardine	Changes in hydrological conditions (upwelling)	Variability in nutrients concentrations, and consequently changes in abundance and composition of phyto- and zoo-planktonic communities	Variability in larval growth and nutritional condition	Mercado et al., 2007	the paper refers to the NW Alboran Sea
Mediterranean anchovy	Temperature increase	Increased primary and secondary production	Stock Biomass increase	Moullec et al., 2019	Results at the Mediterranean level from an integrated modeling chain including a high-resolution regional climate model, a regional biogeochemistry model and a food web model OSMOSE model
Mediterranean sardine	Temperature increase	Increased primary and secondary production	Stock Biomass increase	Moullec et al., 2019	Results at the Mediterranean level from an integrated modeling chain including a high-resolution regional climate model, a regional biogeochemistry model and a food web model OSMOSE model
Mediterranean anchovy	Surface circulation patterns	Surface circulation patterns control retention/dispersal processes of larval stages and largely define recruitment success and yearly biomass	Low retention of larvae in favourable areas will lead to reduced recruitment	Patti et al., 2020	the paper refers to the strait of Sicily

Mediterranean anchovy	Regional atmospheric conditions (measured by the Western Mediterranean Oscillation Index)	Positive WeMOI is linked to increased river discharge, NW winds that push productive waters across the shelf, which are trapped in the mesoscale eddy structure, resulting to more productive waters, enhancing phyto- and zoo-plankton production. Conversely, negative WeMOI is linked to decreasing primary productivity.	Enhanced sardine production with positive WeMOI; reduced sardine production with negative WeMOI	Quattrocchi and Maynou 2017	the paper refers to the Catalan Sea
Mediterranean sardine	Warming temperature	Planktonic chains of smaller size are favoured, which negatively affects sardine growth	Reduced growth and body condition	Queiros et al., 2019	Experimental work on the effect of prey size on tyhe growth and body condition of sardines
Mediterranean anchovy	Combination of reduced river runoff and reduced wind-induced mixing	Decrease of nutrients and thus of primary productivity and zooplanktonic prey	Reduced recruitment (and collapse of the stock in 1987)	Santojanni et al., 2006	the paper refers to the Adriatic and the effect of the Po river
Mediterranean anchovy	Unidentified drivers causing changes in mesozooplankton	Changes in plankton communities	Decrease in body condition and size, slower growth	Saraux et al., 2019	the paper refers to the Gulf of Lions
Mediteranean sardine	Unidentified drivers causing changes in mesozooplankton	Changes in plankton communities	Decrease in body condition and size, slower growth, higher natural mortality, reduced life span	Saraux et al., 2019	the paper refers to the Gulf of Lions
Mediterranean anchovy	Warming temperature	Physiological effects on anchovy juveniles	Reduced growth when temperature increased above the optimum of 24.5 deg C	Schismenou et al., 2014	the paper refers to the North Aegean Sea
Mediterranean anchovy	Unidentified drivers causing changes in mesozooplankton quantity	Changes in mesozooplantkon concentration	Reduced growth of juvenile anchovy	Schismenou et al., 2014	the paper refers to the North Aegean Sea

Mediterranean sardine	Warming temperature	Physiological effects on sardine juveniles	Reduced growth when temperature increased above the optimum of 24 deg C	Schismenou et al., 2016	the paper refers to the North Aegean Sea
Mediterranean anchovy	Warming temperature and decrease in river discharge	Changes in essential habitats of pelagic species (shrinkage for anchovy, expansion for the invasive ctenophore Mnemiopsis leidyi), zooplankton decrease, modified metabolic rates	Reduced biomass	Stergiou et al., 2016	the paper reders to both the Aegean Sea and the entire Mediterranean
Mediterranean anchovy	Reduced river nutrient loads	reduced ecosystem productivity	Stock Biomass decrease	Triantafyllou et al., 2019	The paper refers to the North Aegean Sea
Mediterranean anchovy	Temperature increase	Increased stratification (favoured by an increase in salinity) leads to decreased mixing and reduced ecosystem productivity.	Stock Biomass decrease	Triantafyllou et al., 2019	The paper refers to the North Aegean Sea
Mediterranean anchovy	Temperature increase	consumption by anchovy maximizes at an optimum temperature, whereas the respiration increases continuously with temperature	decrease of net fish somatic growth and associated egg production	Triantafyllou et al., 2019	The paper refers to the North Aegean Sea
Mediterranean anchovy	Temperature increase	increased energy needed to meet maintenance costs at warmer temperatures	early life stages experience higher starvation mortalities	Triantafyllou et al., 2019	The paper refers to the North Aegean Sea
Mediterranean sardine	Warming temperature and decrease of upwelling	Reduced productivity and thus food availability	Reduced biomass and landings, reduced condition of spawners and thus reduced recruitment	Vargas-Yáñez et al., 2020	The paper refers to the Alboran Sea (SW Mediterranean)

Annex 6 : DEFINING PLAUSIBLE, ECOSYSTEM-COHERENT SHOCK SCENARIOS: ATLANTIC OCEAN CASE STUDY

Literature review on climate effects on tropical tuna and linkages with the environment.

Recruitment

Wu et al. (2020): The Atlantic Multidecadal Oscillation (AMO) was determined to be a driver of phytoplankton and zooplankton abundance Changes in marine environments caused by climate indices directly affected the distribution of YFT. Therefore variations across lower trophic levels are likely to affect recruitment, growth rates, mortality and abundances of YFT to a certain degree over varying periods.

Lehody (2003): In the Central and Western Pacific, recruitment of tropical tuna increases during El Niños, and there is a pronounced eastward displacement of those stocks. Albacore (Thunnus alalunga), a sub-tropical species, shows the opposite pattern of low recruitment during El Niños and high recruitment during La Niñas. El Niño events also affect the distribution of tuna stocks in the eastern Pacific and Indian Oceans—and perhaps most importantly, vulnerability to surface gears, such as purse seines (Marsac et al., 1998, Suárez-Sánchez et al., 2004).

Dell'Apa (2018): Rising Sea Surface Temperature (SST) in the Gulf of Mexico (GOM) can potentially increase habitat suitability for larvae of the more tropical skipjack tuna compared to larvae of more temperate species, such as bluefin tuna, and other similar tropical and subtropical species, such as yellowfin tuna, with a predicted expansion of both adult and larval habitat of skipjack tuna by 2090 (Muhling et al., 2015). This result is likely due to adult bluefin and yellowfin tuna avoiding warmer waters (> 30 °C), which can limit their cardiac capacity (Blank et al., 2002), favor overheating (Sharp and Vlymen, 1978) and metabolic stress (Block and Stevens, 2001; Teo et al., 2007b), although yellowfin were found to be less sensitive to SST changes compared to bluefin tuna (Teo and Block, 2010).

Dell'Apa (2018): In the Gulf of Mexico, increased frequency of more intense storms between June and September will likely affect survival of yellowfin tuna and billfish larvae, and will likely be less impacting for BFT larvae (spawning occurs between March and June).

There is good evidence that 'El Niño Southern Oscillation' (ENSO) events have an impact on the recruitment of tuna, their distribution, composition, and species abundances [Lehodey et al., 1997; Lumban-Gaol et al., 2002; White et al., 2004].

Growth

Lehody (2003): Changes in ocean temperature can have a large impact on the growth and survival of larval and early life stages of Albacore tuna.

Dell 'Apa (2018): Increased water temperature can directly (through higher oxygen demand for the biotic compartment within the water column) or indirectly (through the associated water column stratification) favor the transition to less oxygenated or hypoxic water conditions, which are also known to affect the survival and growth rate of yellowfin tuna larvae (Wexler et al., 2011)

Dell'Apa (2018): Changes in microturbulence might affect BFT and YFT larval feeding rate and growth (Kimura et al., 2004).

Distribution / migration

Erauskin (2019) : Over the historical period, suitable habitats 32 shifted poleward for 20 out of 22 tuna stocks, based on their gravity centre and/or one of 33 their distribution limits. Temperate tunas 37 (albacore, Atlantic bluefin and southern bluefin) and the tropical bigeye tuna are expected 38 to decline in the tropics and shift poleward. They estimate an habitat index as a combination of 5 environmental variables that could explain part of the abundance distribution of the adult tuna fish around the world:

- sea surface temperature (SST in ºC)
- sea surface salinity (SSS in PSU)
- sea surface height (SSH, in m)
- mixed layer depth (MLD, in m)
- phytoplankton (log(phyto) in log(mmol/m3))

Miller (2007): In 2003, 2004 and early 2005 yellowfin tuna catches increased substantially throughout the Western Indian Ocean. The Committee has explored two alternative hypotheses—both related, at least in part, to environmental variability: (1) an increase in abundance due to favorable conditions for recruitment; (2) an increase in catchability, perhaps due to changes in the depth of the thermocline and/or in the abundance and concentration of prey species that might have resulted in large aggregations of yellowfin at a depth easily accessible to surface gears.

Strong El Niños, such as the 1982–1983 event, result in a deeper thermocline in the tropical Pacific, suppressed upwelling, and declines in yellowfin tuna catches. However, the declines are typically followed by rapid rebounds, suggesting that a strong El Niño may cause temporary horizontal and vertical displacement of the stocks that reduce their accessibility to harvesters, but there is little evidence of lasting adverse impacts on abundance[19,23,24].

Mohri et al. (1996) Bigeye tuna distribution is better predicted by thermocline parameters, rather than by SST directly. Their study revealed that Bigeye tuna prefer to stay near, and usually below the thermocline.

Feeding

Stéquert and Marsac (1989) note that tuna are constantly swimming in search of food—in some circumstances needing to consume as much as 15% of their body weight per day. ‘‘As a result, the areas of tuna concentration are by no means casual, and migration takes place according to hydrological routes: in which each species finds the optimum environment for survival in every stage of its existence’’ (Stéquert and Marsac 1989, p. 67). In describing the basis for tuna migrations, Sharp [16, p. 384] notes that: ‘‘because they are so energy-consuming, they are dependent on ocean processes and features which promote the aggregation of the prey resources which they must find within finite time periods,or die. These are the fronts, thermoclines and productive shoal regions of the ocean.’’ Climate plays a large role in determining short-term, seasonal and multiyear patterns of variability in the location and productivity of these optimal tuna habitat zones.

Spawning

Reglero et al. (2014): The distributional range in tunas during the larval phase was related to temperature although temperature alone resulted in an overestimation of plausible spawning grounds. Intermediate intensity mesoscale processes (ocean triad hypothesis) were also found to be an important factor in global larval distribution patterns. A combination of the 2 hypotheses (areas delineated both by temperature >20°C and with an intermediate EKE) provided the greatest explanatory power for most larval distributions. The mechanisms linking larval development and survival in relation to the 2 variables (SST and EKE) remain speculative, but likely are related to the speed of development, larval retention and locally enhanced productivity.

Scenario formulation

Environment: Predictions from global climate models indicate that temperature/Mixed Layer Depth/ Productivity/Salinity and Phytoplankton are the most important parameters structuring fish stocks.

Erauskin et al. (2019): Projections of oceanographic variables for the reference period (1980-1999), mid (2040-2059) and the end-of-the-21st-century (2080-2099) were extracted from the average of 16 IPCC AR5 (Fifth Assessment Report of the Intergovernmental Panel on Climate Change) models that contain a biological module (hereinafter Ensemble) with a mean ~1º spatial resolution (Cabré et al., 2014). The highest-carbon-emission scenario (RCP8.5 with 936 CO2 ppm by the end-of-the-century) of the IPCC AR5 (IPCC (2013)). By the end-of-the-century, this scenario projects global average increase of temperature and SSH (2.23ºC and 0.16 m, respectively), and decrease of MLD, SSS and phytoplankton (18.7 m, 0.24 psu and 0.16 mmol/m3, respectively).

Atlantic Meridional Overturning Circulation

Dell A'pa (2018): Temperature and Atlantic Merdional Overturning Circulation (AMOC): Future projections based on global climate models indicated that ocean temperatures in the North Atlantic will experience an increase of~2 °C by the end of the 21st century, with a simultaneous 25% reduction in the strength of the Atlantic Meridional Overturning Circulation (AMOC) (Liu et al., 2012). The AMOC is the primary ocean circulation system in the Atlantic Ocean, contributing to the flow of warm, higher salinity water in the upper layers of the water column and associated heat transport from the South Atlantic and tropical North Atlantic to the subpolar and polar North Atlantic (Schmittner et al.,2005).

Storms and hurricanes

Dell'Apa (2018): According to the most recent climate models, global average tropical cyclones intensity is expected to increase by 2–11% while frequency is expected to decrease by 6–34% (Knutson et al., 2010). This means that the frequency of more intense and damaging tropical storms and hurricanes is projected to increase globally (Biasutti et al., 2012).

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Annex 7 : DEFINING PLAUSIBLE, ECOSYSTEM-COHERENT SHOCK SCENARIOS: WESTERN MEDITERRANEAN CASE STUDY

Environmental impacts on demersal resources in the Mediterranean Sea involves the combination of both large and short scale drivers that can have very different and even contrasting, impacts on the same species in contiguous areas. Some examples are illustrated below. It is also worth noting that although this review is of the Western Mediterranean in general, the species and management units included in this project as case studies are the European hake (*M. merluccius*) of the Balearic Islands (GSA 5) and the red mullet (*M. barbatus*) of the Northern Spain (GSA 6).

Recruitment

Hake

Massutí et al. (2008): Years with high convection and anomalous strong formation of intermediate waters in the Gulf of Lion, forced by winter wind-driven vertical mixing (known as the 'IDEA index', Monserrat et al., 2008), increase the flux of nutrient-rich waters flowing southwards and the general biological productivity of the Balearic sea (Balbín et al., 2013), which in turn favours hake recruitment in the Balearic Islands.

Hidalgo et al. (2019a): This hydroclimatic process has a geographic gradient, with an opposed effect if the aforementioned convection in the recruitment indices in the Balearic Islands and the Gulf of Lions with no effect in the region in-between. This study also showed that recruitment variability in the Northern Spain area with the main nursery off the Ebro delta is related to the interannual variability of the retention success (i.e., self-recruitment) off the Catalan coast.

Red Mullet

Karametsidis et al. (in review): Recruitment success (i.e., recruitment/SSB) is negatively related to the size of adults and positively influenced by juvenile growth.

Juvenile survival

Hake

Hidalgo et al. (2019b): This study showed the survival from age 0 to 1 (and eventually related to natural mortality at age 1) was negatively related to growth between these two age classes, as well as to the mean length of juveniles (age 1), while the influence of mean size or recruits (age 0) was positive.

Red mullet

Karametsidis et al. (in review): The same pattern was shown, as described for hake above, for survival from age 1 to 2. The study showed a negative effect of growth and a positive effect of mean size of age 1. The same study also detected a strong environmental effect on survival from juveniles to adults (from age 2 to 3) with a negative effect of a winter local climatic index (a multivariate index calculated with surface hydroclimatic conditions). Negative values of this index in winter are associated with higher temperatures, higher atmospheric sea level pressure and positive values with higher precipitation rates. This is consistent with studies on red mullet in other areas showing that showed a positive influence by increased SST anomalies (Levi et al., 2003).

Growth

Hake

Karametsidis et al. (in review): There is a direct influence of the environmental scenario triggered in the Western Mediterranean by the degree of winter convection in the Gulf of Lions area on somatic growth of hake recruits in off Northern Spain. This implies that years with higher convection, and anomalously strong formation of intermediate waters in the Gulf of Lion forced by winter wind-driven vertical mixing (Monserrat et al., 2008, Balbí et al., 2014), will trigger a reduction in growth.

Red mullet

Karametsidis et al. (in review): In the case of juvenile growth (from age 1 to 2) a similar pattern was observed as described above for hake, although the effect was weaker. In the case of the growth of young adults (from age 2 to 3), the same negative effect was observed with the local climatic index calculated for spring.

Distribution: The distribution of the two species is generally dependent on bathymetry and geography.

Hake

Druon et al. (2015), Tugores et al. (2018) and Paradinas et al. (2021) reported that the most persistent areas off Northern Spain are associated with the deep continental shelf and upper slope off the Ebro delta, which are the main nursery areas of this species while its occurrence is generally broad in the whole Mediterranean basin. In the Balearic Islands, the two main areas of high concentration of juveniles of this species is also highly persistent in the north and the south off Mallorca Island. All these studies were related to recruits and juveniles.

Red mullet

Paradinas et al. (2020, 2021): These studies revealed small-scale distribution hotspots that, given the season of the survey, are related to the spawning season. These areas are off the Catalan coast, the Ebro delta, and close to Palos cape.

Feeding

There is no long-term dependence reported on diet for any of these species.

Hake

Cartes et al. (2009), Ferraton et al. (2008) and many others have described the trophic ecology of hake reporting ontogenetic changes of diets. All the authors agree on the existence of three general phases based on the composition of the diet: (i) crustacean diet (small recruits), (ii) mixed diet (crustacean and fishes) phase which can begin at sizes between 14 and 18 cm depending on the area, and (iii) mainly ichthyophagous diet in individuals larger than 22-25 cm, although in some areas decapods are also included in the diet of adults. Lloret-Lloret at al (2020) reported that, on a seasonal scale, these diet changes can affect the spatial distribution of the species.

Red mullet

Butista-Vega et al. (2008): It feeds on sub-surface deposit-feeding polychaetes, carnivorous polychaetes, shrimps and brachyurans. It also shows a clear size-related shift in diet, with an increase in polychaete and shrimp consumption with size and a decrease in small crustacean consumption.

Spawning

There is no long-term dependence reported and/or environmental influence affecting spawning onset or spawning habitats for these two species.

Hake

Recasens et al. (2008) described the spawning process in the western Mediterranean which is mainly associated with autumn. It is worth noticing that the spawning stock it is generally considered safe guarded in the area (except for the Catalan coast and Gulf of Lions) due to the lack of a target fishery on large individuals, which generally known as 'spawning refugia' (Caddy 2015).

Red mullet

Tsikliras et al. (2010): In this review, the authors show that spawning season is very consistent in summer across the whole Mediterranean, with no evidence of environmental drivers affecting spawning of the species (Lloret et al., 2007, Ferrer-Maza et al., 2015).

Scenario formulation and implementation

Environmental scenarios

Sea surface temperatures (long term, simulations will be run over 50 years) using copernicus projections and the North Western Winter convection (short term; interannual variation of a given environmental variable)

Scenario implementation Hake in the GSA 5 - Long-term changes (Simulations will be run over 50 years). Recruitment variability (corresponding to the high productive scenario as a consequence of winter deep convection)

Red mullet in the GSA 6 - The potential process to implement are:

- Mortality at age: i) Size-dependent (mean length at age 1) variation of M (from age 1 to 2), and ii) long-term influence of SST on survival from age 2 to age 3
- Growth: i) long-term influence of SST on growth and ii) a negative influence of convection.
- Maturity: not climate-related and no link to growth.
- Recruitment: Negative influence of the mean length of spawners age 3 and positive effect of growth variability. No evidence of climate influence.

Annex 8 BALTIC SEA FISHERIES - EASTERN BALTIC COD, CENTRAL BALTIC HERRING AND BALTIC SPRAT - GADGET MULTISPECIES MULTI FLEET MODEL

BALTIC SEA MULTISPECIES MODEL

While a large part of fisheries management still involves tactical decisions, arguably it is the medium- and long-term implications of such decisions that matter in terms of human impacts on ecosystems' structure, function, and resilience (Francis et al., 2007) the sustainability of fisheries. From a long-term perspective, it is increasingly evident that fisheries management has to consider climate forcing on recruitment and species interactions in order to achieve optimal resource utilization and conservation (Koster et al. 2005).

A Multispecies age-length based model is used to reconstruct the population dynamics of the Eastern Baltic cod (cod.27.24-32; SD 24-32), Baltic sprat (spr.27.22-32; SD 22-32) and Central Baltic herring (her.27.25-2932; SD 25-27,28.2,29,32) stocks (hereafter referred as cod, herring and sprat).

The model is built using the statistical multispecies modelling framework Gadget (www.hafro.is/gadget, Begley, 2017) and it has a particular focus to reconstruct the dynamics of these three stocks while explicitly accounting for predation mortality caused by cod on the clupeids. The model used in this simulation study is an extension of the model presented at WGSAM (ICES 2019a), which was already extending the model initially presented by Kulatska et al. (2019).

The model is quarterly based (Figure 12), single area and multifleets, with an active (bottom trawlers) and a passive (gillnetters) fleet targeting cod, and a pelagic fleet targeting herring and sprat independently from each other. Fishing and natural mortality occur in all time steps. Recruits enter the model once a year in a specified quarter. One or more scientific surveys sample the stocks at different times of the year, providing information on abundance and age-length compositions.

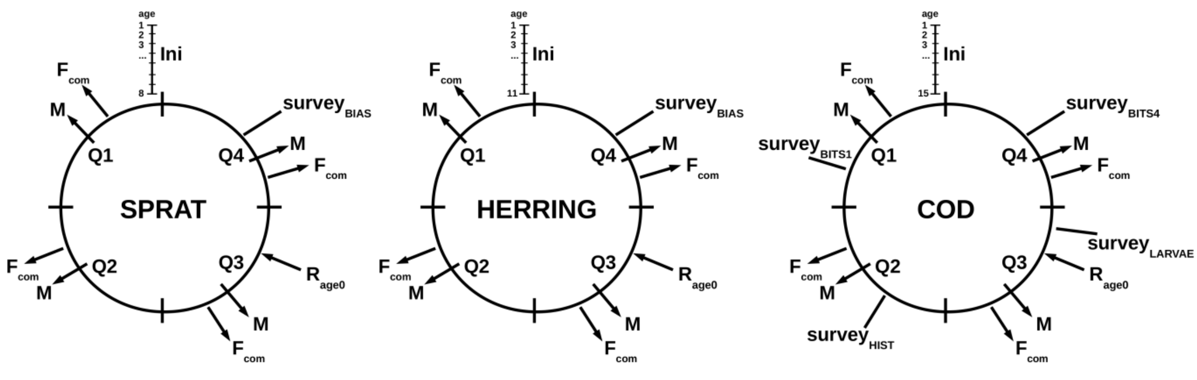


Figure 12 Schematic of the sprat, herring and cod conceptual models with the order of calculation of the main events in stock during one year. Q1-4 are the four quarters, Ini is the age composition at initial condition, F_{com} represent removal of fish by commercial fishing, M is the loss of fish due to natural mortality, R_{age0} is recruitment, $survey_x$ are the different surveys. Within each quarter, the order of calculation of the model is respected. The arrows represent outcome and income of fish from the modelled population due to different processes.

The model is parametrised over the period 1974-2018 using multiple data on the cod, herring and sprat stocks. Datasets include information on catch biomasses harvested by the fisheries involved in the exploitation of the three stocks, information on the age and size composition of the commercial catches, indices of abundance derived from scientific surveys, information on the age and size composition of the stocks from the surveys, biological data (mainly from surveys) and stomach data. All the data used for the model are compiled based on publicly available data retrieved from the ICES database or provided by dedicated ICES working groups. An overview of the data applied in the model is provided in Table 14, and more details can be found in ICES 2019a.

The present fish model is an extension of the model presented at WGSAM (ICES 2019a). Main differences include:

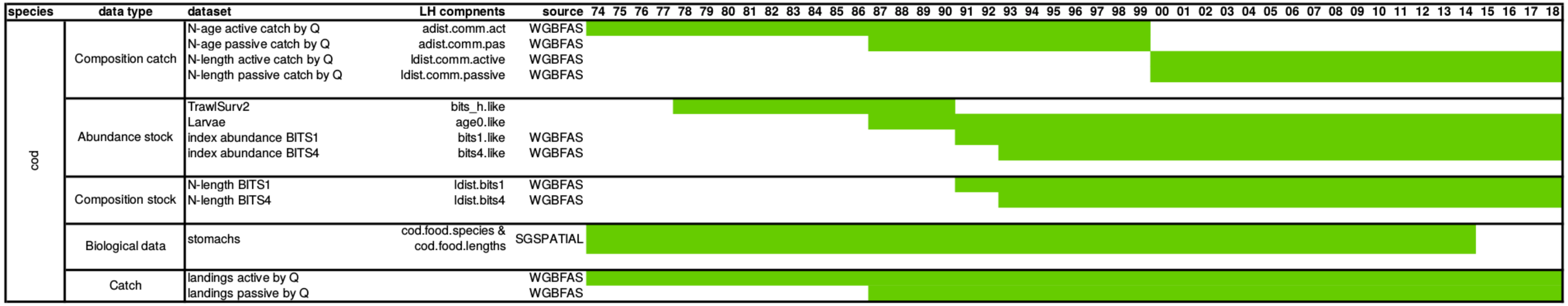
- discrete representation of the immature and mature components of the fish stocks linked via explicit maturity ogives based on age for herring and sprat and on length for cod
- recoding into the mfdb-Rgadget framework (https://github.com/gadget-framework, Elvarsson 2015, Lentin 2014) for easier forecasts

The Gadget model provides estimates of the dynamics of the stock which are generally consistent with the current ICES single-species stock assessments (Figure 13). The SSB values are closer to the ICES assessment for herring, followed by sprat. Correlation is also good for cod but the Gadget model estimates a consistently larger SSB. The model captures the peak accurately in the cod spawning stock biomass estimated in 1984 followed by a crash with a record low in 1992. From that point onward cod fluctuated around a low productivity regime. The model also estimates the well documented major increase in the sprat stock during the 1990s and the steady decrease of herring followed during a period of three decades which brought the herring stock to a minimum in the first 2000s.

Table 14 Summary table with the main datasets available (grey) and used (green) by the model, the source, time span and name of the model likelihood component for those datasets directly fitted by the model (from ICES 2019a).

species	data type	dataset	LH compnents	source	74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18
sprat	Composition catch	N-age catch by Q	spr.adist.comm2	WGBFAS	
		N-age catch by year	spr.adist.comm1	WGBFAS	
		W-age catch by Q	spr.wgtAtAge.comm	SMS	
			spr.wgtAtAge.comm	WGBFAS	
	Abundance stock	indices abundance by age BIAS	spr.bias.a1-8.like	WGBFAS	
		index abundance by rect BIAS		WGBIFS	
		recruitment index BIAS	spr.bias.a0.like	WGBFAS	
	Composition stock	N-length BIAS	spr.ldist.bias	countries	
	Biological data	ALK BIAS	spr.alk.bias	countries	
	Catch	landings by Q		SMS	
				WGBFAS	

species	data type	dataset	LH compnents	source	74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18
herring	Composition catch	N-age catch by Q	her.adist.comm2	WGBFAS	
		N-age catch by year	her.adist.comm1	WGBFAS	
		W-age catch by Q	her.wgtAtAge.comm	SMS	
			her.wgtAtAge.comm	WGBFAS	
	Abundance stock	indices abundance by age BIAS	her.bias.a0-8.like	WGBFAS	
		index abundance by rect BIAS		WGBIFS	
	Composition stock	N-length BIAS	her.ldist.bias	countries	
	Biological data	ALK BIAS	her.alk.bias	countries	
	Catch	landings by Q		SMS	
				WGBFAS	


species
data type
dataset
LH compnents
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74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18
cod
Composition catch
N-age active catch by Q
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N-age passive catch by Q
adist.comm.pas
WGBFAS
N-length active catch by Q
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WGBFAS
N-length passive catch by Q
ldist.comm.passive
WGBFAS
Abundance stock
TrawlSurv2
bits_h.like
Larvae
age0.like
index abundance BITS1
bits1.like
WGBFAS
index abundance BITS4
bits4.like
WGBFAS
Composition stock
N-length BITS1
ldist.bits1
WGBFAS
N-length BITS4
ldist.bits4
WGBFAS
Biological data
stomachs
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SGSPATIAL
Catch
landings active by Q
WGBFAS
landings passive by Q
WGBFAS

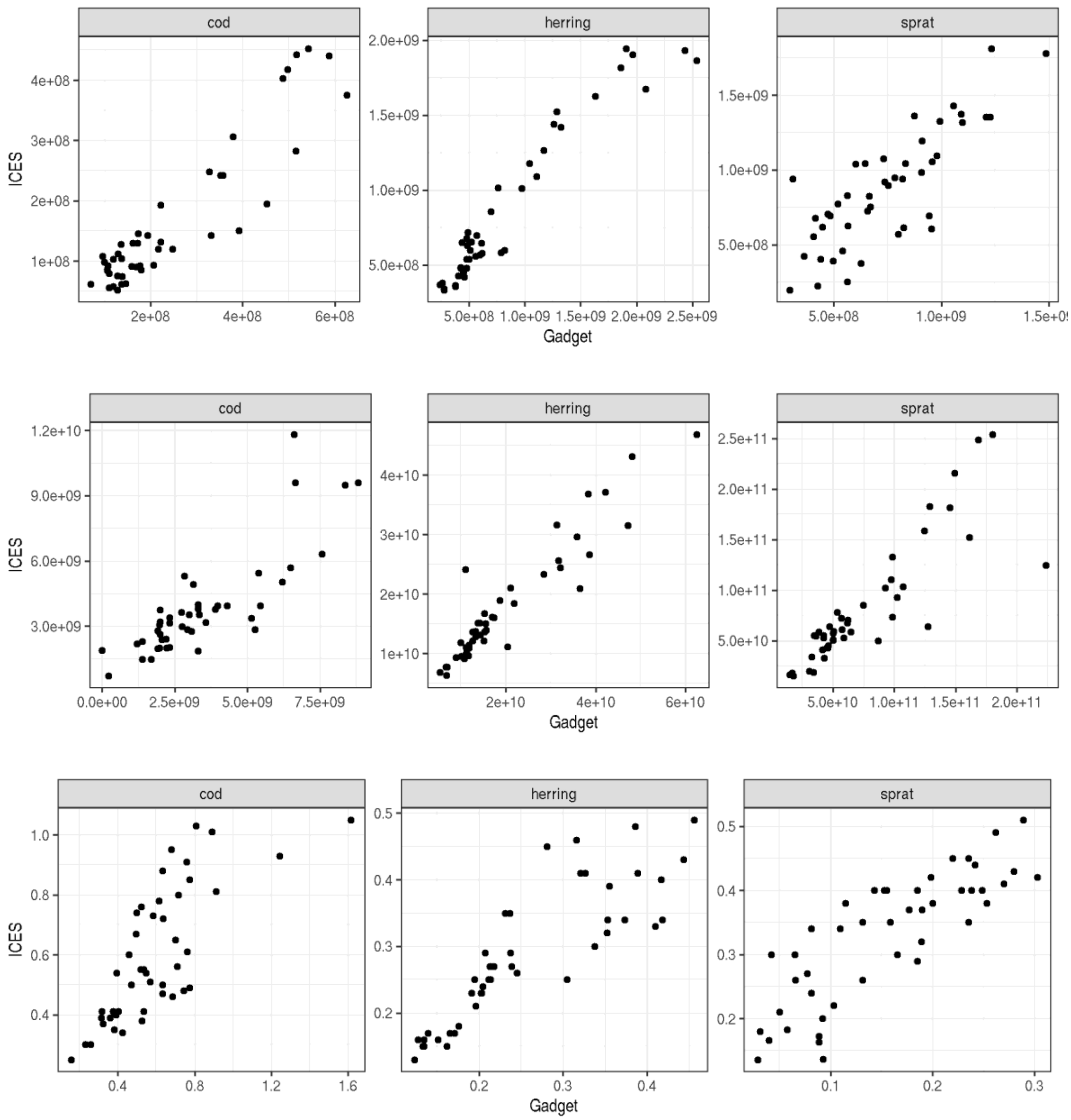


Figure 13 Comparison of SSB (top), Fbar (middle) and Recruitment (bottom) estimated by the Gadget multispecies fish model and the most recent ICES single species assessments (ICES, 2021a,b,c).

SETTING MODEL SIMULATIONS

The terminal year of the multispecies model is 2018. Environmental forcing and testing of different scenarios start in 2020. Year 2019 is treated as an intermediate year with catches and recruitment fixed based on values from the ICES assessments. The assessment estimates of recruitment are scaled to the multispecies model by a linear relationship between the ICES and gadget estimates of recruitment. In the case of sprat and herring an extra step is involved because recruitment is estimated at age1 in the assessment and at age0 in Gadget.

The simulations are forced by:

- Recruitment
- Biological characteristics of the stocks, including maturity, growth and condition
- Natural mortality that in the case of herring and sprat will emerge in part from the dynamics of the predator-prey stocks
- Fishery exploitation levels and selection pattern

Uncertainty on the projected stock trajectories under the different climate scenarios was represented in two main ways: (1) as structural uncertainty in the climate projections and (2) as stochastic deviations of recruitment from a segmented stock-recruitment relationship with an environmental driver (Table 15).

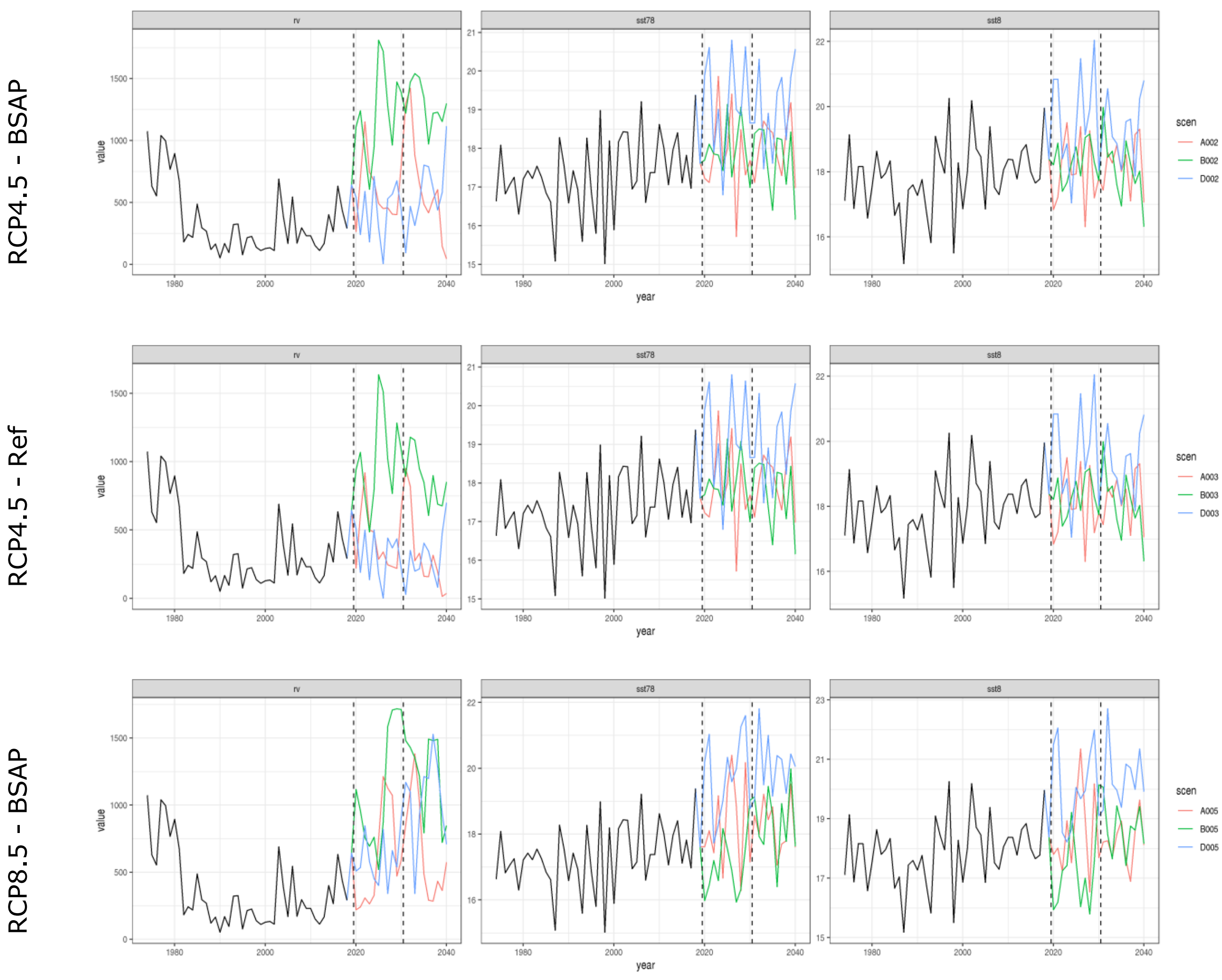
Table 15 Assumptions for long-term changes in fish stocks linked to climate/nutrient scenarios

stock	Biological function	change	Magnitude of the change	
			Most likely scenario	Worst case scenario
cod	Recruitment	Effect of reproductive volume (RV) defined by levels of salinity and oxygen on recruitment success. S-R hockey-stick with deviations linked to RV	RV from the main spawning areas of the stock (SD25,26,28.2) linked to RCP4.5 and BSAP nutrient scenarios	RV from the main spawning areas of the stock (SD25,26,28.2) linked to RCP8.5 and reference nutrient scenarios
	Growth/Condition	Not explicit climate effect but growth at its record low in recent years. von Bertalanffy parameters from the last year of the model (k=0.210682 and Linf=54.3636). Length-weight ($W=\alpha L^{\beta}$) with α= 3.0169 and β = 8.54e-06 for the last period.	Same all scenarios	
	Maturity	No explicit climate effect but maturity at length followed a long-term decrease. L_{50} assumed to remain low as in the recent period. Maturity ogive from the last four years of the model (L_{50} = 21 cm)	Same all scenarios	

stock	Biological function	change	Magnitude of the change	
			Most likely scenario	Worst case scenario
Herring	Recruitment	Effect of sea-surface temperature in August (SST8) on recruitment success. S-R hockey-stick with deviations linked to SST8	SST8 over the entire distribution of the stock (SD25-29, excl. GoR) linked to RCP4.5. Nutrient scenario not relevant for the sea-surface temperature but indirectly via cod predation	SST8 over the entire distribution of the stock (SD25-29, excl. GoR) linked to RCP8.5. Nutrient scenario not relevant for the sea-surface temperature but indirectly via cod predation
	Growth/Condition	Not explicit climate effect but weight-at-age remained low since mid 1990s and it is assumed to stay as such in the projections. Implemented in the model via length-weight ($W=\alpha L^{\beta}$) with β = 5.43e-06 for the last period.	Same all scenarios	
	Predation	Dynamic cod predation	Emergent from each scenario	
Sprat	Recruitment	Effect of sea-surface temperature in July-August (SST78) on recruitment success. S-R hockey-stick with deviations linked to SST8	SST78 in the core of the distribution (SD25-29) linked to RCP4.5. Nutrient scenario not relevant for the sea-surface temperature but indirectly via cod predation	SST78 in the core of the distribution (SD25-29) linked to RCP8.5. Nutrient scenario not relevant for the sea-surface temperature but indirectly via cod predation
	Growth/Condition	Not explicit climate effect but weight-at-age remained low since mid-1990s and it is assumed to stay as such in the projections. Implemented in the model via length-weight ($W=\alpha L^{\beta}$) with β = 8.999465e-06 for the last period	Same all scenarios	
	Predation	Dynamic cod predation	Emergent from each scenario	

Plausible, ecosystem coherent climate scenarios

Reanalysis of observations (until 2019) and projections forced by different climate models and warming regimes were available from Copernicus Marine Environment Monitoring Service and SMHI, respectively. Cod reproductive volume and Summer sea-surface temperatures (sst78 and sst8) were calculated from these hydrographic products to force the fish dynamics (Figure 14). Extraction of these different hydrographic drivers of fish dynamics across different scenarios from the same biogeochemical model (i.e., RCO-SCBI, see T1.1 for more details) provides coherence in the projected physical and biological environment used in this study. Uncertainty on future climate projections is incorporated by the use of three climate models.



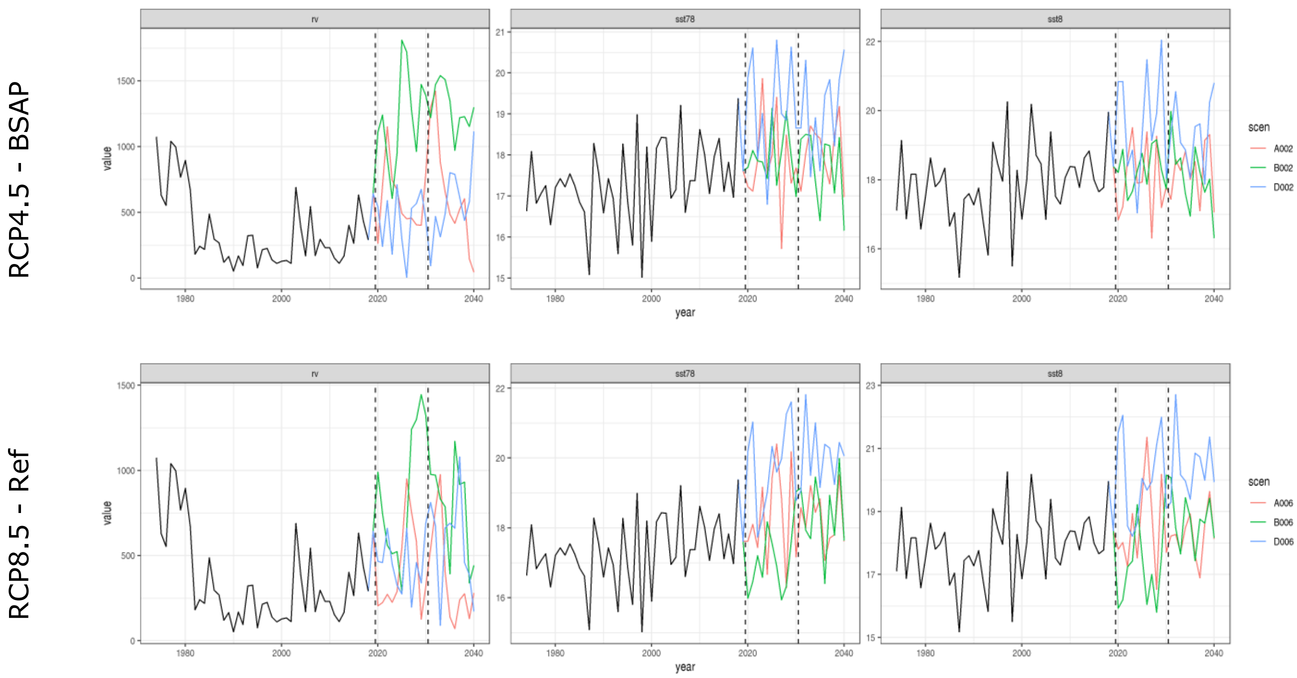


Figure 14 Future projections of coherent hydrographic time series of cod reproductive volume (rv, left), mean sea-surface temperature in July-August (sst78, middle) and sea-surface temperature in August (sst8, right) calculated from three climate models (A: MPI-ESM-LR, B: EC-EARTH, D: HadGEM2-ES) for two warming (RCP4.5, RCP8.5) and two nutrient loads (BSAP, Reference) scenarios.

Environmental sensitive stock-recruitment relationships

Future recruitment projections were based on environmental sensitive stock-recruitment relationships parametrised on the historical time period using Gadget SSB-Recruitment estimates and selected hydrographic variables. A similar simple model formulation was adopted for the three stocks where deviations from a hockey-stick stock-recruitment model were explained by a linear relationship with stock specific hydrographic variables and a log-normal distributed error term. 1000 simulations of recruitment are generated for each scenario.

The S-R models were fitted on data from 1993 onward to reflect more recent stocks productivities after the regime shift and because the hydrographic data from the Baltic Sea reanalysis cover the period 1993-2019. Based on a preliminary literature review the following relationships were confirmed and used to parametrise environmental sensitive stock-recruitment models (Table 16):

Table 16 Summary table of environmental drivers used in the S-R relationships

Stock	Environmental variable	Rational	Time window
Cod	Reproductive volume	Eggs are pelagic and for appropriate development require salinity levels compatible with their neutral buoyancy and	1993-2017 (excl. 2001)

		oxygenated bottoms levels. These define a suitable spawning habitat for recruitment	
Herring	Mean sea-surface temperature in July-August		1993-2018
Sprat	Mean sea-surface temperature in August		1993-2018

The breakpoint of the segmented regressions corresponded to the Blim for each stock and was calculated from the SSB-Recruitment pairs from Gadget following a similar rationale as in the ICES assessment (Figure 15). For cod, ICES sets Blim at 96.5*1e3 tons corresponding to the SSB in 2012, which produced the last strong year-class in the recent period of low productivity (ICES 2019b, 2021a). The year 2012 has the same interpretation also in the Gadget model, and it is used to derive a Blim of 136*1e3 tons. For herring, ICES calculates Blim at 3.3*1e5 tons corresponding to SSB in 2002, which is the lowest SSB that has resulted in above-average recruitment (ICES 2021b). The corresponding value in Gadget is also found in 2002 at 2.77*1e5 tons. For sprat, the ICES Blim is set at 4.1*1e5 tons which are calculated as the average biomass which produces half of the maximal recruitment in the Beverton-Holt and Ricker models (ICES 2021c). In this case, we departed from the ICES rational and used an approach similar to that one adopted for herring and cod, where the Gadget Blim is calculated at 4.47*1e5 tons as the lowest SSB that produced above-average recruitment during the period after the regime shift (Figure 16).

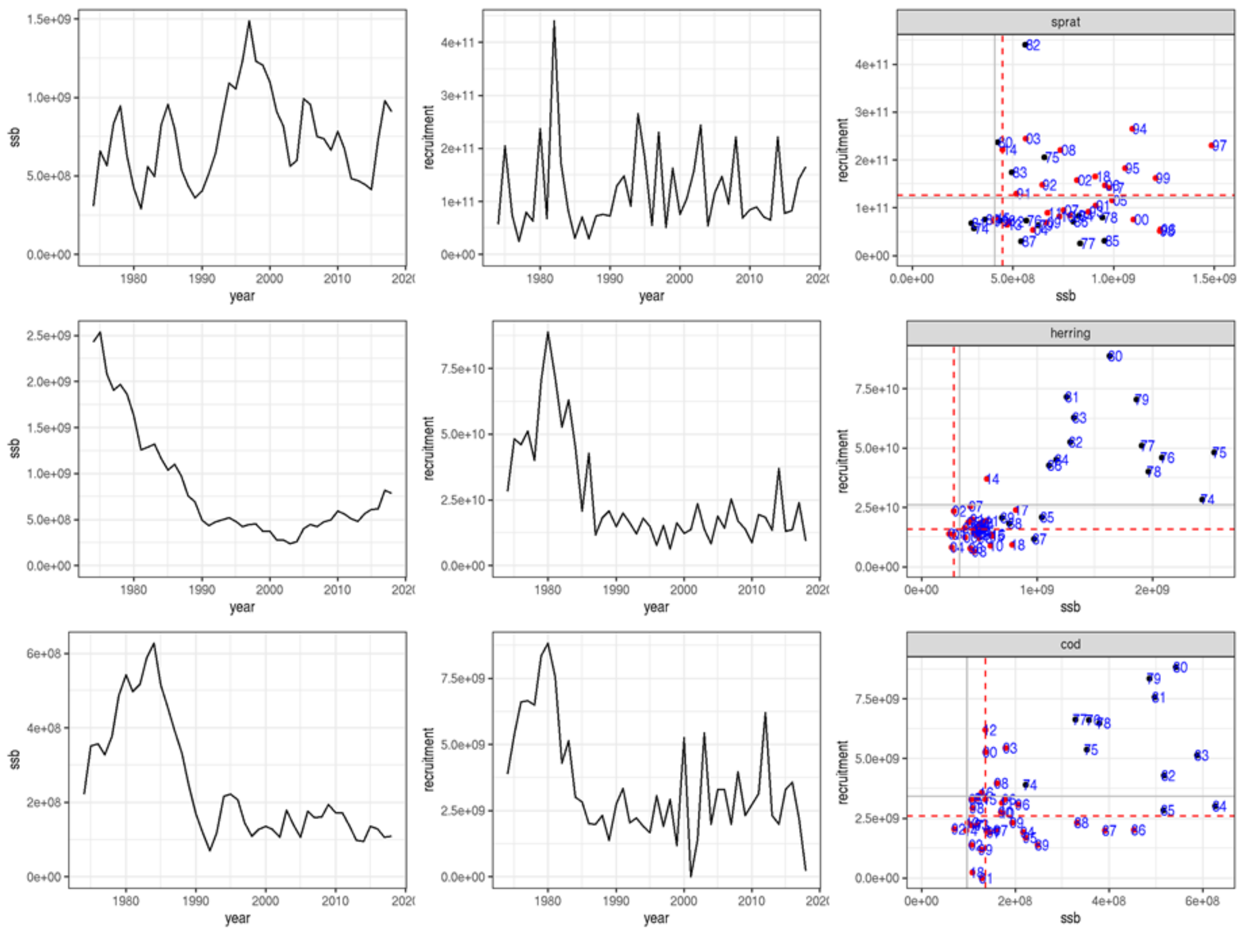


Figure 15 Time series of SSB (left) and recruitment (middle) and SSB-recruitment scatterplot (right) for sprat, herring and cod estimated from the Gadget model for the period 1974-2018. The grey vertical lines are the value of Blim from the ICES and the red vertical lines the corresponding Blim in Gadget.

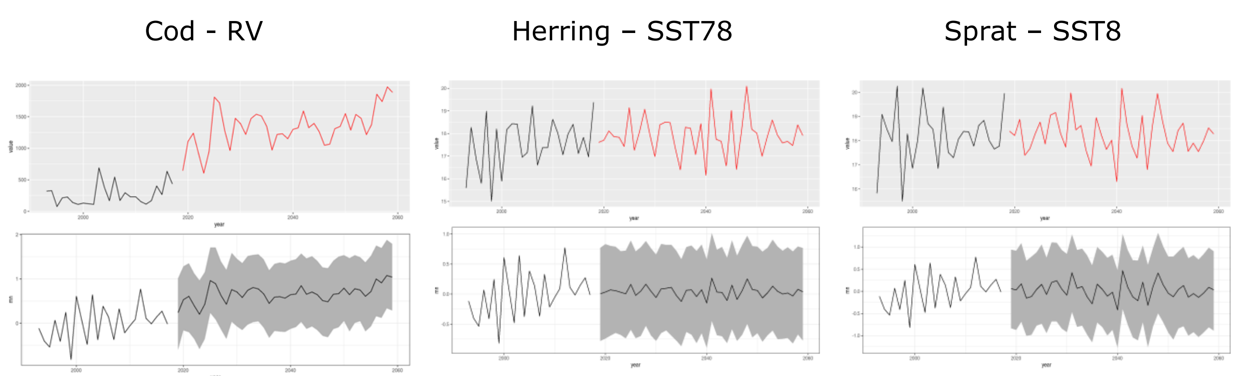


Figure 16 (top) time series of key environmental drivers from one of the GCM models (EC-EARTH) and scenarios (RCP4.5 – BSAP). (bottom) recruitment log-deviations from S-R segmented regressions for cod, herring and sprat illustrated for this specific scenario and climate model.

Other biological assumptions

The growth and condition of cod have progressively deteriorated through time (Casini et al. 2016), and they are at their minimum in most recent years. This is likely driven by a combination of physiological and evolutionary responses to the physical and biological environment as well as fisheries exploitation, but their relative contributions remain unclear. There is no indication of a rapid recovery in the coming years, as also confirmed by the most recent observations from ongoing sampling programs in 2021. von Bertalanffy and length-weight parameters from the terminal period of the model are adopted throughout the simulations.

Condition of both sprat and herring experienced a pronounced decrease during the 1990s and fluctuated in the following period with no clear trend. Length-weight for the projections followed the last time block starting in 1996 for herring and 1997 for sprat.

Maturity-at-length of cod followed a long-term decrease since the end of the 1990s. Estimates of L50 (50% mature) provided from the last benchmark (ICES 2019b) suggest that the L50 decreased from 35-40 cm (males and females combined) in the early 1990s to around 20 cm in most recent years (Figure 17). This early maturation is also assumed for the projection period.

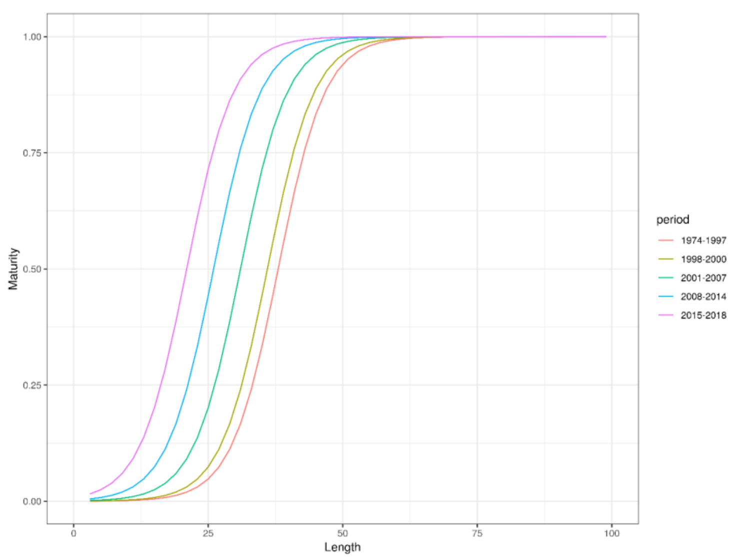


Figure 17 Cod maturity ogive

Maturity of herring and sprat is assumed constant during the whole historical period and maintain as such in the projections. Natural mortality at age of cod is also constant in time until 2000 and for age 3+ annually variable from 2000 according to the ICES assessment (ICES, 2019b). Most recent value of M are used in the projections. Lastlky, natural mortality of herring and sprat is divided into background mortality and predation mortality related to cod feeding on the clupeids. Background mortality is constant in the historical period and continued in the projections. In contrast, cod predation mortality is emergent from each scenario following the cod and clupeids size and abundance dynamics. The other food component completes the diet of cod in the model, and it is maintained constant throughout the historical and simulation period.

Fisheries exploitation pattern

In gadget, the exploitation level is calculated as a harvest rate, set individually for each fleet and steadily applied in the projection period. Two fishing level scenarios are evaluated based on harvest rates which approximate the FMSY and FMSY lower range values.

Fmsy and its lower range for herring and sprat are derived from the ICES values using a linear relationship between the Gadget and assessment estimates of fishing mortality. For cod, large changes in productivity challenge the applicability of the FMSY concept, which assumes a long-term equilibrium. Attempts to estimate FMSY during the last benchmark were unsuccessful or unsatisfactory, and in conclusion, no F reference point is available for this stock (ICES 2019b). In replacement of FMSY scenarios, the exploitation levels of both the active and passive cod fleets were set as the average of the last three years calculated from the model (2016-2018).

Selectivity of all the fisheries is modelled with constant fleet-specific sigmoid functions estimated in the historical period and then projected into the simulations period.

Shock scenarios

Long-term climate-driven changes in the simulations are reduced to environmentally sensitive S-R relationships. At the same time, assumptions on maturity, growth and conditions implicitly reflect the recent effects of environment and fisheries exploitation on the biology of the stocks. In general, the intensity and frequency of extreme climate events such as heatwaves is expected to increase under more severe warming scenarios. However, an understanding of how this links to the central Baltic Sea's hydrography and biological processes influencing the fish stock dynamics is missing. The use of stochastic simulations of recruitment occasionally generates high and low recruitments in the distribution's tails but makes it challenging to investigate the response of the fish stocks specifically. For this reason, it was decided to induce a recruitment failure in the simulation at a specific point in time of the projection (2020) and then evaluate the response of the fish stocks under the influence of different long-term scenarios of climate change, nutrient loads, fishing and the worse case of an additional unpredictable shock event. Three shock scenarios are investigated:

1. No shock (most likely) - recruitment is simulated in line with assumptions on the long-term effect of climate throughout the whole time period 2020-2030
2. One shock (intermediate case) - recruitment failure is assumed in the first year of the projection (2020), corresponding to the lowest recruitment observed in the whole time series
3. Two shocks (worse case) - recruitment failure is assumed in the first year of the projection (2020) and randomly in another year during 2021-2030; in both cases, recruitment is set to levels corresponding to the lowest recruitment observed in the whole time series

OUTCOMES OF THE SIMULATION STUDY

Metrics of resistance and resilience

Fish stocks response to the shock and the performance of exploitation levels corresponding to Fmsy and Fmsy lower range are evaluated in terms of resistance (i.e., ability of the stocks to oppose to the perturbation) and resilience (i.e., the ability of the stocks to recover from the perturbation) (Table 17). The recruitment failure in 2020 sets the evaluation's common starting point for all the tested scenarios. SSB is tracked from 2020 until 2030 to detect a response in the adult population.

Table 17 Metrics used to calculate resistance and resilience of the stocks of cod, herring and sprat to a shock event represented by a recruitment failure. Yearshock is 2020.

Metric	Description	Formulation
Amplitude	Ratio between the minimum SSB reached in response of the 2020 shock and the SSB in 2020	SSBmin/SSB2020
Responsiveness	Number of years between the shock and the minimum observed stock level	YearSSBmin – Yearshock
Biological risk	Probability of SSB falling below Btrigger after the shock in the period 2021-2030	Max(P(SSB<Btrig))
Recovery rate	Probability that stock level is at MSY Btrigger or above in 2030	P(SSB2030 >= Btrig)
Recovery speed	Number of years to reach stock levels corresponding to MSY after the SSB drop from the 2020 shock	YearSSB>=Btrig - Yearmin (after the shock)

Results

To characterize the drop in SSB caused by recruitment failure in 2020, we had to filter out other minima possibly caused by stock dynamics prior to the shock or during the consecutive decade, but that could not be directly linked to the event in 2020. Recruitment is at age0 in all three stocks and it is not expected to contribute to the SSB at least until 2022. For this reason, in each simulation, we looked at both the global minimum in SSB over the period 2022-2030 and a more local minimum described by one or more consecutive decreases in SSB followed by an increase over the same period 2022-2030, which likely better relates to the recruitment failure in 2020. This local minimum was adopted to calculate some of the resistance and resilience metrics.

Results from different scenarios are presented comparatively. The scenario with no shock is added as a reference for comparison to separate the effects of climate, nutrients and shocks from the background development of SSB. The no shock scenarios are not presented for the responsiveness and recovery speed metrics that deal with the time response to the shock.

Amplitude (Figure 18**):** SSB in 2020 at the starting point of the simulation is common for all the scenarios, and by the design of these simulations, the amplitude is measured in response to the same recruitment failure in 2020 for all the scenarios. This provides better control on the tests but likely it reduces the possible differences among the scenarios.

The cod scenarios with no shock and harvest rate fixed to that estimated in recent years (BAU) have amplitude of approx. 0.48 suggesting a common decreasing trajectory of the SSB regardless of climate or nutrient scenarios. Lack of feedback of clupeids on cod in the model prevents to see an effect on cod of different exploitation levels on herring and sprat. Cod shows the largest drop after the shock with SSB reduced to less than 30% of the initial value in 2020. Variability in amplitude is generally low in cod except in the case of a second recruitment failure which could drive the drop in SSB down to values of <0.2.

All the scenarios with no shock show on the short-term an increase in the SSB for sprat regardless of the exploitation level and only marginally also for herring but only under the low FMSY range. Amplitude of the drop is reduced in herring and sprat by a decrease of exploitation from FMSY to the lower range, while the effect of climate on the amplitude of the drop is not significant in both. One recruitment failure generates a drop from approx. 0.9 to 0.83 in herring and from 1.25 to 0.9 in sprat under the FMSY scenarios in comparison to the same climate and fishing scenarios with no shock. The occurrence of a second recruitment failure makes the drop only marginally wider in both the clupeids.

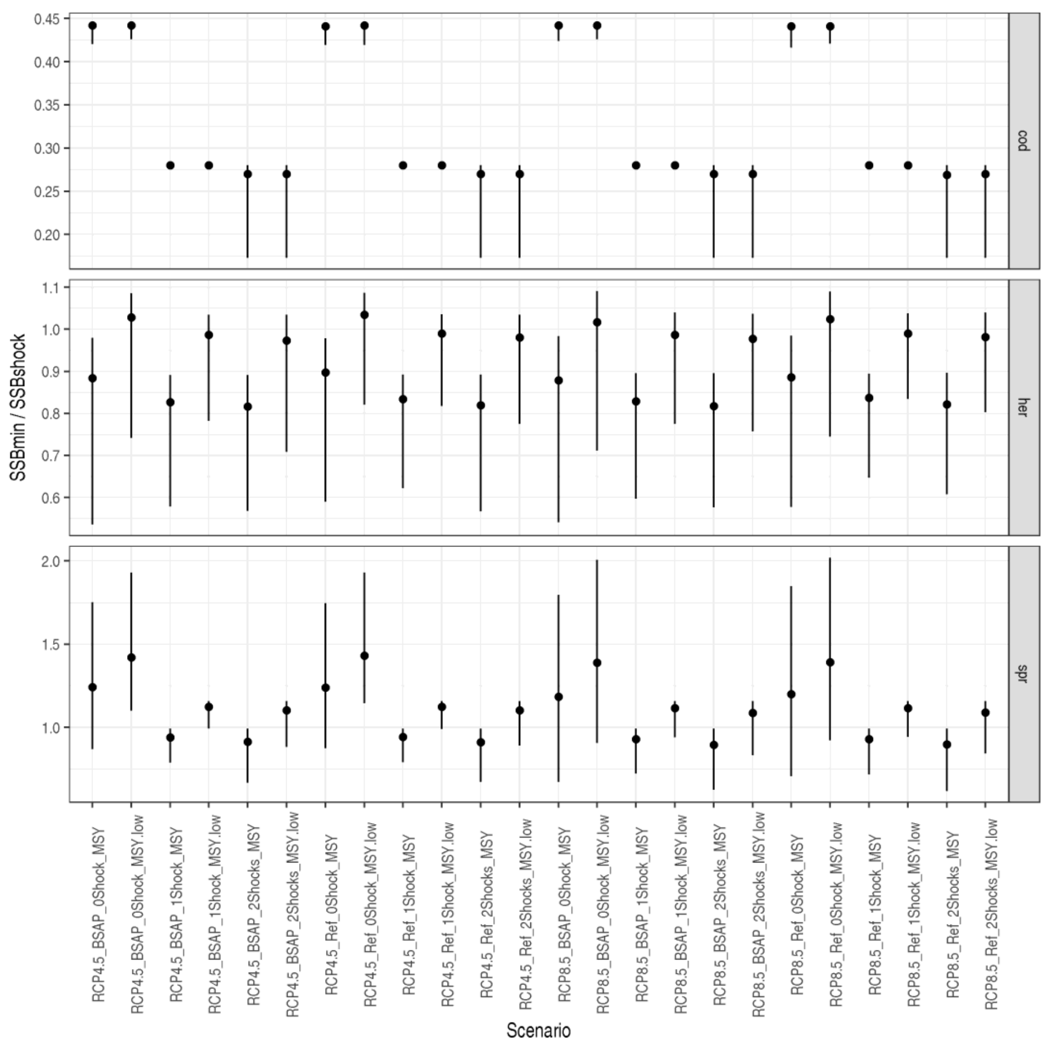


Figure 18 Amplitude of response in cod (top), herring (middle) and sprat (bottom) calculated for each climate (RCP4.5 and RCP8.5), nutrient (BSAP and Ref), shock (0, 1, 2 shocks) and harvest (MSY and MSY lower) scenario. Dot corresponds to the mean and vertical bar to the 95% CI of the simulations.

Responsiveness (Figure 19): as it is calculated, responsiveness represents the time window for the SSB to reach its minimum after a shock in recruitment. Such drop of SSB is reached on average after 3.0 years for cod, 3.5 years in herring and 2.6 years in sprat. The shorter response in sprat is likely the result of an earlier maturity and faster growth compared to the other two stocks. Overall, the differences in responsiveness among the scenarios are small. The occurrence of two recruitment failures has the effect of increasing the amplitude of the drop in SSB and prolonge it in time compared to the occurrence of only one shock, but the differences appear marginal for cod and moderate for herring and sprat. In both herring and sprat, the time window of the drop tends to decrease at a lower exploitation level as a result of a quicker response. In sprat, warmer scenarios tend to have a slightly longer responsiveness time, but the reason is unclear. The slightly longer responsiveness of scenarios under the BSAP nutrient loads in herring might result from interactions with cod.

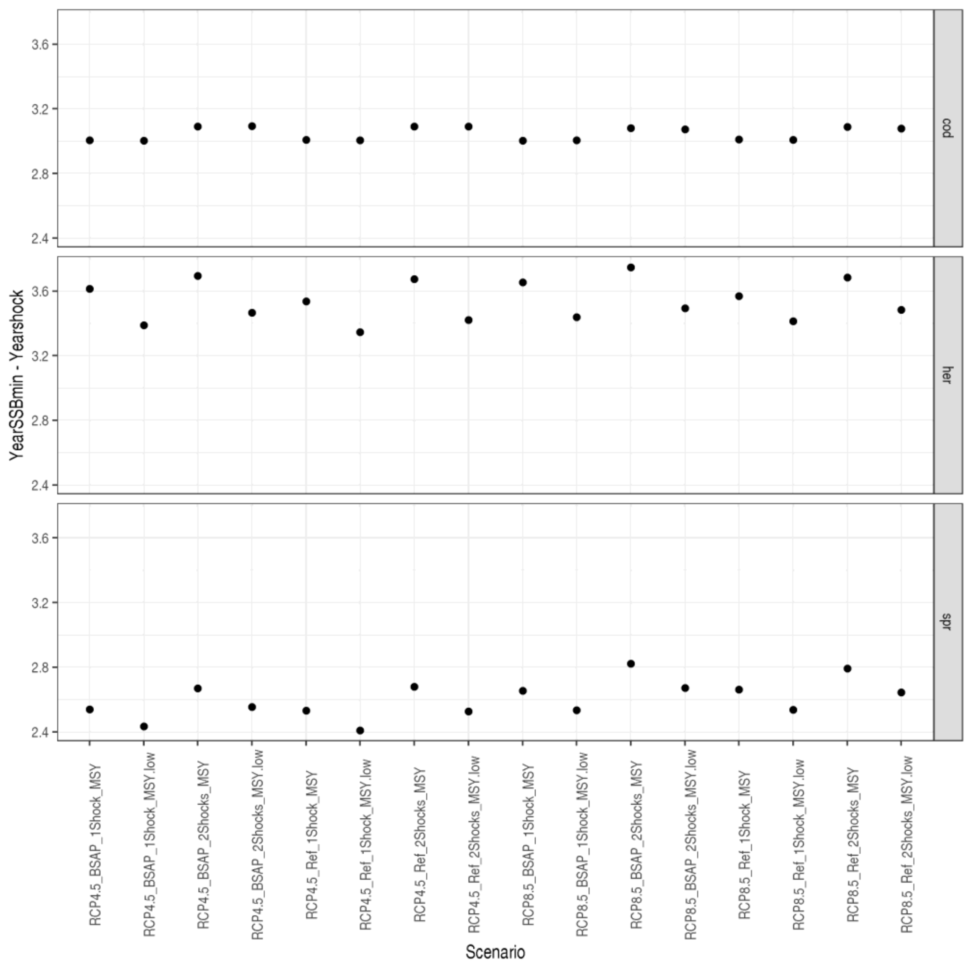


Figure 19 Mean responsiveness of cod (top), herring (middle) and sprat (bottom) calculated for each climate (RCP4.5 and RCP8.5), nutrient (BSAP and Ref), shock (1, 2 shocks) and harvest (MSY and MSY lower) scenario.

Biological risk (Figure 20): The probability of the stocks to falling below MSY Btrig during the period 2021-2030 is particularly high for cod exceeding 85% in the most favourable scenarios with no shock, moderate warming, and reduced nutrients (RCP4.5_BSAP_0Shock), to reach 98% in the most unfavourable characterised by 2 shocks, severe warming and high nutrients loads (RCP8.5_Ref_2Shocks). On the contrary, both herring and sprat have respectively a low (<1.5%) and very low (<0.2%) probability of falling below MSY Btrigger until 2030 under all the scenarios. In herring, the risk is positively correlated with the exploitation level while increasing temperature appears to reduce the risk. For sprat the probability of falling below Btrig is slightly increased by 2 recruitment failures but overall, the risk is so low that no pattern emerges from a comparison of the different scenarios.

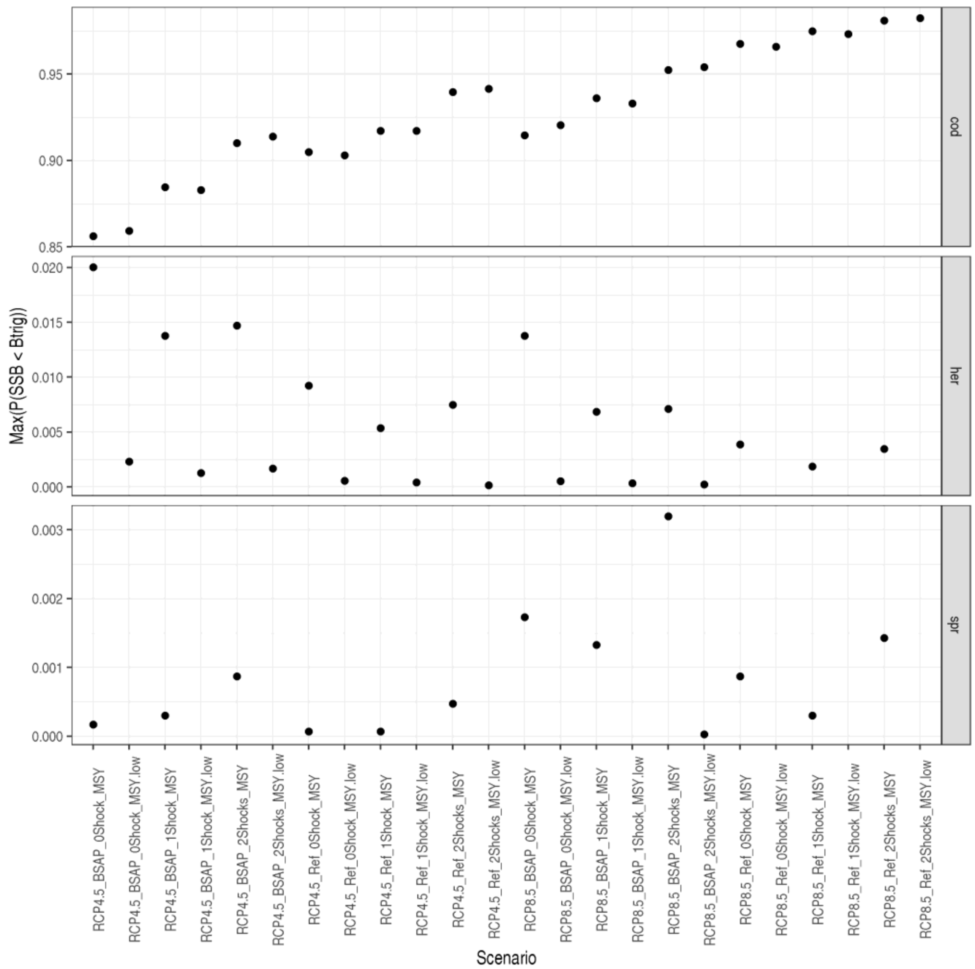


Figure 20 Probability of SSB falling below Btrigger in the period 2021-2030 for cod (top), herring (middle) and sprat (bottom) calculated for each climate (RCP4.5 and RCP8.5), nutrient (BSAP and Ref), shock (0, 1, 2 shocks) and harvest (MSY and MSY lower) scenario.

Recovery rate (Figure 21, Figure 22): Both herring and sprat show probabilities of being above Btrig by 2030 of >90% and >98%, respectively. This is not the case for cod that despite the scenario has a probability of recovery < 33% and in some scenarios down to around 10%.

For cod, the scenarios with 2 shocks have a particularly negative effect on the probability of recovery. The probability of recovery is also negatively affected by the increased amount of nutrient loads as shown by a comparison of BSAP and reference nutrient scenarios. The effect of nutrient loads and temperature appear in interaction as suggested by the approx. 6-7% decrease of probability in the RCP4.5 scenarios and the drop of 20% in probability under the

RCP8.5 warming scenario. The negative effect of warming is only visible when interacting with the nutrients levels (RCP8.5_Ref).

For herring, the lower harvest rate (MSY.low) has an impact on the probability of recovery which is more pronounced under moderate warming (RCP4.5). The simulations also show that more intense warming (RCP8.5) is expected to increase the probability of SSB to reach Btrig by 2030, which is likely a direct result of the simulated increased recruitment. Under the same climate and exploitation scenarios a reduction in nutrient loads (BSAP) reduces the probability of reaching Btrig likely via the predatory effect of cod. The same foodweb mediated effect is present but less pronounced in sprat that shows a minimal range in the probabilities among the scenarios. The scenarios with 2 shocks and the higher exploitation level (FMSY) tend to have marginally lower probabilities. Unexpectedly, slightly lower probabilities are also estimated in some of the most severe warming scenarios but it is noted that the long-term trends in the climate projections are not always visible on the time frame of these simulations limited to 2030.

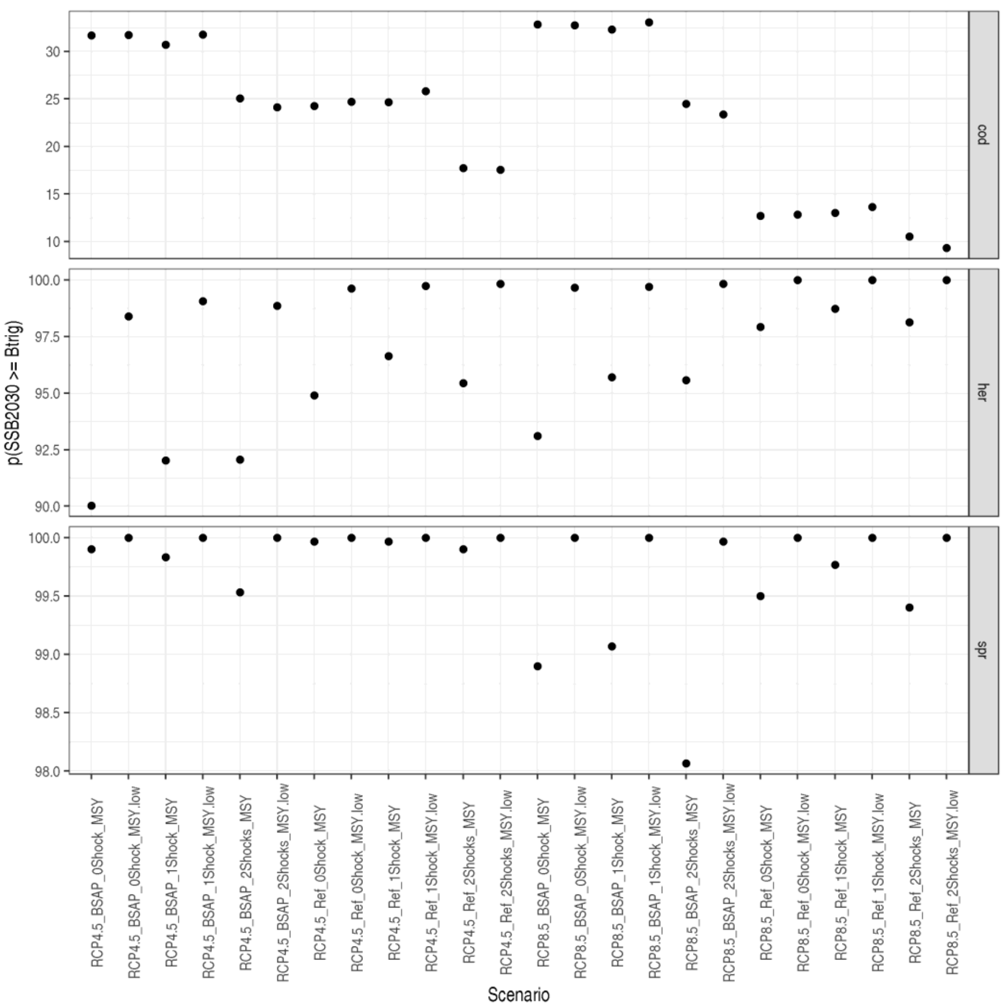


Figure 21 Probability that SSB is at MSY Btrigger or above in 2030 for cod (top), herring (middle) and sprat (bottom) calculated for each climate (RCP4.5 and RCP8.5), nutrient (BSAP and Ref), shock (0, 1, 2 shocks) and harvest (MSY and MSY lower) scenario.

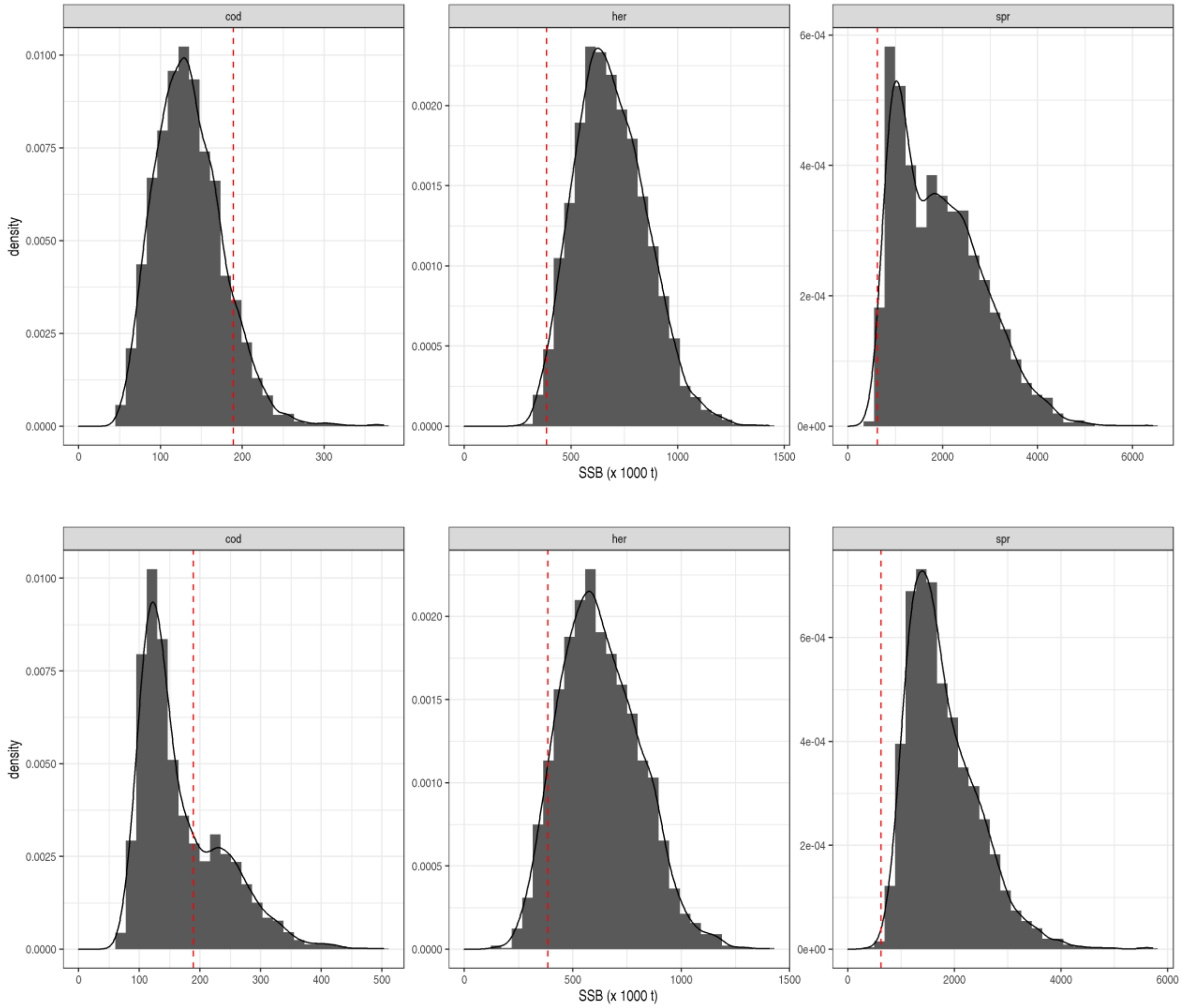


Figure 22 Distribution of SSB of cod, herring and sprat in 2030 from the scenarios RCP8.5_Ref_2Shocks_MSY (top) and RCP4.5_BSAP_1Shock_MSY (bottom). Vertical red line is MSY Btrig.

Recovery speed (Figure 23**):** the recovery speed is calculated in relation to the SSB drop and minimum reached in response to the 2020 recruitment failure. For both herring and sprat the starting level of the simulations is well above MSY Btrig and the drop in SSB caused by the 2020 shock is not able to bring the stocks below that. On the contrary, the recovery of cod above MSY Btrig is expected to take on average between 7.5 and 10 years across the different scenarios, with pronounced tails extending well beyond 2030. Under such large variability in the recovery speed, differences among the scenarios are slight and difficult to interpret. The four scenarios with the most extended recovery speed share the occurrence of 2 shocks, but it does not seem to represent a pattern. Under the most severe warming (RCP8.5), limited nutrient loads (BSAP) seem to benefit the recovery speed, but this pattern is not evident under the moderate warming scenarios (RCP4.5).

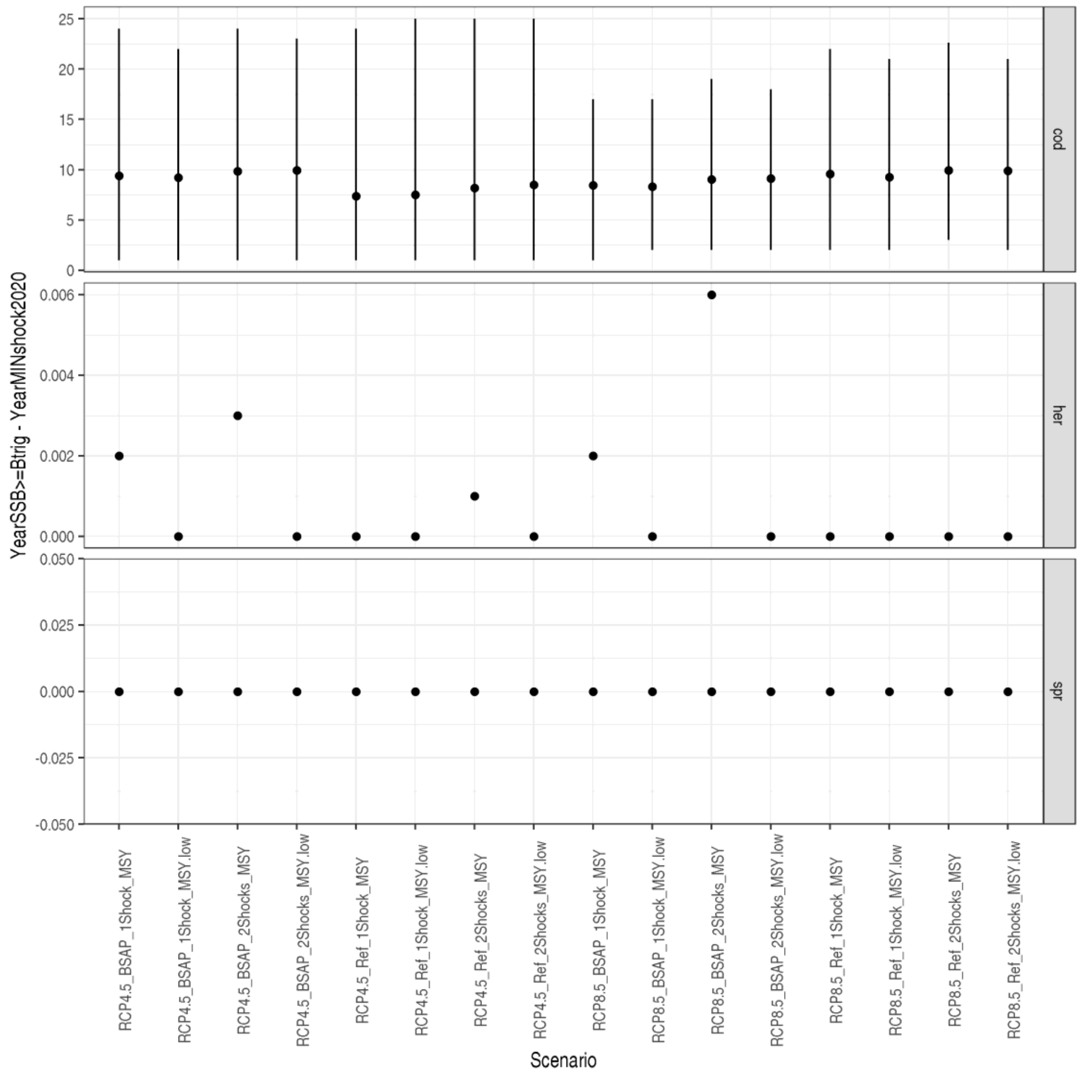


Figure 23 Recovery speed of cod (top), herring (middle) and sprat (bottom) from the SSB in 2020 calculated for each climate (RCP4.5 and RCP8.5), nutrient (BSAP and Ref), shock (1, 2 shocks) and harvest (MSY and MSY lower) scenario. Dot corresponds to the mean and vertical bar to the 95% CI of the simulations.

Caveats and limitations

Differences in response to the shock in 2020 among the scenarios are related only to the long-term effect of climate on recruitments of the three stocks. Other biological responses, i.e. maturation and growth, are assumed to be common among the scenarios meaning that they do not respond dynamically to projected changes in the physical and biological environment.

While the dynamics of herring and sprat are linked to cod by predation, no feedback loop is implemented on the cod stock (i.e., the abundance of herring an sprat does not affect growth or other biological process regulating cod).

In the Baltic Sea, an important part of the cod diet is represented by benthic preys. *Mysis* spp. represent >40% if the diet in weight for cod <20 cm and *Saduria enthomon* can exceed

20% of both juvenile and adult cod diet in some areas. This benthic preys, which are an important part of the other food component in the model, are likely to be highly affected by environmental changes in the Baltic, mainly due to the occurrence of hypoxia in the bottom, but their abundance is assumed constant during the historical period as well as throughout the simulations.

Spatial distribution might have consequences on both trophic interactions between cod, herring and sprat and interactions with the fisheries. The current simulations assumed no changes in the spatial displacement of the three stocks during the period of the simulations.

The pelagic fleets harvesting herring and sprat in the model are represented as separate fleets. In reality, they are largely the same fishery targeting both the species individually and as a mix in different areas and during different times of the year. This is likely to represent a dependency that remains unaccounted for in the present simulations.

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Annex 9 NORTH SEA DEMERSAL MIXED FISHERIES

INTRODUCTION

The following analysis addresses the resilience of North Sea demersal stocks to recruitment shocks. Using a mixed fishery model, the impacts of these shocks are evaluated in terms of direct biological effects to the shocked stock as well as the indirect consequences to the uptake of other stocks caught together by the main demersal fleets. For example, a recruitment shock will negatively affect the biomass of a stock in the future, resulting in lower catch quotas. If the quota of the shocked stock is particularly limiting to fleet (i.e. as the "choke species"), this will reduce the fleet's ability to take up other quotas through the more restricted fishing effort.

The analysis considers several possible scenarios, which affect the magnitude and duration of a recruitment shock as well as the management response in terms of advised quotas. In particular, shock magnitude and duration are divided up into "most-likely" and "worse-case" scenarios that define either anomalously low recruitment for a 1- or 2-year duration, respectively. We define the magnitude of these shocks based on levels of recruitment that are unexpectedly low, even after long-term trends in recruitment have been considered. For example, stock assessors are required to estimate future recruitment when advising future catch quotas for a given stock. These are often based on a combination of stock-recruitment relationships (SRRs) between spawning stock biomass (SSB) and subsequent recruitment, as well as considerations of long-term trends as possibly relating to environmental conditions. Despite these considerations, a degree of unexplained variability remains which relates to the degree of uncertainty in these forecasts. We use this information on remaining unexplained variability to inform the magnitude of highly anomalous recruitment events, the magnitude of which differs for each shocked stock based on its particular historical dynamics. Furthermore, these two scenarios are also influenced by climate conditions relating to RCP4.5 and RCP8.5 trajectories, which affect several environmentally-mediated stock recruitment relationships (EMSRRs).

The effect of the management response is evaluated through the use of either Fmsy target reference points or their more conservative lower range values (FmsyL). The use of FmsyL may be considered a safer option in cases were a given stock's status implies a need for more rapid rebuilding of spawning stock biomass.

For a given shock, stock resilience is measured via several metrics that define the trajectories of the stocks' SSB status. These address the stock's ability to resist a given shock (amplitude, resistance, biological risk) and recovery (probability rate and speed). Btrigger is used as a reference point for defining SSB levels above which it is appropriate to fish at Fmsy. When SSB is below Btrigger, the ICES harvest control rule tapers the target F to allow for faster rebuilding. Thus, in many of the analyses, Btrigger is used as a reference point to indicate good stock status.

METHODS

Model description

The mixed fisheries model of the North Sea is defined using the procedure of WGMIXFISH-Advice, but has been expanded to include several additional stocks. The modelling framework is FLBEIA (Garcia et al. 2017), and includes 42 fleets (137 total métiers) and 24 stocks. Stock dynamics are either age-based (COD-NS, HAD, PLE-EC, PLE-NS, POK, SOL-NS, TUR, WHG-

NS, WIT), biomass-based (ANF, BLL, DAB, LEM, LIN), or fixed (NEP6, NEP7, NEP8, NEP9, NEP5, NEP10, NEP32, NEP33, NEP34, NEPOTH-NS) and differ whether they are actively managed via a TAC advice or, in some cases, considered as bycatch stocks. Stocks included in the FLBEIA North Sea mixed fisheries model are detailed in Table 18.

Table 18 Stocks included in the North Sea mixed fishery model.

Scientific name	Stock code	FAO	Common name	ICES data category	TAC	EMSRR
Gadus morhua	cod.27.47d20	COD	cod	1	X	X
Melanogrammus aeglefinus	had.27.46a20	HAD	haddock	1	X	
Pollachius virens	pok.27.3a46	POK	saithe	1	X	X
Solea solea	sol.27.4	SOL	sole	1	X	
Pleuronectes platessa	ple.27.420, ple.27.7d	PLE	plaice	1	X	X
Merlangius merlangus	whg.27.47d	WHG	whiting	1	X	X
Nephrops norvegicus	nep.fu.5, nep.fu.6, nep.fu.7, nep.fu.8 nep.fu.9 nep.fu.10 nep.fu.32 nep.fu.33 nep.fu.34, nep-IVnotFU	NEP	Norway lobster	Cat. 1 for FUs 6-9, Cat. 4 for other FUs	X	
Scophthalmus maximus	tur.27.4	TUR	turbot	1	X	
Scophthalmus rhombus	bll.27.3a47de	BLL	brill	3	X	
Glyptocephalus cynoglossus	wit.27.3a47d	WIT	witch flounder	1	X	
Limanda limanda	dab.27.3a4*	DAB	dab	3		
Lophius budegassa, *Lophius piscatorius*	ang.27.3a46*	ANF	anglerfish	3	X	
Microstomus kitt	lem.27.3a47d	LEM	lemon sole	3	X	
Molva molva	lin.27.3a4a6-91214	LIN	ling	3	X	

Notes: *EMSRR = *Environmentally-mediated stock recruitment relationship*.

The model is conditioned with historical data up to 2018, and forecasts future conditions thereafter. Stocks are defined using the assessments conducted in 2019 (ICES 2019), as well as the reference points used at that time in harvest control rules (e.g. Fmsy, Blim, Btrigger). One exception is cod, whose reference points have been updated to reflect recent changes (i.e. benchmark assessment in 2021). Fleets and métiers are defined using various data sources; information on catches (landings and discards) by stock are provided by INTERCATCH, while fishing effort and landings value are supplemented with a separate data call by WGMIXFISH. The WGMIXFISH data is specifically valuable in defining fleets as it contains additional information on vessel length, which is an important attribute of the fishery segments in terms of their economic characteristics. Fleets are defined based on their country of origin, main gear employed (e.g. Static, Pelagic, Danish seine, Otter trawl, Beam trawl), and vessel length (<10 m, 10-24 m, and >40 m). Within each fleet, further segmentation of métiers is based on main fishing operations in terms of variations in gear (i.e. mesh size) and geographic area (i.e. ICES areas 3a, 4, 6a, and 7d). Each métier is further parameterized in terms of catchability of each of the stocks based on most recent estimates. These catchabilities are thus used to predict catches under changing effort and stock sizes.

Environmental drivers to recruitment

Environmentally-mediated stock-recruitment relationships (EMSRRs) were used for four stocks (COD-NS, PLE-NS, POK, WHG). In the case of COD-NS, POK, and WHG, we used the framework described by Kühn et al. (2021) to search for EMSRRs that best explained historical recruitment. Stock-recruitment relationships were built using historical sea surface temperature (SST) and sea surface salinity (SSS) data from the AHOI-dataset (Núñez-Riboni and Akimova, 2015) as well as sea surface currents (SSC) data from ORAS5 (Zuo et al., 2019). Time series from the spatiotemporal environmental fields were extracted via EOF-analysis (i.e. temporal principal components, PCs) and fed into a genetic search-algorithm (NSGA-II) (Deb et al. 2002) combined with k-fold repeated cross-validation (5 folds x 30 permutations) for variable selection.

For PLE-NS, the mean sea surface temperatures from the southern North Sea were used (Lat: 52°N – 56°N, Lon: 1°W – 8°E), which is consistent with the findings of Fox et al. (2000). The AHOI-derived SST time series were found to be highly correlated with the COADS-derived time series used by Fox et al. (2000).

In all cases, three possible EMSRRs were tested: Beverton-Holt, Ricker, and Cushing. Ricker and Cushing forms are easily adapted to linear models that include environmental terms (Levi et al., 2003). We followed the proposed method of O'Brien (1999) for fitting the Beverton-Holt model using a reciprocal-link GLM. Final model formulations with selected environmental covariates are listed in Table S1. Initially, a Beverton-Holt GLM was selected for WHG-NS, yet it was determined that the model solution was too unstable to be of practical use in forecasting. We thus used a Hockey-stick (i.e. segmented regression) formulation, which provided a close fit to historical data and was more stable in forecasts (see next sections for climate scenario descriptions). The WHG-NS model is fit in two steps; first the segmented regression is followed by searching for the best combination of an environmental covariate to explain the remaining residuals.

All other category 1 stocks were also fit with segmented-regression stock-recruitment relationships (SRRs) considering the same span of historical years as used by the assessments, but without additional environmental covariates.

For all SRRs, residual relative error (*RE*) between the observed and predicted recruitment was then quantified for each year, y:

$$RE_y = obs_y / pred_y \ ,$$

where *obs* and *pred* are the observed and predicted recruitment, respectively. The standard deviation of the log-transformed RE was used to define coefficient of variance (*CV*) levels to be used in the generation of additional noise in projected recruitment:

$$CV = sd(\log(RE)) \ .$$

Shock scenarios

Two main shock scenarios were conducted: "most-likely" and "worst-case". These differed in terms of the assumed future climate conditions and the duration of a shock to recruitment. *Most-likely* scenarios assume future climate conditions based on RCP4.5 forecasts and shocks to recruitment are only in the first projection year. *Worst-case* scenarios assume future climate conditions based on RCP8.5 forecasts and shocks to recruitment are during the first 2 projection years. A special shock scenario was defined for HAD, which is further described in Section 2.3.2.

In all scenarios, fleet effort is determined by the most limiting stock quota; referred to as a "min" fleet control setting in FLBEIA. This setting is compliant with current management strategies and legal framework, whereby a discard ban is in effect for all stocks that receive quota advice. It should be, however, noted that the strict implementation of these restrictions is optimistic given that discarding continues to some degree despite the existing ban. As a consequence, fleets may be severely limited in their fishing effort during the initial years of the projection due to choking effects.

Quotas are determined according to an ICES harvest control rule (HCR), which assign a target fishing mortality (F) based on a given stock's spawning stock biomass (SSB). When the stock is above a given biomass (Btrigger), stock advice is based on the F that associated with maximum sustainable yield (Fmsy). When below, the advised F is based on a sliding slope. When SSB drops below a reference of the lower limit to biomass (Blim), zero advised catch quotas may result. Two definitions for target F were used in the scenarios; Fmsy and its lower range value ("FmsyL"), which is more conservative and should allow for faster stock growth following shocks and higher probabilities of recovery from shocks. Combined with the "min" fleet control setting, the FmsyL will result in the strongest limitation to fleet fishing effort.

Finally, several reference scenarios were run without shocks and/or climate change. A summary of shock scenarios is listed in Table 19. Further details of climate and shock scenarios are outlined in the following sections.

Table 19 Shock scenarios were conducted, based on combinations of climate change (CC) projection, ICES harvest control rule (HCR) F targets, and shocked stock via changes to recruitment.

Scenario ID*	Scenario type	HCR*	CC*	Shocked stock	Shock description
Fmsy~rcp4.5~COD-NS	most likely	Fmsy	rcp4.5	COD-NS	1-yr reduced recr.
Fmsy~rcp4.5~POK	most likely	Fmsy	rcp4.5	POK	1-yr reduced recr.
Fmsy~rcp4.5~WHG	most likely	Fmsy	rcp4.5	WHG	1-yr reduced recr.
Fmsy~rcp4.5~PLE-NS	most likely	Fmsy	rcp4.5	PLE-NS	1-yr reduced recr.

Fmsy~rcp4.5~SOL-NS	most likely	Fmsy	rcp4.5	SOL-NS	1-yr reduced recr.
FmsyL~rcp4.5~COD-NS	most likely	FmsyL	rcp4.5	COD-NS	1-yr reduced recr.
FmsyL~rcp4.5~POK	most likely	FmsyL	rcp4.5	POK	1-yr reduced recr.
FmsyL~rcp4.5~WHG	most likely	FmsyL	rcp4.5	WHG	1-yr reduced recr.
FmsyL~rcp4.5~PLE-NS	most likely	FmsyL	rcp4.5	PLE-NS	1-yr reduced recr.
FmsyL~rcp4.5~SOL-NS	most likely	FmsyL	rcp4.5	SOL-NS	1-yr reduced recr.
Fmsy~rcp8.5~COD-NS	worst case	Fmsy	rcp8.5	COD-NS	2-yr reduced recr.
Fmsy~rcp8.5~POK	worst case	Fmsy	rcp8.5	POK	2-yr reduced recr.
Fmsy~rcp8.5~HAD	worst case	Fmsy	rcp8.5	HAD	10-yr w/out recr. spike
Fmsy~rcp8.5~WHG	worst case	Fmsy	rcp8.5	WHG	2-yr reduced recr.
Fmsy~rcp8.5~PLE-NS	worst case	Fmsy	rcp8.5	PLE-NS	2-yr reduced recr.
Fmsy~rcp8.5~SOL-NS	worst case	Fmsy	rcp8.5	SOL-NS	2-yr reduced recr.
FmsyL~rcp8.5~COD-NS	worst case	FmsyL	rcp8.5	COD-NS	2-yr reduced recr.
FmsyL~rcp8.5~POK	worst case	FmsyL	rcp8.5	POK	2-yr reduced recr.
FmsyL~rcp8.5~HAD	worst case	FmsyL	rcp8.5	HAD	10-yr w/out recr. spike
FmsyL~rcp8.5~WHG	worst case	FmsyL	rcp8.5	WHG	2-yr reduced recr.
FmsyL~rcp8.5~PLE-NS	worst case	FmsyL	rcp8.5	PLE-NS	2-yr reduced recr.
FmsyL~rcp8.5~SOL-NS	worst case	FmsyL	rcp8.5	SOL-NS	2-yr reduced recr.

* Notes: Scenario ID format is *HCR~CC~Shocked_stock*; *HCR* = ICES harvest control rule target F; *CC* = climate change scenario influencing stocks with environmentally-mediated stock recruitment relationships (EMSRRs) (COD-NS, PLE-NS, POK, WHG).

Future climate conditions

A projection of the future ocean state (2020-2100) under climate change (RCP4.5 and RCP8.5 scenarios) was obtained from three independent ensemble members of a dynamically downscaled version of the global climate model MPI-ESM (Max Planck Institute Earth System Model) (Ilyina et al., 2013; Jungclaus et al., 2013) performed with a high-resolution version of the regionally coupled ocean-atmosphere climate system model MPIOM/REMO (Mikolajewicz et al., 2005; Sein et al., 2015). These projections were bias-corrected to be consistent with the historical trends (1990-2005) of the AHOI data set. In order to account for variability in the covariates, 100 time series with the same variance as the three ensemble members were generated for each covariate, following either a gaussian white noise process or a first-order autoregressive process (AR1) if the time series showed considerable autocorrelation. An example of the resulting environmental time series from the RCP8.5 scenarios are shown in Figure S1. The RCP4.5 and RCP8.5 forecasts were used for the "most likely" and "worst-case" shock scenarios, respectively.

Shock definitions

Shocks were always simulated in the initial years of the forecast (2019-2020). These scenarios were carried out for all stocks with EMSRRs (COD-NS, PLE-NS, POK, WHG) plus North Sea sole (SOL-NS), for which environmental effects to recruitment are hypothesized but have not been explored in detail. As mentioned above, *most-likely* scenarios involved a shock to the first forecast year (2019), while *worst-case* scenarios were shocks to the first two years (2019, 2020). Shocks to haddock (HAD) were defined differently, since periodic recruitment pulses (i.e. strong cohorts), rather than failures, are considered to be the major outliers of importance to management. Therefore, the lack of a recruitment pulse in the first 10 years of the simulation was considered as a special shock scenario under the RCP8.5 conditions (i.e. only for the "worst case" scenario).

Shocks were generally defined as recruitment events that occur at a yearly probability of 5%. Regardless of the underlying SRR used in the operating model, the recruitment time series of all shocked stocks were fit with an 11-year running mean model. This roughly approximates the approach used by many short-term forecasts when setting future quotas. The rationale is that future recruitment is likely to be of a similar magnitude as recent recruitment levels, and long-term changes can be accounted for even if the underlying mechanism isn't known. The residual relative error (*RE*) of the 11-year running mean would thus be a typical level of error expected from short-term forecast assumptions.

The resulting distribution of *RE* was used to determine quantile threshold values for defining deviations from predicated recruitment at a given probability. In the case of recruitment decreases (i.e. shocks for COD-NS, PLE-NS, POK, WHG, and SOL-NS), the 5% quantile values were used (Table 20), which resulted in recruitment deviations ranging between 27% to 66% of the median levels. In the case of HAD, the 95% quantile (2.85; i.e. 285%) was used to define the maximum level of recruitment deviations to allow during the first 10 years of the forecast; thus, hindering larger recruitment pulses.

Table 20 Shock amplitude in terms of decreased recruitment by stock.

Stock	5% quantile*
COD-NS	0.47
WHG-NS	0.66
POK	0.47
PLE-NS	0.55
SOL-NS	0.27

Notes: * For shock years, the 5% quantile value of the residual relative error (RE) of the 11-year running mean model was used to define the deviation in recruitment from of the SRR prediction.

1.1 Resistance and resilience indicators

Resistance and resilience to shocks were measured according to several summary metrics in the mixed fishery scenarios. Resistance refers to a stock's ability to withstand perturbations, while resilience refers to a stock's ability to recover to some pre-disturbance state. The originally-defined metrics are listed in Table 21. In some cases, alternately-defined metrics were used in order to better compare the *relative* impacts of shocks as compared to a given reference scenario (see Results for further details).

Table 21 Preliminary list of indicators to describe resource resilience

Resistance (ability to withstand the perturbation)		
Amplitude	Minimum stock level reached after the shock compared to initial level	$SSB_{min}/SSB_{yearshock}$
Responsiveness	Number of years between the shock and the minimum observed stock level	$Year_{SSBmin} - Year_{shock}$
Biological risk	Probability of SSB falling below Btrigger	Max(P(SSB<Btrigger))
Resilience *stricto sensu* (ability to recover from the perturbation)		
Recovery rate	Probability that stock level is at MSY Btrigger or above in 2030	$p(SSB_{2030}>=Btrigger)$
Recovery speed	Number of years to reach stock levels corresponding to MSY	$Year_{SSB>=Btrigger} - Year_{shock}$

RESULTS

The implementation of fleet control behaviour that limits effort to the most restrictive total allowable catch (TAC) quota shares ("min" setting) allowed all stocks to recover above precautionary reference points in a short amount of time. Two stocks, COD-NS and WHG-NS, were below their respective Btrigger values at the start of the forecast in 2019, yet quickly recovered under all scenarios without shocks (Figure 24). The recovery of SSB was more rapid when the lower FmsyL targets were used, which also resulted in higher equilibria SSB. For stocks whose recruitment is strongly affected by climate change, such as COD-NS and PLE-NS, the most-likely (RCP4.5) scenarios showed similar trajectories to scenarios without climate change up through 2030. Worst-case (RCP8.5) scenarios resulted in noticeably lower SSB, even over the relatively short forecast period.

Recruitment shocks did not affect the stocks' capacity to recover to safe SSB levels under all scenarios, and any delays caused by the shock were relatively short-term (Figure 25). For this reason, the initially-described resilience indicators relating to drops *below* Btrigger were not very illustrative, and we have therefore chosen to focus on the *relative difference* in SSB as compared to corresponding their reference, non-shock scenarios (Figure 26):

$$SSB_{reldiff} = (SSB_{shock} - SSB_{ref})/SSB_{ref} \ .$$

This allowed a clearer measure of the impact of the perturbation and the time required for recovery to equilibrium. For the remainder of the results, reference scenarios for the calculation of relative changes are non-shock scenarios, but with climate impacts remaining.

Perturbation magnitude and recovery trajectories differed among the shocked stocks, which were related to differences in life-histories, SRRs, and the amplitude and duration of the shock. One unique dynamic was the oscillatory-trajectory of POK, which is due to density-dependant processes within its stock-recruitment relationship (i.e. Ricker-type), and the lagged oscillation caused by the shock. The prolonged decrease for HAD is due to the differing nature of the shock, which was defined as a lack of strong recruitment pulses during the first 10 years of the forecast, after which recovery is observed. More detailed views of the shock effects are provided in the following sections regarding specific resilience indicators.

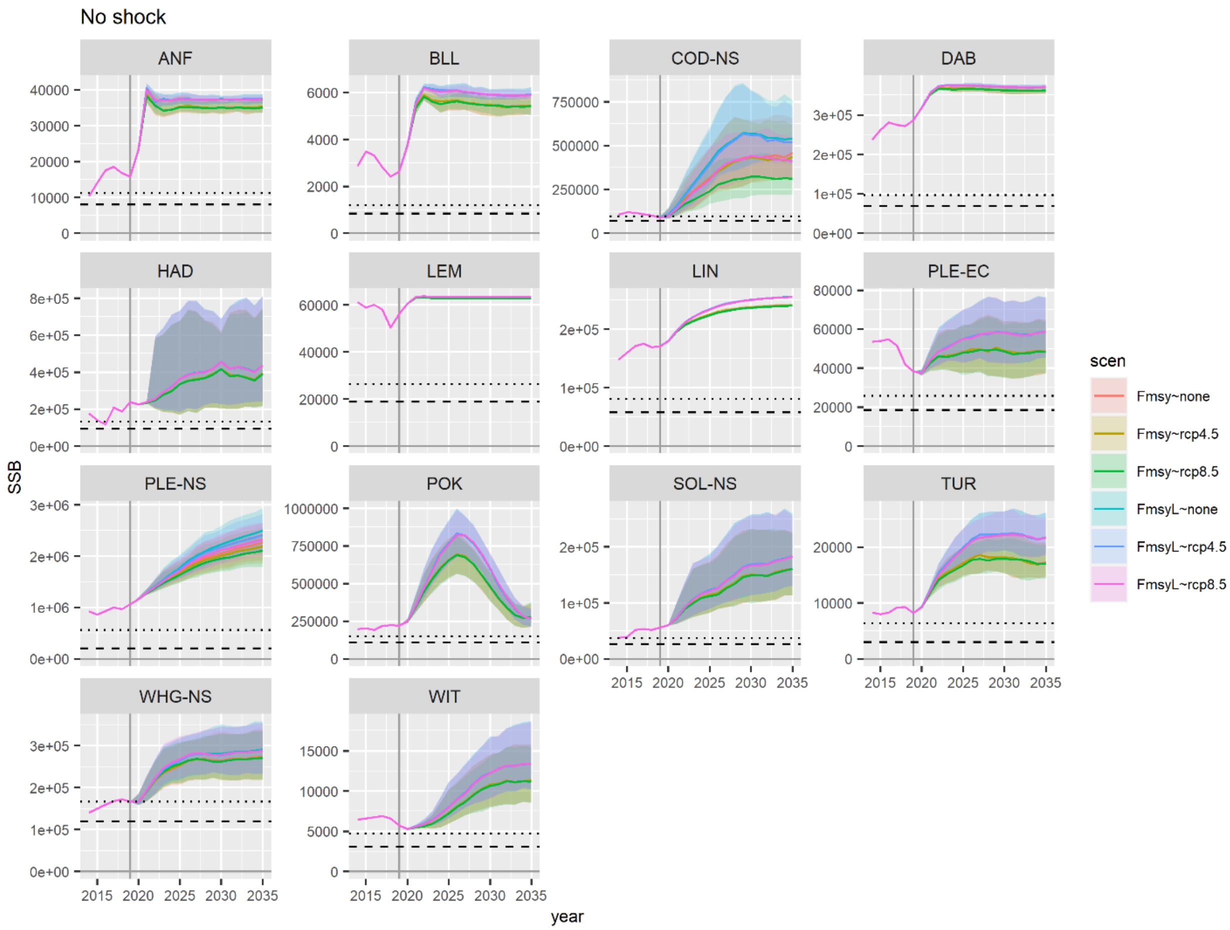

Figure 24 Spawning stock biomass (SSB) by stock, climate change projection, and target F under scenarios without recruitment shocks. Solid grey reference lines indicate zero (horizontal) and the starting projection year (2019). Horizontal black lines denote Btrigger (dotted) and Blim (dashed) reference points for each stock. For each scenario ("scen"), shaded and coloured areas show the 5% and 95% quantiles and solid coloured lines show the median of all runs (n = 100). Scenario ID format is *HCR~CC* (see Table 2 for details).

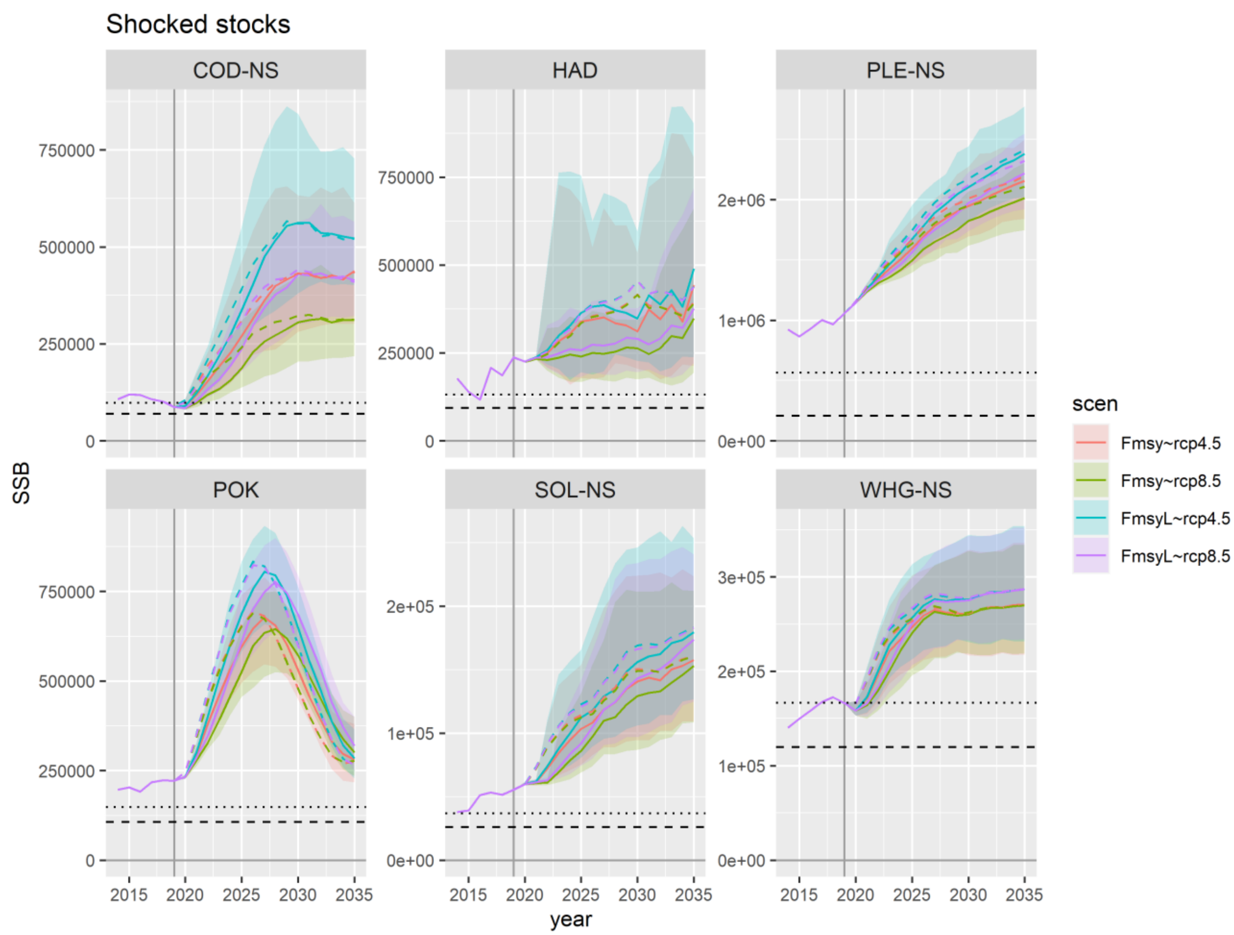

Figure 25 Spawning stock biomass (SSB) by stock, climate change projection, and target F under scenarios with recruitment shock. Solid grey reference lines indicate zero (horizontal) and the starting projection year (2019). Horizontal black lines denote Btrigger (dotted) and Blim (dashed) reference points for each stock. For each scenario ("scen"), shaded and coloured areas show the 5% and 95% quantiles and solid coloured lines show the median of all runs (n = 100). Dashed coloured lines show the respective median of scenarios without shocks. Scenario ID format is *HCR~CC* (see Table 2 for details).

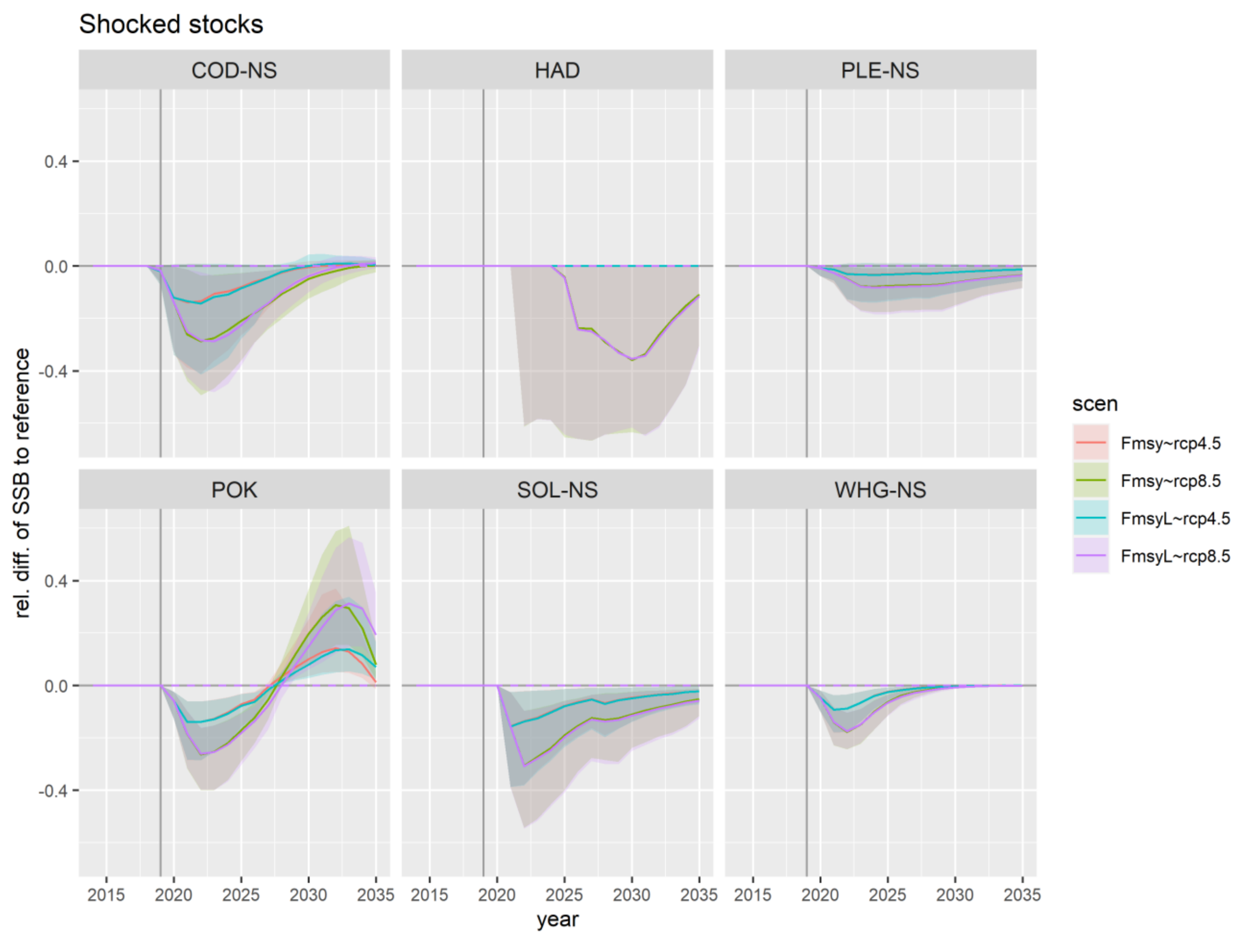

Figure 26 Relative spawning stock biomass (SSB) by stock, climate change projection, and target F for shocked stocks, as compared to their non-shock runs. Solid grey reference lines indicate zero relative SSB (horizontal) and the starting projection year (2019). For each scenario ("scen"), shaded and coloured areas show the 5% and 95% quantiles and solid coloured lines show the median of all runs (n = 100). Scenario ID format is *HCR~CC* (see Table 2 for details).

Resistance

Amplitude

Generally, impacts to spawning stock biomass (SSB) trajectories of the shocked stock were most apparent in the years immediately following the shock, with longer-term SSB recovering to near the levels of the corresponding non-shock runs by 2030 (Figure 26). The amplitude of shocks by scenario are provided in Table 22. The amplitude of change in SSB is less than that of the recruitment shock because SSB reflects an aggregate size of several cohorts, not just the ones that were anomalously low through the recruitment shock. The relatively high recruitment variability for HAD, combined with the lack of strong recruitment events, results in a high degree of variability in SSB as compared to the non-shocked scenarios. Median relative SSB gradually declines by ca. -40% by 2030.

Collateral impacts to the SSB of other stocks were generally very small (Figure 27), and were only really apparent when shocks were to stocks that may have some influence on the choking behaviour of fleets. This is most noticeable when the shock was to COD-NS, which is a main choking stock to many of the fleets, although the impact to the SSB of collateral stocks was on the order of +/- 10% or lower (Figure 28). However, the impact to short-term catches was of a higher magnitude (Figure 29).

The reason for these catch increases in the years following the recruitment shock stems from the fact that the COD-NS quotas were estimated based on assumptions of higher incoming cohort sizes and a certain expectation about the age composition of the catch. The consequence of a reduction in numbers from the incoming recruits is that a higher number of catches from older age classes are required in order to take up the advised quota. This translates to a higher fishing effort by fleets typically choked by COD-NS, which is the overwhelming majority. Thus, the median fishing effort across fleets increased 18-25% in 2020, which resulted in median catches increasing by 15-21% (Figure 30). The opposite response is seen thereafter, whereby the expectation of future recruitment (based on the average recruitment of the last 3 years) is more pessimistic, given that the shock value is included. In both the over-shoot and the subsequent under-shoot there is a mismatch between the perceived fishing effort required for a given target F (and quota) versus the realized F. This mismatch is due to differences between the predicted and true state of the stock status in the future advice years; e.g. in terms of cohort numbers. In particular, future recruitment is predicted based on the recent historical period, and will likely overestimate numbers for the shock year until the cohort can be first observed in catches and surveys. In cases where the incoming cohort contributes significantly to catches of the stock, as is the case with COD-NS, any mis-specifications about the age-structure of future catches can have large consequences in terms of the effort required to uptake the quota.

It should be noted that the assumptions for future recruitment used by many of the assessments in the North Sea (e.g. *Working group on the assessment of demersal stocks in the North Sea and Skagerrak*, WGNSSK) are typically more sophisticated than a simple 3-year average. For example, stocks assessed with the state-space assessment model (SAM) use a resampling procedure of a larger number of historical recruitment values (e.g. 1998-present) over multiple iterations of the forecast. As a result, anomalous recruitment values may still produce advice mismatches, but the oscillatory nature is likely to be of a lower magnitude.

As expected, worst-case scenarios (RCP 8.5) resulted in larger shock amplitudes, largely due to the recruitment shock being applied to two years rather than a single one in the most-likely (RCP4.5) scenarios. The impacts to SSB are of lower magnitude than the original shocks to recruitment given that SSB reflects changes across a wider number of cohorts, thus dampening the shock signal to some degree.

Table 22 Summary of mean shock amplitude for shocked stocks. Values represent the mean percentage change in SSB relative to the SSB of their respective non-shock scenarios. Only responses of stocks to their own shock are shown.

HCR	Scenario type	COD-NS	HAD	PLE-NS	POK	SOL-NS	WHG-NS
Fmsy	most likely (rcp4.5)	-17.5	0.0	-4.4	-15.5	-17.2	-9.7
Fmsy	worst case (rcp8.5)	-27.8	-45.0	-8.8	-26.9	-30.3	-17.6
FmsyL	most likely (rcp4.5)	-17.7	0.0	-4.6	-15.5	-17.3	-9.6
FmsyL	worst case (rcp8.5)	-27.9	-44.2	-9.2	-26.7	-30.5	-17.4

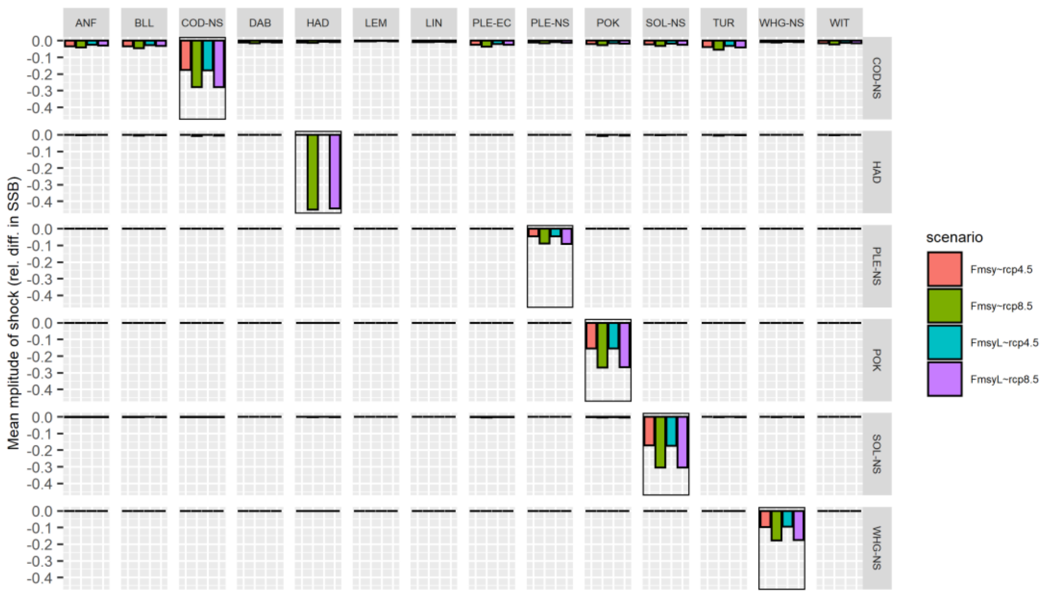

Figure 27 Amplitude of shock in terms of changes in relative SSB as compared to their respective non-shock scenarios. Bar colours show the amplitude of the change by target F and climate change scenarios. Facets separate values according to shocked stock scenarios (vertical) and the responses to all stocks (horizontal). Black boxes highlight values for the shocked stock. Scenario ID format is *HCR~CC* (see Table 2 for details).

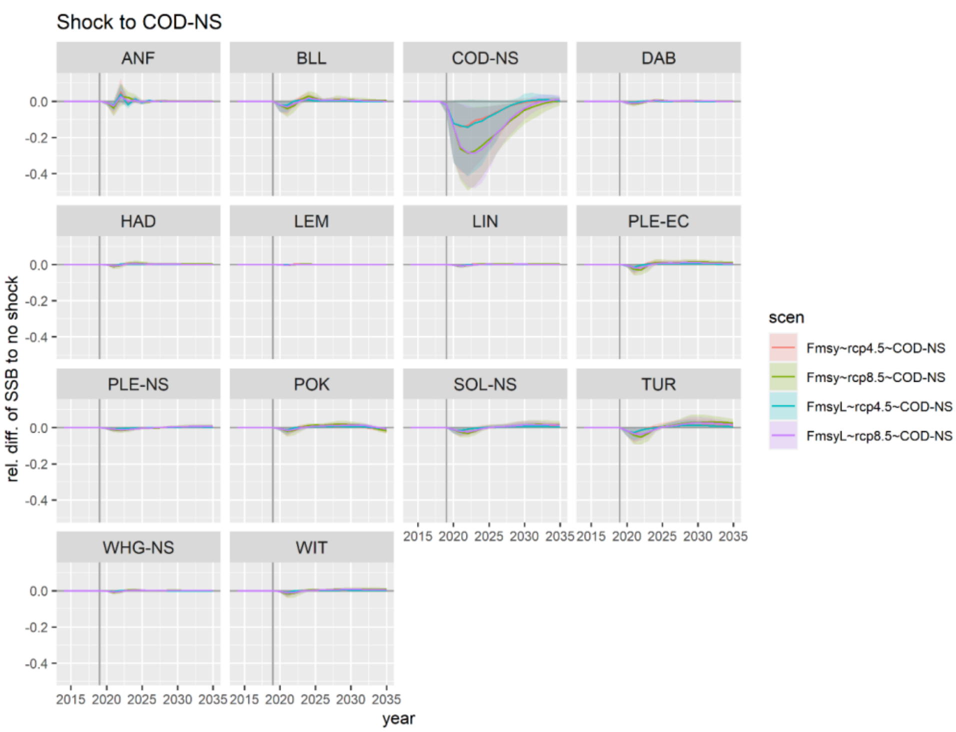

Figure 28 Relative spawning stock biomass (SSB) by stock, climate change projection, and target F under scenarios with recruitment shock to COD-NS as compared to their respective non-shock scenarios. Solid grey reference lines indicate zero (horizontal) and the starting projection year (2019). For each scenario ("scen"), shaded and coloured areas show the 5%

and 95% quantiles and solid coloured lines show the median of all runs (n = 100). Scenario ID format is *HCR~CC~Shocked_stock* (see Table 2 for details).

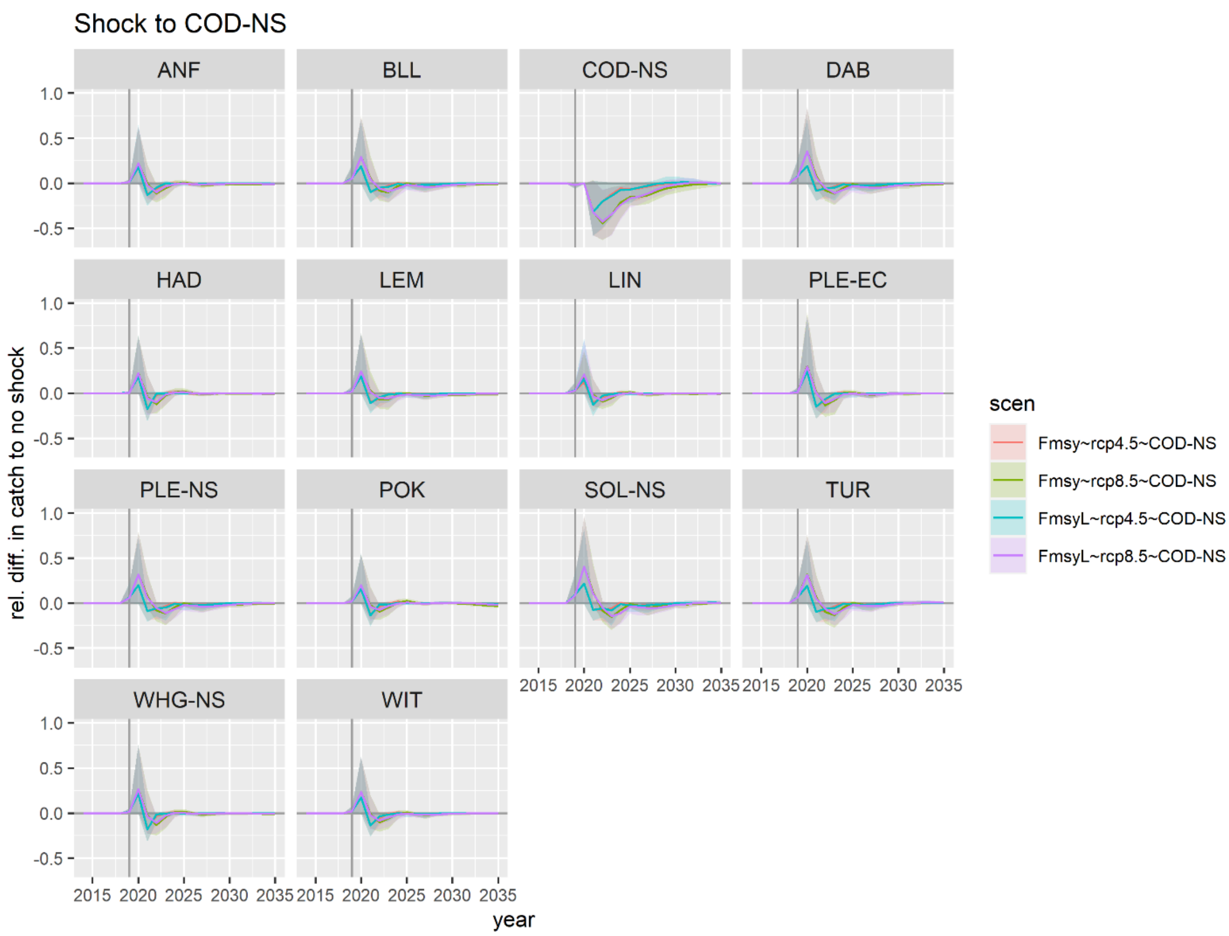

Figure 29 Relative catch by stock, climate change projection, and target F under scenarios with recruitment shock to COD-NS as compared to their respective non-shock scenarios. Solid grey reference lines indicate zero (horizontal) and the starting projection year (2019). For each scenario ("scen"), shaded and coloured areas show the 5% and 95% quantiles and solid coloured lines show the median of all runs (n = 100). Scenario ID format is *HCR~CC~Shocked_stock* (see Table 2 for details).

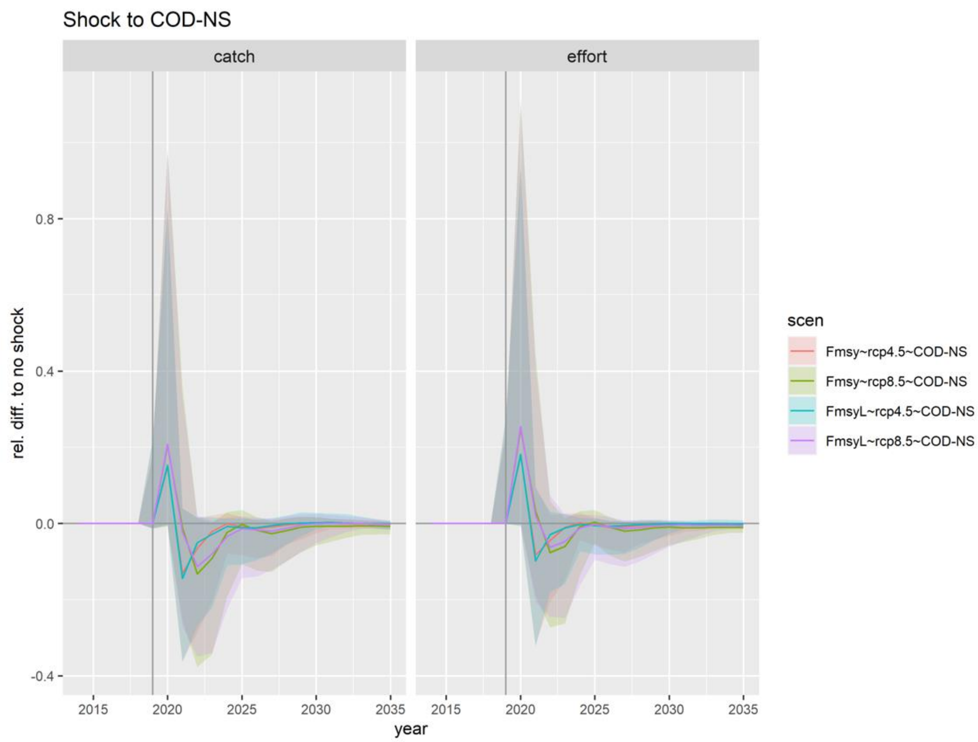

Figure 30 Relative fleet catch and effort by climate change projection and target F under scenarios with recruitment shock to COD-NS as compared to their respective non-shock scenarios. Solid grey reference lines indicate zero (horizontal) and the starting projection year (2019). For each scenario ("scen"), shaded and coloured areas show the 5% and 95% quantiles and solid coloured lines show the median of all runs (n = 100). Scenario ID format is *HCR~CC~Shocked_stock*.

1.1.1 Responsiveness

Since shock impacts to collateral stocks were relatively minor, measurement of their responsiveness, which we define as the time between the shock and the minimum relative SSB, is less informative. We therefore only present the responsiveness indicators for shocked stocks (Table 23). As expected, responsiveness was slightly longer in the worst-case scenarios due to two years of poor recruitment rather than a single year in the most-likely scenarios. Variation among stocks is likely to related to several factors, including each stock's life history and exploitation rate. For example, the longer responsiveness of PLE-NS is likely related to its relatively low exploitation and lower scope for growth, since it is closer to equilibrium. The higher responsiveness of the other shocked stocks reflects their status of being near full exploitation. The longer responsiveness of HAD is due to the impact being cumulative in nature; i.e. the lack of recruitment pulses for a ten-year period.

Table 23 Summary of mean responsiveness by scenario for each shocked stock. Responsiveness is defined as the time (years) from the shock (2019) to min of the relative SSB for the corresponding nom-shock scenario.

HCR	Scenario type	COD-NS	HAD	PLE-NS	POK	SOL-NS	WHG-NS
Fmsy	most likely (rcp4.5)	3.3	-	4.2	2.6	2.2	2.1
Fmsy	worst case (rcp8.5)	3.5	7.0	5.5	3.1	3.1	3.0

FmsyL	most likely (rcp4.5)	3.7	-	4.2	2.6	2.2	2.1
FmsyL	worst case (rcp8.5)	3.8	7.0	5.6	3.2	3.2	3.0

Biological risk

The risk in SSB dropping below Btrigger is confined to the initial years of the forecast, and only for those stocks that are below Btrigger at the start of the simulation in 2019 (COD-NS and WHG-NS). This risk quickly dissipates under the "min" fleet effort control setting, allowing SSB to quickly recover to sustainable levels (Figure 31).

Figure 31 Biological risk by year in terms of probability that SSB is below Btrigger. Coloured lines show risk by target F and climate change scenarios based on 100 model runs. Facets separate values according to shocked stock scenarios (vertical) and the responses to all stocks (horizontal). Black boxes highlight values for the shocked stock. Scenario ID format is *HCR~CC* (see Table 2 for details).

The originally-defined indicator for risk, Max(P(SSB<Btrigger)), quantifies the ***maximum*** probability that SSB is below Btrigger, where the maximum (of the annual probabilities) is taken over *ny* years (e.g. 2019-2030). Using the terminology of WKGMSE (2019a), we will refer to this probability as "Prob3". A less conservative measure of risk is "Prob1", which is the ***mean*** probability that SSB is below Btrigger, where the mean (of the annual probabilities) is taken over *ny* years. Table 24 summarizes the results according to these risk indicators, both for the entire forecast period (2019-2030) as well as for only the final five years of the forecast (2026-2030). The results show that the risk to SSB in COD-NS and WHG-NS is confined to the initial years of the forecasts, which decreases to zero after 2025. Risk exists for both stocks independent of whether they are shocked due to their initial status of SSB <

Btrigger, but shocks only slightly increase this risk during the initial forecast years. As expected, risk is higher during the worst-case scenarios, and risk is somewhat reduced when FmsyL is used as a target, allowing for quicker recoveries.

Table 24 Probability of SSB < Btrigger for COD-NS and WHG-NS under different shock scenarios. Probabilities shown include mean annual (*Prob1*) and maximum annual (*Prob3*). The probabilities are shown for the full forecast period (2019-2030) and for the last five-year period (2026-2030).

Stock	HCR	Scenario type	Shock	Prob1	Prob3	Prob1 (>=2026)	Prob3 (>=2026)
COD-NS	Fmsy	most likely (rcp4.5)	COD-NS	0.166	1.00	0	0
COD-NS	Fmsy	most likely (rcp4.5)	HAD	0.096	0.95	0	0
COD-NS	Fmsy	most likely (rcp4.5)	PLE-NS	0.117	0.99	0	0
COD-NS	Fmsy	most likely (rcp4.5)	POK	0.117	0.99	0	0
COD-NS	Fmsy	most likely (rcp4.5)	SOL-NS	0.117	0.99	0	0
COD-NS	Fmsy	most likely (rcp4.5)	WHG-NS	0.117	0.99	0	0
COD-NS	Fmsy	worst case (rcp8.5)	COD-NS	0.211	1.00	0	0
COD-NS	Fmsy	worst case (rcp8.5)	HAD	0.127	1.00	0	0
COD-NS	Fmsy	worst case (rcp8.5)	PLE-NS	0.127	1.00	0	0
COD-NS	Fmsy	worst case (rcp8.5)	POK	0.127	1.00	0	0
COD-NS	Fmsy	worst case (rcp8.5)	SOL-NS	0.127	1.00	0	0
COD-NS	Fmsy	worst case (rcp8.5)	WHG-NS	0.127	1.00	0	0
COD-NS	FmsyL	most likely (rcp4.5)	COD-NS	0.158	1.00	0	0
COD-NS	FmsyL	most likely (rcp4.5)	HAD	0.096	0.95	0	0
COD-NS	FmsyL	most likely (rcp4.5)	PLE-NS	0.117	0.99	0	0
COD-NS	FmsyL	most likely (rcp4.5)	POK	0.117	0.99	0	0
COD-NS	FmsyL	most likely (rcp4.5)	SOL-NS	0.117	0.99	0	0
COD-NS	FmsyL	most likely (rcp4.5)	WHG-NS	0.117	0.99	0	0
COD-NS	FmsyL	worst case (rcp8.5)	COD-NS	0.186	1.00	0	0
COD-NS	FmsyL	worst case (rcp8.5)	HAD	0.122	1.00	0	0
COD-NS	FmsyL	worst case (rcp8.5)	PLE-NS	0.122	1.00	0	0

COD-NS	FmsyL	worst case (rcp8.5)	POK	0.122	1.00	0	0
COD-NS	FmsyL	worst case (rcp8.5)	SOL-NS	0.122	1.00	0	0
COD-NS	FmsyL	worst case (rcp8.5)	WHG-NS	0.122	1.00	0	0
WHG-NS	Fmsy	most likely (rcp4.5)	COD-NS	0.140	1.00	0	0
WHG-NS	Fmsy	most likely (rcp4.5)	HAD	0.142	1.00	0	0
WHG-NS	Fmsy	most likely (rcp4.5)	PLE-NS	0.137	1.00	0	0
WHG-NS	Fmsy	most likely (rcp4.5)	POK	0.137	1.00	0	0
WHG-NS	Fmsy	most likely (rcp4.5)	SOL-NS	0.137	1.00	0	0
WHG-NS	Fmsy	most likely (rcp4.5)	WHG-NS	0.186	1.00	0	0
WHG-NS	Fmsy	worst case (rcp8.5)	COD-NS	0.137	1.00	0	0
WHG-NS	Fmsy	worst case (rcp8.5)	HAD	0.135	1.00	0	0
WHG-NS	Fmsy	worst case (rcp8.5)	PLE-NS	0.135	1.00	0	0
WHG-NS	Fmsy	worst case (rcp8.5)	POK	0.135	1.00	0	0
WHG-NS	Fmsy	worst case (rcp8.5)	SOL-NS	0.135	1.00	0	0
WHG-NS	Fmsy	worst case (rcp8.5)	WHG-NS	0.228	1.00	0	0
WHG-NS	FmsyL	most likely (rcp4.5)	COD-NS	0.139	1.00	0	0
WHG-NS	FmsyL	most likely (rcp4.5)	HAD	0.142	1.00	0	0
WHG-NS	FmsyL	most likely (rcp4.5)	PLE-NS	0.136	1.00	0	0
WHG-NS	FmsyL	most likely (rcp4.5)	POK	0.136	1.00	0	0
WHG-NS	FmsyL	most likely (rcp4.5)	SOL-NS	0.136	1.00	0	0
WHG-NS	FmsyL	most likely (rcp4.5)	WHG-NS	0.183	1.00	0	0
WHG-NS	FmsyL	worst case (rcp8.5)	COD-NS	0.134	1.00	0	0
WHG-NS	FmsyL	worst case (rcp8.5)	HAD	0.132	1.00	0	0
WHG-NS	FmsyL	worst case (rcp8.5)	PLE-NS	0.132	1.00	0	0
WHG-NS	FmsyL	worst case (rcp8.5)	POK	0.132	1.00	0	0
WHG-NS	FmsyL	worst case (rcp8.5)	SOL-NS	0.132	1.00	0	0
WHG-NS	FmsyL	worst case (rcp8.5)	WHG-NS	0.215	1.00	0	0

Resilience

Resilience indicators measure the rate and speed of recovery. We confine these metrics to shock scenarios involving recruitment decreases, i.e. not including HAD scenarios involving the suppression of recruitment pulses.

Recovery rate

Recovery rate was defined as the probability of SSB > Btrigger in 2030. Again, since this was 100% for all stocks under all shock scenarios, an alternate measure was the probability of SSB to be greater than -5% of their corresponding non-shock (i.e. with climate change) scenarios in 2030 (Table 25).

WHG-NS and POK were seen to fully recover to the SSB levels of their non-shock reference scenarios. WHG-NS likely benefits from a relatively smaller recruitment shock than the other stocks (-34%. In the case of POK, the shock introduces a lag in the oscillatory pattern for SSB, which stems from the density-dependent properties of its Ricker-type SRR, which suppresses recruitment under high SSB levels. As a result, the SSB peak in the shock scenarios begins later in the forecast, resulting in higher 2030 values than their non-shock scenarios.

Table 25 Recovery rates (probability) of shocked stocks by scenario. Recovery rate is defined as the probability that SSB is greater than -5% of the non-shock scenario SSB.

Stock	HCR	Scenario type	Shock	Recovery rate (probability)
COD-NS	Fmsy	most likely (rcp4.5)	COD-NS	0.96
COD-NS	Fmsy	worst case (rcp8.5)	COD-NS	0.51
COD-NS	FmsyL	most likely (rcp4.5)	COD-NS	0.99
COD-NS	FmsyL	worst case (rcp8.5)	COD-NS	0.63
PLE-NS	Fmsy	most likely (rcp4.5)	PLE-NS	0.82
PLE-NS	Fmsy	worst case (rcp8.5)	PLE-NS	0.35
PLE-NS	FmsyL	most likely (rcp4.5)	PLE-NS	0.76
PLE-NS	FmsyL	worst case (rcp8.5)	PLE-NS	0.33
POK	Fmsy	most likely (rcp4.5)	POK	1.00
POK	Fmsy	worst case (rcp8.5)	POK	1.00
POK	FmsyL	most likely (rcp4.5)	POK	1.00
POK	FmsyL	worst case (rcp8.5)	POK	1.00

SOL-NS	Fmsy	most likely (rcp4.5)	SOL-NS	0.55
SOL-NS	Fmsy	worst case (rcp8.5)	SOL-NS	0.13
SOL-NS	FmsyL	most likely (rcp4.5)	SOL-NS	0.51
SOL-NS	FmsyL	worst case (rcp8.5)	SOL-NS	0.12
WHG-NS	Fmsy	most likely (rcp4.5)	WHG-NS	1.00
WHG-NS	Fmsy	worst case (rcp8.5)	WHG-NS	1.00
WHG-NS	FmsyL	most likely (rcp4.5)	WHG-NS	1.00
WHG-NS	FmsyL	worst case (rcp8.5)	WHG-NS	1.00

Recovery speed

Consistent with recovery rate, recovery speed estimates the time needed to recover to SSB greater than 95% of their corresponding non-shock (i.e. with climate change) scenarios. Since individual iterations may not cross this threshold within the timeframe of the forecasts (i.e. 2035), which makes for difficulties in the calculation of mean recovery speed, we present recovery speeds relating to the trajectory of the median relative SSB for each scenario (Table 26).

Biological differences among stocks (e.g. recruitment age, maturity ogives, mortality) will affect the speed at which shocks become visible in the SSB trajectories. Thus, the classification of a recovery is restricted to those years after the minimum relative SSB was observed. For example, since POK recruits at age 3, the impact of a recruitment shock in 2019 will be observed at the earliest in 2021. For most other stocks, the recruitment is age 1. However, delays between a cohort's recruitment and its contribution to the stock's SSB may further influence the lag in the observed impact to SSB. By not taking this lag into account, a recovery may be identified too early, before the full impact of the shock is realized. Finally, recovery speed is measured as the time since the beginning of the recruitment shock (2019), independent of whether the shock duration was 1 or 2 years.

The results of recovery speed reflect largely those of recovery rates, whereby longer recovery speeds are related to lower recovery probability by 2030. Longest median recovery speeds were observed for the worst-case scenarios of COD, PLE-NS and SOL-NS, with SOL-NS failing to recover by 2035 in a majority of the iterations. The minimum relative SSB was most lagged for PLE-NS, which was 5 years after the shock (both for most-likely and worst-case scenarios).

Table 26 Recovery speed was defined time required for the median relative difference in SSB to return to greater than 95% of their respective non-shock scenario.

Stock	HCR	Scenario type	Shock	min. rel. diff. SSB year*	recovery year	recovery speed (years since shock)
COD-NS	Fmsy	most likely (rcp4.5)	COD-NS	2021	2027	8

COD-NS	Fmsy	worst case (rcp8.5)	COD-NS	2022	2030	11
COD-NS	FmsyL	most likely (rcp4.5)	COD-NS	2022	2027	8
COD-NS	FmsyL	worst case (rcp8.5)	COD-NS	2023	2030	11
PLE-NS	Fmsy	most likely (rcp4.5)	PLE-NS	2024	2025	6
PLE-NS	Fmsy	worst case (rcp8.5)	PLE-NS	2024	2032	13
PLE-NS	FmsyL	most likely (rcp4.5)	PLE-NS	2024	2025	6
PLE-NS	FmsyL	worst case (rcp8.5)	PLE-NS	2024	2033	14
POK	Fmsy	most likely (rcp4.5)	POK	2021	2027	8
POK	Fmsy	worst case (rcp8.5)	POK	2022	2028	9
POK	FmsyL	most likely (rcp4.5)	POK	2022	2027	8
POK	FmsyL	worst case (rcp8.5)	POK	2022	2028	9
SOL-NS	Fmsy	most likely (rcp4.5)	SOL-NS	2021	2030	11
SOL-NS	Fmsy	worst case (rcp8.5)	SOL-NS	2022	-	-
SOL-NS	FmsyL	most likely (rcp4.5)	SOL-NS	2021	2030	11
SOL-NS	FmsyL	worst case (rcp8.5)	SOL-NS	2022	-	-
WHG-NS	Fmsy	most likely (rcp4.5)	WHG-NS	2021	2024	5
WHG-NS	Fmsy	worst case (rcp8.5)	WHG-NS	2022	2026	7
WHG-NS	FmsyL	most likely (rcp4.5)	WHG-NS	2021	2024	5
WHG-NS	FmsyL	worst case (rcp8.5)	WHG-NS	2022	2026	7

Notes: * = year when the relative difference in SSB is at a minimum following (shown only for reference).

DISCUSSION

The results of the study should first and foremost emphasize that all modelled stocks were able to achieve safe SSB levels within the 10-year forecast period using the assumption of a compliance with quota advice limits and a ban on discarding. The absolute SSB levels achieved by the end of the simulation were affected by the climate change scenario for those stocks with recruitment mediation by temperature (PLE-NS and COD-NS). RCP4.5 scenarios did not deviate much from scenarios without climate change over the simulated period; however, RCP8.5 scenarios did show marked effects to the equilibrium SSB of those stocks. All stocks were clearly influenced by the use of the lower FmsyL target, which results in higher SSB at the expense of decreased catches. Increases in SSB under FmsyL scenarios are observed for nearly all stocks given that their exploitation rates are mainly driven by the exploitation of COD-NS, which is the primary choke stock across fleets.

Recruitment shock amplitude was determined based on the distribution of residuals from an 11-year running mean model prediction. Such variation levels are typical for most assessments, which typically assume future recruitment levels based on recent historical changes. Such an approach allows for regime changes through time, and is periodically reviewed to best reflect the current productivity expected for the stock. Even in the few cases where EMSRRs have been developed successfully, such as in the case of COD-NS (Kühn et al., 2021), the fitted relationships are likely to explain long-term variability mainly. Thus, our procedure for defining shocks would seem to be appropriate for defining anomalous recruitment events after accounting for long-term trends. Such levels of variability would be typical to those experienced by stock assessors when defining the likely ranges of expected recruitment in forecasts. By using the outer values within this range, we were able to simulate events that are less expected and thus would represent significant shocks to both the stock as well as to the expectations of managers.

The degree of a given recruitment shock, in terms of a percent deviation, translated to a smaller deviation in terms of SSB. Generally, SSB deviations were on the order of -50% that of the shock for the worst-case, 2-year shocks, due to the fact that SSB reflects an aggregate over several cohorts and will be somewhat dampened by this smoothing out across age classes. Despite this lower amplitude, the time required to recover to levels of the non-shock scenarios can last 5-10 years (on average), with even longer recovery speeds in the worst-case scenarios involving 2 consecutive years of low recruitment. Those stocks with faster recoveries were related to a release of density-dependent effects in the SRR (POK) or a lower shock amplitude (WHG-NS). However, differences in the life history characteristics among stocks may also play a role.

The different shock scenario for HAD involved the lack of strong recruitment pulses over a ten-year period. These periodic pulses are typical for the stock, and important for achieving higher biomass and catches. The lack of recruitment pulses had noticeable impacts to the stock dynamics, with median SSB cumulatively decreasing to ca. -40% of the non-shock scenarios in 2030. Once this shock is removed, the median SSB returned quickly to the reference SSB, recovering to ca. -10% by 2035.

As expected, FmsyL targets were shown to be beneficial for achieving higher SSBs, but this is at the expense of lower catches. Over longer periods, reference points may need to be revised in response to productivity changes associated with climate change effects to recruitment or other processes. For the short- to medium-term, Fmsy targets were sufficient to maintain all stocks above Btrigger when quota limits are respected. In the case of COD-NS, the worst-case scenario predicts a significant decrease in the equilibrium SSB due to the impacts of more-extreme warming of the RCP8.5 conditions, which prevents recoveries to levels expected without any climate changes (e.g. CC = none). This is particularly evident for COD-NS given that the fitted environmentally-mediated stock recruitment relationship (EMSRR) is influenced by several seas surface temperature signals, which show changes even in the period up to 2035 in the RCP8.5 scenario.

Figure 32 presents the impacts of shocks to COD-NS as relative SSB changes versus two different non-shock references. The first (left panel) is a non-shock reference that *includes* the long-term climate changes of the RCP4.5 and RCP8.5 scenarios, which were used in the above metrics of resilience. With this reference, we only observe the influence of the shocks, and normalization occurs by the end of the simulated period. The second (right panel) is also a non-shock reference, but *without* long-term climate changes. This perspective emphasizes both the impacts of the shock and any long-term changes in recruitment due to the climate change. As with Figure 1, this perspective reveals the strong shift in SSB equilibria in the worst-case RCP8.5 scenario. The most-likely climate trajectory of RCP4.5 shows minimal differences to the non-climate change scenarios during the simulated period. Under both RCP4.5 and RCP8.5 conditions, and using both Fmsy targets, SSB is maintained at safe levels during the simulated period up to 2035. However, the trajectories begin to decrease after 2030, emphasizing the continuing need to revise reference points in the future in response to stock-specific changes in productivity.

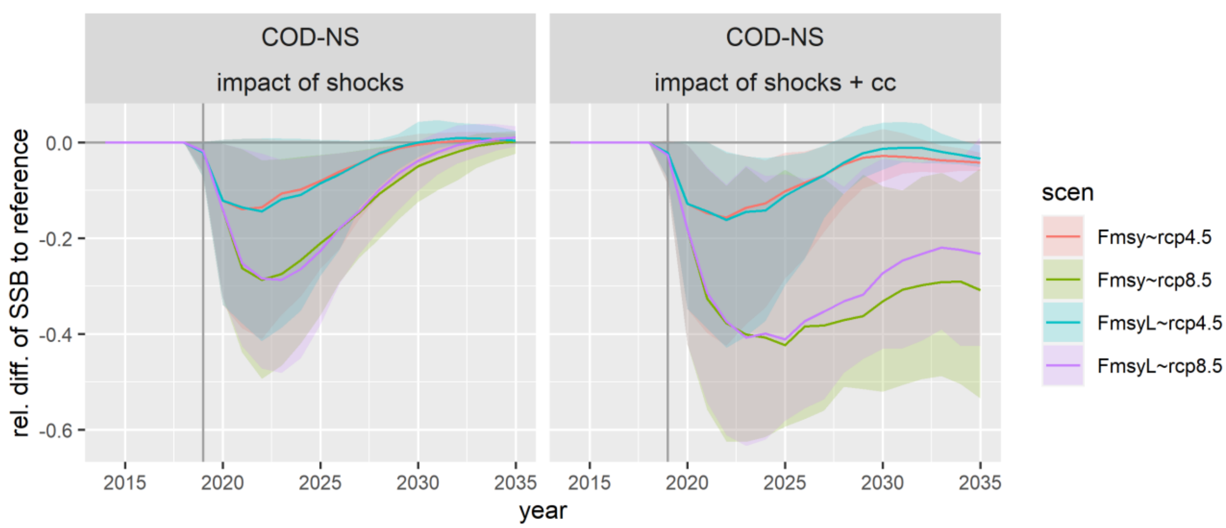

Figure 32 Relative spawning stock biomass (SSB) of COD-NS following recruitment shocks as compared to their respective non-shock scenarios. Trajectories are presented by climate change and target F scenarios. The impact of the shocks alone (left panel) is illustrated by comparing SSB of the shock scenarios to a non-shock reference that includes the long-term climate changes of the RCP4.5 and RCP8.5 scenarios. The impact of the shocks plus climate change effects (right panel) compares to a non-shock reference that excludes the long-term climate changes, emphasizing both the shock impact as well as long-term changes in SSB equilibria.

Solid grey reference lines indicate zero (horizontal) and the starting projection year (2019). For each scenario ("scen"), shaded and coloured areas show the 5% and 95% quantiles and solid coloured lines show the median of all runs (n = 100). Scenario ID format is HCR~CC.

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SUPPLEMENTARY MATERIAL

Environmental-mediated stock-recruitment relationships (EMSRRs)

Table S1: EMSSR models used in the FLBEIA model to inform stock-recruitment

Stock	Functional form	Additional env. Covariates*	Region
Cod	Ricker	$\text{SST.PC1.year}_{lag1}$ $\text{SST.PC2.year}_{lag1}$	North Sea
Whiting	Hockey-Stick	$\text{SST.PC4.DJF}_{lag0}$ $\text{Salinity.PC3.DJF}_{lag0}$ $\text{Currents.PC1.MAM}_{lag0}$	North Sea

		Currents.PC2.MAM$_{lag0}$ Currents.PC2.JJA$_{lag0}$	
Saithe	Ricker	Currents.PC1.DJF$_{lag1}$ Currents.PC2.JJA$_{lag2}$ Currents.PC3.JJA$_{lag3}$	North Sea
Plaice-NS	Beverton-Holt	SSTavg.FM$_{lag1}$	Southern North Sea

Note: *covariate label notation = Covariate name. Principal Component number. season_lag (years).

Projections of environmental variables

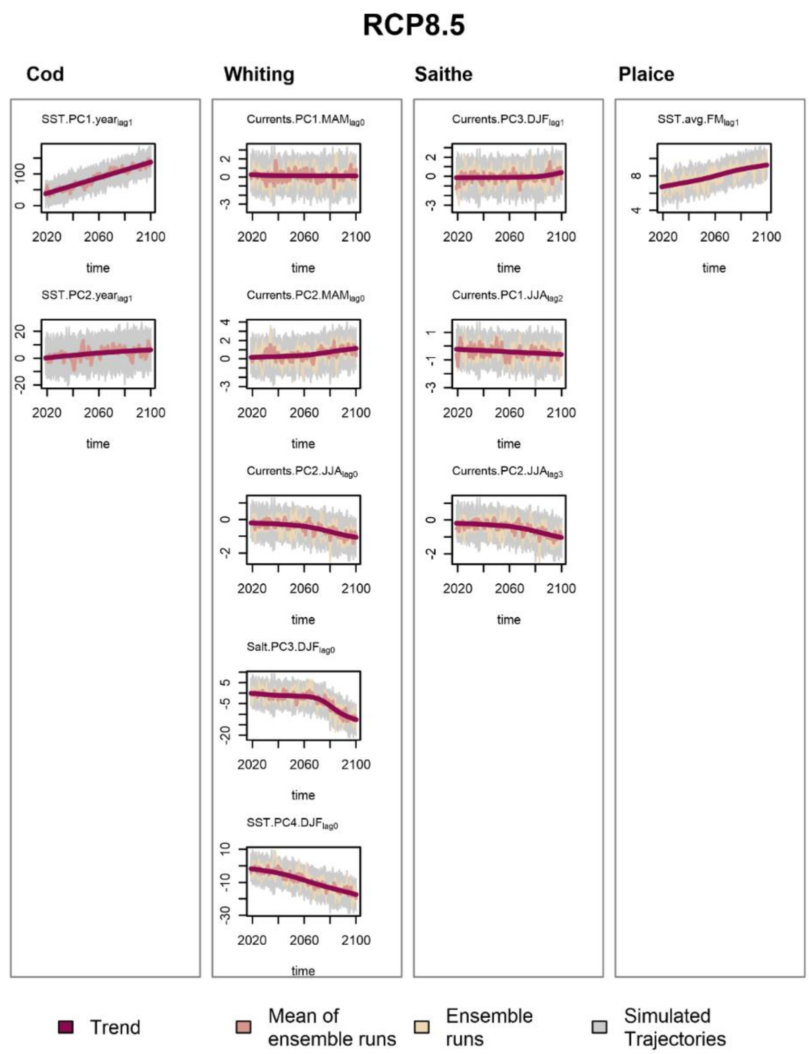

Figure S1: MPIOM environmental covariates for the SRs of cod, whiting, saithe and plaice and the spline-based-trend as well as trajectories simulated used for the stock projections (n = 100), based on the autocorrelation – and variance-structure of the three MPIOM-Ensemble runs

Annex 10 NORTH SEA HERRING STOCK PROJECTIONS UNDER VARIOUS CLIMATE SCENARIOS

INTRODUCTION

North Sea herring assessment

The assessment for North Sea Herring (NSAS) uses commercial and survey data and span the 1947-2020 period. It uses the SAM stock assessment model (Nielsen and Berg, 2014) in a single fleet configuration for the main assessment and a multi-fleet SAM configuration (Nielsen et al., 2021) to inform the forecast on fleet selection patterns. The stock assessment was benchmarked in 2018 (ICES, 2018) and underwent a management strategy evaluation in 2019 (ICES, 2019). Despite the latter, there is no agreed management strategy to date for this stock, and under the ICES framework, the F_{msy} advice rule takes precedence for the advice. A dedicated inter-benchmark was recently performed, focusing o the handling of natural mortality and derivation of new reference points (ICES, 2021a). The latest stock assessment model run is shown in Figure 33. Both the single fleet and multi-fleet models configurations are given in Annex I and II.

Four fleets harvest the North Sea herring stock:

- A fleet: human consumption in the North Sea and Eastern Channel
- B fleet: bycatch of herring (in the sprat fishery) in the North Sea
- C fleet: human consumption in 3.a
- D fleet: bycatch of herring (in the sprat fishery) in the 3.a

The corresponding data for catches at age are available from 1947 but are only disaggregated by fleet from 1997. While most of the catches are from the A-fleet, other fleets are of importance because of the mixing with the Western Baltic spring (WBSS) spawning stock. Also of importance is the selectivity between the different fleets. Whilst the A fleet harvests ages 2+, the fishing pressure from other fleets (B, C and D) is significant for ages 0-1.

The assessment model is informed by 5 surveys:

- IHLS (larvae abundance index, LAI): survey focuses on the early larvae life stage of NSAS and covers the four different stock components: Orkney/Shetland, Buchan, Central North Sea (CNS), Southern North Sea (SNS). The influence of this survey is limited but remain important as it provides information on stock components.
- IBTS-Q1 (age 0): late larvae survey (MIK net) taking place Q1 of each year on all stock components except Downs. This is usually a good indicator of recruitment.
- IBTS-Q1 (age 1): bottom trawl survey takes place Q1 of each year, providing clear information on the survivors to the fishery.
- IBTS-Q3 (age 0-5): bottom trawl survey taking place Q3 of each year
- HERAS (age 2-9+): acoustic survey covering the full extent of the NSAS and WBSS stocks and is conducted yearly in June/July. The derived indices cover age 2+ and are very influential to the stock assessment model.

The observation variance by data source as estimated by the model is shown in Figure 34. The main sources of information are the catches and the HERAS survey over the core ages of the stock (2-6). The reference points as derived during IBPNSherring (ICES, 2021a) are presented in Table 27.

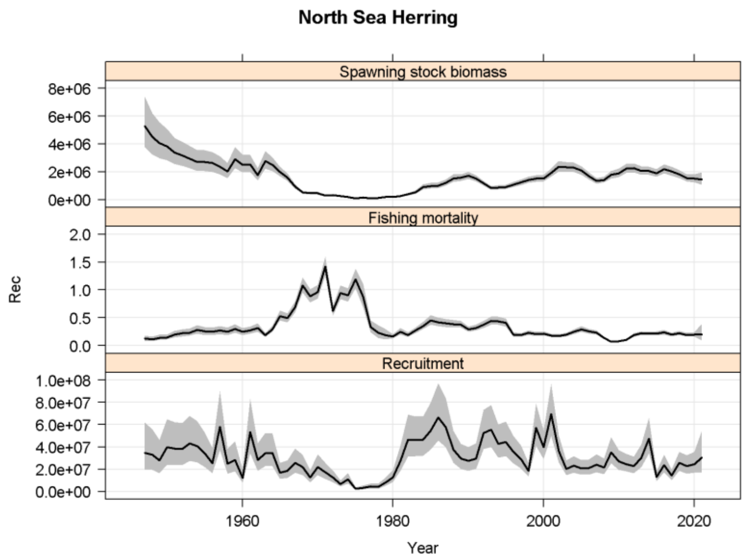

Figure 33 NSAS stock trajectories as estimated by the assessment model.

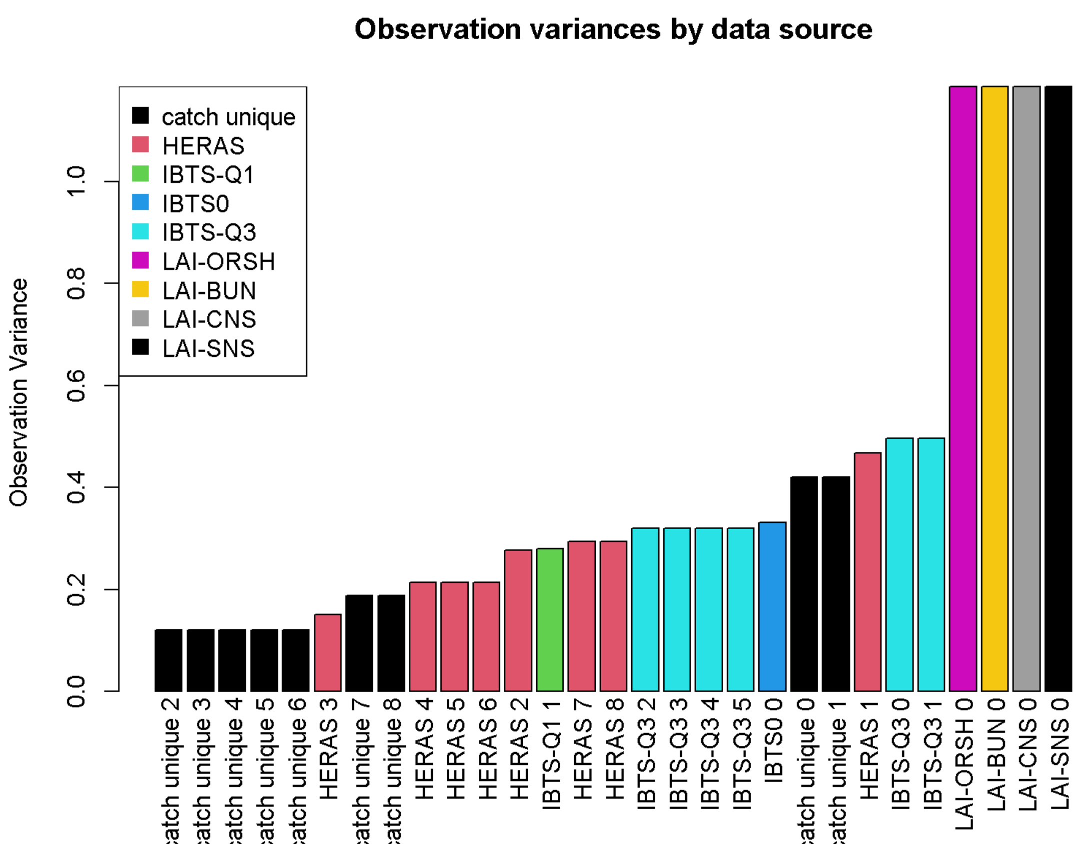

Figure 34 NSAS observation variance by data source as estimated by the assessment model

Table 27 Reference points for the NSAS herring stock.

Framework^	Reference point	Value	Technical basis	Source
MSY approach	MSY $B_{trigger}$	1 232 828	50th percentile of biomass at F_{MSY}	(ICES, 2021a)
	F_{MSY}	0.31	Stochastic simulations (EqSim) with a segmented regression stock–recruitment curve fitted to data from the low productivity period (2002–2020) assuming a break-point at B_{lim}	(ICES, 2021a)
Precautionary approach	B_{lim}	874 198	Breakpoint in the segmented regression of the stock–recruitment time-series (1947–2016, excluding the recovery period 1979–1990)	(ICES, 2021a)a
	B_{pa}	956 483	$B_{pa} = B_{lim} \times \exp(1.645 \times \sigma)$ with $\sigma \approx 0.06$, based on the σ from the terminal assessment year	(ICES, 2021a)
	F_{lim}	0.40	The F that on average leads to B_{lim}	(ICES, 2021a)
	F_{pa}	0.31	The F that provides a 95% probability for SSB to be above B_{lim} (F_{P05} with advice rule [AR])	(ICES, 2021a)

Work scope

A wealth of literature links climate variables to the potential impact on herring stocks. The link with temperature can be variable and is often stock specific. For example, a positive relationship between high temperatures and good recruitment has been observed for the Norwegian Spring Spawning herring stock (Bogstad et al., 2013; Fiksen and Slotte, 2002). In contrast, for North Sea herring, it has been suggested that increased temperature s changed plankton community, in turn impacting herring larval survival (Payne et al., 2009). This was suggested to be a driver of the recruitment regime shift observed around the 2000s. Recruitment was also shown to be correlated with the Atlantic multidecadal oscillation (Gröger et al., 2010). Regarding biological parameters, Brunel and Dickey-Collas (2010) tested the change of van Bertalanffy parameters as a response to climate change across a range of herring stocks, including North sea Autumn Spawners. It was found that temperature correlated negatively with Linf and positively with k. Clausen et al. (2018) identified a negative of climate change on both recruitment and growth (using Calanus finmarchicus abundance as proxy). Hunter et al. (2019) showed a significant relationship in specific areas at specific ages for herring for both growth and maturation (Lp50).

For North sea Autumn Spawning herring, whilst the link between recruitment and temperature change has been shown in several studies, the link with other biological parameters is more tenuous. For this reason, the scope of this study will be limited to modelling the climate effect on recruitment. The effect of short term recruitment shocks will also be investigated. Under the different scenarios, the resistance and resilience of the stock will be tested.

DATA AND METHODS

Model specifications

The modelling employed in this study uses the methodology from WKNSMSE (ICES, 2019). It uses an approach for "full" MSEs (i.e. we did not follow a "short-cut" approach), as described in (ICES, 2013) and (Punt et al., 2016). A flowchart of the approach is provided in Figure 35.

Under the terminology of Figure 35, the Operating Model (OM) represents the true underlying dynamics related to the biology and the fishery, and includes the observation model which adds observation error to OM quantities to derive monitoring data that is passed to the Management Procedure (MP), and the implementation model, which converts the management regulation (e.g. TAC) into a realised catch. The only communication between the OM and MP is through the monitoring data that the OM passes to the MP, and the management regulation that the MP passes back to the OM. The MP consists of an estimation model (e.g. the working group assessment model and forecast procedure), which is used to parameterise the decision model (the management strategy).

A key part of the MSE is the inclusion of uncertainty, and this is introduced through the OM by including parameter estimation error (using e.g. a variance-covariance matrix derived from fitting a model to data,), process error (e.g. in recruitment and survival), observation error (when deriving monitoring data), and implementation error (e.g. introduced by stock mixing and multi-fleet harvesting).

An important principle in our approach is that uncertainty is included in a self-consistent manner. For example, where 1000 replicates are used, each replicate will represent a single parameter set (typically obtained using a variance-covariance matrix) which represents a replicate population and its associated observation and process error parameters. Survival process error will be defined for that replicate and used in projecting its associated population forward in time. Data will be generated from that replicate population based on the observation error parameters for that replicate. In this way, each replicate is self-consistent.

The differences with the MSE model developed during WKNSMSE (ICES, 2019) are as follows:

- A stock-recruitment relationship includes a climate co-variate (sea surface temperature).
- Harvest control rule following the MSY advice rule (as opposed to specific management strategies).
- Inclusion of recruitment shocks.

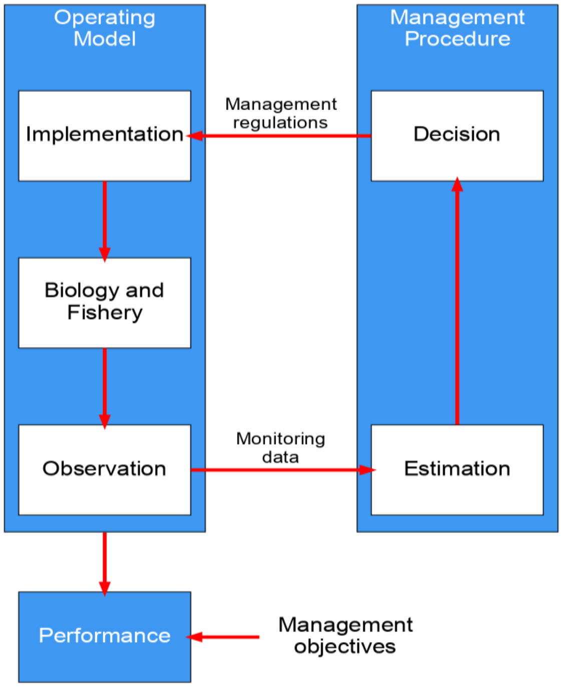

Figure 35 Extracted from (ICES, 2019). A flowchart of the Management Strategy Evaluation approach followed. Extracted from (ICES, 2019).

Climate variable

Central to this study is the inclusion of the effect of climate variables on the stock-recruitment relationship for NSAS herring. To that aim, sea surface temperatures in the North sea are used: bounded to -3<lon<9 and 52<lat<62. These are downloaded from the NOAA physical science laboratory[7] and are available as a mean per month Figure 36. NSAS herring has four different spawning grounds (Dickey-Collas et al., 2010). Three components (Shetland/Orkney, Buchan, Banks) are spawning in September-October, whilst the Downs (southern North Sea) component is spawning in January. In order to strengthen the relationship with sea surface temperature, specific months are selected based on the monthly correlation between SST and NSAS recruitment (Figure 37(a)). This analysis suggested that the correlation is strongest in January, August and September. The temperature used further is the mean over these three months. The SST data are absolute temperature values and these are further normalized in order to yield SST anomalies. This is done by performing a Z-normalization of the SST time series (1947-2020):

[7] https://psl.noaa.gov/cgi-bin/db_search/DBSearch.pl?Dataset=ICOADS+2-degree+Standard&Dataset=ICOADS+2-degree+Enhanced&Variable=Sea+Surface+Temperature

$$SST_{\mathrm{resi}} = \frac{SST - \mathrm{mean}(SST)}{\mathrm{sd}(SST)}. \quad (1)$$

The resulting time series is shown in Figure 37(b). An increase in SST is observable since 2000. Figure 37(c) exemplifies a decrease of NSAS recruitment with increasing SST.

In order to model the effect of climate change on NSAS recruitment, two sets of SST projections are used:

- Intermediate scenario, peak of CO2 emissions in 2040 then decline. This is labelled as the Representative Concentration Pathway 4.5 (RCP45)
- Extreme scenario corresponding to a continuation of CO_2 emissions throughout the 21st century. This is labelled as the Representative Concentration Pathway 8.5 (RCP85)

The predicted SST used here are those from the GFDL-CM3 model from NOAA, with a subset similar to historical values. The GFDL-CM3 model predictions span the 2006-2100 period. In order to calibrate these projections, the 2006-2020 period is used, aligning the mean of the projected time series on the historical time series. The corresponding time series are shown in Figure 38. It is important to note that the RCP45 and RCP85 time series start to diverge at the 2050 horizon. Prior to 2050, the RCP45 scenario yields slightly higher temperature anomalies.

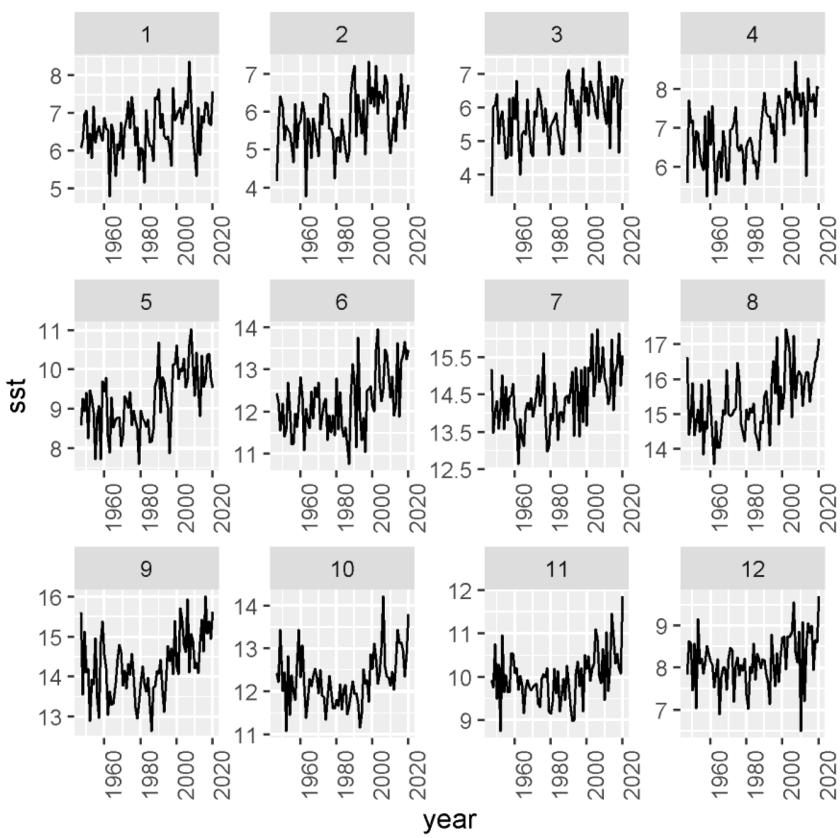

Figure 36 Yearly sea surface temperature across months

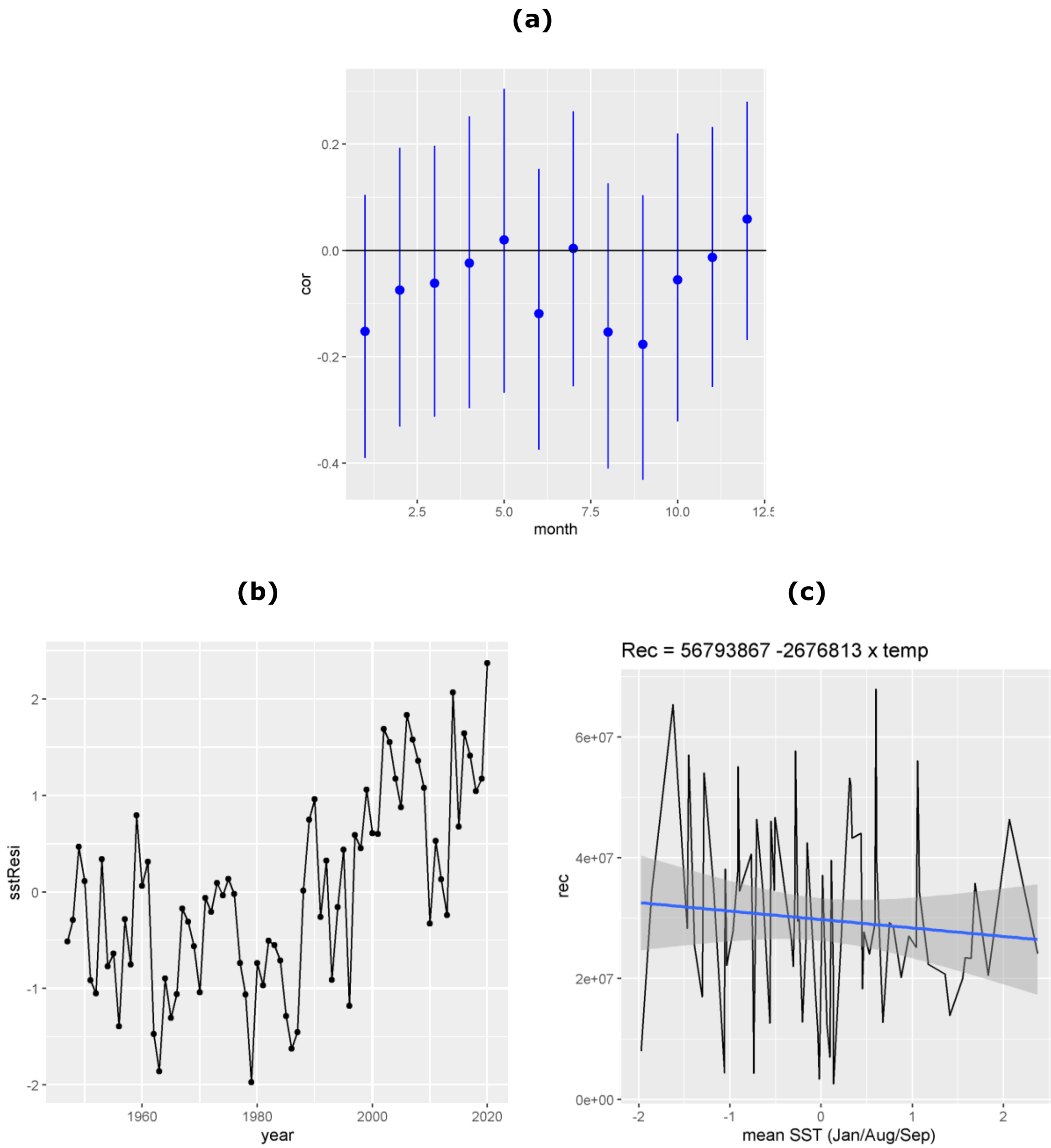

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Figure 37 NSAS recruitment/SST. (a) correlation between NSAS recruitment and SST per month. (b) time series of surface temperature residuals. (c) NSAS recruitment vs mean SST over January/August/September months

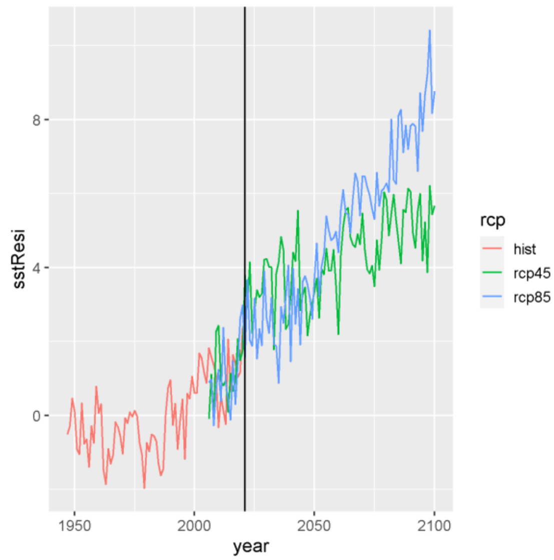


Figure 38 Sea surface temperature projections under different representative concentration pathway scenarios (rcp45 and rcp85). The black vertical line is the starting year of the projections (2021).

Projection of biological parameters

Recruitment: Stock recruitment relationship

Recruits are being added to the future population assuming a Ricker stock-recruitment relationship with a co-variate:

$$R = a \times SSB \times e^{b \times SSB + c \times SST_{\text{resi}}}, \qquad (2)$$

with *a* the density independent parameter, *b* the parameter linked to density dependence and c the parameter linked to the environmental co-variate (here SST). For each model replicate (sampling of parameters using the variance-co-variance matrix), Equation (2) is fitted using the FLSR package with a Nelder-Mead minimizer.

Residuals

Residuals of the fit for each replicate is used to generate future deviations from the stock-recruitment curve. This is modelled using an ARIMA process (stats package in R) to account for auto-correlation in recruitment, following:

X[t] = a[1]X[t-1] + … + a[p]X[t-p] + e[t] + b[1]e[t-1] + … + b[q]e[t-q] (3)

where *X* are recruitment residuals, *t* is time, a and b are the parameters of the autoregressive model, p is number of autoregressive terms, q is the number of lagged errors and e is the error term. The residuals are sampled over the 2002-2020 period, corresponding to the period associated with a shift in productivity (Payne et al., 2009). In the future period, median residuals are expected to be around 0 but do cover the total variation of recruitment residuals observed.

Recruitment shocks

Shocks in recruitment are introduced through altered residuals. For each replicate, the 5% quantile level of the model residuals (R/R_{fitted}) is determined. This value then replaces the recruitment residuals for selected years.

Mean weight at age, maturity, natural mortality and fishing selection patterns

To maintain a certain level of autocorrelation, previously observed natural mortality vectors (all ages at once) are sampled in blocks up to ten years (2010–2020), similar to the low productivity phase for the stock, and glued together until the entire projection period is filled. Additionally, to maintain a degree of correlation between maturity-at-age and weight-at-age (both in the stock and in the fishery), year ranges are shared among these processes. These blocks of years for natural mortality, weight at age and maturity at age are randomized (length of blocks, years in block of years) for each replicate. There is no evidence that M and weight-at-age or maturity-at-age are correlated, and hence M-at-age vectors are drawn separately from the other biological parameters. Catches and survivors in the forecasted years of the stocks are calculated using the (natural and fishing) mortality rates. Pre-smoothed natural mortality estimates from the 2019 SMS key run (ICES, 2021b) are used in the OM.

Fishing mortality may be caused by a variety of fisheries, each associated with different selection patterns and catch targets. The fishing mortality encountered by a stock unit therefore depends on the sum of the fishing mortalities from each fishery.

Each of the fleet catch catching herring exemplifies different selection-at-age patterns. In order to run projections of these selection patterns, those estimated by the multi-fleet assessment are used. The sum of multi-fleet selection is identical to the single-fleet estimated selection. The future selection patterns are assumed to follow an age-correlated random walk (similar to the design in the assessment). Starting from the 2020 estimated selection pattern, each following years' selection is obtained by modelling a change in selection-at-age to the next year. All steps from one year to the next for the entire time series follows a normal distribution with mean 0 and variance estimated based on the covariance of log-transformed F-at-age change (from year y to year y+1) over the years 2010–2020. Steps outside the 95% CI of the distribution were excluded to prevent extreme changes.

Implementation error

In practice, optimisation of the catches in the A-fleet is conditional on the catches from the C- and D-fleets. Both the C-fleet and D-fleet catches are assumed to derive from fixed quotas of 21 604t (WBSS TAC set in 2021) and 6659 t (fixed TAC), respectively, with the C-fleet transferring between 40-50% of its quota to the A-fleet based on the last 10 years' observations. In the A, C and D fleets, however, the catches do not consist of one herring species alone, but contain a mixture of both NSAS (North Sea autumn-spawners) and WBSS (Western Baltic spring-spawners). As the MSE evaluated how precautionary the stocks were to specific management strategies, the mixed nature of the catches has to be accounted for in the simulations.

Over the past 10 years, on average, 34% of the C-fleet catch consists of NSAS and 66% of WBSS. On average, 68% of the D-fleet catch consist of NSAS and 32% of WBSS. The proportion of the A-fleet that comprises WBSS is negligible and is therefore ignored. The impact of this level of mixing for the catches of NSAS in the D-fleet is mimicked in the simulations by assuming that catches of NSAS in this fleet follow a normal distribution with mean equal to the 10-year average mix and variability equal to half the standard deviation (to prevent values smaller or bigger than 1, resulting in values that are in the same range as observed). For the C-fleet, this mixing is encapsulated in the $p_{\text{C-fleet}}$ parameter (see equations below). The utilisation of the B and D fleets is taken into account and simulated by taking a normal distribution with mean equal to the average utilisation and variability half the standard deviation (to prevent values smaller or bigger than 1, resulting in values in the same range as observed). The C-fleet catch after the transfer is derived based on an F-constraint. Analyses of the past 10 years showed that the C-fleet had a varying contribution, though without a trend, in F_{bar} between 1 and 2%.in blocks up to ten years (2010-2020), similar to natural mortality, weight at age and maturity at age. In summary, the catch for each of the fleets is set or derived as follows:

$$\text{CatchNSAS}_C^1 = \text{CatchTot}_\text{C} \cdot \text{Trans}$$

where $\text{CatchTot}_\text{C} = 21604\text{t}\ ; \text{Trans} \sim \text{U}(0.4, 0.5)$

$$\text{CatchNSAS}_C^2 = \text{catch resulting from application of: } p_{\text{C-fleet}} \cdot F_{2-6} \text{ target of the management strategy}$$

where $p_{\text{C-fleet}}$ is the proportion of F for the C-fleet sampled in blocks up to ten years (2007-2017)

$$\text{CatchNSAS}_\text{D} = \text{CatchTot}_\text{D} \cdot \text{Mix}_D \cdot \text{Util}_D$$

where $\text{CatchTot}_\text{D} = 6659\text{ t}\ ;\ \text{Mix}_D \sim \text{N}(0.64, (\sigma_D'/2)^2)\ ; \text{Util}_D \sim \text{N}(\text{mean last 10 years}, (\sigma_D''/2)^2)$

$$\text{CatchNSAS}_\text{B} = \text{CatchTot}_\text{B} \cdot \text{Util}_B$$

where CatchTot_B results from the F_{0-1} target of the management strategy ; $\text{Util}_B \sim \text{N}(\text{mean last 10 years}, (\sigma_B'/2)^2)$

$$\text{CatchNSAS}_\text{A} = \text{Catch resulting from } F_{2-6} \text{ target from the management strategy} + \text{CatchNSAS}_C^1$$

$$\text{CatchNSAS}_\text{Total} = \text{CatchNSAS}_\text{A} + \text{CatchNSAS}_\text{B} + \text{CatchNSAS}_C^2 + \text{CatchNSAS}_\text{D}$$

Evaluation of harvest control rule (HCR) control points

Short term forecast

The perception of the stock unit status in the period after 2020 is generated through the explicit inclusion of stock assessments in the simulation, which is based on fishery-independent (surveys) and -dependent (catch) data.

The stock assessment process results in fishing mortality estimates for year y-1 (the final year of catch data), and survivor and SSB estimates for year y (the intermediate year, i.e. the year during which the assessment is conducted). The assessment output estimates may deviate from the true stock unit characteristics as modelled in the biological operating model because of the observation error associated with the data sources that go into the assessment.

A short-term forecast is used within the MSE to set annual TACs as described below. The short-term forecast for NSAS is similar to the multi-fleet forecast as currently used within the North Sea herring assessment, but ignores any catches that could be realized by the C and D fleet. Through this approach we disconnect the TAC setting procedure for North Sea herring from the Western Baltic TAC setting procedure.

Selectivity by the fleet in the intermediate (y) and advice year (y+1, the year for which the management strategy provides advice) follow the exploitation pattern as estimated within the stock assessment multiplied with the proportional catch numbers by fleet. Recruitment in the advice year (y+1) is fixed to the weighted geometric mean of the period [y–10 : y-1], while recruitment in the intermediate year (y) is taken from the assessment prediction. Stock and catch weight-at-age and time of spawning are similar to the intermediate year settings (i.e. taken from the terminal year of the assessment), while maturity in the intermediate and advice years equals the average maturity estimate over the past three years and natural mortality is averaged over the most recent five years. The exploitation pattern by fleet is scaled up or down to ensure that the catch equals the TAC in the intermediate year. The short-term forecast is an exact replication of the way the short-term forecast is executed in the ICES assessment working group.

However, the proposed TAC is calculated based on numbers, landings selectivity and fleet selectivity obtained from the assessment results which differ from the numbers, landings selectivity and fleet selectivity in the 'true' stocks. Hence, the fishing mortality needed to realise catch equalling the TAC is not identical with the target fishing mortality as set within the management plan. As there is no analytical solution to this equation, an optimisation method is used to calculate 'true' fishing mortality.

ICES harvest control rule

The harvest control rule applied in the MSE model is the ICES approach (applicable for stocks of categories 1 and 2). Because there is no agreed management plan in place for the NSAS herring stock, this approach has been taking precedence in the recent advices issued by ICES. This consists in applying the ICES advice rule (Figure 39(a)). This management strategy is defined by two control points: Btrigger and FMSY. The advice rule with the most recent control points (ICES, 2021a) is plotted in Figure 39 (b) with SSB-recruitment pairs since 2018. It is important to note that whilst in practice rebuilding measures are applicable when the stock falls below Blim, this is not implemented in the hereby MSE model.

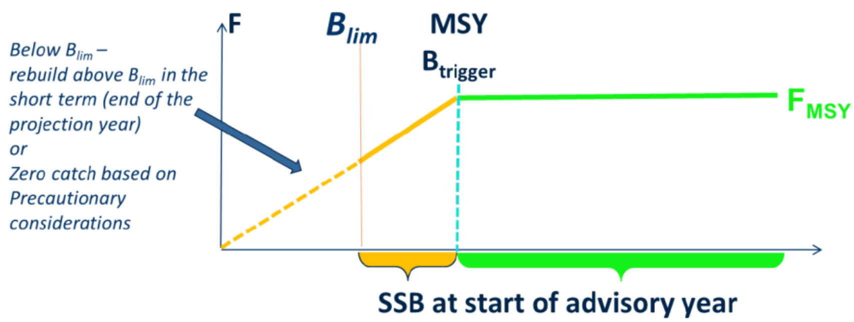
The MSE model developed here is not consistent with the reference points derived during the most recent inter-benchmark (ICES, 2021a) or MSE process (ICES, 2019). This is because the assessment model has been updated in during IBPNSherring (ICES, 2021a) but also because of the alterations in model configuration (see Section 0, most notably the stock recruitment relationship). In order to derive control points consistent with the hereby MSE model, a grid search approach is employed, similarly to WKNSMSE (ICES, 2019).

A grid of F_{target} and $B_{trigger}$ is built by running the MSE model for each combination. For each combination, risk3 (maximum of the annual probabilities of SSB being below B_{lim} for a specified period) is calculated. The optimal combination is the one that maximise long-term yield (in practice lowest $B_{trigger}$ and highest F_{target}) while fulfilling the ICES precautionary criterion (risk3≤5%) in the long term (last 10 years of projection, 2031-2041).

In addition, a set of conservative control points is tested. These alternative reference points are taken from the most conservative eqSim runs from IBPNSherring (ICES, 2021a):

- F_{target} =0.175
- $B_{trigger}$ =1.6*1e06

(a)



(b)

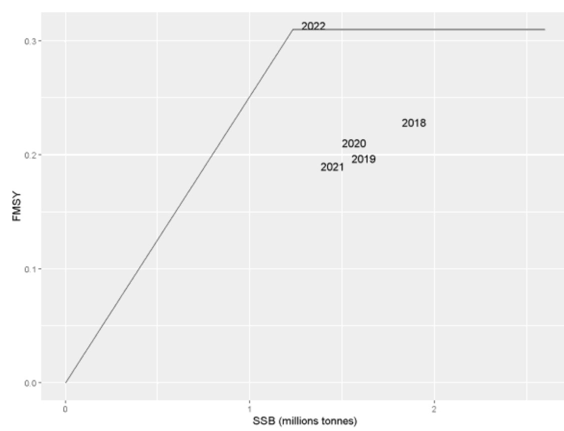


Figure 39(a) ICES advice rule. (b) North Sea herring. FMSY advice rule and SSB/Fbar data point since 2018 (with 2022 as forecast).

Replicates and model projections

The output of the stock assessment model, carried out at ICES (ICES, HAWG, 2018), was used to populate the age-structured (ages 0–8) population model for North Sea Herring. Different replicates for the historical stock numbers at age and fishing mortality-at-age were drawn from a multivariate normal distribution using the variance/covariance matrix estimated using the SAM model with the data available at HAWG 2021 (excluding LAI index). During WKNSMSE (ICES, 2019), it was found that MSE runs with too few replicates introduced a bias in risk3 and in turn the finding of the optima for the grid search. A set of 1000 replicates was deemed conservative. This is Figure 40 where a clear trend in risk 3 is observable with the 200 replicates model run (Figure 40(a)) but not the 1000 replicates model run (Figure 40(b)).

A practical aspect of the MSE model employed here is the computational time. The computational time for a 1000 replicates model run is ~10 hours on a super computer. Computations using 200 replicates decreased the computational time significantly. As a result, the 200 sets of replicates are used for a full Ftarget/Btrigger grid search, while the 1000 set of replicates is used for fine tuning F_{target}/$B_{trigger}$ optima. The final runs use 1000 replicates.

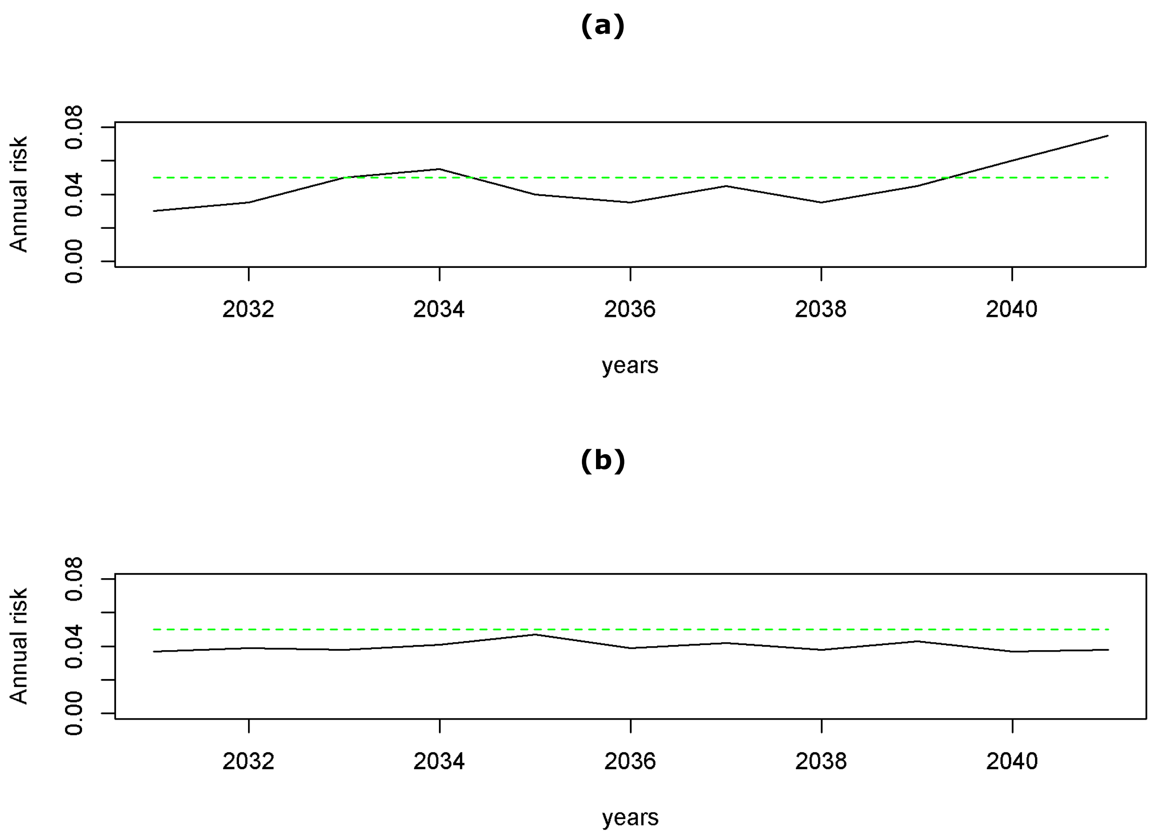


Figure 40 *comparison of annual risk over the 2031-2041 period for the model with 200 iterations (a) and 1000 iterations (b).*

Operating models

For this study, three different operating models are used:

<u>OM1: baseline</u>

- Use of status quo SST (resampled in blocks from the 2010-2020 period)

<u>OM2: rcp45</u>

- Use of the rcp45 SST projections

<u>OM3: rcp85</u>

- Use of the rcp45 SST projections

The different operating models are setup differently with respect to recruitment shocks and HCR control points. A summary of all the runs conducted here is shown in Table 28.

Table 28 ***summary of scenarios.***

Climate effect	OM1 - status quo		OM2 - rcp45		OM3 - rcp85	
Control points	refLow	refHigh	refLow	refHigh	refLow	refHigh
no shock	baseline	baseline	X	X	X	X
1 shock			X	X		
2 shock					X	X

1 Performance metrics

Resistance and resilience to shocks were measured according to several summary metrics in the mixed fishery scenarios. Resistance refers to a stock's ability to withstand perturbations, while resilience refers to the a stock's ability to recover to some pre-disturbance state. The originally-defined metrics are listed in Table 29. In some cases, alternately-defined metrics were used in order to better compare the relative impacts of shocks as compared to a given reference scenario.

Table 29 Resistance and resilience to shocks

Resistance (ability to withstand the perturbation)		
Amplitude	Minimum stock level reached after the shock compared to initial level	$SSB_{min}/SSB_{yearshock}$
Responsiveness	Year at which the minimum stock level is reached after the shock compared to initial level	$Year_{SSBmin}$
Biological risk	Probability of SSB falling below Blim	Max(P(SSB<Blim))
Resistance (ability to withstand the perturbation) relative to no shock scenarios		
Amplitude	Maximum difference with the no shock scenario reached (after the last shock).	$Min(SSB_{shock}/SSB_{noshock})$
Responsiveness	Year at which the maximum difference with the no shock scenario is reached (after the last shock).	$Year(Max(SSB_{shock}/SSB_{noshock}))$
Resilience (ability to recover from the perturbation) relative to management targets		
Recovery rate 2030	Probability that stock level is at MSY Btrigger or above in 2030	$p(SSB_{2030}>=Btrigger)$
Recovery rate 2041	Probability that stock level is at MSY Btrigger or above in 2041	$p(SSB_{2041}>=Btrigger)$
Recovery speed	Year at which one reaches stock levels corresponding to MSY	$Year_{SSB>=Btrigger}$
Resilience (ability to recover from the perturbation) relative to no shock scenarios		
Recovery rate 2030	Probability that stock level is above no shock scenario -5% in 2030	$p(SSB_{2030}>= SSB_{noshock}-5\%)$
Recovery rate 2041	Probability that stock level is above no shock scenario -5% in 2041	$p(SSB_{2041}>= SSB_{noshock}-5\%)$

Resistance (ability to withstand the perturbation)		
Recovery speed	Year at which one reaches stock levels corresponding to no shock scenario - 5%	Year(SSB_{2041}>= $SSB_{noshock}$-5%)

RESULTS

Recruitment with climate covariate parameter

Here, the effect of climate is modelled through the stock recruitment (S-R) relationship with the inclusion of the SST co-variate in a Ricker model (Eq. (2)). Using the outputs of the main assessment model, the S-R can be fitted an evaluated. The results are shown in

Figure 41 and exemplify a satisfying fit. The associated parameter estimates are given in Table 30. The functional form (recruitment vs SST and SSB) of the S-R relationship is plotted in

Figure 42. This relationship follows a negative correlation with SST anomalies. With the MSE model, the S-R is fitted for each replicate using the historical period (1947-2020). The associated parameter estimates are shown in

Figure 43.

Another important aspect of the recruitment modelling is the recruitment residual. As explained in Section 0, the 2010-2020 period is used with an ARIMA process. The resulting residuals are shown in Figure 44(a). For the modelling of recruitment shocks, the residual is fixed at the 5% quantile over all iterations for a given year.

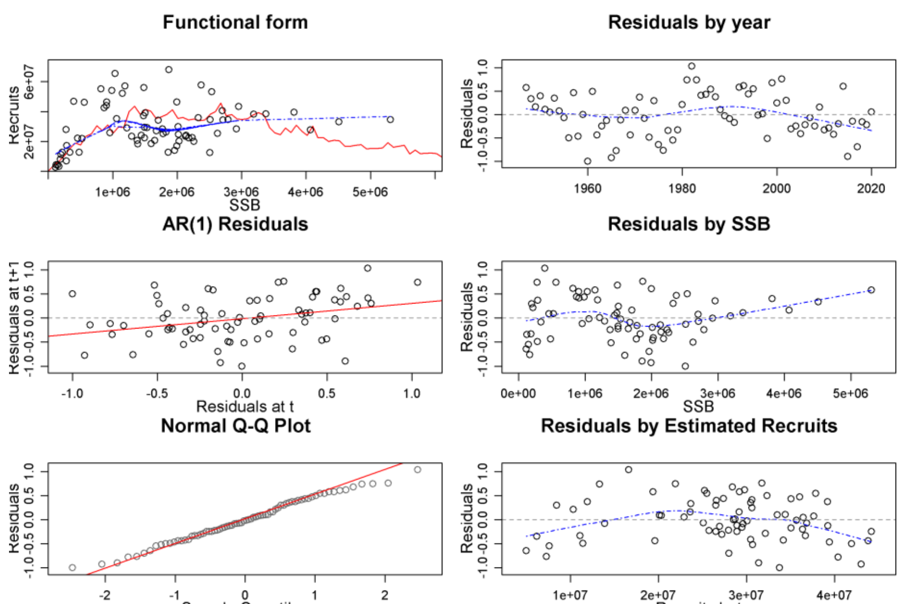


Figure 41 Model fitting of the Ricker stock recruitment relationship with SST as covariate, based on the NSAS stock assessment.

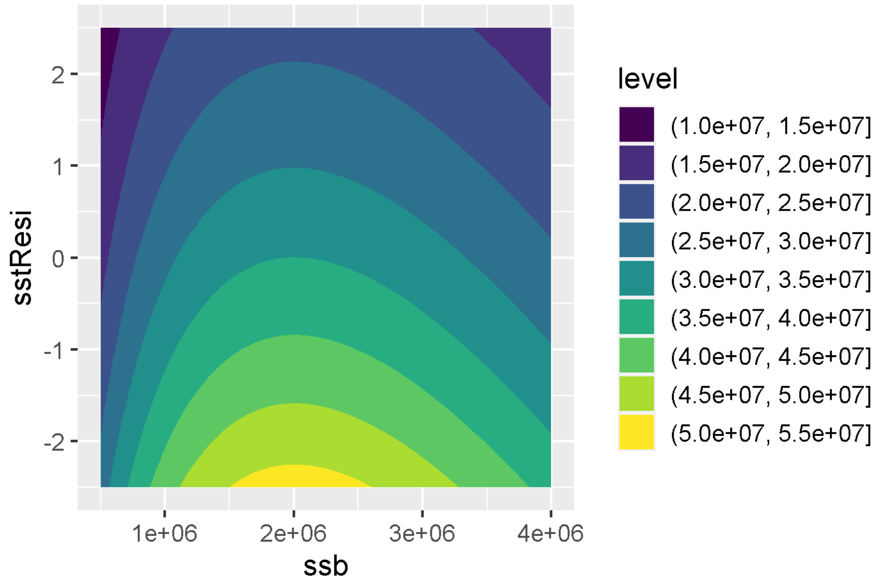


Figure 42 Ricker stock recruitment relationship with SST as covariate, based on the NSAS stock assessment.. Colour contours are recruitment levels.

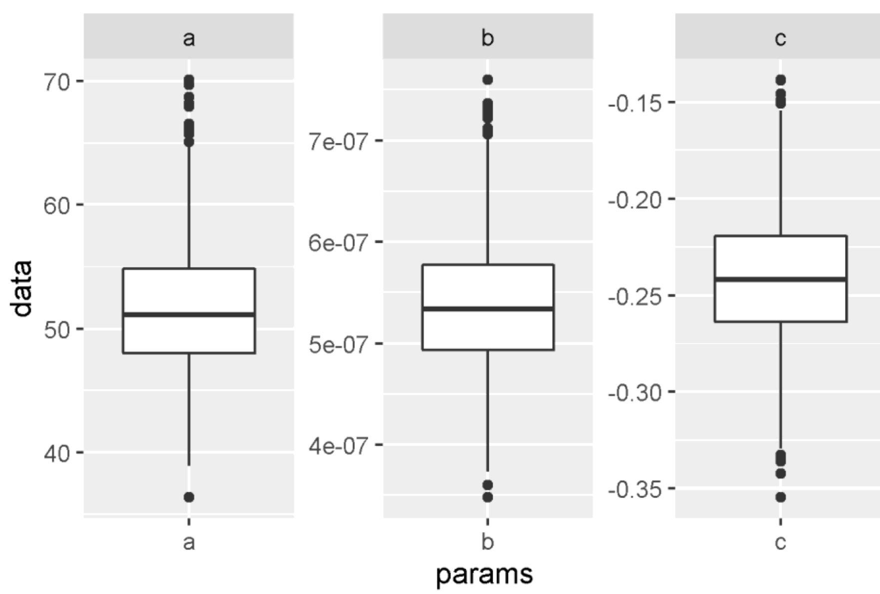


Figure 43 Spread of stock recruitment parameters across iterations (1000 replicates).

(a) **(b)**

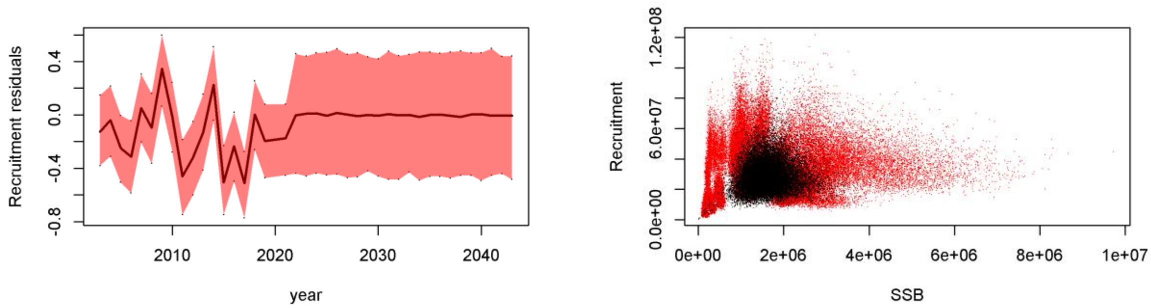


Figure 44 Recruitment projections (1000 replicates). (a) spread in recruitment residuals. (b) scatter plot of recruitments for each replicate for the historical (red dots) and projected (black dots) period.

Table 30 Model parameters Ricker stock recruitment model with SST covariate based on the median trajectory or the NSAS stock assessment.

params	value
a	47.39736
b	4.98E-07
c	-0.15809

Harvest control rule (HCR) control points

Control points derived through grid search

The NSAS assessment model has recently been updated during an inter-benchmark (ICES, 2021a). The reference points were derived using the eqSim software (a "short-cut approach") through this process. In addition, the stock recruitment relationship differs with the inclusion of a Ricker model with a co-variate on SST. In order to have control points consistent with the MSE model employed here, an Ftar/Btrig grid search is performed. Because the running of each model with 1000 replicates take a long time (>8h), the Ftar/Btrig grid is first explored using model runs with 200 replicates. The resulting grid is shown in Figure 45. On this grid, the optimal point (risk3<5% and highest long term catch) is found at Ftar=0.27 and Btrig=1.3*1e06. The grid is then explored using model runs with 1000 replicates around this cell. This is shown in Figure 46. The optimal point is found as:

- Ftar=0.3
- Btrig=1.4*1e06

This combination of Ftar/Btrig will be the basis of the "highRef" scenarios. However, Ftar is relatively high compared to levels of F in recent years (Fbar=0.19 over the 2010-2020 period). In order to test scenarios with lower reference points, a set of control points that are more conservatives are also used.

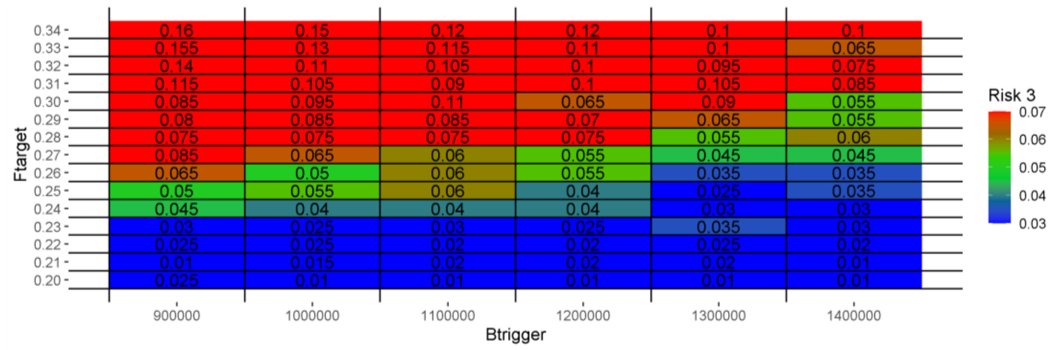


Figure 45 200 iterations grid search. The metrics are calculated over the last 10 years of the projections

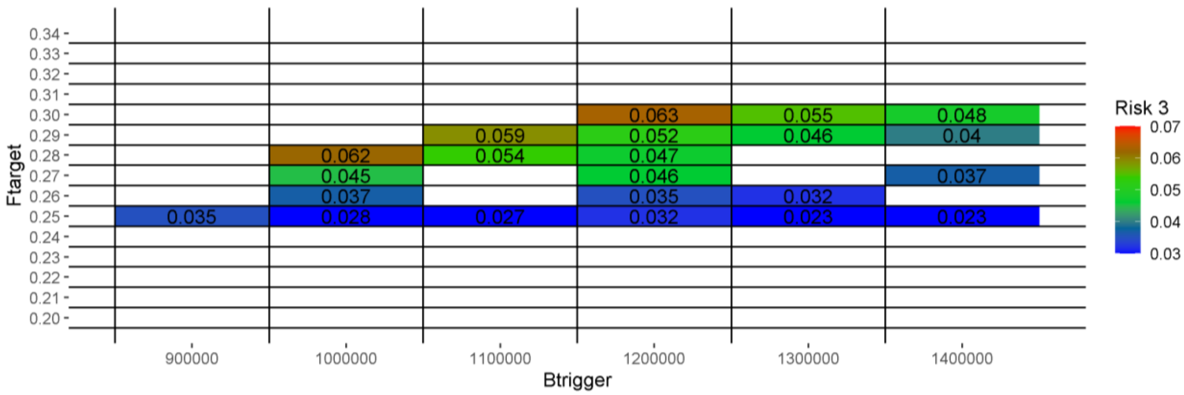
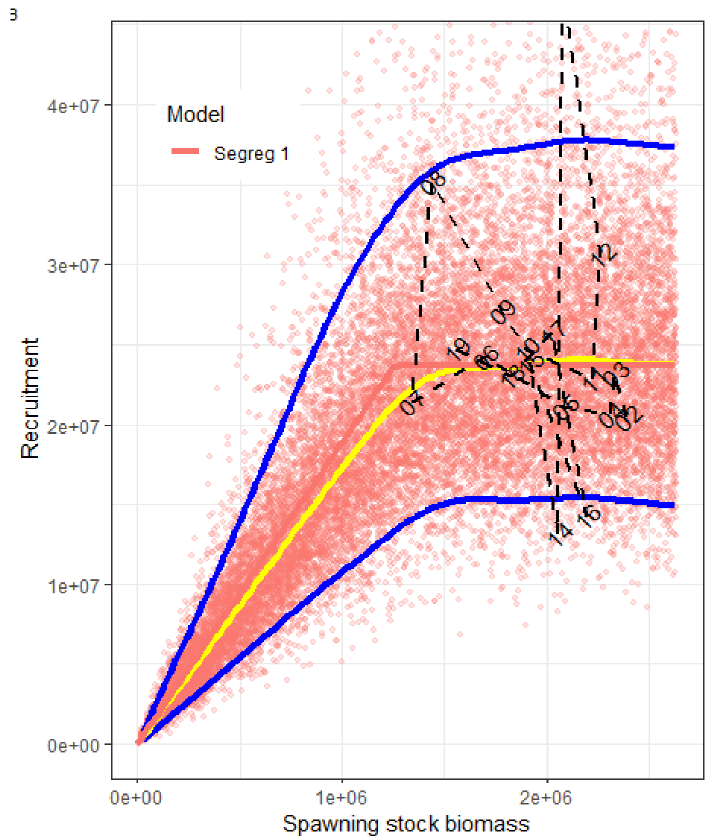


Figure 46 1000 iterations grid search. The metrics are calculated over the last 10 years of the projections.

Control points using a conservative approach

The conservative set of control points is taken as the most precautionary set of reference points derived during the latest inter-benchmark. These were derived using the eqSim software with the following assumptions:

- Time series truncated 2002-2020
- Segmented regression through the data (i.e. breakpoint set at Bloss)



Diagnostics are shown in

Figure 47 (S-R) Figure 48 (MSY diagnostics).

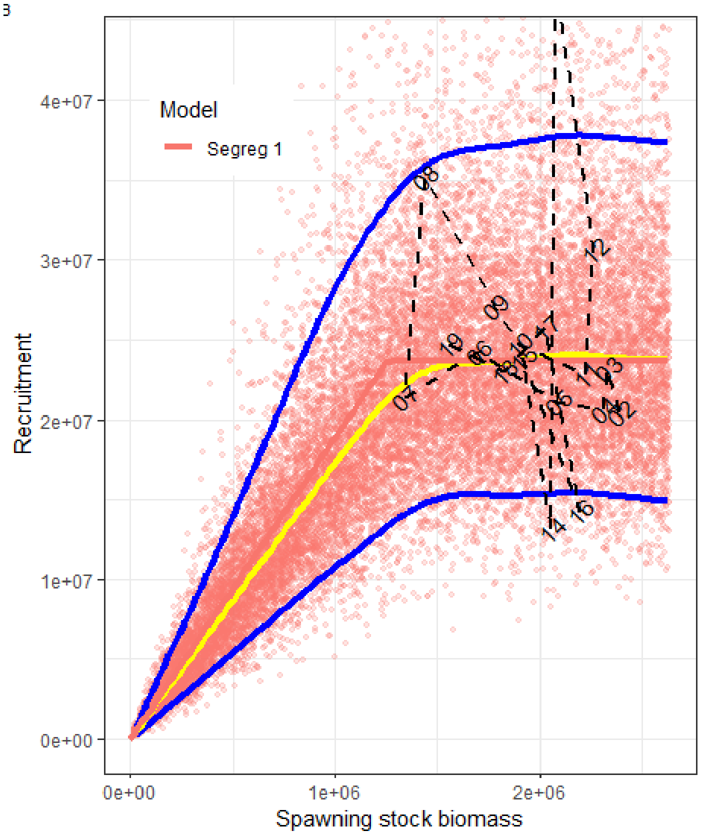


Figure 47 SRR relationships with a segmented regression model using the 2002-onward period.

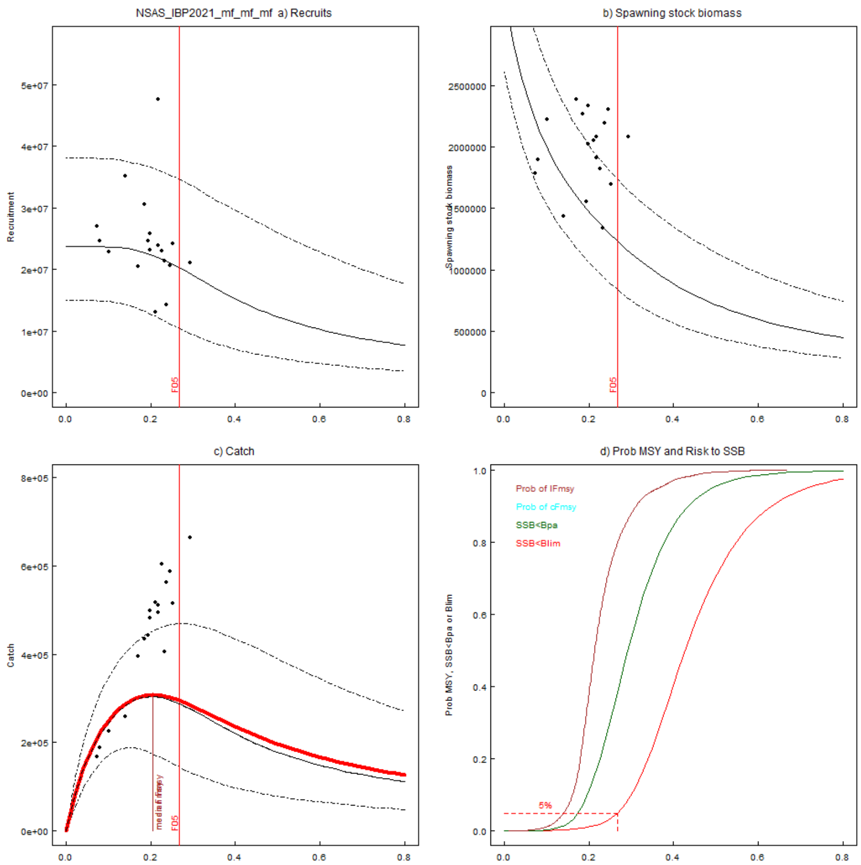


Figure 48 eqSim MSY diagnostics with a segmented regression model using the 2002-onward period.

Summary of scenario testing

Table 31 Summary of reference points for the two cases of HCR control points.

Case	Basis	Fmsy	MSYBtrigger	Blim
refLow	eqSim	0.175	1.6*1e06	874198
highRef	grid search	0.3	1.4*1e06	874198

Projections

For the different scenarios, the results of the projections are shown in Figure 49-Figure 52.

In the basecase scenarios (OM1), the SSB stabilizes in the long term (2030-2041) around 1.5mt with the set of high valued control points and 2mt with the set of conservative control points (Figure 50). This is a result of the lower fishing pressure (from 0.3 to 0.175) but also higher $B_{trigger}$.

The basecase scenario (OM1) corresponds to a status quo in SST anomalies for the projected period. In contrast, the other two operating models OM2 and OM3 use the RCP45 and RCP85 SST projections. In addition, additional scenarios with recruitment shocks are computed for OM2 and OM3: 1 shock in 2021 for OM2 and 2 shocks (2021 and 2022) for OM3. The magnitude of these shocks can be observed in Figure 49.

First, it is clear that the increase in temperature anomalies decreases recruitment level significantly (Figure 49). With the highRef control points, the SSB is close to Blim (median at Blim for OM2 and median slightly above Blim for OM3). When the lowRef control points are applied, the stock remains at higher levels though remaining close to Blim. The ability of the NSAS stock to recover well above the defined biological limit Blim is clearly hampered by the increase in temperature anomaly as modelled in the hereby model. As a result, one always operate on the slope of the HCR (Figure 50) and the realized F is low in both control point cases (

Figure 51). As shown in Figure 38, the SST anomalies under the RCP85 conditions starts to diverge from the RCP45 case at the 2050 horizon. Prior to 2050, the RCP45 case exemplifies larger SST anomalies (in the North Sea over August/September/January). As a result, the operating model using the RCP45 projections (OM2) presents the most pessimistic outlook.

Figure 49 *recruitment projections for the different scenarios. The black vertical line denotes the start of the projections.*

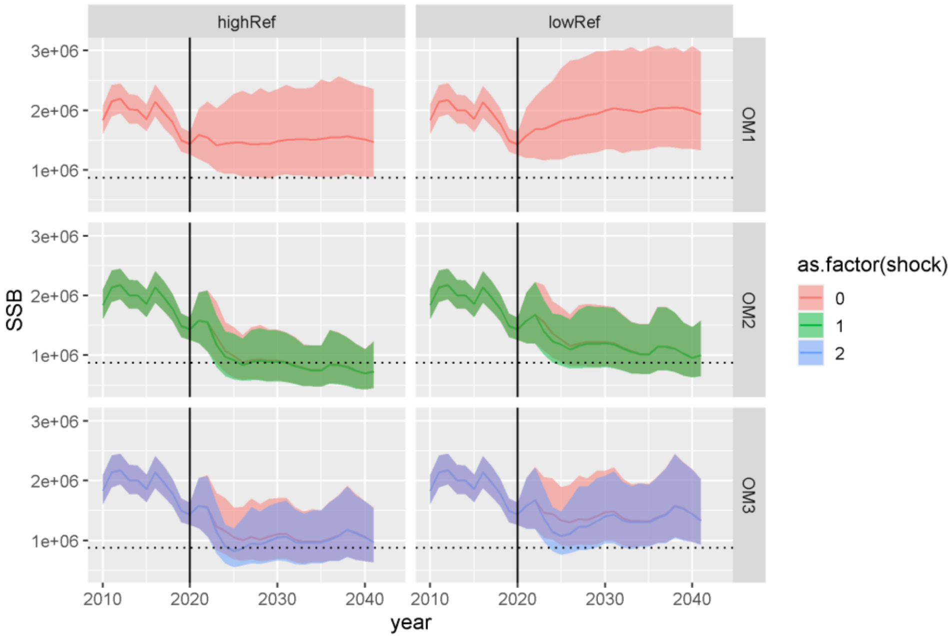


Figure 50 SSB projections for the different scenarios. The black vertical line denotes the start of the projections. The dashed line is Blim.

Figure 51 fbar (age 2-6) projections for the different scenarios. The black vertical line denotes the start of the projections. The dashed lines are Ftargets for both set of control points (0.3 and 0.175)

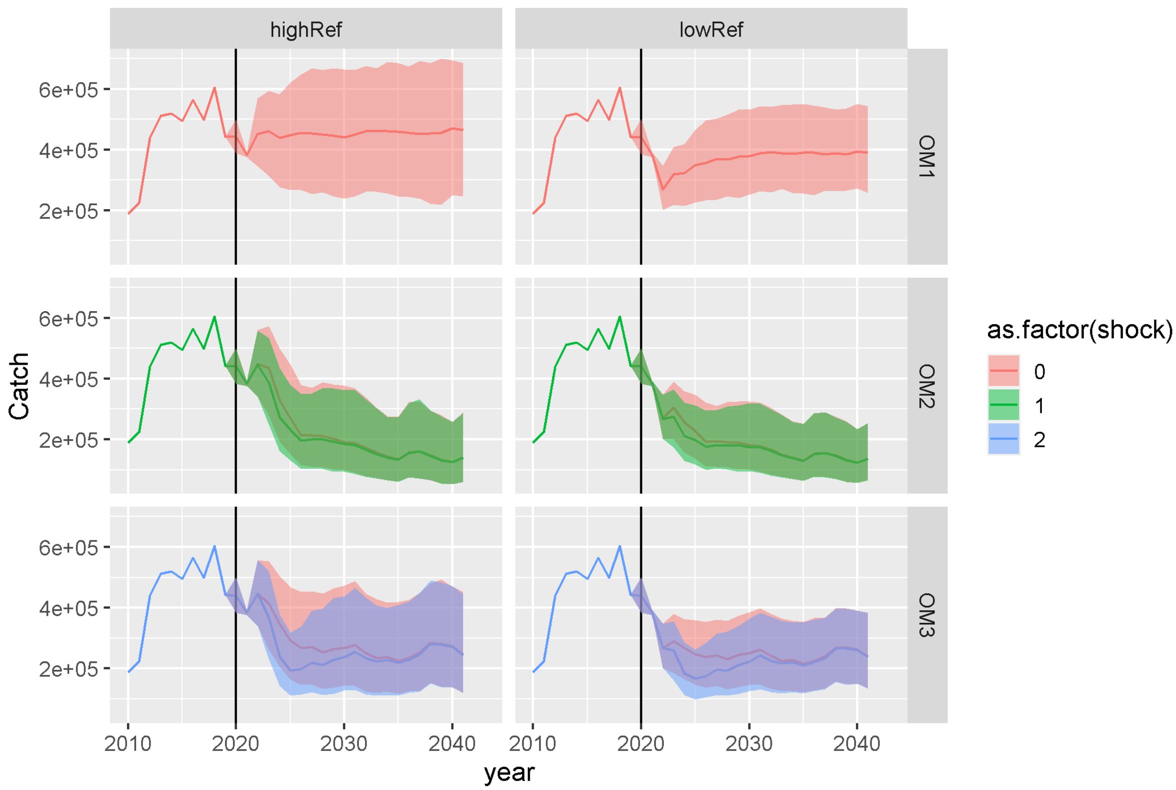


Figure 52 Catches projections for the different scenarios. The black vertical line denotes the start of the projections.

Resistance and resilience

Resistance

The resistance metrics as shown here describe the ability of the stock to withstand shocks in recruitment. This is expressed relative to minimum stock levels and relative to stock trajectories without shocks.

First, with a single shock under OM2 and two shocks under OM3, the stock falls at 47% and 49% of the latest shock year respectively Figure 53. With the low ref control points, the amplitude is lower. However, the responsiveness to the shock is better under OM3 (Figure 53), most likely due to the smaller SST anomalies compared to OM2. The biological risks for all the scenarios are particularly high, e.g. all above the 5% threshold in risk3 used for the grid search. With the use of the highRef control points, the stock is around Blim (Figure 50) in the long term and this is reflected with a very large risk.

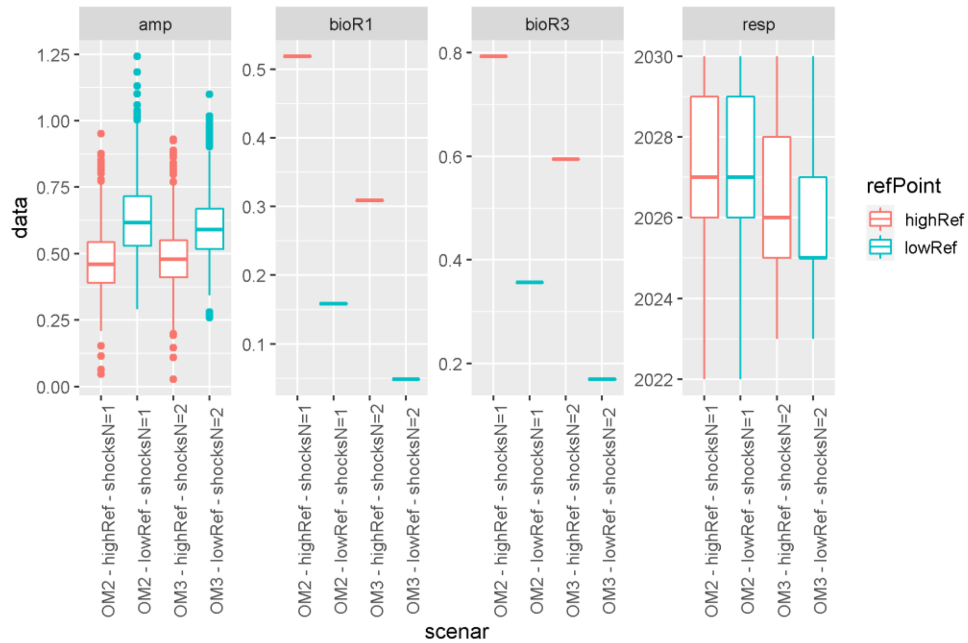


Figure 53 Indicators of stock resistance: amplitude, biological risks (1 and 3) and responsiveness.

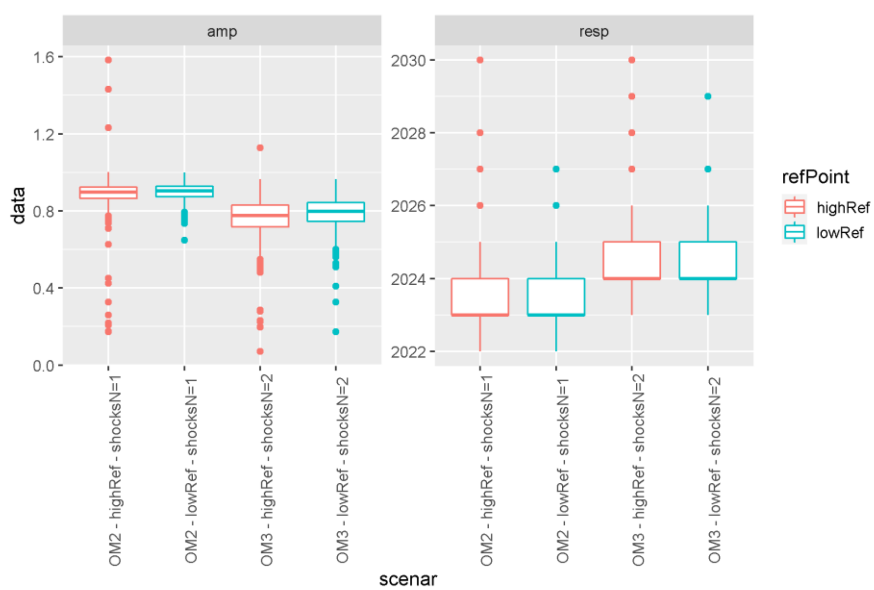


Figure 54 Indicators of stock resistance relative to no shock scenarios: amplitude and responsiveness.

Resilience

Resilience is the ability of the stock to recover to management targets and no shock trajectories. This is shown in Figure 55 and Figure 56, respectively. First, under both the RCP45 and RCP85 climate scenarios, the resilience to management targets (Btrigger) is poor (Figure 55 recovery rate between 0.05 and 0.25). The stock not being able to recover to management targets is due to the low recruitment levels under the RCP45 and RCP85 climate scenarios. Relative to no shock scenarios, these recovery rates are high. This shows that the NSAS stock is potentially vulnerable to an increase in SST.

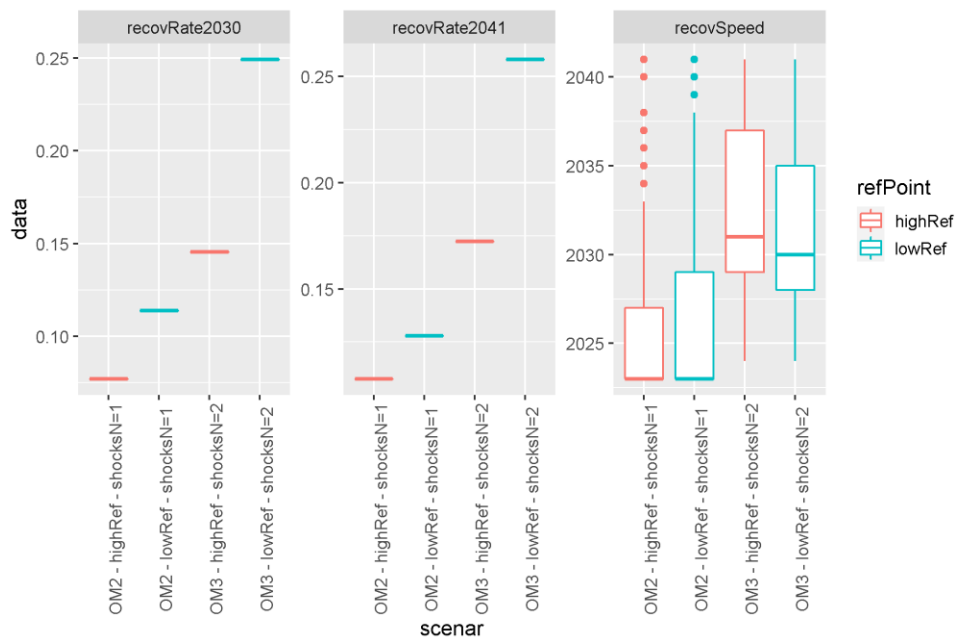


Figure 55 Indicators of stock resilience to management targets: recovery rate at the 2030 and 2041 horizons and recovery speed.

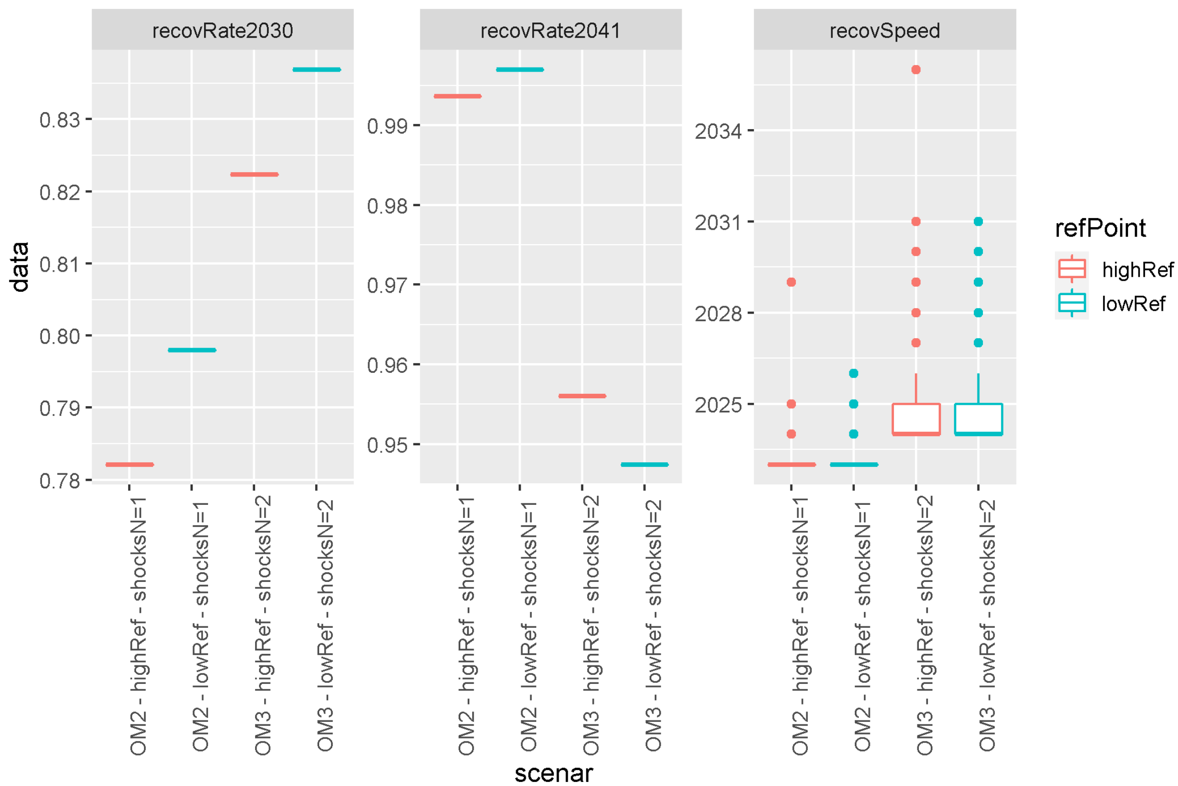


Figure 56 Indicators of stock resilience to stock trajectory without shocks: recovery rate at the 2030 and 2041 horizons and recovery speed.

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ANNEX I: SAM MODEL CONFIGURATION (SINGLE FLEET)

```
An object of class "FLSAM.control"
Slot "name":
[1] "North Sea Herring"

Slot "desc":
[1] "Imported from a VPA file. ( ./bootstrap/data/index.txt ). Wed May 26 11:49:48 2021"

Slot "range":
   min    max plusgroup  minyear  maxyear  minfbar  maxfbar
    0     8     8   1947   2021     2     6

Slot "fleets":
catch unique    HERAS   IBTS-Q1    IBTS0   IBTS-Q3   LAI-ORSH   LAI-BUN   LAI-CNS   LAI-SNS
      0      2      2      2      2      6      6      6      6

Slot "plus.group":
plusgroup
   TRUE

Slot "states":
       age
fleet      0 1 2 3 4 5 6 7 8
 catch unique 0 1 2 3 4 5 6 7 7
```

```
 HERAS    -1 -1 -1 -1 -1 -1 -1 -1 -1
 IBTS-Q1   -1 -1 -1 -1 -1 -1 -1 -1 -1
 IBTS0    -1 -1 -1 -1 -1 -1 -1 -1 -1
 IBTS-Q3   -1 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-ORSH   -1 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-BUN   -1 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-CNS   -1 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-SNS   -1 -1 -1 -1 -1 -1 -1 -1 -1

Slot "logN.vars":
0 1 2 3 4 5 6 7 8
0 1 1 1 1 1 1 1 1

Slot "logP.vars":
[1] 0 1 2

Slot "catchabilities":
      age
fleet      0 1 2 3 4 5 6 7 8
 catch unique -1 -1 -1 -1 -1 -1 -1 -1 -1
 HERAS    -1 1 1 2 2 2 2 2 2
 IBTS-Q1   -1 3 -1 -1 -1 -1 -1 -1 -1
 IBTS0     0 -1 -1 -1 -1 -1 -1 -1 -1
 IBTS-Q3    4 5 6 7 8 9 -1 -1 -1
 LAI-ORSH   10 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-BUN   10 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-CNS   10 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-SNS   10 -1 -1 -1 -1 -1 -1 -1 -1

Slot "power.law.exps":
      age
fleet      0 1 2 3 4 5 6 7 8
 catch unique -1 -1 -1 -1 -1 -1 -1 -1 -1
 HERAS    -1 -1 -1 -1 -1 -1 -1 -1 -1
 IBTS-Q1   -1 -1 -1 -1 -1 -1 -1 -1 -1
 IBTS0    -1 -1 -1 -1 -1 -1 -1 -1 -1
 IBTS-Q3   -1 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-ORSH   -1 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-BUN   -1 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-CNS   -1 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-SNS   -1 -1 -1 -1 -1 -1 -1 -1 -1

Slot "f.vars":
      age
fleet      0 1 2 3 4 5 6 7 8
 catch unique 0 0 1 1 1 1 2 2 2
 HERAS    -1 -1 -1 -1 -1 -1 -1 -1 -1
 IBTS-Q1   -1 -1 -1 -1 -1 -1 -1 -1 -1
 IBTS0    -1 -1 -1 -1 -1 -1 -1 -1 -1
```

```
 IBTS-Q3   -1 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-ORSH   -1 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-BUN   -1 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-CNS   -1 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-SNS   -1 -1 -1 -1 -1 -1 -1 -1 -1

Slot "obs.vars":
      age
fleet      0 1 2 3 4 5 6 7 8
 catch unique 0 0 1 1 1 1 1 2 2
 HERAS    -1 3 4 5 6 6 6 7 7
 IBTS-Q1   -1 8 -1 -1 -1 -1 -1 -1 -1
 IBTS0     9 -1 -1 -1 -1 -1 -1 -1 -1
 IBTS-Q3   10 10 11 11 11 11 -1 -1 -1
 LAI-ORSH   12 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-BUN   12 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-CNS   12 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-SNS   12 -1 -1 -1 -1 -1 -1 -1 -1

Slot "srr":
[1] 0

Slot "scaleNoYears":
[1] 0

Slot "scaleYears":
[1] NA

Slot "scalePars":
   age
years 0 1 2 3 4 5 6 7 8

Slot "cor.F":
[1] 2

Slot "cor.obs":
      age
fleet     0-1 1-2 2-3 3-4 4-5 5-6 6-7 7-8
 catch unique NA NA NA NA NA NA NA NA
 HERAS     -1 NA NA NA NA NA NA NA
 IBTS-Q1    -1 -1 -1 -1 -1 -1 -1 -1
 IBTS0     -1 -1 -1 -1 -1 -1 -1 -1
 IBTS-Q3    0  0  0  0  0 -1 -1 -1
 LAI-ORSH   -1 -1 -1 -1 -1 -1 -1 -1
 LAI-BUN    -1 -1 -1 -1 -1 -1 -1 -1
 LAI-CNS    -1 -1 -1 -1 -1 -1 -1 -1
 LAI-SNS    -1 -1 -1 -1 -1 -1 -1 -1

Slot "cor.obs.Flag":
```

```
[1] ID ID ID ID AR ID ID ID ID
Levels: ID AR US

Slot "biomassTreat":
[1] -1 -1 -1 -1 -1 -1 -1 -1 -1

Slot "timeout":
[1] 3600

Slot "likFlag":
[1] LN LN LN LN LN LN LN LN LN
Levels: LN ALN

Slot "fixVarToWeight":
[1] FALSE

Slot "simulate":
[1] FALSE

Slot "residuals":
[1] FALSE

Slot "sumFleets":
logical(0)
```

ANNEX II: SAM MODEL CONFIGURATION (MULTI FLEET)

```
An object of class "FLSAM.control"
Slot "name":
[1] "North Sea herring multifleet"

Slot "desc":
[1] "Imported from a VPA file. ( ./bootstrap/data/index.txt ). Wed Aug 25 12:28:03 2021"

Slot "range":
   min    max plusgroup  minyear  maxyear  minfbar  maxfbar
    0     8     8   1947   2021     2     6

Slot "fleets":
 catch A catch BD catch C  HERAS IBTS-Q1  IBTS0 IBTS-Q3 LAI-ORSH LAI-BUN LAI-CNS LAI-
SNS sumFleet
    0    0    0    2    2    2    2    6    6    6    6    7

Slot "plus.group":
plusgroup
   TRUE

Slot "states":
```

```
    age
fleet    0 1 2 3 4 5 6 7 8
 catch A -1 0 1 2 3 4 5 6 6
 catch BD 7 8 9 10 10 10 -1 -1 -1
 catch C -1 11 12 13 14 14 14 -1 -1
 HERAS  -1 -1 -1 -1 -1 -1 -1 -1 -1
 IBTS-Q1 -1 -1 -1 -1 -1 -1 -1 -1 -1
 IBTS0  -1 -1 -1 -1 -1 -1 -1 -1 -1
 IBTS-Q3 -1 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-ORSH -1 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-BUN -1 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-CNS -1 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-SNS -1 -1 -1 -1 -1 -1 -1 -1 -1
 sumFleet -1 -1 -1 -1 -1 -1 -1 -1 -1

Slot "logN.vars":
0 1 2 3 4 5 6 7 8
0 1 1 1 1 1 1 1 1

Slot "logP.vars":
[1] 0 1 2

Slot "catchabilities":
    age
fleet    0 1 2 3 4 5 6 7 8
 catch A -1 -1 -1 -1 -1 -1 -1 -1 -1
 catch BD -1 -1 -1 -1 -1 -1 -1 -1 -1
 catch C -1 -1 -1 -1 -1 -1 -1 -1 -1
 HERAS  -1 1 1 2 2 2 2 2 2
 IBTS-Q1 -1 3 -1 -1 -1 -1 -1 -1 -1
 IBTS0   0 -1 -1 -1 -1 -1 -1 -1 -1
 IBTS-Q3  4 5 6 7 8 9 -1 -1 -1
 LAI-ORSH 10 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-BUN 10 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-CNS 10 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-SNS 10 -1 -1 -1 -1 -1 -1 -1 -1
 sumFleet -1 -1 -1 -1 -1 -1 -1 -1 -1

Slot "power.law.exps":
    age
fleet    0 1 2 3 4 5 6 7 8
 catch A -1 -1 -1 -1 -1 -1 -1 -1 -1
 catch BD -1 -1 -1 -1 -1 -1 -1 -1 -1
 catch C -1 -1 -1 -1 -1 -1 -1 -1 -1
 HERAS  -1 -1 -1 -1 -1 -1 -1 -1 -1
 IBTS-Q1 -1 -1 -1 -1 -1 -1 -1 -1 -1
 IBTS0  -1 -1 -1 -1 -1 -1 -1 -1 -1
 IBTS-Q3 -1 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-ORSH -1 -1 -1 -1 -1 -1 -1 -1 -1
```

```
 LAI-BUN -1 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-CNS -1 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-SNS -1 -1 -1 -1 -1 -1 -1 -1 -1
 sumFleet -1 -1 -1 -1 -1 -1 -1 -1 -1

Slot "f.vars":
    age
fleet    0 1 2 3 4 5 6 7 8
 catch A -1 0 1 1 1 1 2 2 2
 catch BD 3 4 4 4 4 4 -1 -1 -1
 catch C -1 5 6 7 7 7 7 -1 -1
 HERAS  -1 -1 -1 -1 -1 -1 -1 -1 -1
 IBTS-Q1 -1 -1 -1 -1 -1 -1 -1 -1 -1
 IBTS0  -1 -1 -1 -1 -1 -1 -1 -1 -1
 IBTS-Q3 -1 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-ORSH -1 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-BUN -1 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-CNS -1 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-SNS -1 -1 -1 -1 -1 -1 -1 -1 -1
 sumFleet -1 -1 -1 -1 -1 -1 -1 -1 -1

Slot "obs.vars":
    age
fleet    0 1 2 3 4 5 6 7 8
 catch A -1 0 1 1 1 1 1 2 2
 catch BD 3 4 5 5 5 5 -1 -1 -1
 catch C -1 6 7 8 8 8 8 -1 -1
 HERAS  -1 9 10 11 12 12 12 13 13
 IBTS-Q1 -1 14 -1 -1 -1 -1 -1 -1 -1
 IBTS0  15 -1 -1 -1 -1 -1 -1 -1 -1
 IBTS-Q3 16 16 17 17 17 17 -1 -1 -1
 LAI-ORSH 18 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-BUN 18 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-CNS 18 -1 -1 -1 -1 -1 -1 -1 -1
 LAI-SNS 18 -1 -1 -1 -1 -1 -1 -1 -1
 sumFleet -1 -1 -1 -1 -1 -1 -1 -1 -1

Slot "srr":
[1] 0

Slot "scaleNoYears":
[1] 0

Slot "scaleYears":
[1] NA

Slot "scalePars":
   age
years 0 1 2 3 4 5 6 7 8
```

```
Slot "cor.F":
[1] 2 2 2

Slot "cor.obs":
    age
fleet   0-1 1-2 2-3 3-4 4-5 5-6 6-7 7-8
 catch A  NA NA NA NA NA NA NA NA
 catch BD NA NA NA NA NA NA NA NA
 catch C  NA NA NA NA NA NA NA NA
 HERAS   -1 NA NA NA NA NA NA NA
 IBTS-Q1  -1 -1 -1 -1 -1 -1 -1 -1
 IBTS0   -1 -1 -1 -1 -1 -1 -1 -1
 IBTS-Q3  0  0  0  0  0 -1 -1 -1
 LAI-ORSH -1 -1 -1 -1 -1 -1 -1 -1
 LAI-BUN  -1 -1 -1 -1 -1 -1 -1 -1
 LAI-CNS  -1 -1 -1 -1 -1 -1 -1 -1
 LAI-SNS  -1 -1 -1 -1 -1 -1 -1 -1
 sumFleet -1 -1 -1 -1 -1 -1 -1 -1

Slot "cor.obs.Flag":
 [1] ID  ID  ID  ID  ID  ID  AR  ID  ID  ID  ID  <NA>
Levels: ID AR US

Slot "biomassTreat":
 [1] -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1

Slot "timeout":
[1] 3600

Slot "likFlag":
 [1] LN LN LN LN LN LN LN LN LN LN LN LN
Levels: LN ALN

Slot "fixVarToWeight":
[1] FALSE

Slot "simulate":
[1] FALSE

Slot "residuals":
[1] TRUE

Slot "sumFleets":
[1] "A" "BD" "C"
```

Annex 11 EVALUATING THE RESILIENCE OF NORTHEAST ATLANTIC MACKEREL TO SHORT-TERM SHOCKS IN THE CONTEXT OF CLIMATE CHANGE

INTRODUCTION

The present document aims to assess the mackerel stock's resilience to short-term shocks, and in the context of long-term effects of climate change on the stock's productivity and on the level of discrepancy between the total catch taken on the stock and the ICES MSY advice.

A literature review is conducted to investigate which aspects of the stock's dynamics are expected to be impacted by short-term climatic anomalies and long-term climate changes. Based on the outcome of this review, scenarios are proposed for the simulations.

The simulations are then conducted using a model that is derived from the latest mackerel MSE. Additions are made to the MSE model to implement the changes in productivity. Simulations are then carried out, and indicators are computed to compare the resilience for the different scenarios. Results are also compared for two levels of target fishing mortality (Fmsy, and the lower bound of the Fmsy range).

SCENARIO ON SHORT-TERM AND LONG-TERM CLIMATE EFFECTS FOR NEA MACKEREL

Literature review on climate effects on mackerel and linkages with the environment.

Recruitment :

- Jansen (2016): the abundance of survivors at the first winter is correlated to Calanus abundance, not temperature or turbulence
- Villamor et al. (2011): strong storms in spring cause more turbulence and stronger shelf current, which leads to high larval mortality and recruitment failure
- Transport of larvae: oceanic circulation patterns around porcupine combined with the location of spawning may be determining where most of the larvae end up (either in successful nursery ground or lost in the oceanic area). However, no apparent link with recruitment success has been made (Reid et al. 2001, Walsh et al. 2005)

Growth :

- early life stage (larvae) growth in the western Atlantic is linked to the availability of planktonic preys (copepods) (Castonguay et al. 2008)

- Agnalt (1989) estimated a negative correlation between the mean length at ages 1 and 2 and the North Sea mackerel stock biomass in the 1970s. A similar link was found again later (Jansen and Burns, 2015) between growth during the first year of life and the density of juveniles on the nursery grounds (same cohort and previous cohort).

- growth in adults is limited by the combined abundance of the mackerel and NSS herring stocks (Olafsdottir et al., 2016)

Distribution / migration :

Feeding

- In the long term, occurrences in Iceland over the last 100 years match with periods of higher temperatures (Astthorsson et al . 2012)
- the geographical expansion of mackerel during the summer feeding season in Nordic Seas between 1997 and 2016 was driven by increasing mackerel stock size and constrained by the availability of preferred temperature and abundance of mesozooplankton (Olafsdotir et al. 2019)

  -however, the latest data from the IESSNS survey (ICES, 2020a) shows that mackerel started switching back eastward since 2018. The SST was low in 2018 but high in 2019 and average in 2020 in the west and around Iceland, while the stock size is estimated to have decreased. There might be a link with plankton abundance, but it is not clearly shown.
- On the other hand, Nikolioudakis et al. (2019) have modelled the IESSNS data using INLA and did not find any overall effect of stock size. Temperature, food (mesozooplankron) and herring abundance were the main factors.
- Boyd et al (2020) used an IBM approach. Best representation of observed historical distribution was obtained when i) local competitors density and ii) sensitivity to food gradients were included in the models
- Pacariz et al (2016) suggest that migration routes are constrained by areas of oligotrophic waters (no planktonic production)

overwintering

- Pre-spawning migration in winter starts as a cooling happens in the shelf edge current (warmer) and the variations of temperature in this current influence the timing of the migration. Overwintering location at the start of winter (Q4) depends on temperature : warmer= deeper in the North Sea, colder = on the west of Scotland (Jansen et al 2012),

Spawning

- Pre-spawning migration ends (school disperse) and spawning starts when temperature in the migration route reaches a given threshold (Reid 2001)
- Spawning habitat is linked to environmental variables such as temperature and salinity (Bruge et al 2016, Brunel et al. 2017), but there is also a strong geographical attachment (core spawning always around Porcupine and along the shelf edge), suggesting that mackerel spawns in areas associated with particular oceanographic features which have proven to lead to successful recruitment (Brunel et al. 2017).

Scenarios formulation:

Environment:

Predictions from oceanographic models (from the CERES project) indicate :

- Sea surface temperatures are projected to rise by up to 4°C over the 21st century under the high-emissions RCP 8.5 scenario. Projected increases are highest to the north of Iceland and south of 45°N, with the region between 50 and 65°N experiencing increases of only around 1°C in the off-shelf area, 2-3°C on-shelf.
  Under the moderate-emissions RCP 4.5 scenario, the projected changes are similar in distribution but about half the size. Much of this region is influenced by the Gulf Stream, which varies in position and strength between global models, so these values should be treated as uncertain (Figure 57).

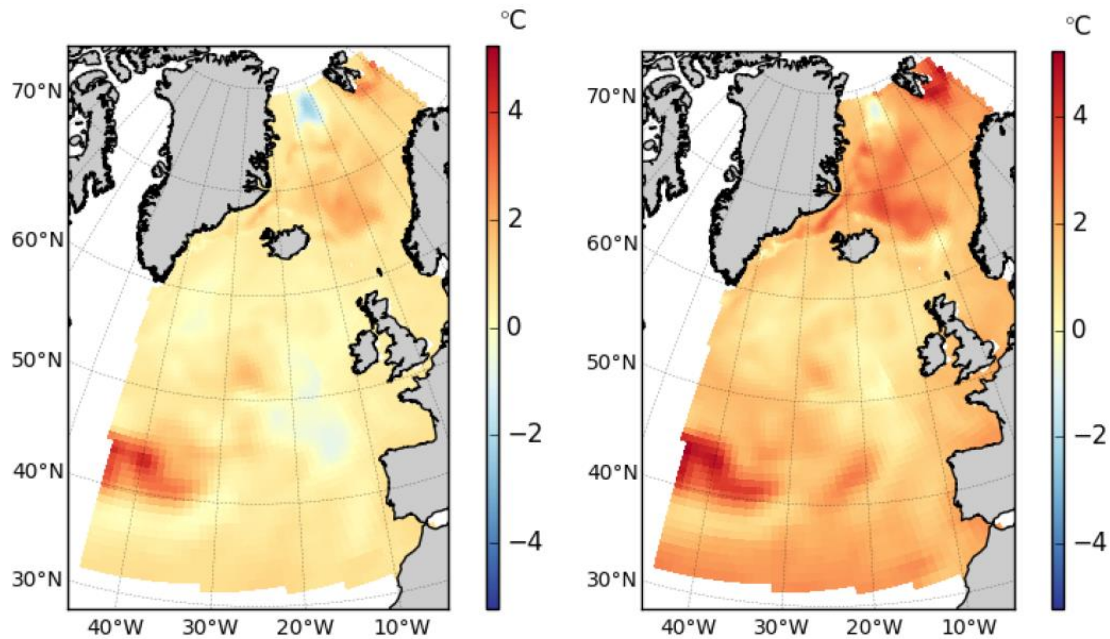

Figure 57 Project change of sea surface temperature for Northeast Atlantic for 2080 – 2099, compared to 2000 – 2019 under RCP 4.5 (left) and RCP 8.5 (right). (Copyright Susan Kay_from Ceres mackerel case study report)

- Ecosystem Productivity has only been projected for the eastern part of the region, within 200 km of the shelf break. The projections show declining productivity under both scenarios near mainland Europe, but static production off Iceland and in the far north.

Scenarios for the Mackerel stock

Long-term (2019-2059)

Productivity functions:

- A declining trend in recruitment resulted from the expected decrease in productivity on the historic nursery grounds. No quantitative relationship is available. Therefore

the rate of decrease corresponding to the RCP4.5 and the RCP8.5 projections is fixed arbitrarily (see methods).
- Growth will not be affected by future climate, but density-dependent growth will be modelled
- Maturity: no change
- Mortality: no change

Distribution
- Summer distribution (Q3 fisheries in Nordic seas) the “potential” habitat remains favourable under the “status quo” scenario, but extends further in the North and north-west under “most likely” and the “worst case” scenario. The “realized” habitat (i.e. the extent to which the stock uses the potential habitat) will depend on stock size (see details below).

short term shock :
- Recruitment failure (corresponding to the occurrence of storms in spring) in the first year of simulation (most likely scenario) and for a second year class in a random year (only for the worst case scenario). The recruitment value for these years is the lowest observed in the stock assessment time series.

IMPLEMENTATION IN THE SCENARIOS IN THE SIMULATION

Baseline model

The 2020 MSE model

The simulation tool used for this study is the MSE tool developed for the latest mackerel management strategy evaluation (ICES, 2020b). This tool implements a full-feedback MSE, in which observations are generated from the OM (true biological stock) to provide input data for the stock assessment model, SAM, which was run each year to reproduce the process leading to the formulation of scientific catch advice.

A detailed description of the assumptions, conditioning and validation of the model is presented in the report (ICES, 2020b) and only the main features are repeated here :

- Basis: WGWIDE 2019 stock assessment (simulations start in 2019).
- Number of replicates: 1000
- Recruitment model: a mixture of models (Ricker – 30%, B&H – 50%, Segmented Regression – 20%) fitted based on the OM S-R pairs for the period 1998-2018, including autocorrelation
- Biological vectors: resampled by year from the 5 most recent data years (2014-2018)
- Fisheries selection: resampled by year from the 5 most recent years (2014-2018)
- Process error in survival applied in the OM as IID Gaussian with variance as estimated by SAM
- Observations (catches-at-age, survey indices, tagging recaptures) generated with the same (iteration specific) catchabilities and observation error structure as in the SAM model

The addition of density dependent growth

As a follow up to the 2020 MSE, a density dependent growth module has been developed to investigate the sensitivity of the estimated reference points to an alternative OM assumption on growth.

The growth model developed consisted of 2 parts :

- Juvenile growth was found to be influenced by the size of cohorts, and this was modelled as a linear relationship between weight-at-age 2 and the recruitment of the corresponding year-class
- For adult growth, a von Bertalanffy growth modelled was fitted, in which the asymptotic weight is a linear function of SSB (the larger the stock size, the lower is the asymptotic weight).

Using this model in a hindcast mode, it was possible to reproduce the general trend in stock mean weight-at-age from the historical recruitment and SSB time series.

This model was implemented in the MSE tool. Figure 58illustrates future weights generated for 2 levels for exploitation, in a situation where SSB increases in the future (F=0), future weight-at-age decline over the simulation period. With higher F (0.29) leading to a decrease in SSB, future weights increase in the future.

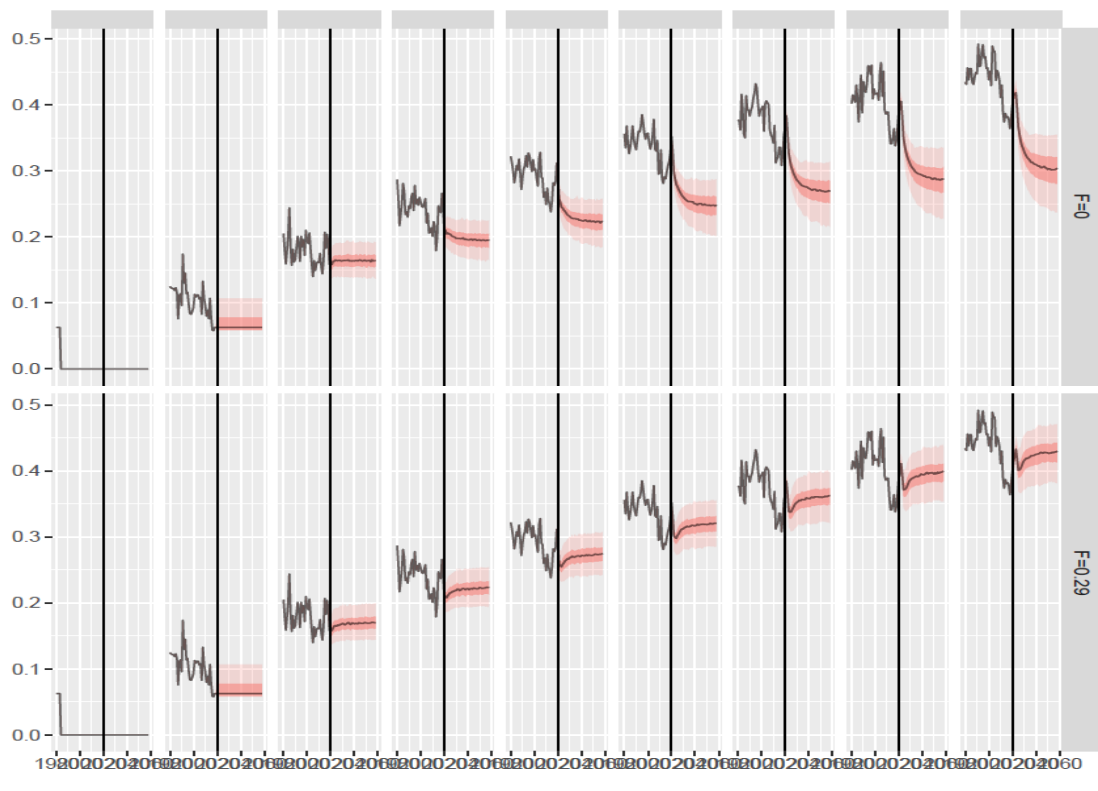

Figure 58 Simulations of the mackerel stock weight-at-age using the density-dependent growth model for 2 levels of fishing mortality (F=0 and F=0.29).

Simplifications of the model for this project

Running the MSE tool implementing the full-feedback is highly time-consuming. For practical reasons (being able to quickly develop and test the model and produce the final runs in time), it was decided to remove the stock assessment part in the yearly loops and run the simulation assuming perfect knowledge.

Considering that the study aims to compare resilience for different scenarios, it did not appear crucial to reproduce the level of uncertainty coming from the stock assessment errors. This simplification made running a 40-year simulation with 500 replicates in under an hour, while the MSE runs took more than a day.

Implementation of the climate scenarios

Productivity

Given the lack of quantitative relationship available linking recruitment and environment, an empirical approach was adopted to model the expected future decline in recruitment expected to result from the lower productivity in the nursery ground.

A linear decrease of a magnitude of -10% and -20% (for the "most likely" and "worst case" scenarios, respectively) at the horizon 2059 (end of simulation) was imposed to the recruitments simulated in the model. This percentage decrease was set arbitrarily.

In addition to this long-term decrease, shocks were implemented in the first year of simulation and, in the case of the "worst case" scenario, also in the second year. The shock consisted of imposing recruitment equal to the lowest observed recruitment in the past (in 2000).

Changes in Distribution model

In order to model future changes in distribution concerning stock future stock size, the relationship between past catches (in tonnes) per country and per ICES sub-division and the mackerel stock SSB was investigated.

Data on mackerel catches in tonnes per country and ICES rectangle covering the period 2006-2019 were downloaded from ICES database[8]. Catches per country were then summed at the level of ICES subdivisions and divided by the yearly ICES catch advice. The resulting dataset contains a time series of the proportion of the ICES catch advice (there after named pICES) taken by each country in each ICES sub-division.

At the start of the period covered by the data (pre-expansion), the TAC set corresponded to the ICES advice, and the total catches were in line with the TAC (Figure 59). Then, as the mackerel distribution expanded and the management system failed to agree on TACs in line with scientific advice, the total catches started exceeding the ICES catch advice (by up to 73% and 85% in 2013 and 2018 respectively). This means that the sum across countries of pICES was close to 1 in 2006, but reached values around 1.73 and 1.85 for the years mentioned above.

[8] https://www.ices.dk/data/dataset-collections/Pages/Fish-catch-and-stock-assessment.aspx

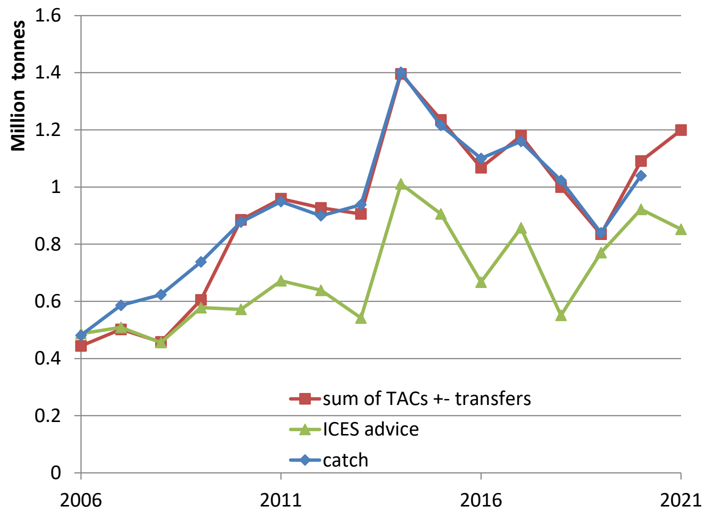

Figure 59 ICES catch advice, the sum of declared TACs and realized catch for NEA mackerel since 2006

In order to investigate whether the distribution of mackerel catches was linked to stock size, linear regressions between pICES per country and ICES subdivision and the SSB of the mackerel stock were fitted for the period covered by the data (Figure 60). The choice of modelling pICES (and not the proportion of the total catch) was made so that this relationship can be applied to the TAC advice in the simulation model, and by summing the resulting catches per country and ICES subdivision, the total realized catch corresponding to this advice can be obtained.

Figure 59 shows the fitted linear regressions for each country and area (countries taking only small proportions of the mackerel catch were filtered out). Amongst the countries taking the largest part of the catches, the general trend is an increase in the proportion of the catches (expressed as pICES) taken in IIa (Norwegian Sea) when the stock is larger, an increase in Va (Icelandic waters), and an increase in XIVb (southeast Greenland). In other important fishing areas, the situation is contrasted. In IVa (northern North Sea) the proportion fished by Denmark decreased with SSB but increased in VIa (West of Scotland), while the opposite was observed for Scotland (GBR.S) and the Netherland (although the regression in VIa was not significant). For Norway, a decrease in IVa of the same magnitude as the increase in IIa is observed.

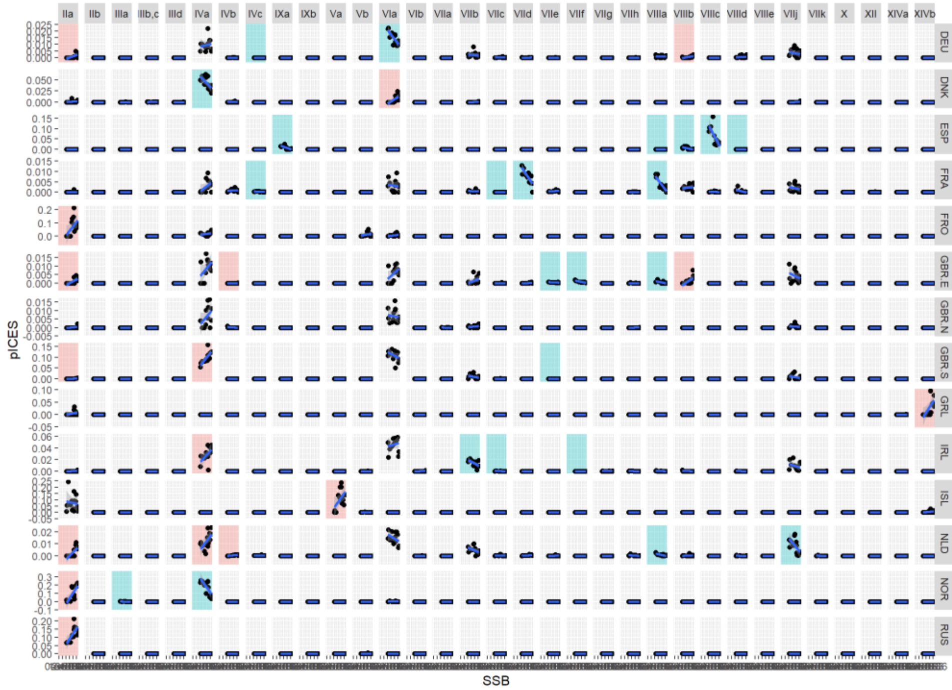

Figure 60 proportion of yearly ICES catch advice (pICES) per country and ICES subdivision, in relation to the SSB of the mackerel stock. The blue lines are the fitted linear regression models, and the colouring indicates significant relationships at the 5% level (positive slope in red and negative slope in blue).

The fitted linear regression was used in "hindcast" mode to predict the pICES for each country and subdivision from the SSB estimates from 2006 to 2019. The predicted proportions were multiplied by the ICES catch advice for the corresponding years, and the outcome was summed across countries and subdivisions to obtain to predicted total catch. The total catch reconstructed based on the pICES-SSB linear regressions broadly matched with the observed total catch (Figure 61), which indicates that this modelling approach reproduced the temporal dynamics of the discrepancies between the ICES advice and the realized catches appropriately. This approach has therefore been implement in the simulation tool, in which the OM is updated for each new year based on a total realized catch that is calculated as described above, based on the ICES catch advice, the SSB values in the OM, and the set of linear regressions linking pICES and SSB for each country and ICES subdivisions.

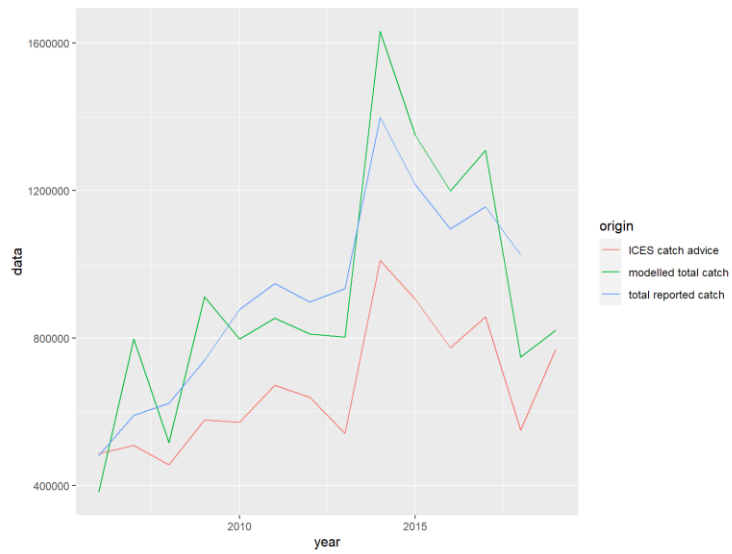

Figure 61 ICES catch advice (red), reported catch (blue) and total catch modelled based on the relationships between pICES and SSB by country and ICES subdivisions (green)

In order to make different assumption under the 3 environmental scenarios considered, it was further assumed that future climate change would increase the area of the suitable habitat for mackerel in the Nordic Seas. Future changes in distribution will then result from the interplay between habitat expansion and density-dependent habitat use.
Again, due to the lack of habitat model for the summer distribution of mackerel, a simple, arbitrary method was applied to represent the future expansion of the habitat : the slopes of the linear regressions between pICES and SSB were increased by 10% and 20% (for the "most likely" and "worst case" scenarios respectively). This will result in increasing the catches in the areas with a positive slope (mainly in the Nordic Seas) for the scenarios with future climate change.

Simulation strategy

The list of scenarios run are detailed in the table below.

shocks	Long term effects		
	Status quo	Moderate	Extreme
None	Baseline	Most likely no shock	Worst case no shock
1 shock		Most likely	
2 shocks			Worst case

These scenarios were run for both Ftarget =Fmsy (0.26) and Ftarget =Fmsy_low (0.18) applying the ICES MSY advice rule with a breakpoint at MSY Btrigger = 2.58mt.

RESULTS

Long-term stock trajectories

BASE CASE

F target = Fmsy (0.26)

In the base-case scenario (no shock and no long-term effect of climate change), the mackerel SSB decreases to stabilize at around 2.8mt (median value across stock replicates) after 2040 (Figure 62). Applying the models that predict the proportion of the ICES advice that each country catches in each ICES division, the total catches in the simulations represent an overshoot of the ICES advice by 1.4 at the start of the simulation (similar to recently observed overshoot, Figure 63). As the stock decreases, the overshoot becomes smaller (1.17). The fishing mortality resulting from this TAC advice based on Fmsy (0.26) and its overshoot increased to around 0.33 in the first years of simulation and then decreased to 0.28 in the long term (Figure 64). The realized catch initially increased to 1.4mt (due to the increase in F) and decreased to stabilize at around 933 kt (figure 9).

F target = Fmsy_low (0.18)

In the base-case scenario (no shock and no long-term effect of climate change), the mackerel SSB increases in the short term (due to the recent good recruitment) and then decreases to stabilize at around 3.7 mt in the long-term. The overshoot of the ICES advice at the start of the simulation is close to 1.4. In the long term, the overshoot decreases slightly (to 1.3), but remains high compared to the scenario based on Fmsy, as the stock remains at high levels. The fishing mortality resulting from this TAC advice based on Fmsy_low (0.18) and its overshoot increased to around 0.23 in the first years of simulation and then decreased to 0.21 in the long term. The catch first increased slightly to 1.2 mt (recent good recruitment) and decreased to 885 kt in the long-term.

MOST LIKELY SCENARIO

In the scenario with moderate long-term effect ("most likely") and without shock, stock trajectories are similar to the baseline in the first part of the simulation. However, differences start appearing in the second half of the simulation. The SSB in the long term is lower than in the base case (2.5mt compared to 2.8mt when Ftarget = Fmsy, and 3.4mt compared to 3.7mt for Ftarget=Fmsy_low). When the stock is managed based on Fmsy, the 5% quantile of the distribution of SSB falls below Blim around 2035, which corresponds to a p(SSB<BLim) >5%. This is not the case when the stock is managed based on Fmsy_low. Catches were similar to the base-case in the short term but lower in the long term (807kt and 867kt for management based on Fmsy and Fmsy_lower, respectively).

When a shock is implemented in the first year, the SSB drops quickly (in the 2-3 years following the shock), followed by a slower decrease towards the same levels at the end of the simulation for the scenarios without shock. The drop in SSB shortly after the shock results in a decrease in the overshoot of the ICES advice, and therefore in Fbar, which might contribute to limiting the short term impact of the shock on the stock. As for the SSB, catches drop in the short term but have a similar value as for scenarios without shock in the long term.

WORST CASE SCENARIO

With the more severe long-term effect of climate change, the stock decreases towards lower levels in the long-term (2.3mt and 3.1mt when management based on Fmsy and Fmsy_low, respectively) in the absence of short-term shock. In the long-term, the overshoot of the ICES advice becomes smaller than for other scenarios (1.2 and 1.3 when management based on Fmsy and Fmsy_low, respectively), in link with the lower stock size.

When the shocks are implemented in the first 2 years, the initial drop in SSB is of a larger magnitude, and is followed by a period of recovery, before the trajectory aligns with the simulation without shock and decreases in the long-term. The decrease in ICES advice overshoot resulting from the drop in SSB is of larger magnitude, resulting in a Fbar substantially lower for a period of 3-4 years than in simulation without shock (Figure 65).

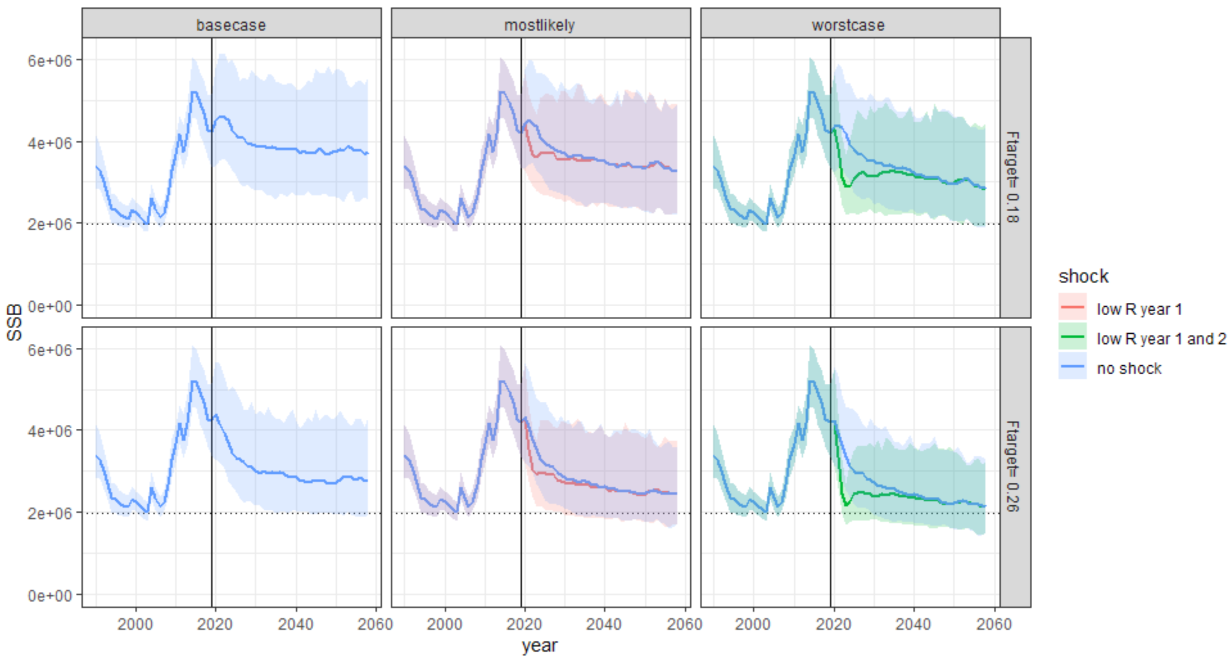

Figure 62 simulated mackerel SSB for the three scenarios on long-term effects of climate change (columns) and for target fishing mortality set at 0.18 (Fmsy_lower) and at 0.26 (Fmsy). The colours depict the different scenarios for the short-term shocks, the horizontal dotted line represents Blim, and the vertical black line shows the starting year of the simulations.

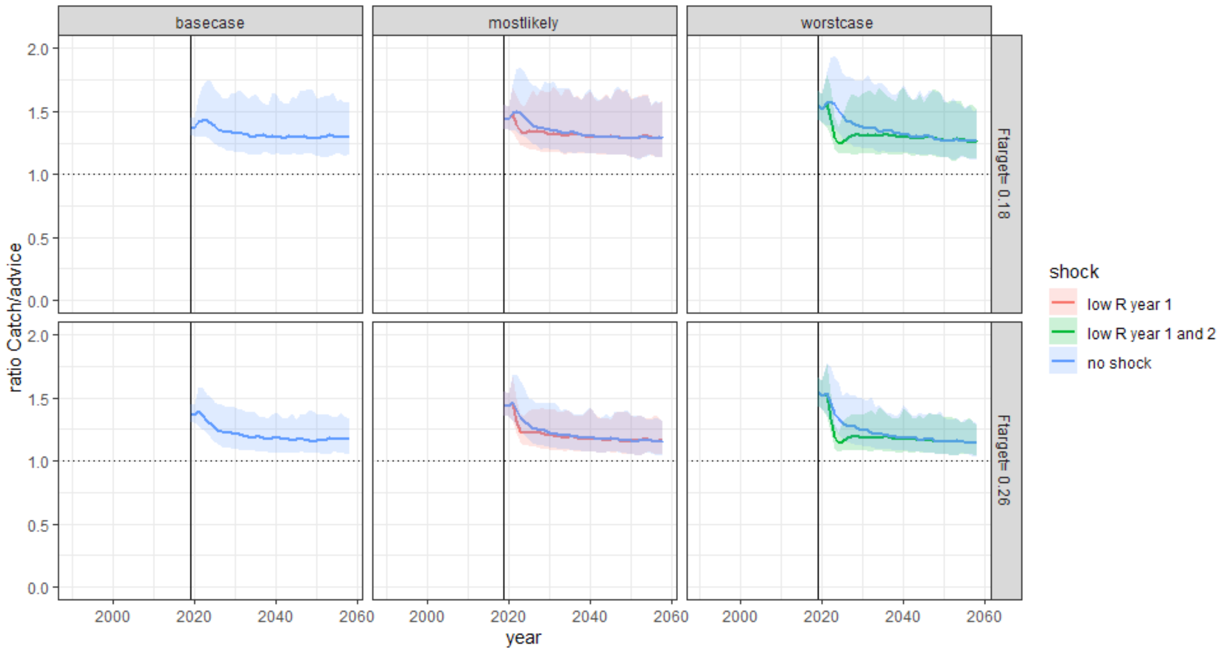

Figure 63 TAC overshoot (realised catch/TAC) for the different scenarios (see figure 6 for description)

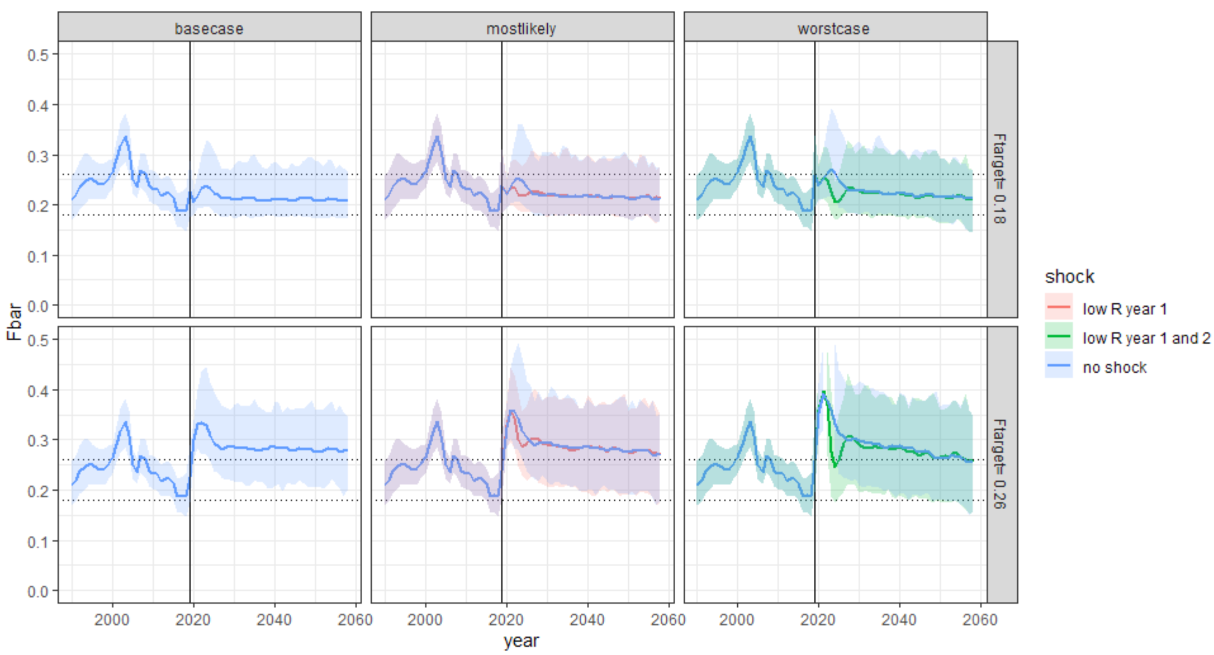

Figure 64 simulated mackerel fishing mortality for the three scenarios on long-term effects of climate change (columns) and for target fishing mortality set at 0.18 (Fmsy_lower) and at 0.26 (Fmsy).

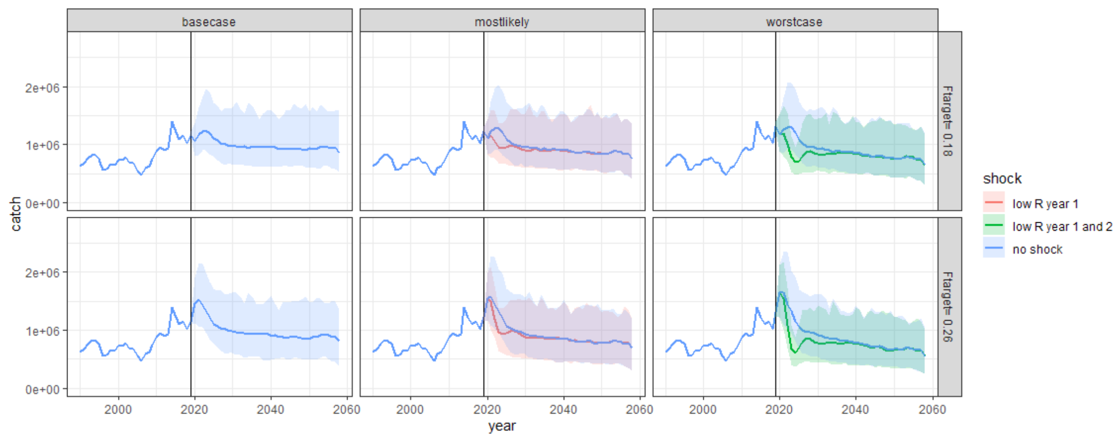

Figure 65 simulated mackerel catches for the three scenarios on long-term effects of climate change (columns) and for target fishing mortality set at 0.18 (Fmsy_lower) and at 0.26 (Fmsy).

Resilience indicators

<u>Resistance (the ability of the stock to withstand the perturbation)</u>

The amplitude of the stock’s reaction to the perturbation caused by the shock is influenced both by the Ftarget value and by the intensity of the short-term shock (Figure 66). When management based on Fmsy, the stock falls at 55% of SSB2019 (1 shock) and 47% (2 shocks). Managing the stock based on Fmsy_lower results in a lower amplitude (70% and 60% respectively). On par with these differences of amplitude, the biological risk is also much lower when management is based on Fmsy_lower (p(SSB<Blim) less than 2%), while it goes up to 8% and 32% when management is based on Fmsy. There were few differences between scenarios regarding responsiveness, the minimum SSB being reached in general between 2026 and 2027.

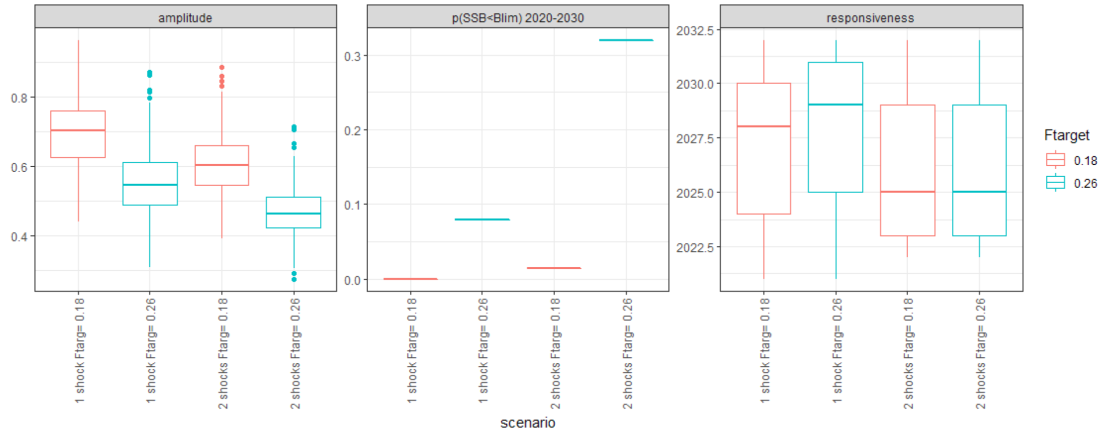

Figure 66 indicators of stock resistance following a short-term shock for the different scenarios. amplitude: ratio between the minimum value of SSB reached after the shock and the initial value ; p(SSB<Blim) 2020-2030: probability of the SSB falling below Blim between 2020 and 2030; responsiveness: year in which the lowest SSB following the shock is reached.

Resilience (the ability of the stock to current management target)

Probability of recovery to management target (MSY Btrigger) by 2030 was around 60% and 40% (for the scenario with 1 and 2 shocks respectively, Figure 67). This increased considerably (94% and 84%) when the stock is managed based on Fmsy_lower. In the long-term (by 2058) probability of recovery is at or close to 100% for all scenarios, expect for the scenario with 2 shocks (and the strongest long-term effects) with management based on Fmsy for which recovery chance is close to 90%.

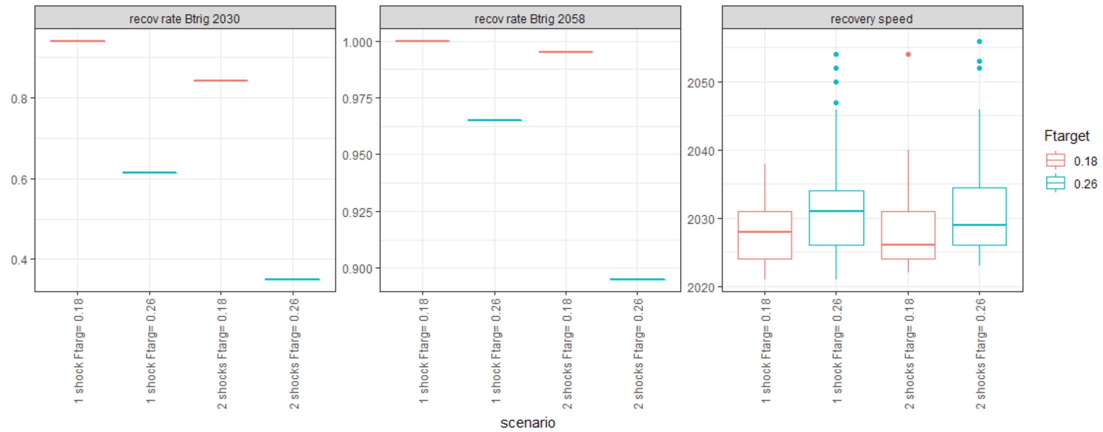

Figure 67 indicators of stock resilience following a short-term shock for the different scenarios with respect to management targets. Recover rate Btrig 2030 and 2058: probability of the stock having recovered to MSY Btrigger by 2030 and by 2058; recovery speed : year by which the stock first recovers to MSY Btrigger

Resilience (the ability of the stock to return to stock trajectory without shock)

The probability of recovery by 2030 to the stock trajectory not affected by any shock was around 65% and 55% (for Ftarget= Fmsy_low and Ftarget=Fmsy respectively, Figure 68) when the stock was impacted by a single shock. When the stock is impacted by two shock, recovery rate by 2030 is very low (22% and 15% respectively). In the long-term (by 2058) the stock always recovers to its trajectory with no shock. With a single shock, recovery mainly happens by 2026-2027 (8-9 years after the shock) while with 2 shocks, recovery happens around 2032-2033 (12-13 years after the second shock).

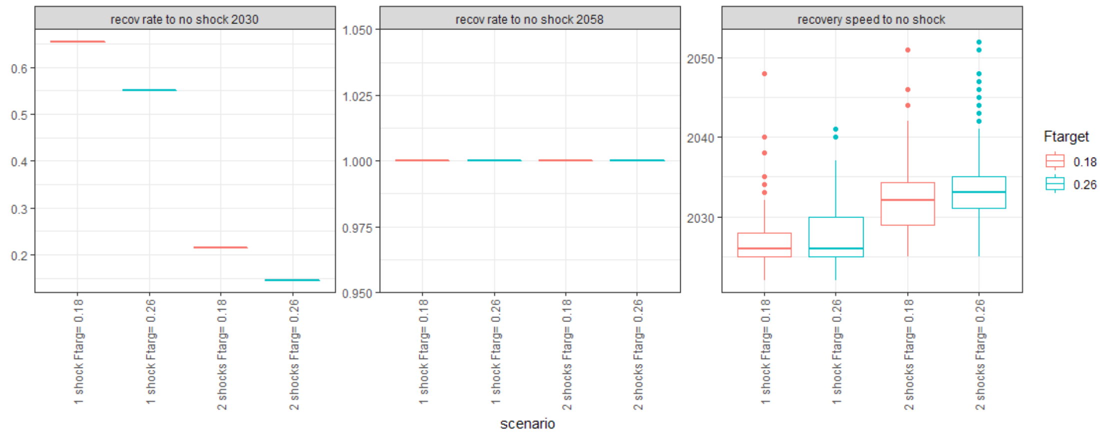

Figure 68 indicators of stock resilience following a short-term shock for the different scenarios with respect to the stock trajectory without shock. Recover rate Btrig 2030 and 2058: probability of the stock having recovered to MSY Btrigger by 2030 and by 2058; recovery speed: year by which the stock first recovers to MSY Btrigger

DISCUSSION/CONCLUSION

Model realism

Modelling the changes in distribution was done only from the perceptive of the total catch. Basically, the larger the stock becomes, the larger the overshoot of the ICES advice. In addition to the changes in total catch, changes in exploitation patterns (F-at-age profile) should also be expected (catches taken in the North corresponding to larger and older fish). Data on catches-at-age per country and ICES subdivision were also analyzed during this project to compute partial fishing moralities. These were used as input to a FLFisheries object (FLR object designed to store information for multiple fleets). Attempts were made to run multi-fleet projections for the simulations using the library FLAsher, but this could not be finalized due to lack of time.

For lack of well-established relationships with climate for this stock, ad hoc assumptions were made on the magnitude of the changes expected (in future recruitment, habitat availability in the Nordic seas) for the three environmental scenarios tested. Therefore, this work should be viewed as a theoretical exercise. The result of the simulations should be considered for scenario comparison purposes and not as likely projections of the future state of this stock.

Resource resilience and impact of management

Due to its current large stock size (SSB(2019) = 4.2mt well above the MSY Btrigger = 2.58mt), the mackerel stock can withstand and recover from 1 or 2 years of poor recruitment. The probability of recovery to levels above MSY Btrigger is not very high by 2030, but nearly at 100% in the long term. However, over the years following the shock, the stock may go through a period of increased biological risk (p(SSB<Blim)) during which other poor recruitment are more likely to happen. This risk is greatly reduced when the management advice for this stock is based on the lower bound of the Fmsy range. Managing based on Fmsy_ low also greatly increases the chance of recovering to MSY Btrigger by 2030. Managing based on Fmsy_lower would imply making lower catches in the short-term, but similar or higher catches than based on Fmsy in the long term.

In the context of climate change (and the long-term effect on mackerel assumed here), current management targets (e.g. MSY Btrigger) will have to be reevaluated in the future, as changes in productivity occur. In the worst case scenario, the partial non-recovery to MSY Btrigger by 2058 is not only a consequence of the stock being highly impacted by the poor recruitment, but also – and mainly – a reflection of the fact that the current MSYBtrigger value may not be achievable when the stock is exploited with the current Fmsy, due to the lower stock productivity in the future.

All simulations assume that the current lack of international agreement for the management of this stock continues in the future (although the magnitude of the resulting overshoot will decrease due to lower stock levels). The current Fmsy (and its range) is estimated by ICES assuming full compliance of the coastal state with scientific advice (i.e no overshoot). If non-compliance was assumed (as in the present work), Fmsy would be estimated at lower values. This means that the Ftarget values tested here (0.26 and 0.18) do not correspond to Fmsy and Fmsy_low in a situation of non-compliance, but are higher. This also means that the resilience of the stock would also be greatly improved if there was an agreement between all parties in the sharing of the mackerel TAC.

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Annex 12 NORTH SEA SPRAT MSE WITH RECRUITMENT SHOCKS

Methods

The MSE methods generally followed those established for this stock in WKspratMSE (2018). The underlying assessment model was updated to the 2021 values.

We initialized stock numbers in season 1 of 2021 in four different ways: the estimate from the 2021 stock assessments, the stock numbers are taken from the year where SSB was its minimum (1986), median (1998), or maximum (1980); these are labelled first SSB "original", "min", "median", and "max" respectively. Then for each replicate simulation trial, we included uncertainty in the stock numbers and exploitation pattern by adding multivariate normal error on the log scale, accounting for the correlations estimated in the 2021 assessment. Thus, each replicate started from slightly different stock numbers and SSB (Figure 69, bottom row). Each replicate also had a slightly different exploitation pattern. In recruitment shock scenarios, we simulated 2022 as a year of very low recruitment regardless of SSB (Figure 70, right column), matching the lowest estimated past recruitment from the stock assessment (1986). In a full factorial design, we simulated scenarios of different staring SSBs, with or without recruitment shocks, and with Fcap values of 0.69, 0.4, 0.5, 0.6, and 0.7. The 2018 benchmark determined 0.69 to be precautionary for this stock at that time. However, the simulations here have been updated to the most recent values for the conditioning of the operating model.

For the scenario with a recruitment shock, with SSB starting at its median, and with Fcap equal to 0.69, we also ran a full MSE with the assessment model SMS in the loop to confirm that the behavior is similar to the short-cut MSE used here.

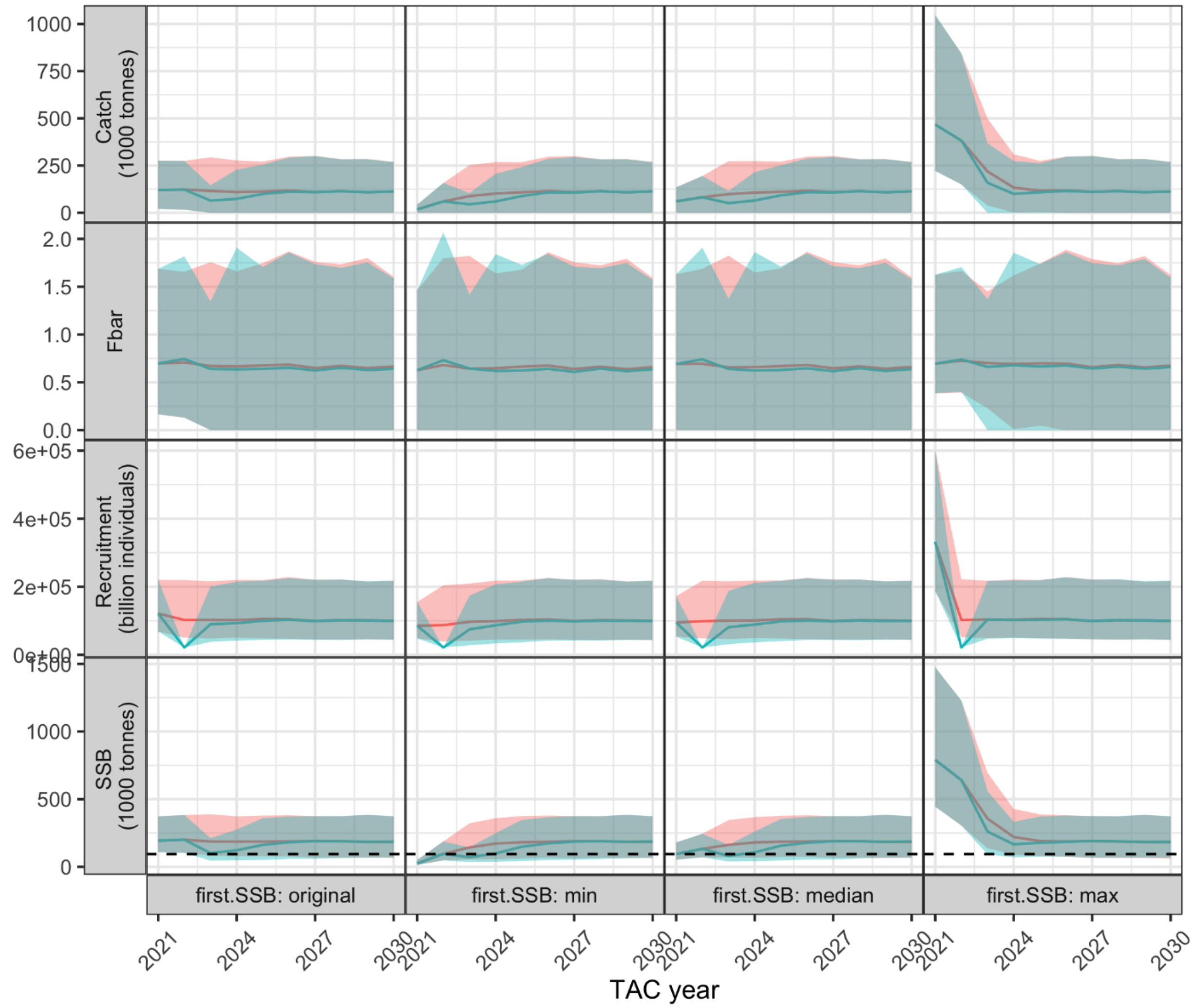

Figure 69 Simulated stock development in MSE. Each row shows a different aspect of the stock status changing across years. Each panel shows the 0.05, 0.5, and 0.95 quantiles of 1000 replicate simulation trials in one scenario. Red scenarios contain shocks of low recruitment in 2022, whereas blue scenarios do not contain recruitment shocks. Each column of panels has a different starting SSB (labeled first.SSB). The values plotted here are for the HCR of the real NS sprat fishery which is an escapement strategy with Fcap of 0.69. The horizontal line in SSB is Blim.

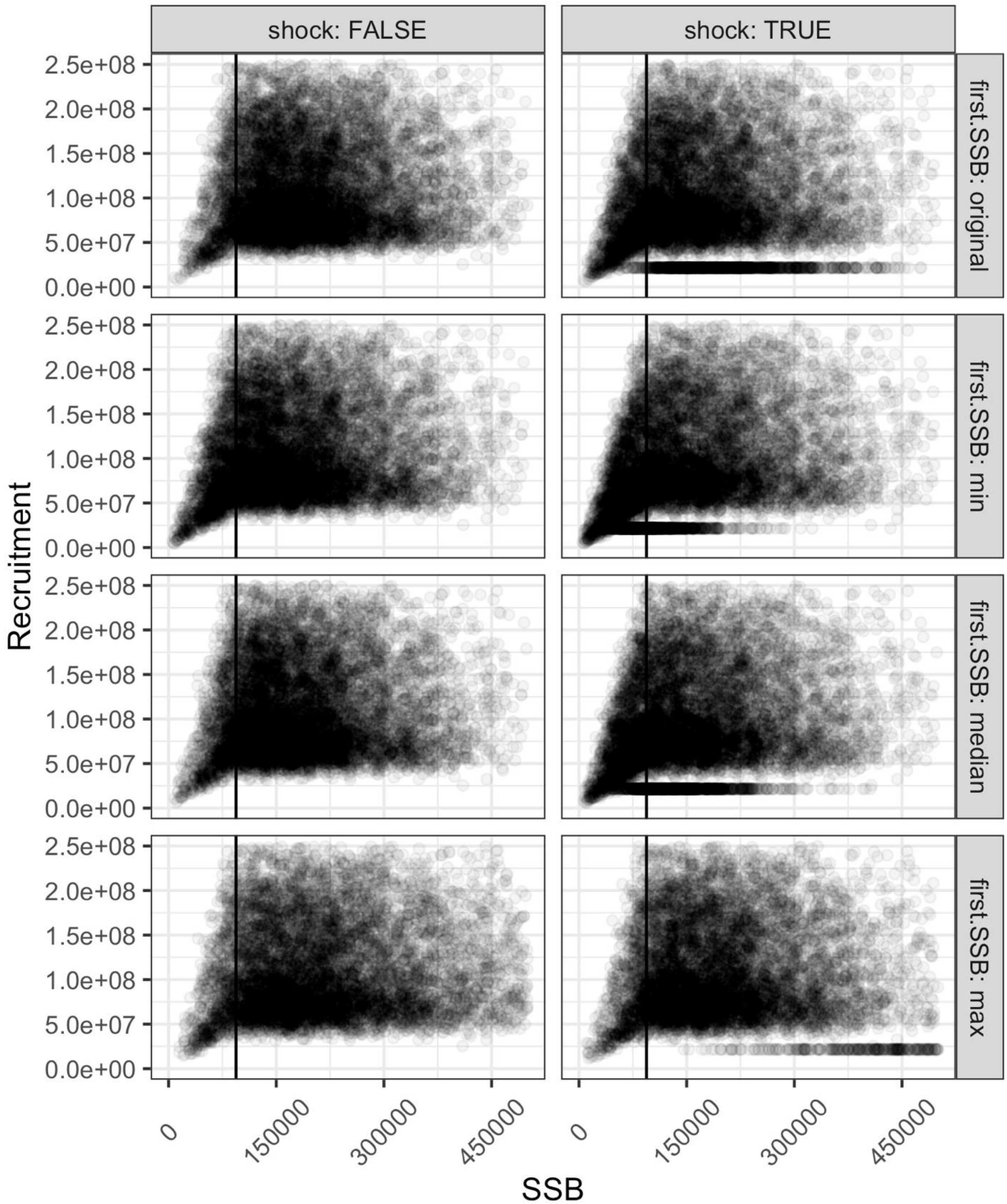

Figure 70 Recruitment was simulated from a hockey-stick model with smoothed residuals around the mean based on the estimated pairs of SSB and recruitment from the assessment model. Each point is a single year of a single replicate of the MSE. In the scenarios in the right column, the low recruitment shocks which occurred in 2022 can be seen. Some points fell outside the bounds of the graph.

Results

Simulations showed that the recruitment shocks had different effects depending on the starting stock status. Scenarios with a high starting SSB showed very little effect of the recruitment shock (Figure 71, column "first.SSB:max"). The three other scenarios with lower starting SSB had an increased risk of SSB being below Blim for about 5 years after the low recruitment year.

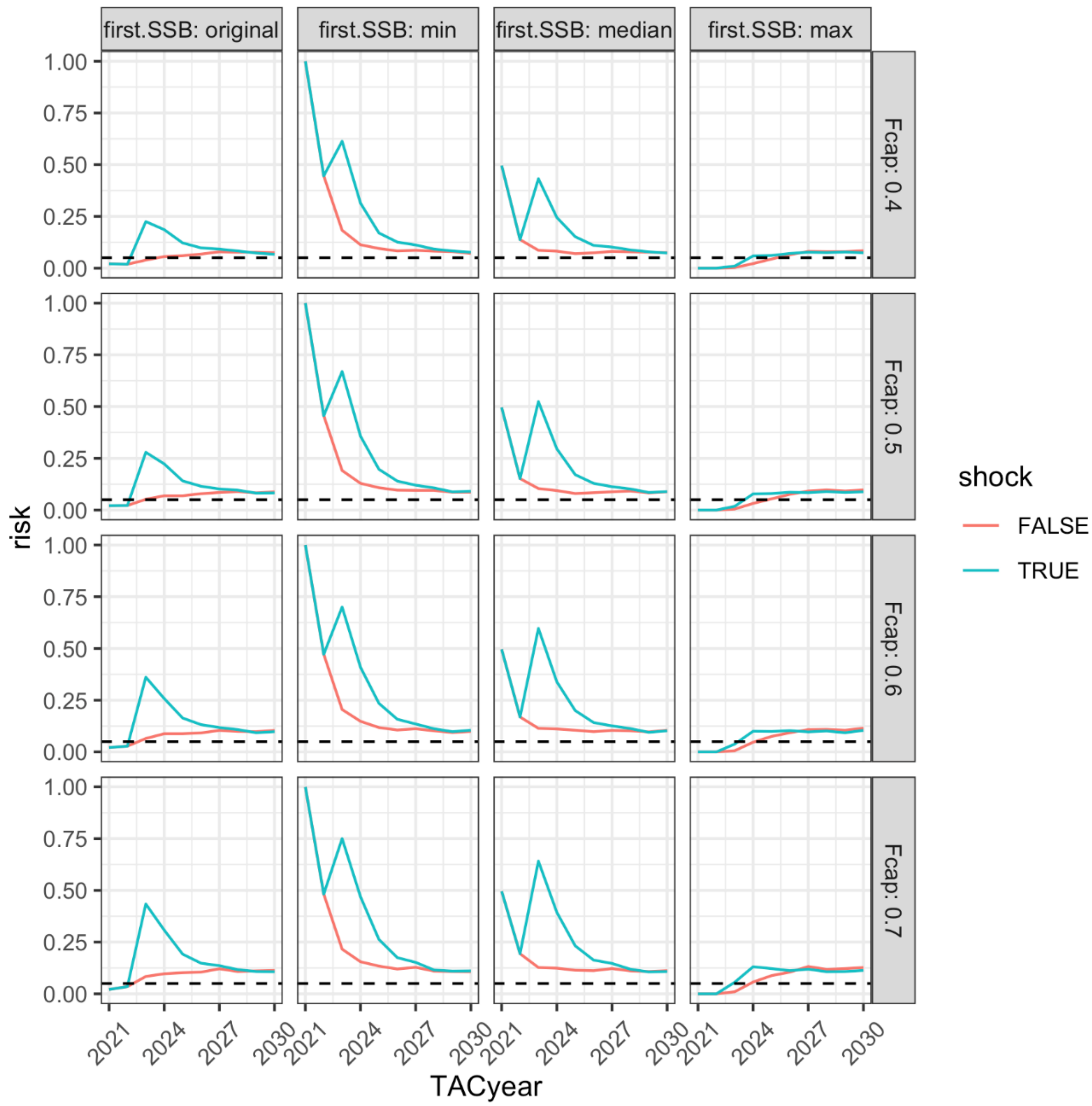

Figure 71 Yearly risk of SSB < Blim under different scenarios and values of Fcap. Each panel shows the proportion of 1000 replicate simulation trials that had SSB<Blim through time. Blue scenarios contain shocks of low recruitment in 2022, whereas red scenarios do not contain recruitment shocks. Each column of panels has a different starting SSB (labeled first.SSB). The horizontal line is 0.05.

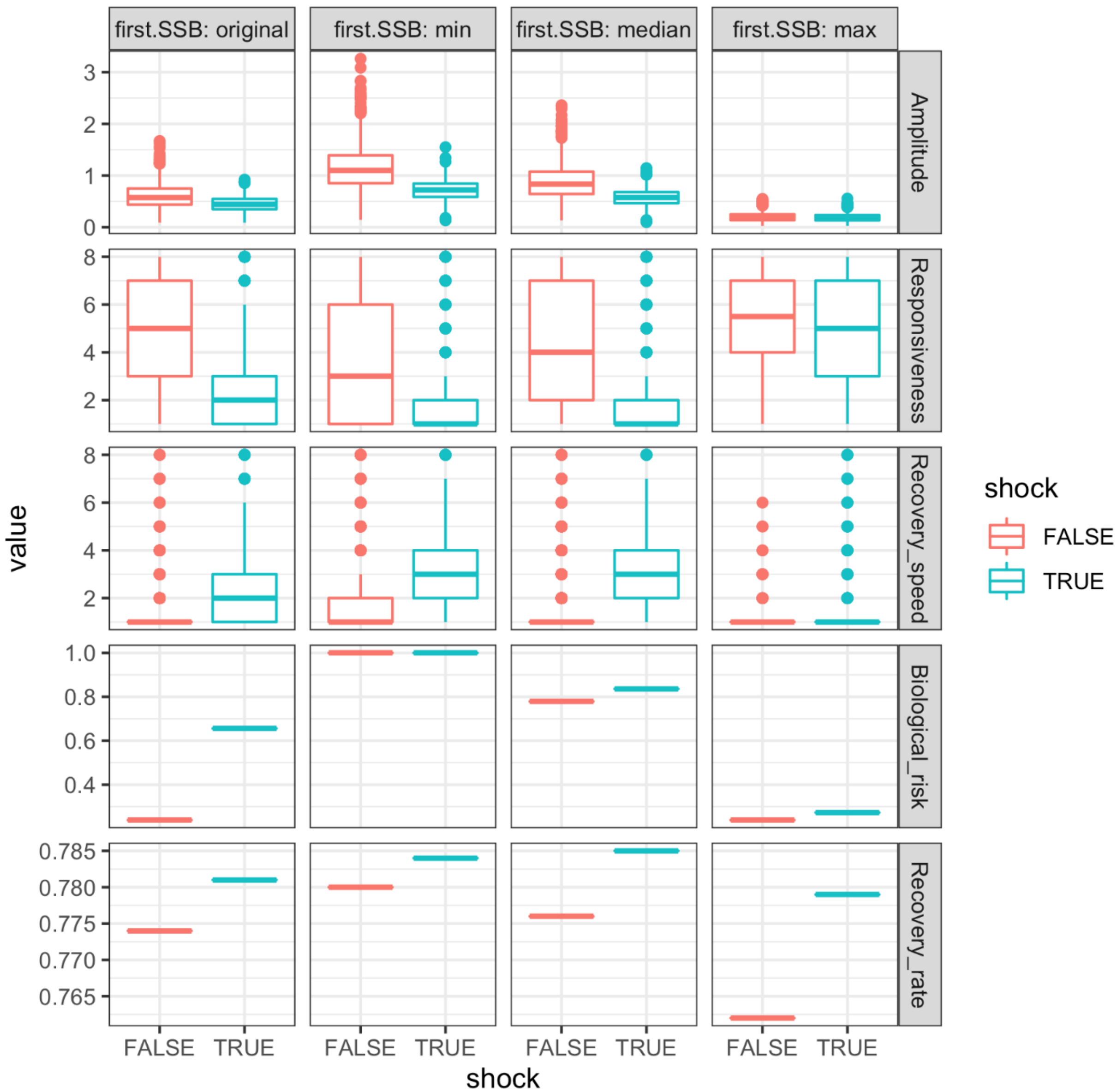

Figure 72. Indicators of resource resilience for North Sea sprat. Blue scenarios had shocks of low recruitment in 2022, whereas red scenarios did not have recruitment shocks. Each column of panels had a different starting SSB (labeled first.SSB). The values plotted here are for the HCR of the real NS sprat fishery which is an escapement strategy with Fcap of 0.69.

The resilience indicators showed a strong dependence on the starting stock status (SSB in 2021, the year before the bad recruitment year) (Figure 72). Amplitude is higher for stocks with low starting SSB, even without the effect of a shock because the denominator of this indicator (SSByearshock) is smaller for these stocks (Fig 72 top row). Stocks with SSB at the median or below had responsiveness on about the same time scale as the age of the maximum age group (age 3+) here (Fig 4, 2nd row from top). Stocks with high starting SSB showed no shock effect in all indicators except recovery rate (Fig 72, 4th column). The recovery rate by 2030 had a small range of values for this stock (0.76 to 0.785) because it is a short-lived stock. However, paradoxically, the recovery rate was slightly higher for stocks with smaller starting SSB and those that experienced recruitment shocks (Figure 72, bottom row). Effects of shocks lasting to 2030 were almost indistinguishable.

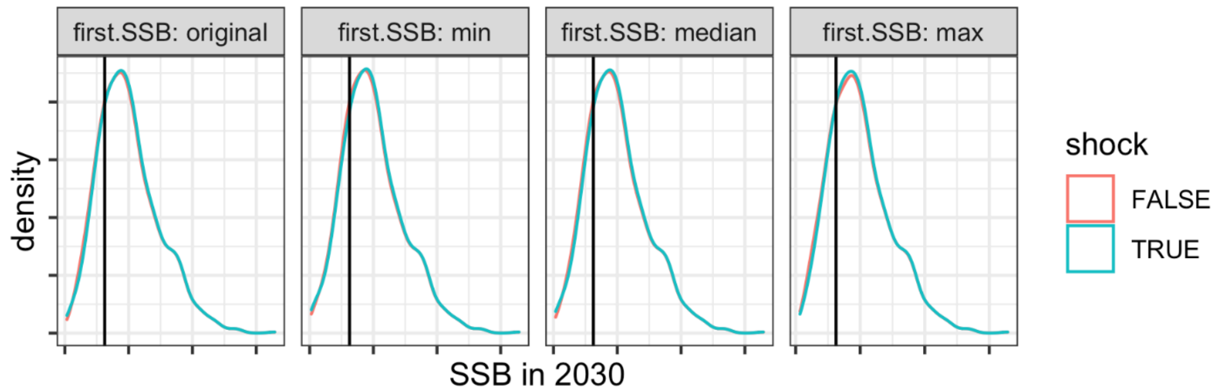

Figure 73. Distribution of SSB in 2030 from 1000 simulated stocks. Blue scenarios had shocks of low recruitment in 2022, whereas red scenarios did not have recruitment shocks. Each column of panels had a different starting SSB (labeled first.SSB). The values plotted here are for the HCR of the real NS sprat fishery which is an escapement strategy with Fcap of 0.69. The black line is Btrigger.

Annex 13 METHODS TO EXAMINE WESTERN MEDITERRANEAN RED MULLET AND HAKE STOCKS

The red mullet stock was associated with the Geographic Subarea (GSA) 6 associated with the central and Northern Spanish Mediterranean coast. While the hake stock was used includes a combination of GSAs (1, 5, 6 and 7) from the Alboran Sea to the Gulf Lion, but it mainly represents the dynamics of the Central and Northern Spanish Mediterranean coast (GSA 6) and Gulf of Lion (GSA 7).

The management regime for red mullet and hake is to fish at F0.1. Red mullet fishing mortality is currently estimated to be below Ff0.1, while SSB is above and catches below the level corresponding to F0.1. However, large changes are seen in the recent estimates, and this may be a retrospective pattern that is a sign of a problem in the assessment, which may result from missing data or changes in natural mortality, biological parameters, recruitment, stock distribution and fishery operations, all of which are likely under climate change (Figure 74). Hake is currently estimated to be overfished and subject to overfishing, although catches are around the MSY level (Figure 75).

For both stocks, projections were performed for F0.1 and FStatus Quo, taken as the recent 3-year average. Climate change scenarios were considered for M, Growth and the stock-recruitment relationship, and compared to Status Quo (i.e. future parameters were the same as their historical values); namely

- M; Status Quo, Trend (25% linear increase from 2020 to 2070), Regime Shirt (25% increase after and including 2020)
- Growth; Status Quo; Trend (25% linear increase from 2020 to 2070),.
- Stock recruitment relationship; Status Quo; Trend (25% decrease from 2020 to 2070)

To test resilience, a shock was simulated as a 50% increase in M in 2020. In the projections, recruitment was assumed to follow a Beverton and Holt stock-recruitment relationship with a steepness of 0.75. Recruitment deviates from being log-normally distributed with a CV of 30% (Figure 76, Figure 77, Figure 78, Figure 79, Table 32).

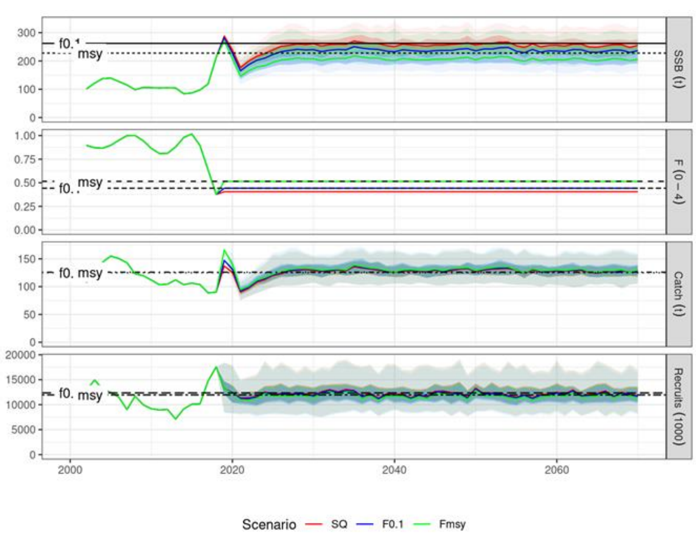

Figure 74 Red mullet projections under Status Quo, and for F0.1and FMSY.

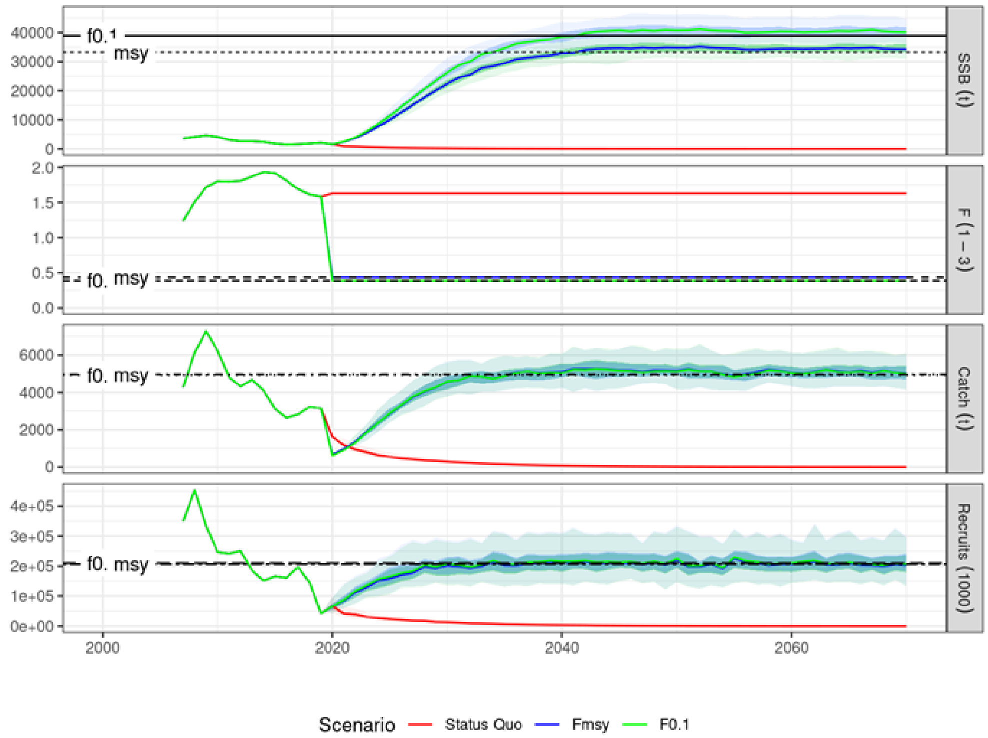

Figure 75 Hake projections under Status Quo, and for F0.1and FMSY.

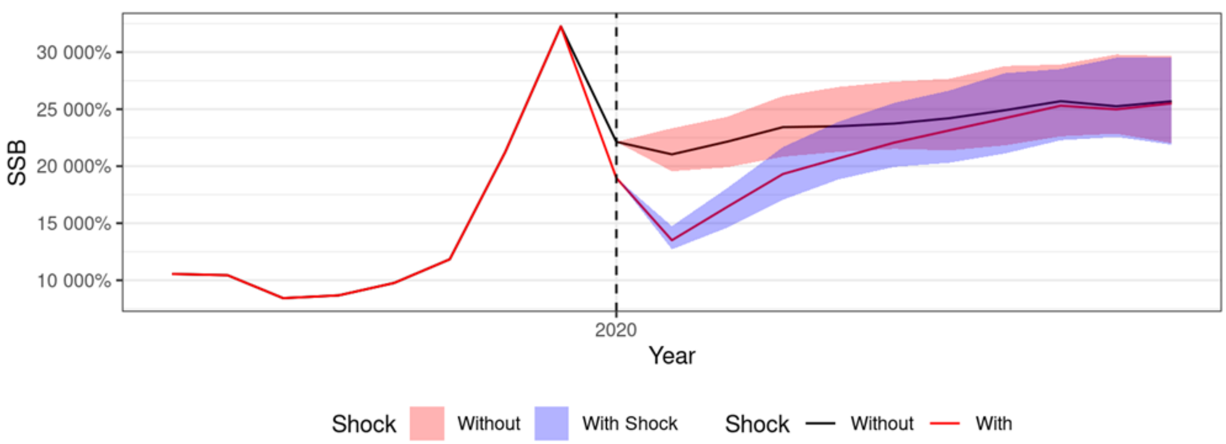

Figure 76 Simulated trajectories of red mullet SSB comparing scenarios with or without shock

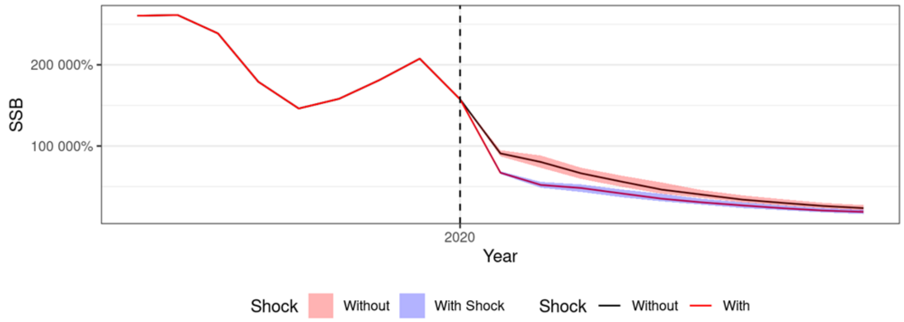

Figure 77 Simulated trajectories of hake SSB comparing scenarios with or without shock

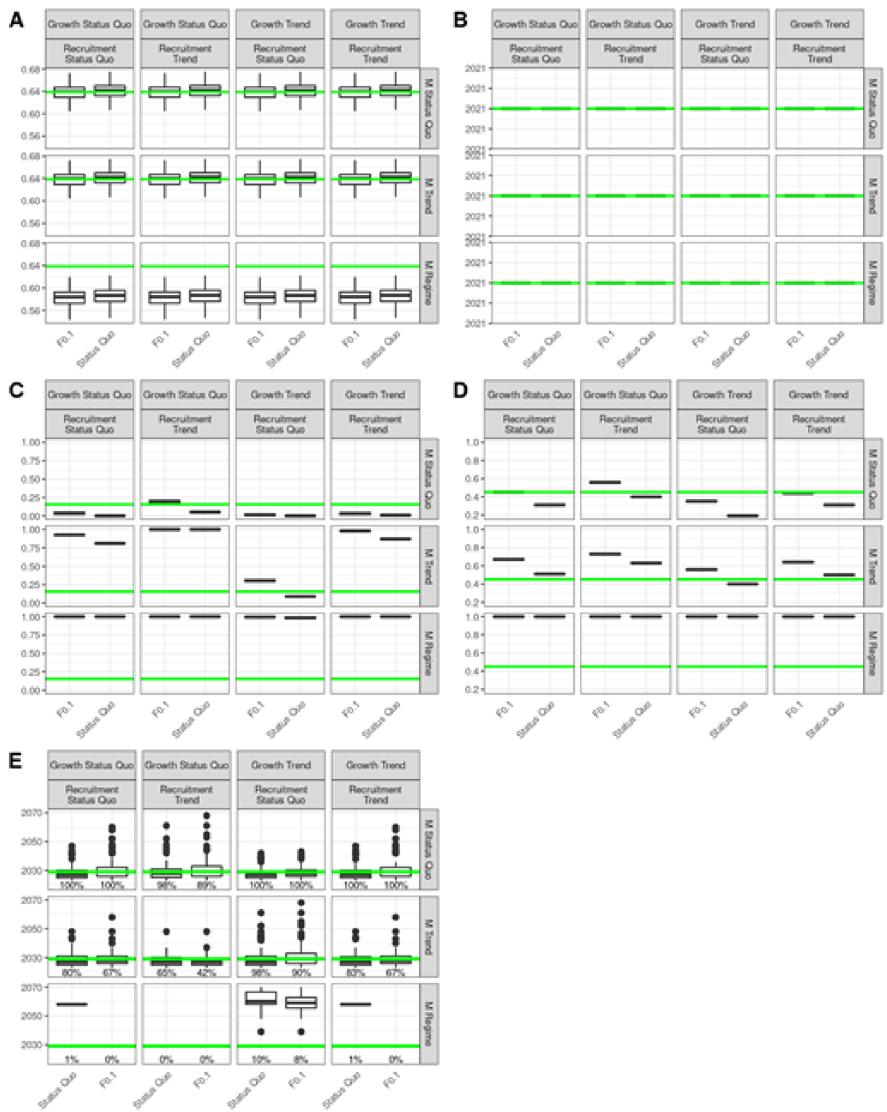

Figure 78 Outcomes on red mullet

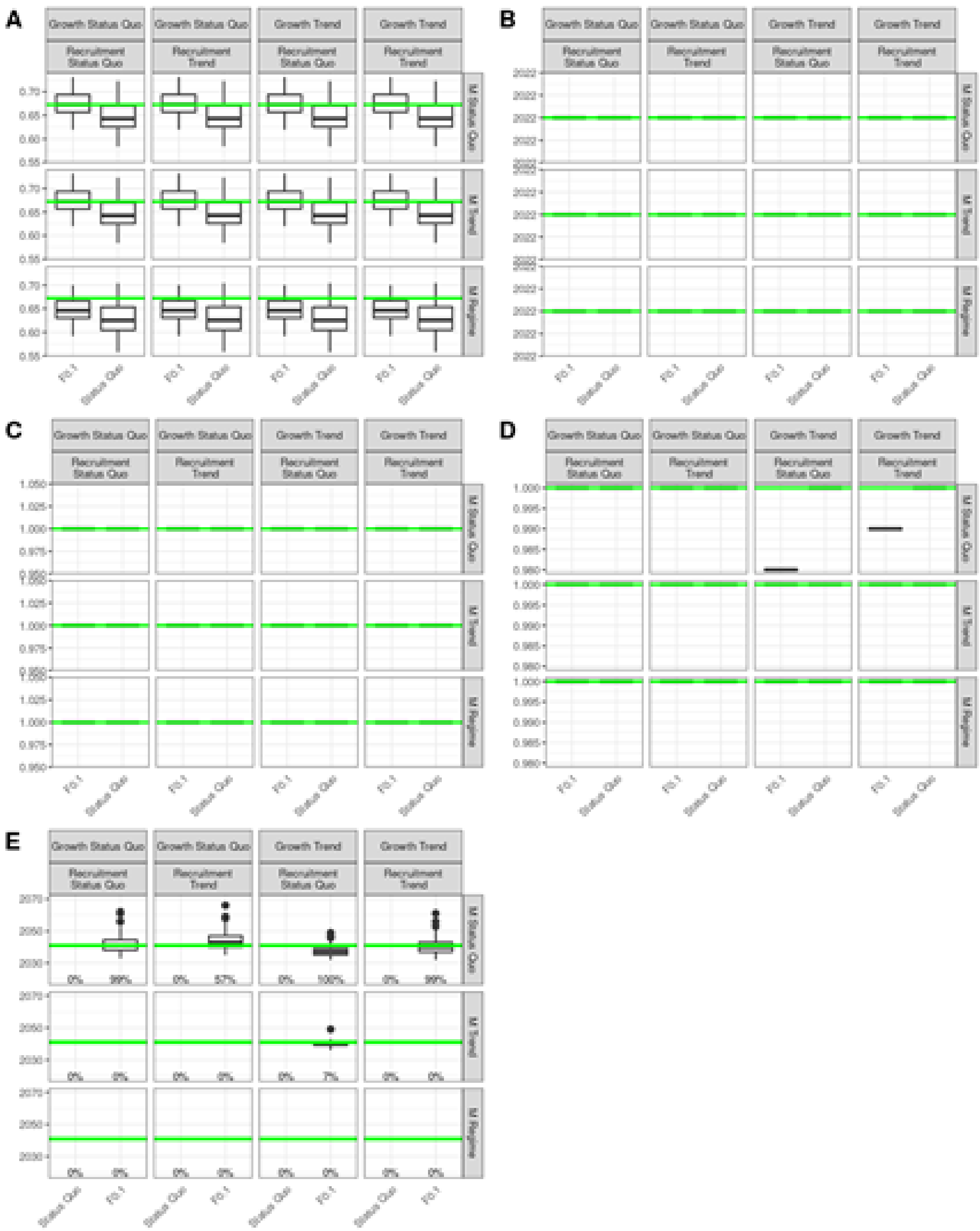

Figure 79 Outcomes on hake

Table 32 Preliminary list of indicators to describe resource resilience

Indicators of resource resilience

Resistance (ability to withstand the perturbation)		
Amplitude	Minimum stock level reached after the shock compared to initial level	SSBmin/SSByear shock
Responsiveness	Number of years between the shock and the minimum observed stock level	YearSSbmin – Yearshock
Biological risk	Probability of SSB falling below 40% of BMSY	Max(P(SSB<0.4BMSY)
Resilience stricto sensu (ability to recover from the perturbation)		
Recovery rate	Probability that stock level is at or above BMSY in 2030	P(SSB2030>=BMSY)
Recovery speed	Number of year to reach BMSY	YearSSB>= BMSY - Yearshock

Annex 14 EVALUATION OF THE ROBUSTNESS OF CURRENT MANAGEMENT ADVICE FOR TROPICAL TUNA (ATLANTIC BIGEYE AND YELLOWFIN) UNDER CLIMATE CHANGE

Introduction

This study aims to evaluate the resilience to climate change of the fisheries management framework used by the International Commission for the Conservation of Atlantic Tuna (ICCAT). We use the tropical tuna stocks, bigeye and yellowfin as a case study. Climate change involves long-term trends due to changes in ecosystems and short-term anomalies due to more frequent extreme weather conditions. Changes are unavoidable, and adaptive harvest rules, i.e. that respond to available biomass, have been shown to provide benefits under both static and changing climates (Gaines et al., 2018). For example, updating target, threshold and limit reference points are detected as changes in stock productivity. Therefore, as a first step, this study tests the resilience of the current management framework adopted by ICCAT, then suggests ways of developing new adaptive management frameworks.

By definition, extreme events are hard to predict. Therefore adaptation to short-term climatic shocks can only be achieved by implementing management systems that contribute to building both ecological and economic resilience. To be resilient, a system must resist damage and recover quickly from stochastic disturbances. Ecological resilience is defined as the capacity of a system to absorb disturbance and reorganise while undergoing change so as still to retain the same essential function, structure, identity, and feedbacks [FAO, 2021[9]]. Economic resilience has two components: instantaneous resilience, which is the ability to limit the magnitude of immediate production losses for a given amount of asset losses, and dynamic resilience, which is the ability to reconstruct and recover (Hallegatte, 2014).

Unlike other quantities being controlled in many management systems, stock biomass can not be observed directly. Instead, status is estimated by stock assessment models using fisheries dependent and independent data such as catch, CPUE, length composition and fixed values or priors for parameters such as natural mortality, growth and fecundity. However, there are uncertainties associated with every phase of the stock assessment process, ranging from data collection, assessment model assumptions, uncertainty about key processes, interpretation of risk, and the implementation of management advice (Jardim et al., 2021). It is also difficult to predict future conditions and the response of stocks to management from past events (Kell et al., 2021), especially under climate change. For these reasons, simulation is commonly used to evaluate the robustness of management strategies. For example using Management Strategy Evaluation (MSE, De Oliveira et. al., 2008), where an Operating Model, representing resource dynamics conditioned for a range of alternative hypotheses representing the main uncertainties, is used to simulate pseudo data to simulation test alternative assessment methods and strategies modelled as feedback control Management Procedures. Feedback is the key component of all control systems, used to correct performance, by adapting future actions based on past experiences. The performance of the candidates can then be compared to statistics derived from the Operating Model, e.g. is Maximum Sustainable Yield achieved (MSY) and overfishing prevented.

MSE is a form of exploratory modelling where computational experimentation is to explore the implications of varying assumptions about uncertain, contested, or unknown model parameters and mechanisms. We do not, however, conduct Management Strategy Evaluation in this study as we do not simulate feedback control.

[9] http://www.fao.org/3/cb3095en/cb3095en.pdf

Material and Methods

Both integrated and biomass dynamic assessment models are used by ICCAT to provide advice for tropical tuna. Integrated assessments are conducted using Stock Synthesis (SS3; Methot and Wetzel, 2013), which implements an age and spatially structured model that reflects the complex population and fishery dynamics of highly migratory tuna stock. As an alternative to the integrated assessment, a biomass dynamic model, based on an explicit production function (e.g. Pella and Tomlinson, 1969), was conducted, which requires the estimation and fixing of fewer parameters and does not require length and age data. The SS3 assessment allows the assessment to be conditioned on a wide range of assumptions reflecting uncertainty and so was used to develop the Operating Model.

The management approaches used by ICCAT are based on the Kobe framework, a common management advice framework used by the Tuna RFMOs (Kell et al., 2016), to provide consistency of advice. The objective is to keep stocks above BMSY and fishing below FMSY. This requires management strategies to be reported regarding the probabilities of maintaining the stock above BMSY and fishing mortality below FMSY. Advice on stock status is normally given in the form of a phase plot with a green quadrant corresponding to the target region (i.e. where the stock is neither overfished (SSB >BMSY) nor subject to overfishing (F<FMSY). The objective of the Kobe framework under a given management option, stocks remain at levels at which their exploitation is still possible (above limits) and can still reach levels at which their exploitation is optimal (e.g. MSY). Atlantic bigeye tuna stock in 2017 was estimated to be overfished and overfishing to be occurring, while the yellowfin stock is estimated to be above BMSY and fishing below FMSY.

Management advice is determined upon which quadrant a stock falls into. If the stock is in the green quadrant, the objective is to maintain the stock in this state with high probability. While if the stock is in the red quadrant, then management measures should be adopted immediately considering the biology of the stock and scientific advice to result in a high probability of ending overfishing in as short a period as possible. No reference points correspond to the ICES Blim, Bpa, Flim, Fpa or MSYBtrigger.

For tropical tuna, under climate change, there are various potential impacts, including changes in spatial distribution and species composition that may affect catches and catch per unit effort (CPUE) of both targeted and by caught species. Biological parameters are also likely to be affected, resulting in changes in size and age structure (Allain et al., 2020), and hence productivity and maximum sustainable yield (MSY) reference points used for management advice. Therefore, to evaluate resilience we first defined plausible, ecosystem-coherent shock scenarios, and then developed an Operating Model to evaluate the ability of current ICCAT advice to achieve management objectives.

Materials

The 2017 bigeye and the 2017 yellowfin SS3 assessments were used to condition the Operating Models. To reflect uncertainty ICCAT conducts stock assessments using an uncertainty grid. For Atlantic bigeye tuna, three factors were considered in the grid, namely two value of natural mortality (M) 0.28 and 0.35; three values of Steepness (h) 0.7 0.8 and 0.9; and the relative importance of the size data (Lambda) 0.1 or 1; While for yellowfin tuna 4 scenarios were considered, namely two values of steepness (0.8 and 0.9); and whether to use or not use the Juvenile Index from Echosounder Buoys.

Potential climatic impacts on tuna stocks and fisheries are changes in productivity due to recruitment, either increased variability or a regime shift; and growth, as climatic change may affect body size in response to ocean warming and lower oxygen. However, it is difficult to predict changes in fecundity and maturity, although these can be modelled via the stock-recruitment relationship. Natural mortality is a function of length and body mass (Gislason et al., 2010, Lorenzen 1996), and can therefore be linked to growth scenarios.

When assessing the status of a fish population for advising management, the spawner-recruit (S-R) relationship, which represents stock productivity, is an important biological process to consider, including the extent to which environmental drivers should be explicitly accounted for in recruitment estimation (Krone et al., 2019). Two methods for incorporating environmental information in an integrated assessment model were evaluated in this study, based on: 1) including an environmental covariate as an additional component of the S-R function; or 2) using the covariate outside the S-R relationship as a survey index of recruitment. Findings indicated that both methods for including an environmental index in the model resulted in relatively high quality estimates for a diverse group of output variables, depending on assumptions regarding bias correction and penalties associated with the recruitment deviation estimates.

Methods

A simulation framework was used to evaluate the ICCAT advice frameworks' ability to achieve management objectives.

The most recent ICCAT stock assessment outputs and assumptions are used to condition the Operating Model, a mathematical-statistical model, that describes the fishery resource in simulations trials. In the Operating Model resource dynamics are known, and so the performance of the ICCAT, advice can be evaluated, i.e. how well do the estimates of reference points correspond to the Operating Model, and is there a loss of yield if the current reference points are used? Simulations are run for a 50-year horizon to evaluate long-term outcomes.

To create an Operating Model based on these data the FLR packages mydas and FLife were used, (see Supplementary Materials). First, an equilibrium per-recruit model was parameterised for growth, maturity and natural mortality-at-age; where the mean of the available values was used for each parameter. The per-recruit model then was combined with a stock recruit relationship. To model uncertainty about parameters and relationships, some scenarios were considered. Virgin biomass was set at a constant value across all stocks and scenarios, as results are presented either in terms of exploitation level or size, and not biomass.

2.2 Simulations

To enable the results to be synthesised a common procedure was used across the case studies, namely

1. Use the FLR framework, which the ices-tools-prod/msy package, a4a and FLBEIA are based upon to estimate MSY based reference points in a standardised manner across case studies.
2. Set up an Operating Model and perform a reference case projection without feedback, for 50 years into the future where F=FMSY
3. Repeat for climate scenarios.
4. Compare realised yields from the reference case and the scenarios

There are two options to implement changes in recruitment:

- An increase in future recruitment variability, which can be implemented via recruitment variability.
- Regime shifts, based on either the expected recruitment at unfished biomass, modelled as R0 in SS3, or a change in the steepness of the stock-recruitment relationship, i.e. mortality of early life history stages (Simone et al., 2012).

Bigeye

Historical Assessments

- Steepness: 0.7, 0.8, 0.9
- Natural Mortality: Reference and Alternative New maximum ag, based on Then, max age increased to 20, 25 from 17, M becomes lower
- Sigma R: 0.2, 0.4 and 0.6

Projections

- Status Quo
- Regime shift: change M and growth for 2020 onwards
- Regime shift: change in Virgin Biomass from 2020 onwards

These are then run these with and without a shock, i.e. increase M in 2020 for 1 season.

Management, i.e. catch

- As advised 65K tonnes
- As realised 75K tonnes

Recruitment is by year, unit and season. Just provide the estimated recruitments. Perform a projection for a TAC for 65K tons

Yellowfin

Historical Assessments
- Steepness: 0.8, 0.9
- Fleets: Annual, Seasonal

Projections
- Status Quo
- Regime shift: change M and growth for 2020 onwards
- Regime shift: change in Virgin Biomass () or from 2020 onwards

These are then run with and without a shock, i.e. increase M in 2020 for 1 season.
Management, i.e. catch
- As advised 110K tonnes
- As realised 130K tonnes

2.2.3 performance statistics

Metrics

A key concept is resource resilience defined by the ability for fish stocks to remain above biomass limits and thresholds at which productivity is impaired and rebuild, in a timely manner, to levels that correspond to management targets.

At the third Workshop on Guidelines for Management Strategy Evaluations (WKGMSE3) performance statistics or summary metrics were defined as a set of statistics used to evaluate the performance of Management Procedures against specified pre-agreed management objectives, and the robustness of these Management Procedures to uncertainties in resource and fishery dynamics of concern to stakeholders and managers. These are properties of the simulated system e.g. foregone catch relative to MSY, or the level of a stock at which recruitment is impaired. There are two main ways to calculate the performance statistics, namely i) using equilibrium assumptions (e.g. Sissenwine and Shepherd (1987) for age based OMs); or ii) though stochastic simulation by projecting at F=FMSY or F=0 (e.g. Carruthers et al. (2016), De Moor, Butterworth, and De Oliveira (2011)). The later approach is preferable where environmental forcing or resonant cohort effects impact on productivity.

ICCAT management is based on MSY reference points, and there are no Bpa, Blim and Btrigger reference points as used by ICES. However, there is a possibility of using a limit reference point defined as 20% of virgin biomass.

Summary statistics, also known as performance statistics or summary metrics, are a set of statistics used to evaluate the performance of Candidate Management Procedures against specified pre-agreed management objectives, and the robustness of these Management Procedures to uncertainties in resource and fishery dynamics of concern to stakeholders and managers. These performance indicators are codified as properties of the system, e.g. the ratio of the realised catch to MSY, and the risk of the stock falling below a level where recruitment is impaired. They may be used to test the robustness of assumptions made in a stock assessment or within a Management Procedure, for example, when B_{MSY} (based on exploitable biomass) or F_{MSY} (based on harvest rate) are used as part of the forecast for biomass dynamic models. These may differ from the corresponding quantities in the Operating Model (where B_{MSY} is based on SSB, and F_{MSY} based on an instantaneous exploitation rate). There are two main ways to derive quantities to be used for performance statistics, namely: (i) using equilibrium assumptions \cite{sissenwine1987alternative}, or (ii) through stochastic simulation e.g. by projecting at F = F_{MSY} or F = 0 (\citep[e.g.][] {carruthers2016performance, de2011management}. The latter approach is preferable where environmental forcing or resonant cohort effects have an impact on productivity.

Discussion and Conclusions

There are also to be two ICES Workshop later this year and early next, WKREF1 and WKREF2. Some of the Terms of Reference are of relevance to this project, namely

- Review the current limit, trigger and target reference point estimation procedures for both biomass and fishing mortality used by ICES, and identify limitations and inconsistencies considering international best practice, the precautionary approach and international policies and legislation.

- Evaluate the robustness, consistency and plausibility of limit and target reference points in relation to current ICES Advice Rule in comparison to alternative approaches.
- Explore alternative methods that can better account for stock dynamics, biological realism and productivity drivers in reference point estimations under climate and environmental uncertainties.

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Annex 15 THE BALTIC ATLANTIS END-TO-END ECOSYSTEM MODEL

The Baltic Atlantis (Figure 80) (Bossier et al., 2021, 2020, 2018; Nielsen et al., 2018) is a three-dimensional, spatially explicit end-to-end ecosystem model covering the Baltic Sea and Kattegat. The model considers all parts of the marine ecosystem - physical, biogeochemical, biological and fisheries dynamics and interactions. The modelled area is divided into 26 geographical boxes (polygons) and three boundary boxes (of which 2 are islands). Each polygon has one sediment layer and a maximum of six water column layers. The model is calibrated and initialised for the year 2005 and operates at 12-hour time steps. A full model run and projection is 127 years, of which the first 35 years consist of a spin-up period. The Baltic Atlantis has 30 biological functional groups, which include: mammals (2), seabirds (1), pelagic fish (3), demersal fish (6), benthic invertebrates (4), commercial benthos (1), pelagic invertebrates (4), benthic primary producers (2), pelagic primary producers (2), bacteria (2), and detritus groups (3). The vertebrate groups (mammals, seabirds, fish) are demographically structured by age groups, while the other groups are non-disaggregated biomass pools. Further model details can be found in Bossier et al. (2018; 2021).

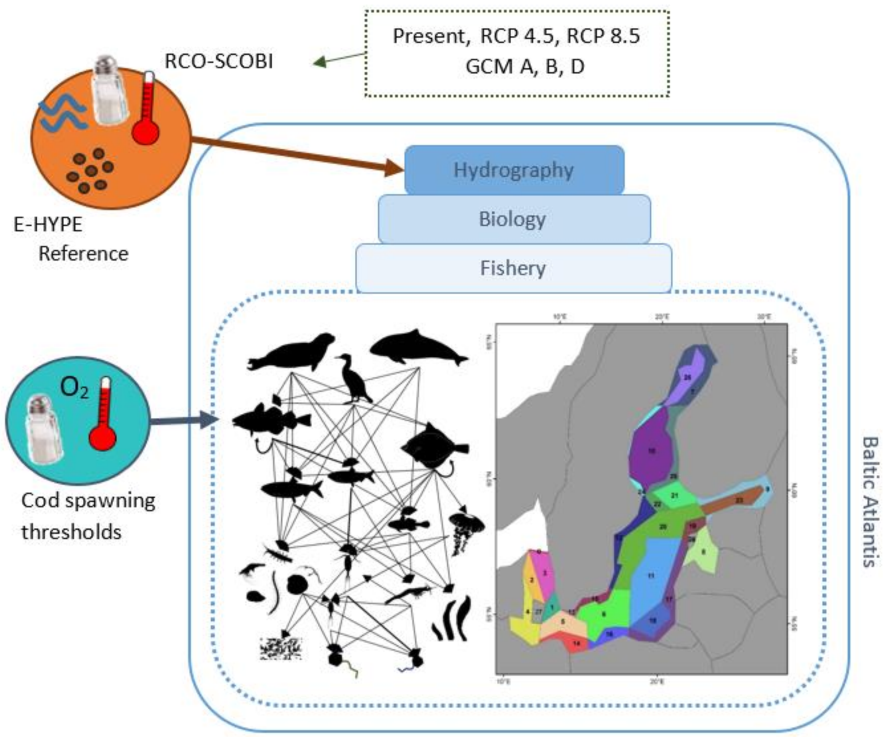

Figure 80 Adjusted from Bossier et al. (2021). Schematic representation of the Baltic Atlantis (Bossier et al., 2020, 2018). Physical forcing of temperature, salinity and fluxes (currents) from the RCO-SCOBI model for GCM A, B and D with nutrient forcing from E-HYPE. We run 3 climate scenarios (present, RCP 4.5 and RCP 8.5) with one reference nutrient scenario. Note that there are still some functional groups of the Baltic Atlantis missing in the food web of this figure to keep it clear.

Fish recruitment is modelled with the Beverton-Holt functional relationship (Beverton and Holt, 1957) and consumption with a Holling type II functional response. A flexible diet matrix enables the functional groups to interact with one another whereby a certain fraction of the available prey biomass is available to a specific predator. For more details on the model framework we refer to the Atlantis manual from Audzijonyte et al. (2019) besides Baltic specific implementation details in Bossier et al. (2018; 2021).

Physical information of temperature, salinity and currents for the year 2005 and for the future projections is provided by the Swedish Meteorological and hydrological Institute (SMHI) using their RCO-SCOBI model (Almroth-Rosell et al., 2011; Eilola et al., 2009; Meier et al., 2012). Riverine nutrient load projections was simulated using their E-HYPE model (Hydrological Predictions for the Environment, http://hypeweb.smhi.se) as forcing for the RCO-SCOBI (for further details see Bossier et al., 2021).

The physiological processes of all functional groups in the Baltic Atlantis, except mammals and seabirds, are affected by temperature. This includes consumption, growth, mortality and reproduction. The temperature scalar is based on the Q_{10} temperature coefficient. This a measure of the temperature sensitivity of an enzymatic reaction rate or a physiological process as a consequence of increasing the temperature by 10°C (Audzijonyte et al., 2019). The Baltic Atlantis uses a reference temperature of 15°C and a standard temperature effect on metabolism (Q10 = 2) (Bossier et al., 2021).

Fisheries in the Baltic Atlantis is defined by seven different fisheries (fleets): pelagic trawlers, small and large meshed otterboard trawlers, demersal seiners / Danish seiners, gillnetters, dredges and others (e.g.fyke nets, longlines, traps, etc.). These fisheries cover the current main fisheries catching the main bulk of commercially exploited species in the Baltic region (ICES, 2019). Fishing is modelled dynamically and catch will fluctuate depending on the available biomass, its spatial dynamics, and the size of the fish. Both the extensive EU STECF database (https://stecf.jrc.ec.europa.eu/dd/effort; STECF, 2018) and information from the ICES stock assessments (e.g.ICES 2019) were used to calibrate and validate the fishery submodule (Audzijonyte et al., 2019; ICES 2019). Fishing effort is kept constant during the current scenarios as the focus will be on short-term shocks and long-term impact of climate change on the Baltic Sea ecosystem. To come with valid predictions of fisheries scenarios would demand that future management reference points according to sustainable harvest following Maximum Sustainable Yield (MSY) would need to be assumed (or re-estimated) to obtain realistic changes in quotas (TAC, Total Allowable Catch) and harvest levels. This relies on strong assumptions as MSY reference points would likely change given the changed recruitment scenarios and climate scenarios affecting species and stock biomasses (and accordingly MSY reference points) of the exploited fisheries resources (e.g. cod, sprat and herring). See also further comments on how this is handled in the simulations and evaluations below.

Model simulations

Short-term:

One or two shocks are induced at the start of the simulation, i.e. right after the 35-year spin-up period. One shock for the “most-likely” scenario (RCP 4.5) and two shocks for the “worst case” scenario (RCP 8.5). The relative effects of 10 years after the first shock are compared to the baseline of 2020.

- A scenario affecting particular species
    - Failure of cod reproduction – cod recruitment will be affected by temperature due to its hydrographic spawning thresholds.
    - Potential failure of sprat and herring reproduction; sprat recruitment will be affected by temperature due to its hydrographic spawning thresholds; herring recruitment will be affected by the increase in storm events; (also given climate change scenarios).
- A scenario affecting the general system:

- Heatwave: Focus on the effects on cod. We assume that spawning thresholds according to different hydrographical factors (temperature, salinity, oxygen) do not change because of the heatwaves including the potential interactions between thresholds. Thresholds are extracted from literature. The heatwaves will in the holistic ecosystem model also affect physiological processes such as growth, clearance rates, mortality, etc. which will be included in the integrated ecosystem model evaluations as well as all derived integrated effects on the ecosystem and the other biological functional groups,i.e.physical environment and biological interactions (again also given climate changes / scenarios).

Long-term:
Long-term climate scenarios of RCP 4.5 and RCP 8.5 for a 100-year projection compared to the baseline of 2020 (no shocks) (See also Bossier et al., 2021) (Table 33).

Table 33 Summary of the scenarios. Short-term shocks of recruitment failure and long-term effects of climate change for both RCP 4.5 ("most likely") and RCP 8.5 ("worst case").

Induced changes (scenarios) in Baltic Atlantis simulations		Status quo = present = baseline	Most likely = RCP 4.5	Worst case = RCP 8.5
Short-term shocks	Manually induced recruitment shock of cod of 50%.	10-year projection after the shock	1 shock at the beginning of the simulation period.	2 shocks (1 in the first year and 1 in the second year of the simulation period).
	Manually induced recruitment shock of sprat of 50%.	1 shock at the beginning of the simulation period.	1 shock at the beginning of the simulation period.	2 shocks (1 in the first year and 1 in the second year of the simulation period).
	Manually induced recruitment shock of herring of 50%.	1 shock at the beginning of the simulation period.	1 shock at the beginning of the simulation period.	2 shocks (1 in the first year and 1 in the second year of the simulation period).
	Heatwave induced shock on cod		Optional	Optional
	Mass mortality shock event on cod (recruitment failure of 100% for all the following years).	1 shock at the beginning of the simulation period.		
Long-term effects of climate change	Long-term forcing, no shock for cod, sprat and herring	100-year projection period.	RCP 4.5 with reference nutrient scenario (Different nutrient scenarios, BSAP, reference and worst case with 2 nutrient sources, E-HYPE and PLC 7 are used in Bossier et al. (2021))	RCP 8.5 with reference nutrient scenario (Different nutrient scenarios, BSAP, reference and worst case with 2 nutrient sources, E-HYPE and PLC 7 are used in Bossier et al. (2021))

Management scenarios

If we see relative changes in carrying capacity biomass estimates by species, then we assume that the stock-specific MSY levels according to biomass will change similarly with respect to level and direction inducing new management conditions and considerations. This takes into account changing environment and biological interactions and indicate whether the current MSY levels on biomass holds or not.

We calculate the relative changes in relation to the following indicators:

- Biomass of cod, sprat and herring
- Demersal-Pelagic ratio (determined by cod, sprat, herring and flatfish)
- Trophic level

Ecological resilience

- Amplitude (Comparison between the indicator minimum/maximum level after the shock and its estimated initial level)
- Responsiveness (Number of years between the shock and the minimum/maximum level reached by the indicator)
- Recovery time (Number of years before the indicator reaches the level it would have had under the lack of a shock or when the indicator does not go back to the level it would have had under lack of a shock, calculate the % recovery of the indicator in 10 years)

Heatwave definition and sensitivity according to that

Heatwaves in general are not well defined. First of all, the heatwave can be either based on pure assumptions (not found optimal, and accordingly not done in present case study) OR based on existing data from e.g.the Copernicus 1993-2018 database (potentially the June-July 2018 or 2015 heatwaves) OR a theoretical index field can be generated from the RCO-SCOBI dataset. The latter dataset has previously been applied with the Baltic Atlantis model with regard to the climate change RCP 4.5 and 8.5 trajectories (Bossier et al., 2021). Secondly, the size and duration of the heatwave can be defined according to anomalies observed in temperature (and salinity) OR a percentiles perspective can be used as a method to extract extremes. For example, observations above the 90% percentile, based on a 30-year historical baseline period, for a period of minimum 5 days, as suggested by Hobday et al. (2016). Daily maxima for the spawning windows can be extracted and averages of those can be used to force the Atlantis model. In the existing RCO-SCOBI dataset, we have three 5-year periods for a century for each of the Baseline, the RCP4.5 and the RCP8.5. Different definitions and extractions can potentially be used in sensitivity testing. Finally, the heatwave used in this study is based on the Copernicus 1993-2018 database. The temperature of the year 2018, which had an actual heatwave, was compared with the temperature of the year 2005, which is the baseline year of the Atlantis model. A Gaussian distribution was then fitted based on the difference in temperature of the two years. The distribution covers the entire horizontal area of the Baltic Atlantis and the top two vertical layers. The other vertical layers are assumed to be unaffected by the heatwave.

Acidification for Baltic Atlantis:

- Atlantis has an option to include effects of acidification on different physiological processes. However, this is not activated in our current Baltic Atlantis calibration and activating this is a very effort demanding and long process which is outside the timeframe of current project.
- Additionally, there has been some studies that found a broad range of potential impacts of acidification in case studies around the world, but there is not extensive (adequate) knowledge yet available on the effects of these processes on the main commercial fish species of the Baltic Sea (where some results for cod were contradicting each other). Accordingly, this would include several assumptions not based on an

adequate knowledge basis to support the assumptions. Further details and considerations on the above cover:

- Herring:
    - "Herring eggs can cope at current temperature conditions with an increase in pCO_2, exceeding future predictions of CO_2-driven ocean acidification, but the yolk sac larvae show a reduced protein biosynthesis capacity and therefore a potential growth reduction." (Franke and Clemmesen, 2011)
- Cod:
    - "No significant effect of decreased pH (decrease of pH to 7.55) on sperm speed, rate of change of direction, or percent motility for Baltic cod." (Frommel et al., 2010)
    - "Our data show that the eggs and early larval stages of Baltic cod seem to be robust to even high levels of OA (3,200 µatm), indicating an adaptational response to CO_2." (Frommel et al., 2013)
    - "A pCO_2 of ~1100 µatm (according to the IPCC RCP 8.5) resulted in a doubling of daily mortality rates compared to present-day CO_2 concentrations during the first 25 days post-hatching (dph) for Western Baltic cod." (Stiasny et al., 2016)

- There seem to be a larger effect on freshwater species (bream, roach, perch) (Hildén and Hirvi, 1987; Hudd et al., 1984; Urho et al., 1990), but this is not the focus of our work in present case-specific evaluations of target species and stocks.
- Usually what is done in other Atlantis publications, is that they ran scenarios of changed mortality or growth to mimic the effect of acidification instead of using the build-in pH-scalar.

Results

Short-term shocks

Changes in the fish population due to the short-term shock and long-term climate change are evaluated in terms of resistance (i.e., ability of the stocks to oppose to the perturbation) and resilience (i.e., ability of the stocks to recover from the perturbation).

It usually takes around 10 years for the system to recover from a single event (1 shock) and 11 years for a double event (2 shocks) (Figure 81, Figure 82, Figure 83). This corresponds to the number of age-groups cod, sprat and herring have in the model. The reaction of some of the other biological functional groups in the food web that either feed directly on the species perturbed or are being eaten by it, are affected 1-2 years after the initial shock and last usually longer than 10 years (e.g. Figure 82, copepods for the sprat perturbation is affected for 13 years, while the seals for 22 years).

The double shock event for sprat and herring shows the biggest relative changes. At the same time, the reaction of the rest of the food web is largest for the sprat perturbations. Here the effects are shown for higher trophic levels such as seals and seabirds to the lower trophic levels such as zooplankton and phytoplankton. This might be because sprat (as a planktivorous and fish prey group) plays a central role in the food web. However, the biomass of sprat in the model is higher than in the surveys (Bossier et al., 2021).

Harbour porpoise is highly affected by the cod mass mortality scenario (Figure 84). Secondly, seals, sprat, herring, copepods and diatoms only show small effects.

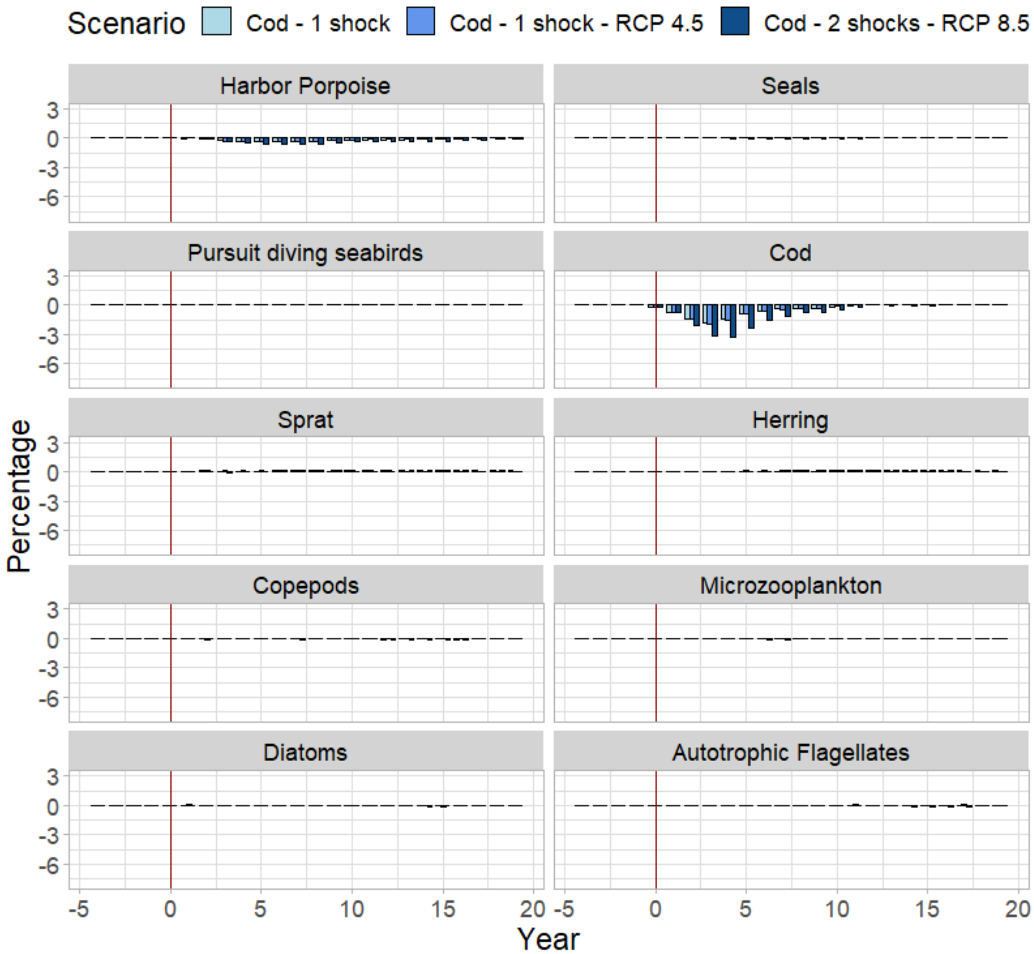

Figure 81 Results for the shock scenarios for cod of –50% recruitment compared to the baseline. The x-axis shows the years of the simulation, with the start of the simulation after the spin-up period (35 years) indicated by the red vertical line. The y-axis shows the relative change in percent of the scenario compared to the baseline. One shock at the beginning of the simulation period for present climate (light blue) and RCP 4.5 (mid blue) and for two shocks (one in the first year of the simulation and the another in the second year) for RCP 8.5 (dark blue). Results are shown for a selection of functional groups according to the objectives and focus of the study.

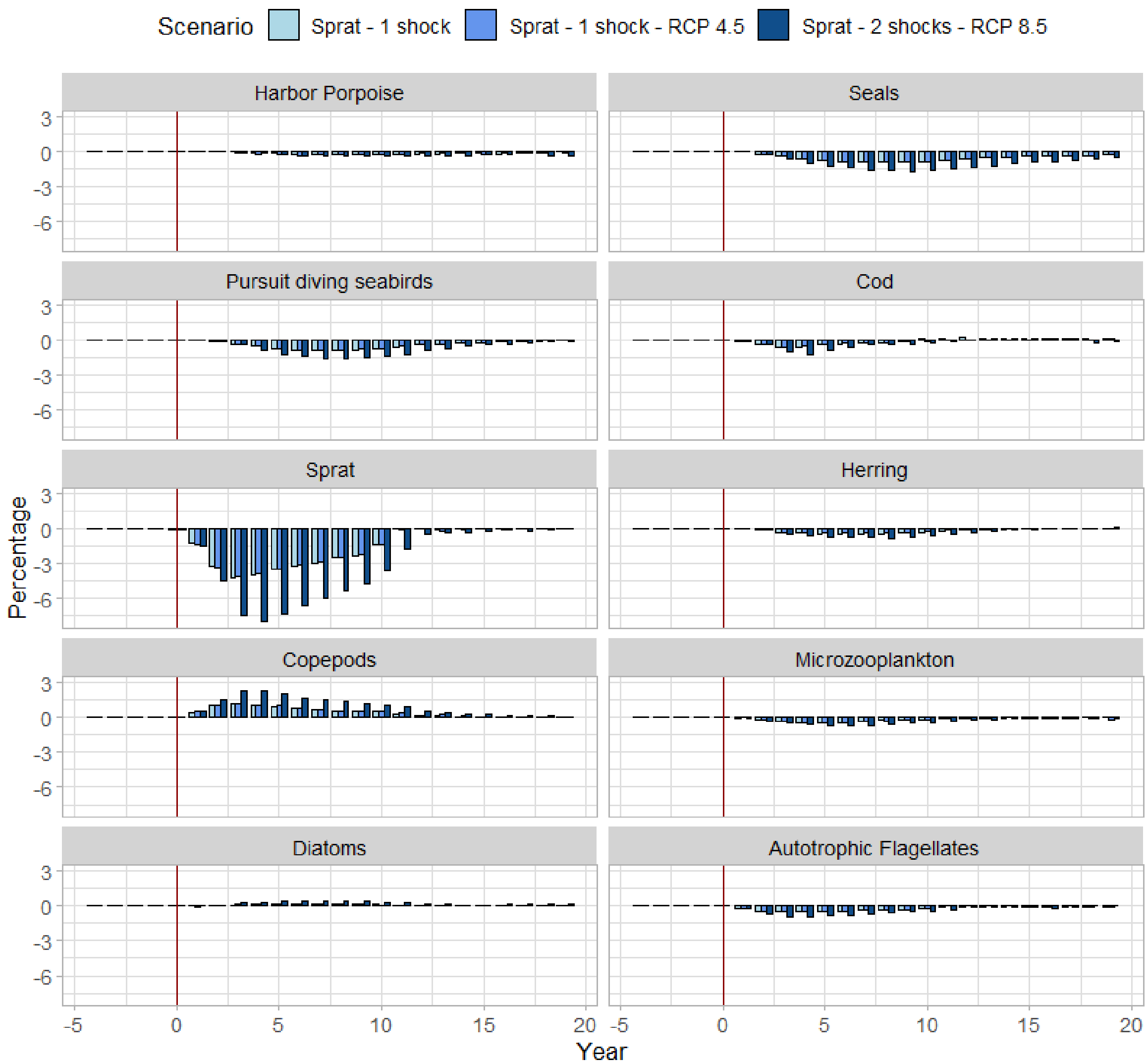

Figure 82 Results for the shock scenarios for sprat of –50% recruitment compared to the baseline. The x-axis shows the years of the simulation, with the start of the simulation after the spin-up period (35 years) indicated by the red vertical line. The y-axis shows the relative change in percent of the scenario compared to the baseline. One shock at the beginning of the simulation period for present climate (light blue) and RCP 4.5 (mid blue) and for two shocks (one in the first year of the simulation and the another in the second year) for RCP 8.5 (dark blue). Results are shown for a selection of functional groups according to the objectives and focus of the study.

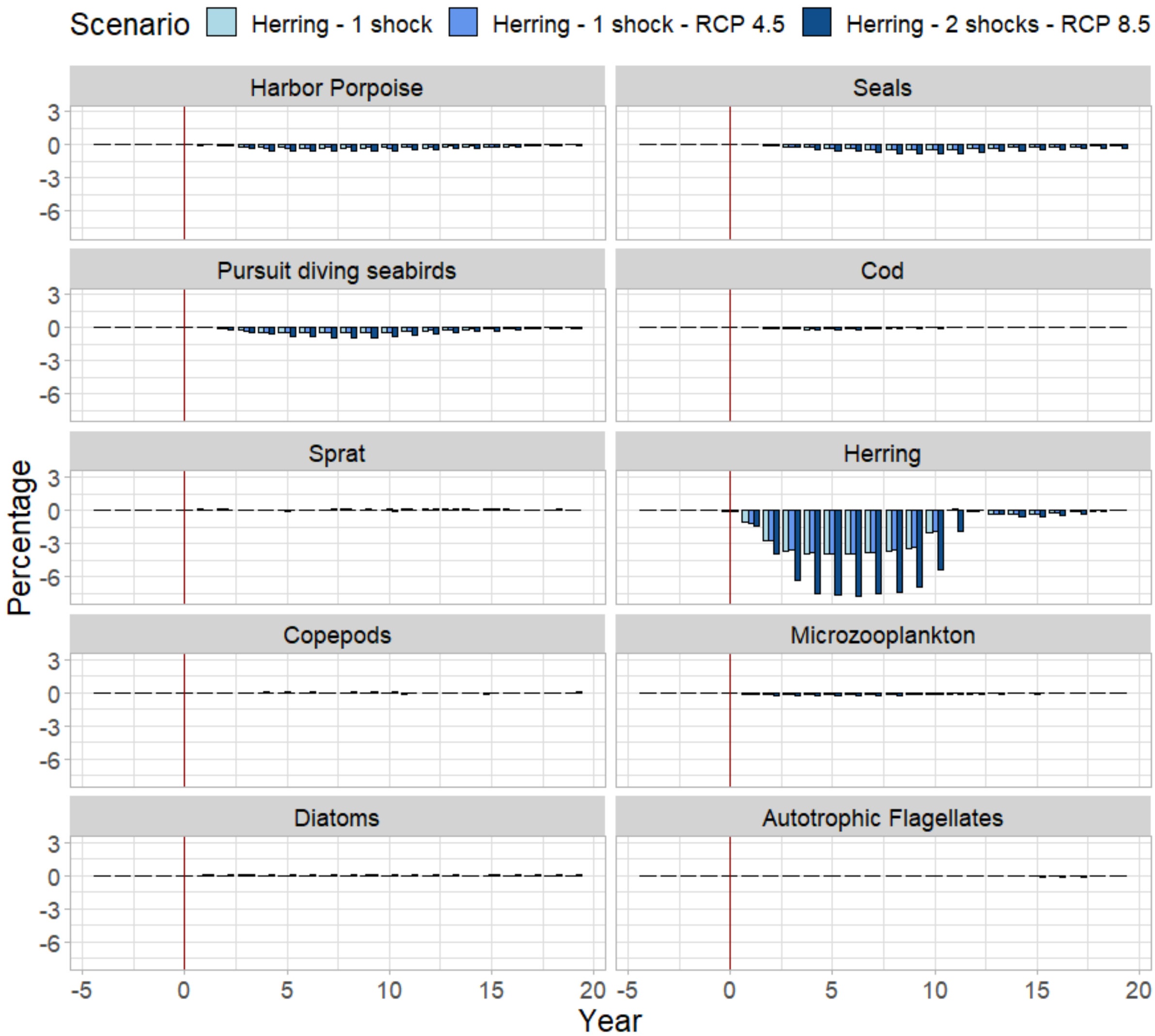

Figure 83 Results for the shock scenarios for herring of −50% recruitment compared to the baseline. The x-axis shows the years of the simulation, with the start of the simulation after the spin-up period (35 years) indicated by the red vertical line. The y-axis shows the relative change in percent of the scenario compared to the baseline. One shock at the beginning of the simulation period for present climate (light blue) and RCP 4.5 (mid blue) and for two shocks (one in the first year of the simulation and the another in the second year) for RCP 8.5 (dark blue). Results are shown for a selection of functional groups according to the objectives and focus of the study.

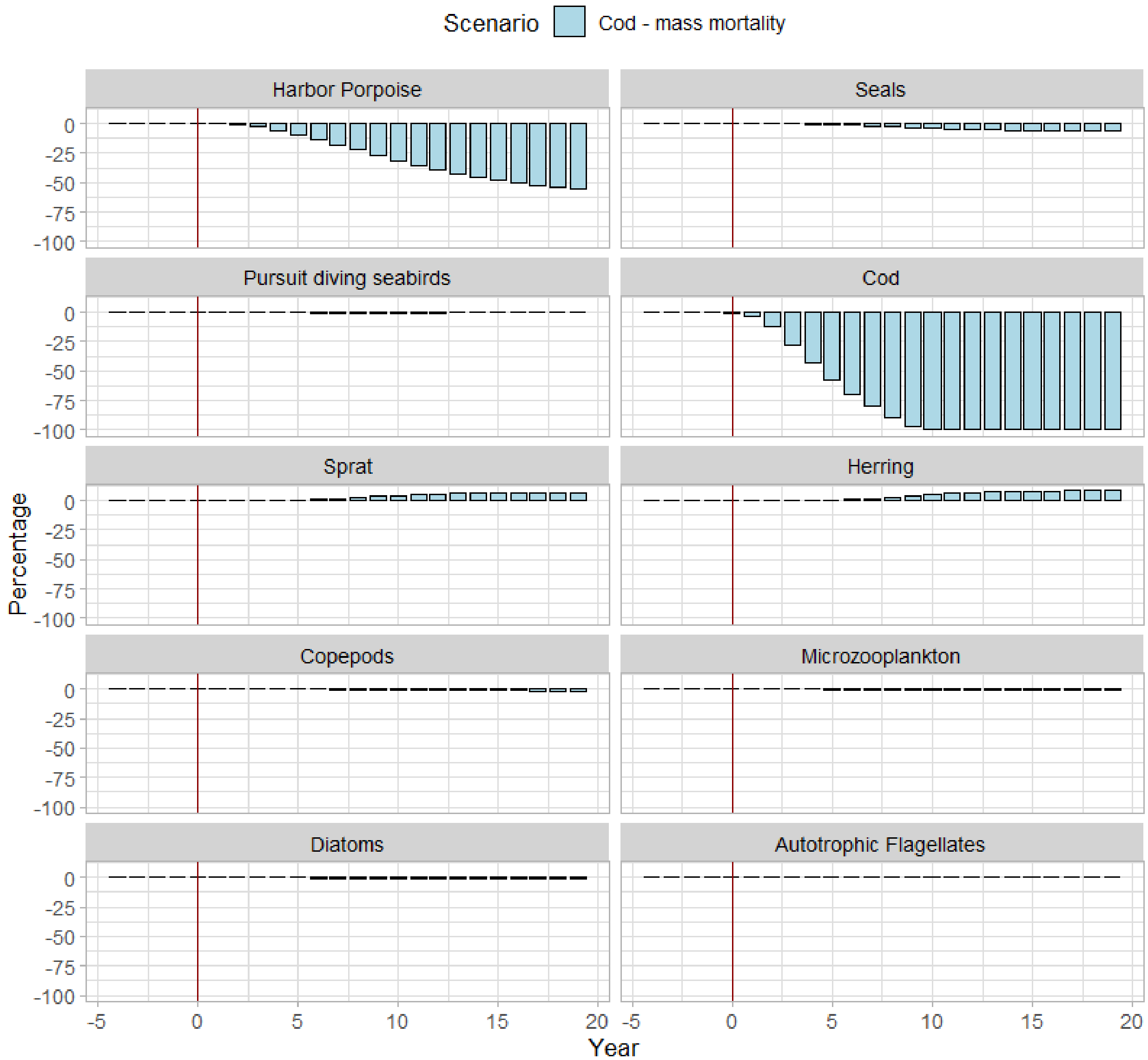

Figure 84 Results for the mass mortality scenarios for cod compared to the baseline. Full recruitment failure (100%) for cod from the start of the simulation onward. The x-axis shows the years of the simulation, with the start of the simulation after the spin-up period (35 years) indicated by the red vertical line. The y-axis shows the relative change in percent of the scenario compared to the baseline. Results are shown for a selection of functional groups according to the objectives and focus of the study.

<u>Demersal-Pelagic ratio</u>

The demersal/pelagic ratio at the start of the simulation (i.e. after the spin-up) is around 0.0134. There is only a small change of the ratio for the different scenarios (Table 2), with a decrease for the cod shock scenarios, an increase for the sprat shock scenarios and no change for the herring shock scenarios. The amplitude is very small for the cod and herring scenarios, while it is more extensive and better identifiable for the sprat scenarios. The responsiveness is usually around 3-4 years for the cod and sprat scenarios, while it is longer for the herring scenarios because of the small change in the demersal-pelagic ratio, i.e., no clear peak was identified (Figure 85). The recovery time is usually around 10-12 years.

Table 2. Results of the demersal/pelagic ratio, the amplitude and responsiveness for the different scenarios. Amplitude is the comparison between the indicator minimum level after the shock and its estimated initial level. Responsiveness is the number of years between the shock and the minimum level reached by the indicator.

	Scenario	ratio at peak	Amplitude	Responsiveness
1	Baseline	NA	NA	NA
2	Baseline RCP 4.5	NA	NA	NA
3	Baseline RCP 8.5	NA	NA	NA
4	Cod recruitment shock	0.0134	-0.0015	3
5	Cod recruitment shock RCP 4.5	0.0133	-0.0067	3
6	Cod recruitment shock RCP 8.5	0.0131	-0.0190	4
7	Sprat recruitment shock	0.0141	0.0475	3
8	Sprat recruitment shock RCP 4.5	0.0140	0.0429	3
9	Sprat recruitment shock RCP 8.5	0.0145	0.0779	4
10	Herring recruitment shock	0.0137	0.0218	9
11	Herring recruitment shock RCP 4.5	0.0136	0.0152	5
12	Herring recruitment shock RCP 8.5	0.0136	0.0176	6
13	Cod mass mortality	0.0136	0.0116	1

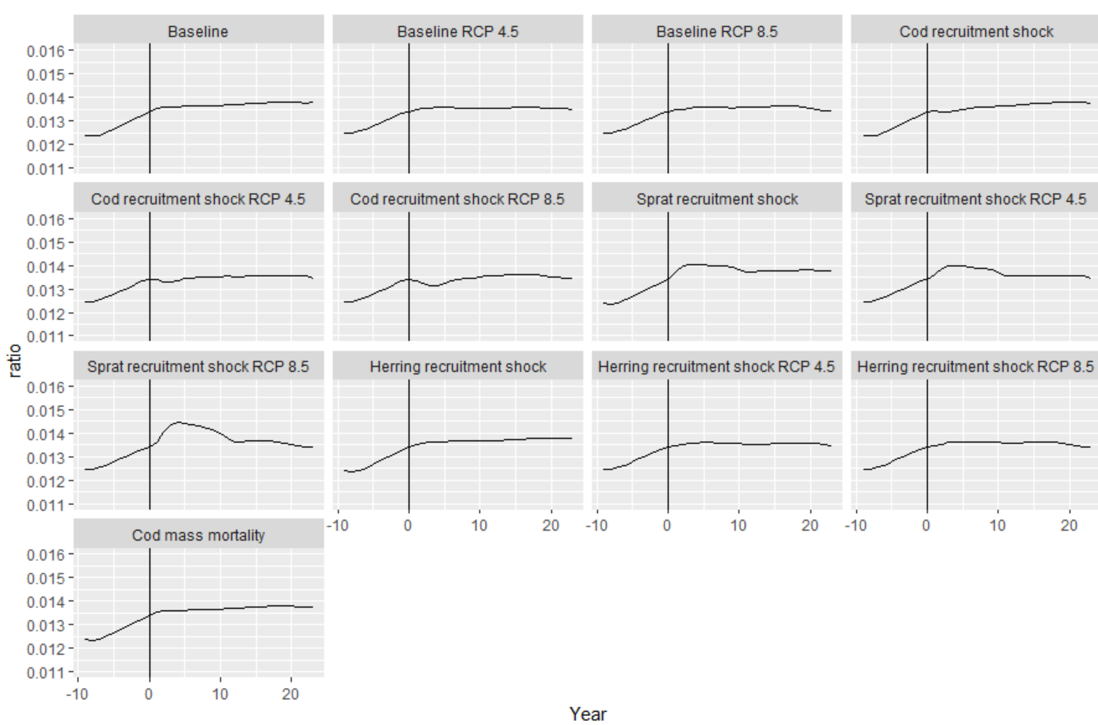

Figure 85 Results for the demersal/pelagic ratio indicator. The x-axis shows the years of the simulation, with the start of the simulation indicated by the vertical line (after the 35-year spin-up period). The y-axis shows the demersal/pelagic ratio. The figure also shows the amplitude, the responsiveness and the recovery time of the indicator of the different scenarios.

Trophic level

The trophic level (Figure 86) shows a clear picture of the trophic level of each functional group for the Baltic Sea food web. Between the different scenarios, however, there is almost no change of the trophic level of any of the functional groups.

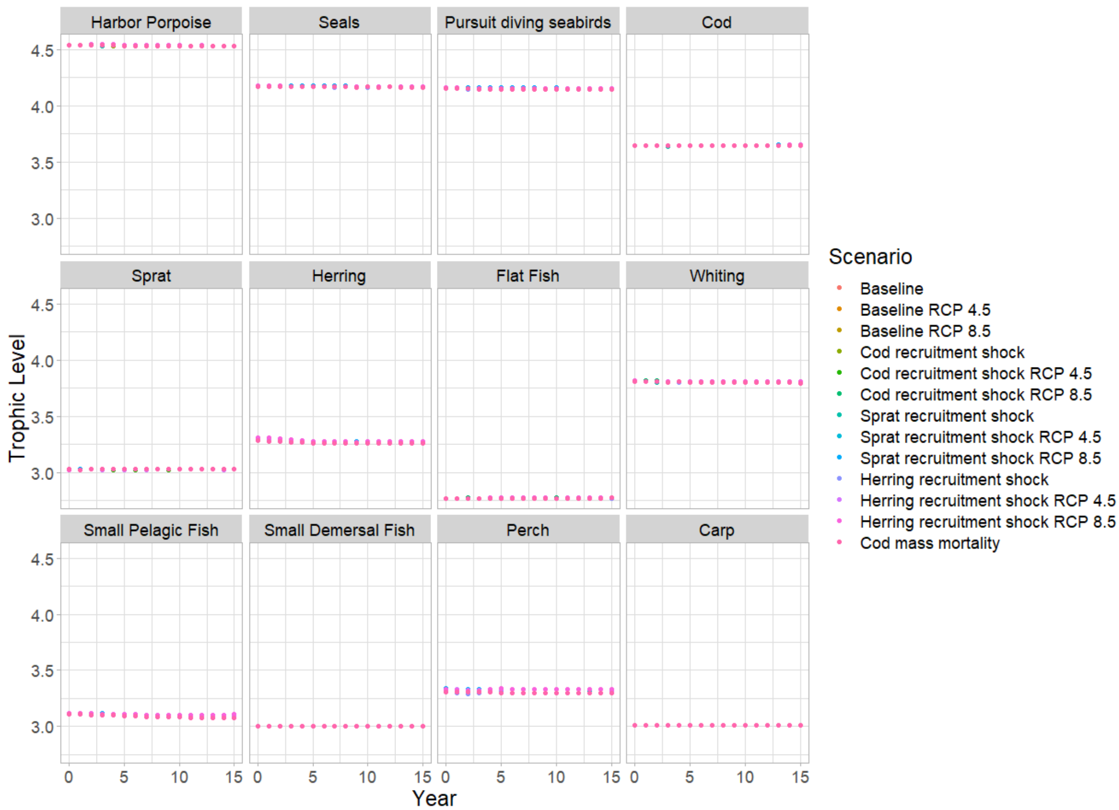

Figure 86 Results for the trophic level of the higher trophic levels for the different scenarios. The x-axis shows the years of the simulation, starting after the spin-up period. The y-axis shows the trophic level.

Long-term effect

RCP 8.5 has, for most cases, a stronger effect compared to RCP 4.5 (Figure 87). In general, cod biomass decreases, while sprat and herring biomass increases. Seabirds and harbour porpoise decrease as well, while seals slightly increase for RCP 8.5. There is no difference between the different shock scenarios of cod, sprat and herring because the system went back to equilibrium around 10 years after the shock. The results of sprat and seals for the RCP 4.5 scenario show a decrease in biomass, while it increases for the RCP 8.5. The decrease in biomass compared to the baseline is that sprat goes to another equilibrium. Therefore, we cannot use the sprat and seals results of the RCP 4.5, because it is not an actual result from the climate effect, but it results from a combination of a change in equilibrium and the climate effect.

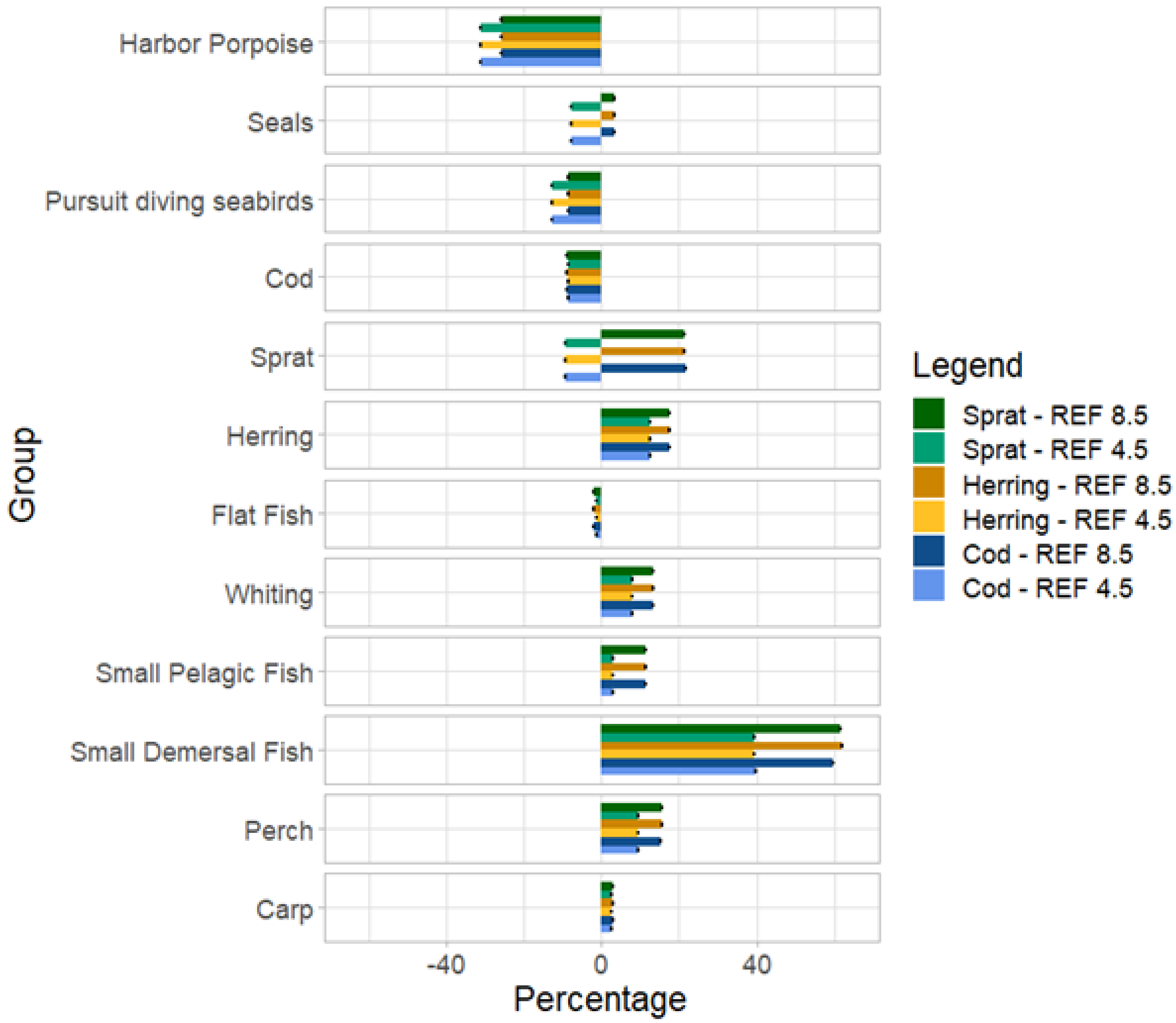

Figure 87 Long-term effect of climate change impact RCP 4.5 and RCP 8.5 on the higher trophic levels of the Baltic Sea food web for each of the shock scenarios compared to the baseline. Model output results, averaged for the last five years of the simulation period (2092–2096), for the change in biomass. The x-axis shows the relative change in percent. (Bossier et al., 2021).

Conclusions

The recovery rate of the short-term shocks is usually around 11 years for a 1-year shock and 12 years for a 2-year shock. This coincides very much with the number of age groups in the model (10 age groups for cod, sprat and herring). This needs to be taken into consideration when perceiving the results from the analyses of these scenarios. In addition, the Baltic Sea Atlantis has a relatively high sprat biomass (Bossier et al., 2021) which results in only a small change in the demersal/pelagic ratio for the cod and herring short-term shocks.

Baltic Sea cod
Summary of the results / conclusions: The cod stock is only slightly impacted by the short-term shocks. However, on the long term, the stock decreases due to the changes in the climatic conditions. Resilience could be improved if the eutrophication issue was considered as well in the integrated evaluations (see Bossier et al., 2021). In addition, climate change will have a severe impact on the Baltic Sea cod population once the hydrographic spawning thresholds such as salinity and oxygen are reached (see Bossier et al., 2021).

Stock	Scenario	Short-term development with shock	Resilience	Remarks
Baltic Sea and Kattegat stock(s)	Baseline	Stock decreases by 2 %.	A slight decrease of the demersal/pelagic ratio, with peak after 3 years. Recovery after 10 years.	
	Most likely	Stock decreases by 2 %.	A slight decrease of the demersal/pelagic ratio, with peak after 3 years. Recovery after 10 years.	
	Worst case	Stock decreases by 3 %.	A slight decrease of the demersal/pelagic ratio, with peak after 4 years. Recovery after 11 years.	
	Scenario	Long-term development without shock	Resilience	Remarks
	Most likely	Stock decreases by 10 %.		
	Worst case	Stock decreases by 10 %.		

Baltic Sea sprat				
Summary of the results / conclusions: The sprat stock is moderately impacted by the short-term shocks. The results of the short-term shock scenarios of sprat have a higher impact on the other groups in the ecosystem, such as seals, seabirds, zooplankton and phytoplankton compared to the cod and herring scenarios. The long-term climate change impact results in an increase of the stock.				
Stock	Scenario	Short-term development with shock	Resilience	Remarks
Baltic Sea and Kattegat stock	Baseline	Stock decreases by 4 %.	Demersal/pelagic ratio increases and peaks after 3 years. Recovery after 11 years.	
	Most likely	Stock decreases by 4 %.	Demersal/pelagic ratio increases and peaks after 3 years. Recovery after 11 years.	
	Worst case	Stock decreases by 8 %.	Demersal/pelagic ratio increases and peaks after 4 years. Recovery after 12 years.	
	Scenario	Long-term development without shock	Resilience	Remarks
	Most likely	NA		Sprat jumps to another equilibrium in this scenario. Therefore, while the results showed a decrease in its biomass compared to the baseline, we cannot rely on this with certainty. This is because it is not a stand-alone true

				result from the climate effect, but it is a result from a combination of a change in equilibrium and the climate effect.
	Worst case	Stock increases by 21 %.		

Baltic Sea herring				
Summary of the results / conclusions: The herring stock is moderately impacted by the short-term shocks. However, the long-term climate change impact results with an increase of the stock with a higher change for the "worst case" compared to the "most likely".				
Stock	Scenario	Short-term development with shock	Resilience	Remarks
Baltic Sea and Kattegat stock(s)	Baseline	Stock decreases by 4 %.	Demersal/pelagic ratio does not change much and no clear peak is identifiable. Recovery after 11 years.	
	Most likely	Stock decreases by 4 %.	Demersal/pelagic ratio does not change much and no clear peak is identifiable. Recovery after 11 years.	
	Worst case	Stock decreases by 8 %.	Demersal/pelagic ratio does not change much and no clear peak is identifiable. Recovery after 12 years.	
	Scenario	Long-term development without shock	Resilience	Remarks
	Most likely	Stock increases by 17 %.		
	Worst case	Stock increases by 19 %.		

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Annex 16 SOUTHERN NORTH SEA AND IRISH SEA - GRADIENT APPROACH TO ASSESS THE RESILIENCE OF EXPLOITED STOCKS TO CLIMATE INDUCED STRESSES

INTRODUCTION

The following report documents the use of two ecosystem models to improve our understanding of the impact of environmental shocks on commercial stock biomass and ecosystem response, structure, and resilience. We compare results for the Irish Sea and southern North Sea ecosystems using a novel approach that simulates ranges of environmental shocks to build an understanding of (i) the impact of shock magnitude, (ii) the propagation of effects through the food webs, and (iii) where thresholds and tipping-points may exist.

METHODS

Ecopath with Ecosim

The Ecopath with Ecosim (EwE) software (version 6.6.6 beta) was used to simulate the impacts of environmental shocks on both Irish Sea and southern North Sea ecosystems. EwE has three main components: Ecopath – a static, mass-balanced snapshot of the system; Ecosim – a time dynamic simulation module for policy exploration; and Ecospace – a spatial and temporal dynamic module primarily designed for exploring impact and placement of protected areas (Christensen and Walters, 2004). Both Ecopath and Ecosim were used and a new version of the software was developed for the purpose of this study to allow ecological indicators from the EcoInd plugin (Coll and Steenbeek, 2017) to be extracted using the Multi-Sim plugin: a routine that systematically perturbs environmental drivers and extracts multiple scenario results (Steenbeek et al., 2016).

Southern North Sea

The EwE model reflecting the highly complex ecosystem of the southern part of the North Sea (ICES areas 4b and 4c) and is based on an EwE model published for the Greater North Sea (Mackinson and Daskalov, 2007; Stäbler et al., 2014, 2016). It has a strong focus on higher trophic level and commercial species and encompasses overall 68 functional groups. For seven commercially exploited species, Atlantic cod (Gadus morhua), whiting (Merlangius merlangus), haddock (Melanogrammus aeglefinus), herring (Clupea harengus), sole (Solea solea), plaice (Pleuronectes platessa) and brown shrimp (Crangon crangon) are included as multi-stanza representations, displaying different life stages of these functional groups (Walters et al., 2010). Fishing is represented by twelve Ecopath fishing fleets. The Ecopath model represents the state of the ecosystem in 1991, due to the best reliable stomach data, based on the "year of the stomach" (Hislop et al. 1997). The temporal component Ecosim is currently fitted to data from 1991-2010. Recently, the model was extended by the spatial representation Ecospace (Püts et al., 2020). For detailed information on the model and adaptations thereof see Stäbler et al., 2016, 2018, 2019 and Püts et al., 2020.

Irish Sea

The Irish Sea EwE model is a food web model originally designed to focus on the species of commercial importance within an ecosystem context as part of the ICES workshop on an ecosystem approach to fishery management for the Irish Sea (WKIrish; ICES 2015). The model includes Irish Sea fishing fleets which are defined by gear type and fishers' knowledge which was used to parameterize species interactions (Bentley et al., 2019a) and historic fishing effort trajectories (Bentley et al., 2019b). The model has been used to develop new approaches for indicator analysis (Bentley et al., 2019c), identify the environmental drivers underpinning commercial stock trends (Bentley et al., 2020), and provide a case-study for the use of ecosystem information to enhance single-stock catch advice (Bentley et al., 2021). The model has been approved as a key run by ICES and thus serves as a quality assured source for scientific input to ICES advice products (ICES 2019).

Environmental forcing and gradient approach

Environmental forcing

Both EwE models were forced with temperature data to reproduce changes to the ecosystem under future conditions. For the southern North Sea model, two data sets were added to the existing model. Present-day conditions were reproduced with mean annual sea surface temperature (SST) from 1991 – 2017, based on the Adjusted Optimal Interpolation (AHOI; Núñez-Riboni and Akimova, 2015). Model behaviour under future conditions was modelled with SST projections based on three ensemble runs of the regionally coupled ocean-atmosphere climate system model MPIOM/REMO (Jungclaus et al., 2013).

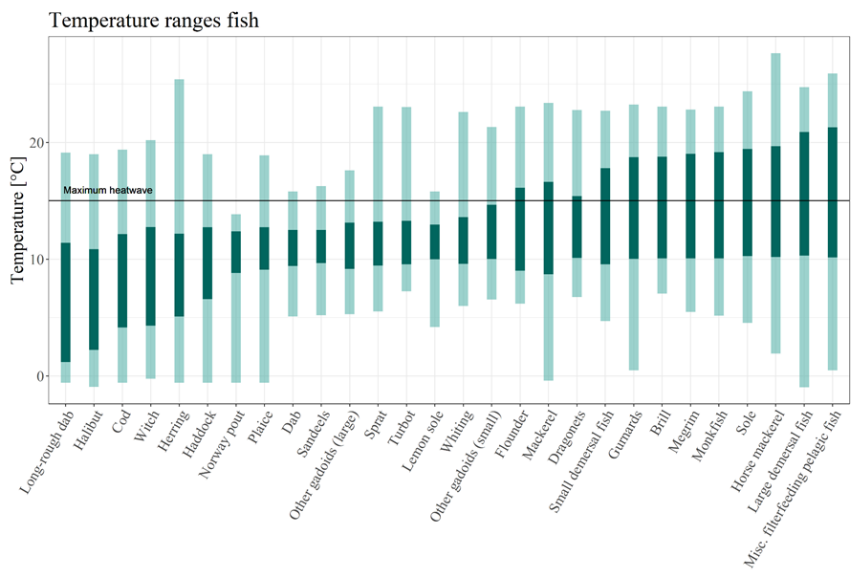
The Ecosim component of the Irish Sea EwE model simulates the ecosystem from 1973 to 2017. The model has been calibrated against biomass and catch time series and is driven by multiple fishing and environmental drivers. Fishing fleet effort in the Irish Sea model is driven by trends of fishing effort taken both from scientific data and fishers' knowledge. The recruitment trends of cod and whiting are driven by sea surface temperature and the natural mortality of large zooplankton (>2mm) is driven by the North Atlantic Oscillation winter index (NAOw). To assess the impacts of long-term climate change, the Irish Sea Ecosim component was projected forward under future temperature projections for two IPCC scenarios: RCP 4.5 and RCP 8.5. These sea surface temperature (SST) forecasts for the Irish Sea were simulated using available IPCC model sets (42 models for RCP 4.5; 39 models for RCP 8.5). Data were extracted from http://climexp.knmi.nl/plot_atlas_form.py.

Temperature preference ranges for both models were implemented to link environmental responses of functional groups in Ecosim to changes in temperature (see Bentley et al., 2017). Temperature tolerance ranges for functional groups were extracted from aquamaps (https://www.aquamaps.org/) (Figure 88: southern North Sea; Figure 89: Irish Sea). For multi-species functional groups, temperature tolerance ranges were weighted by the biomass each species contributed to the overall group. Tolerance ranges were entered as a trapezoid functions. Temperature functional responses impact the consumption rates of predators:

$$Q_{ij} = \frac{a_{ij} \times v_{ij} \times B_i \times P_j \times T_i \times T_j \times M_{ij}/D_j}{v_{ij} + v_{ji} \times T_i \times M_{ij} \times P_i \times T_j/D_j} \times f(Env_{function}, t)$$

where a_{ij} is the effective search rate for predator j feeding on a prey i, v_{ij} is vulnerability expressing the rate with which prey i moves between being vulnerable and not-vulnerable, B_i is prey biomass, P_j is predator abundance, T_i represents prey relative feeding time, T_j is predator relative feeding time, M_{ij} is mediation forcing effects, and D_j represents handling time as a limit to consumption rate (Christensen et al., 2005, Ahrens et al., 2012). $f(Env_{function}, t)$ is the environmental response function that restricts the size of the foraging arena to account for external environmental drivers which change over time, such as temperature, salinity or ocean acidity.

The functional response imposes a multiplier on the consumption equation which can range from zero to one. Between a groups preferred minimum and preferred maximum temperature, consumption is multiplied by one, therefore temperature has no effect on consumption. As temperature moves away from a group's preferred range the multiplier moves towards zero, therefore reducing the consumption rate. At a group's upper and lower tolerance levels the multiplier is equal to zero and groups are unable to ingest energy and thus die.



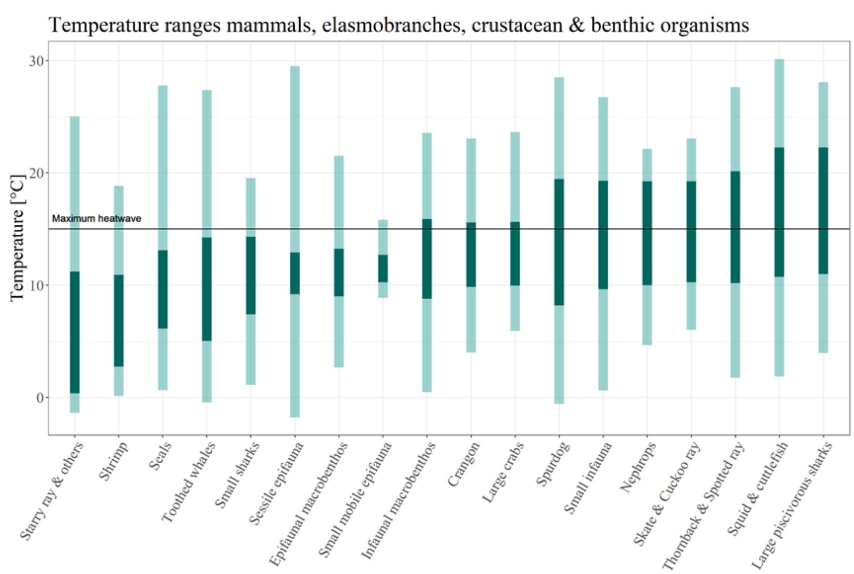


Figure 88 Temperature tolerance ranges for functional groups in the southern North Sea Ecosim model. Dark green reflects functional groups 'preferable range', within which temperature will not diminish group consumption rates. Faded areas represent the extremes of each groups tolerance ranges, where consumption rates are negatively impacted in a linear fashion until consumption is equal to 0 at the minimum and maximum points of the tolerance range. The horizontal line marks the maximum SST heatwave scenario.

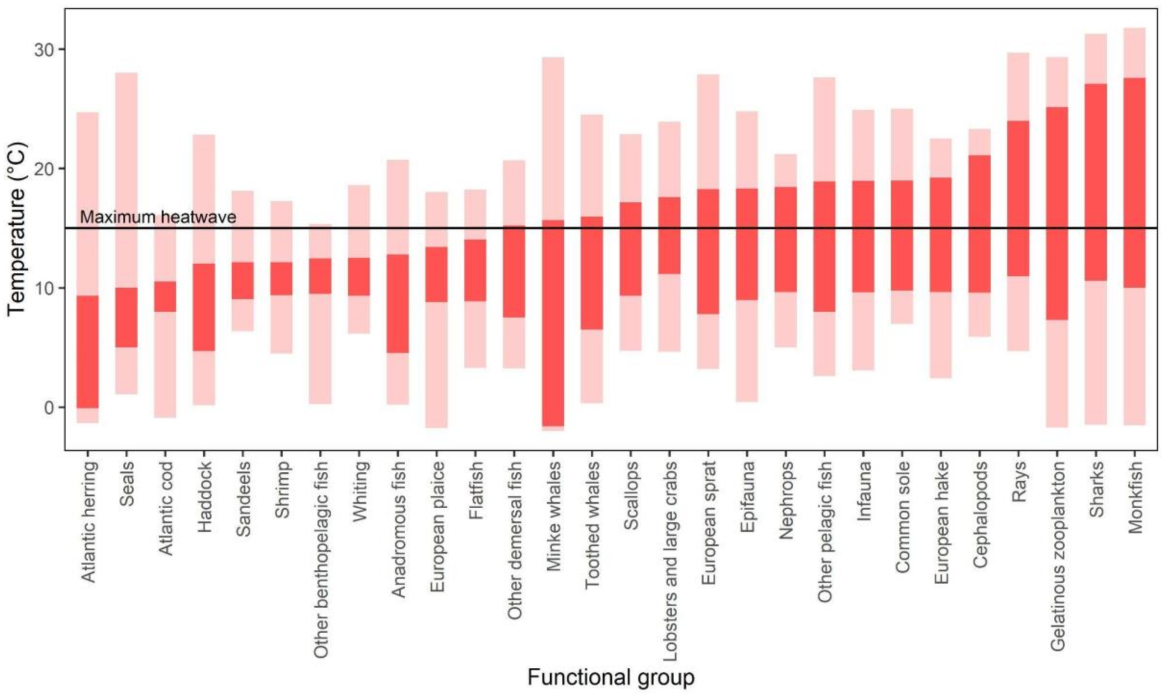


Figure 89 Temperature tolerance ranges for functional groups in the Irish Sea Ecosim model. Dark red areas reflect functional groups 'preferable range', within which temperature will not diminish group consumption rates. Faded red areas represent the extremes of each groups tolerance ranges, where consumption rates are negatively impacted in a linear fashion until consumption is equal to 0 at the minimum and maximum points of the tolerance range. The horizontal line marks the maximum SST heatwave scenario.

Gradient approach and scenarios

The range of extreme events such as marine heatwaves, recruitment failure or strong changes in bottom-up production are difficult to predict and it is likely that the magnitude of the event will lead to alternate stock and ecosystem responses. While some relationships between shock intensity and ecosystem response may be linear, due to the complexity of marine ecosystems, relationships may be non-linear and tipping-points or thresholds may exist, beyond which the relationships between shock and response could change. Therefore, all shocks used in model simulations were implemented using a gradient approach, where a range of shock magnitudes were simulated (Figure 90). For this, the EwE plug-in Multi-Sim was used, which enables the execution of Ecosim with gradually changing forcing (Steenbeek et al., 2016).

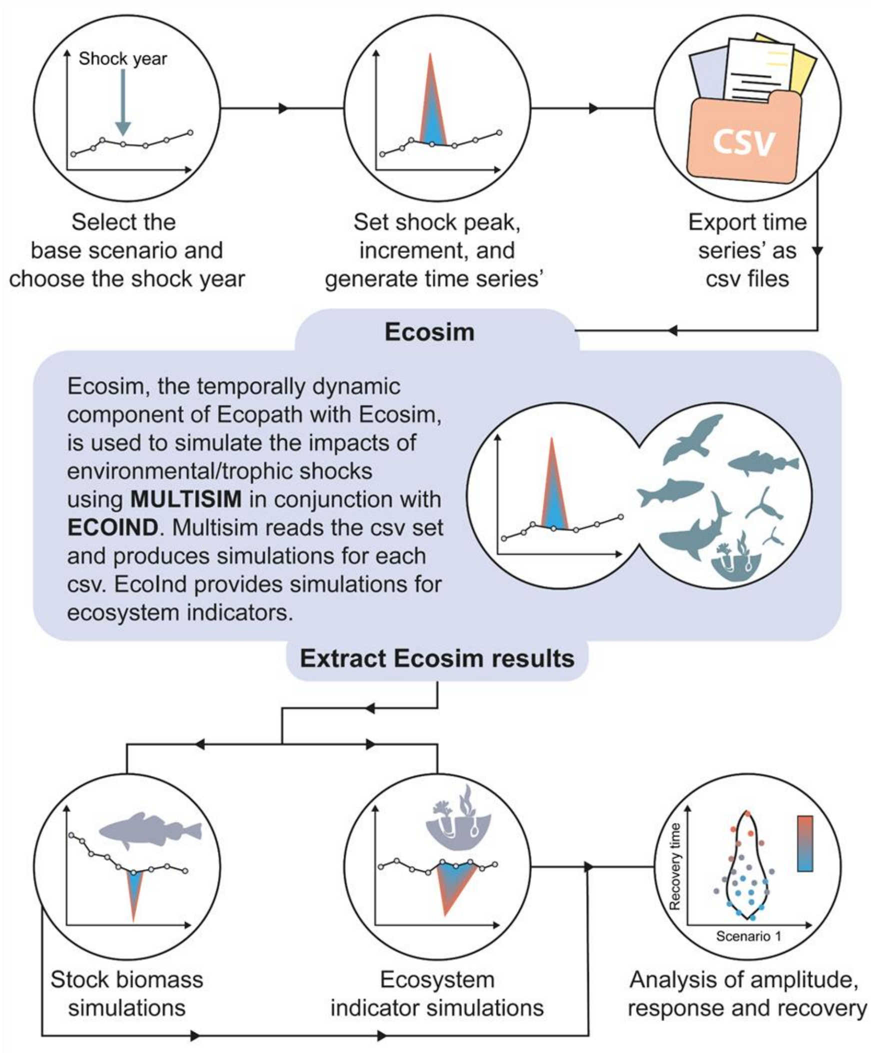


Figure 90 Conceptual illustration of the gradient approach applied to simulate the Irish Sea and southern North Sea Ecopath with Ecosim models under a range of shock magnitudes. The illustration describes (i) how shock scenario sets were generated, (ii) how scenario sets were used in Ecosim, and (iii) how Ecosim outputs were used to provide analyses of stock and indicator response to shocks of varying magnitude.

For marine heatwaves, maximum SST was set at 15°C to reflect the temperature increases predicted under RCP8.5 by the end of the century , with increments of 0.02°C. Heatwave shocks on all components of the simulated ecosystem were executed for one (2021) and two years (2021 and 2022) in combination with long-term temperature projections. Furthermore, to test possible implications of CFP fishing pressure targets, a range of fishing effort scenarios were simulated (see Figure 91 with scenarios). Gradient heatwaves were combined with different fishing effort strategies. Starting in 2021 and kept constant until 2100, heatwave effects were combined with fishing effort reflecting (1) business as usual (no effort change from baseline), (2) half the base fishing effort (2), (3) no fishing (0 effort), (4) double demersal fishing effort, and (5) double pelagic fishing effort.. Fishing effort was manipulated as opposed to fishing mortality (F) as F in EwE is calculated as a harvest rate (catch/biomass) and thus assumptions of fishing rates from stock assessments are not directly transferable.

Fishing effort in EwE acts as a multiplier of the base F, with fishing effort in the first year of model simulations being equal to 1.

This gradient approach was furthermore applied to the recruitment rates of commercially important fish species in both ecosystems (cod, herring, and plaice in the southern North Sea; cod, haddock, whiting and plaice in the Irish Sea). Decreases in recruitment were implemented by adding multipliers to the base recruitment rate, ranging from 1 (no change) to 0.1 (10% of base recruitment), with increments of 0.01. It should be noted that, in the Ecosim model for the southern North Sea, a recruitment rate function was implemented prior to this study. It simulates the negative impact of the North Atlantic Oscillation (NAO) on the reproduction of cod in the past and ends with a multiplier of 0.7287. This is the starting point for the gradient recruitment production for cod in the southern part of the North Sea.

Finally, shocks to lower trophic productivity were also tested. Primary production was adjusted by altering the production rate of phytoplankton in each model. Scenarios of primary production increase were simulated from 1 to 2-times the initial production at increments of 0.01. Scenarios of primary production decline were simulated from 1 to 0.1-times the initial production, again at increments of 0.01. We also simulated the impacts of reduced benthic macrofauna biomass, as could be associated with destructive fishing and bottom disturbance. To implement this, the "other mortality" of epifaunal macrobenthos was increased up to 2-times its base mortality at increments of 0.01. "Other mortality" in EwE is the proportion of a group's mortality not directly explained in the model, such as death due to disease, old age, starvation, or environmental change. The 'other mortality' rate is a component of Ecosim's coupled differential equations for the calculation of growth rates (production) at each time interval.

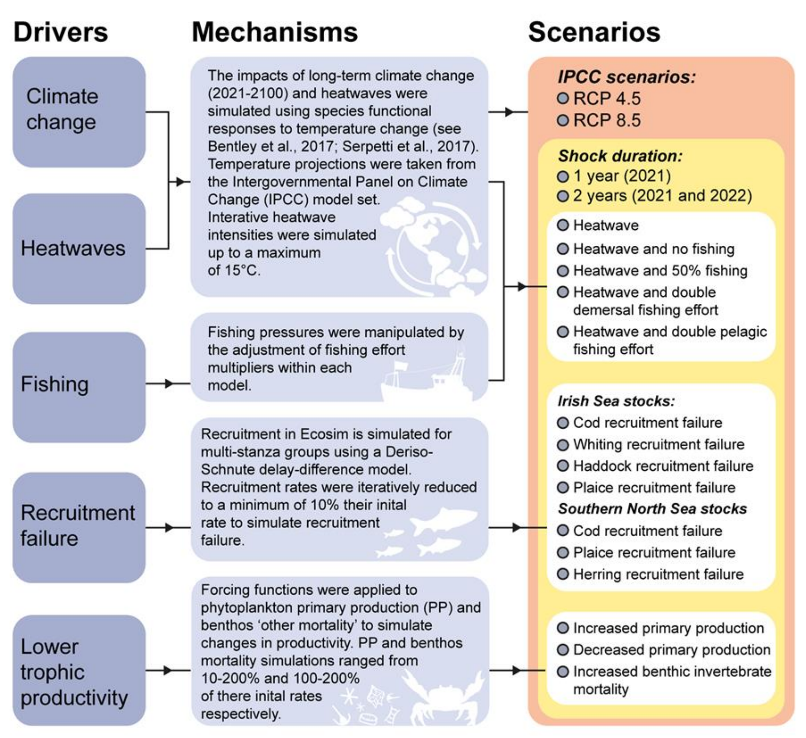


Figure 91 Scenarios used to simulate the response of the Irish Sea and southern North Sea food web models to a range of potential shock scenarios.

Indicators

Ecosystem response and resilience were evaluated based on changes in a pre-defined set of ecological indicators (Table 34). These indicators were created with the EwE plug-in ECOIND (Coll and Steenbeek, 2017). In order to obtain these indicators, traits need to be assigned to functional groups and the species represented by each group. Therefore, species information was added for each functional group, including relative contribution to biomass and catch of the entire functional group. Most important for the current study was the information for each species whether it is a demersal or pelagic species.

Table 34 Ecosystem indicators used to measure food web model response to heatwave, recruitment, and lower trophic production shocks.

Indicator	Equation	Description	Reference
Demersal/Pelagic ratio	$\frac{\sum Demersal\ biomass}{\sum Pelagic\ biomass}$	Information about the structure of the community.	Pennino and Bellido (2012)
Shannon diversity (H)	$H = 1\sum_{i-1}^{n} p_i log(p_i)$	This Shannon entropy-based metric of total flow diversity captures the effects of both richness (the length of the vector, n) and the evenness of the distribution. In this application p_i is the proportion of group i relative to the total number of groups.	MacArthur (1955)
Kempton's Q ($Q90$)	$Q90 = \frac{0.8S}{log(R_2/R_1)}$	$Q90$ represents the slope of the cumulative species abundance curve, where $S$is the total number of functional groups in the model and $R_1$and R_1 are the representative biomass values of the 10th and 90th percentiles in the cumulative abundance distribution.	Ainsworth and Pitcher (2006)
Bray Curtis dissimilarity (BC)	$BC = \frac{\sum\lvert B_i - B_j\rvert}{\sum(B_i + B_j)}$	Displays differences between two populations, applied here to represent differences between two ecosystem states (in this case the system with and without added shocks), ranges from 0 (all equal) to 1 (completely different systems).	Bray and Curtis (1957)
Trophic level (TL)	$TL_i = 1 + \sum j(TL_j \times DC_{ij})$	TL_i signifies the position group i occupies within the food web, where TL_j is the fractional TL of prey j and DC_{ij} is the fraction of j in the diet of i.	Odum and Heald (1975), Christensen et al. (2008) and Coll and Steenbeek (2017)
Mean trophic level of the catch (TL_{catch})	$TL_{catch} = mean(TL_{catch})$	Catch includes both landings and discards.	
Mean trophic level of the community (TL_{com})	$TL_{com} = mean(TL_{com})$	Community includes all organisms in the model.	

Parameters assessed to identify resilience of the ecosystems	
Recovery time	Number of years until the indicator returns to the level it would have had without the shock.
Responsiveness	Years until the minimum/maximum of the indicator after the onset of the shock is reached.
Amplitude	Maximum deviation from the base scenario in response to the shock.

RESULTS

Differences between RCP4.5 and RCP8.5 scenarios

All shock scenarios were projected to 2100 under RCP4.5 and RCP8.5. The RCP scenario had a large impact on the biomass of commercial stocks and ecosystem indicators by the end of the century. However, as there is little divergence between RCP 4.5 and RCP 8.5 temperature projections prior to 2050, differences between responses to shocks implemented in 2021 were negligible. Amplitude, recovery, and responsiveness metrics were not impacted by RCP scenario in the short-term. The bulk of the results section will thus focus on simulation results under RCP4.5.

Differences between one-year and two-year shocks

All shock scenarios were simulated with one-year (2021) and two-year (2021 and 2022) durations. Increasing the duration of the shocks increased the amplitude of the response and the recovery time for stock biomasses and ecosystem indicators. The directions of the stock and indicator response remained unchanged. The impacts of two-year shocks are illustrated in Table 2 for the RCP4.5 heatwave scenario. The bulk of the results presented focuses on one-year shocks and the differences between scenarios.

Heatwave shock and variations in fishing intensity

Southern North Sea

Among the three stocks analysed, a negative response to the heatwave shock was found for cod and plaice, while it induced an increase in biomass for herring (Figure 92). The increase in biomass for herring is counterintuitive, since the temperatures simulated with the heatwave shock exceed the thermal optimum window of herring. However, results suggest that a reduction in predators, especially cod and other large gadoid species (such as whiting, pollack, hake and ling) outweigh effects directly caused by temperature in the model. For cod and plaice biomass, the negative amplitude was lowest with no fishing effort after 2021 and highest with doubled fishing effort of demersal fleets. On average, the difference in relative biomass between the scenarios are around 2% for cod and 1% for plaice. Doubling the effort of demersal fleets extended the recovery time of the heatwave shock for plaice. For herring, recovery time was shortest without any fishing pressure on the system. Simultaneously, recovery time of cod was longest without any fishing pressure on the system. This effect is a result of the way recovery was defined for this study. Recovery time is measured at the point when stock biomass returns to the state it would have been in without the shock, regardless of whether the effect induced is positive or negative. Cod relative biomass without fishing first decreased due to the heatwave shock, followed by a strong increase, exceeding biomass measured without a heatwave shock, profiting from high prey abundance and the missing pressure of fishing. Only after a relatively long time period, the stock returned to baseline conditions without shock(s).

The amplitudes measured for the ecological indicators after a heatwave shock was, as for the commercial stocks, similar across heatwave shock scenarios with different fishing intensities. Changes in amplitude of Bray-Curtis dissimilarity were relatively small, yet they showed that removing fishing pressure entirely did reduce the overall impact of the heatwave shock on the ecosystem to a small extent. However, recovery time was extended with decreasing fishing pressure until the ecosystem reached a state equal to the corresponding state without any shock. Furthermore, a small separation in recovery time for lower heatwave intensities and higher intensities was found, suggesting a threshold after which the recovery of the system is extended. Recovery from the heatwave shock was longest for the Bray-Curtis dissimilarity indicator followed by Kempton’s Q. The direction of Kempton’s Q indicator (positive or negative) showed no clear trend between the scenarios in amplitude. Temperature thresholds exist where the amplitude direction changes from positive to negative and vice versa with increasing heatwave intensity. Shannon diversity displayed an overall negative impact of the heatwave shocks in all scenarios. Here once more the impact of the heatwave on the Shannon diversity indicator was least severe for the scenarios with reduced and no fishing pressure, yet differences were on average relatively small. Changes in the trophic level of catch and community were comparatively small, with a minimal increase in trophic level of catch, at the same time the ratio of demersal-pelagic biomass increased with increasing heatwave shock. Responsiveness towards the heatwave shock was on average less than a year for all stocks and indicators.

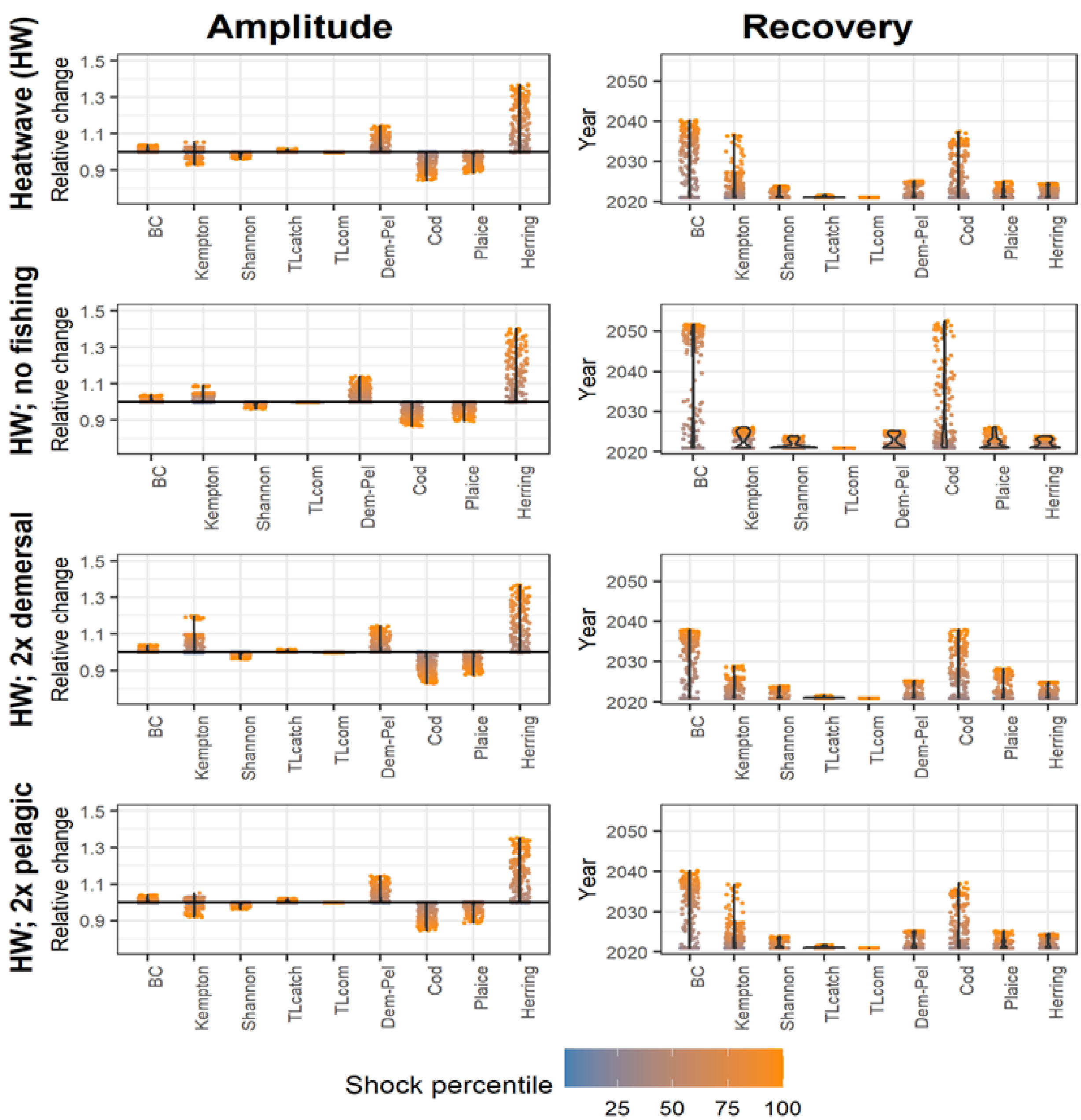


Figure 92 Changes in biomass and indicator values for the ecosystem in the southern part of the North Sea. Fishing regimes displayed are: business as usual, no fishing effort, double demersal fishing effort, and double pelagic fishing effort. 207 heatwaves were simulated from the baseline temperature in 2021 (10.87°C, 0 percentile) to 15°C (100 percentile) at increments of 0.02°C. Amplitude illustrates the maximum biomass deviation from the base scenario (no shock); recovery illustrates the number of years taken for the biomass to return to the level of the base scenario (i.e. where it would have been in the absence of a system shock).

Irish Sea

Cod, whiting and herring all showed negative biomass responses to the heatwave shock as the temperature increased above their preferred optimum (Figure 93). While cod and herring showed negative responses at the lower end of the heatwave gradient, there was a notable tipping point for whiting where, prior to temperature exceeding its preferred optimum, the stock biomass increased in response to reduced predation from cod. Haddock and Nephrops also showed positive responses to the heatwave due to the reduction of predation mortality from cod. Simulating the heatwave with the removal of fishing reduced the negative amplitude responses of cod and herring and reduced the time taken for whiting to recover from the heatwave shock. Increasing the demersal fishing effort at the same time as the heatwave increased the time taken for cod to recover from the shock, while increasing pelagic fishing effort led to greater reductions in herring biomass in response to the 2021 heatwave.

Ecosystem indicators showed similar responses across the heatwave scenarios despite changing fishing strategies (Figure 94). The Bray Curtis dissimilarity indicator increased with increasing heatwave magnitude, taking longer to recovery to the base scenario following stronger heatwaves. The demersal/pelagic biomass indicator increased following heatwave shocks due to increases in demersal groups including gurnards, haddock and reductions in herring. The production of demersal groups such as gurnards and haddock increased in response to reduced predation mortality from cod. Kempton's Q decreased as heatwave strength increased, suggesting that heatwaves have a negative impact on the systems biodiversity evenness. The Shannon index also declined with increasing heatwave intensity, yet at a much lower amplitude. Heatwave shocks had a small negative impact on the trophic level of the catch following reduced catches of species such as cod, whiting and increased catches of Nephrops and sprat. Heatwaves had limited impact on the trophic level of the community.

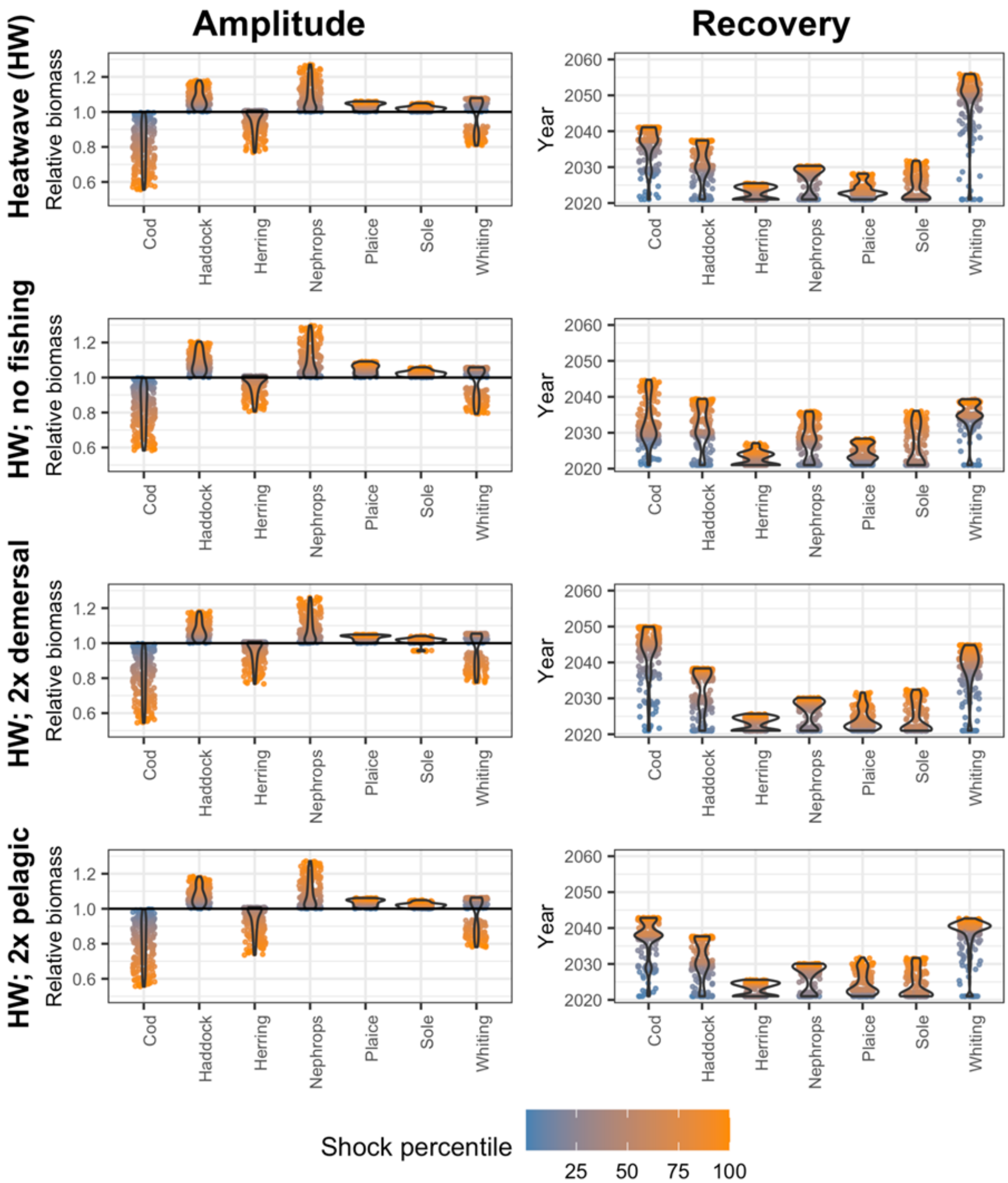


Figure 93 Distributions of biomass responses for commercial stocks from the Irish Sea following heatwave shocks under alternate fishing strategies: business as usual, no fishing effort, double demersal fishing effort, and double pelagic fishing effort. A set of 206 heatwaves were simulated from the baseline temperature in 2021 (10.88°C, 0 percentile) to 15°C (100 percentile) at increments of 0.02°C. Amplitude illustrates the maximum biomass deviation from the base scenario (no shock); recovery illustrates the number of years taken for the biomass to return to the level of the base scenario (i.e. where it would have been in the absence of a system shock).

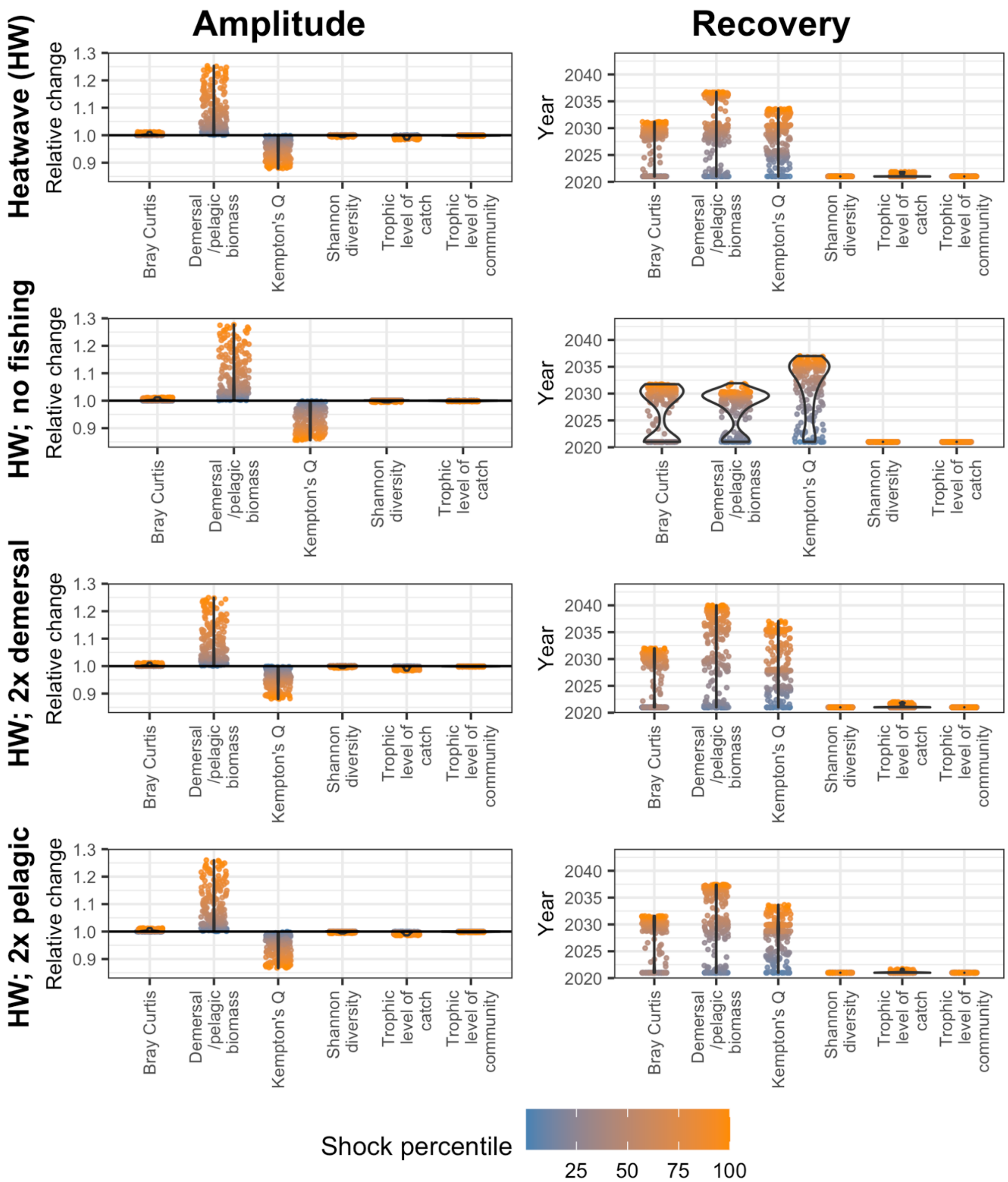


Figure 94 Distributions of Irish Sea ecosystem indicator responses to heatwave shocks under alternate fishing strategies: business as usual, no fishing effort, double demersal fishing effort, and double pelagic fishing effort. A set of 206 heatwaves were simulated from the baseline temperature in 2021 (10.88°C, 0 percentile) to 15°C (100 percentile) at increments of 0.02°C. Amplitude illustrates the maximum indicator deviation from the base scenario (no shock); recovery illustrates the number of years taken for the indicator to return to the level of the base scenario (i.e. where it would have been in the absence of a system shock).

Reproduction failures in commercial species

Southern North Sea

A reduction in reproduction in combination with the RCP long-term predictions led overall to a reduction in the stock the pressure was applied to (Figure 95). Biomass decreased with a decrease in reproduction rate. The effect measured was strongest for cod biomass, while it was similar in amplitude for herring and plaice. Cod benefitted in the plaice shock scenario indicating competition for food in the model. Recovery time is similar between herring and cod, while, on average, plaice recovered faster from reproduction failure. Cod was impacted by the reproduction failures of both other stocks as well, with comparatively small changes in the plaice scenario and stronger for the herring scenario. For this scenario cod biomass strongly fluctuates, which indicates that the decrease of an important prey item like herring destabilised the cod stock in the model. Amplitude is measured in this study as the maximum effect (positive or negative), and was only marginally higher for the positive increases in cod biomass. Minimum or maximum levels were reached within the first year of the shock (responsiveness) in all scenarios and on average within the first and second year for two years of consecutive reproduction failure. Changes in the Bray-Curtis dissimilarity index did not show large changes in amplitude. However, the recovery time of the index was extended with increasing reproduction failures for all species, most severe when a reproduction failure for cod was simulated. Responsiveness of Bray-Curtis was on average between two and three years after the shock.

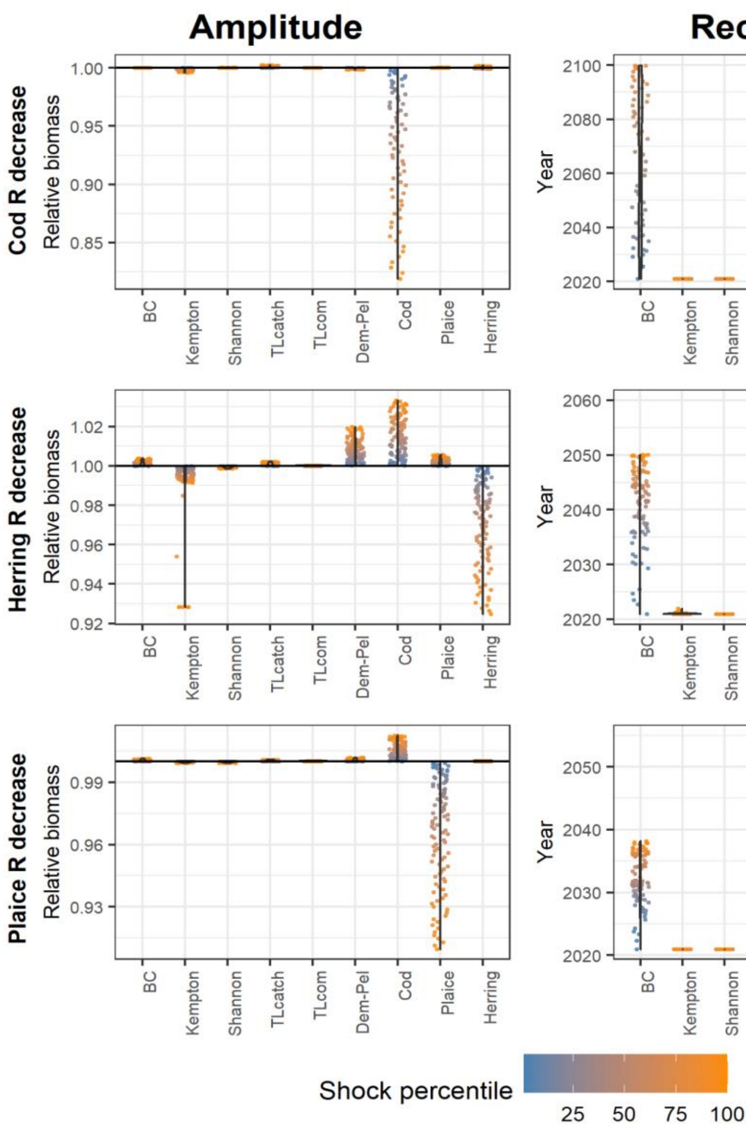


Figure 95 Changes in biomass and indicator values for the ecosystem in the southern part of the North Sea. Recruitment shocks were simulated for cod, herring and plaice. Recruitment rates were reduced from 100% (legend=0 percentile) to 10% (legend=100 percentile) of their rates in 2021. Amplitude illustrates the maximum biomass deviation from the base scenario (no shock); recovery illustrates the number of years taken for the biomass to return to the level of the base scenario (i.e. where it would have been in the absence of a system shock).

Irish Sea

Recruitment shocks led to decreases in the biomasses of corresponding stocks (Figure 96). For cod, whiting, and plaice, larger shocks led to larger biomass declines. Cod recruitment shocks reduced the predation pressure on other stocks leading to increases in the simulated biomasses of haddock, herring, plaice, sole, Nephrops and whiting. Shocks to whiting recruitment led to the largest observed relative biomass reductions with the longest recovery times. For haddock, low intensity recruitment led to initial stock biomass increases due to reduced competition between adults and juveniles. Although biomass did dip following these low intensity shocks, the initial uplift was of greater magnitude than the following decline. Past the tipping-point of 65% reduction in recruitment, declines in haddock biomass were greater than the initial biomass uplift associated with reduced completion.

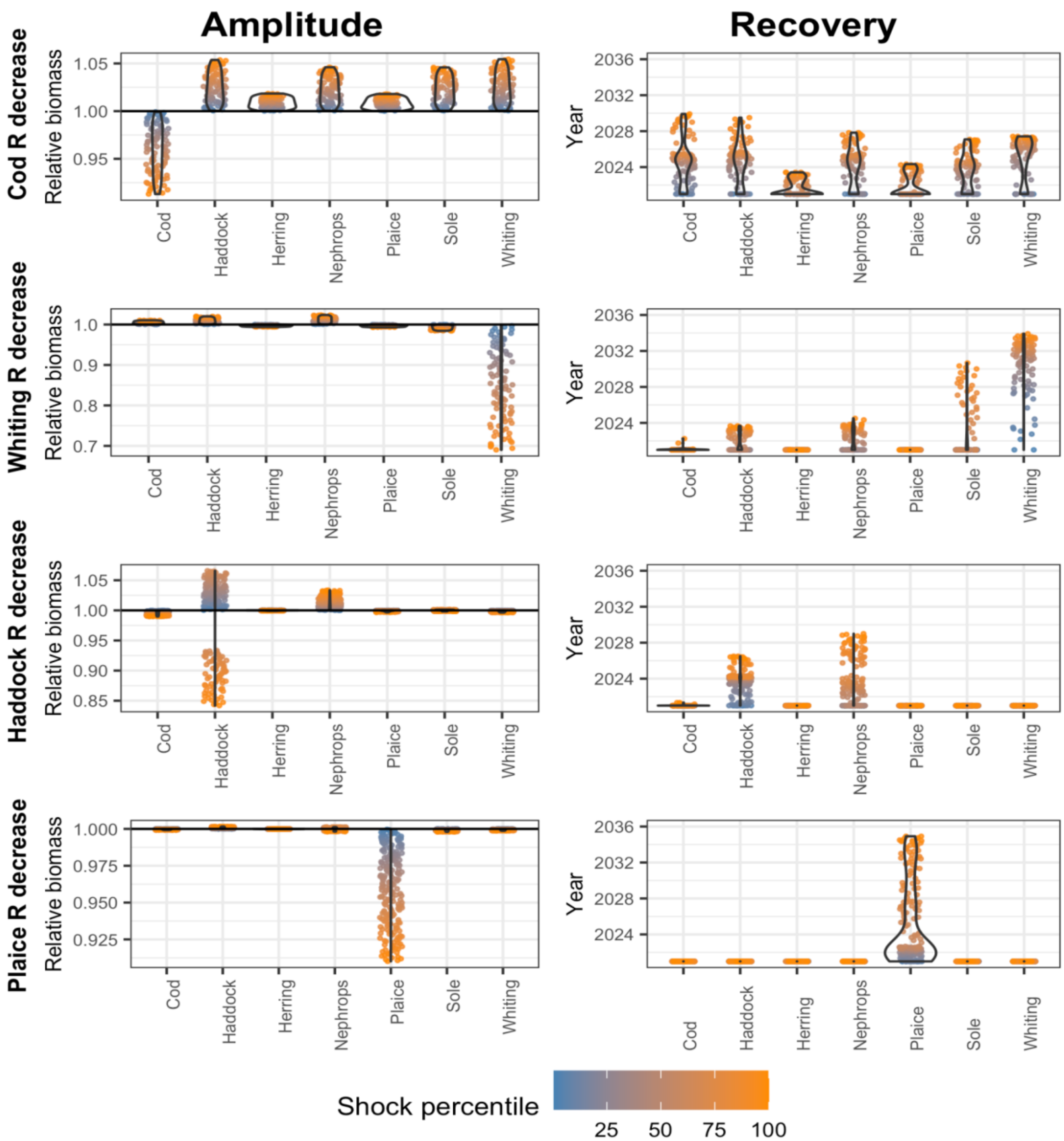


Figure 96 Distributions of biomass responses for commercial stocks from the Irish Sea following recruitment shocks for cod, whiting, haddock, and plaice. A set of 90 recruitment shocks were simulated for each stock, where recruitment rates were reduced from 100% (legend=0 percentile) to 10% (legend=100 percentile) of their rates in 2021. Amplitude illustrates the maximum biomass deviation from the base scenario (no shock); recovery illustrates the number of years taken for the biomass to return to the level of the base scenario (i.e. where it would have been in the absence of a system shock).

Bottom-up effects

Southern North Sea

Among all scenarios, changes to primary production induced the biggest changes within the ecosystem indicators and for the individual stocks (Figure 97). All three fish species showed highest amplitudes among all scenarios in relation to a primary production increase or decrease, highlighting the importance of understanding the dynamics at lower trophic levels. Herring biomass showed the strongest response to changes in primary production. As a planktivorous predator, the food chain length towards primary production is shorter for herring as for plaice and cod, thus responses to changes in primary production are more direct. Recovery time is faster in the case of a primary production increase for cod and herring. A decrease in primary production led to a large range of recovery years between gradients for cod, while for herring even the smallest decrease in primary production induces changes that recover earliest after 2030. The scenario with a reduction of primary production down to almost 0 led to a recovery of herring in ~2065. The decrease in epifaunal macrobenthic species by doubling other mortality caused only small changes across the stocks under investigation. This indicates that the availability of other benthic, primarily invertebrate functional groups as alternative prey compensated for the impact of decreased primary productivity shocks on epifaunal macrobenthos mortality. The decrease in epifaunal macrobenthos led to a reduction in biomass for cod and a small increase for plaice. This is a result of the underlying predator prey relationships. Cod and plaice both feed on epifaunal macrobenthos in the model. The difference is, that plaice also feeds strongly on small swarming crustaceans and polychaetes. As these groups are prey for epifaunal macrobenthos, they increase as these predators decrease, thereby plaice profits. For cod the increase in other prey groups is not as strong, therefore the reduction in epibenthic species led to a reduction in available prey and thus a negative impact on the biomass.

The strong impact of changes in primary productivity is also reflected by the response of the ecological indicators. Bray-Curtis dissimilarity was larger for scenarios including primary production shifts, with a maximum change of ~30% caused by a reduction of primary production. Recovery time was comparable to the heatwave scenarios for Bray-Curtis dissimilarity. Kempton's Q and Shannon both increased with increasing productivity. However, Kempton's Q only increased with small productivity increases and slightly decreased in all other cases. Both diversity indicators decreased with a reduction in productivity, with a long recovery time for Kempton's Q. The effects on trophic level of community and catch again were comparatively small. Demersal-pelagic biomass ratio decreased with increasing productivity and increased with decreasing productivity. The decrease in epifaunal macrobenthos led to a reduction in all ecological indicators, however with a short recovery time, indicating a negative effect on a resilient ecosystem with regards to the reduction of a benthic functional group in the model. Response time to changes in productivity range from one year and a half to around three years, indicating that the effect of changed reproduction needs time to cascade fully through the food web.

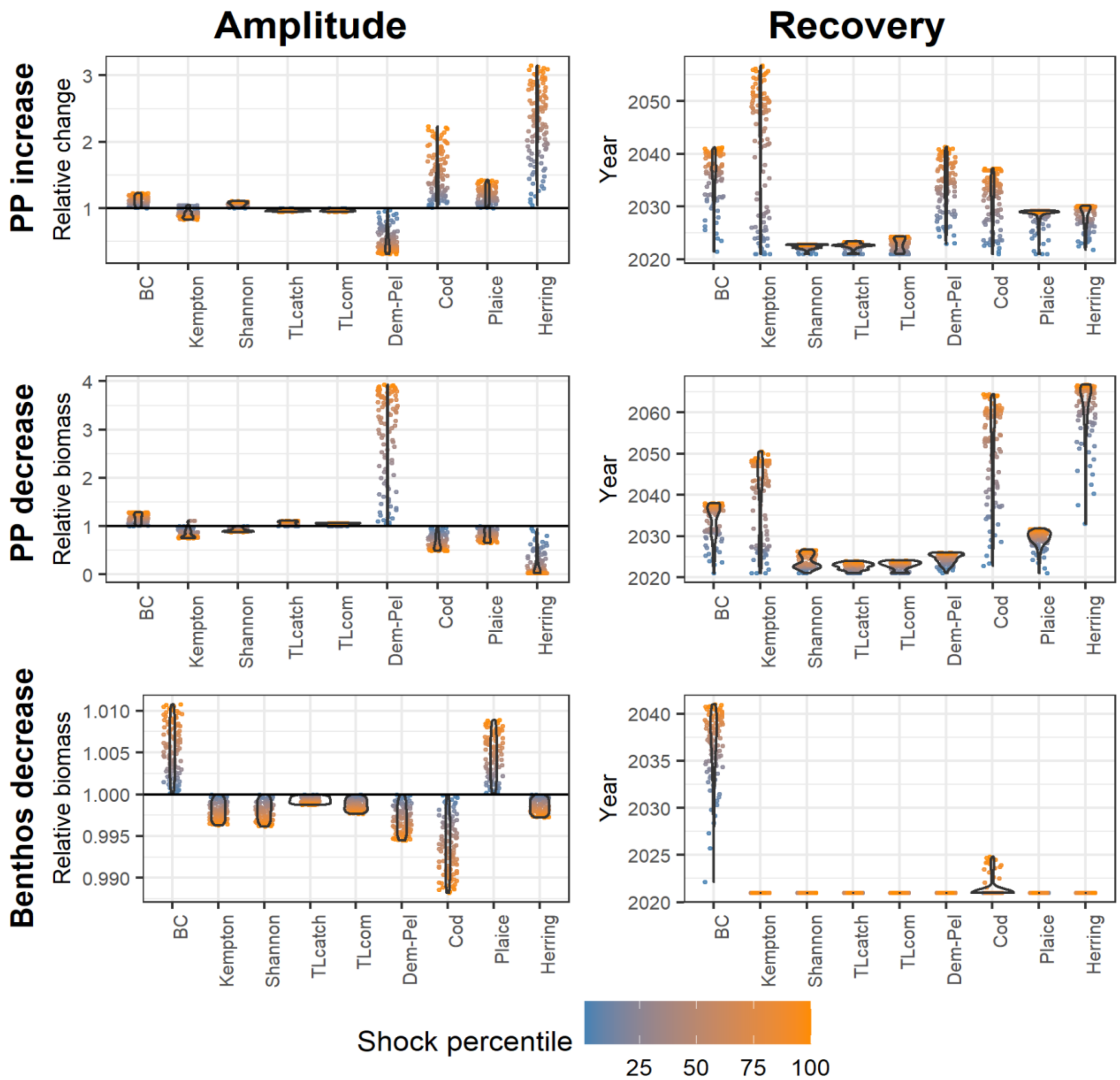


Figure 97 Changes in biomass and indicator values for the ecosystem in the southern part of the North Sea. Shocks were applied to lower trophic productivity: increase in primary production, decrease in primary production, and increase in benthos mortality. For primary production (PP) increase, the model was simulated under a set of 100 shocks, where PP was increased by increments of 1% until doubled. In the PP decrease scenario, a set of 90 shocks were simulated where PP iteratively fell by 1%, reaching a minimum of 10% initial PP. For benthos mortality increase, the model was simulated under a set of 200 shocks, where mortality was increased by increments of 0.5% until doubled. Minimum and maximum shock extremes are reflected in the shock percentile legend.

Irish Sea

Commercial stock biomasses increased in response to increases in primary production, with the largest relative biomass increases simulated for herring (2.4 times baseline) and whiting (2.3 times baseline, Figure 98). Conversely, all commercial stock biomasses declined under reduced primary production scenarios. Under the most extreme simulations, herring biomass declined to 44% of the baseline biomass and failed to recover to the baseline scenario until the end of the century. Increasing the mortality of benthos as a system shock led to declines in the biomasses of cod, haddock, Nephrops and plaice due to the reduction of prey in the foraging arena. Sole and whiting showed slight positive biomass responses to increased benthos mortality due to the negative impact it had on their predators, thus reducing their predation mortality.

Shocks to lower trophic productivity had markedly larger impacts on ecosystem indicators when compared to the impacts of heatwave shocks and fishing scenarios (Figure 99). Bray Curtis dissimilarity was highest under primary production decrease shock scenarios, suggesting that reduced primary production shocks had the most profound impact on the structure and function of the ecosystem. The demersal/pelagic biomass indicator showed an interesting response to increasing primary production, where initially the indicator declines as fast-growing pelagic biomass increases and then increases as the biomass of slower growing demersal species increase. Past the 167% primary production scenario, the latter demersal biomass increase outweighs the early increase in pelagic biomass, thus highlighting a tipping point for the indicator. The demersal/pelagic biomass indicator increased in response to reduced primary production following the large declines of herring, sprat, and other pelagics, whereas the indicator decreased following shocks to benthos mortality due to the reduced food availability for demersal groups.

Biodiversity indicators (Kempton’s Q and Shannon’s index) generally increased in response to increases in primary productivity and decreased in response to declines in primary productivity and increased benthos mortality. Both the trophic level of the catch and the trophic level of the community increased with increasing primary production shocks. Trophic indicators declined following negative shocks to primary production. However, trophic indicators showed a common pattern of increasing initially as lower trophic species declined and then decreasing as higher trophic species also gradually declined. For the trophic level of the catch, in the worst-case scenarios this initial increase in indicator was larger than the subsequent decrease due to the high mortality of lower trophic groups.

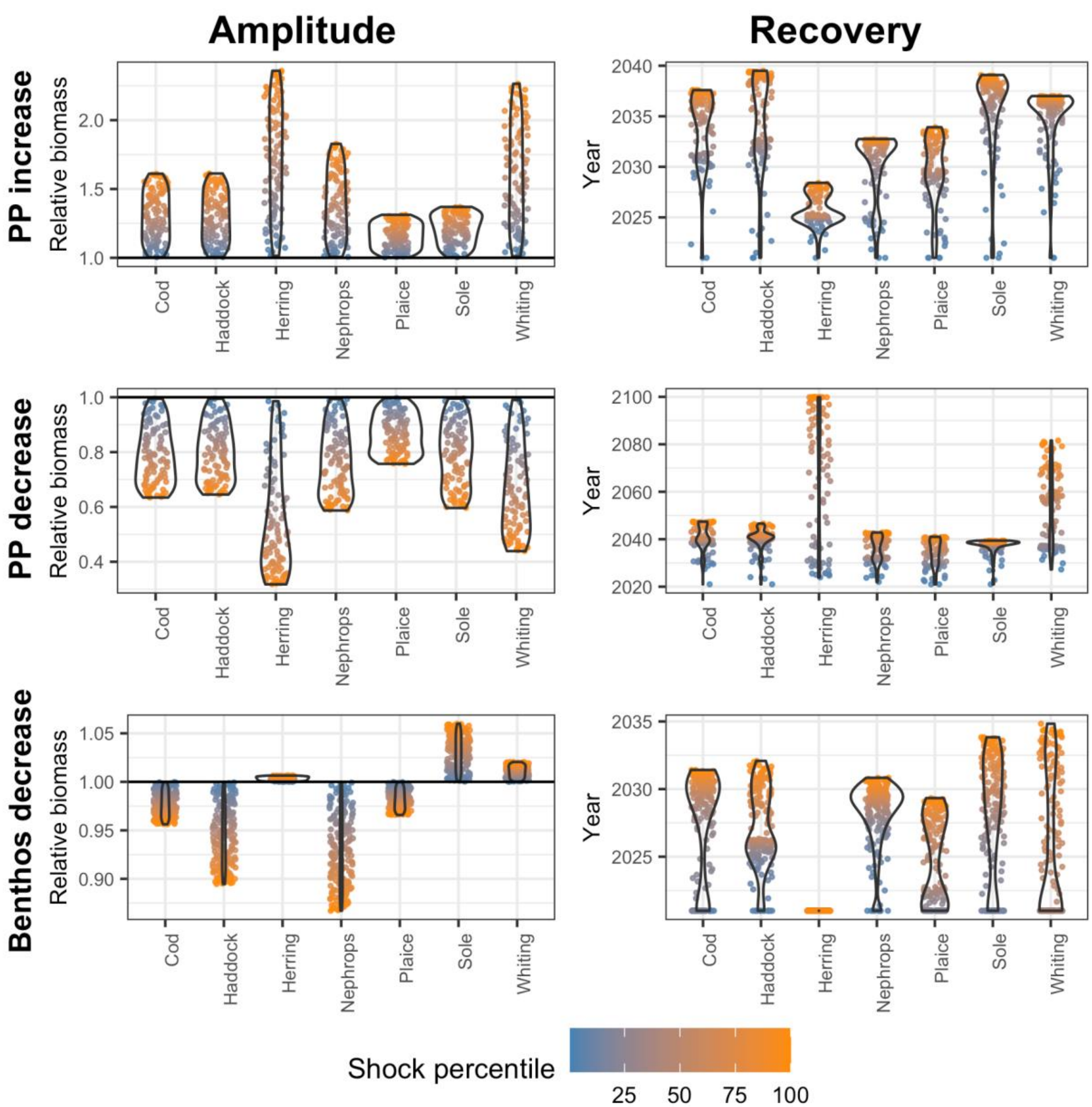


Figure 98 Distributions of biomass responses for commercial stocks from the Irish Sea following shocks to lower trophic productivity: increase in primary production, decrease in primary production, and increase in benthos mortality. For primary production (PP) increase, the model was simulated under a set of 100 shocks, where PP was increased by increments of 1% until doubled. In the PP decrease scenario, a set of 90 shocks were simulated where PP iteratively fell by 1%, reaching a minimum of 10% initial PP. For benthos mortality increase, the model was simulated under a set of 200 shocks, where mortality was increased by increments of 0.5% until doubled. Minimum and maximum shock extremes are reflected in the shock percentile legend.

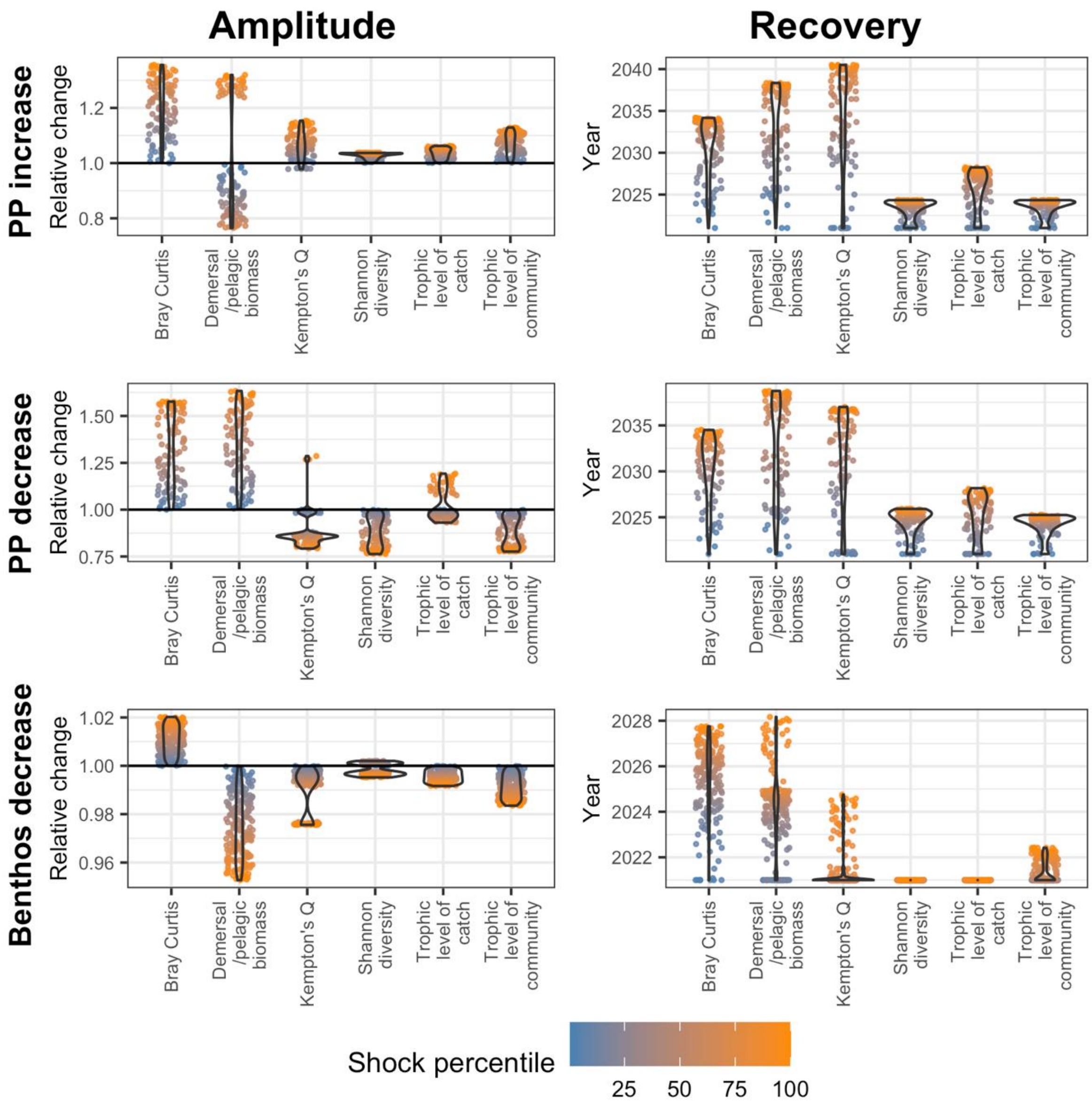


Figure 99 Distributions of Irish Sea ecosystem indicator responses following shocks to lower trophic productivity: (i) increase in primary production, (ii) decrease in primary production, and (iii) increase in benthos mortality. For primary production (PP) increase, the model was simulated under a set of 100 shocks, where PP was increased by increments of 1% until doubled. In the PP decrease scenario, a set of 90 shocks were simulated where PP iteratively fell by 1%, reaching a minimum of 10% initial PP. For benthos mortality increase, the model was simulated under a set of 200 shocks, where mortality was increased by increments of 0.5% until doubled. Minimum and maximum shock extremes are reflected in the shock percentile legend.

3.6. Model comparisons

Overall, simulations from the Irish Sea and southern North Sea EwE models showed similar stock and indicator responses to heatwave, recruitment, and lower trophic productivity shocks (Figure 100). Of the 116 scenario/indicator combinations the models shared in common, model amplitude responses to 89 combinations were within 10% of each other (Figure 100 a). Recovery responses showed greater dissimilarity between the Irish Sea and southern North Sea models, with 30 of the 116 recovery responses being within 10% of each other (Figure 100 b).

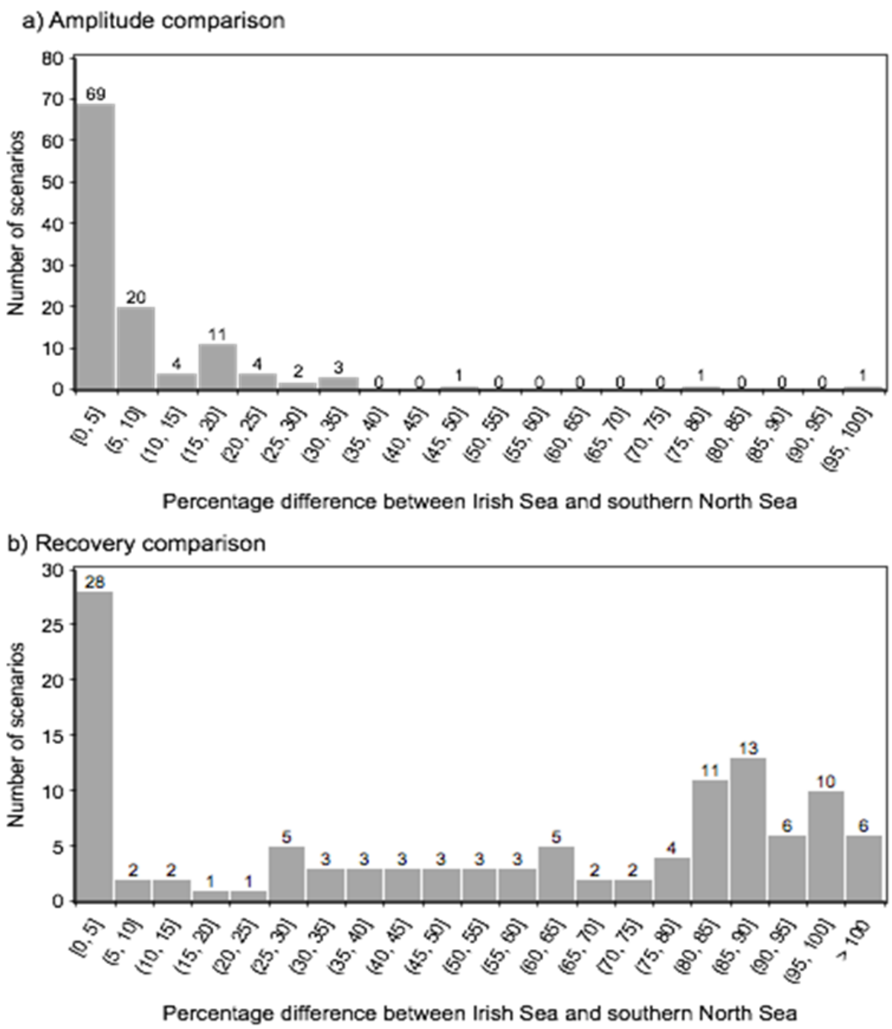


Figure 100 Comparison of Irish Sea and southern North Sea EwE outputs in response to shock scenarios.

DISCUSSION

The gradient methodology, developed as part of this study, facilitated the assessment of a wide range of shock scenarios with gradually increasing pressure. Using this gradient approach with different forcing (i.e., environmental, reproduction, other mortality and productivity) enabled us to build a more coherent understanding of the relationships between shocks and ecosystem response. Possible tipping-points for individual stock and indicator responses could be detected, which would otherwise be missed by an approach testing only single shock values. Three tipping-points were identified from Irish Sea scenarios:

- Whiting biomass response to heatwave shock:
    - Heatwave scenarios for the Irish Sea ranged from 10.88°C to 15°C at intervals of 0.02°C. At heatwaves ranging from 10.88°C to 14.34°C, whiting biomass increased due to reductions in predation mortality, despite whiting being outside of its preferred temperature range. From heatwave scenarios of 14.36°C -15°C, whiting biomass declined as the benefit of reduced predation mortality no longer outweighed the negative impact of whitings reduced consumption rate (as altered by temperature functional responses).
- Haddock biomass response to recruitment shock:
    - Haddock recruitment rate was reduced from 100% to 10% of its base model recruitment rate at intervals of 1%. Haddock showed small yet positive biomass responses to reductions in recruitment until 36% of the initial rate. Haddock biomass showed an increasingly negative response to recruitment below 35% of the initial rate. Haddocks delayed negative response to recruitment shock were linked to reductions in competition between adults and juveniles but was likely also buffered by the stocks high SSB at the time of the shock.
- Demersal/pelagic biomass indictor response to increased primary production:
    - The demersal/pelagic biomass indicator provides an insight to the structure of the fish community. Following positive primary production shocks, most functional groups in the Irish Sea ecosystem model had positive biomass responses. Due to the faster growth rates of the pelagic community, the demersal/pelagic indicator initially dropped to reflect the larger pelagic community. Demersal species, with slower growth rates, had a lagged biomass response which led to a following increase in the demersal/pelagic indicator. PP increase scenarios ranged from 100-200%. From 100-168%, the initial pelagic biomass increase created a greater (-ve) amplitude response than the following demersal increase. From 169-200%, the demersal biomass increase caused a greater (+ve) amplitude response than the initial pelagic increase due to changes in food availability and predation mortalities.

Main conclusions

The analysis of the ecosystem indicators revealed that all shocks applied within the large set of scenarios did not lead to a long-term change in the entire ecosystem simulated by both models, or aregime shift, as it was detected previously for the southern North Sea (Beaugrand, 2004; Weijerman et al., 2005). Bray-Curtis dissimilarity, the difference between two ecosystem states (i.e., the ecosystem with and without a shock) showed that the ecosystem returns to its original state latest by the end of the long-term projection. The number of years until the maximum/minimum deviation from a scenario with no shock were reached (responsiveness) revealed that impacts on the entire ecosystem, such as a heatwave, leads to an instantaneous reaction, while shocks in reproduction need to cascade through the ecosystem prior to inducing a change in ecosystem indicators that reflect the majority of the ecosystem. Furthermore, in both models, shocks cascaded through the food web through trophic interactions (predation and competition). Thus, shocks had direct and indirect impacts on commercial stocks and ecosystem indicators.

Results also revealed that responses to shocks in the near term (i.e. in 2021 or 2021/2022) were comparable when executed with RCP4.5 or RCP8.5 long-term projections. Temperature projections, extracted from the IPCC model set, were not expected to differ greatly between these two RCP scenarios until around 2050, where they are expected to diverge. If a shock occurs after 2050, it is likely that underlying long-term projections will have a greater impact.

Shocks to lower trophic productivity had the most profound impacts on commercial stock biomass and ecosystem structure and function, highlighting the importance of including changes in productivity in future management considerations. The southern North Sea and the Irish Sea ecosystems have been previously identified to be highly sensitive towards changes in secondary and primary production compared to top-down impacts, such as changes in top predators like seals (Stäbler et al., 2019; Bentley et al., 2020). Therefore, further investigation of a combined impact of changes in primary productivity and fishing intensity might shed light on the possibilities to counteract effects of reduced productivity or even increase yields with increasing productivity.

See the Appendix of this case study for further details on all outcomes

What this means for CFP

In the light of an increasing demand to integrate ecosystem information into fisheries management, the results presented in this study showed the importance of accounting for trophic effects in management considerations. Both case studies revealed the strong influence of ocean warming and changes to lower trophic productivity on the ecosystem and commercial stocks. Additionally, simulations of heatwave shocks, in combination with different fishing strategies, revealed for both ecosystems that the underlying fishing strategy mediated the overall impact of the heatwave shock.

Combining tactical single-species advice with strategic ecosystem information regarding changes in lower-trophic productivity or ocean temperature could enhance advice for single stocks or mixed fisheries (Howell et al., 2021). For example, the use of an ecosystem-based fishing mortality reference point (F_{ECO}; Bentley et al., 2021) has recently been adopted into advice by ICES, and work is ongoing to establish how it will be used in practice. The F_{ECO} approach uses strategic ecosystem information, such as that delivered by this report, to advise thresholds within the 'pretty-good yield' ranges to minimise cumulative impacts of fishing and environmental change. The benefit of such an approach can be seen with Irish Sea cod, for example, for which at the maximum tested heatwave intensity, the stock recovered by (1) 2041 under base fishing effort, (2) 2036 under half fishing effort, and (3) 2050 under double demersal fishing effort. While long-term yields may remain similar under different fishing strategies, adapting to environmental change, such as ocean warming, may provide a biomass buffer during poor productivity phases and prevent overly cautious yields during good productivity phases.

Limitations and recommendations

The approach used for these two ecosystems allowed us to assess ecosystem resilience and recovery potential. However, some limitations have to be addressed. Structural differences in the models likely impacted model results and comparisons, especially recovery time. Furthermore, complex ecosystem models include a range of uncertainties (Link et al., 2012), which can be structural, parametric, or scenario-based (Payne et al., 2016). In order to overcome these uncertainties and possibly enhance the results derived from models such as the EwE models applied in this study, an ensemble of models could be necessary to address these uncertainties and increase predictive power further.

Both models show strong similarities in the different scenarios in the trend of amplitude, responsiveness and recovery when compared directly to one another (Appendix). However, some effects were not as strong in the southern part of the North Sea as for the Irish Sea. With the increased complexity of the model and the ecosystem (southern part of the North Sea) the shocks were found to be less severe when compared to the Irish Sea model. This might hint at a different maturity of the two systems, but it could also be an effect of model complexity. The shared approach in simulating these scenarios made the direct comparison between shock impacts possible. However, structural differences have to be taken into account. The ecosystem model of the southern part of the North Sea consists of 68 functional groups and twelve fishing fleets, and seven multi-stanza groups. In comparison, the Irish Sea model includes 41 functional groups, eight fishing fleets, and four multi-stanza groups. This variation in complexity, along with different means and sources of parameterisation, potentially impacts the amplitude and recovery rates, which might underestimate the impact's strength. Finally, it is also likely that differences in stock responses to shocks were linked to differences in stock condition. For example, whiting in the Irish Sea, which is currently below B_{lim}, had slow recovery times when compared to other stocks, many of which saw greater biomass declines in response to the shocks.

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Supplementary

Table 1: Geometric mean per indicator, parameter and scenario. In the case of amplitude, 1 equals the baseline scenario with no shocks, while values greater indicate a positive and below 1 a negative impact. Responsiveness and recovery are shown in years. Black numbers refer

to the results for the model of the southern part of the North Sea, blue numbers to the Irish Sea EwE.

Scenario/indicator	EwE model	Amplitude	Recovery	Responsiveness
Scenario: Heatwave (2021; RCP4.5)				
Bray Curtis	Irish Sea	1.003	1.034	0.321
	S. North Sea	1.010	1.888	0.389
Cod biomass	Irish Sea	0.789	12.770	0.980
	S. North Sea	0.948	1.126	0.306
Demersal/Pelagic B	Irish Sea	1.079	3.800	0.801
	S. North Sea	1.041	0.483	0.206
Haddock biomass	Irish Sea	1.073	6.160	1.663
Herring biomass	Irish Sea	0.942	0.745	0.552
	S. North Sea	1.106	0.490	0.198
Kempton's Q	Irish Sea	0.946	4.287	2.112
	S. North Sea	0.998	0.779	0.248
Nephrops biomass	Irish Sea	1.087	2.751	0.783
Plaice biomass	Irish Sea	1.034	1.331	0.807
	S. North Sea	0.971	0.319	0.196
Shannon diversity	Irish Sea	0.999	0.000	0.000
	S. North Sea	0.991	0.184	0.110
Sole biomass	Irish Sea	1.020	1.038	0.655
TL catch	Irish Sea	0.993	0.055	0.045
	S. North Sea	1.005	0.034	0.000

TL community	Irish Sea	0.999	0.000	0.000
	S. North Sea	0.999	0.000	0.000
Whiting biomass	Irish Sea	0.989	20.673	3.776
Scenario: Heatwave (2021; RCP8.5)				
Bray Curtis	Irish Sea	1.004	1.257	0.340
	S. North Sea	1.013	2.552	0.460
Cod biomass	Irish Sea	0.799	12.219	0.977
	S. North Sea	0.935	1.730	0.395
Demersal/Pelagic B	Irish Sea	1.079	3.445	0.784
	S. North Sea	1.050	0.640	0.259
Haddock biomass	Irish Sea	1.066	5.930	2.250
Herring biomass	Irish Sea	0.929	1.285	0.702
	S. North Sea	1.135	0.670	0.268
Kempton's Q	Irish Sea	0.950	3.875	2.004
	S. North Sea	0.993	0.828	0.391
Nephrops biomass	Irish Sea	1.089	3.034	0.784
Plaice biomass	Irish Sea	1.028	1.015	0.784
	S. North Sea	0.961	0.455	0.255
Shannon diversity	Irish Sea	0.998	0.000	0.000
	S. North Sea	0.989	0.233	0.131
Sole biomass	Irish Sea	1.018	0.982	0.617
TL catch	Irish Sea	0.994	0.041	0.008

	S. North Sea	1.006	0.056	0.000
TL community	Irish Sea	0.999	0.000	0.000
	S. North Sea	0.999	0.000	0.000
Whiting biomass	Irish Sea	0.953	19.140	2.748
Scenario: Heatwave (2021 and 2022; RCP4.5)				
Bray Curtis	Irish Sea	1.005	2.708	0.342
	S. North Sea	1.017	1.961	0.359
Cod biomass	Irish Sea	0.704	18.523	1.984
	S. North Sea	0.926	1.648	0.306
Demersal/Pelagic B	Irish Sea	1.136	6.515	1.666
	S. North Sea	1.035	0.616	0.281
Haddock biomass	Irish Sea	1.147	8.749	1.899
Herring biomass	Irish Sea	0.904	3.442	1.690
	S. North Sea	1.131	0.594	0.253
Kempton's Q	Irish Sea	0.914	6.928	3.167
	S. North Sea	0.983	1.141	0.362
Nephrops biomass	Irish Sea	1.162	3.786	1.596
Plaice biomass	Irish Sea	1.042	4.374	1.578
	S. North Sea	0.956	0.501	0.196
Shannon diversity	Irish Sea	0.998	0.008	0.000
	S. North Sea	0.985	0.268	0.149
Sole biomass	Irish Sea	0.991	2.922	2.678

TL catch	Irish Sea	0.991	0.208	0.100
	S. North Sea	1.006	0.046	0.000
TL community	Irish Sea	0.998	0.000	0.000
	S. North Sea	1.000	0.000	0.000
Whiting biomass	Irish Sea	1.057	28.322	5.977
Scenario: Heatwave (2021 and 2022; RCP8.5)				
Bray Curtis	Irish Sea	1.006	2.648	0.344
	S. North Sea	1.023	2.714	0.449
Cod biomass	Irish Sea	0.711	17.700	1.981
	S. North Sea	0.908	2.645	0.389
Demersal/Pelagic B	Irish Sea	1.136	6.118	1.648
	S. North Sea	1.037	0.766	0.332
Haddock biomass	Irish Sea	1.134	8.553	2.009
Herring biomass	Irish Sea	0.883	2.592	1.396
	S. North Sea	1.171	0.826	0.331
Kempton's Q	Irish Sea	0.925	6.441	2.954
	S. North Sea	0.975	1.453	0.446
Nephrops biomass	Irish Sea	1.169	3.982	1.599
Plaice biomass	Irish Sea	1.025	3.944	1.632
	S. North Sea	0.940	0.764	0.260
Shannon diversity	Irish Sea	0.997	0.015	0.004
	S. North Sea	0.980	0.390	0.202

Sole biomass	Irish Sea	0.982	2.755	1.488
TL catch	Irish Sea	0.991	0.174	0.016
	S. North Sea	1.008	0.069	0.009
TL community	Irish Sea	0.998	0.000	0.000
	S. North Sea	0.999	0.000	0.000
Whiting biomass	Irish Sea	0.984	27.083	4.744
Scenario: Heatwave and double demersal fishing effort (2021)				
Bray Curtis	Irish Sea	1.004	1.125	0.416
	S. North Sea	1.010	1.839	0.389
Cod biomass	Irish Sea	0.782	18.501	0.980
	S. North Sea	0.941	1.379	0.322
Demersal/Pelagic B	Irish Sea	1.077	4.272	0.795
	S. North Sea	1.041	0.486	0.206
Haddock biomass	Irish Sea	1.070	6.525	1.470
Herring biomass	Irish Sea	0.941	0.775	0.557
	S. North Sea	1.106	0.515	0.202
Kempton's Q	Irish Sea	0.947	4.523	1.754
	S. North Sea	1.051	0.568	0.250
Nephrops biomass	Irish Sea	1.084	2.463	0.771
Plaice biomass	Irish Sea	1.029	1.404	0.789
	S. North Sea	0.968	0.446	0.200
Shannon diversity	Irish Sea	0.999	0.000	0.000

	S. North Sea	0.991	0.184	0.110
Sole biomass	Irish Sea	1.014	1.024	0.774
TL catch	Irish Sea	0.993	0.061	0.023
	S. North Sea	1.004	0.022	0.000
TL community	Irish Sea	0.999	0.000	0.000
	S. North Sea	0.999	0.000	0.000
Whiting biomass	Irish Sea	0.959	12.842	2.830
Scenario: Heatwave and double pelagic fishing effort (2021)				
Bray Curtis	Irish Sea	1.004	1.225	0.306
	S. North Sea	1.010	1.903	0.390
Cod biomass	Irish Sea	0.789	13.768	0.980
	S. North Sea	0.948	1.115	0.311
Demersal/Pelagic B	Irish Sea	1.081	4.193	0.801
	S. North Sea	1.042	0.484	0.206
Haddock biomass	Irish Sea	1.074	6.353	1.594
Herring biomass	Irish Sea	0.931	0.834	0.578
	S. North Sea	1.102	0.489	0.202
Kempton's Q	Irish Sea	0.941	4.385	2.178
	S. North Sea	0.996	0.777	0.252
Nephrops biomass	Irish Sea	1.087	2.700	0.783
Plaice biomass	Irish Sea	1.034	1.673	0.813
	S. North Sea	0.971	0.321	0.193

Shannon diversity	Irish Sea	0.999	0.000	0.000
	S. North Sea	0.991	0.184	0.110
Sole biomass	Irish Sea	1.020	0.948	0.655
TL catch	Irish Sea	0.994	0.030	0.025
	S. North Sea	1.005	0.045	0.000
TL community	Irish Sea	0.999	0.000	0.000
	S. North Sea	0.999	0.000	0.000
Whiting biomass	Irish Sea	0.967	12.881	3.086
Scenario: Heatwave and half all fishing effort (2021)				
Bray Curtis	Irish Sea	1.004	1.379	0.297
	S. North Sea	1.010	2.662	0.386
Cod biomass	Irish Sea	0.798	9.730	0.980
	S. North Sea	0.952	1.142	0.306
Demersal/Pelagic B	Irish Sea	1.084	3.898	0.813
	S. North Sea	1.040	0.470	0.198
Haddock biomass	Irish Sea	1.080	5.768	1.506
Herring biomass	Irish Sea	0.949	0.687	0.552
	S. North Sea	1.110	0.454	0.191
Kempton's Q	Irish Sea	0.943	5.220	2.019
	S. North Sea	1.030	0.877	0.622
Nephrops biomass	Irish Sea	1.092	2.820	0.795
Plaice biomass	Irish Sea	1.040	1.740	0.826

	S. North Sea	0.972	0.303	0.193
Shannon diversity	Irish Sea	0.999	0.000	0.000
	S. North Sea	0.991	0.183	0.111
Sole biomass	Irish Sea	1.022	1.091	0.672
TL catch	Irish Sea	0.994	0.047	0.047
	S. North Sea	1.005	0.035	0.000
TL community	Irish Sea	0.999	0.000	0.000
	S. North Sea	0.999	0.000	0.000
Whiting biomass	Irish Sea	0.970	12.414	3.175
Scenario: Heatwave and no fishing effort (2021)				
Bray Curtis	Irish Sea	1.004	1.472	0.351
	S. North Sea	1.010	2.574	0.384
Cod biomass	Irish Sea	0.808	9.361	0.980
	S. North Sea	0.956	1.207	0.306
Demersal/Pelagic B	Irish Sea	1.087	3.367	0.819
	S. North Sea	1.040	0.464	0.194
Haddock biomass	Irish Sea	1.085	6.663	0.888
Herring biomass	Irish Sea	0.955	0.643	0.547
	S. North Sea	1.114	0.417	0.188
Kempton's Q	Irish Sea	0.932	6.523	2.227
	S. North Sea	1.030	0.806	0.327
Nephrops biomass	Irish Sea	1.096	3.335	0.807

Plaice biomass	Irish Sea	1.046	1.944	0.844
	S. North Sea	0.974	0.327	0.189
Shannon diversity	Irish Sea	0.999	0.000	0.000
	S. North Sea	0.991	0.180	0.107
Sole biomass	Irish Sea	1.024	1.633	0.695
TL community	Irish Sea	0.999	0.000	0.000
	S. North Sea	0.999	0.000	0.000
Whiting biomass	Irish Sea	0.968	10.203	2.976

Table 2: Geometric mean per indicator, parameter and scenario. In the case of amplitude, 1 equals the baseline scenario with no shocks, while values greater indicate a positive and below 1 a negative impact. Responsiveness and recovery are shown in years. Black numbers refer to the results for the model of the southern part of the North Sea, blue numbers to the Irish Sea EwE.

Scenario/indicator	**EwE model**	**Amplitude**	**Recovery**	**Responsiveness**
Scenario: Cod recruitment failure (2021)				
Bray Curtis	Irish Sea	1.001	6.590	1.908
	S. North Sea	1.000	35.738	2.706
Cod biomass	Irish Sea	0.958	2.200	0.022
	S. North Sea	0.928	2.317	0.794
Demersal/Pelagic B	Irish Sea	1.017	0.989	0.693
	S. North Sea	0.999	0.000	0.000
Haddock biomass	Irish Sea	1.025	1.617	0.857
Herring biomass	Irish Sea	1.009	0.209	0.086
	S. North Sea	1.000	0.000	0.000

Kempton's Q	Irish Sea	0.995	4.125	3.053
	S. North Sea	0.998	0.000	0.000
Nephrops biomass	Irish Sea	1.022	1.421	1.336
Plaice biomass	Irish Sea	1.008	0.217	0.171
	S. North Sea	1.000	0.000	0.000
Shannon diversity	Irish Sea	1.001	0.000	0.000
	S. North Sea	1.000	0.000	0.000
Sole biomass	Irish Sea	1.022	1.227	0.650
TL catch	Irish Sea	0.998	0.000	0.000
	S. North Sea	1.001	0.000	0.000
TL community	Irish Sea	1.000	0.000	0.000
	S. North Sea	1.000	0.000	0.000
Whiting biomass	Irish Sea	1.025	1.829	1.829
Scenario: Haddock recruitment failure (2021)				
Bray Curtis	Irish Sea	1.000	0.000	0.000
Cod biomass	Irish Sea	0.995	0.004	0.002
Demersal/Pelagic B	Irish Sea	0.997	0.000	0.000
Haddock biomass	Irish Sea	0.980	1.846	1.163
Herring biomass	Irish Sea	1.000	0.000	0.000
Kempton's Q	Irish Sea	0.971	1.540	0.939
Nephrops biomass	Irish Sea	1.012	0.457	0.247
Plaice biomass	Irish Sea	0.999	0.000	0.000

Shannon diversity	Irish Sea	1.000	0.000	0.000
Sole biomass	Irish Sea	1.000	0.000	0.000
TL catch	Irish Sea	1.000	0.000	0.000
TL community	Irish Sea	1.000	0.000	0.000
Whiting biomass	Irish Sea	0.998	0.000	0.000
Scenario: Herring recruitment failure (2021)				
Bray Curtis	S. North Sea	1.002	18.077	2.721
Cod biomass	S. North Sea	1.015	0.602	0.003
Demersal/Pelagic B	S. North Sea	1.009	0.143	0.000
Herring biomass	S. North Sea	0.970	2.092	0.452
Kempton's Q	S. North Sea	0.991	0.010	0.000
Plaice biomass	S. North Sea	1.002	0.000	0.000
Shannon diversity	S. North Sea	0.999	0.000	0.000
TL catch	S. North Sea	1.001	0.000	0.000
TL community	S. North Sea	1.000	0.000	0.000
Scenario: Plaice recruitment failure (2021)				
Bray Curtis	Irish Sea	1.000	0.000	0.000
	S. North Sea	1.001	10.372	2.360
Cod biomass	Irish Sea	1.000	0.000	0.000
	S. North Sea	1.006	0.030	0.000
Demersal/Pelagic B	Irish Sea	0.999	0.000	0.000
	S. North Sea	1.001	0.000	0.000

Haddock biomass	Irish Sea	1.001	0.000	0.000
Herring biomass	Irish Sea	1.000	0.000	0.000
	S. North Sea	1.000	0.000	0.000
Kempton's Q	Irish Sea	1.058	2.134	0.128
	S. North Sea	1.000	0.000	0.000
Nephrops biomass	Irish Sea	1.000	0.000	0.000
Plaice biomass	Irish Sea	0.959	1.663	1.297
	S. North Sea	0.965	1.422	0.152
Shannon diversity	Irish Sea	1.000	0.000	0.000
	S. North Sea	1.000	0.000	0.000
Sole biomass	Irish Sea	0.999	0.000	0.000
TL catch	Irish Sea	1.000	0.000	0.000
	S. North Sea	1.000	0.000	0.000
TL community	Irish Sea	1.000	0.000	0.000
	S. North Sea	1.000	0.000	0.000
Whiting biomass	Irish Sea	0.999	0.000	0.000
Scenario: Whiting recruitment failure (2021)				
Bray Curtis	Irish Sea	1.001	0.133	0.053
Cod biomass	Irish Sea	1.005	0.005	0.003
Demersal/Pelagic B	Irish Sea	0.995	0.000	0.000
Haddock biomass	Irish Sea	1.010	0.278	0.169
Herring biomass	Irish Sea	0.997	0.000	0.000

Kempton's Q	Irish Sea	0.969	1.934	1.354
Nephrops biomass	Irish Sea	1.012	0.422	0.118
Plaice biomass	Irish Sea	0.997	0.000	0.000
Shannon diversity	Irish Sea	1.000	0.000	0.000
Sole biomass	Irish Sea	0.992	0.282	0.003
TL catch	Irish Sea	0.996	0.000	0.000
TL community	Irish Sea	1.001	0.000	0.000
Whiting biomass	Irish Sea	0.844	7.925	3.038

Table 3: Geometric mean per indicator, parameter and scenario. In the case of amplitude, 1 equals the baseline scenario with no shocks, while values greater indicate a positive and below 1 a negative impact. Responsiveness and recovery are shown in years. Black numbers refer to the results for the model of the southern part of the North Sea, blue numbers to the Irish Sea EwE.

Scenario/indicator	EwE model	Amplitude	Recovery	Responsiveness
Scenario: Benthos mortality increase (2021)				
Bray Curtis	Irish Sea	1.011	3.586	0.538
	S. North Sea	1.006	14.970	1.471
Cod biomass	Irish Sea	0.977	3.186	2.217
	S. North Sea	0.994	0.065	0.040
Demersal/Pelagic B	Irish Sea	0.975	1.735	1.468
	S. North Sea	0.997	0.000	0.000
Haddock	Irish Sea	0.944	4.393	1.771
Herring biomass	Irish Sea	1.003	0.000	0.000
	S. North Sea	0.999	0.000	0.000

Kempton's Q	Irish Sea	0.990	0.103	0.092
	S. North Sea	0.998	0.000	0.000
Nephrops biomass	Irish Sea	0.928	5.771	2.223
Plaice biomass	Irish Sea	0.982	1.499	0.988
	S. North Sea	1.004	0.000	0.000
Shannon diversity	Irish Sea	0.999	0.000	0.000
	S. North Sea	0.998	0.000	0.000
Sole biomass	Irish Sea	1.030	3.633	3.592
TL catch	Irish Sea	0.996	0.000	0.000
	S. North Sea	0.999	0.000	0.000
TL community	Irish Sea	0.991	0.140	0.000
	S. North Sea	0.999	0.000	0.000
Whiting biomass	Irish Sea	1.011	0.835	0.643
Scenario: Primary production decrease (2021)				
Bray Curtis	Irish Sea	1.295	7.996	0.720
	S. North Sea	1.155	11.372	1.963
Cod biomass	Irish Sea	0.784	17.710	2.708
	S. North Sea	0.653	26.010	3.193
Demersal/Pelagic B	Irish Sea	1.336	8.804	1.301
	S. North Sea	2.648	3.256	1.602
Haddock biomass	Irish Sea	0.794	16.957	1.821
Herring biomass	Irish Sea	0.519	34.177	1.625
	S. North Sea	0.114	39.195	2.613

Kempton's Q	Irish Sea	0.877	5.980	1.384
	S. North Sea	0.835	12.564	1.748
Nephrops biomass	Irish Sea	0.754	13.598	1.577
Plaice biomass	Irish Sea	0.865	10.959	1.650
	S. North Sea	0.809	7.775	2.568
Shannon diversity	Irish Sea	0.881	2.669	0.979
	S. North Sea	0.920	2.138	0.379
Sole biomass	Irish Sea	0.782	14.889	1.802
TL catch	Irish Sea	1.014	2.315	0.904
	S. North Sea	1.060	1.184	0.420
TL community	Irish Sea	0.881	2.613	1.282
	S. North Sea	1.038	1.214	0.691
Whiting biomass	Irish Sea	0.647	28.166	1.850
Scenario: Primary production increase (2021)				
Bray Curtis	Irish Sea	1.197	8.325	0.659
	S. North Sea	1.119	13.690	1.904
Cod biomass	Irish Sea	1.290	11.282	2.226
	S. North Sea	1.490	8.448	1.762
Demersal/Pelagic B	Irish Sea	0.973	9.535	1.446
	S. North Sea	0.494	12.001	1.459
Haddock biomass	Irish Sea	1.289	11.131	1.731
Herring biomass	Irish Sea	1.669	4.393	1.184
	S. North Sea	2.188	6.726	1.892

Kempton's Q	Irish Sea	1.061	7.111	2.269
	S. North Sea	0.913	12.187	2.461
Nephrops biomass	Irish Sea	1.371	7.809	1.389
Plaice biomass	Irish Sea	1.156	6.830	1.453
	S. North Sea	1.207	6.187	2.548
Shannon diversity	Irish Sea	1.028	1.659	1.080
	S. North Sea	1.064	1.234	0.270
Sole biomass	Irish Sea	1.201	12.391	1.479
TL catch	Irish Sea	1.035	2.785	1.070
	S. North Sea	0.969	1.155	0.573
TL community	Irish Sea	1.069	1.953	1.266
	S. North Sea	0.970	1.090	0.403
Whiting biomass	Irish Sea	1.561	12.176	1.561

Annex 17 BLACK SEA - CLIMATE CHANGE AND RESILIENCE OF EXPLOITED STOCKS TO THE CLIMATE INDUCED STRESS

Introduction

Hydro-climatic conditions in the Black Sea allow for a great variety of temperature regimes, including amplitudes of about 0 to 30C in coastal brackish areas and a strong thermocline (strengthened by the permanent pycnocline) in summer dividing warm surface waters from deeper cooler water (bellow 20-50 m) of about constant temperature of 8-9°C (Simonov and Altman, 1991, Sorokin 2002). Consequently, fish stocks are well adapted to live in their preferred temperature niches, through movements and migrations, and in this way to avoid possible thermal extremes (Daskalov and Prodanov 1998). For example, in summer, so-called cold water species of Atlantic origin (e.g. sprat, whiting) inhabit the deeper water layers below the thermocline with an almost constant ambient temperature of 8-9°C (Daskalov and Prodanov 1998). Although fish stock dynamics has been found to correlate to variations in SST (and other environmental variables such as wind speed, SLP, turbulence, Daskalov 1999), the causal factors behind these correlations are thought not to relate directly thermal conditions to fish physiology, but rather been an indirect effect of environmentally modulated feeding conditions on fish survival.

Ecopath with Ecosim (EwE) model of the Black Sea

Several EwE models of the Black Sea have been developed, including time and space dynamics and time-dynamic coupled with biogeochemical models (Daskalov 2002, Zavatarelli et al. 2013, Georgieva 2020). The present EwE model was upgrading upon previous models. It refers to the 1995-2016. The model structure is set to 34 trophic groups, including phytoplankton (2 groups), macrophytobenthos (4 groups), protozoans (2 groups), invertebrates (zooplankton and zoobenthos, 11 groups), fish (11 groups), dolphins (1), and detritus groups (1 group). Fisheries consist of 5 fishing fleets. The present model is upgraded with data from the latest Black Sea stock assessments up to 2016 (STECF 2017; RECFISH 2019; Daskalov et al. 2020). Three functional groups are added based on the new stock assessment: bonito, bluefish and red mullet. The time-dynamic model Ecosim is adequately adjusted and validated by fitting to empirical time series. The Ecosim model is validated by using empirical time series of biomass and catches from the latest Black Sea stock assessments.

In order to simulate climate change scenarios forcing functions are applied in the EwE model, by forcing either the primary production of the phytoplankton groups or consumption rate of the fish groups.

Ecosystem scenarios

In this study, we are simulating the effects of climate change on the Black Sea ecosystem and fish stocks over the future period of 2017-2100 in 3 ways (Table 35):

1. By forcing the primary production in the EwE model of the Black Sea (Figure 1)

2. By forcing the consumption rate of specific fish stocks using empirical relation between SST and fish biomass (Table 35, Figure 101).

3. Inducing a 50% reduction in the consumption rate of specific fish stocks to illustrate a thermal shock's negative effect (for one or two consecutive years).

Forcing of primary production (PP) of phytoplankton biomass is simulated using coefficients linking PP with the SS obtained in coupled models of Chust et al. (2014) and Cannaby et al. (2015) applied to SST projections (2020-2100) from CMIPS 6 (RCPs 4.5 and 8.5, https://cds.climate.copernicus.eu/cdsapp#!/dataset/10.24381/cds.d7eaec3d?tab=form, Fig. 1). SST projections were smoothed using linear smoothers in order to retain only long-term variations. The consumption rates of priority fish stocks were forced using coefficients obtained in regression analyses between fish biomass and SST (Table 36) using SST projections from CMIPS 6. Only projections of sprat and anchovy have significant effects on the functional groups in the EwE model, and only they were further analysed and presented here (Figure 101).

The effects of climate change are then analysed on resulting time trajectories (2017-2100) of functional groups biomasses and fisheries catches, as well as in some ecosystem indicators (Figure 102,Figure 103 Figure 104, Figure 105, Figure 106, Figure 107, Figure 108, Figure 109). We use three robust metrics as indicators of whole ecosystem resilience: Demersal to Pelagic fish Biomass Ratio (DPBR); Trophic Level (TL) of the catch, and Kempton's Q as an indicator of the diversity of functional groups in the EwE model.

Results of simulations are also examined as in 2030 with the baselines scenarios (Figure 109).

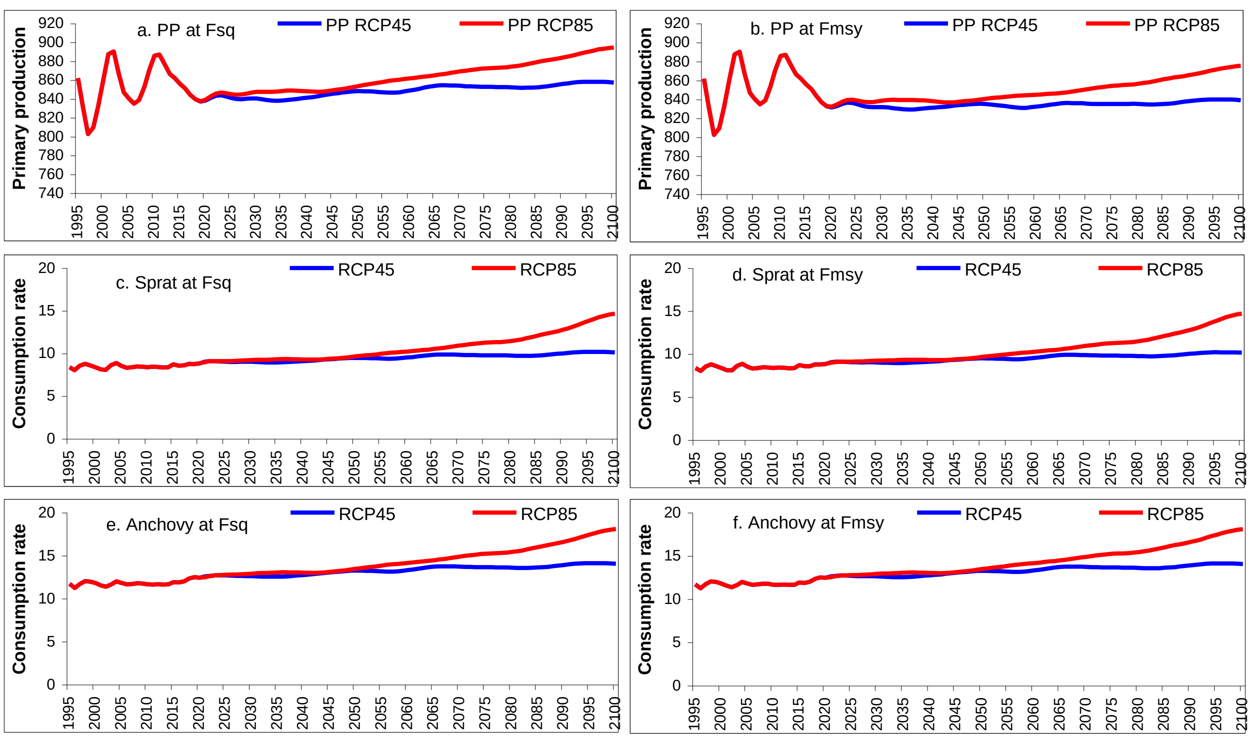

Figure 101 Forcing yearly primary production (PP ab) and consumption rates of sprat (cd) and anchovy (ef) with the RCP 4.5 and RCP 8.5 realisations of SST, when fishing at Fsq and Fmsy.

Indicators of ecosystem resilience

Potential shock effects of sudden climate change are analysed using scenarios of 50% reduction in the consumption rate of priority fish stocks (for one or two consecutive years). Only projections of sprat and anchovy have significant effects on the functional groups in the EwE model, and only they were further analysed and presented here (Figure 110, Figure 111, Figure 112, Figure 113). Three indicators of shock effects and resilience to climate-induced stress were explored: amplitude of the change in biomass as a response to the shock, speed of response or responsiveness, and recovery time from the onset of the shock (i.e. the year when 50% reduction in the consumption rate has been induced: Figure 112, Figure 113). The amplitude can be positive or negative and is measured as % change of the baseline; responsiveness is measured as the number of years from the onset year, and recovery time is the number of years when the indicator returns to the level before the shock. The point at which recovery is achieved is set to 5% of the size of the amplitude of the biomass response.

Table 35 Ecosystem scenarios using EwE in the Black Sea

Scenario	Baseline scenario	Best case or most likely scenario	Worst case scenario
Fishing scenarios	Fishing mortality of 2016 of all fished stocks projected to 2100	Fmsy of all fished stocks projected to 2100	Fsq of all fished stocks increased by 30% projected to 2100
Long term effects of climate change on ecosystem productivity	Fsq or Fmsy without climate forcing	Primary production affected by SST from RCP 4.5 projection	Primary production affected by SST from RCP 8.5 projection
Long term effects of climate change on fish stocks	Fsq or Fmsy without climate forcing	Fish stocks affected by SST from RCP 4.5 projection	Fish stocks affected by SST from RCP 8.5 projection
Short term shocks	Fsq	50% reduction in consumption rate in one year	50% reduction in consumption rate in two concecutive years
Short term shocks combined with long term effects of climate change	Fsq	50% reduction in consumption rate in one year + Primary production affected by SST from RCP 4.5 projection	50% reduction in consumption rate in two concecutive years + Primary production affected by SST from RCP 8.5 projection

Table 36 Parameters of univariate regression analyses of SST (predictor) to fish stocks (total biomass, dependent variable). Stocks in bold show statistically significant correlations with SST.

	Intercept	slope	r2	t	p	Data points
Sprat	7.50	0.36	0.41	4.47	0.0001	31
Anchovy*	10.93	0.20	0.14	2.21	0.0350	31

Horse mackerel*	22.45	-0.75	0.44	-4.54	0.0001	28
Whitihg*	18.46	-0.50	0.48	-5.16	0.0000	31
Turbot	7.46	0.07	0.09	1.65	0.1108	31
Dogfish	35.17	-1.71	0.72	-8.59	0.0000	31
Red mullet*	8.60	0.05	0.01	0.48	0.6319	27
Bonito	10.29	0.06	0.11	1.88	0.0707	31
Bluefish	13.89	-0.21	0.26	-3.18	0.0035	31

* Stock biomass is corrected for effects of fishing

Fishing scenarios

The effects of fishing are simulated by predicting future fishing mortality in 2017-2100 in three ways (Table 37, Figure 102): the baseline scenario expends the fishing mortality in 2017 (average of the fishing mortality in 2014-2016) in the model (Fsq) until 2100 – F status quo scenario; fishing at MSY scenario, using reference fishing mortality Fmsy and excessive fishing scenario of 30% increase of F over Fsq (F30, Table 37). Fmsy was taken from the most recent single species assessments (STECF 2017, RECFISH 2019, Daskalov et al. 2020). Fishing mortality in EwE is expressed as yearly exploitation rate (catch/biomass), and linear regressions of time series of catch/biomass and mean fishing mortality (Fbar) from single-species assessments were built and used to estimate respective Fmsy in terms of exploitation rate (Table 37).

Table 37 Parameters used in forcing of the fishing scenarios: Fsq = baseline status quo scenario; Fmsy = fishing at MSY; F30= 30% increase of F over Fsq.

Fishing mortality	Sprat	Anchovy	Horse Mackerel	Bonito	Bluefish	Whiting	Turbot	Dogfish	Red mullet
Fsq	0.143	0.198	0.418	0.264	0.278	0.358	0.439	0.086	0.519
F30	0.186	0.258	0.544	0.343	0.362	0.466	0.570	0.111	0.674
Fmsy (VPA)	0.64	0.4	0.4	0.148	0.123	0.47	0.14	0.08	0.64
Fmsy (EwE)	0.18	0.134	0.216	0.148	0.123	0.205	0.174	0.105	0.328

Results from the fishing scenarios are presented in Figure 102, Figure 109. As expected, the biomass is increasing in most stocks when fishing at Fmsy, and respectively decreasing when fishing at F30. However, biomass, and to a lesser extend catches of sprat are responding in an opposite way (Figure 102, Figure 109). These effects of sprat can be interpreted as resulting from a similar effect on zooplankton (Figure 102a) resulting from opposite effects on anchovy, which has a dominant effect on zooplankton by means of its greater biomass and higher production rate. The effects induced from anchovy on zooplankton also affect other planktivores such as alien comb-jelly Mnemiopsis leidyi (Figure 102b) and its alien comb-jelly predator Beroe ovata (Figure 102c). Therefore, fishing at Fmsy appears to affect negatively invasive species in the Black Sea ecosystem. Apart from the direct effects of reduced or increased fishing on their biomass and catches the predatory fish stocks like bonito, bluefish and turbot are affected indirectly by the increase (in Fmsy scenario) or decrease (F30 scenario) of anchovy biomass as most of them feed on anchovy (Figure 102, Figure 109). The effects on whiting and horse mackerel biomasses are minimal in either scenario, possibly because of cancelling trophic effects on these species situated in the middle of the food pyramid. Unexpectedly, the catch of dogfish is expected to rise by more than 20 % in 2030 when fishing at Fmsy (Figure 109b). Red mullet, dogfish and turbot biomasses seem to be positively influenced in the long-term by fishing at Fmsy. In particular, the rise in the red mullet biomass also indirectly benefits its predators, such as bluefish, turbot, and dogfish. The long-term rise in turbot and dogfish biomasses looks like recovery to a historically high level after those stocks have been driven to extremely low levels since the 1990s.

By 2030 the biomass of most stocks is expected to rise from 10 to 60%, when fishing at Fmsy, except for sprat, whiting and horse mackerel (Figure 109 top left panel). Their biomass is expected to decrease if fishing is increased by 30% (F30) by 20-60%, with same exceptions. Catches in 2030 would naturally follow the assumed strategies i.e. to decrease when fished at Fmsy or increase at F30, except for dogfish where an inverse tendency is observed, probably due to recovery of its biomass from an extremely low level, when fishing at Fmsy (Figure 102, Figure 109).

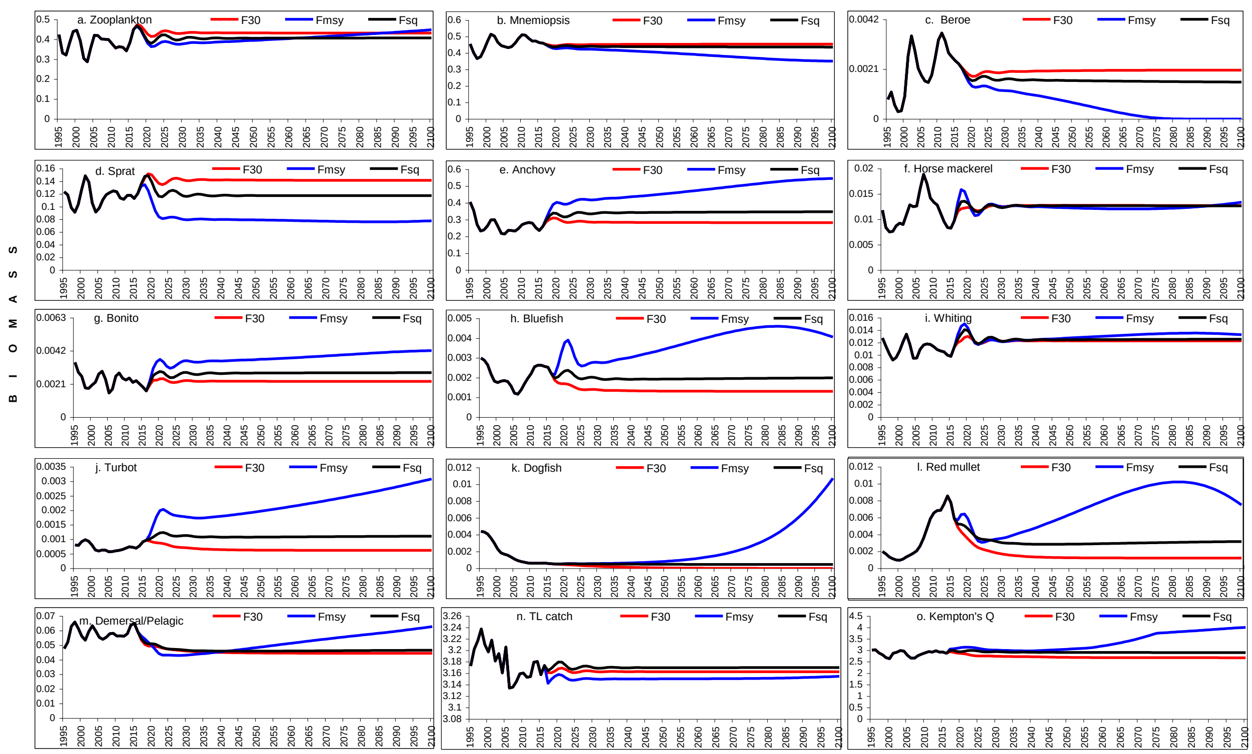

Figure 102 Biomass density (gC m−2 yr−1) in the fishing scenarios: Fsq = baseline status quo scenario; Fmsy = fishing at MSY; F30= 30% increase of F over Fsq. Last row shows effects on ecosystem indicators: m. Demersal/pelagic fish biomass ratio (DPBR) ; n. Trophic level (TL) of the catch and o. biodiversity indicator – Kempton's Q.

Ecosystem indicator DPBR shows an increasing long-term trend related to recovery of demersal stocks due to applying the Fmsy management strategy (Figure 102m). The TL catch is decreasing below the level of Fsq fishing in both F30 and Fmsy scenarios (Figure 102n) because of the greatest decrease in demersal catches, and Kempton's Q is increasing when fishing at Fmsy, because of the biomass recovery in several stocks (Figure 102o).

Long term effects of climate change on ecosystem productivity

Long term effects of climate change on ecosystem productivity are explored by forcing the primary production in the EwE model with the RCPs 4.5 and 8.5 projections of SST (Figure 101a, b). These forcings are applied to the model running with fishing mortalities of Fsq (Figure 103) and Fmsy (Figure 104), respectively.

When primary production PP forcing is applied when fishing at Fsq, the effects on biomass and catches are negative for most stocks (Figure 103, Figure 109). This can be explained by the inverse indirect effect on zooplankton (Figure 103a) by both invertebrate planktivores, such as Mnemiopsis and planktivorous fish. Predatory fish also tend to decrease in biomass and catch by 2030 (Figure 109). The effects of the RCPs 4.5 and 8.5 projections have the same directions in fish stocks when fishing at Fmsy (Figure 104, Figure 109). The exception is the red mullet stock which is increasing in both RCPs 4.5 and 8.5 scenarios. We believe that it also benefits its predators bluefish and turbot which also show increasing biomasses by the end of the simulation period in both RCPs 4.5 and 8.5 scenarios (Figure 103, Figure 104). Curiously, the stocks of red mullet seem to be rising in several areas in the Mediterranean and the Black Sea over the recent decade in correspondence with increasing water temperature.

The trends in the catches in most stocks follow the trends in biomass closely, decreasing by 1 to 6% by 2030 (Figure 109c, d). Exception is red mullet with increases in biomass and catches by 3-9% in different scenarios, horse mackerel with almost no change, and sprat where negative change is observed related only to the RCP 8.5 at Fsq scenario (Figure 109c, d).

As a result of the relatively long term increase in demersal and predatory fish, the DPBR and Kempton's Q increase with both RCPs 4.5 and 8.5 scenarios, while the TL of the catch does not show a significant change (Figure 103, Figure 104).

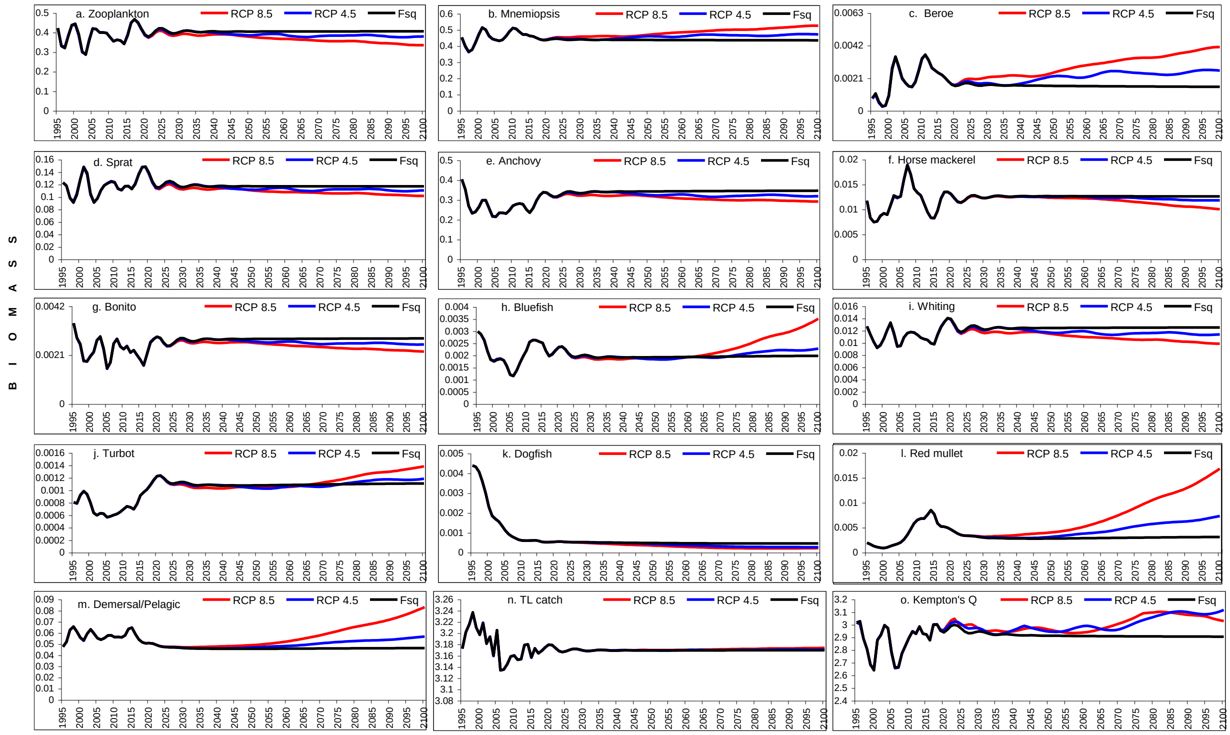

Figure 103 Biomass density (gC m−2 yr−1) in ecosystem productivity scenarios: Fsq = baseline status quo scenario; in RCP 4.5 and RCP8.5 scenarios the primary production rate (PP) is forced with the RCP 4.5 and RCP 8.5 realisations of SST . Last row shows effects on ecosystem indicators: Demersal/pelagic fish biomass ratio (DPBR); n. Trophic level (TL) of the catch and o. biodiversity indicator – Kempton's Q.

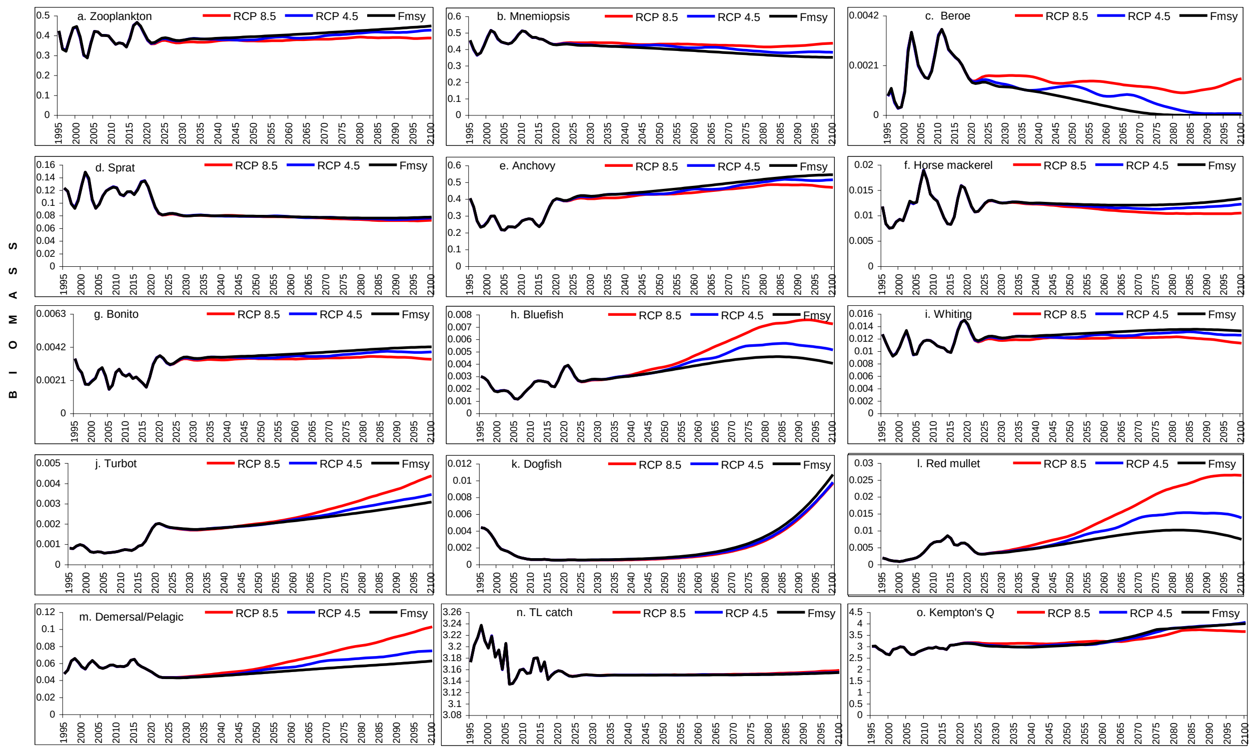

Figure 104 Biomass density (gC m−2 yr−1) in ecosystem productivity scenarios: Fmsy = fishing at Fmsy no PP forcing; in RCP 4.5 and RCP8.5 scenarios the primary production rate (PP) is forced with the RCP 4.5 and RCP 8.5 realisations of SST when fishing at Fmsy. The last row shows effects on ecosystem indicators: Demersal/pelagic fish biomass ratio (DPBR); Trophic level (TL) of the catch and biodiversity indicator – Kempton's Q.

Long term effects of climate change on fish stocks

The consumption rates of priority fish stocks were forced using coefficients obtained in regression analyses between fish biomass and SST using SST projections from CMIPS 6. Only projections of sprat and anchovy have significant effects on the functional groups in the EwE model, and only they were further analysed and presented.

Sprat biomass is positively influenced by SST and consequently by the two SST scenarios when fishing at Fsq and Fmsy (Figure 105d, Figure 106d). As seen in the previous analyses, the reaction to sprat increase is a decrease in anchovy as these species compete for zooplankton food (Figure 105e, Figure 106e). Consequently, zooplankton is decreasing (Figure 105a, Figure 106a), but interestingly the comb-jelly Mnemiopsis is increasing (Figure 105b, Figure 106b). This is maybe due to the decrease in anchovy and consequent release of small zooplankton (not shown), which is common food of both anchovy and Mnemiopsis. As a consequence of the Mnemiopsis increase, its comb-jelly predator Beroe is also increasing (Figure 105c, Figure 106c). The decrease in anchovy leads to a decrease in its predators, the most pronounced of which is bonito and to less extend bluefish and dogfish (Figure 105g, i, k and Figure 106g, i, k). The decrease in red mullet is probably following the drop in zooplankton which is part of its diet (Figure 105l, Figure 106l), and the increase of turbot in the RCP 8.5

at Fmsy scenario (Figure 106j) is probably led by the more substantial increase in sprat under this scenario.

The trends in the catches again follow the trends in biomass closely, decreasing by 2030 (Figure 109e, f) with sprat biomass and catches increasing by 15-20% in different scenarios, anchovy, bonito, red mullet and dogfish biomasses and catches decreasing by 5 to 15%, and only minor changes in horse mackerel, bluefish, and whiting. As mentioned turbot seems to benefit from the biomass increase in sprat and consequently, its biomass and catches increase by 5 % in the RCP 4.5 - 8.5 at Fmsy scenarios.

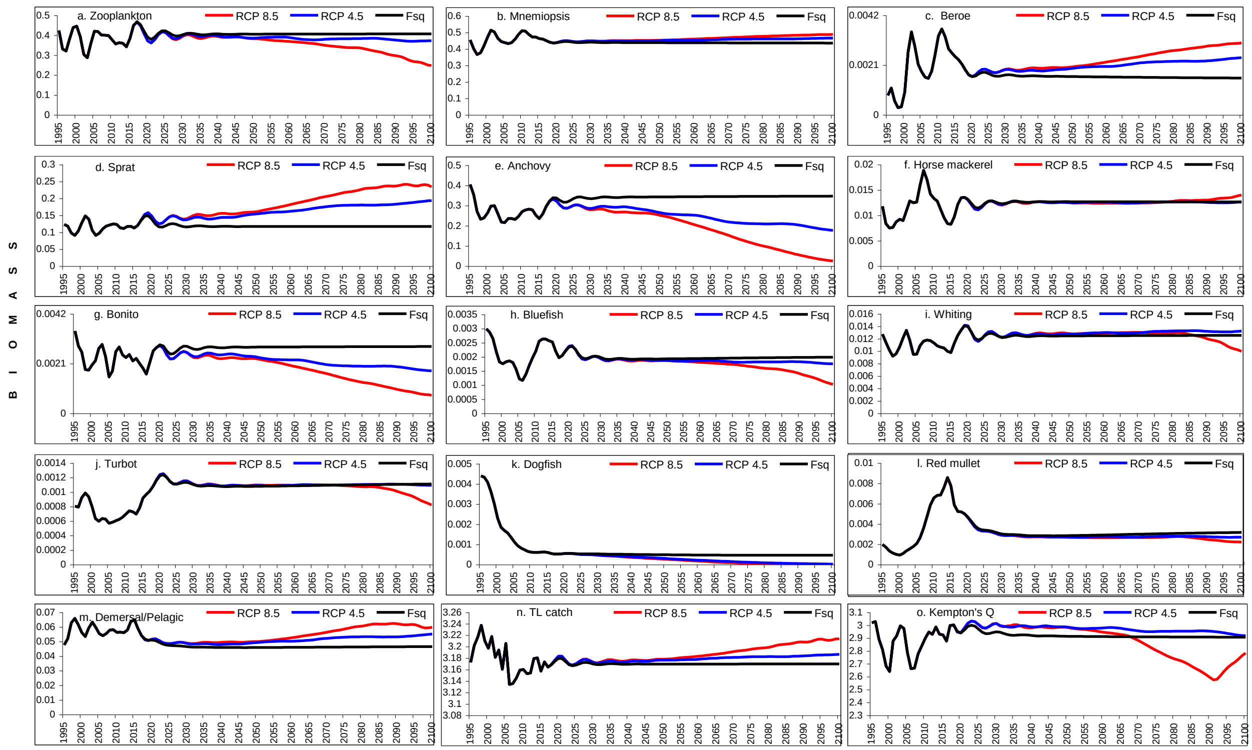

Figure 105 Biomass density (gC m−2 yr−1) in scenarios of forcing of the sprat stock when fishing at Fsq. Fsq is the baseline status quo scenario; in RCP 4.5 and RCP8.5 scenarios, the consumption rate of sprat is forced with the RCP 4.5 and RCP 8.5 realisations of SST, when fishing at Fsq. Last row shows effects on ecosystem indicators: Demersal/pelagic fish biomass ratio(DPBR); Trophic level (TL) of the catch and biodiversity indicator – Kempton's Q.

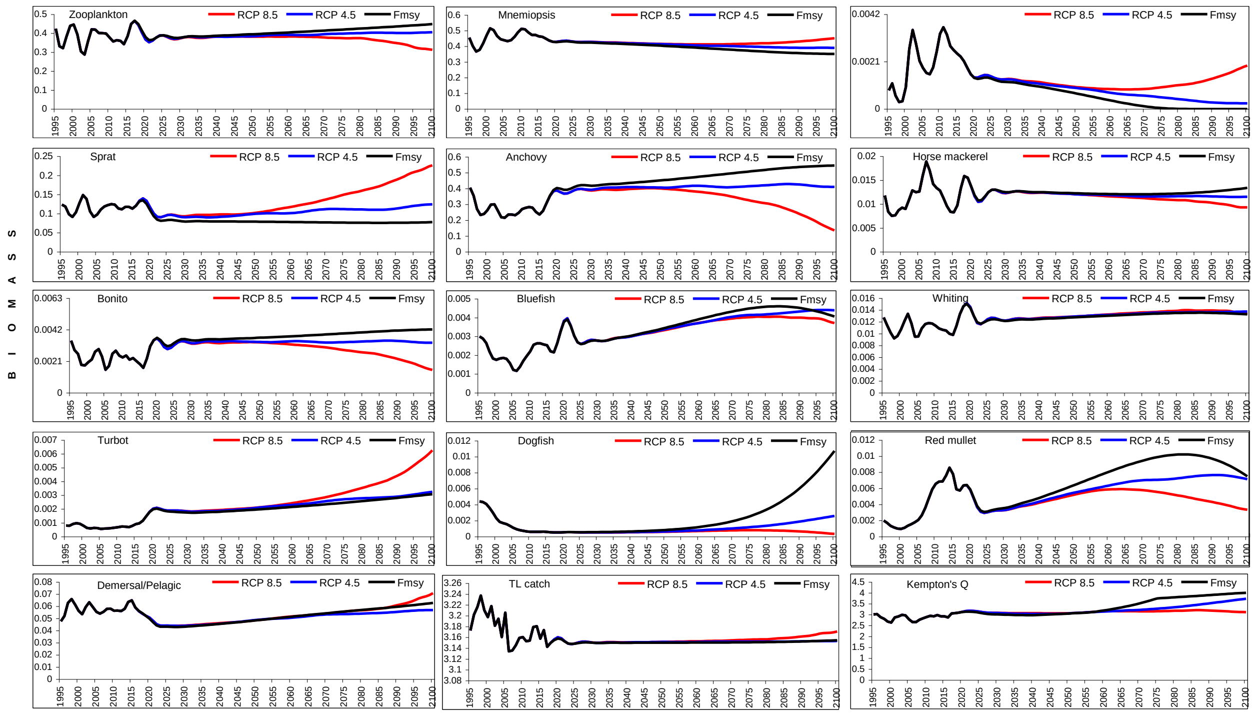

Figure 106 Biomass density (gC m−2 yr−1) in scenarios of forcing of the sprat stock when fishing at Fmsy. Fmsy is the baseline status quo scenario; in RCP 4.5 and RCP8.5 scenarios the consumption rate of sprat is forced with the RCP 4.5 and RCP 8.5 realisations of SST, when fishing at Fmsy. Last row shows effects on ecosystem indicators: Demersal/pelagic fish biomass ratio (DPBR); Trophic level (TL) of the catch and biodiversity indicator – Kempton's Q.

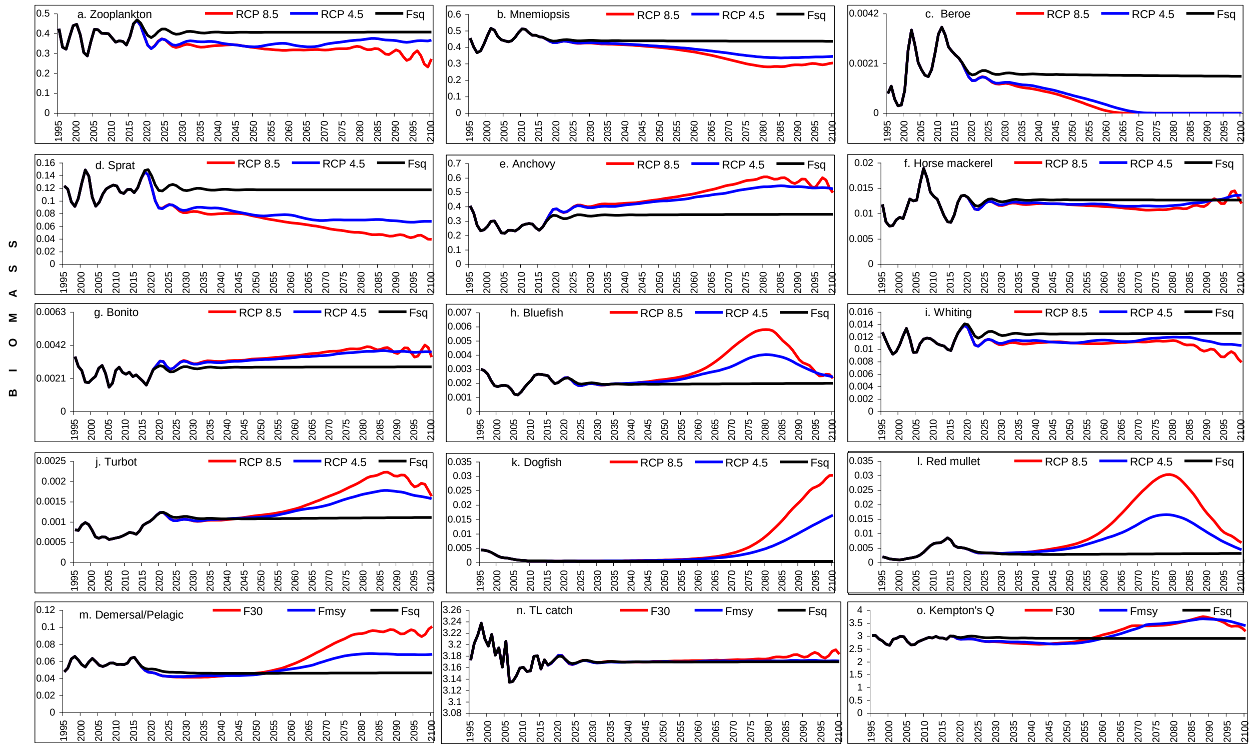

Figure 107 Biomass density (gC m−2 yr−1) in scenarios of forcing of the anchovy stock when fishing at Fsq. Fsq is the baseline status quo scenario; in RCP 4.5 and RCP8.5 scenarios, the consumption rate of sprat is forced with the RCP 4.5 and RCP 8.5 realisations of SST, when fishing at Fsq. Last row shows effects on ecosystem indicators: Demersal/pelagic fish biomass ratio (DPBR); Trophic level (TL) of the catch and biodiversity indicator – Kempton's Q.

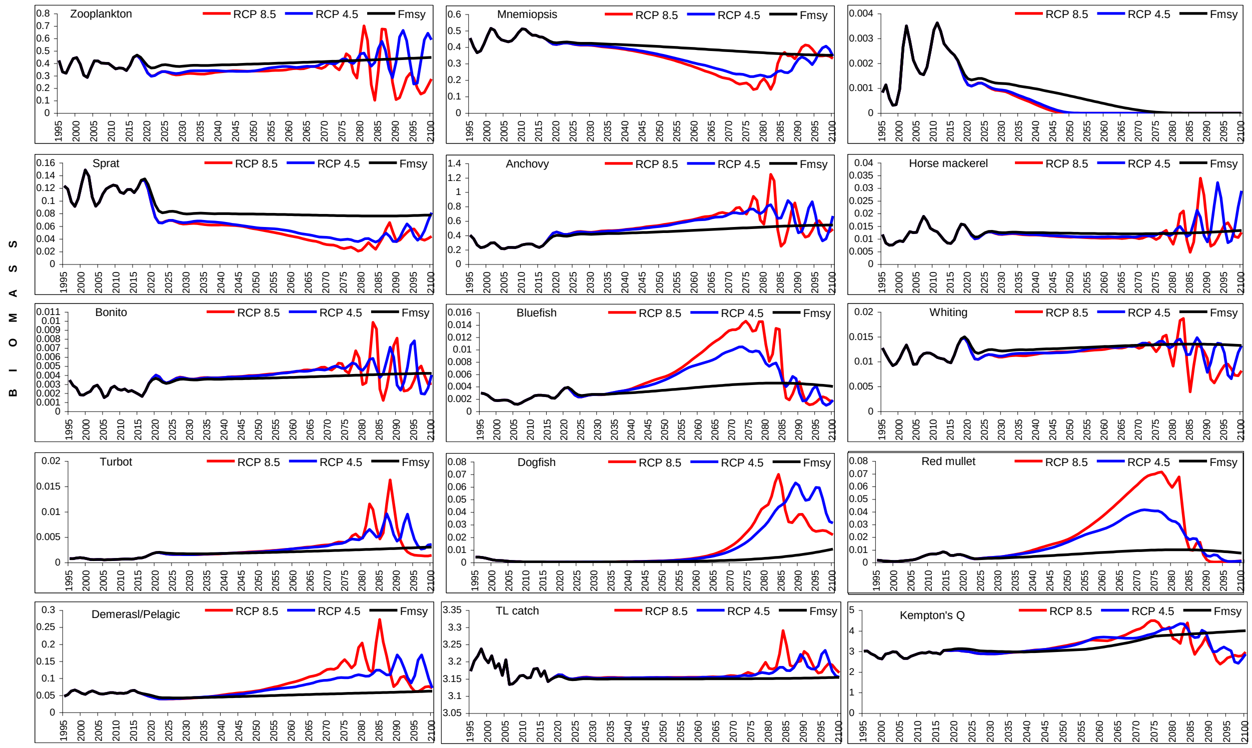

Figure 108 Biomass density (gC m−2 yr−1) in scenarios of forcing of the anchovy stock when fishing at Fmsy. Fmsy is the baseline status quo scenario; in RCP 4.5 and RCP8.5 scenarios the consumption rate of sprat is forced with the RCP 4.5 and RCP 8.5 realisations of SST, when fishing at Fmsy. Last row shows effects on ecosystem indicators: Demersal/pelagic fish biomass ratio (DPBR); Trophic level (TL) of the catch and biodiversity indicator – Kempton's Q.

The sprat productivity scenario yield some increases in the DPBR and TL of the catch (Figure 105o, Figure 106o), that result from the decrease in anchovy, which is the most abundant small pelagic fish in the Black Sea. The biodiversity indicator - Kempton's Q is decreasing by the end of the period in the RCP 8.5 at Fmsy scenario.

Anchovy biomass is also positively influenced by SST (Figure 101e,f). That results in increase in anchovy and bonito, and decreases in zooplankton, Mnemiopsis, Beroe, sprat and whiting, (Figure 107 a,b,c,d,e). The combination of the increase in the consumption rate of anchovy in the RCP 4.5 and 8.5 scenarios and the increase due to fishing at Fmsy create some instability in the model in the end of the simulation period which translates across all functional groups (Figure 108). Interestingly, the biomass of red mullet is also positively influenced in these scenarios. The possible relation between increases in anchovy and red mullet is through indirect links of their planktonic and respectively benthic food that is influenced as indirect effect of anchovy increase. Bluefish, turbot and dogfish also increase by the end of the period following the red mullet increase (Figure 107h,j,k,l).

However, biomass and catches of bluefish and turbot decrease by 2030 (Figure 109g, h) influenced probably by the decrease in sprat, which is also their main food. Biomass and catches of sprat decrease by 20-30% in 2030, while those of horse mackerel and whiting decrease by 5-10% (Figure 109g, h). Increases in biomass and catches by 5 to 25% should be noted in anchovy, bonito, dogfish and red mullet.

The main changes in the ecosystem indicators are related to the increase in red mullet and associated stocks at the end of the simulation period: increase in DPBR, TL of the catch, and Kempton's Q (Figure 107 m,n,o and Figure 108m,n,o).

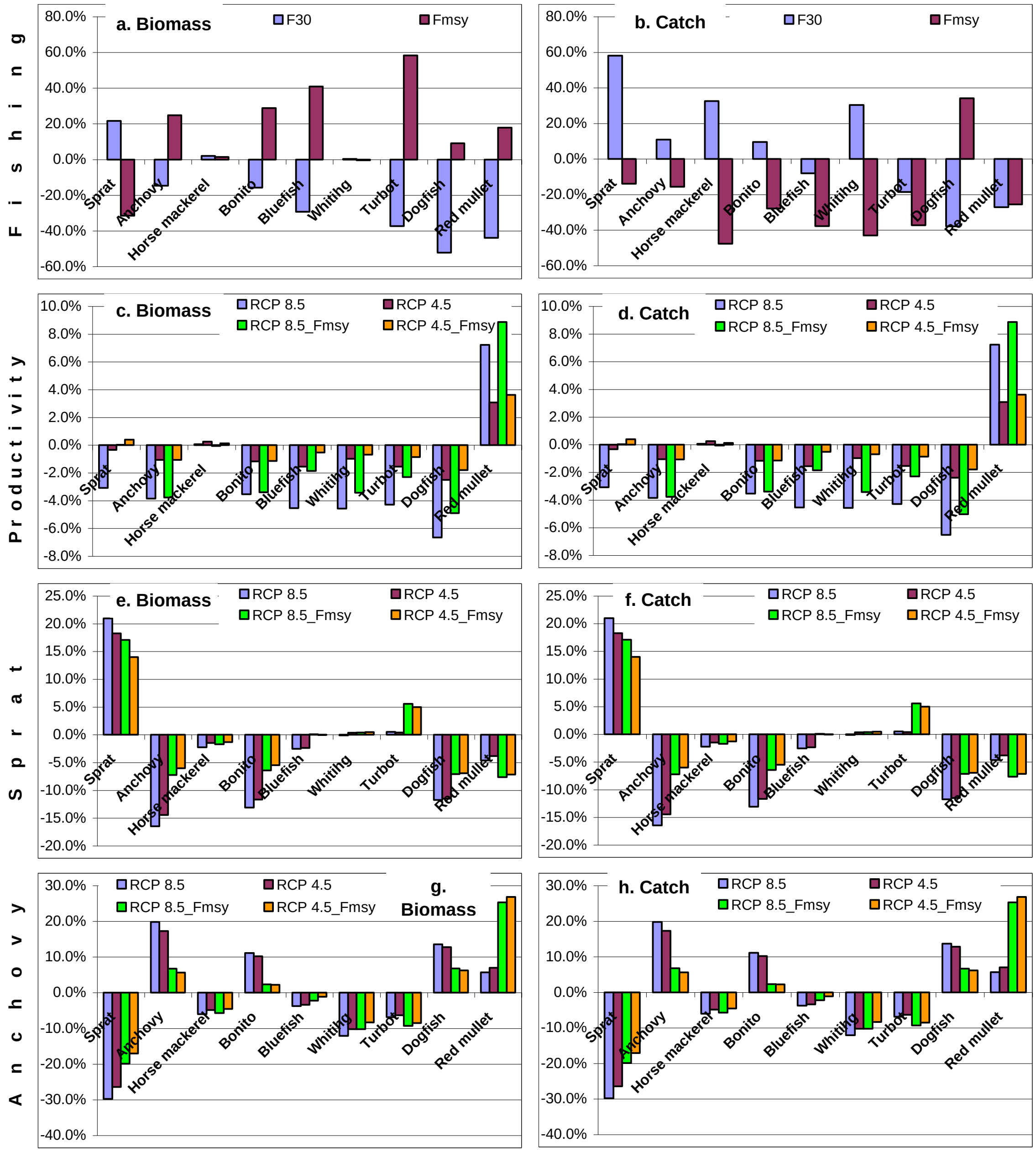

Figure 109 Effects of long-term change scenarios on fish biomass and catches in 2030 in % of baseline. Upper row: fishing scenarios – a. biomass and b, catches at Fmsy and F30, as percentage of the Fsq scenario. Second rows down: Ecosystem productivity scenarios – c. biomass, and d. catches at in the RCP 4.5 and RCP 8.5 scenarios, as percentage of the Fsq and Fmsy scenarios, respectively. Bottom two rows biomass and catches in the sprat (e, f)and anchovy (g, h) forcing with RCP 4.5 and RCP 8.5 scenarios, as percentage of the Fsq and Fmsy scenarios, respectively.

Evaluation of ecosystem resilience from short term shock scenarios

Potential shock effects of climate change were analysed using scenarios of 50% reduction in the consumption rate of sprat and anchovy as only they have significant effects on the functional groups in the EwE model (Figure 110, Figure 111, Figure 112, Figure 113).

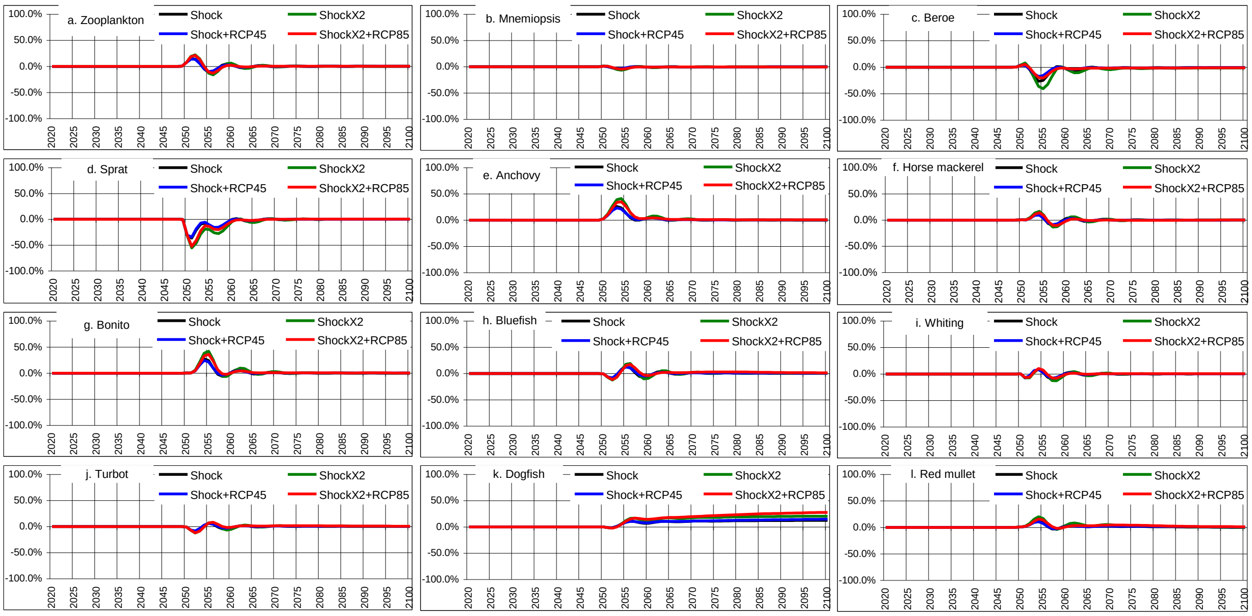

Figure 110 Short term shock scenarios on sprat in % of baseline Fsq scenario: Shock is 50% reduction of sprat biomass in 2050; ShockX2 is 50% reduction of sprat biomass in 2050 and 2051. In Shock+RCP 4.5 and ShockX2+RCP8.5 scenarios long-term effects on ecosystem productivity are added to the first two scenarios.

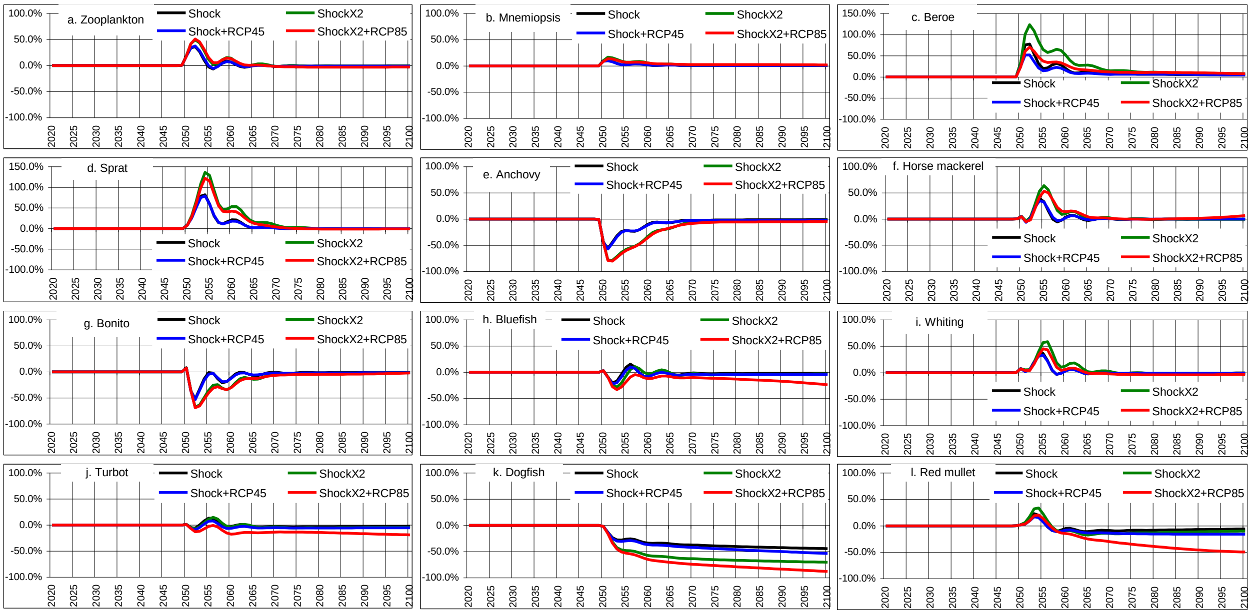

Figure 111 Short term shock scenarios on anchovy in % of baseline Fsq scenario: Shock is 50% reduction of anchovy biomass in 2050; ShockX2 is 50% reduction of anchovy biomass in 2050 and 2051. In Shock+RCP 4.5 and ShockX2+RCP8.5 scenarios long-term effects on ecosystem productivity are added to the first two scenarios.

The direction of indirect effects (posititive or negative) of perturbation of sprat and anchovy on the other functional groups, confirm the effects observed when simulating climate effects presented in the section Long term effects of climate change on fish stocks. The 50% reduction of sprat biomass brings proportional effects on zooplankton, whiting and turbot, and inverse effects on Mnemiopsis, Beroe, anchovy, horse mackerel, bonito, bluefish, dogfish and red mullet (Figure 112a). The 50% reduction of anchovy biomass brings proportional effects on bonito, bluefish, dogfish and red mullet, and inverse effects on zooplankton, Mnemiopsis, Beroe, sprat, horse mackerel, whiting and turbot (Figure 113a). We account the effect of the shock on anchovy on red mullet by measuring the amplitude of its first negative peak (Figure 111i).

The amplitude of the effects of the perturbation of sprat is higher in sprat about 35-55% in different scenarios, anchovy and bonito up to about 40% following two consecutive shock years, and lowest in Mnemiopsis – about 5% (Figure 112a). The amplitude of the effects of the perturbation of anchovy is higher, because of the strongest effects caused of the perturbation of the most abundant stock of anchovy: up to 120-130% in Beroe and sprat, down to 70-80% negative amplitude in anchovy, bonito and dogfish (Figure 113a). There is no significant effect on amplitude of the long-term environmental forcing (primary production forced at RCP 4.5 and 8.5) added to the 50% biomass reductions (Figure 112a and Figure 113a) as it is very small proportionally to shocks, so the main effect is between 1 year and 2 years of biomass reduction i.e. between a shock and shockX2 (Figure 112a and Figure 113a).

In general, the time of response to the disturbance increases in trophically distant groups from the directly impacted sprat and anchovy (Figure 112b, Figure 113b). Sprat and anchovy biomasses respond in the next year after perturbation, zooplankton - after 2-3 years, other zooplanktivores – after 3-4 years, and predators – in 5 years and beyond (Figure 112b, Figure

113b). Some predators that directly feed on sprat and anchovy also respond after 2-3 years, such as bonito and bluefish (preying on dominantly on anchovy) and turbot (preying on dominantly on sprat). Red mullet, which is influenced via planktonic-benthic links as well as being influenced by predation, tend to have a longer response time.

Recovery time is more difficult to measure because of instabilities arising after perturbation along the trophic pathways. In some groups (dogfish red mullet) recovery seem not to happen; in others, such as Mnemiopsis and Beroe, the biomass after the perturbation is slightly different from the one prior to the perturbation. In dogfish, there are continuous effects that resemble state shifts, but because this stock is with very low biomass, it is difficult to interpret its reaction to natural environmental stress. The long term climate change may accentuate the lack of recovery as we can see that scenarios applying primary production forcing, especially at RCP 8.5 tend to lack recovery for at least 50 years (the limit of these simulations, Figure 110, Figure 111).

When perturbing sprat, it recovers after about 10-15 years, and zooplankton, anchovy, bonito - after 15-20 years, horse mackerel and whiting after 20-25 years, and Mnemiopsis and Beroe, bluefish, turbot and red mullet after more than 30 years (Figure 112c). After perturbation of anchovy it takes again 15-25 years for most of the groups to recover (Figure 113c), however other groups change slightly or more pronouncedly their biomass level, with climate forcing seemingly contributing to these changes.

Discussion

It is clear that using food web models in forecasting environmental change relies on a great amount of uncertain information and sometimes of rather ambiguous assumptions about the links between the environment and ecosystem and what may happen to them in the future (Link et al. 2012). Therefore, it is important to know what models can tell us about the future environmental change besides their limitations and how to interpret, in all modesty, their responses to some plausible questions asked by defining possible scenarios.

This study has confirmed previous ideas that ecosystems, as represented by food web models, respond to external perturbation by a multitude of indirect effects often cascading through the entire trophic pyramid (Ulanowicz and Puccia 1990, Daskalov 2002, Liblarato et al. 2006). Apart from top-down cascades (from predators down to producers), there is also evidence of horizontal linkages, for instance, via plankton and benthos, transferring effects between species of similar trophic levels such as anchovy (TL=3.1) and red mullet (TL=3.2). Red mullet is a new stock introduced on the purposes of this study to the Black Sea EwE model, which has shown rather interesting dynamics in response to environmental perturbations. Curiously, the red mullet catches have significantly increased in the Black Sea and in some areas of the Mediterranean over the last years. This may be associated with the trend of increasing water temperature; however, the results from our study indicate that the linkages may be rather complicated.

Another species that may benefit from the increasing “mediterranisation” of the Black Sea is anchovy. Usually, it carries out overwintering migrations to the southern Black Sea (Turkish waters), where it is fished by massive purse seine fleets (Daskalov et al. 2008). Over the last years, there has been a tendency of warmer winters, when big anchovy schools remain in the western shelf areas, where the Bulgarian pelagic fleet fishes them. Our results indicate that anchovy may benefit from long term climate change and respond by increasing biomass that may also lead to expanding geographical areas.

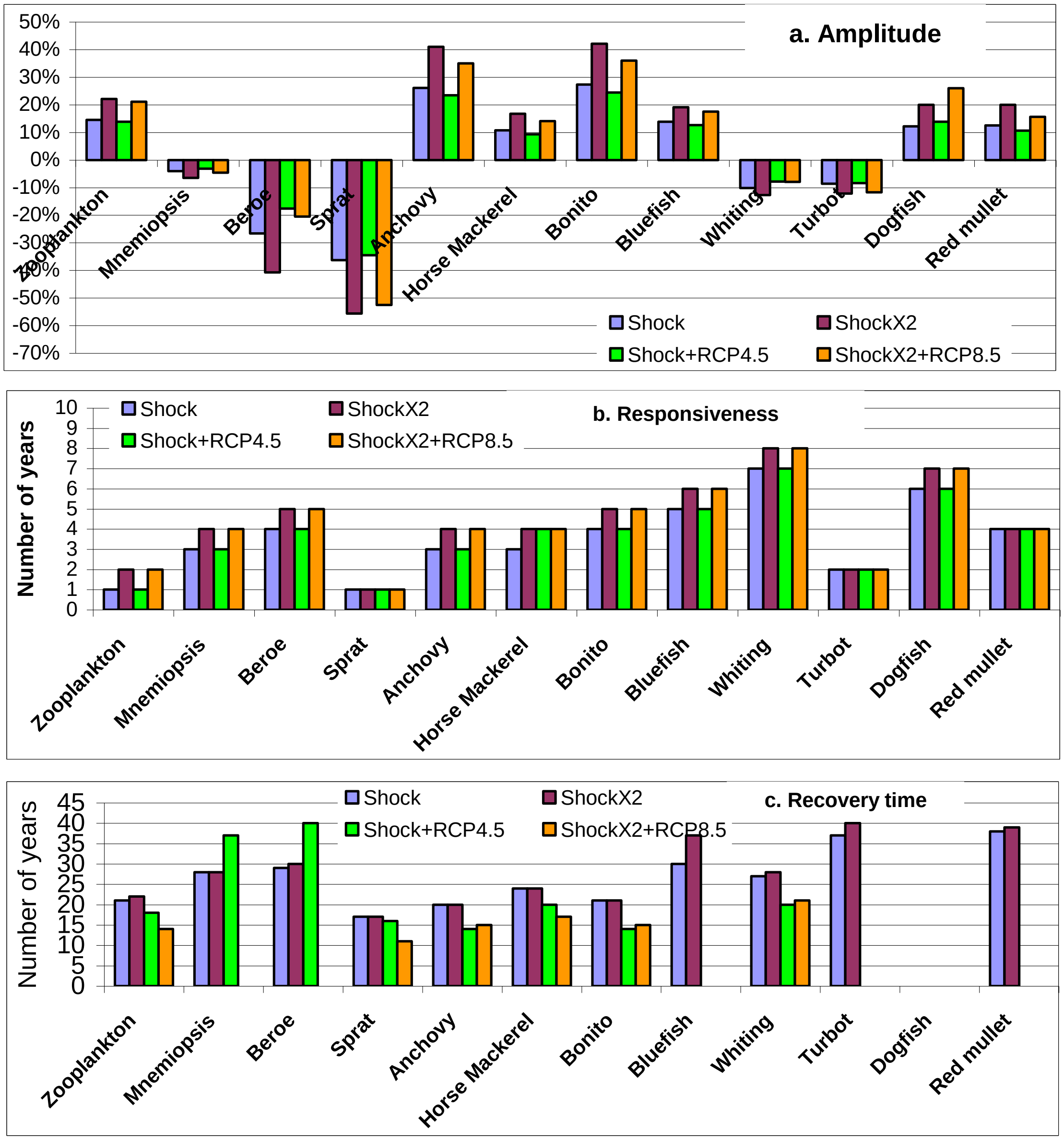

Figure 112 Ecosystem resilience indicators: a. Amplitude; b. Responsiveness; c. Recovery time, estimated from short term shock scenario of 50% reduction of sprat biomass (legend is as in Figures 10 and 11).

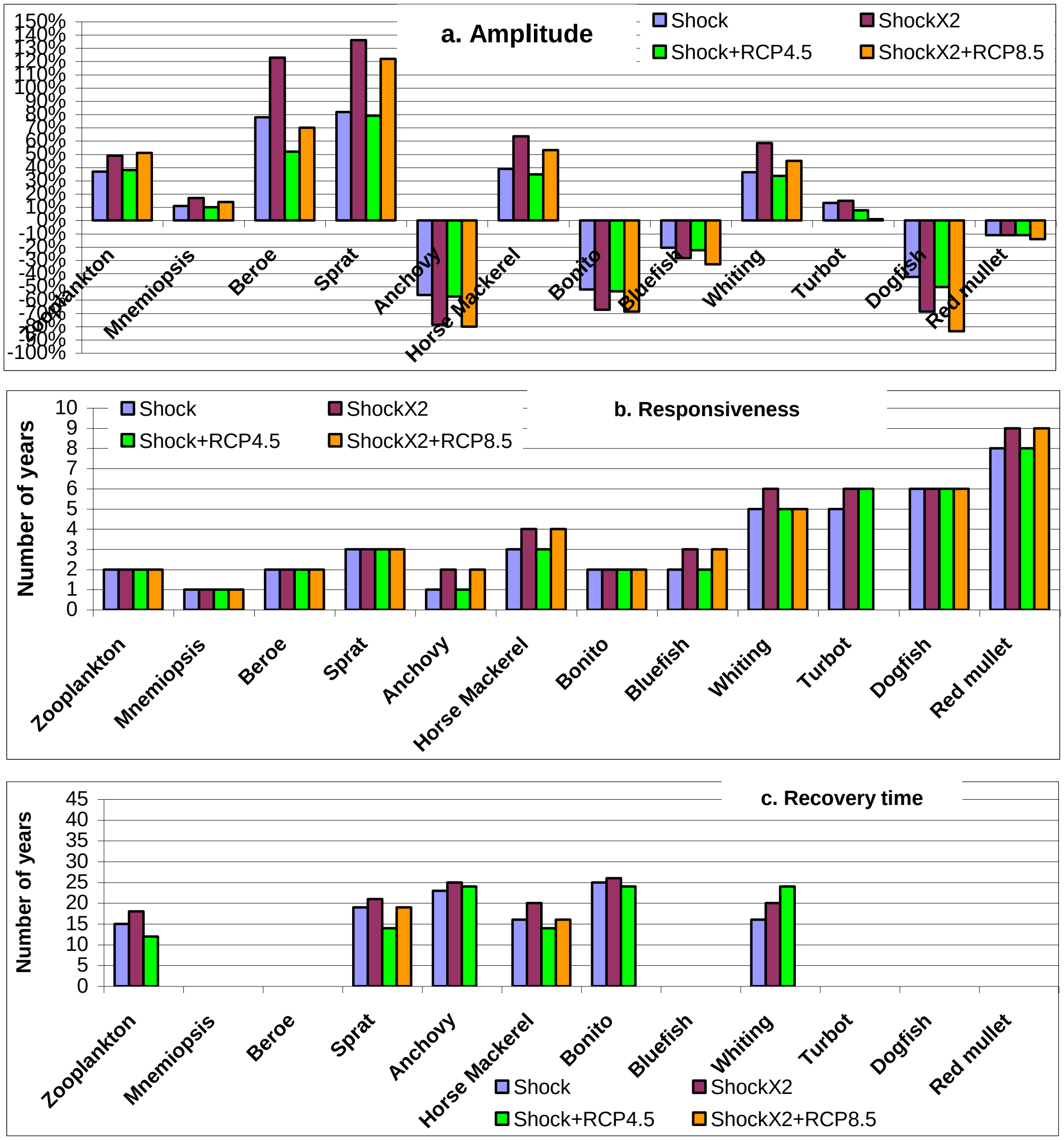

Figure 113 Ecosystem resilience indicators: a. Amplitude; b. Responsiveness; c. Recovery time, estimated from short term shock scenario of 50% reduction of anchovy biomass (legend is as in Figures 10 and 11).

Our results suggest that the two major small pelagic stocks, anchovy and sprat, may compete for zooplankton resources, inducing inverse responses to environmental forcing. That said, we should be aware that these two species have mutually evolved to explore alternative spatial and trophic niches in the Black Sea (Daskalov and Prodanov 1998), that are not fully accounted for by the present EwE model. Eventually, the sprat, a cold water species of Atlantic origin, may appear more apt to suffer from climate warming. On the other hand, sprat is known to inhabit the deeper water layers below the thermocline, so the influence of climate change should first be tracked down to the basin water dynamics influencing the deep layers.

Our results indicated that, due to the variety of trophic interactions involved, the effects of both fishing or long-term climate change might mutually cancel for some stocks in the middle of the trophic pyramid, such as whiting and horse mackerel, which appear to change little in all scenarios. On the other hand, these stocks showed relatively strong indirect responses to violent short-term disturbance of sprat and anchovy, which means their response may be proportional to the size of disturbance applied.

The model results point to the chance that some depleted stocks, such as turbot and dogfish, may recover if reducing fishing mortality to Fmsy level. The increase of anchovy potentially influenced by climate change may also benefit those stocks long-term, along with other predators such as bonito and bluefish. The results however indicate that short-term shock disturbance of their preys sprat and anchovy may induce long-term state changes, especially in dogfish, which stock is very low. This problem needs to be further investigated by exploring regime shift and recovery options for the dogfish, which is also listed as a vulnerable species in the INCN red list.

The long-term climate change scenarios seem to lead to some increase of alien ctenophores Mnemiopsis and Beroe that lead to greater competition between them and the planktivorous fish for zooplankton resources. On the contrary, the fishing at Fmsy leads to reduced biomasses of Mnemiopsis and Beroe, which may favour the increase of zooplankton biomass and small pelagic fish stocks in a long term (Daskalov et al. 2007).

Accounting for whole ecosystem effects, especially in food web models, by necessity aggregating some species into larger functional groups, could be challenging and sometimes not very accurate (Cury et al. 2005, Pinnegar et al. 2005). We used three indicators of ecosystem state (demersal to pelagic fish biomass ratio (DPBR); trophic level (TL) of the catch and Kempton’s Q) which are relatively robust to trophic aggregation and easier to interpret. Most of the responses of the ecosystem indicators are consistent with the responses of the contributing fish stocks. As expected, the reduction of fishing mortality under the MSY policy leads to an increase of DPBR and biodiversity but a decrease in the TL of the catch. The long-term climate change scenarios also seem to lead to some increase in DPBR and biodiversity (through beneficial effects on demersal fishes), but not to affect the TL of the catch.

Conclusions

Scenarios of reduced (at Fmsy level) and increased by 30% fishing mortality resulted in an expected increase and respectively reduction of most stocks’ biomasses, except for sprat that reacted in the opposite way due to resource competition with the more abundant anchovy stock. Stocks of depleted turbot and dogfish show signs of recovery in the long-term when fished at Fmsy.

The long-term climate changes of ecosystem productivity as described by previous research (Chust et al. 2014; Cannaby et al. 2015) seem to have relatively small negative effects on most of the fish stocks, except on red mullet which increased, and also influenced positively its predators such as bluefish and turbot.

The short-term shock scenarios of reducing 50% of the biomass of sprat and anchovy proved to affect most of the model's functional groups substantially, bringing immediate (to trophically close groups) or more delayed (to trophically distant) groups) response of the perturbations. The ecosystem resilience measured by recovery from the perturbation also depends on the trophic position, i.e. “closeness” to the perturbed species. Annoyingly, the depleted stock of dogfish has not recovered in one of the scenarios, seemingly entering a new even lower biomass regime. This last problem may need to be further explored given the worrisome situation with this stock and its conservational importance.

This study was necessarily limited by the lack of sufficient knowledge on the causality of the relationships between the environmental conditions and marine populations and limitations and uncertainty of both the food web model and information needed for building it. Further analyses will benefit from developing better exploratory and explicative models of environment-to-fish relationships and food web forecast models specifically tailored to explore vast areas of specific options of fishing policies and environmental change scenarios.

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Annex 18 NORTH AEGEAN SEA ECOPATH WITH ECOSIM (EWE)

Introduction

The North Aegean Sea (Strymonikos gulf and the Thracian Sea; Figure 114) is one of the most productive areas of the - generally oligotrophic - Eastern Mediterranean Sea, due to (i) its extended continental shelf, (ii) the influence of nutrient-rich, low saline Black Sea water inflows, (iii) river inputs and (iv) complex hydrodynamic formations that enhance local productivity (Tsagarakis et al., 2010). This is also reflected in its fisheries catches which make up for 30% of Greek catches, i.e. a highly disproportionate share in relation to the area that this ecosystem extends. The most important fishing activity in the area in terms of catches is Purse Seine fishing, while small pelagic fish dominate the landings, with anchovy and sardine constituting ~48% of total catches.

The aim of the current Case Study was to use ecosystem modelling (i.e. EwE methodology) to investigate ecosystem resilience under different climate simulations and fishing practices. Resilience was evaluated by exploring the response of a set of indicators after applying shock scenarios linked to small pelagic fish (anchovy and sardine) dynamics, as defined under subtask 1.1 after performing a literature review. In addition, the response of anchovy and sardine biomass was inspected to investigate resource resilience.

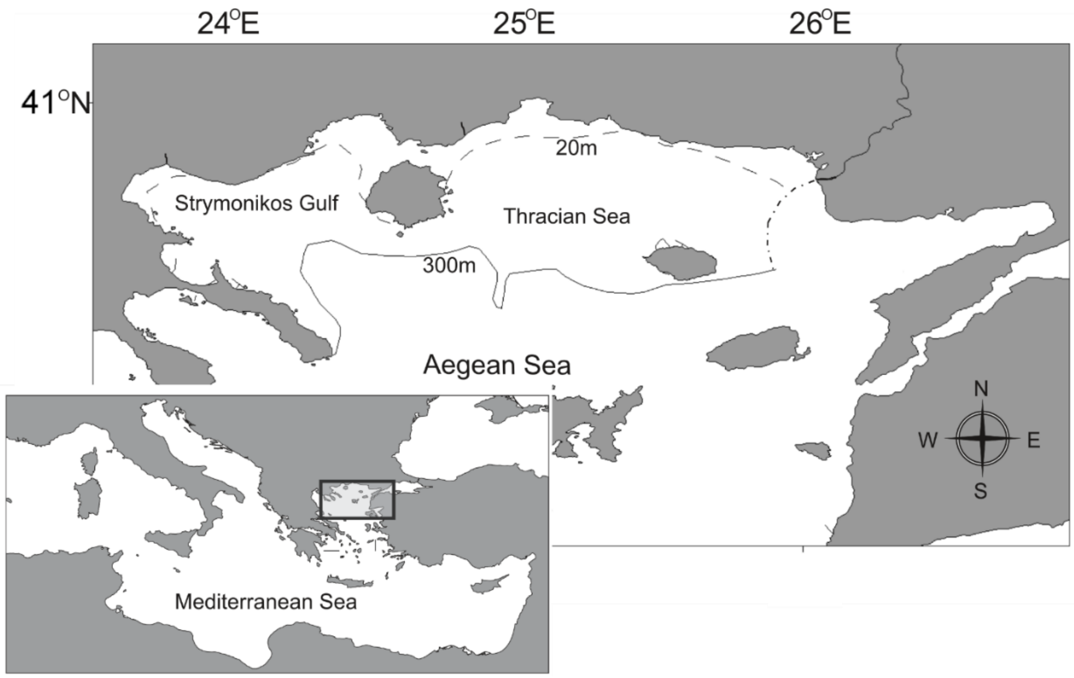

Figure 114. The North Aegean Sea (Strymonikos Gulf and Thracian Sea). The isobaths of 20 m and 300 m define the area of the modeled ecosystem.

Methodology

Ecopath with Ecosim model parameterization

An Ecopath model was built from 1991-1993 comprising 40 Functional Groups (FGs) and five fishing fleets (Purse Seines, Bottom trawls, Static nets, Longlines and Troll baits, Traps and Pots) was used as the base model. The time-dynamic Ecosim model was parameterized after fitting 15 biomass and 27 catch time series used for hindcasting during the period 1993-2020. A stepwise fitting approach was followed to parameterize the model, while the best model was selected based on minimising SS and AIC. Drivers of the finally selected model included:

1. **Fishing Effort.** Fishing capacity (total GT) was used as a proxy of the fishing effort and was included as a driver of the model. A technology creep factor of 0.79% per year was assumed for bottom trawls (Damalas et al., 2014) while for the remaining fishing gears for which no information on gear efficiency improvement was available, a factor of 2% per year was chosen after testing for alternative levels (0% and 1%).
2. **Sea Surface Temperature (SST).** The inclusion of SST within the model is described below.
3. A **PP Anomaly** function with 6 spline points was included in the model. The PP Anomaly was estimated by the model after testing for different number of spline points.
4. Optimization of the **trophic interactions ("vulnerabilitis")** among the FGs, after using the software's routine for searching vulnerabilities by predator. After testing among different number of vulnerabilities, a model with 30 estimated vulnerabilities was selected.

SST forcing

Sea Surface Temperature environmental responses were incorporated in 28 out of 38 living FGs in EwE (Figure 115). A Gaussian distribution was assumed, which has been widely used to describe thermal responses (Angilletta 2006), including in similar studies (Bentley et al. 2017; Serpetti et al. 2017). To represent the Gaussian response, temperature limits for each species were retrieved from Aquamaps (Kaschner et al. 2021); specifically, optimum temperatures were estimated by averaging the 10th and 90th percentiles of the observed species-specific temperature variation, while tolerance limits (i.e. minimum and maximum temperatures) were used to estimate the range of thermal tolerance. For the latter, the SD left and right parameters were modified in the EwE dedicated feature in order to modify the data width and better represent the Gaussian response. For multi-species FGs, the temperature parameters were estimated after weighing with the biomasses of individual species (or landings when biomass estimates were not available), for the species with at least 98% cumulative contribution of the total FGs biomass.

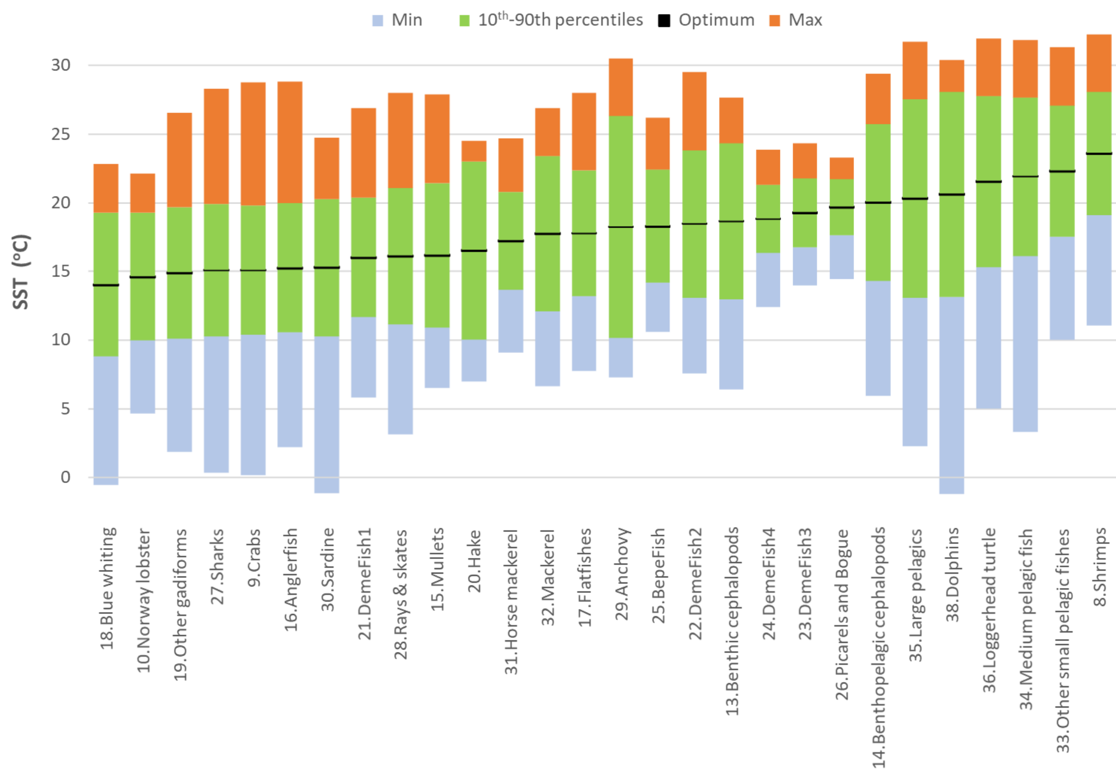

Figure 115. Optimum temperatures (black lines), lower tolerance limits (lower values of blue bars), higher tolerance limits (higher values of orange bars) and 10th – 90th preference range (green bars) that were used to parameterize thermal responses for each FG in EwE. FGs are ranked by increasing optimal temperature.

Simulations

Climate simulations

SST data from the CMIP5 scenario runs, accessed through the Royal Netherlands Meteorological Institute (KNMI) (http://climexp.knmi.nl/selectfield_cmip5.cgi?id=someone@somewhere#ocean; KNMI Climate Explorer tool) were used for the representation of the climate change scenarios. The MPI-ESM-LR model was chosen as giving a better representation of the ensemble (CERES, 2018) and as practiced in other Mediterranean studies (e.g. Chefaoui et al. 2018). Three climate scenarios were simulated, (i) one with stable SST (same as in 2020 for the whole projection period), (ii) RCP4.5 which is the most likely scenario, and (iii) RCP8.5 which is the worst-case scenario.

Fishing scenarios

Two alternative fishing scenarios were applied: (i) under current (i.e., in year 2020) fishing mortalities (Fcur) and (ii) under optimum exploitation (Fopt). Since the target of the simulations in the Mediterranean CS are anchovy and sardine, which are mainly exploited by the purse seine fishing fleet, the objective of the Fopt scenario was to modify the fishing mortality (F) of these two species. According to the most recent assessments (GFCM, 2021) both species were fished above optimum levels in 2019 (Table 38), however, the assessments were characterized by high uncertainty (GFCM, 2021). According to the GFCM Stock Assessment Group for Small Pelagics, the optimal fishing mortality levels for both species rely on the Exploitation Rate (E=F/Z) and should be below 0.4. It should be noted that the assessments are performed at the GFCM GSA 22 level, which includes the whole Aegean Sea, while the EwE model used here includes only the Northern part of the Aegean Sea, which is a hotspot for small pelagics. Therefore, the Fishing mortality levels in 2020 based on the model's outputs for the two species do not match the GFCM stock assessment results, but they both agree that sardine is less sustainably fished than anchovy. Specifically, in the EwE model, sardine was fished above E=0.4 with a Fcur/Fmsy=1.32, while anchovy was fished below E=0.4 (and Fcur/Fmsy<1). Therefore, the Fopt fishing scenario included the reduction of fishing mortality for sardine, while the one for anchovy was not modified.

Table 38 Comparative results of a4a, FLSAM and SPiCT regarding SSB, and fishing mortality for Anchovy (left) and Sardine (right) from the most recent GFCM stock assessments (GFCM, 2021)

	A4a 2019	FLSAM 2019	SPiCT 2019	A4a 2018
SSB (2019)	60530	16872	19538	76344
$F_{current}$	0.729	1.096	0.679	0.222
F_c/F_{MSY}	1.56	2.35	1.721	0.475

	A4a 2019	FLSAM 2019	SPiCT 2019	A4a 2018
SSB (2019)	19 005	14 168	16 133	37 326
$F_{current}$	2.208	2.183	0.64	0.518
F_c/F_{MSY}	4.39	4.35	1.756	1.01

Shock scenarios

As defined in subtask 1.1, two shock types were applied (Table 1), both related to bottom-up processes: (i) a Primary Productivity (PP) shock, simulated by modify PP Anomaly values for one year (i.e. 2021) and (ii) a Gelatinous Plankton shock, simulated by forcing the biomass of the respective FG included in the model, again for year 2021. In addition, a combination of the two scenarios (PP+ Jellyfish) was applied in a third scenario. The Gelatinous Plankton (which comprises the invasive ctenophore *Mnemiopsis leidyi* and other Jellyfishes) shock mainly intended to simulate a potential increase in the biomass of *M. leidyi* (Stergiou et al. 2016). *Mnemiopsis leidyi* can affect the populations of small pelagic fish either through direct predation on eggs and larvae stages or through competition; it should be noted however than within the current modelling approach, only the second mechanism can be reproduced because the model does not explicitly include the early life history stages of the two fish species as separate groups.

The shock levels, were defined after taking into account model outputs for the hindcast period. Specifically, the minimum "historical" PP Anomaly value was 0.75, i.e. deviating -0.25 from the default value of 1, and therefore the shock level was set to double this deviation (i.e. PP Anomaly value equal to 0.5) (Figure 116).

For the Gelatinous Plankton shock, a similar approach was first followed, i.e. setting the shock level to double of the maximum deviation from the initial Jellyfish biomass, resulting in 2.6 times their initial biomass; however, after preliminary results, this shock level was considered too moderate and eventually, a 10-fold increase in Gelatinous plankton biomass was applied (Figure 116).

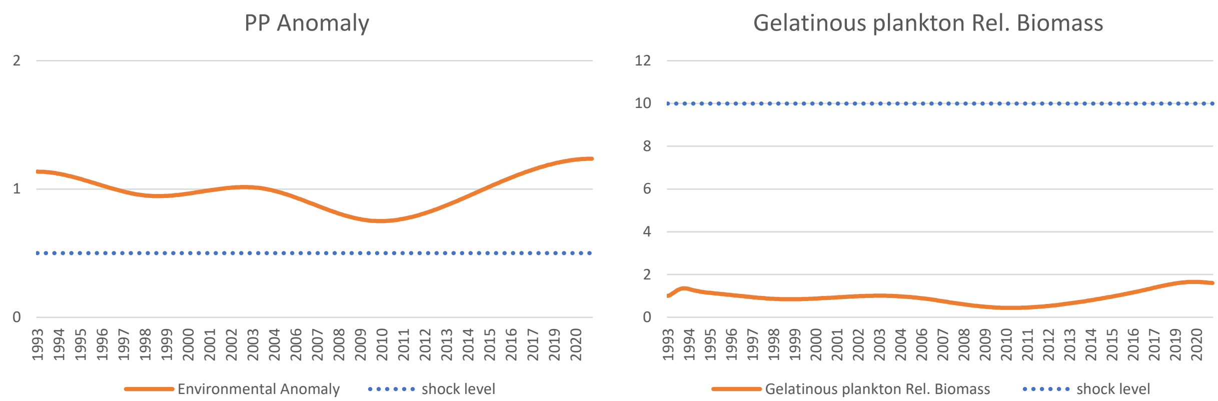

Figure 116 Values (orange lines) of (left) Primary Production (PP) Anomaly used to fit the model and (right) relative biomass of Gelatinous plankton predicted by the model during the hindcast period as opposed to shock levels (blue dotted lines) used for the scenarios.

In total, 24 scenarios were explored, i.e. 3 climate X 4 shocks (including the baseline) X 2 fishing scenarios (Figure 117; Table 39). The outputs of these scenarios are presented in the Results section in three sets (one set for each climate simulation) of eight baseline and shock scenarios (four with Fcur and four with Fopt).

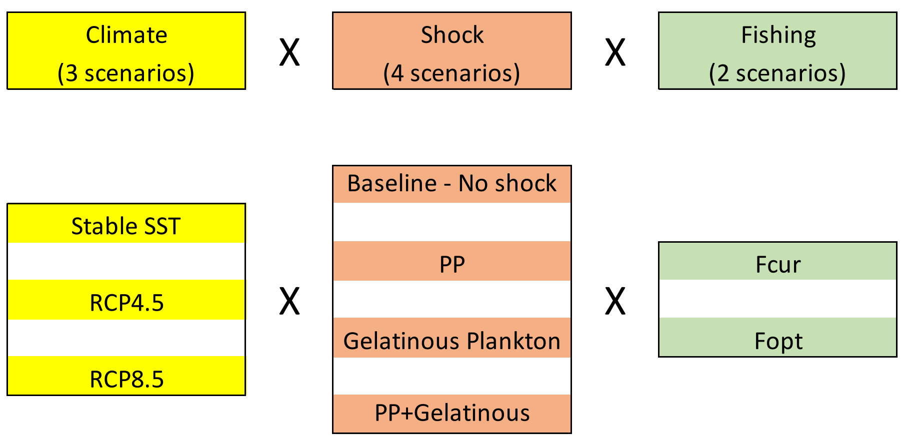

Figure 117 Schematic representation of the 24 scenarios explored

Table 39 Scenarios implemented in the Eastern Mediterranean Case Study (North Aegean Sea) using EwE.

Scenario code	Scenario description
Stable/RCP45/RCP85	1. Baseline scenario for each climate projection *SST according to climate scenario, no other environmental forcing, no changes in fishing*
Fopt	2. Fishing at optimum levels *SST according to climate scenario, no other environmental forcing, no changes in fishing; keep fishing mortality of anchovy and sardine at levels suggested by the current advice*
ShockPP	3. Shock PP

Scenario code	Scenario description
	Abrupt decrease in Primary Production at the start of the simulation period
ShockJelly	4. Shock Gelatinous plankton *Abrupt increase in the biomass of the Gelatinous plankton group at the start of the simulation period*
ShockPP+Jelly	5. Shock PP + Fishing at optimum levels *Equals scenarios 2+3*
ShockPP_Fopt	6. Shock Gelatinous plankton + Fishing at optimum levels *Equals scenarios 2+4*
ShockJelly_Fopt	7. Shocks PP and Gelatinous plankton *Equals scenarios 3+4*
ShockPP+Jelly_Fopt	8. Shocks PP and Gelatinous plankton + Fishing at optimum levels *Equals scenarios 2+3+4*

Indicators

The following ecological Indicators were estimated and their values were projected for the period 2021:

- **Biomass of anchovy** (as a metric or resource resilience).
- **Biomass of sardine** (as a metric or resource resilience).
- **Demersal/Pelagic ratio**, estimated as the biomass sum of all demersal against pelagic living FGs. Phytoplankton and Gelatinous plankton were excluded since the biomass of these two FGs was manipulated to simulate the shock scenarios (Phytoplankton: indirectly, through modifying PP Anomaly; Gelatinous plankton: directly through biomass forcing).
- **Kempton's Q diversity index**, as estimated by EwE software (Ainsworth and Pitcher 2006).
- **Shannon diversity index**, as estimated by EwE software.
- **Bray-Curtis Dissimilarity index**. The index reflects the difference between an ecosystem state and the reference state and is calculated as: $BC = sum(|B_i-B_j|)/sum(B_i+B_j)$, where B_i is the total biomass in each year for the baseline scenario and B_j the total biomass for the same year for the shock and/or fishing scenario.
- **Mean Trophic Level of the Catch** (TLc).
- **Mean Trophic Level of the community** (TLco), calculated as the biomass-weighted Trophic Level of all living components, excluding Phytoplankton and Gelatinous plankton.

The values of the indicators were evaluated against the baseline scenarios (stable SST, RCP4.5 or RCP8.5 with no other forcing) for each year to evaluate the following attributes of resilience:

- **Amplitude**: comparison between the indicator minimum level after the shock and its estimated level under the baseline scenario. Amplitude was presented as relative change (%) to compare across indicators.
- **Responsiveness**: number of years between the shock and the minimum (or maximum if the indicator increased after the shock) level reached by the indicator.

- **Recovery time**: number of years before the indicator reaches the level it would have had under the lack of a shock, i.e. under the baseline scenario. The indicators were considered to reach their baseline trajectories when the difference with the reference state was less than ±1%.

Risk, i.e. the probability of the indicator falling below a reference level, was not assessed due to the lack of reference limits for these indicators.

Results

In the long term, anchovy biomass stabilized at lower level under Fopt scenarios compared to the baseline ones (Figure 118). This was due to the fact that its fishing mortality remained unchanged while at the same time, sardine was favoured by a decrease in fishing mortality and exerted higher trophic competition on anchovy. Under Jellyfish shock in stable SST, anchovy decreased by 16% (Table 40) within two years (Table 41), while under PP and combined PP and Jellyfish shocks, anchovy decreased by 29% and 53%, respectively. Anchovy's biomass recovered 3 or 4 (Table 42) years after the shock, depending on the scenario. In the Fopt scenarios, the forecasts were very similar (slightly worse). Increasing temperature favoured anchovy in the long term as seen in the climate simulations, however in the short term, the shocks had only slightly more moderate effects than the one under stable temperature.

The biomass of sardine stabilized at a much higher level when fishing at optimum levels, while all shocks had a more moderate impact when fished sustainably (Figure 119). Under Jellyfish shock in stable SST, biomass decreased by 15% (Table 40) within two years (Table 41), while under PP and combined PP and Jellyfish shocks, it decreased by 44% and 59%, respectively. It took 6-8 years for sardine's biomass to recover, while recovery time was much shorter when fishing at optimum levels (Table 42). In the climate change scenarios, amplitude did not differ much compared to the stable SST scenarios, however the recovery time was even less when fishing at optimum levels compared to current fishing levels.

In the case of Demersal/Pelagic ratio (Figure 120), the recovery time was higher (6-10 years; Table 42) than for single species biomass, despite than the relative change (amplitude) did not exceed 37% (Table 40) in the "worst" shock (Jellyfish + PP). For most scenarios the highest value of the indicator was forecasted one year after the shock, but for the Gelatinous plankton shock one or two more years were needed (Table 41). Results were very similar among the three climate projections for all resilience attributes, while fishing at optimum levels decreased the recovery time by one year only in the Gelatinous plankton shock under stable SST (Table 42).

The effect of the shocks on the Trophic Level of the Catch (Figure 121) was much lower; no substantial change (<1%) was observed in the Gelatinous plankton shock while amplitude did not exceed 4% in any other shock (Table 40). Maximum values were obtained 1-2 years after the shock (Table 41) and within 4-5 years, the TLco had returned to the baseline trajectory (Table 42). Fishing at optimum levels did not reduce the impact of the shocks but resulted in long-term stabilization of the indicator at slightly higher levels (Figure 121).

Similar results were observed for the Trophic Level of the Community (Figure 122). The indicator declined by ~1.6% after the Gelatinous plankton shock and increased by 4.6% and ~2.1% after the PP and the PP+Jellyfish shocks respectively (Table 40). Minimum/maximum values were always seen in the first year after the shock (Table 41). The TLco recovered within 2, 4 and 5 years after the Jelly, Jelly+PP and PP shocks, respectively (Table 42). Fishing at optimum levels did not reduce the impact of the shocks but in the RCP4.5 and RCP8.5

climate scenarios it resulted in long-term stabilization of the indicator at slightly higher levels (Figure 122).

The combined Gelatinous plankton and PP shock had the most prominent effect on the Shannon diversity index (Figure 123) which led the indicator to a 25% decline in the first year for all climate projections and fishing scenarios. The Gelatinous plankton shock reduced the indicator by ~17.5% in one year and the PP shock by 5.6-6% in two years after the shock (Table 40; Table 41). The indicator fluctuated for a longer time period than the aforementioned ones; recovery time was relatively short for the Gelatinous plankton shocks (always 4 years) and higher for the remaining shocks (>7 years), reaching 10 years in several cases (Table 42). Fishing at optimum levels resulted in quicker recovery for PP shocks only under stable SST and RCP4.5. Contrary, for the Jelly+PP shock under stable SST, fishing at optimal levels resulted in longer recovery (9 years instead of 8).

Kempton's Q diversity index also fluctuated for more than a decade and was characterized by the fact that it didn't reach its minimum levels shortly after the shocks but 10-12 years after in most scenarios (Figure 124; Table 41). The values of Kempton's Q under stable SST didn't meet the baseline trajectory but stabilized at different levels than the baseline after more than a decade. Overall, the indicator did not reveal a clear pattern on the effect of climate change, however the overall fluctuations were quite different under the three climate simulations. The PP shock had the highest impact on the indicator, resulting in a 30%, 24% and 29% decline under stable SST, RCP4.5 and RCP8.5 scenario, while fishing at optimum levels had a negative effect on the values of the indicator (Table 40) as well as on recovery time (Table 42).

Finally, the Bray-Curtis Dissimilarity index reached its maximum levels always 1 year after each shock (Figure 125; Table 41) and fluctuated for several years (usually more than 12) before stabilizing. Since it never reached zero (i.e. the scenarios never met the baseline trajectories) the recovery time was not estimated. The most abrupt changes were observed for the Jelly+PP shocks (BC~0.29), followed by PP shocks (BC~0.23) and Gelatinous plankton shocks (BC~0.16). The amplitude of the BC Dissimilarity index was not substantially affected by neither the climate projections not by the fishing levels.

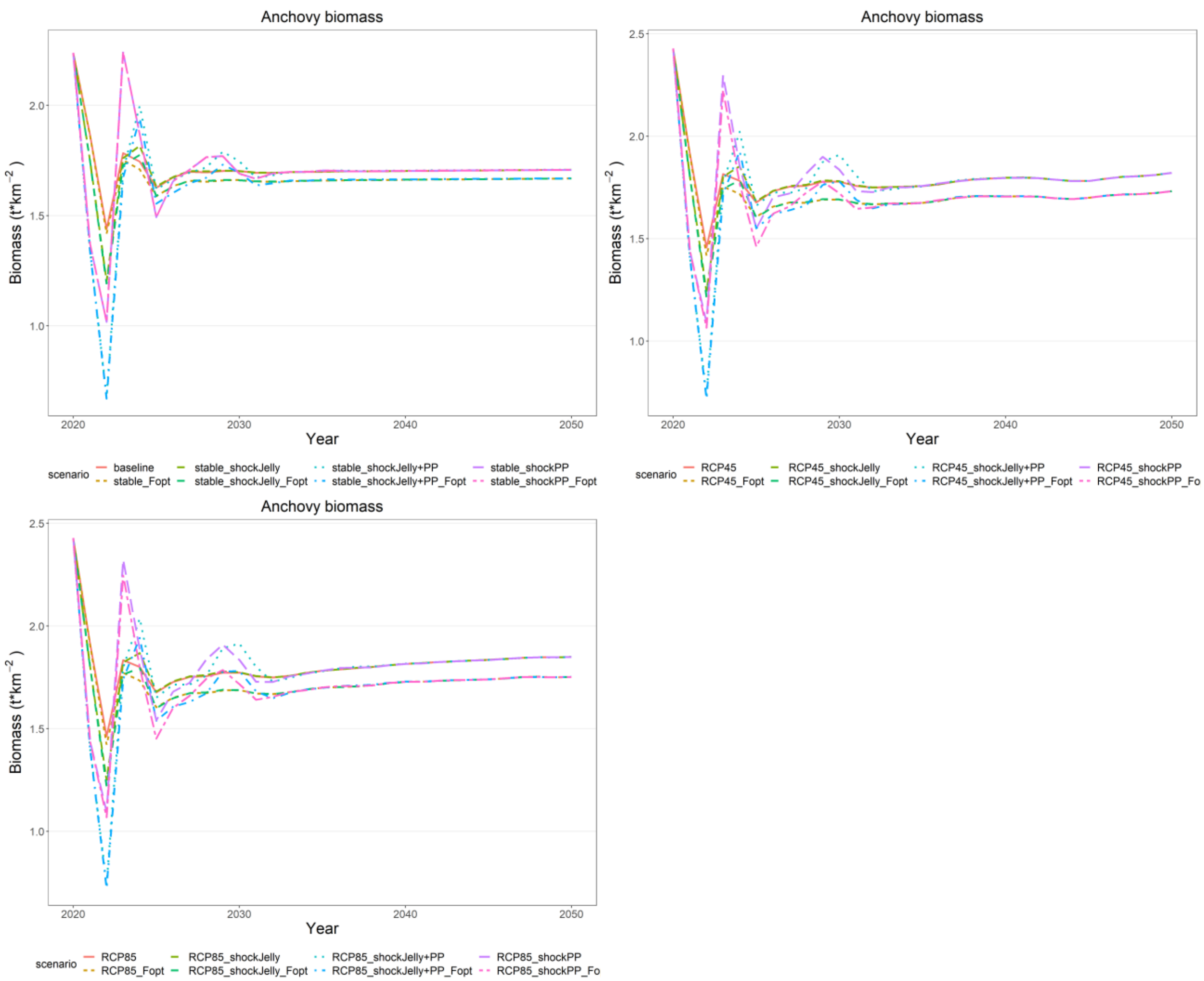

Figure 118 Anchovy biomass in different climatic (stable SST, RCP4.5, RCP8.5), shock (PP decline, Increase of Gelatinous plankton, and combination of both) and F (F current, F optimum) scenarios

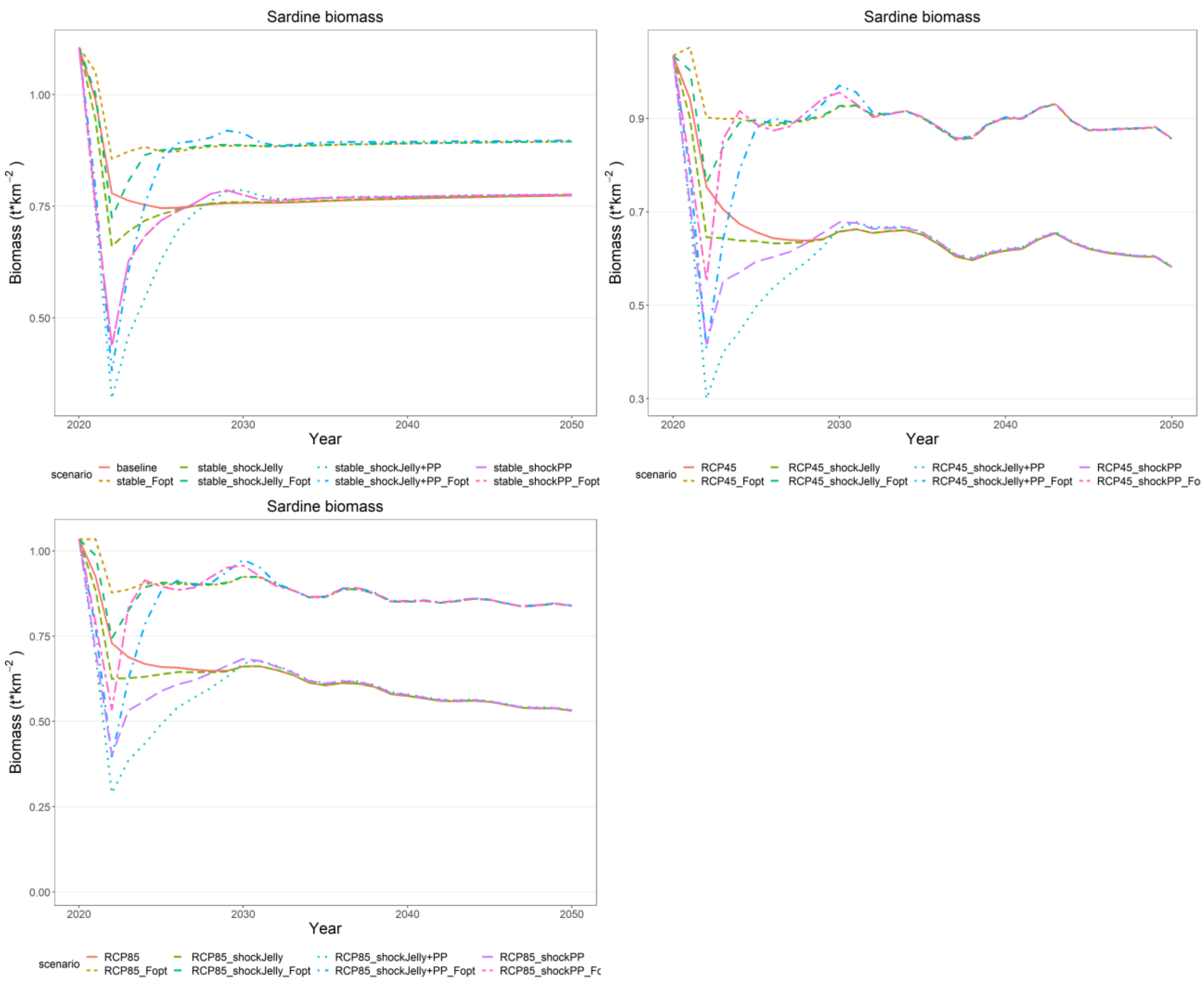

Figure 119 Sardine biomass in different climatic (stable SST, RCP4.5, RCP8.5), shock (PP decline, Increase of Gelatinous plankton, and combination of both) and F (F current, F optimum) scenarios

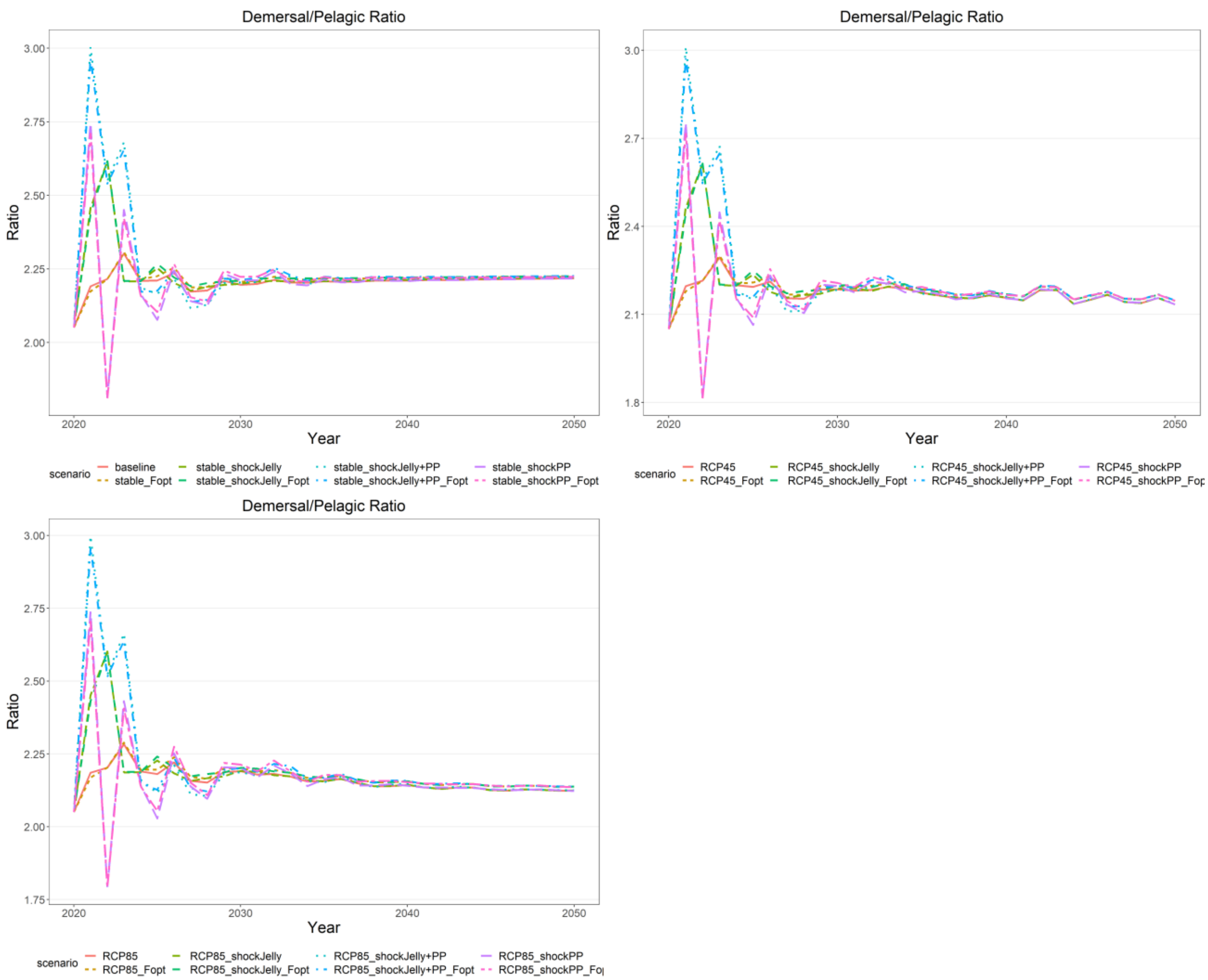

Figure 120 Demersal/Pelagic ratio in different climatic (stable SST, RCP4.5, RCP8.5), shock (PP decline, Increase of Gelatinous plankton, and combination of both) and F (F current, F optimum) scenarios

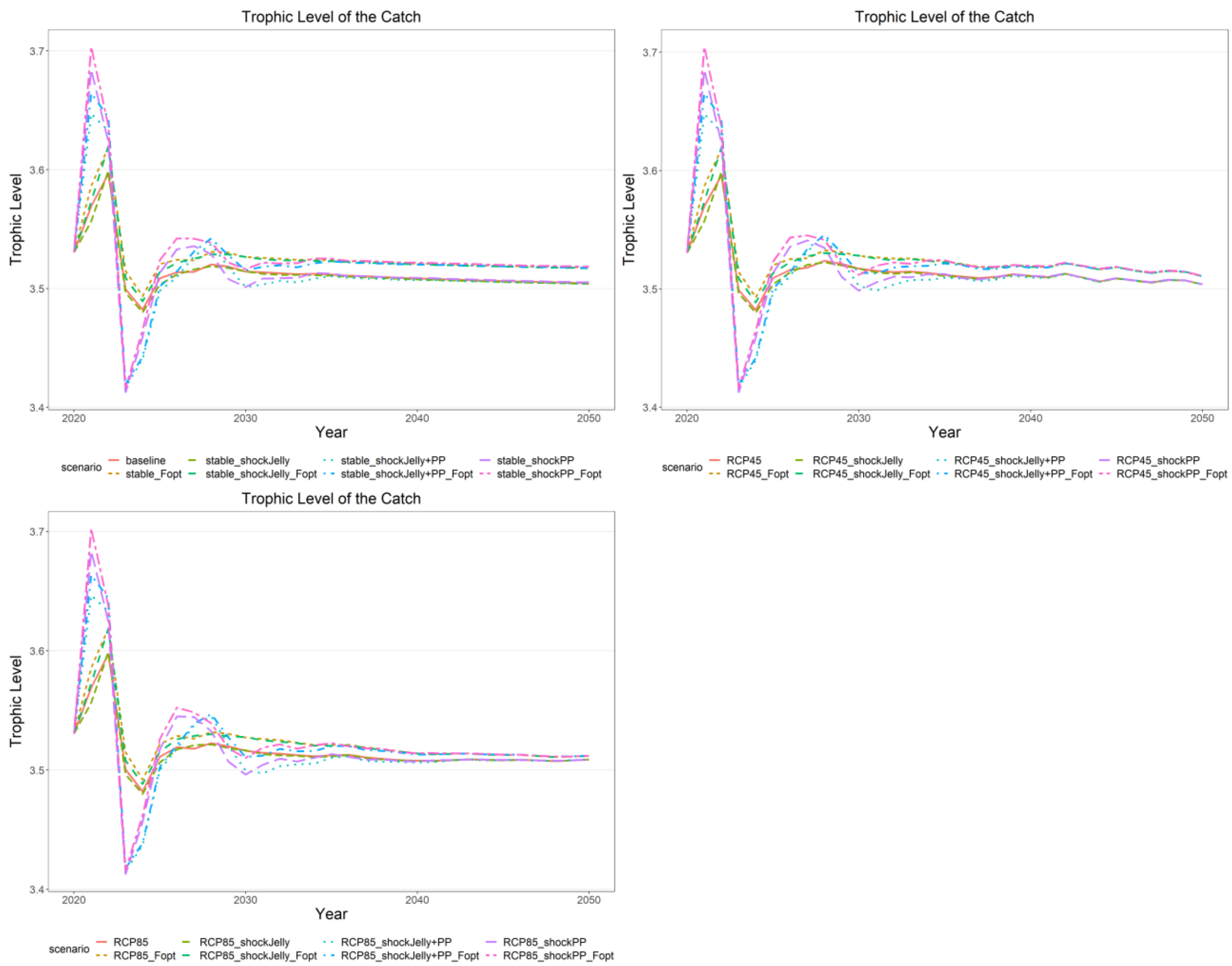

Figure 121 Trophic Level of the Catch under different climatic (stable SST, RCP4.5, RCP8.5), shock (PP decline, Increase of Gelatinous plankton, and combination of both) and F (F current, F optimum) scenarios

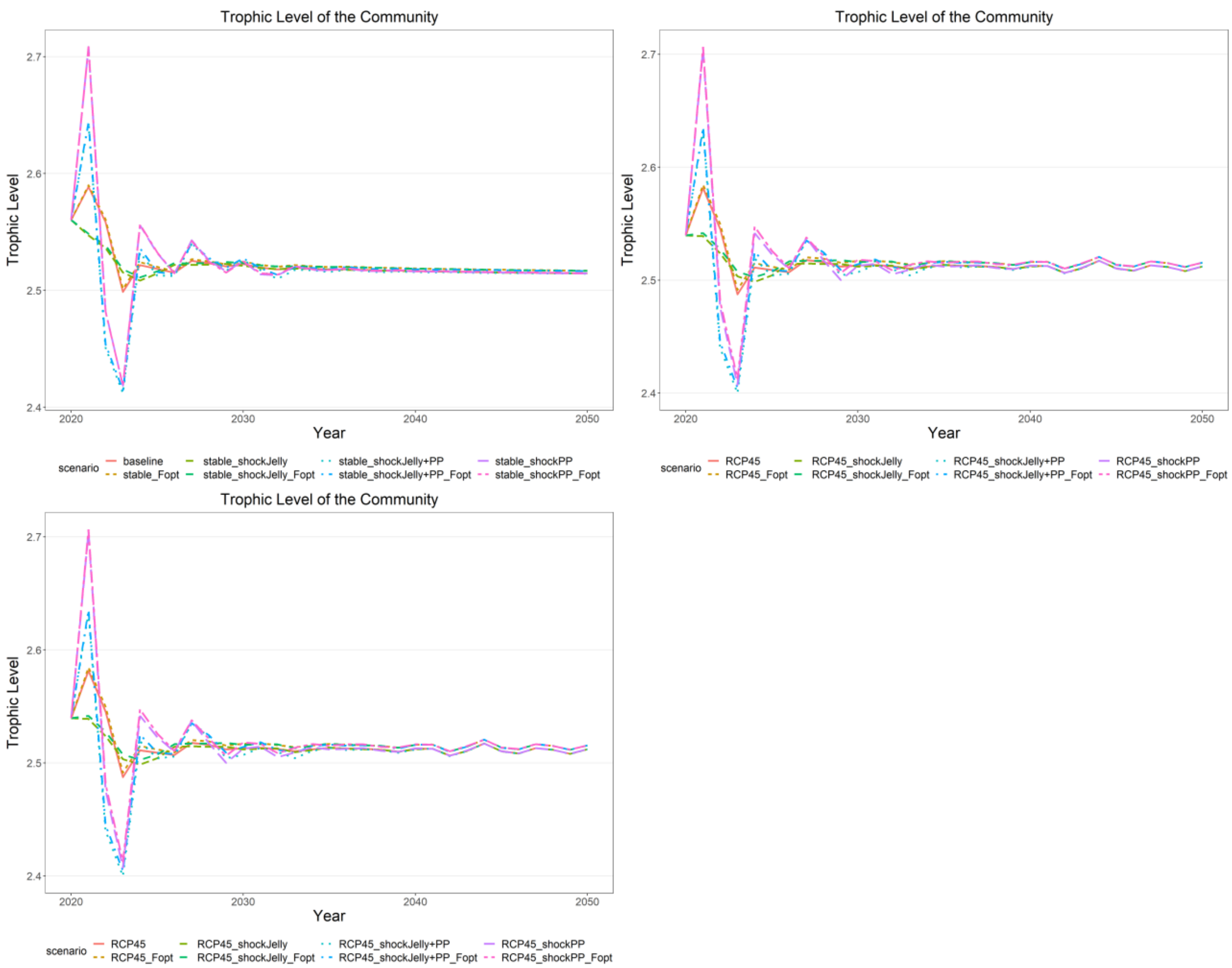

Figure 122 Trophic Level of the Community under different climatic (stable SST, RCP4.5, RCP8.5), shock (PP decline, Increase of Gelatinous plankton, and combination of both) and F (F current, F optimum) scenarios

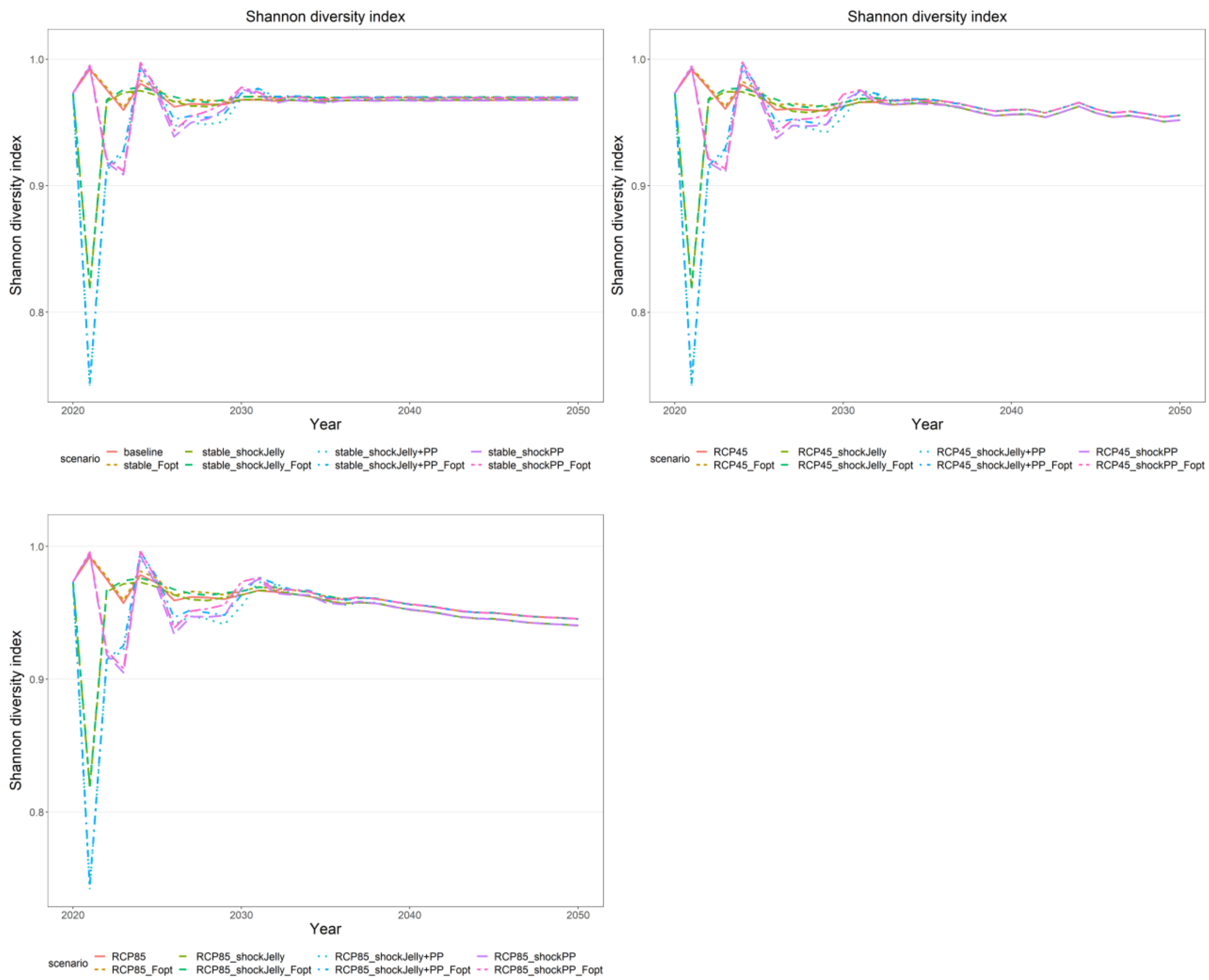

Figure 123 Shannon diversity index under different climatic (stable SST, RCP4.5, RCP8.5), shock (PP decline, Increase of Gelatinous plankton, and combination of both) and F (F current, F optimum) scenarios

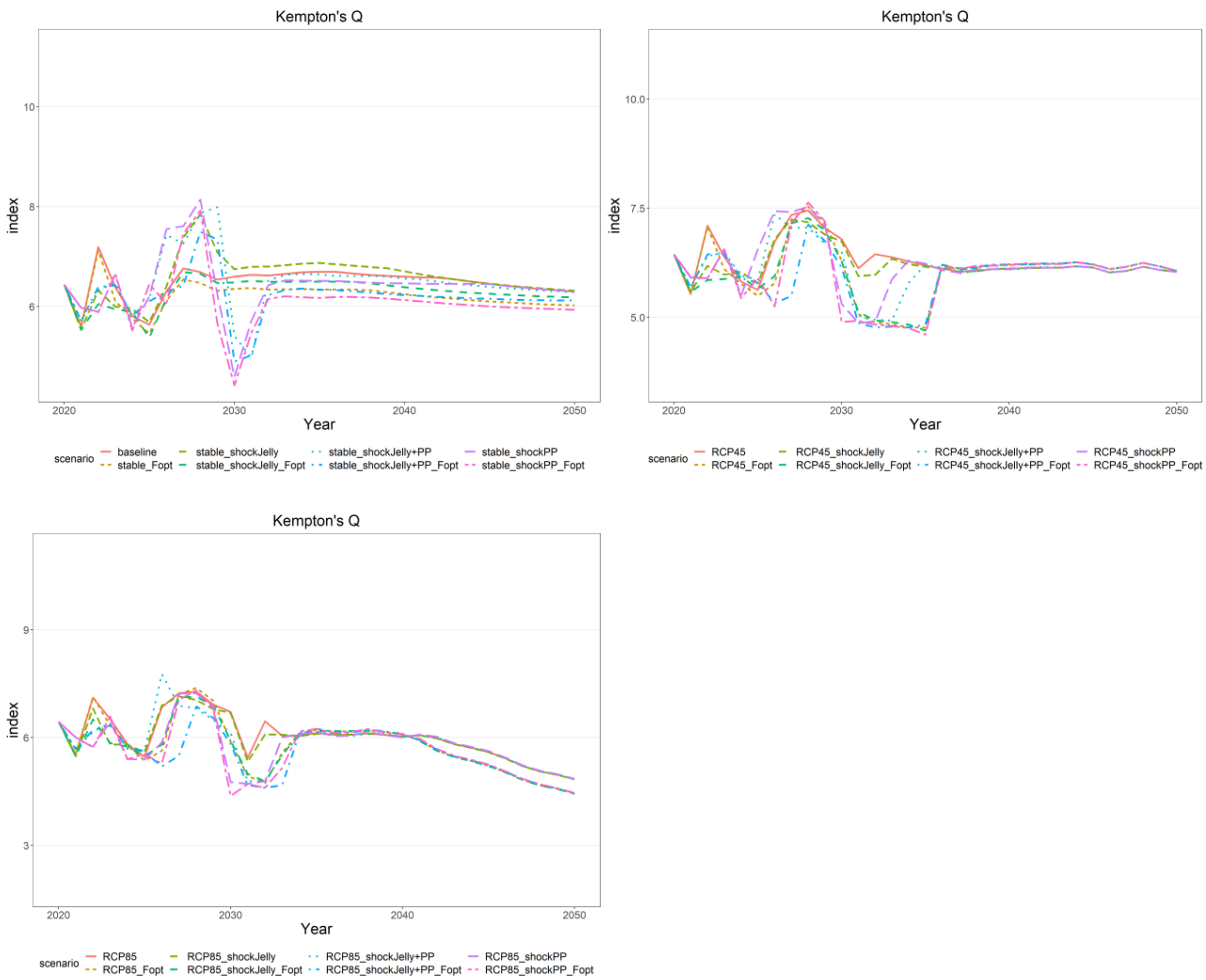

Figure 124 Kempton's Q index under different climatic (stable SST, RCP4.5, RCP8.5), shock (PP decline, Increase of Gelatinous plankton, and combination of both) and F (F current, F optimum) scenarios

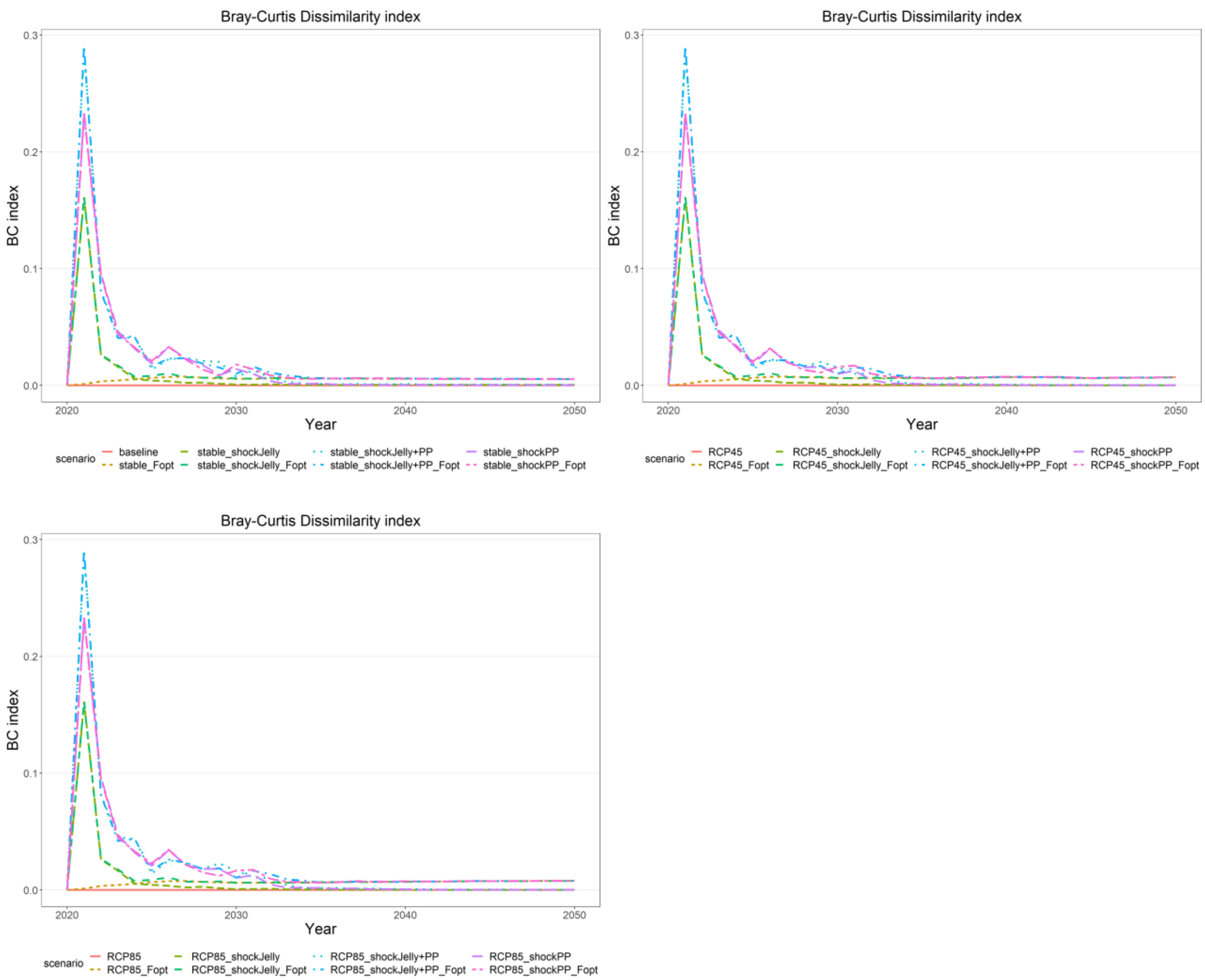

Figure 125 Bray-Curtis dissimilarity index under different climatic (stable SST, RCP4.5, RCP8.5), shock (PP decline, Increase of Gelatinous plankton, and combination of both) and F (F current, F optimum) scenarios

Conclusions

- Among the three shock scenarios considered, the most severe effects in terms of amplitude and recovery time were observed for the combined Gelatinous plankton and PP shock, followed by the PP shock alone and the Gelatinous plankton shock alone, as revealed by most indicators. In the case of the Mean Trophic Level indicators, the Gelatinous plankton and PP shocks led the indicators to opposite directions, therefore the combined shock had an intermediate effect. Kempton's Q diversity index was an exception since PP shock alone had the highest effect.
- In all climate scenarios considered, almost all ecosystem indicators returned to their baseline trajectories either in the short (within 3-4 years) or in the long term (after more than a decade), with few exceptions (e.g. Kempton's Q in the stable SST scenario), denoting a relatively resilient system which is able to recover after abrupt changes.

- The long-term effect of climate projections was indicator-specific; the demersal/pelagic ratio, the diversity indicators (Kempton's Q and Shannon) and sardine biomass were negatively impacted by SST warming, contrary to TLco and TLc, which seemed unaffected and to anchovy biomass which seemed to be favoured by climate change.
- However, in the short-term, there were no important differences in the amplitude, responsiveness and/or recovery time of the indicators after the same shocks in different climate projections; few exceptions were observed, e.g. the recovery time of the diversity indicators were generally longer in RCP4.5 and RCP 8.5 compared to stable SST.
- In many shocks, fishing at optimum levels moderated the amplitude and/or recovery time of the indicators, despite the fact that fishing changes were limited only to reducing the fishing mortality of sardine.
- Resource resilience was also high for anchovy, which was able to fully recover within 3 or 4 years, while recovery for sardine was slower, possibly because it is fished at levels higher than Fmsy at the time period that the shocks were applied.
- Fishing at optimum levels had a very positive effect on sardine, substantially reducing or even eliminating the amplitude of the shocks as well as shortening the recovery time. At the same time, this had no adverse effect on anchovy, a sardine's competitor for which no change in fishing mortality was applied.
- Since different responses are observed among indicators, the combined use of several indicators provides a more holistic view of the effects of possible shocks on the ecosystem and fisheries resources.

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Table 40 Amplitude (%change compared to the baseline climate scenario) for each indicator, after applying different perturbations (shocks) under current (2020) and optimal Fishing mortality (Fopt) for anchovy and sardine. Bray-Curtis Dissimilarity index is given as absolute value instead of percentage due to the nature of its estimation.

Scenario	Anchovy biomass	Sardine biomass	Demersal/Pelagic ratio	Trophic Level of the catch	Trophic Level of the community	Shannon diversity index	Kempton's Q diversity index	Bray-Curtis Dissimilarity index
stable_shockJelly	-16.43%	-15.17%	18.07%	0.08%	-1.60%	-17.51%	-12.11%	0.1613
stable_shockJelly_Fopt	-17.38%	-6.98%	18.08%	0.65%	-1.55%	-17.39%	-15.85%	0.1616
stable_shockJelly+PP	-52.82%	-59.03%	37.07%	2.18%	2.09%	-25.20%	-25.09%	0.2907
stable_shockJelly+PP_Fopt	-53.46%	-51.12%	35.31%	2.67%	2.15%	-25.04%	-25.76%	0.2900
stable_shockPP	-29.25%	-44.02%	25.28%	3.22%	4.63%	-5.92%	-30.43%	0.2336
stable_shockPP_Fopt	-29.25%	-44.02%	23.77%	3.76%	4.62%	-5.62%	-33.03%	0.2327
RCP45_shockJelly	-14.77%	-14.30%	18.02%	0.08%	-1.66%	-17.49%	-12.99%	0.1613
RCP45_shockJelly_Fopt	-16.67%	0.00%	18.03%	0.66%	-1.56%	-17.38%	-24.09%	0.1616
RCP45_shockJelly+PP	-49.54%	-60.19%	37.04%	2.19%	1.98%	-25.18%	-23.24%	0.2905
RCP45_shockJelly+PP_Fopt	-50.67%	-46.05%	35.28%	2.68%	2.08%	-25.03%	-26.04%	0.2898
RCP45_shockPP	-25.06%	-44.72%	25.26%	3.23%	4.74%	-5.98%	-23.86%	0.2333
RCP45_shockPP_Fopt	-26.87%	-26.81%	23.73%	3.77%	4.84%	-5.69%	-27.91%	0.2324
RCP85_shockJelly	-14.69%	-14.34%	18.12%	0.09%	-1.65%	-17.52%	-10.99%	0.1613
RCP85_shockJelly_Fopt	-16.58%	0.00%	18.12%	0.60%	-1.55%	-17.41%	-25.91%	0.1616
RCP85_shockJelly+PP	-49.42%	-60.25%	37.12%	2.17%	1.99%	-25.22%	-26.04%	0.2909
RCP85_shockJelly+PP_Fopt	-50.57%	-45.76%	35.36%	2.65%	2.08%	-25.06%	-28.68%	0.2901
RCP85_shockPP	-25.10%	-44.95%	25.30%	3.21%	4.73%	-5.84%	-29.08%	0.2339
RCP85_shockPP_Fopt	-26.91%	-26.74%	23.80%	3.74%	4.82%	-5.54%	-34.88%	0.2330

Table 41 Responsiveness (number of years between the shock and the minimum / maximum level reached by the indicator) for each indicator, after applying different perturbations (shocks) under current (2020) and optimal Fishing mortality (Fopt) for anchovy and sardine.

Scenario	Anchovy biomass	Sardine biomass	Demersal/Pelagic ratio	Trophic Level of the catch	Trophic Level of the community	Shannon diversity index	Kempton's Q diversity index	Bray-Curtis Dissimilarity index
stable_shockJelly	2	2	3	2	1	1	2	1
stable_shockJelly_Fopt	2	2	3	2	1	1	2	1
stable_shockJelly+PP	2	2	1	1	1	1	11	1
stable_shockJelly+PP_Fopt	2	2	1	1	1	1	10	1
stable_shockPP	2	2	1	1	1	2	10	1
stable_shockPP_Fopt	2	2	1	1	1	2	10	1
RCP45_shockJelly	2	2	2	2	1	1	2	1
RCP45_shockJelly_Fopt	2	0	2	2	1	1	15	1
RCP45_shockJelly+PP	2	2	1	1	1	1	12	1
RCP45_shockJelly+PP_Fopt	2	2	1	1	1	1	12	1
RCP45_shockPP	2	2	1	1	1	2	12	1
RCP45_shockPP_Fopt	2	2	1	1	1	2	10	1
RCP85_shockJelly	2	2	2	7	1	1	3	1
RCP85_shockJelly_Fopt	2	0	2	2	1	1	12	1
RCP85_shockJelly+PP	2	2	1	1	1	1	12	1
RCP85_shockJelly+PP_Fopt	2	2	1	1	1	1	12	1
RCP85_shockPP	2	2	1	1	1	2	10	1
RCP85_shockPP_Fopt	2	2	1	1	1	2	10	1

Table 42 Recovery time (years) for each indicator, after applying different perturbations (shocks) under current (2020) and optimal Fishing mortality (Fopt) for anchovy and sardine.

Scenario	Anchovy biomass	Sardine biomass	Demersal/Pelagic ratio	Trophic Level of the catch	Trophic Level of the community	Shannon diversity index	Kempton's Q diversity index
stable_shockJelly	4	6	7	-*	2	4	10
stable_shockJelly_Fopt	4	2	6	-*	2	4	6
stable_shockJelly+PP	4	8	9	5	4	8	13
stable_shockJelly+PP_Fopt	4	4	9	5	4	9	13
stable_shockPP	3	7	10	4	5	9	14
stable_shockPP_Fopt	3	7	10	4	5	8	14
RCP45_shockJelly	3	7	7	-*	2	4	13
RCP45_shockJelly_Fopt	4	1	6	-*	2	4	16
RCP45_shockJelly+PP	4	10	9	5	4	10	15
RCP45_shockJelly+PP_Fopt	4	4	9	5	4	10	16
RCP45_shockPP	3	8	9	4	5	10	14
RCP45_shockPP_Fopt	3	3	9	4	5	7	16
RCP85_shockJelly	3	8	7	-*	2	4	4
RCP85_shockJelly_Fopt	4	1	6	-*	2	4	14
RCP85_shockJelly+PP	4	10	9	5	4	10	14
RCP85_shockJelly+PP_Fopt	4	4	9	5	4	10	14
RCP85_shockPP	3	9	9	4	5	10	13
RCP85_shockPP_Fopt	3	3	9	4	5	10	14

* values do not deviate more than ±1% than the baseline scenari

Annex 19 NORTH SEA FLATFISH PROJECTIONS

INTRODUCTION

The current study analyses simulation results obtained with the model SIMFISH applied on the Dutch Flatfish fishery in the North Sea. The simulations aim to give a better understanding of the response of the fishery in a changing environment, including recruitment shocks, longer-term recruitment changes due to change in water temperature, different management targets and different paths to more fuel-efficient fishery.

For this analysis, we consider 30 different scenarios taking the aspects mentioned above separately and in combination. We then run the deterministic simulations for ten years (2020-2030). The three Dutch beam trawl fleets included target flatfish, shrimp or a mix of both. While we only simulated biological changes to the flatfish, the response of the fishery can impact the shrimp stock exploited by the same fleets.

We measure the simulated response of the fleets and the stocks using some resource and economic resilience indicators. In addition, we also estimate the fuel consumption needed to catch the fish in the different situations and compare them to understand the relationship between stock size and fuel use.

METHODS

SIMFISH description

For the application of the North sea flatfish fishery, the bio-economic spatially explicit SIMFISH model was used (Bartelings, Hamon et al. 2015). The model has already been used for climate change simulations (Groeneveld, Bartelings et al. 2018, Hamon, Kreiss et al. 2021) and includes commercial species distributional changes due to climate change.

For this specific project, a few features have been added to the model:

- Recruitment shocks: possibility to implement a recruitment failure at a level specified relative to the expected recruitment for specific years
- Temperature-dependent recruitment: implementing the Beverton and Holt model adding an environmental covariate to be used for plaice. The final form of the model is as follow:

$$\boldsymbol{R_{y+1}} = \mathbf{1}/(\boldsymbol{\alpha} + \boldsymbol{\beta}/\mathbf{SSB}_{\boldsymbol{y}} + \boldsymbol{\gamma}\,\mathbf{env}_{\boldsymbol{y}})$$

Where *R* is the recruitment in thousand individuals, *SSB* is the Spawning stock biomass in tonnes and *env* the average sea surface temperature of the Southern North sea in °C. The parameters α, β and γ were estimated by Taylor et al. (see FLBEIA North Sea application).

- Phasing out of a specific gear: to account for the specificity of the North Sea flatfish circumstances at the beginning of the simulation period (the pulse trawl was phased out between 2020 and 2021), we needed to allow the ban of a particular gear impacting the fleets reallocating their activity to other gears.

Initial situation and model parameterisation

The model has been updated with 2018-2020 data for the initialisation.

<u>Updated econ data</u>

Economic data have been updated using Dutch data collected by Wageningen Economic Research. The data collected at the trip level for a panel representing about 25% of the cutter fleet allow us to estimate the costs per vessel at the gear level. Landings and effort data were taken from logbook data.

Updated biological data

Four species are included in this application of SIMFISH, three flatfish (sole, plaice and turbot) and brown shrimp. Those four species cover at least 90% of the value of landings of the three fleets.

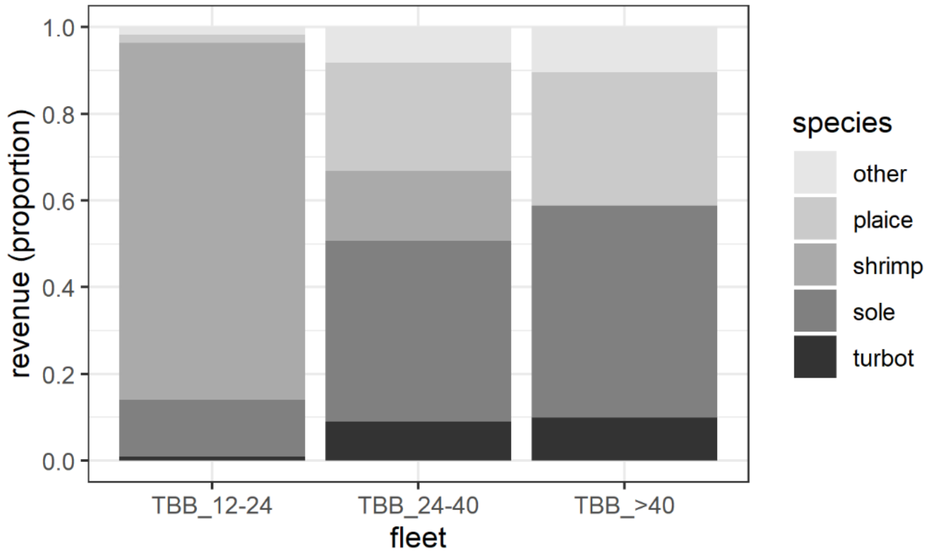

Figure 126 Application of SIMFISH

In the model, sole and plaice are included structured in age, shrimp with a polynomial population function and turbot is only included as bycatch with a fixed catch rate without underlying biological dynamics. Biological data was for the most part, taken from ICES stock assessment data:

- For sole and plaice: data at age was updated using 2021 ICES stock assessment data
- For shrimp, the total production is estimated using the latest (2020) ICES data, for 2020, the same biomass as in 2020 due to lacking data

The age composition of the catch (landings and discards) per gear was taken from FDI data prepared by Wageningen Marine Research (FDI, not published). The spatial distribution of sole, plaice and shrimp are taken from previous studies (Hamon et al. 2021). The stock-recruitment relationship used for sole is the one of the stock assessment (segmented regression), for plaice we use the temperature-dependent one described earlier

SCENARIOS

Baseline description

In the last two years, the fishery has undergone large changes due to amongst other the application of the ban on pulse trawling. The fishing technique had been used since the end of the 2000's by the Dutch fishery due to its fuel efficiency and its efficiency at catching sole.

Since the decision by the European Union to ban the technique, Dutch fisheries have been phasing it out between 2019 and 2021 (with the last vessels stopping with this gear in June 2021). To allow for realistic projections, we first introduced this "pulse ban" in the model alone to create a baseline to which other scenarios can be compared.

To assess the effect of the ban on pulse trawling, it is compared to a business as usual scenario in which the fishery is allowed to continue operating with the gear. In the business as usual scenario:

- Pulse trawling is allowed
- The recruitment of sole is projected using a segmented regression (as in the 2021 stock assessment) and plaice is projected using the Beverton and Holt stock-recruitment model with fixed 2020 temperature as a covariate.
- The biological distribution of sole and plaice is set as the one projected to be the 2020 distribution from EU project CERES, and shrimp distribution remains unchanged.
- The TAC for sole and plaice (the two species with a full feedback loop) is set at the level of landings using Fmsy. Shrimp catch is not limited and the TAC of turbot is held constant at the 2020 level.
- The landing obligation is implemented with an exemption for plaice, limiting its impact.
- The gear specific fuel consumption per sea day remains as in the input data.

Climate scenarios

Climate change is introduced in two ways in the scenarios, as recruitment shocks and as long term changes. Both for the stocks and long term changes, two options are included: a mild and likely option and a severe or worst-case scenario (Table 43).

Table 43 short and long term climate effects on sole and plaice recruitment and distribution

		Current	**Shocks (short term)**		**Long term changes**	
			mild	severe	mild	severe
Sole	Recruitment	Segmented regression as in the stock assessment	Low recruitment (ca. 27% of the predicted recruitment) for the first year of the forecast	Low recruitment (ca. 27% of the predicted recruitment) for the first year and second year of the forecast		
	Distribution	Distribution of 2020 as projected in CERES for RCP8.5			CERES distribution change RCP4.5	CERES distribution change RCP8.5
Plaice	Recruitment	Based on Beverton and Holt SR model with fixed 2020	Low recruitment (ca. 55% of the predicted recruitment) for the first	Low recruitment (ca. 55% of the predicted recruitment) for the first year and	Based on Beverton and Holt SR model with RCP 4.5	Based on Beverton and Holt SR model with RCP 8.5

		temperature as covariate	year of the forecast	second year of the forecast	temperature as covariate	temperature as covariate
	Distribution	Distribution of 2020 as projected in CERES for RCP8.5			CERES distribution change RCP4.5	CERES distribution change RCP8.5

Six climate change scenarios were added to the two baseline scenarios. The scenarios and their characteristics are described in Table 44. The long term climate impacts are also used in combination of management and fuel consumption scenarios.

Table 44 Description of the SIMFISH scenarios. baseline scenario to which others are compared to is in bold. empty cells are the same value as in the baseline (temp. dep. Rec.: temperature-dependent recruitment; PLE: plaice)

	Pulse gear	**TAC**	**Recruitment shocks**	**Stock-recruitment relationships**	**Biological distribution SOL and PLE**	**Fuel consumption decrease % per year**
0-BAU	authorised	Set at Fmsy	None	Current	2020 CERES	
1-Pulse ban	**banned**	**Set at FMsy**	**None**	**Current**	**2020 CERES**	**0**
2-Mild short-term (ST)			1 year shock SOL and PLE			
3-Mild long-term (LT)				temp. dep. Rec. for PLE (RCP4.5)	RCP4.5	
4-Mild (ST and LT)			1 year shock SOL and PLE	temp. dep. Rec. for PLE (RCP4.5)	RCP4.5	
5-Severe short-term (ST)			2 years shock SOL and PLE			
6-Severe long-term (LT)				temp. dep. Rec. for PLE (RCP8.5)	RCP4.5	
7-Severe (ST and LT)			2 years shock SOL and PLE	temp. dep. Rec. for PLE (RCP8.5)	RCP4.5	
Fuel efficiency 1						1.4%
Mild LT Fuel efficiency 1				temp. dep. Rec. for PLE (RCP4.5)	RCP4.5	1.4%
Severe LT Fuel				temp. dep. Rec. for PLE (RCP8.5)	RCP4.5	1.4%

efficiency 1						
Fuel efficiency 2						4%
Mild LT Fuel efficiency 2				temp. dep. Rec. for PLE (RCP4.5)	RCP4.5	4%
Severe LT Fuel efficiency 2				temp. dep. Rec. for PLE (RCP8.5)	RCP4.5	4%
FMSY high		Set at Fmsy high				
Mild long-term (LT)		Set at Fmsy high		temp. dep. Rec. for PLE (RCP4.5)	RCP4.5	
Severe long-term (LT)		Set at Fmsy high		temp. dep. Rec. for PLE (RCP8.5)	RCP4.5	
Fuel efficiency 1		Set at Fmsy high				1.4%
Mild LT Fuel efficiency 1		Set at Fmsy high		temp. dep. Rec. for PLE (RCP4.5)	RCP4.5	1.4%
Severe LT Fuel efficiency 1		Set at Fmsy high		temp. dep. Rec. for PLE (RCP8.5)	RCP4.5	1.4%
Fuel efficiency 2		Set at Fmsy high				4%
Mild LT Fuel efficiency 2		Set at Fmsy high		temp. dep. Rec. for PLE (RCP4.5)	RCP4.5	4%
Severe LT Fuel efficiency 2		Set at Fmsy high		temp. dep. Rec. for PLE (RCP8.5)	RCP4.5	4%
FMSY low		Set at Fmsy low				
Mild long-term (LT)		Set at Fmsy low		temp. dep. Rec. for PLE (RCP4.5)	RCP4.5	

Severe long-term (LT)		Set at Fmsy low		temp. dep. Rec. for PLE (RCP8.5)	RCP4.5	
Fuel efficiency 1		Set at Fmsy low				1.4%
Mild LT Fuel efficiency 1		Set at Fmsy low		temp. dep. Rec. for PLE (RCP4.5)	RCP4.5	1.4%
Severe LT Fuel efficiency 1		Set at Fmsy low		temp. dep. Rec. for PLE (RCP8.5)	RCP4.5	1.4%
Fuel efficiency 2		Set at Fmsy low				4%
Mild LT Fuel efficiency 2		Set at Fmsy low		temp. dep. Rec. for PLE (RCP4.5)	RCP4.5	4%
Severe LT Fuel efficiency 2		Set at Fmsy low		temp. dep. Rec. for PLE (RCP8.5)	RCP4.5	4%

Environmental drivers to recruitment

We used two temperature time-series used as input for the different scenarios (Table 45):

- One RCP4.5 mean of the three RCP4.5 forecast runs used in FLBEIA
- One RCP8.5 mean of the three RCP8.5 forecast runs used in FLBEIA

The forecast runs used in FLBEIA come from the projection of the future ocean state (2020-2100) under climate change (RCP4.5 and RCP8.5 scenarios) obtained from the dynamical downscaling of the global model MPI-ESM (Max Planck Institute Earth System Model) (Ilyina et al., 2013; Jungclaus et al., 2013) performed with a high-resolution version of the regionally coupled ocean-atmosphere climate system model MPIOM/REMO (Mikolajewicz et al., 2005; Sein et al., 2015). The difference between the scenarios is not very clear and probably not significant for the coming ten years.

We used the 2020 temperature in scenario RCP4.5 for the all projection period for the current situation.

Table 45 Temperature forecast used for the projections of plaice recruitment in °C

	2020	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
current	6.54	6.54	6.54	6.54	6.54	6.54	6.54	6.54	6.54	6.54	6.54
RCP 4.5	6.54	6.20	6.33	7.71	6.87	6.98	6.72	6.60	6.65	6.85	7.17
RCP 8.5	7.21	6.59	6.63	6.61	6.78	6.84	6.87	6.93	7.25	6.94	7.27

Management scenarios – TAC setting

Both sole and plaice are being managed with TAC in the North Sea. Both stocks are currently under a multi-annual management plan in which Fmsy is used to calculate the TAC. For both stocks, a range is available with Fmsy low and Fmsy high.

	Fmsy low	Fmsy	Fmsy high
Sole	0.123	0.207	0.311
Plaice	0.146	0.21	0.3

Fuel consumption scenario

We use two scenarios projecting the evolution of fuel consumption. Both have been used and described in Hamon et al. (2021).

- Scenario 1.4% decrease in fuel consumption per year corresponds to the fleet meeting half of the Paris ambitions of the EU regarding CO2 emissions and is, therefore, the pessimistic scenario.
- Scenario 4% decrease on fuel consumption per year corresponds to the fleet meeting the Paris ambitions of the EU regarding CO2 emissions and is the most ambitious scenario.

Note that here we purely assume that fuel consumption is reduced by improving engine or hulls, not by adapting fishing techniques that would also impact the catch of the fleet.

INDICATORS

Resistance and resilience indicators (detailed in Table 46, Table 47)

Table 46. List of indicators to describe resource resilience

Indicators of resource resilience		
Resistance (ability to withstand the perturbation)		
Amplitude	Minimum stock level reached after the shock compared to initial level	$SSB_{min}/SSByear_{shock}$
Responsiveness	Number of years between the shock and the minimum observed stock level	$Year_{SSbmin} - Year_{shock}$
Biological risk	Probability of SSB falling below Btrigger	$Max(P(SSB<B_{trigger}))$
Resilience *stricto sensu* (ability to recover from the perturbation)		
Recovery rate	Probability that stock level is at MSY Btrigger or above in 2030	$p(SSB_{2030}>=Btrigger)$
Recovery speed	Number of year to reach stock levels corresponding to MSY	$Year_{SSB>=}\ B_{trigger} - Year_{shock}$

Table 47. List of resilience indicators to describe fisheries economic resilience based on the set of economic indicators tracked in the STECF 20-11 Balance capacity report[10].

Indicators of economic resilience

[10] Scientific, Technical and Economic Committee for Fisheries (STECF) –Assessment of balance indicators for key fleet segments and review of national reports on Member States efforts to achieve balance between fleet capacity and fishing opportunities (STECF-20-11). EUR 28359 EN,Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-27163-5, doi:10.2760/414107, JRC123057.

Break-even revenue ratio (BER)	Does the revenue cover the operating costs and salaries?	P(BER>=BER_baseline)
Gross Value Added (GVA)	What is the contribution of the fishing activity to the national economy?	P(GVA>=GVA_baseline)
Net Value Added per Full-Time Equivalent (NVA/FTE)	What is the labour productivity?	P(NVA/FTE>=NVA/FTE_baseline)
Net profit margin	What the resource productivity measured as the economic performance of the fleet is?	P(NetProfitM>= NetProfitM _baseline)
Return on fixed tangible assets (RoFTA)	What is the capital productivity? Is the long-term profitability of the fishing fleet segment larger than other available investment?	P(RoFTA>=RoFTA_baseline)
Number of active vessels	What the number of vessels active in the segment is?	P(NoV>= NoV_baseline)
Vessel Utilisation Ratio	What the proportion of the capacity in the segment used is?	P(VUR>= VUR_baseline)

Fuel consumption indicators

Indicators of fuel consumption		
Fuel consumption per kg of fish	How does fuel consumption vary with the different scenarios	Litre fuel/kg fish landed

RESULTS

Situation now: baseline scenario

In this first part of the result, we look at the anticipated impacts of banning pulse trawling ("pulse_ban", a scenario that we use as the baseline for the rest of the study) on the current Dutch flatfish fishery.

Unsurprisingly, the effort of pulse trawl decreases rapidly in the first two years in case of a pulse ban (see Figure 127), while it actually increases to a higher level in the business as usual scenario (the phasing out had already started in the initiation data and the fleets would benefit economically if they targeted sole with pulse instead of beam trawls). In a symmetrical way, the effort of the sole beam trawl (TBB_80) increases for all fleets under a pulse ban and the effort of the larger mesh size beam trawl (TBB_>100) increases slightly for the two larger fleets (TBB_2440 and TBB_40XX). The effort targeting shrimp (TBS) increases after the second year for the TBB_2440, indicating that some of the effort was reallocated to the shrimp fishery. While the effort of the smaller fleet (TBB_1224) stabilises rapidly, the total effort of the medium (TBB_2440) and large vessel (TBB_40XX) fleets, decreases in 2024 and 2025.

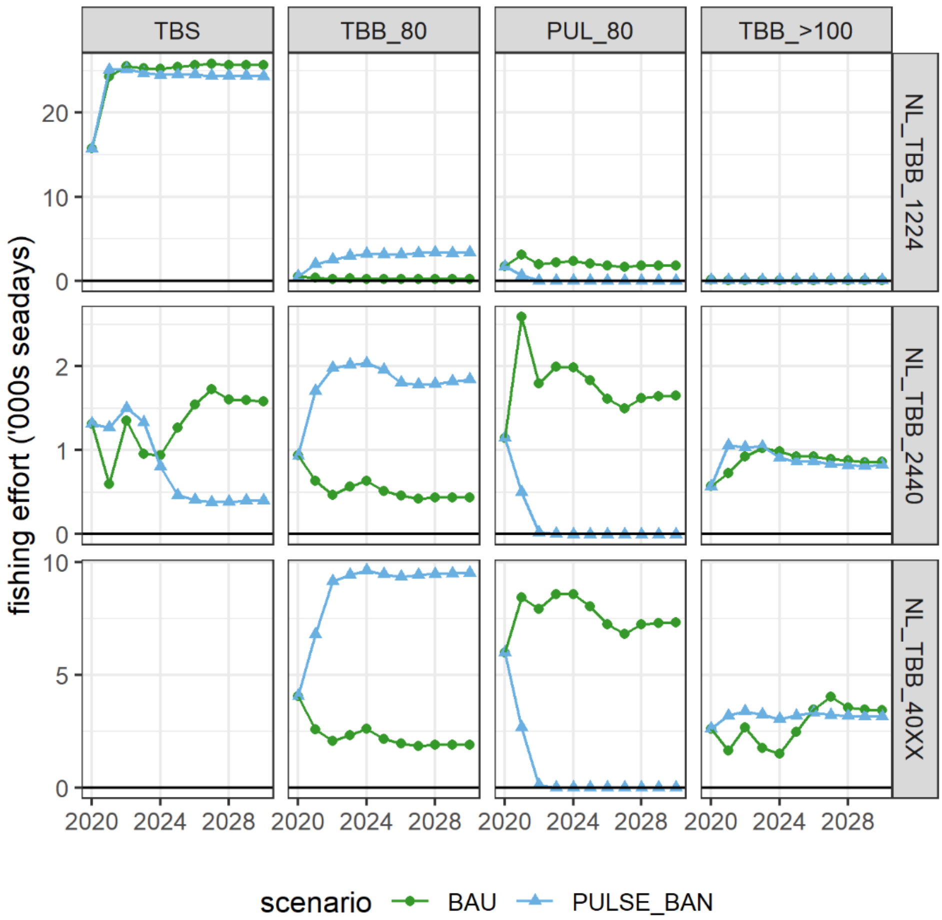

Figure 127 Simulated fishing effort per fleet and per gear in scenarios business as usual (BAU) and pulse ban (PULSE_BAN) in thousands seadays for 2020-2030. Gear codes are as follow TBS : shrimp beam trawl, TBB_80 : sole beam trawl (80-99mm meshsize), PUL_80 : sole pulse trawl (80-99mm meshsize) and TBB_>100 : plaice beam trawl (>= 100mm meshsize)

The switch in effort distribution in the pulse ban scenario has consequences in the simulations on the composition of the landing of the fleets (Figure 128). The most affected stock is the sole (SOL) for which the Dutch landings are reduced to about 50% of those of the business as usual. Conversely, turbot is caught a bit more due to the limited dynamics available in the model.

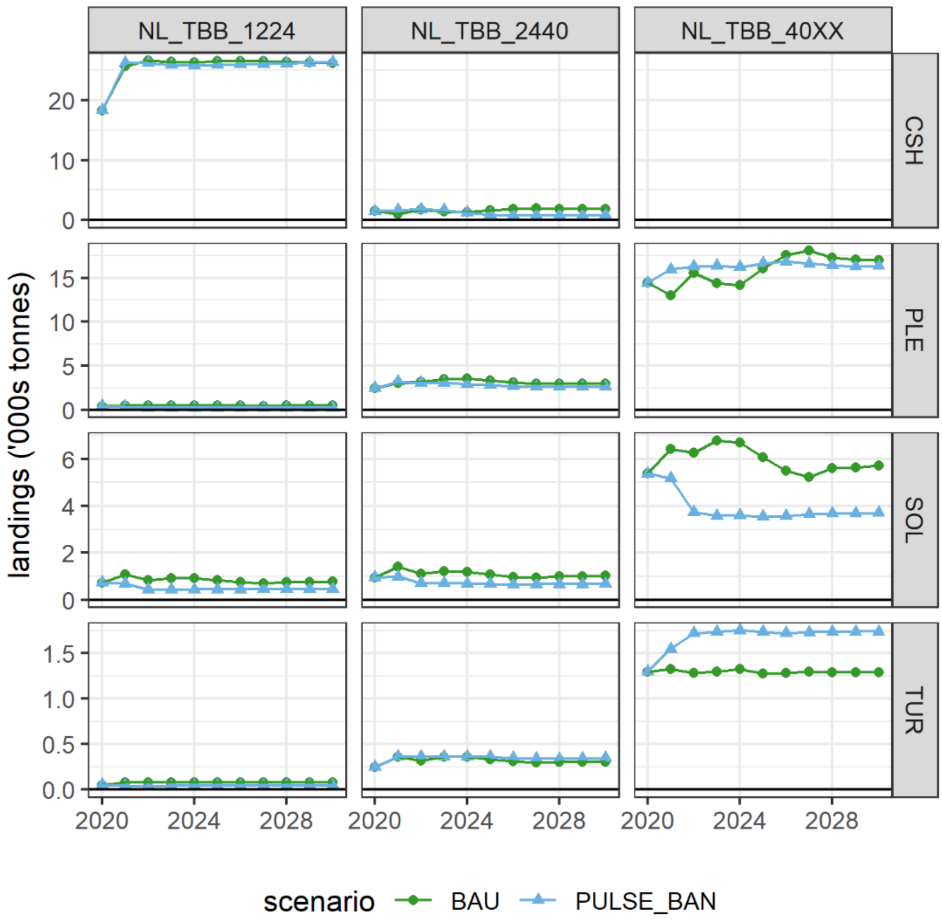

Figure 128 Simulated landings per fleet and per species in scenarios business as usual (BAU) and pulse ban (PULSE_BAN) in thousands tonnes for 2020-2030.

The total profit of the fleet can be seen in Figure 129. In 2022, in the simulations the profit of all fleets would decrease sharply in case of a pulse ban. As a result, the TBB_2440 fleet would record losses during 2021-2025 before their profit would return and get positive again. The TBB_40XX would remain profitable but at a much lower level than in the business as usual case. It is also true for the smaller vessels, but they manage to keep a positive profit, lower than in the business as usual scenario.

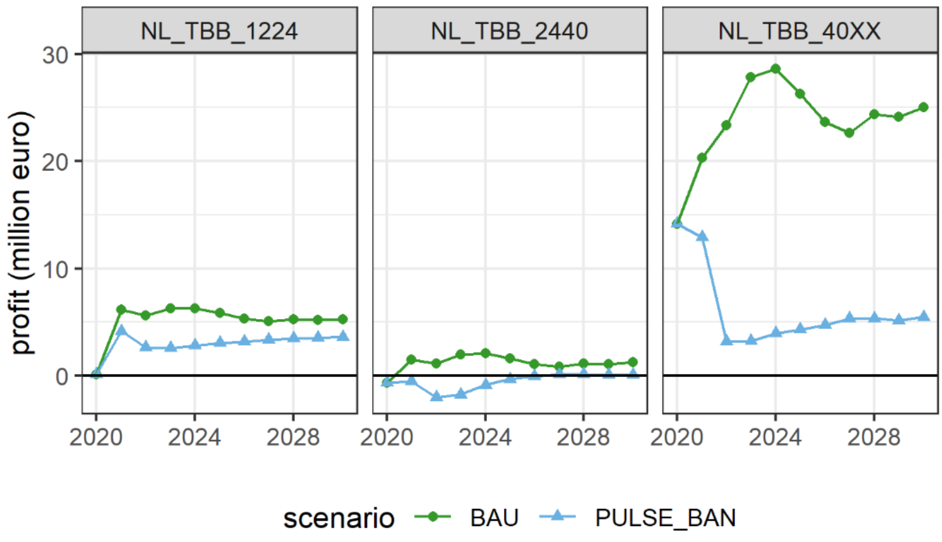

Figure 129 Simulated profit per fleet in scenarios business as usual (BAU) and pulse ban (PULSE_BAN) in million euro for 2020-2030.

A period of losses induced a disinvestment for the fishery in the simulations as seen in Figure 130. From 2024, about a third of the vessels in the TBB_2440 fleet would leave the fishery (about 9 vessels). The number of vessels in the fleets TBB_1224 and TBB_40XX would remain unchanged.

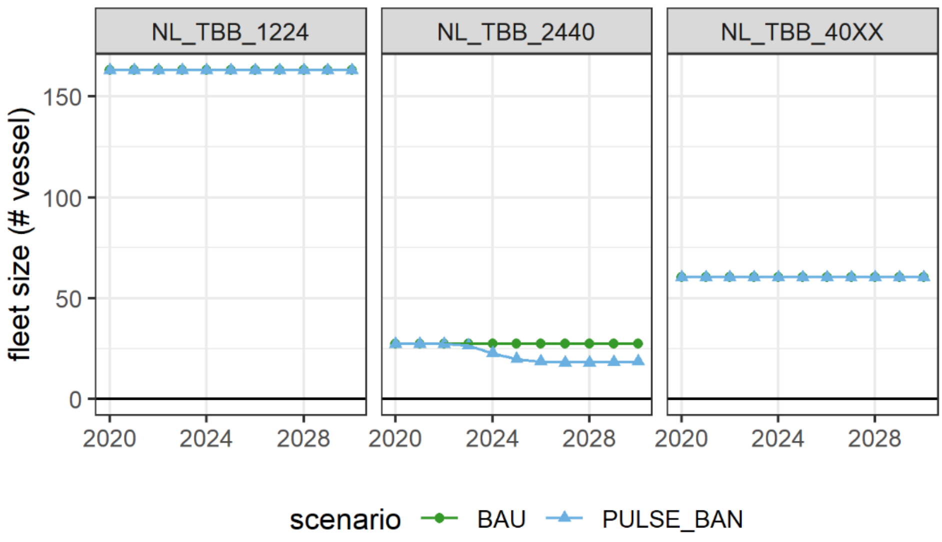

Figure 130 Simulated number of active vessels per fleet in scenarios business as usual (BAU) and pulse ban (PULSE_BAN) for 2020-2030.

The biomass evolution of the sole stock in the simulations is quite different for the two scenarios (Figure 131). In the business as usual scenario, the sole SSB oscillate around 50 thousand tonnes while it increases to almost 100 thousand tonnes in the pulse ban scenario. The other two stocks would change only slightly.

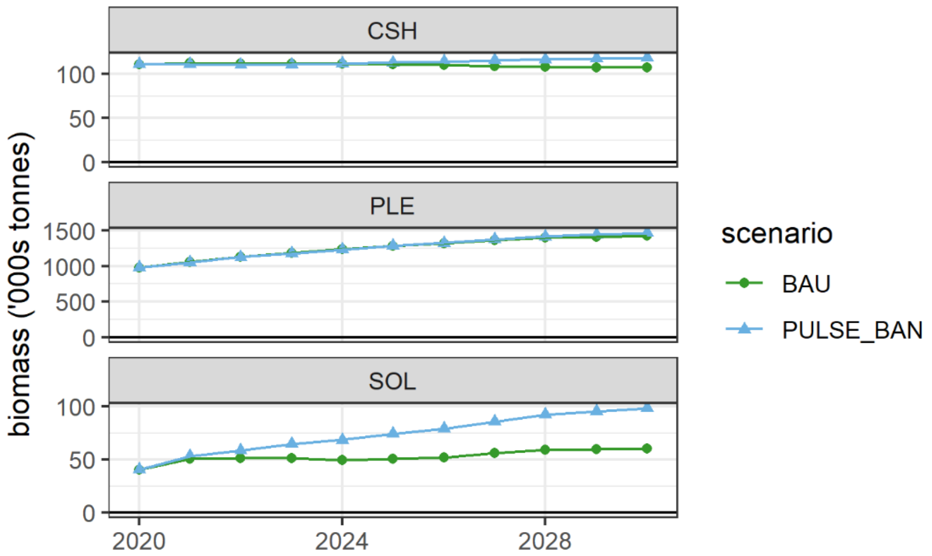

Figure 131 Simulated biomass (SSB for SOL and PLE) per stock in scenarios business as usual (BAU) and pulse ban (PULSE_BAN) for 2020-2030. CSH: shrimp, PLE: plaice, SOL: sole

Resilience

The resilience of the system to shocks is evaluated by comparing scenarios 2 to 7 to the baseline scenario where the profits would be lower . The scenarios MILD ST and MILD are subjected to a one year shock (2021) in recruitment for sole and plaice and the scenarios SEVERE ST and SEVERE are subjected to a two year shock (2021 and 2022) in recruitment for sole and plaice. In scenarios MILD LT and MILD, long term dynamics, including the distribution of sole and plaice and the recruitment of plaice are affected by the expected water temperature (following RCP4.5 projections). The same long term dynamics are driven by the RCP8.5 projected temperatures in scenarios SEVERE LT and SEVERE.

Resource resilience

Table 48 summarises the resource indicators for the six biological scenarios. The shocks only led to a decrease in biomass in case of a severe shock for the sole (SEVERE ST and SEVERE). For all other scenarios, sole biomass remained above the 2021 level of about 53 thousand tonnes, which is also above the trigger biomass for the stock. For plaice, the biomass remained higher than the initial biomass for all scenarios in the simulations.

Table 48 Resource resistance and resilience indicators for sole and plaice

		MILD ST	MILD LT	MILD	SEVERE ST	SEVERE LT	SEVERE
Sole	Amplitude	1	1	1	0.96	1	0.96
	Responsiveness	-	-	-	2	-	2
	Biological risks	0	0	0	0	0	0
	Recovery rate	1	1	1	1	1	1
	Recovery speed	0	0	0	0	0	0

		MILD ST	MILD LT	MILD	SEVERE ST	SEVERE LT	SEVERE
Plaice	Amplitude	1	1	1	1	1	1
	Responsiveness	-	-	-	-	-	-
	Biological risks	-	-	-	-	-	-
	Recovery rate	1	1	1	1	1	1
	Recovery speed	-	-	-	-	-	-

The shocks in recruitment translate to the SSB via the maturity indices. For sole age two fish are still considered immature while age three fish and older are considered fully mature. For plaice, half of the age two and three fish are mature, and all age four and older are mature. This difference in maturity index explains that while the shocks happen in the same years for both species, the responses are asynchronous.

On Figure 132 we see that despite the biomass increased in the simulations (for sole this is mainly due to the pulse ban), the shocks were felt by all species. The effects of the biological scenarios on the SSB were felt in different years. For sole, impacted the most, the effect of the recruitment shocks were seen two years after the first recruitment failure, in 2023 when the "weak" year class is recruited. The "MILD" shock scenarios (MILD and MILD ST) led to a loss of about 13% of the sole SSB in 2023 relative to the baseline, and the SEVERE shock scenarios (SEVERE and SEVERE ST) led to a loss of 25% of the sole SSB in 2024 in relative to the baseline. The long term effect (change in distribution) does not affect the sole biomass. By the end of the simulation period, the sole biomass has grown back close to the baseline level.

The effect of shocks was lower for the plaice stock, about 4% SSB loss in 2025, four years after the mild shock (MILD ST), and 7.5% SSB loss in 2026, four years after the last year of the severe shock (SEVERE ST). For plaice, the shock effect added to the long term effect. In the mild scenario, the long term effect (MILD LT) of temperature on recruitment and on the stock could be seen after year 2026. The long term effect of the severe scenario (SEVERE LT) would be seen from 2022. In the MILD and SEVERE scenarios, the shocks and long term effects cumulated, leading to longer-lasting effects on the SSB. In general, the plaice stock seemed to recover slower from shock and was proportionally further from its baseline than the sole stock.

Limited effects can also be seen on the shrimp stock following the reallocation of effort when the sole stock increased slower than in the baseline.

Table 49 Modified resource amplitude indicators for sole and plaice. Comparing to baseline instead of to base year.

		MILD ST	MILD LT	MILD	SEVERE ST	SEVERE LT	SEVERE
Sole	Amplitude compared to baseline	0.87	1	0.87	0.75	1	0.75
	Responsiveness	2	-	2	2	-	2
Plaice	Amplitude compared to baseline	0.96	0.98	0.94	0.92	0.96	0.91

		MILD ST	MILD LT	MILD	SEVERE ST	SEVERE LT	SEVERE
	Responsiveness	4	8	5	4	8	5

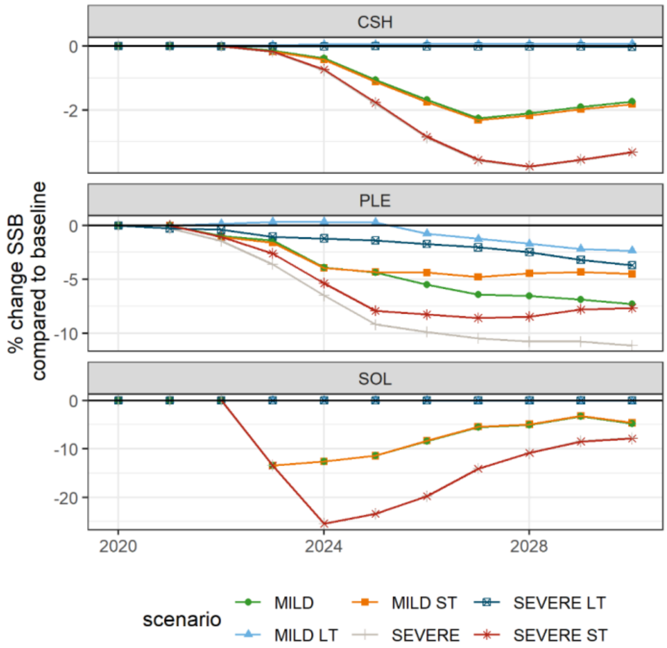

Figure 132 Simulated biomass change relative to the baseline for shrimp (CSH), plaice (PLE) and sole (SOL) for the biological shocks (ST) and long term changes (LT), mild and severe.

Economic resilience

The economic indicators shown in Figure 133 display similar trends from the simulations. For all fleets, the scenarios with changes in the long term biological dynamics (MILD LT and SEVERE LT) had limited effect. The short term shocks seemed to drive the response of fleets both for the mild and severe scenarios.

The dynamics of the two larger fleets (TBB_2440 and TBB_40XX) were similar. For the shock scenarios, the economic performance indicators (BER_Ratio, GVA, NPM, GVA_per_FTE and RoFTA) decreased in 2023, or 2 years after the first recruitment failure. In the mild scenarios (MILD ST and MILD), the decreases slowed down and stabilised from 2024. From 2025, the economic indicators improved while the number of active vessels strongly decreased. Economic indicators decreased again when the number of active vessels increasee again in the last year of simulation. By the end of the simulation period, the TBB_2440 fleet still counted 17% and 27% less active vessels in respectively the MILD ST and SEVERE ST compared to the baseline, the TBB_40xx fleet was only affected in the most severe case with 10% fewer active vessels in the SEVERE ST scenarios than in the baseline. The capacity reduction decreased the fixed costs, allowing the remaining active vessels to be still profitable.

The TBB_1224 fleet was slightly negatively affected between 2024 and 2029. By the end of the simulation period (2030) the fleet seemed to perform as well as in the baseline.

In all scenarios, the fleet capacity was used to its maximum in the simulations, compensating for the high fixed costs and the low-profit margin of fishing by working more.

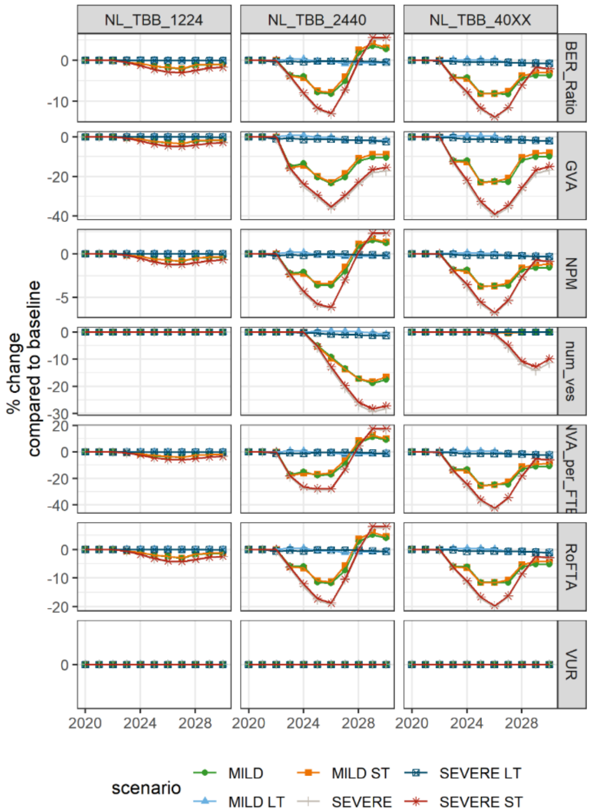

Figure 133 Economic indicators of the simulated Dutch flatfish fleets relative to the baseline

Fuel consumption

The ban on pulse trawling had a strong influence on the fuel consumption of the TBB_2440 and TBB_40XX fleets (Figure 10). After introducing the pulse ban, the fuel consumption of the two fleets stabilised between 25 and 30% higher than in the business as usual scenario. The fleet TBB_1224 displayed lower fuel consumption per kilo of landings, due to the difference in targets, this fleet targets mainly shrimps and the live weight of the landings is taken in the calculation of the indicator leading to a quite different level for crustaceans as to fish.

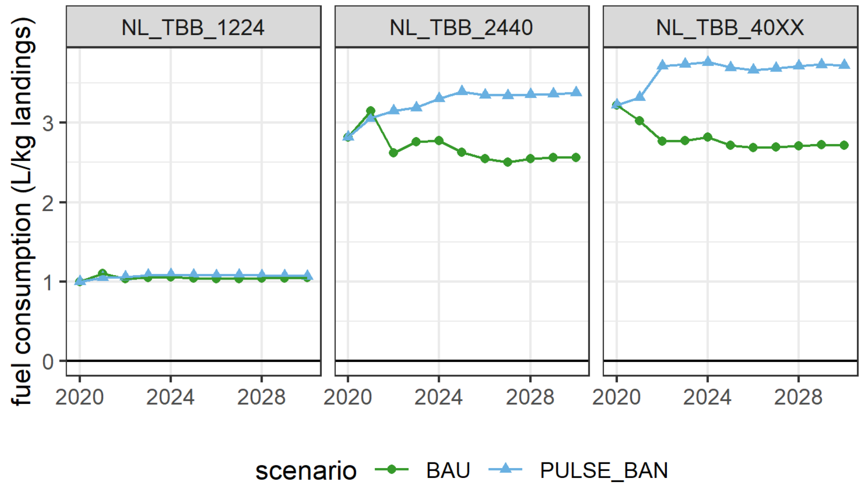

Figure 10 Fuel consumption (L/kg landings) in the business as usual case and in the PULSE BAN (baseline) for the three fleets

From Figure 11, the simulated change in fuel consumption between scenarios can be seen. The change in fuel efficiency had the most impact on the fuel consumption per kg of landings. An annual decrease of 1.4% and 4% of fuel consumption translated into a total improvement of fuel consumption of 13 and 34% respectively in the fuel efficiency 1 (fueleff1) and fuel efficiency 2 (fueleff2) scenarios compared to the baseline efficiency. Further, the long term biological changes had a slight negative impact on the fleets TBB_2440 and TBB_40XX which respectively use 1 and 2% more fuel per kg of landings by 2030 in case the plaice recruitment is temperature dependent. Little difference can be observed between the MILD and SEVERE scenarios. Finally the F target of sole and plaice used to set the TAC had no influence on the fuel consumption in the simulations.

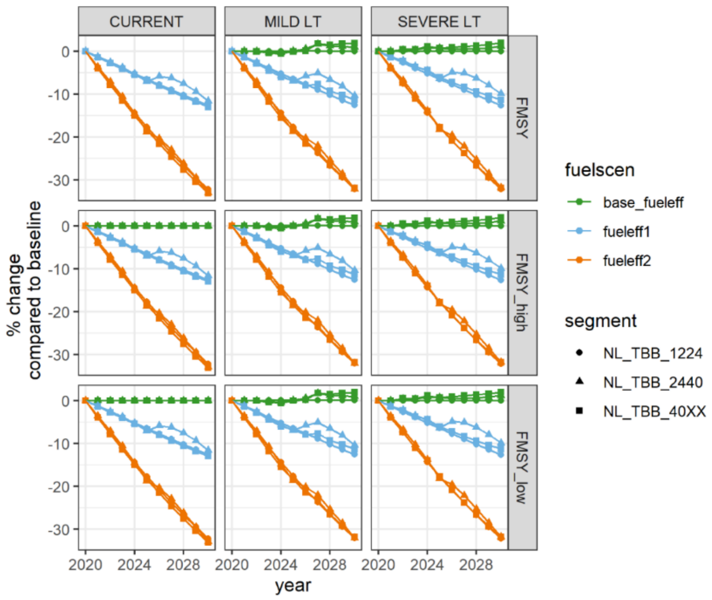

Figure 11 Fuel consumption per segment per year compared to the baseline for different scenarios. The fuel efficiency scenarios are shown in different colours, the long term biological changes in columns and the FMSY scenarios in rows.

DISCUSSION/CONCLUSION

Phasing out pulse trawling: lowering profitability for the fishers, sole stock benefits

The ban on pulse trawling redirected the effort to alternative, less economically efficient gears, leading to a loss in landings, increase in fuel costs and lower levels of profit of fleets. As a result the number of active vessels in the two fleets highly dependent on sole could decrease from the disinvestment we modelled, and the total effort decrease. The TAC was not caught, which would lead to an increase in sole biomass, well above the MSY Btrigger of about 42.000 tonnes and a general improvement of the economic conditions of the remaining vessels, possibly leading to some vessels entering back the fishery from the investment dynamics we modelled.

Sole stock more affected by shocks, but in safe biological limits due to ban on pulse trawling

When looking at the chosen indicators, the sole was hardly affected by the shocks and anyway the stock stayed at levels above the MSY Btrigger. This is mainly due to the ban on pulse trawling that reduced the Dutch landings and alleviates the stock's pressure, allowing it to continue growing despite the bad recruitment shocks. Hence, if the pulse trawling would have still been allowed, the stock level would be lower and the stock biomass would decrease by 20% in case of a severe shock. The plaice stock in the simulation results suggest that it can sustain the shocks, mild or severe, and the long-term recruitment changes without a negative effect on the SSB.

Fleet still affected by shocks in 2030, fewer active vessels allow the remaining ones to be profitable

Given the lower profitability in the baseline (see Figure 129), the fleets heavily dependent on flatfish were more vulnerable to recruitment shocks. Economic indicators showed large decrease two years after the shocks, around the time the weak year classes were recruited in 2023. Continued l economic performances induced by the shocks led in the simulations to vessels exiting the fishing fleets starting in 2025 (TBB_40XX) and in 2027 (TBB_2440). The decrease in fishing capacity from the disinvestment dynamics modelled here led to lower fixed costs and allowed the rest of the fleet to improve its economic profitability. The economic indicators oscillated around the baseline as the result of the feedback loop modelling entry-exit of vessels (the economic situation improves, the fleets grows again, leading to degrading the economic profit, and possibly to a new exit of vessels). By 2030 the fleets still would not have recovered from the mild shock (MILD and MILD ST scenarios). The SEVERE scenarios showed the oscillations with a larger amplitude.

The effect of the shocks on the fishing fleets was highly dependent on the initial economic situation of the fleets. If a fleet is close to breaking even, then any increase in costs/decrease in revenue would lead to an economic loss, threatening the long-term economic viability of the fleets. In contrast, if a fleet generates a high profit, a slight increase of costs or decrease in revenue will not substantially impact short-term profitability. However, it is noted that the model is likely to overestimate the re-investment in the fishery when the biomass increases. In reality, fishers who leave a fishery may not come back quickly a few years later. They may have sold their vessels and their crew is likely to have moved on.

Fuel consumption mainly affected by improvement in fuel efficiency

Improvement of fuel efficiency was the main driver anticipated for fuel consumption in the scenarios. Fuel consumption was also slightly negatively impacted by the long term effect of temperature on the recruitment of plaice in the simulations.

Effect of management

This effect was found minimal as the quota remained underused in the baseline. Therefore reducing or increasing quotas did not really impacted the fleets in the simulations.

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Annex 20 BALTIC SEA CASE STUDY WITH THE DISPLACE SPATIAL FISHERIES MODEL

Defining plausible, ecosystem-coherent shock scenarios

We defined three environmental scenarios for the Baltic Sea region (current, most likely, and worst-case scenarios). These scenarios correspond to particular climatic paths, respectively no further change in the climate, intermediate IPCC scenario (RCP4.5), and one pessimistic IPCC scenario (RCP8.5). Each of these climatic scenarios leads to a series of environmental changes that would affect the individual physiology of the animals impacted and the phenology of the species. In this study, we did not relate the biological impact of these changes on the different stocks considered quantitatively due to a lack of empirical observations relating causal changes to an effect. Information from the literature review has instead been used to assume the nature and direction of the impact of these environmental changes on different stocks. The intensity of this biological response further depends on the scenario (Table 50). Scenarios recognize that life-history parameters are correlated, e.g. faster-growing individuals may mature smaller and be subject to higher natural mortality.

For each scenario and long-term environmental changes, assumptions are made on short-term stresses and their impacts on the biology of the stocks. However, the intensity and frequency of these shocks would ideally vary between the three scenarios. The first step was to propose plausible, ecosystem-coherent scenarios of biological responses to long-term climate change and short-term stress for the three scenarios.

In the Baltic Sea, the main environmental drivers affected by climate change and affecting the productivity of target and non-target species include increasing temperature and decreasing salinity as synthesized by the ICES WGIAB in Integrated Ecosystem Assessments (IEA) in the sub-regions of the Baltic Sea. However, the decrease in salinity is less certain because more frequent influxes of saline waters from the North Sea into the Baltic Sea might counteract it. Besides this, oxygenation is likely an essential component of the conjugated effects. For example, stormy weather may decide on, e.g. the reproductive volume of cod, therefore, the strength of the incoming year classes. In addition to the fact that fishing pressure is an essential driver per se of the marine population dynamics, it is also seen as a factor creating possible trophic cascades. If the effects of fishing could be smoothed up to a certain point by compensatory effects into the food web, a tipping point might also be reached. These abrupt cascading effects could ultimately stabilize the Baltic Sea marine ecosystem toward alternative relative species biomasses and productivity regimes.

To this aim, we have run a simulation study for using a calibrated DISPLACE model application (calibrated to 2019) for the Baltic Sea system. This includes the interactions among cod, sprat and herring, flatfish, and the different national fleets at the Baltic Sea wide scale, up to the 2030 horizon.

Compared to a baseline run, scenarios are a combination of mild long term change on productivity, i.e. changing recruits and growth parameters (RCP 4.5), severe change (RCP 8.5), short term shock (i.e. massive background mortality event on the first y), a spatial range contraction, and fishing mortality (F) at FMSY or FMSY_lower. Again, the weak point in this study will be that the effect sizes of the plausible scenarios changes are pretty arbitrary in a lack of proper empirical observations, making the lessons learnt from the simulations more qualitative than quantitative. Nevertheless, the scenario translated into changed parameters for stock productivity, i.e. SSB-recruits relationships and growth (Figure 134).

The tested change would capture the long term changes in biological functions (recruitment, growth, maturation, natural mortality, reflecting possible correlations between traits), as well as long term changes in the spatial distribution.

There was no biological scenario implemented on flatfish. Hence the change in simulation outcomes on these species will result from changing fishing patterns only.

Table 50 A suite of "what if" scenarios affecting the stock productivity and spatial distributions of main Baltic Stocks tested with DISPLACE. No environmental forcing is implemented in the model (… in the absence of proper proportional relationships). Tested impact with multipliers on input parameters. SSB-R stands for Spawning stock biomass-Recruits relationships deduced from the Ricker function with the two parameters alpha and beta. VBGF stands for Von Bertalanffy Growth Function with the two parameters Linf and K. M stands for natural mortality.

Scenarios	Species	Drivers	Multi on SSB-R Ricker alpha	Multi on SSB-R Ricker Recru beta	Multi on VBGF Linf	Multi on VBGF K	Absolute FMSY	Massive M at y=0	Vessel stops if choked	Spatial Range contraction
Baseline (i.e. FMSY)	Cod, Herring, Sprat	Productivity change	1	1	1	1	1	0	1	0
Mild change	Cod, Herring[1]	Productivity change	1	1.1	0.9	1.5	1	0	1	0
	Sprat[2]		1.1	1.0	0.9	1.5	1	0	1	0
Mild change + FMSY low	Cod, herring	Productivity change	1	1.1	0.9	1.5	1	0	1	0
	Sprat		1.1	1.0	0.9	1.5	1	0	1	0
Severe change	Cod, herring	Productivity change	0.8	1.5	0.8	1.5	1	0	1	0
	Sprat		1.1	1.0	0.8	1.5	1	0	1	0
Severe change + FMSY low	Cod, Herring	Productivity change + F Management	0.8	1.5	0.8	1.5	1	0	1	0
	Sprat		1.1	1.0	0.8	1.5	1	0	1	0
Severe change + shoke	Cod, Herring	Productivity change	0.8	1.5	0.8	1.5	1	20%	1	0

	Sprat		1.1	1.0	0.8	1.5	1	20%	1	0
Severe change + FMSY low + shoke	Cod, Herring	Productivity change + F Management	0.8	1.5	0.8	1.5	1	20%	1	0
	Sprat		1.1	1.0	0.8	1.5	1	20%	1	0
Spatial range contraction	Cod, Herring, Sprat [3]	Spatial distribution change	1	1	1	1	1	0	1	10%
Spatial r. contract. + FMSY low	Cod, Herring, Sprat	Spatial distribution change + F Management	1	1	1	1	1	0	1	10%
FMSY + Effort max	Cod, Herring, Sprat	Continue fishing and discard	1	1	1	1	1	0	0	0
FMSY low + Effort max	Cod, Herring, Sprat	Continue fishing and discard	1	1	1	1	1	0	0	0
FMSY + 30% fuel saving when towing nets	trawlers	none	1	1	1	1	1	0	0	0

Table footnote: [1]increase density-dependent effects, e.g. increase of adverse inter-individual interactions from resource scarcity; [2]positive effect of warmer water column temperature on sprat; [3] Process a spatial shift. e.g. a range contraction of 10 % (of each size group of a stock) toward the core area. (see GenerateSpatialShiftForBiolsceStaticAvai.R)

A plausible short term shock induced by climate change could result from the mortality affecting fish and other demersal animals. This may be caused by the combined effects of warmer temperatures and water oxygen content. Marine populations are susceptible to low oxygen events that may increase in frequency and severity with the anticipated warming waters. Increased temperature increases metabolism for animals such as fish which require more oxygen consumed, and more detritus that trigger the microbial loop creating hypoxia areas for demersal fish and invertebrates, even more, when the stratification in the water column is increased. Even if fish can escape the unsuitable areas, benthos invertebrate species that are preyed on by fish will not survive, making fish possibly starve from the reduced resource or affecting the growth and reproduction.

In the pelagic system, the primary productivity (phytoplankton) may also drastically reduce the mixing of water layers or short term events. These episodes may induce high mortality anomalies to heavily environmentally-driven recruits such as those of pelagic species.

In the meantime, there are continual directional changes to species distributions that are ongoing in the background. Hence, the possible spatial shift of species distribution induced by a changing climate is additional. Hence, Mackenzie et al. (2007) predicted a change in the fish community in terms of biomass and a change in the spatial distribution, for example, due to the contraction of the ranges of marine species. The resource base supporting individual communities could likely be displaced, affecting the economics of fisheries and the communities. Natural geographical boundaries in the Baltic Sea is limiting this northward shift movement in response to changing climate. The Baltic Sea being semi-closed, the finfish and shellfish in the Baltic Sea will more be affected by a contraction of the range of the species distribution toward their core areas, even more, when some of these species are already at the edge of their natural distributions dictated by their tolerance range in environmental conditions.

Besides biological scenarios, the modelling platform is capable of assuming different fishermen behaviour or other fleet-related effects. Hence we included a scenario related to the decision of individual vessels not to stop fishing even if the quota of the limiting stock is reached (the so-called "Effort max" scenario in a mixed fisheries context, see ICES WGMIXFISH). We also included a scenario that assumes a hypothetical 30% fuel saving during towing the nets that would arise from designing innovative trawls.

From the simulation outcomes, we expect to calculate a range of metrics to quantify resource (and economic) resilience based on the trends in simulated stock size concerning limit and trigger reference points and the temporal dynamics of these changes.

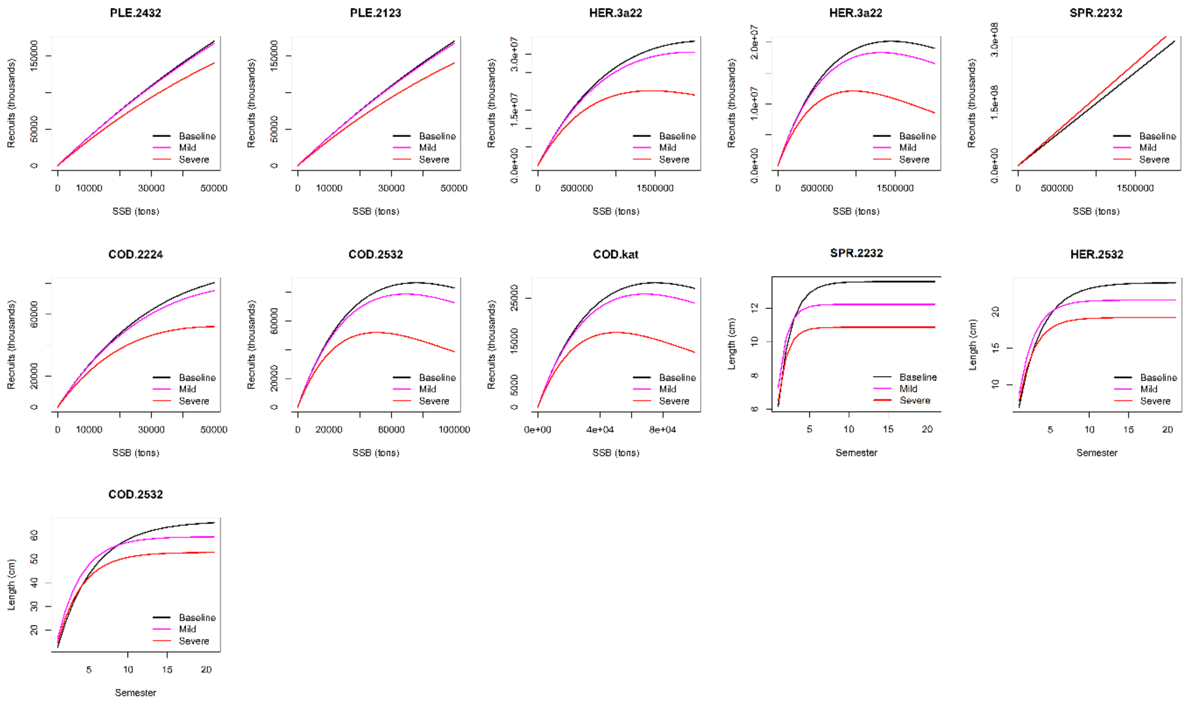

Figure 134 Stock-recruits relationships based on the Ricker model for predicting the number of recruits at y+1 depending on the spawning stock biomass SSB at y. Each Baltic Sea stock assumed affected by the three climate scenarios.

Conditioning DISPLACE on the Baltic Sea fish stocks system

We used the DISPLACE modelling platform (Bastardie et al. 2014) as a comprehensive management strategy evaluation tool to assess how different spatial fishery management options affect fish stocks and fisheries under climate change scenarios. The core of DISPLACE is a spatial bio-economic model for simulating the movement of individual fishing vessel agents combined with an underlying spatial population dynamics model. In

DISPLACE, individual agents optimize their decision-making on the fly depending on their given catch rates by zones and the expected cost to reach the zone and return to the harbour. Each vessel depletes the target stocks individually, which depends on the gear type in use.

In the Baltic Sea, fisheries target a relatively small number of species, mostly finfish as cod, herring and sprat, and also flatfish of commercial interest. This study focuses on the most important species and stocks regarding fisheries resources in the Baltic Sea. Cod, herring, and sprat constitute about 95% of the total commercial catch in terms of catch weight (ICES, 2018). The ICES Baltic Fisheries Assessment Working Group (WGBFAS) focuses on assessing 17 stocks integrated into the DISPLACE model. Besides stock number-at-age issued by the last available ICES analytical assessment estimates (2019), we included fish life-history and ontogenetic growth for modelling the different populations with a body size-based model. Processes affecting population dynamics are often size-dependent (such as growth, mortality, maturity, condition, settling, and recruitment). Fishing is also a selective process that applies differently along with animal body size. Hence, the model handles 14 size groups (5 cm length groups) pooled in 3 size categories (small, medium, and large animals) for describing size-specific spatial distributions and marketable categories (Bastardie et al., 2014). From Von Bertalanffy growth parameters (infinite length Linf, the growth rate K and t0 parameters), we generate stock-specific growth transition matrices (GTM) using the Von Bertalanffy growth curve model for simulating individual stochastic growths (see Bastardie et al., 2014). We run the same procedure also to obtain Age-Length Keys ALKs. To account for predator-prey trophic interactions between fish species (Figure 135), we informed the DISPLACE size-spectra model (based on Blanchard et al. 2014) with specific growth parameters, Winf as the asymptotic weight in grams and k as the standard metabolism factor in yr-1, and diet preferences (Jacobsen et al., 2014, 2017). The stochastic trajectories modelled in DISPLACE arise from two additional parameters inducing the stochastic trajectories: CV for lognormal error added on recruits is 0.2, and CV for lognormal error added on quarterly-based growth transition matrix is 0.1.

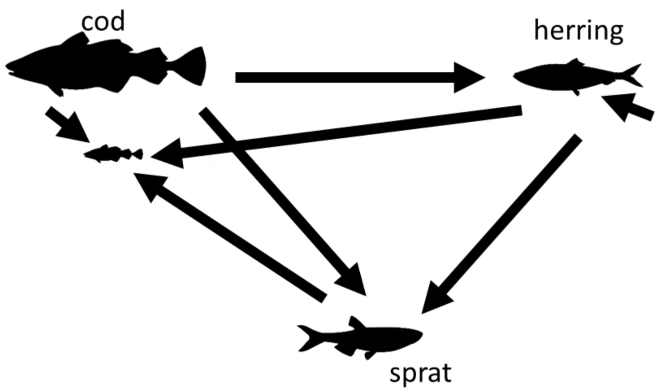

Figure 135Figure 2. Trophic interactions implemented in the DISPLACE application with the sizeSpectra module option modelling calculating additional M2 predation (with Displace scaling factor 1e7), besides the background size-based natural mortality. Cannibalism of juveniles by adult fish is present for cod and herring.

The baseline scenario has some default DISPLACE options on the fleet dynamics activated: focus_on_high_profit_grounds, TACs, FMSY, area_monthly_closure, discard_ban, stopGoingFishingOnFirstChokedStock, and on the population dynamics that are: sizeSpectra and stochasticGrowth. Details on biological and fisheries parameters and other input data can be found on the GitHub online repository https://github.com/frabas/DISPLACE_input_Baltic21

The simulation study aims at extrapolating the stock trajectories to domains where there is some uncertainty about the central parameter values (i.e. future stock productivity and spatial distribution), and describing possible courses of the system, depending upon a choice of parameter values that are likely to be impacted by the climate change effects. As described by Harfoot et al. (2014) in Mouquet et al. (2015), these anticipatory predictions are therefore not meant to represent the actual future. The fact that the projection do not match reality does not count against the validity of the underlying hypotheses. Instead, the simulation study should be regarded as a guide for present action.

DISPLACE Baltic Sea simulation study outcomes

Most fish stocks projection showed spawning biomass SSB stock increased, and mortality F reduced at the horizon 2030 for the baseline runs applying the current F-MSY strategy to Baltic fisheries (Figure 136). Kattegat cod (COD.kat), Herring (HER.2532), Sprat (SPR.2232) are the exception and showed declining/collapse trends in SSB and increased in F compared to the reference points and initial states, and plaice (PLE.21.23) a marked increase in F (Figure 136).

There is, however, substantial uncertainty in the future status of cod stocks both in Kattegat and Western Baltic. For both stocks, the beforehand calibration of the final runs led to affect weight at age with a factor of 30 the COD.KAT and 5 the COD2224 for obtaining similar simulated levels of historical assessed SSBs and Fs by ICES. Such calibration is a sign of imperfect knowledge on these two stocks regarding either L50 Maturity, weight-at-age or estimated N-at age, or a mixture of all these population features in the meantime. Extra caution should also be paid to the COD 2224 status since we observed this stock could collapse in the simulations when an East to West migration of adults is implemented. Migration is a factor known to currently affect the perceived status of the west cod stock (Hussy et al. 2016, Bastardie et al. 2017), concerning the accuracy of catch limits to be advised (also due to averaging the weight at age in West between East and West) putting the stock at high risk of collapse when repeated imbalanced TACs are advised in the management procedure. Besides this, in the simulations, the western herring stock HER.3a22 reached possibly unrealistic biomass level (up to 40 times the initial levels).

Regardless of these uncertainties, applying different F-strategies facing climate change long-term effects or episodic stress, the simulation study anticipates that the regional response to applying FMSY-lower makes little difference and is not beneficial for all stocks ensure a level above the reference points at the horizon 2030. In case the F-MSY-lower strategy is followed, this will be sufficient to counteract the effect of climate change for SPR.2232 (at RCP4.5 level), but is not robust for east cod COD.2532, and does not help for declining herring HER.2232 and collapsing cod COD.KAT (Figure 3). In addition to this, such climate-induced change could worsen the declining status of SPR.2232 (Figure 136).

The response of the stock status to a range contraction of cod, sprat and herring population spatial distribution affected positively the COD.2532, is beneficial to herring and plaice stocks, and minimize the reduction of SPR.2232 (Figure 136). This is likely due to reduced access to the productive fishing grounds that become out of the range of the smaller coastal vessels with lower mobility capability (usually using passive gears). This led to recovery and a possible future under exploitation of the Baltic herring stocks. In addition to this, because the degree of overlap will change, the likelihood that the predator-prey relationships in the ecosystem would be altered is high under a scenario of range contraction, also diminishing the predation of cod on herring and sprat.

Applying the FMSY-lower strategy to all stocks simultaneously is beneficial on the fleet indicators leading to a more than 10% increase in income for bottom-contacting gears that comes with more energy-efficient fisheries (+5%, Figure 137). This is mainly the result of the demersal trawling fleets not choked on the North Sea and Baltic Sea cod stocks. The same effort is applied at sea from a similar number of trips, but each of them may have higher catch rates when the resource levels is better aligned with the TACs. Indeed if TACs are not limiting, landings are strongly increased. Greater short-term opportunities on flatfish stocks induce slightly more revenue for vessels using passive gears as well.

Long-term climate-induced effects on the environmental drivers led to an even larger fleet revenue (NPV ca. >20%) and energy efficiency (ca. >10%), from higher landings on Baltic cod seeing its overall abundance decreasing. Lower anticipated landings on the Baltic herring stocks, sprat and plaice are not counteracting this outcome at this fleet aggregation level (Figure 137).

The possible appearance of a shock on top of the long term climate effect of RCP8.5 background change is actually adversely impacting the fleet income and the energy efficiency, unless the FMSY-lower strategy is applied, in this case correcting for the loss of opportunity induced by the shock (especially on Baltic and North Sea cod) and by decreased catch rates if long term change applied (Figure 137).

In case of a spatial range contraction, the economic income and energy efficiency is strongly affected, with a loss of more than 20%. This results from limiting landings realized on COD.2224, COD.2532, and flatfish for passive gears, and HER.3a22 and HER.2532 for active gears (Figure 137).

Overall effect

At the entire Baltic basin scale, the overall economic return appears to be beneficial in the long run with the F-MSY strategy and opportunities are gained when applying a systematic FMSY-low strategy (Figure 138, Figure 139). The FMSY-low strategy is not limiting the fisheries even in a situation of increasing stocks, and because of increasing stocks. The energy efficiency is also stable over the long run at the Baltic wide scale (Figure 140). The climate change is in overall positively affecting the anticipated revenue and the F-MSY-low strategy is enable to counteract the loss on some stocks. Unexpectedly, simulations shows that a shock may also slightly improve the anticipated revenue by stimulating the stock productivity (i.e. counteracting the density dependence effects). On the contrary an adverse effect is anticipated as soon as the climate-induced change on the harvested stocks translates into a contraction of the stock distribution. In this latter case, the gross value added becomes negative due to fixed and variable costs exceeding landings incomes and other revenues (Figure 139). The energy efficiency is also severely affected by longer trip duration and lower catch rates. This is likely the result of some part of the stocks becoming out of range of small coastal fisheries. Besides this, non-compliance to the LO increases energy efficiency (Figure 142), but with dramatic consequences on the GVA (Figure 141) from the underlying long-term stock declining developments (results not shown). FMSY-strategy is also more rewarding for the fleet economy than FMSY-lower (Figure 143, Figure 144).

Following the F-MSY-lower strategy is likely to increase the catches made by fleets fishing upon the central part of the Baltic Sea for cod fish (Figure 146, spatial distribution of catches). The effect of climate is to reduce these increased opportunities. However, when using lower FMSYs could have shocked the Baltic cod, sprat and herring fleets, the benefit on recovering populations might have been counteracted with the negative long term climate trend effect redirecting the pressure on eastern cod. The range contraction significantly reduces the spatial extent of the fishing ground but increases the fishing opportunities on the core areas, even if mostly farther from the coastline.

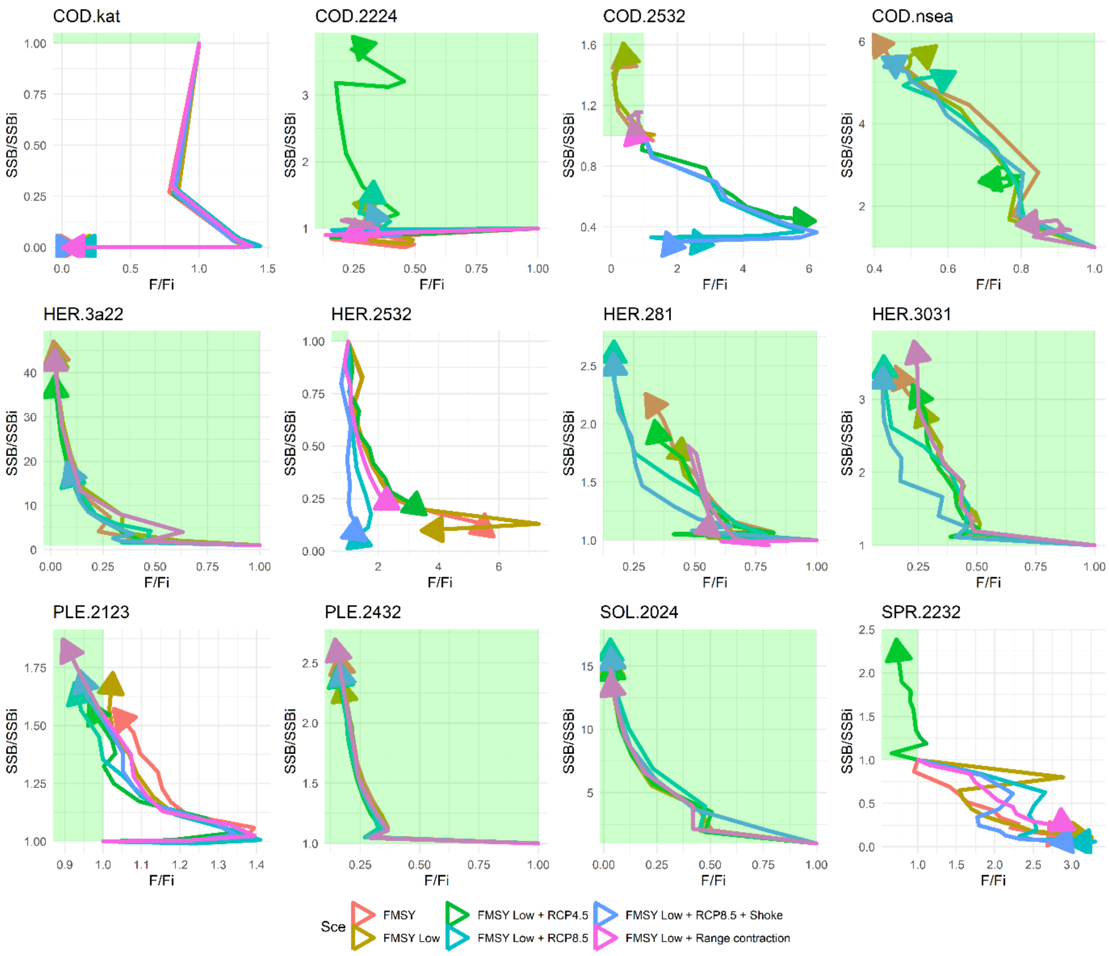

Figure 136 A bi-dimensional plot of average scenario outcomes on F/FMSY and SSB/SSBtrigger as simulated temporal trajectories from 2020 to horizon 2030. The wished green corner for the yearly drift of the indicators is the top left (i.e. increase in SSB, reduction in F, compared to initial values).

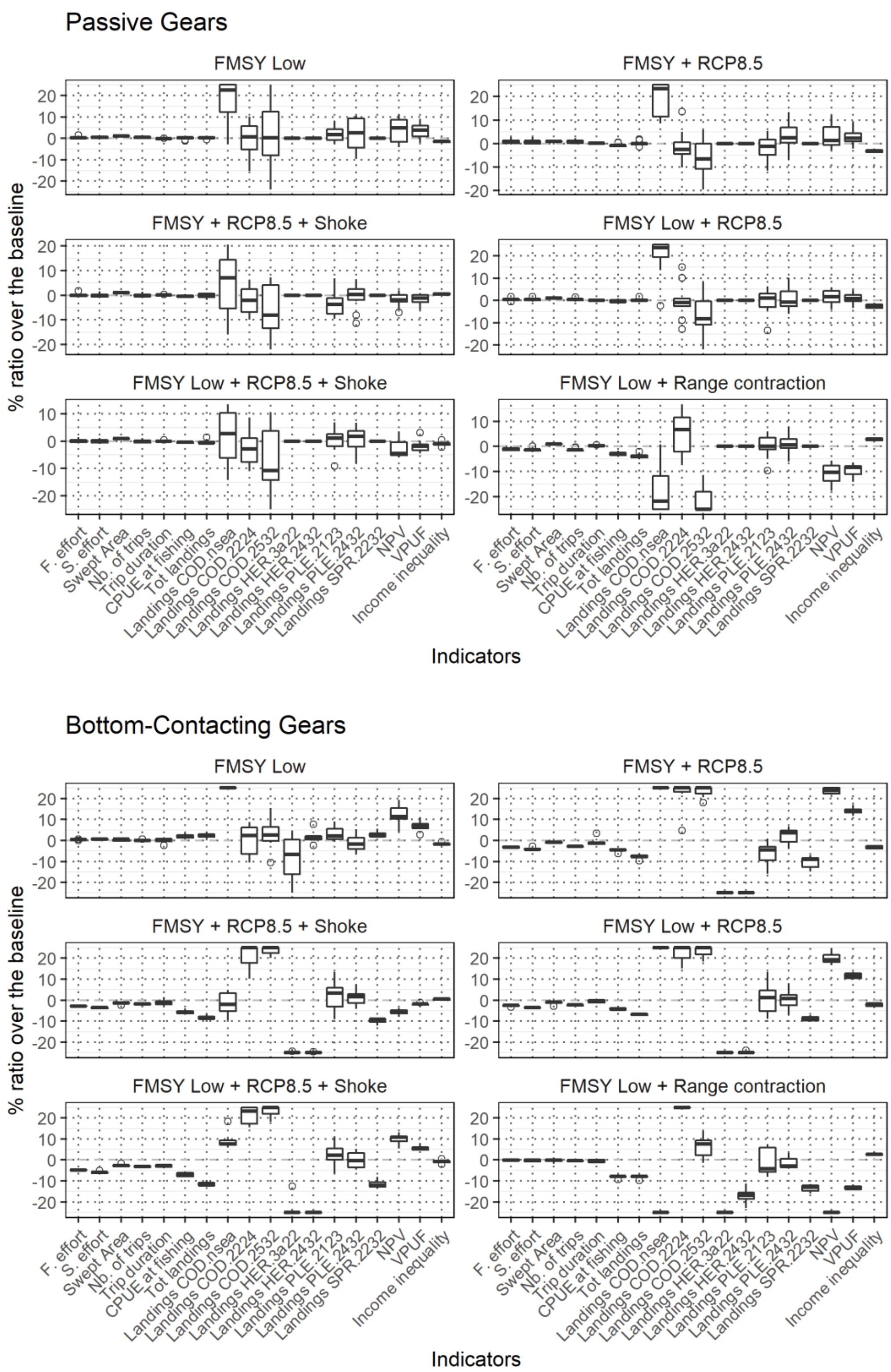

Figure 137 Fleet indicators integrating the differences to baseline (i.e. the FMSY-strategy alone) over the entire simulation period for selected scenarios. Indicators: Fishing Effort, Steaming Effort, Swept Area, Number of Trips, Trip duration, CPUE at fishing, Landed kg, Net Present Value (NPV), Value Per Unit of Effort (VPUF), and income inequality.

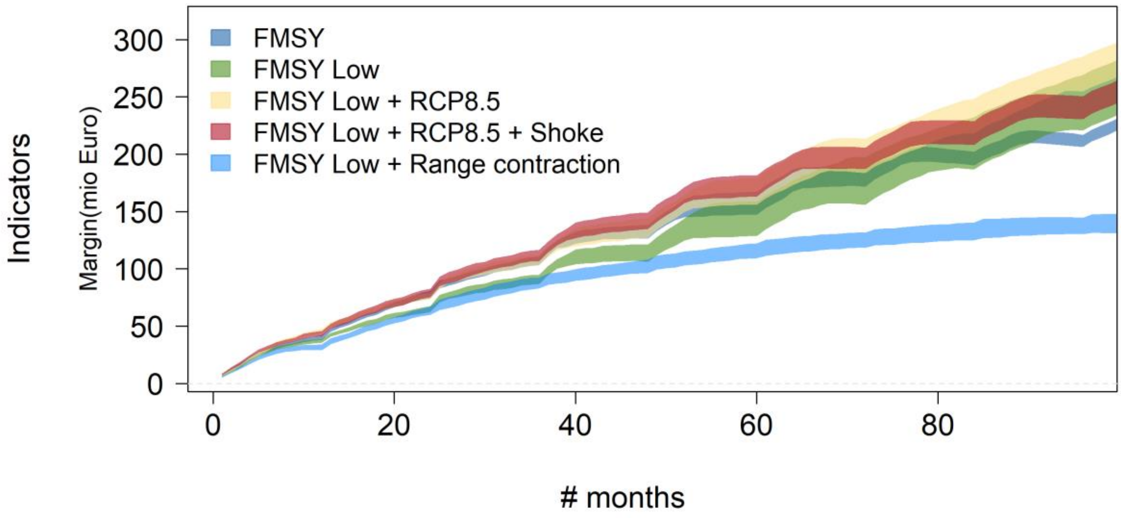

Figure 138 Simulated accumulated contribution margin (in millions euros, first removed) over the 10y for selected scenarios.

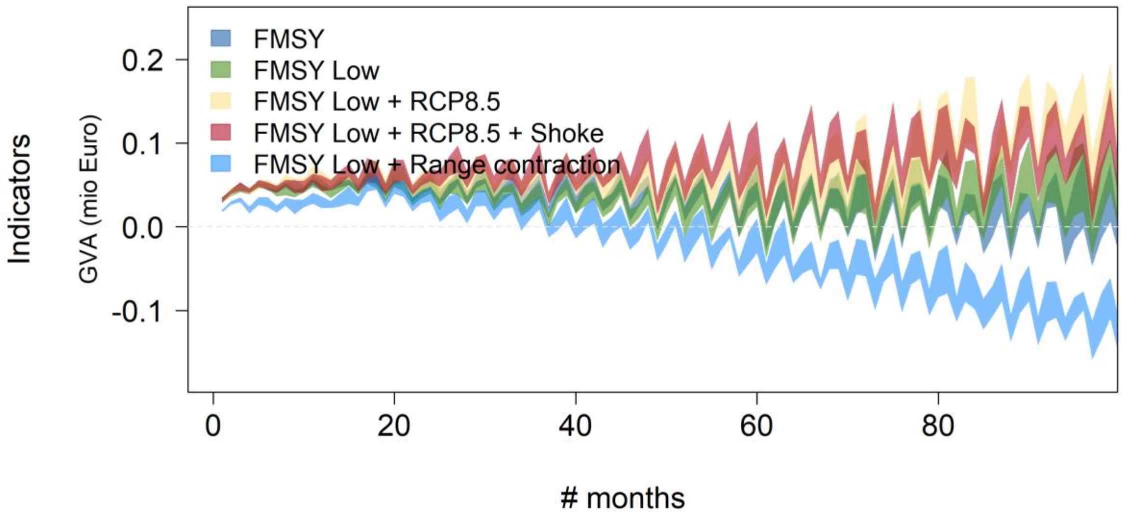

Figure 139 Monthly gross added value (GVA) calculated as a monthly average per vessel from all vessels fishing in the Baltic Sea combined for a selection of scenarios.

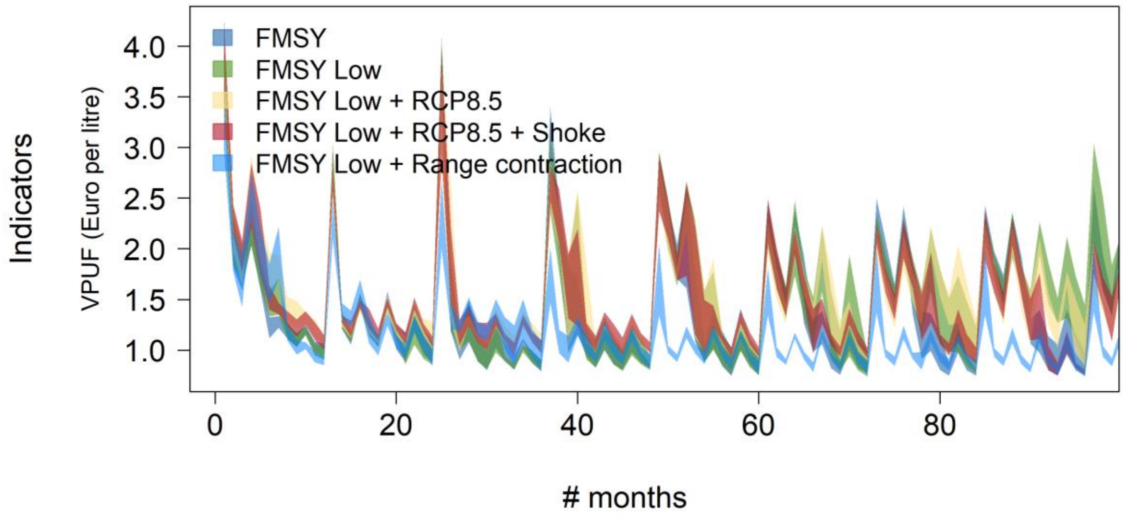

Figure 140 Monthly Value Per Unit Fuel (VPUF) as a proxy for energy efficiency calculated as a monthly average per vessel from all vessels fishing in the Baltic Sea combined for a selection of scenarios.

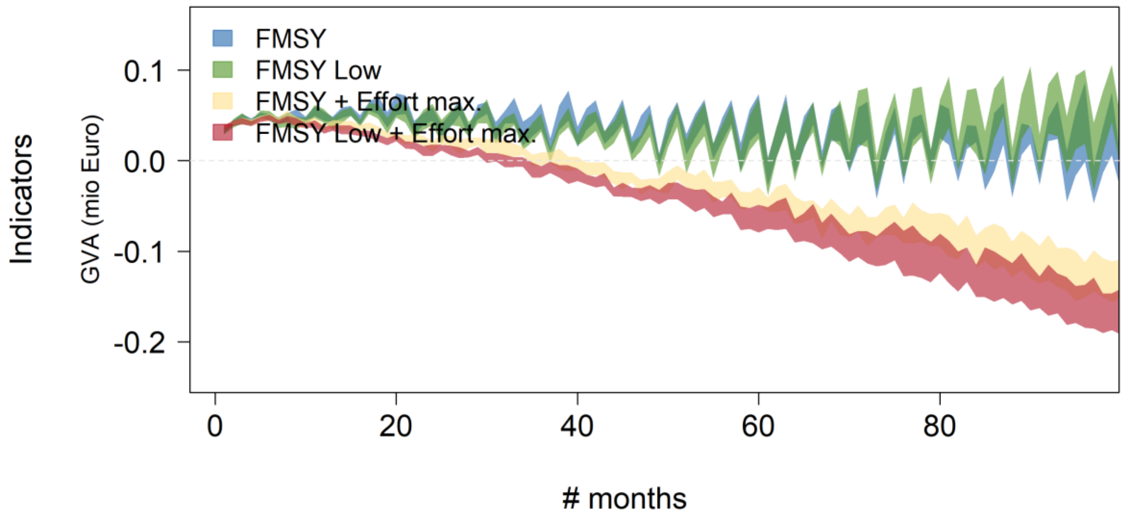

Figure 141 Monthly gross added value (GVA) calculated as a monthly average per vessel from all vessels fishing in the Baltic Sea combined for a selection of scenarios comparing compliance to the Landing Obligation (i.e. default is "stop fishing if choked") to non-compliance (continue fishing and discard i.e. "effort max." scenarios).

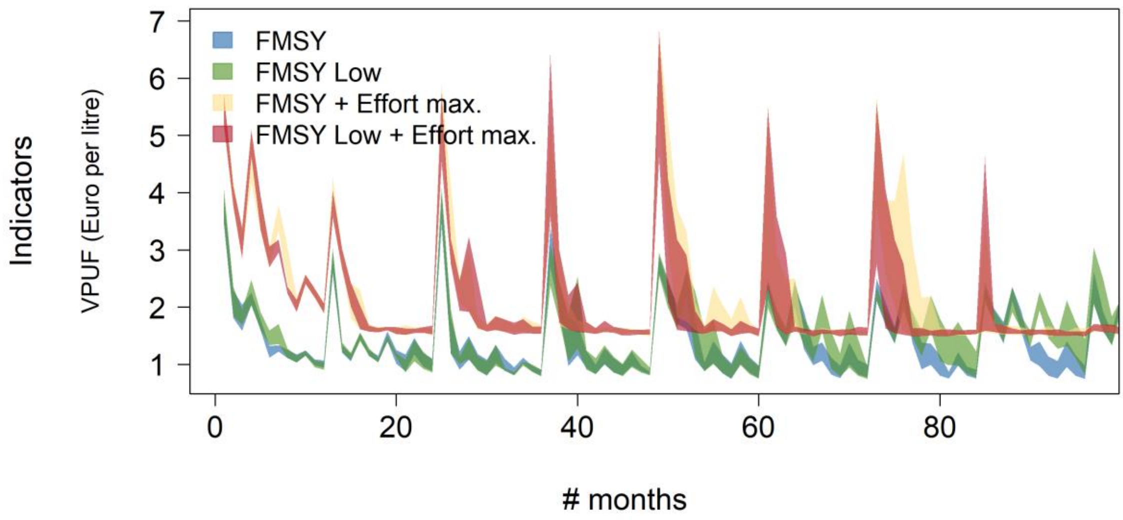

Figure 142 Monthly Value Per Unit Fuel (VPUF) calculated as a monthly average per vessel from all vessels fishing in the Baltic Sea combined for a selection of scenarios comparing compliance to the Landing Obligation (i.e. default is "stop fishing if choked") to non-compliance (continue fishing and discard, i.e. "effort max." scenarios).

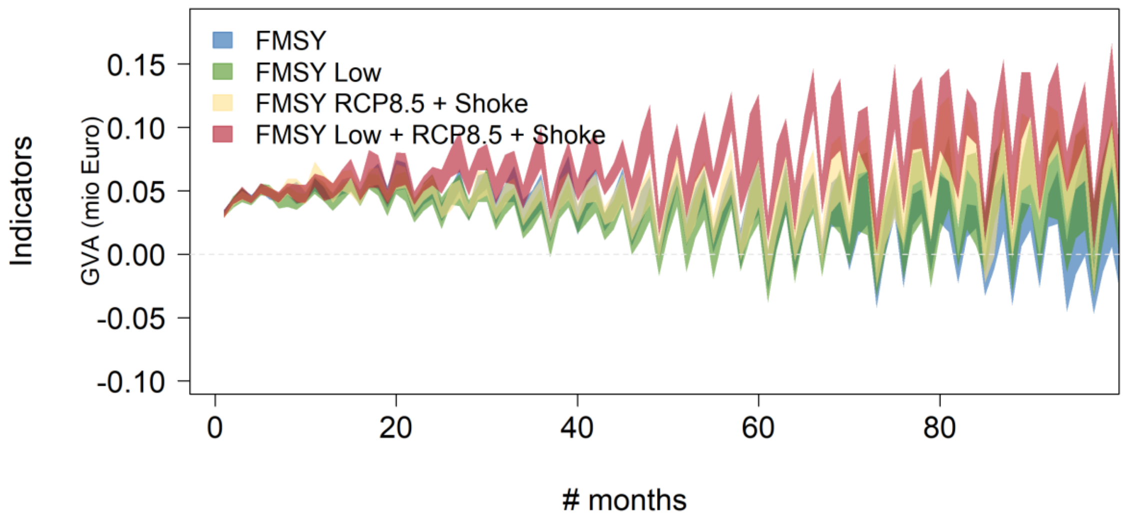

Figure 143 Monthly gross added value (GVA) calculated as a monthly average per vessel from all vessels fishing in the Baltic Sea combined for a selection of scenarios comparing FMSY vs FMSYlower in a situation or the absence of climate change.

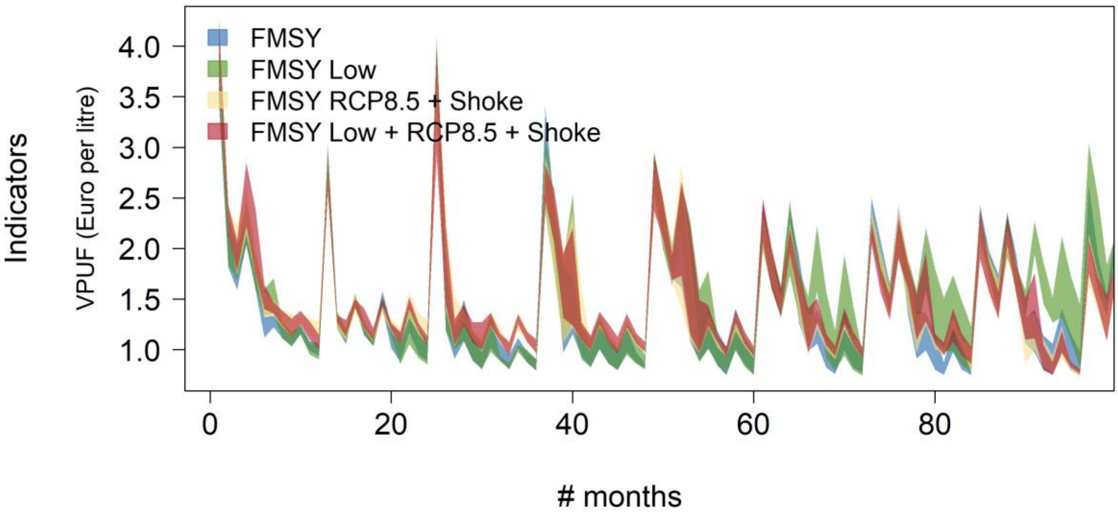

Figure 144 Monthly Value Per Unit Fuel (VPUF) calculated as a monthly average per vessel from all vessels fishing in the Baltic Sea combined for a selection of scenarios comparing FMSY vs FMSYlower in a situation or the absence of climate change.

Fleet-specific effects

However, climate change will likely reduce the benefits from lower yield in future for particular national fleets (Figure 145). It is apparent that none of the national fleets except the Danish fleet will benefit from climate change and some shock events, mainly because the pathways under the baseline F-MSY strategy are on declining trends. Besides this, some of the fleets (German, Lithuanian and Latvian fleets) might gain from a spatial range contraction, likely from a redistribution of resources spatially that make part of it inaccessible to some fleets and accessible to some others.

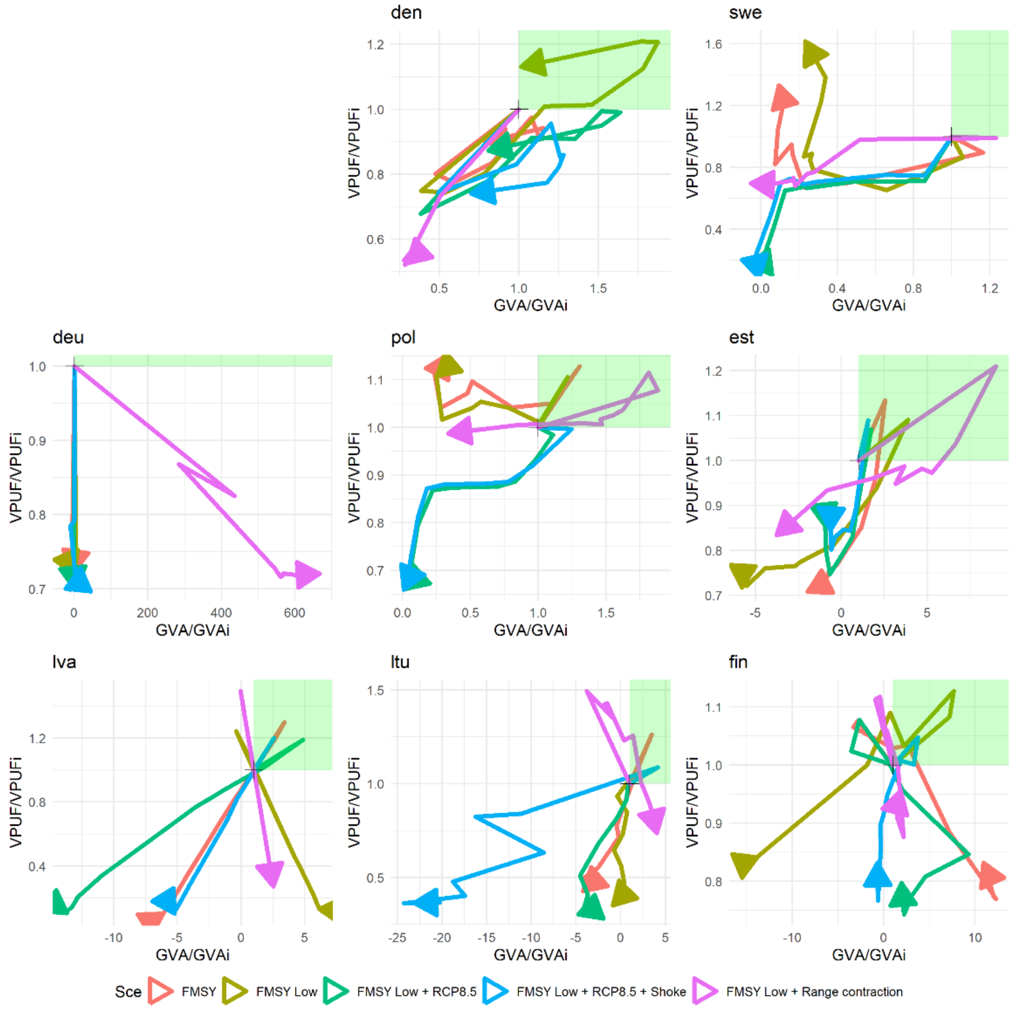

Figure 145 A bi-dimensional plot of average scenario outcomes on country-based ratios of VPUF/VPUFi and GVA/GVAi as simulated temporal trajectories from 2020 to horizon 2030. Countries are den: Denmark, swe: Sweden, deu: Germany, pol: Poland, est: Estonia, lva: Latvia, ltu: Lithuania, fin: Finland. The ratio at 1 on both indicators (symbol '+') gives the initial estimates in 2020—the wished green corner for the drift of the indicators in the top right.

The climate change-induced effects on the fleet economy in the Baltic Sea is also likely dependent upon the types of fishing methods (Figure 146). Passive gears (GNS) lose both in anticipated revenue and fuel efficiency in all scenarios. Pelagic OTM and PTM will also lose in GVA along with a gain in energy efficiency for PTM. On the contrary, SDN and OTB showed a marked improvement of both GVA and energy efficiency following the FMSY strategies but were downplayed by the climate-induced effects. PTB will gain on GVA but lose on energy efficiency.

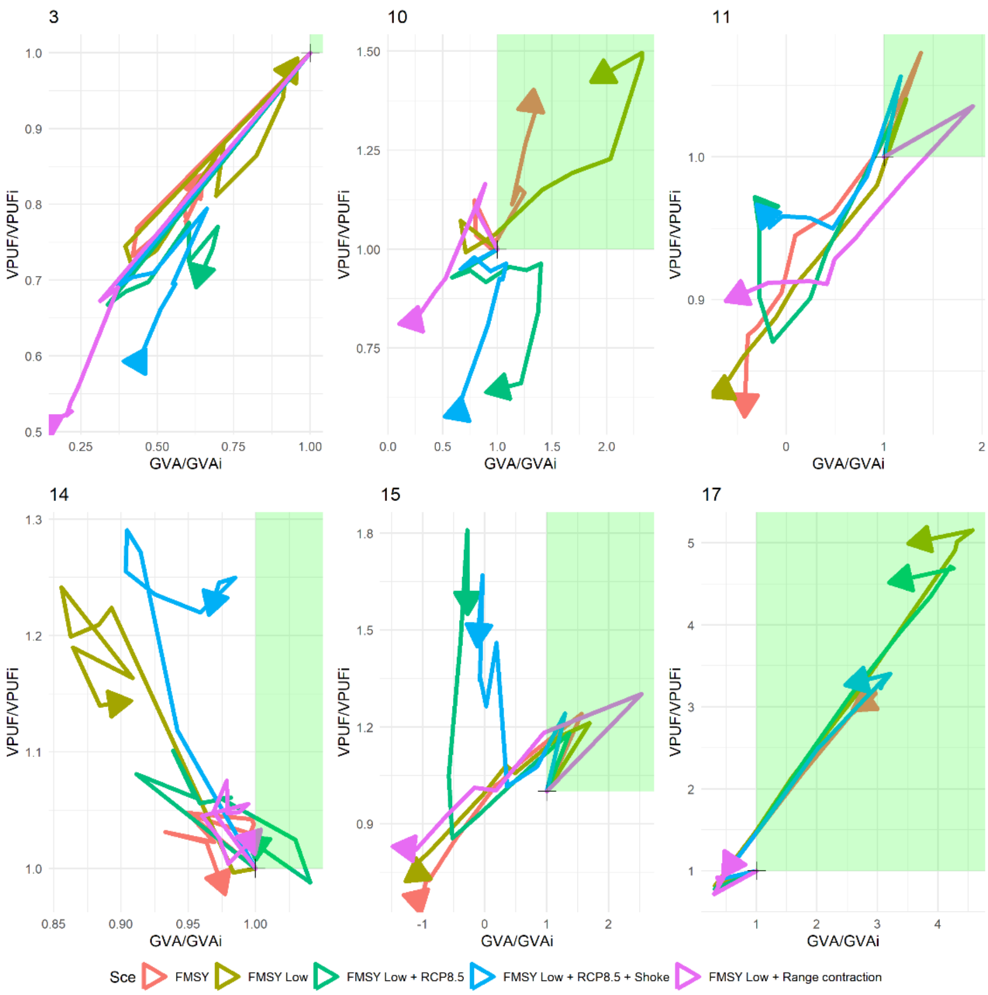

Figure 146 A bi-dimensional plot of average scenario outcomes on metier-based ratios of VPUF/VPUFi and GVA/GVAi as simulated temporal trajectories from 2020 to horizon 2030. Metiers/gear used are 3: GNS, 10: OTB, 11: OTM, 14: PTB, 15: PTM, 17: SDN. The wished green corner for the drift of the indicators in the top right.

More efficient fuel use effects

Vessels saving fuel when towing (e.g. from limiting the hydrodynamic drag required to tow the gear in contact with the bottom, or assuming less fuel intense gear specification for pelagics) led in the simulations to better development of anticipated revenue from fishing (Figure 147).

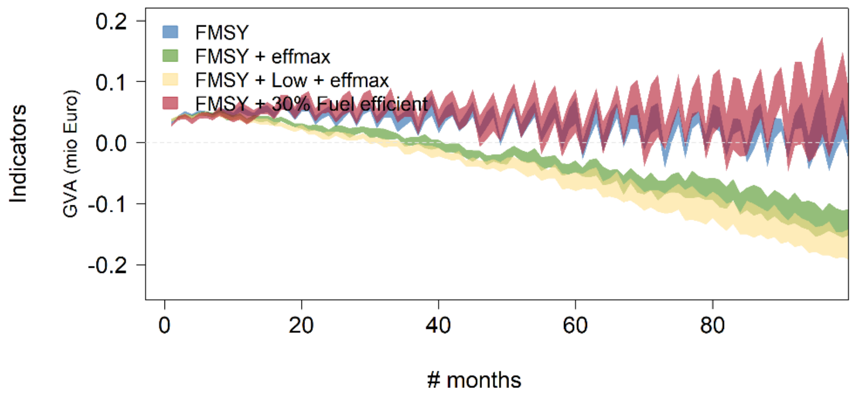

Figure 147 Monthly gross added value (GVA) calculated as a monthly average per vessel from all vessels fishing in the Baltic Sea combined for a selection of scenarios comparing FMSY vs FMSY_lower in a situation or the absence of climate change.

Besides the direct effect on reducing fuel costs, more fuel-efficient fishing has a marked indirect impact on west Baltic cod and plaice by increasing stock abundance (Figure 148) and subsequent TACs due to higher catch rates and less operating costs releasing the pressure on those stocks. Given the nature of the model, this change is likely the result of a change in spatial effort allocation, e.g. possibly toward more distant fishing grounds that are now becoming more attractive when the fuel is less limiting the expected profit on zones, a determining factor for vessels when selecting where to fish.

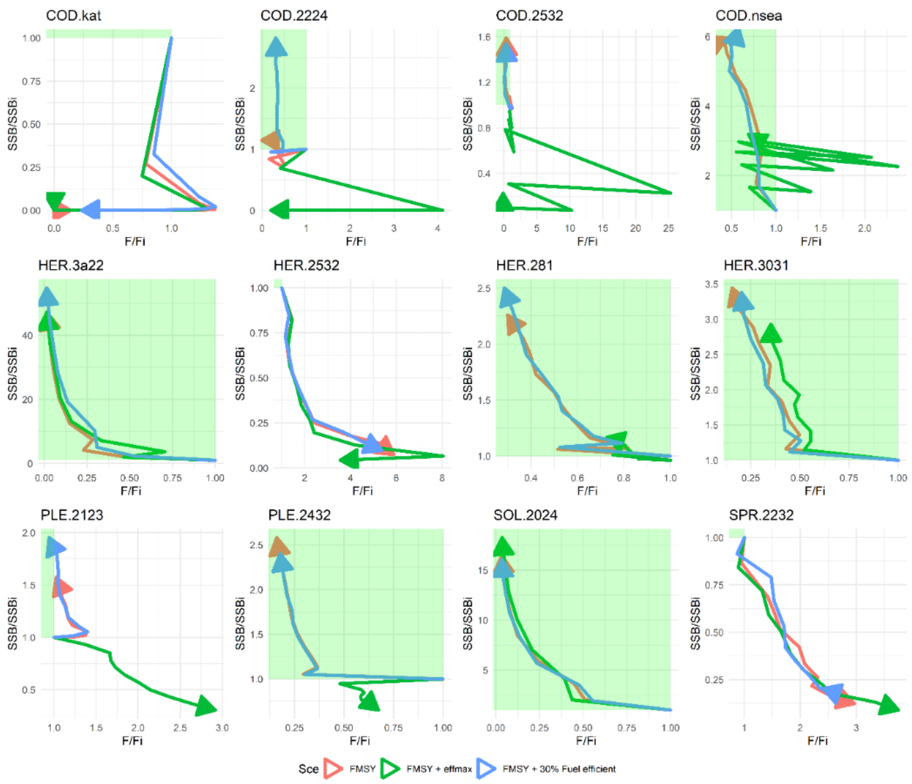

Figure 148 A bi-dimensional plot of average scenario outcomes on F/FMSY and SSB/SSBtrigger as simulated temporal trajectories from 2020 to horizon 2030. The wished green corner for the yearly drift of the indicators is the top left (i.e. increase in SSB, reduction in F, compared to initial values).

Concluding remarks and recommendations

All the plots can be retrieved from an R Shiny application delivered online (http://ono.dtuaqua.dk:8282/Baltic21). This eases the exploration of the outcomes across the species, fleets and scenarios. Probability plots to exceed or keep below references points are not shown because the simulation outcomes show that the system derives towards new levels below or above the references. Equally, no estimates are provided in terms of per cent change for both stock development and fleet economy, and time for recovery, as no recovery is observed at the scale of the study, but diverging paths instead.

Keep us in the green zone: The purpose of the fisheries management should be to implement rules that should keep the system in the green area (see the Kobe plots). Given that the FMSY approach is implemented in the current CFP, it is also questionable if it is sufficient to face new challenges such as climate change or if climate-aware fisheries management/harvest control rules should be added, including a revision of the reference points before they go outdated.

Overall, the simulation study shows that the F-MSY-lower does provide better pathways for future stock developments compared to F-MSY and is slightly more robust to climate change effects, including short-term shocks. Surprisingly, the simulations showed that these shocks might actually be beneficial along with following the FMSY-strategy (likely from counteracting density-dependence effects and effects mediated by the trophic interactions).

Because FMSY should be considered a limit and not a target per se, fishing at FMSY up to Fupper has regularly been criticized for putting future stocks at risk. The rationale for Fupper is to help the fishing sector to cope with possible choke species by mitigating the mixed fisheries issue often ignored. Here it is shown that indeed some TACs might choke some fisheries from time to time. Our findings also show that sticking to F-MSY lower is not rewarding for fishing in short to medium term because limiting the fishing opportunities with early closure. It does not appear that following an F-MSY strategy in the actual FMSY ranges is sufficient to counteract the risk induced by a changing climate, which seems especially acute on the Baltic herring stocks. The undesired trajectories are even more pronounced when vessels are not complying with the LO (i.e. GVA declines along with stock developments on collapse trajectories if vessels continue fishing after being choked). It comes as no surprise for modellers that it is indeed not coherent to increase the fishing pressure beyond FMSY and the associated operating variable costs to likely achieve poor yield and put some of the stocks (especially the short-lived ones like the pelagic herring and sprat) at risk of collapse (see, e.g. the discussion in Earle 2021 in ICESJMS doi:10.1093/icesjms/fsab037), as the Baltic Sea MAP would allow.

A fleet-based approach: When the LO is fully enforced, the simulations suggest that the most significant uncertainty for the stocks and fisheries facing climate change would arise from how the stock distribution would react spatially to a change in environmental drivers and tolerance limits. The loss or the redistribution of fishing areas and opportunities might not be compensated for, even if the stock is developing better under the FMSY-lower strategy. Hence, it is required to follow a fleet-based approach to identify who might be impacted and who contribute the most to degradation or who will be hit the most by the management or climate change.

Keep aware of the interlinked dynamics: Unfortunately, even in a simulation study, the interpretation of anticipated benefits is still uncertain because possible opportunity loss may arise either from degraded and degrading stocks or, on the contrary, from improved and improving stocks when some of the TACs are choking the fishing fleets. Therefore it appears that the best management is to match opportunities with the catch allowances and stock levels, which is mainly a challenge when technical and biological interactions are ruling.

Account for collateral effects: Fishing to FMSY should address other environmental concerns, i.e. "collateral" effects, i.e. on the ecosystem. Target/optimisation is of no use there, and the thinking is better on finding the way forward for minimizing the impacts of fisheries as the CFP specify it. This would require coherence among references levels to manage the fisheries. This includes fishing impacts on the seafloor and the benthic habitats, especially removing contradiction between the ones for sensitive species and habitat and the ones for commercially exploited species. Not saying anything about mixed fisheries and choke species. Such evaluation requires additional information to ensure the sustainability of the impact, as different fishing methods combined with the habitat's vulnerability and the fishing intensity. We first expected the energy efficiency to be related to the fishing footprint on such other ecosystem components of the marine ecosystem. However, our simulation study shows that the link is not straightforward, as saving fuel might sometimes lead some vessels to spend more time at sea instead of less. Hence, it is not apparent to the scientific community what is the best scientific rationale in advising special fishing gears in different areas. It might also be recognized that ten times fishing with less impacting gears might be just as harmful as one time fishing with more impacting fishing gear, which requires the trade-offs in fisheries management to be made well explicit. It is expected that evaluating the respective energy efficiency of different types of gears might help reconcile this apparent dilemma as, for now, the more energy-efficient fishing methods are also likely the less impacting gears. To minimize such effects, (e.g. the harmful fishing gears are also the ones spending more fuel at sea), management should also ideally account for spatial (e.g. closed areas) and non-spatial effort management (e.g. effort reduction plans) besides the output control TAC management.

Organize model coupling: To ease accounting for ecosystem models beyond single stocks or fleet-based approach, more than one model and more strategic models (i.e. ecosystem models) are required. Because one big complex model can quickly become untractable, a way forward is to arrange model coupling. Hence our simulation study could pass some viability check for the ecosystem by using its outcomes for informing the input of ecosystem models (e.g. use the effort time series or the exploitation patterns from different scenarios as input to ecosystem models)

More investigation on the fuel use intensity: The simulation shows no apparent link with the energy use intensity apart from saving on costs that benefit the economy of fishing. There are likely dominating compensatory/rebound effects that prevent saving fuel from stocks in better shape. We, however, showed a possible indirect effect arising from saving energy on fished stocks levels, including more time spent at sea or redirecting fishing toward areas that become attractive when fuel use is less limiting, which is possibly unwished side effects.

Limitations of the present simulation study

The study is not addressing possible important drivers in population dynamics, including:

- Predictions of harmful algal blooms and eutrophication zones;
- Identification of the impact of climate change on species diversity;
- A possible effect of a change in land use in the Baltic Sea catchment area including effects of pollution;
- Possible helpful management options such as the design of marine protected areas and other management measures;
- Understanding seasonal patterns of fish spawning and spatial migration.

The study is not addressing possible important drivers in fleet dynamics, including:

- Possible different fishing styles (e.g., risk-takers vs risk-averse fishers etc.)

- Profitability at the company level (possibly owning several vessels)
- Insurance against risks provided by POs or fishing communities, or quota swapping
- Fishing outside the known historical footprint
- An abrupt change in catching power from technological innovations
- Market integration and prices dynamics from external markets

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Annex 21 BAY OF BISCAY - SCENARIOS FOR ANCHOVY AND SIMULATION STRATEGY TO TEST RESOURCE RESILIENCE AND ECONOMIC IMPACT

Introduction

The anchovy (Engraulis encrasicolus) stock in the Bay of Biscay is distributed along the ICES Subarea 8 and is considered to be isolated from a small population in the English Channel and from the populations in western Iberia. Thus, ICES considers that the anchovy in this area should be dealt with as a single stock for assessment and management (ICES, 2020). It is mainly targeted by Spanish purse-seiners and French purse-seiners, and pelagic trawler fleets. The fisheries were closed from July 2005 to December 2009 due to poor condition of the stock, and it was reopened in 2010. In 2013 and 2014, the STECF evaluated a set of harvest control rules to manage the Bay of Biscay anchovy stock (STECF, 2013; STECF 2014). In 2016 The harvest control rule named "G3" was evaluated to be precautionary and was chosen to form the basis of the ICES annual advice. This stock is evaluated yearly using an analytical stock-assessment model, and the TAC is established by applying the agreed management plan. Nowadays, the stock is considered healthy, with the highest estimated SSB values in the available time series.

Defining plausible, ecosystem-coherent scenarios

A literature review on the current state of knowledge about environmental/climate effects on this stock was conducted. It has been seen that the spawning peak advanced at a rate of 5.5 days/decade from 1987 to 2015, and the gonadosomatic index (as a proxy of spawning activity) generally increased (Erauskin-Extramiana et al., 2019b). This might be associated with changes in primary production, which anchovy feeds on. The sea warming and the changes in other oceanographic variables related to climate change for the end of the century could lead to a larger increase on anchovy egg density in its spawning area according to the ecological niche models (Erauskin-Extramiana et al., 2019b). Enhanced recruitment is also expected due to water enrichment through upwelling from March to May (Allain et al. 2007, Andonegi et al. 2011) and the retention of larvae and juveniles over the French shelf from May to September (Allain et al. 2007). Concerning the growth, smaller individuals related to a decrease in zooplankton concentration or Zooplankton phenology shift to a late-winter bloom (Perk et al., 2020). A decreasing trend in weight at age has been observed during the last decade. Lower survival scenarios have also been reported in relation to the advection of larvae due to dominant north-easterly winds in summer (Cotano et al. 2008) or due to turbulence-induced temperature decrease and wind-induced transport to unfavourable conditions areas due to strong winds (Allain et al. 2007). Table 51 provides a summary of ecosystem drivers and possible effects.

Table 51 Examples of linkages per stock/fishery in order to design plausible scenarios for environmental changes and possible responses further investigated in the simulation studies.

Fish stock/fishery	Possible drivers	Possible effects	Possible impacts
European anchovy	Warmer temperature (2) Warmer temperature (1) Decrease in zooplankton concentration (1) Zooplankton phenology shift to a late-winter bloom (1)	Occupation of other areas (2) Growth rate (1)	Dispersed distribution (2) Anchovy biomass increase (1) Smaller individuals (1)

	North-easterly winds from March to September (3)		Enhanced recruitment (3, 4)
		Water enrichment through upwelling from March to May (3)	Enhanced recruitment (3)
		Retention of larvae and juveniles over the French shelf from May to September (3)	
	Dominant north-easterly winds in summer (5)	Advection of larvae (5)	Lower survival (5)
	Winds stronger than 14-15 m/s for 2 days or stronger than 12-13m/ for 4 days (3)	Turbulence-induced temperature decrease and wind-induced transport to unfavourable areas (3)	Lower survival (3)
	Phytoplankton increase (6)	Anchovy spawning peak advance in a rate of 5.5days/decade and increase of GSI and thus egg production (6)	Expansion of spawning area (6)

Defined scenarios
Proposed scenarios do not cover all the possible climate effects reviewed in the literature. Some of them have been selected based on data availability and software capability. No quantitative relationships are available, and they have to be set arbitrarily.

Long-term changes
- Mortality: lower survival due to advection of larvae (most likely and worst-case scenarios are implemented).
- Recruitment: increasing trend in recruitment (most likely and worst-case scenarios are implemented).
- Growth: decreasing trend of individual’s weight at age (most likely and worst-case scenarios are implemented).
- Combination of growth and recruitment changes.

Short term shock
- Recruitment failure (corresponding to the occurrence of storms in spring) in the first year of simulation (most likely scenario) and for a second random year (worst case scenario).

Long-term changes are combined with short-term shock.

Assessing resource and economic resilience
To carry out the analysis an age-structured Management Strategies Evaluation (MSE) model is used implemented in the FLBEIA R package. The model is based on the model used for the “Evaluation /Scoping of Management plans - Data analysis for support of the impact assessment for the management plan of Bay of Biscay anchovy” (STECF, 2014) (Figure 149).

The historic assessment until 2020 (Bayesian stock-assessment model output consisting of 500 MCMC iterations) is used to condition an Operating Model (OM), which is then be projected forward to 2030, under an agreed set of climate scenarios linked to hypotheses about biological and ecological processes. In addition, the OM is projected to 2050 to evaluate expected equilibrium behaviour.

Operating model

The population dynamics is described in terms of numbers at age (with age groups 0, 1, 2 and 3plus) by semesters (i.e. on half year basis). Recruitment, which refers to the number of individuals at age 0, enters the population at the beginning of the second semester. Uncertainty on recruitment in the projection period is introduced using the residuals from the fitting of the Ricker stock-recruitment model. The population dynamics are modelled using an exponential mortality model with the Pope's approximation to F. Recruitment is modelled as a function of the spawning stock biomass at the middle of the year, according to a Ricker stock-recruitment model. There is one fleet operating in each semester. As there was no data available to include the effort dynamics, it is assumed that all the TAC is taken.

Observation error

Estimates of biomasses are simulated independently in the MSE loop as a random observation of the biomasses at age 1 and at age 2+ respectively, both taken from lognormal distribution with mean (in log scale) equal to the OM Biomass by age in January of the assessment year and a standard deviation corresponding to a CV=0.25.

Management procedure

The assessment process is considered together with the observation process in the MSE loop. This is so because the stock assessment process could not be included in the MSE loop. The TAC is set following the agreed management plan, using the following harvest control rule:

$$TAC_{y+1} = \begin{cases} 0 & if\ \widehat{SSB}_{y+1} \leq 24000 \\ -2600 + 0.40 \cdot \widehat{SSB}_{y+1} & if\ 24000 < \widehat{SSB}_{y+1} \leq 89000 \\ 33000 & if\ \widehat{SSB}_{y+1} > 89000 \end{cases}$$

where SSBy+1 is the expected spawning-stock biomass in mid-May year y+1.

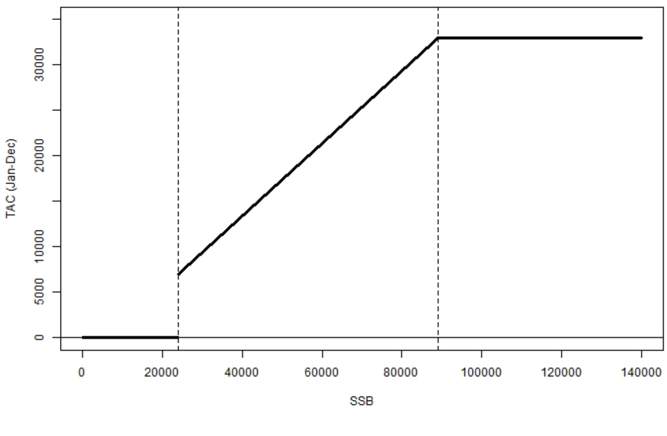

Figure 149 Harvest control rule implemented agreed in the management plan for anchovy in BoB and implemented for the simulation work.

Implementation of climate change scenarios

Five different climate effects have been tested in this case study, for each of the effects, an intermediate scenario (most likely scenario) and a pessimistic scenario (worst case scenario) have been implemented, as well as the status quo scenario. The long-term climate effects have after been combined with the short-term shocks. A total of 19 cases were implemented (Figure 150, Figure 151, Figure 152).

- No climate change effect (status quo)
  - Projections starting in 2021 are carried out following the conditioning based on the last stock assessment (2020).
- Shock effect (applied to status quo)
  - Most likely scenario: the recruitment in 2021 is decreased to a 10% of the expected recruitment without a shock.
  - Worst case scenario: another random shock year is simulated in addition to the 2021 shock during the first 10 projection years.
- Lower survival effect (with and without shock effect)
  - Most likely scenario: the natural mortality for age 0 was increased a 30% of the original M value (leading to a M~0.52 for age 0).
  - Worst case scenario: the natural mortality for age 0 was increased a 50% of the original M value (leading to a M~0.6 for age 0).
- Decreasing weight at age effect (with and without shock effect)

  A linear regression was performed for the anchovy weight at age with the last 15 years data obtaining an estimated negative slope.

  - Most likely scenario: this trend is extended with an asymptotic shape, reaching a lowest values of 9gr for age one individuals in the first 10 years of projection period.

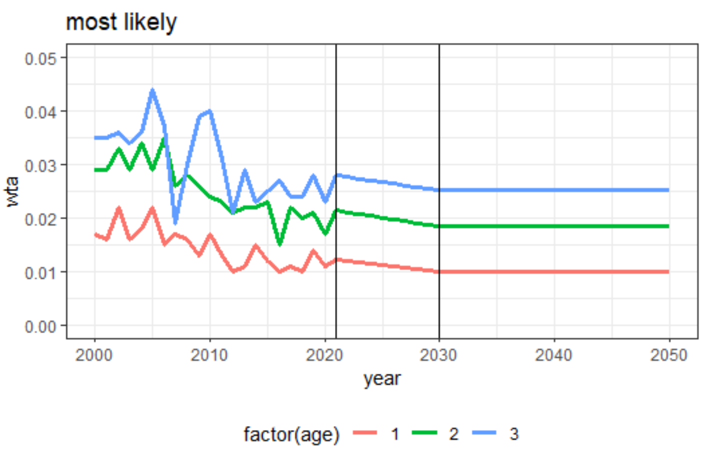

Figure 150 Historical and assumed weights at age for the most likely scenarios.

- Worst case scenario: this value is decreased until 7gr (lowest values recorded for other anchovy stocks) gradually during the first 20 projection years.

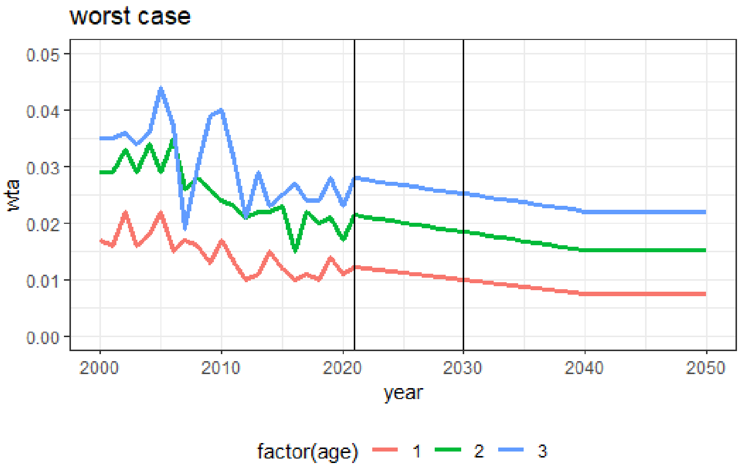

Figure 151 Historical and assumed weights at age for the worst case scenarios.

- Enhanced recruitment effect (with and without shock effect)

A Ricker stock-recruitment relationship is used to model recruitment in the projection period for this stock. The fitting to different length time series have been analysed in order to quantify the change in the SR relationship over time. The difference between the SR curve fitted to the series 1987-2008 and the fitted curve for the series 2008-2020 (used as status_quo) was quantified. The change in the alpha and beta parameters was used as a base to define the most likely and the worst-case scenarios.

- Most likely scenario: the alpha parameter of the Ricker SR obtained for the period 2008:2020 has been multiplied by 1.2
- Worst case scenario: the alpha and beta parameters of the Ricker SR obtained for the period 2008: 2020 have been multiplied by 1.2 and 0.8, respectively.

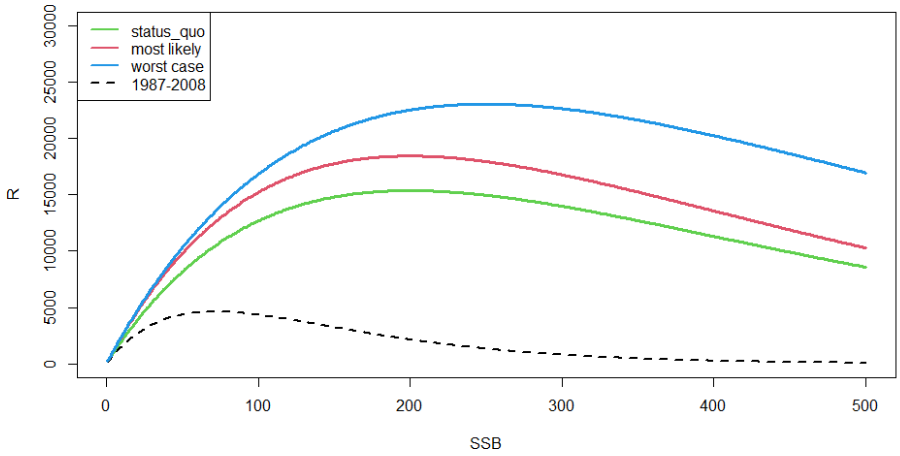

Figure 152 Stock-recruitment Ricker curves used for different scenarios.

- Enhanced recruitment + Decreasing with at age effect (with and without shock effect)
    - Most likely scenario: Most likely scenario for enhanced recruitment + Most likely scenario for decreasing weight at age
    - Worst case scenario: Worst case scenario for enhanced recruitment + Most likely scenario for decreasing weight at age

Economic component

No changes in the fleet's dynamics have been projected, assuming current dynamics for future simulated years. Thus, costs are assumed to be invariant in projections year, focusing on the change on the income.

Prices were obtained from first sale notes from Spanish catches between 2014 and 2017, and averages were computed to use as final prices. These prices are variable depending on the anchovy size, which has also been taken into account. Price categories are given in terms of the number of individuals per kilogram (Figure 153), from where the equivalent weight was computed for each price category (as w=1/units). This weight-price relation was then used to compute the income from the catches at age for each scenario.

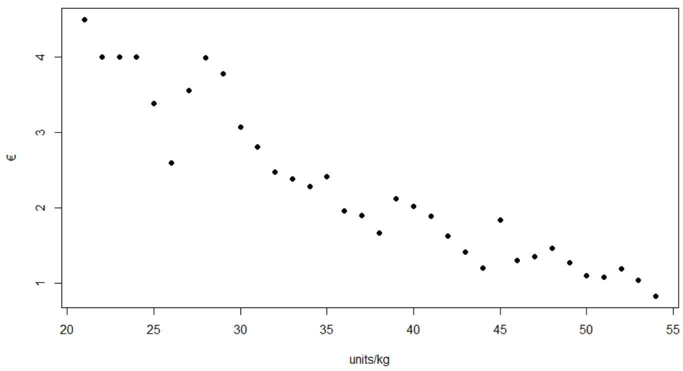

Figure 153 Prices for anchovy in the BoB by units/kg categories used for the simulation work.

Comparison of climate change scenarios
Stock trajectories over the 10 and 50 projected years have been compared in terms of SSB, and relative income. Median values and 5% and 95% quantiles have been computed from the 500 iterations run for each climate effect and scenario. Indicators such as Amplitude, Responsiveness, Recovery rate, Recovery speed or the relative income have also been computed (Figure 154).

Results
The anchovy in the Bay on Biscay case study shows that short term shocks under long-term climate effects result in median SSB values that are lower than the status quo levels (expect for the enhanced recruitment scenario, where the stock SSB increases) but are still well above Blim. The SSB level at which the stock stabilises in the long term seems to be determined by the long-term climate effect and is not modified by the short term shocks. However, the time needed to reach this stabilisation is affected by the short term shock, needing a longer period for the worst-case scenarios. Results for each tested case are shown separately below.

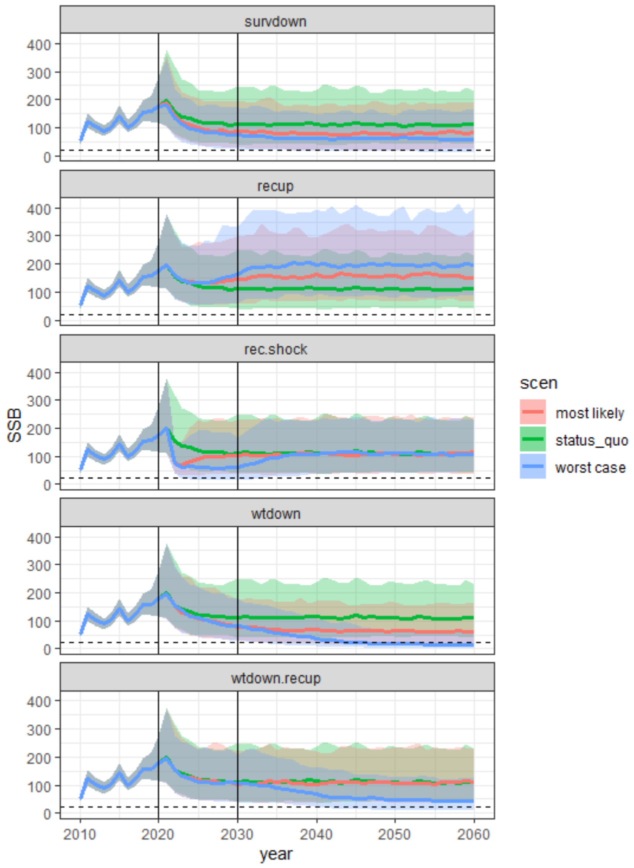

Figure 154 Spawning stock biomass (SSB) by climate change effects and scenarios. Solid vertical black lines indicate the starting projection year (2021) and the 10 years time horizon (2030). Horizontal dashed lines denote Blim reference point. For each scenario ("scen"), shaded and coloured areas show the 5% and 95% quantiles and solid coloured lines show the median of all runs (n = 500). Green colour represents the status quo scenario (same for all panels) and red and blue represent the most likely and worst case scenarios respectively, for each climate effect (survdown stands for the dressing trend in age 0 survival, recup stands for increasing tren in recruitment, rec.shock stands for punctual decrement on recruitment, wtdown stands for decreasing trend on weights at age, wtdown.recup stands for the combination of the last to effects; the most likely scenario for recup with the two scenarios for wtdown).

- Status quo

After some very high SSB values in the last years of the historical series, due to the conditioning on mean values, the stock stabilises around recent period mean values of approx. 110 thousand t, well above Blim (21 thousand t). The probability of being below Blim is lower than 5%, along the projection period. Catches oscillate around the maximum allowed by the agreed harvest control rule, and the income respect 2020 does not show changes along the projection period in median (Figure 155, Figure 156).

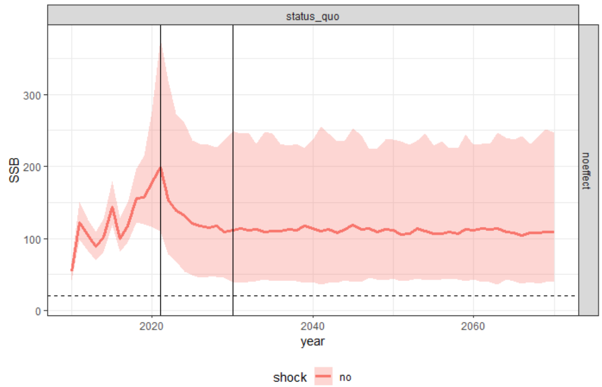

Figure 155 Spawning stock biomass (SSB) for the status quo scenario. Solid vertical black lines indicate the starting projection year (2021) and the 10 years time horizon (2030). Horizontal dashed lines denote Blim reference point. Shaded and coloured areas show the 5% and 95% quantiles and solid coloured lines show the median of all runs (n = 500). Red colour represents the scenarios without short-term shock and the blue colour represents scenarios with short-term shock.

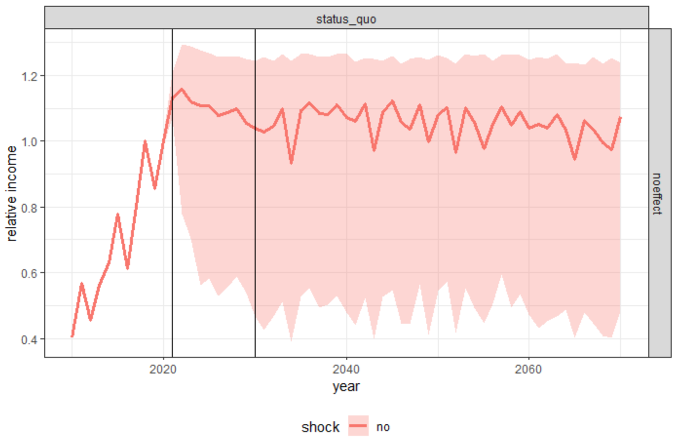

Figure 156 Relative income (computed as the ratio between the computed income in each iteration and the median income from the status quo scenario in 2020) for the status quo scenario. Solid vertical black lines indicate the starting projection year (2021) and the 10 years time horizon (2030). Horizontal dashed lines denote Blim reference point. Shaded and coloured areas show the 5% and 95% quantiles and solid coloured lines show the median of all runs (n = 500). Red colour represents the scenarios without short-term shock and the blue colour represents scenarios with short-term shock.

- Shock effect

For the most likely scenario, the shock results in a large SSB reduction in the first year. It is able to recover to values near the status quo by 2030. It has a big effect in the very short term (5 years) not in the medium and long term.

For the worst-case scenario the shocks result in a large SSB reduction in the first years. The median SSB in 2030 is 40% lower in comparison with the status quo, is able to recover to these values by 2040. It has a big effect in the very term (10 years) and in the medium term, not and long term. The probability of being below Blim in the short term is >5%.

Total catches decrease around during the first years. They reach maximum values again by 2040. The relative income decreases to half of the income for the worst-case scenario in the very short term, however it is recovered to the reference value in the long term for both scenarios (Figure 157, Figure 158).

Figure 157 Spawning stock biomass (SSB) for the status quo scenario with and without shocks. Solid vertical black lines indicate the starting projection year (2021) and the 10 years time horizon (2030). Horizontal dashed lines denote Blim reference point. Shaded and coloured areas show the 5% and 95% quantiles and solid coloured lines show the median of all runs (n = 500). Red colour represents the scenarios without short-term shock and the blue colour represents scenarios with short-term shock. Each panel represents an scenario; most likely or worst case.

Figure 158 Relative income (computed as the ratio between the computed income in each iteration and the median income from the status quo scenario in 2020) for the status quo scenario with and without shocks. Solid vertical black lines indicate the starting projection year (2021) and the 10 years time horizon (2030). Horizontal dashed lines denote Blim reference point. Shaded and coloured areas show the 5% and 95% quantiles and solid coloured lines show the median of all runs (n = 500). Red colour represents the scenarios without short-term shock and the blue colour represents scenarios with short-term shock. Each panel represents an scenario; most likely or worst case.

- Lower survival effect (with and without shock effect)

Fort the most likely scenario without shocks, this climate effect results in a gradual decrease of the SSB for the short and long term, stabilising at around 73% of the median SSB level in the status quo scenario. The effect in the short term is kept in the long term. The probability of being below Blim is below 5% along the projection period. When a shock applied, SSB levels decrease even more in the first year and are below the SSB levels without the shock. The probability of being below Blim is still below 5% along the projection period, reaching the same SSB levels as the case without shock by 2040 (Figure 159, Figure 160).

For the worst-case scenario without shocks, this climate effect results in a gradual decrease of the SSB for the short and long term, stabilising at around 55% of median SSB level in the status quo scenario. The effect in the short term is kept in the long term. The probability of being below Blim in the short and long term is >5%. When a shock applied SSB levels in the first year decrease even more and are below the SSB levels without the shock. The probability of being below Blim is above 5% along the projection period, reaching the same SSB levels as the case without shock by 2060.

Total catches decrease gradually and stabilise in the long term. The relative income stabilises around a 75% of the 2020 median income for the most likely scenario while it decreases to a 50% for the worst-case scenario. When shocks are applied the decrease in the first years is higher and faster, reaching similar levels to the case without shock from 2040 on.

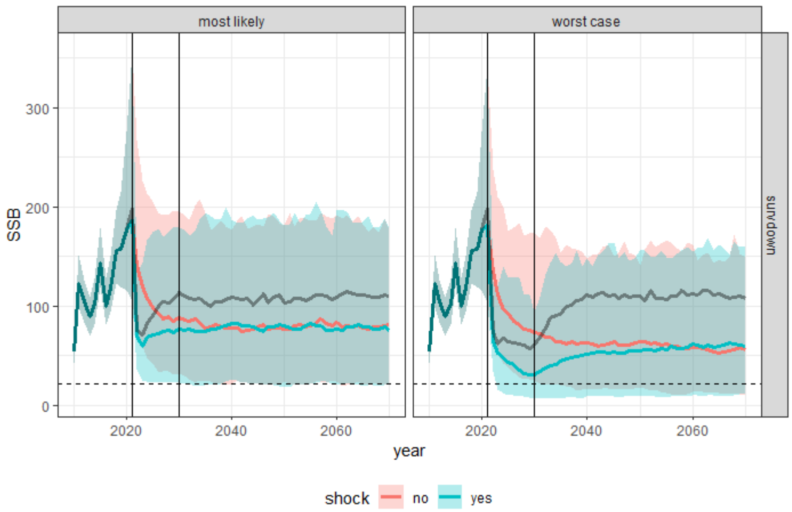

Figure 159 Spawning stock biomass (SSB) for the lower survival climate effect with and without shocks. Solid vertical black lines indicate the starting projection year (2021) and the 10 years time horizon (2030). Horizontal dashed lines denote Blim reference point. Shaded and coloured areas show the 5% and 95% quantiles and solid coloured lines show the median of all runs (n = 500). Red colour represents the scenarios without short-term shock and the blue colour represents scenarios with short-term shock. They gray solid lines represent the equivalent median values for the status quo scenario with shocks. Each panel represents an scenario; most likely or worst case.

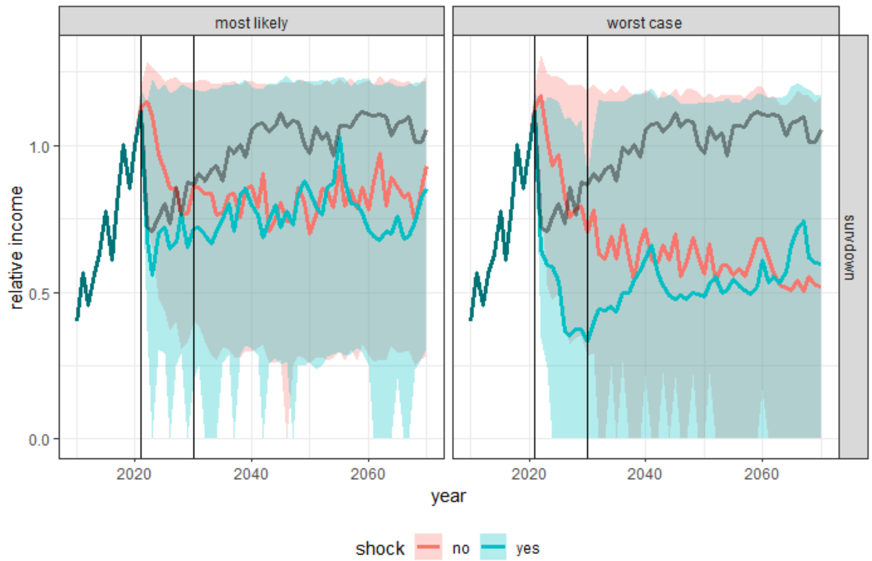

Figure 160 Relative income (computed as the ratio between the computed income in each iteration and the median income from the status quo scenario in 2020) for the lower survival climate effect with and without shocks. Solid vertical black lines indicate the starting projection year (2021) and the 10 years time horizon (2030). Horizontal dashed lines denote Blim reference point. Shaded and coloured areas show the 5% and 95% quantiles and solid coloured lines show the median of all runs (n = 500). Red colour represents the scenarios without short-term shock and the blue colour represents scenarios with short-term shock. They gray solid lines represent the equivalent median values for the status quo scenario with shocks. Each panel represents an scenario; most likely or worst case.

- Decreasing weight at age effect (with and without shock effect)

Fort the most likely scenario without shocks, this climate effect results in a gradual decrease of the SSB for the short and long term, stabilising at around 55% of median SSB level in the status quo scenario by 2040. The effect in the short term is increased in the long term. The probability of being below Blim in the short term is <5%, although not in the long term. When a shock is applied SSB levels in the first year decrease even more and are below the SSB levels without the shock. The probability to be below Blim is still below 5% in the short term, although not in the long term, reaching the same SSB levels as the case without shock by 2040 (Figure 161, Figure 162).

For the worst case scenario without shocks this climate effect results in a gradual decrease of the SSB for the short and long term, stabilising at around a 55% of median SSB level in the status quo scenario by 2040. The effect in the short term is increased in the long term. The probability of being below Blim in the short term is <5%, although not in the long term. When a shock is applied SSB levels in the first year decrease even more and are below the SSB levels without the shock. The probability to be below Blim is now above 5% along the whole projection period, reaching the same SSB levels as the case without shock by 2050.

Total catches decrease gradually and stabilise in the long term (not for the worst-case scenario that keeps decreasing until recurrent fishery closures.) The relative income stabilises around 55% of the 2020 median income for the most likely scenario in the long term. In the short term, both scenarios present a 75% relative income.

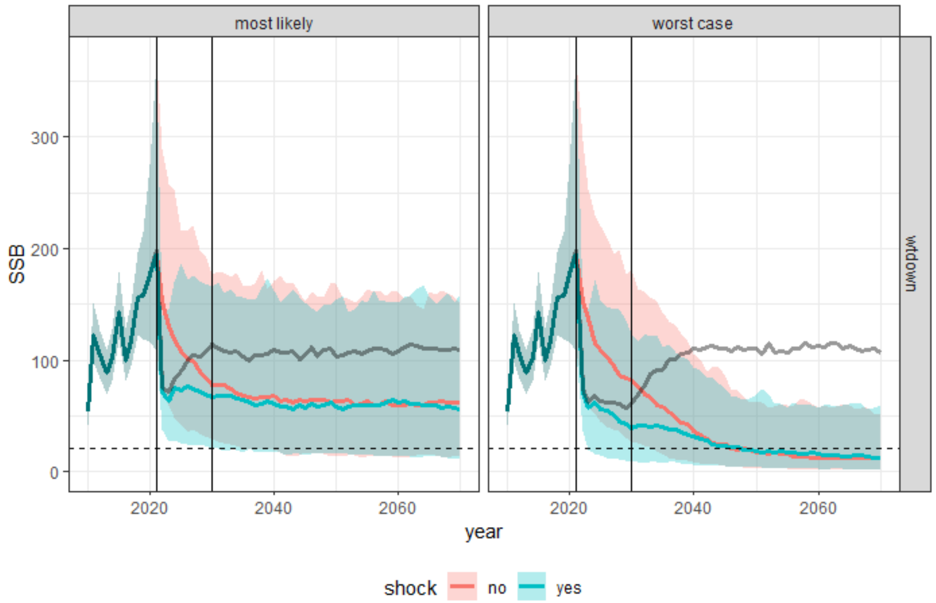

Figure 161 Spawning stock biomass (SSB) for the decreasing weight at age climate effect with and without shocks. Solid vertical black lines indicate the starting projection year (2021) and the 10 years time horizon (2030). Horizontal dashed lines denote Blim reference point. Shaded and coloured areas show the 5% and 95% quantiles and solid coloured lines show the median of all runs (n = 500). Red colour represents the scenarios without short-term shock and the blue colour represents scenarios with short-term shock. They gray solid lines represent the equivalent median values for the status quo scenario with shocks. Each panel represents an scenario; most likely or worst case.

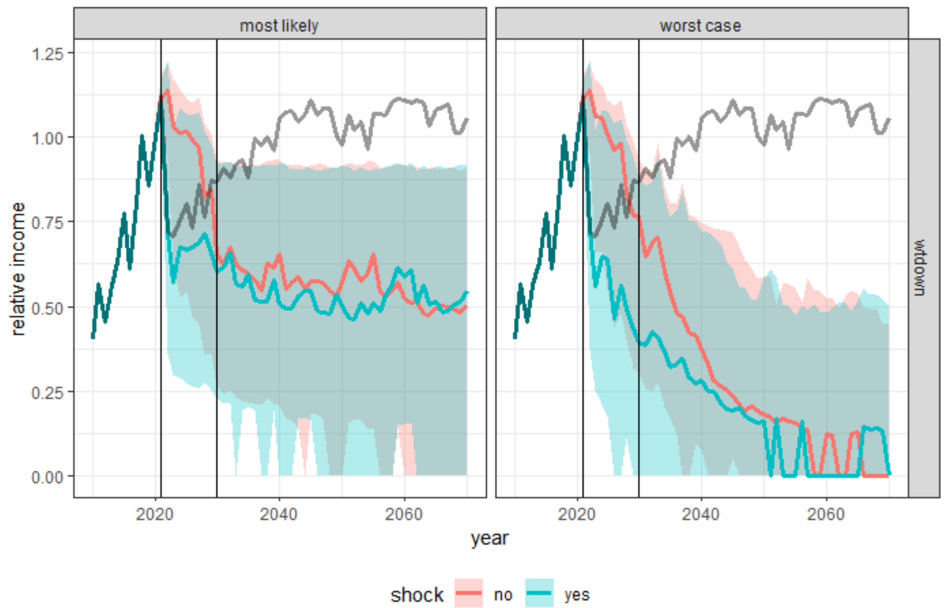

Figure 162 Relative income (computed as the ratio between the computed income in each iteration and the median income from the status quo scenario in 2020) for the decreasing weight at age climate effect with and without shocks.

Solid vertical black lines indicate the starting projection year (2021) and the 10 years time horizon (2030). Horizontal dashed lines denote Blim reference point. Shaded and coloured areas show the 5% and 95% quantiles and solid coloured lines show the median of all runs (n = 500). Red colour represents the scenarios without short-term shock and the blue colour represents scenarios with short-term shock. They gray solid lines represent the equivalent median values for the status quo scenario with shocks. Each panel represents an scenario; most likely or worst case.

- Enhanced recruitment effect (with and without shock effect)

For the most likely scenario without shocks, this climate effect results in a gradual increase of the SSB for the short and long term, stabilising at around 145% of median SSB level in the status quo scenario by 2035. The effect in the short term is kept in the long term. The probability of being below Blim in the short and long term is <5%. When shocks are applied, SSB levels suffer a big decrease during the first year, but is recovered to mentioned high values in less than 15 years, with a probability to be below Blim <5% in the whole time series (Figure 163, Figure 164).

For the worst case scenario without shocks this climate effect results in a gradual increase of the SSB for the short and long term, stabilising at around 180% of median SSB level in the status quo scenario by 2035. The effect in the short term is kept in the long term. The probability of being below Blim in the short and long term is <5%. When shocks are applied, SSB levels suffer a big decrease during the first year, but is recovered to mentioned high values in less than 15 years, with a probability to be below Blim <5% in the whole time series.

Total catches are in maximum values, resulting in a median relative income of 115% all along the projection period.

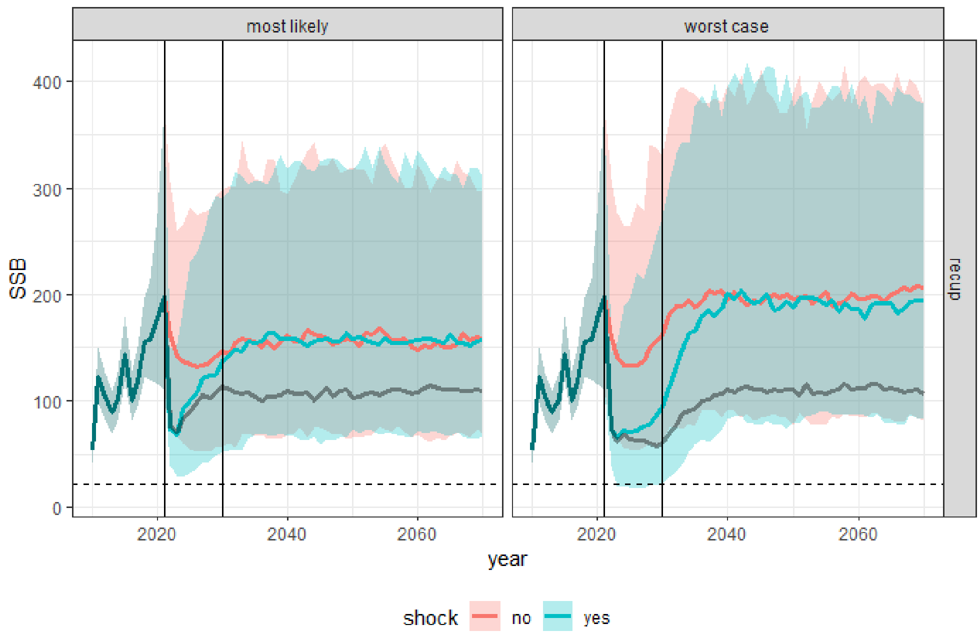

Figure 163 Spawning stock biomass (SSB) for the enhanced recruitment at age climate effect with and without shocks. Solid vertical black lines indicate the starting projection year (2021) and the 10 years time horizon (2030). Horizontal dashed lines denote Blim reference point. Shaded and coloured areas show the 5% and 95% quantiles and solid coloured lines show the median of all runs (n =

500). Red colour represents the scenarios without short-term shock and the blue colour represents scenarios with short-term shock. The gray solid lines represent the equivalent median values for the status quo scenario with shocks. Each panel represents a scenario; most likely or worst case.

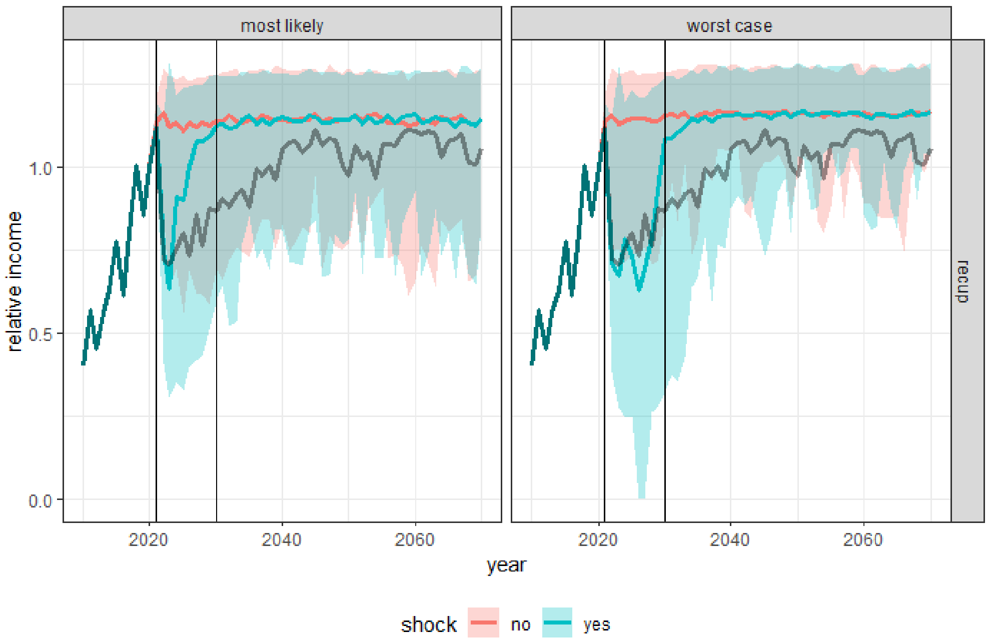

Figure 164 Relative income (computed as the ratio between the computed income in each iteration and the median income from the status quo scenario in 2020) for the enhanced recruitment at age climate effect with and without shocks. Solid vertical black lines indicate the starting projection year (2021) and the 10 years time horizon (2030). Horizontal dashed lines denote Blim reference point. Shaded and coloured areas show the 5% and 95% quantiles and solid coloured lines show the median of all runs (n = 500). Red colour represents the scenarios without short-term shock and the blue colour represents scenarios with short-term shock. The gray solid lines represent the equivalent median values for the status quo scenario with shocks. Each panel represents a scenario; most likely or worst case.

- Enhanced recruitment + Decreasing with at age effect (with and without shock effect)

For the most likely scenario without shocks, the combination of these climate effects results in a similar stock status as in the status quo scenario, stabilising at around 110 thousand t as median SSB. The probability of being below Blim is lower than 5%, along the projection period. When applying shocks, SSB levels suffer a big decrease during the first year. Status quo levels are recovered by 2030, with the probability of being below Blim is lower than 5% along with the whole time series (Figure 165, Figure 166, Table 52).

For the worst case scenario without shocks the combination of these climate effects results in a similar stock status as in the status quo scenario, only for the short term. In the long term, the decreasing weights lead to a decrease on SSB stabilising at around 40% of median SSB level in the status quo scenario by 2055. When shocks are applied, SSB values decrease drastically, that in contrast with the status quo case, are not able to recover to higher values, stabilising at around 40% of median SSB level in the status quo scenario by 2055 with a probability of being below Blim >5% for the whole time series.

Total catches decrease slightly and stabilise for the most likely scenario (not for the worst-case scenario that keep decreasing along the time.) The relative income results in 80% of the 2020 income for the most likely scenario, while in the worst case, it goes below 50%.

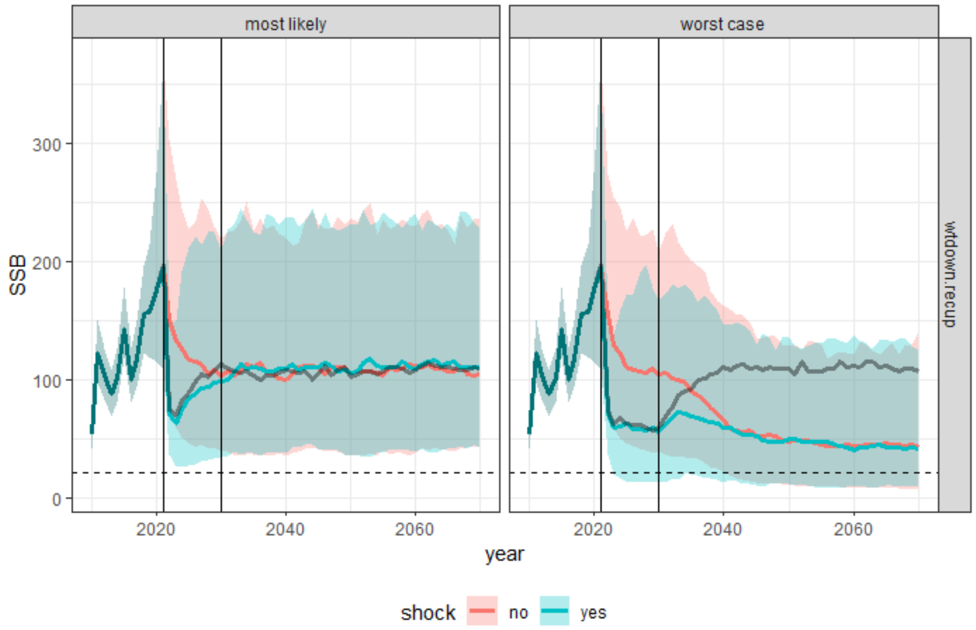

Figure 165 Spawning stock biomass (SSB) for the enhanced recruitment combined with enhanced recruitment climate effect with and without shocks. Solid vertical black lines indicate the starting projection year (2021) and the 10 years time horizon (2030). Horizontal dashed lines denote Blim reference point. Shaded and coloured areas show the 5% and 95% quantiles and solid coloured lines show the median of all runs (n = 500). Red colour represents the scenarios without short-term shock and the blue colour represents scenarios with short-term shock. The gray solid lines represent the equivalent median values for the status quo scenario with shocks. Each panel represents a scenario; most likely or worst case.

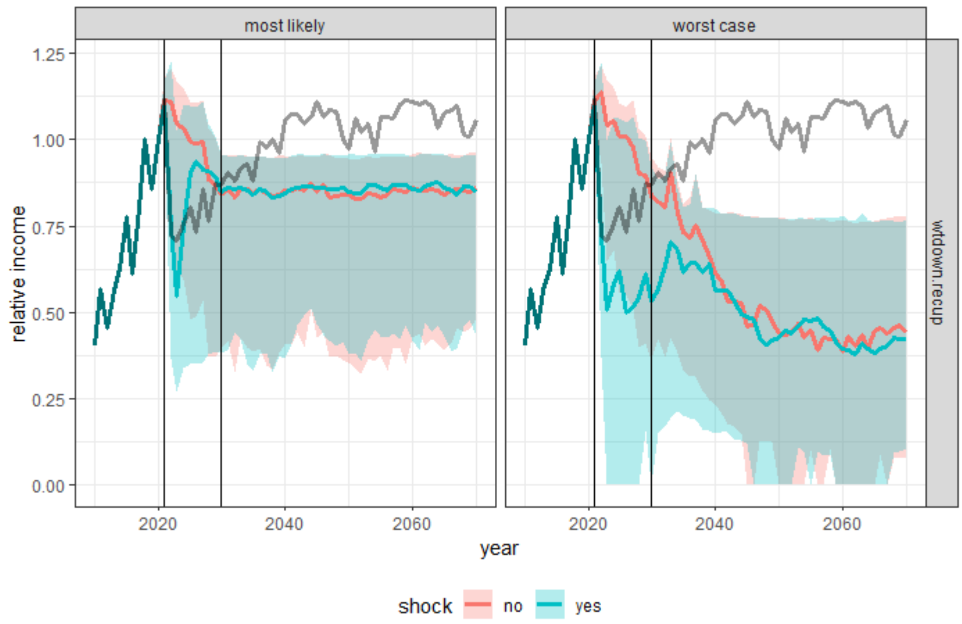

Figure 166 Relative income (computed as the ratio between the computed income in each iteration and the median income from the status quo scenario in 2020) for the enhanced recruitment combined with enhanced recruitment climate effect with and without shocks. Solid vertical black lines indicate the starting projection year (2021) and the 10 years time horizon (2030). Horizontal dashed lines denote Blim reference point. Shaded and coloured areas show the 5% and 95% quantiles and solid coloured lines show the median of all runs (n = 500). Red colour represents the scenarios without short-term shock and the blue colour represents scenarios with short-term shock. The gray solid lines represent the equivalent median values for the status quo scenario with shocks. Each panel represents a scenario; most likely or worst case.

Table 52 Table with resource and financial indicators (computed for 10 years projection) for each climate effect (survdown stands for the dressing trend in age 0 survival, recup stands for increasing tren in recruitment, rec.shock stands for punctual decrement on recruitment, wtdown stands for decreasing trend on weights at age, wtdown.recup stands for the combination of the last to effects; the most likely scenario for recup with the two scenarios for wtdown) and scenario (ML stands for most likely and WC for worst case).

Indicators							
		scenario	**status quo**	**survdown**	**recup**	**wtdown**	**Recup+ wtdown**
Resource							
Amplitude	SSBmin/SSByear shock	ML	0.37	0.29	0.43	0.28	0.36
		WC		0.26	0.45	0.31	0.36
		ML+shock	0.28	0.21	0.29	0.21	0.26
		WC+shock	0.14	0.10	0.20	0.13	0.16

Responsiveness	YearSSbmin – Yearshock	ML	7	7	6	8	7
		WC		4.5	5	8	7
		ML+shock	3	7	2	6	3
		WC+shock	9	7	5	8	6
Biological risk	Max(P(SSB<Blim))	ML	<0.01	0.02	<0.01	0.02	<0.01
		WC		0.05	<0.01	0.03	0.01
		ML+shock	0.02	0.05	0.02	0.05	0.02
		WC+shock	0.12	0.35	0.07	0.24	0.13
Recovery rate	p(SSB2030>=Blim)	ML	0.99	0.98	1	0.98	0.99
		WC		0.94	1	0.98	0.99
		ML+shock	0.99	0.97	1	0.95	0.99
		WC+shock	0.90	0.65	0.95	0.77	0.89
Recovery rate 2070	p(SSB2070>=Blim)	ML	0.99	0.95	1	0.90	0.99
		WC		0.88	1	0.32	0.77
		ML+shock	0.99	0.95	1	0.87	0.99
		WC+shock	0.99	0.86	1	0.30	0.80
Financial							
Relative income 2030	income 2030/ income 2020	ML	1.04	0.86	1.14	0.65	0.84
		WC		0.70	1.15	0.76	0.84
		ML+shock	0.97	0.72	1.12	0.60	0.84
		WC+shock	0.75	0.33	1.08	0.39	0.53
Relative income 2070	income 2070/ income 2020	ML	1	0.93	1.14	0.5	0.86
		WC		0.52	1.16	0	0.44
		ML+shock	1	0.85	1.14	0.54	0.85
		WC+shock	1	0.60	1.16	0	0.42

Conclusions

Under the current management plan for the anchovy stock in the Bay of Biscay, using the agreed harvest control rule, "most likely" scenarios result in SSB levels in median well above Blim for all tested climate effects in the short term (10 years of projection). The probability of being below Blim for all these cases is <5%. For the "worst-case" scenarios, none of the tested climate effects leads to median SSB levels below Blim in the short term. However, the probabilities for being below Blim are above 5% when a decreasing trend in the survival of age zero individuals is applied or when two punctual decrements on recruitment are applied.

In the long term (50 years of projection), most scenarios tend to stabilize at a certain SSB level, either below or above the SSB resulting from the status quo projection: Most of the tested climate effects do not lead the median SSB level below Blim, except when a decreasing trend for wights at age is applied in the worst-case scenario.

When shocks are incorporated into the tested climate effects, the resulting stock status in the long term is similar, and the stock reaches the same SSB levels as when no short term shocks are applied for all climate effects. However, in the short term, applying the shock results in lower SSB median levels in all cases and in the worst-case scenarios, the probability of being below Blim is >0.05. More years are needed for stabilization when these shocks are applied.

Concerning the last historical year's computed median income, the relative income indicator shows a similar trend as the SSB, obtaining relative income levels around a 50% of the median income in 2020 for the most climate effects. The prices vary depending on the individual weight at age, which increases the effects in the climate scenarios assuming a decreasing weight at age trend in time.

The current health status of the stock and the agreed precautionary management plan make the resource resilient for most of the tested scenarios, resulting in median SSB values that are lower than the status quo levels (expect for the enhanced recruitment scenario, where the stock SSB increases) but are still well above Blim. The unique scenario where the stock reaches a very poor status is the worst-case scenario assuming a severe decreasing trend in weights at age along 20 years. However, the enhanced recruitment effect (more realistic scenario) leads to SSB median values above Blim, both with and without short term shocks.

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Annex 22 CAPACITY OF GOVERNANCE MECHANISMS TO IMPROVE RESILIENCE

Reviewing existing governance mechanisms with respect to their capacity to improve resilience

Climate change is affecting fish stock productivity and causes changes in their geographical distribution (Baudron et al. 2020). These changes both affect the fishing fleets, fishing strategies as well as the (instruments and governance of) the EU fisheries management system under the CFP. This section investigates whether the EU fisheries governance system is adequately equipped to accommodate such changes and if it can contribute to the improved resilience. This question is in fact, threefold:

1) At the general level of the fisheries governance system, is the CFP adequately equipped to deal with a widespread change in fishing patterns in terms of management instruments such as relative stability and technical measures.
2) At the fisheries system level, can the CFP accommodate the fishing fleets' socio-ecological challenges regarding fishing rights distribution and TAC and quota regulations.
3) At the ecosystem level, is the EU management toolkit fit for purpose to accommodate the ecological aspects of climate change.

Fisheries Governance

Fisheries governance can be defined as: *'... the whole of public and private interactions to solve societal problems and create societal solutions. It includes the formulation and application of principles guiding those interactions and care for institutions that enable them'* (Kooiman et al. 2005). Fisheries governance relates to three orders of governance; the day to day management of fisheries, the institutions (institutional arrangements, procedures, organisations, rules, regulations, mechanisms) and the principles (policy objectives, values). The discourse on the effects of climate change on the CFP has already been highlighted by authors such as Daw and Gray (2005), Sissenwine and Symes (2007) and Arnason (2012) who states that through climate change the optimal fisheries policies will have to change which poses a significant challenge to the EU common fisheries policy (Arnason 2012). Ojea et al. (2021) recently assessed countries' social-ecological resilience to fisheries affected by climate change and proposed adaptation pathways for the fisheries. They developed a resilience index that included institutional factors that increase resilience of the fishery: co-management, property rights, multi-level governance, quotas and compliance (Ojea et al. 2021). They argue that participation of stakeholders in management results in more resilient fisheries (also referring to Gutiérrez et al. 2011), that having ownership and market flexibility through property rights and quota's (especially when linked to co-management) increases fishers resilience, that having the possibility to govern at different scales increases flexibility and finally that compliance with regulations is an important factor. Johnsen (2014) also makes the argument that governability increases when governing instruments (i.e. TACs) are co-produced by the actors involved. Johnson emphasises the importance of information feedback mechanisms for governability[11] (Kooiman et al. 2008), which also makes sense for dealing with climate induced change.

[11] Governability is defined as the governance status of a societal sector or system such as a fishery or a coastal region as a whole. The assessment of such governability is approached by recognizing this whole to consist of three coherent analytical components: the system-to-be-governed , its governing system and their governance interactions.

Challenges related to climate change for the fisheries

For the fisheries, the impact of climate change will be *métier* specific; based on the specific assemblage of species targeted in the fisheries, combined with a specific geographical area and use of a specific fishing technique will the climate change affect the fishing opportunities of the individual fisheries. As a result of the geographical movement of stocks, fishers may have to either change gear and/or target species or to follow the stocks and change the area fished. Hence climate change triggers changes in fishing patterns related to the dependency of the fleets on certain species. When fishers remain active in the area, they are currently operating in, but with a change in gear and/or target species, there might be potential divergences with technical measures and relative stability, including the necessity for introducing management measures for new species. Moreover, by changing gear and/or target species there may be a possible conflict with other fleets which were already targeting these species (Arnason 2012). When the fleets follow the stocks, similar issues may arise. Such changes are a challenge to accommodate in EU waters, but case in point are the bilateral agreements with third countries, such as Norway or Iceland. Such changes and the need to come to an agreement might be difficult and may result in for example, the ‘Mackerel War’ (in: Spijkers and Boonstra 2017).

The instruments of the CFP

Climate change hence potentially has a significant influence on the operations of fishing fleets. Consequently, this will challenge the current CFP and its instruments in two ways: are the current CFP instruments still fit for purpose, given the changes in fishing patterns, how can the CFP instruments facilitate a transition towards a new resilient fisheries management?

- Minimum conservation reference sizes

For those species which have a climate change-induced change in growth pattern, current MCRS may need adjustment.

- TAC setting rules

with a climate change-induced change in the carrying capacity of the marine ecosystem, with changes in stock sizes and productivity, the optimal level of exploitation determining the Maximum Sustainable Yield (MSY) may need adjustment. These developments affect the way the Total Allowable Catch (TAC) is being determined.

- Definition of fishing quotas

Currently TACs are distributed between Member States (MS) using the principle of Relative Stability; the allocation of fishing rights among MS through fixed percentages of the TAC. Already in the past, the shelf life of the relative stability has been questioned (van Hoof 2015, Peñas Lado 2016) as fishing patterns of European fleets changed over time which was not reflected by an adjustment in the allocation of fishing opportunities over the MS. This situation is mirrored by the vast quantity of quota swaps between MS (van Hoof 2013, Hoefnagel et al. 2015, Harte et al. 2019). Part of these quota swaps has even developed into a traditional annual quota swap between MS. In addition, depending on developments in the actual fisheries, throughout the year MS can seek to swap quota.

The system of Relative Stability has proven to be very stable over time (Peñas Lado 2016) mainly because it reflects a political deal between MS rather than it being the result of an economic reflection on how resources can best be allocated in a rational manner. Reopening this debate is not desired (Peñas Lado 2016). Behind this debate, there are two schools of thought with quite the opposite views. On the one hand, there is the school of thought that TAC allocation should follow historical track records, that is, on the demonstrated activity of fleets (Peñas Lado 2016). On the other hand, there is a school of thought that promotes the allocation to be based on the proportion of the fish that occurs in the waters under the MS' jurisdiction (Peñas Lado 2016). With the climate-driven changes in stock geographic distribution, a number of countries today lean towards the latter school of thought: with the increasing abundance of stocks in their waters, they claim the right to a larger proportion of the TAC. This is clearly reflected in the bilateral negotiations between the EU and third countries. A case in point is the negotiations over the mackerel TAC of late.

Next to the allocation of TACs over MS, there is the allocation of the national TAC through individual quota over the fishing fleets. With changes in fishing patterns and species abundance there are two options: either TAC and quota do not change over time or TAC and quota are adjusted to fishing practices (métiers).

If TAC/quota are not being adjusted, this will force the individual fisher to stick to current fishing practices. If the target species have relocated to a different geographical area this implies that either the fisher has to spend more time steaming to the fishing ground (which especially impacts the shorter trip fisheries) and hence having less time available for fishing (or has to extend the duration of the fishing trip which affects labour conditions on board as well as social aspects such as shore life), or remain fishing at the traditional fishing grounds with reduced fishing opportunities.

Changes in TAC/quota allocation is rather at odds with the grandfathering principle (Anderson et al. 2011, Lynham 2014), which is often used in the first allocation of individual quota. This principle allocates catch rights based on a historical track record. Under changing conditions, traditional track records do not reflect accurately current fishing operations and hence the need for a specific quota allocation to the individual fishers. A case in point is the Dutch example in which Individual Tradable Quota were introduced, followed by a massive trade in quota. Apparently, the initial allocation of quota was not in line with the fishing practices of the day, and hence the desire of the fishers to massively trade quota to be in line with fishing opportunities (Van Ginkel 2009, van Hoof 2010).

- <u>Framework for the regulation of technical measures</u>

European fisheries legislation has been populated with numerous regulations, amendments, implementing rules and temporary technical measures throughout the years, aimed at closing gaps and resolving emerging problems. In the considerations of Regulation (EU) 2019/1241 it is stated that the current regulatory structure in relation to technical measures is unlikely to achieve the objectives of the CFP, and a new approach should be taken to increase the effectiveness of technical measures, focusing on adapting the governance structure. There is a need to develop a framework for the regulation of technical measures. That framework should establish general rules which are to apply across all Union waters and also provide for the adoption of technical measures that take account of the regional specificities of fisheries through the regionalisation process introduced by Regulation (EU) No 1380/2013 (EU 2019).

In a changing marine ecosystem, with changing fishing practices, two developments can be envisaged. Fishers with changing fishing practices can adapt to prevailing technical measures, with the need for additional investments in fishing gears and techniques. Second, with changes in productivity, distributional patterns and stocks in terms of sizes and fecundity, there may be a need to develop and/or change current technical measures. Hence, technical measures can play a role in both facilitating fishers to adapt to changing fishing practices as well as in managing the conservation of fish stocks under changing conditions. This may well have a bearing on the landing obligation. With changes in MCRS, technical measures and the relation between stock size and catch opportunities, by-catch rates may be affected. When operating with an individual quota holding of the fishers, not matching the catch opportunities, there is in a multi-species fishery the risk of choke species hampering fishing practices: a fisher with a low quota holding of a species can cause a vessel to stop fishing even if they still have quota for other species (Mortensen et al. 2018, Calderwood et al. 2021).

- regionalisation

With changes in the geographical distribution of stocks, this will have a bearing on the regional level. Perhaps from a stock perspective, decentralised fisheries management has to be organised in a different way, reflecting the relevant interests of riparian states in a particular sea basin. As mentioned above, bilateral agreements with third countries, such as for example, Norway, the UK or Iceland, would be affected by climate change and require strengthening cooperation in political and scientific matters between the EU and those counterparts. And especially for highly migratory species, the role of the Regional Fisheries Management Organisations (RFMOs) may need to be further developed and strengthened (Table 53).

Table 53 Toward renewed or adapted CFP instruments to fit the new challenges induced by climate change stresses

Climate-induced stresses	Challenges	Impacted current CFP instruments	CFP instruments to deploy/adapt
Changing fishing patterns	Maladaptation to the new situation, imbalanced fleets	Total allowable catch (TAC) and quotas Technical measures (landing sizes and selectivity requirements) Bilateral agreements	Annual TACs, quotas and current minimum conservation reference sizes (MCRSs) defined in the EU Technical Measures Regulation (EC, 2019) may need adjustment to new carrying capacity Fishing rights would need to adjust to the available fishing opportunities with quota swapping and via the bilateral agreements negotiated every year with non-EU fleets Continue the regionalisation (CFP Art. 18) for adapting the governance structure, besides EU level generic measures, to decentralised, regionalised measures based on sound scientific advice and stakeholder anticipation
Transition towards a new climate-aware fisheries management	Barriers to transition (path dependencies, costs, social	Grandfathering (i.e. allocation based on historical landings) Prevailing technical measures (EU, 2019)	Flexible quota allocation (e.g., individual fishing quotes (ITQs) or at least an easier system to exchange quota between companies of two MS)

Climate-induced stresses	Challenges	Impacted current CFP instruments	CFP instruments to deploy/adapt
	acceptance)		Promote investment in new gears Adapt the landing obligation to limit the risk in multi-species fishery of choke species "on the move"

Improving resilience with the current the CFP

Is the current European governance system of fisheries management, with its existing instruments, adequately equipped to accommodate this change or is a fundamental change in the management system required?

Based on insights on resilience and anticipatory governance, two things are essential: firstly, the ability to anticipate what is to come, which as we have seen is not a merely ‘neutral’ exercise but also is about politics, governance, and what future ‘can be imagined, negotiated, used and /or ignored’ (Vervoort and Gupta 2018) and, secondly, the ability to respond to change (i.e., adaptive management). Here we will first focus on the resilience of the current management system to implement a fisheries policy under changing conditions. Next, we will address how the CFP is equipped to manage the changes in the ecosystem, providing sufficient input for stock conservation (Table 54).

Table 54 Potentials for resilience within the current or a reformed CFP governance

Actions	Entities	Potential for resilience	Obstacles
Anticipate the change	Fishing fleet	High profitability	Overcapitalisation and overfishing impairing profitability
	CFP governance	Dynamic management (e.g., update biological reference points regularly) Ecosystem approach to fisheries management (EAFM) (e.g., account for supporting ecosystem services)	A demanding scientific knowledge acquisition and the need for a detailed, robust, and shared understanding of the marine ecosystems' dynamics Moving targets (e.g., fluctuating quotas) making future profit uncertain "Relative stability" principle
Response to change	Fishing fleet	Adapt to local circumstances Follow the stocks spatially	Additional effort to reach the fishing grounds Crossing jurisdictions

Actions	Entities	Potential for resilience	Obstacles
			Mismatched opportunities with species assemblage (e.g., risk for choke species)
	CFP governance	Redesign of the principle of relative stability, or quota swapping and quota transfers	Inertia of historical rights (path dependency)
	Common market organisation (CMO)	Stimulate demand through marketing strategies and informative campaigns Producer Organisations (POs) have the potential to adapt EU fisheries to the new context of resource availability and evolving market conditions	Consumer habits may impose a barrier for trade of newly abundant resources

The analysis will be framed against the backdrop of two scenarios: The fishers will follow the stocks in the first scenario. In the second scenario, the fishers will adapt to the changing stock composition of the regional sea. Of course, these signify two of the extreme scenarios. Moreover, in reality, a mix of responses from the fishers is expected: some adapting to local circumstances, others following the stocks and all sorts of thinkable in-between solutions. In addition, it should be noted that these are gradual processes of change: both the change in the ecosystem and the change in fishing operations take place over a prolonged period. And what the final state of the socio-ecological system will be is as yet not fully known.

In cases where fishers can follow the stocks, from a managerial point of view, there will be no major changes, provided that with changes in the characteristics of fish stocks (productivity, growth rate, fecundity) and the changing carrying capacity of the marine ecosystems, TACs can still be appropriately determined. For fishers, it will most likely imply additional time is needed for steaming to the fishing grounds. And, in case the fish stocks move to different jurisdictions, negotiations of TACs will have a significant impact on fishing opportunities. In addition, depending on the assemblage fished for in a particular métier and the degree to which all of the stocks arrive at a new geographical distribution, the individual quota portfolio of a fisher may have a significant impact on the actual fishing opportunities.

In case fishers adapt to the changing stock composition in the regional sea, there will be a need to adjust the individual quota portfolio to reflect the current stock assemblage and catches realised. Noting the rigidity of the system of relative stability, it can be queried whether the system is resilient enough to accommodate this change. Not only does it require a reallocation of TACs between MS, but it may also call for the development of quota for 'new' species in the area and the allocation of these quotas between fishers who will not have a prior track record of catches. What also is important here is that monitoring such changes can be complicated. Fishers often are the first to observe species coming in their catches. These observations might not be reflected in data collection, as the species might not be landed.[12] Either the fish cannot be landed, as fishers have no quota or need not be landed as catches are below the threshold, or fishers do not want to land them officially because they are too valuable, such as bluefin tuna.

In addition, redesigning métiers, changing species composition in catches and/or changing fishing techniques and operations may call for adjustments of technical measures and may have implications for the landing obligation, for example, with over-quota catches. In a period in which species composition of stocks in a regional sea is changing against a backdrop of fixed quota holdings by fishers there is the possibility, especially in mixed fisheries, of the development of choke species. The latter also holds true in those cases were species move into an area where fishers currently have had no or only small quota holdings.

Hence, in case of a need to provide resilience to fishers in a changing ecosystem, the CFP instruments need to be made more flexible. This calls for a redesign of the principle of relative stability. In addition, in the international context, there is the need to strengthen cooperation in fisheries management and address the effect of climate change in sustainable fisheries agreements, both within RFMOs and third countries.

The presence of new species in areas where the fishing activity and trade have developed around other species requires adaptation throughout the whole supply. Particularly relevant is stimulating the markets' demand with education campaigns and consumers education (Peck and Pinnegar, 2018). In the Adriatic Sea, for example, the presence of non-indigenous thermophilic species has given rise to new fishing activities, which require raising awareness of fishers and consumers, among others, and the development of marketing strategies and value-adding (Climefish project, 2019). The Common Market Organisation (CMO) as per Regulations EU No 1380/2013 and No 1379/2013 promotes the consumption of the available species and provision of information to consumers. Within the CMO, Producer Organizations (POs) are key actors that can play a key role through the production and marketing plans to adapt their supply to the changing availability of fishing resources. Moreover, these organisations are able to make good use of the opportunities provided by the European Maritime and Aquaculture Fisheries Fund (EMFAF) as per Regulation EU 2021/1139 for adaptation to climate change in terms of adaptation of the harvesting activity, promotional campaigns for new products, and infrastructures, amongst others.

Changing the CFP for resilience

On the other side of the coin, the question is: Can the resilience of the natural system be safeguarded within the current management framework? It should be noted that resilience to change simultaneously as a change in the ecosystem occurs at a grand scale is rather at odds with one and another. When at the local level stock abundance changes due to a geographical redistribution of fish, how severe does one need to uphold local conservation measures (i.e. plaice box)?

However, at the level of the stocks, as mentioned above, provided the scientific advice is still adequate to provide TACs, the CFP provides an ample framework for management at the stock level. An issue lies with the entry of new species into the system, especially when it concerns invasive species. In order to implement an ecosystem approach to fisheries management under these changing conditions, there is a need for a dynamic management framework.

[12] In anticipation of future decisions on quotas for ‚new species‛ many MS urge their fishers to report all catches/landings of a group of species. For some species a more or less directed fishery already started in some areas (like in the English channel on a cuttlefish species).

The most important factor that needs to be taken into account is that although the marine ecosystem is of course, always dynamic and in flux, today, there is a trend of climate change observed in this development. However, the end-state of this development is yet not known. This implies for example, that quite an array of reference points for fisheries management no longer have significant value. The management system has to become more adaptive and perhaps develop from a (single) species oriented framework towards an adaptive regional fisheries oriented framework. In this framework, the balance between regional fishing capacity and catch opportunities is leading. The framework to be adaptive from a management perspective reflects the fishing reality of the fleets. One option under such a framework would be the introduction of pan-European tradable fishing rights which would allow for stock management at TAC levels. At the same time, fishers can adjust their local catch opportunities by trading in fishing rights across Europe (for those regional seas working with TACs). Another option might be to facilitate a system of (semi-permanent) quota swaps between MS to reflect the actual presence of species in regional and local waters.

CFP instruments to mitigate the effects of fishing on climate

The EU is committed to reducing the impact of fishing activity on climate. In fact, climate change and energy efficiency have been highlighted as needs by the "Europe 2020 strategy. A strategy for smart, sustainable and inclusive growth" as well as within the Europe Green Deal. The CFP is consistent with the EU 2020 Strategy and the achievement of its objectives. The basic CFP regulation includes provisions for Member States to provide incentives for energy-efficient vessels when it comes to the distribution of fishing possibilities as per Article 17 (EU, 2013). In turn, the EMFF (EU, 2014) is aligned with the Europe 2020 Strategy and includes energy efficiency as one of the eligible actions. Union Priority 1 of the EMFF encompasses provisions to strengthen technological development and innovation, including investment on board to reduce emissions, development of energy-efficient gear designs, improvements in propulsion systems and hull designs to reduce energy consumption, provisions for environmental protection, and improvement of safety and working conditions in land infrastructures, such as ports, shelters, and auction halls, amongst others.

In addition, the fund provides funding for the adaptation of the sector to fishing possibilities trough the producer and organisation plans of the POs. Thus, the fund can also be regarded as increasing the resilience of the fishing sector to climate change at the harvesting level and throughout the rest of the supply chain. In July 2021, the new European Maritime, Fisheries and Aquaculture Fund (EMFAF) entered into force and have provided more flexibility to the renewal and replacement of engines in comparison to the previous fund. The EMFAF is aligned with the European Green Deal, and its Farm to Fork Strategy, which will tackle climate change, environment protection, and biodiversity preservation.

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Annex 23 EXAMINING FISHING STRATEGIES FOR IMPROVING ENERGY USE EFFICIENCY

Data retrieval

Within this work, differential energy use by fishing activity was examined, the time series of the Data Collection Regulation (DCR) and the Data Collection Framework (DCF) was retrieved from the Joint Research Centre (JRC) database (data used for the production of the Annual Economic Report of STECF (e.g. STECF 2020). Historical energy use has been estimated for all MS, based on DCR and DCF data to retrieve fuel efficiency in terms of litres per day at sea and litres per kg of fish landed for economic fleet segments. For some MS, the data available allows retrieving fuel use time series between 2002 and 2018.

The state of play of the European fishing industry was examined. For this, energy used in capture fisheries by year and by fishing activity since 2002, especially since 2013, for which more consistent data is available related to the actual catch was analysed. The Annual Economic Report (AER) data is available on an economic fleet segment level with yearly costs and earnings (including energy costs) and the total amount of consumed fuel. Those data were used in the past for studies on fuel efficiency, but fuel consumption was not linked to specific stocks in those cases. The estimates were on the segment level for all catch combined, such as the EU funded Energy Saving in Fisheries project (van Marlen 2006) or a study by Guillen et al. (2015).

Data is collected and therefore available on a yearly basis for a sample of vessels. Each MS has its own methodology to elevate the sample at the population level, which is usually performed using a specific "economic segmentation", which is different from the Fisheries Dependent Information (FDI) métiers. For example, a vessel taking part in the segment FRA NAO DTS 1012 may participate in several trawl fisheries, as well as several dredging fisheries, including deploying passive gears (nets or pots) on specific occasions. Despite this, such diversity of métiers is not apparent in the economic data, with the fuel information at the vessel level aggregated annually. Moreover, there is no standard method to disaggregate costs from an economic segment to the different métiers, notably how to apportion the variable costs to metiers having different power needs. Although there has been some effort recently to disaggregate economic data to be able to link the 'economic segments' to fisheries or different areas (e.g., vessels from Denmark fishing in the North and Baltic Sea), despite this the method is not developed far enough to disaggregate the data to the metier level (see Döring, 2019). Several methods combining logbooks and Vessel Monitoring System (VMS) data have been proposed (Hintzen et al., 2012; Curtin, 2021), but a common European approach has still to be elaborated.

The data retrieved was then analysed to find correlations between certain types of fishing activities, fishing effort, or fisheries on particular stocks and the amount of fuel consumed by the fishing vessels.In this respect, for each economic fleet segment within each MS, fuel intensity has been examined, as well as its two underlying indicators: fuel efficiency and catch efficiency. Importantly, the indicators of fuel efficiency and catch efficiency are not independent at the vessel level, as management measures and gear modifications may affect both indicators. For example, stock size variation (i.e., due to changes in quotas or effort restrictions) will impact only catch efficiency, while gear modifications (e.g., technical changes in gears, which may modify the physical resistance of the gears in the water and therefore fuel consumption, as well as impact the size of the catch), may affect both indicators. However, in order to understand the evolution of fuel use intensity, it is essential to assess the evolution of fuel efficiency and LPUE independently.

Fuel use intensity is usually expressed in terms of litres of fuel burnt per kg of fish landed. The fuel use intensity metric can be decomposed into two indicators: (i) energy efficiency, summarised as consumption of fuel per unit of effort; and (ii) catch efficiency, summarised as landings per unit of effort;

Fuel efficiency (energy consumption per unit of effort) is predominantly associated with the physical vessel characteristics (hull design and engine power); and
Catch efficency is landings per unit of effort, which is a function of the stock sizes and some vessel characteristics (gear set-up, metier).

Determining how MS collect data on fuel consumption

Annual plans and national reports provided by each MS were compiled to understand how fuel consumption data is collected. Three main methods are used across Member States (MS):

Specific questions in surveys: some MS collect this information by surveys, asking vessel owners about their annual fuel consumption. According to some correspondents, this type of data is sometimes "patchy and not really consistent". Fuel consumptions are statistically estimated for all vessels (in and out survey sample).
Deriving fuel consumption from other indicators gathered during surveys: fuel costs (collected from vessel owners during surveys or through accounting data) and fuel prices (usually collected from fuel providers).
Deriving fuel consumption from the vessels' technical characteristics, such as gear, target species, and physical characteristics of the vessel (size, power and/or GT).

For some MS, the estimation procedure developed is a combination of these three methods: fuel consumption is derived from models integrating fuel costs, fuel prices, technical characteristics, also taking into account survey answers to redress the results. For some MS, several methods are employed simultaneously, however, this is detrimental to the homogeneity. However, none of the three methods directly measure fuel consumption. Contrary to other physical characteristics describing the activity of fishing vessels (e.g., effort, catch), fuel consumption is always estimated by indirect methods. Moreover, some MS' have modified the way fuel consumption is calculated between years without re-estimating previous years. Where the MS has undertaken such modification, there is little capability to determine whether interannual variations fuel consumption is due to technical change or change in fishing patterns or just the difference in the methodology employed. Where possible it has been have highlighted where MS' have modified their methodology across the time series.

Without any specific information on the type of fuel burned by fishing vessels, the greenhouse gas contribution from fuel consumption has been obtained using the conversion coefficient of 3.05 kg CO2-equivalent, per litre used. It is important to note that this conversion factor covers fuel consumption on-board fishing vessels and the GHG emissions associated with the production and distribution of fuel (Parker and Tyedmers, 2015; Parker et al. 2018).

Issues with data used in the analysis

For the majority of MS', fuel consumption has been estimated at the economic segment level on an annual basis. Therefore, evaluating the fuel consumption at the metier level (level 5 or 6) is not possible and would need modifications in the way economic data is collected, including methodological developments to define a commonly accepted disaggregation methodology.

For most DCF/DCR segments, fuel consumption per day at sea is varying interannually; this indicator should be relatively stable. This is because fuel consumption per day at sea is highly dependent on the physical characteristics of the fishing vessel (hull design and engine system) and on the metiers performed by the vessel. For most EU vessels, these characteristics are stable from one year to the next at the segment level.
For some gears and for some vessel lengths, there is a discontinuity between the DCR and the DCF, resulting in discontinuous time series between 2002 to 2018.

There are yearly gaps in the submitted data from some MS', who have not submitted relevant annual data; these data gaps have been identified by the Scientific, Technical and Economic Committee for Fisheries (STECF), but very few gaps have been backfilled.
Sources of GHG emissions from fishing vessels not directly due to vessel fishing activities (e.g., refrigerant leaks, packaging, ice making, bait), have not been covered in calculations performed in this project. It is therefore not possible to assess total GHG emissions of the production stage through the public data currently available. In line with this project not taking into account non-fishing activities, Parker (2012) notes that within most projects looking at GHG emissions of fishing vessels, when information of non-fuel related GHG emissions are integrated into the analysis, a high level of uncertainty is applied to any output.
An analysis of the potential link between annual catch, management measures and stock size is only possible for the DCF data (2008-2018); landing information in the DCR data is not aggregated at a level to establish a link to specific stock assessments, and effort information is not disaggregated by sea basins.
Due to its sequential implantation and availability of fuel consumption data up to 2018, the effect of the landing obligation on fuel use consumption may not be visible in the fuel intensity figures.

There is substantial interannual variation in fuel use intensity across the majority of MS' (Figure 167), though this is likely due to inconsistencies in collecting fuel consumption data. For example, there is strong interannual variability in fuel use intensity within some of the Dutch segments (drift and fixed nets (DFN), passive gears, trawlers (DTS and TBB)) It is however one of the hurdles to identify the main drivers explaining those variations. This analysis allows notably to re-estimate the range of fuel use intensity per main gear type in the EU (and see the online profiles).

This work utilised a stakeholder engagement questionnaire on the fuel consumption of vessels and the overall landings of those vessels. Unfortunately, there were only a few questionnaires where the fishers provided information on the overall fuel consumption and landings per vessel. The following table summarizes the information received, which is also limited to the Mediterranean Sea.

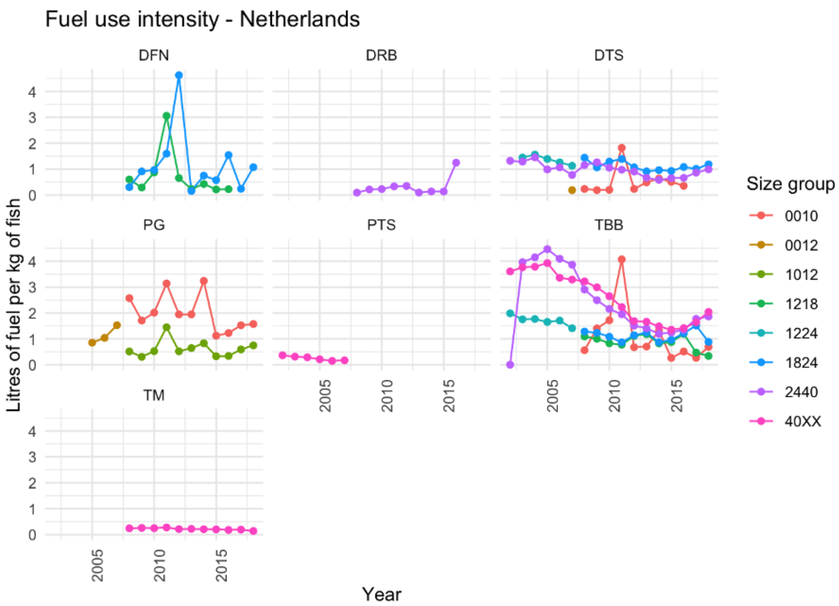

Figure 167 Fuel use intensity for Dutch fleets. *NB. The legend pertains to the different sized vessels in the analysis: 0010 (0m to 10m LOA), 0012 (0m to 12m LOA), 1012 (10m to 12m LOA), 1218 (12m to 18m LOA), 1224 (12m to 24m LOA), 1824 (18m to 24m LOA), 2440 (24m to 40m LOA), 40XX (40m to >40m LOA)*

Issues with the analysis of retrieved data

Interannual variation in fuel efficiency dominates patterns in fuel use for the majority of economic fleet segments. For example, variation in each of fuel intensity, fuel efficiency and catch efficiency observed for the large demersal trawlers operating in North-East Atlantic have no other explanation than inconsistencies in the data collection and aggregation for these specific segments. Therefore, in understanding whether there has been an improvement in fuel efficiency for these particular segments, this data cannot disaggregate whether a decrease in fuel intensity be linked to an improvement in catch efficiency (at least for the French and the British segment) or whether such patterns are solely due to inconsistencies in data collection (Figure 168).

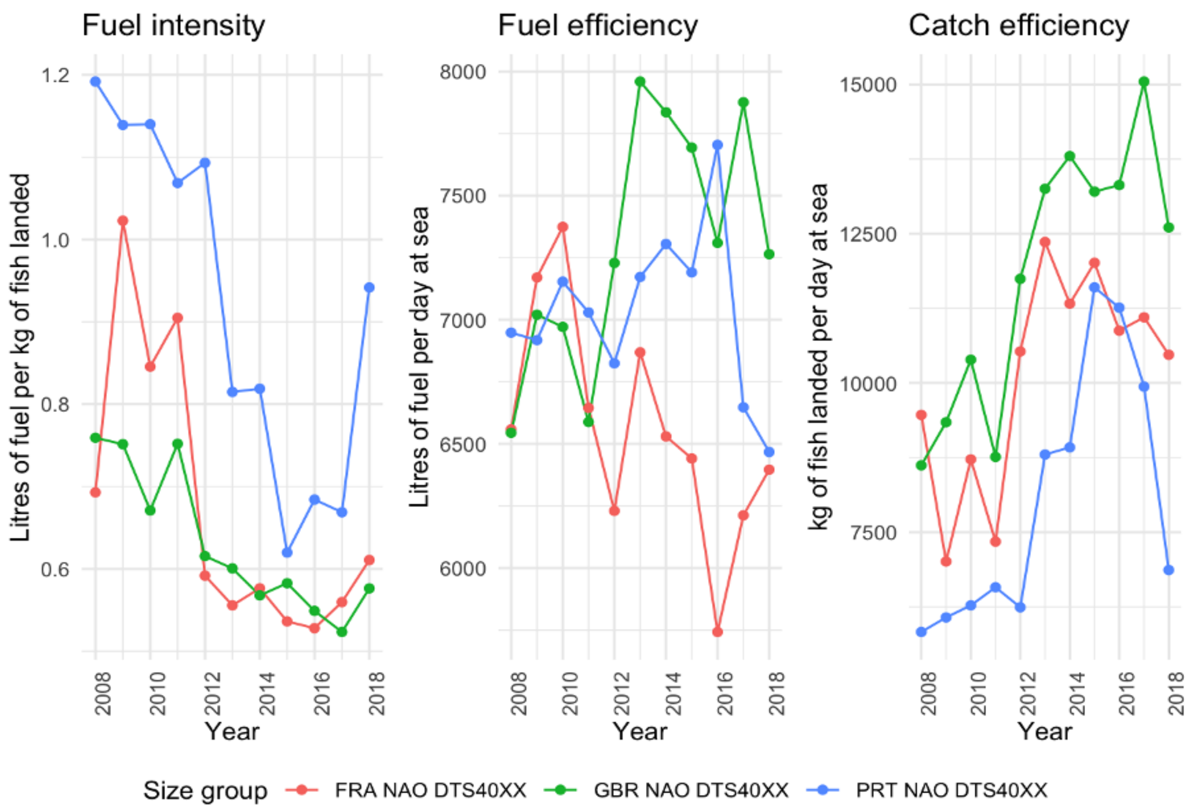

Figure 168 Fuel intensity for selected demersal trawler over 40m in the North East Atlantic

Link between stock status and fuel intensity

This section explores the potential links between the status of targeted stocks and the fuel intensity for selected segments.

In theoretical bioeconomic models, such as Gordon-Shaeffer models, the fuel intensity of a fishing fleet diminishes when the status of the exploited resource improves. This can be translated in the improvement of landing per unit of effort ($LPUE$) when the stock biomass improves. We're proposing a method to test if this relationship can be observed for European fleets. To test this, we have combined several information:

- landing information at the DCF economic segment level, retrieved from the STECF website. In the database publicly accessible on the STECF website, each segment is associated with the annual catch (volume and value) per ICES stock.

- effort information published at the DCF economic segment level, also retrieved from the STECF website.
- stock status information, retrieved from the ICES website.

Two synthetic indicators are calculated annually for each segment:

- the Combined targeted stocks status $CTSS$, expressed as an indicator which by construction is between 0 and 1,
- the normalised $LPUE$, also ranging by construction from 0 to 1.

The Combined targeted stock status:

For each stock evaluated by the ICES, we create a stock status indicator ranging from 0 to 1. In order to maximise the number of stocks for which the indicator may be evaluated, we based our calculations on the annual stock biomass indicator SBi_t reported by ICES. Depending on the stock, this indicator can be the Spawning Stock Biomass (SSB), an abundance index or any other metrics defined by the ICES working groups. For each stock, we determine the maximum of the stock biomass indicator SBi_{max}, allowing us to normalise the annual stock status indicator (SSi_t):

$$SSi_t^{stock} = \frac{SBi_t^{stock}}{SBi_{max}^{stock}}$$

if a stock is not assessed by the ICES, $SSi_t = 0$. By construction, SSi_t is therefore taking its value between 0 and 1.

We then calculate each stock contribution to the total segment landings:

$$Share_t^{stock} = \frac{Landings_t^{stock}}{Total\ landings_t}$$

By construction $Share_t^{stock}$ is also taking its value between 0 and 1.

For each segment, annual stock biomass indicators are combined in a Combined targeted stock status ($CTSS_t$), adjusted from the importance each stock in the total landings:

$$CTSS_t = \sum^{stock} (SSi_t^{stock} \cdot Share_t^{stock})$$

By construction, this indicator takes also its value between 0 and 1. It is easily demonstrable that the indicator grows with the improvement of the stock statuses. A higher indicator is therefore the translation of an improvement of the status of the stocks targeted by the segment.

The normalised LPUE:

For each segment, landing per unit of effort may be calculated as the ratio between total landings ($Total\ landings_t$) and effort expressed in days at sea (DAS_t):

$$LPUE_t = \frac{Total\ landings_t}{DAS_t}$$

The $LPUE$ is normalised by dividing the annual LPUE by the maximal LPUE observed for each segment ($LPUE_{max}$):

$$nLPUE_t = \frac{LPUE_t}{LPUE_{max}}$$

By construction, the normalised LPUE is comprised between 0 and 1, with the higest LPUE translated in a normalised LPUE equal to 1.

Combined targeted stock status and normalised LPUE: We have calculated these indicators for all segments identified in the economic data collection and have kept only the segments that had more than 50% of their landings assessed by the ICES. Among the 47 segments identified in the process, only 11 present a downward trend in the relationship between combined targeted stock status and normalised LPUE (with or without a log transformation) (Figure 170).

This tends to indicate that for 36 segments, the relationship between stock status and LPUE follows the expected pattern identified in monospecific theoretical models: landings per unit of effort increase when the stock status improves. In the absence of technological advances, the relationship extends to the fuel intensity (fuel quantity burned to catch one kilogram of fish): the improvement of the stock status is translated in an improved fuel intensity, as less fuel is required to catch one kilogramme of fish. This relationship should however be tested with longer trends, as the power of the regressions are quite low (only 18 segments have a significant trend at the 5% threshold).

Figure 169 Relationship between the combined targeted stock status and the normalised LPUE - quadrants are based on the main gear - each line represents a segment

Annex 24.. PILOT STUDY FOR FUEL USE INTENSITY ANALYSED ON FINELY RESOLVED (DANISH) FISHERIES DATA

Within this work, a preliminary investigation was undertaken to examine fuel used per fishery using finely resolved spatial Danish fisheries data and fuel consumption model (Bastardie et al. in press). The investigation shows fuel use intensity measured as litre fuel use per kilo catch, accounting for the fuel consumed by the main engine during the fishing operations at sea. The analysis split the Danish vessels' overall fishing effort deployed at sea into a categorization based on the type of fish and shellfish stocks being fished, area fished (FAO 27.3 or 27.4), fishing gear (Otter Bottom Trawl OTB, Danish Seine SDN, Beam Trawl TBB, Pelagic or Mid-Water Trawl TM, dredge DRB), and the mesh size used (large vs small/no mesh). Time series (2005–2019) was reconstructed on effort, catch volume and catch value based on the economic data collected under the EU data collection framework for the European fishing fleets and reported in fishers logbooks. Fuel use intensity was based on trip-based records in fishers logbooks coupled with individual vessel geospatial VMS (Vessel Monitoring System) data for large vessels (>12m) following the Bastardie et al. (2010) and Hintzen et al. (2012) approach. For smaller vessels (<12m), for which carrying VMS equipment on-board is not compulsory, logbooks were used coupled to AIS (Automatic Identification System) data (results not shown).

As an illustration, the time development of the fuel use intensity (FUI) as litre of fuel per catch kg is shown for vessels larger than 12 m in length and using bottom-contacting gears with large meshes (Figure 170) or with no or small mesh size (Figure 171, Figure 172).

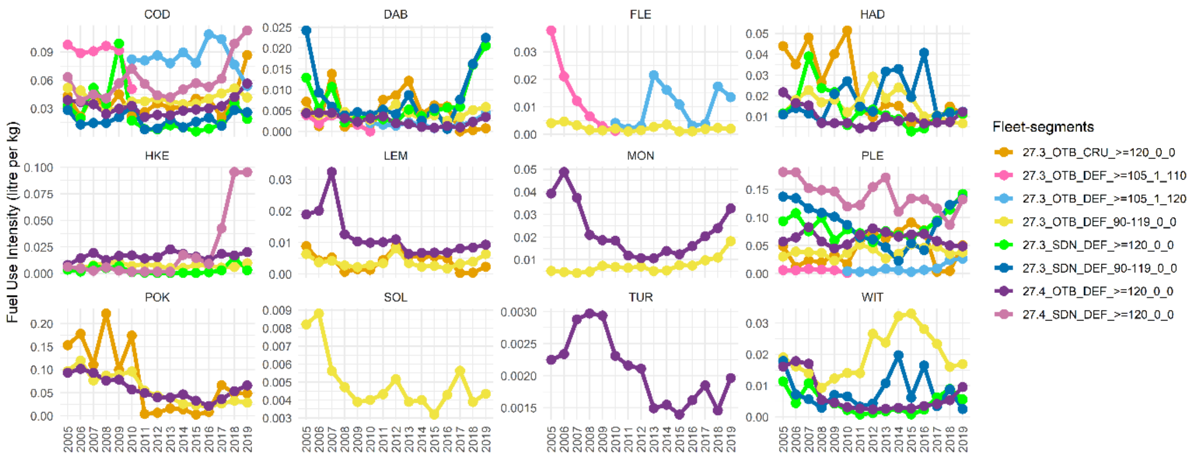

Figure 170 Time development of average fuel per unit of catch kg (FUI) per harvested species over the 2005-2019 period for fish and shellfish species captured by bottom-contacting fishing gears with large mesh sizes. One time series per fleet-segment is given, and a given species could have been caught by several fleet segments. Combinations of segment-stock-year representing less than 100 tons have been filtered out for readability and get rid of ratios that are misleading because with low catch kg.

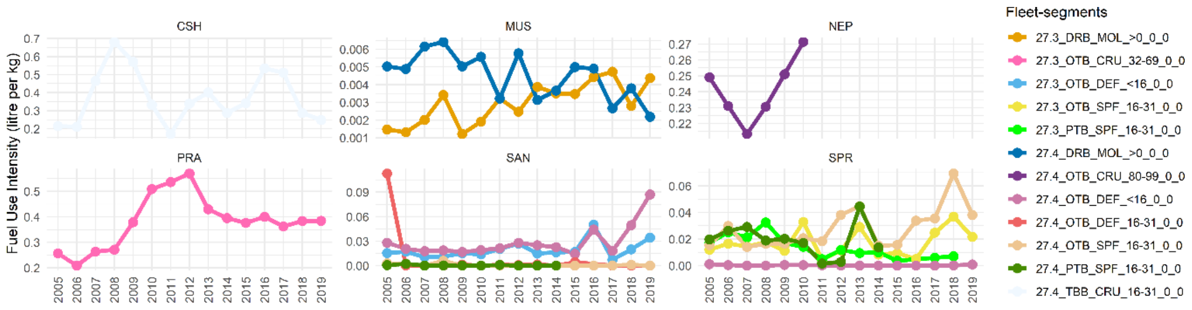

Figure 171 Same configuration as above, but displaying FUI for species captured by bottom-contacting gears with no or small mesh sizes. Combinations of segment-stock-year representing less than 1000 tons have been filtered out for readability.

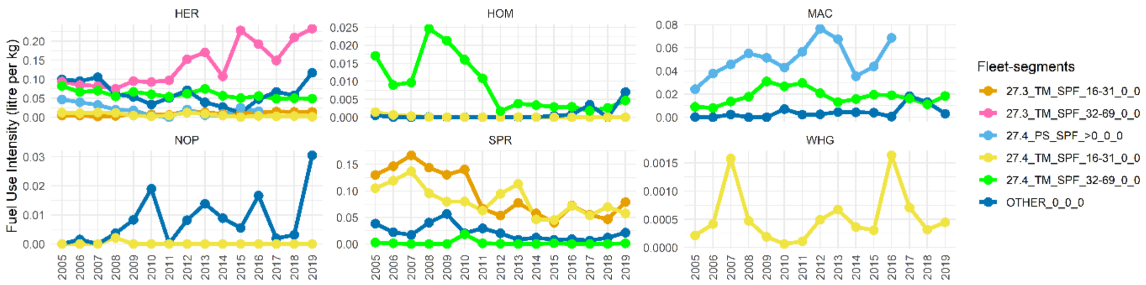

Figure 172 Same configuration as above, but displaying FUI for species captured by large vessels with pelagic gears. Combinations of segment-stock-year representing less than 1000 tons have been filtered out for readability.

All the time series show significant interannual variations with no particular trend over the 2005-2019 time period examined for most species, especially the pelagic. On the contrary, some activities on demersal species could have been on decreasing trends.

The most striking outcome is showing that some of the fleet segments or fishing techniques have been demonstrated more efficiently for the same or different species than others. The fuel use intensity is much higher for some species, particularly for crustacean species (Northern Shrimp PRA, Nephrops NEP, Crangon CSH). The latter represents a very high volume of fuel consumed for the relative catch volume but high income from landings. On the contrary, if in absolute value the overall fuel consumption for these segments targeting pelagic species is large and much more extensive than for other segments, pelagic species being geographically spread over an extended and offshore area, the fuel use intensity is low for pelagics. The fuel use intensity is shown even lower for dredge fishing on molluscs (MUS).

Extensive details on relative fuel use intensity per fishery and species, and the link to the underlying stock development are given in Bastardie et al. (in press). The data processing code is stored on a public repository: https://github.com/frabas/BENTHIS_2020 and can be reused to apply to other EU Member states countries as long as the data comply with the standard format used in input.

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Bastardie F., Hornborg S., Ziegler F., Gislason H., and Eigaard O.R. in press. Reducing the fuel use intensity of Danish fisheries: through efficient fishing techniques and recovered fish stocks. Frontiers in Marine Science, in press
Hintzen, N. T., Bastardie, F., Beare, D., Piet, G. J., Ulrich, C., Deporte, N., Egekvist, J., and Degel, H. (2012). VMStools: Open-source software for the processing, analysis and visualization of fisheries logbook and VMS data. Fisheries Research, 115-116, 31-43.

Annex 25.. DEFINING AND DISCUSSING METHODS AND RESULTS FOR FLBEIA AND SIMFISH

Two bio-economic models (FLBEIA and SIMFISH) were applied to assess the effect of changes in stock levels on fuel consumption under different climate change scenarios. FLBEIA was utilised to model the impacts of climate on demersal groundfish fishery (roundfish stocks) in the North Sea, while SIMFISH was used to model the impact off climate scenarios on the North Sea flatfish fisheries.

For each climate scenario, simulations were conducted until 2030 assuming that the fish stocks will be either fished at FMSY or at the lower bound of FMSY (FMSY_lower), or at the upper bound of FMSY (FMSY_upper) as defined by ICES information. In the simulations, fleets and metiers were assumed to stop fishing when their first quota is exhausted (i.e., 'min' scenario under the landing obligation). As an additional scenario, it was assumed that fishing will continue until the last quota is exhausted (i.e., 'max' scenario, assuming the landing obligation was not enforced) to cover the full range of possible management outcomes.

FLBEIA

FLBEIA is a simulation model to carry out bio-economic impact assessments of fisheries management strategies (e.g., Garcia et al. 2013). However, as the economic part of that North Sea model was not available to run scenarios of different fisheries management measures and estimate changes in core economic indicators, this model run focused on undertaking a limited assessment of changes in fishing effort, spawning stock biomass (SSB) and catch per unit of effort when applying different management and climate scenarios (e.g., FMSY in 2025).

Four harvest control rules (hcr) were applied:

Fixed effort - the fleet is always fishing at this effort level;
Fmsy - the fleet is fishing at the Fmsy level;
FmsyH - the fleet is fishing at the upper Fmsy level from the Fmsy ranges;
FmsyL - the fleet is fishing at the lower Fmsy level from the Fmsy ranges.

Additionally, the climate scenarios were applied:

None - prolonging the environmental conditions from today;
RCP 4.5 - Climate scenario from the IPCC with lower temperature increase;
RCP 8.5 - Climate scenario from the IPCC with higher temperature increase.

The results, need to be interpreted with caution as FLBEIA does not include a spatial component. In case of stocks moving (e.g., north with changes in water temperature) the fleet has to adapt by fishing in other fishing grounds.

SIMFISH

The Spatially Integrated bio-economic Model for FISHeries (SIMFISH) includes both short and long term behaviour of fishing fleets. The model, as an adaptation from a non-spatial model FISHRENT (Salz et al., 2011), includes a spatial component and is a tool to simulate effects of fisheries management measures on multi-species and multi-fleet fisheries using biological and economic data collected under the DCF (Bartelings et al., 2015). SIMFISH is used as a simulation model that optimizes the effort allocation to maximize annual profit for a consecutive number of years. In opposite to the FLBEIA North Sea model, SIMFISH includes feedback loops between the biology of the stocks included in the model and the fisheries behaviour on both short term (effort allocation) and longer term (entry-exit in the fishery). In addition, due to profit maximisation, with this model behaviour fuel cost is an important driver of effort allocation.

The problem in utilising the SIMFISH model for this specific project was the ban of the pulse trawl from July 1st 2021. More or less all vessels for which data are available and which are included in the SIMFISH model used the pulse trawl over the last years. Despite this, within this project the pulse trawl data was used for the base scenario, while further scenarios were run without the pulse trawl. The climate scenarios RCP 4.5 and RCP 8.5 have been applied from the CERES project (Harmon et al. 2021), with such scenarios also including assumptions on fuel price development, which can be seen as the best available information to assess the longer term climate effects in fisheries. As stock development is not included in the scenarios, runs used in FLBEIA for RCP 4.5 and RCP 8.5 were applied to predict stock status over the next years. The assessment of fuel efficiency was assessed using HCRs (Fmsy, FmsyH, FmsyL), while two fuel efficiency scenarios were tested with a decrease of fuel consumption of 1.4% or 4% per year.

FLBEIA long-term simulations

Within this work is provided the results of the FLBEIA application including a description of the model. Here we add the results for the long-term simulations for the North Sea demersal fisheries.

Figure 173 includes the plots for the development of the Spawning Stock Biomass for 2020-2060. For most species the curve is quite stable after the first years while for a limited number of species, like cod and plaice, the scenarios show a decreasing trend for the stocks.

In Figure 174 we show the development in effort for the main fleet segments. Due to the model characteristics (no spatial resolution) the effort levels are flat after some years. Also here we can see a few exemptions depending on the climate scenarios. Those fleet segments fish specifically on North Sea cod or Flatfish species (especially plaice).

For the assessment of the influence of the development in stocks on the effort of the fleet we then analysed the development of the Catch per Unit of Effort (CPUE). An increasing CPUE relates to a decreasing consumption of fuel – at least of the fishing activity itself. The vessels catch more fish with the same effort and same amount of fuel used for that effort.

For many fleet segments we can conclude that CPUE decreases over time which has to do with the decrease in stock size due to climate change impacts (Figure 175).

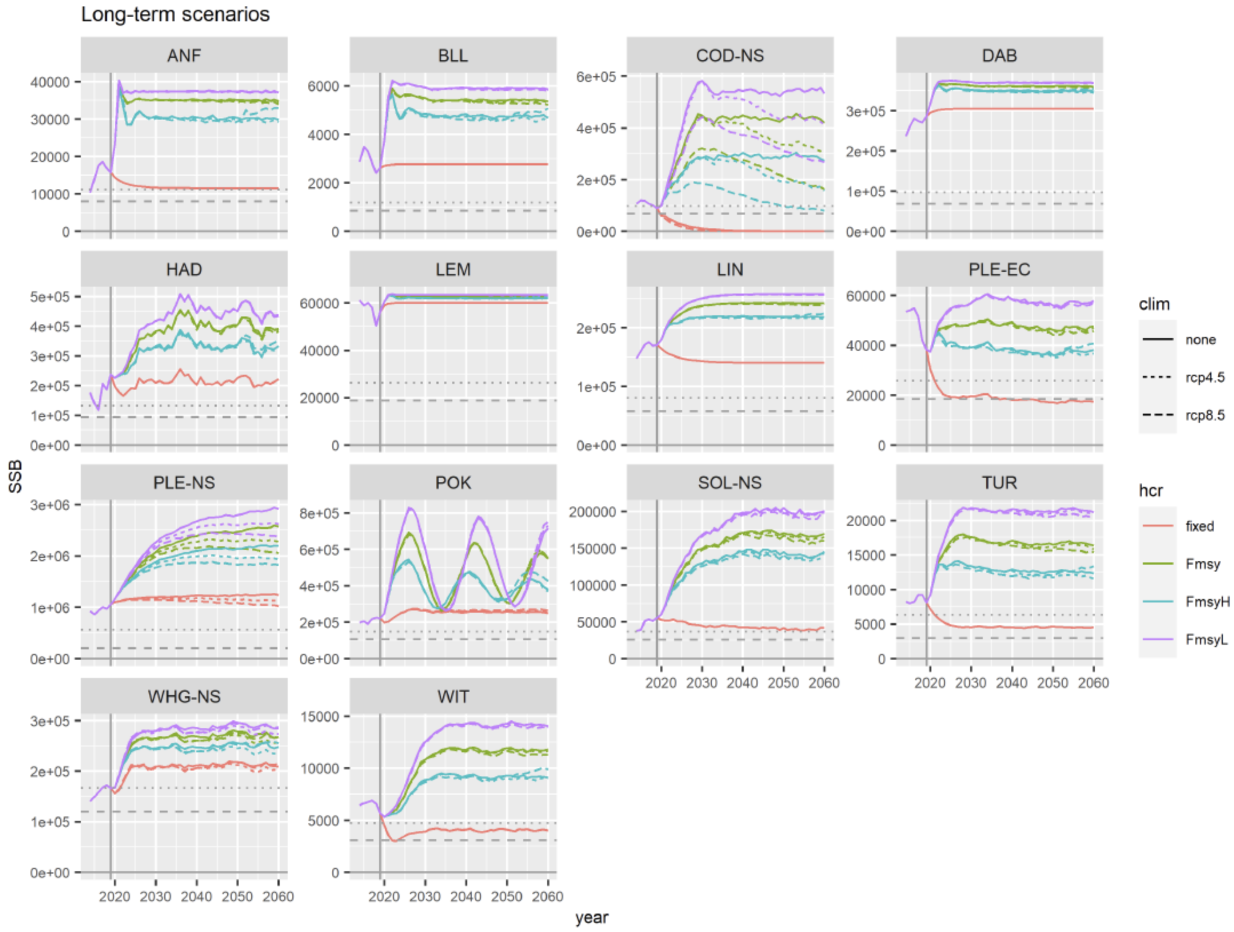

Figure 173 Development of spawning stock biomass

Figure 174 Effort levels for fleet segments in the North Sea

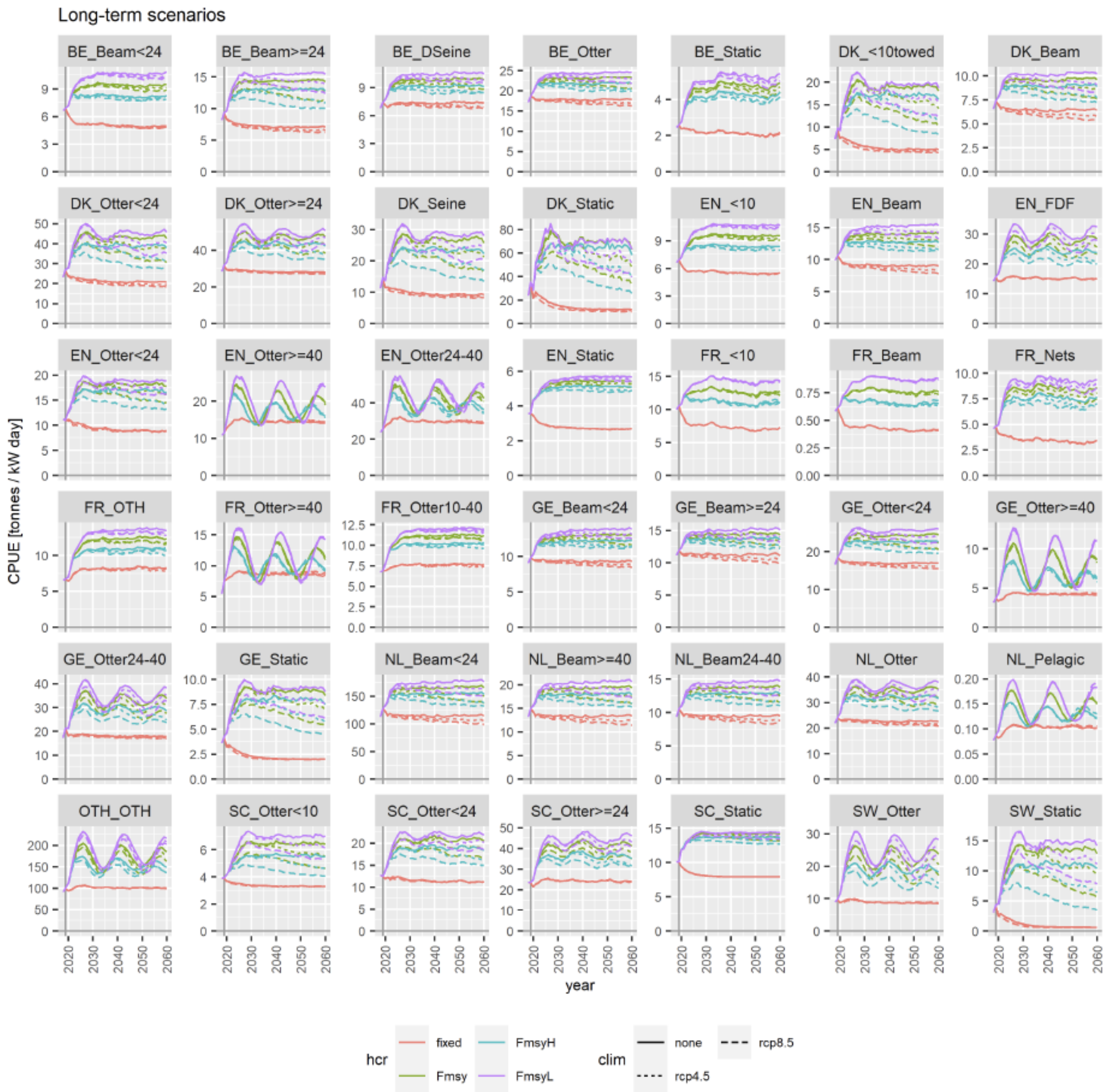

Figure 175 Development of CPUE for fleet segments in the North Sea

Annex 26.. REDUCING GHG EMISSIONS BY TECHNICAL MEANS

Pilot data extraction and standardization procedure

Data on energy efficiency applied to fisheries were gathered from two sources: (1) an exhaustive literature review, and (2) a consultation to scientific and commercial stakeholders through questionnaires.

The collation of studies for the literature review followed a two-tier approach linked to the type of information and access to them: 1) Information in published peer-reviewed scientific studies was accessed through a dedicated search in the Scopus literature database on 23 February 2021 non-peer-reviewed or unpublished studies and project reports were identified through in-house expert knowledge.

The consultation to stakeholders aimed at collecting information regarding the experiences undertaken on board fishing vessels on reducing the fuel consumption or greenhouse gas emission, and their views on the subject. Two stakeholder groups were targeted: scientists and commercial stakeholders.

Potential energy efficient technologies were listed based on the in-house knowledge and grouped in three categories. The list was further amended after the completion of the literature review and stakeholders' consultation. The three categories are the following:

Strategies to improve the fishing in operation such as route optimization, onboard fuel control and monitoring, and slow steaming.

Technologies to improve *vessel structure* and onboard equipment such as hull and propeller improvements, improved propulsion and auxiliary engines, improved fuel performance, LED lighting, alternative refrigerants, and assisted fishing.

Fishing ***gear*** technologies to reduce fuel consumption, such as new netting and gear designs that reduce drag, fishing gears that improve catch efficiency.

A fourth category was also included "Regulatory and management measures" to report of measures proposed in the literature and stakeholder consultation that discussed how to improve the energy efficiency by regulatory or management means.

Table 55 Exhaustive classification of energy efficiency measures adopted on board fishing vessels.

Category	Target	Subcategories
Vessel	Drag force reduction (hull)	Hull improvements
		Improved hull designs
		Ducted rudders
		Addition of a bulb
		Use of stabilizer fins
		Antifouling coatings and cleaning
		Polyester covering of hull to reduce friction
	Fuel consumption and GHG emissions	Improved propulsion and auxiliary engines
		Improved propulsion system (engines, gearbox, propellers)

		Renewable energy (for propulsion and onboard consumers) Improved maintenance Heat recovery systems Magnetic devices Frequency converters Shore power/shore supply of electricity
		Energy consuming machinery Shift from mechanical-hydraulic consumers to electric consumers onboard Led lighting Alternative refrigerants for cooling system
		Improved fuel performance Alternative fuels Additives
Strategy	Route optimization	Route optimization (based on metocean data) Slow steaming, speed optimisation Autopilot Fishing zone prediction systems Route planning systems, route optimisation
		Change of fishing ground Change the fishing ground based on the catch and changing the return day
	Energy consumption control and management	Onboard control and monitoring Energy audits Onboard energy monitoring devices and operative advice
Gear	Drag force reduction (gear)	New netting designs New or improved designs (incl. mouth opening, net shape, wings) Alternative materials (DyneemaTM) Different mesh size, type of knots, panel cuttings
		Operational improvement Electronically controlled gears
		New gear designs

		Change from demersal to semi pelagic trawling doors Alternative designs of trawl doors, trawl net, Sumwing Ground gear Alternative ropes (Helix ropes) Sledges
	Fishing gear change	From active to passive Gear change: from trawl to gillnet
		Within active: Gear change: from mid-water trawl to purse seine Gear change: from bottom trawl to pulse trawling Change the number of rigs from single trawling Assisted fishing
	Catchability	Improve catchability Selective fishing: led lighting and selective gears Technology to increase catch efficiency

The information collected either by the literature review or the stakeholder consultation was collected in an excel file, and included the following information:

- Literature type, Reference, DOI, Year, Keywords, Abstract (for the case of the literature review)
- Country involved, ocean, fishery, gear, target species, description target assemblage
- Main engine (hp / kW), length (m), category (level 1 improvement), target (level 2, improvement type), subcategories (level 3, improvement specifications), improvement specifications by author, narrative details about the specific improvement, investigation type (level of development), readiness level.
- Regulatory measure, barrier or incentive, drivers of change
- Drag reduction %, fuel consumption reduction (% or in kg), GHG reduction (in % or kg), GHG targeted, vessel activity targeted, total landings increase %, total revenue increase (%)
- Costs (euro), cost explanation, advantages, disadvantages

The information regarding the savings (i.e., fuel consumption, GHG emissions) and catch increase was organised according to the four overarching classifications: (Categories > Target > Subcategories > Measures).

The suitability of the considered excel fields for extracting key information was tested by a pilot data extraction procedure, which consisted in reviewing 3 relevant scientific papers and 3 grey literature reports (3 studies identified in the systematic search of the scientific literature and 3 key grey literature reports). The fields were amended when needed and the final version of the excel was used as a template (named ‘technology template’) to gather all the information extracted from the reviews.

Systematic review of the scientific literature

The systematic review of the scientific literature followed three steps, similar to Bastardie et al. (2021): (1) record identification, (2) screening of relevance to the objective and (3) data extraction. The first step consisted of an iterative process of identifying peer-reviewed papers by two independent expert teams in fisheries science. The two resulting databases were matched using common DOIs and compiled into one common database of scientific peer-reviewed studies. In the second step, this database was screened in greater detail to assess the studies for eligibility to reduce fuel use and increase energy efficiency. The final step consisted in the data extraction of possible measures identified in each study and in registering them on the 'technology template'.

Two teams of fisheries scientists independently identified studies using search strings with relevant combinations of keywords in the Scopus literature database. The first team consisted of three Lot-2 scientists from AZTI (ESP). The second team consisted of two Lot-1 scientists from ILVO (BE). The final list of peer-reviewed studies contained 293 papers, including 127 papers related to *Vessel* and *Strategy* categories, 69 to *Gear*, and additional 97 that discussed common energy efficiency issues. Team 1 screen the paper grouped under the categories *Vessel* and *Strategy* and the common references, and Team 2 the *Gear*-related ones (Annex 27). After the screening, both teams selected the most relevant papers and discussed their final selection amongst Team 1 and 2 members. As a result, 97 papers were considered as key for a more in-depth screening of the papers (26% of the papers were *Vessel* related, 24% *Gear* related, 5% *Strategy* related, and 45% discussed general energy efficiency/management/policy issues on energy applied to fisheries). Upon completion of the screening process less than 20 papers were identified as having significant relevance. Consequently, it was concluded that the vast majority of the 293 scientific papers returned from the systematic search only had peripheral relevance to the core information and data of interest; technological and regulatory changes/innovations that could be quantified and dated.

Grey literature search

The search of the non-peer-reviewed or unpublished studies and project reports through in-house expert knowledge so far resulted in the selection of 17 reports from both national and international research and development projects (Gabrielii and Jafarzadeh, 2020; ICES, 2020b; Notti and Sala, 2014; Taal and Klok, 2014; Hansen et al., 2013; Sala et al., 2013; Sala et al., 2012; Van Marlen 2012; Van Marlen et al 2011; Van Duren et al 2011; Huyghebaert et al 2010; Van Marlen, 2009; ILVO, 2008; Vanderperren, 2008; Depestele et al, 2007; EC, 2006; Wileman 1984).

Scientific and commercial stakeholder surveys

A questionnaire survey was design to complement the information obtained from the literature review with the knowledge and practical experience of stakeholders. A first questionnaire 'scientific questionnaire' (Annex 28) was tailored to experts in the field of fisheries science; and a second questionnaire 'commercial questionnaire' (a modified version of the first questionnaire) was prepared for commercial stakeholders, including fishers, producer's organisations, gear manufacturers and shipbuilding companies across Europe to target experiences directly from commercial practices.

The questionnaires included questions regarding strategies or technologies applied to improve the energy efficiency, savings obtained, investment and implementation cost, reasons that encouraged fishers to apply these measures, barriers encountered, drivers that stimulate or hamper the implementation of strategies, and reasons for stop using them.

General discussion on energy efficiency applied to fisheries

Energy efficiency has been a cornerstone for fisheries since the fleets started to get modernised, and the fuel consumption and GHG emissions from fisheries increased significantly with the reliance on larger vessels, more powerful engines, use of additional technologies for gear operation, onboard processing, refrigeration and ancillary services, and the search for previously unharvest species and new fishing grounds (Parker and Tyedmers, 2015; Parker et al., 2018). The global annual estimations on GHG emissions from fisheries vary according to the source consulted, from 40.7 million tonnes CO_{2eq} according to latest International Maritime Organization (IMO) estimates (MEPC, 2020) to 179 million tonnes CO_{2eq}. estimated by Parker et al. (2018) for early 2010s, difference that highlights the decoupling between research in fisheries and the IMO.

Yet, first publications on energy efficiency only started in mid 80s, mainly related to the use of sail assisted propulsion to power fishing vessels combined with low resistance hull designs and large slowly rotating propellers; the 90s had almost no relevant publications regarding energy efficiency; and it was not until the end of the 2000s that the number of publications started to grow as a rebound effect of the increase in the oil price worldwide (Figure 176). Nonetheless, the number of peer-reviewed papers (Figure 176) on the subject is quite reduced in comparison with other topics, such as Carbon Footprint, which had 706 publications (Yue et al., 2020) in 2018, when the price of fuel was still high, in comparison to the 10 of fishing related energy efficient ones.

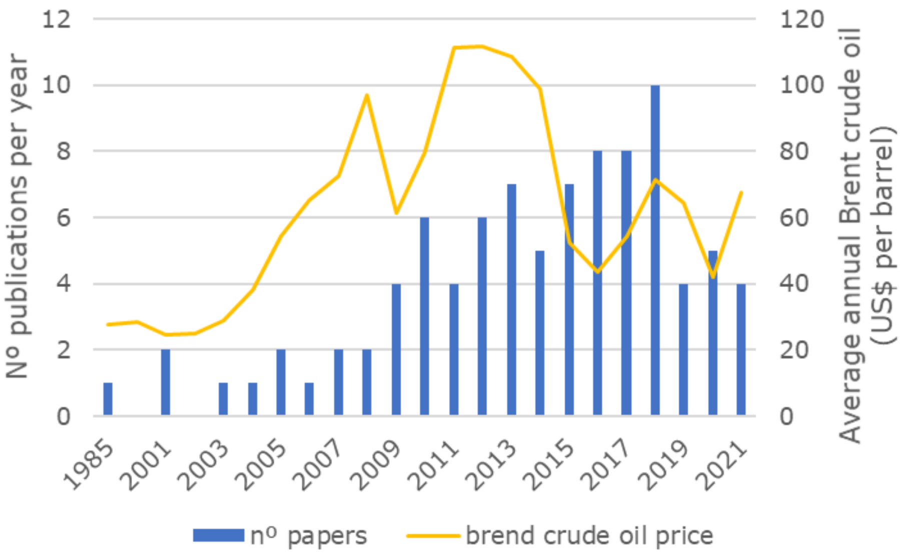

Figure 176 Trend on relevant peer-reviewed publications on energy efficiency in fisheries in relation to average yearly crude oil price (oil price source: Statista 2021[13]).

Energy efficiency in fishing has been actively considered by the European Commission since 2006. Prior to that, some initiatives were already undertaken on the topic, e.g., CLEANHULL project (2002-2003)[14] developed under the FP5-GROWTH Programme, or

[13] https://www.statista.com/statistics/262860/uk-brent-crude-oil-price-changes-since-1976/

[14] CLEANHULL project "Protecting and ensuring water quality and increasing marine fuel efficiency with up to 30% by an innovative under water hull cleaning process".

SUPERPROP project (2005-2008)[15] of FP6-SUSTDEV programme. In 2006 a dedicated website (https://energyefficiency-fisheries.jrc.ec.europa.eu) was created by DG MARE to exchange ideas, best practices, projects, new rules, etc. on the subject. In parallel the European Fishing Technology Platform (EFTP) through its Working Group 2 started to have discussions on energy efficiency (http://www.eftp.eu/energyeficiency.htm). Already then, several measures were suggested to reduce fuel consumption such as (1) fishing behaviour changes, e.g., 7% reducing the speed may involve a reduction of 16% of fuel; and (2), by technical adaptation of vessels and gears, e.g., 40% of reduction by improving the trawl doors and net, 10% of saving by replacing the engine (Peña Castellot, Workshop of Energy efficiency in fisheries, Madrid, 2012). Some studies and pilot projects were carried out by the support of the European Fisheries Fund (EFF) during 2007-2013 e.g.: 'Options of improving fuel efficiency in the UK fishing fleet' (Curtis et al., 2006), 'Energy Saving in Fisheries' (Imares, 2009), 'Effects of engine replacement on the fuel consumption reduction in fisheries' (CNR-Ismar, 2012). Within the EFF, the articles 25.2 and 25.3 covered the energy efficiency and engine replacement, respectively. The condition for any project was to assure the improvement did not increase the ability to catch fish. And in the 2010s, the DG MARE through the JRC completed the collection of three chapters about Information Collection on Energy Efficiency for Fisheries (ICEEF) with the most relevant initiatives on how improve energy efficiency in fishing sector (Sala et al., 2012; Sala et al., 2013; Notti and Sala, 2014).

Onboard a vessel, fuel (mainly marine diesel oil) is burnt by main and auxiliary engines (MEPC, 2020). The energy produced is used to propel the vessel or to power the onboard energy consumers. GHG emissions, however, are directly linked to the fuel consumption and the use of refrigerants in the onboard cooling systems. Therefore, a reduction of GHG emissions of fisheries can be driven by different means, such as reducing the fuel consumption, using alternative fuels or refrigerants with less GHG emissions, or by increasing the catch for the same amount of fuel consumed. Several terms are commonly used to refer to energy efficiency, some are interchangeably used; however, they have slightly different meaning. Table 56 lists the commonly used terms in energy efficiency lexicon.

Table 56 Terms related to energy efficiency

Term	Definition
Energy efficiency	'Energy efficiency' means the ratio of output of performance, service, goods or energy, to input of energy (Directive 2012/27/EU). In other words, it measures how much energy is used by any system or equipment to provide the desired level performance. E.g. units: L fuel/t catch.
Energy consumption	Energy is required by energy consumers onboard a vessel. Some energy consumers turn the energy produced from burning fuel into mechanical energy (e.g. main engine that consumes fuel to propel the vessel), some others turn the energy into electricity (auxiliary engines) so the onboard electricity consumers can be powered (e.g. onboard lighting), there are others that use the electricity produced by the auxiliary engines to power the hydraulic system or machinery onboard (e.g. winches).
Fuel consumption	It relates to the amount of fuel consumed by onboard engines (main and auxiliary engines). But often they only refer to the fuel consumption of the main engine, leaving the fuel consumption of the auxiliary engines uncounted. E.g. units: litres or kg.
Energy saving	'Energy saving' refers to the amount or % of saved energy determined by measuring and/or estimating consumption before and after implementation of an energy efficient measure (Directive 2012/27/EU). E.g. units: kg or l fuel

[15] SUPERPROPO project "Superior life-time operation economy of ship propellers". http://canal.etsin.upm.es/superprop/

Carbon footprint	Each of the GHG has an associated Global Warming Potential index (GWP), which depends on both the efficiency of each of the gases and their atmospheric lifetime. GWP is measured relative to the same mass of CO_2 and evaluated for a specific timescale. That is why the unit of kg of CO_2 equivalent is often used to quantify the amount of GHG gas emission and their effects. Carbon footprint refers to the kg of CO_2 equivalents emitted to the atmosphere. The emission factor of each fuel type is available in the literature; hence the transformation of fuel into GHG emissions or Carbon footprint is direct. For instance: the conversion factor for marine diesel oil is 3.206 t CO_2 eq./t diesel-gasoil (IMO, 2009). E.g. units: kg CO_{2eq}.
Greenhouse gas emission	Emission to the atmosphere of gases that trap heat in the atmosphere. Some of the gases are carbon dioxide (CO_2), methane (CH_4), Nitrous oxide (N_2O), and fluorinated gases. E.g. units: kg $CO_{2\ eq.}$

Energy efficiency is assessed by different indicators in the literature and regulations:

- Energy intensity (GJ/t) - energy requirement to produce a given weight of fish (Cheilari et al., 2013).
- Fuel Use Intensity 'FUI' expressed in terms of litres of fuel burned per tonne of live weight landings, i.e. L fuel/t catch (Cheilari et al., 2013).
- Carbon footprint (CO_2 equivalent) – GHG emissions produced for a given weight of fish). The Carbon footprint is calculated by multiplying the fuel consumption by the emission factor of the fuel used.

$$Carbon\ footprint = Fuel\ consumption\ [L\ fuel] \cdot Emission\ factor\ [g\ CO_2/L\ fuel]$$

- Fuel efficiency of fish capture: dimensionless ratio proposed by the EU in the Common Fisheries Policy (CFP) between the value of the fish landings and the fuel costs incurred in their extraction (Cheilari et al., 2013).
- Profitability - fuel cost share on total costs and the operating profits per vessel (Thomas et al., 2010)
- Edible protein Energy return on investment 'EROI' - A dimensionless ratio between energy inputs and the energy provided (edible protein) by the fish (Tyedmers, 2004; Vázquez-Rowe et al., 2014).
- EEOI (Energy Efficiency Operational Index) as a measure of fuel efficiency of a ship operation proposed by the IMO (Basurko et al., 2022).
- DIST (kg CO_{2eq} / nm) or TIME (t CO_{2eq}/hr) are proposed by the IMO to estimate carbon intensity (MEPC, 2020).

FUI is encouraged as a proxy for management effectiveness (Parker and Tyedmers, 2015) as it is widely used as to address energy efficiency in fisheries research. Considering this, the reference to energy efficiency in this document has been based on this indicator. The discussion of Task 3 regarding the ways to increase energy efficiency in fisheries has, therefore, included measures that have been discussed in the literature and stakeholder consultation to reduce the fuel consumption or to increase the landings.

Different factors affect the fuel consumption and the energy efficiency of fisheries, which can be classified as human, biological, technological and political factors, such as the target species, status of the stock, fish quotas, quota allocation policies, harvesting methods, distance to the fishing ground, fleet age, skipper effect, sale system and fuel cost, technical regulations and spatial and temporal limitation of fisheries, structural policies, and the availability of fuel subsidies/taxes (Jafarzadeh et al., 2016; Sala et al., 2012). While there is a broad agreement on the factors, there is still debate on which aspects should be prioritised. Some authors suggest that using energy saving technologies and strategies should be a short-term solution, whereas the improvement of the stocks should be the long-term solution; hence, it should be prioritised (Jafarzadeh et al., 2016; Parker and Tyedmers 2015).

Efforts to reduce fuel consumption, costs, and emissions in fisheries need to be tailored to the nature of individual fisheries (Parker et al., 2017); however, solutions are often presented as one-fit-all solutions, even the potential savings are reported as a whole, and little insights are given to whether the savings are applicable to all fisheries or to a certain activity mode (e.g. steaming or fishing). In fact, defining a vessel's energy (or fuel consumption) and activity patterns[16] are key to propose tailored solutions (Basurko et al., 2013); energy audits are seen as the mean to obtain this information (Basurko et al., 2013; Thomas et al., 2010). Basurko et al. (2013) lists the fuel consumption patterns of different fisheries as an example. The energy pattern is, in most cases, highly related to whether the fishery employs passive or active fishing gears (Table 57). Particularly, active ones that require towing a gear, such as trawlers or Danish seines, tend to consume most of their fuel during the fishing mode. Same is observed in trollers that spend most of the fishing trip sailing at fishing speed while towing the gear. In the case of trawlers, measures designed to reduce the fuel consumption while at fishing result the most cost-efficient. This is also observed in the high number of publications devoted to reducing the drag in trawling fisheries in comparison to actions undertaken to improve other measures related to the *Vessel* or *Strategy* categories, since drag reduction is their main concern to improve the energy efficiency. In contrast, purse seiners and pole and liners are more conditioned on the target pelagic species, that are migratory; hence, they spend large part of their time and effort sailing to the fishing grounds or finding fish. This translates in presenting higher fuel consumption during the steaming stage; hence measures such as route optimisation and slow steaming are the most suitable for this type of fisheries.

Table 57 Fishing gears and codes

	Code	Main fishing gear
Active	OTB	Bottom otter trawls
	OTM	Midwater otter trawls
	OTT	Twin bottom otter trawls
	PTB	Bottom pair trawls
	PTM	Midwater pair trawls
	TTB	Beam trawls
	DTS	Demersal trawls and demersal seiners
	PS	Purse seine
	LTL	Trolling lines
Passive	FPO	Pots
	GNS	Set gillnets
	GTR	Trammel nets
	LHM	Mechanised lines and Pole and lines
	LHP	

[16] *Energy pattern* understood as energy consumed by main and auxiliary engines whilst the vessel is engaged in different activities during the fishing trip (e.g. steaming, finding fish, fishing, in port during a fishing trip); *activity pattern* as time spent per trip at each of the abovementioned activities.

	Code	Main fishing gear
	LLD LLS	Handlines and hand-operated pole-and-lines Drifting longlines Set longlines

Stakeholders' participation and viewpoint

A total of 22 stakeholder questionnaires were completed, mainly by commercial fishery stakeholders from the Mediterranean Sea (Figure 177). It is apparent but not irrational that scientific respondents tended to respond with solutions that focused on experimental measures, whereas commercial stakeholders highlighted successful measures (Figure 178). A total of 108 energy saving measures were proposed across three categories: the Vessel, Strategy and Gear category. Passive fisheries prioritized improvements to the 'Vessel' category (N=24) with some strategic measures (N=2). Pelagic fisheries focused on both the 'Vessel' (N=8) and the 'Strategy' category (N=4), as did generic measures (N=10). Bottom trawl fisheries included measures for all categories and were the only gear type that included the 'Gear' as a category (N_{Vessel}=18, $N_{Strategy}$=11, N_{Gear}=31). More so, most energy saving measures in bottom trawl fisheries related to improvement of the bottom trawl. This is not surprising, as the energy use of fishing gears in passive fisheries is by definition negligible, while gears of pelagic fisheries only experience hydrodynamic drag and bottom trawl fisheries experience both hydrodynamic and geotechnical drag. Figure 179 shows the type of energy saving measures applied by stakeholders and fishery and down below a summary of the applied measures classified by fishery.

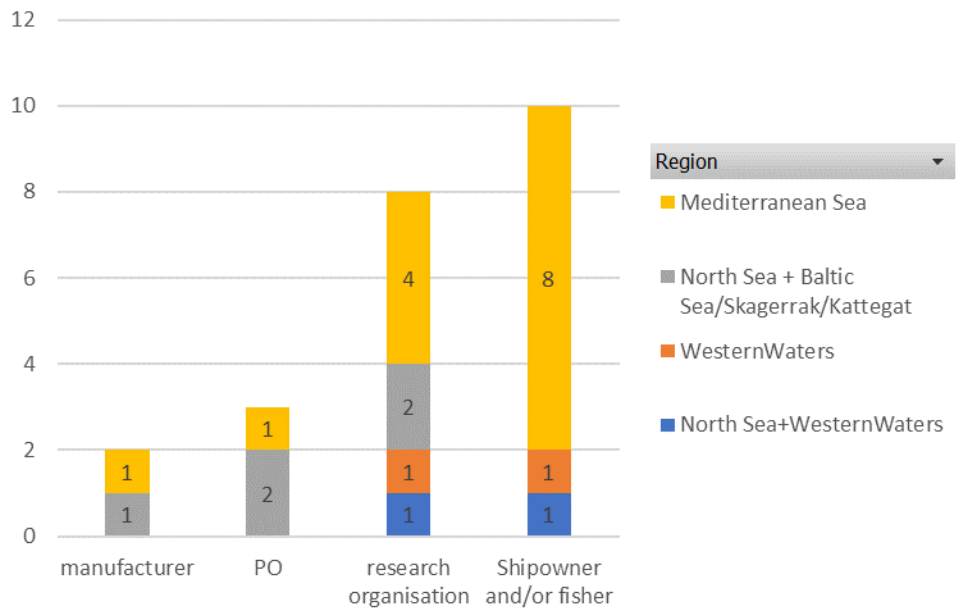

Figure 177 Respondents of the stakeholder questionnaires

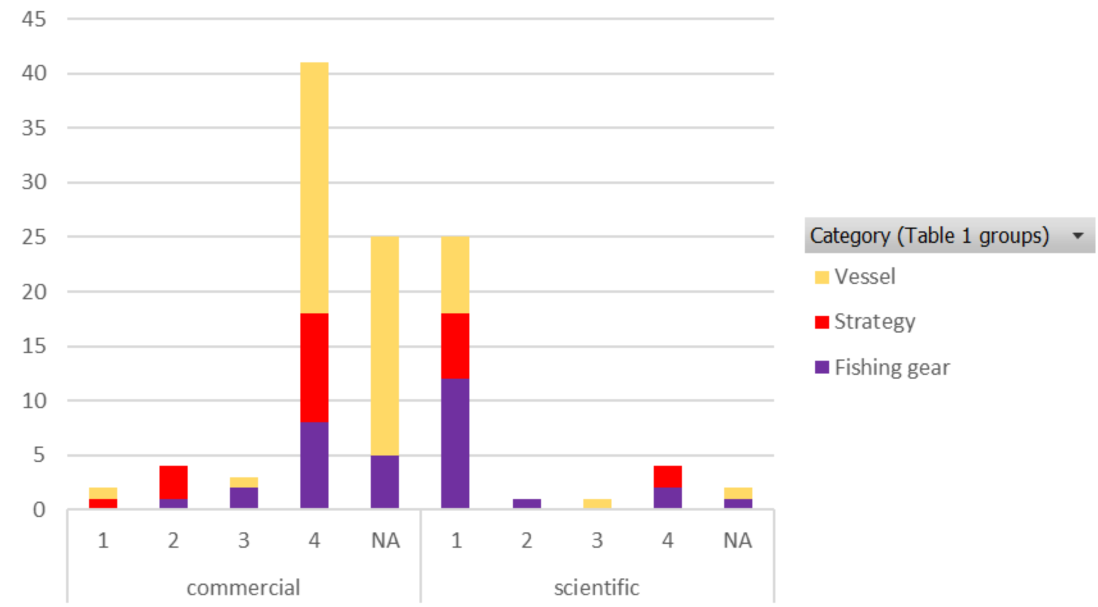

Figure 178 The level of implementation of the energy saving measures varied from the experimental level or low success rate (1) to implementations at fleet level or high success rate (4). Commercial fisheries questionnaires clearly showed higher success rates than responses from scientific questionnaires.

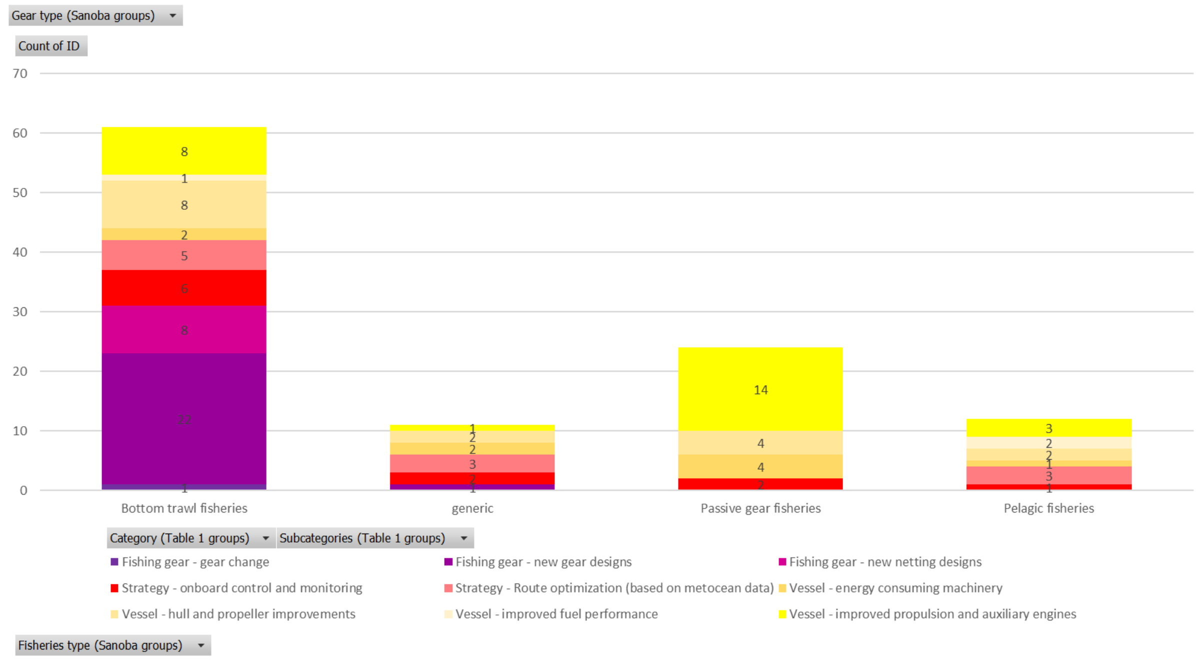

Figure 179 Specifications of the subcategories of energy efficiency improvements for the main categories 'Vessel' (yellow hues), 'Strategy' (red hues) and 'Gear' (purple hues).

Bottom trawl fisheries: Vessel-related measures included improvements of the (1) hull, (2) propulsion, and (3) engine. Alternative energy systems like solar or wind energy supply or improved fuel performance using additives were rarely mentioned and if so, they were not seen as additional energy supplies for other machinery than propulsion. Hull improvements related to an optimized hull shape, a bulbous bow and cleaning of the hull. Propulsion improvements included a ducted propeller, controllable pitch and propeller diameter. Engine improvements related to engine maintenance and technology, such as using modern technology, an electronic controller of the fuel pump and engine with low-energy specifications.

The Strategy improvements in bottom trawl fisheries focused on adjustments of steaming speed (steaming slower), on training skippers to use the engine optimally, on promoting the use of fuel monitoring systems, on autopilot installations, on using trawl geometry electronics and on fishing in accordance to waves and currents. Improvements were perceived both as experimental and operational, depending on the fishery (small-scale vs large-scale) and the group of respondents (scientific vs commercial).

Gear improvements were dominated by means to reduction of drag force by new netting or gear designs were, in contrast, highly important in bottom trawl fisheries. Solution to reduce energy use in beam trawl fisheries focused mainly on new gear designs, such as the replacement of the beam by a Sumwing, the replacement of trawl shoes by roller wheels and the use of lighter chains. The replacement of conventional beam trawls by pulse trawls and gear change option were also proposed. All of these improvements are implemented. One solution was mentioned related to the use of Dyneema™ netting, but this improvement was not perceived as ready for implementation. In bottom otter trawl fisheries, the use of new netting designs was mentioned more frequently (N=7), but its implementation level varied according to the way reduced drag was achieved. The use of bigger meshes was discussed as possible measure (e.g. in wings and front belly of the trawl), whereas the use of low-drag netting material (e.g. Dyneema™) and new netting configurations were assessed as experimental. New gear designs were also frequently mentioned to improve energy use in bottom otter trawl fisheries with a major focus on improvement of the otter boards. Reducing the hydrodynamic drag of otter boards by lifting them off the seabed was seen as the main solution. The success rate of improved otter board designs was both as experimental and as fully operational. The use of electronic equipment to monitor operational characteristics of the trawl and the trawl doors were mentioned as well.

Passive gear fisheries: Energy saving solution were provided by respondents from Greece and Sweden. Swedish solutions related to the energy supply from the shore and to exchanging the engine, whereas Greek solutions varied between solutions that were operational and those that had a low success rate. Operational solutions included the use of an autopilot, optimization of the engine speed, cleaning the hull, replacing wooden vessels by polyester hulls, the installation of a refrigerator and using photovoltaic panels. Improvements with a low success rate related to changes in propulsion systems, such as the use of hybrid engines, replacement of engines and kites to aid propulsion.

Pelagic fisheries: Vessel-related measures to improve energy efficiency include the replacement of the engine, replacement from diesel to gas or electric power supply, hull design and shore power supply. Strategic measures related to improved fish finding capacity, steaming speed and real-time monitoring of fuel use.

Generic measures: Some measures were not attributed to a specific fishery. Those included the use of energy-saving equipment for processes other than fishing, e.g. LED lights for lighting, and the use of electric instead of mechanical-hydraulic power supplies. Other potential improvements were the use of fuel monitoring systems, reducing steaming speed, the skipper’s mindset (e.g. slow steaming irrespective of fuel prices), maintenance of the hull and propulsion systems.

Technological measures for energy efficiency

In general terms, from the 41 technological solutions proposed to improve energy efficiency (Table 58), a wide variety of technologies were discussed in the scientific and grey literature (each covering the 79% of all the proposed solutions); however, stakeholders have only mentioned the application of the 50% (commercial stakeholders) or the 36% of the solutions (scientific stakeholders). This diversity of results highlights two things: the first, that limited number of solutions are transferred to the fishing sector from research, perhaps due to limited knowledge transfer on the technologies or because not all proposed solutions in scientific literature are applicable due to the existence of barriers or that not all solutions are suitable for all; and second, the information among different stakeholders (scientific, policy-makers and fishers) is not fluid, this may generate trust problems towards innovations.

Improving hull designs, propulsion systems and associated maintenance, application of the slow steaming and onboard monitoring, and using alternative designs of doors, trawl nets, ground gears or even changing from demersal trawl gears to more pelagic ones to reduce the drag are shown as suitable solutions by all consulted means. Some solutions are proposed by the scientific community (scientific literature and scientific questionnaire) and the grey literature but are not reflected by commercial stakeholders; this is the case of the use of LED lights for lighting onboard. And there are two solutions discussed by commercial stakeholders as suitable options to improve energy efficiency (i.e., the covering of the hull with polyester to reduce the friction, and the installation of the autopilot) that are not discussed as in the literature and by scientific questionnaire, perhaps because they are either not needed or already included in the more modernized fleets. The section below briefly introduces the energy efficient measures discussed in the scientific and grey literature and by the consulted stakeholders.

Table 58 Energy efficient technology usage reported in the scientific and grey literature and by consulted stakeholders

Category	Target	Subcategories	Source of info*				% Fuel saving potential[i]	Source
			S	G	CQ	SQ		
Vessel	Drag force reduction (hull)	**Hull and propeller improvements**						
		Improved hull designs					3-20	Notti and Sala, 2014; Basurko et al., 2013; Sala et al., 2012; Sala et al., 2011; Thomas et al., 2010
		Use of rudders					5	Sala et al., 2012; Van Marlen, B., 2009
		Addition of a bulb					6-30	Notti and Sala, 2014; Basurko et al., 2013; Thomas et al., 2010; Van Marlen, B., 2009; EC, 2006
		Use of stabilizer fins					2 (in drag)	Thomas et al., 2010
		Use of stern post					11 (Antifouling) 0.8–5 (Hull cl.)	Notti et al., 2019; Thomas et al., 2010; Van Marlen, B., 2009;
		Antifouling coatings and cleaning					26	
		Polyester covering of hull to reduce friction					3-20	Notti and Sala, 2014; Basurko et al., 2013; Sala et al., 2012; Sala et al., 2011; Thomas et al., 2010
	Fuel consumption and GHG emissions	**Improved propulsion and auxiliary engines**						
		Improved propulsion system					5 - 100	Bastos et al., 2021; Tadros et al., 2020; Jaurola et al., 2020; Gabrielii and Jafarzadeh, 2020; Notti and Sala, 2014; Basurko et al., 2013; Sala et al., 2012; Sala et al., 2011; Thomas et al., 2010; Van Marlen, B., 2009; EC, 2006;
		Renewable energy (sail-assisted propulsion)					5 – 25	Schau eta al., 2009; Van Marlen, 2009; Ziegler and Hansson, 2003; Bose and Macgregor, 1987; Amble 1985
		Renewable energy (for onboard consumers)					***	Gabrielii and Jafarzadeh, 2020
		Improved maintenance (predictive maintenance)					3 - 8	Basurko et al., 2015; Van Marlen, 2009
		Heat recovery systems					5 - 10	Gabrielii and Jafarzadeh, 2020; Palomba et al., 2017; Notti and Sala, 2014; Wang and Wang 2005
		Magnetic devices					2 - 6	Gabiña et al., 2016a; Notti and Sala, 2014
		Frequency converters					9.1 - 25	Lee and Hsu, 2015; Notti and Sala, 2014; Basurko et al., 2013
		Shore power/shore supply of electricity					90- 100 (consump. in port)	Gabrielii and Jafarzadeh, 2020
		Shift from mechanical-hydraulic consumers to electric consumers onboard					10-15	Gabrielii and Jafarzadeh, 2020; Notti and Sala, 2014; Sala et al., 2012
		Energy consuming machinery						
		Led lighting					26 - 55	Basurko et al., 2013; Sala et al., 2012; Thomas et al., 2010
		Alternative refrigerants for cooling system					50 (in electricity)	Sandison et al., 2021; Ziegler et al., 2013
		Improved fuel performance						

		Alternative fuels					1.2 (1.9% for CO2 red.)	Gabrielii and Jafarzadeh, 2020; Gabiña et al., 2019; Uriondo et al., 2018; Jafarzadeh et al., 2017; Gabiña et al., 2016b; Thomas et al., 2010; Schau et al., 2009; Goldsworthy, 2009;
		Additives					-	Hsieh et al., 2009
		Autopilot					3	
Strategy	Route optimization	**Route optimization (based on metocean data)**						
		Slow steaming, speed optimisation					15 - 59	Chang et al., 2016; Basurko et al., 2013; Sala et al., 2011; Van Marlen, 2009; Parente et al., 2008; EC, 2006; Latorre 2001
		Fishing zone prediction systems						
		Route planning systems, route optimisation						Granado et al., 2021; Groba et al., 2020; Chang et al., 2016
		Change of fishing ground						
		Change the fishing ground based on the catch and changing the return day						
	Energy consumption control and management	**Onboard control and monitoring**						
		Energy audits					**	Basurko et al., 2022; Basurko et al., 2013; Sala et al., 2012; Sala et al., 2011; Thomas et al, 2010
		Onboard energy monitoring devices and operative advice					3 - 15	Notti and Sala, 2014; Basurko et al., 2013; Sala et al., 2011; Van Marlen, 2009; EC, 2006; Latorre 2001;
Gear	Drag force reduction (gear)	**New netting designs**						
		New or improved designs					17 - 22	ICES, 2020b; Lee et al., 2018; Balash et al., 2015a; Notti and Sala, 2014; Hansen et al., 2013; Sala et al., 2012; Sala et al., 2011; Van Marlen, 2009; Priour 2009, Parente et al., 2008; EC, 2006;
		Alternative materials (Dyneema™)					2 – 40	ICES, 2020b; Lee et al., 2018; Balash et al., 2015a; Notti and Sala, 2014; Hansen et al., 2013; Sala et al., 2012; Van Marlen, 2009; EC, 2006
		Different mesh size, type of knots, panel cuttings					25 - 27	Lee et al., 2018; Hansen et al., 2013; Khaled et al., 2012; Sala et al., 2012; Sala et al., 2011; Van Marlen, 2009; Parente et al., 2008; EC, 2006
		Operational improvement						
		Electronically controlled gears					>15	ICES, 2020
		New gear designs						
		Change from demersal to semi pelagic trawling doors					1.6 – 19	ICES, 2020b; Lee et al., 2018; Guijarro et al., 2017; Notti and Sala, 2014; Basurko et al., 2013; Hansen et al., 2013; EC, 2006
		Alternative designs of trawl doors, trawl net, Sumwing					4.5 - 20	ICES, 2020; Lee et al., 2017; Notti and Sala, 2014; Sala et al., 2012; Priour 2009; Van Marlen, 2009; EC, 2006
		Ground gear					**	ICES, 2020b; Larsen et al., 2018; Van Marlen, 2009
		Alternative ropes (Helix ropes)					**	Kebede et al., 2020; ICES, 2020b; Sistiaga et al., 2015; Van Marlen, 2009;
		Sledges					***	Kaykac et al., 2017; Van Marlen, 2009
	Fishing gear change	**From active to passive**						
		Gear change: change from trawl to gillnet					***	Van Marlen, 2009

		Within active						
		Gear change: change from mid-water trawl to purse seine					5 – 25	Parker and Tyedmers, 2015; Driscoll and Tyedmers, 2010; Van Marlen, 2009
		Gear change: pulse trawling					35 - 54	Batsleer et al., 2016; van Marlen et al., 2014; Taal K. and A. Klok, 2014; Sala et al., 2012; Van Marlen, 2009; EC, 2006
		Change the number of rigs from single trawling					10-30	Broadhurst et al., 2013; EC, 2006; Van Marlen, 2009; Ziegler and Hansson 2003
		Assisted fishing					***	Sala et al., 2012
	Catchability and reduced mortality	**Improve catchability and reduce mortality**						
		Selective fishing: led lighting						Kuo and Shen, 2018; An et al., 2017; Bryhn et al., 2014; Matsushita et al., 2012; Yamashita et al., 2012
		Selective fishing: use of selective gears					8 – 25	ICES, 2020b; Jørgensen et al., 2017; Ziegler and Hornborg, 2014; Hornborg et al., 2012; Van Marlen, 2009
		Technology to increase catch efficiency						Chassot et al., 2021

* Savings are reported for several measures together; ** No quantitative data is presented about the reduction in grey literature, ***There is a mention about the potential for saving but no quantitative data are shown.

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[i] **Fuel saving Potential**: only the cases reporting a fuel saving by 1 technology is included. Those citing savings by several measures are excluded. The ranges reported consider different TRLs.

Technological measures to improve VESSEL's energy efficiency

Drag force reduction (hull)

Hull improvements:

- Improved hull designs: computational CFD models are successfully used to: optimise the hydrodynamic shapes of ships, including appendages such as rudders, keel, bow, stern (Notti and Sala, 2014); study vessels response to different sea conditions (Martelli et al., 2017); and improve the stability and sea keeping of the vessel. Changes in hull shapes, propeller designs together with propulsion systems could provide improvements of 3–20 % in fuel efficiency (Gabrielii et al., 2020; Schau 2009). An experience with optimised hull design on an Italian pelagic trawler reported potential fuel consumption savings up to 22%. Besides, Martelli et al. (2017) discusses that the saving linked to the new hull designs are limited, especially in new vessels in comparison to older vessels (exceeding 25 years) as shown for Polish fishing fleet (Notti and Sala, 2014).

- Ducted rudders: all vessels have additions to the underwater hull, normally known as appendages, that affect vessel's hydrodynamics. These include bilge keels, transducer mounts, cooling water pipes and the rudder. The use of aerofoil section rudder instead of a flat4plate rudder has shown to reduce the frictional resistance (van Marlen, 2009). Likewise, the use of controllable pitch (CPP) or contracted and loaded tip (CLT) propellers can also affect the performance of rudders, sometime even increasing the ship's response to rudder action (Sala et al., 2012). However, numerical simulations show that a potential of improvement of 5% on the efficiency is expected when the rudder is ducted, especially in trawlers.

- Adding of a bulbous bow: one common way to reduce drag during steaming mode is to add a bulbous bow to decrease wave making resistance. Therefore, bulb acts positively on the propulsive efficiency, especially in trawlers. The investment cost of a bulb for an Italian otter bottom trawler was estimated to be 50.000 € (in 2009), thanks to which a fuel saving of 6% could be obtained. Some authors have estimated larger savings (10-30%) for small fishing vessels during steaming.

- Use of stabilizer fins: bilge fins and other anti-roll systems are part of hull appendages. According to Thomas et al. (2010), the use of bilge fins in Australian trawlers have helped some vessel to reduce vessel drag by 2%.

- Antifouling coating: antifouling and foul release coatings are applied to the hull surface of the vessel to avoid the growth of fouling organisms, which increase the surface roughness, friction drag and hydrodynamic weight. Thus, they decrease shipping speed and manoeuvrability, as a result, higher fuel consumption is necessary to maintain the required speed and navigation settings (Selim et al., 2017). The operational aspects of coating performance are affected by factors such as time in port, time at sea, ship speed, geographical area and sea water conditions, season and fouling pressures, ballast and freeboard, mechanical damage etc (van Marlen, 2009). Foul release antifouling coatings have become the alternative to traditional copper-based antifouling paints due to their use of nontoxic biocide. Silicone based foul release coatings do not inhibit the fouling settlement but provide self-cleaning when sailing at a certain speed at a certain activity, typically minimally 15 kn at minimum 75% of the time. Newer generations of silicone hydrogel foul release coatings have been designed for idle speeds of 13 kn at minimum 60% of activity[17]. Nonetheless, some authors questioned the suitability of some self-release

[17] https://www.iims.org.uk/updated-third-generation-silicone-fouling-release-coatings/

polishing paintings for fishing vessels with the exception of tropical freezer purse seiners) as they are designed for higher sailing speeds and most of fishing vessels do not travel quickly enough to activate the self-release (van Marlen, 2009). Following this need, newly developed fluoropolymer-based coatings provide significant improvements with respect to the best silicone-based products, especially at slow speed (Notti et al., 2019) that make them more suitable for fishing vessels. Tests onboard a Mediterranean bottom trawler showed that foul release paints provided a fuel consumption saving of 11%, and that the saving remained the same after 2 years of applying the antifouling (Notti et al., 2019).

- Polyester covering of hull (reduction of friction): a small-scale Greek pelagic longliner reported that covering their wooden hull with polyester covering substantially reduced friction and fuel consumption. According to the shipowner this was a success as it reduced the vessels annual consumption by 26%, the maintenance also got reduced from 15-20 days per year to 5 days, and it allowed them to target larger pelagic by operating greater distances from shore.

Fuel consumption and GHG emissions

Improved propulsion and auxiliary engines:

- Improved propulsion system: a typical propulsion system consists of several components, including the diesel engine, shaft, a gear box system, and a propeller. In general terms, ship propulsion improvements can lead to reducing fuel consumption by 5 to 10% (Notti and Sala, 2014; Basurko et al., 2013). The main improvements of the propulsion system are listed below.

  Engine simulation models: to achieve a minimum value of fuel consumption, the propeller needs to be designed for the minimum level of the normal operating area of the engine (Tadros et al., 2020). Engine simulation models are used to design efficient combination of engines-ships.

  Ducted Propeller: the choice of the propeller configuration affects the energy efficiency. In trawlers that use ducted propellers the propeller operates at low advance coefficients during fishing, implying higher loads and lower efficiency (Martelli et al., 2017). And a selection of appropriately designed ducted propeller can increase the towing force of about 25 – 30%, which can involve a fuel saving of 15% (van Marlen, 2009; Sala et al., 2012). Ducted propellers are mainly used in Trawlers.

  Controllable pitch propeller: fixed blade propellers exhibit their optimal efficiency only at their designed point; hence, they present optimal performance when steaming to the fishing grounds and are less efficient when trawling (and vice versa) (van Marlen, 2009). In the case of trawlers, the energy demand and conditions during steaming and fishing are very different, which make the process inefficient Propellers can adapt to the needs of the engine, by maximising the engine power both for steaming and fishing ('trawling') and allowing the engine to be operated under optimum rpm and load conditions for each both steaming and fishing. Thus, the use of controllable pitch propellers instead of fixed propellers has become a common energy efficiency solution for trawlers (Sala et al., 2011; van Marlen, 2009).

  Propeller gear box: inclusion of propeller and its propulsion control in the power management and the design of the machinery to be installed onboard, early in the process, make the vessel more energy efficient (e.g. propeller operating points of a combined diesel-mechanical and/or diesel-electric propulsion system with a PTI/PTO gearbox). Jaurola et al. (2020) proposed a tool called TOpti that can make these comparisons by designing the whole ships' power system, including the power sources and the consuming power to optimally design ship machinery.

Hybrid propulsion (diesel + electric + batteries): hybrid propulsion allows several operating modes, to match speed and auxiliary requirements, enabling flexible and fuel-efficient operation. A review of the different hybrid propulsion solutions is provided by Gabrielii and Jafarzadeh (2020). It is attractive for some fisheries whose vessel's engine run at partial load for a significant part of its running time (EC, 2006). Although in late 2000s, the technology was not ready, vessels with hybrid propulsion are available in early 2020s (EC, 2006). Generation of energy onboard is optimized by a better integration of propulsive and auxiliary engines and recovering and using the exhaust gas heat. Diesel electric systems are estimated to provide savings of 10%.

- Renewable energy for propulsion: this measure was quite discussed in the 80s, which led to several scientific papers (Amble, 1985; Bose and Macgregor, 1987) even to organise a workshop exclusively on the topic[18] . Then, it was left aside for several decades, until the mid-2010s and early 2020s when the topic gained back interest for maritime researchers and entrepreneurs, as a solution for larger ships[19]. In the 2020s, the advances made in the shipping industry (e.g. conferences organised by RINA[20]) led to seeing it as one of the decarbonisation solutions for shipping. The use of sail assisted propulsion was studied for a Norwegian small-scale coastal fishing vessel (10 m length) (Amble, 1985). Sea tests highlighted that fuel savings of 8-15% in winds of 10 to 20 knots could be obtained. But the author highlighted that though savings were possible, the cost of the sailing rig could jeopardise the return of the investment, since the fuel consumption of this vessel types were not very fuel dependent. Sea tests were also undertaken for a coastal Scottish seine/trawler (27 m length), and the study concluded that annual fuel savings of 20-25% could be obtained for all modes of operation (steaming and fishing) by using wind turbines for propulsion. Also, in large beam trawler (24-40 m) in late 2000s where Skysail™ was proposed as an additional mean of propulsion during steaming, expecting a fuel saving of 20% (despite a large initial investment cost of 600.000€ for the reference vessel in 2008). In all cases, the propulsive potential will depend on the type of sail used and the wind speed and angle (Schau et al., 2009). Studies on prevailing weather conditions suggest that in areas with strong winds like Liverpool Bay, the Central North Sea, the German Bight and the southern coast of Ireland, a reduction of 20% in fuel consumption on an annual basis is feasible; in contrast, in coastal waters and the Bay of Biscay, wind conditions are less favourable resulting in lower fuel savings. Besides, the use of wind assisted propulsion would certainly affect the routines on-board and require a motivated and skilled crew (Ziegler and Hansson, 2003).

- Renewable energy for onboard consumers: the use of a hybrid propulsive system that includes batteries can result beneficial for fishing vessels with varying power demand and large electric power demand in port. Use of batteries facilitates the integration of intermittent renewable power (solar, wind) production on-board and for storing regenerated energy from heavy winches for fishing gears (Gabrielii and Jafarzadeh, 2020).

- Improved maintenance: a good and regular maintenance of the main and auxiliary engines ensures a larger durability of the engines and can contribute to reduce the fuel consumption. Italian commercial stakeholder reported savings up to 2.8% in a trawler due to a good maintenance. Basurko and Uriondo (2015) even suggested that modelling the performance of the engines could help in the fault detection and

[18] https://repository.library.noaa.gov/view/noaa/9676
19 https://bound4blue.com/en/
[20] https://www.rina.org.uk/Wind_Propulsion_2021.html

diagnosis before the faults even occurred (i.e., condition-based maintenance), for that, they proposed a predictive modelling for a Basque otter bottom trawler (43 m).

- Heat recovery systems have been discussed for fishing vessels for the last decade, estimating a saving potential of 9% of waste heat recovery (from exhaust gases) and 1% for cold heat recovery (from refrigeration system). While some authors have proposed the potential of using steam turbines for power generation from exhaust gases with a potential saving of 10% for trawlers; others have mathematically modelled the possibility of designing a NH_3-H_2O absorption refrigeration plat powered by a heat recovery system from exhaust gases of a trawler chiller fishing vessel (Fernández-Seara et al., 1998); even there are who have studied the feasibility of using waste heat for the refrigeration of fish or ice-making by using an sorption technologies (Palomba et al., 2017; Wang and Wang, 2005). However, ORC has risen interest in the past years as a promising option for fishing vessels. EfficientShip project estimated a potential saving of 5-10% using an ORC system for Irish coastal trawler. Yet, no real implementations have taken place in fishing vessels so far, and it also implies challenges in relation to waste heat availability and sizing of heating and cooling equipment (Gabrielii et al., 2020).

- Magnetic devices: when the fuel is exposed to a magnetic field prior to combustion the ions in the fuel are aligned into straight chains, which burn more efficiently as the oxygen can mix with the fuel better (van Marlen, 2009). The use of magnetic devices as fuel treatment to improve energy efficiency has been discussed by the industry and they seem a suitable and fast alternative to reduce fuel consumption. Gabiña et al. (2016a), who reported fuel savings (~2%) and exhaust gas emissions (~0.6%) reduction, however highlighted that the savings were lower than expected by manufacturers. Others have found higher fuel savings by testing them under real operation conditions in an Italian bottom trawler, with accounted fuel savings of 4-6% (Notti and Sala, 2014).

- Frequency converters: they are an electronic or electromechanical device that converts alternating current (AC) of one frequency to alternating current of another frequency. In order words, they convert a basic fixed-frequency (line power) to a variable-frequency (variable-voltage output used to control speed of induction motors). That is why they are common energy-saving practice in industry, and they could be used in all type of fishing vessels using electricity to power machinery. For example, in a trawler, frequency convertors could be applied in condenser pump and compressor of the ice-making machine, and the refrigeration seawater pump of the main engine. According to manufacturers they could provide a 25% of fuel saving, and the return of investment could be of few years (Basurko et al., 2013). Also linked to electric systems, some authors have proposed the use of withdrawable capacitor module to improve the power factor in marine electrical systems as a way to improve energy efficiency by 8% (Lee and Hsu, 2015). However, the payback time (return-on-investment) will depend on the alternator running hours per year and the price of fuel.

- Shore power/shore supply of electricity: when a vessel is connected to the shore supply, auxiliary engines are not needed; hence emissions are reduced totally. This requires the vessel to be equipped either with a diesel-electric engine that can be charged with shore power to power electric machinery such as winches and cranes, or to a connection to shore supplied, also known as cold ironing and batteries. In Norway the reduction of GHG emissions by applying cold ironing is estimated to reduce tin 90% the GHG emission by switching from diesel to grid energy. By August 2020, 7 fishing vessels were equipped_with batteries and were operative, and 11 were on order (Gabrielii and Jafarzadeh, 2020). Swedish purse seiners have also reported to be equipped with batteries and they use shore power, although the fuel and GHG emission savings have not been reported yet.

- Shift from mechanical-hydraulic consumes to electric consumers onboard: this solution is also linked to the electrification of the vessels together with the hybrid propulsion and the shore power supply. Choosing electrically powered machinery onboard can increase the efficiency by benefitting from the abovementioned. Italian scientist stakeholders have tested this shift and suggested a saving between 10-15% in energy.

Energy consuming machinery

- LED lighting: changing the interior and exterior lighting for more energy efficient LED lights is a one of the non-intrusive solutions for many vessels to reduce the electrical lighting load. This solution is applicable to all fishing vessels. It is estimated that the saving could be in the order of 0.5 to 3% regarding the annual fuel consumption (Basurko et al., 2012; Thomas et al., 2010)

- Alternative refrigerants for cooling systems: the type of the refrigerant employed in the cooling systems plays an important role in a fishing vessel's contribution to GHG emissions, according to Iribarren et al. (2011), this contrition can be as high as 13%. With the entry in force of Regulation (EC) No 2037/2000 (EU, 2000) and No 1005/2009 (EU, 2009) related to decreasing the use of substances that deplete the ozone layer (Sandison et al., 2021), vessels built after 2004 had to replace the traditionally used refrigerant (hydrochlorofluorocarbon HCFC R22) by a more environmentally friendly alternative. Within the options, the ammonia is highlighted as the most suitable replacement for the entire cooling system onboard (Ziegler et al., 2013). Furthermore, it is cheaper than synthetic refrigerants and more efficient (Ziegler et al. 2010). However, this change implies higher initial costs despite the return of the investment is short. Norwegian fishing sector already started to work on this issue in the early 2010s by replacing R22 by ammonia systems (Ziegler et al., 2013). In order to quantify the GHG emissions associated to fisheries, it has to be born in mind that the leakage rates depend on the machinery employed and the time used. For instance, lower leakage rates are associated to the pelagic fleet, who use refrigerated seawater systems to cool the catch because they require less refrigerant per tonne of fish kept compared to the refrigeration systems used on demersal vessels (Ziegler et al., 2013).

Improved fuel performance

- Alternative fuels: 93% of the fuel used in global fisheries is Marine Diesel Oil (MEPC, 2020). Several alternatives have been studied to replace this fossil fuel.

  LNG: although the potential of alternative fuels including low-quality distillate, liquefied petroleum gas (LPG), biodiesel, fish oil, ethanol, and hydrogen have been studied as a substitute to diesel to reduce the GHG emissions (Gabrielii and Jafarzadeh, 2020), the Liquified Natural Gas (LNG) appears to be the most viable fuel for fishing vessels (Gabrielii and Jafarzadeh 2020; Goldsworthy, 2009), for example for Norwegian coastal shrimp trawlers (Jafarzadeh et al., 2017). However, the use of LNG as fuel presents several difficulties such as high initial cost of conversion (25% more compared to oil-fuelled vessels), complexity, safety, and additional training needs to operate it safely (Jafarzadeh et al., 2017; Thomas et al., 2010). Application of LNG for fishing vessels have been furthered studied in Norway (Jafarzadeh et al., 2017; Jafarzadeh et al., 2012) and Australia (Goldsworthy, 2009).

  Waste oils: waste-oil from recycled waste automotive lube oil has been tested with good results as a replacement to diesel for fishing vessels (Gabiña et al., 2016b, 2019; Uriondo et al., 2018). Tests undertaken onboard a Basque bottom otter trawler under real operating condition indicated that this type of alternative fuel provides 15% of NO_X emissions reductions. Despite CO_2 emissions were slightly reduced, CO emissions increased (by 15%) by using this waste oil.

- Additives: additives are used in fuel to enhance the quality and efficiency of fuels allowing the use of higher compression ratios for greater efficiency and power. Despite the use of additives can contribute to improve the energy efficiency, no experiences have been reported yet on the benefits of additivation the fuel used in fishing vessels.

- Autopilot: although autopilot is present in many vessels, according to Greek otter bottom trawler fishing owner an autopilot system onboard fishing vessels can decrease the fuel consumption by 3% and increase safety and convenience by selecting an economical navigation speed.

Technological measures to improve STRATEGY's energy efficiency

Route optimization

Route optimization (based on metocean data)

- Slow steaming: this measure is suitable for fisheries which main fuel consumption occurs while steaming, e.g., purse seiners, gillneters, handliners, pole and liners. It consists of reducing the steaming speed and adopting the optimal service speed according to the particularities of the main engine and the vessel, that guarantees the minimum fuel usage per tonnage mile reached (Chang et al., 2016). Slow steaming may therefore slightly increase the duration of the trip or for the same duration of a fishing trip, reduce the number of the sets per trip. Basurko et al. (2013) analysed the application of slow steaming in trawlers and they concluded that for keeping the same activity pattern of the vessel, the slow steaming would imply having 2 fewer fishing sets per trip; therefore, the number of fish caught may decrease. In contrast, fuel savings were reported by Basque trollers (20% fuel saving was obtained by not exceeding 8kn during steaming) and purse seine - pole and liner (15% fuel saving by not exceeding 9.5kn during steaming), which compensated the potential reduction of fish caught and the extended arrival time. Latorre (2001) also discussed the benefit of slow steaming in regard to the reduction of NO_x emissions (15% reduction). However, to assess the suitability of this measure, shipowners would need to balance the benefit of reducing the fuel consumption, in comparison to a reduction in income (Basurko et al., 2013).

- Route planning system, route optimisation: different options of route planning are available to optimize the routes to the fishing grounds. The ocean weather associated with eddies, meanders, storm likelihood, ocean surface waves, sea ice and tides are commonly used for planning and optimizing the route to fishing grounds (Chang et al., 2016). The use of route optimization Decision Support Systems, widely used in the shipping industry, has been rarely applied in fisheries (Granado et al., 2021). Distant-water vessels like tropical purse seiners are currently the fleet that can more easily benefit from such decision support system, named 'fishing route optimization decision support systems (FRODSS)' (Granado et al., 2021). However, tropical freezer purse seiners use drifting Fish Aggregating Devices (FADs) (man-made surface floating objects deployed in the ocean that attract a number of marine species, including tunas (Castro et al., 2002)), which has greatly increased the efficiency and catchability of purse seiners over the last decade (Chassot et al., 2021). These dFADs are usually equipped with satellite linked echo-sounder buoys, which provide skippers with accurate geo-location information and rough estimates of the biomass associated underneath (Davies et al., 2014; Lopez et al., 2014). Despite the use of FADs is a common practice in this fleet since the 1991 and these vessels follow the information provided by the FADs for route planning for the fishing ground, yet the energy efficiency of using FAD versus opting for a more traditional free-swimming school strategy (Basurko et al., 2022). Latest research, however, suggests that sharing FAD information optimizes the use of fuel and time for entire fleets. And this can be done by applying game theory approach and decision support systems to improve their routing (Groba et al., 2020).

Energy consumption control and management

Onboard control and monitoring

- Energy audits: energy audits are procedures that enable organisations to know their status with respect to energy use. They provide a detailed scan of the energy flows of an activity and propose measures to help reducing the energy demand; hence they obtain an economic and environmental savings (Basurko et al., 2013). Energy audits are one of the most valid solutions to assess the energy performance of the fleets and propose tailored energy-efficient solution for fisheries (Guillen et al., 2016; Notti et al., 2014; Cheilari et al., 2013), due to the energy consumption depends on the nature of individual fisheries, the relative roles of onboard technology, human behaviour and management (Parker et al., 2017). Despite the importance of energy audits in adopting a suitable energy efficiency solution, only three research teams from Australia, Italy and Spain have experience in using them in fisheries (Thomas, et al., 2010; Sala et al., 2011; Basurko et al., 2013, 2020).

- Onboard energy monitoring devices and operative advice: closely related to energy audits and slow steaming, continuous onboard energy monitoring devices help shipowners and skippers have a better control over the energy flow onboard, and fuel and GHG emission savings. Several of these devices are available in the market (FCM[21], GESTOIL[22]), others are still prototypes as part of EFIOIL or Peixe Verde projects (Basurko et al., 2013; Villarroya et al., 2009). Fuel consumption reduction between 5 to 15% have been reported by only making skipper and shipowner aware of the relative fuel consumption of the vessel, e.g. showing the vessels fuel consumption per nautical mile (Basurko et al., 2013; Notti and Sala, 2014).

Technological measures to improve GEAR's energy efficiency

Introduction

Gear modifications to improve energy efficiency is closely related to the reduction in total gear drag. Although a mechanistic description of the relationship between total gear drag and fuel consumption was not found, reductions in fuel use with decreasing drag have been demonstrated (e.g. Broadhurst et al., 2013). The drag experienced by fishing gears can be split into hydrodynamic and contact drag (O'Neill and Ivanović, 2016). Hydrodynamic drag (assuming no contact with the seabed) has been predicated using a mechanistic relationship with towing speed and the frontal area of gear components (O'Neill and Summerbell, 2016; Rijnsdorp et al., 2021). The increased of hydrodynamic drag with towing speed shows a power-relationship, implying that very high speeds cause a proportionally higher drag for similar frontal areas (Liu et al., 2021). The relationship of hydrodynamic drag with towing speed and the surface area of gear components shows that a reduction in fuel consumption and the total trawl drag can be expected by reducing the surface area of the trawl components (e.g. smaller doors, reduced netting surface, number of flats and ground gear equipment) in combination with a reduced towing speed (Valdemarsen and Hansen, 2006). O'Neill et al. (2018) demonstrated that contact drag of

[21] https://www.silecmar.com/es/productos/fcm-gestion-consumos/

[22] https://www.azti.es/proyectos/gestoil/

gear components depends not only on their geometry, but also on the weight of the gear components, the type of sediment on which they are towed and whether they are rolling or not.

When drag is considered as a major contributor to fuel efficiency, it is not surprising that most studies have focused on active fishing methods to improve energy efficiency by the use of gear modifications. Indeed, the conducted questionnaires show that bottom trawl fisheries were the only fishery where modifications to the 'fishing gear' were considered as a possibility to reduce fuel consumption. More so, most energy saving measures in bottom trawl fisheries related to improvement of the bottom trawl (N_{Vessel}=18, $N_{Strategy}$=11, N_{Gear}=31). This is not surprising, as the energy use of fishing gears in passive fisheries is by definition negligible, while gears of pelagic fisheries only experience hydrodynamic drag and bottom trawl fisheries experience both hydrodynamic and contact drag.

Developments in the fishing gear may reduce fuel consumption to a maximum of 20% by modifying bottom trawls (EC, 2006), although substitution of conventional gears with innovative ones may reduce fuel consumption further (up to 50%) but comes with other considerations related to the legislation of the new gear (e.g. pulse trawl fisheries).

This section assesses the gear measures to improve energy efficiency for bottom trawl fisheries: beam trawl and otter trawl fisheries. Nonetheless, each measure has been presented separately, independently to the applied fishery.

Measures for Beam trawl fisheries

There were no peer-reviewed papers retrieved to assess gear-related measures to reduce fuel consumption in beam trawl fisheries. All gear measures to reduce fuel consumption in beam trawl fisheries result from grey literature reports. Two respondents from the questionnaire survey (1 commercial and 1 scientific response) made suggestions on how to reduce energy use in beam trawl fisheries. The proposed gear measures focused mainly on new gear designs, such as the replacement of the beam by a Sumwing and the replacement of trawl shoes by roller wheels and the use of lighter chains. All of these improvements are implemented in Belgian fisheries. One solution was related to the use of Dyneema™ netting, but this improvement was not perceived as ready for implementation. The replacement of conventional beam trawls by pulse trawls was the only gear change resulting from the questionnaires. All these responses are recurring the grey literature review.

Modifying beam trawls to reduce drag resistance

- Netting modifications in beam trawlers: a first series of net modifications that is hypothesized to reduce fuel consumption is related to the improvement of beam trawl selectivity. These included benthos release panels (Fonteyne and Polet, 2002), T90 codends (Polet and Depestele 2010) and large mesh top panels (Van Marlen, 2009; Van Marlen, 2012). The effect on fuel consumption was only measured during experiments onboard a 1200 hp beamer using beam trawls with chain matrices and large mesh top panels (30cm mesh size over 2/3 of the top panel). A ballpark estimate of 5 to 10% reduction in fuel consumption was reported, together with a reduced catch efficiency for haddock and whiting but not for flatfish (Depestele et al., 2007; Van Marlen, 2009).

  The second type of netting modifications were the replacement of traditional nylon netting with Dyneema™. Dyneema™ netting has a smaller twine diameter leading to 70% weight reduce in netting material and 12% less hydrodynamic drag. Replacing the traditional nylon netting with Dyneema™ reduced the average fuel use from 5450 litres per day with 6.7 tonnes of warp load to 4940 litre per day and a warp load of 5.9 tonnes. Including all baseline trips showed that the use of Dyneema™ could reduce fuel consumption by 8.8% (Van Marlen, 2009).

- Modifications to the beam trawl configuration: the reduction in beam trawl weight to save fuel is mentioned as an obvious measure to reduce the drag of beam trawls (Polet, 2006; Rossiter, 2006; Van Balsfoort, 2006). Lighter weights can be achieved by reduced the weight of the trawl shoes and the chains, reducing the beam size as well as running the chain mat for longer, implying that they become lighter. No estimates of the effect of these measures have been retrieved, but the applicability is generally seen as very high.

  Another feasible measure was the replacement of trawl shoes with rolling wheels. Rolling wheels were used by UK beamers prior to the 2008 fuel crisis, but their use expanded in the UK and to the Belgian beam trawler fleet following the 2008 fuel crisis (Rossiter, 2006). A wide series of rolling wheels were tested in the Belgian and Dutch fleet (ILVO, 2008; Van Marlen, 2009). Most large chain mat beamers in Belgium continued using two larger wheels to assist the trawl shoes after the testing period of 2007-2008 (ILVO, 2008; Van Marlen, 2009: 356-357). Assisting the trawl shoes with rolling wheels reduced geotechnical drag on hard soils and resulted in 5% fuel savings for chain mat beam trawls. Warp load in soft fishing grounds may in contrast have increased. Van Marlen (2009) modelled the reduced fuel consumption for tickler chain beam trawls assuming 15.5% drag reduction, which resulted in 16% fuel reduction.

  The 2008 fuel crisis also stimulated research whereby the cylindrical beam was replaced by a hydrofoil wing, called the 'Sumwing' or the 'pulsewing' when it's used in combination with the pulse trawl (Figure 180). The manufacturer of the Sumwing showed that the combination of a Sumwing with the pulse trawl leads to a 40% reduction in fuel consumption, whereas the use of the Sumwing only (without electric fishing) leads to 12% reduction in fuel consumption[23]. These estimates are confirmed by various sources. Turenhout et al. (2016) and ICES (2020a) estimated a reduced fuel consumption of 16% and 13% respectively using fleet data for large Dutch beamers. Experimental North Sea trials in 2008 showed that fuel consumption was reduced by 11% without compromising the catches during beam trawl trips using Sumwing instead of the conventional cylindrical beam (ICES, 2010 in Van Marlen, 2012). Catch comparisons in Belgian fisheries resulted in similar fuel reduction (13-23%) without substantial changes to the catching efficiency across species (Huyghebaert et al., 2010). Sumwings are currently successfully deployed in beam trawls using tickler chains, but they are not used in chain mat beam trawls. Instead, chain mat beam trawls are using roller wheels.

  Beam trawl fisheries deploy tickler chain or chain mat beam trawls. Both are targeting flatfish using chains to stimulate the fish from the seabed. Tickler chain trawls are widely used in the Dutch beam trawl fishery, while chain mat beam trawls are typically used by Belgian fishers and fishers from the South of the Netherlands. Tickler chain beam trawls operate at high speeds on clean grounds (6-7 knots), chain mat beam trawls tow at 3-5 knots, allowing them to also fish in rougher grounds as the chain matrix prevents large boulders from entering the trawl (Figure 181). Van Marlen (2009) reported an average fuel consumption of 4144 litres per day using the chain mat instead of 5420 litres per day using the tickler chains for the same vessel. Based on these results from the fuel economy meter, a fuel saving of 24% can be achieved by switching from tickler chain to chain mat beam trawls (Van Marlen, 2009: 356). Since the prohibition of pulse trawling, several Dutch beam trawlers have considered to switch from tickler chain

[23] http://www.sumwing.nl/SumWing.pdf, accessed 30/06/2021

to chain mat beam trawling using roller wheels to reduce their fuel consumption. The Dutch fishers also want to test whether the chain mat beam trawls can also be used in the fishing ground where pulse trawls were deployed (Visserijnieuws, 2021c).

Figure 180 top panels: rolling wheels assist trawl shoes to reduce drag in chain mat beam trawl fisheries, lower left panel pulsewing, lower right panel: Sumwing with tickler chains (© top left: Z36 Sophie 2021, © other pictures ILVO)

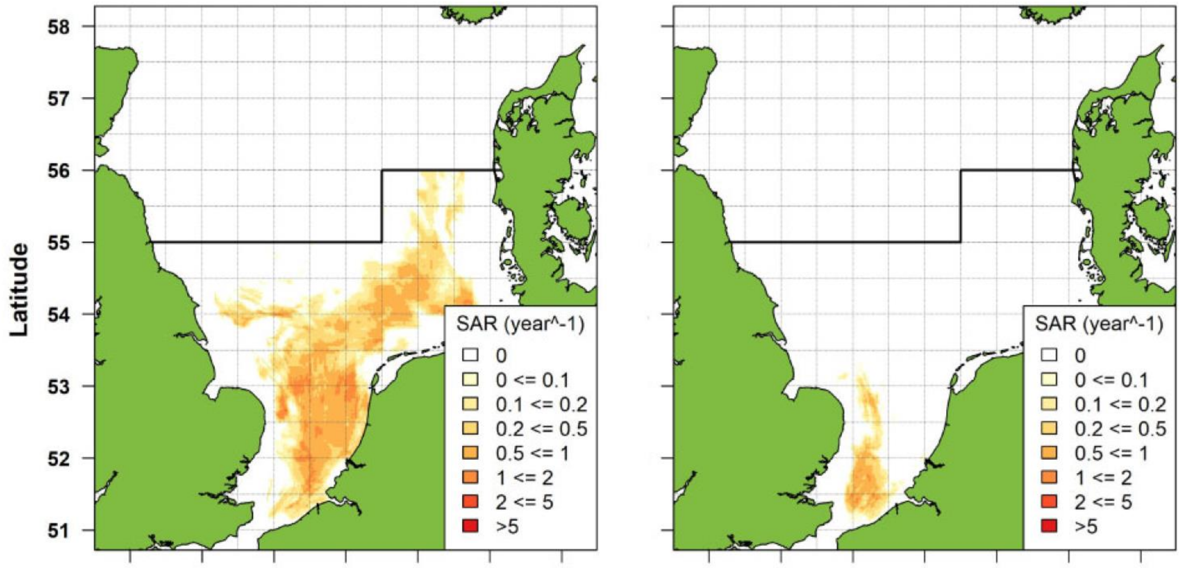


Figure 181 Annual swept area ratio (SAR) of the conventional tickler chain beam trawl (left) and chain mat beam trawl (right) in the period 2009–2010 (taken from Rijnsdorp et al., 2021).

Substitution of beam trawls

- Alternative non-electrical catch stimuli-water jets: alternative catch stimuli are categorized as a gear substitution because they entail a substantial change in the catching principle and by consequence to the geotechnical drag and fuel consumption. Catching principle is used to classify gear in Bjordal (2002) but not in He et al. (2021). Instead of using mechanical stimulation by chains, fishers have proposed using water flow along the beam or as jets to startle a response in flatfish.

  Water flow as catch stimuli was tested for two types of water jets in the REDUCE project (Keegan, 2002). A second series of developments was instigated by the fuel crisis of 2008 and led to the so-called 'hydrorig'. The Hydrorig used the horizontal opening of the beam but replaced the chains by semi-spherical cups to stimulate a waterflow by turbulent vortices (Figure 182) (Polet and Depestele, 2010; Polet et al., 2010; van Duren and De Kleermaeker, 2011; Van Marlen et al., 2011; Van Marlen, 2012; Visserijnieuws, 2009). These trials were abandoned, because of their reduced catch efficiencies and the upcoming success of the pulse trawl. However, since the prohibition of pulse trawling in 2021, there are renewed efforts in the Dutch fishing industry to use water spray to catch flatfish (Visserijnieuws 2021a, 2021b).

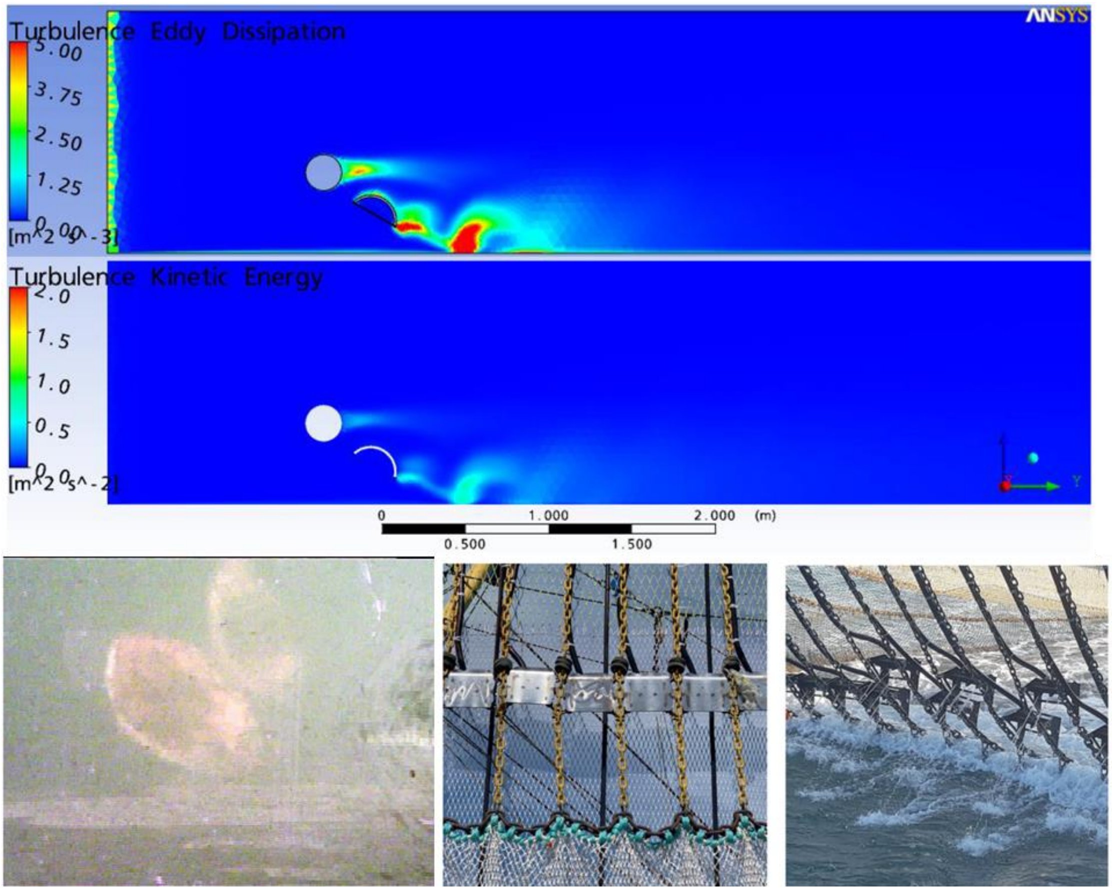


Figure 182 Upper panels: Turbulence of the water flow behind the beam and the semi-spherical cups of the Hydrorig. Lower panel left: simulated movement of sediment and dummy fish following the passages of the gear in an angle of 45° (taken from van Duren and De Kleermaeker, 2011). Lower panel middle and right: water spray system tested onboard SCH 63 (taken from Visserijnieuws 2021b).

- Alternative electrical catch stimulus-pulse trawl: pulse trawls replace the mechanical stimulation by tickler chains, bobbins or chain mats by electrical stimulation with electrodes inducing electric pulses. Pulse trawling was experimentally investigated since the early 1970s, but was only introduced onboard a commercial fishing vessel in 2004. The beam trawler fleet fishing for sole and plaice in the North Sea suffered from high fuel prices starting in 2006 (EC, 2006) and reaching high levels that compromised profitability in 2008, which incentivized further developments of the pulse trawl. In 2008 five commercial fishing vessels demonstrated the reliability and profitability of the technique, after which licences for pulse trawling expanded to a total of 84 pulse licences after 2014 (Haasnoot et al., 2016). The innovative gear was further refined by the integration of a wing-shaped foil instead of the beam which had further reduced fuel use for large beamers (Taal and Klok, 2014). Since July 2021 its use was banned following political debate and voting in the European Parliament (EU, 2019).

  A series of different pulse trawl types were developed, and the modelled estimates of their hydrodynamic drag showed that hydrodynamic drag was reduced from 4.71 to 2.66 kN m-1 for large beamers (>221kW) but increased for small beamers (≤221kW) from 2.48 to 2.6 kN m-1 (Rijnsdorp et al. 2021).

  Fuel consumption of pulse trawls not only results from the drag, but also from the use of a lighter gear (chains are replaced by electrodes) and reduced towing speeds

(Poos et al. 2013). Large Dutch beamers reduced their mean fuel consumption from 7600 to 4100 litres per day at sea (-46%), while fuel consumption of small beamers decreased only by 12% (from 1673 to 1911 liters per day at sea). Reduced fuel consumption is based on fleet estimates between 2009 and 2014 (Turenhout et al., 2016). ICES (2020a) estimated that pulse trawls (without Sumwing) consumed 33% less fuel (313 to 192 to litres per day) and pulsewing trawls consumed 47% less fuel for large beamers between 2009 and 2017.

While experimental trials showed that the total landings of pulse trawling decreased with 33% (largely owing to -41% plaice landings), the landings of the target species (Dover sole, Solea solea) increased by 14 % (Taal and Klok, 2014). Together with lower fuel consumption (-48%), the ratio of fuel by kg fish improved (-25%). Van Marlen (2009) reported a reduced fuel consumption of 34.6% and a loss of total landings of 22.5%.

Overall, the increased profitability of both a substantial reduction in fuel consumption and increase in the catch of sole, the high value target species, rapidly outweighs the investment costs (~345000 euro for large and ~230000 euro for small beamers, Turenhout et al., 2016) and makes this alternative the most fuel-efficient alternative to the conventional beam trawls to catch sole.

- Outrigger trawl: outrigger trawls are otter trawls with a limited wing-end spread which are rigged to replace the conventional beam trawls on the outrigger booms on each side of a beamer (Figure 183). Outrigger trawls can be operated by eurocutters (small beamers ≤221kW) and large beamers. Their application in commercial practice is limited in Europe (Vanderperren, 2008; Van Marlen, 2012), although they are used in commercial prawn trawling in Mexico and Australia (Balash et al., 2016).

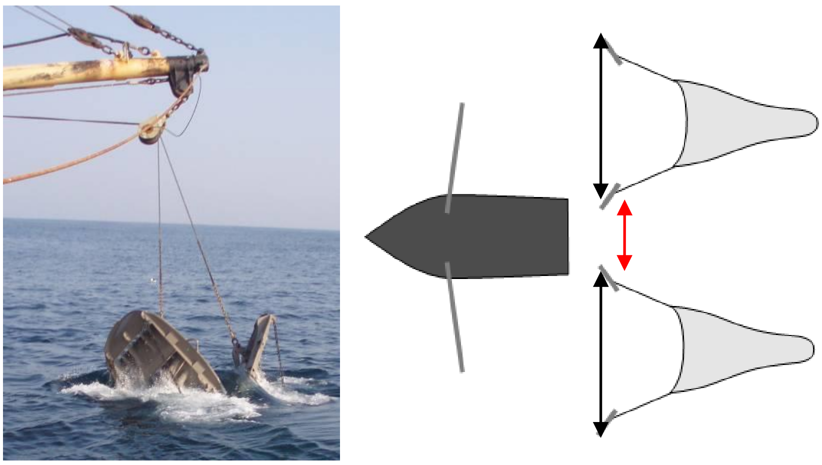


Figure 183 Outrigger trawl are otter trawls operated from the outrigger booms on each side of a beamer

Fuel consumption of beamers are reduced by 40% to 70% owing to the use of a lighter gear and towing speeds of ~3knots instead of 5-7 knots for beam trawling (Van Marlen, 2009). This fishing method could easily be introduced as the investment costs are limited to 20000-50000 euros (Van Marlen, 2009). Maintenance and running costs are also lower than in beam trawls. It allows to substitute beam trawls relatively easily and quick, though it requires knowledge on how to handle the doors on the outrigger booms.

However, outrigger trawling inevitably leads to reduced catch efficiencies for Dover sole (-10 to -16%). The loss of target species is not fully compensated by the catches of plaice (+5 to + 40%) or other demersal species like rays or Norway lobster (Polet et al., 2006; Depestele et al., 2007; Vanderperren, 2008; Van Marlen, 2009; Van Marlen, 2012). While the method was commercially used by at least one small Belgian beamer, the profitability of outrigger trawling by large beamers was highly variable and unstable outside the 12 nautical miles zone. The reduced catch efficiency of larger beamers is due to the limited horizontal net opening (15-20m) which is imposed by the length of the outrigger booms. The reduced catch efficiency for sole and the limited wing-end spread implied that outrigger trawling has not been assessed as a viable and widely applicable alternative for large Belgian and Dutch sole-directed beamers.

- Switching to other active or passive fisheries: twin rig otter trawl, Danish seining, fly-shooting or set nets: several beam trawl vessels are equipped with net drums to deploy twin rig otter trawls from their stern which may serve as an alternative fishery when targeting other species than sole. Danish seining and flyshooting have similarly been proposed as alternatives to beam trawling, but both gears are not used for catching Dover soles. While these gears may provide an alternative with intermediate to high investments for conversion from regular beam trawlers, they can only be deployed when a change in catch composition is acceptable (Van Balsfoort, 2006; Depestele et al., 2007).

  The only alternative gear that is capable of targeting Dover sole are gillnets and trammel nets. These passive gears are more extensively used in member states like France and Denmark and are due to the nature of their operational mode less dependent on fuel. Switching from beam trawling to set net fisheries requires new fishing vessels, the development of new skills and culture (deployment of the gear, fishing operation, fishing grounds and so on) and brings about other issue like the incompatibility between active and passive fishing gears in the same fishing grounds. Shifting from active to passive fisheries would restructure the fleet, crews and change overall landings and economic performance of a fishery. While it is clear that the fuel consumption is lower for gillnets than for beam trawls (0.24 instead of 2.5 litres per kg fish), switching to this type of gear is far from easy without governance support (Depestele et al., 2007).

Measures for bottom otter trawl fisheries

Otter trawls are common throughout Europe and fish a variety of species, the most common being demersal fish such as cod and whiting, Nephrops, shrimps, cuttlefish, and squid. They fish in shallow seas such as the North Sea to more deep-sea fishing in the Atlantic. The most common type is shown below, the otter board trawl.

There are different types of otter trawls such as the twin and multi-rig otter trawls, the pair trawl and the semi- and mid-pelagic otter trawls of which the last two are shown in Figure 185.

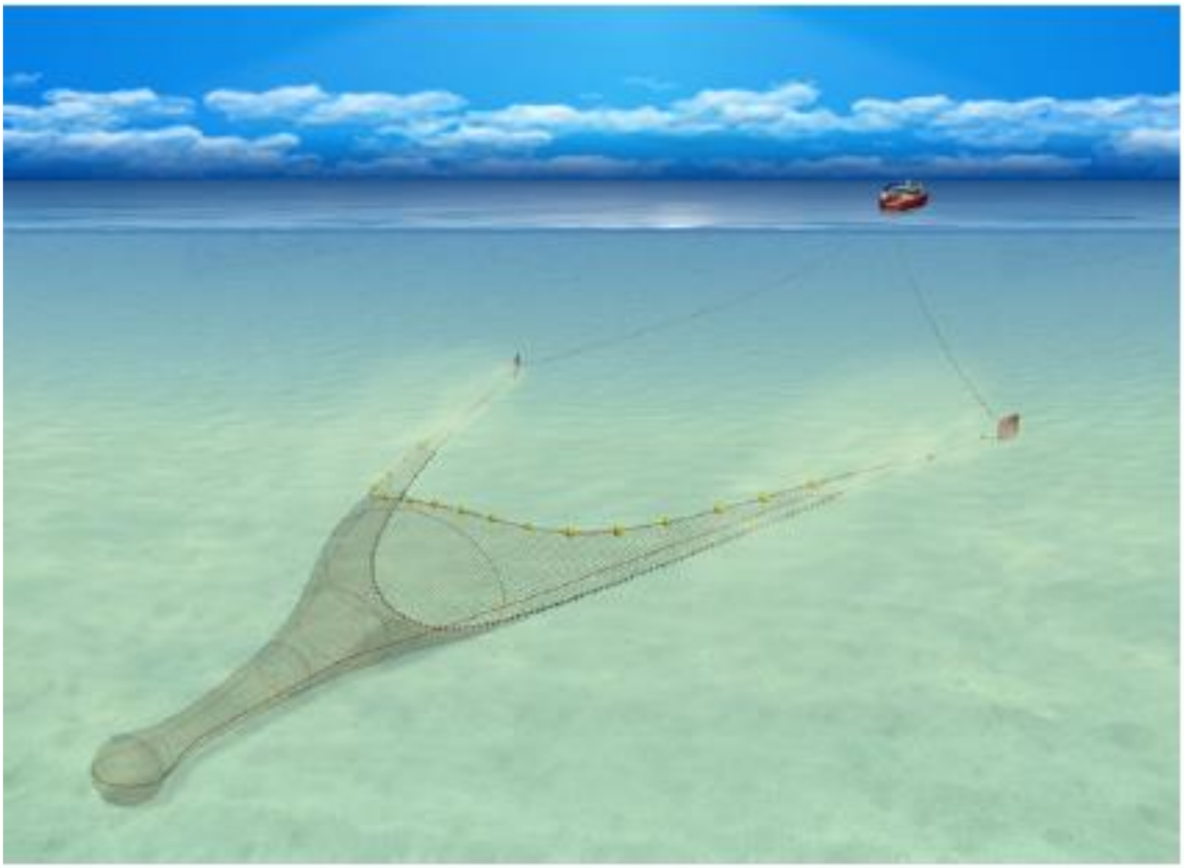
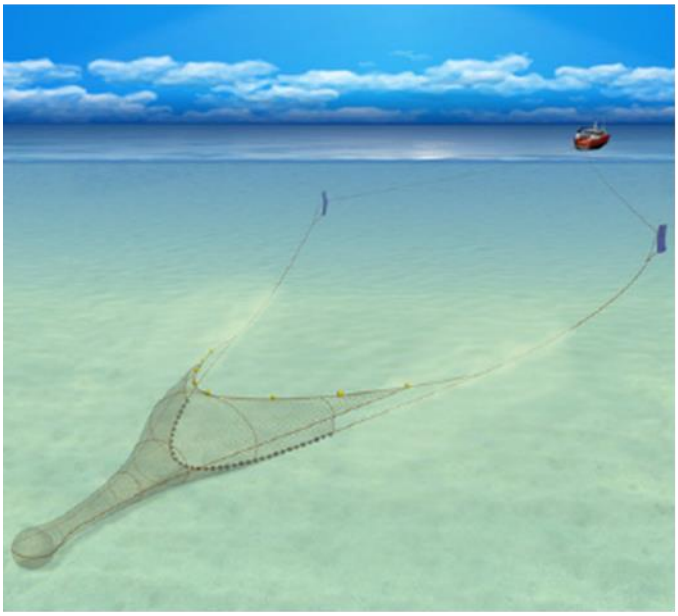


Figure 184 Single vessel with a single rig otter board bottom trawl. Image obtained from www.seafish.org on 24/11/21.



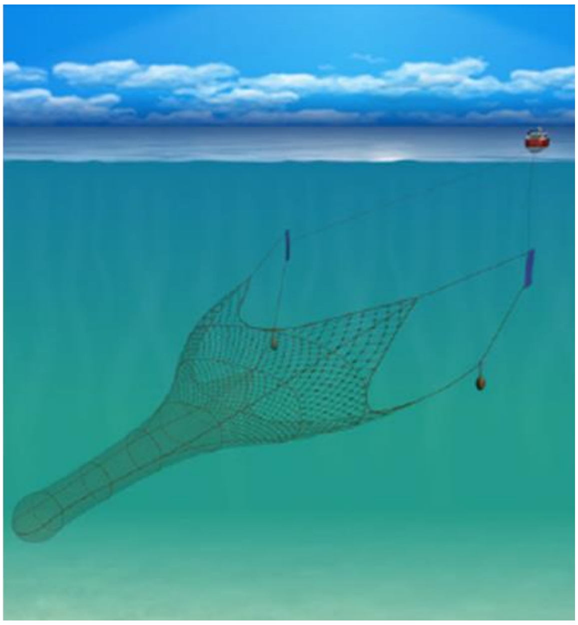


Figure 185 Semi-pelagic otter trawl where the doors are lifted of the seabed while the ground gear remains in contact with the seafloor (left). Midwater or pelagic trawl where none of the gear is touching the seabed. The doors in both types of trawls have a higher height aspect ratio when compared to bottom otter trawls to generate the necessary lift (right). Image obtained from www.seafish.org on 24/11/21

In general, the components of the otter trawls are the same no matter the type of trawl even though the specifics can alter between the types. In Figure 186 the most important components are named.

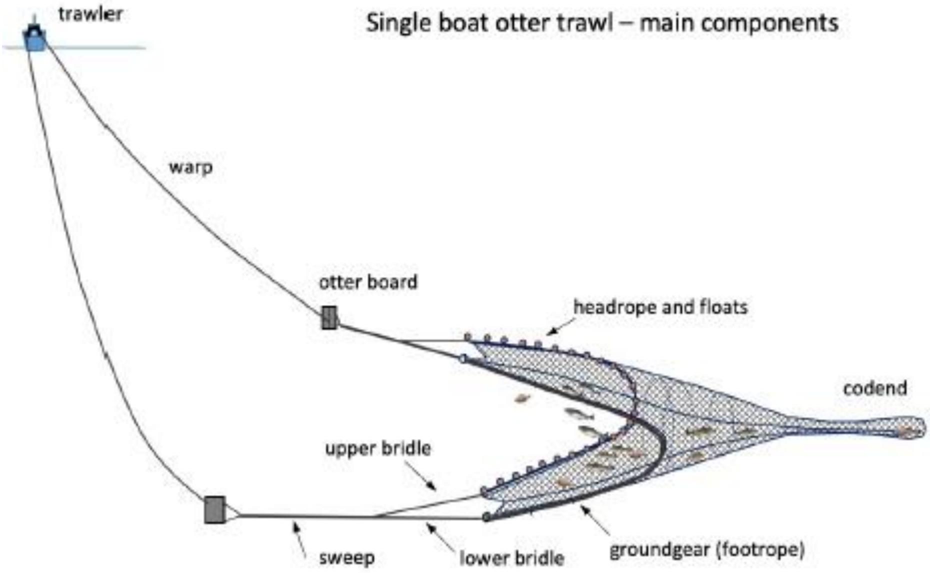


Figure 186 Different components of a traditional (normal) otter trawl. Image obtained from www.seafish.org on 24/11/21

Total drag of bottom otter trawls can be broken down into the drag of the interacting components, which shows the gear components that contribute the most to the total drag and fuel consumption. Although gear drag inevitably varies between types of otter trawls, Wileman (1984), Valdemarsen and Hansen (2006), Parente et al. (2008), and Khaled et al. (2013) show the primary importance of the drag of the net (45-63%) followed by the otter boards (20-24%) and the ground gear (4-12%) (Figure 187). The highest gain in improvement of energy efficiency will thus be gained by looking at trawl netting followed by otter boards and ground gear.

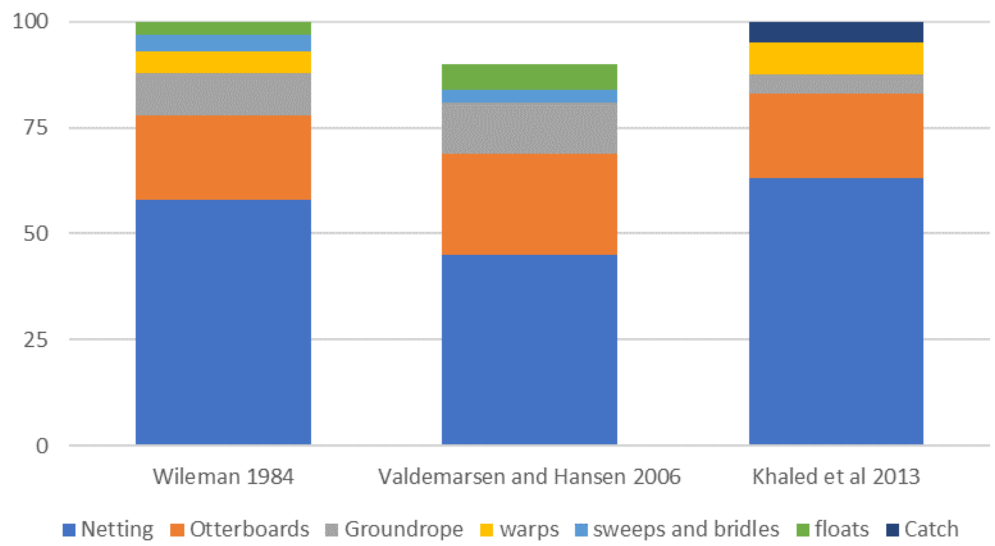


Figure 187 Relative importance of gear components to total gear drag in a single demersal otter trawl based on Wileman 1984, Valdemarsen and Hansen (2006) and Khaled et al. (2013). Note that the total drag of the gear components in Valdemarsen and Hansen (2006) is 90% and that warps were not accounted for (in contrast to Wileman 1984 and Khaled et al. 2013)

Modifying otter trawls to reduce drag resistance

- <u>New netting designs, materials and net modifications</u>: the questionnaires mentioned the use of new netting designs more frequently for otter trawl than for beam trawl fisheries (N=7), but its implementation level varied according to the way reduced drag was achieved. The use of bigger meshes is achievable (e.g. in wings and front belly of the trawl), whereas the use of low-drag netting material (e.g. Dyneema™) and new netting configurations were assessed as experimental. In both the grey and scientific literature, four major adaptations to the net design were found: cutting in the net itself, alterations in mesh sizes, panels and net design, Dyneema™ twine, and T90 codends.

  An easy way to reduce the drag of a net is to reduce the amount of netting material. Through models and automatic optimization and fish distribution tools, parts of the wings and belly panels are cut out in a steeper level. To further improve this, bigger mesh sizes and thinner (nylon) twine can be included in the respective sections of the net which also allows for the increase in the mouth and sweep area without adding drag to the net. Often the changes in the net are combined with a T90 codend or square mesh codends which can already reduce the fuel consumption by 8%. When most of the above stated alterations have been applied, the reduction in drag varies between 8 to 52% although most lie in the ballpark of 15 to 25% and the reduction in fuel consumptions between 15 and 23% (Sala, 2002; Fiorentini et al., 2004; Parente et al., 2008; Sala et al., 2008 Priour, 2009; Sala et al., 2011; Khaled et al., 2012). The costs for these adaptations to the design and used materials of the net vary between €12 700 and €75 000 depending on the type and number of adaptations one incorporates. Another way to reduce drag is to ensure that the net is lifted of the ground, which also increases it lifetime. This was done by Valdemar and Hansen (2006) who introduced "kites" in the net. This constitutes of adding plastic sheets between the float line and an extra line which would cause the net to be lifted.

The usage of Ultra High Molecular Weight Polyethylene (UHMW PE), such as Dyneema™ and Dynex™, as alternative twining material for the nets has multiple advantages. They are stronger and thinner twines that reduces the weight and volume of the net on board. Dynex™ and Dyneema™ thus improves operational characteristics by the prevention or decreasing of shrinking, mesh closure and increased net opening while also enabling fishing at higher speeds or with bigger nets with elastic zones and as such can increase catches. For otter trawls, usage of this type of netting can reduce drag between 8 and 28% depending on the fisheries, location and type of otter trawl. The estimated reduction in fuel consumption during fishing ranges from 2 to 25% where most cases show a reduction around 17%. These experimenters include both computer models and tests in flume tanks as trials at sea on commercial vessels (Valdemar and Hansen, 2006; Vincent and Roullot, 2006; Van Marlen, 2009; Sala et al., 2013, 2014; Balash et al., 2015; ICES, 2020b). It is important to mention that UHMW PE ropes are about 3 times more expensive than normal rope (Sala et al., 2014).

- Door modifications: semi-pelagic doors: new gear designs to improve energy use in bottom otter trawl fisheries were also frequently mentioned in the questionnaires with a major focus on improvement of the otter boards. Reducing the hydrodynamic drag of otter boards by lifting them off the seabed was seen as the main solution. The success rate of improved otter board designs was assessed as both experimental and fully operational, showing the difference in implementation levels. In the grey and published scientific literature we generally found three types of modifications: altering their shape and size, semi-pelagic or floating doors, and adding sensors to the doors. In Figure 188 typical otter boards are shown.

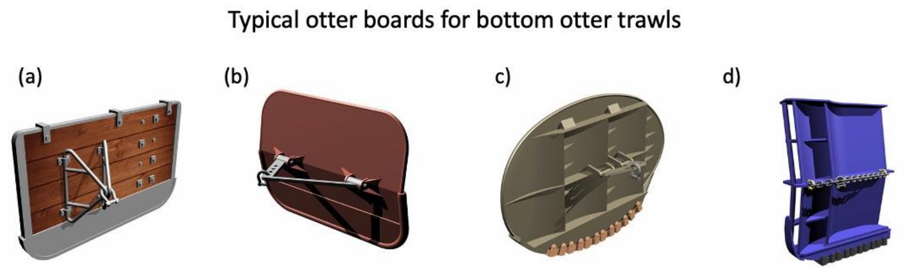


Figure 188 Four most common otter boards. a) The traditional wooden otter board b) a V-door c) an oval otter board d) a pelagic otter board for semi- and pelagic otter trawls. Image obtained from www.seafish.org on 24/11/21.

Innovative doors, lighter materials, and new designs aim to reduce the weight and size of the doors themselves or to change the angle of attack in order to reduce the drag and increase the spreading of the net and gear. Even though most tests in computer models or flume tanks show good results with between 10 and 20% drag reduction and around 10% fuel consumption reduction, to obtain the optimal setup by fishermen at sea can proof difficult and might negate possible reductions in fuel consumption (Valdemar and Hansen, 2006; Vincent and Roullot, 2006; Van Marlen, 2009; Sala et al., 2014). Some specific novel doors that have been tested at sea are the Wing Trawling System (WTS) reducing fuel use by 24 L/h and the Danish Thyboron which has 40% more door spread and up to 20% of fuel reduction compared with the traditional V-door (Sala et al., 2011, 2014). Another new door type are the batwings which obtain 13% less drag, 90% less sediment disturbance and turbulence and obtain a bigger spread of the gear by attaching canvas sail doors to the wingends instead (Sala et al., 2013). Prices vary according by door type between €6 250 and €26 000 (Van Marlen, 2009; Sala et al., 2014).

Next to changing the design of the doors, efforts have also been done to raise the doors from the seabed floor which damages the ecosystem significantly less and reduces fuel consumption, pollution and greenhouse gas emissions (ICES, 2020b). Again, operation of these semi-pelagic doors is difficult as Guijarro et al. (2017) shows no improvement due to the skipper taking up to half a year to get the gear adjusted to the fishery. Others were more successful when lifting the doors as drag reductions were noticed between 7 to 18% with seabed contact reductions up to 95% leading to fuel savings were between 12 and 19% (Basurko et al., 2013; Hansen et al., 2013; Sala et al., 2014). and when the spreading element of the door was separated (and floating) from the weight element (on the bottom), a 7% catch increase was found, costing about €80 000 for the doors (Hansen et al., 2013). Same results for Sala et al. (2014) who combined DynexTM warps with semi-pelagic doors who saw a 16% reduction in fuel consumption combined with a 13% revenue increase. Although care must be taken as these advantages do not apply to all as Sistiaga et al. (2015) showed that lifting the doors and consequently the sweeps can lead to substantial catch losses as was the case for cod fisheries (-33%).

In order to circumvent the problem of suboptimal handling of the doors and gears sensors are added onto them or incorporated in the door design. The questionnaires also mentioned that the use of electronic equipment to monitor operational characteristics of the trawl and the trawl doors is an important element for energy-efficient otter trawling. In pelagic doors they reduced fuel consumption by 7.5%, moreover they increased the catch by with just under 20% increased catch per hour. This means that payback time of the innovative doors with sensors which cost between €52 000 to €120 000, can be obtained within a year (Sala et al., 2014). An example of such doors are the Poseidon controllable trawl doors (ICES, 2020b) and SIMRAD door sensor which costs €150 000 (Hansen et al., 2013).

- <u>Warp modification: a</u>s is with all gear, optimisation of the warps in relation to the power of the vessel and the doors can result in an estimated 5% fuel consumption reduction with an investment of €25,500. Furthermore, using Dyneema^{TM} or Dynex^{TM} for the warps has the earlier mentioned advantages over normal rope and can facilitate raising the doors for semi-pelagic fisheries. This can lead to fuel consumption reductions between 10 and 20% with 7% landings increase and up to 13% annual revenue increase for an investment cost of €35,000 to €50,000 (Van Marlen, 2009; Hansen et al., 2013; Sala et al., 2014).

- <u>Ground gear, rope and line modifications:</u> in this part grey and peer reviewed literature focused on the rockhopper and the sweeps. When looking at the rockhopper there were two alternatives for the traditional rockhopper which can have a low catch efficiency of only 76% (Larsen et al., 2018). The first is semicircular spreading gear (SCSG) which can have a significantly higher catch efficiency, between 4.5 and 12.3% while reducing the underneath escape rate by 70%. The SCGS weighs 30% less and most likely reduces the bottom impact and friction with smaller mud clouds as a consequence (Larsen et al., 2018). The second improvement consists of adding plates to the wings and rockhopper of the net. This causes for the ground gear to spread itself and the doors can be reduced in size adding up to a 15% reduction in drag (Valdemar and Hansen, 2006).

  Just as with the semi-pelagic doors, making the ground gear floating reduces the contact and drag with the bottom and has a positive impact on the ecosystem. Making the sweeps floating can reduce bycatch and fuel reduction while maintaining the catch of Nephrops (ICES, 2020b), although for other fisheries this can cause losses as show earlier. A more radical approach was taken in the Softbrush where the ground gear floats above the substrate and to which chain droppers are attached and have contact with the seafloor. This reduces the linear bottom contact by 63% with probable reductions in fuel consumption (ICES, 2020b).

Just like in the netting some easy drag and fuel savings can be obtained by optimising the length and weight of the ropes and ground gear. By altering the cable length of the warps, bridles, headline and footrope Khaled et al. (2013) found a 46% reduction in trawl drag and catch efficiency ratio. Similarly, reducing the sweeps length and optimising the bridles and warps and making the sweeps floating (if appropriate) allows for smaller doors (Van Marlen, 2009).

Next to UHMW PE, Helix ropes can replace the normal ropes in warps, sweeps, bridles, headline, fishingline, and forward panels of the trawl (Garner, 1978; Sainsbury, 1996) in Kebede et al. (2020). They have been tested for mid-water trawls and could theoretically increase the mouth opening of a trawl, allowing vessels to reduce the door size, floatation on the headline, and weights on the footline which would then reduce fuel consumption, gear size, and improve fishing efficiency (Kebede et al., 2020)

- Assisted fishing modifications: for the assisted fishing there were two modifications in the grey literature; the first is a grid sensor for Nephrops that uses and echo to quantify the catch which can help fill the quota faster and as such reduce fishing time (ICES, 2020b). The second is a self-powered light source that illuminates the trawl path which leads to a 30% weight decrease in bycatch and a 5.5% increase in the catch of prawn (Sala et al., 2013).

- Complete setup modifications: the previous modifications showed their potentials on fuel savings when applied alone or in combination with one or two other adaptations. Here below are a few results from trials at sea from the scientific and grey literature that combine many of the earlier mentioned modifications in one fishing vessel. Guijarro et al. (2017) showed that for the Spanish bottom otter trawl, changing the doors (not to semi-pelagic) and using lighter gear implies shorter warp needs, better door hydrodynamics, less door friction and sweeps' length, and thus, less tension and higher filtration in comparison to the traditional gear with a consequent fuel consumption reduction of 5 to 12%. For a midwater trawl with new net design with a hexagonal mesh, a kite, different net material (UHMWPE nets), and slotted type trawl doors a 17% of the fuel consumption can be obtained per voyage; however, the gear itself (including trawl nets, trawl doors, and rigging) costs 20% more than traditional netting (Lee et al., 2018b). In Sala et al. (2013), two more multi-modifications setups were tested. The first one was in the USA flatfish fisheries where a new large-mesh, fine-diameter trawl net with semi-pelagic otter boards, and energy audits of the fishing boat took place. This reduced fuel consumption by 23% and 12% for the two vessels respectively without loss of commercial catch. Furthermore, they used acoustic codend catch sensors to signal a predetermined catch volume and by doing so managed to reduce tow duration by as much as 50%. In the second one the warps were made of Dyneema™, the doors changed to pelagic doors, and an innovative trawl design, with netting in T90 and made from Dyneema™. They managed to save over 40% of energy consumption per kg of fish caught, leading to a revenue increase of about 33%.

Substitution of single otter trawls

Substitution of single otter trawls: not only modifying the gear of the otter trawl can cause significant improvements in fuel use or reductions in drag. Changing the single otter trawl to a different gear type can bring major changes in drag, fuel use, and catch. This change can be to be a different type of otter trawl, such as pair trawling or multi-rig trawls, but it can also constitute a whole different metier such as gill netting or seine fishing.

Single to multi-rig trawls and pair trawls: in the grey literature there were two cases where the single trawl was replaced by a twin trawl. This would reduce the towing tension reducing the drag by 27%, and can increase landings by 30% although a reduction in swept area can follow. The investment costs are €3000 (Vincent and Roullot, 2006; Van Marlen, 2009).

Despite the promising results above Rihan (2004; 2005) suggests turning back to traditional single rig trawling from twin rigs in order to decrease fuel consumption based on two Irish vessels. Both vessels found that by reverting to a single trawl that fuel consumption reduced by approximately 10 and 21% (Khaled et al., 2012).

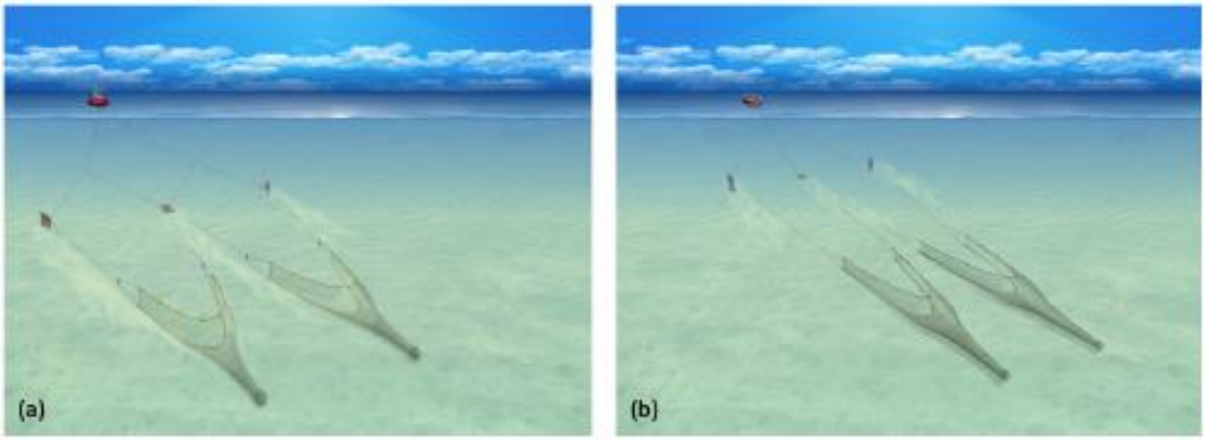


Figure 189 Two types of twin rigs where a) has four warps attached to the doors and the central weight clump. In b) there is only one warp attached to the weight clump in the centre. Image obtained from www.seafish.org on 24/11/21.

According to Broadhurst et al. (2013) for the Penaeid trawls, the single rig had the least fishing capability due to having the lowest wing-end spread (spread ratio (SR) of 63.50%), but the greatest drag, and required the most fuel (predicted mean of 2.88 L/ha trawled). The twin rig had a higher wing-end spread (SR of 68.76%) using less fuel (2.44 L/ha trawled). However, triple and quad rigs similarly achieved the greatest spread (SR of 75.46% and 74.37%) with lower drag and fuel consumptions (2.13 and 2.21 L/ ha trawled, respectively). This results a reduction in fuel use by 13.65 and 12.21% accordingly. Although the twine areas in the triple- and quadrigs were greater than in the single and twin rig, the sleds and additional warps allowed for substantial reductions in otter-board areas which reduced drag and fuel by approximately 18%/ha trawled, while wing-end spread increased by up to a meter due to the higher ratio of otter board-to twine area for each trawl. As a conclusion the triple rig performs the best.

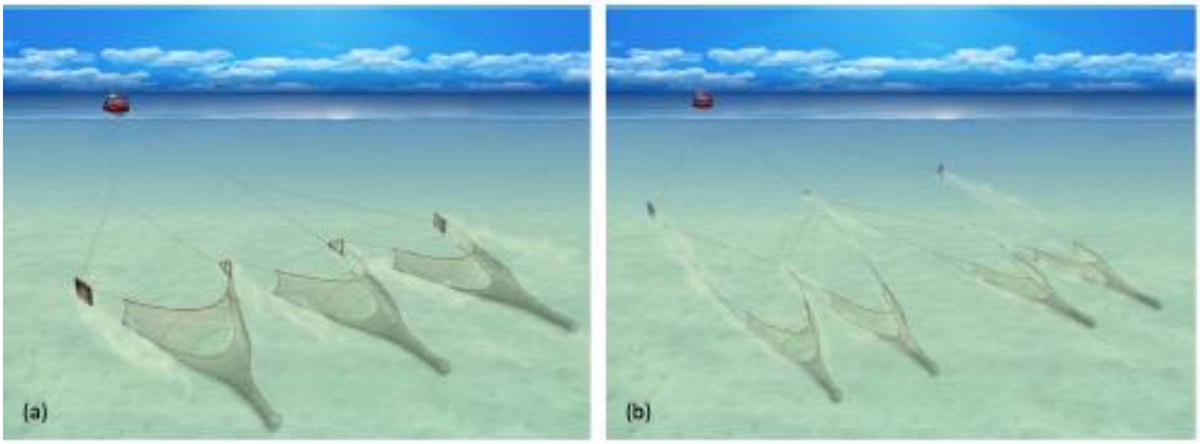


Figure 190 Triple rig on the left and the quad rig on the right. Image obtained from www.seafish.org on 24/11/21

Pair-trawling is more energy-efficient than when a vessel trawls on its own, mainly because there is no need for trawl doors (for which about 30% of the engine power is used) (Ziegler and Hansson, 2003). Thomsen (2005) has shown that skippers who converted from single trawling to pair trawling saved 40 to 45% fuel (Khaled et al., 2012).

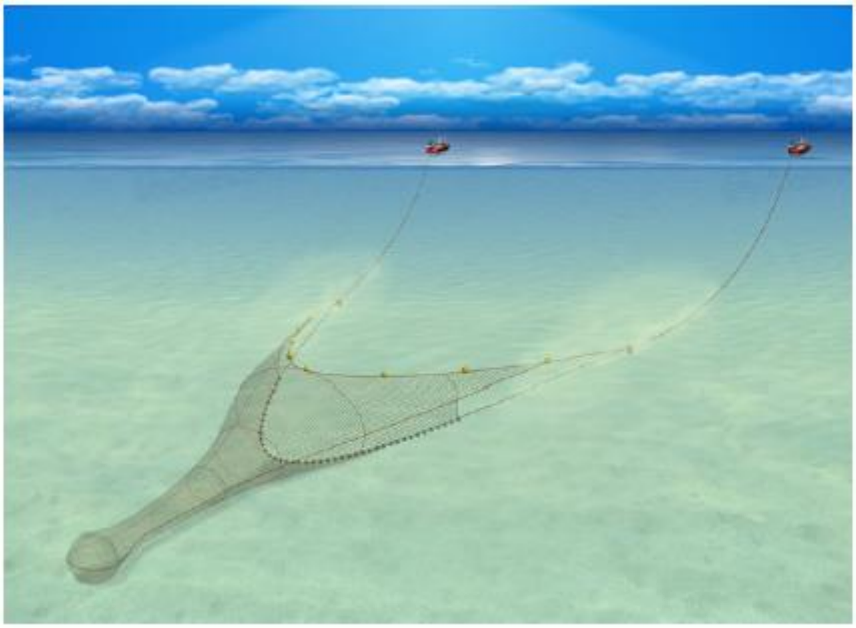


Figure 191 Pair trawl where there is no need for doors as the ships take up take function. Image obtained from www.seafish.org on 24/11/21.

Single otter to Seine netting: in the grey literature there were two computer simulations for changing from otter trawl to Seine netting. Seine netting is regarding as being a more fuel-efficient method than trawling. In Van Marlen (2009) the results obtained vary between 10 to 25% of fuel reduction. Although it is estimated that a typical 20-24m seine net vessel would have an annual fuel consumption of around 225,000-250,000 litres compared to the reference vessel of around 500,000-650,000 litres. This equates to a saving of fuel of around 50% although the two vessels referred to are not fully comparable hence the lower expectation of 25%. This can be accompanied with a loss of catch of about 25 to

30% (Van Marlen, 2009). The cost of this investment in metier change is €68 500. Macdonald et al. (2007) have compared jig fishing to trawling (Khaled et al., 2012).

<u>Measures for Midwater trawl fisheries</u>

Modifying midwater trawls to reduce drag resistance

- <u>New netting designs, materials and net modifications</u>:
- In Lee et al. (2018b) a combination of a new net design with hexagonal meshes and Dyneema^{TM} as netting material with a kite, and slotted type trawl doors has reported a fuel saving of 17%. The costs of this new gear is 20% higher than of its traditional counterpart. In Van Marlen (2009), the usage of hexagonal meshes instead of diamond and square meshes, already reduced fuel consumption by almost 25%.

- <u>Helix ropes</u>: Helix ropes can make up the warps, sweeps, bridles, headline, fishingline, and forward panels of the trawl (Garner, 1978; Sainsbury, 1996) in Kebede et al. (2020). When used they can theoretically increase the mouth opening of a trawl, achieving the same mouth opening as conventional trawls, but with reduced door size, floatation on the headline, and weights on the footline,reducing fuel consumption, gear size, and improve fishing efficiency (Kebede et al., 2020).

<u>Catchability</u>

Catchability can be improved by means that increase the catch efficiency or by using more selective gears and technologies. Most of the modifications that have been discussed above, although primarily designed to reduce fuel, they also induced catchability changes by being more selective or increasing the catch of the target species in bottom trawling fisheries. Rather than discussing the catchability details of those modifications, the following section discusses catchability measures and potentials for other fishing metiers.

- **Improve catchability** <u>Selective fishing</u>

  By using lighting: the use of LED lights has been mainly proposed in certain Taiwan-Korean fisheries to reduce the fuel consumption. Particularly experiences have been demonstrated in saury fishing with fuel saving of 20% (13% in regards to FUI indicator) (Kuo and Shen, 2018), in Korean hairtail angling fishery (An et al., 2017), and in Korean-Japanese squid-jigging with savings of 24% but in this particular case the authors highlighted that the number of lamps had to be studied in detail for each vessel and period fishing as the light needed depends on the lunar phase (Matsushita et al., 2012; Yamashita et al., 2012). In Europe, the use of light for fishing has been proposed for pots targeting cods as a way to increase catchability; and the experiments have shown that the use of green light caught about 80% more large cod than pots with-out artificial light (Bryhn et al., 2014).

  By using selective gears: species-selective trawling can contribute to increase fuel consumption as a result of a lower associated catch (Hornborg et al., 2012; Ziegler and Hornborg, 2014). However, the opposite trend was observed in smaller vessels in Swedish trawl fisheries (Ziegler and Hornborg, 2014).

- <u>Technologies to increase catch efficiency</u>: the practices followed to increase catch efficiency are related to tropical Purse seiners efficiency by the use of FADs which is assisted by support vessels to keep the FAD network operative (Chassot et al., 2021). Bottom trawlers may reduce fuel consumption and increase catch efficiency simultaneously by resizing their gear according with fish catch and fuel usage and changing the fishing ground based on the catch and changing the day of come back. While pot fisheries are low in energy use, their catch efficiency is also low for many fish species (Suuronen et al. 2012). In order to make pot fisheries a viable alternative for whitefish trawl fisheries, increased catch efficiency are required. Low catch rates of pots are possibly due to the low ingress rate of fish rather than their attraction to the pots (Thomsen et al. 2010). In Europe, the use of light for fishing has been proposed for pots targeting cods as a way to increase catchability; and the experiments have shown that the use of green light caught about 80% more large cod than pots without artificial light (Bryhn et al., 2014).

Conclusions

The summary of the measures applicable to improve energy efficiency in beam trawl gears, and otter trawls are listed in Table 59. For demersal trawl gear such as from otter trawls and beam trawls, the required energy to tow the gear is positively correlated to the drag of the gear. In order to improve the efficiency related to the gear, Prior (2009) stated that you can increase the swept area or decrease the drag. According to O'Neill et al (2018), contact drag of the gear components depends on their weight, geometry, the type of sediment on which they are towed and whether they are rolling or not.

Gear-related measures to improve energy efficiency in beam trawl fisheries were not published in peer-reviewed literature. Instead, grey literature reports have shown that gear measures were developed primarily during and following the fuel crisis around 2008. The most profitable gear modifications were introduced in the fishery. Dutch beam trawl fisheries have implemented pulse trawling which was most profitable (increased target catches and reduced fuel consumption). Since the recent prohibition of pulse trawling, the Dutch beam trawl fishing industry is investigating alternative solutions to improve energy efficiency by gear-related measures. Belgian and UK beam trawl fisheries have implemented roller wheels on the trawl shoes for chain mat beam trawls and Sumwings for tickler-chain beam trawls. None of the implemented measures resulted a change of the landings (Table 59). Gear measures that altered catch composition, and particularly those that reduced the landings of the target species (*Dover sole*) were not implemented in beam trawl fishery.

For otter board trawls and midwater trawls, the found literature offered a variety of modifications that can reduce fuel consumption. As the doors and net are the biggest sources of drag and fuel consumption, most innovations focused on reducing their surface area or using alternative materials such as the Ultra High Molecular Weight Polyethylene twines (Dyneema™ or Dynex™). These modifications showed promising results with reductions in fuel use. Changing from bottom otter trawl to a semi-pelagic fisheries not only reduced fuel use, but also has positive changes on the environment although for some fisheries this can incorporate losses in catch. Optimising the ropes and ground gear can have great reductions on the fuel consumption although it is often difficult for fishermen to actually fish optimally with the gear. Adding sensors and adjustable doors can circumvent this problem leading to fuel reductions as found in flume tanks and models. If many or most of these modifications are applied to a bottom otter trawl, energy savings can be acquired of up to 40% with increased catches. Alternating from a single rig to a multi-rig also shows potential to reduce fuel use where the triple rig is most promising. Literature offered proof for a potential switch from otter trawling to Seine netting.

Table 59 Changes in fuel consumption and landed catches from gear measures to improve energy efficiencies in beam trawl fisheries

Gear measure	**Fuel or drag* change (%)**	**Landings change (%)**	**Readiness level**	**Reference**
Beam trawls				

Trawl netting in DyneemaTM	8.8	Unknown	Intermediate	Van Marlen, 2009
Large mesh top panel	-5 to -10	Loss of whiting and haddock	Intermediate to high	Polet et al., 2006
	Unknown	Loss of whiting and haddock	Intermediate to high	Van Marlen, 2012
Rolling wheels assisting trawl shoes	-5 (chain mat) -16 (tickler chain)	No change	High (chain mat) Low (tickler chains)	Van Marlen, 2009
Beam trawl using Sumwing	-13.1	No change	Low (chain mat) High (tickler chains)	ICES, 2020a
	-16	No change	Low (chain mat) High (tickler chains)	Turenhout et al., 2016
	-11	No change	Low (chain mat) High (tickler chains)	ICES 2010 in Van Marlen 2012
	-13 to -23	No change	Low (chain mat) High (tickler chains)	Huyghebaert et al., 2010
Tickler chain to chain mat trawl	-24	Altered catch composition	Intermediate	Van Marlen, 2009
Beam to outrigger trawl	-39 to -61	Loss of target species (-10)	Low	Polet et al., 2006
	-40 to -70	-48	Low	Van Marlen, 2009
	-45	Loss of target species	Low	Van Marlen, 2012
Beam trawl to pulse trawl	-33.3	Loss of total landings, increased landings of target species	High	ICES, 2020a
	-34.6	-22.5 (Loss of total landings, increased landings of target species)	High	Van Marlen., 2009
	-48	-30 (loss of total landings, increase of target species)	High	Taal and Klok, 2014
Beam trawl to pulsewing	-46.5	Loss of total landings, increased landings of target species	High	ICES, 2020a

Beam trawl to pulse trawl, pulsewing	-12 (small beamers) -46 (large beamers)	Loss of total landings, increase of target species	High	Turenhout et al., 2016
Otter trawls				
Redesigned otter trawl: using an automatic optimization procedure for panel cutting	-16 to -52*	Unknown	Low (model simulations)	Khaled et al., 2012
Redesigned otter trawl: W-trawl, the forward extensions of the upper and lower panels form two additional towing points for the trawl	-8.3*	Unknown	Low (model simulations, flume tank and field experiments for Australian prawn trawls)	Balash et al., 2015a, 2015b
Warp length optimization	-2*	+80 (mouth opening of the trawl as proxy for landings)	Low (model simulations)	Khaled et al., 2013

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Annex 27.. SELECTION OF PAPERS FOR REVIEWING ENERGY-EFFICIENT TECHNOLOGIES FOR FISHERIES

Two teams of fisheries scientists achieved record identification, independently assessing search strings with relevant combinations of keywords in the Scopus literature database. The first team consisted of three Lot-2 scientists from AZTI (ESP) who selected relevant keywords using expert knowledge. The relevant keywords were trialled iteratively and assessed for their number of relevant papers and recursively modified (Table 4). Coarse assessment of the relevance of the identified studies was based on broad-brushed screening of the title, abstracts and keywords. The final selected search string was: 'TITLE-ABS-KEY (fishing OR fisheries) AND (greenhouse OR fuel) AND NOT (agricul* OR *bird* OR *plastic* OR acoustic* OR whale OR spill* OR river OR acoustic* OR *welling OR metabol* OR lake OR safe* OR survei* OR genet* OR ({spatial planning}) OR (coral) OR (security) OR ({marine energy}) OR (household) OR (health) OR (*plankt*) OR (seism*) OR (endanger*) OR (ghost)) AND (LIMIT-TO (LANGUAGE,"English"))' and resulted in 596 results in Scopus on 23 February 2021.

The second team consisted of two Lot-1 scientists from ILVO (BE). This team collated relevant studies from an unsupervised search in inhouse databases of fisheries science literature that were collated over the last fifteen years by two fishing gear experts (including >10000 records). Text mining on author and indexed keywords, titles and abstracts was conducted on these expert databases to identify recurrent search terms to be used in the Scopus systematic search. The following keywords occurred at least respectively 10, 15, 30 and 5 times in the author and indexed keywords, the abstract and the titles: fuel, consumption, energy, efficiency, fishing and fisheries. The keywords 'emissions' was recurrent all except in the title. The keyword 'carbon' occurred in indexed keywords and titles, and 'engine' occurred in indexed keywords and the abstracts. These keywords were selected from on the expert knowledge databases (Figure 192) and where then iteratively trialled and assessed in a similar way as the first team did (Table 5). The final search selection used 35 simple queries, which combined five keywords ('fuel consumption', 'energy efficiency', 'greenhouse gas', 'carbon footprint' and 'diesel engine') with 6 types of fishing gears ('trawl', 'sein*', 'long lin*', 'fish* pot*', 'gill net*' and 'trammel net*') and with 'fishing vessel'.

The search strategies of both expert teams yielded respectively 596 (team 1) and 823 (team 2) records. Broad-brush screening downsized the number of relevant studies to 447 and 257 studies respectively.

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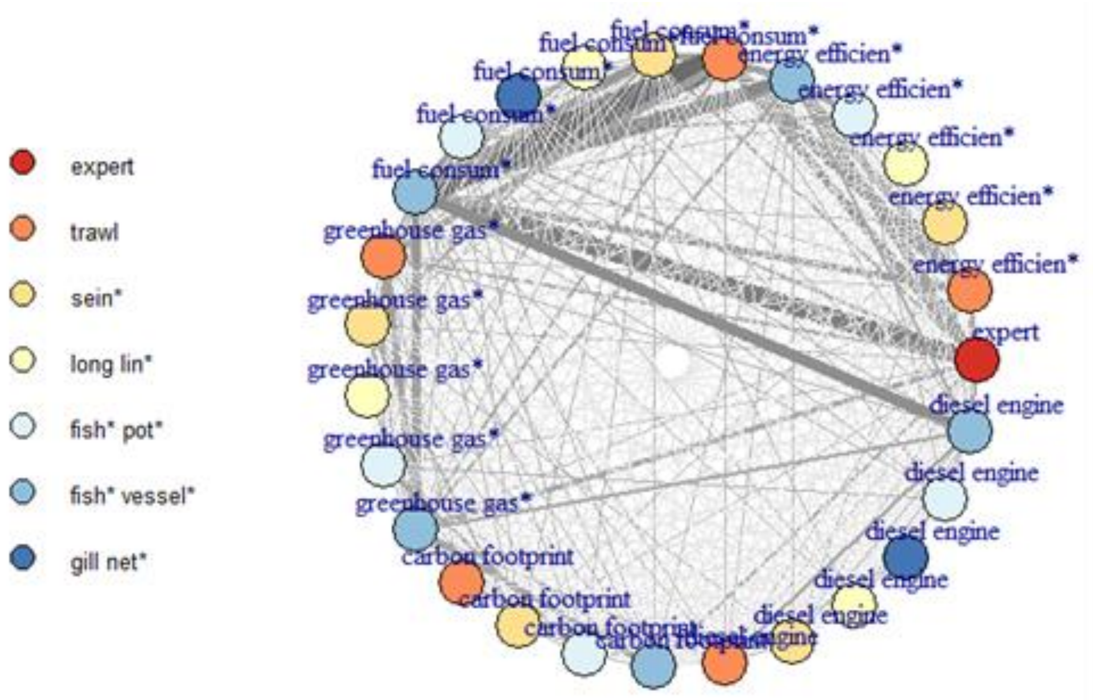


Figure 192 Overlap of DOIs between the literature database from experts (red node) and 30 simple searches, combining 5 relevant search terms (fuel consump*, greenhouse gas*, carbon footprint, energy efficien* and diesel engine) with 6 relevant fishing types (no records were identified for 'trammel net*').

NB. The thickness of the lines shows the overlap between the nodes. The 'expert' database (red node) has most references in common with the references found in the query combining 'fuel consum*' AND 'fish* vessel*' (blue node).

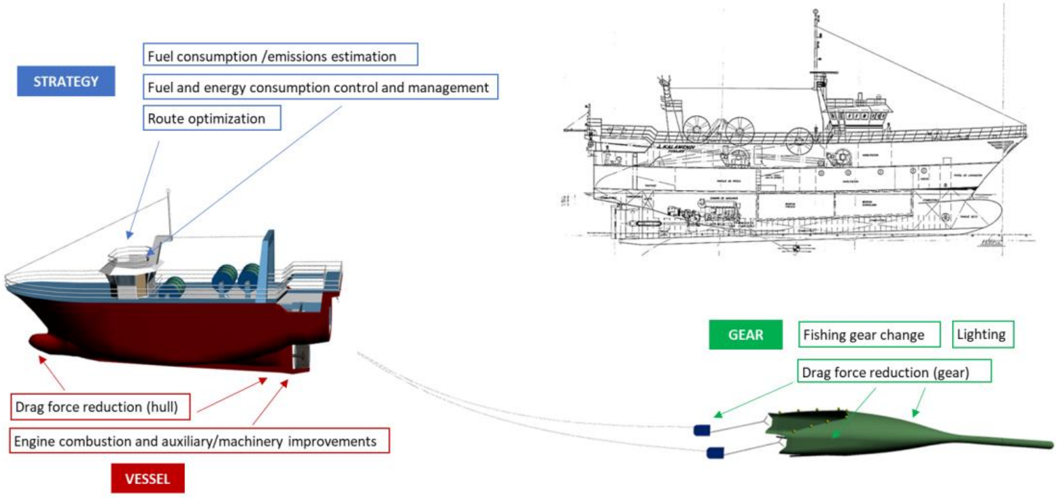
Annex 28 ..QUESTIONNAIRE ON ENERGY EFFICIENCY MEASURES IN THE EUROPEAN FISHING FLEET

If you have received this questionnaire, it is because you have relevant experience and knowledge in the fishing sector and energy efficiency issues. In the EU-funded project "Climate change and the Common Fisheries Policy: adaptation and building resilience to the effects of climate change on fisheries and reducing emissions of greenhouse gases from fishing"[24], the consortium is seeking information about energy efficient practices applied in the European fishing sectors.

The aim of the questionnaire and project is to collect and disseminate knowledge on technologies, strategies or regulatory measures that are currently developed or applied in European fisheries to reduce fuel consumption. The questionnaire also represents an opportunity for the respondents to highlight the technical and scientific fields that they consider key in the EU efforts to reduce the climate footprint of European fisheries.

Looking for solutions to improve the fuel efficiency (litres fuel/t catch landed) or to reduce the carbon footprint (CO_2 eq./t catch landed) of a fishery in terms of:

Strategies to improve the fishing strategy such as route optimization, onboard fuel control and monitoring and slow steaming.
Technologies to improve vessel structure and onboard equipment such as hull and propeller improvements, improved propulsion and auxiliary engines, improved fuel performance, LED lighting, alternative refrigerants and assisted fishing.
Gear technologies to reduce fuel consumption, such as new netting and gear designs that reduce drag, fishing gears that improve catch efficiency.
Regulatory measures that affect fuel consumption.



Thank you for your support!

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Name of the institute and country you work for:

Institute: Country:

[24] The project corresponds to the Specific Contracts EASME/EMFF/2020/3.2.6-Lot1/SC07/SI2.840435 and EASME/EMFF/2020/3.2.6-Lot2/SC08/SI2.840436, signed with the Executive Agency for Small and Medium-sized Enterprises (EASME) and funded by the European Union.

Select from the list below your experience (you can select more than one if relevant):

- ☐ Fishing gear technology (catch efficiency, selectivity, etc.)
- ☐ Fisheries biology (e.g. stock assessments)
- ☐ Marine engineer (vessel structure, engines, onboard equipment…)
- ☐ Fisheries economist
- ☒ Fisheries sociologist
- ☐ Technology developers (developing gears, engines, etc.)
- ☐ Fisheries modeller (e.g. fleet dynamics)
- ☐ Other

If Other, please define your job experience.

Strategies and technologies: Which ones? Do they work well?

List all the strategies and technologies to improve energy efficiency in the fishery that you have experience with (regardless of whether they are applied during steaming, fishing or while the vessel is in port)

Understanding of the strategies and technologies

Strategies and Technologies (*One line for each strategy or technology*)	To which gear was it applied?	Vessel sizes (LOA, gross tonnage, main + auxiliary engine power)	Target species of the fishery (e.g. Nephrops and mixed fish assemblage)	Region of implementation (e.g. North Sea, ICES Division 4c)	Where was the focus of the improvement?
					☐ Fishing strategy; ☐ Vessel; ☐ Fishing gear

Reference material of the strategies and technologies listed in Q1

Strategies and Technologies (*One line for each strategy or technology*)	Reference material: full reference of grey reports, peer-reviewed papers, any links to information *(including e.g., cruise reports)*
1. etc	

Characterize the strategies and technologies listed in Q1

Tested and used strategies *(same list as in Q1)*	What was the level of implementation? *(e.g. experimental test, 5 vessels, entire fleet representing 20 vessels)*	In what year was it tested or first implemented?	If the strategy or technology is no longer used, when + why was it stopped?	Degree of success* of the strategy or technology: *1 (bad) → 4 (good)*
				1 2 3 4

*Degree of success:
1 – the measure was unsuccessful; it did not help to reduce fuel nor the carbon footprint
2 – the measure was successful, but only lasted the duration of the testing period

3 – the measure was successful, and it was used for several year after its implementation, but it is not-longer operative
4 – the measure was successful, and it is still being used

Efficiency of the strategies and technologies (same list as Q1)

Strategies and Technologies *(same list as in Q1)*	What is the change in fuel consumption using the strategy or technology?				What is the change in catch (landings) using the strategy or technology?			
	Amount			Unit eg. liter fuel /year	Amount			Unit eg. kg target sp/year
	Before	After	% change		Before	After	% change	

Cost of the strategies and technologies (same list as Q1)

Tested and used strategies and technologies *(same list as in Q1)*	Purchasing and implementation cost		Annual running cost	
	☐ < 1,000€	☐ 1,000 – 10,000€	☐ < 1,000€	☐ 1,000 – 5,000€
	☐ 10,000 – 25,000€	☐ 25,000 – 50,000€	☐ 5,000 – 10,000€	☐ 10,000 – 20,000€
	☐ 50,000 – 100,000€	☐ >100,000€	☐ 20,000 – 50,000€	☐ >50,000€

NB. If Purchasing and implementation cost is >100,000€ please, give further or relevant information here (e.g., total cost, technical retrofit, estimated return of investment, retrofit works duration time, subsidies…)

Motivation of the strategies and technologies (same list as Q1)

Strategies and Technologies *(same list as in Q1)*	Why was this strategy or technology tested?	If this strategy or technology was used by fishing vessels in practice, describe the reasons for fishers to actually start using it e.g. high fuel prices, environmental consciousness, others have shown that the technology works well, and so on
	☐ to improve catch efficiency ☐ to decrease fuel consumption ☐ to decrease GHG emissions ☐ Other. If Other, please define:	

Drivers that stimulate or hamper the implementation of strategies and technologies to reduce fuel consumption

Which regulatory measures (current or past) have helped to improve energy efficiency (e.g. quota regulations, renewal subsidies)?

1.
Etc

Are there strategies or technologies that are not used, because something is holding fishers back? (e.g., lack of technological knowledge, funding, incentives, regulations like gear and capacities limitations, etc.) What is holding fishers back to use the strategy or technology?

1.
Etc

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