DELIVERABLE 6.7

SEAwise Report on consistency of existing targets and limits for indicators in an ecosystem context

Version 1.1

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SEAWISE

Executive summary

SEAwise deliverable 6.7 is the first of two deliverables in task 6.4. It investigates the consistency of existing targets and limits from the Common Fisheries Policy (CFP) and the Marine Strategy Framework Directive (MSFD). Trade-offs between different objectives (ecological, economic, social), targets and limits are highlighted. A wide range of model types (from bio-economic to full ecosystem models) has been applied to various case study areas across the North East Atlantic and Mediterranean. Although model predictions are by nature uncertain, this study provides important information on likely inconsistencies between existing targets and limits and trade-offs expected under ecosystem-based fisheries management (EBFM). The scenarios investigated include the current range of management applied in terms of the Maximum Sustainable Yield (MSY) concept (i.e. strict MSY approach vs. Pretty Good Yield (PGY) approach allowing sustainable deviations from single species F_{MSY} point estimates). The landing obligation is a key aspect of current fisheries management and was fully considered, in particular for mixed demersal fisheries.

Maintaining current fishing effort without further management measures was the least sustainable option in nearly all cases studies. This approach led to increased risk of stocks falling below critical biomass limits. Although the fishing effort adaptions needed is highly case specific, this indicates that further management measures are likely to be needed to ensure a sustainable exploitation of all stocks.

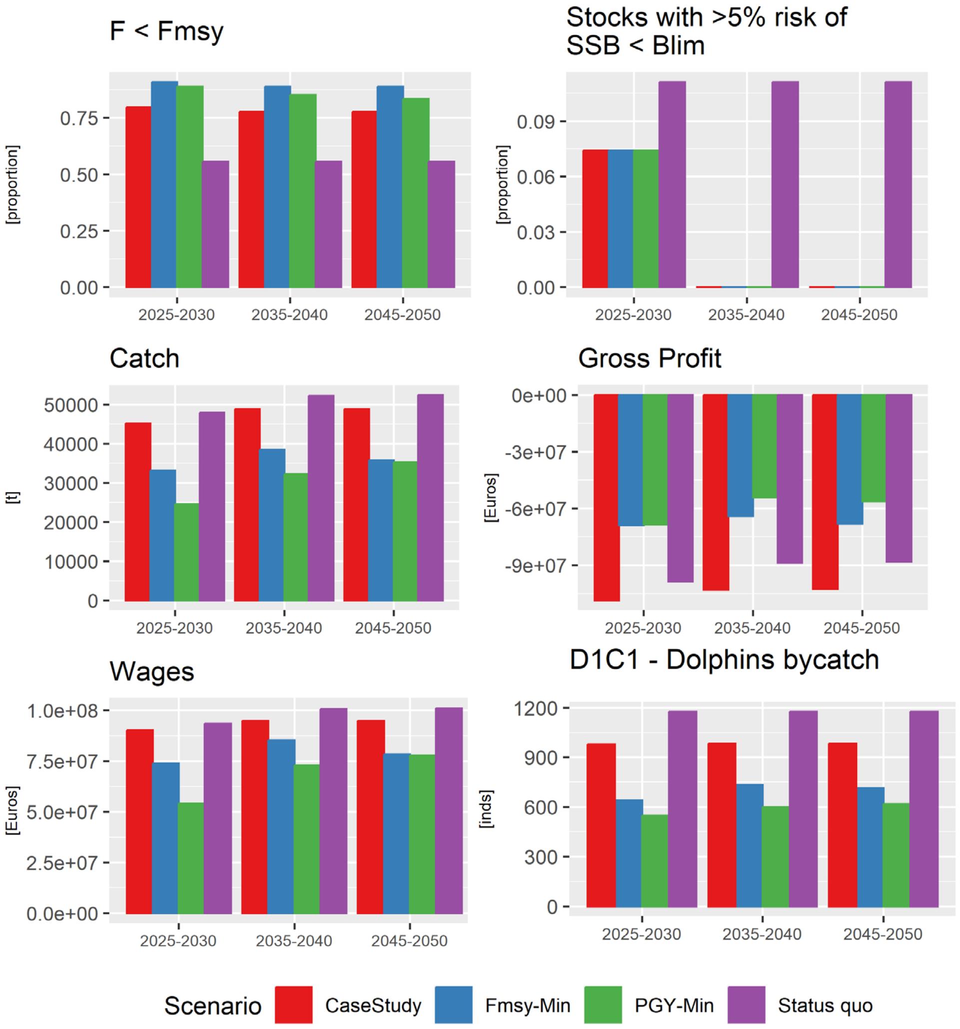
Scenarios applying a strict MSY approach in combination with the landing obligation (i.e. F_{MSY} as upper limit with fisheries ending when the first stock reaches F_{MSY}) in most case studies led to the lowest fishing effort. This had positive effects on MSFD related indicators such as bycatch of Protected, Endangered and Threatened (PET) species, benthic impact and the Large Fish Indicator as well as global indicators such as CO_2 emission or ecosystem-based indicators like catch per km^2. However, this scenario often led to the lowest catches from mixed demersal fisheries due to strong choke effects because fleets had to stop when their first quota was exhausted. This reduces social indicators such as food security, employment and wages. In terms of economic performance, the gains and loses were highly case specific. Scenarios applying the Pretty Good Yield concept and allowing sustainable deviations from the F_{MSY} point estimate when stocks are in a healthy state often outperformed the scenarios applying F_{MSY} as strict upper limit. Such scenarios, applying a more flexible interpretation of the MSY concept, led to reduced fishing effort compared to the status quo effort, but relaxed choke situations in mixed demersal fisheries to some extent leading to higher gross profits and in some case studies also to higher catches. Hence, they may constitute a compromise between the need to attain social as well as ecological objectives. Whether the associated effort levels lead to conflicts with MSFD objectives must be analysed when more internationally agreed thresholds become available for e.g., bycatch of PET species or benthic impact.

The majority of case studies exceeded suggested thresholds for the global ecosystem indicators catch per km^2 or primary production even under scenarios with high effort reductions. This can be explained to some extent by the fact that these indices are mainly driven by pelagic and industrial fisheries not always part of the models applied. Nevertheless, it indicates potential conflicts with such more holistic ecosystem indicators in their current form.

Additional trade-offs in terms of yield were identified within the food web if e.g., demersal piscivorous predators feed on small pelagic fish and both groups are fished. Further, in case studies where small-scale fisheries (SSF) play an important role (e.g., Eastern Ionian Sea) additional trade-offs became apparent as different scenarios led to different ratios between revenues from small scale fisheries and revenues from large-scale fisheries. This adds another level of complexity when such aspects need to be taken more into account in future fisheries management under EBFM.

The modelling assumed current selectivities and catchabilities will be maintained in the future. Especially trade-offs arising from fleets having to stop fishing when their first quota is exhausted or when e.g., a threshold for bycatch of PET species is reached may be resolved by improving selectivities via technical measures (e.g., closed areas or innovative gears) in the future. Deliverable 6.8 in month 36 will test such scenarios. Furthermore, the list of

indicators and their targets and limits will be updated based on research within and outside SEAwise. Predictive capability of models will be enhanced by incorporating improved biological and economic sub-models in relation to environmental change. Climate change scenarios will be run and new harvest control rules (HCRs), proposed by SEAwise, will be tested. Finally, consistent targets and limits will be proposed for implementing EBFM.



Example of model estimates of the impact of different management scenarios for demersal fisheries in the Bay of Biscay on ecological and social indicators.

Contents

1. SEAwise background

The SEAwise project works to deliver a fully operational tool that will allow fishers, managers, and policy makers to easily apply Ecosystem Based Fisheries Management (EBFM) in their own fisheries. With the input from advice users, SEAwise identifies and addresses core challenges facing EBFM, creating tools and advice for collaborative management aimed at achieving long-terms goals under environmental change and increasing competition for space. SEAwise operates through four key stages, drawing upon existing management structures and centered on stakeholder input, to create a comprehensive overview of all fisheries interactions in the European Atlantic and Mediterranean. Working with stakeholders, SEAwise acts to:

- Build a network of experts - from fishers to advisory bodies, decision makers and scientists - to identify widely-accepted key priorities and co-design innovative approaches to EBFM.
- Assemble a new knowledge base, drawing upon existing knowledge and new insights from stakeholders and science, to create a comprehensive overview of the social, economic, and ecological interactions of fisheries in the European Atlantic and Mediterranean.
- Develop predictive models, underpinned by the new knowledge base, that allow users to evaluate the potential trade-offs of management decisions, and forecast their long-term impacts on the ecosystem.
- Provide practical, ready-for-uptake advice that is resilient to the changing landscapes of environmental change and competition for marine space.

The project links the first ecosystem-scale impact assessment of maritime activities with the welfare of the fished stocks these ecosystems support, enabling a full-circle view of ecosystem effects on fishing productivity in the European Atlantic and Mediterranean. Drawing these links will pave the way for a whole-ecosystem management approach that places fisheries at the heart of ecosystem welfare. In four cross-cutting case studies, each centered on the link between social and economic objectives, target stocks and management at regional scale SEAwise provides:

- Estimates of impacts of management measures and climate change on fisheries, fish and shellfish stocks living close to the bottom, wildlife bycatch, fisheries-related litter and conflicts in the use of marine space in the Mediterranean Sea,
- Integrated EBFM advice on fisheries in the North Sea, and their influence on sensitive species and habitats in the context of ocean warming and offshore renewable energy,
- Estimates of effects of environmental change on recruitment, fish growth, maturity and production in the Western Waters,
- Key priorities for integrating changes in productivity, spatial distribution, and fishers' decision-making in the Baltic Sea to create effective EBFM prediction models.

Each of the four case studies will be directly informed by expert local knowledge and open discussion, allowing the work to remain adaptive to change and responsive to the needs of advice users.

1.1 The role of this deliverable

Task 6.4 combines target and limit reference points from improved management evaluation models from Tasks 6.2 and 6.3 and models of ecological impact from Tasks 3.5, 4.2, 4.3, 4.4 and 4.5. This allows SEAwise to propose management strategies that align Common Fisheries Policy (CFP) and Marine Strategy Framework Directive (MSFD) objectives (Descriptors 1, 3, 4, 6 and 10) as well as global objectives such as carbon emission reduction, providing the basis for defining reference levels for good environmental status (GES) compatible with Multi Annual Plans (MAPs), and vice versa.

SEAwise deliverable 6.7 is the first out of two deliverables in task 6.4. It establishes a baseline for the consistency of existing targets and limits from the CFP and the MSFD. Trade-offs between different objectives (ecological, economic, social), targets and limits are highlighted and processes behind inconsistencies are explained. The report focuses on current management measures and multispecies models available in the project after 1.5 years. Deliverable 6.7 tries to incorporate early project results from WP4 tasks where bycatch, benthic impact, food webs and sources of marine litter are analysed to provide MSFD related targets and limits. Where possible, it uses the same parameterisation for stock dynamics as defined in Task 3.5, where single species reference points are estimated.

Deliverable 6.8 in month 36 will further develop the list of indicators (e.g. also including social indicators), targets and limits based on research within SEAwise. Models will be improved by incorporating additional important processes (e.g., improved economic sub-models (Task 2.2), environmentally mediated stock recruitment relationships (Task 3.2), density dependent processes (Task 3.3) and enhanced predictive models of fish survival (Task 3.4). Climate change scenarios will be evaluated and new harvest control rules (HCRs), proposed by SEAwise, will be tested. Finally, consistent targets and limits will be proposed for the implementation of EBFM.

1.2 Contributors

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1.3 Acronyms and abbreviations

Blim: Limit Biomass. Below Blim, recruitment gets impaired

CFP: Common Fisheries Policy

EBFM: Ecosystem Based Fisheries Management

EwE: Ecopath with Ecosim

F: Fishing Mortality

FLBEIA: Bio-Economic Impact Assessment using FLR

GSA: GFCM Geographical Sub Area

GES: Good Environmental Status

GFCM: General Fisheries Commission for the Mediterranean

HCR: Harvest Control Rule

HELCOM: The Baltic Marine Environment Protection Commission (also known as the Helsinki Commission)

ICES: International Council for the Exploration of the Sea

MAP: Multi Annual Plan

MSFD: Marine Strategy Framework Directive

MSY: Maximum Sustainable Yield

PETs: Protected Endangered and Threatened Species

PGY: Pretty Good Yield

OSMOSE: Object-oriented Simulator of Marine ecOSystEms

OSPAR: The Convention for the Protection of the Marine Environment of the North-East Atlantic (name derived from the Oslo and Paris Commissions)

SAR: Stocks at Risk

SHI: Sustainable Harvest Indicator

SMS: Stochastic Multi Species model

SSB: Spawning Stock Biomass

STECF: Scientific Technical and Economic Committee for Fisheries

StrathE2E: Strathclyde End to End ecosystem model

2. Existing indicators, targets and limits impacting fisheries management

The Common Fisheries Policy (CFP; European Commission 2013) and the Marine Strategy Framework Directive (MSFD, European Commission 2008, 2017, 2022) are the two most important overarching policy instruments impacting fisheries management directly. To implement the CFP and MSFD with their various ecological, economic and social objectives, indicators have been developed over time to measure the achievement of these objectives. While CFP indicators for ecological objectives as well as their targets and limits are in many cases internationally agreed (e.g., reference points to implement the maximum sustainable yield (MSY) concept), the situation is different for economic and social objectives of the CFP. While many indicators exist (e.g., gross profit, employment, labour condition etc.), hardly any targets and limits have been agreed so far. The MSFD indicators have been proposed and there is now guidance on which indicators to use to monitor good environmental status (GES) (European Commission 2022). However, agreed MSFD-related targets and limits for the various indicators under the different descriptors are only available for a subset of examples in the different case study regions. Scientific (i.e. ICES and

STECF) and regionally oriented (i.e., OSPAR and HELCOM) bodies have conducted first analyses where they propose candidate thresholds for some of the indicators (e.g., bycatch limits for some marine mammal populations or the Large Fish Indicator (LFI)).

SEAwise collected information on existing targets and limits of CFP and MSFD indicators for the different case study regions. Simulations were carried out with models available to SEAwise task 6.4 after the first 1.5 years. Scenarios were agreed for the North East Atlantic and the Mediterranean case studies, simulating the currently available range of management options (e.g., F_{MSY} ranges or effort levels to reach certain objectives in the Mediterranean) with varying degree of implementation (i.e. of the landing obligation). Model output was used to calculate as many CFP and MSFD related indicators as possible to analyse whether existing targets and limits are consistent with each other or whether trade-offs must be expected because of technical or biological interactions or inconsistent objectives (e.g., ecological vs. socio-economic objectives; MSY vs. GES).

3. Methodology

3.1 General approach

Deliverable 6.7 is based on existing indicators, targets and limits identified in SEAwise Task 6.5 (Performance of existing management plans and measures) and WP4 tasks (Figure 3.1). Scenarios were run under current environmental conditions and harvest control rules (see the description under 3.3 for more details on scenarios). Based on model outputs, as many indicators as possible were calculated (including estimates not internally forecasted by the simulation models which were based on e.g., relationships with predicted effort by metier). Where targets and limits were available, the model predictions were compared to the respective values to identify which targets and limits were respected in each scenario and which not. Where targets and limits have yet to be agreed, scenarios were ranked based on the desired direction of indicator development.

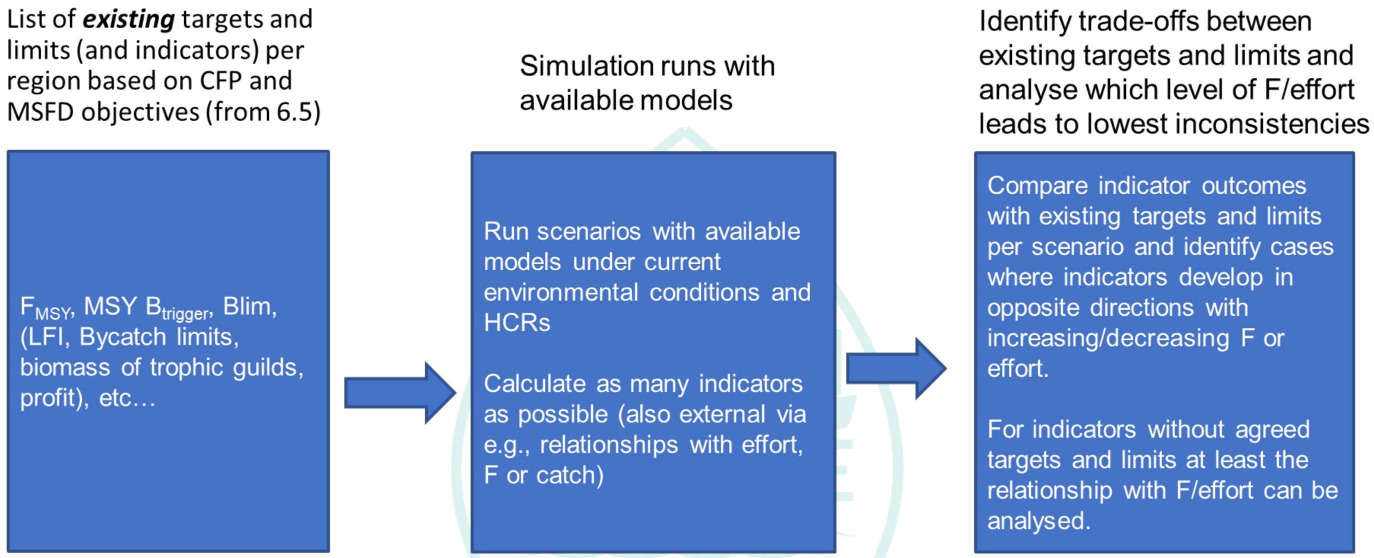


Figure 3.1. General approach to test the consistency of existing targets and limits for indicators in an ecosystem context.

Task 6.4 received input from various tasks (Figure 3.2). The following input has been received:

- Task 3.5: Parameterisation of single species stock dynamic models. Current single species reference points (CFP: MSY-related indicators; MSFD: Descriptor 3)
- Task 4.2: Catch per unit of effort (CPUE) for sensitive species by gear type and region based on ICES WGBYC. Bycatch thresholds for examples per case study (MSFD Descriptor 1)
- Task 4.3: Approach to exchange effort by metier has been discussed for Deliverable 6.8.
- Task 4.4: List of food web indicators (MSFD Descriptor 4)
- Task 4.5: Information about relationships between effort and observed litter (MSFD descriptor 10)
- Task 6.2: Improved ecological models (mainly relevant for month 36)
- Task 6.3: Improved socio-economic models
- Task 6.5: First set of management strategies as well as CFP and MSFD indicators to measure performance in relation to CFP and MSFD objectives

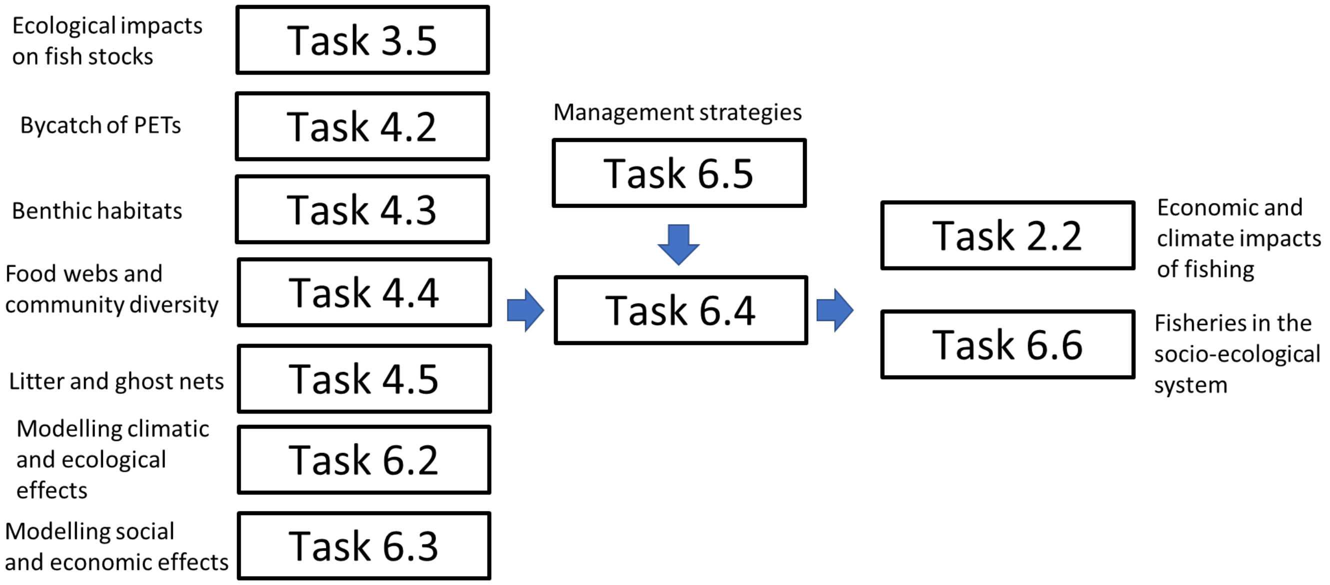


Figure 3.2: Flow of data and information to and from task 6.4

3.2 **Available Models**

For each case study region, a suite of models for a range of stocks and fisheries was available (Table 3.1). For deliverable 6.8 in month 36, further models developed in SEAwise will become available (e.g., Osmose for the North Sea, FLBEIA and Ecopath with Ecosim for the Celtic Sea, Isis-Fish model for the Bay of Biscay, SMS for Baltic Riga herring). For further details on models and their parameterisation see Annexes.

Table 3.1. Models available for SEAwise deliverable 6.7

Case study	Model name	Model type	Spatial extent	Species/stocks included	Fleets/metiers/fisheries included
North Sea	Bio-Economic Impact Assessment using FLR (FLBEIA)	Bio-economic mixed fisheries simulation model	ICES areas 4, 7d, 3a20 and 6a for stocks extending to 6a (cod, saithe, haddock, anglerfish)	Cod, whiting, haddock, saithe, plaice (4; 7d), sole (4; 7d), turbot, witch, anglerfish, lemon sole, ling, brill, dab, Nephrops FUs	Demersal Fleets and Metiers (42 fleets and 132 metiers)
	Object-oriented Simulator of Marine ecOSystEms (Osmose)	Multispecies and individual based model	Ices area 7d	Mackerel, horse mackerel, sardine, herring, poor cod, North Sea cod, whiting, pouting, striped red mullet, dragonet, lesser spotted dogfish, sole, plaice, squids	None (F by species/stock)
	Strathclyde End to End ecosystem model (StrathE2E)	End to end model	North Sea	End-to-end, nutrients, plankton, benthos, fish, birds, pinnipeds, cetaceans but all as function groups not species	Pelagic and demersal fisheries
	Stochastic Mult Species model (SMS)	Multispecies stock assessment model	ICES area 4	Cod, haddock, saithe, whiting, hake, plaice, sole, herring, sprat, sandeel, Norway pout, mackerel, horse mackerel, seals, harbour	None (F by species/stock)

				porpoise, grey gurnard, starry ray, 8 bird species.	
Western Waters	FLBEIA	Bio-economic mixed fisheries simulation model	ICES area 8	Hake, megrim, monkfish, horse mackerel, mackerel, sole, blue whiting, thornback ray, black-bellied angler, Nephrops, seabass, starry smooth-hound, cuckoo ray, undulate ray	Demersal fleets and metiers
	FLBEIA	Bio-economic mixed fisheries simulation model	ICES area 8	Anchovy, North East Atlantic mackerel, western horse mackerel, northern hake, sardine in Bay of Biscay, Iberian sardine, bluefin tuna, albacore	Pelagic fleets and metiers
	StrathE2E	End to end model	Celtic Sea	End-to-end, nutrients, plankton, benthos, fish, birds, pinnipeds, cetaceans but all as function groups not species	Pelagic and demersal fisheries
Baltic	BEE-FISH	Bio-economic simulation model	ICES Subdivisions 25-32, Central Baltic, ICES SD 22-24, Western Baltic	Cod, herring, sprat	Trawl fisheries
Mediterranean	FLBEIA	Bio-economic mixed fisheries simulation model	GFCM GSA20	European hake, red mullet, deep water rose shrimp, striped red mullet, others (all other commercial stocks caught by the fleets to be treated as one biomass dynamic stock)	Demersal fleets (OTB, SSF)
	BEMTOOL	Bio-economic simulation model	GFCM GSAs 17, 18 and 19 (Southern Adriatic and Western Ioanian Sea)	European hake (GSAs 17-18 combined; GSA 19), red mullet (GSAs 17-18 combined; GSA 19), deep water rose shrimp (GSAs 17-18-19 combined) giant red shrimp (GSAs 18-19 combined), Norway lobster (GSA 17-18 combined).	Demersal Fleets and Metiers: specifically, 1) Mixed demersal trawlers 2) Mixed deep waters trawlers; 3) Small scale; 4) Longliners. In total: 16 fleet segments and related metier.

3.3 **Scenarios**

The parameterisation of the biological part was the same as used for Task 3.5 to forecast stock developments in a base scenario (i.e. no environmental changes) if possible. Where this was not possible, the parameterisation (i.e. stock recruitment relationship(s), biological parameters as M, weight at age etc.) were chosen as close as possible to the latest benchmark decisions for a given stock. Uncertainty was included at least for the biological parameters (i.e. recruitment) whenever possible. In addition, assessment and/or advice error in a Management Strategy Evaluation (MSE) shortcut approach was added if feasible.

3.3.1 North East Atlantic case studies (North western waters, Bay of Biscay and Iberian waters, North Sea, Baltic)

The ICES MSY approach is the most important management strategy applied to provide advice on fishing opportunities in the North East Atlantic. In addition to the ICES MSY approach, sustainable F_{MSY} ranges delivering at least 95% of the maximum yield (Pretty Good Yield (PGY) concept) from multi annual plans (MAPs) for the North Sea, Baltic and Western Waters are considered. As further important management measure, the landing obligations exist for all EU, UK and Norwegian waters of the North East Atlantic.

Next to a baseline scenario applying current effort/F levels, in total 3-4 scenarios were run for task 6.4 to mimic current management approaches:

a) A “status quo” effort/F scenario. The effort/F is set to the average of the last three years *OR* to the value of the most recent year if trends are obvious.

b) A “min” scenario. The ICES F_{MSY} harvest control rule is applied with F_{MSY} as target for each stock. The fleets/metiers stop when the first quota is exhausted. The scenario implies a strict implementation of the landing obligation.

c) A “pretty good yield” scenario: Same as the min scenario, but using the fishing mortality ranges to provide more flexibility to the catch advice setting. In some cases F_{MSY} was replaced by fishing at the “F_{MSY} upper” level (F_{MSY} upper indicates the upper limit of sustainable fishing mortalities delivering at least 95% of the maximum yield) is allowed when stocks are in good status; i.e. above MSY $B_{trigger}$ at the beginning of the advice year. In addition, a buffer to year-to-year advice variability could be introduced, such that TACs are limited to max. +/- 20 percent from one year to the next, but limited to TACs associated with F_{MSY} upper or lower. The scenario is somewhat more flexible in the use of the upper FMSY range, possibly releasing some choking behaviour when most-limiting stocks are in good status. In other cases, F_{MSY} was replaced by the fishing mortality produced by a multi-stock HCR that tried to balance the single stock fishing mortality targets with the aim of maximizing fishing opportunities within the fishing mortality ranges.

d) An additional case-specific scenario that mimics the current situation in the region regarding fleet dynamics, uptake of quotas or likelihood of certain species/stocks becoming choke species under the current level of implementation and control of the landing obligation.

3.3.2 Mediterranean case studies (Central and Eastern Mediterranean)

For the *Central Mediterranean Case study* (GSA17-18-19), the GFCM MAP for demersal stocks in the Adriatic (Recommendation GFCM/43/2019/5), establishing maximum capacity and effort limits for both bottom and beam trawlers, was used as baseline. The MAP is aimed at achieving the MSY target in 2026 for all key stocks through a fishing effort regime.

For the *Eastern Mediterranean Case study* (GSA 20) there is no MAP, but there is a national management plan for trawlers using bottom otter trawls (OTB) which has been in effect since 2013 and several management measures for Small Scale Fisheries (SSF). The management measures in this national plan are generally based on MSY targets in line with the EU-MAP objectives.

For the Mediterranean Case study the following scenarios were explored for task 6.4:

a) Status quo (same effort as in the last historic year used to parameterise the model or average last three years);

b) Effort reduction to achieve the F0.1 (used as F_{MSY} proxy) of the most overexploited stock in 2026;

c) Effort reduction to achieve a combined F_{MSY} (or PGY) on all the target stocks;

d) F_{MSY} range (low and upper, 2 scenarios) of the most overexploited stock. One of these additional scenarios could be overlapping with scenario 3, in which case it could not be necessary to run both scenarios of this point.

If the type of model (e.g., ecosystem models) was not able to run the base scenarios, simple F multipliers were applied to status quo effort or fishing mortality to demonstrate the direction of change in indicators with increasing or decreasing fishing pressure. For more details on scenarios implemented for each case study and model, see Annexes.

3.4 **Indicators**

The set of indicators was agreed based on the indicators used to measure the performance of current management in task 6.5 (Table 3.2). Ecological and socio-economic indicators in relation to CFP and MSFD objectives as well as global ecosystem indicators were included in the analysis to cover a broad range of indicators. For each indicator, the averages over the prediction years 2025-2030, 2035-2040, 2045-2050 (i.e. 6-year periods as suggested by the most recent MSFD guidelines (European Commission 2022)) were calculated. Not all indicators could be calculated for all models (for more details see Annexes) but the strength of each model was utilised to cover as many indicators as possible in each case study region.

Table 3.2. Set of indicators to be considered for each case study and model. D[x] followed by C[y] indicates the respective MSFD descriptor and criterion.

Type of indicator	Indicator	Targets or limits available?	Comments
CFP ecological	Proportion of stocks fished at or below F_{MSY}	Yes	Also relevant for MSFD D3C1
	Proportion of stocks with median SSB below MSY $B_{trigger}$	Yes	Also relevant for MSFD D3C2
	Proportion of stocks with >5% probability to fall below B_{lim}	Yes	Also relevant for MSFD D3C2
	Proportion of fleets with Sustainable Harvest Indicator (SHI) above 1	Yes	Details can be found in balance indicator guidelines (COM 2014, 545 final)
	Proportion of fleets with number of stocks at risk (SAR) > 0	Yes	Details can be found in balance indicator guidelines (COM 2014, 545 final)
CFP socio-economic	Landings (average of yearly sums across fleets/metiers)	No	
	Unwanted catch/discards (average of yearly sums across fleets/metiers)	No	
	Revenue (average of yearly sums across fleets/metiers)	No	
	Gross profit (average of yearly sums across fleets/metiers)	No	Gross profit (GP) = Income from landings + other income – crew costs – unpaid labour - energy costs – repair and maintenance costs – other variable costs – non-variable costs[1]
	Gross value added (average of yearly sums across fleets/metiers)	No	Gross value added (GVA) = Income from landings + other income – energy costs – repair costs – other variable costs – non-variable costs[1]
	Employment (average of yearly sums across fleets/metiers)	No	

	Wages (average of yearly sums across fleets/metiers)	No	
	Average yearly ratio of current revenue/break even revenue (sum across fleets/metiers) Ratio landings value fleets <=24m/landings value fleets >24m	Yes	CR/BER = revenue / break-even revenue = Income from landings + other income / BER[1] BER = (Fixed costs + opportunity costs of capital +depreciation) / (1-(crew costs + unpaid labour + energy costs + repair and maintenance costs + other variable costs)/Revenue)[1]
	Accident rates	No	
MSFD related indicators (Descriptor 3 indicators are already included under CFP indicators)	D1C1: Bycatch or risk for PET species	Partly (for some species and regions). For details see Annex 10.	Biological Extraction of, or mortality/injury to, wild species (by commercial and recreational fishing and other activities)[2]
	D4C1: Biodiversity within trophic guilds[3]	No	Simpson or Shannon indices could be used to measure biodiversity[2]
	D4C2: Balance between trophic guilds[3]	No	Biomass per guild is preferable over abundance[2]
	D4C2: Biomass of forage fish	No	Indicator to detect potential food limitation for higher trophic level species
	D4C3: Size structure within guilds[3]	No	Examples of size-based indicators applied for fish include the large fish indicator (LFI), typical/median//95th percentile of length, and mean maximum length (MML). The LFI relies on the estimation of the size of a 'large fish' to be estimated separately by guild and region, and the indicator is therefore not directly comparable between regions but may provide useful results within a region. Mean maximum length (MML) integrates aspects of species diversity and size structure (mean possible length in the guild) and has the advantage that it can be estimated without information on size distribution of individuals in the guild. [2]
	D4C4: Average recruitment success within guilds[2]	No	R/SSB may be used as proxy for recruitment success.[2]
	D6: Effort by demersal gear type	No	Provides indications for pressure indicators D6C1 (physical loss of seabed) and D6C2 (physical disturbance to the seabed). Impacts on benthic habitats (State) will be analysed together with SEAwise task 4.3 following deliverable 6.7.
	D10: Amount of marine litter	No	According to the MSFD Descriptor 10 Marine litter should not cause harm to the coastal and marine environment. Litter in the environment (D10C1) includes litter on the coastline, on the surface and on the seabed. For seafloor litter, the assessment is based on annual surveys. A trend analysis detects the direction of development of the parameter (number or mass/km^2)[2]. In SEAwise, this is analysed using several litter categories that allow to evaluate also risks of entanglement, ingestion and transport.
Global indicators	Carbon emission from fisheries (average of yearly sums across fleets/metiers)	No	
	Ratio of fisheries catches to Primary production (Fogarty ratio in Link and Watson 2019)[4]	No	On the basis of simple trophic transfer calculations, the Fogarty ratio of catches relative to PP ranges from 0.1 to 3‰. This again is suggestive of reasonable limits to catch potential and hence a possible threshold. Thus, given

			worldwide catches of 0.1 to 0.42 Gt year−1 would imply an expected ratio of catch to PP of 0.22 to 0.92‰, suggesting a possible „Not to Exceed“ threshold ~1. Even an extreme estimate of catches near 1 Gt year−1 would result in a value of 2.2‰ (~2.5‰).[4]
	Catches per km^2 per year (Ryther index in Link and Watson 2019)[4]	No	Given that the surface area of the world’s ocean is approximately 363 M km2, one can estimate the areal values of catch, which can be reasonably expected. Link and Watson call this the Ryther index. Ryther’s original work not only related landings to PP but also provided a global thinking and evaluation of fisheries catch. Thus, world wide catches of 0.1 to 0.42 Gt year−1 would result in a yield of 0.27 to 1.14 t km−2 year−1, suggestive of a possible „Not ot Exceed“ threshold ~1. Even extreme estimates of global total catch around 1 Gt year−1 would result in a value of 2.7 t km−2 year−1 (~3 t km−2 year−1).[4]
	Ratio of fisheries catches to Chorophyl a (Friedland ratio in Link and Watson 2019)[4]	No	Acknowledging that estimates of PP are not always available but that satellite imagery able to produce estimates of chlorophyll a may be more so, Link and Watson propose a proxy index. Coupling catch statistics with chlorophyll a estimates, and acknowledging all the important nuances of chlorophyll a and different pathways of production, they propose a unitless ratio of catch: Chlorophyll a to evaluate relative fishery productivity in those instances where PP estimates are not readily available. They call this the Friedland ratio index. Using logic similar to the Fogarty ratio, an empirical „Not to Exceed“ threshold ~1 emerges.[4]

[1] Scientific, Technical and Economic Committee for Fisheries (STECF): The 2021 Annual Economic Report on the EU Fishing Fleet (STECF 21-08) Annex. EUR 28359 EN. Publications Office of the European Union, Luxembourg, 2021. ISBN 978-92-76-43549-5, doi:10.2760/549599, JRC 126139.

[2] European Commission 2022. MSFD CIS Guidance Document No. 19, Article 8 MSFD, May 2022.

[3] Trophic guilds according to European Commission (2022): Apex fish predators, Apex marine mammal predators, Sub-apex demersal predators, Sub-apex pelagic predators, Planktivorous fish and invertebrates, Benthic feeding invertebrates, Benthic filter feeding invertebrates, Secondary producers, Benthic primary producers, Pelagic primary producers

[4] Link, J.S. and Watson, R.A. 2019. Global ecosystem overfishing: Clear delineation within real limits to production. Sci. Adv. 5. eaav0474

4. Results

For the different case studies and models a sub-set of indicators were selected to demonstrate main trade-offs between indicators and to compare model results to existing targets and limits. More indicators and description of models, methods and results can be found in the respective Annexes.

4.1 **North Sea**

4.1.1 FLBEIA North Sea (27.4), Skagerrak (27.3.a.20) and Eastern English Channel (27.7.d)

The bio-economic model FLBEIA for the North Sea, Skagerrak and Eastern English Channel was applied to analyse the effect of different harvest strategies in relation to the MSY concept and implementation level of the landing obligation. Further details on the model, methods and results can be found in Annex 1.

The scenarios chosen were designed as baseline runs, excluding any additional effects of climate change, species interactions or economic developments that will be explored in future work within Seawise. We explored four baseline scenarios:

One “Status quo” effort scenario, where the fleets can fish with the effort of the last data year (2021) without choking effects and three landing obligation scenarios with different interpretations of the MSY concept. The first landing obligation scenario is a classic “Fmsy-Min” scenario, applying the ICES harvest control rule with F_{MSY} as target fishing mortality. Fleets stop fishing when their first quota is exhausted. A second Pretty good Yield (PGY) landing obligation scenario (“PGY-Min”) allows harvesting up to the upper sustainable F_{MSY} range, if the stock is above MSY Btrigger. Additionally, we considered a 20% limit to year-to-year TAC changes, as stability of income and harvest has a high value among fishermen. A last landing obligation scenario, which is case study specific to the North Sea (“Case Study”) relaxes the degree of choking stocks by excluding witch as a choking stock as witch is currently managed under a combined TAC with lemon sole, making choking effects less likely. Additionally, we only allowed more southerly distributed fleets fishing with Beam Trawls or TR2 gears (mesh sizes between 80mm and 100mm, typically used in the fisheries for sole and plaice) to be choked by sole and plaice, whereas the other fleets have a reduced number of potential choking stocks. Furthermore, we looked at the effects of an additional 27% implementation error on the TAC limits of cod when TACs are set below 35000 tonnes. TAC overshoots for North Sea cod were observed in the last years according to ICES advice indicating a lack of control of the landing obligation in reality.

Main results:

Scenarios with an implemented landing obligation outperformed the Status quo effort scenario in all aspects (ecological and individual economic) apart from the total amount of catches (food security). The strictest implementation of the MSY concept and of the landing obligation (Fmsy-Min scenario), however, led to losses in economic and social indicators compared to the more flexible scenarios (PGY-Min and Case specific). In relation to MSFD related and global indicators, a strict implementation of the landing obligation and interpretation of the MSY concept (Fmsy-Min) was the best option.

Under the Status quo scenario, several of the stocks were harvested above F_{MSY}, leading to an increased risk of stocks falling below B_{lim} (Figure 4.1.1). The scenario with a strict implementation of the landing obligation and MSY approach (Fmsy-Min) allowed for more sustainable harvesting and no stocks had an increased risk of falling below B_{lim}. Relaxing the choking situation in the PGY-Min and Case Study scenario, led to an increased proportion of stocks being fished above F_{MSY} (but below F_{MSY} upper indicating the upper limit of sustainable fishing mortalities delivering at least 95% of the maximum yield). None of the stocks had a risk above 5% to fall below B_{lim} in these scenarios. Therefore, the Status quo was the scenario clearly exceeding existing targets and limits, while for PGY-min and the case specific scenario it depends on the interpretation of the MSY concept and whether sustainable F_{MSY} ranges are allowed.

Looking at the Gross profit across fleets for the different time periods showed clear economic gains in scenarios with an implementation of the landing obligation (Figure 4.1.1). The Status quo effort scenario generated the lowest gross profit indicating benefits of reducing fishing effort in the future. Relaxing the choking situation in the PGY and Case study specific scenario generated the highest Gross profit over all periods, with the Case study specific scenario performing best. The Fmsy-Min scenario performed better than the Status quo effort scenario but worse compared to the other landing obligation scenarios. The same ranking could be also observed for catches and wages between the landing obligation scenarios. However, in terms of catch the status quo effort scenario outperformed the other scenarios at the cost of more depleted stocks and lower economic performance.

As the bycatch of harbour porpoise and seals was assumed proportional to the effort of specific gears in the model, the scenarios with highest bycatch was the scenario with the highest effort being the Status quo scenario, followed by the Case Study specific, PGY-min and the FMSY-min scenario (Figure 4.1.2). Bycatch levels in the landing obligation scenarios could be reduced by 30-53 % for harbour porpoise and 27-49 % for seals relative to the Status quo scenario, through the reduction in fishing effort. For harbour porpoise the highest bycatch from the Status Quo scenario of 1547 individuals is slightly below the estimated threshold of 1622 individuals (see Annex 10 for details on thresholds). For seals, the highest bycatch of 2146 individuals in the Status Quo scenario is also lower than the PBR threshold set by OSPAR of 7617 individuals (see Annex 10 for details on thresholds). However, these predictions of bycatch are highly uncertain as both the current level of bycatch is very poorly known and a simple linear relationship between effort and bycatch numbers may not be true in reality. Therefore, these values can only be seen as indicative of the likely direction and ball park magnitude of change.

The biomass ratio of apex fish predators (AFP) to sub-demersal predators (SDP) revealed the highest proportion of AFP (in our case cod) for the Fmsy-Min scenario, relative to all the benthic gadoids and flatfish in the model (Figure 4.1.2). The other scenarios group themselves again in the pattern from lowest to highest fishing mortality with a higher amount of AFP in scenarios with lower fishing pressure.

The proportion of large fish in the three landing obligation scenarios with values between 0.27 – 0.29 was higher than the Status quo scenario with values around 0.2, reflecting that lower exploitation levels in the landing obligation scenarios lead to a higher proportion of older age classes and a shift in age-distribution (Figure 4.1.2). The differences between Fmsy-Min having the highest LFI compared to the two relaxed choking scenarios (Fmsy-Upper and Case Study) could be explained by the lower exploitation, leading to a high biomass of stocks with large fish sizes (cod, saithe and plaice). In general, stock recovery and accompanying shift in age class distribution under the landing obligation scenarios could help in reaching a target LFI for the North Sea of LFI > 0.3 currently discussed as potential threshold.

The potential highest benthic impact followed the effort of the demersal gears and was highest in the Status quo scenario, followed by the Case study specific scenario, PGY-Min and Fmsy-Min scenarios. Only for Beam trawls, effort levels of the PGY-min scenario increase over the simulation period, reaching higher levels than the Case study specific scenario by 2035 – 2040, due to higher exploitation levels of the flatfish plaice, sole and witch, which are caught predominantly with Beam trawls.

Carbon emissions by the fishery are highest under the Status quo effort scenario, followed by the Case study specific scenario, PGY-Min and Fmsy-Min, reflecting the general effort pattern of the scenarios (Figure 4.1.3). The Fogarty ratio (catch per net primary production) and Ryther index (catches per surface area) for the North Sea simulations exceed the threshold of 1 and are even at their upper limit (2.2 for Fogarty) or exceed it (2.7-3 for Ryther), indicating severe ecosystem overfishing for all scenarios. However, changes in the demersal fisheries does not have a large impact on these indicators as the main catches come from pelagic and industrial species that had to be assumed constant for this analysis.

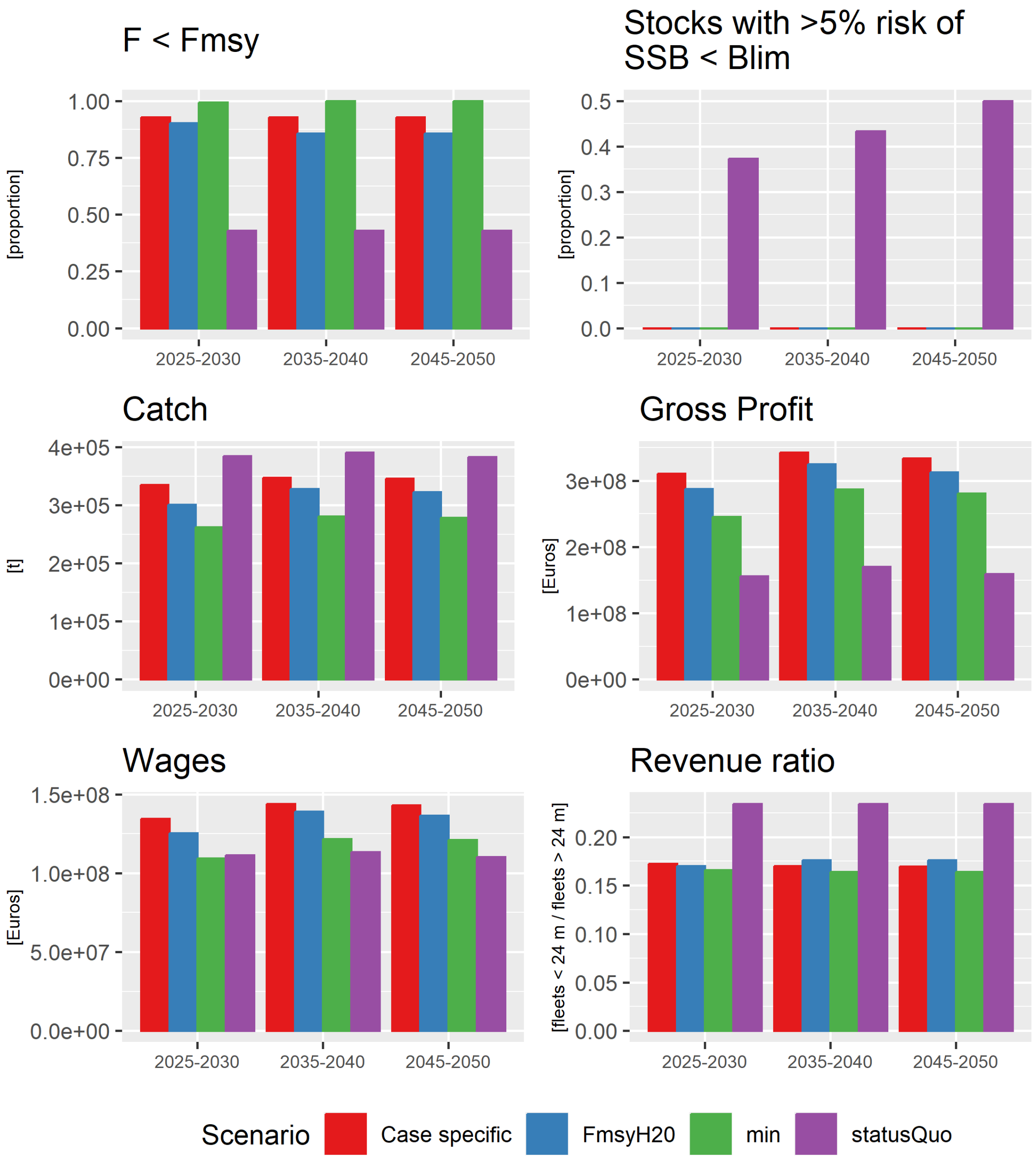


Figure 4.1.1. CFP related indicators by scenario and time-period predicted from the FLBEIA model for the North Sea, Skagerrak and Eastern English Channel

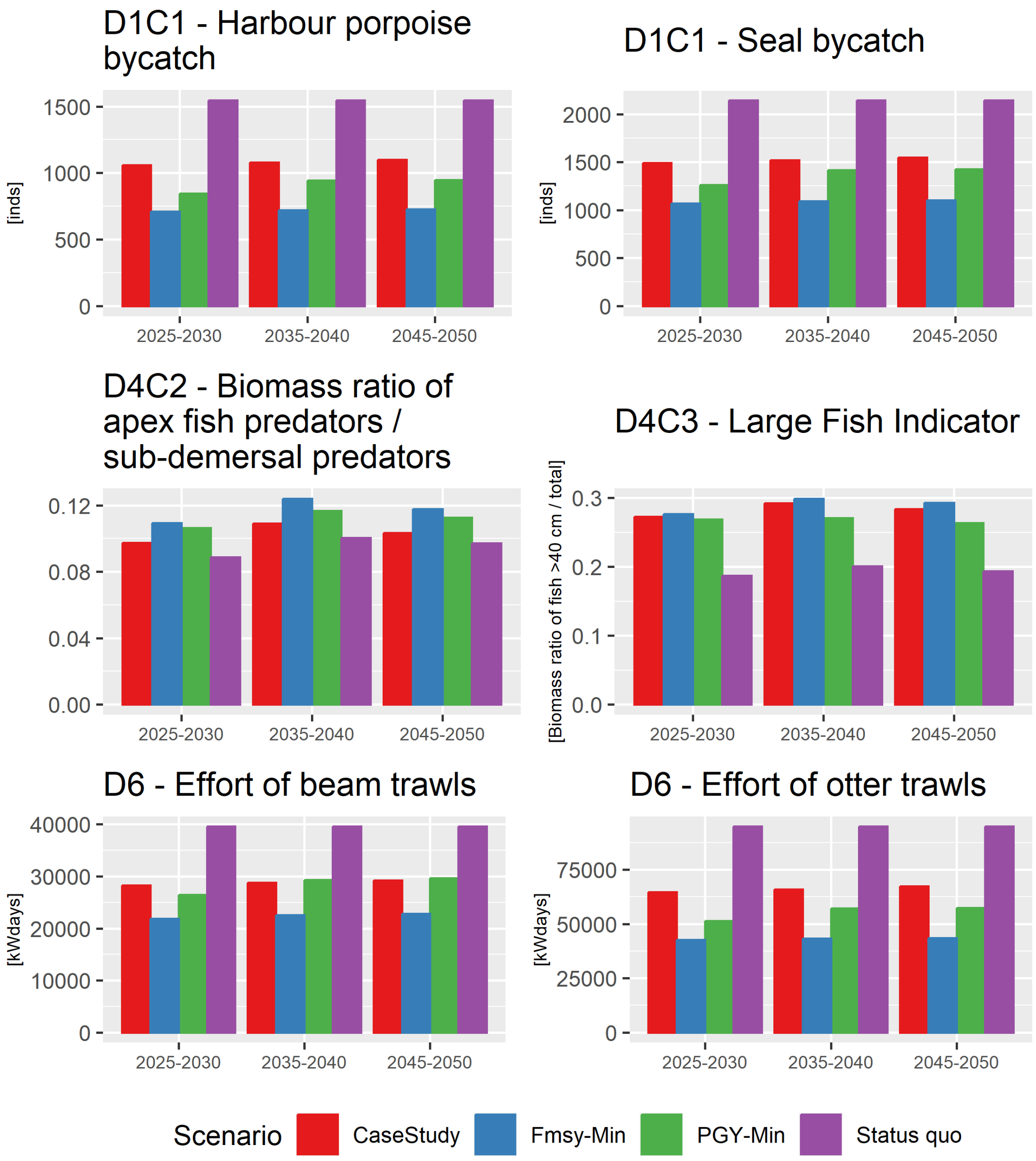


Figure 4.1.2. MSFD related indicators by scenario and time-period predicted from the FLBEIA model for the North Sea, Skagerrak and Eastern English Channel

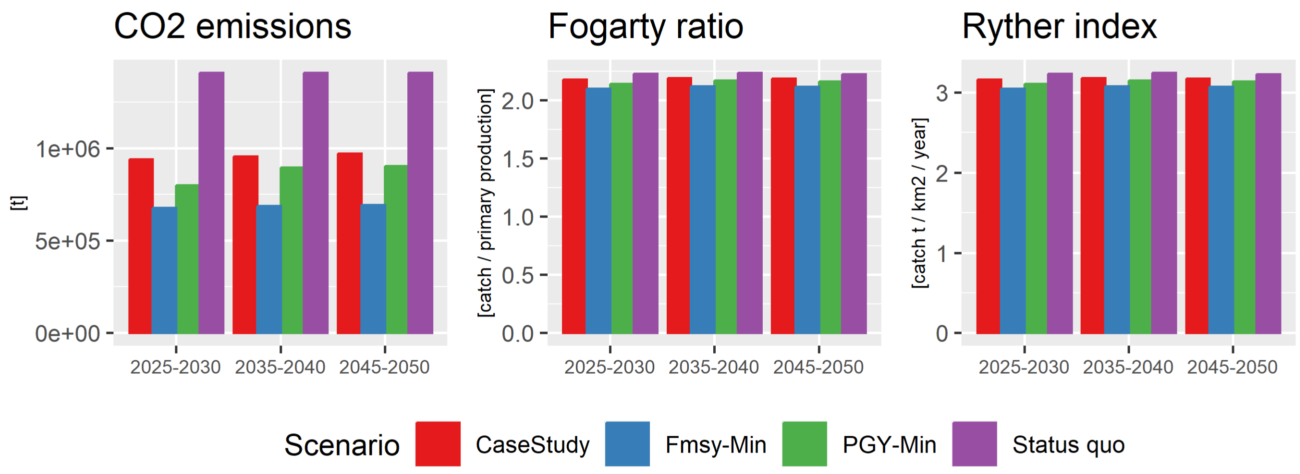


Figure 4.1.3. Global indicators by scenario and time-period predicted from the FLBEIA model for the North Sea, Skagerrak and Eastern English Channel.

4.1.2 Osmose in the English Channel

An Osmose model for the English Channel was used to run straightforward scenarios including status quo fishing mortalities and status quo multiplied with a factor of 0.8 and 0.6 (Figure 4.4). The focus was on MSFD and food web related indicators. More details can be found in Annex 2. The predicted biomass of Apex predators decreased with increasing fishing pressure, while e.g., the biomass of forage fish was less clearly related to fishing pressure indicating benefits of released predation pressure in the model when fishing harder on predators. Also, the response of sub-demersal predators was non-linear, while benthic risk was clearly highest in the status-quo scenario.

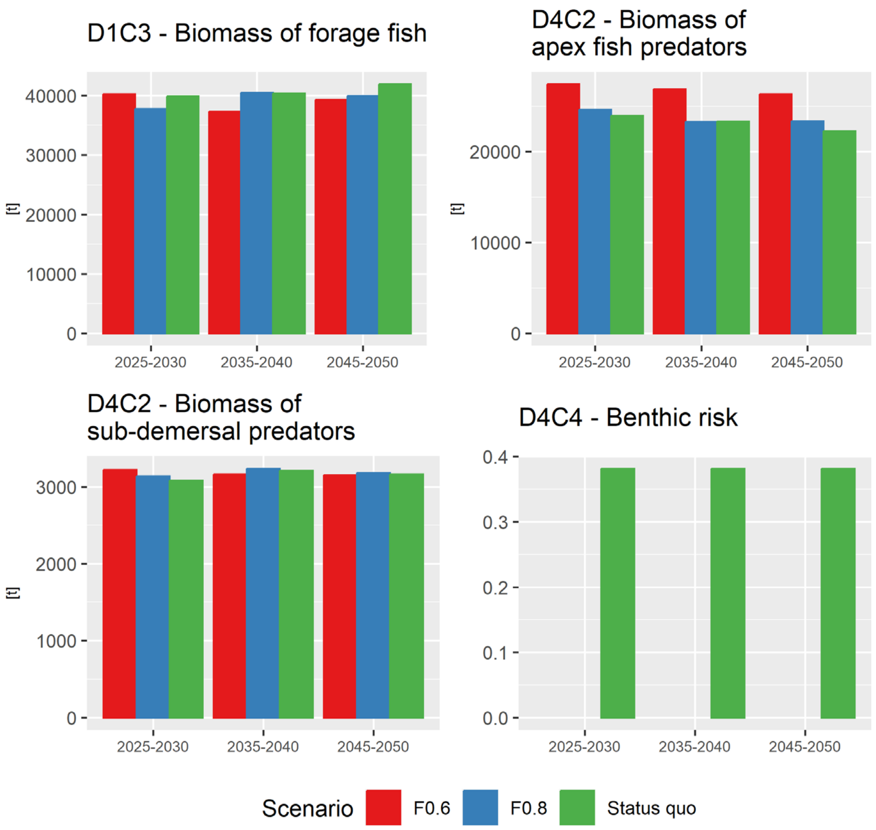


Figure 4.1.4. MSFD related indicators by scenario and time period predicted with the Osmose model for the Eastern English Channel.

4.1.3 StrathE2E – North Sea

The end-to-end ecosystem model StrathE2E was used to analyse the impact of different levels of fishing pressure on the North Sea ecosystem. This section focuses on ecological and ecosystem wide indicators. Other aspects including e.g., catch levels and revenues can be found in Annex 3.

Biomasses of fish and top predators decreased with increasing effort multiplier (Figure 4.1.5). Released from predation, the biomass of carnivorous zooplankton increased. Small cascading trophic effects were present at the phytoplankton and zooplankton levels. Migratory fish appeared resilient to increasing fishing effort in the model. This was because this guild was not a permanent resident in the model domain. A seasonal immigration flux of migratory fish into the model was part of the boundary conditions for the model, which was independent of the effort multiplier scenarios – therefore the global biomass of the migratory fish stock (archetype: mackerel) was not affected by harvesting within the model domain. The assumption is that harvesting within the North Sea model represents a minor component of the total annual removals from the global stock in the northeast Atlantic. Nevertheless, the net migration flux of migratory fish (annual immigration less annual emigration) was dependent on the fishing effort, since their biomass was harvested inside the model.

The scaling of fishing effort had a large effect on the biomasses of the top predators in the model (birds, pinnipeds and cetaceans), which were severely depleted relative to an unfished state, even in the baseline model (Figure 4.1.5). This was partly due to direct by-catch by certain gears, and partly as a bottom-up trophic effect of depletion of their food supply. The ratio of biomasses of top predators to fish declined with increasing fishing. By-catch quantities, and in the case of cetaceans the directed landings quantity, varied in response to changing abundances in the sea, and the changing mortality rate due to fishing gears. However, the predictions of bycatch are highly uncertain as both the current level of bycatch is very poorly known and a simple linear relationship between effort and bycatch numbers may not be true in reality. Therefore, these values can only be seen as indicative of the likely direction and ball park magnitude of change. Further, the controlling effect of food supply on several of these species has not been confirmed by data analysis (Engelhard et al. 2014).

Net primary production decreased with fishing effort (Figure 4.1.6). In StrathE2E, phytoplankton dynamics are integrated into the model food web and so primary production is subject to top-down cascading trophic effects arising from the removal of higher trophic levels from the system. The Fogarty index included this dynamic aspect of the primary production. Levels of the Fogarty index and the Ryther index in even the baseline model both exceeded the thresholds suggested by Link and Watson (2019) as representing optimal harvesting of the ecosystem, and were clearly in the realm of ecosystem over-exploitation according to Link and Watson (Figure 4.1.6).

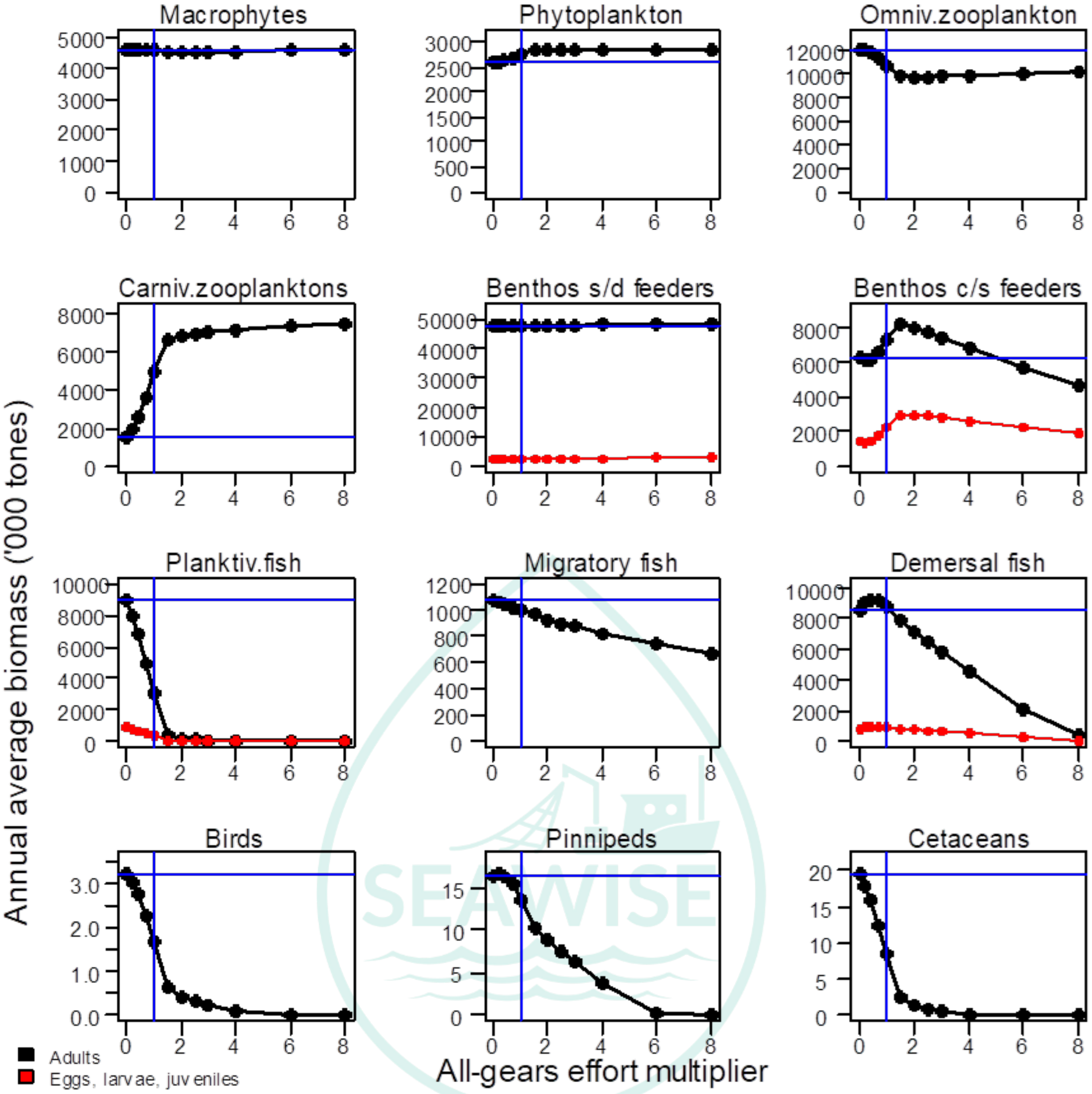


Figure 4.1.5. Steady state annual average biomasses (thousands of tonnes) for each guild in the North Sea relative to effort multiplier scenarios.

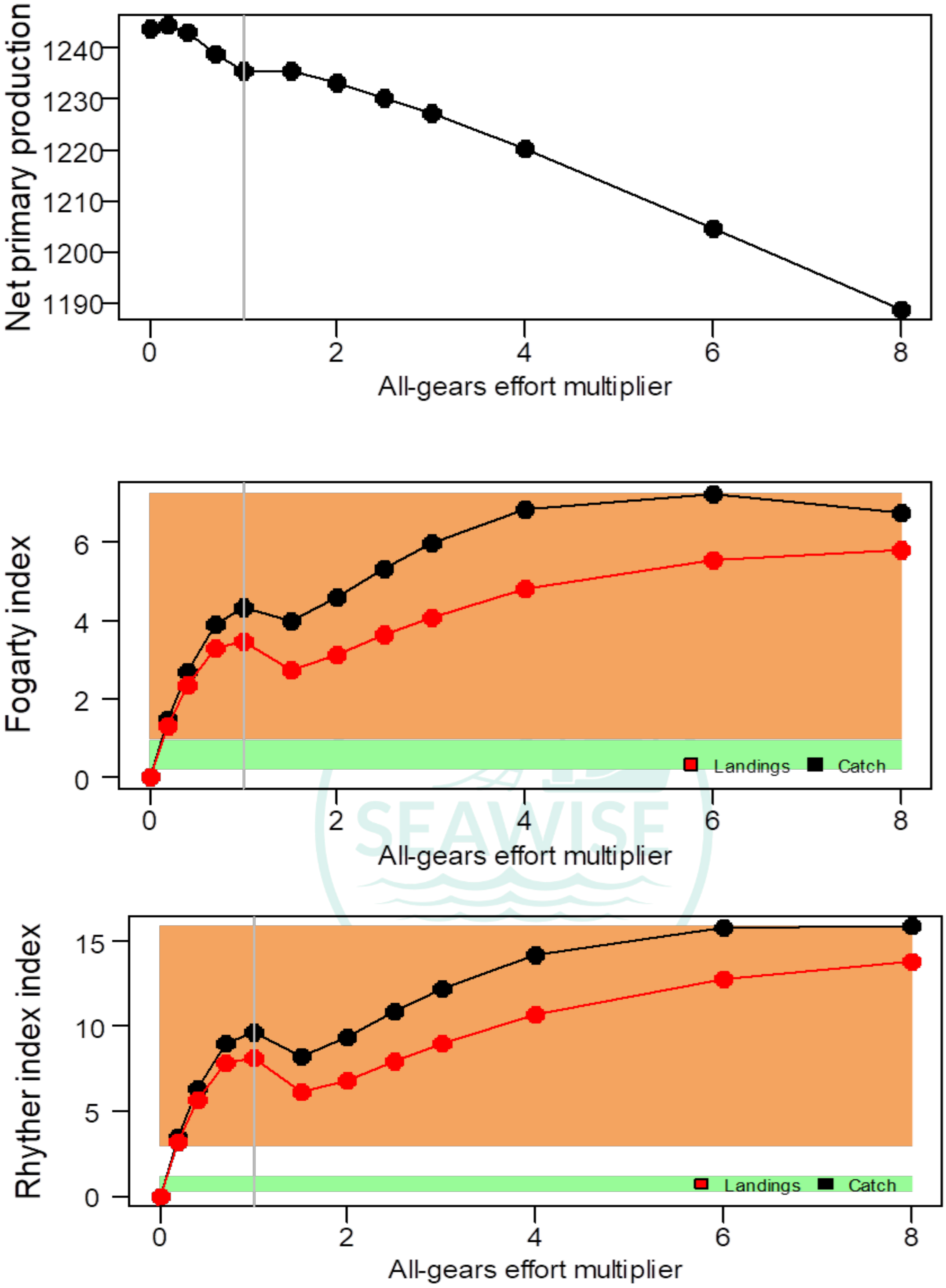


Figure 4.1.6. Upper panel: Annual net primary production (mMolesN.m^{-2}.y^{-1}) simulated by the North Sea model in relation to effort multiplier scenarios. Middle panel: Fogarty index (landings or catch divided by net primary production) relative to effort multiplier scenarios. Lower panel: Ryther index (catch or landings tonnes.km^{-2}.y^{-1}) relative to effort multiplier scenarios. Green shaded areas in the Fogarty index and Ryther index panels are regarded as optimal ranges (Link & Watson 2019; Beet & Gaichas 2022). The orange shaded areas are regarded as representing ecosystem overfishing. Vertical grey line at effort multiplier = 1 in each panel represents the baseline 2003-2013 model.

4.1.4 Stochastic Multi Species model SMS for the North Sea

The multi species model SMS (ICES, 2021) was run for the North Sea to analyse food web interactions between demersal fish predators and small pelagics (herring, sprat, Norway pout and sandeel). The fishing mortality trajectories for the main demersal predators (cod, haddock, whiting, saithe) predicted from the North Sea FLEBIA scenario runs (Status quo, Fmsy-Min, PGY-Min, Case study) were directly implemented in SMS. This allowed demonstration of the resulting impact of different realized fishing mortalities for demersal predators on small pelagics and industrial species when simulating dynamic predation mortalities. In all scenarios, the herring stock was fished according to the ICES MSY approach, while the industrial species sprat, sandeel and Norway pout were managed by an escapement strategy. For further details see Annex 4.

Trophic cascades in SSB developments were obvious (Figure 4.1.7). The higher the fishing mortalities for demersal fish in the different scenarios, the lower the predicted SSB of the top predatory fish saithe and cod. However, sub-apex predators like haddock and whiting increased in SSB despite higher fishing mortalities due to lower predation from cod and saithe. The resulting impact on small pelagics was highly dependent on the main predators feeding on them. Herring and Norway pout benefitted from higher average fishing mortalities on gadoids (indicating that the reduction of predation from cod and saithe was more important than the increase in predation from haddock and whiting), while sprat and sandeel showed the opposite pattern. Yield (Figure 4.1.8) for the small pelagics and industrial species followed the same patterns as presented for SSB. Within the range of scenario F for the demersal species, yield of forage fish varied by more than 25%. Annual yield of herring increased by 150 kt (~33%), while yield of sandeel decreased by 75 kt (~15%) due to a higher demersal F.

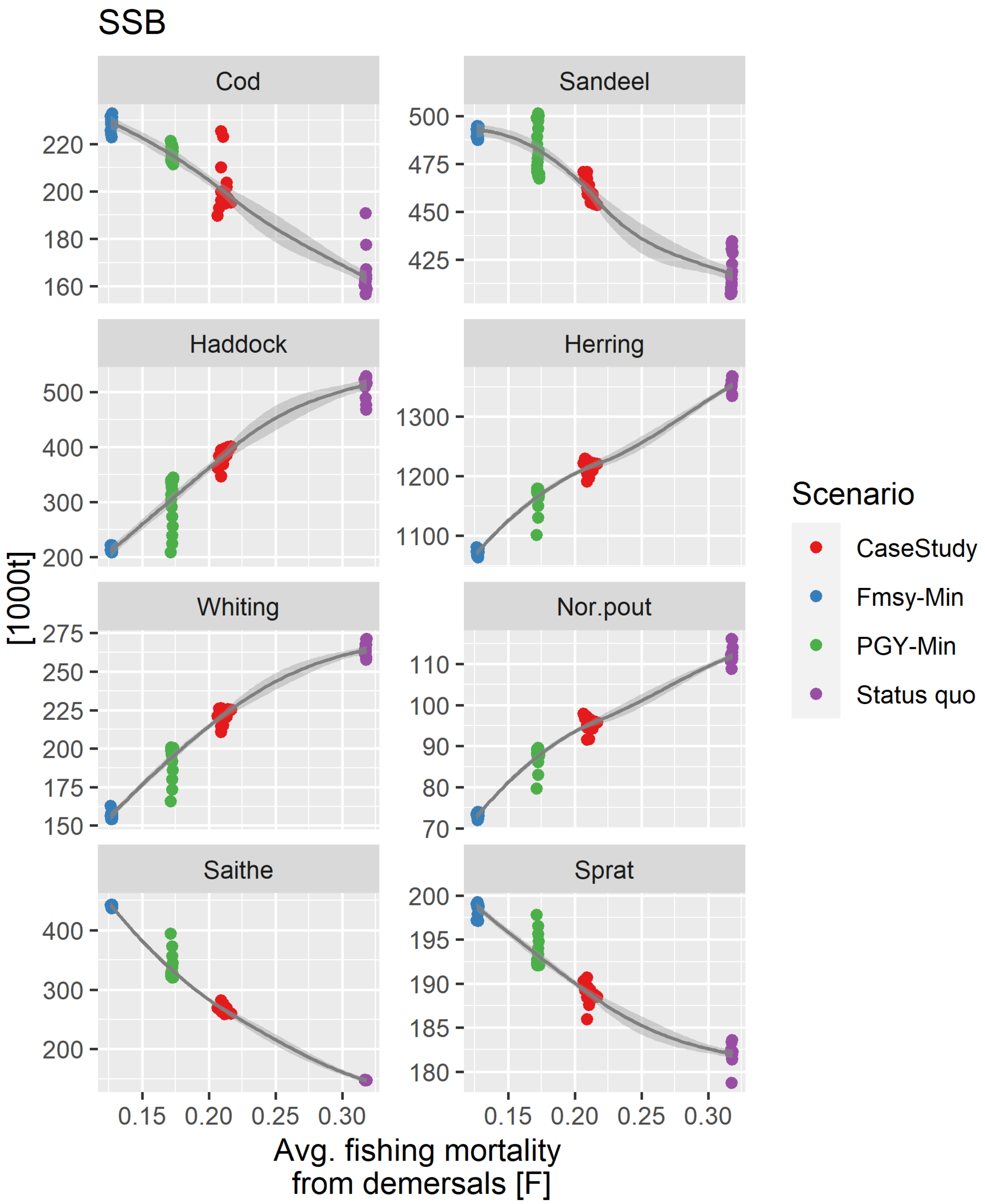


Figure 4.1.7. Spawning stock biomass in relation to average fishing mortality applied for the demersal predators cod, haddock, whiting and saithe. A loess-smoother is added for easier interpretation.

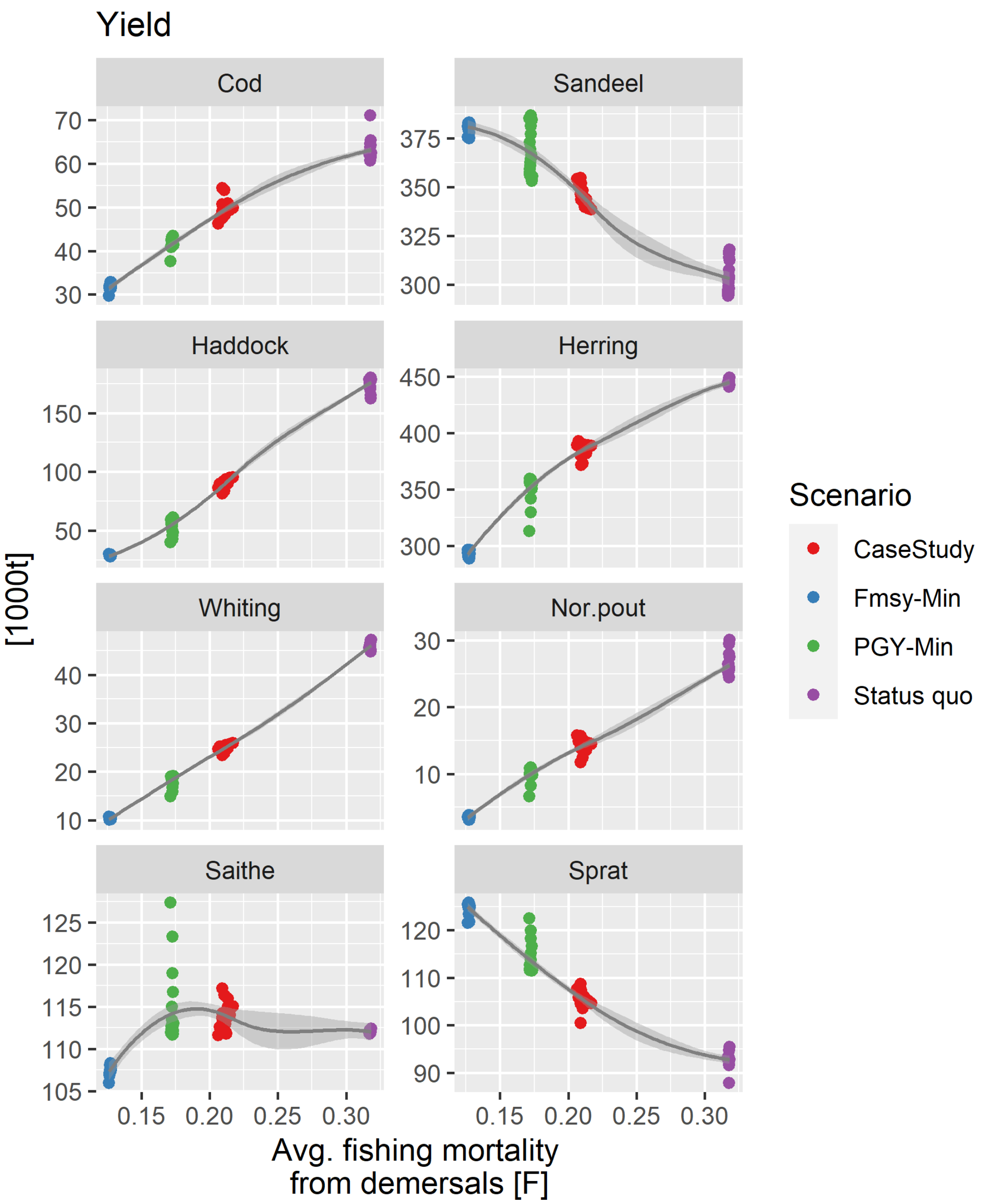


Figure 4.1.8. Yield in relation to average fising mortality applied for the demersal predators cod, haddock, whiting and saithe. A loess-smoother is added for easier interpretation.

4.2 **Western Waters**

4.2.1 FLBEIA for the Bay of Biscay (mixed demersal fisheries)

The bio-economic model FLBEIA was used to simulate dynamics in the mixed demersal fisheries of the Bay of Biscay. Details on the model, methods and more results can be found in Annex 5.

The following four scenarios were tested:

Status quo: In this scenario the effort and its distribution among metiers was kept constant in the projection and equal to the last three data years. The aim of having this scenario is twofold, on one hand is a control scenario that allows to identify problems in the conditioning of the model and on the other hand it provides a scenario against which to compare the rest of the scenarios.

Fmsy-Min: In this scenario, the fleet fully complies with the landing obligation and stop fishing when the first of the quota is consumed. There is no adaptability mechanism in the target fishing mortality (F_{MSY} for all stocks), the catchability or the effort share, therefore it could create a significant loss in fishing opportunities.

PGY-Min: The fleet dynamics are the same as in the 'min' scenario but the advice is generated with a multi-stock HCR that operationalizes the F_{MSY} fishing mortality ranges in Pretty Good Yield (PGY) scenario. The multi-stock HCR is based on the single stock advice and the maximization of fishing opportunities.

Case specific: The effort share along metiers is given as input data and is equal to the mean of the most recent data. The total effort is calculated based on the catch quotas and the previous year effort. First, the effort corresponding to each of the catch quotas is calculated and then among those efforts the one that is more similar to the previous one is selected. Thus, the fleet dynamics have some inertia to the past but being constrained by the quotas.

Main results:

For demersal species any of the scenarios resulted in biomasses above B_{lim} with high probability in the mid-to long-term (Figure 4.2.1). For Horse Mackerel, which started the simulation below B_{lim}, the probability was dependent on the scenario. The status quo scenario resulted in a probability higher than 25% to fall below B_{lim}, whereas in the case specific and the other scenarios, the probability was almost null. Therefore, only the Status quo scenario was incompatible with existing biomass limits agreed within ICES.

The Fmsy-Min and PGY-Min scenarios resulted in 100 % of the stocks fished at or below F_{MSY}, while the Status quo and case specific scenario did not reach 100 % (Figure 4.2.1). In most of the cases, the exploitation of the stocks was within the fishing mortality ranges, which ensures that the long-term yield is not lower than 95% of the maximum sustainable yield. For anglerfish, the fishing mortality in F_{MSY}-min and Status quo and for sole in the F_{MSY}-min scenario was below the lower bound of the range, which implies a loss in fishing opportunities. This indicates a trade-off coming from technical interactions in mixed fisheries when fishing fleets must stop if the first quota is exhausted (choke species problem).

The gross profit was lowest for the status quo and case specific scenario and Fmsy-Min and PGY-Min showed a better performance. Gross profit for many of the fleets was negative, which resulted in an overall negative gross profit in all scenarios (Figure 4.2.1). Some of the vessels considered in the simulation move to other areas along the year and not all the bycatch species in the Bay of Biscay were introduced which could be the main reason for having negative results. Moreover, the economic data comes from the STECF and the fleet segments used here and in the STECF data base do not fully match, which could also have an impact. For catch, as indicator of food security and wages, as a social indicator, the pattern was exactly the opposite (Status quo best and Min scenarios worst), showing a clear trade-off between indicators.

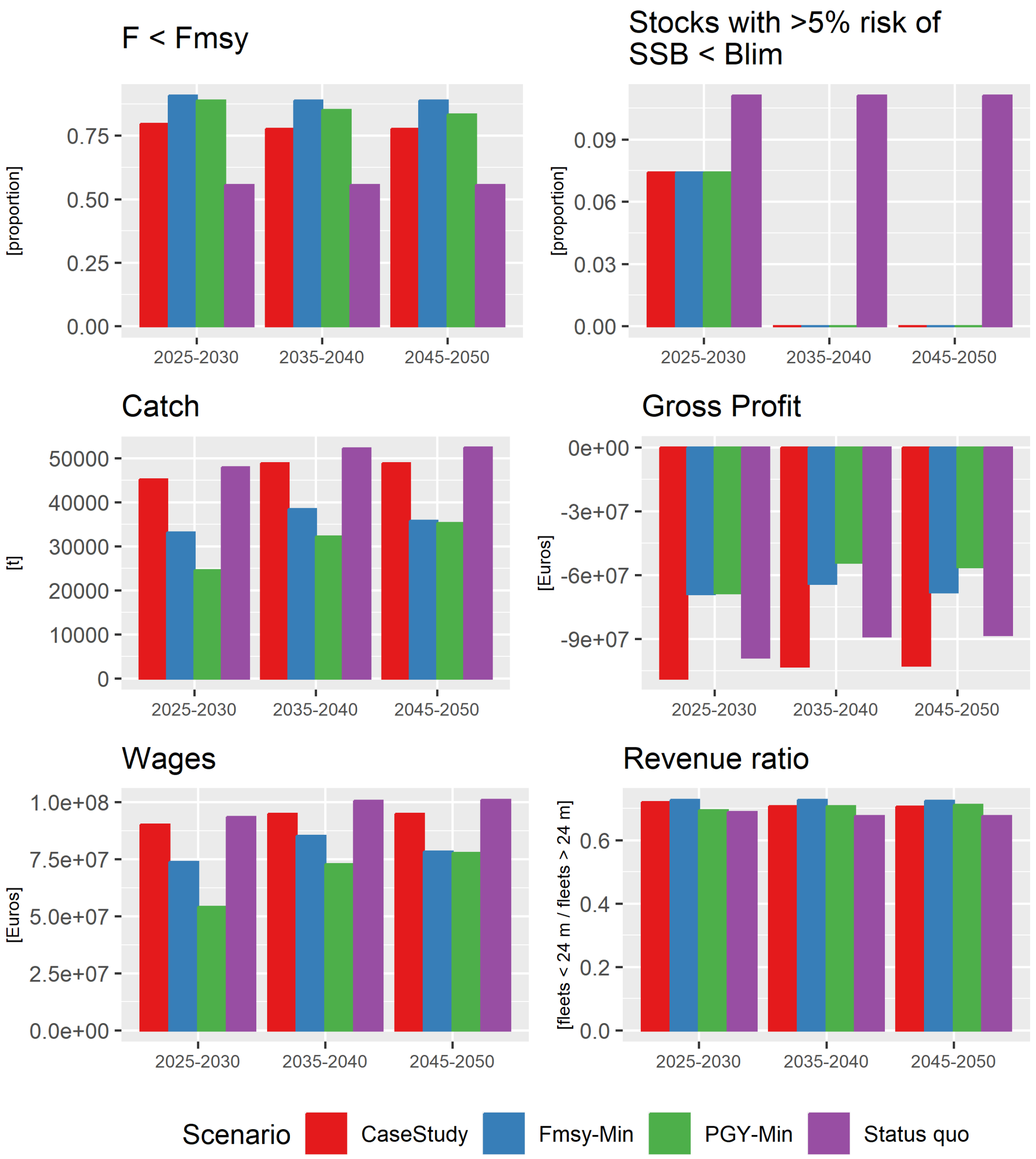


Figure 4.2.1. CFP related indicators by scenario and time-period predicted from the FLBEIA model for the demersal mixed fisheries in the Bay of Biscay

With regard to MSFD related indicators, many of the processes in the projection were linearly related with effort (Figure 4.2.2). The bycatch was assumed proportional to effort, but the bycatch rate depended on the gear and the stock, hence the trend was different for each of the stocks. The case specific and status quo scenarios on the one hand and Fmsy-Min and PGY-Min on the other showed similar trends over time. While the highest bycatch for Dolphins was observed in the Status quo scenario, for the rest of the PET species, the highest bycatch was observed in the case specific scenario. Much lower bycatch was predicted for the Fmsy-Min and PGY-Min scenarios. When comparing to bycatch thresholds discussed in literature for Balearic shearwater (Genovart et al. (2016) calculates a threshold of 101 individuals; see Annex 10), this threshold gets exceeded in all scenarios. This happens without the fisheries in the Mediterranean indicating a serious mismatch between fisheries and environmental objectives. For common dolphin different thresholds are available (985 individuals in ICES 2021 and 4927 in ICES 2020; see also Annex 10) dependent on the method to derive acceptable bycatch levels. Especially the predictions for the Status quo scenario would exceed the more restrictive threshold, while especially the FMSY-min and PGY-min scenarios would be below. However, the predictions of bycatch are highly uncertain as both the current level of bycatch is very poorly known and a simple linear relationship between effort and bycatch numbers may not be true. Therefore, these values can only be seen as indicative of the likely direction and ball park magnitude of change.

The Ryther index calculated for the demersal mixed fisheries is below one in the Fmsy-Min and PGY-Min scenarios and around one in the Status quo and case specific scenarios (Figure 4.2.3). However, when combining the estimates with the ones observed for the pelagic fisheries, the status quo and case specific scenario would be above one indicating at least slight ecosystem overfishing according to Watson and Link (2019). In addition, not all catches from the region are represented in the model.

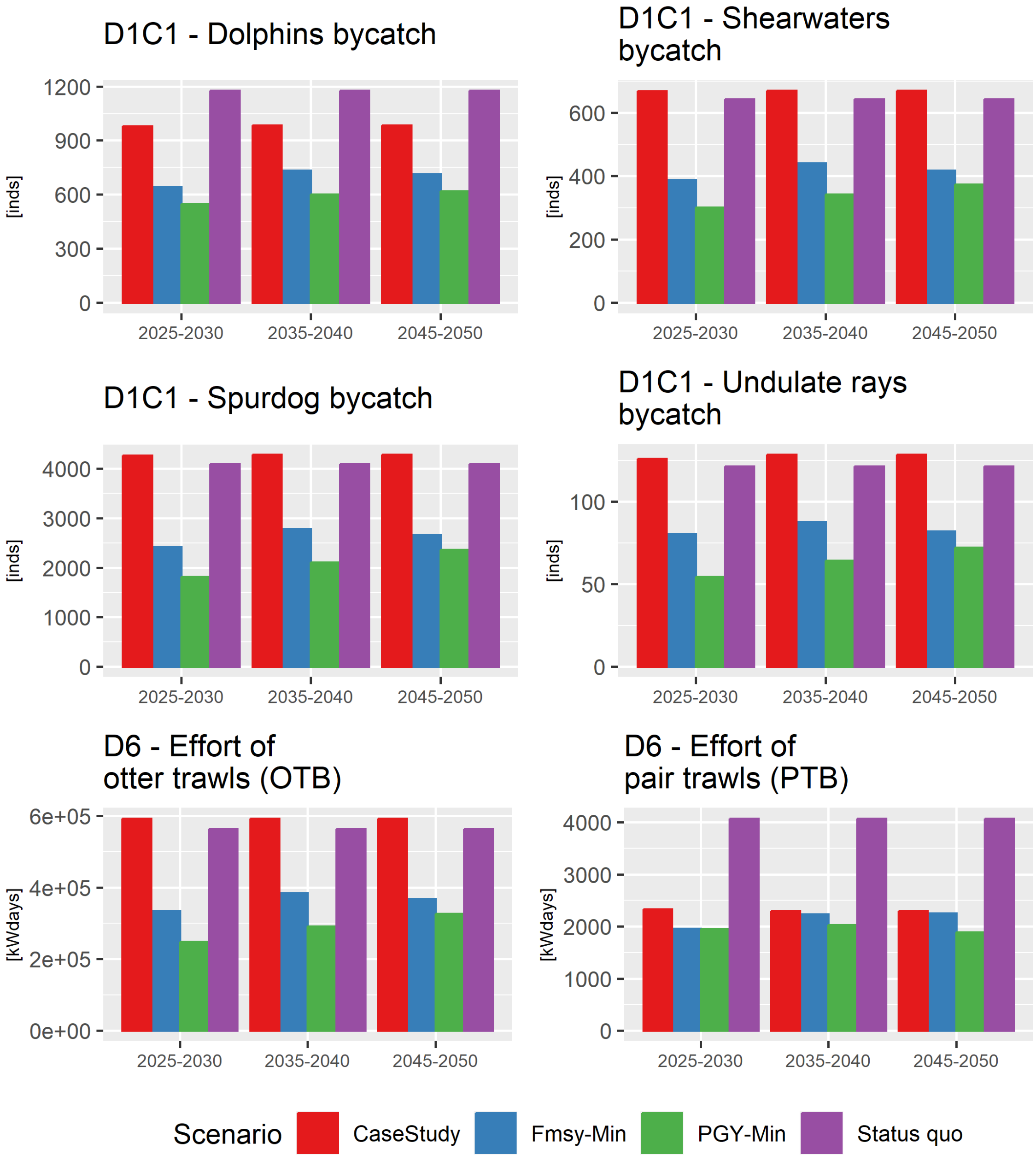


Figure 4.2.2. MSFD related indicators by scenario and time-period predicted from the FLBEIA model for the demersal mixed fisheries in the Bay of Biscay

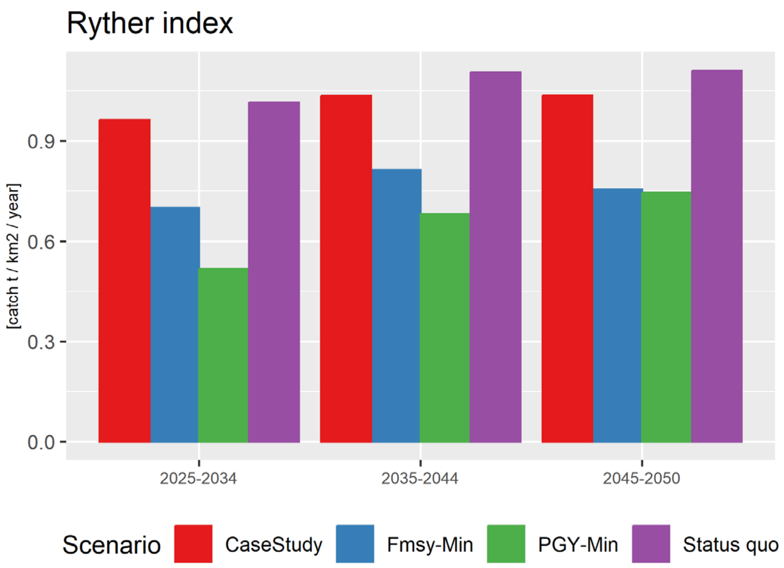


Figure 4.2.3**.** Global indicator by scenario and time-period predicted from the FLBEIA model for the demersal mixed fisheries in the Bay of Biscay

4.2.2 FLBEIA for the Bay of Biscay (pelagic).

The bio-economic model FLBEIA has been parameterised for the pelagic fleets fishing in the Bay of Biscay. For details on the model, methods and detailed results can be found in Annex 6. These fleets are characterized by catching several species along the year but at fishing operation level the catch is composed almost 100% by a single stock. The target stock depends on the season with some overlap between species in specific months.

Two scenarios were run to compare different fishing strategies. A Status quo effort where the effort is and its distribution along metiers is equal to the last three year mean and a scenario where the total effort and distribution are those that maximise the profit (“maxprof”) of the pelagic fisheries. In this case the landing obligation scenario does not make a difference because the discards in this fishery are null or very low.

The “maxprof” scenario had a positive effect on the proportion of stocks fished at or below F_{MSY} and also the number of stocks with more than 5% risk to fall below B_{lim} was lower (Figure 4.2.4). However, both scenarios exceeded existing reference points in the long-term.

The maximisation of profit led to higher gross profit (also still, negative in the long-term). This came at the cost of much lower catches and wages indicating a trade-off between the economic objectives and food security as well as social benefits (Figure 4.2.4). Small vessels benefited from the status quo effort scenarios, while the large vessels (being more effective) benefited from the profit maximisation.

The maximisation of profit led to substantially less fishing effort having a positive effect on the bycatch of dolphins (Figure 4.2.5). However, the predictions of bycatch are highly uncertain as both the current level of bycatch is very poorly known and a simple linear relationship between effort and bycatch numbers may not be true. Therefore, these values can only be seen as indicative of the likely direction and ball park magnitude of change. CO_2 emissions and the Ryther index as indicator for ecosystem overfishing were considerably lower under the “maxprof” scenario (Figure 4.2.6).

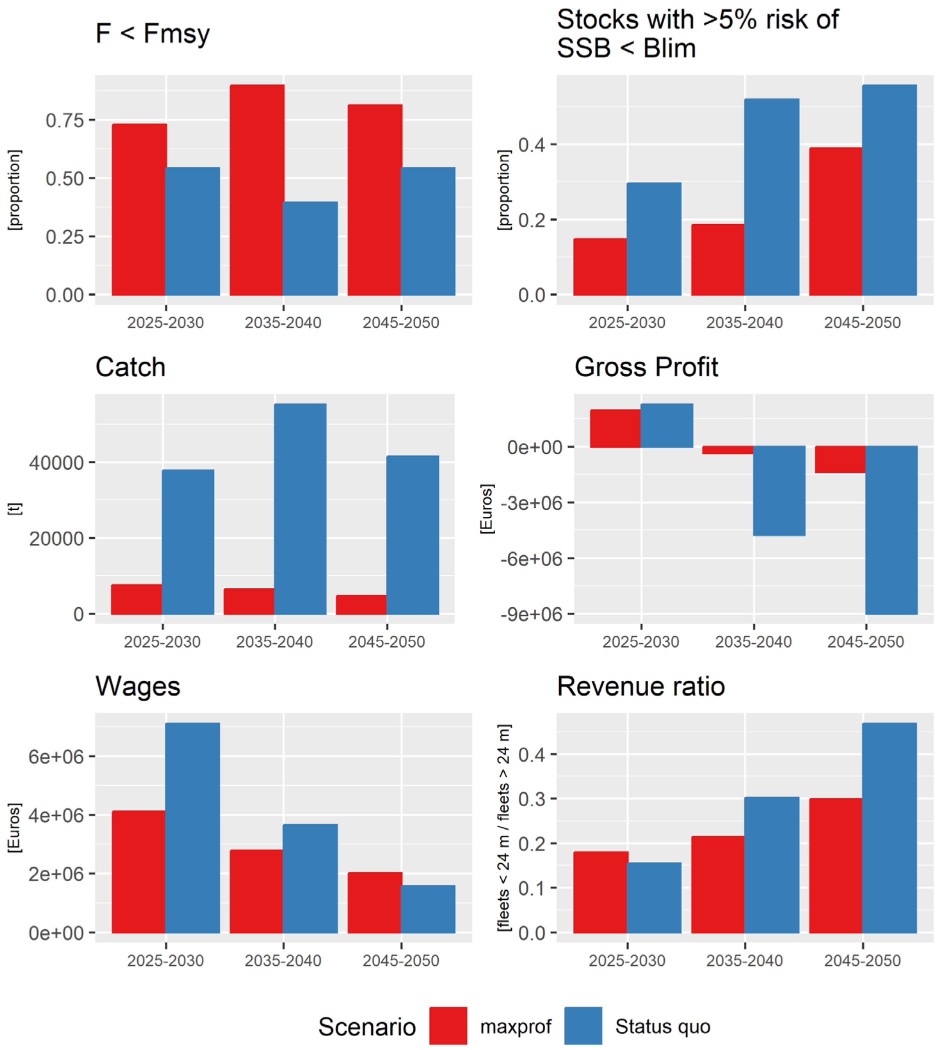


Figure 4.2.4. CFP related indicators by scenario and time-period predicted from the FLBEIA model for the pelagic fisheries in the Bay of Biscay.

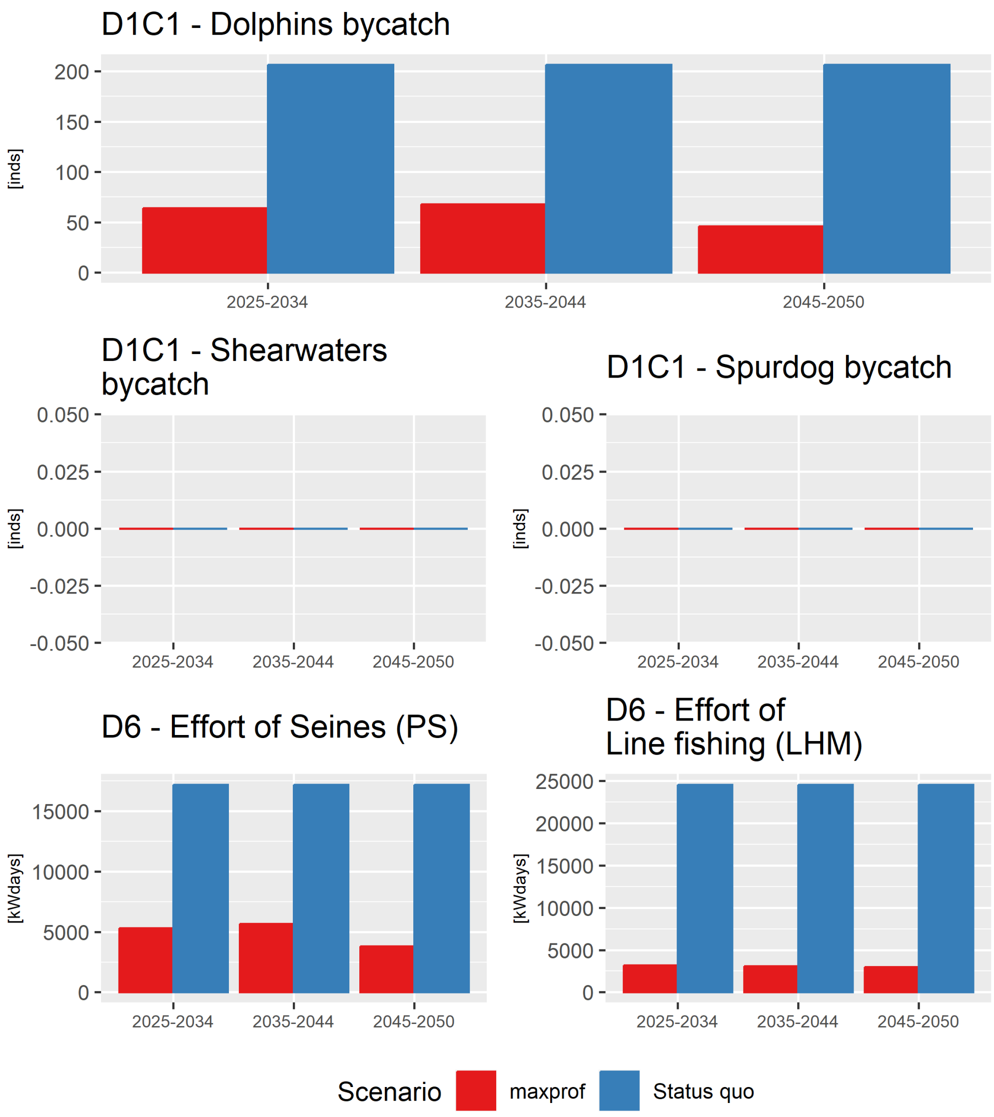
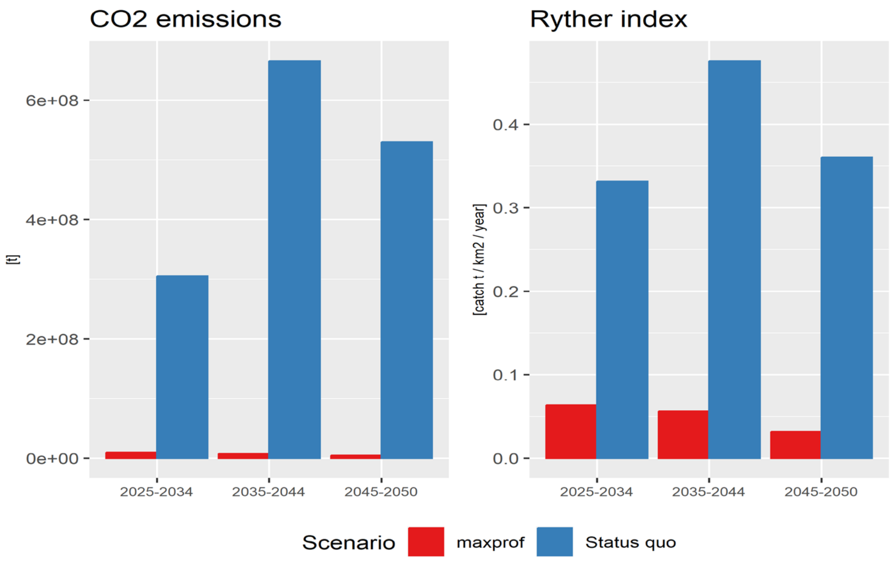


Figure 4.2.5. MSFD related indicators by scenario and time-period predicted from the FLBEIA model for the pelagic fisheries in the Bay of Biscay.



4.2.6. Global indicators by scenario and time-period predicted from the FLBEIA model for the pelagic fisheries in the Bay of Biscay fisheries.

4.2.3 StrathE2E – Celtic Sea

The end-to-end ecosystem model StrathE2E was used to analyse the impact of different levels of fishing pressure on the North Sea ecosystem. This section focuses on ecological and ecosystem wide indicators. Other aspects including e.g., catch levels and revenues and further details can be found in Annex 3.

As in the North Sea model, biomasses of fish and top predators decreased with increasing effort multiplier (Figure 4.2.7). Released from predation, the biomass of carnivorous zooplankton increased. Small cascading trophic effects were present at the phytoplankton and zooplankton levels. Migratory fish – which were sustained by a constant annual boundary immigration regardless of fishing effort as in the North Sea model – formed the major part of landings and revenue at high fishing effort multipliers. The resident planktivorous and demersal fish in the model were depleted and extirpated at the highest fishing efforts.

Bird and pinniped guilds in the baseline 2003-2013 Celtic Sea model were more severely depleted relative to an unfished state than in the equivalent North Sea baseline. All top predator guilds were extirpated by even modest increases in effort compared to the North Sea. Direct effects of fishing on the top-predators were entirely due to bycatch, there being no hunting for cetaceans in the Celtic Sea.

Net primary production decreased with fishing effort (Figure 4.2.8), as in the North Sea. Overall levels of both the Fogarty and Ryther indices were lower than in the North Sea, but still exceeded the thresholds suggested by Link and Watson (2019) as representing optimal harvesting of the ecosystem, even in the baseline 2003-2013 fishing effort scenario. Higher effort scenarios were clearly in the realm of ecosystem over-exploitation.

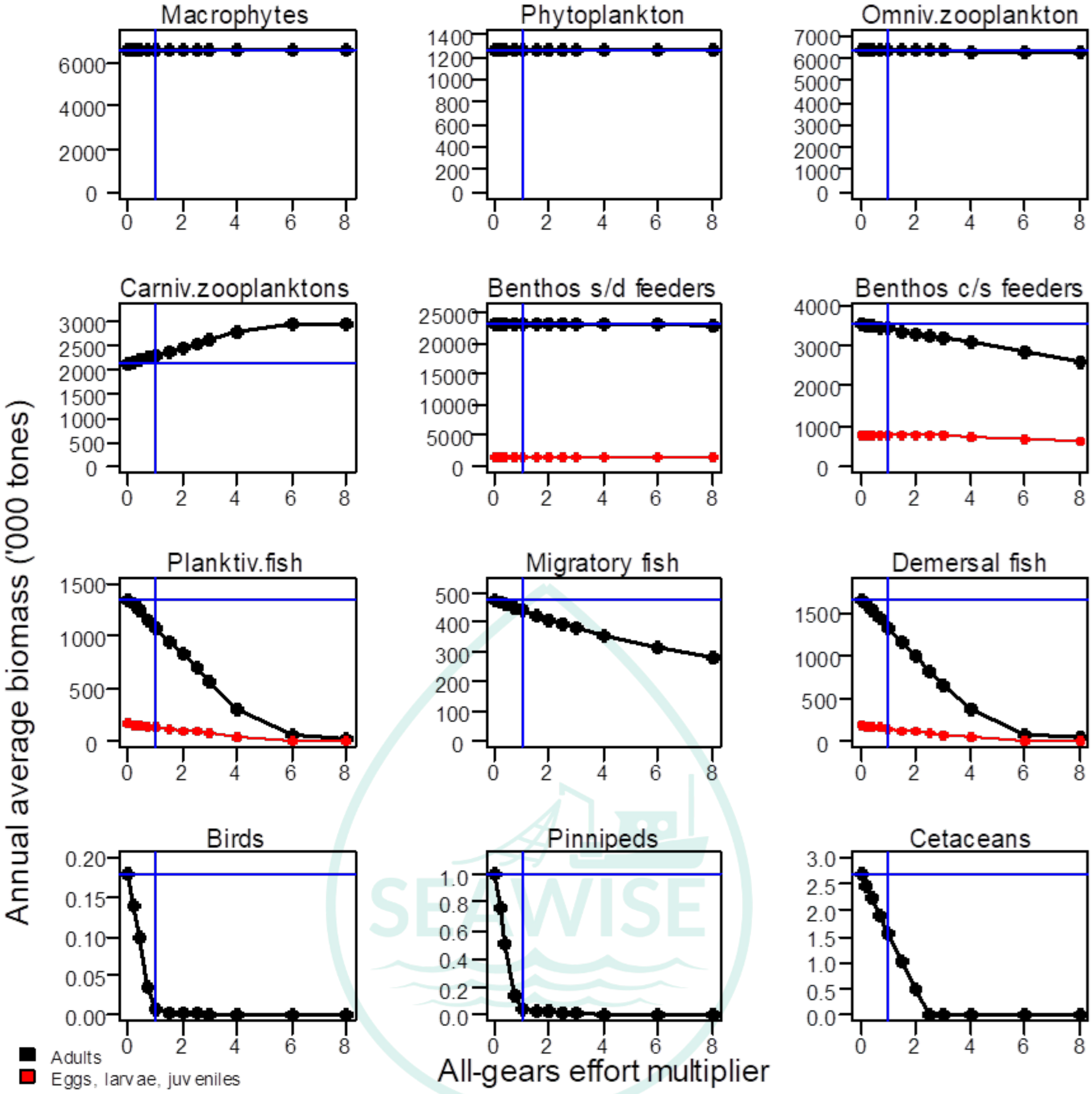


Figure 4.2.7. Steady state annual average biomasses (thousands of tonnes) for each guild in the North Sea relative to effort multiplier scenarios.

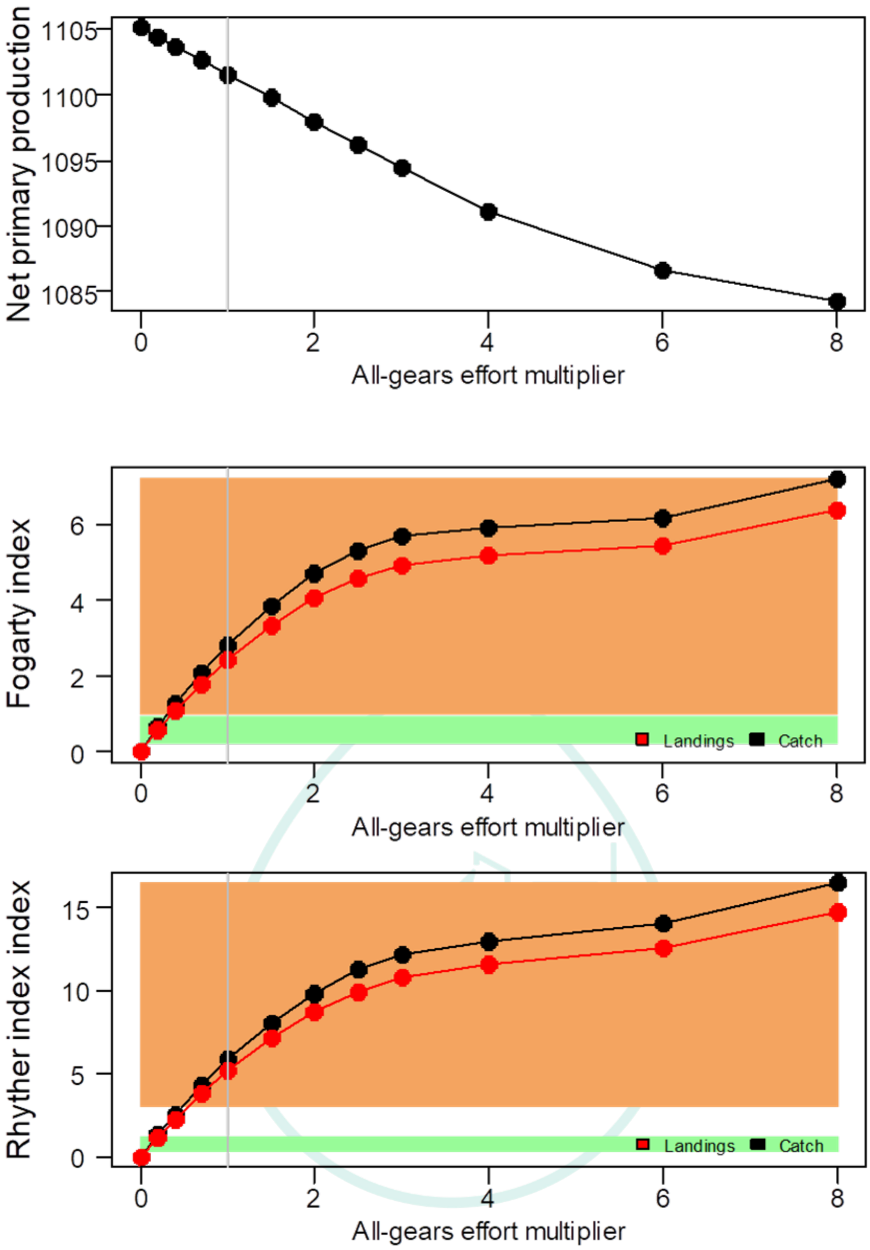


Figure 4.2.8. Upper panel: Annual net primary production (mMolesN.m^{-2}.y^{-1}) simulated by the Celtic Sea model in relation to effort multiplier scenarios. Middle panel: Fogarty index (landings or catch divided by net primary production) relative to effort multiplier scenarios. Lower panel: Ryther index (catch or landings tonnes.km^{-2}y^{-1}) relative to effort multiplier scenarios. Green shaded areas in the Fogarty index and Ryther index panels are regarded as optimal ranges (Link & Watson 2019). The orange shaded areas are regarded as representing ecosystem overfishing. Vertical grey line at effort multiplier = 1 in each panel represents the baseline 2003-2013 model.

4.3 **Baltic**

Model runs with the bio-economic model BEE-FISH were simulated for the Western Baltic (ICES Sub-divisions 22-24) and the Central Baltic (ICES Sub-divisions 25-32) separately. The simulations were carried out with partly strong differences in target fishing mortality (Status-quo, Fmsy, Fmsy-upper). A case specific “welfare” scenario was run additionally. In this case-specific scenario, the objective was to maximize the intertemporal welfare, as the sum of consumer surplus (gross consumer benefit minus expenditure) and profits (revenues minus harvesting costs). For details see Annex 7.

4.3.1 BEE-FISH western Baltic

In the Western Baltic, trade-offs between catch (i.e. food security objective), stock status in relation to existing reference points, and fishery profits became obvious (Figure 4.3.1). Depending on the focus, different management strategies would be favorable. A Status-quo management will in no case lead to the most desirable outcome and puts several stocks at risk to fall below the limit biomass B_{lim}. In addition, the proportion of stocks fished at or below F_{MSY} is only 50% under Status-quo management. Setting F_{MSY} as target (Fmsy-Min) created the highest catches without exceeding targets and limits for stock status in the mid- to long-term. The Pretty Good Yield (PGY) scenario allowing fishing in the sustainable range above F_{MSY} (i.e. up to Fmsy-upper) created highest profits without exceeding biomass limits. The inclusion of a welfare optimization scenario led to lowest gross profits among the scenarios. Further work on this objective is planned, including inserting side conditions like non-negative profits and minimum stock sizes, to refine trade-off analysis and offer management-ready alternatives. More details can be found in Annex 7.

Figure 4.3.1. CFP indicators per scenario and time period predicted by the BEE-FISH model for the Western Baltic

4.3.2 BEE-FISH central Baltic

Similar to the Western Baltic, also the Central Baltic Sea case study showed trade-offs between landings, stock status, and fishery profits (Figure 4.3.2). Landings did not directly translate to revenues, or profits. This is explained by the inclusion of a demand system in the model framework, so that prices react on harvest levels. Out of the three input-F scenarios (F_{msy}, Status Quo, Fmsy-upper (PGY)), Fmsy-upper created the highest landings, but was also most problematic in terms of exceeding biomass limits and fishing above F_{MSY}. The F_{MSY} strategy, generated higher profits at lower fishing mortality values and led to a recovery of stocks leading for all stocks to less than 5% probability to fall below B_{lim} after 2030. The Status Quo fishery scenario resulted in the worst combination of outcomes. More details can be found in Annex 7.

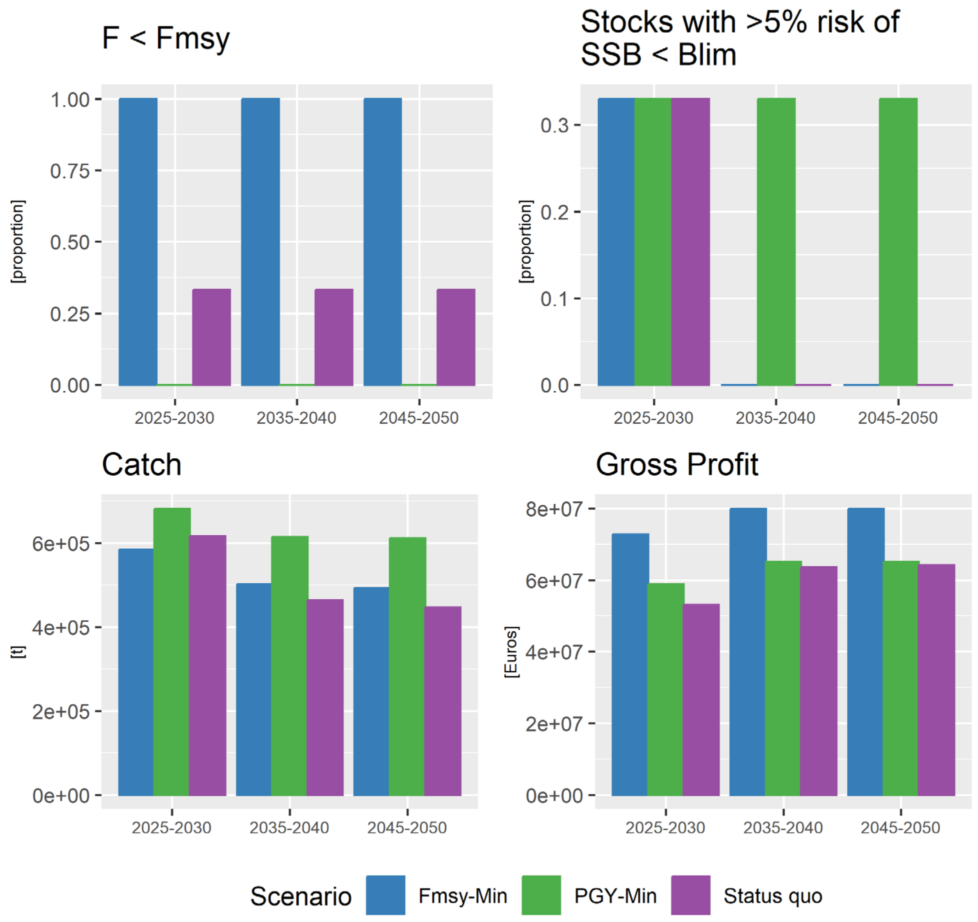


Figure 4.3.2. CFP indicators per scenario and time period predicted by the BEE-FISH model for the Central Baltic

4.4 **Mediterranean**

4.4.1 FLBEIA Eastern Ionian Sea (GFCM Geographical Sub Area 20)

The bio-economic mixed fisheries simulation model FLBEIA was run to compare scenario outcomes for different implementations of the MSY concept and associated effort management. Further details can be found in Annex 8.

From the two demersal fleet segments of the eastern Ionian fishery, only the large-scale fleet (LSF) utilizing Otter Trawls (OTB) is under a management plan (in effect since 2013). This sets MSY-based targets for the main stocks of the fishery, namely European hake (HKE), deep water rose shrimp (DPS) and mullets (MUT). The small-scale fleet (SSF) is under certain spatiotemporal regulations and technical restrictions, but is not managed, although it produces ~70% of landings and ~80% of landings value. During the scenario specification in this study, MSY sustainability targets for hake, the most overexploited stock in the fishery, could not be achieved even if the OTB gear was to be banned. Hence, scenarios were defined that apply to both fleets.

In particular, scenarios that aim to achieve F_{01} (as proxy for F_{MSY}) or F_{MSY} lower (Flw) or F_{MSY} upper (Fup) as target fishing mortality for HKE were applied. These are achieved with 47%, 26% and 63% effort reduction from both fleets, respectively. Two scenarios combining multiple species objectives were also applied. A multi-stock Pretty Good Yield scenario (PGY), which relaxes the MSY objective by defining a range of fishing mortalities per stock corresponding to 80%MSY, was also explored. In the eastern Ionian fishery, the PGY scenario for hake, shrimp and mullet was achieved by doubling the LSF effort and reducing the SSF effort by half (Figure 4.4.1) indicating a trade-off between the LSF and SSF fleets. In addition, an F_{MSY} combined scenario (Fcomb) was defined, which sets a target fishing mortality that is the average of the target fishing mortalities of the main stocks, weighted by their contribution to the catch. Finally, the Status quo scenario projected the future of the fishery under the current situation, i.e. considering the effort is fixed to its historical average value in the period 2018-2020.

Results showed a trade-off between the amount of catch and social indicators one one side and the profitability of the fleets and fishing effort applied as proxy for the strength of impacts on the ecosystem on the other. PGY is by far the most profitable scenario for the LSF in terms of catch increase, followed by Status quo and all other scenarios ranked by the effort reduction applied. This was not the case for the SSF, where differences depended on the species. Combining both fleets, PGY was the most profitable scenario (Figure 4.4.2). The better performing scenarios in terms of Gross profit were the ones applying the greatest effort reduction (e.g. Flw, followed by PGY, F01 and Fup; Figure 4.4.3), even though economic indicators were still negative across all scenarios (Figure 4.4.2). This was a result of a reduction of costs that were greater than the increase of the revenue and was an effect of including the imputed cost of unpaid labour in variable costs.

For hake, the highest catch was predicted for Flw and F01. For striped red mullet, it was the Fcomb scenario that gave the highest catch and for red mullet the Status quo scenario. Overall, the highest total catches (i.e. in terms of food security) were achieved in the status-quo scenario followed by the Fcomp scenario (Figure 4.4.2). Wages were also highest in the Fcomb and Status quo scenarios associated with overall higher fishing effort compared to other scenarios. The ratio of revenues coming from the small vessels compared to the revenues coming from larger vessels was also highest for the Fcomb scenario as no reduction of fishing effort in the SSF was predicted.

In terms of biological indicators, Flw was the scenario with the biggest SSB and total biomass for hake, deep water rose shrimp and red mullet and the lowest fishing mortality in terms of F/F_{MSY} ratio (Figure 4.4.2). The proportion of stocks fished at or below Fmsy was higher for Flw and F01 followed by Fcomb and Fup (Figure 4.4.2). In the PGY scenario, 25% of the stocks were below MSY Btrigger with their median SSB, which was due to the increase of the harvest of the shrimp stock, which was sustainably exploited in all other scenarios. None of the scenarios had a greater than 5% risk of falling below Blim (Figure 4.4.2).

Among the MSFD indicators, the highest turtle bycatch (mean annual bycatch in individuals) were estimated for the Fcomb and Status quo scenarios (Figure 4.4.3). The greater impact on the benthic community as derived by the effort of OTB gear as a proxy was greater under the PGY scenario, which was the only scenario foreseeing an increase of OTB gear effort. This indicates potential trade-offs between CFP socio-economic and MSFD indicators as e.g., wages were highest in the Fcomb scenario, catches were highest in the Status quo effort scenario and gross profit was highest in the PGY scenario.

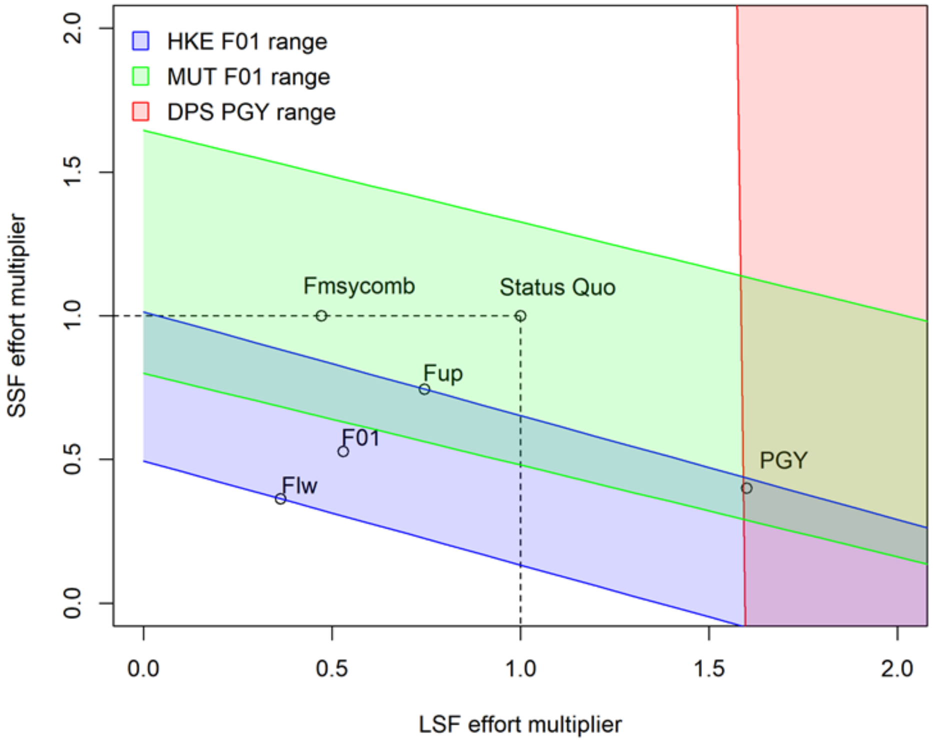


Figure 4.4.1. Effort multipliers by fleet for the six scenarios defined for the eastern Ionian Sea (GSA 20) bioeconomic projections. The coloured areas correspond to fishing mortality ranges of the three main stocks; Fup to Flw range for red mullet (MUT) and hake (HKE) and PGY (fishing mortality corresponding to 80%MSY) for deep water rose shrimp (DPS). The effort multiplier set for the PGY scenario is defined on the intersection of the three species ranges.

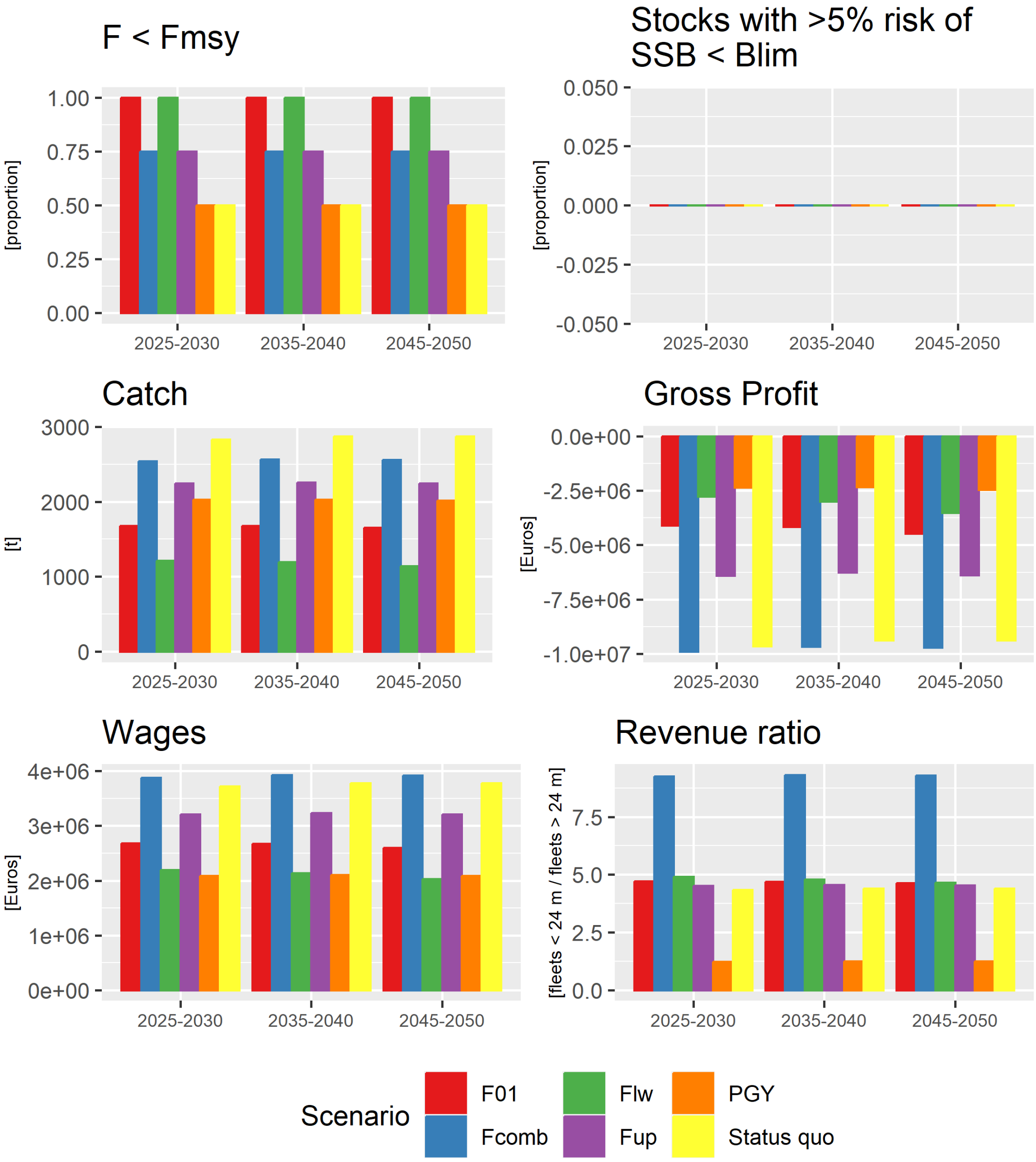


Figure 4.4.2. CFP related indicators per scenario and time period predicted by the FLBEIA model for the Eastern Ionian Sea (GSA20)

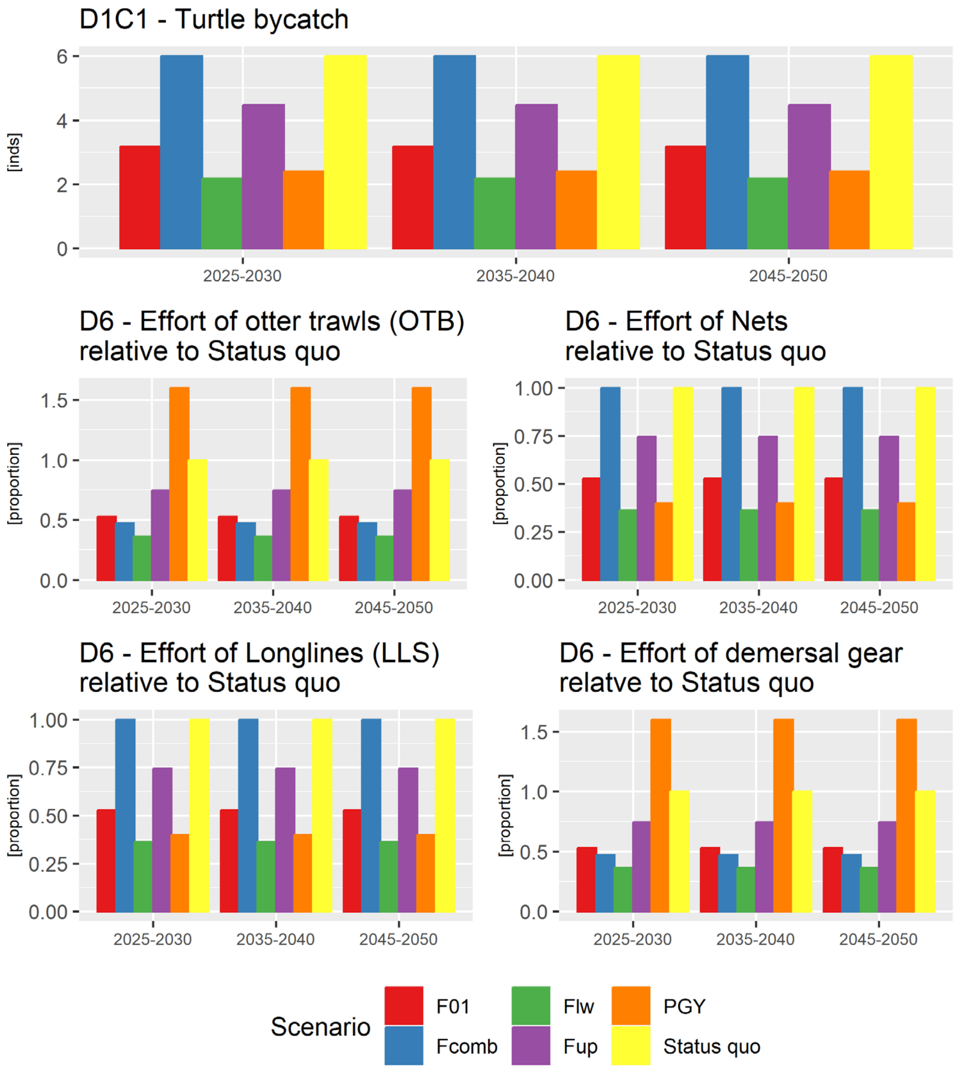


Figure 4.4.3. MSFD related indicators per scenario and time period predicted by the FLBEIA model for the Eastern Ionian Sea (GSA20).

4.4.2 BEMTOOL and Ecopath with Ecosim in the Adriatic and western Ionian Seas (GFCM Geographical Sub Areas 17-18-19)

In this case study, the bio-economic model BEMTOOL and the ecosystem model Ecopath with Ecosim (EwE) were applied consistently to estimate not only CFP but also MSFD relevant indicators. Details can be found in Annex 9.

The following scenarios were analysed:

Status quo: effort equal to fishing opportunities of 2023 for GFCM Geographical Sub Area (GSAs) 17-18, while for GSA 19 same effort as in 2021;

Fmsy_DPS: Effort reduction to achieve the $F_{0.1}$ (used as F_{MSY} proxy) of the most overexploited stock in 2026: this corresponds to an effort reduction of 69% on trawlers in GSAs 17-18-19, toward the $F_{0.1}$ of Deep Water Shrimp (DPS) in GSAs 17-18-19.

Fcomb_(PGY): Effort reduction to achieve a F_{MSY} combined (here considered as a proxy of PGY) on all the target stocks (HKE 17-18, MUT 17-18 and DPS 17-18-19): this corresponds to an effort reduction of 58% for trawlers in GSAs 17-18-19 towards a combined reference point estimated weighing the $F_{0.1}$ of the above mentioned stocks by their total catch.

BEMTOOL was used to forecast several ecological and socio-economic CFP indicators (Figure 4.4.4; more indicators can be found in Annex 9). Overall, reducing effort resulted in improvement of ecological, economic and social indicators especially in the long-term in the more restrictive scenarios FMSY_DPS and Fcomb_PGY compared to the Status quo scenario. A stronger reduction of effort (i.e. 69% in the FMSY_DPS scenario)) would not produce greater advantage to the system compared to the 58% reduction in the Fcomp_PGY scenario, as some stocks would remain underutilized, while the challenge for the economic-social systems would be very impacting in the FMSY_DPS scenario, especially for trawlers and in the short term.

Regarding the ecological indicators, the proportion of stocks fished at or below F_{MSY} is 0.2 in the Status quo scenario in all time periods of the simulation and 0.8 for the FMSY and the Fcomb-PGY scenarios in the first period of the simulation and then stabilized at 1. In the Status quo scenario the proportion of stocks with a higher than 5% probability to fall below B_{lim} was 0.2, while in other scenarios the proportion was zero. Therefore, only the status quo scenario led to problems with existing reference points for the stocks simulated in the model.

While higher catches were predicted for the Status quo scenario in the first time period (2025-2030) analysed, in the longer-term the other two scenarios outperformed the Status quo scenario with the Fcomb-PGY scenario having the highest overall catches. However, on an individual fleet level, the ranking of scenarios may be different (see Annex 9). The same overall ranking of the scenarios was occurred for gross profit. The ranking of scenarios for wages and the ratio of revenues from vessels <=24m to vessels above 24m (<=18m and >18 used in the model) was more variable, however, the Status quo scenario was always the least preferred one (Figure 4.4.4).

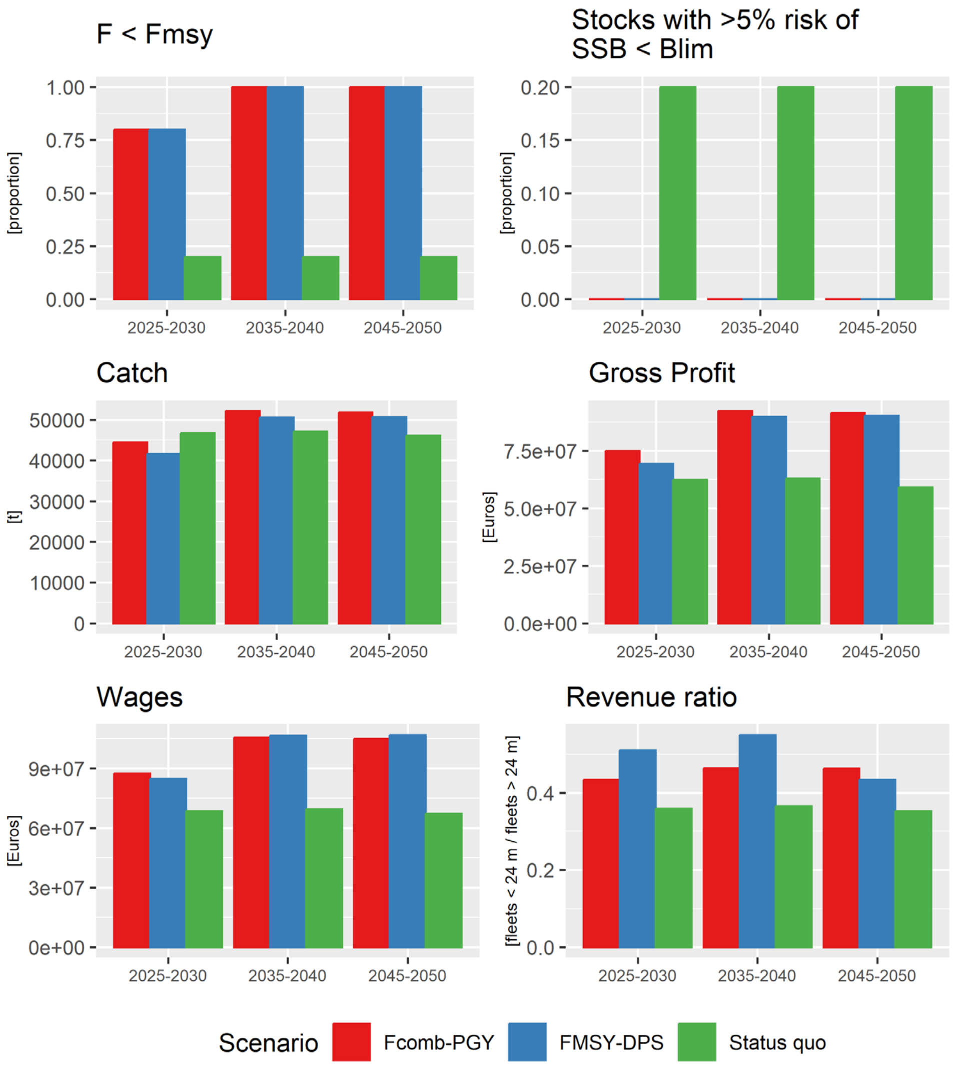


Figure 4.4.4. CFP related indicators per scenario and time period predicted by the BEMTOOL model for the Adriatic and western Ionian Seas (GFCM Geographical Sub Areas 17-18-19).

MSFD food web indicators were calculated by EwE at guild level, according to scenarios of fishing effort reduction (i.e. the same effort reductions predicted by BEMTOOL for the three scenarios) and by time periods. Overall, benefits of effort reductions occurred, but also trade-offs within the food web.

A 69% or 58% reduction of fishing effort produced positive effects on piscivores in terms of biodiversity, when compared to Status quo scenario (Figure 4.4.5); the biodiversity of benthivorous fish showed an initial increase with lower fishing pressure, and then it was quite stable (see Table 8.7 in Annex 9). Conversely, biodiversity of planktivorous and that of top predators was very similar across fishing scenarios.

The biomass of both piscivorous and benthivorous fish increased under reduced fishing effort, reflecting the reduction of mortality on these groups when bottom trawling was reduced (Figure 4.4.6). The biomass of planktivorous fish declined in the model, plausibly because of the increasing predation from the piscivorous fish. Similarly, the biomass of top predators declined, possibly as a result of competition from piscivorous fish. The biomass increased faster than the biodiversity index (see Annex 9), and it also increased for benthivorous, in contrast to the biodiversity index. This confirms that biomass did not capture all information: plausibly, in the benthivorous fish the biomass increased only for few groups which dominate the guild, leading to a lower biodiversity. The change in biomass, however, were only substantial for the piscivorous fish: for all other groups the differences between scenarios were too small to be distinguished visually in plots and only discernible when looking at Table 8.8 of Annex 9.

For the Maximum Mean Length (MML) indicator, the effect of the effort scenarios across trophic guilds was clearly visible (Figure 4.2.5): the reduction of effort led to a higher MML which stabilized around a value above 40 cm (often used as potential threshold associated with large fish indicators) in both effort reduction scenarios. Conversely, the status quo scenario showed a stabilization below 40 cm. When considering the individual guilds (see Table 8.9 in Annex 9), the most important change observed with a large increase in MML under effort reduction took place for the piscivorous fish, with benthivorous and planktivorous showing minor changes. The small reduction of MML in benthivorous fish is attributed again to the predation of piscivorous fish. The change in piscivorous fish is attributed to a rapid growth in the average size of this group, possibly a result of the avoided decline of specific groups (e.g. piscivorous demersal slope fish).

Figure 4.4.5. Diversity of piscivorous fish (left) and mean maximum length (MML) across guilds under three effort scenarios.

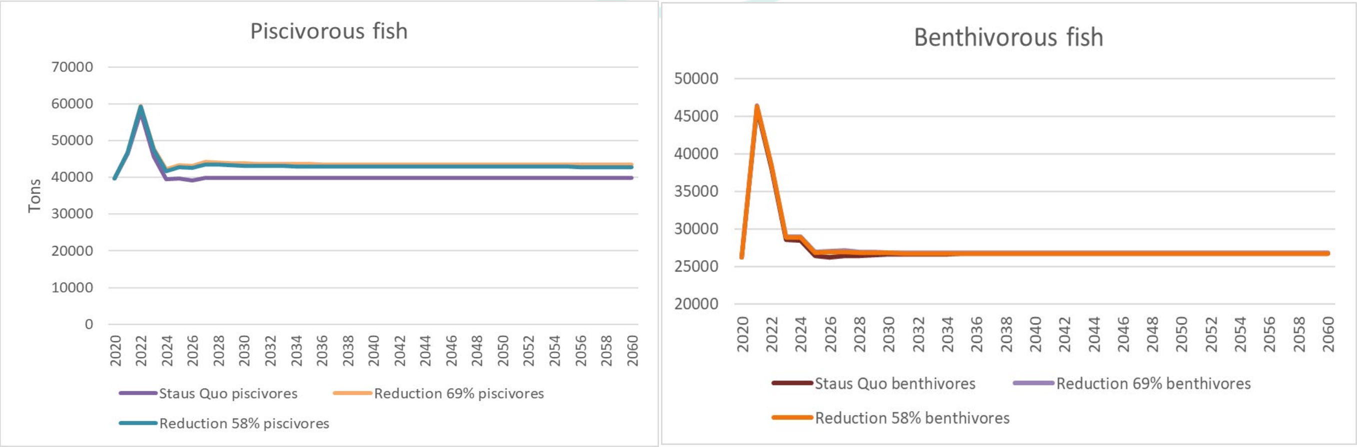


Figure 4.4.6. *Biomass in tons of piscivorous (left) and benthivorous (right) fish under the three effort reduction scenarios.*

5. Conclusions

A wide range of model types (from bio-economic to full ecosystem models) has been applied to various case studies across the North East Atlantic and Mediterranean to test the consistency of different types of indicators relevant to the CFP and MSFD and to identify main trade-offs.

Model predictions are by nature uncertain and can also be biased to some extent because of structural uncertainties and assumptions behind modelling approaches and data availability and details on sources of uncertainty and model assumptions can be found in the Annexes. Thus, the results should be interpreted in the context of the models used and assumptions made. Additionally, it should be kept in mind that these baseline runs are simplified scenarios not considering effects of climate change or future fuel and fish price developments that will likely change yield and profits of fishermen as well as ecosystem impacts. In some cases important limitations have been identified that will be improved in future model implementations. Moreover, some of the reference points used were estimated from other models than those applied in SEAwise and they might not be consistent with the implemented operating models. Uncertainties in the modelling approaches were mainly restricted to uncertainties from the biological system (i.e. from the stock recruitment relationships). Additional sources of uncertainties (e.g. catchability, fleet dynamics or implementation error) in full MSE loops may increase the chance to fall below B_{lim} for some of the stocks investigated. In spite of these uncertainties, this modelling study provides important information on trade-offs that have to be expected under ecosystem-based fisheries management (EBFM) when bringing in additional targets and limits in a more ecosystem context when moving forward from the current single stock MSY approach for commercially important fish stocks.

The scenarios investigated the current range of management strategies applied in terms of fishing opportunities aligned with the maximum sustainable yield concept (i.e. strict MSY approach vs. Pretty Good Yield (PGY) approach allowing sustainable deviations from e.g., single species FMSY point estimates). The landing obligation as further important corner stone of current fisheries management was also simulated in the context of mixed demersal fisheries in the North East Atlantic. Across case studies the following main conclusions can be drawn:

- The current fishing effort (without further management via e.g., TACs and the landing obligation) were the least sustainable option in nearly all cases studies (apart from the Eastern Baltic Sea), leading to increased risk of stocks falling below B_{lim}. Although the degree of fishing effort adaptions needed is highly case specific, this indicates that further reductions in fishing effort are likely to be beneficial to ensure a sustainable exploitation of all stocks.

- Scenarios applying a strict MSY approach (i.e. F_{MSY} point estimates as upper limit) in combination with the landing obligation (FMSY-min scenarios) led in most case studies to the lowest fishing effort applied. This had positive effects on MSFD related indicators (e.g., bycatch of PET species, benthic impact, Large fish indicator) as well as global indicators as CO2-emission or ecosystem indicators like the Ryther or Fogarty indices suggested by Watson and Link (2019). However, this scenario often led to much lower catches (compared to e.g., Status quo) due to strong choke effects because fleets had to stop fishing when their first quota was exhausted. This reduced food security, but also employment and wages as social indicators. In terms of economic performance, the gains and loses were highly case specific, but often scenarios applying the Pretty Good Yield concept and allowing sustainable deviations from the F_{MSY} point estimate when stocks were in a healthy state outperformed the scenarios with the F_{MSY} point estimate as strict limit in terms of gross profit (e.g., Mediterranean case studies, western Baltic Sea, Bay of Biscay and North Sea).

- The scenarios applying a more flexible interpretation of the MSY concept (PGY or average MSY across stocks in the Mediterranean) may constitute a compromise as they also led to reduced fishing effort compared to the status quo effort in all scenarios, but relaxed choke situations in mixed demersal fisheries to some extent leading to higher gross profits and in some case studies also to higher catch. Whether the associated effort levels lead to conflicts with MSFD objectives should be analysed when internationally agreed thresholds become available for e.g., bycatch of PET species or benthic impact.

- Bycatch thresholds currently discussed were tested e.g., for the North Sea and Bay of Biscay case studies. For the North Sea conflicts with bycatch limits were estimated to be unlikely although bycatch rates were highly uncertain (e.g., bycatch of harbour porpoise would more than double if an outlier is used in the calculations, see ICES 2021). In the Bay of Biscay all scenarios exceeded the threshold discussed for Balearic shearwater indicating at least a potential mismatch between fisheries and environmental objectives. For dolphins, the sustainability of bycatch levels was unclear, because different methods lead to very different acceptable bycatch thresholds. However, these predictions of bycatch are highly uncertain as both the current level of bycatch is very poorly known and a simple linear relationship between effort and bycatch numbers may not be realistic. Therefore, the conclusions can only be seen as indicative of the likely direction and ball-park magnitude of change. Overall, this highlights that further work is required to come to certain conclusions regarding actual bycatch in absolute numbers and acceptable bycatch limits for PETs. The comparison between scenarios in relative terms, instead of absolute values, is probably more accurate.

- All models assumed current selectivities and catchabilities to be sustained in the future. However, fishers can to some extent to regulate the catchabilities to mitigate choking effects. Further, trade-offs coming from choke species problems or e.g, bycatches of PET species may be resolved by improving selectivities via technical measures (e.g., closed areas or innovative gears). Adaptability of fishers and alternative selectivities will be tested in deliverable 6.8 in month 36.

- The majority of case studies exceeded the suggested thresholds for the Fogarty/Ryther indices even under their scenarios with highest effort reduction, indicating ecosystem overfishing. This can be explained to some extent by the fact that these indices are mainly driven by pelagic and industrial fisheries not always part of the models (e.g., FLBEIA for the North Sea). The values for these indicators are also highly model dependent indicating substantial structural uncertainties and may not be fully comparable across ecosystems.

- Especially in case studies where small-scale fisheries (SSF) play an important role (e.g., Eastern Ionian Sea, pelagic fisheries in the Bay of Biscay) different scenarios led to additional trade-offs as seen in different ratios between revenues from SSF and large-scale fisheries. This adds another level of complexity to be considered in fisheries management.

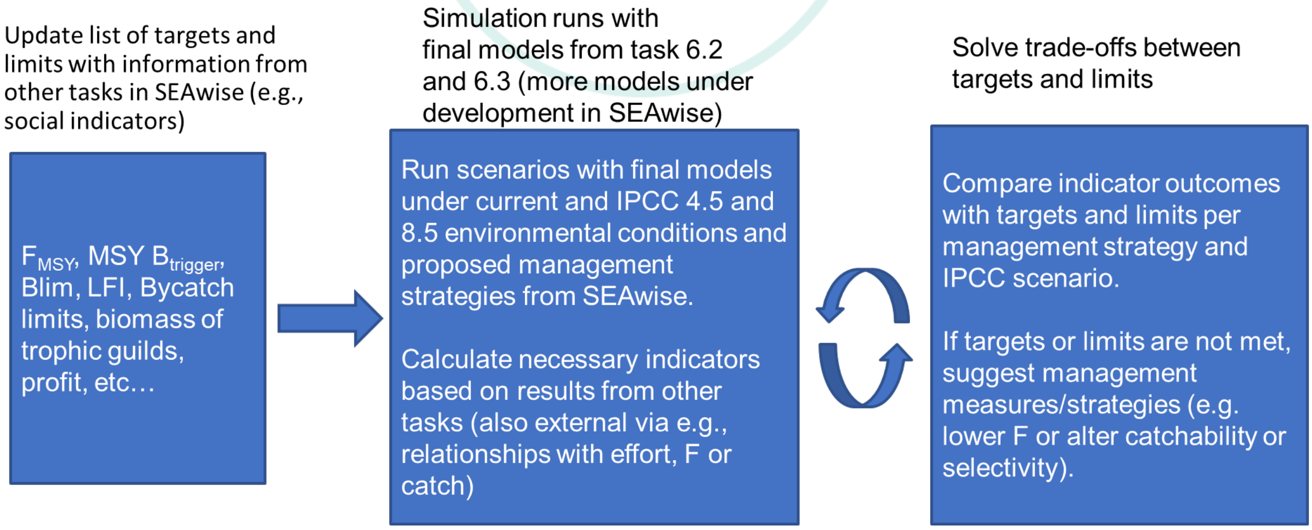
- Food web interactions can also lead to trade-offs between species and yield that can be taken from them (e.g., Demersal piscivorous predators vs. small pelagic fish; Osmose in the English Channel, SMS for the North Sea, StrathE2E for the North Sea and Celtic Sea). With improved models from task 6.2 this topic will be further investigated in month 36.

6. Further work

Deliverable 6.7 sets the baseline for further work in SEAwise on indicators, targets and limits. Additional social indicators will be derived from work in SEAwise WP2. The MSFD related indicators will be also re-evaluated for the final deliverable 6.8 in month 36 based on final results and improved models from SEAwise WP4 tasks. For example, Swept Area Ratio (SAR) maps delivered by Task 5.3 in month 18 will be used to distribute effort by fleets and metiers into space. SAR will be scaled according to the predicted effort from the model scenarios in task 6.4. Finally, based on SAR by c-square, the Relative Benthic Status (RBS) used in task 4.3 can be calculated for each scenario and compared to thresholds that have to be agreed soon according to the EU Action Plan 2023. More internationally agreed bycatch limits will likely become available for PET species according to this plan. The update of the indicator list and knowledge becoming available from further work in SEAwise will allow for an improved assessment of scenario outcomes in month 36. The resulting impact of scenarios with shifts in fishing effort due to spatial management options will be evaluated using information on changes in catchabilities and selectivities coming from SEAwise WP 5 and the impact on indicators will be evaluated.

Deliverable 6.8 in month 36 will enhance results from deliverable 6.7 by incorporating climate change effects via improved task 6.2 models for the simulation of stock dynamics (Figure 6.1). Although the general approach remains similar to the one of deliverable 6.7, the aim in month 36 will be to test harvest control rules developed within SEAwise that help to harmonize goals mentioned in the CFP and MSFD. The analyses will make targets and limits consistent with each other where this is possible, and highlight trade-offs where this is not the case. Models will also be improved in their socio-economic parts via SEAwise task 6.3 and e.g., scenarios of price developments will be investigated together with climate change impacts.

Next to this, additional models will become available to complete the matrix of models available and indicators that can be calculated within each case study region. SEAwise PIs are working for example on: a model for the Gulf of Riga herring, a FLBEIA bio-economic model for the Celtic Sea, an Isis-Fish model for the Bay of Biscay and an OSMOSE model in the North Sea. The OSMOSE model in the North Sea it is a spatially explicit (1/9 ICES Statistical Rectangle), individual-based ecosystem model that simulates the interactions between individuals via food web dynamic processes (predation and resource competition). A novel fleet model will be developed to represent the dynamic and strategic choices fishers make, as well as their socioeconomic priorities with respect to fishing in the North Sea. Also the construction of an Ecopath with Ecosim (EwE) ecosystem model is currently in progress for the Celtic Sea area, i.e. ICES subdivisions 7e, 7f, 7g, 7h and 7j2. The ecosystem is represented in 53 functional groups (either multi-species or single-species groups). 40 out of 53 functional groups will be targeted by fisheries which are represented by 44 fishing fleets. The effects of environment will be also modelled through temperature time series (sea surface and bottom temperature) coupled with species response functions to temperature variations. These two models will possibly allow an explicit evaluation of some MSFD indicators that cannot be directly evaluated using mixed-fisheries models. Furthermore, OSMOSE will provide means for testing spatial management measures.



Update list of targets and limits with information from other tasks in SEAwise (e.g., social indicators)

F_{MSY}, MSY $B_{trigger}$, Blim, LFI, Bycatch limits, biomass of trophic guilds, profit, etc…

Simulation runs with final models from task 6.2 and 6.3 (more models under development in SEAwise)

Run scenarios with final models under current and IPCC 4.5 and 8.5 environmental conditions and proposed management strategies from SEAwise.

Calculate necessary indicators based on results from other tasks (also external via e.g., relationships with effort, F or catch)

Solve trade-offs between targets and limits

Compare indicator outcomes with targets and limits per management strategy and IPCC scenario.

If targets or limits are not met, suggest management measures/strategies (e.g. lower F or alter catchability or selectivity).

Figure 6.1. Schematic workflow for deliverable 6.8 in month 36.

7. References

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8. Appendix

8.1 Annex 1: Description of analyses carried out with the FLBEIA model for the North Sea.

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1. Description of the FLBEIA model of the North Sea mixed demersal fishery

The mixed fisheries model of the North Sea is defined using the procedure of WGMIXFISH-Advice (ICES, 2021, 2022). The modelling framework is FLBEIA (Garcia *et al.*, 2017), and includes 42 fleets (137 total métiers) and 20 stocks for the North Sea mixed fisheries. Stock dynamics are either age-based (COD-NS, HAD, PLE-EC, PLE-NS, POK, SOL-NS, SOL-EC, TUR, WHG-NS, WIT), 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 listed in Table 1.

Table 1: Stocks included in the North Sea mixed fishery model, Scientific name – binominal nomenclature showing genus and species, stock code – ICES stock code, FAO – species code used by the FAO, ICES data category – determines the type of data and assessment available for the stock (1 – data rich with quantitative assessment, 2 – qualitative assessment, 3 – stocks, for which survey-based indices and assessment are available, 4 – stocks, for which only commercial catch data is available, 5 – data poor stocks, where only landings data are available, 6 – neglectable stocks caught primarily as bycatch), Model abreviation – the stock code used in the model)

Scientific name	Stock code	FAO	Common name	ICES data category	Model abbreviation
Gadus morhua	cod.27.47d20	COD	cod	1	COD-NS
Melanogrammus aeglefinus	had.27.46a20	HAD	haddock	1	HAD
Pollachius virens	pok.27.3a46	POK	saithe	1	POK
Solea solea	sol.27.4 sol.27.7d	SOL	sole	1	SOL-NS SOL-EC
Pleuronectes platessa	ple.27.420, ple.27.7d	PLE	plaice	1	PLE-NS PLE-EC
Merlangius merlangus	whg.27.47d	WHG	whiting	1	WHG-NS
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	NEP5 NEP6 NEP7 NEP8 NEP9 NEP10 NEP32 NEP33 NEP34 NEPOTH-NS
Scophthalmus maximus	tur.27.4	TUR	turbot	1	TUR
Glyptocephalus cynoglossus	wit.27.3a47d	WIT	witch flounder	1	WIT

The model is conditioned with historical data up to 2021, and forecasts future conditions thereafter. Stock dynamics are based on the assessments conducted in 2022. Fleets and métiers are parameterized based on the work conducted during WGMIXFISH for this model, which is specifically valuable in defining fleets as it contains additional information on vessel length - an important attribute of the fishery segments in terms of their economic characteristics. Fleets are defined based on their country of origin (Belgium – BE, Denmark – DK, England – EN, France – FR, Germany – GE, Netherlands – NL, Norway – NO, Scotland – SC, Sweden- SW, Other – OTH), main gear employed (e.g. Static, Pelagic, Danish seine, Otter trawl, Beam trawl), and vessel length (<10 m, 10-24 m, 24–40m 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 these catchabilities, catches are predicted under changing effort and stock sizes.

2. Description of model parameterisation

The North Sea FLBEIA model includes assumptions about future catchability, effort, capacity and quota shares. Future catchabilities were based on historic data and kept constant as last year values for the simulations. The effort model mainly determines how fleets derive to their catch, by simulating the tactical behaviour of the fleets in each time step related to the stock abundance, management restrictions and effort-shares among metiers. The effort per fleet and effort share among its métiers determined at each time step is based on the FLBEIA-internal 'simple mixed fisheries behaviour' (SMFB), taking a fixed effort share per métier as input and calculating realised effort based on stock abundance and management restrictions ('min' fleet control for landing obligation scenarios, 'fixed' for status-quo effort). A detailed description of this model can be found in the Technical manual for FLBEIA (García *et al.*, 2017).

Briefly, the effort of each fleet is restricted by the quotas for a list of restrictive stocks (COD-NS, HAD, POK, WHG-NS, PLE-NS, PLE-EC, SOL-NS, SOL-EC, TUR, WIT). The effort to catch the given quota for a stock is calculated via the Cobb-Douglas production function, dependent if the stock is age-based or biomass-based. The fleet control determines how an overall effort for a fleet is calculated, given the individual efforts for each of its stocks caught. In the scenario with a landing obligation, a "min" fleet control was used, that limits the effort to the minimum among possible efforts and to stay below/equal to the capacity for this fleet. Subsequently the catch is calculated with the derived effort level and compared to the quotas for each of the stocks. This process is reiterated until the derived effort level matches the quota restrictions as close as possible. Any deviations between actual catch and quota for a given season is proportionally added/removed to the shares of remaining seasons under the constraint that the annual quota shares remain the same (not relevant for our model, since we do only consider annual quotas).

As capital model, we assumed 'fixed capital' where future capacity is unchanged during the simulation. Quota shares among countries down to métier in the model is set to the average catches of the last three historical data years, reflecting a situation where quota swapping already has taken place as this was not explicitly modelled in the North Sea FLBEIA model.

The cost model does not affect fleet behaviour, but simply upscales/downscales variable costs based on the costs per unit of effort, crew share per unit of landings and capital costs per unit of capital. Fixed costs are taken directly from the input data. Similary we assumed a constant price model, assuming constant price development based on the input from WGMIXFISH.

Economic variables for fleets and métiers were defined using data available from the Scientific, Technical and Economic Committee for Fisheries (STECF) from the recent Annual Economic Report (AER) (STECF 22-06) (STECF, 2022). This data release includes economic information (e.g. costs, revenue) for different fishing segments over the period of 2008-2020. We used average values from the last 3 data years (2018-2020) to condition economic parameters in the FLBEIA model for the most recent data year (2021). Due to the differences in the level of fleet segmentation between the STECF data and the FLBEIA model (ICES WGMIXFISH fleet definition), fleets could only be matched to the lowest level possible, not considering further métier segmentation regarding gear, mesh size and finer spatial scale operations within the North Sea, as the data only specifies aggregated information over the larger FAO Area 27. Also, as landing (monetary) values were only reported as aggregate, the STECF data might contain species not considered in our model. To overcome this mismatch, the FLBEIA model was conditioned with the relative costs to revenue ratio to match the level of profitability reported for fleet segments in the STECF data. With this concession, the final results of the economic outcomes may be more appropriately interpreted in relative terms between scenarios rather than absolute terms. To split the related costs in the FLBEIA model into fixed costs, variable costs and crew share the following STECF data categories were used:

Fixed costs – Calculated as the sum of "Consumption of fixed capital" and "Other non-variable costs". "Consumption of fixed capital" was referred to as "Annual depreciation costs" in previous versions of the STECF data. These costs are defined at the fleet level in the FLBEIA model, and are constant over time (i.e. we do not assume any changes in the fleet size).

Variable costs – Calculated as the sum of "Fuel costs", "Value of unpaid labour", "Repair and maintenance costs" and "Other variable costs". These costs are defined at the métier level in the FLBEIA model, and are a function of changes in fleet effort over time multiplied by the effort share of a given métier. Fuel costs are of particular interest in the future scenarios and were examined for their consistency to particular fishing operations. A large degree of variability is observed, which is seen to be in part determined by the type of fishing operation, e.g. use of active vs. passive gears. Further variability is likely due to vessel size, and thus efficiency.

Crew share costs – A large part of salaries paid to fishers is in the form of a proportion of the landings value. These rates are not provided within the STECF data, but were assumed to make up the bulk of the "Personnel costs" category, which is technically defined as the "*Total remuneration, in cash or in kind, payable by an employer to an employee (regular and temporary employees as well as home-workers)*". Thus, the crew share was calculated as the ratio of *Personnel costs / landings value,* which was quite stable over time among fleets and lends support for this assumption. Furthermore, these crew shares were roughly on the scale often reported (Guillen *et al.*, 2017). Crew share costs are defined at the fleet level in the FLBEIA model and are a function of the changes in landings value (i.e. revenue).

Revenue and scaling of costs in FLBEIA

Revenue by fleet is based on the total landings value, which is provided at the fleet/métier level for each stock, but does not differentiate prices for different sizes/ages (i.e. €/kg) of the landings. Fish prices for 2021 were taken directly from the WGMIXFISH data call. Using the ratios *fixed costs / revenue* and *variable costs / revenue* derived from the STECF data, the fixed and variable cost of the FLBEIA fleets and métiers could be estimated based on their revenue. The last data year (2021) thus represents these STECF cost / revenue ratios exactly, but will change during the forecasts to reflect changes in catches and fishing effort.

3. CFP/MSFD and Global Indicators

Indicators

We calculated the CFP, MSFD and Global indicators as described in the template for task 6.4.

Scenarios

The scenarios were designed as baseline runs, excluding any additional effects of climate change, species interactions or economic developments that will be explored in future work within Seawise. We explored four baseline scenarios: a status quo effort scenario, where the fleets can fish with the effort of the last data year (2021), without choking effects and three landing obligation scenarios ("Min fleets control") with various implementation levels. The first landing obligation scenario is a classic "Min" scenario, applying the ICES harvest control rule with F_{MSY} as Ftarget. A second landing obligation scenario ("PGY-Min") allows harvesting up to the upper F_{MSY} range, if the stock is above Btrigger. Additionally we considered a 20% limit to year-to-year TAC changes, as stability of income and harvest has a high value among fishermen. This rule is also only applicable if the stock is above Btrigger. A last landing obligation scenario, which is case study specific to the North Sea ("Case study") now relaxes the degree of choking stocks by excluding Witch as a choking stock and only allowing more southerly distributed fleets (EN, BE, NL and FR) fishing with Beam Trawls or TR2 gears to be choked by sole and plaice, whereas the other fleets have a reduced number of potential choking stocks. Additionally we looked at the effects of an additional 27% implementation error on the TAC limits of cod, as there was a TAC overshoot on the North Sea cod stock in the last years (2020, 2021).

Table 2: Description of the FLBEIA scenarios run in task 6.3 and 6.4 as baseline runs

Scenario	**Abbreviation**	**Harvest control rule**	**Additional changes**	**Stock restrictions**	**Description**
Baseline Status Quo Effort	Status Quo effort	None	None	None	Simulating that fleets fish with the effort of the last data year with no restrictions on choking species
Baseline F_{MSY} Min	FMSY-Min	ICES-HCR F_{MSY}	None	COD-NS, PLE-NS, PLE-EC, SOL-NS, SOL-EC, WHG-NS, POK, WIT, TUR, NEP6, NEP7, NEP8, NEP9	Simulating a perfect implementation of the landing obligation with F_{MSY} as F_{target}, where fleets need to stop fishing if their first quota is exhausted
Baseline F_{MSY}Upper Min + TAC buffer	PGY-Min	ICES-HCR F_{MSY}Upper	Limit year-to-year TAC changes to ± 20% if the stock is above Btrigger	COD-NS, PLE-NS, PLE-EC, SOL-NS, SOL-EC, WHG-NS, POK, WIT, TUR, NEP6, NEP7, NEP8, NEP9	Simulating a relaxation of the effects from the landing obligation, allowing fleets to fish at F_{MSY}Upper if stocks are above Btrigger, with the additional constraint of limiting advised year-to-year TAC-changes by 20%
Baseline Case Study specific	Case study	ICES-HCR F_{MSY}	27% TAC implementation error for cod, if the TAC is set below 35000t	COD-NS, WHG-NS, POK , TUR, NEP6, NEP7, NEP8, NEP9 for all fleets; Beam trawlers and TR2 of EN, BE, FR and NL fleets being additionally choked by PLE-NS, PLE-EC, SOL-NS and SOL-EC	Simulating a scenario that reflects the current situation, with an enforced landing obligation("Min scenario"), but a more realistic choking situation with only beam trawlers and TR2 gears belonging to the English, Dutch, French or Belgian fleets being choked by sole and plaice and witch being not limiting anymore. Additionally there is an assumed 27% implementation error on the cod TAC-advice, as there was a TAC overshoot

					on the North Sea cod stock in the last years (2020, 2021)

4. Main results.

Stock dynamics

Comparing the different, baseline management scenarios shows a clear pattern of higher biomass in the scenarios with lower F and vice versa (Figure 1). Fishing with the effort of the recent past (Status Quo effort), without considering any choking effects leads to the lowest biomass for all stocks, with increased risk of falling below Btrigger for COD-NS, HAD-NS, PLE-EC, POK, SOL-EC, SOL-NS, TUR and WIT and even below Blim for PLE-EC, SOL-NS and SOL-EC. The catches in this scenario are the highest for the majority of stocks, however cannot prevail at such a high level especially for those stocks dropping below Blim (SOL, PLE). Contrary in the FMSY-Min scenario, fleets are choked early by Witch (WIT-NS) and fished below F_{MSY} (except for Witch) (Figure 2). Therefore, stocks are rebuilding to the largest biomass levels across scenarios due to lower catches. The other two scenarios (PGY-Min, Case study specific), are in between these two extrema, leading to a later choking than in the FMSY-Min scenario either through a higher Ftarget (FMSYUpper) if stocks are above Btrigger or a general modification of restrictive stocks (Case study specific). Still, the majority of stocks (except for Witch) are fished below their single species F_{MSY} values. Witch was the main choking stock in the FMSY-Min scenario, followed by North Sea sole and PLE-EC. A similar pattern can be found for the PGY-Min scenario with SOL-EC being the dominant choking stock, followed by witch at least in the 2025 – 2030 period. However, this changes again, with witch as the dominant choking stock in the later periods. Lifting some of the choke restrictions in the Case study specific scenario, with no choking on witch and only certain fleets being choked by flatfish, allowed for a majority of fleets, who catch only few flatfish to have a higher quota utilisation of the gadoid stocks, which lead to saithe being the dominant choking species now.

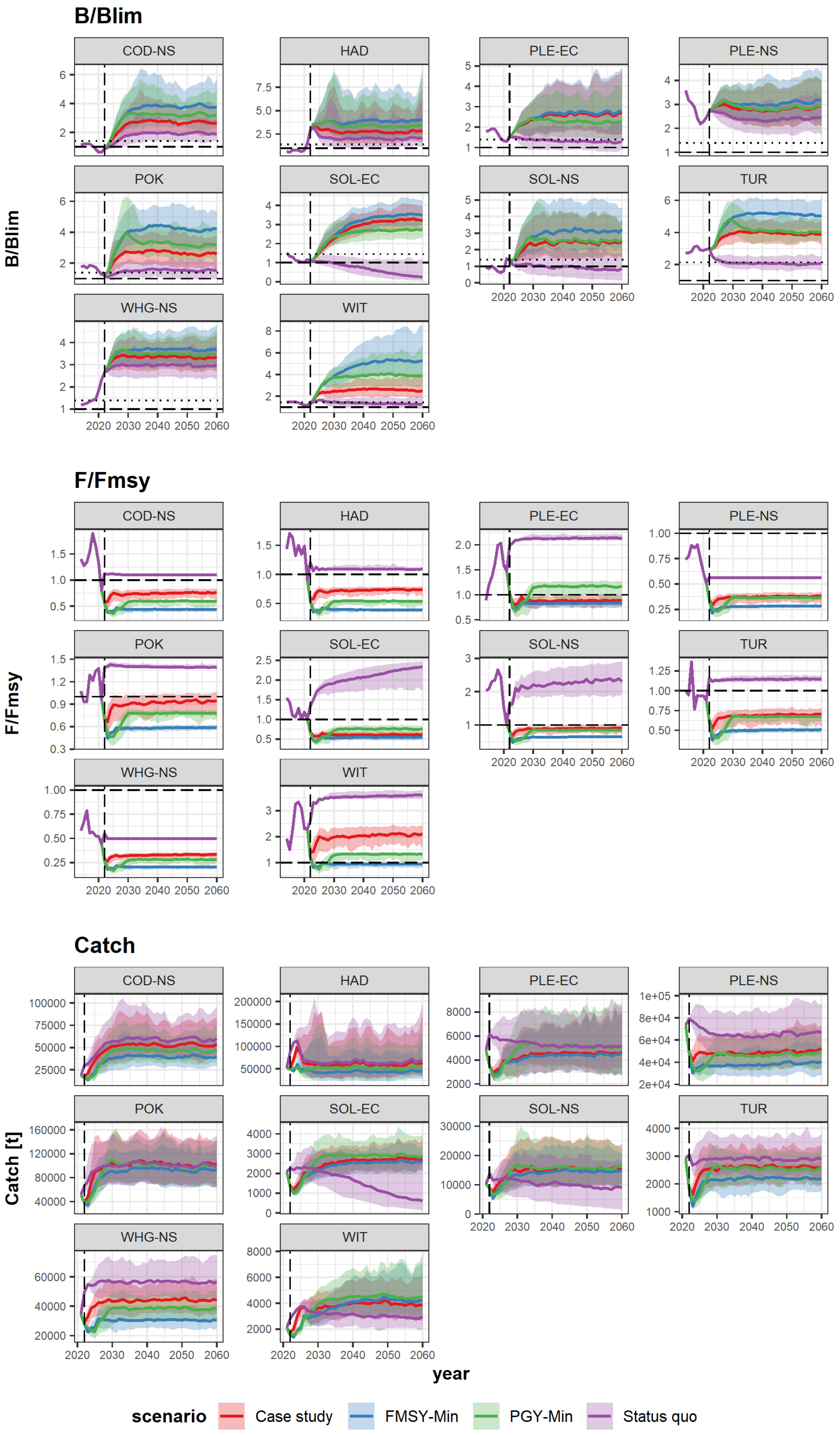

Figure 1: B/Blim, F/Fmsy and Catch for the age-based stocks per scenario (colour) in the FLBEIA North Sea model, median trajectories with uncertainty (5-95% quantiles) are shown. Reference points (Blim and Fmsy) and the first projection year are shown as dashed lines. The dotted line denotes Btrigger.

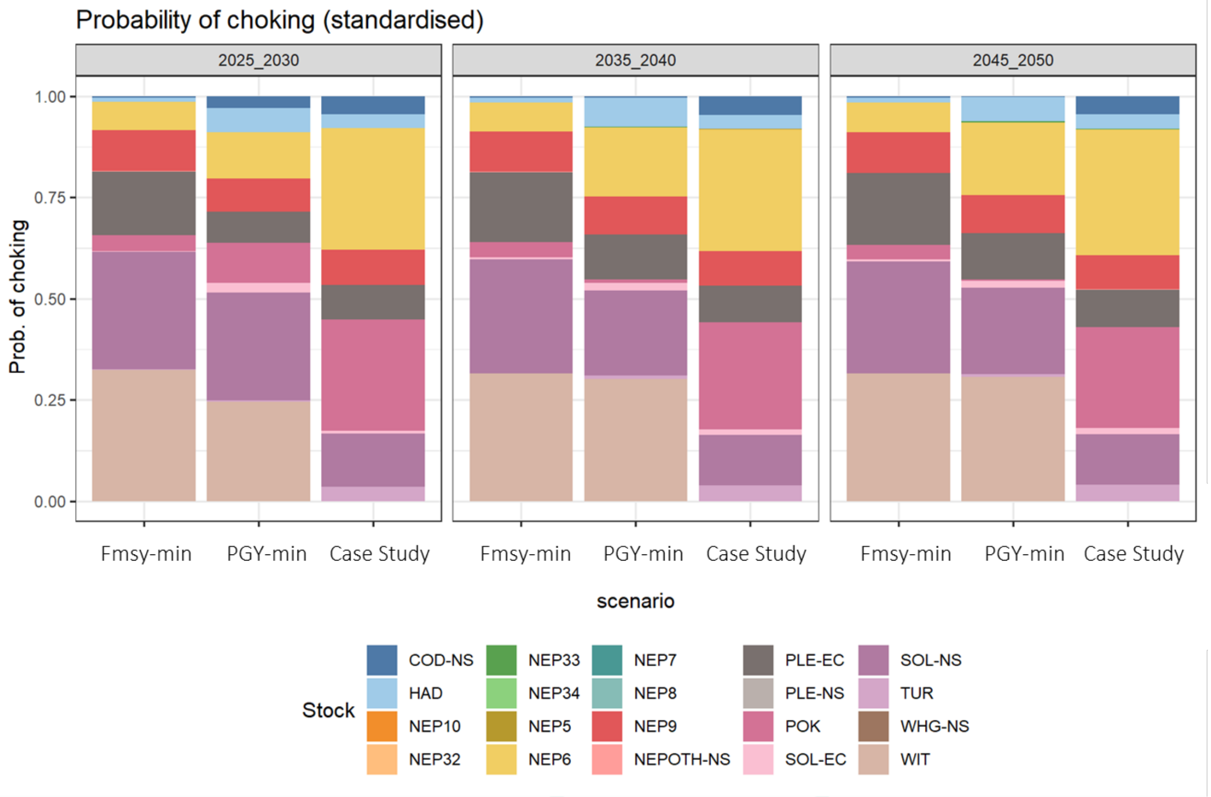

Figure 2: Probability of choking (standardised) per stock (colour) across all fleets per scenario (x-axis)

CFP Indicators

Ecological indicators

Percentage of stocks < F_{MSY}/ risk of falling below Blim/ SHI and SAR

Under the Status Quo scenario the majority of stocks was harvested above F_{MSY}, leading to an increased risk of stocks falling below Blim, a circa 42% of fleets having a Sustainable harvest Indicator (SHI) above 1 and the risk indicator SAR (number of fleets with stocks at risk) increasing to approx. 30% (Figure 3). The scenarios with a landing obligation (Min-Scenario) allowed for more sustainable harvesting, with a SHI and SAR indicator of 0, as no stocks had an increased risk of falling below Blim. Still, relaxing the choking situation in the PGY-Min and Case study specific scenario, lead to an increased proportion of stocks being fished above F_{MSY}, compared to the FMSY-Min scenario, where all stocks were fished below F_{MSY}.

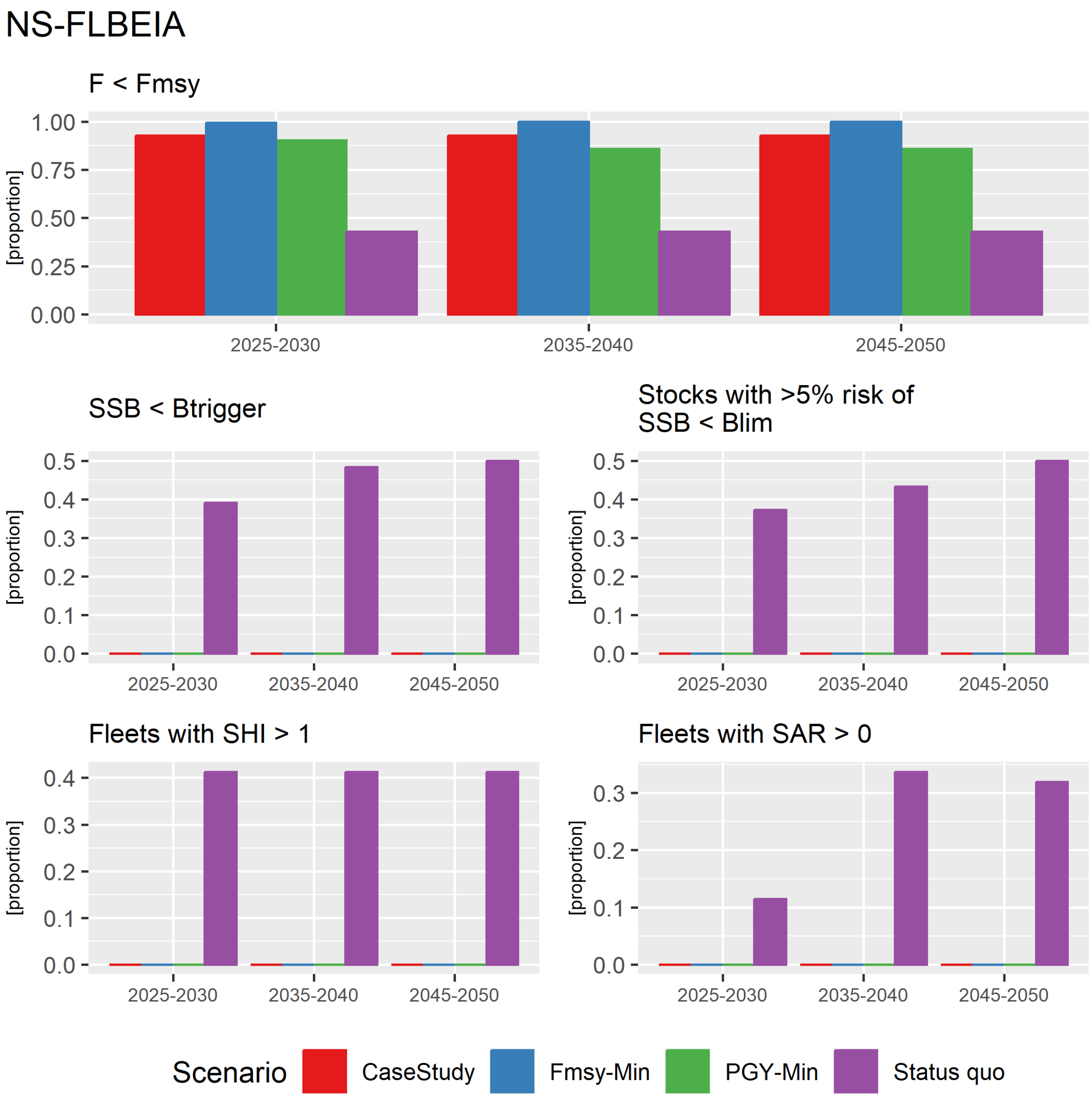

Figure 3: Ecological CFP Indicators of the North Sea FLBEIA model per scenario and time period

Socio-economic indicators

Catch/ Landings/ Discards

Catch differences between scenarios were dependent on fishing pressure, with highest catches under Status quo and lowest catches under FSMY-Min (Figure 4). However, discarding under the Status quo scenario was highest leading to landings in the Status quo scenario that were approximately equal (2025-2030) to the PGY-min scenario or slightly below (2035-2050). Overall landings were highest for the Case study specific scenario, followed by PGY-Min, Status quo and lowest for FMSY-Min.

Revenues/ Gross profit/ Gross value added/ Wages

Looking at the total revenues, Gross profit, and Gross Value added (Figure 4) across fleets for the different time periods shows clear economic gains in favour of the baseline scenarios with an implementation of the landing obligation. Although revenues where lowest for the FMSY-Min scenario from 2025 – 2030, it changed throughout the simulation as stocks could recover, leading to higher revenues in the later periods (2035 – 2050) than the Status

Quo effort scenario. Trying to relax the choking situation in the PGY-Min and Case study specific scenario could generate the highest revenues from landings over all periods, with the Case study specific scenario performing best. Gross Profit and Gross value added show a similar pattern with the Status Quo effort scenario performing the worst over all time periods considered.

Wages

The Wages as a social indicator showed the same pattern as revenues (Figure 4), with wages being minimal for the FMSY-Min scenario in the beginning of the simulations due to the stark drop in fishing effort. However, wages could recover above the level of the Status quo scenario which remained relatively constant throughout the simulation period. Highest wages could be achieved in the two Min-scenarios, where the choking situation was relaxed (PGY-Min and Case Study specific).

Revenue to Break even revenue (BER)

The indicator “Revenue to BER” is a measure for how good are fleets able to cover next year’s costs with the current revenues made. The general pattern of the landing obligation scenarios outperforming the Status Quo effort scenario also holds here (Figure 4). Among the scenarios with a landing obligation the PGY-Min scenario is slightly better than the other two, likely related to the fact that trade-off between exploitation levels, stock sizes and needed effort to fill the quota is best for this scenario.

Revenue ratio of small to large fleets

The revenue ratio of small (<24m) to large fleets (>24m) was highest for the Status quo scenario and at a similar level for all other scenario in the order PGY-Min, Case Study and FMSY-Min (from large to small) (Figure 4). The pattern is possibly as with lower stock sizes under the Status quo effort scenario, large fleets having a lower CPUE than small fleets.

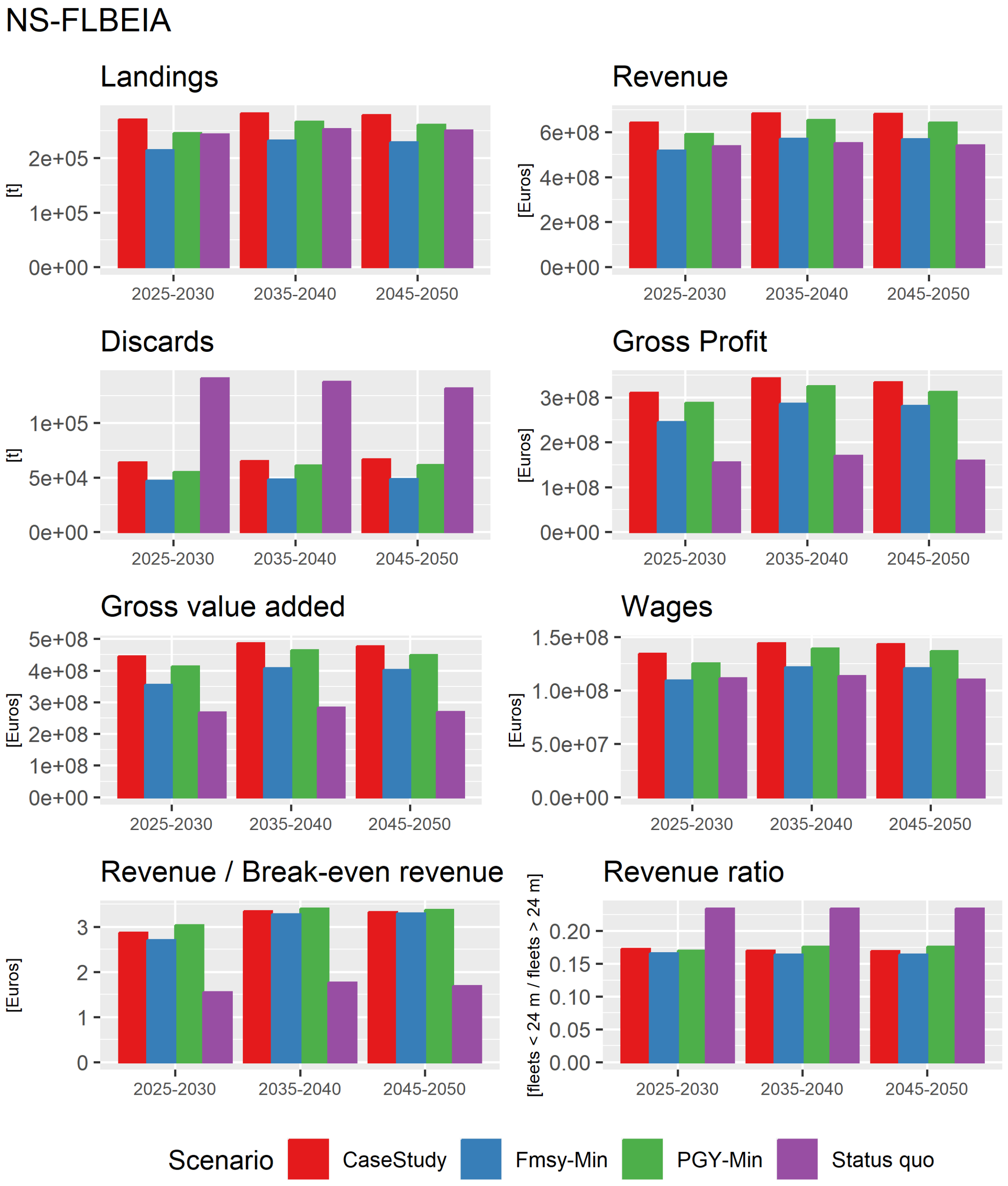

Figure 4: Socio-economic CFP Indicators of the North Sea FLBEIA model per scenario and time period

MSFD Indicators

Bycatch of harbour porpoise and seals

As the bycatch of harbour porpoise and seals was directly linked to the effort of the specific gears in the model, it reflects the main effort pattern between the different scenarios, with highest bycatch in the scenario with the highest effort being the Status quo scenario, followed by Case Study specific, PGY-Min and the FMSY-Min scenario (Figure 5). Bycatch levels in the landing obligation scenarios could be reduced by 30-53 % for harbour porpoise and 27-49 % in seals relative to the Status quo scenario, simply through higher stock biomass of target species and an accompanying reduction in effort. Bycatch levels were in general lower than the historical bycatch levels, the implementation was based on (year 2020), due to lower effort levels. For harbour porpoise the highest bycatch from the Status Quo scenario of 1547 individuals is slightly below the estimated threshold of 1622 individuals by PBR. For seals, the highest bycatch of 2146 individuals in the Status Quo scenario is also lower than the PBR threshold set by OSPAR of 7617 individuals.

Biomass ratios

The biomass ratio (Figure 5) of apex fish predators (AFP) to sub-demersal predators (SDP) revealed the highest proportion of AFP (in our case cod) for the FMSY-Min scenario, relative to all the benthic gadoids and flatfish in the model. The other scenarios group themselves again in the pattern from lowest to highest fishing mortality with a higher amount of AFP in scenarios with lower fishing pressure. The ratio of sub-demersal predators to sub-pelagic predators (only saithe) is highest for scenarios with high fishing pressure (Status quo) and lowest for scenarios with lower fishing pressure (FMSY-Min). This holds also for the ratio of Apex fish predators (AFP) to sub-pelagic predators.

Large fish indicator (LFI)

The proportion of large fish (LFI) in the landing obligation scenarios with values between 0.27 – 0.29 was higher than the Status quo scenario with values around 0.2, reflecting that lower exploitation levels in the landing obligation scenarios lead to a higher proportion of older age classes and a shift in age-distribution (Figure 5). The differences between FMSY-Min having the highest LFI compared to the two relaxed choking scenarios (Fmsy-Upper and Case Study) could be explained by the lower exploitation, leading to a high biomass of stocks with large fish sizes (cod and plaice). Differences between exploitation levels of the flatfish plaice, sole and witch, which contribute relative little to the LFI due to their smaller sizes also determine the LFI in the model. A higher exploitation level of these leads to a larger proportion of stocks, which are generally larger in size (like cod and saithe). In general, we could see that the stock recovery and accompanying shift in age class distribution under the landing obligation scenarios could help in reaching the target LFI for the North Sea of LFI > 0.3.

Recruitment success

R/SSB as a measure of recruitment success was in general not a suitable ecosystem indicator (Figure 5), at least not for the current scenarios, as no guild (Apex fish predators, Sub-demersal predators, sub-pelagic predators) seemed to be dominated by impaired recruitment, even though some stocks (e.g. SOL-EC) had impaired recruitment under the Status Quo effort scenario. Therefore differences in the indicators are only due to their differences in SSB levels, with high R/SSB for scenarios with higher fishing mortality (Status quo & Case Study), due to their lower SSB levels. This makes an interpretation in terms of recruitment success questionable.

Effort of demersal gears

Effort of the demersal gears Danish Seines/Seines and Otter trawls showed similar pattern with highest effort and potential highest benthic impact of the Status quo scenario, followed by the Case study specific scenario, PGY-Min and Fmsy-Min (Figure 5). For Beam trawls, effort levels of the PGY-Min scenario increase over the simulation period, reaching higher levels than the Case study specific scenario by 2035 – 2040, due to higher exploitation levels of the flatfish plaice, sole and with, which are caught predominantly with Beam trawls.

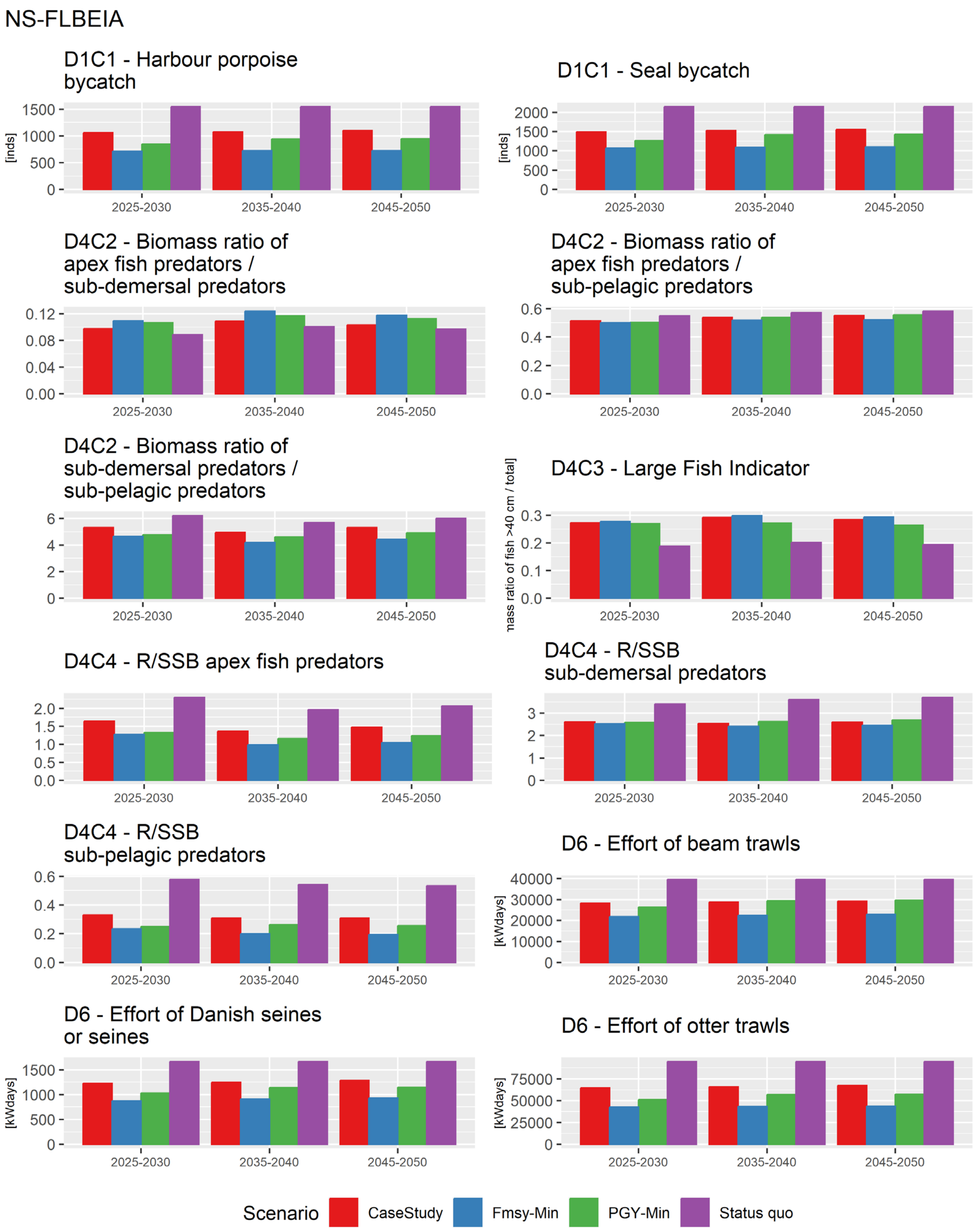

Figure 5: MSFD Indicators of the North Sea FLBEIA model per scenario and time period

Global Indicators

CO2 emissions

Carbon emissions by the fishery are highest under the Status quo effort scenario, followed by the Case study specific scenario, PGY-Min and Fmsy-Min, reflecting the general effort pattern of the scenarios (Figure 6).

Fogarty Ratio/Ryther index

The Fogarty ratio (catch per primary production) and Ryther index (catches per surface area) for the North Sea simulations exceed the threshold of 1 and are even at their upper limit (2.2 for Fogarty) or exceed it (2.7-3 for Ryther), indicating severe ecosystem overfishing for all scenarios (Figure 6).

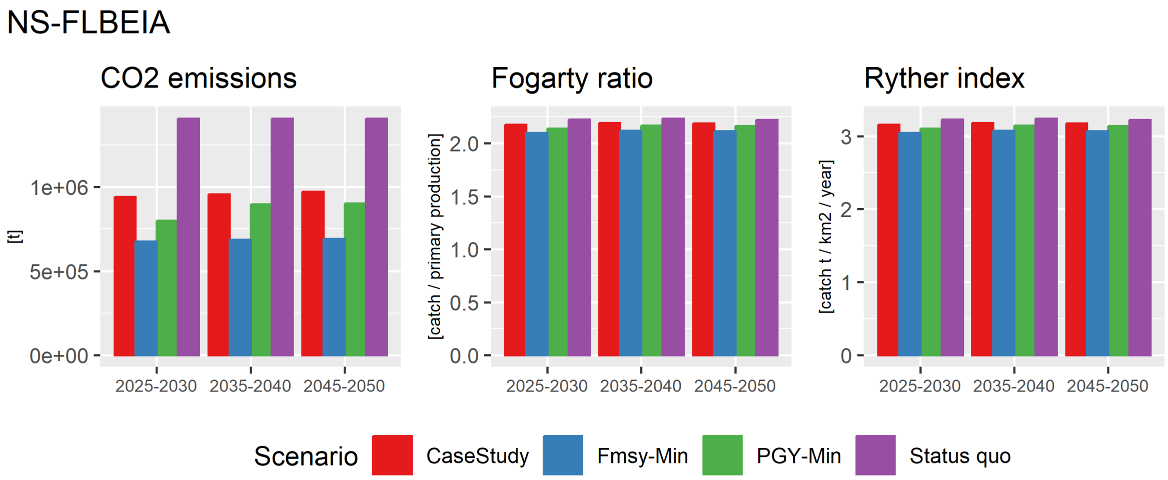

Figure 6: Global Indicators of the North Sea FLBEIA model per scenario and time period

5. Conclusions

Comparing the different scenario in terms of ecological, economic, social and global indicators revealed various trade-off between those different objectives. The Status quo effort scenario was suboptimal in all indicators, showing considerable overharvesting above F_{MSY} for some stocks, an increased risk of falling below Blim and economic losses in terms of revenue, gross profit and a decreased ability to invest as the Break-even revenue ratio indicates. Indicators of ecosystem health like the LFI showed shifts in the age-distribution of the stocks. Additionally the scenario was characterised by an increased impact on bottom habitats through demersal gears and the highest carbon emissions among scenarios. Although bycatch levels remained below thresholds (harbour porpoise and seals) in the North Sea, the Status quo scenario had the highest bycatch levels, possibly underestimating the real impact also on other species.

The reduction in effort under all landing obligation scenarios allowed for sustainable harvesting, even though some conditions were relaxed to match economic objectives. Scenarios with greater flexibility could economically profit from increased yield, by simultaneously balancing ecological and ecosystem objectives. However, global indicators like the Fogarty/Ryther indices pointed towards a potential underestimation of ecosystem impacts by the other indicators considered, as current catch levels seem to be largely above thresholds. Additionally, it should be kept in mind that these baseline runs are simplified scenarios not taking into account effects of climate change, species interactions or future fuel and fish price developments that will likely change yield and profits of fishermen as well as ecosystem impacts.

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8.2 Annex 2: Description of analyses carried out with OSMOSE for the Eastern English Channel (EEC)

1. Description of the model used

An end-to-end model was implemented in the Eastern English Channel to represent the ecosystem functioning by coupling two existing sub-models, the multispecies individual-based model OSMOSE, representing the dynamics of exploited species and the biogeochemical model ECO-MARS3D which provide plankton prey fields. OSMOSE_EEC is a spatially explicit individual-based model. It represents the life cycle of 14 high trophic level species from egg to adult stages, grouped into schools and defined by their size, weight, age, taxonomy and spatial position. The two sub-models were linked through trophic interactions to characterize the food web structure of the Eastern English Channel ecosystem from plankton up to top predators for the period 2000 - 2009. The trophic interactions depend on opportunistic predation based on prey size selection and spatio-temporal co-occurrence between predators and their preys over space and time. There are no fleets in the model. The fishing pressure is modelled using a species-specific fishing mortality rate.

2. Description of model parameterization and scenarios

Model parameterization

The basic units of OSMOSE are fish schools, which are composed of individuals that belong to the same species, and which have the same age, size, food requirements and, at a given time step, the same geographical coordinates. From the school states, biomass and abundance can be tracked at the population or community levels along with the size, age, and spatial dimensions.

The OSMOSE_EEC model was calibrated for the period 2000 – 2009 and it operates on a time step of 15 days. The spatial resolution of the grid is 0.1° x 0.1°. Different groups are represented in OSMOSE_EEC:

- 2 groups (dinoflagellates and diatoms) considered as forcing variable (LTL biotic resources)
- 3 groups (microzooplankton, mesozooplankton, macrozooplankton) considered as forcing variable (LTL biotic resources)
- 5 benthic invertebrate groups depending on size considered as forcing variables
- 1 explicit squid group (high trophic level species)
- 13 explicit species (high trophic level species)

The fishing activity is described in the model through a global fishing mortality rate by species only. The fishing management is not taken into account in the model.

The main biological processes occurring in each time step are movement, mortality (predation and other sources of mortality), growth and reproduction.

- Movement

At each time-step, schools are moved following a random walk method within their distribution area set up as a presence/absence map.

- Mortality

Within each time step, the total mortality of a given school is comprised of predation mortality caused by other schools, starvation mortality, fishing mortality, and diverse other natural mortality rate. The four different mortalities are computed so as to represent quasi simultaneous processes, and we consider that there is competition and stochasticity in the predation process. Within each time step, OSMOSE considers each pair of school/source of mortality in turn in a random order. To ensure that the random order of the mortality sources and of the schools does not bias the resulting instantaneous mortality rates applied and effectively correspond to the mortality rates specified in input, all the mortality events are iterated within a time step over a fixed number of sub-time step.

The main assumption in OSMOSE is that predation is an opportunistic process, which depends on:

- the overlap between predators and potential prey items in the horizontal dimension
- size adequacy between the predators and the potential prey (determined by predator/prey size ratios)
- the accessibility of prey items to predators, which depends on their vertical distribution (this being determined by means of accessibility coefficients). Thus, in OSMOSE, the food web structure emerges from local predation and competition interactions.

In OSMOSE_EEC the fishing mortality is species-specific. It was parameterized by providing an annual fishing rate by species (*F)*. The number of dead fishes in a school is computed as follows:

$$N_{fished} = N \times (1 - exp^{-F})$$

- Growth

Individuals of a given school are assumed to grow in size and weight at a given time only when the amount of food they ingested fulfill maintenance requirements (i.e., only when their predation efficiency at that time is greater than the predation efficiency ensuring body maintenance of school). The growth of individuals is calculated using a Von Bertalanffy model.

- Reproduction

For a given species, the number of eggs released in the system depends on:

- the spawning stock biomass
- the proportion of females
- the relative fecundity of females (the number of eggs emitted per gram of mature female)
- the seasonality of spawning

Scenarios

Three scenarios were simulated:

- A statu-quo scenario which corresponds the reference model. In this scenario, the fishing mortality corresponds to the average situation of the ecosystem for the period 2000 – 2009.
- A scenario where F of demersal species was reduced by 20% to represent likely management towards GES (i.e. protecting seabed habitats).
- A scenario where F of demersal species was reduced by 40% to represent likely management towards GES (i.e. protecting seabed habitats).

All the scenarios are run for 100 years with 15 replicates to take into account the stochasticity of the model. All the indicators were averaged over the 3 periods: 2025 – 2030, 2035 – 2040, and 2045 – 2050.

3. Indicators, targets and limits

List of indicators

Indicators	**Target groups**
Catch	Species level
Biomass	Species level
	Forage fish
	Sub apex demersal predators
	Planktivorous
	Sub apex pelagic predators
	Apex predator
H index	Planktivorous
	Apex predator
	Sub apex demersal predators
	Sub apex pelagic predators
Large Fish Index 30	Apex predator
	Planktivorous
	Sub apex demersal predators
	Sub apex pelagic predators
Community Risk*	Benthic communities

* Community Risk is a score that gives more weight to risk of collapse of a species than to widespread risk of depletion of many species.

Composition of target groups

Species	Forage fish	Sub apex demersal predators	Planktivorous	Sub apex pelagic predators	Apex predator
Lesser Spotted Dogfish					X
Red Mullet		X			
Mackerel				X	
Herring	X		X		
Sardine	X		X		
Squids				X	
Pouting		X			
Whiting					X
Poor Cod		X			
Cod					X
Dragonet		X			
Sole		X			
Plaice		X			
Horse Mackerel				X	

Indicators targets from Task 4.4 analysis**

	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
ind_target_Demersal_biomass	122926.12	137049.67	138785.75	139821.12	143100.50	152398.51
ind_target_Benthivorous/Planktivorous	0.16	0.17	0.18	0.18	0.19	0.19
ind_target_Benthivorous_biomass	14592.67	15029.92	15512.61	15757.06	16630.54	17240.65
ind_target_LFI50	0.46	0.51	0.55	0.54	0.56	0.61
ind_target_Mean_Maximum_Length	51.75	53.36	54.27	54.29	55.40	56.66
ind_target_total_biomass	264098.87	282100.02	286878.98	289207.55	301031.70	307926.99
ind_target_Typical_Length_Indicator	56.04	57.34	58.83	58.69	59.73	60.74

Indicators limits from Task 4.4 analysis**

Community risk index	Threshold	Index
0.05	138991.347	Biomass_demersal
0.1	130294.827	Biomass_demersal
0.2	112901.788	Biomass_demersal
0.05	0.18302151	Biomass ratio Benthivorous/Planktivorous
0.1	0.1713971	Biomass ratio Benthivorous/Planktivorous
0.2	0.14814828	Biomass ratio Benthivorous/Planktivorous
0.05	16009.5954	Biomass_Benthivorous
0.1	15250.2087	Biomass_Benthivorous
0.2	13731.4354	Biomass_Benthivorous
0.05	0.63525018	LFI50
0.1	0.55751622	LFI50
0.2	0.40204829	LFI50
0.05	56.2109701	Mean Maximum Length
0.1	53.623335	Mean Maximum Length
0.2	48.448065	Mean Maximum Length
0.05	295036.069	Total_biomass
0.1	284601.6	Total_biomass
0.2	263732.662	Total_biomass
0.05	62.0859021	Typical Length Indicator demersal
0.1	59.3269852	Typical Length Indicator demersal
0.2	53.8091514	Typical Length Indicator demersal

** The trophic guilds used to compute targets and limits of the indicators are different between WP4.4 and WP6.4.

8.3 Annex 3: Seawise D6.7 – report on StrathE2E modelling for the North Sea and Celtic Sea

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23 Feb 2023

StrathE2E is a shelf-sea ecosystem model which combines a coarsely spatially explicit end-to-end ecology model, and a fishing model (Heath et al. 2020). The ecology model is a set of coupled, time-dependent ordinary differential equations representing the (daily) rates of change in mass due to flows of nutrient through a network of food web guilds spanning dissolved material, detritus and microbes, through plankton, benthos and fish to megafauna (Table 1). The flows represent predation, food assimilation, metabolism, excretion, reproduction, passive advection, active migrations, and fishery captures. The spatial resolution is coarse, in keeping with the guild granularity of the food web - two horizontally well-mixed zones ("inshore" and "offshore"), linked by advection and migration. Each zone is further subdivided into seabed habitats and water column layers. Habitats are seabed biogeochemical compartments representing spatial variability in the processing of detritus and nutrient recycling, and the sensitivity of these to disturbance e.g. by fishing abrasion. External environmental drivers of the ecology model are annual cycles of time-varying physical and chemical data (temperatures, hydrodynamics, sea surface light, turbidity, inorganic nutrient inputs) which are inherently climate-sensitive.

The StrathE2E fishing model integrates properties of a set of up to 12 fishing gears (Table 2; annual averaged activity rate, distribution of activity across habitats, selectivity for guilds, catching power, discard and seabed abrasion rates), to generate guild-level fishing mortality and discard rates, and habitat-level abrasion rates. These are injected annually as parameters into the ecology model and assumed to remain constant over each upcoming year of simulation.

The StrathE2E model is available as an R-package (https://www.marineresourcemodelling.maths.strath.ac.uk/strathe2e/index.html), and as a web-app (https://outreach.mathstat.strath.ac.uk/apps/StrathE2EApp/). Here, we used version 4.0.0 of the R-package to implement models for the North Sea and the Celtic Sea during the period 2003-2013. The North Sea model is provided as a working example within the R-package. The Celtic Sea implementation is available from https://www.marineresourcemodelling.maths.strath.ac.uk/strathe2e/articles/Implementations.html). Maps of the geographic domain, inshore and offshore zones and seabed sediment habitats are shown in Figure 1 and Table 3.

Both models relied on physical environmental driving data from a 7km resolution NEMO-ERSEM model (https://www.uk-ssb.org/science_components/work_package_4/). Other driving data were obtained from ICES and BODC data archives (ocean nutrient data), EMEP (https://www.emep.int/; atmospheric nutrient inputs), and fishing fleet data (activity, selectivity and power, discard and seabed abrasion rates) from ICES and STECF (https://www.ices.dk/data/dataset-collections/Pages/Fish-catch-and-stock-assessment.aspx and https://stecf.jrc.ec.europa.eu/dd/fdi). Full documentation on the paramteterisation of the models is available from https://www.marineresourcemodelling.maths.strath.ac.uk/resources/StrathE2E2/documents/4.0.0/StrathE2E2_North_Sea_model.pdf . In summary, the model ecology parameters were optimised so as to maximise the likelihood of a database of ecosystem state measurements for the North Sea given physical and chemical driving data for corresponding time periods. The same basic ecology parameters were then used in the Celtic Sea model, which was validated against an equivalent set of observational data (Figure 2 & 3).

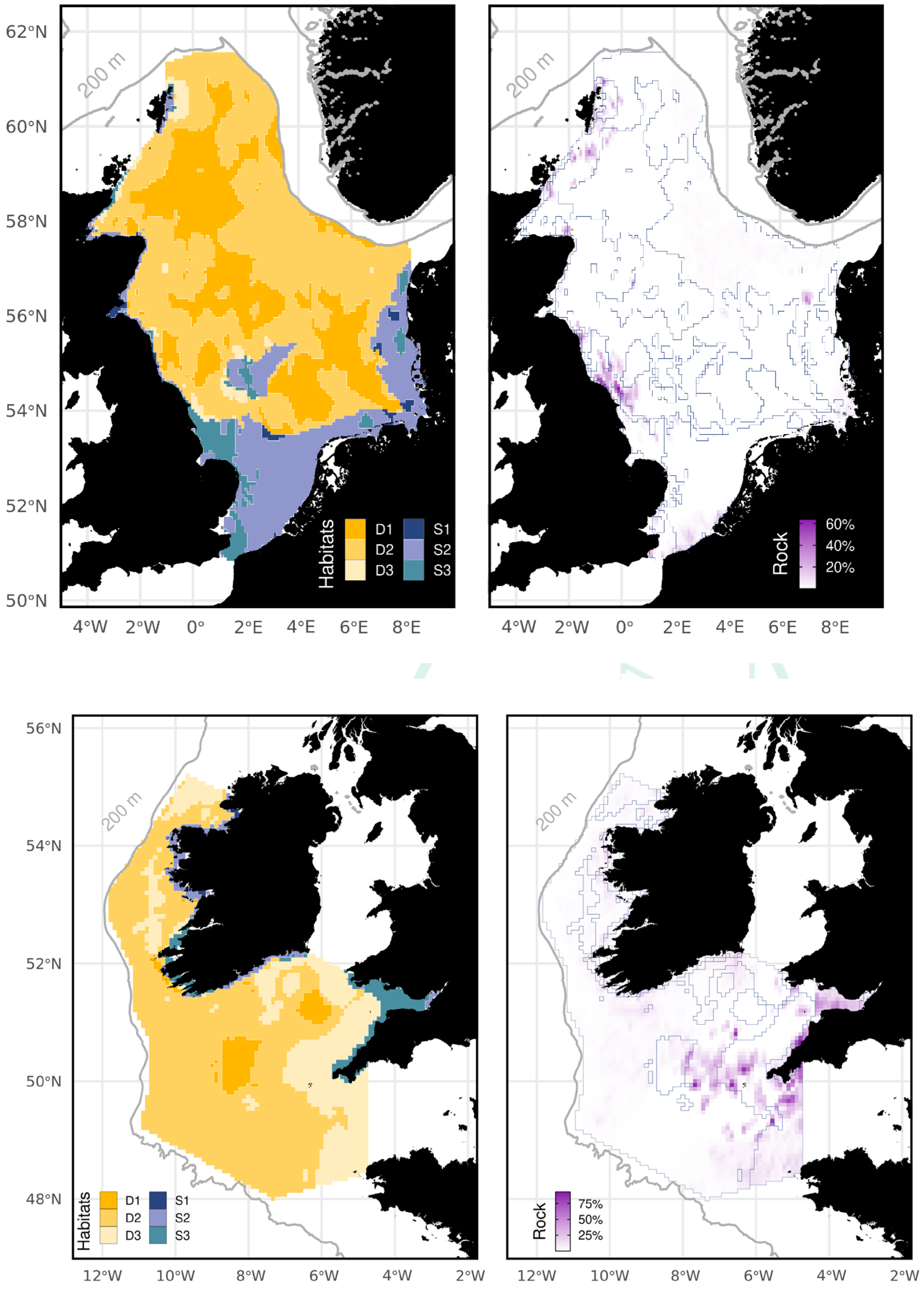

Figure 1. Maps of the North Sea (upper) and Celtic Sea (lower) implementations of StrathE2E. In the left-hand panels, blue shades indicate the inshore zone of each model, orange shades the offshore zone. Percentage cover of rock is shown in the right-hand panels. Sediment classes are indicated by coloir shads in the left hand panels (D1/S1 muddy sediments; D2/S2 sandy sediments, D3,S3 gravelly sediments.

Table 1. Ecological guilds or classes of dead and living material included in the StrathE2E model. Detritus and bacteria were represented as a composite guild.

Type of guild or class	StrathE2E
Dissolved inorganic nutrients	• Nitrate in water column, sediment porewaters. • Ammonia in water column, sediment porewaters
Dead organic material and bacteria	• Suspended detritus and bacteria • Labile sediment detritus and bacteria • Refractory sediment detritus • Macrophyte debris • Corpses • Fishery discards
Primary producers	• Phytoplankton • Macrophytes
Zooplankton	• Omnivorous zooplankton • Carnivorous zooplankton • Larvae of planktivorous fish • Larvae of demersal fish • Larvae of suspension and deposit feeding benthos • Larvae of carnivore and scavenge feeding benthos
Benthos	• Suspension and deposit feeders • Carnivore and scavenge feeders
Fish	• Planktivorous • Migratory • Demersal (benthic-piscivorous)
Upper (apex) trophic levels	• Seabirds • Pinnipeds • Cetaceans

Table 2. Fishing gears represented in the North Sea and Celtic Sea fishing models. Each gear is defined by its power per guild in the ecology model (expresses the harvest ratio (equivalent to fishing mortality) per guild generated per unit of activity), seabed abrasion rate, discard rate per guild, and at-sea processing rate per guild (which generates offal return s to the sea. The driving variable associated with each gear is its activity rate (time spent fishing per unit sea surface area per day over each seabed habitat in the ecology model).

Gear	**Model region**
Pelagic trawls and seines	North Sea and Celtic Sea
Sandeel and sprat trawls (Otter trawls 30-70mm and TR3)	North Sea and Celtic Sea
Longlines targeting mackeral	North Sea and Celtic Sea
Beam trawls (BT1 and BT2)	North Sea and Celtic Sea
Demersal seine	North Sea and Celtic Sea
Demersal otter trawl (TR1)	North Sea and Celtic Sea
Gillnets and longlines targeting demersal fish	North Sea and Celtic Sea
Beam trawls targeting shrimp	North Sea and Celtic Sea
Nephrops trawls (TR2)	North Sea and Celtic Sea
Pots and creels	North Sea and Celtic Sea
Mollusc dredges	North Sea and Celtic Sea
Whale hunting harpoon vessels	North Sea only
Kelp harvesting vessels	Celtic Sea only

Table 3. Areas of each seabed sediment habitat in the North Sea and Celtic Sea models as proportions of the whole model domain.

Spatial zone	Sediment category	North Sea area proportion	Celtic Sea area proportion
Inshore	Rock	0.0030	0.0110
Inshore	Mud	0.0110	0.0024
Inshore	Sand	0.1878	0.0343
Inshore	Gravel	0.0478	0.0440
Offshore	Rock	0.0057	0.0380
Offshore	Mud	0.2665	0.0469
Offshore	Sand	0.4595	0.6009
Offshore	Gravel	0.0187	0.2225
Whole model area	All sediments	1.0000	1.0000

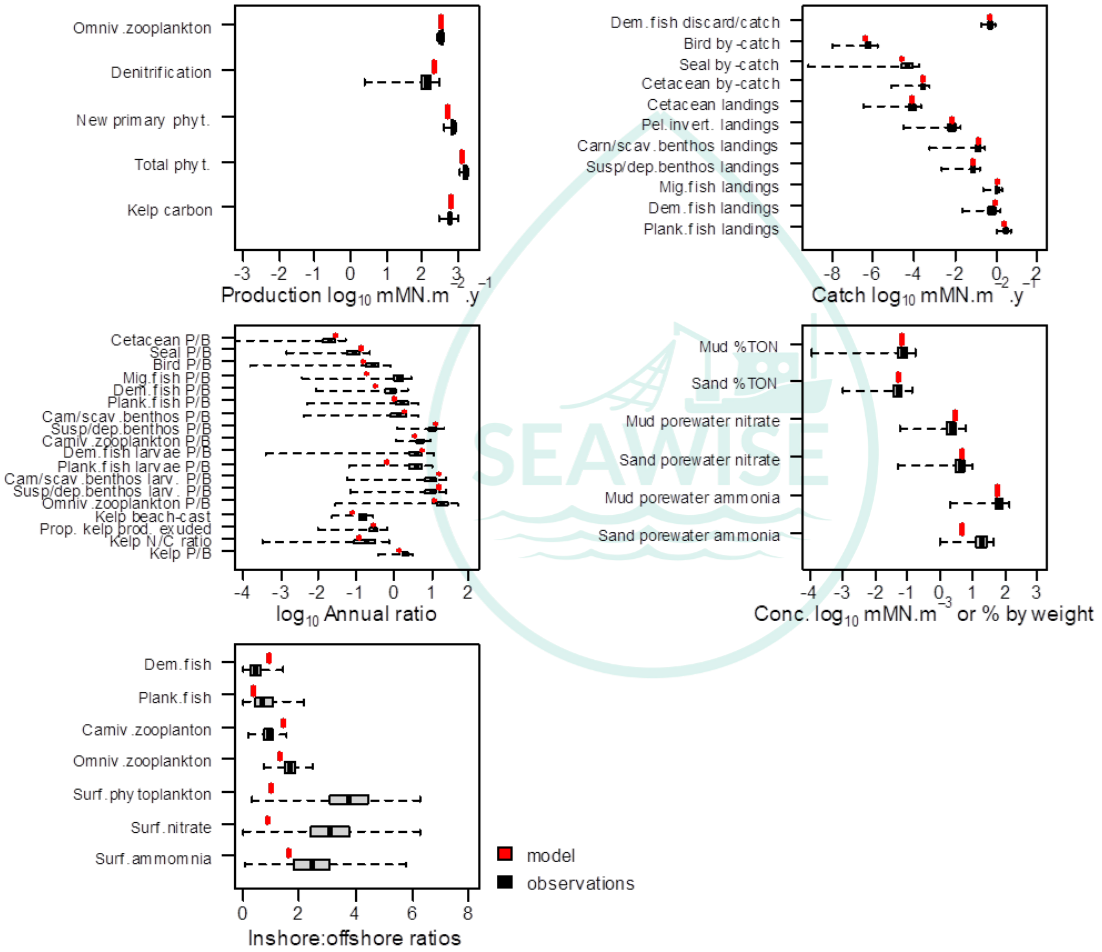

Figure 2. Comparison of model outputs and observed data for the North Sea during 2003-2013, using the optimised ecology model parameters.

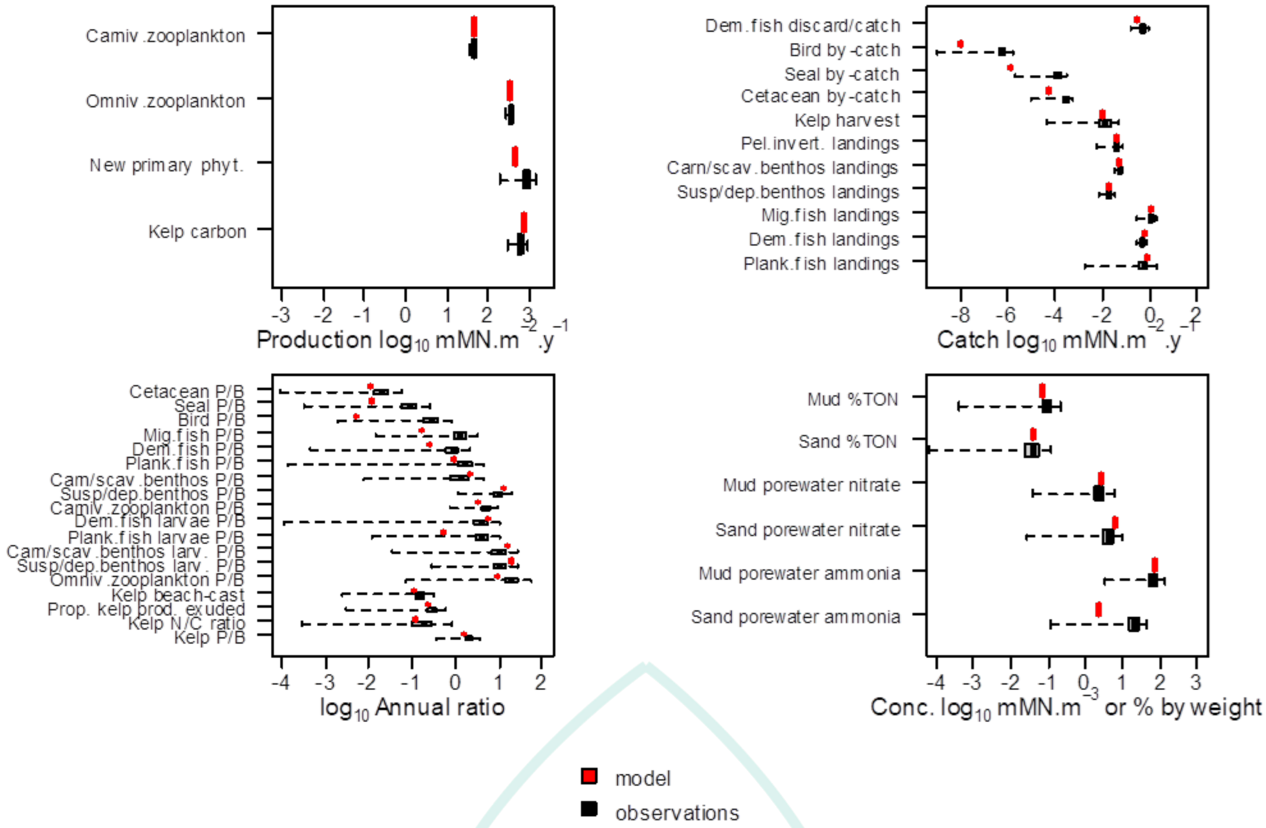

Figure 3. Comparison of model outputs and observed data for the Celtic Sea during 2003-2013, using the optimised ecology model parameters.

Annual averaged fishing gear activity rates across the seabed habitats in the North Sea and Celtic Sea models (2003-2013) are shown in Figures 4. These were inputs to the fleet model, which returned harvest ratios (fishing mortalities) for each guild to the ecology model, along with seabed swept area ratios and discard rates (Figures 5 - 7).

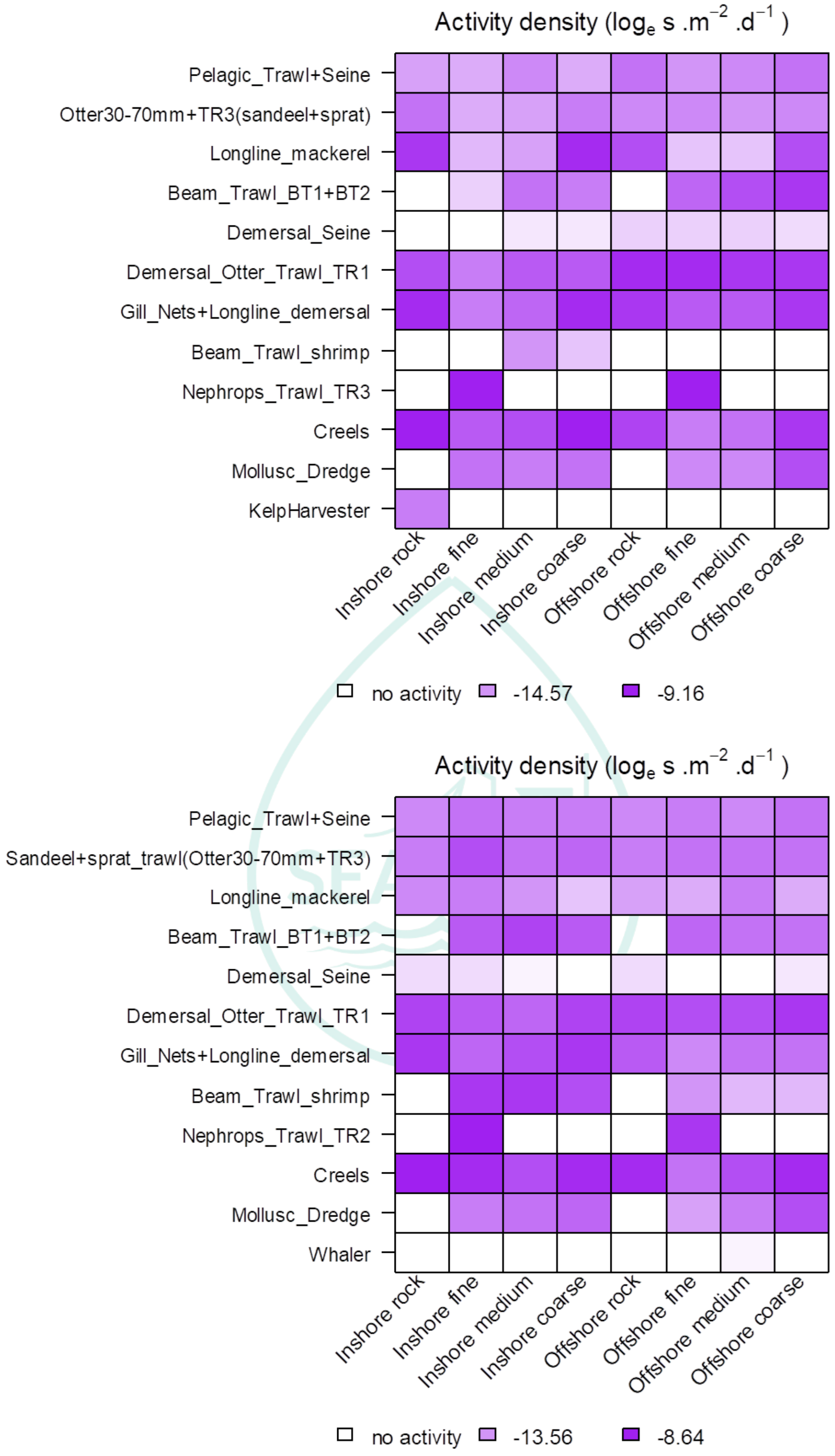

Figure 4. Activity density (seconds m^{-2} d^{-1}) by each gear over each seabed sediment habitat of the 2003-20123 North Sea (upper panel) and Celtic Sea (lower panel) models.

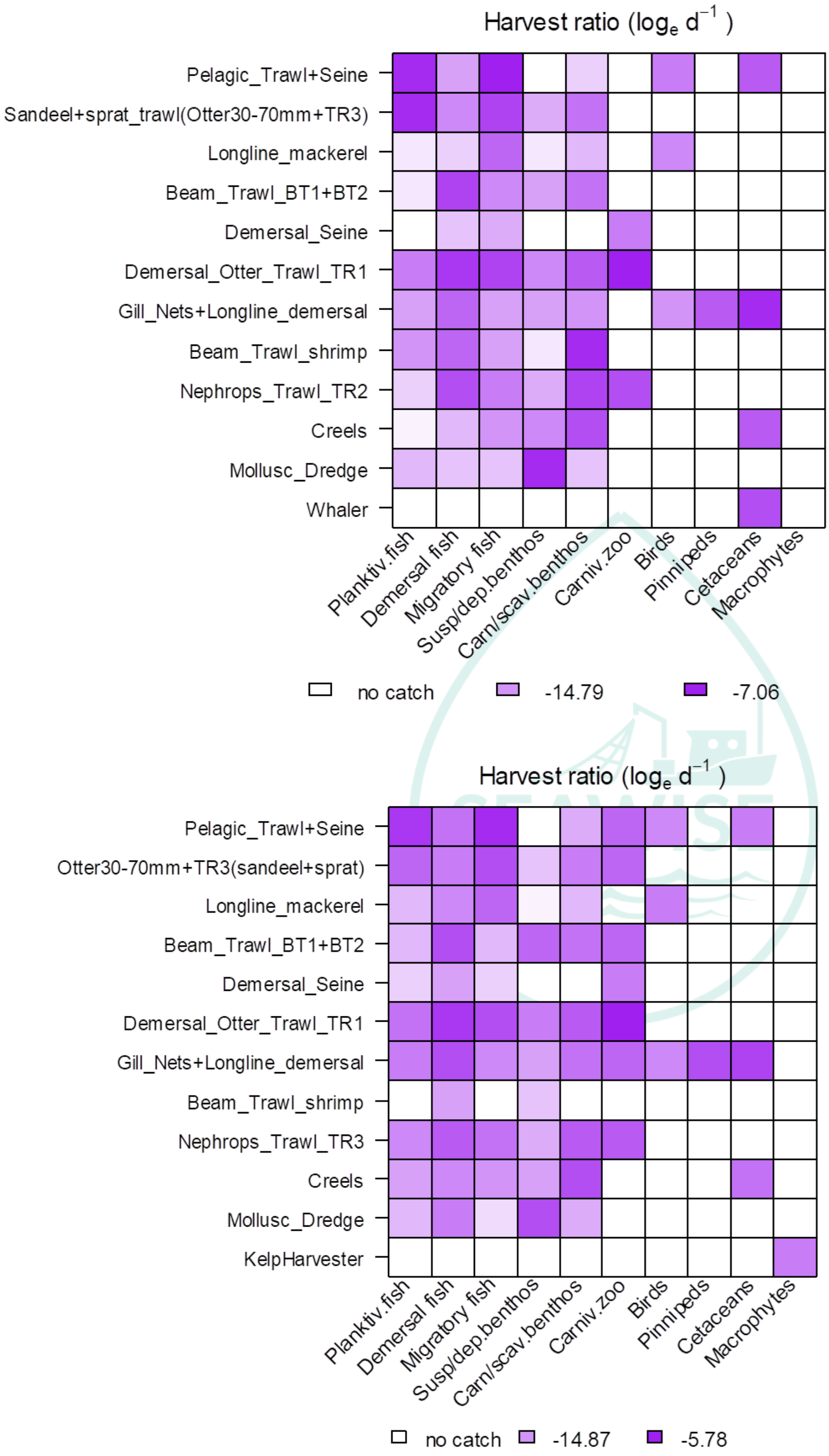

Figure 5. Harvest ratios (d^{-1}) by each gear on each guild in the 2003-2013 North Sea (upper panel) and Celtic Sea (lower panel) models.

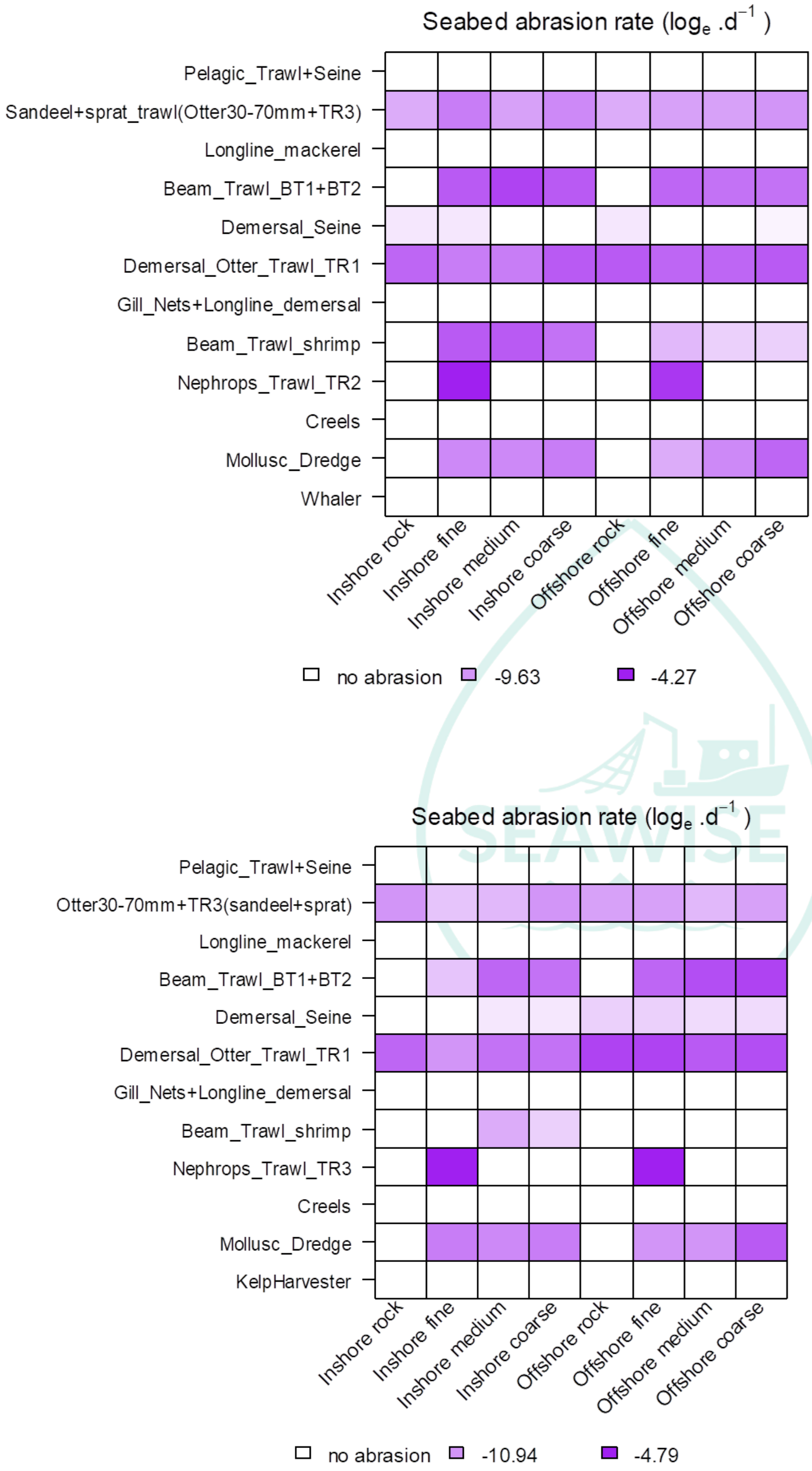

Figure 6. Seabed abrasion rates (area proportions d^{-1}) by each gear in each seabed sediment habitat of the 2003-2013 North Sea (upper panel) and Celtic Sea (lower panel) models.

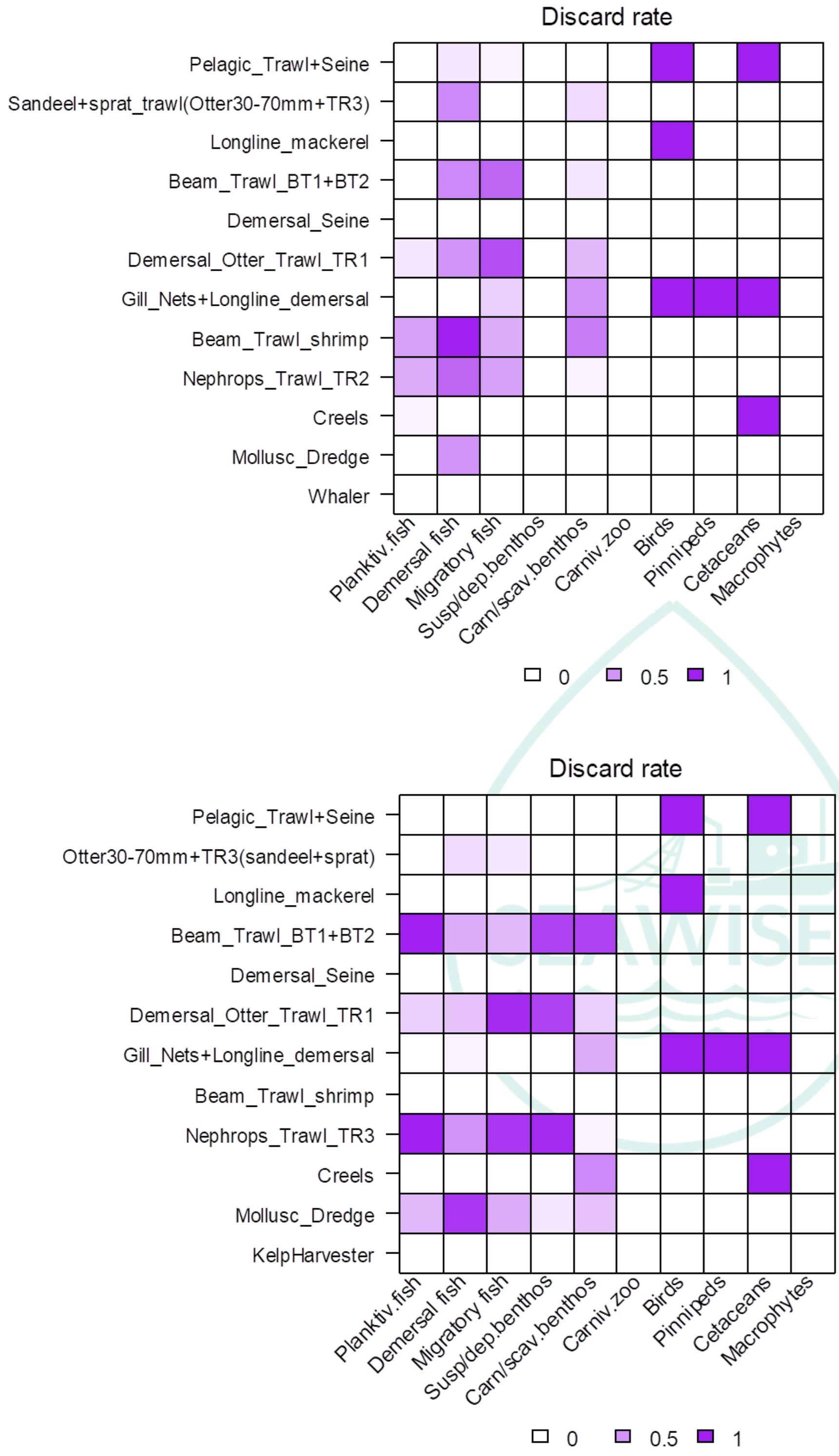

Figure 7. Discard rates (proportion by weight of catch by each gear on each guild in the 2003-2013 North Sea (upper panel) and Celtic Sea (lower panel) models.

Integrated annual harvest ratios of each guild by all gears combined in the 2003-2013 models are shown in Table 4. These integrate both landings and discarded by-catch of, for example, birds, pinnipeds and cetaceans. Similarly, the annual swept area ratios (proportion of seabed area swept per year) integrated across gears for each sediment habitat and for the whole model areas are shown in Table 5.

Table 4. Annual integrated harvest ratios on each guild due to all gears in the 2003-2013 North Sea and Celtic Sea models

Guild	**North Sea**	**Celtic Sea**
Planktivorous fish	0.2135	0.0870
Demersal fish	0.0823	0.1267
Migratory fish	0.3623	0.3810
Benthos suspension/deposit feeders	0.0827	0.0239
Benthos carnivore/scavenge feeders	0.1172	0.0378
Carnivorous zooplankton (squids)	0.1968	1.1332
Birds	0.0006	0.0008
Pinnipeds	0.0059	0.0279
Cetaceans	0.1142	0.0467
Macrophytes	0	0.0004

Table 5. Annual integrated swept area ratios for each sediment habitat due to all gears in the 2003-2013 North Sea and Celtic Sea models

Spatial zone	Sediment category	North Sea	Celtic Sea
Inshore	Rock	0.1787	0.0503
Inshore	Mud	5.6319	3.0205
Inshore	Sand	1.0520	0.0872
Inshore	Gravel	0.6392	0.0815
Offshore	Rock	0.2311	0.3082
Offshore	Mud	1.9297	2.2346
Offshore	Sand	0.2841	0.2817
Offshore	Gravel	0.4817	0.7459
Whole model area	All sediments	0.9458	0.4662

Model scenario runs

Each model was run with the baseline (2003-2013) activity rates of all gears scaled by a vector of multiplers: (0, 0.2, 0.4, 0.7, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 6.0, 8.0) for 100 years.

The StrathE2E model outputs data on daily and annual averaged biomasses of all the guilds in the food web. In addition, the annual integrated fluxes between all nodes in the network, along with all imports and exports from the model system, are saved as a flow matrix. The flow matrix is formatted for input to the R-package NetIndices, which generates a range of Graph Theory network metrics (Soetaert & Kones 2014).

The currency of the StrathE2E model is micro-moles of nitrogen m^{-2}. These units were converted to Tonnes wet weight (WW) in the whole model region assuming domain areas of 485,605 km^2 for the North Sea, and 217,131 km^2 for the Celtic Sea. Conversions for mMN to gWW are shown in Table 6.

Table 6. Conversion rates between molar weights of nitrogen and wet weight for guilds in the ecology model.

Guild	mMN . gWW^{-1}
Macrophytes	2.070

Phytoplankton	1.258
Omnivorous zooplankton	1.258
Carnivorous zooplankton	1.258
Benthos suspension/deposit feeders larvae	1.258
Benthos carnivore/scavenge feeders larvae	1.258
Benthos suspension/deposit feeders	0.503
Benthos carnivore/scavenge feeders	1.006
Planktivorous fish lavae	1.258
Planktivorous fish	2.038
Migratory fish	2.314
Demersal fish larvae	1.258
Demersal fish	1.296
Birds	2.516
Pinnipeds	2.516
Cetaceans	2.516

Landed weights of guilds in the model were converted to revenue (euro, deflated to 2013) using data on ex-vessel prices per guild for the North Sea and Celtic Sea (Table 7). For fish and invertebrates these were assembled from landed weight and value per species in the supporting datasets of the Scientific, Technical and Economic Committee for Fisheries (STECF) 2019 Annual Economic Reports (AER) on the EU Fishing Fleets (STECF 19-06; Carvalho et al. 2019). This particular report was selected from the annual series of such reports as it was the last to include data from the UK following its exit from the European Union. Species-level data were aggregated to guilds using a database of species-guild associations built in support of the model. Comprehensive coverage of nations and species was available for the period 2008 – 2018, and these data were averaged for use in the model.

Data on ex-vessel prices per fresh body weight of cetaceans (Minke whales) hunted in the North Sea were assembled form a forensic assembly and analysis of Norwegian whale hunting data from 1993-2021 (Heath, unpublished).

Data on French ex-vessel prices for harvested kelp in the Celtic Sea were obtained from BIM 2020

Table 7. Ex-vessel prices of landings for each of the guilds in the model (euro, deflated to 2013).

Guild	**Price per tonne (euro, deflated to 2013)**
Macrfophytes (kelp)	45.00
Pelagic invertebrates	3785.67
Benthos suspension/deposit feeders	581.24
Benthos carnivore/scavenge feeders	3452.63
Demersal fish	2344.72
Planktivorous fish	313.26
Migratory fish	1012.09
Pinnipeds	0.00
Birds	0.00
Cetaceans	1061.66

Annual average guild biomasses, landings and discards in the final year of each 100 year scenario run were used as the basis for deriving indices and revenues

Derived indices were:

- Ratio of the annual average biomass of apex predators (birds, pinnipeds and cetaceans) to fish;
- Annual trophic levels (calculated by NetIndices) aggregated to the whole ecosystem using biomass weighting;
- Fogarty index (Beet & Gaichas 2022, Link & Watson. 2019)
- Ryther index Beet & Gaichas 2022, Link & Watson 2019)

The formula for calculating trophic level, is contained in the NetIndices documentation (Soetaert & Kones 2014).

The Fogarty index is defined as ratio of total catches to total primary productivity in an ecosystem (Link & Watson, 2019). The units are parts per thousand, assuming the same currency for catch and primary production (in our case mMolesN.m^{-2}.y^{-1}. Annual net primary production is an output from the StrathE2E model, derived as the gross nitrate and ammonia uptake less metabolic losses.

The Ryther index is defined as total catch per unit sea surface area in the ecosystem (Link & Watson, 2019). The units are mt km^{-2} y^{-1}

RESULTS

North Sea

Guild-level biomasses, catch and landed weights, and revenues in the North Sea model in relation to the effort multiplier scenarios are shown in Figures 8 – 11. Biomasses of fish and top predators decreased with increasing effort multiplier. Released from predation, the biomass of carnivorous zooplankton increased. Small cascading trophic effects were present at the phytoplankton and zooplankton levels.

Migratory fish appeared resilient to increasing fishing effort in the model. This was because this guild was not a permanent resident in the model domain. An seasonal immigration flux of migratory fish into the model was part of the boundary conditions for the model, and this was independent of the effort multiplier scenarios – ie the global biomass of the migratory fish stock (archetype: mackerel) was not affected by harvesting within the model domain. The assumption is that harvesting within the North Sea model represents a minor component of the total annual removals from the global stock in the northeast Atlantic. Nevertheless, the net migration flux of migratory fish (annual immigration less annual emigration) was dependent on the fishing effort since biomass was harvested inside the model.

The model was able to sustain increasing total landings and revenue with increasing fishing effort even out to 8x the baseline rates. However, this was sustained largely by the annual immigration of migratory fish. The resident planktivorous and demersal fish in the model were depleted and extirpated at the highest fishing efforts.

The scaling of fishing effort had a large effect on the biomasses of the top predators in the model (birds, pinnipeds and cetaceans), which were severely depleted relative to an un-fished state, even in the baseline model (Figures 12 – 14). This was partly due to direct by-catch by certain gears, and partly as a bottom-up trophic effect of depletion of their food supply. The ratio of biomasses of top predators to fish declined with increasing fishing. By-catch quantities, and in the case of cetaceans the directed landings quantity, varied in response to changing abundances in the sea, and the changing mortality rate duee to fishing gears.

Mean trophic levels of the entire food web, the upper part of the web (fish and top predators, and the predators themselves, along with the components of the catch (landings and discards), all declined with increasing fishing effort (Figure 15). This reflected the progressive loss of high trophic level guilds from the food web.

Net primary production decreased with fishing effort (Figure 16). In StrathE2E, phytoplankton dynamics are integrated into the model food web and so primary production is subject to top-down cascading trophic effects arising from the removal of higher trophic levels from the system. The Fogarty index included this dynamic aspect of the primary production. Levels of the Fogarty index and the Ryther index in even the baseline model both exceeded the thresholds suggested by Link and Watson (2019) as representing optimal harvesting of the ecosystem, and were clearly in the realm of ecosystem over-exploitation.

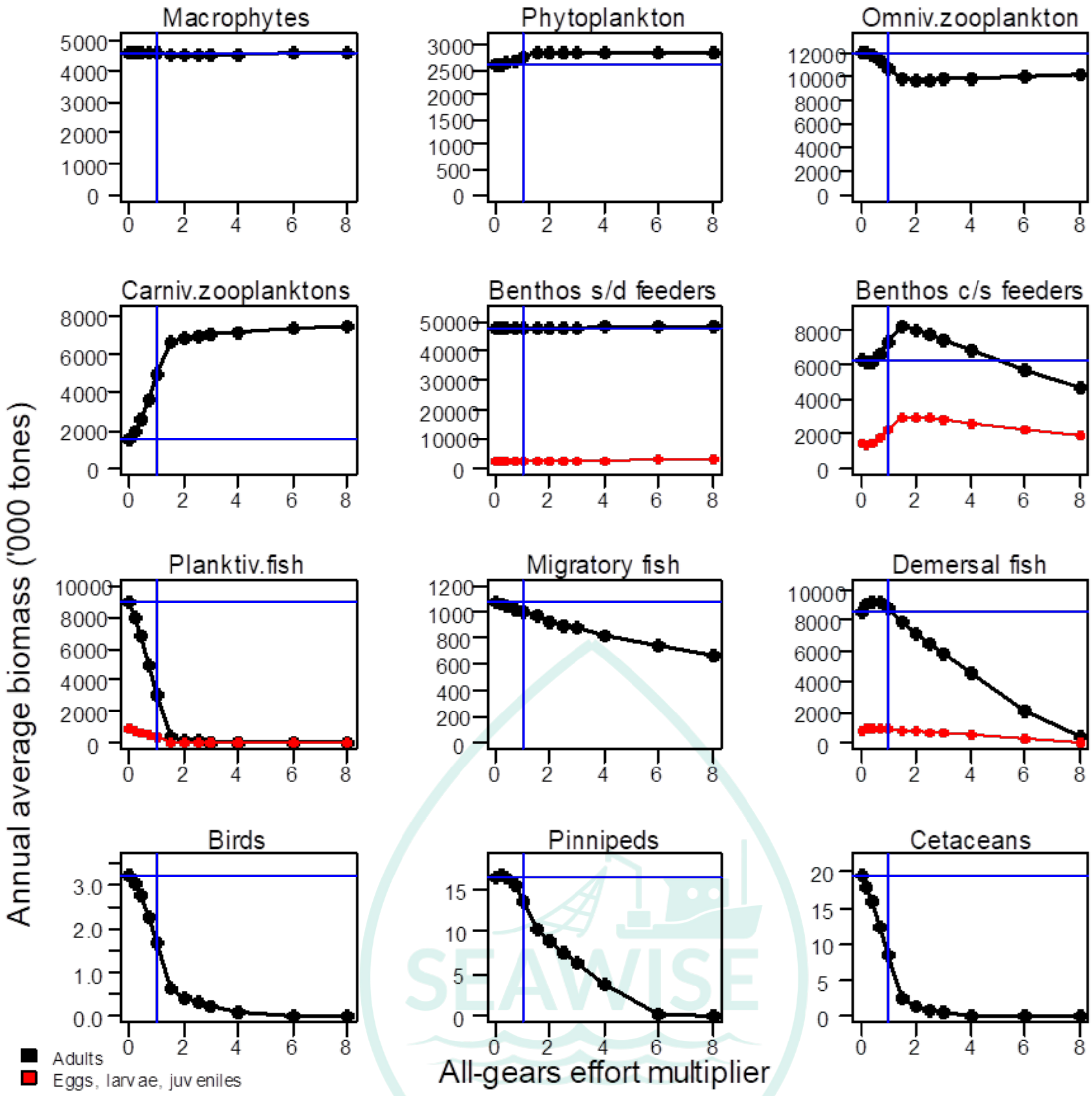

Figure 8. Steady state annual average biomasses (thousands of tonnes) for each guild in the North Sea relative to effort multiplier scenarios.

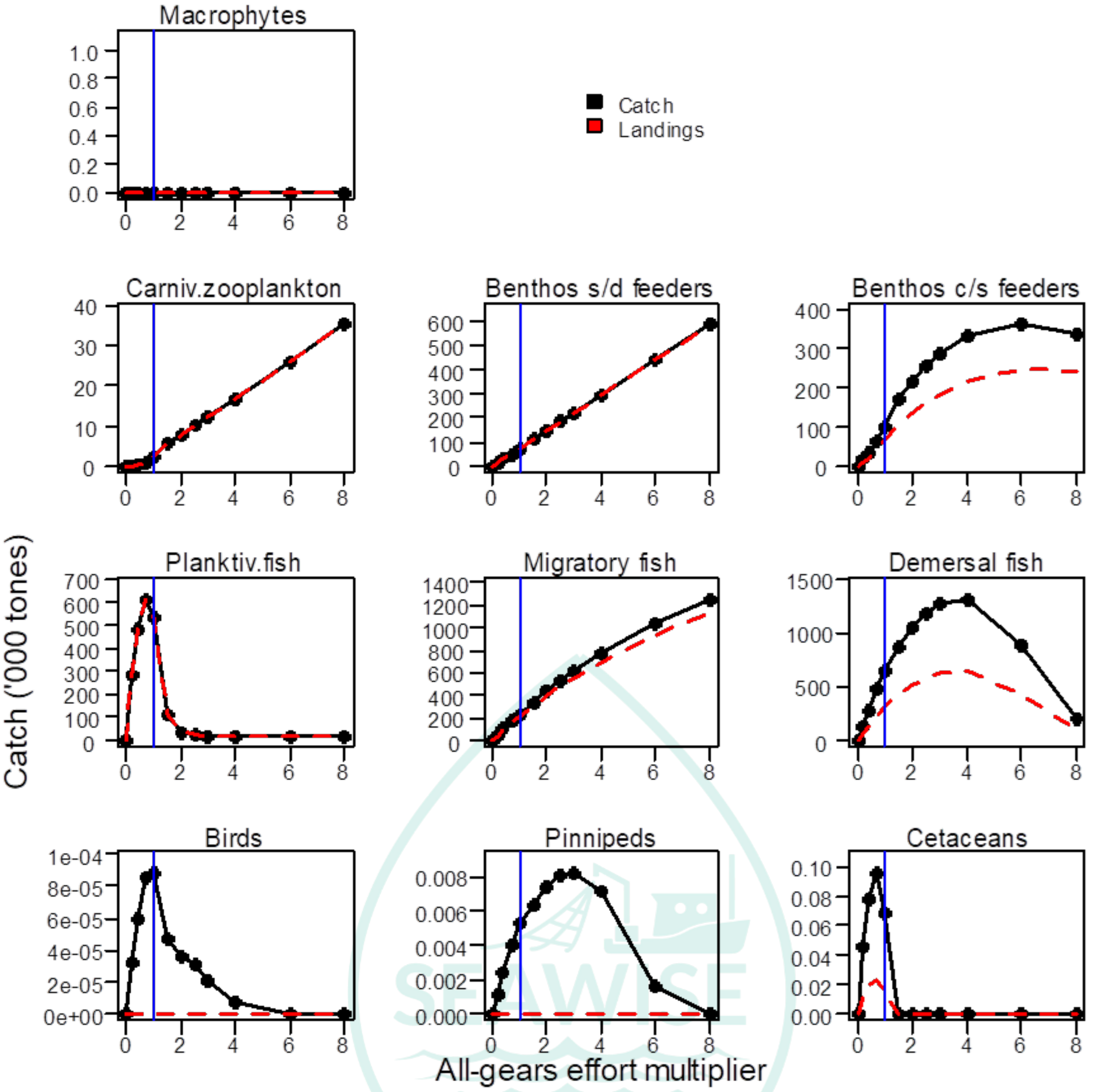

Figure 9. Steady state catch and landing weights (thousands of tonnes) for each guild in the North Sea relative to effort multiplier scenarios

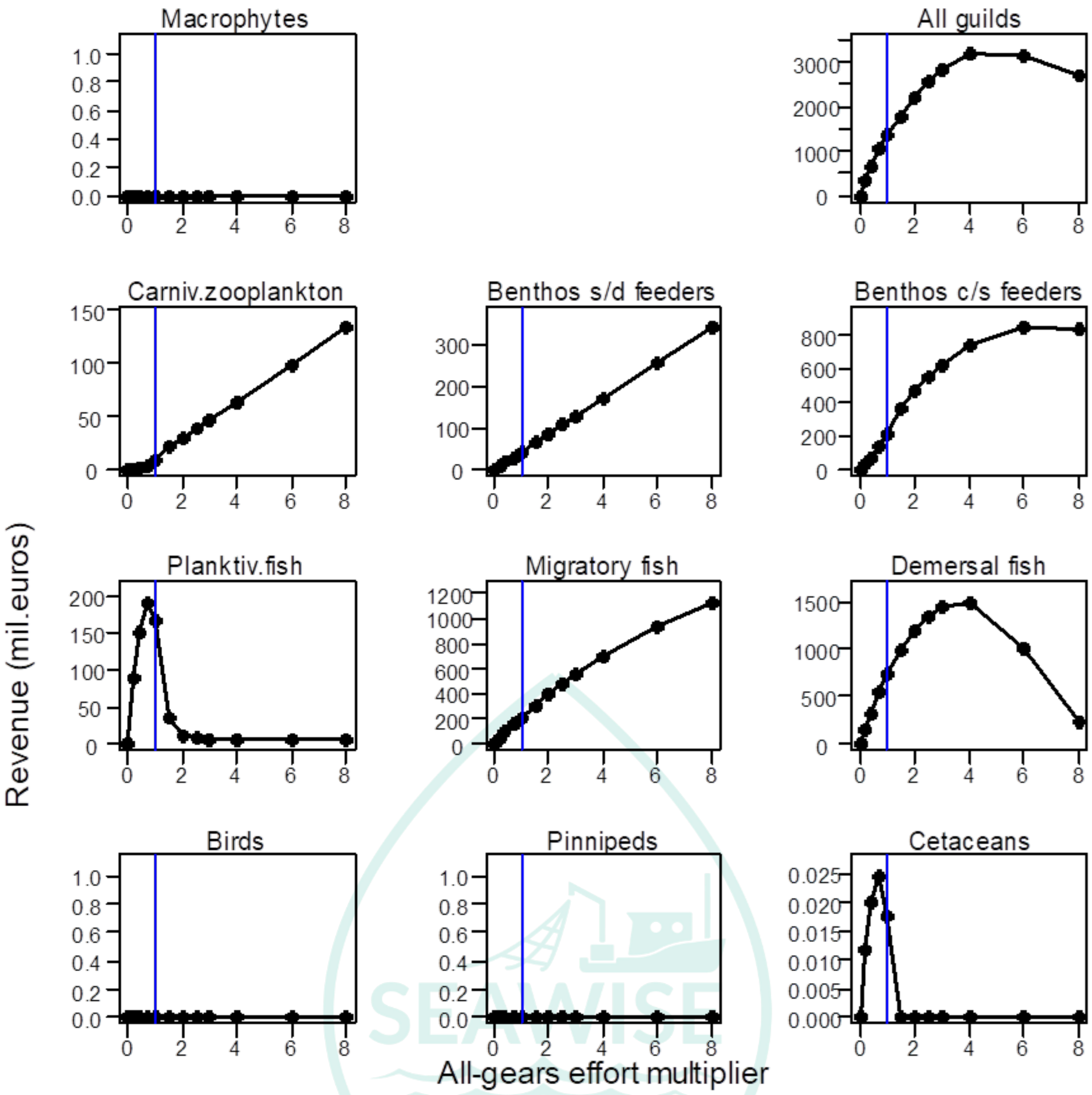

Figure 10. Steady state revenues (millions of euros deflated to 2013) for each guild in the North Sea relative to effort multiplier scenarios

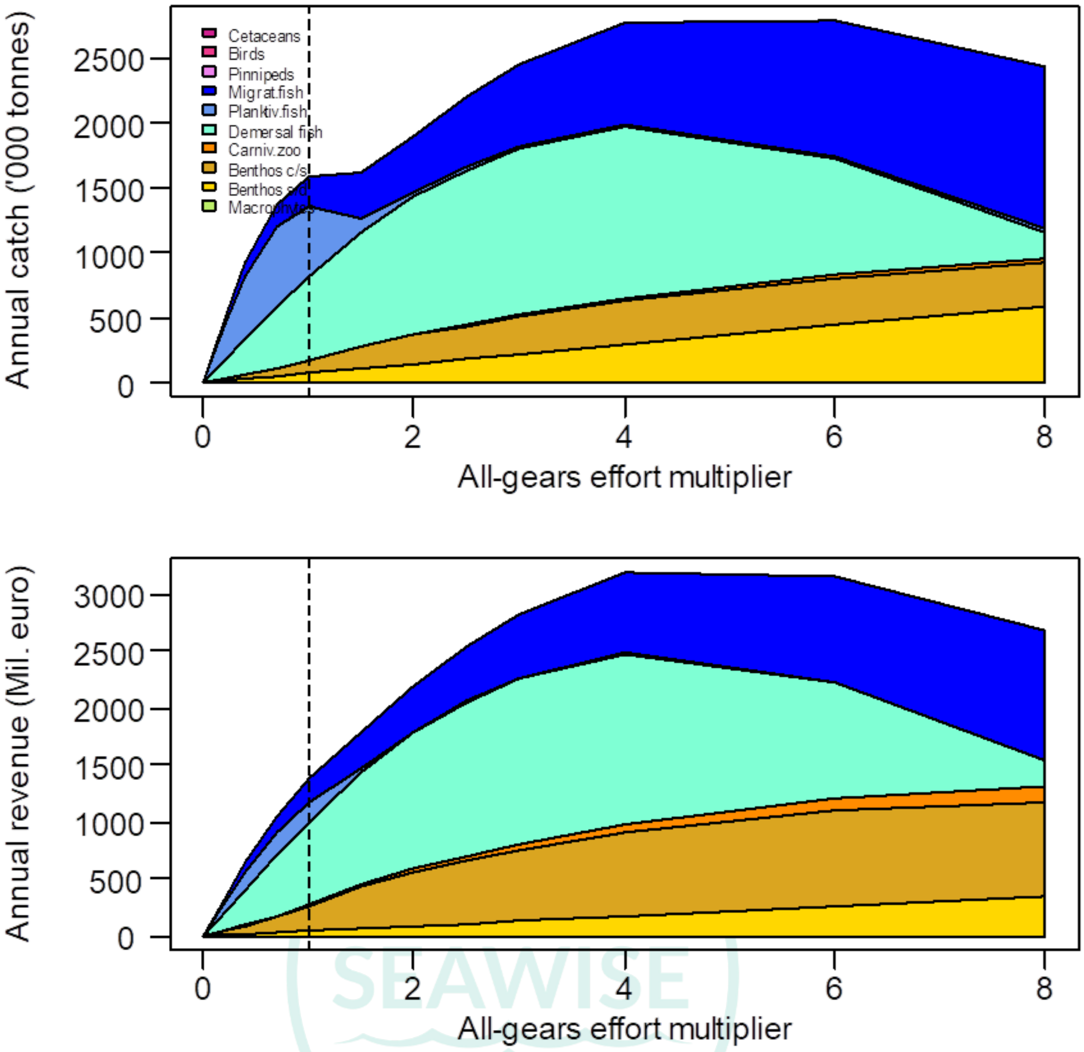

Figure 11. Steady state total catch weight (thousands of tonnes) and revenues (millions of euros deflated to 2013) broken down by guild in the North Sea relative to effort multiplier scenarios

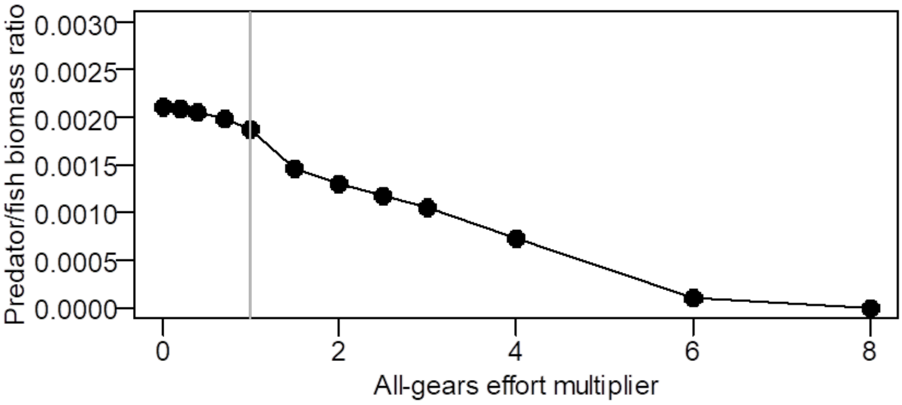

Figure 12. Steady state ratios of annual average biomasses of apex predators (birds, pinnipeds and cetaceans) to the biomass of fish in the North Sea model, relative to effort multiplier scenarios

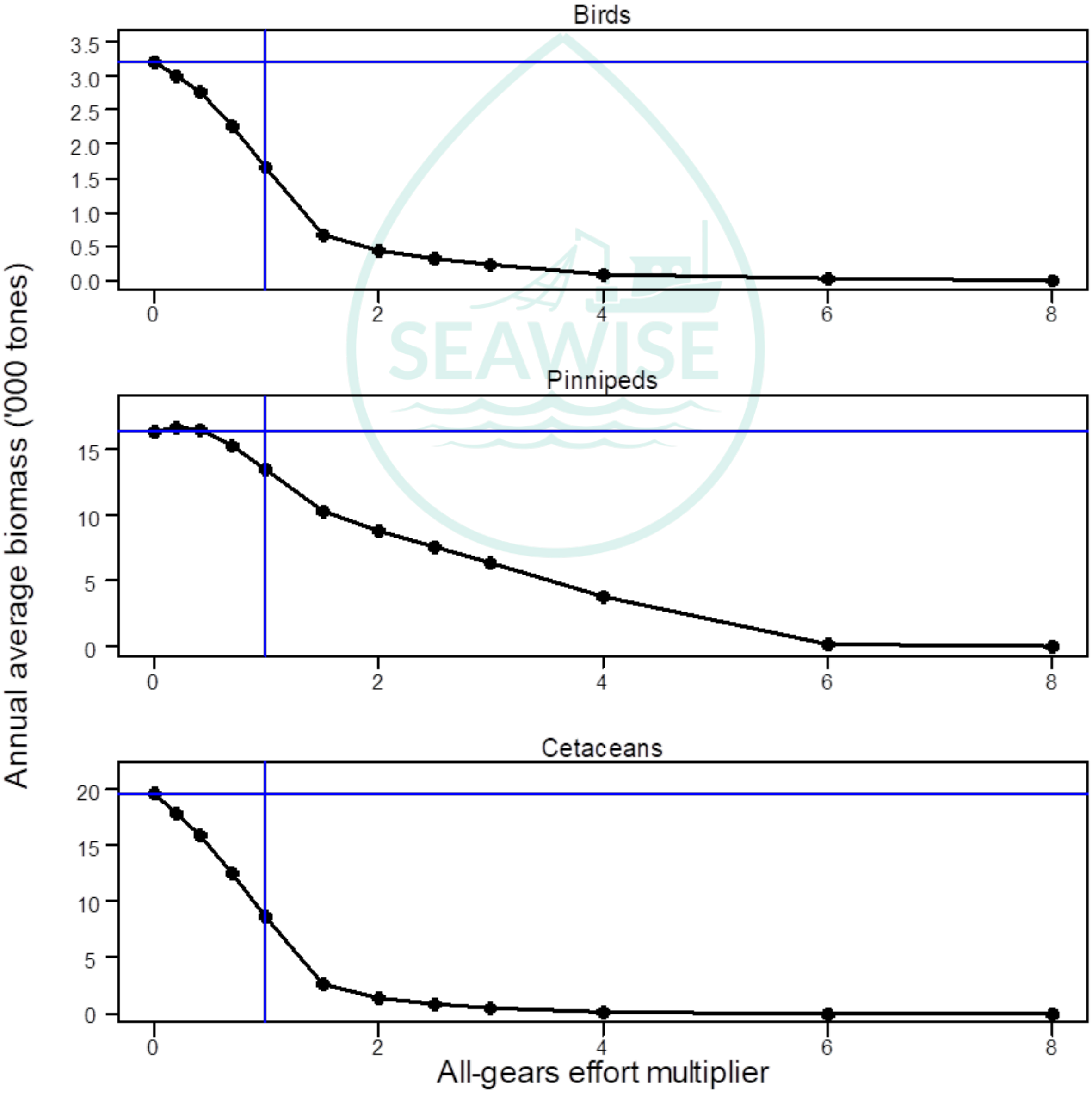

Figure 13. Steady state annual average biomasses of the apex predators in the North Sea model, relative to effort multiplier scenarios

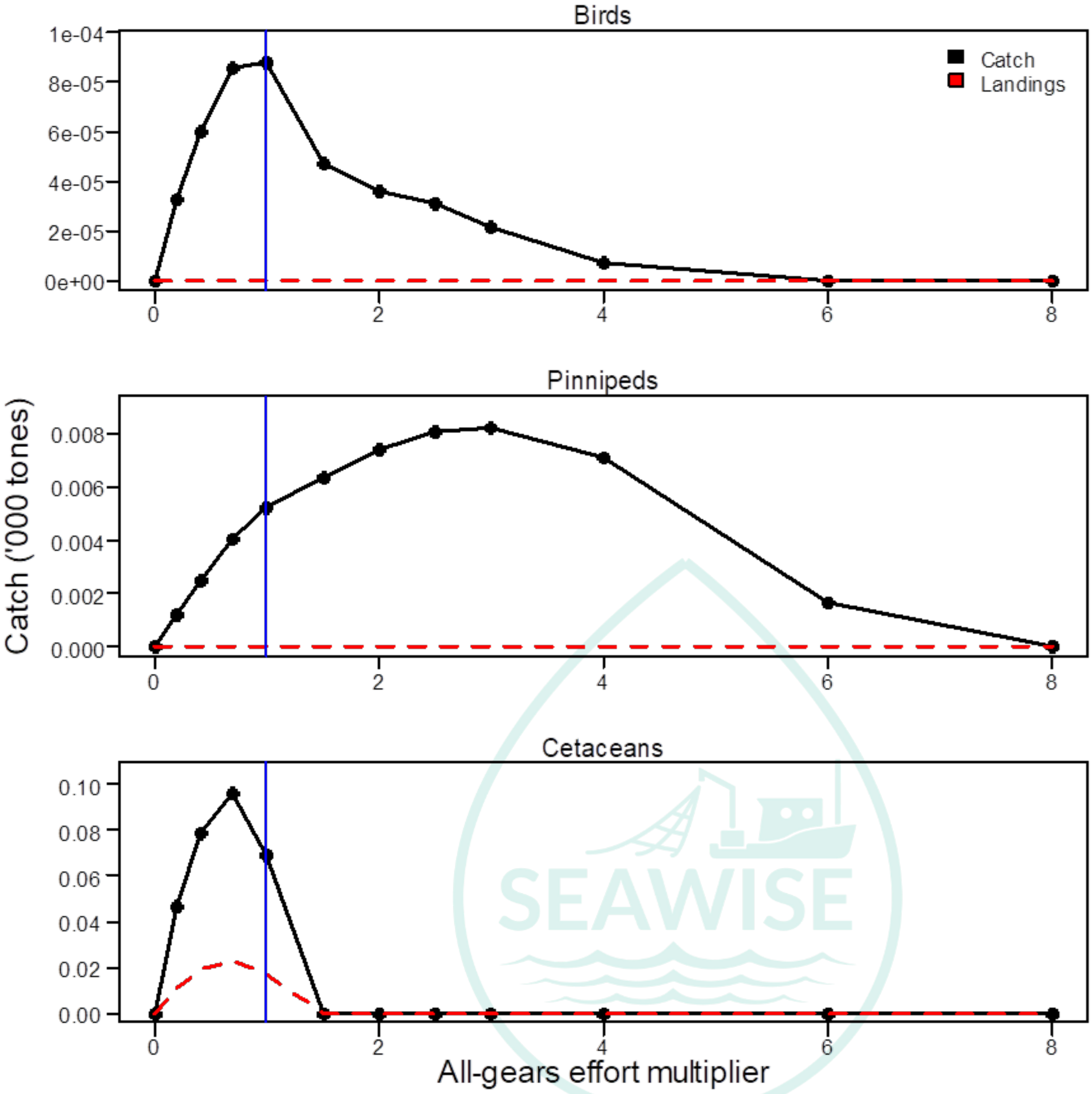

Figure 14. Steady state annual catches and landings of the apex predators in the North Sea model, relative to the effort multiplier scenarios

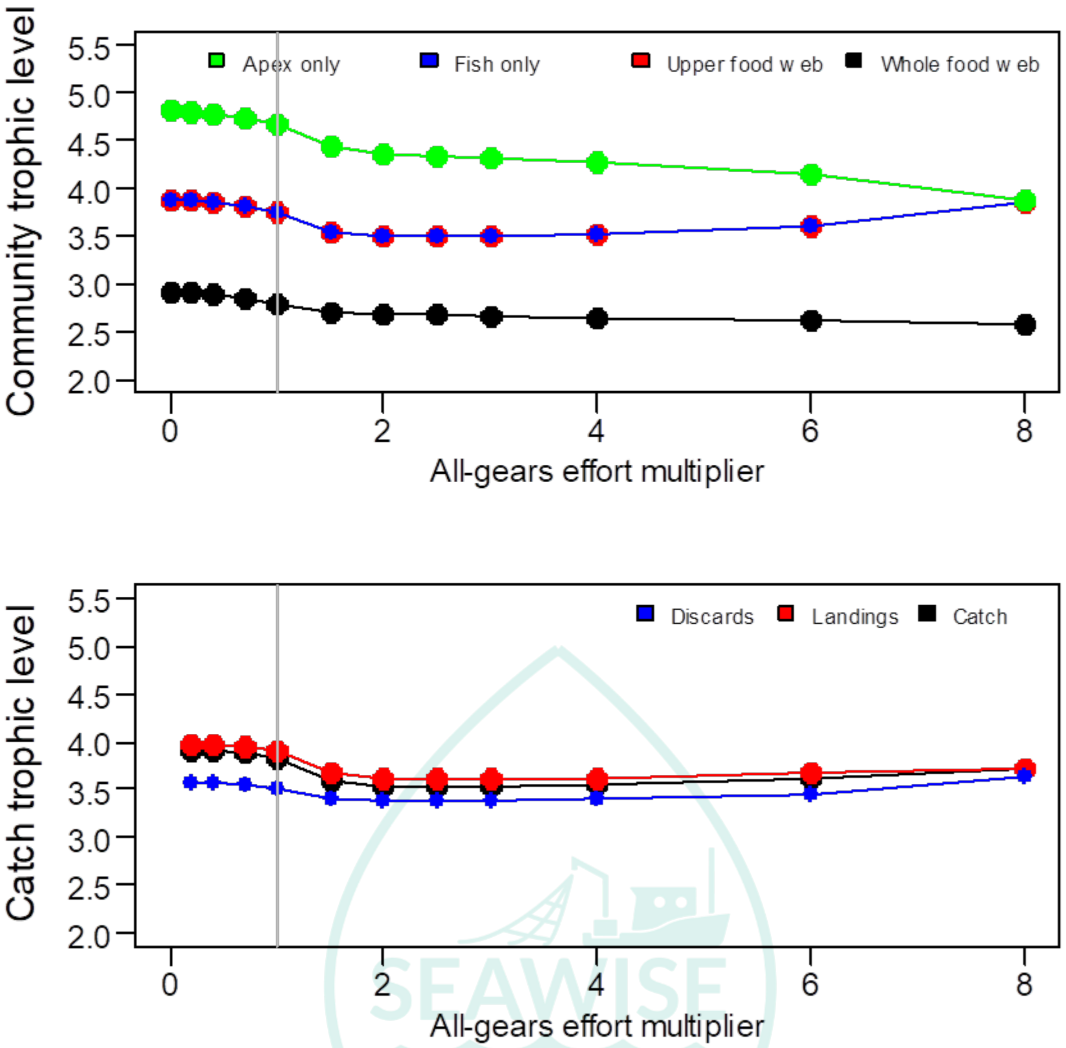

Figure 15. Community trophic level of combined guilds in the model as a function of the multiplier applied to all gears in the North Sea. Upper panel: trophic levels in the sea. Lower panel: trophic levels in the catch

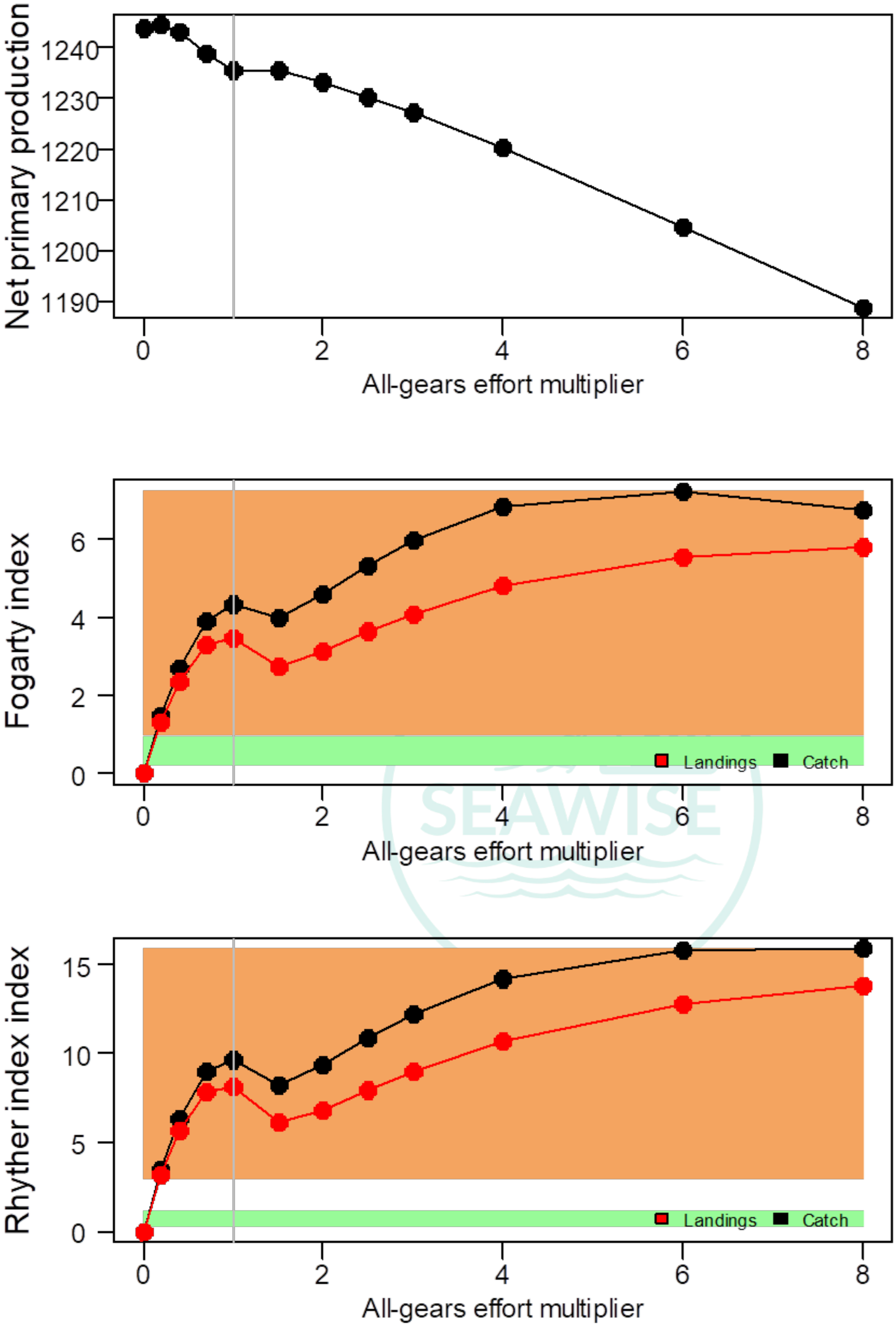

Figure 16. Upper panel: Annual net primary production (mMolesN.m^{-2}.y^{-1}) simulated by the North Sea model in relation to effort multiplier scenarios. Middle panel: Fogarty index (landings or catch divided by net primary production) relative to effort multiplier scenarios. Lower panel: Ryther index (catch or landings tonnes.km^{-2}.y^{-1}) relative to effort multiplier scenarios. Green shaded areas in the Fogart index and Ryther index panels are regarded as optimal ranges (Link & Watson 2019; Beet & Gaichas 2022). The orange shaded areas are regarded as representing ecosystem overfishing. Vertical grey line at effort multiplier = 1 in each panel represents the baseline 2003-2013 model.

Celtic Sea

Guild-level biomasses, catch and landed weights, and revenues in the Celtic Sea model in relation to the effort multiplier scenarios are shown in Figures 17 – 20. As in the North Sea model, biomasses of fish and top predators decreased with increasing effort multiplier. Released from predation, the biomass of carnivorous zooplankton increased. Small cascading trophic effects were present at the phytoplankton and zooplankton levels.

Migratory fish – which were sustained by a constant annual boundary immigration regardless of fishing effort as in the North Sea model – formed the major part of landings and revenue at high fishing effort multipliers. The resident planktivorous and demersal fish in the model were depleted and extirpated at the highest fishing efforts.

Bird and pinniped guilds in the baseline 2003-2013 Celtic Sea model were more severely depleted relative to an unfished state than in the equivalent North Sea baseline (Figures 21 – 23). All top predator guilds were extirpated by even modest increase sin effort compared to the North Sea.
Direct effects of fishing on the top-predators were entirely due to bycatch, there being no hunting for cetaceans in the Celtic Sea.

As in the North Sea, mean trophic levels of the entire food web, the upper part of the web (fish and top predators, and the predators themselves, along with the components of the catch (landings and discards), all declined with increasing fishing effort (Figure 24). This reflected the progressive loss of high trophic level guilds from the food web. IN addition, the model indicated that trophic levels were overall lower in the Celtic Sea than in the North Sea across all effort scaling scenarios, suggesting a less efficient transfer of energy up the food web.

Net primary production decreased with fishing effort (Figure 25), a sin the North Sea. Overall levels of both the Fogarty and Ryther indices were lower than in the North Sea, but still exceeded the thresholds suggested by Link and Watson (2019) as representing optimal harvesting of the ecosystem, even in the baseline 2003-2013 fishing effort scenario. Higher effort scenarios were clearly in the realm of ecosystem over-exploitation.

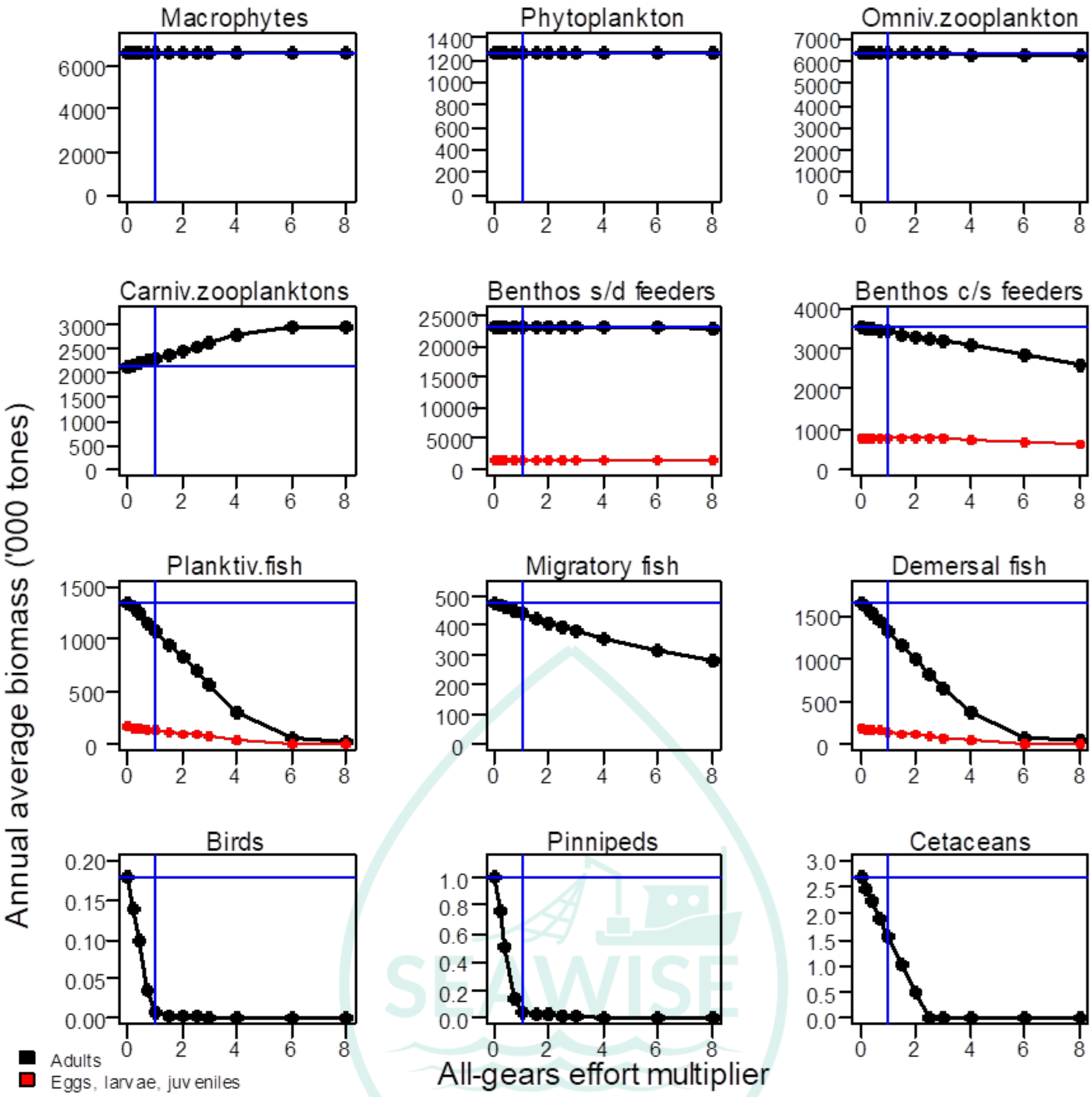

Figure 17. Steady state annual average biomasses (thousands of tonnes) for each guild in the Celtic Sea relative to effort multiplier scenarios.

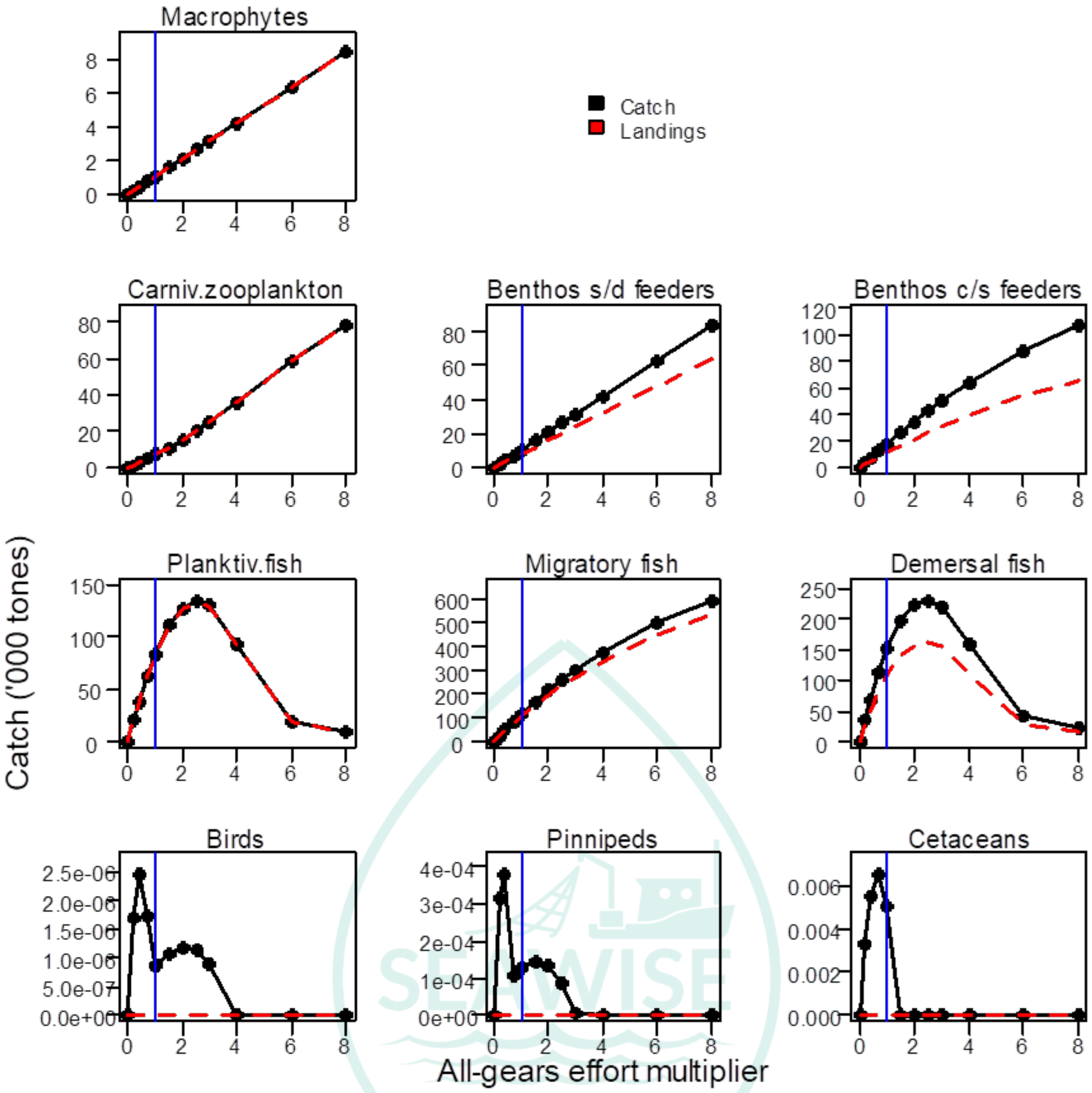

Figure 18. Steady state catch and landing weights (thousands of tonnes) for each guild in the Celtic Sea relative to effort multiplier scenarios

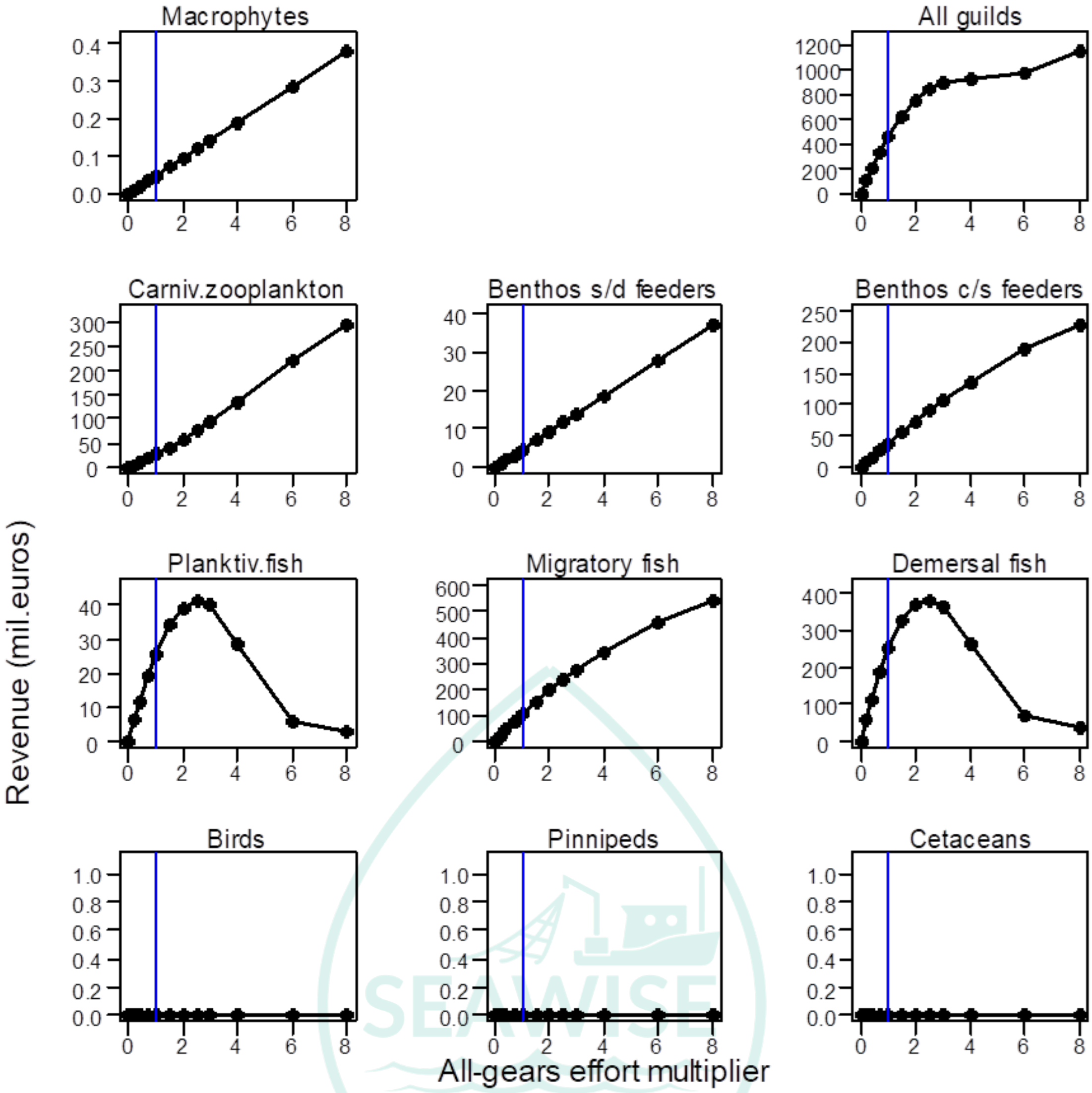

Figure 19. Steady state revenues (millions of euros deflated to 2013) for each guild in the Celtic Sea relative to effort multiplier scenarios

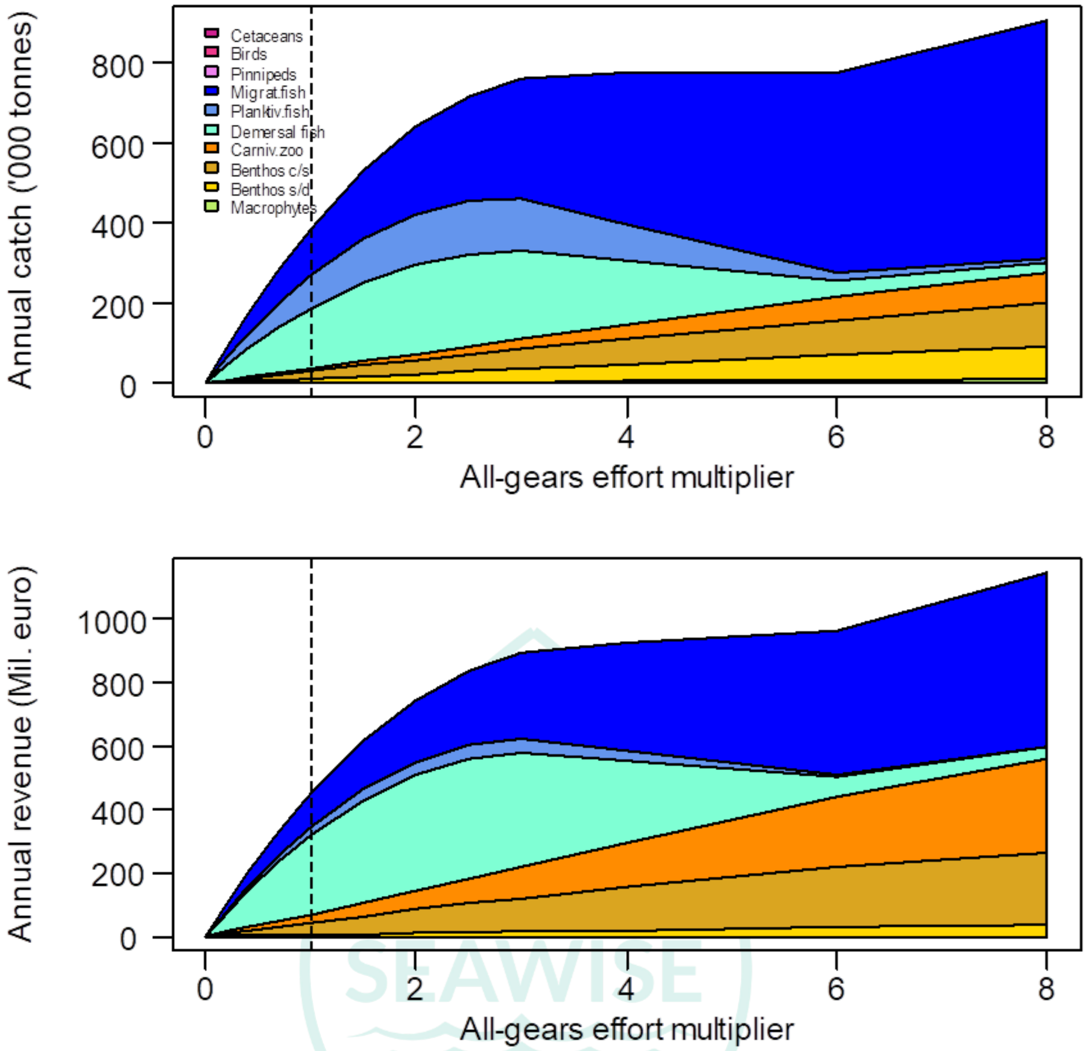

Figure 20. Steady state total catch weight (thousands of tonnes) and revenues (millions of euros deflated to 2013) broken down by guild in the Celtic Sea relative to effort multiplier scenarios

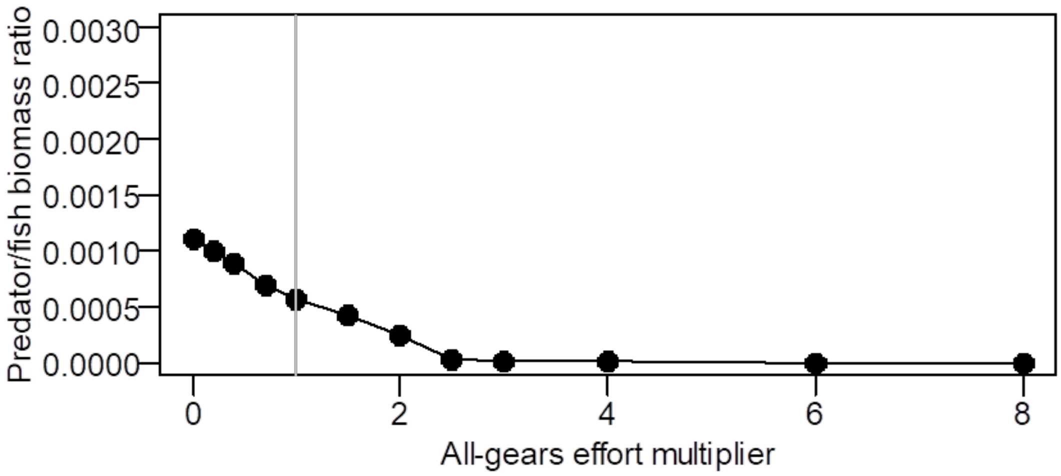

Figure 21. Steady state ratios of annual average biomasses of apex predators (birds, pinnipeds and cetaceans) to the biomass of fish in the Celtic Sea model, relative to effort multiplier scenarios

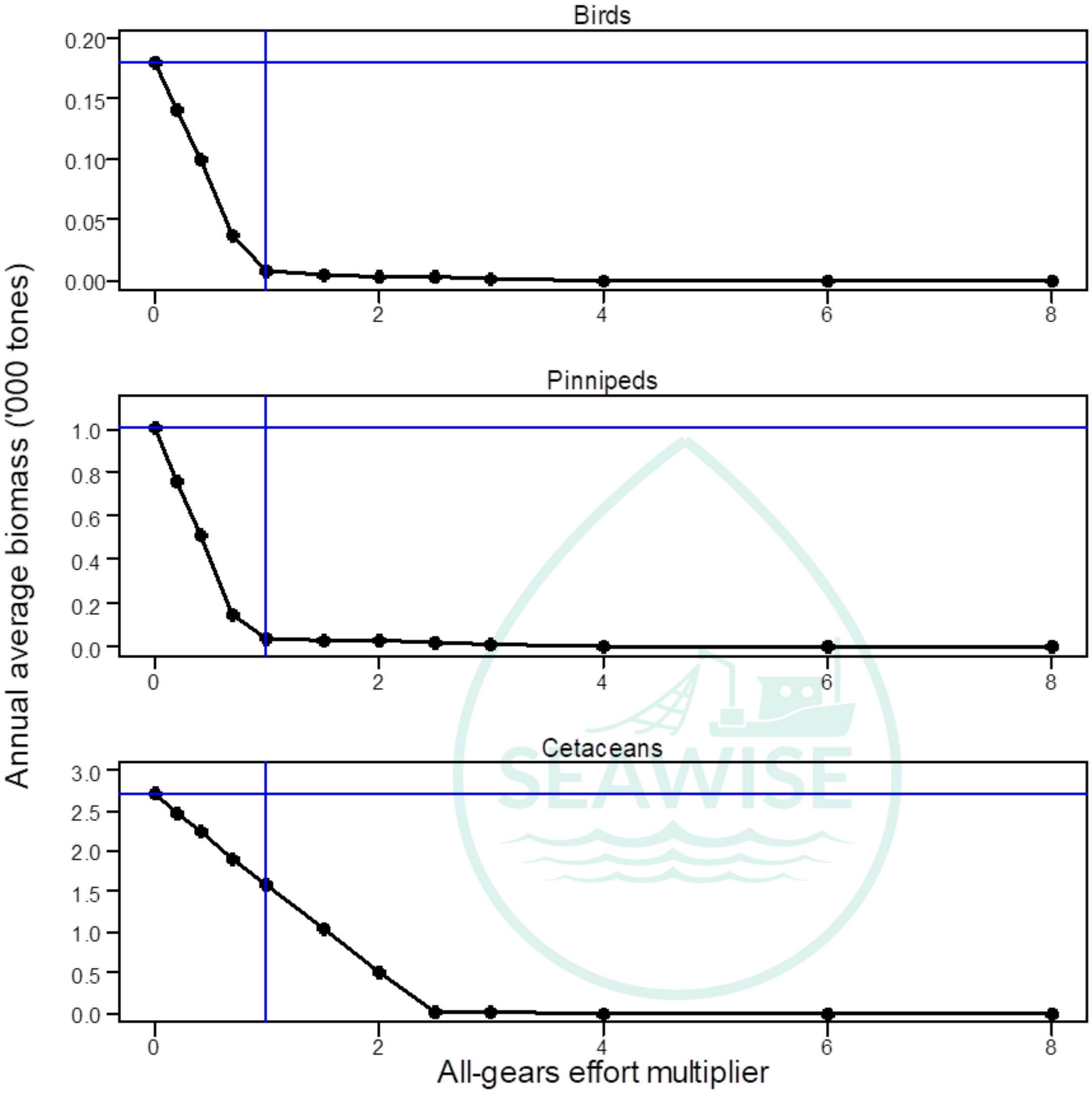

Figure 22. Steady state annual average biomasses of the apex predators in the Celtic Sea model, relative to effort multiplier scenarios

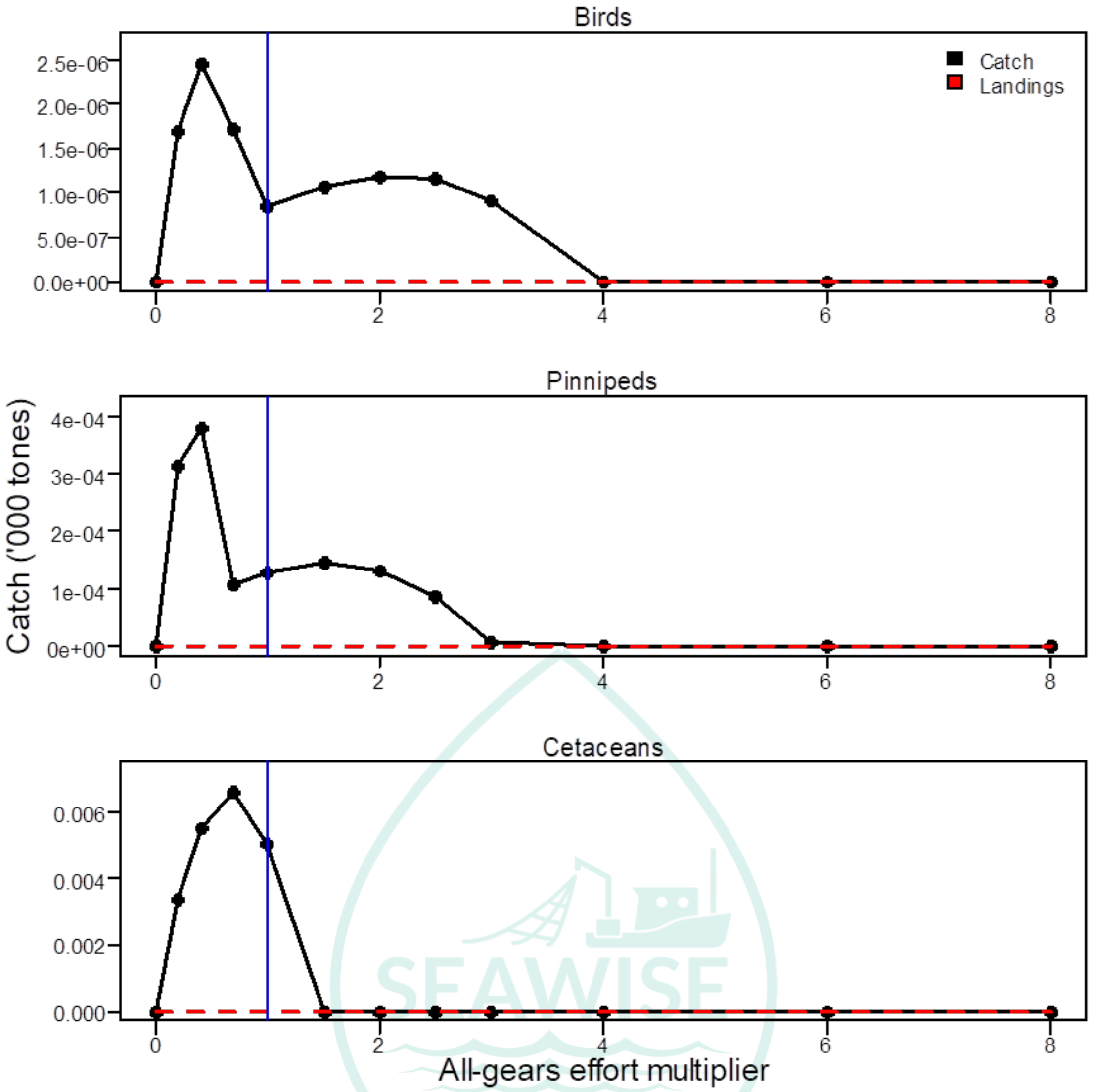

Figure 23. Steady state annual catches and landings of the apex predators in the Celtic Sea model, relative to the effort multiplier scenarios

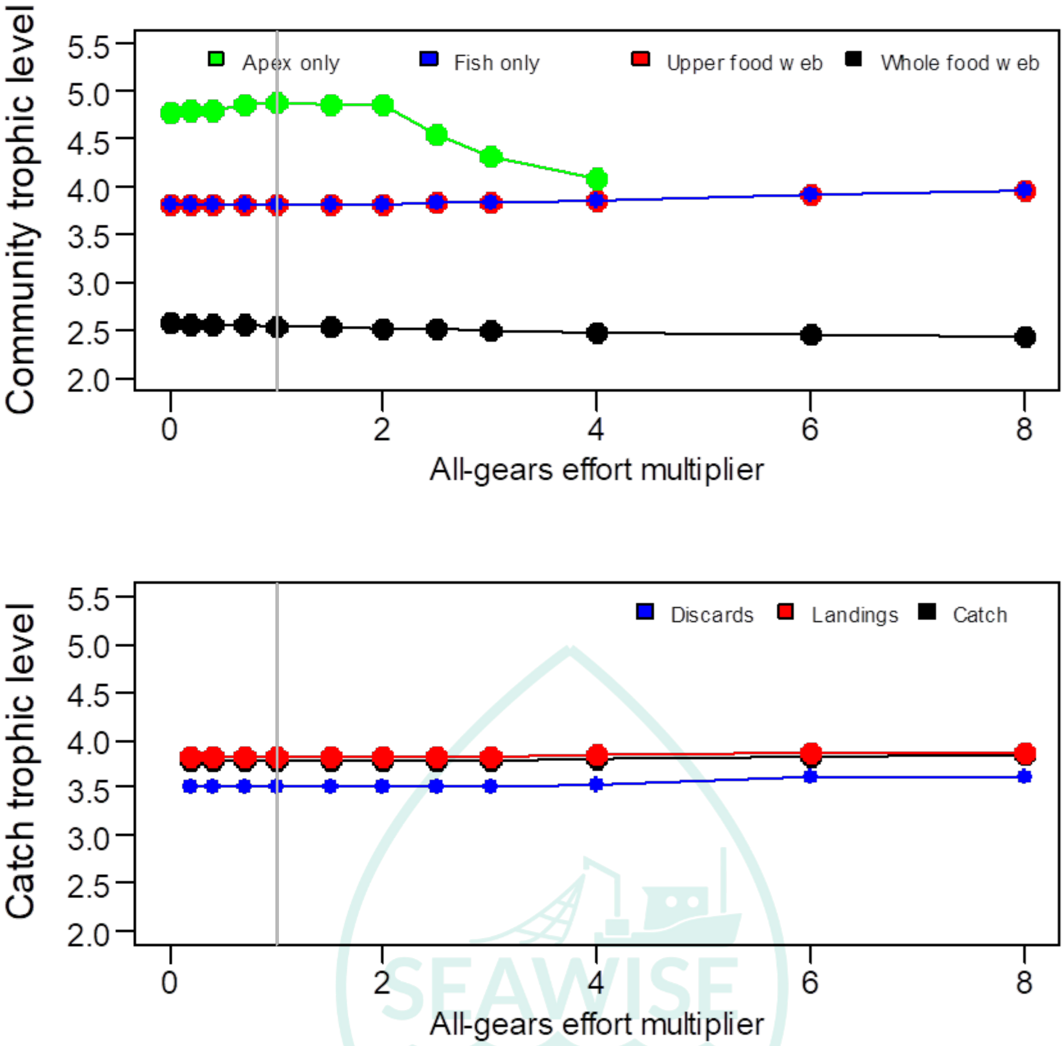

Figure 24. Community trophic level of combined guilds in the model as a function of the multiplier applied to all gears in the Celtic Sea. Upper panel: trophic levels in the sea. Lower panel: trophic levels in the catch

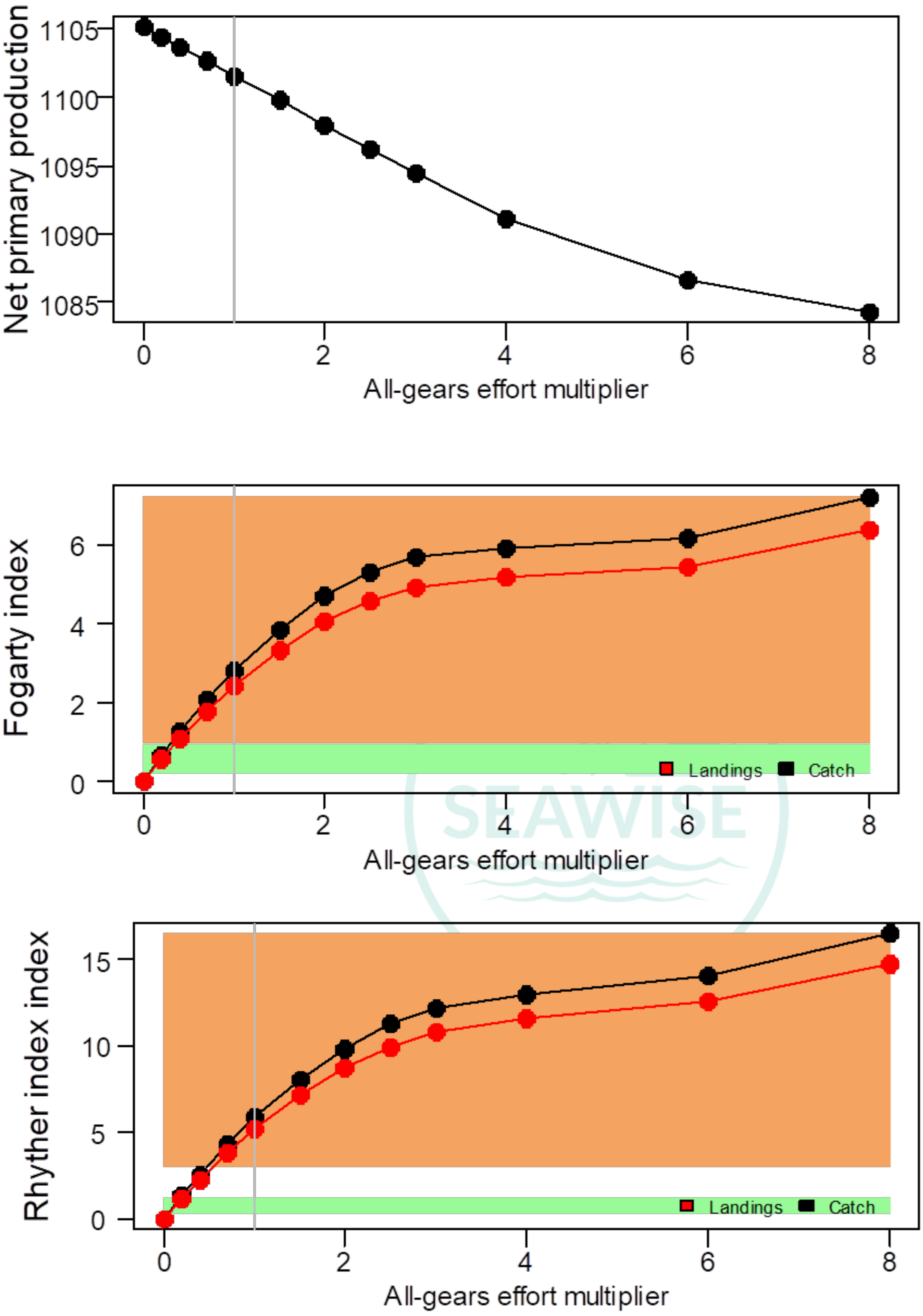

Figure 25. Upper panel: Annual net primary production (mMolesN.m^{-2}.y^{-1}) simulated by the Celtic Sea model in relation to effort multiplier scenarios. Middle panel: Fogarty index (landings or catch divided by net primary production) relative to effort multiplier scenarios. Lower panel: Ryther index (catch or landings tonnes.km^{-2}.y^{-1}) relative to effort multiplier scenarios. Green shaded areas in the Fogart index and Ryther index panels are regarded as optimal ranges (Link & Watson 2019; Beet & Gaichas 2022). The orange shaded areas are regarded as representing ecosystem overfishing. Vertical grey line at effort multiplier = 1 in each panel represents the baseline 2003-2013 model.

CONCLUSIONS

Both the North Sea and Celtic Sea StrathE2E models illustrate the trade-offs between economic yield from fisheries and conservation of the ecosystem. Sustained by the seasonal invasion of these shelf ecosystems by portions of the wider northeast Atlantic stocks of migratory fish (especially Atlantic mackerel), the models indicate that it would be technically possible to generate higher economic yields than in the baseline 2003-2013 cases. However this assumes that harvesting within each ecosystem does not significantly impact the wider ocean-scale stock, and the penalty would be extirpation of the rest of the fish and top-predator guilds in the food web.

The simulated Fogarty and Ryther indices both suggest that even the baseline 2003-2013 systems are subject to ecosystem exploitation. Top predator depletion and mean trophic levels suggest that the baseline Celtic Sea is in a more heavily exploited state than the North Sea.

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8.4 Annex 4: Evaluating FLBEIA scenarios for North Sea demersal stocks in a multispecies (SMS) context.

Morten Vinther, DTU Aqua, March 2023

Summary

Scenarios for North Sea stocks with Fishing mortality (F) for demersal species estimated externally from FLBEIA runs, and F on pelagic and short-lived estimated dynamically within the SMS model showed that the actual F chosen for demersal species affect the stock size and yield of prey species like herring, sandeel, sprat and Norway pout. Yield of these species may differ by more than 25% as an effect of F and stock sizes on the demersal species. Due to predation and cannibalism estimated within the SMS scenarios, the yield of demersal species will also differ from the yield estimated by FLBEIA scenario.

Introduction

A series of forecast scenarios for the North Sea demersal stocks (cod, whiting, haddock, saithe, plaice and sole) was made using the FLBEIA model (see section 8.1, Annex 1). These scenarios were made assuming a constant natural mortality (M), i.e. assuming that predation mortality is independent of the stock sizes of predators and preys. The SMS model, with the most recent review by ICES WGSAM (ICES, 2021c) of the hindcast mode, can make similar scenarios, however with dynamic estimation of M, as function of the stock size of predator and prey sizes. The purpose of such scenarios would be to analyse the effect on pelagic and industrial species given input F values (from FLBEIA) for the demersal species.

Data and methods

For a useful comparison of scenario F values from one model FLBEIA, in another model SMS, requires as a minimum that the historical data (assessments) are similar for the two models. FLBEIA scenarios are based on the most recent ICES assessment, while the SMS key-run (ICES, 2021c) was based on available data in the autumn 2020. Several stocks have however been benchmarked by ICES since 2020. For some stocks, input data have changed considerably, while reference points have just been changed for other stocks. The following changes were made for the SMS (catch data used by SMS were left unchanged due to workload for updating such):

Cod: Benchmarked in 2021. Survey data and reference points were changed. Natural of mortality of ages 3+ were updated with *ad hoc* values since 2011 by adding 0.16 per year for M1. This is approximately the same as done by ICES WGNSSK to model a potential natal migration of “North Sea cod” back to area 6a.

Whiting: Interbenchmarked in 2021 and revised in 2022. Updated survey data and reference points in SMS.

Haddock: Benchmarked in 2022. Change of survey data and reference points.

Saithe: Interbenchmark in 2019. Update of reference points.

Mackerel: SMS uses the estimated stock numbers from the ICES assessment as input. No changes made to SMS even though the ICES assessment result in 2022 are considerably different from the results for 2020.

Herring: Inter-benchmarked in 2021. Reference points were updated in SMS.

Plaice: Benchmarked in 2022. Update of survey data, natural mortality and reference points

Sole: Benchmarked in 2022. Update of survey data and reference points.

Assumptions for F in 2020.

The FLBEIA scenarios include F values from 2021, while the terminal year for SMS is 2019. F in 2020 for used in SMS scenarios was derived from the relative change in F as estimated by the ICES assessment between 2019 and 2020, and the F in 2019 as estimated from SMS.

Table 1. Average F as estimated by SMS for 2019, F for 2019 and 2020 as estimated by ICES in the most recent stock assessment, and F used for SMS in 2020.

Stock	SMS 2019	ICES 2019	ICES 2020	ICES change	SMS 2020
Cod	0.54	0.49	0.36	73%	0.40
Whiting	0.187	0.21	0.19	90%	0.17
Haddock	0.33	0.33	0.28	85%	0.28
Saithe	0.31	0.49	0.44	90%	0.28
Mackerel	0.187	0.18	0.23	128%	0.24
Herring	0.21	0.196	0.198	101%	0.21
N.sandeel	0.134	no data	no data		0.13
S.sandeel	0.06	no data	no data		0.06
Nor.pout	0.54	0.26	0.26	100%	0.54
Sprat	0.38	1.22	1.83	150%	0.57
Plaice	0.32	0.109	0.095	87%	0.28
Sole	0.3	0.47	0.33	70%	0.21

Scenario F values

For the demersal stocks, the FLBEIA model has produces a list of annual F per year, stock and scenario. These are applied directly by SMS even though the FLBEIA scenarios assume constant M, while M is estimated and variable between years in SMS scenarios.

Scenario F values for herring and mackerel are calculated by year within SMS from the ICES Advisory Rule (AR). The short lived species sandeel, sprat and Norway pout are managed by the "escapement strategy" where TAC is set such that a minimum biomass is left (escaped) after the fishery has taken place. This approach is combined with the use of an F_{cap} (and upper limit for F). The escapement strategy is not implemented in SMS. Instead, a HCR is applied, which estimate forecast F from the total biomass (TSB) in the beginning of the TAC year. F becomes zero for TSB below trigger1 and set at F_{cap} for TSB above trigger2. With TSB between trigger1 and trigger2, F is reduce linearly from $F_{cap.}$

Table 2. Parameters for HCR for short lived species

Stock	Ftarget (Fcap)	Trigger 1 (1000 t)	Trigger 2 (1000 t)
N.sandeel	0.30	940	1060
S.sandeel	0.60	390	800
Nor.pout	0.70	200	350
Sprat	0.69	175	400

For comparison, an extra scenario, "ICES-AR" was added. This scenario uses the ICES advice rule as HCR for all species except the short-lived. In contrast to the FLBEIA scenarios, F-values in the ICES-AR scenario are estimated dynamically from the HCR and model SSB in the scenario year.

Results

Updating the SMS input data to follow the presently applied ICES data had in general a minor effect on the results. Major changes are seen for cod (Figure 1), whiting (Figure 2) and plaice (Figure 3). The plaice assessment has changed considerably, but as plaice is not considered as a predator or prey in SMS, the changes will only affect the plaice assessment.

Figure 4 show the applied stock recruitment relations fitted in the SMS hindcast and used for scenarios.

Figures 5-16 shows the SMS hindcast and scenario results. There is a large initial increase in SSB for both cod (Figure 5) and whiting (Figure 6) as a result of the decrease in scenario F. SSB stabilizes afterwards at a lower value due to predation mortality and the SSB-recruitment relations applied.

Haddock (Figure 7) maintains a higher scenario SSB, due to the lower F, probably due to the lower cannibalisms, compared to cod and whiting.

Saithe (Figure 8) is not considered as a prey in SMS, and scenario results for saithe will only differ due to the chosen F.

All scenarios for mackerel (Figure 9) are identical. Mackerel is not considered as a prey in SMS, such that the scenario results are independent of other species. The same F values, derived from ICES AR, are used in all scenarios because FLBEIA scenarios do not include mackerel.

The same HCR (ICES AR) is applied for all scenarios for herring (Figure 10). The difference in output between scenarios is an indirect effect caused by the different stock sizes of predators and preys derived from the varying F values used by the FLBEIA scenarios. Yield of herring varies between 20-25% due to the chosen F for demersal species by the FLBEIA scenarios

The same picture is seen for Northern sandeel (Figure 11) and Southern sandeel (Figure 12), where yield of sandeel depends on the chosen F for demersal species. Yield of Northern Sandeel seems more sensitive to F on demersal species, than for Southern sandeel.

In relative terms, yield of Norway pout (Figure 13) seems very sensitive to F on demersal species, Scenario yield is however relatively small compared to the hindcast value, which might be an effect of a too restrictive proxy for the escapement strategy.

As a short-lived prey species, yield of sprat (Figure 14) is also sensitive to F and stock sizes of demersal species.

Plaice (Figure 15) and Sole (Figure 16) are not considered as a predator or prey in SMS, so the F and stock dynamic of these two species will not affect the other species.

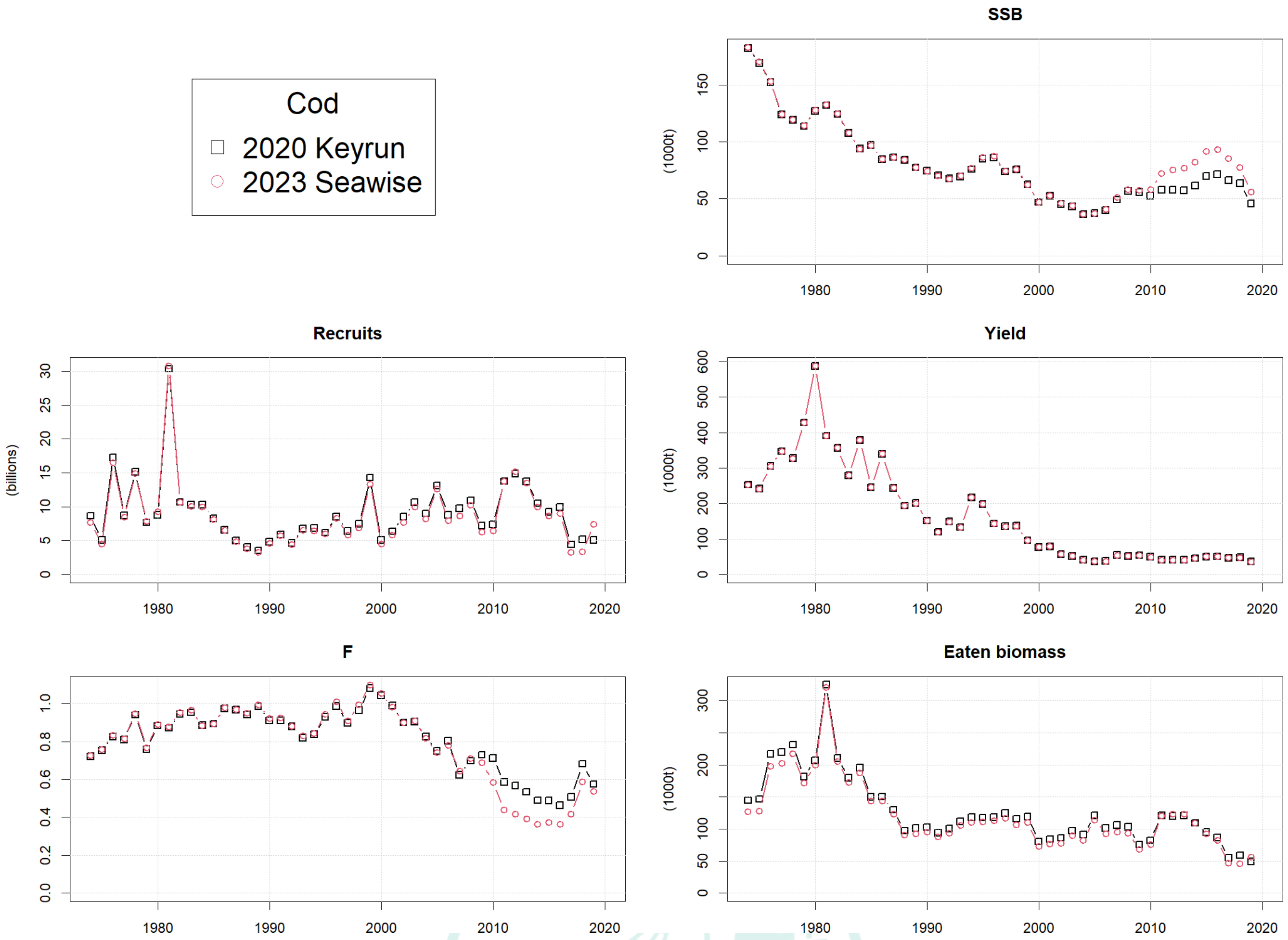

Figure 1: Cod. Comparison of the result from the SMS 2020 key-run and the SMS configuration where SMS input data are updated with the most recent input data from the ICES assessment.

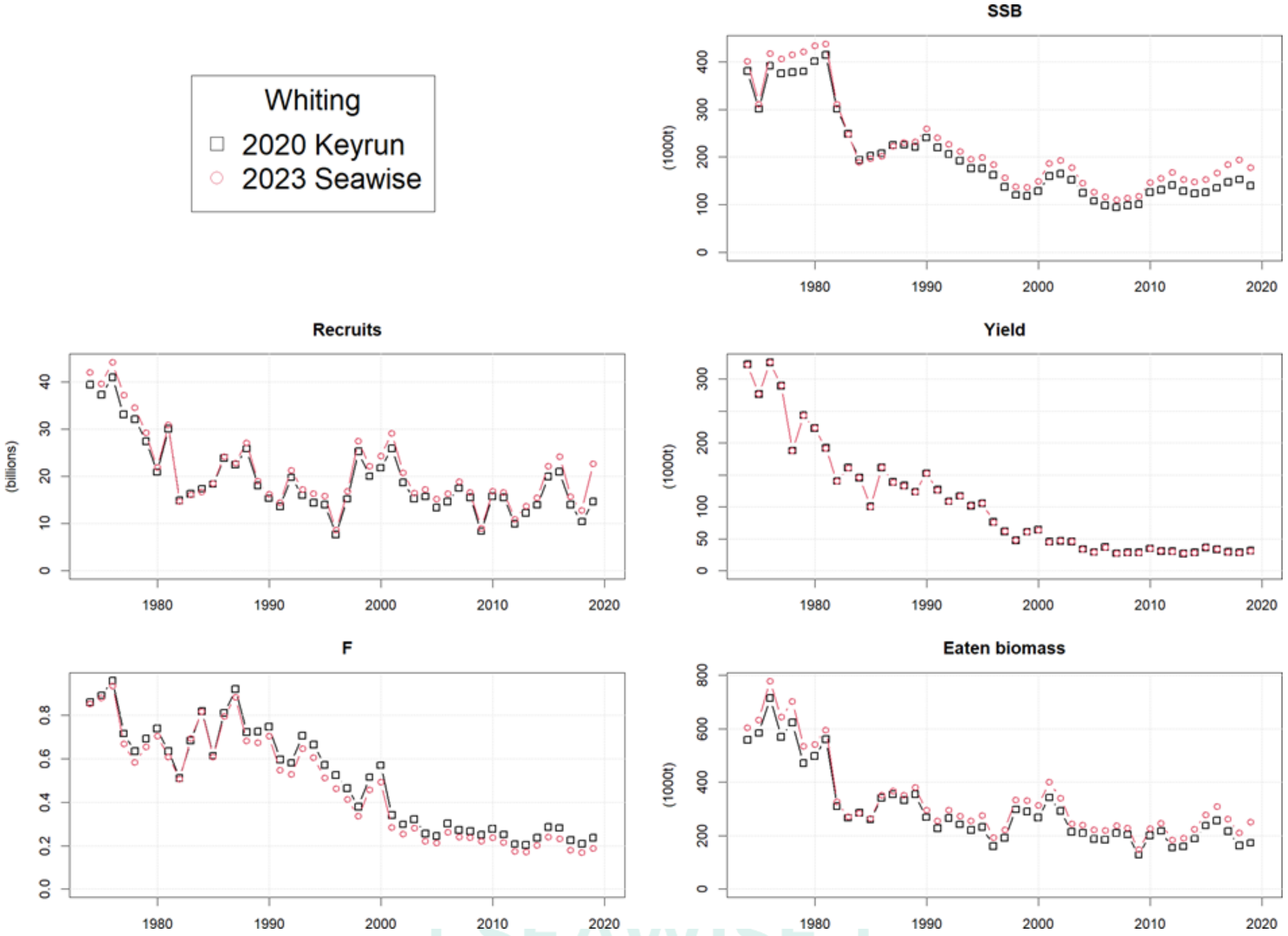

Figure 2: Whiting. Comparison of the result from the SMS 2020 key-run and the SMS configuration where SMS input data are updated with the most recent input data from the ICES assessment.

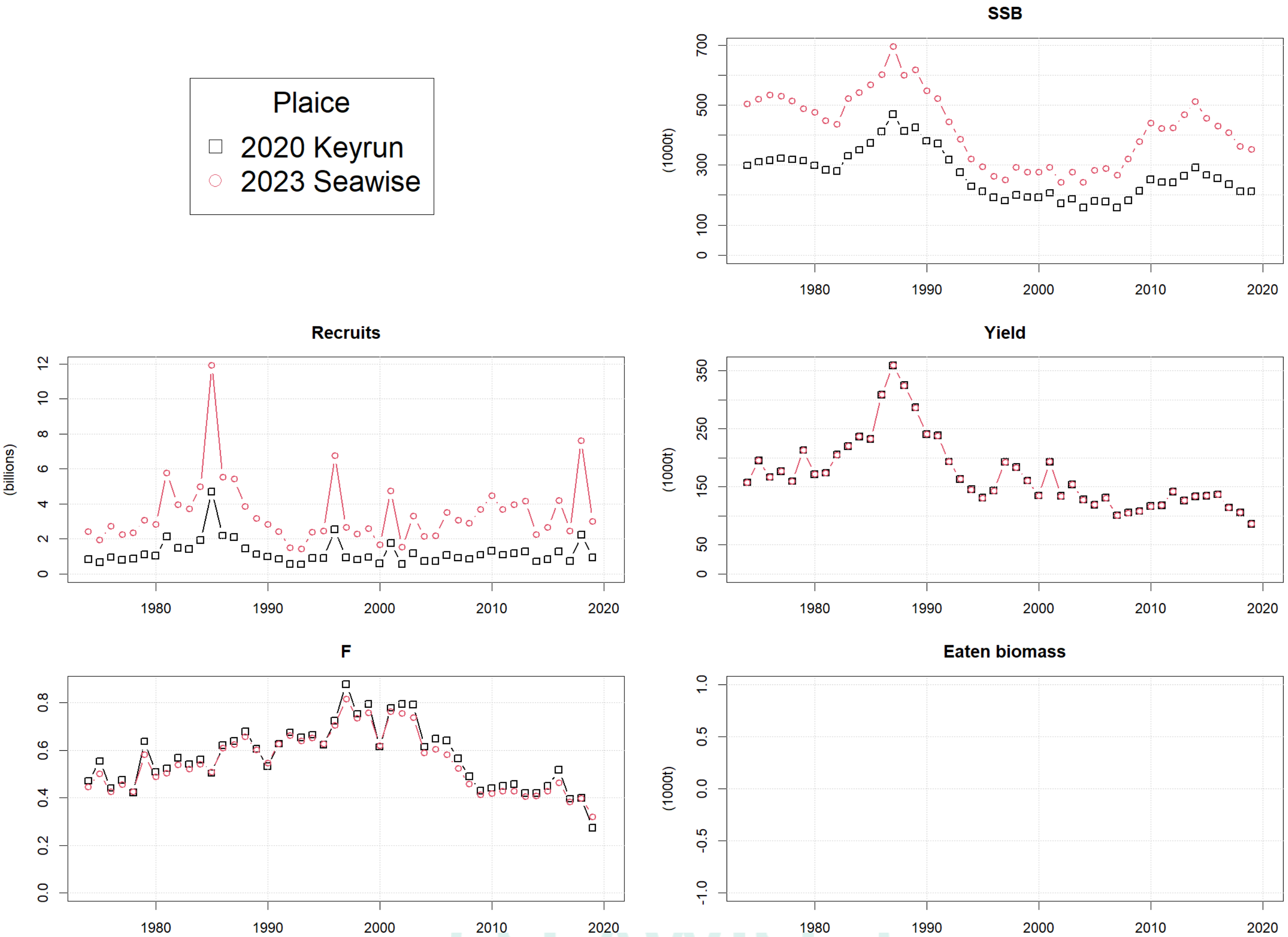

Figure 3: Plaice. Comparison of the result from the SMS 2020 key-run and the SMS configuration where SMS input data are updated with the most recent input data from the ICES assessment.

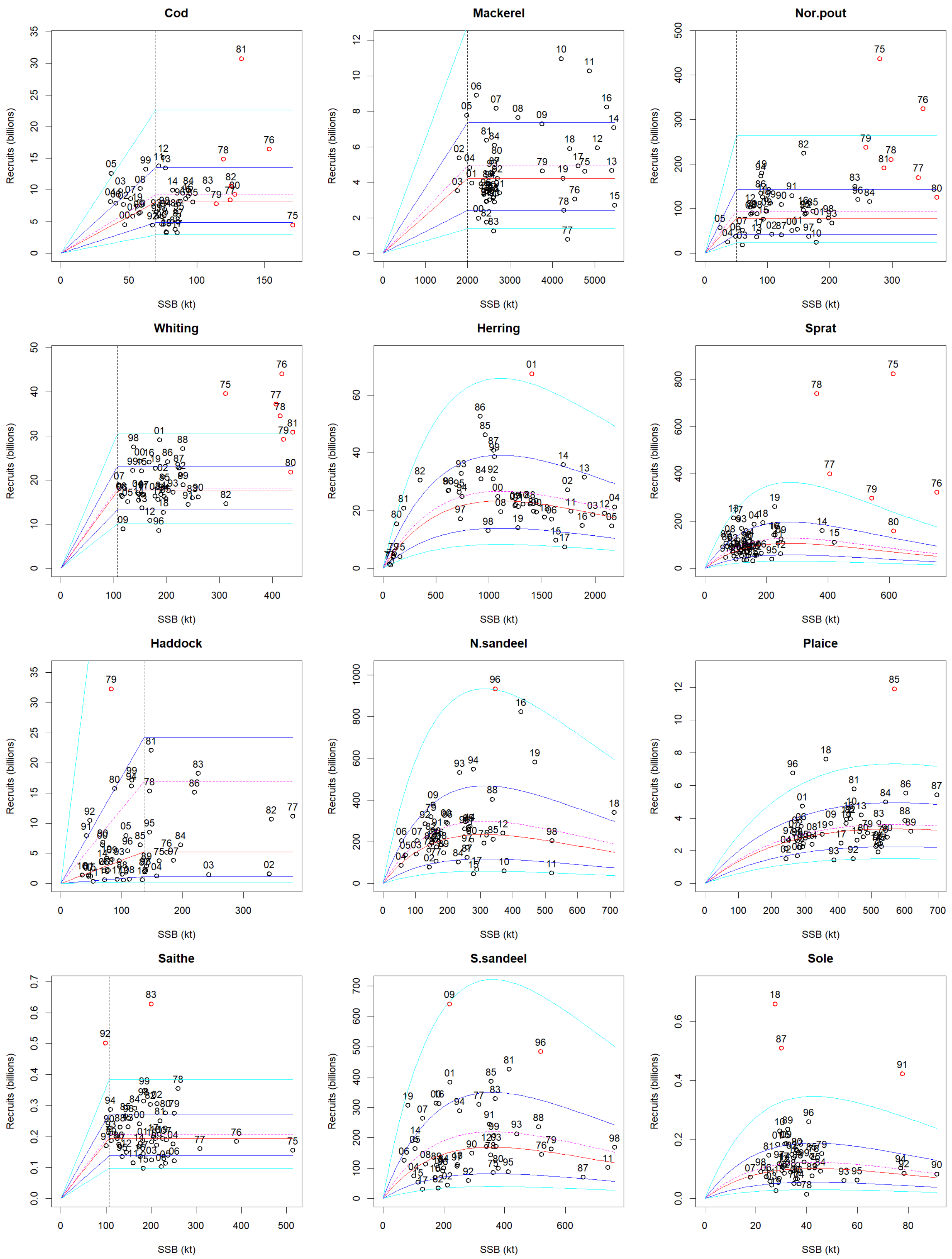

Figure 4: SSB-recruitment relations, showing, median and ± 1 and ± 2 std. The mean values (dotted line) are also shown. Years shown in red are not applied in the fitting

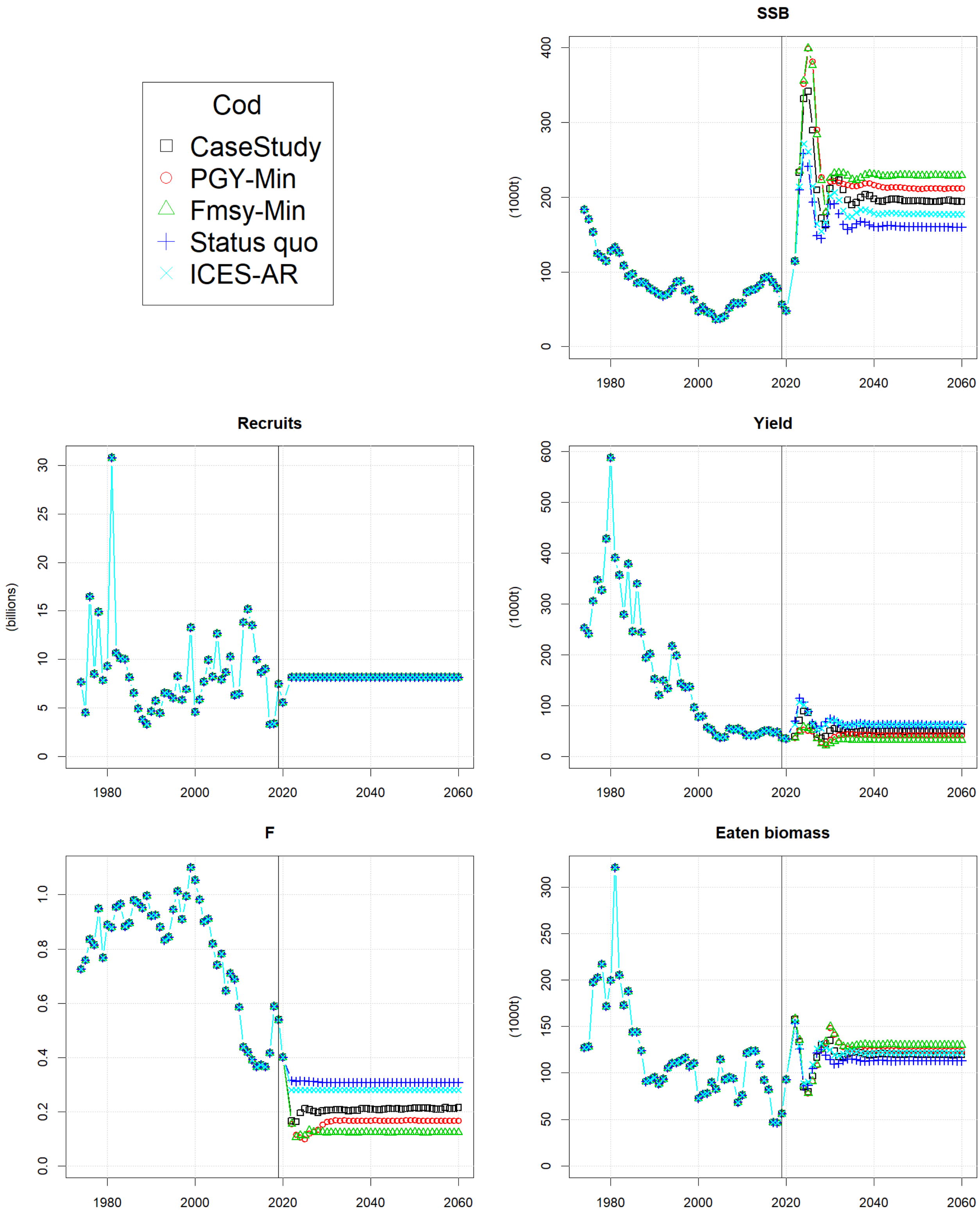

Figure 5: Cod. SMS results from scenarios with given input F values (2020-2060) for demersal species estimated within FLBEIA scenarios and from the ICES Advisory Rule. ”Eaten biomass” is the biomass of the given species eaten by the all SMS predators.

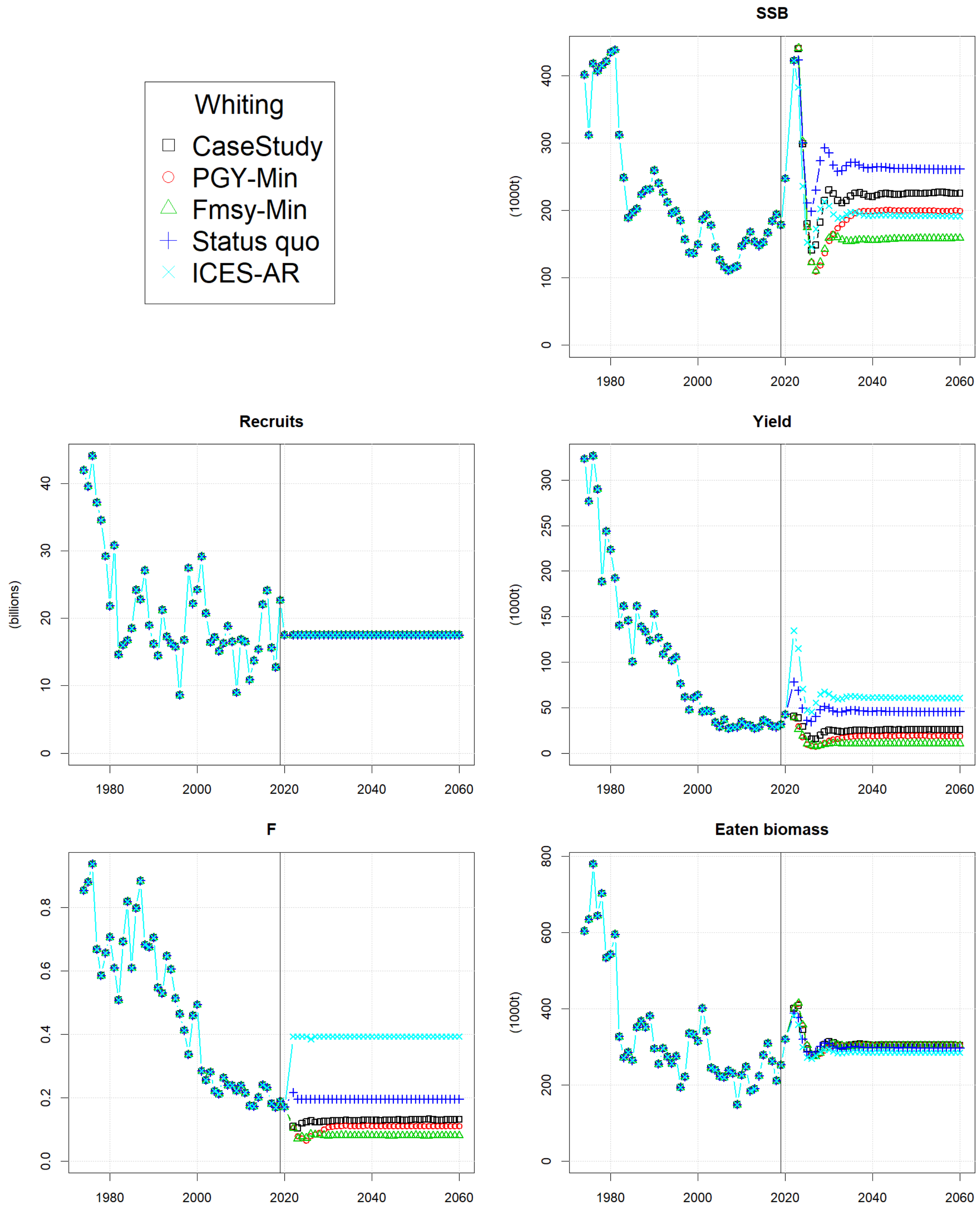

Figure 6: Whiting. SMS results from scenarios with given input F values (2020-2060) for demersal species estimated within FLBEIA scenarios and from the ICES Advisory Rule. ”Eaten biomass” is the biomass of the given species eaten by the all SMS predators.

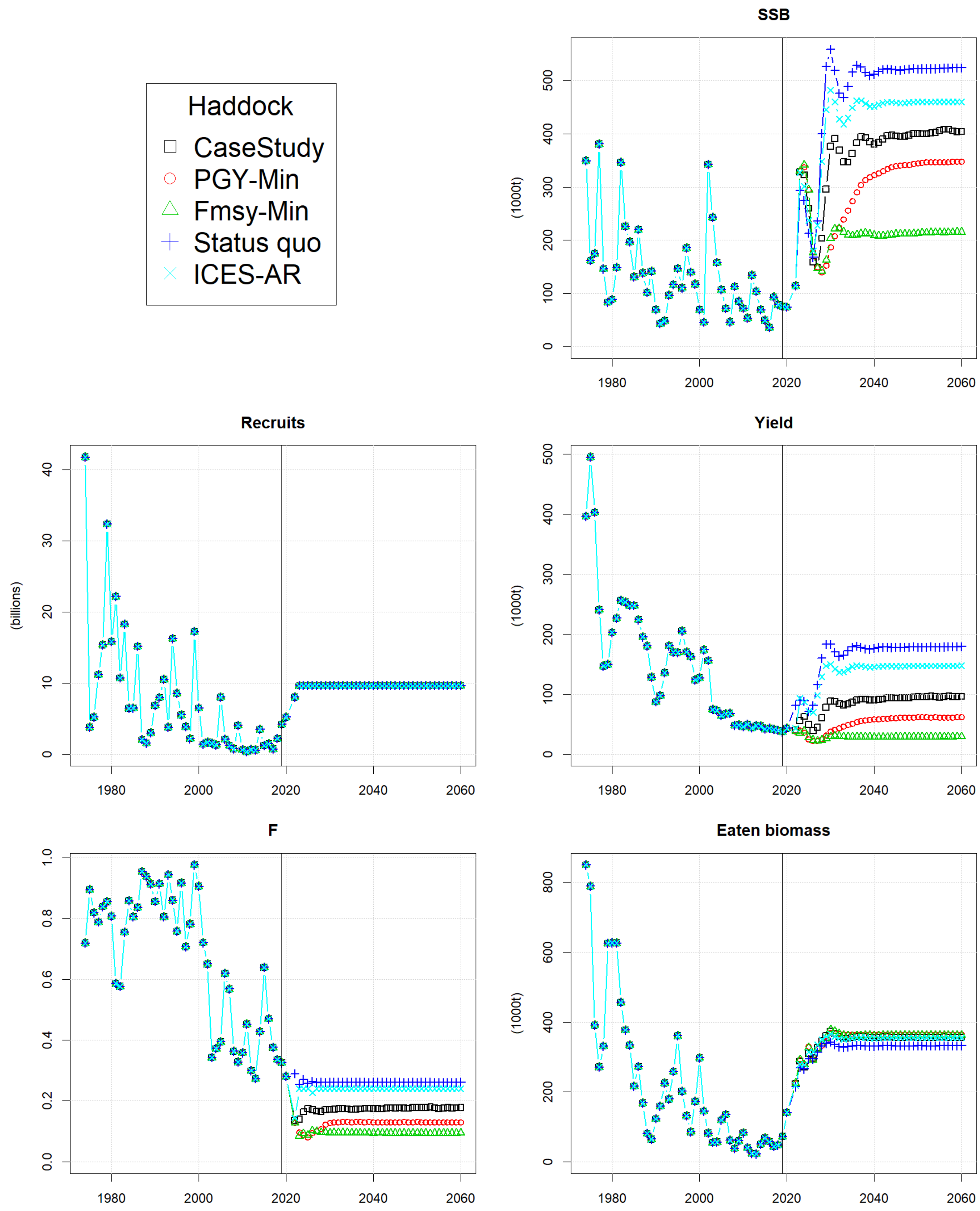

Figure 7: Haddock. SMS results from scenarios with given input F values (2020-2060) for demersal species estimated within FLBEIA scenarios and from the ICES Advisory Rule. ”Eaten biomass” is the biomass of the given species eaten by the all SMS predators.

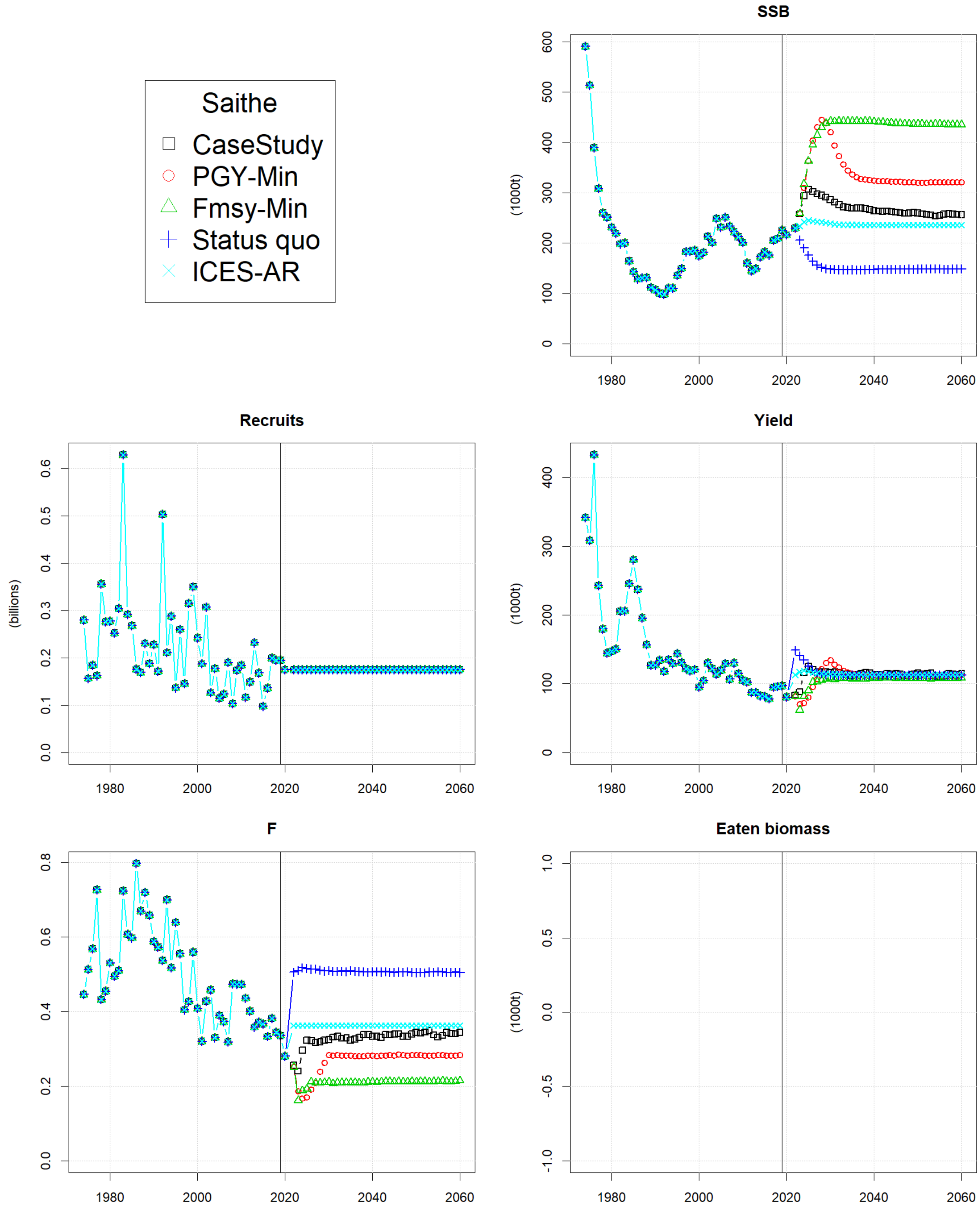

Figure 8: Saithe. SMS results from scenarios with given input F values (2020-2060) for demersal species estimated within FLBEIA scenarios and from the ICES Advisory Rule. ”Eaten biomass” is the biomass of the given species eaten by the all SMS predators.

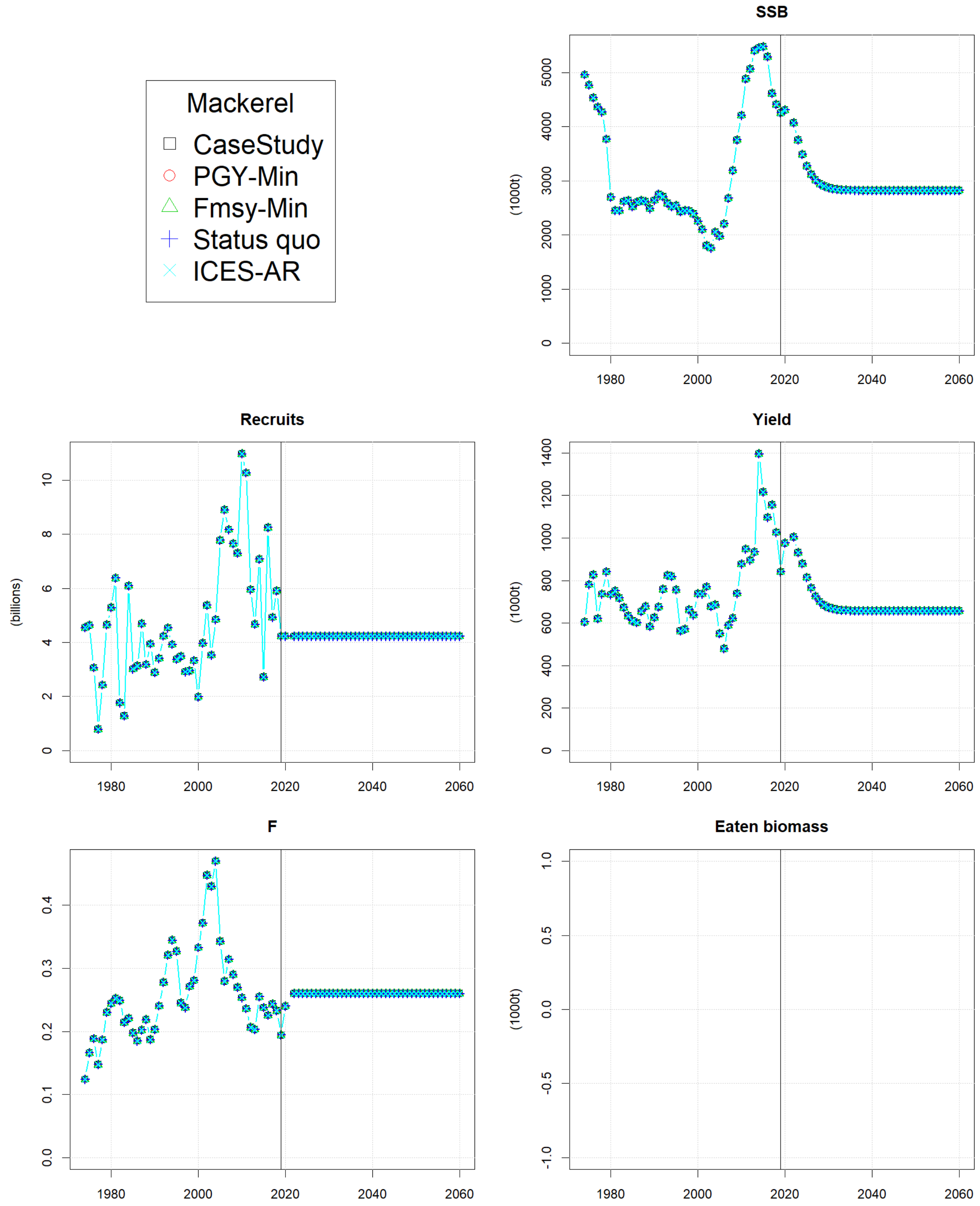

Figure 9: Mackerel. SMS results from scenarios with given input F values (2020-2060) for demersal species estimated within FLBEIA scenarios and from the ICES Advisory Rule. "Eaten biomass" is the biomass of the given species eaten by the all SMS predators.

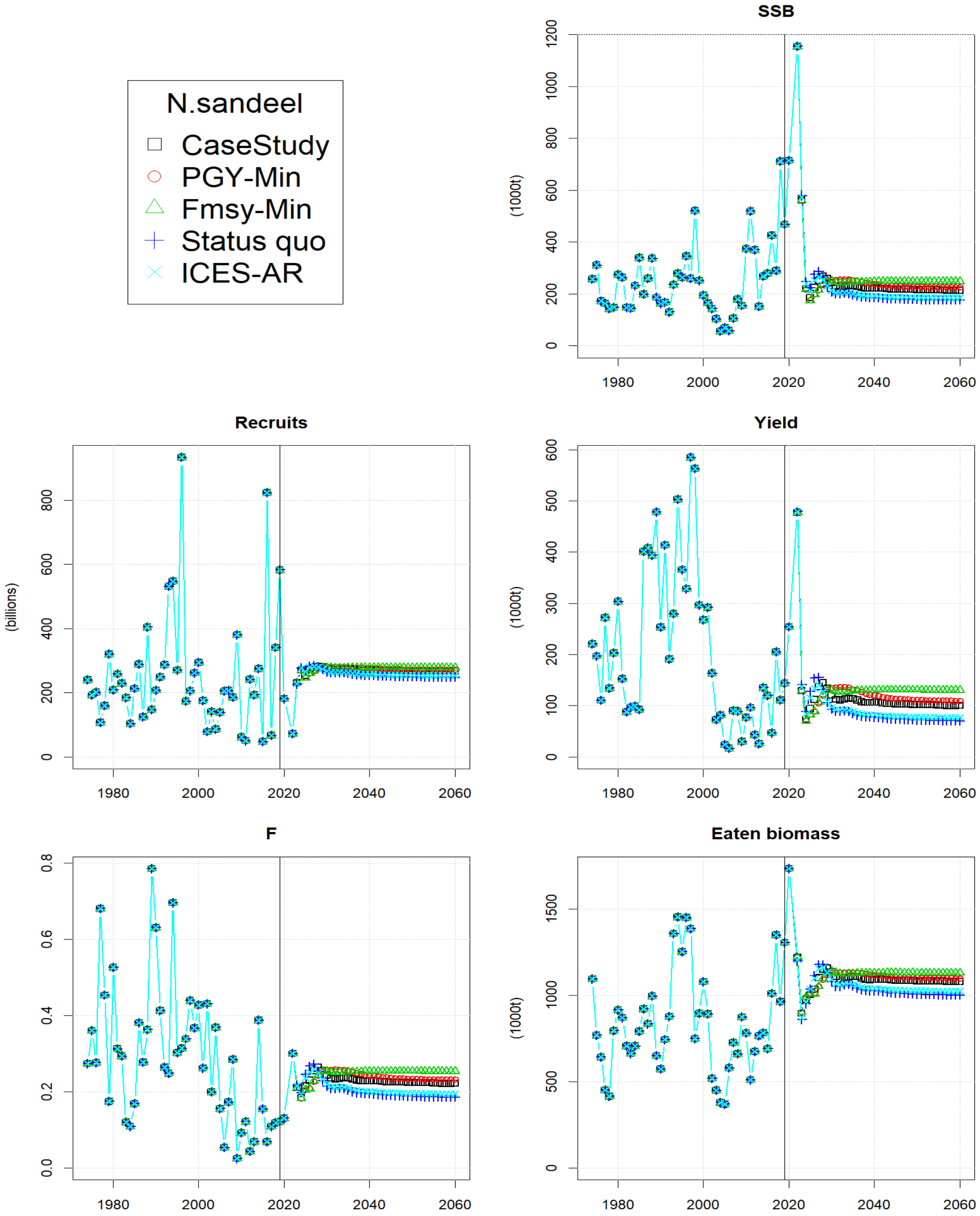

Figure 10: Herring. SMS results from scenarios with given input F values (2020-2060) for demersal species estimated within FLBEIA scenarios and from the ICES Advisory Rule. ”Eaten biomass” is the biomass of the given species eaten by the all SMS predators.

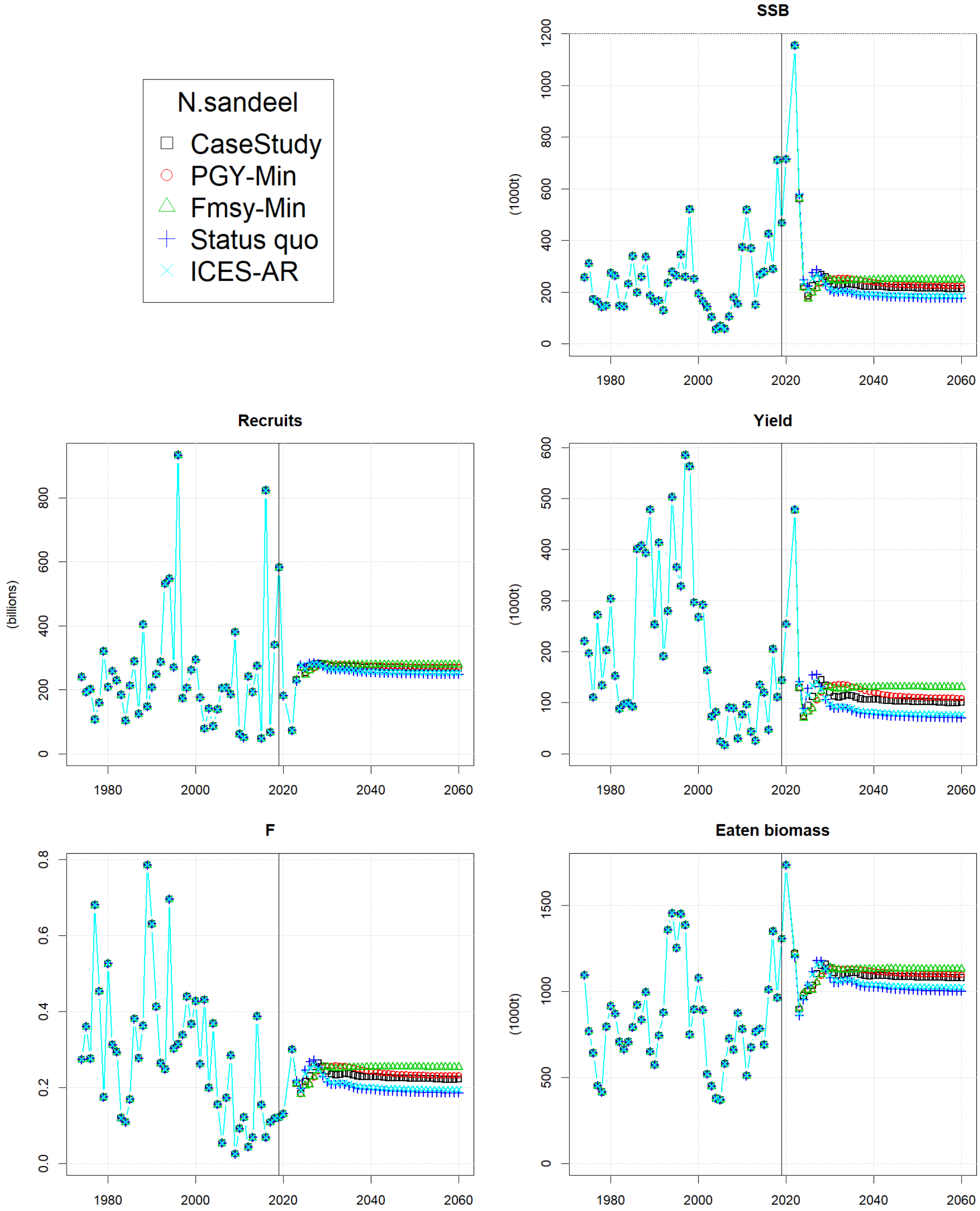

Figure 11: Northern sandeel. SMS results from scenarios with given input F values (2020-2060) for demersal species estimated within FLBEIA scenarios and from the ICES Advisory Rule. "Eaten biomass" is the biomass of the given species eaten by the all SMS predators.

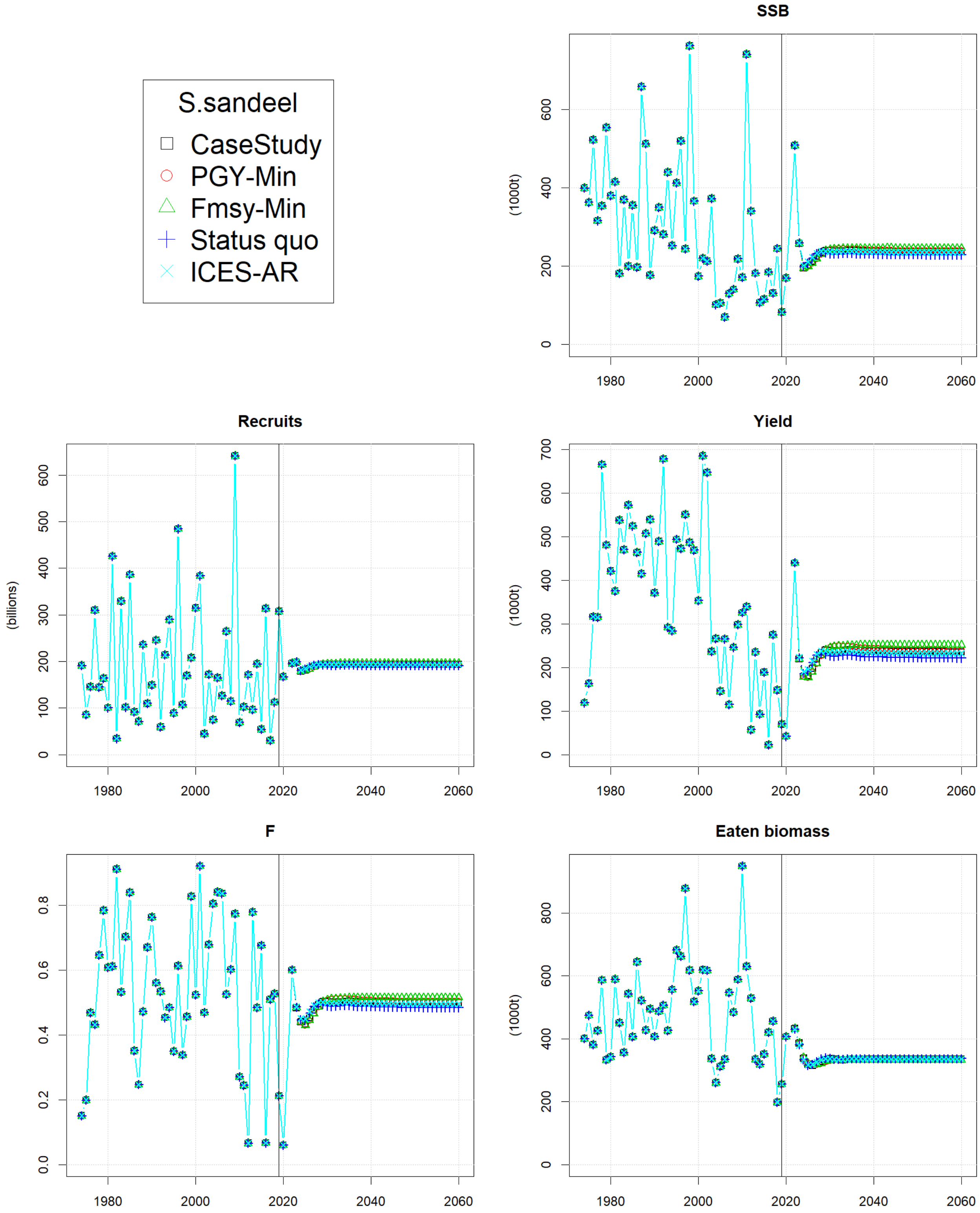

Figure 12: Southern sandeel. SMS results from scenarios with given input F values (2020-2060) for demersal species estimated within FLBEIA scenarios and from the ICES Advisory Rule. "Eaten biomass" is the biomass of the given species eaten by the all SMS predators.

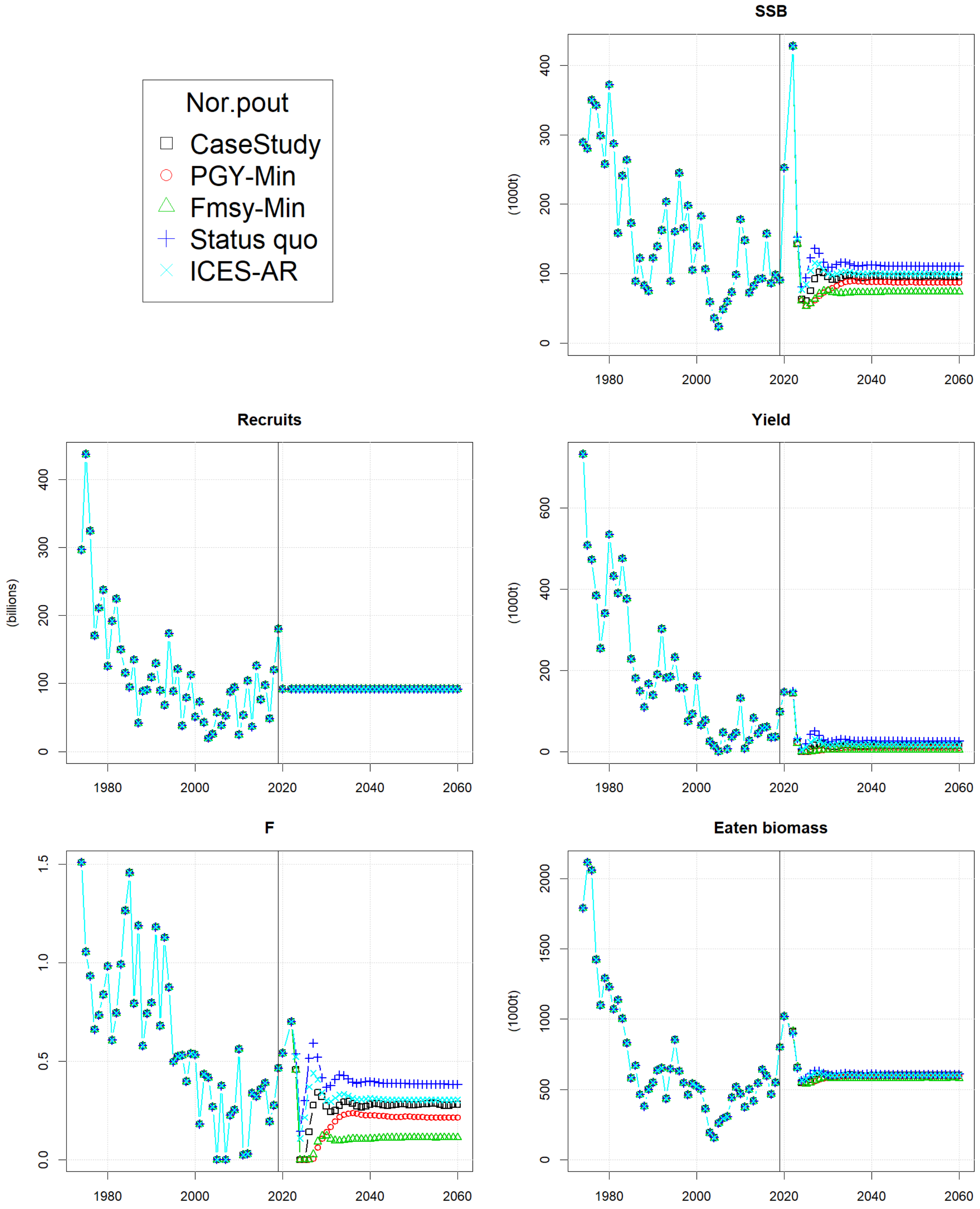

Figure 13: Norway pout. SMS results from scenarios with given input F values (2020-2060) for demersal species estimated within FLBEIA scenarios and from the ICES Advisory Rule. "Eaten biomass" is the biomass of the given species eaten by the all SMS predators.

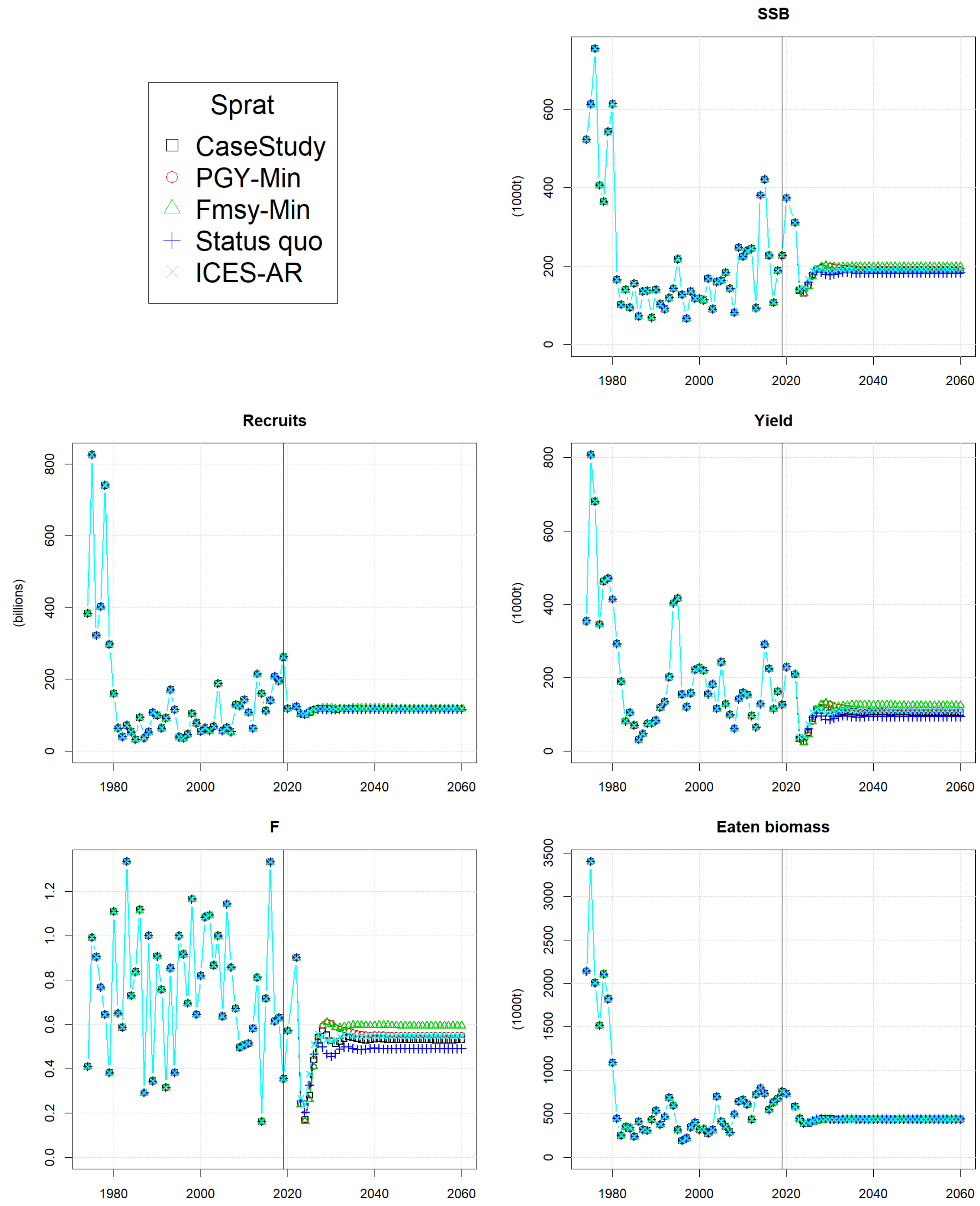

Figure 14: Sprat. SMS results from scenarios with given input F values (2020-2060) for demersal species estimated within FLBEIA scenarios and from the ICES Advisory Rule. ”Eaten biomass” is the biomass of the given species eaten by the all SMS predators.

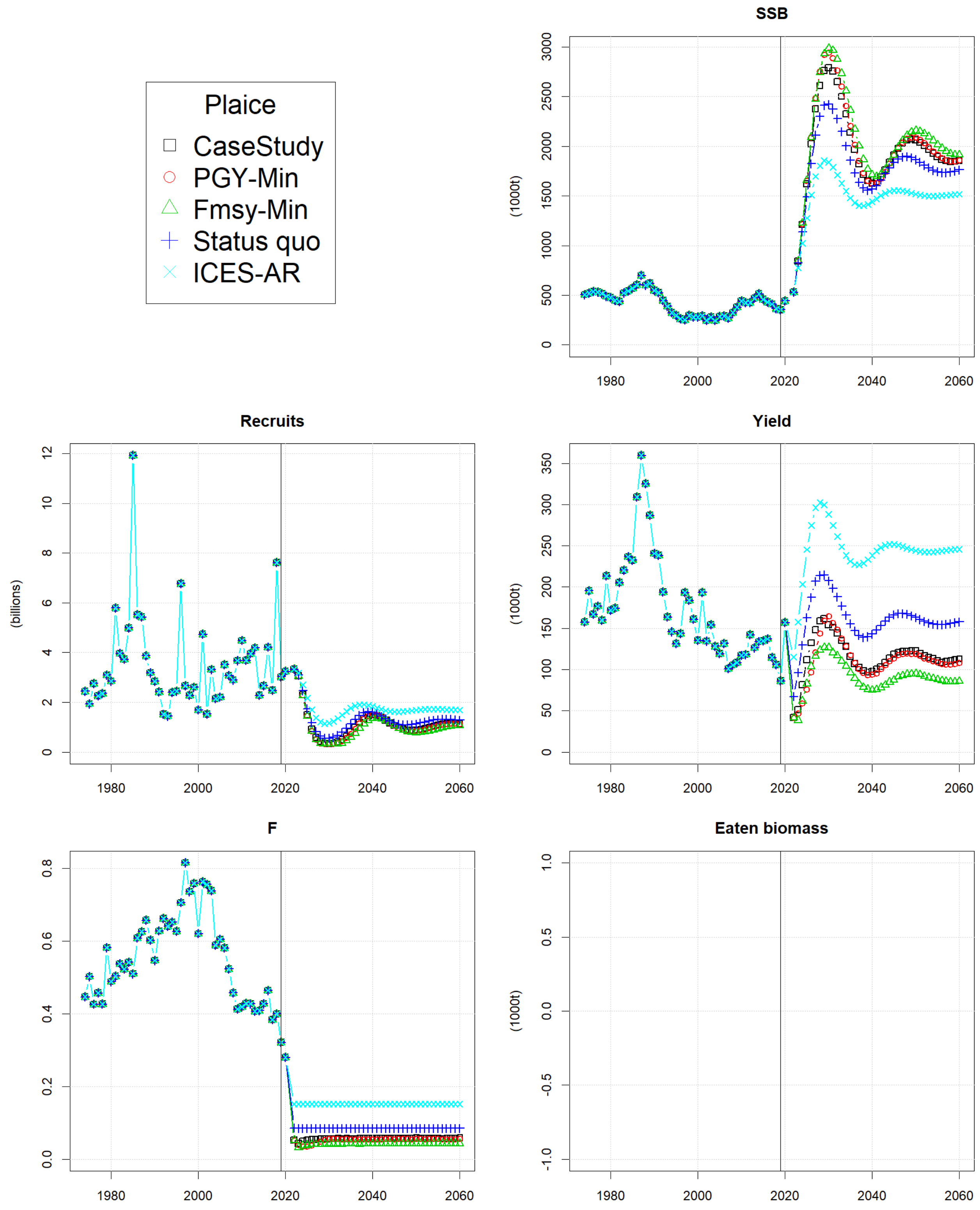

Figure 15: Plaice. SMS results from scenarios with given input F values (2020-2060) for demersal species estimated within FLBEIA scenarios and from the ICES Advisory Rule. ”Eaten biomass” is the biomass of the given species eaten by the all SMS predators.

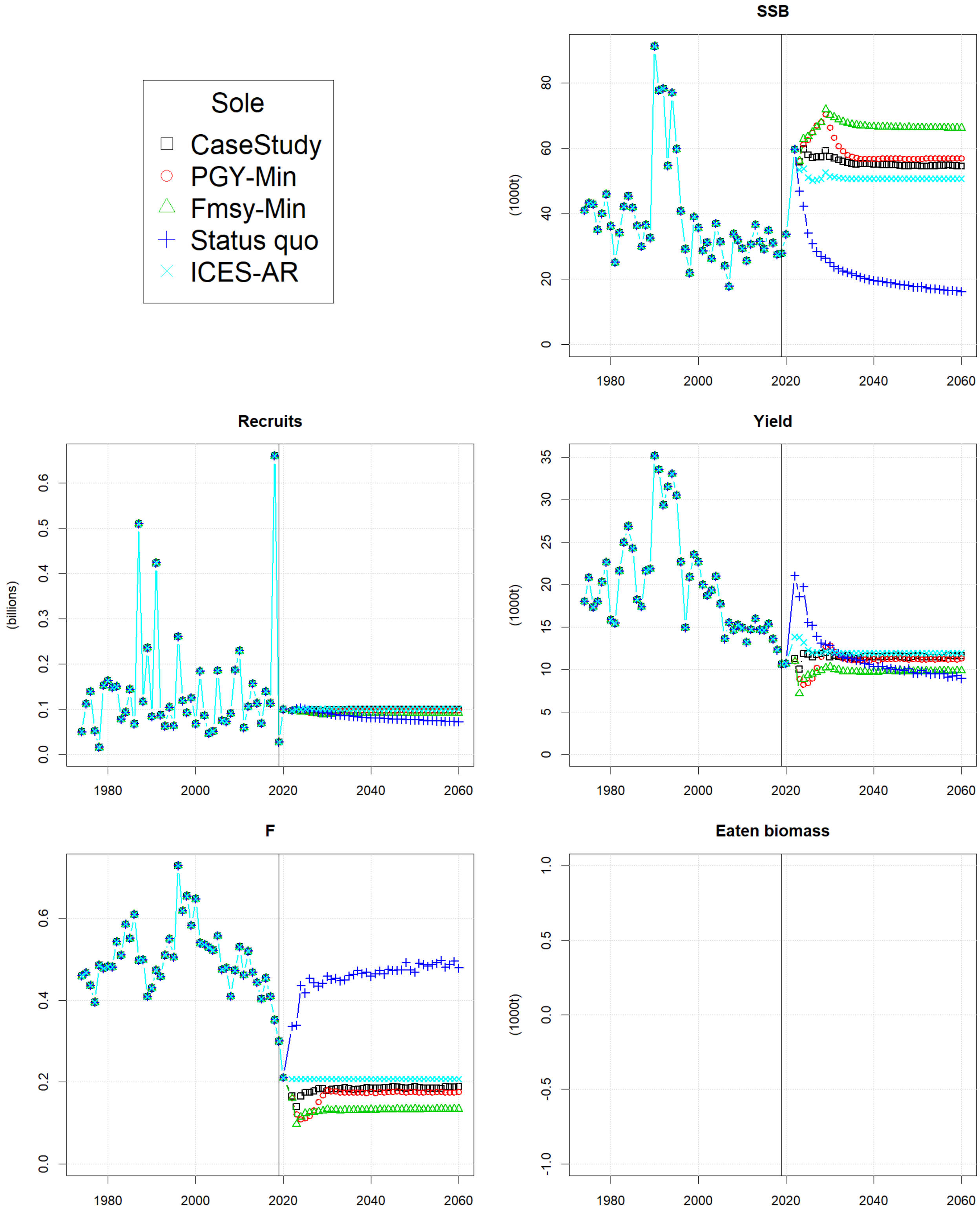

Figure 16: Sole. SMS results from scenarios with given input F values (2020-2060) for demersal species estimated within FLBEIA scenarios and from the ICES Advisory Rule. "Eaten biomass" is the biomass of the given species eaten by the all SMS predators

8.5 Annex 5: Description of analyses carried out with FLBEIA for the demersal mixed fisheries in the Bay of Biscay.

Dorleta Garcia, Marga Andrés, Sonia Sanchez and Leire Ibaibarriaga

1. Description of the model used

FLBEIA (Garcia, Sanchez, et al. 2017) has been used to simulate the impact of management strategies for the mixed demersal fishery in the Bay of Biscay. FLBEIA follows the MSE approach (Punt, Butterworth et al. 2016) and as such the simulation is divided into two blocks, the Operating Model (OM) and the Management Procedure (MP) (Figure 1). The OM is the part of the model that simulates the true dynamics of the fishery system (the real population). Biological populations and fleets are its essential elements and they interact through fishing effort and catch (Figure 1). The MP describes the management process and it is divided into three modules, the observation model (the link between the OM and the MP), the assessment procedure and the management advice. The observation model together with the assessment model generate the perceived population based on which the management advice is calculated. The advice is given in terms of catch and it can also be combined with technical management measures such as gear restrictions, temporal closures or capacity limitations.

The stochasticity in the model is introduced using Monte Carlo simulation (Refsgaard, van der Sluijs et al. 2007).Uncertainty can be introduced in all the variables used to describe the system. Each input variable can be conditioned using a single value or a vector, in this last case, each model replicate is conditioned taken a single value from this vector each time.

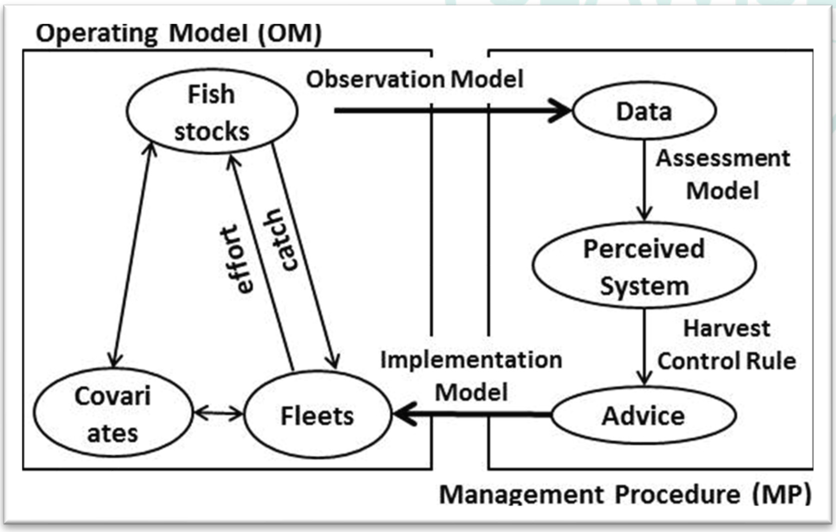

Figure 1: Conceptual diagram of the FLBEIA model.

Biological operating model

The stocks can be age structured or aggregated in biomass. Three models are available to describe stock dynamics. In the first model the stock abundance in the projection is given as input data and is maintained unchanged in the simulation. Implicitly it assumes that population growth is independent of fleets' catch. This model can be useful for example when nothing is known about the dynamics of a certain stock, but its incorporation into the model is justified due to the economic relevance of the stock for a particular fleet. A second model projects age structured populations one season ahead using a stock-recruitment model for incoming recruitment and an exponential survival model for the existing age classes. Finally, populations aggregated in biomass are projected using a Pella–Tomlinson growth model (Pella and Tomlinson 1969). In the three models, the catch is assumed to take place in the middle of the season in accordance with the fleet dynamics models implemented

Fleets operating model

Fleets OM is divided into four processes: effort allocation, catch production, price formation and capital dynamics. The models used to describe these processes can differ from fleet to fleet.

Effort model: It describes fleet's short-term dynamics or tactical behaviour. Each season it models how much effort is exerted and how it is distributed along métiers. In the *status quo* scenario presented in this deliverable the distribution of the effort along métiers is given as input data, whereas in the maximum profit scenario, the effort allocation is the one that gives the highest possible profits. In the status quo scenario the total effort and its distribution among métiers is fixed and equal to the mean of last three years. Whereas in the maximum profit scenario the total effort depends on the catch quotas of the stocks and their market prices.

Catch model: It describes the relationship between catch and effort. In this deliverable the Cobb-Douglas production model (Cobb and Douglas 1928) which is widely used in economy to describe production in industry has been used.

Price formation: It describes how price changes as a function of other factors, for example landings. Price varies at fleet and stock level. There are two models available to describe its dynamic. The constant model and a model where the price depends on the ratio between current landings and landings in a baseline time period (Kraak, Buisman et al. 2004)

Capital model: It describes the long-term dynamics of the fleet or strategic behaviour; the investment or disinvestment of fishermen in new vessels or technological improvements. In FLBEIA the capital dynamics can be modelled through changes in fleet's capacity or changes in fleet's catchability (technological improvements). Fleet's capacity can be modelled using a constant model or the model described by (Salz, Buisman et al. 2011).

2. Description of model parameterisation and scenarios

The conditioning of the model was based on the ICES single stock assessments and mixed fisheries data for fleets operating in Bay of Biscay. Moreover, economic data was obtained from the STECF annual economic report, sales data and regional data.

The simulation started in 2022 and the stocks and fleets were projected into the future until 2050. The simulation had 500 model replicates (iterations). In each iteration the uncertainty was introduced in the stock recruitment relationship and biological parameters which was propagated in the rest of model variables in the simulation.

2.1 Stocks

16 stocks were included in the biological operating model which are listed in Table 1. Stocks in ICES category 1, except *nephrops*, were included in the simulation using an age structured assessment model. The survival from one year class to the next was simulated using the classical exponential survival model and recruitment was simulated using an stock recruitment relationship. The parameters for the stock recruitment model and the biological parameters used in the projection were those used by ICES benchmarks in the calculation of reference points. The last assessment from 2022 was used to condition all the stocks, except SDV and WHG that are in category 3 and were assessed for the last time in 2021.

Table 1. List of stocks included in the simulation, FAO code used in the analysis, common name, ICES category and distribution of the stock across ICES divisions.

Code	Names	ICES category	Distribution (ICES divisions)
ANK	White anglerfish	1	78abd
BSS	Seabass	1	8ab
HKE	Hake	1	3a46-8abd
HOM	Horse Mackerel	1	2a4a5b6a7a-ce-k8
MAC	Mackerel	1	NEA
MEG	Megrim	1	78abd
MON	Monkfish	1	78abd
SOL	Sole	1	8ab
WHB	Blue whiting	1	1-91214
RJC	Raja clavata	3	8
RJN	Raja naevus	3	678abd
SDV	Smooth-hounds	3	NEA
NEP	Nephrops	1	8ab FU23-24
RJU	Raja undulata	3	8ab
WHG	Whiting	3	89a
POL	Pollack	3	89a

2.2 Fleets

The demersal Spanish and French fleets operating in Bay of Biscay were included in the simulation. The segmentation of the fleets and the metiers was based on the data provided to the WKMIXFISH and are listed in Table 2. Most of the stocks included in the simulation cover an area wider that the Bay of Biscay (Table 1) and to account for the catch outside the area one ghost fleet was included for each of the stocks to account for this catch.

Table 2. List of Spanish and French fleets and metiers included in the simulation

COUNTRY	FLEET	Metier	Target stock	Mess size
SP	ES_GNS_<10	GNS_DEF_100-119_0_0_all	DEF	100-119
	ES_GNS_10<24m	GNS_DEF_>=100_0_0	DEF	>=100
		GNS_DEF_100-119_0_0_all	DEF	100-119
	SP_GNS_2440	GNS_DEF	DEF	all
	ES_GTR_<10m	ES_GTR	DEF	all
	ES_GTR_10<24m	ES_GTR	DEF	all
	ES_LLS_<10m	ES_LLS	DEF	all
	ES_LLS_10<24m	ES_LLS	DEF	all
	ES_LLS_24<40m	ES_LLS	DEF	all
	ES_MIS_all	ES_MIS	MIS	all
	ES_OTB_>=40m	OTB_DEF	DEF	all
		OTB_MPD	MPD	all
	ES_OTB_24<40m	OTB_DEF	DEF	all
		OTB_MPD	MPD	all
		OTB_MCF_>=70_0_0	MCF	>=70
	ES_PTB_24<40m	ES_PTB	DEF	all
FR	SP_OTB_40XX	OTB_MPD	MPD	all
		SP_PTB	MIS	all
		OTB_DEF	DEF	all
	SP_GNS_2440	OTB_MCF_<=70_0_0	MCF	>=70
	SP_LLS_1040	OTB_MPD	MPD	all
	FR_GNS_XX10	GNS_DEF_100-119_0_0_all	DEF	100-119
	FR_GNS_1024	GNS_DEF_60-79_0_0	DEF	60-79
		GNS_DEF_all_0_0_all	DEF	all
		GNS_DEF_100-119_0_0_all	DEF	100-119
	SP_OTB_40XX	GNS_DEF_60-79_0_0	DEF	60-79
	FR_GTR_10-24m	GNS_DEF_all_0_0_all	DEF	all
		GTR_DEF_100-119_0_0_all	DEF	100-119
	FR_GNS_XX10	GTR_DEF_40-59_0_0	DEF	40-59
	FR_LHM_all	GTR_DEF_all_0_0_all	DEF	all
		LHM_DEF	DEF	all
	FR_LLS_<24m	LLS_DEF	DEF	all
	FR_LLS_24<40m	LLS_DEF	DEF	all
	FR_MIS_all	FR_MIS	MIL	all
	FR_OTB_<10m	OTB_CRU	CRU	
		OTB_CRU_>=70_0_0	CRU	>=70_0_0
		OTB_CRU_All_0_0_All	CRU	all
	FR_LHM_all	OTB_DEF_<16_0_0_all	DEF	<16
	FR_LLS_<24m	OTB_DEF_>=70_0_0	DEF	>=70
	FR_LLS_24<40m	OTB_DEF_16-31_0_0	DEF	16-31
	FR_MIS_all	OTB_DEF_32-69_0_0	DEF	32-69
	FR_OTB_10<24m	OTB_CRU	CRU	
		OTB_CRU_>=70_0_0	CRU	>=70
		OTB_CRU_All_0_0_All	CRU	all
		OTB_DEF_<16_0_0_all	DEF	<16
		OTB_DEF_>=70_0_0	DEF	>=70
		OTB_DEF_16-31_0_0	DEF	16-31
		OTB_DEF_32-69_0_0	DEF	32-69
	FR_OTB_24<40m	OTB_DEF_<16_0_0_all	DEF	<16
	FR_OTM_<10	OTB_DEF_>=70_0_0	DEF	>=70
	FR_OTM_10<24m	OTM_DEF	DEF	all
	FR_OTM_24<40m	OTM_DEF	DEF	all
		OTM_DEF_32-69_0_0_all	DEF	32-69
		OTM_DEF_70-99_0_0_all	DEF	70-99
		OTM_DEF	DEF	all
	FR_OTB_24<40m	OTM_DEF_70-99_0_0_all	DEF	70-99
	FR_OTT_10<24m	OTT_DEF	DEF	all
	FR_OTT_24<40m	OTT_DEF	DEF	all
	FR_SSC_10<40m	SSC_DEF_70-99_0_0_all	DEF	70-99

The economic data was obtained from different sources. Below each data source is described:

- Landings: Data from ICES MIXFISH that use Intercatch and Accessions data (ICES, 2022). These data are reported by national institutions. Intercatch data that includes the vessel size, effort by fleet and number of vessels has been also used.
- Price**:** The price of Spanish fleet has been estimated from First Sale Notes, from 2016 to 2021 at metier level. In the case of French fleet, the First Sale Notes were not available, thus, the price has been estimated form the STECF data (STECF 22 06 - EU Fleet Economic and Transversal data_fleet segment), from 2017 to 2020 and at case study level.
- Number of vessels: In the case of Spanish fleet, the number of vessels was estimated from the LoogBooks data, selecting those vessels that operate with the target gear in the target area and catching target species. Vast majority of the target vessels were Basque, then, in this case study only the Basque fleets were considered as representative of the whole fleet. In the case of French fleet, the number of vessles was obtained at metier level from the ICES Accesions data. The problem was that the same vessel can operate in one or more metiers. Thus, the sum of all the number of vessels by metier related to one fleet segment could result in an overestimation of the number of vessels. Thus, the maximum number of vessels by metier has been taken as the number of vessels of a given fleet segment, but this figure can underestimation.

- Effort: The effort comes from ICES MIXFISH, that comes from 'Intercatch' and the 'Accessions' (ICES, 2022).
- Costs: All the costs (variable costs, fixed costs, labour costs and capital cost) were estimated using STECF data. ('STECF 22 06 - EU Fleet Economic and Transversal data_fleet segment.xlsx ', 'FS data' sheet). From this data, the fleet, supra region, geo_indicator and fishing_tech were selected, and costs were estimated at metier and fleet level. The estimation was not straightforward since the definition of fleet or metier from ICES MIXFISH does not correspond to the definition of AER data in terms of length of the vessel or fishing gear. For those fleets and metiers that had a direct correspondence, this data was taken directly from AER; in th¡osee cases when the gear was not specifically defined in AER data, the general gear was that includes the target gear was selected; when the vessel length was more disaggregated in AER data, the weighted average was computed. The following variables were conditioned using this data:

  At fleet level:
    - Crew share (% of the gross value): Personnel costs / Gross value of landings
    - Fixed costs (by vessel): (Repair & maintenance costs + Other non-variable costs) / Number of vessels
    - Capital value: Value of physical capital
    - Fixed salaries (per crew member): 0, the whole salary is assumed variable.
    - Maximum effort: Maximum days at sea
    - Employees (by vessel): Engaged crew / Number of vessels
    - Depreciation (by vessel): Consumption of fixed capital / Number of vessels
    - Vessels (of the fleet): Number of vessels (values for simulations taken from ARVI data)
    - New vessel, investment share, w1, w2 (for capital dynamics) (Not applicable in the current case studies)

  At fleet and metier:
    - Fuel cost (per unit of effort): Energy costs / Fishing days
    - Other variable cost (per unit of effort) : Other variable costs / Fishing days

There are several problems associated to this data:

- The fleet segments are not the same in Intercatch and in the STECF data. Thus, correspondences between fleets and metiers need to be found, and both data bases do not always match perfectly.
- In the cost data base, the spatial dimension it is not defined at ices area level, only at supra-region area.

- The fleet is defined at country level, not at regional level, thus, the representativeness of the fleet in the national level is uncertain.

2.3 Scenarios

Four scenarios were run which differed in the dynamic of the fishery in response to management and how the advice is generated.

- **Statu quo:** In this scenario the effort and its distribution among metiers was kept constant in the projection and equal to the last three data years. The aim of having this scenario is twofold, on one hand is a control scenario that allows to identify problems in the conditioning of the model and on the other hand it provides scenarios against which to compare the rest of the scenarios.
- **min:** In this scenario the fleet fully complies with the landing obligation and they stop fishing when the first of the quota is consumed. There is not adaptability mechanism in the catchability or the effort share, so it could create a significant loss in fishing opportunities.
- **pre**: The effort share along metiers is given and equal to the mean of the most recent data and the total effort is calculated based on the catch quotas and the previous year effort. First, the effort corresponding to each of the catch quotas is calculated and then among those efforts the one that is more similar to the previous one is selected. Thus, the fleet dynamics have some inertia to the past but constrained by the quotas.
- **min.ms:** the fleet dynamics are the same as in the 'min' scenario but the advice is generated with a multistock HCR (Garcia, Dolder et al. 2019) that operationalizes the fishing mortality ranges based on the single stock advice and the maximization of fishing opportunities.

3. Indicators, targets and limits

The biomass and fishing mortality reference points used in the harvest control rules where those used by ICES in the generation of annual catch advice.

Performance statistics or indicators used to analyze the performance of the system were the same proposed within Task 6.4 to be used in general to summarize the results and no additional indicators were defined.

4. Main results.

4.1 Stock level

SSB

The SSB for the main stocks in the area are shown in Figure 1. The SSB of all the stocks was well above the limit and trigger reference points in the projection period. For sole and seabass the biomass on the 'min' scenarios and the 'pre' and 'fix' scenarios was very different, with higher biomass in the 'min' scenarios. The SSB in the 'min' scenarios for all the stock was higher than the biomass in the 'pre' scenarios but the relative level of SSB depended on the stock. For sole and seabass in the 'min.ms' scenarios the biomass increased significantly. However, for the other stocks and scenarios the SSB level maintained similar to the historical ones.

Fishing mortality

The fishing mortality in the status quo scenario did not correspond, in general, with the highest fishing mortality scenario. The fishing mortality in the last data year 2021 was below Fmsy for most of the stocks, thus the statu quo effort led to a fishing mortality below the Ftarget. The exceptions were Sole and the pelagic stocks. For the pelagic stocks the statu quo was the scenario with the highest fishing mortality and the other three scenarios resulted basically in the same fishing mortality which was around the target. For the rest of the stocks except Monkfish the scenario that provided the highes fishing mortality was the 'pre' scenario. For Monkfish the highest fishing mortality was obtained with the min.ms scenario as the harvest control rule increased the advice fishing mortality for this stocks when trying to harmonize the catch advice. In most of the cases the fishing mortality was within the ranges, but for anglerfish, seabass and sole the min.ms scenario resulted in a fishing mortality below the range, and also the status quo scenario and the min scenario in the case of anglerfish and seabass.

Average age

The scenarios had a significant impact in the average age and differences of one year between scenarios were common. The lower the fishing mortality in the scenario the higher the mean age in the population. In the medium term there were big changes in the mean age, positive in some cases, and negative in others, but then it was quite stable. However, it did not fully stabilished. The trend in the medium term was related with the trend in the SSB, if the SSB increased so did the mean age, and on the contrary it decreased if SSB decreased.

4.2 Fleet level

Effort

Effort time series for the four scenarios is shown in Figure 1 for Spanish fleets and in Figure 2 for French fleets. For most of the Spanish fleets the status quo effort scenario was the scenario with the highest effort level, except for Longliners and Gillneters on the size range 24-40m. For these two fleets the effort in the 'pre' scenario and the status quo scenario was similar or even lower in the status quo scenario. The biggest difference between the 'min' and the 'pre' scenario was in these two fleets too, which means that the catch quotas in these fleets were less aligned than in the rest of the fleets. The min scenario was the more variable scenario for all the fleets. The 'min' and 'min.ms' scenario produced similar values but the effort in the min.ms scenario was somewhat lower and more stable.

In the French fleets the status quo and the 'pre' scenario were similar and in several cases the 'pre' scenario was higher. As for Spanish fleet the min scenario was very variable. In general, the effort in the min scenario was significantly lower than in the pre scenario. The effort in the min.ms was always below the effort in the min scenario and in all the cases had an increasing trend.

The uncertainty in the min scenario was very low or almost null because in all the iterations the limiting species was a category 3 species which did not include uncertainty in the projection.

SHI, SAR and p(SSB<Blim)

SHI was always 0 and SAR was positive only in statu quo scenario in the first time period because of the high fishing mortality for mackerel. In that scenario the fishing mortality was also high for the other two pelagic species but apparently their contribution to the value was not high enough to have a real impact in the SAR indicator.

The stocks simulated with a dynamic model in the projection where all well above the Biomass target in all the scenarios except Horse mackerel at the beginning of the simulation and Black anglerfish. Horse mackerel SSB was below Blim at the beginning of the simulation with 100% probability. In all the scenarios except the 'sq' scenario the probability decreased rapidly and by 2030 the probability was close to 0. However, although vert low, remained positive afterwards. In the case of status quo scenario the probability decrease but maintained above 25% in the whole projection. In must be taken into account that the contribution of Demersal fleet in BoB to the total catch of horse mackerel is very low. Thus, the dynamic of this fleet has very limited impact of its dynamics and the performance of the stock is directly linked to the dynamic of the 'ghost' fleet that accounts for the rest of the catch and it is assumed to fish exactly the advised catch, except in the status quo scenario where the effort of this fleet is maintained constant.

For black anglerfish the probability of being below Blim was positive in some years in all the scenarios but the status quo scenario. But the probability was lower than 2% in all the cases. Black anglerfish was the only stocks for which the status quo scenario resulted in the higher biomass. This is an artefact of how the fishing activity outside Bays of Biscay is modelled and the current exploitation status of the stock. Currently the stock is exploited below Fmsy, thus in the scenarios different to status quo scenario the fishing mortality is increased in general, specially in the fleet outside Bay of Biscay that is force to catch exactly the corresponding quota.

As prices were constant along the whole simulation the revenue followed exactly the same trends as landings (Figure 8). The same happened for wages which were obtained as constant proportion of the revenues. Overall the biggest landings were obtained in the status quo scenario and they increased slightly over time. The pre scenario showed a similar trend in terms of landings but the landings were somewhat lower. In the min sceanrio the landings were 30% lower than in the status quo scenario, they increased in the second time period and decreased again in the last period. The min.ms scenario produced the lowest landings,which increased over the years and in the last time period they were similar to the landings in the min scenario.

The unwanted catches (discards) showed similar trend as landings but there were slight differences, the discards in the medium and long term in ‘pre’ and status quo scenarios were similar, and the difference between min and min.ms scenarios increased in the long term (Figure 8).

The overall gross profit was negative in the whole simulation period (Figure 8). In the min scenario the gross profit did not improve in the long term, but they did in the rest of the scenarios. The most negative results were obtained in the ‘pre’ scenario, followed by ‘status quo’ scenario and the less negative were the min scenarios.

The sing of the gross value added (GVA) depended on scenario and the time period. Under the min scenario GVA was always positive and the highest value was obtained in the medium term. In the pre sceanrio the GVA was always negative but it improve significantly over time. In the min and status quo scenario the GVA was negative in the first year of the simulation but became positive afterwards. In the long term the min.ms scenario provided the best results.

The ratio of revenue between vessels smaller than 24 metres and bigger was similar along time and between scenarios. Around 70% of the revenue came from vessels smaller than 24m. In the min scenario the percentage was the highest and in the status quo scenario the lowest.

Bycatch

The bycatch was proportional to effort but the bycatch rate depended on the gear and the stock, hence the trend was different for each of the stocks. Pre and status quo scenarios on the one hand and min and min.ms in the other showed similar trend over time. While the highest bycatch for Dolphins was observed in the status quo scenario, for the rest of the stocks the highest was observed in the pre scenario. The lowest bycatch level ocurred in the min.ms scenario.

Catches per Km2

The area covered by the fleets was constant over time and the same in all the scenarios, hence, the catches per km2 followed the same as the sum of landings and unwanted catches.

5. Discussion and conclusions

For demersal species any of the scenarios resulted in biomasses above Blim with high probabiliy. For Horse Mackerel that started the simulation below Blim, the probability depended on the scenario, whike the status quo scenario resulted in a probability higher than 25%, in the pre scenario the probability was almost null.

In most of the cases the exploitation of the stocks was within the fishing mortality ranges what ensures that the long term yield is not lower than 95% of the maximum sustainable yield. For anglerfish the fishing mortality in min.ms and status quo and for sole in the min.ms scenario was below the lower bound of the range, which implies a loss in fishing opportunities.

As some of the stocks were exploited below Fmsy at the beginning of the simulation the status quo scenario was not always the scenario that resulted in the highest exploitation.

The limiting stocks were usually the stocks not dynamically simulated in the projection which resulted in low uncertainty in effort time series because no uncertainty was introduced in those stocks.

The pelagic stocks are important for the fleets in the Bay of Biscay but as the contribution of the demersal fleets in the Bay of Biscay to the overall exploitation of these stocks is very low, the management in this area had very limited impact in their dynamics.

The gross profit for many of the fleets was negative, which resulted in an overall negative gross profit. Some of the vessels considered in the simulation move to other areas along the year and not all the bycatch species in the Bay of Biscay were introduced which could be the main reason for having negative results. Moreover, the economic data comes from the STECF and the fleet segments used here and in the STECF data base do not fully much which could have an impact too.

The evolution in mean age depended on the stock biomass at the beginning of the projection, if the biomass level was high the mean age decreased in the projection and the other way around.

As many of the processes in the projection where linearly realted with effort, the trend in the indicators was explained by the trends in effort.

The contribution of the vessels smaller than 24m to the revenue was around 70%.

The multistock HCR (min.ms scenario) (Garcia, Dolder et al. 2019) did not have the expected results and the limitation in effort was higher than in the min scenario. The HCR produced a reduction in the fishing mortality of all the stocks but monkfish. This happened because overall monkfish was the most restrictive stock but not for the demersal fleets in the Bay of Biscay. This was related with the fact that only seabass and sole stocks belonged exlclusively to the bay of biscay. The exploitation of other demersal stocks is higher outside the Bays of Biscay, hence the performance of the system is highly driven by the ghost fleets introduced to account for all the catch outside the Bay os Biscay. Including Celtic Sea demersal fishery within the case study would solve the problem but would highly increase the complexity.

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7. Figures

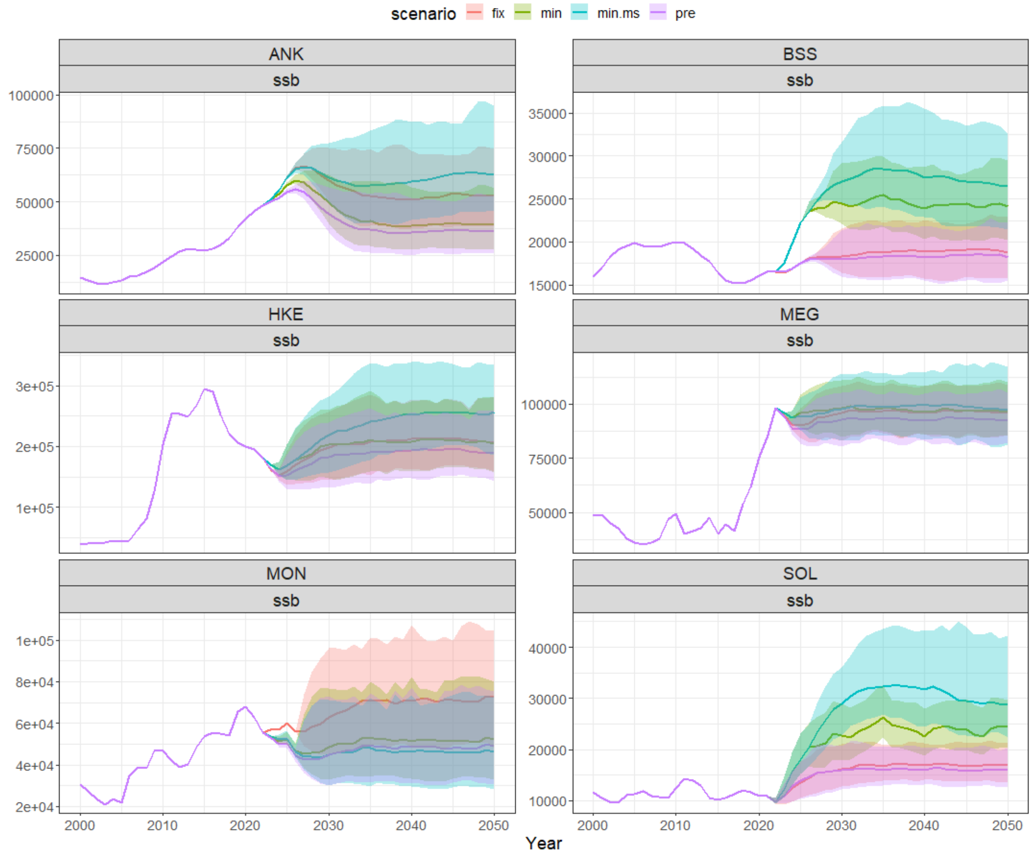

Figure 1. Spawning stock biomass time series for demersal stocks in the Bay of Biscay. The lines represent median values and the shaded are corresponds with the 90% confidence interval.

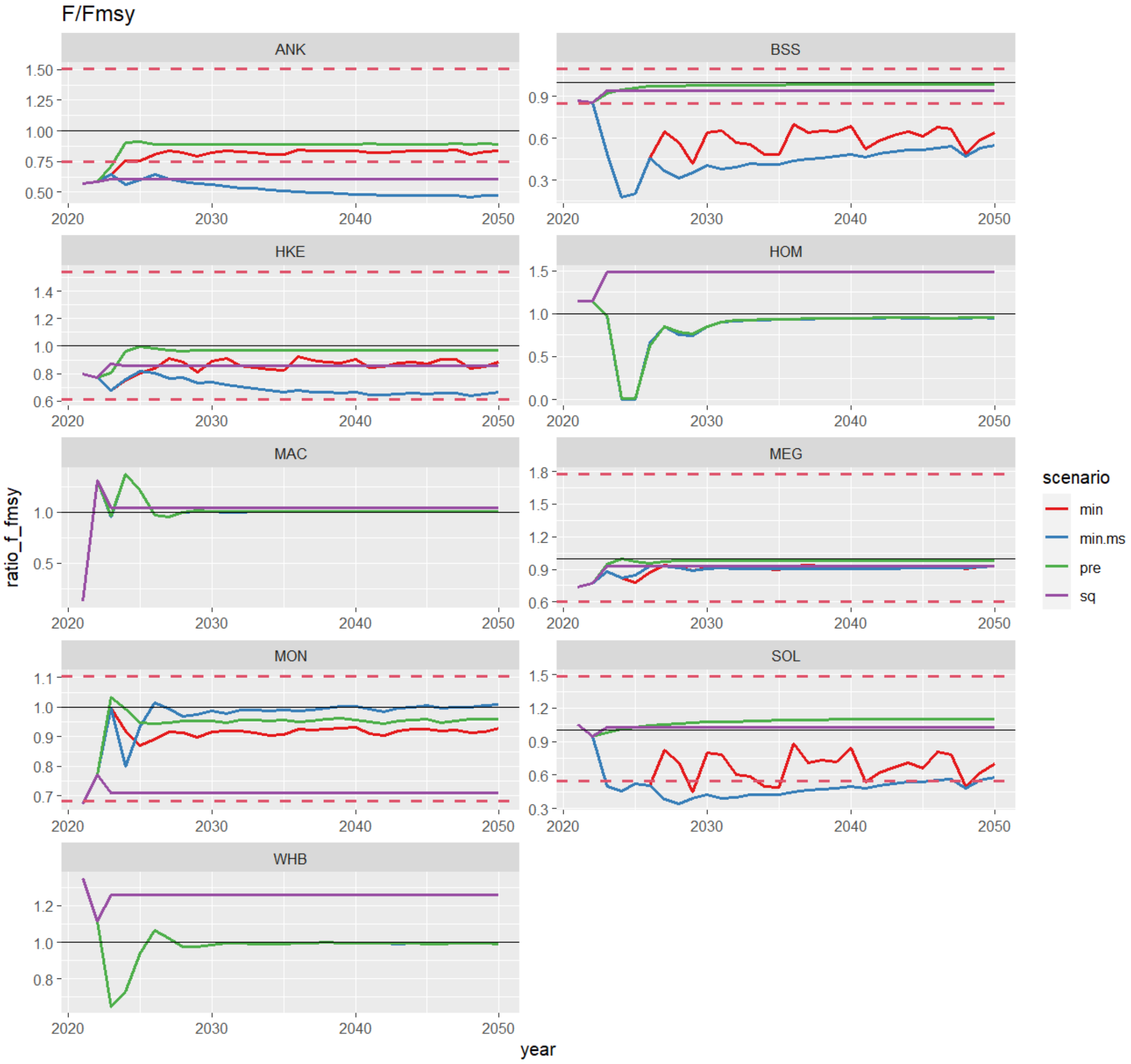

Figure 2. Ratio between fishing mortality and Fmsy time series. For demersal species the horizontal red dashed lines correspond with Fupp and Flow and for all the stocks the horizontal black line with Fmsy.

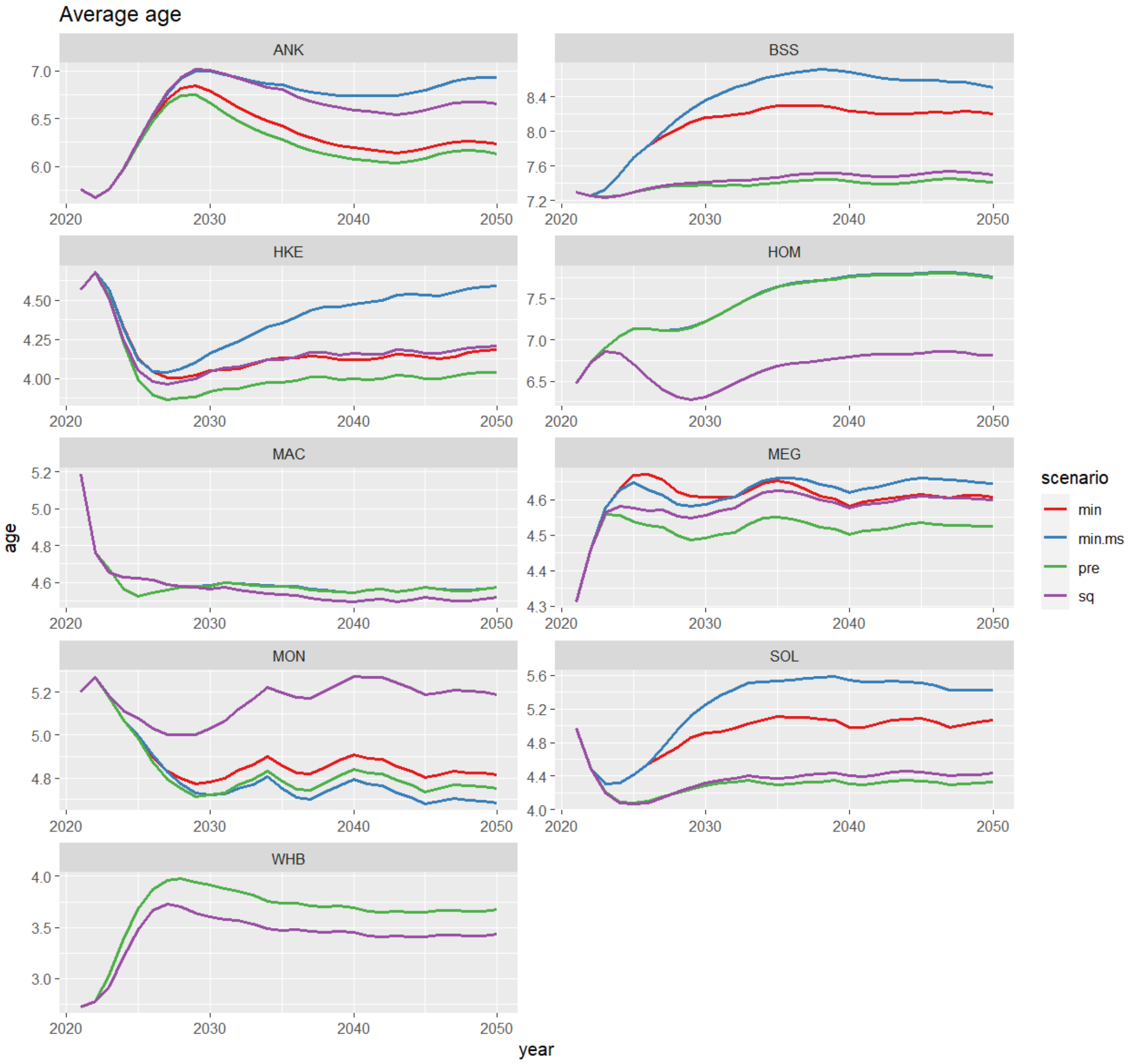

Figure 3. Mean age time series over time by scenario.

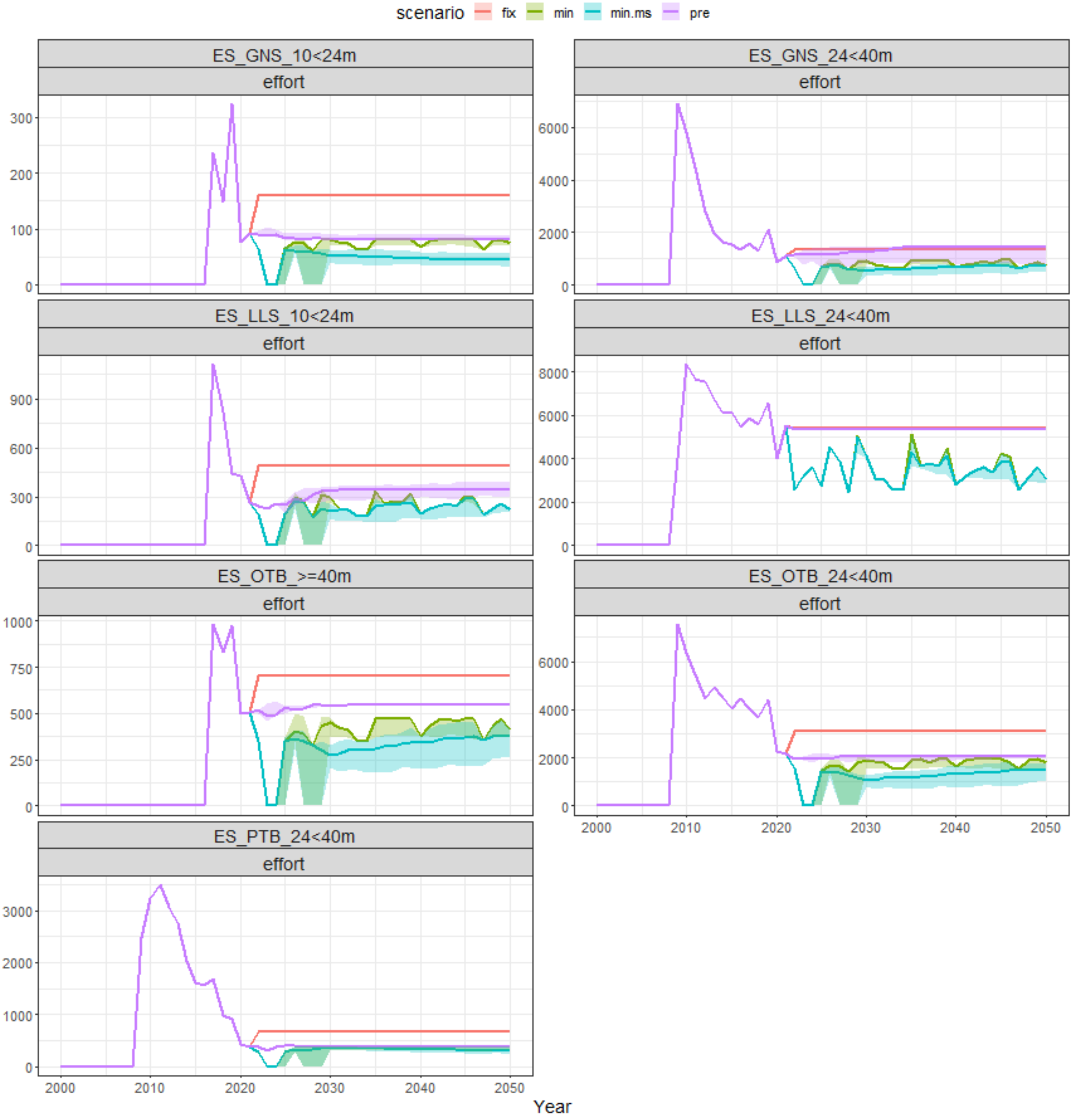

Figure 4. Effort time series for the Spanish fleets. The fleets are listed in Table X. The area correspond with the 90% confidence interval.

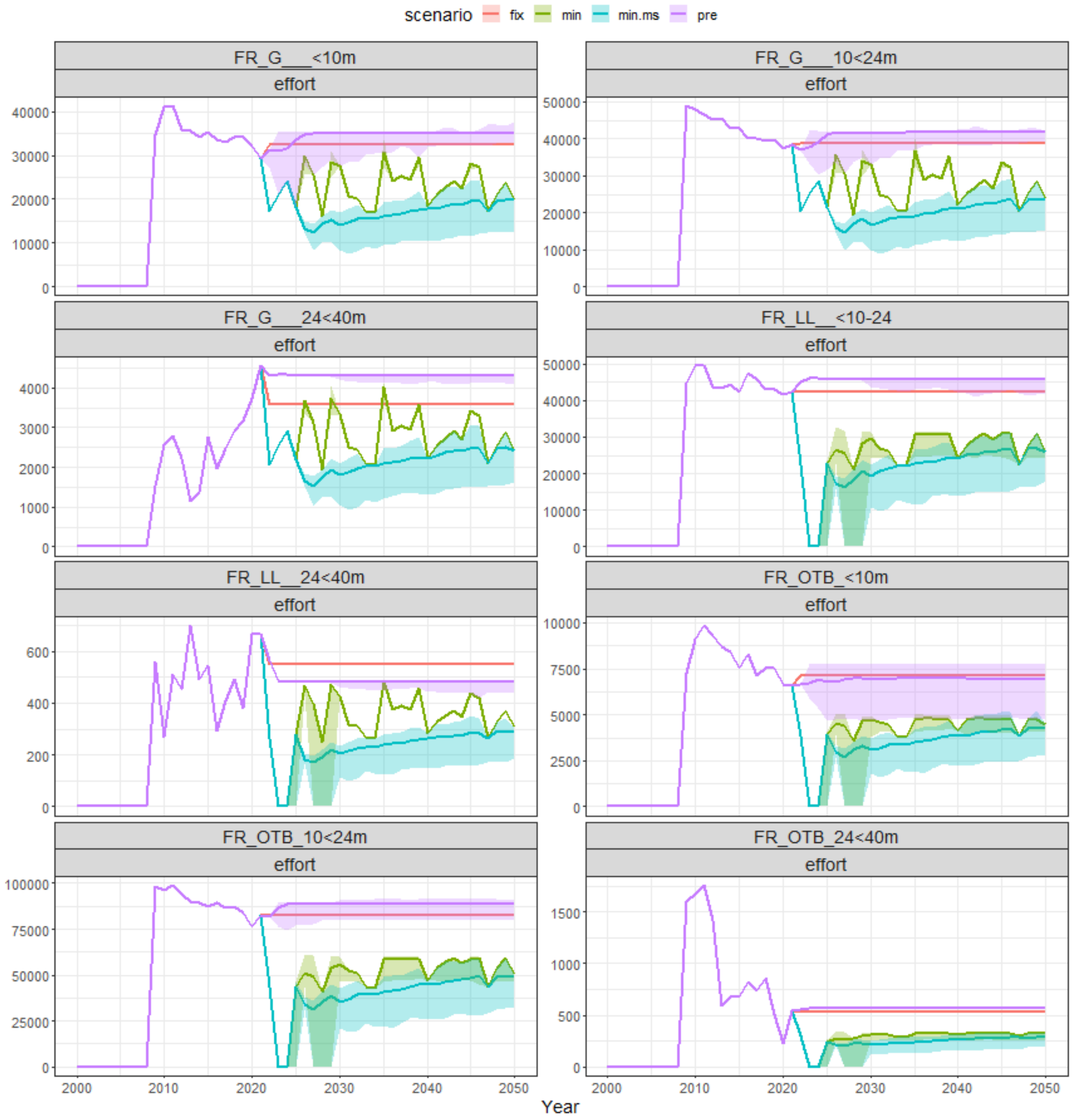

Figure 5. Effort time series for the Spanish fleets. The fleets are listed in Table X. The area corresponds with the 90% confidence interval.

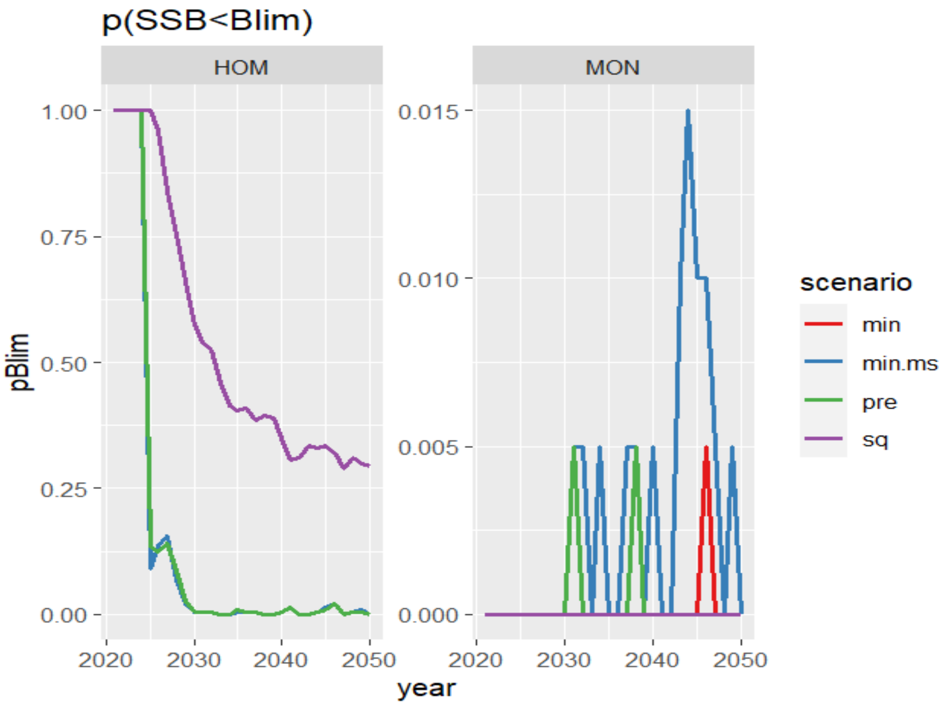

Figure 6. p(SSB<Blim) time series for the stocks for which this probability is positive in some year.

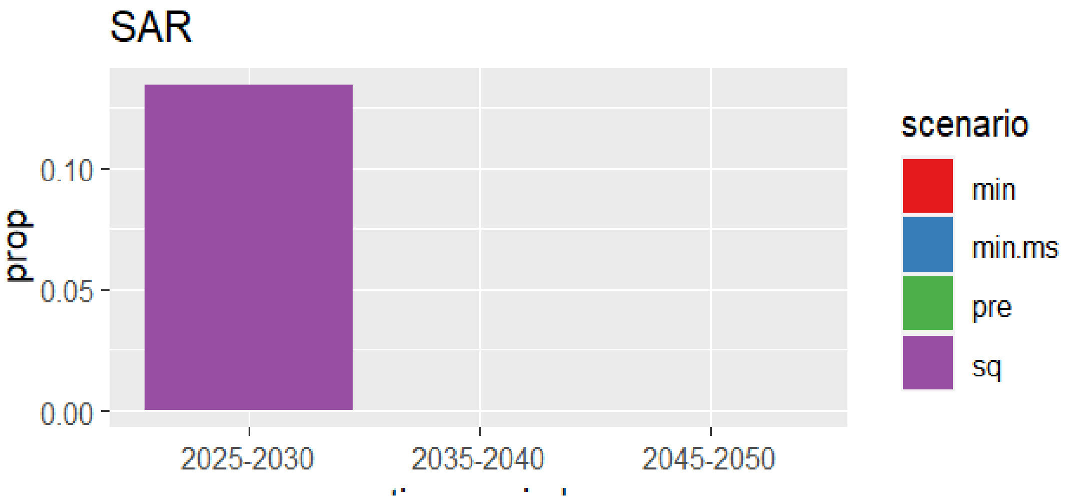

Figure 7. Average SAR indicatorr over stocks and years in each time period.

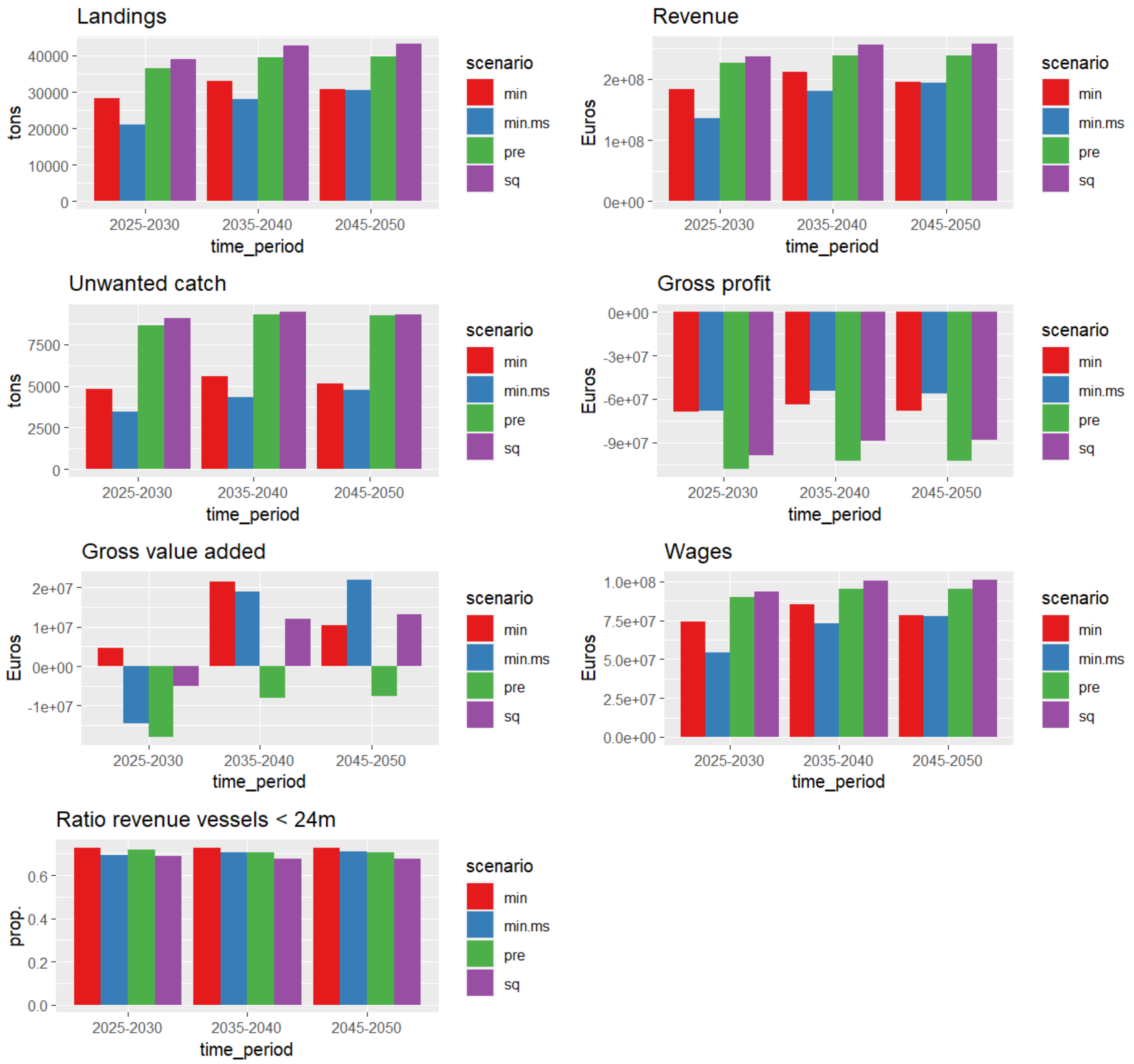

Figure 8. Average economic and fishing activity indicators over given time periods, landings, revenue, unwanted catch, gross profit, gross value added, proportion of revenues coming from vessels smaller than 24m.

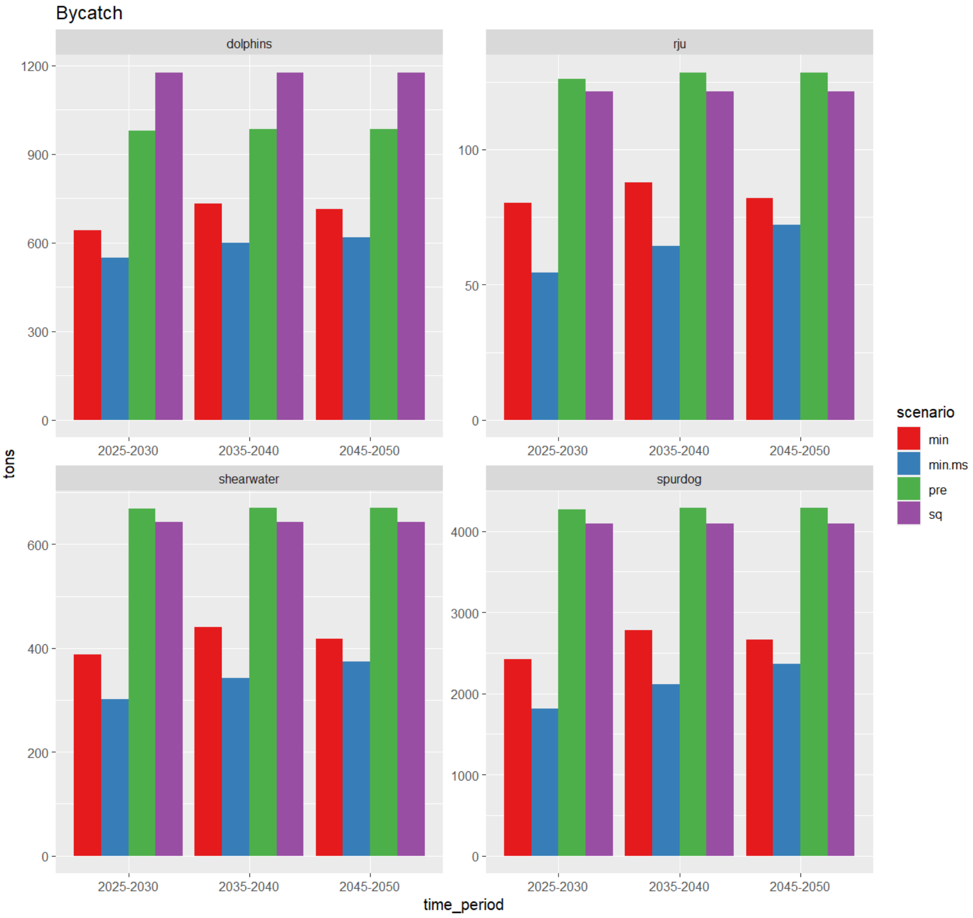

Figure 9. Average catch of bycatch stocks over given time periods for the scenarios run.

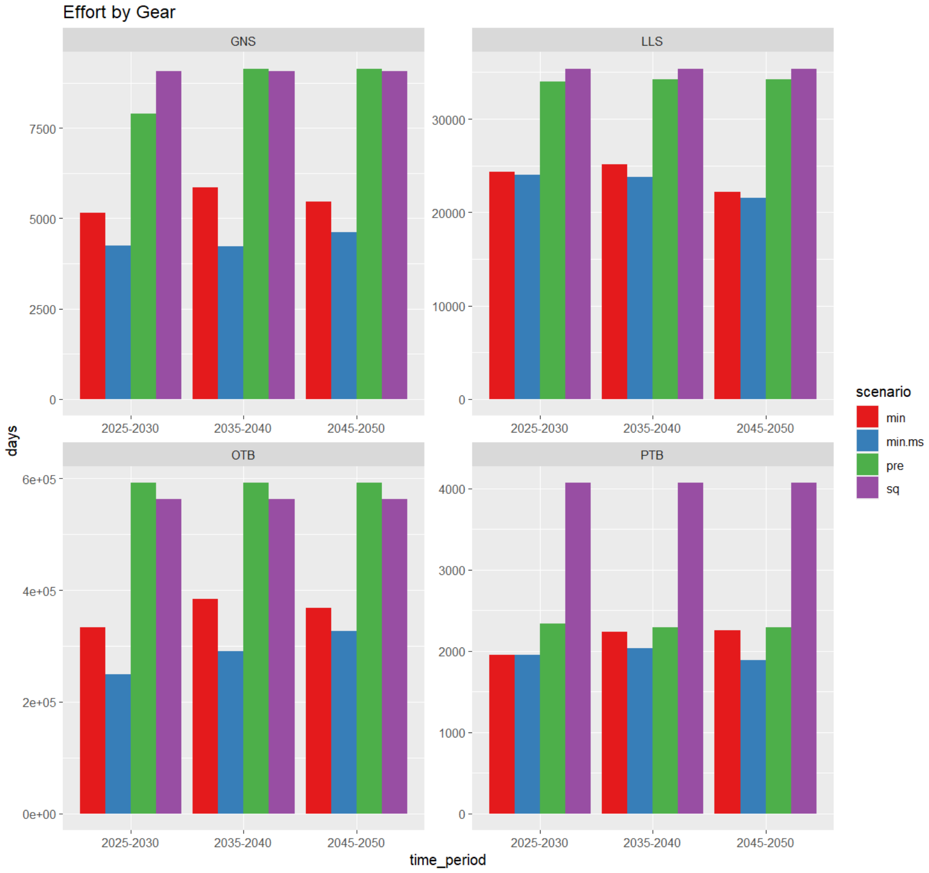

Figure 10. Average effort by gear and scenario in given time periods.

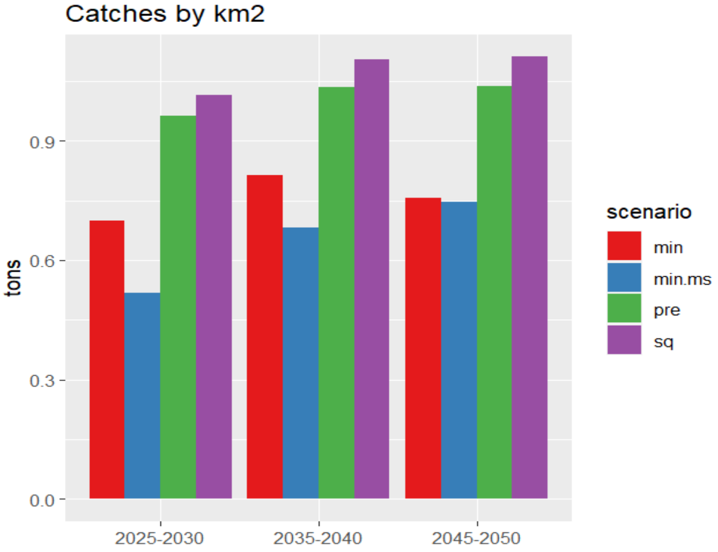

Figure 11. Overall catches by km2 in given time periods for the scenarios run

8.6 **Annex 6: Description of analyses carried out with model FLBEIA for the Basque inshore pelagic fishery in Subarea 8 (Bay of Biscay).**

Sonia Sánchez-Maroño, Marga Andrés and Dorleta García.

1. Description of the model used

FLBEIA has been used to simulate the impact of management strategies for the inshore pelagic fishery in the Bay of Biscay. FLBEIA follows the MSE approach (Punt *et al*., 2016) and as such the simulation is divided into two blocks, the Operating Model (OM) and the Management Procedure (MP) (**Figure 7**). The OM is the part of the model that simulates the true dynamics of the fishery system (the real population). Biological populations and fleets are its essential elements, and they interact through fishing effort and catch (Figure 1). The MP describes the management process, and it is divided into three modules, the observation model (the link between the OM and the MP), the assessment procedure and the management advice. The observation model together with the assessment model generate the perceived population based on which the management advice is calculated. The advice is given in terms of catch and it can also be combined with technical management measures such as gear restrictions, temporal closures or capacity limitations.

The stochasticity in the model is introduced using Monte Carlo simulation (Refsgaard *et al., 2007).* Uncertainty can be introduced in all the variables used to describe the system. Each input variable can be conditioned using a single value or a vector, in this last case, each model replicate is conditioned taking a single value from this vector each time.

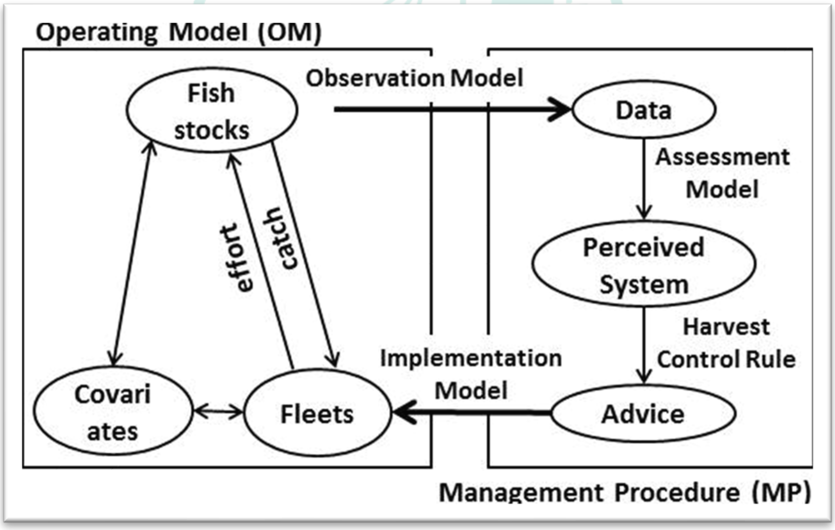

Figure 7: Scheme of FLBEIA model.

Biological operating model

The stocks can be age structured or aggregated in biomass. Three models are available to describe stock dynamics. In the first model the stock abundance in the projection is given as input data and is maintained unchanged in the simulation. Implicitly, it assumes that population growth is independent of fleets’ catch. This model can be useful for example when nothing is known about the dynamics of a certain stock, but its incorporation into the model is justified due to the economic relevance of the stock for a particular fleet. A second model projects age structured populations one season ahead using a stock-recruitment model for incoming recruitment and an exponential survival model for the existing age classes. Finally, populations aggregated in biomass are projected using a Pella–Tomlinson growth model (Pella & Tomlinson, 1969). In the three models, the catch is assumed to take place in the middle of the season, in accordance with the fleet dynamics models implemented.

Fleets operating model

Fleets OM is divided into four processes: effort allocation, catch production, price formation and capital dynamics. The models used to describe these processes can differ from fleet to fleet.

Effort model: It describes fleet's short-term dynamics or tactical behaviour. Each season it models how much effort is exerted and how it is distributed along métiers. In the *status quo* scenario presented in this deliverable the distribution of the effort along métiers is given as input data, whereas in the maximum profit scenario, the effort allocation is the one that gives the highest possible profits. In the status quo scenario the total effort and its distribution among métiers is fixed and equal to the mean of last three years. Whereas in the maximum profit scenario the total effort depends on the catch quotas of the stocks and their market prices.

Catch model: It describes the relationship between catch and effort. In this deliverable the Cobb-Douglas production model (Cobb and Douglas, 1928) which is widely used in economy to describe production in industry has been used.

Price formation: It describes how price changes as a function of other factors, for example landings. Price varies at fleet and stock level. There are two models available to describe its dynamic. The constant model and a model where the price depends on the ratio between current landings and landings in a baseline time period (Kraak *et al*., 2004)

Capital model: It describes the long-term dynamics of the fleet or strategic behaviour; the investment or disinvestment of fishermen in new vessels or technological improvements. In FLBEIA the capital dynamics can be modelled through changes in fleet's capacity or changes in fleet's catchability (technological improvements). Fleet's capacity can be modelled using a constant model or the model described by Salz *et al*. (2011).

2. Description of model parameterisation and scenarios

The conditioning of the model was based on the ICES single stock assessments and mixed fisheries data for the Basque pelagic inshore fleets operating in Bay of Biscay. Moreover, economic data was obtained from the STECF annual economic report, sales data, logbooks and regional data.

The simulation started in 2022 and the stocks and fleets were projected into the future until 2050. The simulation had 500 model replicates (iterations). In each iteration the uncertainty was introduced in the stock recruitment relationship and biological parameters which was propagated in the rest of model variables in the simulation.

2.1 Stocks

In the biological OM, this case study includes 10 stocks (Table 3). All except one were explicitly incorporated in the model using an age structured model, where survival was simulated using the exponential survival model and recruitment using a stock-recruitment model. Biological parameters and those in the stock recruitment model were estimated based on the latest available assessment of the stock and given the same assumptions made by the assessment teams (in ICES or ICCAT). To condition the stocks assessed within ICES (anchovy, hake, horse mackerel, mackerel and sardines), all in Category 1, the 2022 assessment output was used (ICES, 2022a,b,c). For the tuna species (albacore and bluefin tuna), assessed within ICCAT, as several assessments are carried out, one of the alternative assessments was selected to condition the operating model based on expert knowledge (ICCAT, 2020; Rouyer *et* al., 2022).

There were other species included all together in the category OTH (other species), just to cover all the catches by stock and the revenues of the modelled fleets. In this case the population was assumed constant and big enough to avoid conditioning the operation of the fleet in the model.

Table 3: Stocks explicitly included in the inshore case study.

Common name	Species	FAO	CODE	ICES stock	Distribution
Anchovy	*Engraulis encrasicolus*	ANE	ANE	ane.27.8	Subarea 8 (Bay of Biscay)
Mackerel	*Scomber scombrus*	MAC	MAC	mac.27.nea	Subareas 1–8 and 14, and in Division 9.a (Northeast Atlantic and adjacent waters)
Horse mackerel	*Trachurus trachurus*	HOM	HOM	hom.27.2a4a5b6a7a-ce-k8	Subarea 8 and divisions 2.a, 4.a, 5.b, 6.a, 7.a–c, and 7.e–k (Northeast Atlantic)
Northern hake	*Merluccius merluccius*	HKE	NHKE	hke.27.3a46-8abd	Subareas 4, 6, and 7, and in divisions 3.a, 8.a–b, and 8.d, Northern stock (Greater North Sea, Celtic Seas, and the northern Bay of Biscay)
Southern hake	*Merluccius merluccius*	HKE	SHKE	hke.27.8c9a	Divisions 8.c and 9.a, Southern stock (Cantabrian Sea and Atlantic Iberian waters)
Bay of Biscay sardine	*Sardina pilchardus*	PIL	BPIL	pil.27.8abd	Divisions 8.a-b and 8.d (Bay of Biscay)
Iberian sardine	*Sardina pilchardus*	PIL	IPIL	pil.27.8c9a	Divisions 8c and 9a (Cantabrian Sea and Atlantic Iberian Waters)
Bluefin tuna	*Thunnus alalunga*	BFT	BFT	ICCAT	East Atlantic bluefin tuna
Albacore	*Thunnus thynnus*	ALB	ALB	ICCAT	Northeast Atlantic albacore

2.2 Fleets

This modelled fishery was based on those vessels operating in the Bay of Biscay targeting pelagic species. There are two countries involved in this case study: Spain and France. In Spain, the number of vessels is approximately 153, and the number of vessels in France is currently around 12 pairs of trawlers (24 vessels), that target pelagic species such as anchovy. Due to data availability, in this case study the economic component was defined only for the Basque fleets, which was composed by 67 vessels, for which detailed data was available.

The Basque pelagic fishery is characterized by a multi-fleet and multi-species fisheries (Murillas & Andrés, 2016) and presents clear seasonal effort dynamics in the catch profile. The main target species in this case study are mackerel (*Scomber scombrus*), anchovy (*Engraulis encrasicolus*), albacore (*Thunnus alalunga)* and bluefin tuna (*Thunnus thynnus*) (Andrés & Prellezo, 2012; Villamor *et al*., 2008). In recent years sardine (*Sardina pilchardus)* is also targeted by this fleet.

In this case study, two main fleets were included, the first one is the purse seiners fleet (PS) and the second one hand line (LHP) and trolling fleet (LTL). The Basque purse seiner fleet was divided into several homogeneous fleet segments according to the fishing profile and fishing gear (Andrés & Prellezo, 2012): (i) pure purse seine (BC_PPS); (ii) purse seine and pole and line live bait tuna fishery (BC_PSB); (iii) purse seine and pole and line live bait tuna fishery with high catchability of BFT (BC_PSBB); and (iv) purse seine and trolling (BC_PST). The second fleet, using handline (LHL) and trolling (LHP), was considered as an unique fleet segment (BC_HLT). Métiers of each fleet segment were defined considering the specific fishing gear and fishing profile of catches in each season of the year. Although catch profile may vary from one year to another, the sequential pattern remains approximately stable over the years (Andrés & Prellezo, 2012). In each season, the fleet targets one main species together with other secondary species with a low importance in terms of catches. In the case of purse seine fleet, the year starts with the mackerel season (February-April) in which the fleet also catches sardine and other species. The main target species of second season of the year (March-June) is anchovy with the horse mackerel, sardine and other species as secondary species. Next, comes the tuna season (June-October), targeting albacore (ALB) and bluefin tuna (BFT). At the end of the year (November), there could be a small anchovy (ANE) season. In parallel, in recent years there were a PIL season at the end of the year (October-November). In the case of handline and trolling fleet, the seasonality is marked by semesters, with the mackerel (MAC) season in the 1st semester and the ALB season in the 2nd one. Therefore, métiers were defined based on the fishing gear, main target species and the season of the year. Overall, the Basque inshore fleet was defined with 5 fleet segments that in turn were structured into a total of 41 métiers.

Table 4: Fleets, métiers and main target species by métier of the inshore case study

FLEET	FLEET DESCRIPTION	MÉTIER	MÉTIER TEMPORAL DESCRIPTION	MAIN TARGET SPECIES
BC_PPS	Basque fleet pure purse seiner	PPS_ANE1	Semester 1	ANE
		PPS_ANE2	Semester 2	ANE
		PPS_HOM	Year	HOM
		PPS_MAC	Year	MAC
		PPS_OTH	Year	OTH
		PPS_PIL1	Semester 1	BPIL
		PPS_PIL2	Semester 2	BPIL
BC_PSB	Basque fleet purse seiner and live bait	PSB_ANE1	Semester 1	ANE
		PSB_ANE2	Semester 2	ANE
		PSB_ALB	Year	ALB
		PSB_BFT	Year	BFT
		PSB_HOM	Year	HOM
		PSB_MAC	Year	MAC
		PSB_OTH1	Semester 1	OTH
		PSB_OTH2	Semester 2	OTH
		PSB_PIL1	Semester 1	BPIL
		PSB_PIL2	Semester 2	BPIL
BC_PSBB	Basque fleet purse seiner and live bait with high catchability of BFT	PSBB_ANE1	Semester 1	ANE
		PSBB_ANE2	Semester 2	ANE

		PSBB_ALB	Year	ALB
		PSBB_BFT	Year	BFT
		PSBB_HOM	Year	HOM
		PSBB_MAC	Year	MAC
		PSBB_OTH1	Semester 1	OTH
		PSBB_OTH2	Semester 2	OTH
		PSBB_PIL1	Semester 1	BPIL
		PSBB_PIL2	Semester 2	BPIL
BC_PST	Basque fleet purse seiner and trolling	PST_ANE1	Semester 1	ANE
		PST_ANE2	Semester 2	ANE
		PST_ALB	Year	ALB
		PST_HOM	Year	HOM
		PST_MAC	Year	MAC
		PST_OTH	Year	OTH
		PST_PIL1	Semester 1	BPIL
		PST_PIL2	Semester 2	BPIL
BC_HLT	Basque fleet hand line and trolling	HLT_ALB	Year	ALB
		HLT_HOM	Year	HOM
		HLT_MAC	Year	MAC
		HLT_HKE	Year	SHKE
		HLT_OTH1	Semester 1	OTH
		HLT_OTH2	Semester 2	OTH

The fleet segmentation was done in such manner that the seasonality of the fleet could be captured using a suitable effort dynamics model.

In this case study only, the Basque fleet was modelled, due to data availability constraints, and was considered as representative of the whole Spanish fleet. The economic data was obtained from different sources, depending on the availability of the data. These data could be required at fleet-segment lever or at métier level.

Fleet level data

- **Number of vessels:** The number of vessels by fleet segment was estimated from Logbooks data, identifying the vessels that use the specific fishing gears targeting pelagic species in the area of interest.
- **Effort:** The effort, measured in number of operating days, has been estimated at métier level, allocating the adequate métier to each fishing trip, and computing the number of days between the starting and ending day of the fishing trip. The data source where the Logbooks.

- **Fixed costs:** All the costs were extracted from regional statistics (https://www.euskadi.eus/pesca-cuentas-economicas/web01-a2estadi/es/), where data was available at fleet level. Data at vessel level was also available, but just until 2009. As fixed costs were at fleet segment level, and the updated data was available only at fleet level, we took updated data of regional statistics at fleet level and, considering the relative differences of the fleet segments in relation to the fleet as a whole, data at fleet segment level was estimated.
- **Capital value:** Information was compiled from regional statistics.

Métier level data

- **Landings:** It was assumed that catches were equal to landings. The landings by métier and year were estimated from logbook data. In this first phase, the catches were estimated without taking into account the commercial category or age and consequently, same age composition as in the assessment was assumed.
- **Price**: The average price was estimated at métier level, with information for 2016 to 2021 from the First Sale Notes. The price by size or age of the fish was not considered. The price of 'OTH' species was estimated as the sum of landing value of all non-target species divided by the total catches of those species.
- **Fuel costs**: Fuel costs were estimated as fuel costs by unit of effort at métier level. From Basurko *et. al*. (2013), we estimated the number of litres required to catch one tone of target species by a given fishing gear. From these data, together with the catches from logbooks, we estimated the total litres of fuel consumed per métier and year, and by multiplying this value by the fuel price we got the estimation of fuel costs at métier level.
- **Other variable costs:** Variable costs were calculated from regional statistics (available at fleet level). Then, to split these variable costs by métier, we considered the number of days allocated to each métier. The total variable costs were split among métiers according to the number of days multiplied by the number of hours operating for each métier. In those years that the data was not available (2009 onwards), we maintained the costs share.
- **Crew share**: The crew share, defined as the percentage of gross value assigned to crew as salary, comes from expert knowledge.

2.3 Scenarios

Two scenarios were run which differed in the dynamic of the fishery in response to management and how the advice is generated.

- **Status quo (sq):** In this scenario the effort and its distribution among métiers was kept constant in the projection and equal to the mean of the last three data years (2019-2021). The aim of having this scenario is twofold, on the one hand is a control scenario that allows to identify problems in the conditioning of the model and on the other hand it provides a scenario against which to compare the rest of the scenarios.
- **Maximum profit under Landing Obligation (maxprof):** This scenario was selected as the alternative of traditional 'min' scenario. In the min scenario the fleet fully complies with the landing obligation, and they stop fishing when the first of the quotas is consumed, but this scenario is too restrictive for a seasonal and sequential fishery (therefore giving very inconsistent results). In a sequential fishery, when the quota of a given species is consumed, they start targeting other species. In fact, these fisheries can be considered a non-mixed fishery. 'maxprof' scenario is then more flexible than the 'min' approach and simulates sequential fisheries dynamics. This scenario seeks the total effort and effort allocation among métiers that maximises profit, considering the seasonal behaviour of the fleet and the availability of the stocks in the fishing grounds. For that, the total effort exerted by each fleet segment and the effort allocation among métiers is calculated by maximizing the profits but with the following constrains: (i) the total effort was constrained by the capacity of the fleet; and (ii) the catch quota by stock; and (iii) the effort share among métiers was restricted by an interval (defined as the maximum and minimum effort that the fleet can allocate to a given métier). These limits were set according to the historical behaviour of the fleet. The aim of these constraints was to reflect that, although there might be one métier that could be more profitable than another one, the fleet cannot necessarily allocate all its available effort to the more profitable one because the species might not be available all year round.

In all the scenarios the effort of the fleets is constrained by the capacity of the fleet that is obtained from the number of vessels and the maximum number of days a vessel operated along the year.

3. Indicators, targets and limits

The socio-economic indicators used to analyse the socio-economic performance of the system were those proposed within the Task and no extra indicators were calculated.

The biomass and fishing mortality reference points used in the harvest control rules where those used by the assessment teams to generate the advice on fishing opportunities.

Regarding the ratio of landings value for the fleets below 24m, it was not possible to calculate this indicator at métier level, because in present case study the métiers were not defined based on the length of the vessels. Therefore, being not possible to estimate it directly, an approximation was calculated based on the historical percentage of the income of those vessels with less than 24m length.

4. Main results.

All the code and results were stored at a private GitHub repository (https://github.com/Fundacion-AZTI/seawise) and can be made available under request (at https://github.com/Fundacion-AZTI/seawise/archive/b92693dd9ea9525cb846d6bc45f21a08084821c1.zip).

4.1. Stock level

SSB

The 'maxprof' scenario yields higher values of SSB for almost all species, the sardine stocks (IPIL and BPIL) are the exception (**Figure 8**). For both sardines, the catches in 'maxprof' increase in the projected period, while the fixed effort the catches are almost 0. For anchovy (ANE) and mackerel (MAC) the abundance is decreasing along the whole projected period.

The SSB of most of the stocks was well above the limit and trigger reference points in the projection period for the 'maxprof'. However, in the latest years of the projection period, the sardines, the mackerel, and the anchovy reach high biological risks (of falling below B_{lim}). In the 'sq' scenario, the albacore (ALB), the mackerel and the southern hake are the stock with higher biological risks.

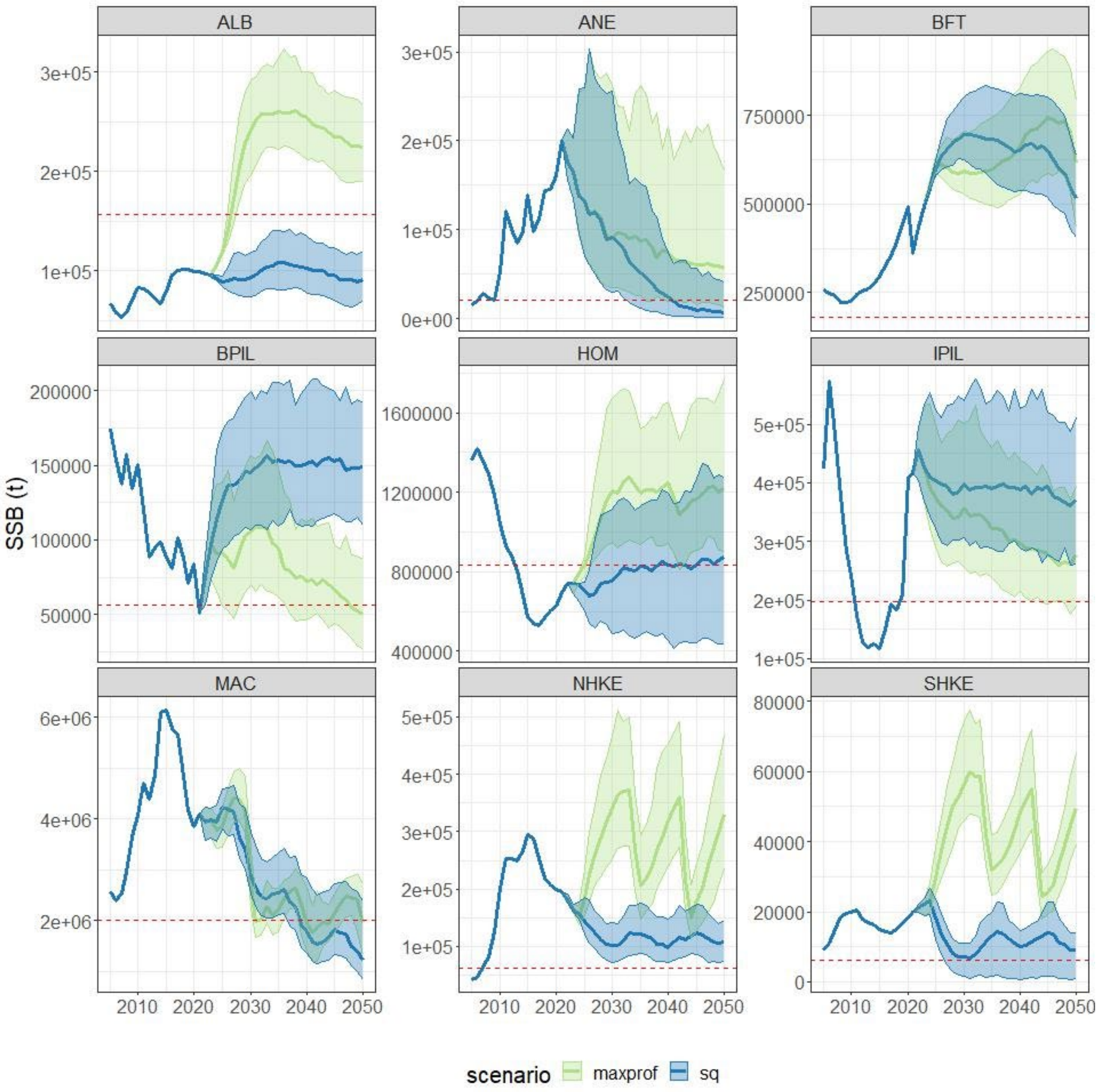

Figure 8: SSB timeseries (in tonnes) for the modelled stocks (Table 3) by scenario (sq: status quo -green-, and maxprof: profit maximisation under the landing obligation -blue-). Solid line corresponds to the median and shaded area to the 90% confidence interval. Horizontal dashed line corresponds to B_{lim}.

Fishing mortality

The fishing mortality in the status quo scenario generally corresponds to the highest fishing mortality scenario, except for the sardines (**Figure 9**). Moreover, in most of the cases, this mortality is at or above the fishing mortality target (F_{MSY}). In the maxprof scenario, the fishing mortality fluctuates around F_{MSY}, but reaching values well above the target.

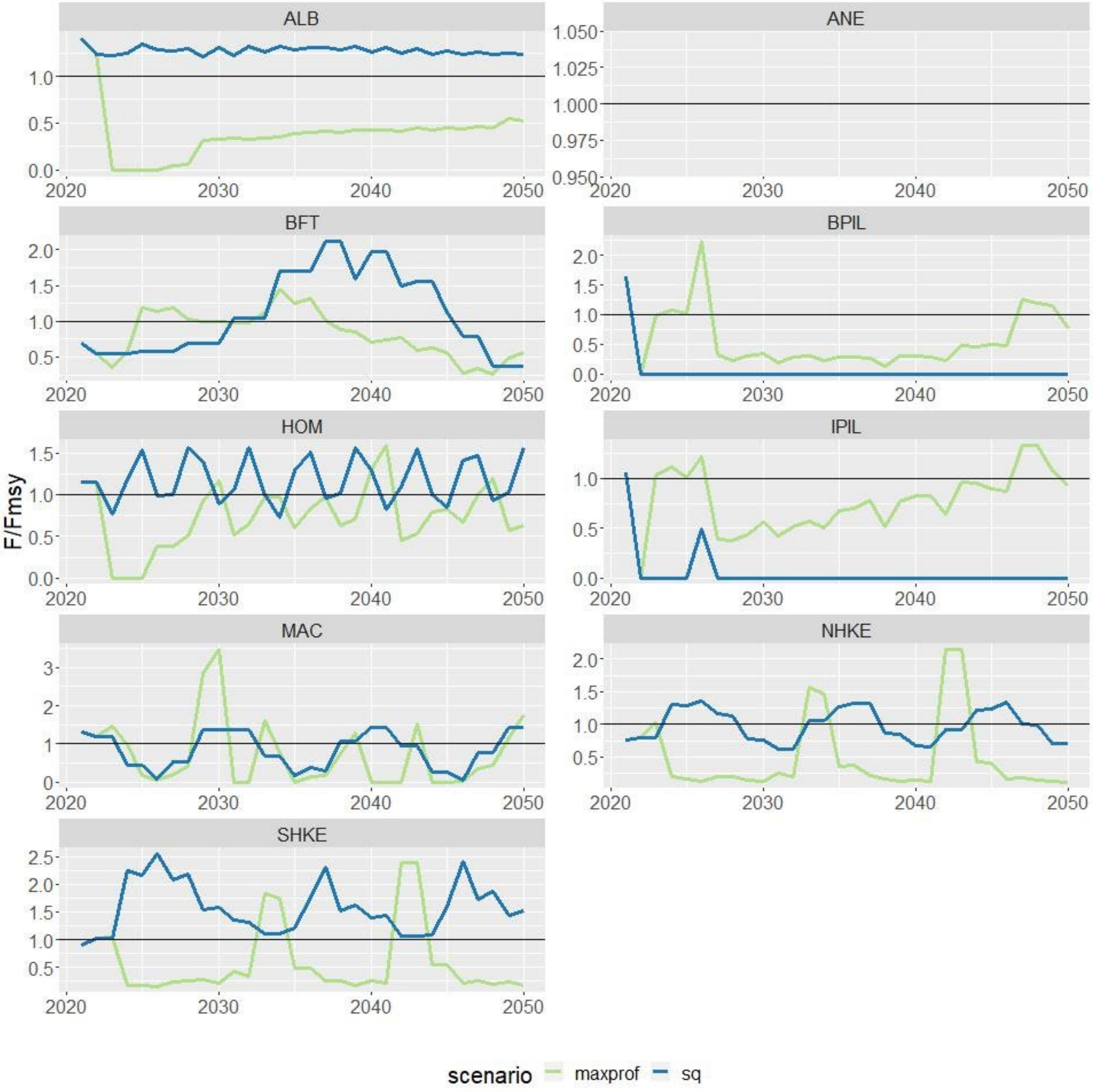

Figure 9: F/F_{MSY} ratio for the modelled stocks (Table 3) by scenario (sq: status quo -green-, and maxprof: profit maximisation under the landing obligation -blue-) in the projection period. Horizontal line corresponds to F_{MSY} level.

Average Age

Important differences are observed in the mean age among scenarios (**Figure 10**). In the 'maxprof' the mean age of all the stocks is bigger at the end of the projection period (between more than 2 years for the bluefin tuna (BFT) and 0.15 years for the Iberian sardine -BPIL-), with the exception of the anchovy (ANE) that has a very minor reduction in its mean age. Whereas for the status quo scenario, there are different trends between stocks. A big reduction for the hakes (up to half age) and lower for albacore and anchovy (0.13 and 0.07, respectively). And a great increase for the rest of stocks of around 1 year and up to 2 years for the albacore. Bluefin tuna and mackerel have very similar trends in both scenarios.

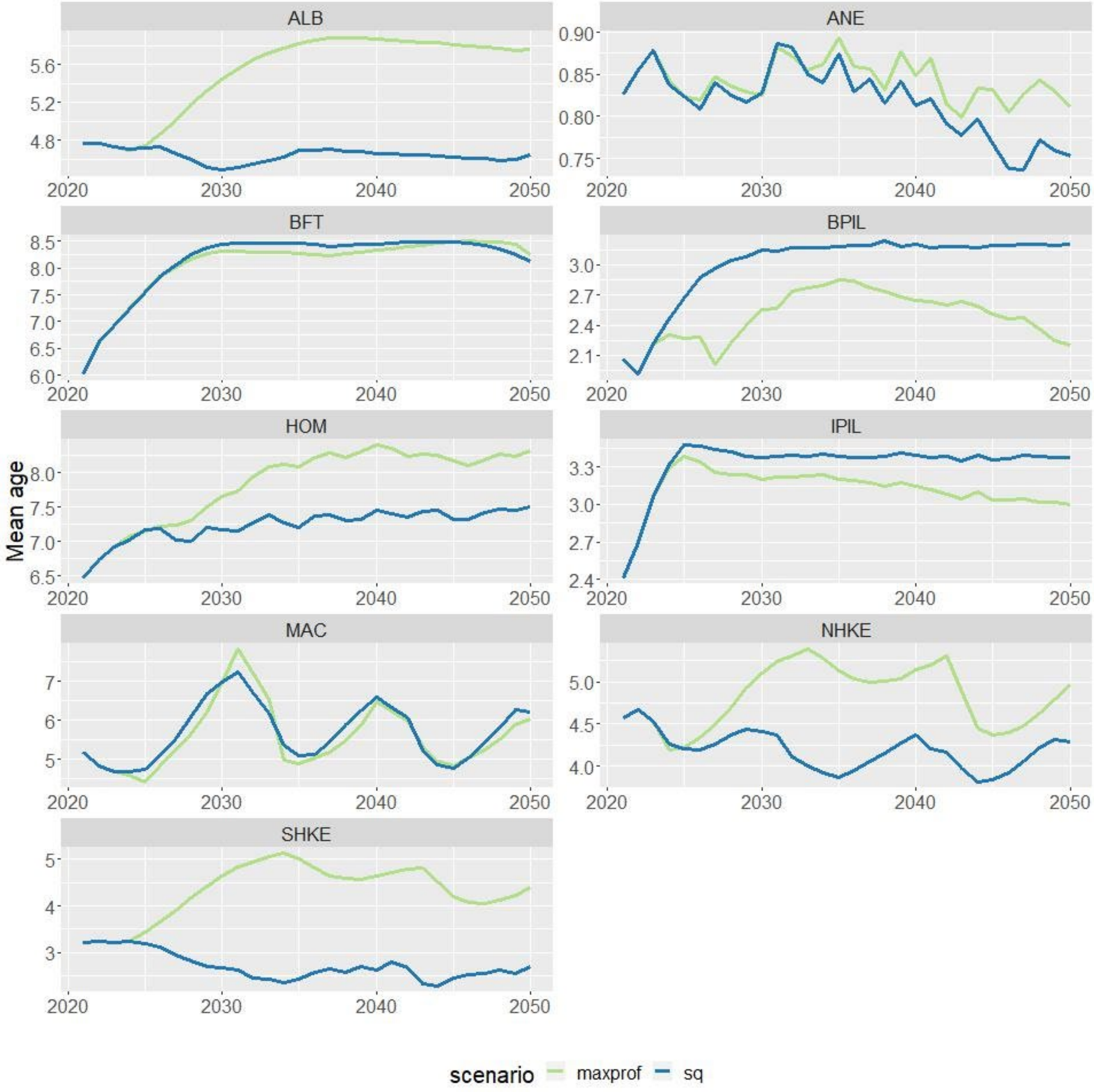

Figure 10: Expected mean age for the modelled stocks (Table 3) by scenario (sq: status quo -green-, and maxprof: profit maximisation under the landing obligation -blue-) during the projection period.

4.2. Fleet level

Effort

Effort time series for the two scenarios at fleet level is shown in **Figure 11** for Basque fleets. For all the fleets, in the 'maxprof' scenario the effort was lower than in the status quo. The reduction is especially remarkable for those fleets targeting big pelagics (BC_HLT, BC_PSB, BC_PSBB and BC_PST), where the fleets drastically decrease their effort to levels well below to the historical observed efforts (at around 10% of the original values). Even in the pure purse seine fleet segment (BC_PPS), which is the only one that does not target big pelagics, effort levels are around half relative to the ones in the status quo scenario.

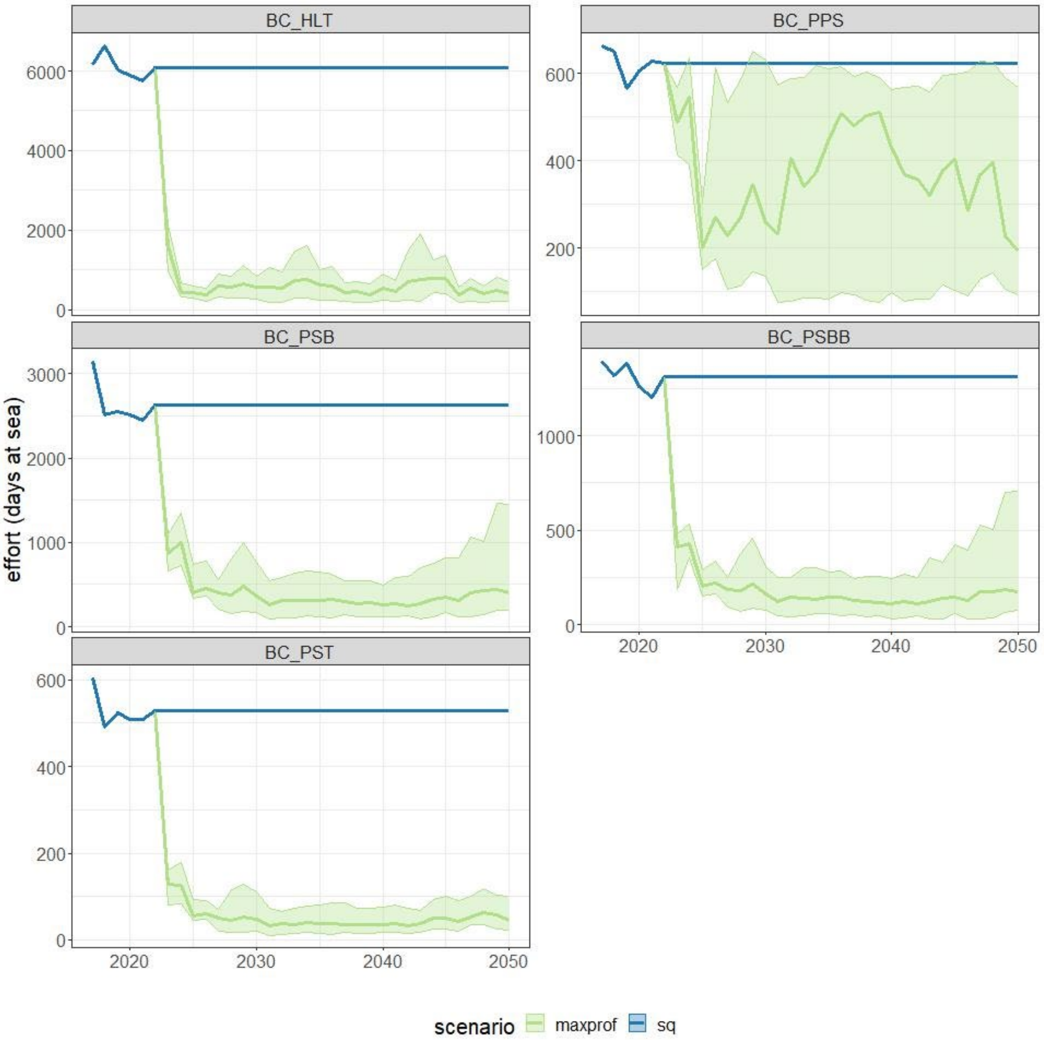

Figure 11: Effort timeseries (number of days at sea) for the Basque fleets (Table 3) by scenario (sq: status quo -green-, and maxprof: profit maximisation under the landing obligation -blue-). Solid line corresponde to the median and shaded area to the 90% confidence interval.

Landings + Revenue

In the short term, the economic indicators are more favourable in the status quo scenario than in the ‘maxprof’ scenario (Figure 12). However, these economic results get worse as projection time advances and in the long term the tendency is changed (i.e., more favourable economic indicators in the ‘maxprof’ scenario). The higher revenues are achieved always at the expense of very high unwanted catch in the status quo scenario, which is completely avoided in the ‘maxprof’ scenario under the landing obligation.

Total fleet landings, revenues and wages decrease with time, but more rapidly in the status quo scenario. Gross profit turn from positive values in the short-term, to negative values in the long term, especially remarkable in the status quo scenario. Gross value added is also reduced with time reaching to values near to zero in the ‘maxprof’ scenario and to very big negative values in the status quo. Small vessels (less than 20 metres long) take advantage in both scenarios, but benefits are higher in the status quo scenario.

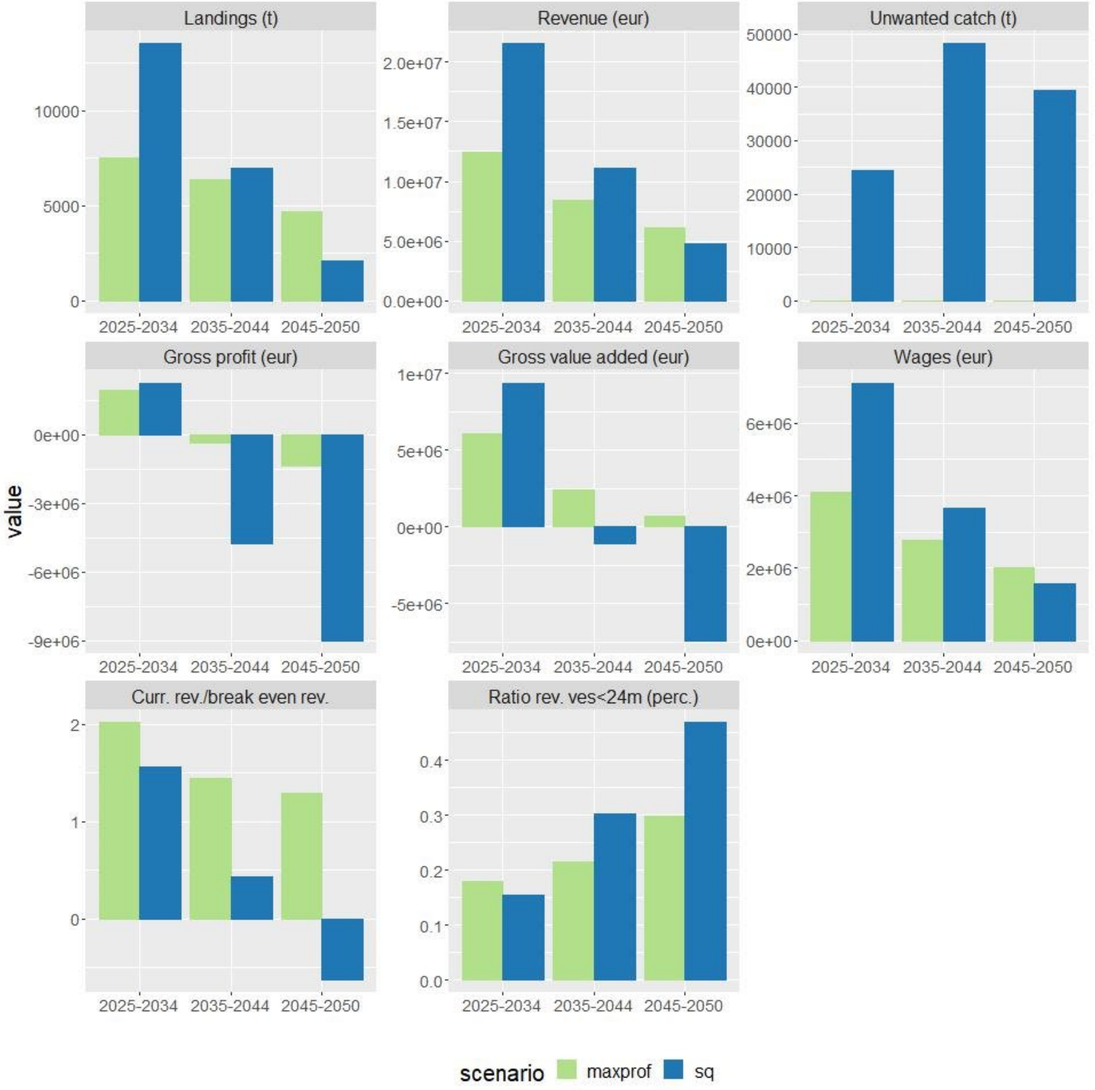

Figure 12: Economic indicators for several periods by scenario (sq: status quo -green-, and maxprof: profit maximisation under the landing obligation -blue-) for all the Basque fleets (Table 4). Solid line corresponde to the median and shaded area to the 90% confidence interval.

Bycatch

In the Basque fleets, the bycath issue affects exclusively to the purse seiners, which incidentally capture dolphins. The bycatch is much lower in the 'maxprof' scenario, than in the status quo one (Figure 13). Due to the sharp reduction in effort experienced in the 'maxprof' scenario.

Effort by Gear

For all the gears used by the Basque fleet, in the 'maxprof' scenario there is sharp reduction of the effort compared to the status quo (Figure 14). The purse seine fleet is the one with lower reduction (~70%), followed by the pole lines (~87%). Whereas hand and trolling lines experiment an almost complete reduction (≥99%).

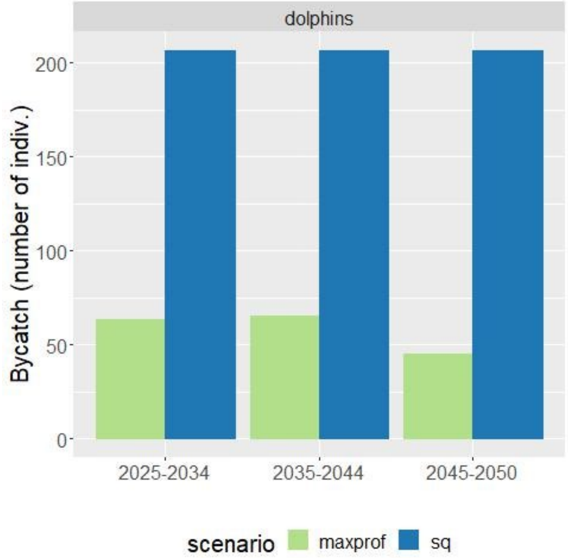

Figure 13: Bycatch of dolphins (number of individuals) for the Basque fleets (Table 3) by scenario (sq: status quo -green-, and maxprof: profit maximisation under the landing obligation -blue-).

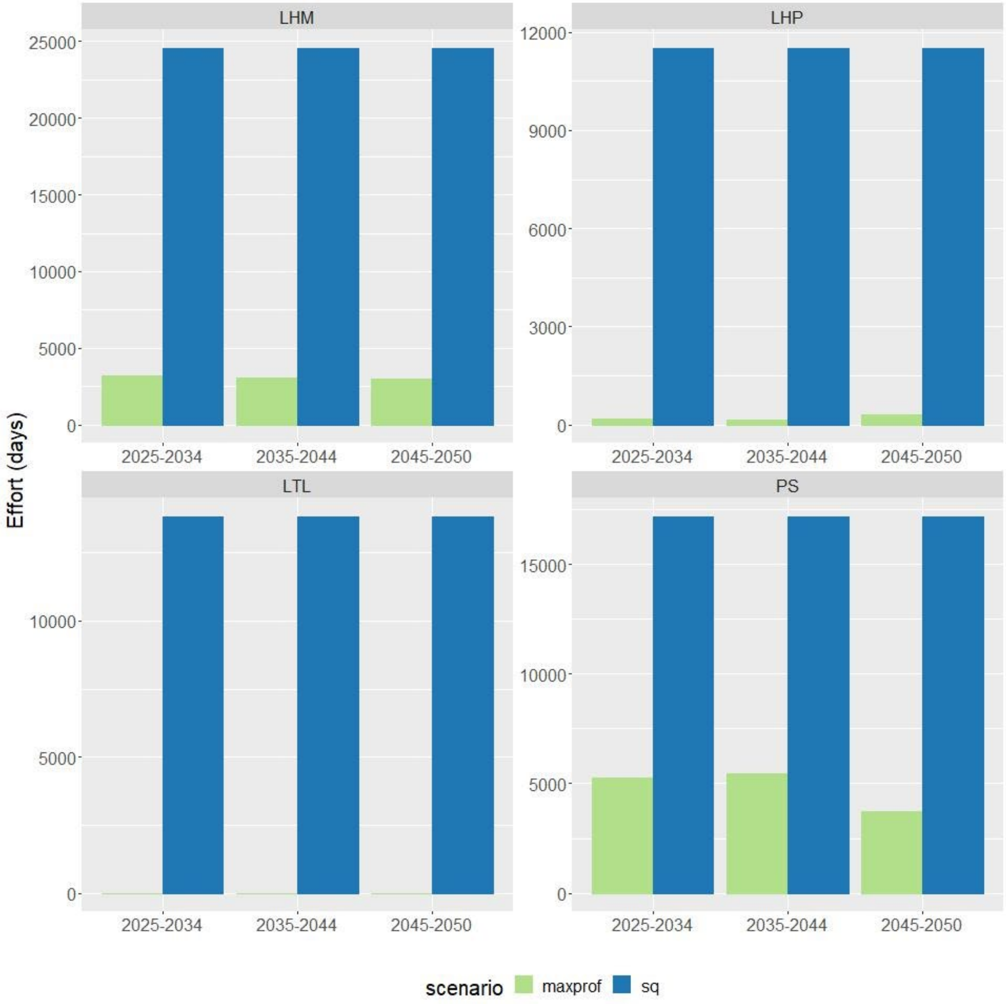

Figure 14: Effort (number of days at sea) by gear (LHM: pole lines; LHP: hand lines; LTL: trolling lines; and PS: purse seine), time period for the Basque fleets (Table 3) and scenario (sq: status quo -green-, and maxprof: profit maximisation under the landing obligation -blue-).

Catches by km^2

Not having analysed the spatially explicit information for the historical catches and therefore assuming a distribution of the catches all along the ICES subarea 8 (675 745 km^2), the reduction of catches for the 'maxprof' scenario, implies also a reduction of the catches by km^2 (Figure 15).

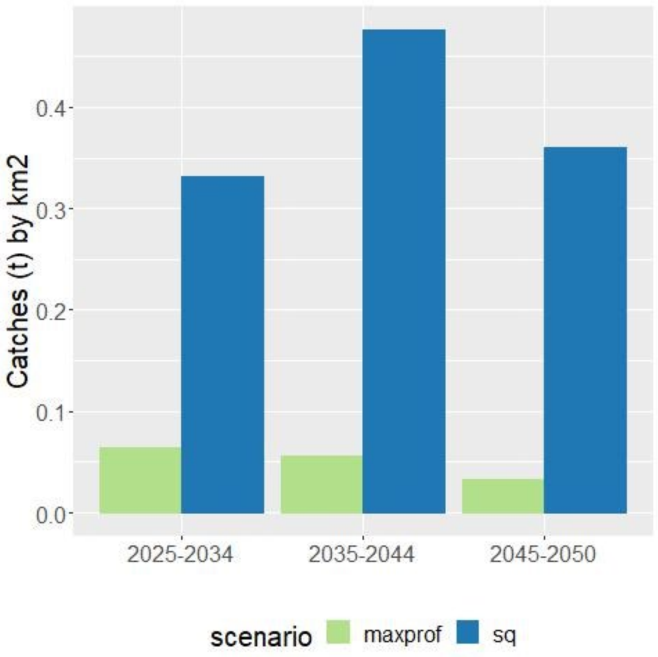

Figure 15: Catches (tonnes) by km^2 for the Basque fleets (Table 3) by scenario (sq: status quo -green-, and maxprof: profit maximisation under the landing obligation -blue-). Given the catch distribution all along the ICES subarea 8 (675 745 km^2).

5. Conclusions

The scenario assuming that the fleet distribution is based on the maximisation of profits under the landing obligation, seems to be less favourable in the short-term. However, it turns economically more favourable in the long term. The maximisation of profits, leads the Basque pelagic fleet to reduce the effort of the métiers targeting big pelagic species (i.e., albacore and bluefin tuna) almost to zero. This is probable due to the increase of the variable costs in these métiers, due to the increase in the fuel costs in the last years and to the fact that these stocks are appearing more northern, so that the fleet must do larger trips to reach the fishing grounds. These factors and the assumption of fixed prices independent to the amount of landings, make these métiers not profitable anymore. However, it is highly probable that prices fluctuate based on the total landings and therefore modelling the elasticity of prices would give a more reliable perspective.

Regarding the biological risks, the maximisation of profits leads to a reduction of the fishing effort, and consequently a reduction in fishing mortality, that implies that most of the stocks are fished below F_{MSY}. Therefore, the number of stocks with risk of falling below B_{lim} above 5% (the maximum acceptable level by ICES) is lower than in the status quo scenario. However, specifically risks for sardines are higher, because the métiers fishing these species gain importance at the expenses of the reduction of the effort in the tuna directed métiers.

All the economic indicators deteriorate as time passes. However, the deterioration is bigger in the status quo scenario, than when the fleet is pursuing profit maximisation. This is motivated by the reduction of effort and consequently landings, that has a positive effect on the biological populations, and consequently allows higher catches at similar effort levels. Moreover, this reduction of effort, has a positive effect on the expected bycatch, which allows a reduction of the bycatch of dolphins.

Status quo scenario is not expected to be a potential scenario for the Basque inshore fleet, due to characteristics of this pelagic fleet. Because the fleet is highly selective and consequently, an adaptation of the effort by métier is expected based on the available quotas for the different fleets. However, the translation of this effort is limited. As these fleets are seasonal and sequential (i.e., main target stock of the fleets is changing in each season), if the stock related to one season is not available, the effort allocated to this season would be really low (because for a period of time they do not have any alternative main species available to be fished). Thus, they have a limited capacity of increasing the effort allocated to one métier when another métier has a low quota.

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8.7 Annex 7: Description of analyses carried out with model BEE-Fish for areas Western Baltic Sea (WBS) & Central Baltic Sea (CBS).

1. Description of the model used

Ecological-economic modeling

We developed and applied a coupled three- (CBS) and two (WBS)-species, age-structured ecological-economic model, which is taking most recent biological, e.g. predation rates, as well as economic information into account. We investigate the effects of different management scenarios, reflecting different strategic long-term management objectives. Our model is an update of the ecological-economic multispecies model of Voss et al. (2014a, b), using new ecological as well as economic parametrization. It builds on the fisheries economic module of a single-species age-structured fishery model for Baltic cod developed by Tahvonen et al. (2018) and expands it to include interactions with herring and sprat stocks. We use the subscript $i \in \{C, S, H\}$ for the cod (*C*), sprat (*S*), and herring (*H*) fisheries. For all three fisheries we consider total economic surplus, i.e. the sum of consumer surplus and producer surplus (fishing profits).

2. Description of model parameterization and scenarios

We specify iso-elastic inverse demand functions

$$p_i(t) = \bar{p}_i H_i(t)^{-\eta_i}\ , \tag{1}$$

with $\bar{p}_i > 0$, meaning that the price p_{it} of species *i* in year *t* decreases with the quantity of fish H_{it} supplied to the market (i.e., the catch from that species in the given year) with an elasticity $\eta_i > 0$. This assumes that the price is the same for all age (and thus size) groups. We further specify harvesting cost functions as

$$C_i(H_i(t), X_i(t), t) = c_i(t) X_i(t)^{-\chi_i} H_i(t) \tag{2}$$

where we allow for a time trend in the cost parameter with $c_i(t) = c_{i0} \exp(\phi_i t)$. The variable $X_i(t)$ is the *efficient biomass* of species *i* in year *t*. It is obtained as

$$X_i(t) = \sum_{\text{ages}=1}^{8} w_i(s) q_i(s,t) x_i(s,t), \tag{3}$$

where $w_i(s)$ is the weight of an individual fish of species *i* at age *s*, $x_i(s,t)$ is the number of fish in stock of species *i* and age *s* in year *t*, and $q_i(s,t)$ is the 'catchability' of that species at age *s*. Given that fishing gear is size-selective, it depends on the age of the fish, and may vary over time as gear selectivity changes, for example due to changing mesh sizes.

For estimating the economic model parameters, we use the method developed by Tahvonen et al. (2018). To this end, we consider the profit margin $\pi_i(t)$, i.e. the profit of harvesting species *i* as a percentage of revenues for that species. Using the specification of harvesting cost function, this gives

$$\pi_i(t) = \frac{p_i(t)H_i(t) - c_{i0}\exp(\phi_i t)X_i(t)^{-\chi_i} H_i(t)}{p_i(t)H_i(t)} \tag{4}$$

Rearranging, taking logs, and adding an error term ε_{it}, we obtain the following equation that can be estimated using data on catches, efficient biomass, and prices:

$$\ln((1-\pi_i(t))p_i(t)) = \ln(c_{i0}) - \chi_i \ln(X_i(t)) + \phi_i t + \varepsilon_{it}. \tag{5}$$

Using the specification of an iso-elastic inverse demand function, we further get

$$\ln(H_i(t)) = \ln\left(\left(\frac{(1-\pi_i(t))\overline{p}_i}{c_{i0}}\right)^{\frac{1}{\eta_i}}\right) + \frac{\chi_i}{\eta_i}\ln(X_i(t)) - \frac{\phi_i}{\eta_i}t + \xi_{it}. \tag{6}$$

For cod, we use the estimates of Tahvonen et al. (2018), for herring and sprat, we use $\pi_i(t) = 0$, as these fisheries have been hardly profitable in the past (Quaas et al. 2012), data from ICES (2019) on landings, age-specific fishing mortalities, and stock sizes, and time series of prices (sprat: 2002, herring: 1988 to 2019) from the annual (until 2003) and monthly (since 2003) reports of the German Federal Office for Agriculture and Food.

We define the case-specific scenario of MMEY management where the objective is to maximize the intertemporal welfare, as the sum of consumer surplus (gross consumer benefit minus expenditure) and profits (revenues minus harvesting costs). The objective thus is to maximize the present value of the differences between gross consumer benefit and harvesting costs for all species:

$$\max \sum_{\text{time}\,t=0}^{\infty} \sum_{\text{species}\,i} \left(\frac{1}{1+r}\right)^t \left(\frac{\overline{p}_i}{1-\eta_i} H_i(t)^{1-\eta_i} - c_i X_i(t)^{-\chi_i} H_i(t)\right) \tag{11}$$

We use an interest rate of *r*=1% per year.

The constraints to the optimization are that fishing mortalities must be non-negative $F_i(t) \geq 0$, the given initial stock numbers $x_i(s,0)$ for all three species in all age groups , and the age-structured multi- $s = 1,\ldots,8$ species population dynamics, i.e.

$$x_i(1,t+1) = \varphi_i$$
$$x_i(s,t+1) = \alpha_i(s-1,\mathrm{ssb}_c(t))\big(1-q_i(s)\big(1-\exp(-F_i(t))\big)\big)x_i(s-1,t) \qquad \text{for } s = 2,\ldots,7$$
$$x_i(8,t+1) = \alpha_i(7,\mathrm{ssb}_c(t))\big(1-q_i(s)\big(1-\exp(-F_i(t))\big)\big)x_i(7,t) + \alpha_i(8,\mathrm{ssb}_c(t))\big(1-q_i(8)\big(1-\exp(-F_i(t))\big)\big)x_i(8,t)$$

(13)

Age-specific natural survival rates are derived from natural mortalities as

$$\begin{aligned}
&\alpha_C(s,\mathrm{ssb}_C(t)) = \exp(-M_C(s)) \\
&\alpha_S(s,\mathrm{ssb}_C(t)) = \exp\left(-M_{S1}(s) - M_{S2}(s)\mathrm{ssb}_C(t)\right) \\
&\alpha_H(s,\mathrm{ssb}_C(t)) = \exp\left(-M_{H1}(s) - M_{H2}(s)\mathrm{ssb}_C(t)\right)
\end{aligned} \tag{14}$$

They depend on cod predation for herring and sprat populations, which increases with the size of the cod stock. As indicator for stock abundance, we use spawning stock biomass

$$\mathrm{ssb}_i(t) = \sum_{s=1}^{8} w_i(s)\gamma_i(s)x_i(s,t)\,, \tag{15}$$

of species *i*, which depends on the weights $w_i(s)$, maturities $\gamma_i(s)$ and stock numbers $x_i(s,t)$ at age *s* and in year *t*. Estimates for predation mortalities are based on the 2019 key-run (ICES, 2019b) of a stochastic multi-species model (SMS: Lewy and Vinther, 2004). Age-specific weights $w_i(s)$ and maturities $\gamma_i(s)$ are taken from the ICES (2019a) assessment reports for the three stocks, using the values from 2018. All biological input data is reported in the Supplementary Material (Tab. S2).

Age-specific catchabilities $q_i(s)$ were estimated based on mean age-specific fishing mortalities for the years 2002 to 2019 as reported in ICES (2019a) with qi(amax)=1 for the age class amax with highest mortality by normalization.

Numerical optimization

In order to determine the optimal MMEY management, while respecting any given constraints in the management scenarios, we solved the optimization problem numerically. For this, the dynamic optimization was performed using the interior-point algorithm of the Knitro (version 12.1) optimization software with AMPL (A Modeling Language for Mathematical Programming, AMPL Optimization LLC, Albuquerque, USA).

3. Indicators, targets and limits

Model output included a set of ecological indicators:

- Total stock biomass
- Spawning stock biomass
- Mean age in the stock, weighted by age-specific weight

as well as fisheries indicators:

- Landings
- Effort

and socio-economic indicators:

- Value of landings

- Employment
- Producer surplus
- Consumer surplus
- Gross profit

Model outcome was compared to indicators and limit reference points developed by ICES.

4. Main results.

The simulations were carried out with partly strong differences in target fishing mortality (Tab. 1). The Status Quo values reflect the already successful reduction of F for the collapsed stocks (e.g. CBS_Cod, WBS_Herring) or in contrast, the not-yet successful conservations attempts (e.g. WBS_Cod).

Tab. 1: Values of target fishing mortality used as input in the model runs. CBS: Central Baltic Sea; WBS: Western Baltic Sea

Scenario	CBS_Cod	CBS_Herring	CBS_Sprat	WBS_Cod	WBS_Herring
F_{MSY}	0.3	0.21	0.31	0.26	0.31
Status Quo	0.1	0.39	0.38	0.9	0.15
F_{MSY_upper}	0.59	0.26	0.41	0.44	0.379

For the Central Baltic Sea trade-offs between landings, revenues, and fishery profits become obvious (Tab. 2). Landings do not directly translate to revenues, or profits. This is explained by the inclusion of a demand system in the model framework, so that prices react on harvest levels. Out of the three input-F scenarios (F_{MSY}, Status Quo, F_{MSY_upper}), F_{MSY_upper} creates the highest landings, and revenues. The F_{MSY} strategy, however, generates higher profits at lower fishing mortality values. Following the Status Quo fishery scenario resulted in the worst combination of outcomes. Including a Welfare optimization scenario (case specific scenario) offers the inclusion of additional, interesting indicators, i.e to include a consumer perspective by analysing the consumer surplus.

Tab. 2: Central Baltic Sea: Comparison of model outcomes for different fishing mortality scenarios. “Welfare” refers to a case-specific scenario, in which total welfare is optimized.

	Landings	Revenues	Profits
F_{MSY}	0	0	++
Status Quo	-	-	0
F_{MSY_upper}	+	++	+

Welfare	++	++	-

Surprisingly, optimization for the objective of welfare leads to lower stock sizes, and lower profits for the fishery as in the other scenarios. This can be explained by the relatively higher importance of consumer surplus in the optimization objective. The welfare-optimization will therefore need to be further restricted by side conditions, i.e. non-negative profits and/or minimum stock sizes, as has already been shown for the Central Baltic Sea (Voss et al., 2022). A reduction in consumer surplus under constrained optimization, as done in Voss et al. (2022) did not proportionally translate to changes in fishery profits. In most cases, the fisheries gained profits, but not always. Management faces several levels of trade-offs: a consumer to producer surplus trade-off, and a consumer surplus to ecological goals trade-off (as implementing minimum stock sizes reduces consumer surplus). Even within the fishery, trade-offs between the species were identified. However, we also find a win-win constellation, as accepting B_{lim} levels in the management increases ecological performance as well as total profitability of the fisheries. Generally, management which applies lower F-values, will lead to a faster recovery of the depleted stock in the Baltic.

In the Western Baltic, trade-off between landings (i.e. food security objective), revenues, and fishery profits are obvious, too. Depending on the variable of choice, a different management strategy would be favorable. Only a Status Quo management will in no case lead to the most desirable outcome. Again, the inclusion of a welfare optimization scenario will lead to a substantially different outcome. Further work on this objective is planned, including inserting side conditions like non-negative profits and minimum stock sizes, to refine trade-off analysis and offer management-ready alternatives.

Tab. 3: Western Baltic Sea: Comparison of model outcomes for different fishing mortality scenarios. “Welfare” refers to a case-specific scenario, in which total welfare is optimized.

	Landings	Revenues	Profits
F_{MSY}	++	0	0
Status Quo	-	-	+
F_{MSY_upper}	0	+	++
Welfare	+	++	-

5. Conclusions

We used updated ecological and economic data to investigate fisheries management outcomes for the Baltic Sea. Ecological-economic multispecies models have been shown to be useful to study trade-offs between different management objectives (Voss et al., 2014a, b). Only by including the economic dimension, a balanced resource use, their equitable distribution and conservation, i.e. the “triple bottom line in fisheries management” (Halpern et al., 2013) can be addressed. The identification of trade-offs as well as potential synergies among multiple ecosystem goods and services is a central issue in ecosystem-based management (EBM; McLeod and Leslie, 2009) and it is urgently needed to progress Baltic fisheries management into this direction.

Management which is based on a multi-annual plan (EU, 2016), offers some flexibility, as fishing mortality ranges are defined, which are centered around F_{MSY} estimates. For cod, however, F_{MSY} is currently not defined and the basis for the scientific advice is the precautionary approach (ICES, 2021). Earlier results (Voss et al., 2022) suggest that fisheries management in the central Baltic, in a multispecies context and respecting economic objectives, should head for Maximum Multispecies Economic Yield (MMEY) instead of using MMSY to define objectives. MMEY seems closer to the ideas of EBM, as the economic dimension is explicitly included in formulating the management objectives. While both concepts (MMSY and MMEY) needed to include side conditions in order to reach the triple bottom line of fisheries management, MMEY only had to be complemented by one side condition, i.e. setting a minimum stock size for cod. Changing the minimum stock size of cod in our simulations from B_{lim} to the more precautionary B_{PA} (Precautionary Approach) did not change the results qualitatively.

Synergies and trade-offs

So far, fishery management often fails to adequately address issues of socio-economic equity (Lam and Pitcher, 2012). This is a problem, as management that neglects the fair distribution of benefits that ecosystems provide causes low acceptance and compliance (Lam and Pitcher, 2012; Lam and Calcari, 2012). Our model framework offers the opportunity for a more holistic analysis by including producer as well as consumer benefits. By doing so, Voss et al. (2022) discovered a win-win situation between producer surplus (the fishery) and respecting minimum stock size limits. Environmentalists, concerned about the conservation status of cod, and the fishing industry, concerned about conservation of a viable fishery and its cultural heritage, both benefit from rebuilding the cod stock. This result is caused either by increasing cod prices due to lower supply if quotas are set more restrictive, or by decreasing costs for the cod fishery due to the stock effect (which implies that unit operating costs will be sensitive to the size of the exploited fish stock; Hannesson, 2007) or a combination of both. The consumer only pays for the stock conservation, if prices increase. Which effect is dominant can, however, not be resolved by our model.

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8.8 **Annex 8: FLBEIA in Eastern Ionian Sea GSA 20**

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Introduction

In the Eastern Ionian Sea operate both small pelagic fishery including purse seine fleet (PS) and demersal fishery. The latter consists of two main fleet categories: the otter bottom trawl fleet (OTB) and the small scale fleet (SSF) comprising multi-licence coastal vessels exploiting a variety of gears (mainly longlines and gillnets, but also pots, traps and dredges). The fishery can be further categorized in 22 fleet segments according to main gear and vessel length (STECF, 2021). In 2020, ~30 PS, 26 OTB vessels and ~3000 SSF vessels were active in the eastern Ionian Sea waters (DCF, 2021). The demesral fishery catches a varied mix of species (up to 100 commercial species) with European hake (*Merluccius merluccius*), Red mullet (*Mullus barbatus*), Striped red mullet (*Mullus surmuletus*) and Deep water rose shrimp (*Parapenaeous longirostris*) being the most important stocks, comprising up to 25% of total catch and total landings value (DCF, 2021). Other important stocks are Picarel (*Spicara smaris*), Bogue (Boops boops), Octopus (*Octopus vulgaris*), Common pandora (*Pagellus erythrinus*), and Common cuttlefish (*Sepia officinalis*) (Anonymous, 2021). From these stocks, only hake and red mullet are regularly assessed in STECF and GFCM groups (STECF, 2020; FAO, 2022), while assessments exist for the other 5 stocks in the Annual fleet report of 2021 (Anonymous, 2021). The rest of the commercial species of the fishery remain un-assessed. From the assessed stocks, hake, red mullet and common pandora are considered overexploited in the eastern Ionian Sea, while the rest are sustainably exploited (Anonymous, 2021; FAO, 2022; STECF, 2020).

The fishery is managed by input control rules, restricting the fleets' effort in days at sea, and a fixed number of fishing licenses. The OTB fleet is allowed to operate 8 months during the year between October and May (except 24-31 December and 24-31 May), while it is not allowed to fish less than 3 miles from the coast or at depths less than 50m and in any case not less than 1.5 miles from the coast, according to the Management plan for the Greek bottom trawls following the EU regulation 1967/2006 (Anonymous, 2013). The SSF fleet is allowed to fish all year long, however, the actual days at sea of the fleet are much less (~140 days) for reasons having to do with seasonal fish abundance (e.g. fish targeted by longlines are not abundance throughout the year), weather conditions, but also the fact that for many vessel owners fishing is a secondary occupation. A special restriction applying to the SSF fleet is the ban of the targeted fishing of hake (i.e. more than 20% of the catch consisting of hake individuals) during February (Anonymous, 2013). Both fleets are subject to spatial restrictions (closured areas). According to Petza *et al.* (2017), 37% of national waters are subject to spatial restrictions and 27,8% are subject to spatiotemporal restrictions and similar percentages apply to the eastern Ionian Sea. Technical measures apply for both fleets specifying minimum catching sizes and gear configurations. The demersal fisheries in the Mediterranean (including Greece) have been exempted from the discard ban (EU regulation 2015/812) and a minimum discard rate of 5% per year is allowed for the OTB fleet, while 3% and 1% discard rates are allowed for nets and longlines respectively (EU regulation 2020/4).

A particularity of the Greek demersal fishery is the large number of SSF vessels (~10000 active vessels), which are operated by local fishers and their families as a means of living. The SSF fleet may not be always profitable but can still provide sufficient income to support the fishing families (Liontakis *et al.*, 2020). By contrast, the OTB fleet is profitable adding annually around 50 million euros to the country's GDP. The fishing fleet has been in decline since mid-1990, with withdrawal of 3,333 vessels (17.57%) in the period 2003-2020, which corresponds to a capacity reduction (GT) of 31,27% (Anonymous, 2021).

Main problems of management are the ineffective monitoring and surveillance (in part due to the large number of vessels). This causes the coastal fishery to be largely unregulated, while a big issue is the Illegal, Unreported and Unregulated (IUU) fishing. Beneficial management rules have been the ban of the OTB fleet from fishing within 1.5 miles from coast according to EU regulation (EC 1967/2006), which has helped the mullets (red mullet and striped red mullet) populations to increase. In addition, the introduction of the 40mm square mesh size for the OTB fleet (EC 1967/2006) has had very positive effects on the hake stock (Mytilineou et al., 2021).

Description of the model used

The bioeconomic future of the eastern Ionian Sea demersal fishery under the current management regime was projected using the FLBEIA bio-economic simulation software (Garcia *et al.*, 2017). The model is conditioned using catch and biomass data since 1994, where available. The projections start in 2021 (first projection year) and go up to 2050. The initialization is done using the average of each parameter in the historical period 2018-2020.

The model considers two demersal fleets (large scale fleet: LSF and small scale fleet: SSF) and three main stocks, i.e. European hake (HKE), red mullet (MUT) and deep water rose shrimp (DPS). In addition, stripped red mullet (MUR) is included as a separate stock, while all other commercial stocks caught by the demersal fleets (~70) are considered as one stock (OTR) with pooled biomass and catches. To correctly project the biomass dynamics of this OTR stock, an auxiliary fleet targeting only OTR had to be defined (AUX), which represents the effort and catches of Purse Seines and Beach Seines. Table I shows the fleet structure and catch shares of species by fleet/métier combination. The small-scale fleet (SSF) has two métiers, nets (NET) and long-lines (LLS), while the large-scale fleet (LSF) has one metier, otter bottom trawl (OTB). The fishing effort, is expressed in days_at_sea*GT for the LSF, and days_at_sea for the SSF.

Table I. *Catch shares by fleet and stock for the Eastern Ionian Sea demersal fishery (average values in the period 2013-2020, excluding 2015 and 2017). Stocks: HKE - European hake, MUT - red mullet, MUR - striped red mullet, DPS: deep water rose shrimp and OTR -the rest of the stocks combined. Fleets: LSF – otter bottom trawls, SSF: small scale fishery with two métiers (NET: nets, LLS: long-lines) and an auxiliary fleet (AUX) catching only the OTR stock.*

catch shares	OTB	SSF:NET	SSF:LLS	AUX
HKE	0.265	0.677	0.058	-
MUT	0.242	0.758	-	-
MUR	0.092	0.908	-	-
DPS	1	-	-	-
OTR	0.127	0.386	0.062	0.425

Description of model parameterisation

Stock dynamics

HKE and MUT are modelled as age-structured stocks, utilizing a4a (Jardim *et al.*, 2015) stock assessment from GFCM (FAO, 2022). DPS, MUR and OTR are modelled as biomass dynamic stocks, assessed with the time-varying productivity extension of the SPiCT model (Mildenberger *et al.*, 2020). From the three stocks only DPS shows significant increase in its productivity in the reference period (1994-2020). Assessment results for BD stocks are included in Appendix A.

Stock Recruitment (SR) relationship

For age structured stocks (MUT and HKE) a Ricker SR relationship has been fitted to the SSB and recruitment estimates of the a4a stock assessments. The fit was repeated for 300 randomly selected iterations. Results of these fits are included in Appendix B.

Uncertainty

Uncertainty of stock assessment parameters and SR relationships was taken into account for all modelled stocks in a Monte Carlo setting. In this, 300 different initializations were defined. From those, a subset of 292 iterations were valid (for the rest the SR fits did not converge) and were finally used.

Fishery sub-models

The fishery submodel considers a constant effort regime. The effort changes per scenario are applied once, in 2021, and the projection evolves with no further changes in effort or advice.

Economic sub-models

The economic sub-models consider fixed prices (which are size dependent for the structured stocks), a fixed capital model and a CobbDouglas production function.

Scenarios tested, Biological indicators, targets and limits

Scenarios tested

The main scenarios agreed for the Mediterranean case study were applied to the eastern Ionian fishery projections. In particular, the F01, Fup and Flw scenarios were applied in reference to the HKE stock, which is the most overexploited stock in the fishery. Reference points of the main stocks of the fishery are presented in Table II. Although the initial envision was to project scenarios only for the LSF (i.e OTB), which is currently under a management plan, it was finally decided that the scenarios will apply to both fleets. As is evident from Table I, for the majority of landings of HKE come from the SSF (~70%). For this reason, even the full closure of the LSF would not suffice to achieve the F01 (or even Fup) objective for this stock. Two scenarios combining all three stocks' objectives were applied, the PGY and Fcomb scenarios. The PGY scenario is defined as the intersection of PGY ranges of the three stocks (see Figure 1). For DPS, the PGY range corresponds to the fishing mortalities that achieve 80% of MSY, while for MUT and HKE the 'PGY ranges' are assumed equal to the Fup-Flw ranges (not strictly following the definition of PGY). Finally, the Fmsy combined scenario (Fcomb) defines a combined target Fishing mortality that is the average of the target fishing mortalities of the three stocks, weighted by each stock's share of the catch, i.e.,

$$F_{comb} = \frac{lands_{HKE} \times F_{01\_HKE} + lands_{MUT} \times F_{01\_MUT} + lands_{DPS} \times F_{msy\_DPS}}{lands_{HKE} + lands_{MUT} + lands_{DPS}}$$

For the Fcomb scenario, it was decided to have management consequences only for the LSF fleet, to have a balance between LSF and SSF in the set of scenarios investigated (see Figure 1). The final set of scenarios adapted to the eastern Ionian Sea (GSA20) are the following:

a) **SQ**: Status quo (same effort as in the period 2018-2020);

b) **F01**: Effort reduction to achieve the F0.1 (used as FMSY proxy) for HKE;

c) **Fup**: Effort reduction to achieve Fup for HKE;

d) **Flw**: Effort reduction to achieve Flw for HKE ;

e) **Fcomb**: Effort reduction to achieve a combined FMSY on all main stocks (HKE, DPS, MUT);

f) **PGY**: Effort change to achieve Pretty Good Yield (PGY) from all main stocks (HKE, DPS, MUT);

Table II. *Current fishing mortality and reference points for the three main stocks of the eastern Ionian Sea (GSA20) demersal fishery in 2020. For age structured stocks, HKE and MUT, reference points were estimated using FLRef package in R (Winker, 2022; R core team, 2022) and assuming a Ricker SR relationship (i.e the mean Ricker curve fitted). F01 for MUR and DPS were defined on the Yield-F curve as the points where the slope is 10% of that in the origin. MSY and biomass are in tons.*

Ref point	DPS	HKE	MUT	MUR
F01	0.490	0.201	0.285	0.475
Fup	0.669	0.283	0.399	0.648
Flw	0.327	0.138	0.194	0.316
Fmsy	0.540	0.565	0.379	0.21
MSY	329.000	958.861	406.042	240
Bmsy	607.000	3796.300	1122.303	458
Blim	NA	2521.714	985.453	NA
SSBmsy	NA	2521.714	985.453	NA
Fcur	0.190	0.380	0.320	0.11
F/Fref	0.350	1.861	1.100	0.53

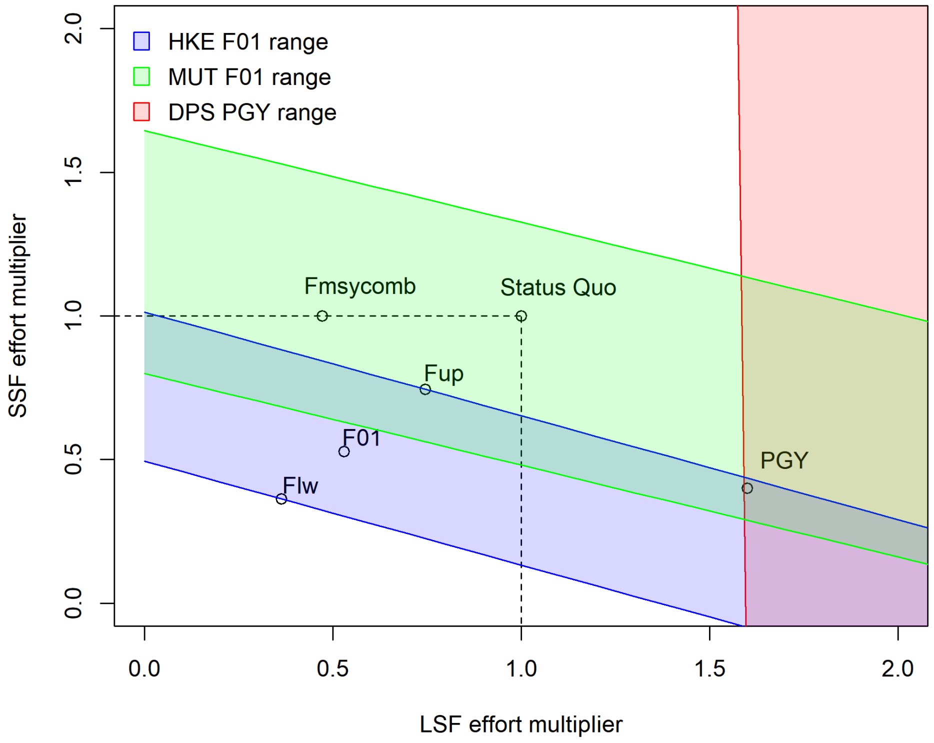


Figure 1. *Effort multipliers by fleet for the six scenarios defined for the eastern Ionian Sea (GSA 20) bioeconomic projections. The coloured areas correspond to fishing mortality ranges of the three main stocks; Fup to Flw range for MUT and HKE and PGY (fishing mortality corresponding to 80%MSY) for DPS. The effort multiplier set for the PGY scenario is defined on the intersection of the three species ranges.*

Table III. *Effort multipliers by scenario and fleet used in the bioeconomic projections of the eastern Ionian sea demersal fishery. LSF: large scale fleet, SSF: small scale fleet.*

scenario	LSF	SSF
Status quo	1	1
F01	0.529	0.529
Fup	0.745	0.745
Flw	0.363	0.363
Fcomb	0.472	1
PGY	1.6	0.4

Indicators, targets and limits

The aim in Deliverable 6.7 was to test the consistency of a wide range indicators and their associated targets and limits (where available). Therefore, a set of indicators has been agreed based on the indicators used to measure the performance of current management. As types of indicators ecological and socio-economic indicators in relation to CFP objectives as well as MSFD related indicators and global indicators were included to cover a broad range of indicators.

For each indicator the average over the prediction years 2025-2030, 2035-2040, 2045-2050 (i.e. 5-year periods as suggested by the most recent MSFD guidelines (European Commission 2022)) were calculated. In Table IV you may find the list of indicators calculated for this case study and D6.7

Table IV. Set of indicators that were calculated for GSA20 fishery within D6.7.

Type of indicator	Indicator	Targets or limits available
CFP ecological	Proportion of stocks fished at or below F_{MSY}	Yes
	Proportion of stocks with median SSB below MSY $B_{trigger}$	Yes

Type of indicator	Indicator	Targets or limits available
	Proportion of stocks with >5% probability to fall below B_{lim}	Yes
CFP socio-economic	Landings (average of yearly sums across fleets/metiers)	No
	Unwanted catch/Discards (average of yearly sums across fleets/metiers)	No
	Revenue (average of yearly sums across fleets/metiers)	No
	Gross profit (average of yearly sums across fleets/metiers)	No
	Gross value added (average of yearly sums across fleets/metiers)	No
	Employment (average of yearly sums across fleets/metiers)	No
	Wages (average of yearly sums across fleets/metiers)	No
	Average yearly ratio of current revenue/break even revenue (sum across fleets/metiers)	Yes
	Ratio landings value fleets <=24m/landings value fleets >24m	
MSFD related indicators (Descriptor 3	D1C1: Bycatch or risk for PET species (here sea turtles)	Partly (for some species and regions)

Type of indicator	Indicator	Targets or limits available
indicators are already included under CFP indicators)	D6: Relative effort of OTB gear (as proxy of impact on benthic communities	No

4. Main results

Tables V-VII Indicators showing the proportion of stocks fished at or below Fmsy, the proportion of stocks with median SSB below SSBmsy (median B<Bsmy for biomass dynamic stocks) and proportion of stocks with >5% probability to fall below Blim, provided for each scenario. Stock specific landings and landings' value are included in Table C1 in Appendix C. Figures 2 to 4 present the changes in the biological indicators depending on the scenario applied whereas Figures 5 to 6 show the respective changes in the socio-economic indicators.

Table V. *Indicators showing the proportion of stocks fished at or below Fmsy, the proportion of stocks with median SSB below SSBmsy (or B<Bmsy for biomass dynamic stocks) and proportion of stocks with >5% probability to fall below Blim, provided for each scenario.*

Scenario	Time period	Proportion of stocks fished at or below F_{MSY}	Proportion of stocks with median SSB below MSY $B_{trigger}$	Proportion of stocks with >5% probability to fall below B_{lim}
F01	2025-2030	1	0	0
F01	2035-2040	1	0	0
F01	2045-2050	1	0	0
Fcomb	2025-2030	0.75	0	0
Fcomb	2035-2040	0.75	0	0
Fcomb	2045-2050	0.75	0	0
Flw	2025-2030	1	0	0
Flw	2035-2040	1	0	0
Flw	2045-2050	1	0	0
Fup	2025-2030	0.75	0	0
Fup	2035-2040	0.75	0	0
Fup	2045-2050	0.75	0	0
PGY	2025-2030	0.5	0.25	0
PGY	2035-2040	0.5	0.25	0
PGY	2045-2050	0.5	0.25	0
Status quo	2025-2030	0.5	0	0
Status quo	2035-2040	0.5	0	0
Status quo	2045-2050	0.5	0	0

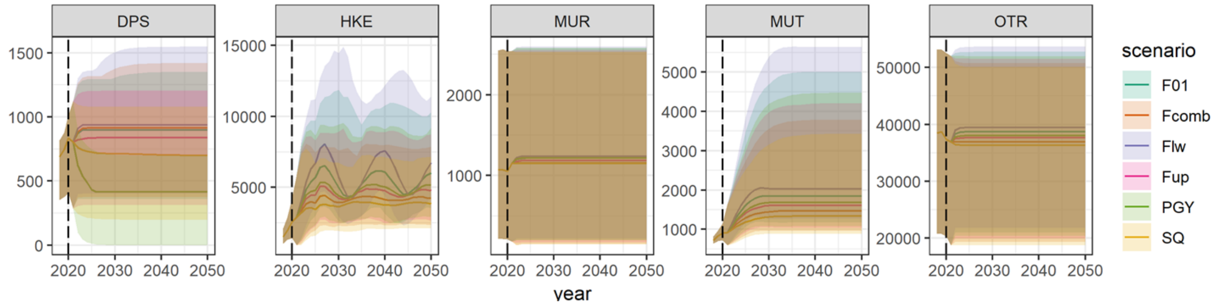
Table VII. *Socioeconomic indicators, given as average values of the given time periods, for each scenario.*

Scenario	*Time period*	*Landings*	*Revenue landings*	*Discards*	*Gross profit*	*Gross value added*	*Employment (FTE)*	*Wages*	*CR/BER*	*Rev_SSF /LSF*
F01	2025-2030	1670.1	2241778	7.3	-4102856	1271212	1095.9	2685807	1.9	4.7
F01	2035-2040	1671.4	2232116	8.1	-4154144	1188904	1095.9	2670297	1.9	4.7
F01	2045-2050	1646.0	2136600	7.6	-4479450	723273	1095.9	2600134	1.4	4.6
Fcomb	2025-2030	2535.8	3118009	7.3	-9899357	-2140488	2025.5	3878207	-3.4	9.2
Fcomb	2035-2040	2556.8	3177980	7.3	-9683411	-1824444	2025.5	3928256	-3.2	9.3
Fcomb	2045-2050	2551.8	3163629	7.1	-9725543	-1885815	2025.5	3918636	-3.2	9.3
Flw	2025-2030	1205.6	1712266	4.9	-2763625	1623666	752.4	2192418	0.6	4.9
Flw	2035-2040	1188.4	1653444	5.8	-2982657	1301426	752.4	2140814	0.3	4.8
Flw	2045-2050	1137.6	1494914	5.0	-3503151	559781	752.4	2030239	-0.5	4.7
Fup	2025-2030	2232.1	2783164	10.9	-6407684	11396	1543.0	3208313	2.7	4.5
Fup	2035-2040	2246.6	2825720	11.2	-6252486	227335	1543.0	3238684	3.1	4.5
Fup	2045-2050	2237.5	2798500	10.9	-6380272	42954	1543.0	3210386	2.9	4.5
PGY	2025-2030	2007.7	2418949	22.2	-2349774	2266745	934.2	2090482	12.0	1.2
PGY	2035-2040	2007.1	2456572	23.3	-2321556	2320383	934.2	2103192	11.9	1.2
PGY	2045-2050	1995.0	2416104	22.5	-2457367	2144865	934.2	2083339	11.4	1.2
Status quo	2025-2030	2814.9	3265435	15.6	-9643901	-2193498	2071.8	3723974	2.8	4.3
Status quo	2035-2040	2855.6	3344614	15.3	-9373853	-1806977	2071.8	3782211	3.2	4.4
Status quo	2045-2050	2856.7	3345854	15.2	-9376433	-1812731	2071.8	3780624	3.2	4.4

Table VIII. *MSFD related indicators regarding relative effort for each metier (OTB, NET, LLS as proxies of the impact on marine communities), turtles bycatch (mean annual bycatch in individuals) and relative effort of OTB gear type as proxy of impact on the benthic communities, given as average values of the given time periods and for each scenario.*

Scenario	*Time period*	*OTB (effort change, as a proportion relative to SQ)*	*NET (effort change, as a proportion relative to SQ)*	*LLS (effort change, as a proportion relative to SQ)*	*D1C1: Turtles Bycatch*	*D6: Relative effort of OTB gear (as proxy of impact on benthic communities*
F01	2025-2030	0.529	0.529	0.529	3.174	0.529
F01	2035-2040	0.529	0.529	0.529	3.174	0.529
F01	2045-2050	0.529	0.529	0.529	3.174	0.529
Fcomb	2025-2030	0.472	1	1	6	0.472
Fcomb	2035-2040	0.472	1	1	6	0.472
Fcomb	2045-2050	0.472	1	1	6	0.472
Flw	2025-2030	0.363	0.363	0.363	2.178	0.363
Flw	2035-2040	0.363	0.363	0.363	2.178	0.363
Flw	2045-2050	0.363	0.363	0.363	2.178	0.363
Fup	2025-2030	0.745	0.745	0.745	4.47	0.745
Fup	2035-2040	0.745	0.745	0.745	4.47	0.745
Fup	2045-2050	0.745	0.745	0.745	4.47	0.745
PGY	2025-2030	1.6	0.4	0.4	2.4	1.6
PGY	2035-2040	1.6	0.4	0.4	2.4	1.6
PGY	2045-2050	1.6	0.4	0.4	2.4	1.6
Status quo	2025-2030	1	1	1	6	1
Status quo	2035-2040	1	1	1	6	1
Status quo	2045-2050	1	1	1	6	1

a) SSB, by stock and scenario



b) Biomass by stock and scenario

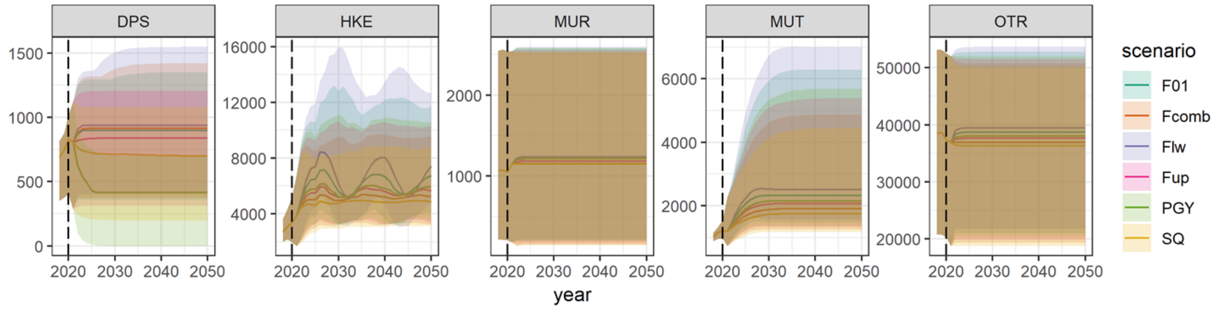
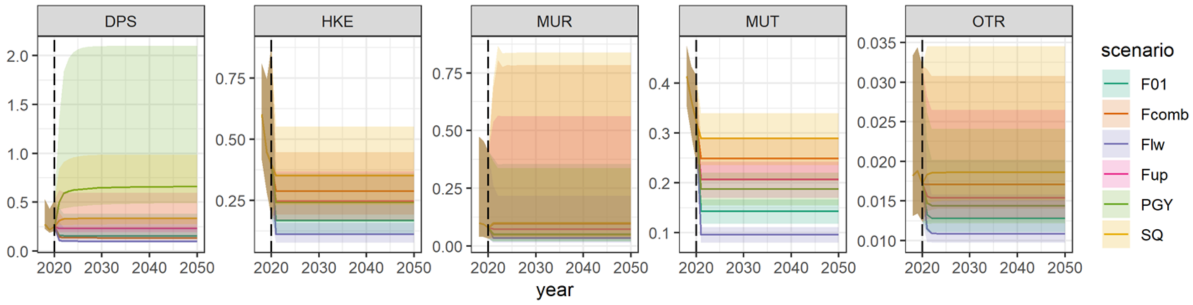


***Figure 2**. **Biological indicators** a) Spawning stock biomass (SSB), b) total biomass of the stocks under consideration (DPS, HKE, MUT, MUR, OTR) by scenario in the eastern Ionian Sea. Coloured ranges correspond to 95% intervals from 292 iterations.*

a) Fishing mortality (f) by stock and scenario



b) FFmsy by stock and scenario

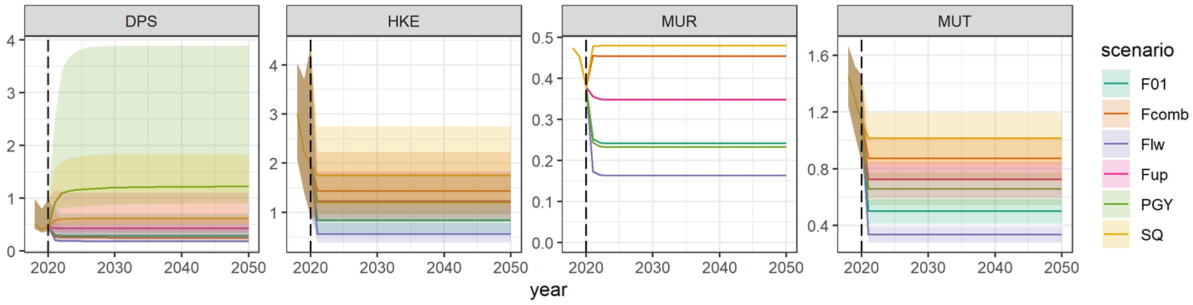


***Figure 3**. **Biological indicators** a) fishing mortality, b) FFmsy of the stocks under consideration (DPS, HKE, MUT, MUR, OTR) by scenario in the eastern Ionian Sea. Coloured ranges correspond to 95% intervals from 292 iterations.*

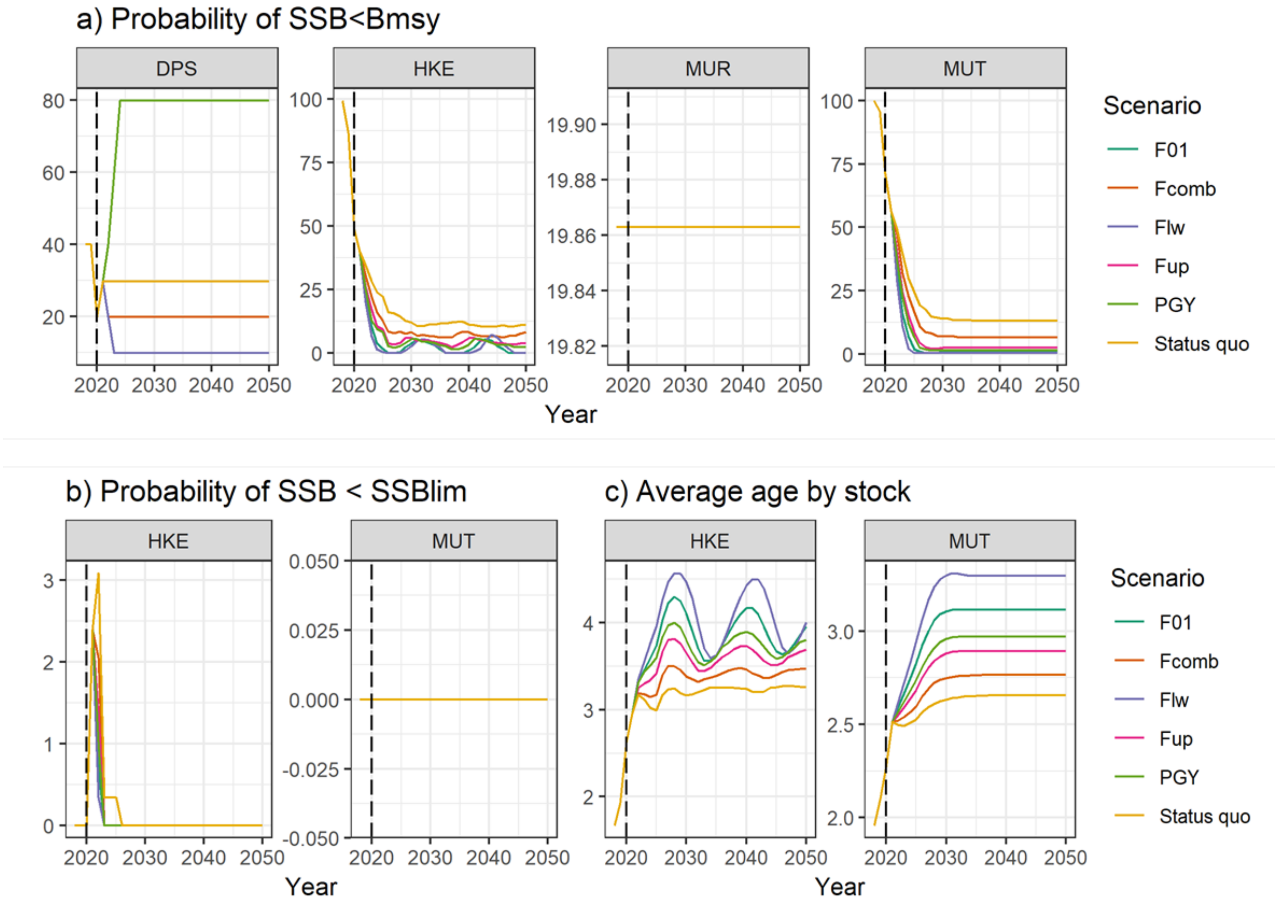
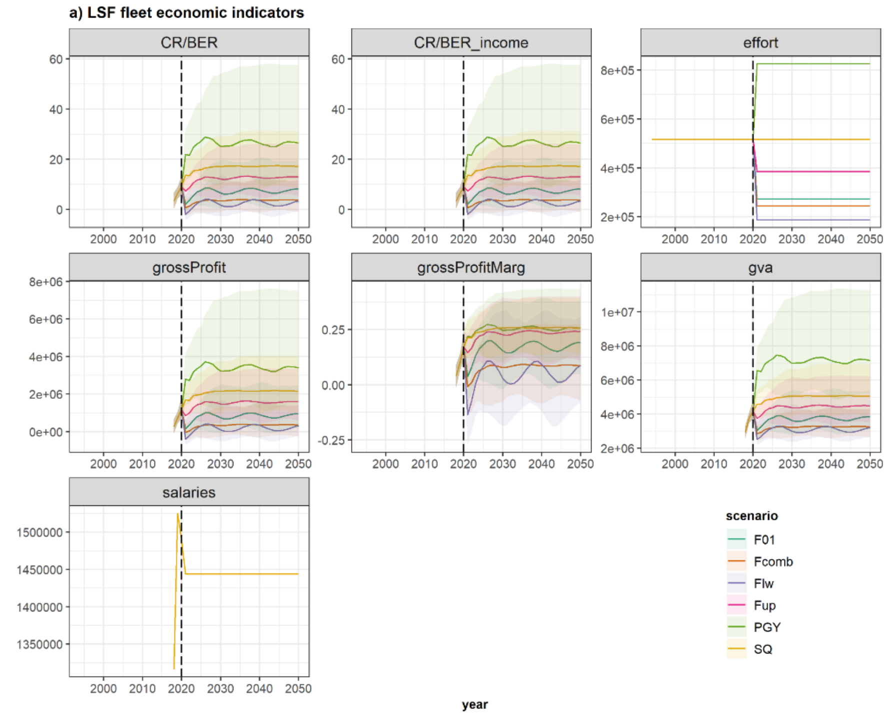


***Figure 4*. Biological indicators** *a) Probability of SSB falling below SSBmsy (or B below Bmsy for BD stocks), b) probability of SSB falling below SSBlim, c) average age (weighted by biomass at age) of the stocks under consideration (DPS, HKE, MUT, MUR) by scenario in the eastern Ionian Sea.*



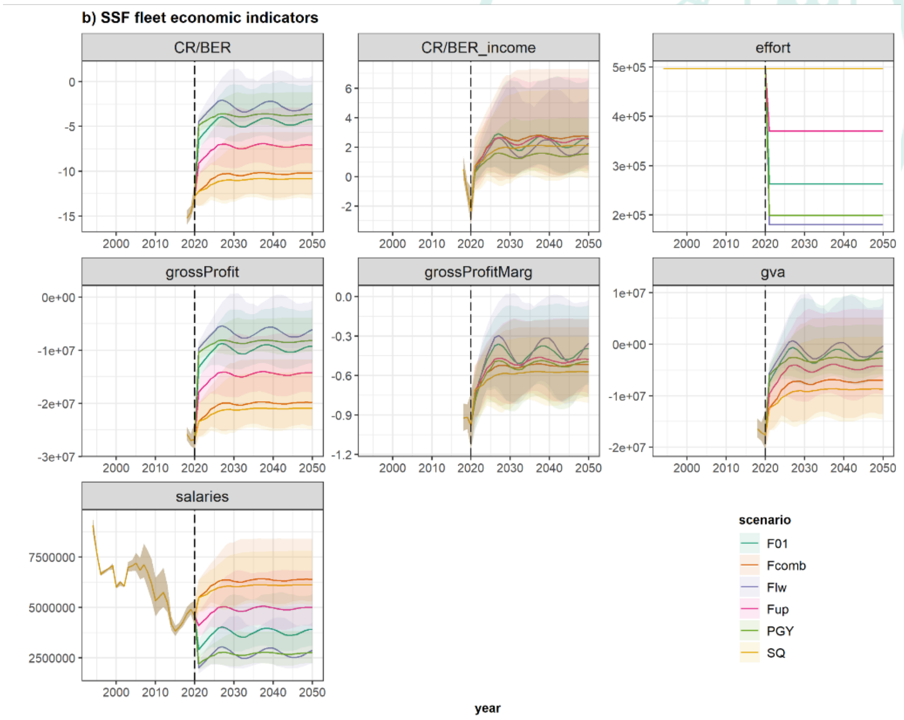
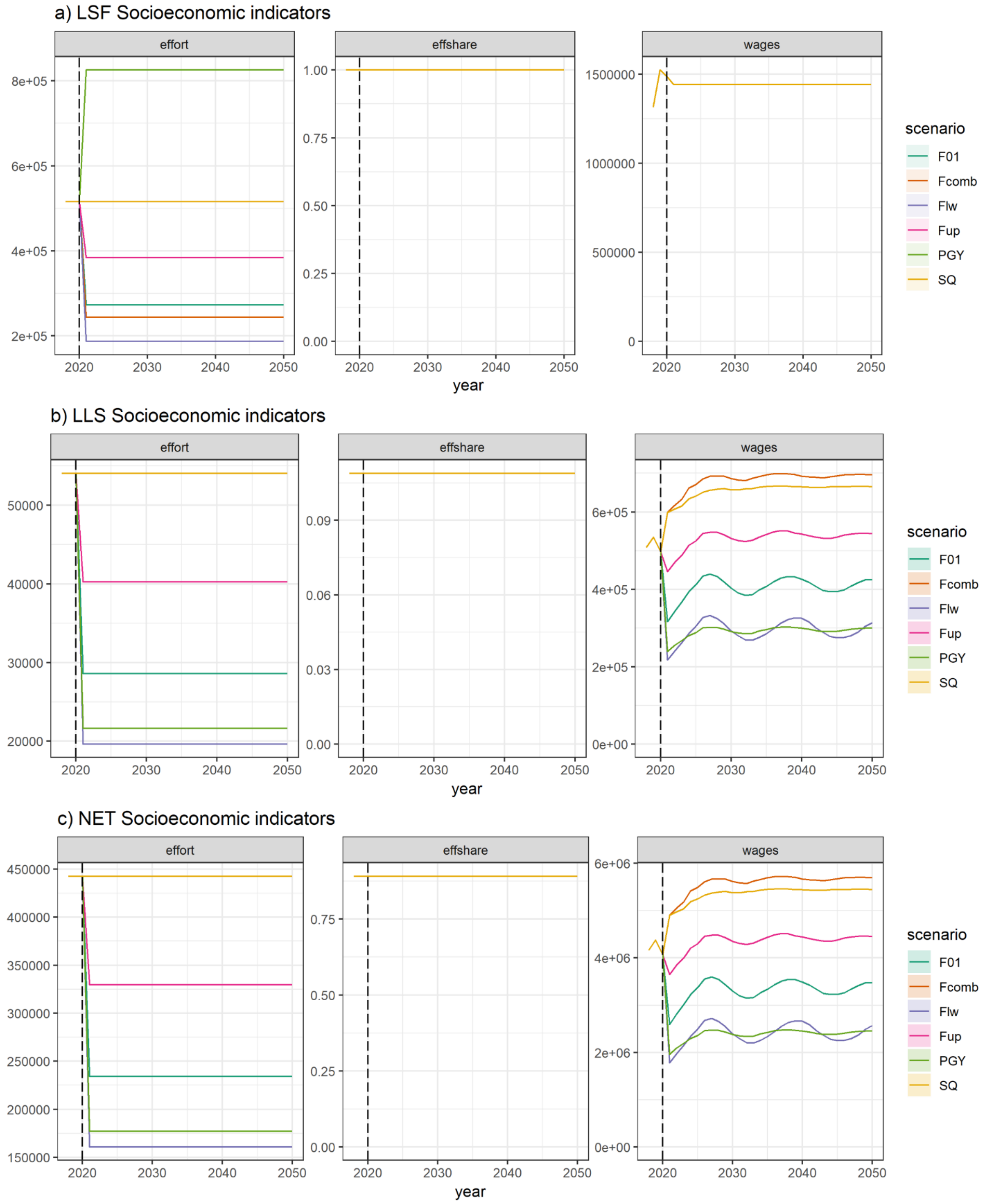


***Figure 5**. **Economic indicators** for a) Large scale fleet (OTB) and b) Small Scale Fleet (SSF) by scenario (comparative plot) for: grossProfit, gross, ProfitMargin, gross value added (gva), Current Revenue to Break-Even Revenue (CR/BER) and CR/BERunpaid (i.e., excluding unpaid labour for costs for the SSF fleet) and effort (expressed in days-at-sea*GT for OTB fleet, and days-at-sea for SSF). Coloured ranges correspond to 95% intervals from 292 iterations.*



a) LSF Socioeconomic indicators

b) LLS Socioeconomic indicators

c) NET Socioeconomic indicators

***Figure 6**. **Socioeconomic indicators** Effort (days-at-sea*GT for OTB fleet, and days-at-sea for SSF), effort share, and salaries (Wages) by scenario for each metier (OTB, LLS, NET) of the eastern Ionian Sea (GSA20)*

Conclusions

From the two demersal fleet segments of the eastern Ionian fishery, only the large scale fleet (LSF) utilizing OTB gear is under a management plan, in action since 2013 (Anonymous, 2013). This sets MSY based targets for the main stocks of the fishery, namely european hake, deep water rose shrimp and mullets. The small scale fleet (SSF) is under certain spatiotemporal regulations and technical restrictions, but is not managed, although it produces ~70% of landings and ~80% of landings value. During the scenario specification in this study it became apparent that MSY sustainability targets for hake (the most overexploited stock in the fishery) could not be achieved even if the OTB gear was to be banned. Hence, scenarios were defined that apply to both fleets.

In particular, scenarios that aim to achieve F01 and Fw or Fup fishing mortality reference points for HKE were applied. These are achieved with 47%, 26% and 63% effort reduction from both fleets, accordingly. Two scenarios combining multiple species objectives were applied. A multistock Pretty Good Yield scenario (PGY), which relaxes the MSY objective by defining a range of fishing mortalities per stock (typically those corresponding to 80%MSY) and attempts to find effort allocations which fall on the intersection of the different stock ranges (Hilborn, 2010). In the eastern Ionian fishery, the PGY scenario for hake, shrimp and mullet is achieved by a doubling of the LSF effort and reducing of the SSF effort to half. In addition, an Fmsy combined scenario was defined, which sets a target fishing mortality that is the average of the target fishing mortalities of the main stocks, weighted by their contribution to the catch. Finally, the Status quo scenario projects the future of the fishery under the current situation, i.e. considering the effort is fixed to its historical average value in the period 2018-2020.

Results showed a common high uncertainty trait in all scenarios mainly driven by the uncertainty of stock assessment, especially of BD stocks. PGY is by far the most profitable scenario for the LSF in terms of catch increase, followed by Status quo and all other scenarios ranked by the effort reduction applied. This is not the case for the SSF, where differences occur depending on the species. For hake the highest catch is for Flw, F01, for striped red mullet it is the Fcomb that gives the highest catch and for red mullet the Status quo scenario.

In terms of biological indicators, differences occured depending on the species. The Flw is the scenario with the biggest SSB and total biomass regarding hake, deep water rose shrimp and red mullet and the lowest fishing mortality and FFmsy ratio. The proportion of stocks fished at or below Fmsy is higher for Flw and F01 followed by Fcomb and Fup (Figure 2). It is only in the case of FPGY that 25% of the stocks can be with median SSB below MSY $B_{trigger}$ and this is practically due to the increase of the harvest of shrimp stock, which is sustainably exploited in all other scenarios (Figure 3). Moreover, for hake and red mullet, the two stocks that an age structure model was available, an increase in the average age was predicted for the Flw and the F01 scenarios (Figure 4).

From the MSFD indicators we examined the turtles bycatch (as mean annual bycatch in individuals) and the effortof OTB gear as a proxy of the impact on the benthic communities for each scenario. For turtles' bycatch the highest values were estimated for the Fcomb and Fup scenarios. The greater impact on the benthic community is expected under the PGY scenario, which is the only scenario foreseeing an increase of OTB gear effort.

In terms of economic indicators, PGY is by far the most profitable scenario for the LSF, followed by Status quo and all other scenarios ranked by the effort reduction applied. The picture is different for the SSF fleet, whereby the better performing scenarios in terms of gva, gross profit and CR/BER are the ones applying the greatest effort reduction (e.g. Flw, followed by PGY, F01 and Fup), event though these economic indicators are still negative across all scenarios. This is a result of a reduction of costs that is greater than the increase of the revenue and is an effect of including the imputed cost of unpaid labour in variable costs. Indeed, if one looks at the Income based indicators like FFI, CR/BER_income and Revenues, the Fcomb scenario is better performing (SEAWISE deliverable report D6.4). In this scenario, the effort of the SSF fleet does not change but the LSF fleet effort is reduced by half, allowing the recovery of hake biomass and increase of biomass of all stocks, leading to an overall higher harvest. In Flw and PGY scenarios the SSF activity cannot be sustained as the Income becomes negative on average.

The effort scenarios investigated, were applied considering a decrease or increase of days at sea. Alternative management could be applied that controls the number of fishing vessels. Although this might be more difficult to implement (on a social level) it should be more profitable in economic terms for the remaining vessels, and provide win-win situations for both the fleet viability/efficiency and the ecological sustainability (Sgardeli *et al.*, 2022). In fact, the fishing fleet of both the LSF and the SSF has been in decline since the mid-90s, with an equilibrium not yet reached. As a result, the historical cathes of both fleets show declining trends. This declining trend of the fishing fleet has not been taken into account in the projections, whereby the number of vessels of both fleets has been considered constant and equal to the average of the period 2018-2020.

A main source of uncertainty originates from the SR relationship of the two age structured stocks, hake and red mullet. The SR of these stocks has been modeled with a Ricker SR relationship, fitted to the historical stock assessment estimates of Spawning Stock Biomass (ssb) and recruitment. The fitted SRs show a strong density dependence for hake, with declining recruitment above ~2500 tons of SSB. Such a result is not unrealistic and can be attributed to increased interspecific competition and in particular to the effect of predation of hake on hake juveniles (cannibalism), which becomes more intense at higher densities of recruits. Similar effect has been found in SEAWISE deliverable report on the effect of environmental variables in recruitment (SEAWISE Deliverable 3.2 – eastern Ionian Sea case study). The red mullet stock shows very weak density dependence.

To achieve the sustainable fishing of the HKE stock (i.e. scenarios F01, Fup and FLw), an effort reduction was applied to both fleets in equal proportions. In practice, there are multiple other effort re-allocations, not investigated herein, that can achieve the given target and it is a management decision, which re-allocation provides a better trade-off between ecological, economic, social or other objectives.

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Appendix A: Stock assessment of Biomass dynamic stocks

Stock assessment of DPS GSA 20 with time varying productivity SPiCT model.

DPS GSA 20

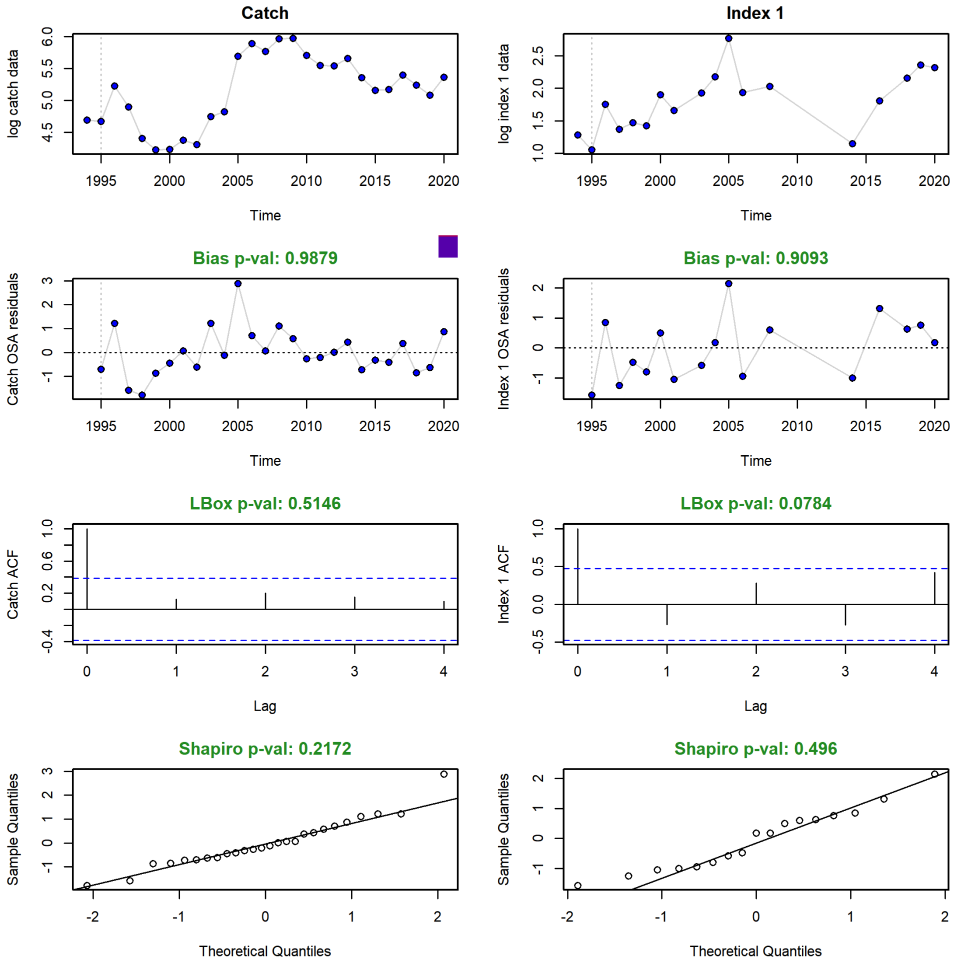

Figure A1. Residual diagnostics of DPS GSA20 SPiCT time varying productivity assessment.

Table A1. Average estimates of SPiCT time varying productivity fit for DPS GSA 20 stock.

K	r	MSY	B	F	Bmsy	Fmsy	BBmsy	FFmsy
1222	1.089	329	966.56	0.19	607	0.54	1.59	0.35

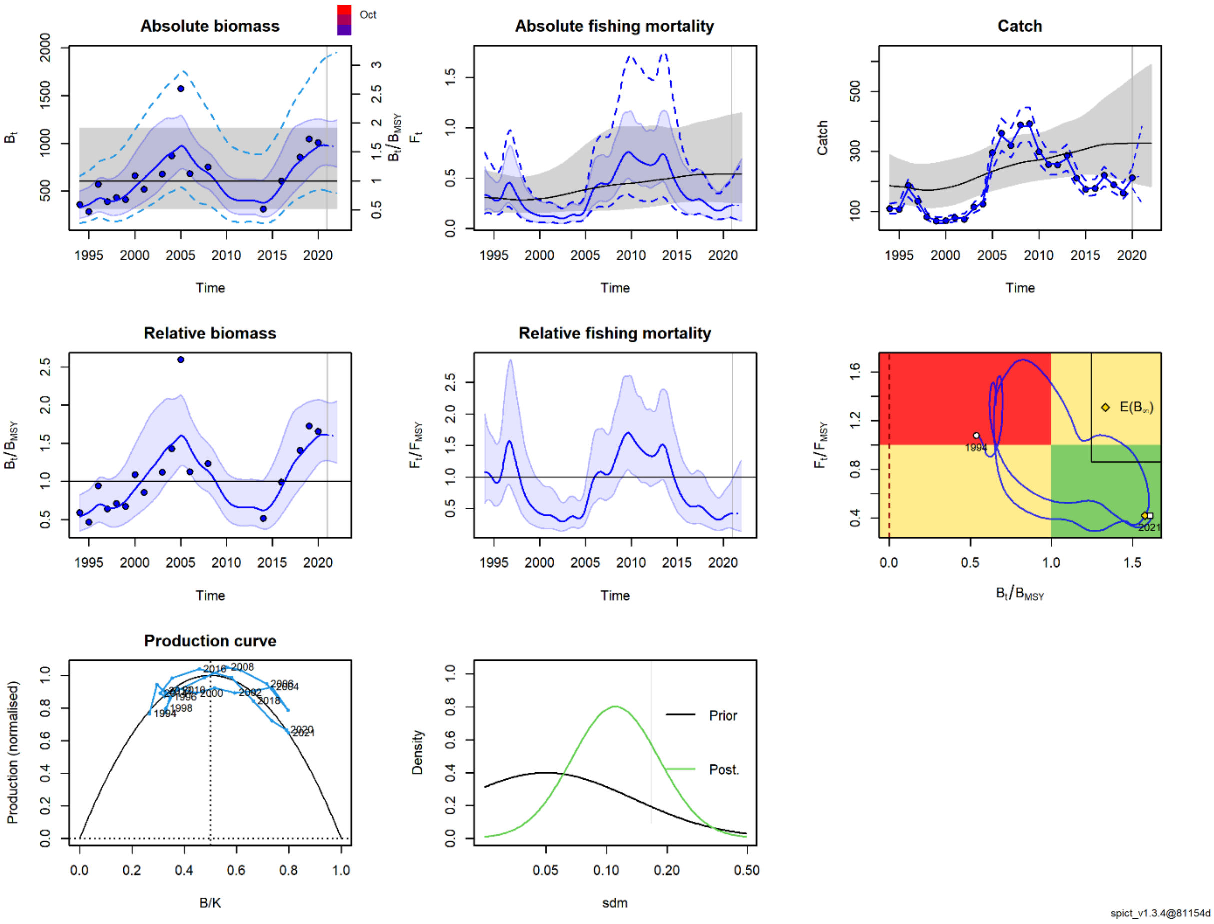

Figure A2. Fit of DPS GSA20 SPiCT time varying productivity assessment.

MUR GSA 20

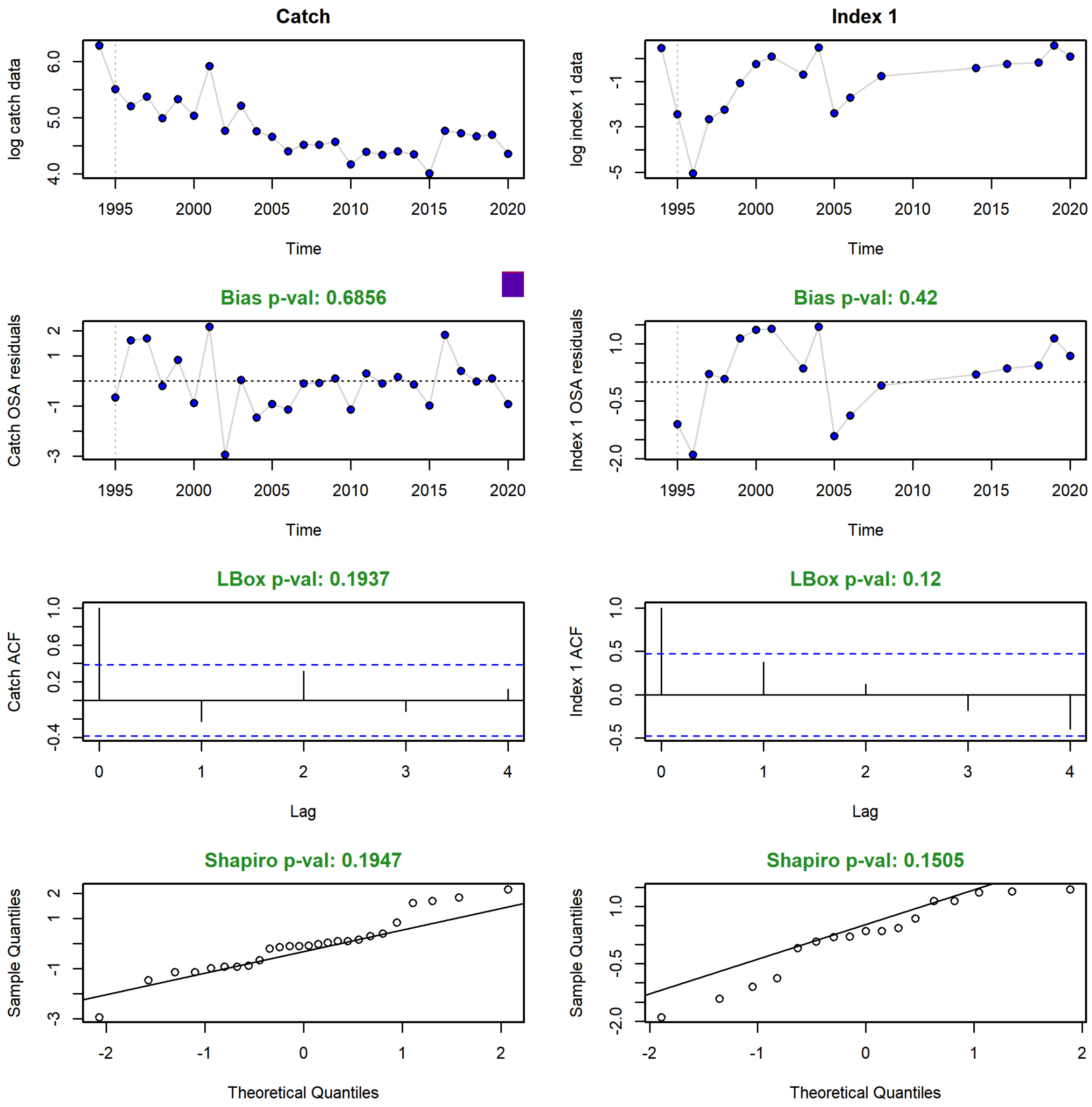

Figure A3. Residual diagnostics of MUR GSA20 SPiCT time varying productivity assessment.

Table A2. Average estimates of SPiCT time varying productivity fit for MUR GSA 20 stock.

K	r	MSY	B	F	Bmsy	Fmsy	BBmsy	FFmsy
924	1.055	240	821.22	0.11	458	0.53	1.79	0.21

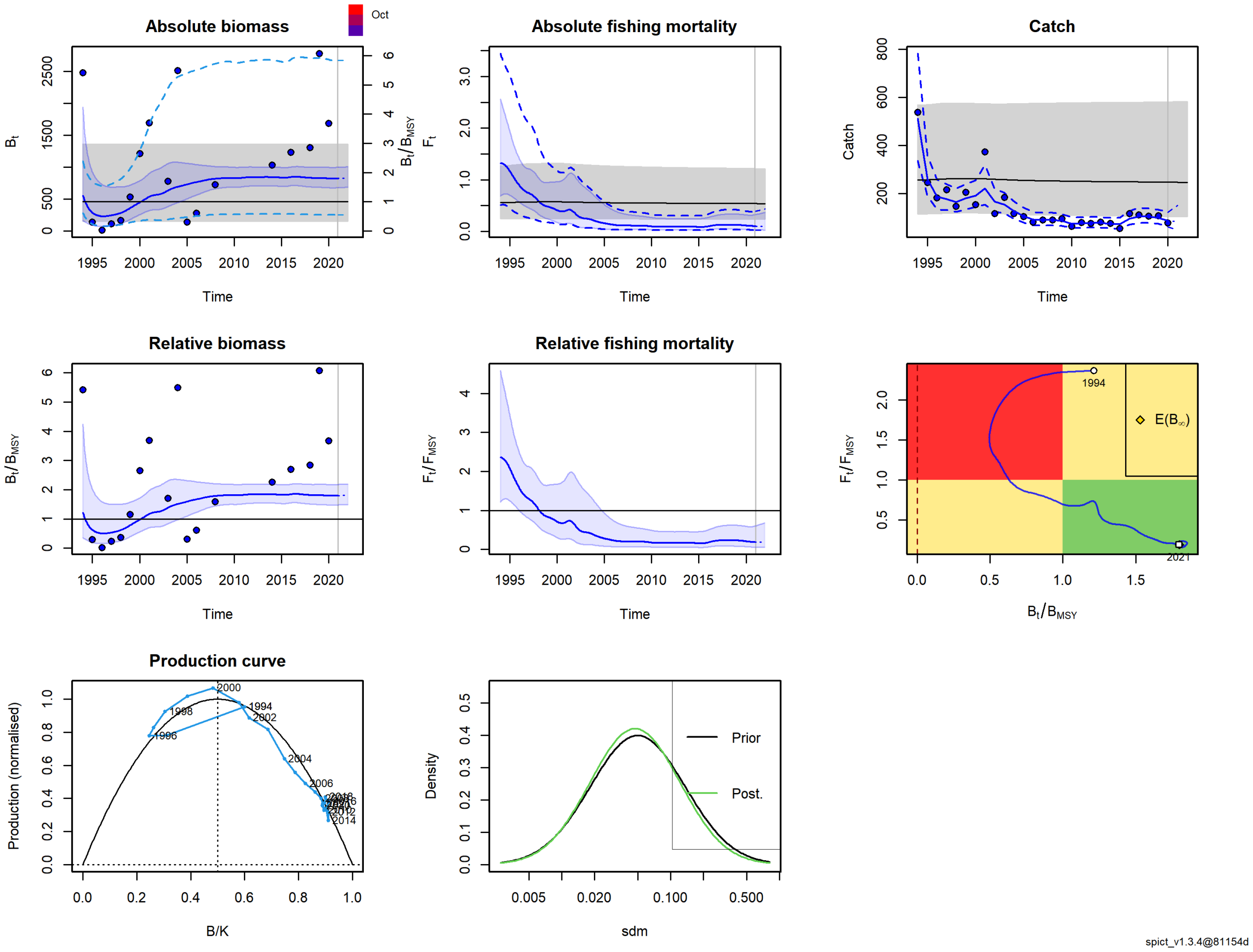

Figure A4. Fit of MUR GSA20 SPiCT time varying productivity assessment.

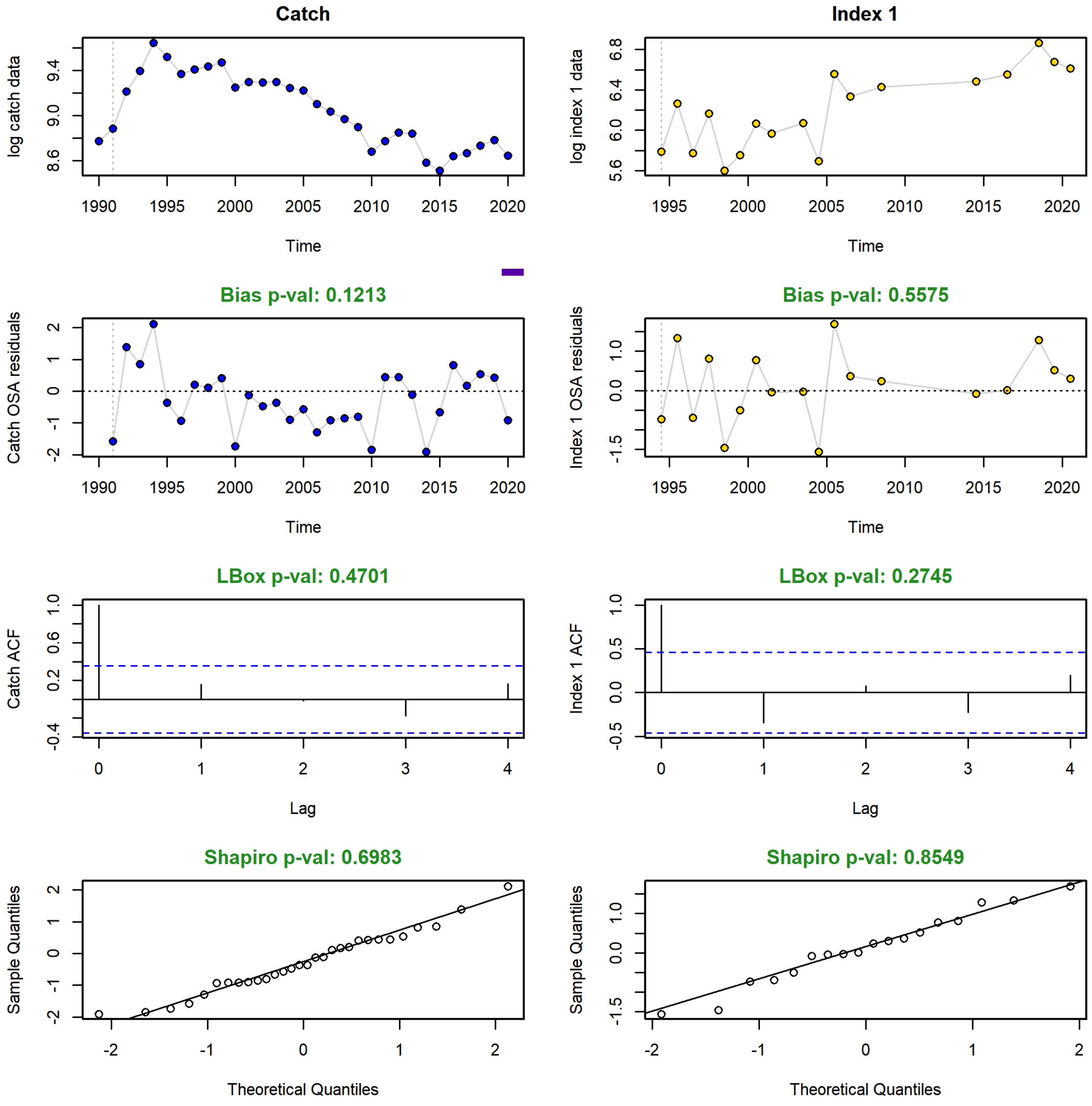

Figure A5. Residual diagnostics of OTR GSA20 SPiCT time varying productivity assessment.

Table A3. Average estimates of SPiCT time varying productivity fit for OTR GSA 20 stock.

K	46513
r	1.091
MSY	12606
B	40415.43
F	0.15
Bmsy	23163
Fmsy	0.54
BBmsy	1.74
FFmsy	0.27

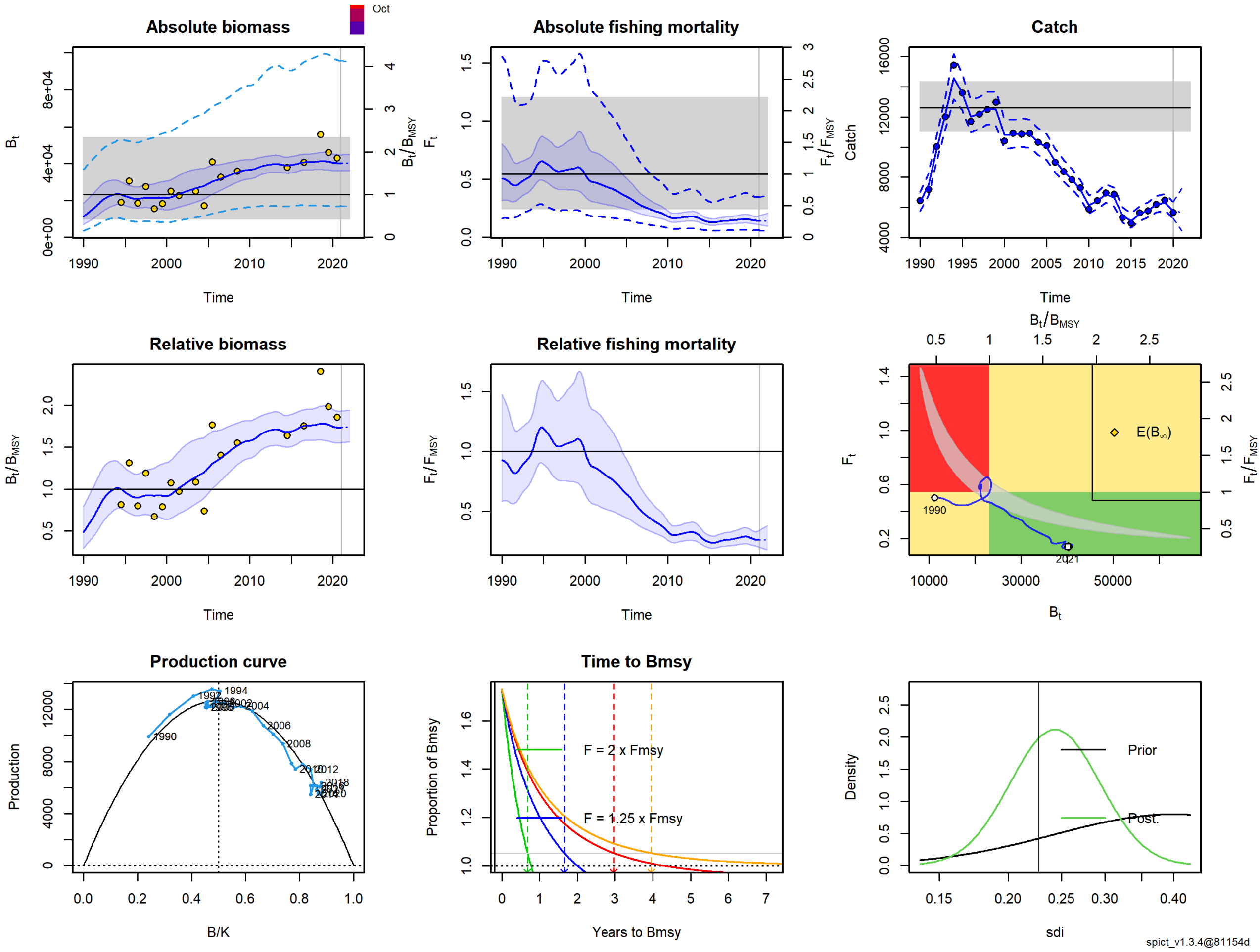

Figure A6. Fit of MUR GSA20 SPiCT time varying productivity assessment.

Appendix B: Stock recruitment relationships for HKE and MUT

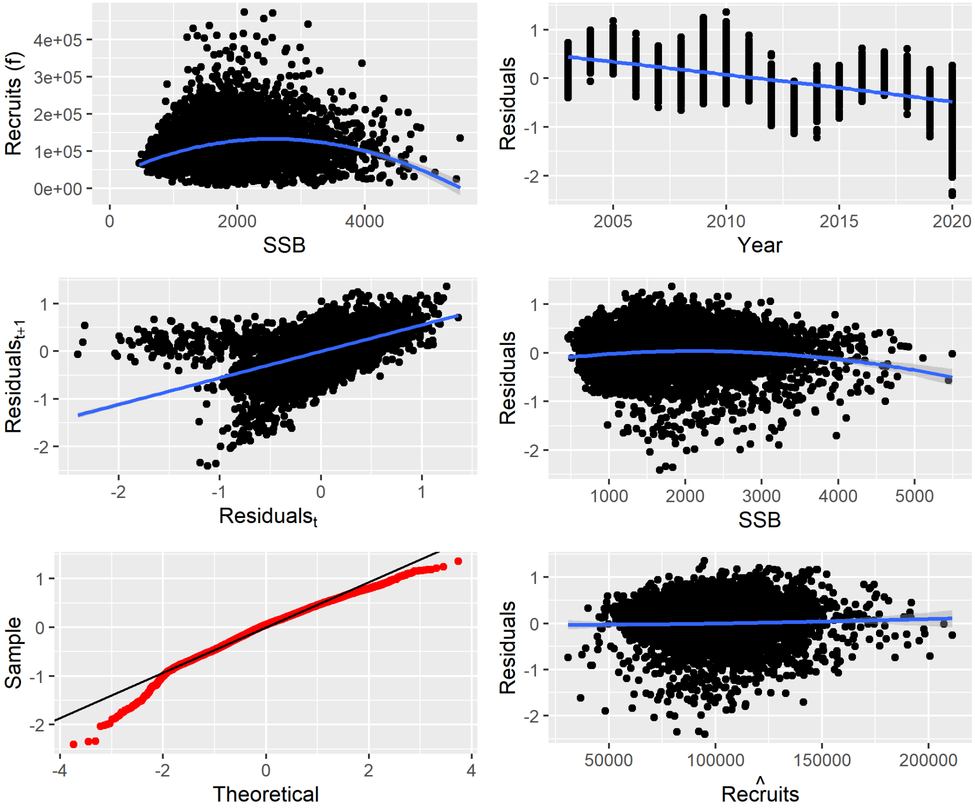

Figure B1. Fit of Ricker stock recruitment relationship to recruitment and ssb estimates for HKE stock in GSA20.

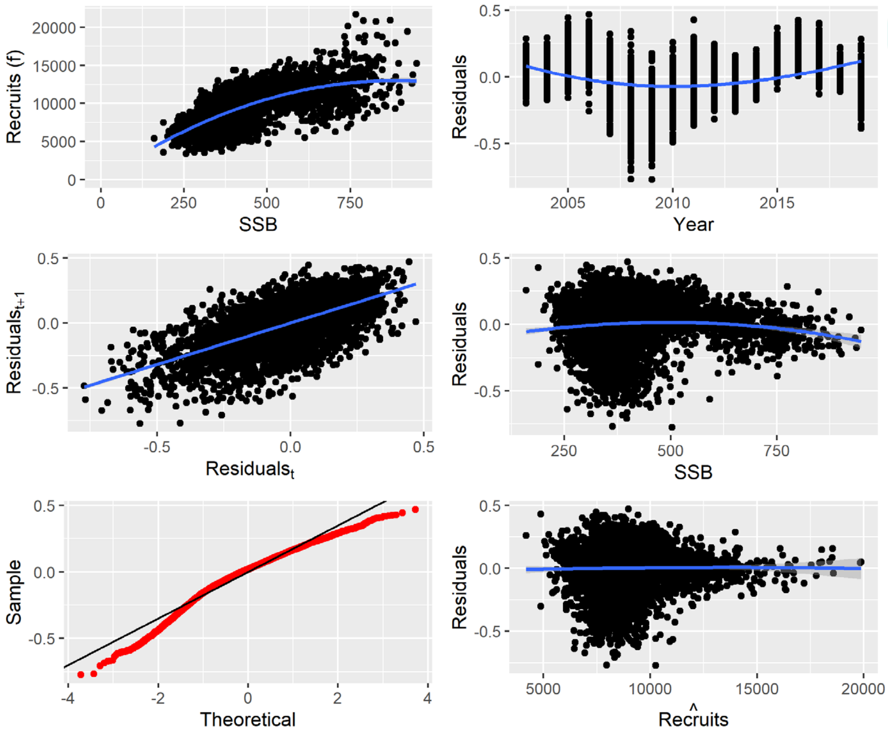

Figure B2. Fit of Ricker stock recruitment relationship to recruitment and SSB estimates for MUT stock in GSA20.

Appendix C. Revenues by stock

Table C1. *Average Revenues and Landings (t) estimated for the indicated time periods, by scenario, fleet segment and stock, for the eastern Ionian sea demersal fishery. LSF: large scale fleet, SSF: small scale fleet.*

Scenario	Time period	Fleet segment	Stock	Revenues	Landings
F01	2025-2030	GSA20_LSF	DPS	692540	141.6
F01	2025-2030	GSA20_LSF	HKE	999611	111.6
F01	2025-2030	GSA20_LSF	MUR	60050	5.2
F01	2025-2030	GSA20_LSF	MUT	409868	55.9
F01	2025-2030	GSA20_LSF	OTR	2598542	467.4
F01	2025-2030	GSA20_SSF	HKE	3642735	561.5
F01	2025-2030	GSA20_SSF	MUR	799959	51.3
F01	2025-2030	GSA20_SSF	MUT	2746524	202.0
F01	2025-2030	GSA20_SSF	OTR	5777540	1650.7
F01	2035-2040	GSA20_LSF	DPS	693941	141.9
F01	2035-2040	GSA20_LSF	HKE	989010	109.9
F01	2035-2040	GSA20_LSF	MUR	60050	5.2
F01	2035-2040	GSA20_LSF	MUT	435445	57.9
F01	2035-2040	GSA20_LSF	OTR	2598544	467.4
F01	2035-2040	GSA20_SSF	HKE	3471284	524.2
F01	2035-2040	GSA20_SSF	MUR	799959	51.3
F01	2035-2040	GSA20_SSF	MUT	2982310	211.9
F01	2035-2040	GSA20_SSF	OTR	5777543	1650.7
F01	2045-2050	GSA20_LSF	DPS	693943	141.9
F01	2045-2050	GSA20_LSF	HKE	895054	99.7
F01	2045-2050	GSA20_LSF	MUR	60050	5.2
F01	2045-2050	GSA20_LSF	MUT	435507	57.9
F01	2045-2050	GSA20_LSF	OTR	2598544	467.4
F01	2045-2050	GSA20_SSF	HKE	3101882	471.2
F01	2045-2050	GSA20_SSF	MUR	799959	51.3
F01	2045-2050	GSA20_SSF	MUT	2982189	212.0
F01	2045-2050	GSA20_SSF	OTR	5777543	1650.7
Fcomb	2025-2030	GSA20_LSF	DPS	625198	127.9
Fcomb	2025-2030	GSA20_LSF	HKE	715019	84.8
Fcomb	2025-2030	GSA20_LSF	MUR	53680	4.6
Fcomb	2025-2030	GSA20_LSF	MUT	259551	39.2
Fcomb	2025-2030	GSA20_LSF	OTR	2310650	415.6
Fcomb	2025-2030	GSA20_SSF	HKE	4801003	775.8
Fcomb	2025-2030	GSA20_SSF	MUR	1514466	97.1
Fcomb	2025-2030	GSA20_SSF	MUT	3647770	296.6
Fcomb	2025-2030	GSA20_SSF	OTR	10880212	3108.6
Fcomb	2035-2040	GSA20_LSF	DPS	626402	128.1
Fcomb	2035-2040	GSA20_LSF	HKE	716897	82.7
Fcomb	2035-2040	GSA20_LSF	MUR	53680	4.6
Fcomb	2035-2040	GSA20_LSF	MUT	282203	41.4
Fcomb	2035-2040	GSA20_LSF	OTR	2310650	415.6

Scenario	Time period	Fleet segment	Stock	Revenues	Landings
Fcomb	2035-2040	GSA20_SSF	HKE	4888194	774.1
Fcomb	2035-2040	GSA20_SSF	MUR	1514466	97.1
Fcomb	2035-2040	GSA20_SSF	MUT	3980811	316.6
Fcomb	2035-2040	GSA20_SSF	OTR	10880213	3108.6
Fcomb	2045-2050	GSA20_LSF	DPS	626403	128.1
Fcomb	2045-2050	GSA20_LSF	HKE	705573	81.4
Fcomb	2045-2050	GSA20_LSF	MUR	53680	4.6
Fcomb	2045-2050	GSA20_LSF	MUT	282426	41.4
Fcomb	2045-2050	GSA20_LSF	OTR	2310650	415.6
Fcomb	2045-2050	GSA20_SSF	HKE	4828953	766.3
Fcomb	2045-2050	GSA20_SSF	MUR	1514466	97.1
Fcomb	2045-2050	GSA20_SSF	MUT	3984408	316.7
Fcomb	2045-2050	GSA20_SSF	OTR	10880213	3108.6
Flw	2025-2030	GSA20_LSF	DPS	488654	99.9
Flw	2025-2030	GSA20_LSF	HKE	785844	86.4
Flw	2025-2030	GSA20_LSF	MUR	41165	3.5
Flw	2025-2030	GSA20_LSF	MUT	326743	42.6
Flw	2025-2030	GSA20_LSF	OTR	1783760	320.8
Flw	2025-2030	GSA20_SSF	HKE	3020367	456.5
Flw	2025-2030	GSA20_SSF	MUR	548381	35.2
Flw	2025-2030	GSA20_SSF	MUT	2211725	155.4
Flw	2025-2030	GSA20_SSF	OTR	3965972	1133.1
Flw	2035-2040	GSA20_LSF	DPS	489439	100.1
Flw	2035-2040	GSA20_LSF	HKE	750147	83.3
Flw	2035-2040	GSA20_LSF	MUR	41165	3.5
Flw	2035-2040	GSA20_LSF	MUT	344935	43.5
Flw	2035-2040	GSA20_LSF	OTR	1783761	320.8
Flw	2035-2040	GSA20_SSF	HKE	2677765	403.1
Flw	2035-2040	GSA20_SSF	MUR	548381	35.2
Flw	2035-2040	GSA20_SSF	MUT	2389537	161.8
Flw	2035-2040	GSA20_SSF	OTR	3965974	1133.1
Flw	2045-2050	GSA20_LSF	DPS	489440	100.1
Flw	2045-2050	GSA20_LSF	HKE	591009	65.8
Flw	2045-2050	GSA20_LSF	MUR	41165	3.5
Flw	2045-2050	GSA20_LSF	MUT	345182	43.5
Flw	2045-2050	GSA20_LSF	OTR	1783761	320.8
Flw	2045-2050	GSA20_SSF	HKE	2065635	310.3
Flw	2045-2050	GSA20_SSF	MUR	548381	35.2
Flw	2045-2050	GSA20_SSF	MUT	2391311	161.8
Flw	2045-2050	GSA20_SSF	OTR	3965974	1133.1
Fup	2025-2030	GSA20_LSF	DPS	918770	187.9
Fup	2025-2030	GSA20_LSF	HKE	1201067	139.5
Fup	2025-2030	GSA20_LSF	MUR	84662	7.3
Fup	2025-2030	GSA20_LSF	MUT	468243	68.0
Fup	2025-2030	GSA20_LSF	OTR	3654084	657.2
Fup	2025-2030	GSA20_SSF	HKE	4052115	636.6
Fup	2025-2030	GSA20_SSF	MUR	1127831	72.3
Fup	2025-2030	GSA20_SSF	MUT	3115550	244.2

Scenario	*Time period*	*Fleet segment*	*Stock*	*Revenues*	*Landings*
Fup	*2025-2030*	*GSA20_SSF*	*OTR*	*8124407*	*2321.3*
Fup	*2035-2040*	*GSA20_LSF*	*DPS*	*919815*	*188.1*
Fup	*2035-2040*	*GSA20_LSF*	*HKE*	*1212619*	*136.5*
Fup	*2035-2040*	*GSA20_LSF*	*MUR*	*84662*	*7.3*
Fup	*2035-2040*	*GSA20_LSF*	*MUT*	*508450*	*71.6*
Fup	*2035-2040*	*GSA20_LSF*	*OTR*	*3654086*	*657.2*
Fup	*2035-2040*	*GSA20_SSF*	*HKE*	*4060990*	*629.6*
Fup	*2035-2040*	*GSA20_SSF*	*MUR*	*1127831*	*72.3*
Fup	*2035-2040*	*GSA20_SSF*	*MUT*	*3413574*	*259.5*
Fup	*2035-2040*	*GSA20_SSF*	*OTR*	*8124413*	*2321.3*
Fup	*2045-2050*	*GSA20_LSF*	*DPS*	*919823*	*188.1*
Fup	*2045-2050*	*GSA20_LSF*	*HKE*	*1176302*	*132.2*
Fup	*2045-2050*	*GSA20_LSF*	*MUR*	*84662*	*7.3*
Fup	*2045-2050*	*GSA20_LSF*	*MUT*	*508436*	*71.6*
Fup	*2045-2050*	*GSA20_LSF*	*OTR*	*3654086*	*657.2*
Fup	*2045-2050*	*GSA20_SSF*	*HKE*	*3961861*	*610.2*
Fup	*2045-2050*	*GSA20_SSF*	*MUR*	*1127831*	*72.3*
Fup	*2045-2050*	*GSA20_SSF*	*MUT*	*3413565*	*259.5*
Fup	*2045-2050*	*GSA20_SSF*	*OTR*	*8124413*	*2321.3*
PGY	*2025-2030*	*GSA20_LSF*	*DPS*	*1368085*	*279.8*
PGY	*2025-2030*	*GSA20_LSF*	*HKE*	*2601441*	*296.3*
PGY	*2025-2030*	*GSA20_LSF*	*MUR*	*181616*	*15.6*
PGY	*2025-2030*	*GSA20_LSF*	*MUT*	*1076540*	*152.5*
PGY	*2025-2030*	*GSA20_LSF*	*OTR*	*7855664*	*1412.9*
PGY	*2025-2030*	*GSA20_SSF*	*HKE*	*2265899*	*350.3*
PGY	*2025-2030*	*GSA20_SSF*	*MUR*	*604850*	*38.8*
PGY	*2025-2030*	*GSA20_SSF*	*MUT*	*1794652*	*137.5*
PGY	*2025-2030*	*GSA20_SSF*	*OTR*	*4366526*	*1247.6*
PGY	*2035-2040*	*GSA20_LSF*	*DPS*	*1345319*	*275.1*
PGY	*2035-2040*	*GSA20_LSF*	*HKE*	*2642956*	*296.0*
PGY	*2035-2040*	*GSA20_LSF*	*MUR*	*181616*	*15.6*
PGY	*2035-2040*	*GSA20_LSF*	*MUT*	*1165455*	*160.1*
PGY	*2035-2040*	*GSA20_LSF*	*OTR*	*7855670*	*1412.9*
PGY	*2035-2040*	*GSA20_SSF*	*HKE*	*2271452*	*344.8*
PGY	*2035-2040*	*GSA20_SSF*	*MUR*	*604850*	*38.8*
PGY	*2035-2040*	*GSA20_SSF*	*MUT*	*1969087*	*145.6*
PGY	*2035-2040*	*GSA20_SSF*	*OTR*	*4366530*	*1247.6*
PGY	*2045-2050*	*GSA20_LSF*	*DPS*	*1345026*	*275.1*
PGY	*2045-2050*	*GSA20_LSF*	*HKE*	*2526480*	*282.5*
PGY	*2045-2050*	*GSA20_LSF*	*MUR*	*181616*	*15.6*
PGY	*2045-2050*	*GSA20_LSF*	*MUT*	*1165443*	*160.0*
PGY	*2045-2050*	*GSA20_LSF*	*OTR*	*7855670*	*1412.9*
PGY	*2045-2050*	*GSA20_SSF*	*HKE*	*2164371*	*331.3*
PGY	*2045-2050*	*GSA20_SSF*	*MUR*	*604850*	*38.8*
PGY	*2045-2050*	*GSA20_SSF*	*MUT*	*1968993*	*145.6*
PGY	*2045-2050*	*GSA20_SSF*	*OTR*	*4366530*	*1247.6*
Status quo	*2025-2030*	*GSA20_LSF*	*DPS*	*1086370*	*222.2*
Status quo	*2025-2030*	*GSA20_LSF*	*HKE*	*1383050*	*165.3*

Scenario	Time period	Fleet segment	Stock	Revenues	Landings
Status quo	2025-2030	GSA20_LSF	MUR	113447	9.8
Status quo	2025-2030	GSA20_LSF	MUT	483115	75.6
Status quo	2025-2030	GSA20_LSF	OTR	4875027	876.8
Status quo	2025-2030	GSA20_SSF	HKE	4148776	677.4
Status quo	2025-2030	GSA20_SSF	MUR	1511287	96.9
Status quo	2025-2030	GSA20_SSF	MUT	3192082	268.9
Status quo	2025-2030	GSA20_SSF	OTR	10839024	3096.9
Status quo	2035-2040	GSA20_LSF	DPS	1069931	218.8
Status quo	2035-2040	GSA20_LSF	HKE	1403387	164.5
Status quo	2035-2040	GSA20_LSF	MUR	113447	9.8
Status quo	2035-2040	GSA20_LSF	MUT	525586	80.3
Status quo	2035-2040	GSA20_LSF	OTR	4875010	876.8
Status quo	2035-2040	GSA20_SSF	HKE	4320176	694.6
Status quo	2035-2040	GSA20_SSF	MUR	1511283	96.9
Status quo	2035-2040	GSA20_SSF	MUT	3491757	285.6
Status quo	2035-2040	GSA20_SSF	OTR	10838988	3096.9
Status quo	2045-2050	GSA20_LSF	DPS	1069395	218.7
Status quo	2045-2050	GSA20_LSF	HKE	1401775	163.0
Status quo	2045-2050	GSA20_LSF	MUR	113447	9.8
Status quo	2045-2050	GSA20_LSF	MUT	526016	80.4
Status quo	2045-2050	GSA20_LSF	OTR	4875010	876.8
Status quo	2045-2050	GSA20_SSF	HKE	4325191	690.9
Status quo	2045-2050	GSA20_SSF	MUR	1511283	96.9
Status quo	2045-2050	GSA20_SSF	MUT	3494748	285.8
Status quo	2045-2050	GSA20_SSF	OTR	10838988	3096.9

8.9 ANNEX 9. Description of analyses carried out with modelling for indicators, targets and limits in the Adriatic and western Ionian Seas (GFCM Geographical Sub Areas 17-18-19).

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8.1 Description of the model used

The analysis was conducted in the Adriatic and western Ionian Seas (GFCM Geographical Sub Areas 17-18-19) using 1) using BEMTOOL bioeconomic model for the estimation of the indicators related to the stock status and fisheries, including economic and social indicators, and 2) Ecopath with Ecosim model (EwE) for the ecosystem indicators related to the Descriptor 4 of the Marine Strategy Framework Directive (MSFD).

8.1.1 BEMTOOL

BEMTOOL is an integrated bioeconomic modelling tool that follows a multi-fleet and multiple species approach, simulating the effects of management scenarios on stocks and fisheries (e.g. STECF, 2019; 2020; 2021a; Russo, Bitetto et al., 2017; Rossetto et al., 2015). Such effects in mixed fisheries are measured by a suite of indicators with associated uncertainty.

In this case study, BEMTOOL is implemented in the Adriatic and western Ionian Seas (GFCM Geographical Sub Areas - GSAs 17, 18 and 19) to inform and support the modelling of indicators, targets and limits, linked to the management of key stocks: European hake (HKE), red mullet (MUT) and deep water rose shrimp (DPS). These stocks are among the main target of the fisheries and of the Multi Annual Management Plan in the Adriatic region (GFCM Recommendations GFCM/43/2019/5; GFCM/44/2021/1). In the GSA19 a MAP for demersal stocks is not yet in place. However, considering the possible connectivity of the populations in the whole area (Spedicato et al. 2022) also HKE and MUT in GSA19 were included in this analysis.

In details the stocks included are:

- European hake in GSAs 17-18 (HKE17-18);
- European hake in GSA 19 (HKE19);
- Red mullet in GSAs 17-18 (MUT17-18);
- Red mullet in GSA 19 (MUT19);
- Deep-water rose shrimp in GSAs 17-18-19 (DPS17-18-19).

The relevant fisheries are subject to an effort regime to progressively achieve the MSY (F_{MSY}) target in 2026 for all the key stocks. There are, thus, fishing opportunities already established for 2023.
In the simulation and forecast scenarios 22 fleets are considered. These include both active and passive demersal gears operated by fleet segments that rely on, and influence some or all of the stocks above mentioned. These fleets encompass all small and medium scale fisheries that will allow to investigate potential differences in the dynamic of the indicators induced by the simulated scenarios.

The following scenarios were explored for task 6.4 until 2050:

S0_Status quo: effort equal to fishing opportunities of 2023 for GSAs 17-18, while for GSA 19 same effort as in 2021;

S1_Fmsy_DPS: Effort reduction to achieve the $F_{0.1}$ (used as F_{MSY} proxy) of the most overexploited stock in 2026: this corresponds to an effort reduction of 69% on trawlers in GSAs 17-18-19, toward the $F_{0.1}$ of DPS 17-18-19.

S2_Fcomb_(PGY): Effort reduction to achieve a F_{MSY} combined (here considered as a proxy of PGY) on all the target stocks (HKE 17-18, MUT 17-18 and DPS 17-18-19): this corresponds to an effort reduction of 58% on trawlers in GSAs 17-18-19 toward a combined reference point estimated weighing the $F_{0.1}$ of the above mentioned stocks by their total catch.

A similar reduction would have been required by using as reference Flow of European hake.

8.1.2 Ecopath with Ecosim (EwE)

The model includes single species for the most important commercial ones, i.e. European hake, red mullet, anchovy, sardine, Bluefin tuna, swordfish, blue and red shrimp, giant red shrimp, deepwater rose shrimp, mantis shrimp, Norway lobster, cuttlefish, and functional groups for other species with lower or no commercial importance. Several groups are split by depth range into shelf and slope groups, to account for the differences in the catch and bycatch in the fisheries targeting deepwater shrimps. None of these groups is resolved at age stanzas levels.

The most important fleets included are the bottom trawlers, divided by area and LOA; other fleets included in the model are the pelagic fisheries for small pelagic fish, longlines (demersal and pelagics aggregated), and polyvalent gears, which include setnets and other gears typical of small scale fisheries. Finally, the pelagic purse seine for tuna and dredges for clams are included. The fleets of eastern GSA18 (Albania and Montenegro) are aggregated by country with no resolution on the gears.

Ewe model was parameterized based on year 2008 and fitted to time series from 2008 to 2020, the model was limited so far to the South Adriatic and Western Ionian Sea (GSA 18 and 19).

8.2 Description of model parameterisation

8.2.1 BEMTOOL

The stock dynamics was modelled consistently with the most recent stock assessments (STECF-EWG 22-16 and STECF-EWG 21-15) and associated Reference Points aligned with the objectives of Maximum Sustainable Yield (MSY). From stock assessment outputs, *FLStock* objects have been created to be used by the *FLCore* R package (Kell et al. 2007), including catch data and estimated stock parameters up to 2021.

To project the scenarios, stock-recruitment relationships of the stocks were estimated using Eqsim (Table 8.1). An example is reported in Figure 8.1.

Table 8.1. Summary of the estimated SRR parameters by stock.

Stock	SRR type	coefficient a	coefficient b
HKE1718	Segmented regression	330.50	1300
HKE19	Bevholt	169.63	2.50E-03
MUT1718	Bevholt	1083131	1000
MUT19	Ricker	154.3937	6.33E-04
DPS171819	Segmented regression	1510.992	1500

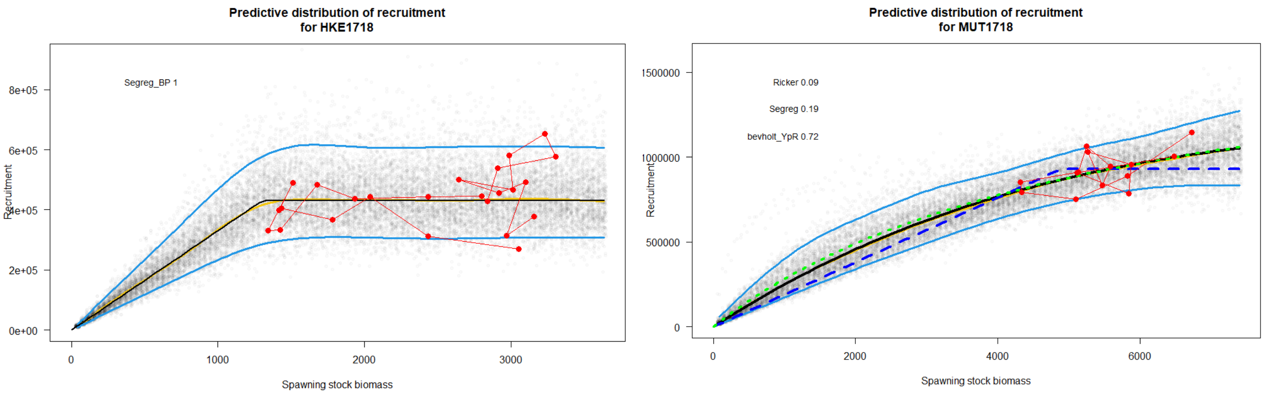

Figure 8.1 Stock recruitment relationships for HKE17-18 (segmented regression) (left upper panel) MUT17-18 (Beverton and Holt) (right panel).

Process uncertainty is considered in the projections, using the Eqsim SRR coefficients and Monte Carlo realizations combined with a multiplicative error on the estimated recruitments.

DCF data were used to parameterize the different components of BEMTOOL model:

- ✓ FDI time series 2013-2021 as regards landings, discards and fishing effort (https://stecf.jrc.ec.europa.eu/dd/fdi);
- ✓ Annual Economic Report (AER) as regards landings and fishing effort (https://stecf.jrc.ec.europa.eu/dd/fleet) for the years not covered by the FDI in the Mediterranean, i.e. 2008-2012;
- ✓ Data Call launched in SEAwise to gather data from MED&BS Data Call as regards biological parameters, catches and discards by length and age, as well as economic data at GSA level by Member State.

Considering possibility of including the effects of changes in the exploitation pattern in future applications of the model the following configuration was used:

$$F_f(a) = (Z_{inp} - mean(M)) * Sel_f(a) * f_{act,f} * p_f$$

where *F* is fishing mortality, *Z* total mortality, *M* natural mortality, *fact,f* in the forecast is the ratio between the product of the number of fishing days, the number of vessels and the average GT (or Kw) of the fleet segment *f* for each month of forecast to the product of the number of fishing days, the number of vessels and the average GT (or Kw) of the fleet segment *f* in the last year of the simulation. This quantity is considered as reference for the application of change in fishing effort. $Sel_f(a)$ is the fleet selectivity at a given length/age; p_f is the monthly ratio between the fleet segment catch to the total catch in the simulation (in the forecast it is fixed as an average of the last (n) years).

For HKE17-18 and HKE19, the model was parameterized using the maximum total mortality at age Zmax associated with a dome-shaped fleet selectivity (asymmetric normal), tuned according to the F at age of the assessment, starting from the selectivity parameters in Sala and Lucchetti (2011) (SL50%= 14.2, SR= 3.6 cm).

For MUT 17-18 and MUT19, the model was parameterized using Zmax associated with a dome-shaped fleet selectivity (asymmetric normal), tuned according to the F at age of the assessment, starting from the parameters in Sala and Lucchetti (2011) (SL50%= 0.7, SR= 4.6 cm).

For DPS17-18-19 the value of Zmean in the age range 0-3 was used, tuned according to the F at age of the assessment, starting from the parameters in the ImpleMed project (2021).

Discard was modelled through a reverse ogive model for the trawl fleets.

Reference points for all the stocks, as obtained during the stock assessment process at STECF and GFCM, are reported in Table 8.2. Following STECF decision in the absence of full MSY evaluations, and/or biomass reference points $F_{0.1}$

forms a good proxy for MSY. Thus, for all stocks with analytical assessments F0.1 is provided based on the stock conditions over the last three years. MSY advice in terms of F and catch for 2023 are based on this approach (STECF 2021b; 2023). $F_{0.1}$ is usually estimated using the *FLBRP* available in FLR.

F_{MSY} ranges, Fupper and Flower, are estimated from the following empirical relationships provided by STECF EWG 15-06 (STECF, 2015):

Flow = 0.00296635 + 0.66021447 x F0.1

Fupp = 0.007801555 + 1.349401721 x F0.1

However, as these ranges cannot be tested according to the ICES procedure, Fupper is not considered for advice, while Flow can be used, given that it is a precautionary RP.

Table 8.2 Stock assessment results used to parameterize BEMTOOL model.

Stock	Ref. year	F current	F_{MSY} ($F_{0.1}$)	F/ F_{MSY}	Fupp	Flow	SSB current	Blim	Bpa	Source	Assessment method
HKE17-18	2021	0.390	0.232	1.681	0.250	0.120	3054	1344	1881	STECF-EWG 22-16	SS3
HKE19	2021	0.335	0.211	1.588	0.292	0.142	1527	NA	NA	STECF-EWG 22-16	a4a
MUT17-18	2020	0.370	0.360	1.028	0.490	0.230	8815	NA	NA	STECF-EWG 21-15	a4a
MUT19	2021	0.533	0.380	1.403	0.540	0.270	611	NA	NA	STECF-EWG 22-16	XSA
DPS17-18-19	2021	2.410	0.750	3.213	1.010	0.500	2199	NA	NA	STECF-EWG 22-16	a4a

The scenarios are defined reducing accordingly the effort (total days as vessels*average day per vessel) by fleet segment. Only the fishing effort of trawl fleets was reduced by decreasing the fishing days until 2026, while the number of vessels has not been modified.

Price dynamic was modelled as a function of the variation of landing (modified from Salz et al., 2011), through an elasticity coefficient.

The variable costs (fuel and other) have been assumed to vary proportionally to the annual fishing days, while fixed and the maintenance costs depending on the annual GT on the basis of the historical data. The capital costs depend on the annual GT (Saltz et al., 2011; Frost et al., 2013).

In 2019 the AER revisited and updated the calculation method used for depreciation costs and capital value. The opportunity cost was based on capital value and inflation and interest rate, through the formula:

Opportunity cost =capital value*(1+interest rate)/(1+inflation rate)-1

Annual values of interest rate and inflation rate were obtained from sdw.ecb.europa.eu/ and https://it.inflation.eu/, respectively. Total capital costs were calculated as the sum of opportunity and depreciation cost.

The labour costs have been assumed in line with the crew share system on the difference revenues minus variable costs, and the depreciation costs depending on the annual GT.

Before launching the scenarios, the model was first parameterized in the hindcasting mode for testing and the assessed fishing mortality, spawning stock biomass and observed catches were compared with the simulated ones.

Figure 8.2 reports two examples of hindcasting of the catches, F and SSB related to the stocks of HKE17-18 and MUT17-18.

Figure 8.2. Examples of hindcasting replicating the stock assessments for HKE17-18 and MUT17-18. Catches, F and SSB with confidence intervals.

The scenarios have been projected until 2050.

8.2.2 Ecopath with Ecosim (EwE)

The stocks included in the model are modelled as biomass pools, based on the biomass in the surveys and catches reported in the AER data. The model is fitted to time series of catches and biomass, and driven by the effort annual time series at fleet level, obtained from AER. The dynamics of the main species are generally captured satisfactorily, with general increasing and decreasing trends observed in the data well replicated by the model, while annual fluctuations are not always perfectly captured, as expected by this modelling approach.

Also in Ewe the scenarios S0, S1 and S2 were tested until 2050.

8.3 Indicators, targets and limits

The CFP ecological and socio-economic indicators were estimated in BEMTOOL, while the MSFD related indicators (except Descriptor 3 indicators) in EwE. Table 8.3 summarizes the estimated indicator and if a target or a limit reference point is available.

In **BEMTOOL** the ecological and socio-economic indicators were estimated following the methods applied in the stock assessment working groups (e.g. STECF 2022a; and GFCM) and in the Annual Economic Report (AER, e.g. STECF 2022b).

Table 8.3 Set of indicators considered in the Case Study

Type of indicator	Indicator	Targets or limits available	Comments
CFP ecological	Proportion of stocks fished at or below F_{MSY}	Yes	Yes
	Proportion of stocks with median SSB below MSY $B_{trigger}$	Yes	Not estimated at this stage
	Proportion of stocks with >5% probability to fall below B_{lim}	Yes	Estimated for few stocks
	Proportion of fleets with Sustainable Harvest Indicator (SHI) above 1	Yes	Not estimated at this stage
	Proportion of fleets with number of stocks at risk (SAR) > 0	Yes	Not estimated at this stage
CFP socio-economic	Landings (average of yearly sums across fleets/metiers)	No	Yes
	Unwanted catch/Discards (average of yearly sums across fleets/metiers)	No	Yes for the target stocks
	Revenue (average of yearly sums across fleets/metiers)	No	Yes
	Gross profit (average of yearly sums across fleets/metiers)	No	Yes
	Gross value added (average of yearly sums across fleets/metiers)	No	Yes
	Employment (average of yearly sums across fleets/metiers)	No	Yes
	Wages (average of yearly sums across fleets/metiers)	No	Yes
	Average yearly ratio of current revenue/break even revenue (sum across fleets/metiers)	Yes	Yes
	Ratio landings value fleets <=24m/landings value fleets >24m	No	Yes, however we used the following ratio landings value fleets <=18m/landings value fleets >18m because oft he aggregation level we used for the selected fleets, as the segments 24-40 LOA was poorly represented
	Accident rates	No	No
MSFD related indicators (Descriptor 3	D1C1: Bycatch or risk for PET species	Partly (for some	No

indicators are already included under CFP indicators)		species and regions)	
	D1C3: Biomass of forage fish	Yes	No
	D4C1: Biodiversity within trophic guilds[3]	No	Yes, Shannon indices per the guild
	D4C2: Ratio between trophic guilds[3]	No	Yes, we used biomass per guild
	D4C3: Large fish indicator across guilds[3]	No	Yes we used the mean maximum length (MML) and Large Species Indicator (LSI) across guilds
	D4C4: Average recruitment success within guilds[1]	No	No
	D6: Effort (translated into swept area ratio)? by demersal gear type (at least Otter Trawls, Beam Trawls, Seines where possible)	No	Yes as relative effort of trawling gears
	D10: Amount of marine litter	No	Developed a trend analysis on litter numbers and mass and spatial mapping of main marine litter categories. Relationships with effort not clear.
Global indicators	Carbon emission from fisheries (average of yearly sums across fleets/metiers)	No	Not developed at this stage
	Ratio of fisheries catches to Primary production (Fogarty ratio in Link and Watson 2019)	No	Not developed at this stage
	Catches per km2 per year (Ryther index in Link and Watson 2019)	No	Not developed at this stage
	Ratio of fisheries catches to Cholophyl a (Friedland ratio in Link and Watson 2019)	No	Not developed at this stage

In **Ecopath with Ecosim (EwE)** the indicators are provided at guild level, using the guild resolution divided into top predators, piscivores, benthivores and planktivores. According to the guild repartitions, only fish are considered in the piscivores, benthivores and planktivores groups, while the top predator guild includes fish (e.g. pelagic sharks, tuna, swordfish) as well as seabirds, marine mammals, and sea turtles.

The indicators used are: Shannon index of biodiversity (MSFD D4C1); Biomass (MSFD D4C2) and Mean Maximum Length (MML; MSFD D4C3). This is based on the maximum reported length of the most abundant species in each functional group. Reported length from survey or catch data specific to the study area were used, where available, rather than absolute maximum size which can be considerably larger for the same species in other systems. The Large Species Indicator (LSI) was also calculated, and provided for comparison. The LSI was also based on the maximum reported length of the most abundant species in each functional group. A threshold for what is considered a “large” fish is set at 40 cm, dividing the community into categories of size (“large” and “small”). The representative species per functional group and their maximum size and size category are reported in Table 8.4. The MML was provided across guild (as per MSFD definition) but also calculated at guild level.

Table 8.4. Functional groups of fish (excluding top predators), with their most representative species, their guild, maximum reported size in the study area (used for MML), and size category based on the 40 cm threshold (used for LSI).

functional group	**Representative species**	**Guild**	**Max reported size (cm)**	**Size category**	**Source**
Rays and Skates	*Raja clavata*	benthivore	91.5	Large	DCF Biological sampling
Demersal sharks	*Galeus melastomus*	benthivore	59.5	Large	MEDITS
Medium pelagic fish	*Sarda sarda*	piscivore	58	Large	Fishbase
Demersal piscivorous fish Slope	*Conger conger*	piscivore	265	Large	Fishbase
Demersal piscivorous fish Shelf	*Lepidopus caudatus*	piscivore	178	Large	Fishbase
Anglerfish	*Lophius piscatorius*	piscivore	136.5	Large	MEDITS
Bogue and picarels	*Boops boops*	planktivore	29.5	Small	MEDITS
mesopelagics		planktivore	10	Small	guesstimate
Jellyfish feeding pelagics	*Centrolophus niger*	planktivore	94	Large	Fishbase
Demersal fish Slope	*Helicolenus dactylopterus*	benthivore	34	Small	MEDITS
Demersal fish Shelf	*Micromesistius poutassou*	benthivore	47.5	Large	MEDITS
Other small pelagics	*Liza ramada*	planktivore	57	Large	CAMPBIOL
Anchovy	*Engraulis encrasicolus*	planktivore	19.5	Small	MEDITS
Sardine	*Sardina pilchardus*	planktivore	22.5	Small	MEDITS
Mackerel	*Scomber scombrus*	piscivore	39	Small	CAMPBIOL
Horse mackerel	*Trachurus trachurus*	planktivore	46	Large	CAMPBIOL
Red mullet	*Mullus barbatus*	benthivore	33.5	Small	MEDITS
Hake	*Merluccius merluccius*	piscivore	100	Large	CAMPBIOL

8.4 Main results

8.4.1 BEMTOOL

Table 8.5 and 8.6 report the CFP indicators, ecological and socio economic respectively. Regarding the ecological indicators, the proportion of stocks fished at or below F_{MSY} is 0.2 and it increases to 0.8 in the first period of the simulation and then stabilized at 1. It is worth noting that the fishing mortality of the most part of the stocks was already decreasing in the last period of the hindcasting phase (Figure 8.3) that contributes to the recovery of the stock since the initial phase of the simulation. In scenarios 1 and 2 F decreases below the F_{MSY} for all the stock except DPS17-18-19 that attained the F_{MSY}.

Figure 8.4 clearly presents the increase of the SSB in S1 and S2 while in S0 the risk of the decrease of the DPS SSB is high.

Table 8.5 CFP indicators (eco)

Scenario	Time period (provide average values over the time period)	Proportion of stocks fished at or below FMSY	Proportion of stocks with median SSB below MSY Btrigger	Proportion of stocks with >5% probability to fall below Blim
S0_Status quo	2025-2030	0.2	NA	0.2
S0_Status quo	2035-2040	0.2	NA	0.2
S0_Status quo	2045-2050	0.2	NA	0.2
S1_Fmsy_DPS	2025-2030	0.8	NA	0
S1_Fmsy_DPS	2035-2040	1	NA	0
S1_Fmsy_DPS	2045-2050	1	NA	0
S2_Fcomb_(PGY)	2025-2030	0.8	NA	0
S2_Fcomb_(PGY)	2035-2040	1	NA	0
S2_Fcomb_(PGY)	2045-2050	1	NA	0

Table 8.6 CFP indicators (socio-economic)

Scenario	Time period (provide average values over the time period)	Landings (average of yearly sums across fleets/metiers) **all stocks**	Revenue landings (average of yearly sums across fleets/metiers)	Unwanted catch/Discards (average of yearly sums across fleets/metiers) **target stocks**	Gross profit (average of yearly sums across fleets/metiers)	Gross value added (average of yearly sums across fleets/metiers)
S0_Status quo	2025-2030	46200	265681005	564.5	62351368	130949876
S0_Status quo	2035-2040	46589	267266042	532.4	62880177	132534914
S0_Status quo	2045-2050	45595	261080061	519.4	59127261	126348933
S1_Fmsy_DPS	2025-2030	41389	236791393	245.1	69327947	154191455
S1_Fmsy_DPS	2035-2040	50366	275765263	226.7	89968081	196616511
S1_Fmsy_DPS	2045-2050	50522	276395642	227.6	90254234	197246890
S2_Fcomb_(PGY)	2025-2030	44226	252846151	317.9	75047338	162511885
S2_Fcomb_(PGY)	2035-2040	51896	286130289	304.3	92363419	197961198
S2_Fcomb_(PGY)	2045-2050	51526	284774565	302.0	91627248	196605474

Table 8.6 continuation CFP indicators (socio-economic)

Scenario	Time period (provide average values over the time period)	Employment (average of yearly sums across fleets/metiers)	Wages (average of yearly sums across fleets/metiers)	Average yearly ratio of current revenue/break even revenue (sum across fleets/metiers)	Ratio landings value fleets <=24m/landings value fleets >24m (used <=18 and >18)
S0_Status quo	2025-2030	10019	68598508	0.4202	0.359
S0_Status quo	2035-2040	10019	69654737	0.4232	0.365
S0_Status quo	2045-2050	10019	67221672	0.4025	0.353
S1_Fmsy_DPS	2025-2030	10019	84863508	0.4587	0.510
S1_Fmsy_DPS	2035-2040	10019	106648430	0.5723	0.551
S1_Fmsy_DPS	2045-2050	10019	106992656	0.5740	0.435

S2_Fcomb_(PGY)	2025-2030	10019	87464546	0.4900	0.434
S2_Fcomb_(PGY)	2035-2040	10019	105597779	0.5858	0.465
S2_Fcomb_(PGY)	2045-2050	10019	104978227	0.5817	0.463

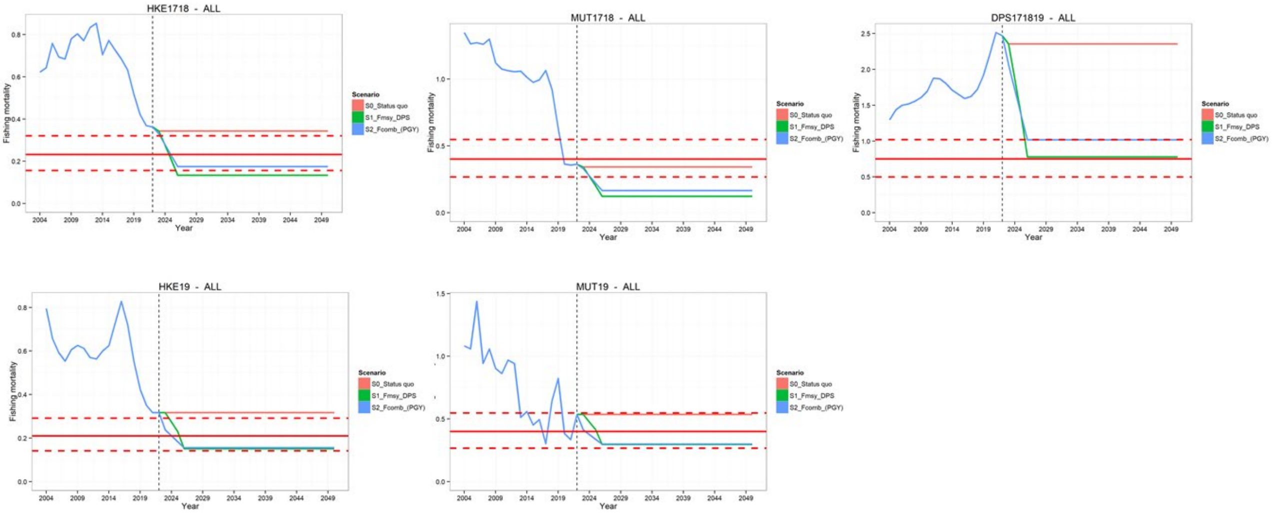

Figure 8.3 Trajectories of fishing mortality for the three scenarios and the five stocks tested.

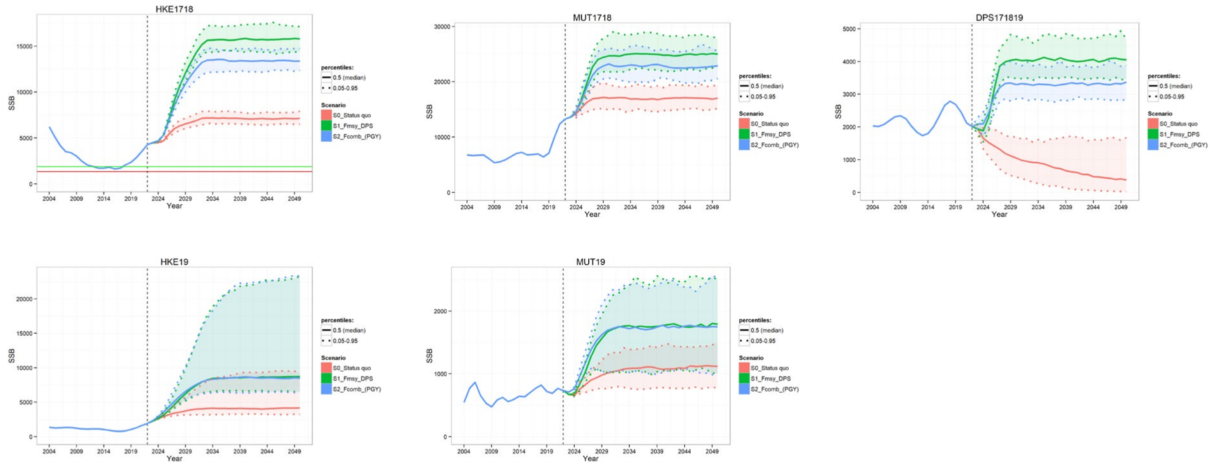

Figure 8.4 Trajectories of the SSB for the three scenarios and the five stocks tested.

Figure 8.5 illustrates some examples of the trajectories of the total landings and GVA for the three scenarios. Landings of three trawl fleet segments (LOA1840) after a decrease in the short terms tend to recover reaching a level similar to the status quo situation. Small scale fleets (e.g. PGP and HOK) that are not reduced take an advantage of the stock recovery as their landings remarkably increase. The total landings reflect mirror the compensation of the effects of the reduction of the fishing effort of trawlers in the production system. The indicator GVA reflects the landing dynamics of this mixed fishery.

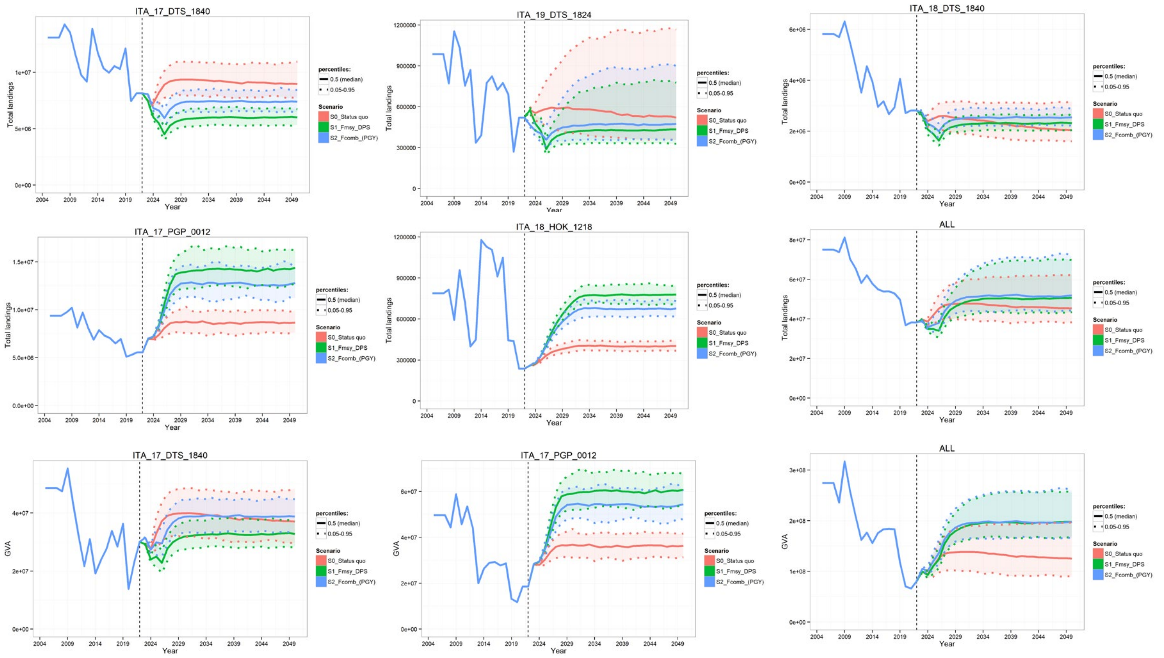

Figure 8.5 Examples of the trajectories of the total landings and GVA for the three scenarios: landings of three trawl fleet segments (LOA1840) (upper panel), of the two small scale fleets (PGP and HOK) and total landings (central panel); GVA of a trawl segment (LOA 1840), of a small scale fleet segment (PGP0012) and all the fleet.

8.4.2 Ecopath with Ecosim (EwE)

All the MSFD indicators were calculated at guild level, according to scenarios of fishing effort reduction and by time periods. The indicators show that, under a 69% or 58% reduction of fishing effort produced positive effects on piscivores in terms of biodiversity, when compared to status quo scenario (Figure 8.6); the biodiversity of benthivorous fish shows an initial increase with lower fishing pressure, and then it is quite stable (Table 8.7). Conversely, biodiversity of planktivorous and that of top predators is very similar across fishing scenarios.

The biomass of both piscivorous and benthivorous fish increases under scenarios 1 and 2, reflecting the reduction of mortality on these groups when bottom trawling is reduced (Figure 8.7). The biomass of planktivorous fish declines, plausibly because of the increasing predation from the piscivorous fish. Similarly, the biomass of top predators decline, possibly as a result of competition from piscivorous fish. The biomass increases faster than the biodiversity index, and it also increases for benthivorous, in contrast to the biodiversity index. This confirms that biomass does not capture all information: plausibly, in the benthivorous fish the biomass increases only for few groups which dominate the guild, leading to a lower biodiversity. The change in biomass, however, are only substantial for the piscivorous fish: for all other groups the differences between scenarios are too contained for visually appreciating in the plots (e.g. Figure 8.7), and only discernible when looking at Table 8.8.

For the MML indicator, the effect of the effort scenarios across trophic guilds is clearly visible (Figure 8.6): the reduction of effort leads to a higher MML which stabilizes around a value above 40 cm in both scenarios. Conversely, the status quo scenario shows a stabilization below 40 cm. When considering the individual guilds (Table 8.9), the most important change observed with a large increase in MML under effort reduction takes place for the piscivorous fish, with benthivorous and planktivorous showing minor changes. The small reduction of MML in benthivorous fish is attributed again to the predation of piscivorous fish. The change in piscivorous fish is attributed to a rapid growth in the average size of this group, possibly a result of the avoided decline of specific groups (e.g. piscivorous demersal slope fish).

The Large Species Indicator shows a similar patter as MML: LSI increases for piscivorous fish. Compared to MML, however, there is also a slight increase in the benthivorous fish LSI (Table 8.10), while no change is observed in planktivorous fish. The increase in benthivorous fish shown by the LSI but not by MML under effort reduction may point at how the two indicators include size, with the rough "large/small" categorization not necessarily reflect well the structure changes in the community. The MML patterns are closer to what we expect to find, and observe in the other indicators.

Table 8.7. Shannon's H index of biodiversity calculated by guilds for projected time periods under scenarios of effort reductions.

		Shannon's H			
	Years	Top predators	piscivores	benthivores	planktivores
Scenario 0	2025-2030	0.575	0.689	0.57	2.024
	2035-2040	0.851	0.851	0.647	2.13
	2045-2050	0.834	0.836	0.64	2.143
Scenario 1	2025-2030	0.575	0.689	0.57	2.024
	2035-2040	0.849	0.912	0.655	2.125
	2045-2050	0.832	0.908	0.638	2.133
Scenario 2	2025-2030	0.575	0.689	0.57	2.024
	2035-2040	0.849	0.902	0.654	2.125
	2045-2050	0.832	0.897	0.638	2.134

Table 8.8. Biomass calculated by guilds for projected time periods under scenarios of effort reductions.

		Biomass			
	Years	Top predators	piscivores	benthivores	planktivores
Scenario 0	2025-2030	38742	39718	26420	171955
	2035-2040	38126	39893	26684	172129
	2045-2050	38085	39877	26732	172077
Scenario 1	2025-2030	38576	43728	26956	170497
	2035-2040	38002	43556	26806	170538
	2045-2050	37968	43484	26832	170466
Scenario 2	2025-2030	38576	43101	26846	170695
	2035-2040	37971	42956	26728	170753
	2045-2050	37934	42882	26750	170686

Table 8.9. Mean Maximum Length calculated across guilds (all species) and by guilds for projected time periods under scenarios of effort reductions.

		Mean MaMean Maximum Length			
	Years	All species	piscivores	benthivores	planktivores
Scenario 0	2025-2030	39.56	81.42	47.27	31.49
	2035-2040	39.45	80.51	47.54	31.46
	2045-2050	39.43	80.38	47.56	31.46
Scenar	2025-2030	41.11	86.71	47.14	31.37

	2035-2040	41.13	87.33	47.09	31.32
	2045-2050	41.11	87.32	47.1	31.31
Scenario 2	2025-2030	40.86	85.88	47.17	31.39
	2035-2040	40.87	86.45	47.16	31.33
	2045-2050	40.86	86.44	47.17	31.33

Table 8.10. Large Species Indicator calculated across guilds (all species) and by guilds for projected time periods under scenarios of effort reductions.

		Large Species Indicator			
	Years	All species	piscivores	benthivores	planktivores
Scenario 0	2025-2030	0.4	0.77	0.49	0.33
	2035-2040	0.4	0.76	0.49	0.33
	2045-2050	0.4	0.76	0.49	0.33
Scenario 1	2025-2030	0.41	0.8	0.53	0.33
	2035-2040	0.41	0.8	0.53	0.32
	2045-2050	0.41	0.8	0.53	0.32
Scenario 2	2025-2030	0.41	0.79	0.52	0.33
	2035-2040	0.41	0.8	0.52	0.32
	2045-2050	0.41	0.8	0.52	0.32

Figure 8.6. Diversity of piscivorous fish (left) and mean maximum length across guild under three effort scenarios.

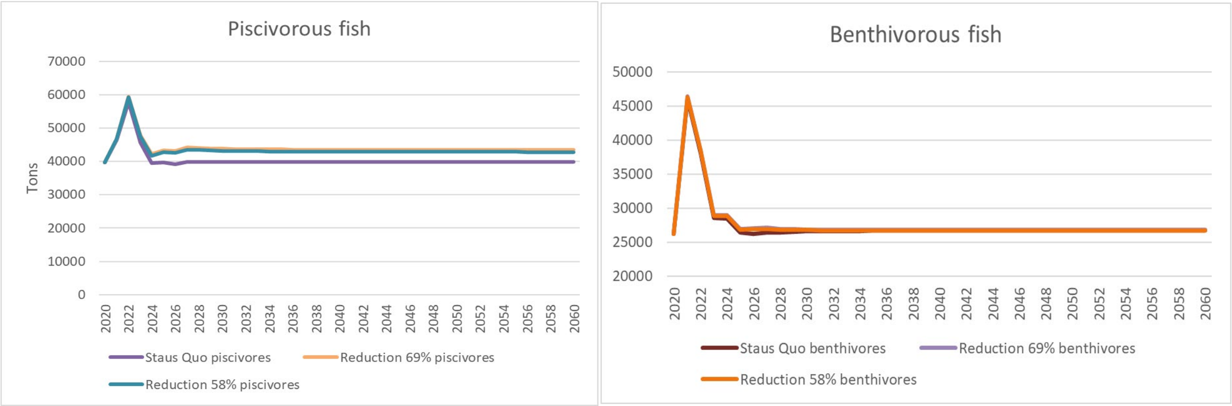

Figure 8.7. Biomass in tons of piscivorous (left) and benthivorous (right) fish under three effort scenarios.

8.5. Conclusions

We observed in the scenarios the concurrence of CFP ecological and socio-economic indicators capturing the effects of reduction of fishing effort in the biological and economic-social systems.

The number of CFP ecological indicators is quite limited in the Mediterranean, where the shortness of the time series has constrained so far the implementation of more structured schemes, including biomass reference points in addition to F_{MSY} proxy, as $F_{0.1}$, for more stocks. This impacts the possibility of estimating stock-recruitment relationships that enable to better capturing the stock dynamic. There are recent progresses aiming at filling such gap (STECF 2022a), given that also the length of the time series is in the meanwhile increasing. It should also be noted that during this year a benchmarking stock assessment process is taking place at GFCM level. Along the present and following months, most of the stocks here analyzed are in this process that will produce updated, but also more robust stock assessments. These can be used at a following step in SEAwise to improve and expand our results.

The situation of the stocks in the Mediterranean is considered critical though some signs of improvement are detected (FAO, 2022). Indicators of the CFP ecological system, as SSB and fishing mortality, also highlight these improvements in the stocks' trajectories of the scenarios modelled in this deliverable, especially for the Adriatic, where a MAP is in place and so a reduction of fishing opportunities already started. The scenarios of fishing effort reduction, however, are evidencing that a stronger reduction of effort (i.e. 69%) would not produce greater advantage to the system compared to a 58%, as some stocks can remain underutilized, while the challenge for the economic-social systems would be likely too impacting, especially for trawlers and in the short terms. Indeed the indicator "Ratio landings value fleets <=24m/landings value fleets >24m (used <=18 and >18)" is increasing that would demonstrate a potential advantage for the fleets not impacted by the reduction of effort opportunities.

The simulations in these scenarios have not implemented a suite of specific submodels, e.g. fishers'behaviour, fuel consumption, differentiated fish price, or impact on the employment that remain constant given that a reduction of vessels is not considered. These sub-models are under study and could be part of the process in the next working steps of SEAwise.

We have not introduced in the simulated scenarios other possible options, as an improvement of the fleet selectivity or the closure of key hot spot areas that will be further explored in SEAwise and can also elucidate the effects of such measures on target and limit reference points, as a consequence of improvement of the exploitation pattern.

In conclusion, in EwE we observe that the indicators respond according to expectation, with recovery of some indicators in the piscivorous fish groups after reduction of the fishing pressure; the benthivorous groups instead show worsening indicators, possibly a result of the recovery of piscivorous fish with consequent increase in predatory pressure. Observing the temporal changes allows to disentangle the time dynamics of the different groups, permitting a finer understanding of the consequences of fishing reduction across the trophic web (e.g. some groups responding faster than others) and offering an example of the complementarity of the indicators (e.g. biodiversity and biomass indicators showing lagged and differing patterns).

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8.10 **Annex 10: Potential bycatch thresholds**

Background

When marine megafauna are under threat and/or of conservation concern it is often useful to estimate targets or limits for removals that population can sustain in order to help meet conservation objectives (Good et al. 2020). In the related research area of fisheries assessment and management, reference points are a good example of the combined use of targets and limits to improve the status of managed populations (Hilborn & Walters 2013, Hilborn et al. 2020). For conservation of protected, endangered and threatened (PET) species, thresholds have been used to indicate the level of incidental mortality (e.g. fisheries bycatch) a population can sustain and also trigger management action in order to achieve conservation targets (Berggren et al. 2002, Dillingham & Fletcher 2008, Geijer & Read 2013, Casale & Heppell 2016, Marchowski 2022).

The majority of work on thresholds has focused on marine mammal populations (Wade 1998, Winship et al. 2009, Hammond et al. 2019, Genu et al. 2021). In **cetaceans**, in particular, approaches for setting threshold values for removals of protected cetacean species have been extensively discussed in Europe (ICES 2019), with a focus on three approaches in particular: fixed percentages of abundance, Potential Biological Removal (PBR) and the Catch Limit Algorithm (CLA) and/or its analogous Removal Limit algorithm (RLA).

The fixed percentage of abundance is the simplest management approach while CLA/RLA is the most data demanding approach that requires both a time series of abundance estimated and anthropogenic removals. Due to lack of available data, it is not often implemented, although it is the most appropriate method to set limits on the bycatch of harbour porpoises or common dolphins according to ICES (ICES 2013).

PBR was designed to set limits to anthropogenic mortality of small cetaceans and pinnipeds with minimal data requirements and was developed and applied, as part of an adaptive management framework, in the USA under the Marine Mammal Protection Act (Wade 1998). It defines the maximum number of animals, in addition to natural mortality, that may be removed from a stock while allowing it to reach or maintain its optimum sustainable population (at or above the level that will result in maximum productivity). Given uncertainties associated with defining this threshold in data poor conditions, PBR is regularly recalculated as population abundance is updated.

PBR is the product of a minimum population estimate (Nmin), to account for uncertainties associated with the abundance estimation process, and half of the maximum theoretical productivity rate (Rmax). The latter approximates the minimum maximum net productivity of the population (assuming that there is no density-dependence effects in population dynamics). This potential biological removal number is then further censored to account for practical uncertainties associated with the management of the population and their lethal threats. As with any other thresholds, PBR is estimated in relation to a given management objective and therefore is set to maximise the chances to meet this management objective. The N_{min}½R_{max} product is multiplied by a recovery factor (Fr) between 0.1 and 1.0 which aims to integrate information about the population trajectory and status, and the uncertainties associated with the estimation of the number of removals the population faces.

$$PBR = \frac{R_{max} N_{min} f}{2} \tag{1}$$

For small cetaceans, the maximum productivity rate -Rmax- is very difficult to estimate in practice, so a default value of 4% is used (Wade 1998). In contrast, Nmin and Fr values may change depending on the conservation objectives, so they need to be estimated, typically by means of simulations (also called tuning).

Under the Marine Mammal Protection Act, the conservation objective was defined to “maintain or recover a population at/to its maximum net productivity level -typically 50% of the populations carrying capacity- with 95% probability within a 100-year period”. PBR estimates were deemed robust to uncertainties and able to reach that objective when Nmin was established as the 20th percentile of the abundance (assuming a log normal distribution), while Fr was set at 0.5 as default (Wade 1998). This value is used for populations which are threatened or of unknown status and provides a safety factor to account for levels of unknown bias or estimations problems that have been observed in some population of marine mammals. Values between 0.1-0.3 are usually reserved for endangered species or population known to be in decline, while values higher than 0.5 are used for populations known to be at their optimum sustainable population level, or of unknown status but known to be increasing (Wade 1998).

This approach, originally designed for marine mammals, it has been also applied to other taxonomic groups such as seabirds, although issues with the method have been highlighted more recently (Miller et al. 2019). In **seabirds**, ideally a population viability analysis (PVA) should be conducted to estimate a threshold but often the data is not available (Dierschke 2022). Alternatively, a method called the BirdLife International Threshold (BLT) offers a relatively simple and data moderate quantitative method for obtaining threshold values. These values are indicative of the resilience of a population to incidental mortality from fisheries bycatch and can be useful for management.

BLT is a relatively new method proposed at a OSPAR-HELCOM workshop (OSPAR-HELCOM 2019), recommended by (BirdLife International 2019) and further endorsed in an OSPAR pilot assessment (Dierschke 2022). A recent study by Marchowski (2022) used the two different methodologies, BLT and PBR, in a review of seabird *bycatch* in the Southern Baltic. In this short report, we use a similar approach and apply both the BLT and PBR methodologies to obtain a range of thresholds for Northern gannet and Northern fulmar populations in Irish waters.

In **turtles**, the already mentioned PBR or the Reproductive Value Loss Limit (RVLL, generalized from the PBR management model) have been applied (Curtis & Moore 2013, Casale & Heppell 2016) while in **fishes**, the concepts of maximum sustainable yield (MSY) and maximum rate of fishing mortality (FMSY as a threshold for the sustainability of the stock) are well developed and tested. In many cases those management measures work well (Hilborn & Ovando 2014) exemplifying the robustness of those models. Moreover, the MSY is conceptually comparable with the CLA and PVA models proposed for marine mammals and birds.

Cetaceans

There is not a clear consensus yet on an operationalised conservation objective that should be achieved in European waters. In the Workshop on Fisheries Emergency Measures to Minimize Bycatch (WKEMBYC; ICES 2020b) the conservation objective adopted by the Marine Mammal Protection Act (to maintain or recover a population at/to 50% of the population carrying capacity with 95% probability within a 100-year period) was followed. At OSPAR's Marine Mammal Expert Group, in contrast, a different objective was set, more akin to a restoration objective, (i.e., ASCOBANS objective), which established that "a population should [be able to] recover to or be maintained at 80% of carrying capacity, with probability 0.8, within a 100-year period".

As an appropriate interpretation of the European ambition into an operationalised conservation objective is still being debated, here we estimated PBR using two alternative approaches. On one hand, we used the preestablished parameters values estimated by Wade (1998) under the conservation objective of Marine Mammal Protection Act (conventional PBR), meaning that Nmin should be the 20th percentile of the abundance and Fr should be 0.5 by default, although lower values (typically for endangered species or in decline) o higher values (for populations known to be at their optimum sustainable population level, or increasing) can be applied as well.

Secondly, we applied the parameters obtained from the bias trial conducted under ASCOBANS's conservation objective (Genu et al. 2021, ICES 2021b), where Nmin was also established as the 20th percentile of the abundance, but the default value of Fr was defined between 0.1 and 0.15, depending on the case study and the degree of conservationism (modified PBR, mPBR hereafter).

Common dolphins in Northeast Atlantic

Common dolphin is one of the most widespread and abundant cetacean species globally and it is widely distributed from tropical to cool temperate waters of both hemispheres in all major ocean basins (Murphy et al. 2019). At European level, common dolphin's assessment unit encompasses a large part of the Northeast Atlantic, i.e., OSPAR regions II, III and IV (Fig. 1), although its major abundance is concentrated in the Bay of Biscay (Hammond et al. 2017). In 2013, its conservation status for the European Marine Atlantic was assessed as 'Unfavourable-Inadequate' based on the known human pressure of fishery bycatch (Murphy et al. 2019).

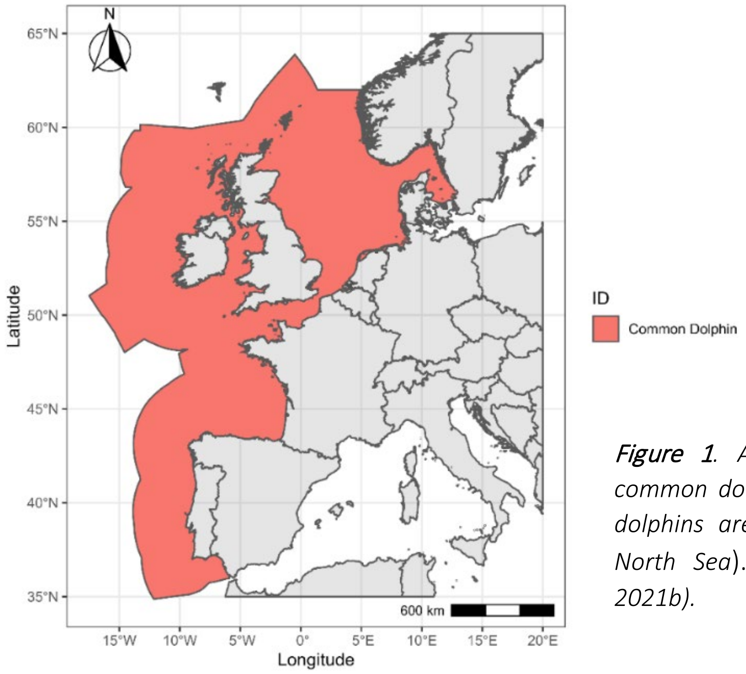

Figure 1. Assessment unit for the common dolphin (note that common dolphins are rarely observed in the North Sea). From WKMOMA (ICES 2021b).

For the PBR estimation, we used the latest and most comprehensive abundance estimate provided by SCANS III and ObSERVE surveys for the European Atlantic waters: 634286 individuals (95% CI 352 227–1 142 213, CV=0.307)(ICES 2020b). As Fr values, 0.5 and 0.1 were used for conventional PBR and mPBR approaches, that provided a limit of 4927 and 985 individuals respectively (Table 1).

Table 1. Bycatch thresholds estimated through the two alternative PBR approaches. Parameters needed to estimate the thresholds are also included as well as the organisms and/or the studies that apply them.

Species	*Method*	*N*	*Nmin*	*Rmax*	*Fr*	*Threshold*	*Organization*	*Reference*
Common dolphin	PBR	634286	492653	0.04	0.5	4927	ICES	ICES (2020b)
	mPBR	634286	492653	0.04	0.1	985	OSPAR	ICES (2021b)

According to the data presented in the latest Working Group on Bycatch of Protected Species for the 2017-2021 period (WGBYC; ICES 2022d), common dolphin in the Northeast Atlantic is caught, although in different rates, in midwater pair trawls (PTM), midwater otter trawls (OTM), bottom otter trawls (OTB), bottom pair trawls (PTB), gillnets (GNS) and trammel nets (GTR), purse seiners (PS) and otter twin trawls (OTT), longlines (LLS) and beam trawls (TBB) (Table 2).

Bycatch rates for these metiers were estimated using the number of animals recorded bycaught divided by days at sea observed. The number of bycaught animals and days at sea observed were aggregated by ICES Ecoregion and Métier Level 4 (rates based on less than 50 days at sea observed should be taken with caution). Confidence intervals around the bycatch rates were estimated assuming a binomial distribution (ICES 2022d).

Note that those bycatch numbers are only associated with the observed DaS. In 2017, the bycatch rates extrapolated to the fishing effort resulted in 8904 bycatch deaths (95% CI 3142–20 026) in the Bay of Biscay and 9373 (95% CI 3184–21956) when also considering the Greater North Sea and Celtic Seas Ecoregions (ICES 2020b). In 2020, the total number of animals bycaught was estimated to be 6,404 individuals (95% CI 3,051–9,414) for the entire assessment area (ICES 2021b). In both cases, the number of bycaught animals exceeded by far the limits considered to be acceptable

Table 2. *Common dolphin bycatch rates (no. of animals per day) and 95% confidence intervals around the rates provided by métier level 4 over the 2017-2021 period. Days at Sea (Das) refers to observed effort while coverage (not always available) refers to the % of days observed respect to total effort.*

Region	*Metier*	*DaS*	*Total effort in days*	*Coverage (%)*	*No. of animals*	*Rate*	*CI5-CI95*
Bay of Biscay - Iberian Coast	PTM	1080	18988	5.6	115	0.106	0.090-0.123
Celtic sea		333		--	1	0.003	0-0.009
Bay of Biscay-Iberian Coast	OTB	1637	79099	2	2	0.001	0-0.003
Celtic sea		3842		--	12	0.003	0.001-0.004
Greater North Sea		4194		--	5	0.001	0.0004-0.002
Bay of Biscay-Iberian Coast	GNS	2875	64250	4.5	23	0.008	0.005-0.010
Celtic sea		1285		--	8	0.006	0.003-0.010
Greater North Sea		8170			4	0.0004	0.0001-0.0009
Bay of Biscay-Iberian Coast	GTR	1730	148398	1.1	26	0.015	0.010-0.020
Celtic sea		108		--	1	0.009	0-0.027
Greater North Sea		641		--	3	0.004	0.001-0.009
Bay of Biscay-Iberian Coast	PTB	682	9515	7.1	85	0.124	0.102-0.146
Bay of Biscay-Iberian Coast	OTM	15	1279	1.1	2	0.129	0-0.322
Bay of Biscay-Iberian Coast	PS	914	68418	1.3	11	0.012	0.006-0.018
Greater North Sea		57		--	5	0.08	0.035-0.159
Celtic Sea	OTT	1990		--	2	0.001	0-0.002
Bay of Biscay-Iberian Coast	LLS	1637	79099	2.1	2	0.001	0-0.003
Greater North Sea	TBB	1526		--	1	0.0006	0-0.001

Harbour porpoise in the Baltic region and North Sea

There are three populations of harbour porpoise (*Phocoena phocoena*) in the Baltic region (Fig. 2): 1) the North Sea population, with a management range from the northern Kattegat, through Skagerrak to the entire North Sea, 2) the Belt Sea population in the western Baltic Sea, Belt Sea, the Sound and southern Kattegat, and 3) the Baltic Proper population in the inner Baltic Sea (Owen et al. 2022).

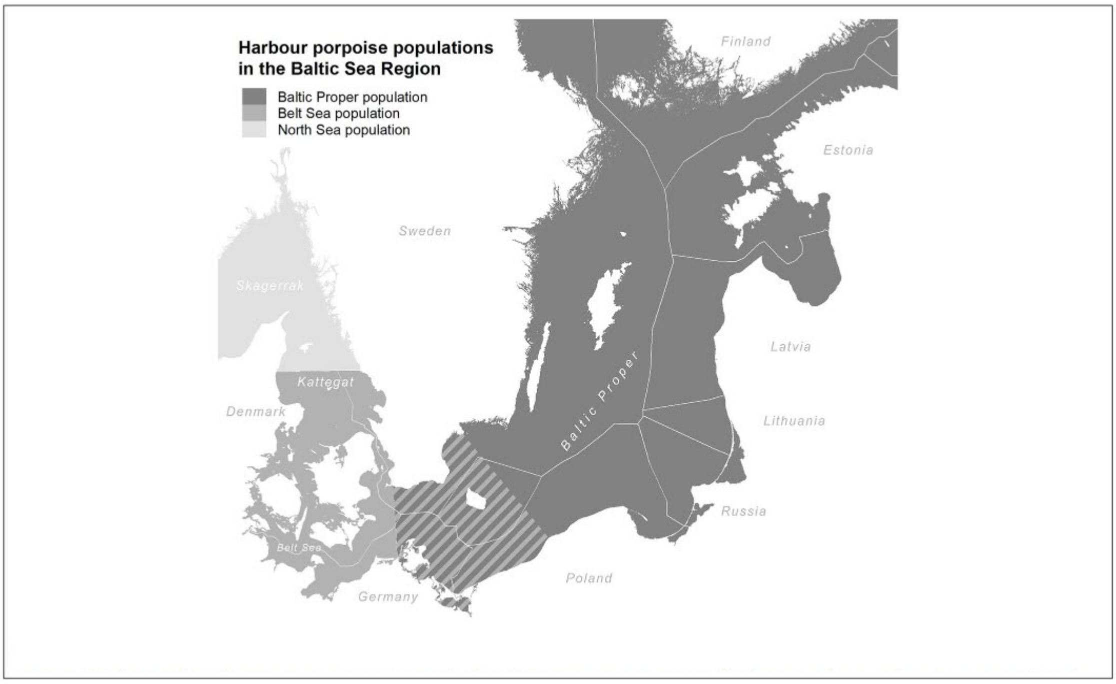

Figure 2. Map showing the approximate distributions of harbor porpoise populations in the Baltic Sea Region From Carlén et al. (2021).

The Baltic proper population is listed by the International Union for Conservation of Nature (IUCN) and the Baltic Marine Environment Protection Commission (HELCOM) as critically endangered. Its abundance was estimated in a two-year acoustic survey in 2011–2013, resulting in an estimate of 497 animals (95% CI 80–1091; CV=0.42) (ICES 2020b). While pollution and disturbance through underwater noise may be contributing to the population failing to recover, bycatch is the one acute threat causing direct mortalities in significant numbers (ICES 2020b). For this population, conventional PBR was applied but using Fr=0.1 (instead of the default value of 0.5) given its critical conservation status (Wade 1998). This led to a maximum of 0.7 animals bycaught per year (Table 3).

For the Belt Sea population, we considered the latest abundance estimate (Lacey et al. 2022) but adapted to cover the Kattegat (ICES area IIIa21), the Sound (ICES area 266 IIIb23), and the Belt Seas (ICES area IIIc22), resulting in 16,678 individuals (CV=0.2). For this population, conventional PBR and mPBR were applied but with two levels of assumptions: in the first, a classical value of 0.5 was used as Fr for PBR and 0.15 for mPBR following Genu et al. (2021). This led to 141 and 42 individuals respectively. The second estimate incorporated knowledge, as planned in the PBR and mPBR robustness scenarios, on the precision of the abundance and bycatch rate estimates. Under these assumptions, 1.0 was used as Fr for PBR and 0.35 for mPBR (Kindt-Larsen et al. 2023). This led to 282 and 99 individuals, respectively.

In the North Sea, the overall abundance of harbour porpoise was estimated to be 345,000 individuals (95% CI 246,526-495,752; CV= 0.18) based on SCANS-III survey in 2016 (Hammond et al. 2017). For this population, Removals Limit Algorithm (RLA) was calculated, which provided a threshold of 1622 individuals (ICES 2021b) (Table 3).

This approach is considered a more sophisticated management procedure than PBR (Palialexis et al. 2021) and requires both bycatch and abundance estimates. From these data, it estimates, through a population dynamic model (usually fit in Bayesian framework), two key parameters: current depletion Dt, and population growth rate, r (Hammond et al. 2019). Once these two parameters have been estimated, the anthropogenic mortality limit is computed as:

$$\text{Antropogenic mortality limit} = \quad N \times r \times \max(0, Dt - IPL) \tag{2}$$

where is the best available abundance estimate and *IPL* is the internal protection level set to 0.54 (i.e. 54% of carrying capacity K). If the estimated depletion level of the population is below the IPL, then the bycatch limit is set to 0.

Table 3. *Bycatch thresholds estimated through different methods. Parameters needed to estimate the thresholds are also included as well as the organisms and/or studies that apply them (note that RLA estimation does not follow PBR procedure).*

Population	*Method*	*N*	*Nmin*	*Rmax*	*Fr*	*Threshold*	*Organization*	*Reference*	
	Baltic proper population	PBR	497	360	0.04	0.1	0.7	ICES	ICES (2020b)
Belt Sea population	PBR mPBR	16678	14116	0.04	0.5-1 0.15-0.35	141-282 42-99	--	Kindt-Larsen et al. (2023)	
North Sea population	RLA	--	--	--	--	1622	OSPAR	ICES (2021b)	

According to the data presented in the latest Working Group on Bycatch of Protected Species for the 2017-2021 period (WGBYC; ICES 2022d), harbour porpoise is caught in the Baltic and North Sea in bottom otter trawls (OTB), gillnets (GNS) and trammel nets (GTR) and Danish seines (SDN) (Table 4).

Bycatch rates for these metiers were estimated using the number of animals recorded bycaught divided by days at sea observed. The number of bycaught animals and days at sea observed were aggregated by ICES Ecoregion and Métier Level 4 (rates based on less than 50 days at sea observed should be taken with caution). Confidence intervals around the bycatch rates were estimated assuming a binomial distribution (ICES 2022d).

Table 4. *Harbour porpoise bycatch rates (no. of animals per day) and 95% confidence intervals around the rates provided for the Baltic Sea and Greater North Sea by métier level 4 over the 2017-2021 period. Days at Sea (Das) refers to observed effort while coverage (not always available) refers to the % of days observed respect to total effort.*

Region	*Metier*	*DaS*	*Coverage (%)*	*No. of animals*	*Rate*	*CI5-CI95*
Baltic Sea	GNS	1116	--	30	0.026	0.018-0.034
	GTR	105	--	1	0.009	0-0.028
Greater North Sea	GNS	8170	--	416	0.050	0.046-0.055
	GTR	641	--	11	0.017	0.009-0.026
	SDN	107	--	1	0.009	0-0.028
	OTB	4194	--	1	0.0002	0-0.0007

Whilst the above thresholds are estimated for three porpoise populations, bycatch rates can only be found for two ecoregions. Data presented in previous reports, however, suggest that for the Baltic proper population, the bycatch estimated for 2017 (7 animals) and for the years 2000-2012 (3 animals per year on average) exceed the threshold of 0.7 animals (ICES 2020b).

For the Belts Sea, the average annual bycatch for 2020 was predicted to be 938 (249-3676) porpoises when no pinger was used, and 861 (238-31968) when pingers were used. In both cases, the predicted total bycatch amount was above the sustainable bycatch limits or thresholds (Kindt-Larsen et al. 2023).

For the north Sea, the total number porpoises that were bycaught in 2020 was estimated to be 5929 (95% CI 3176-10739) when including all countries (but believed to be heavily skewed) and 1627 (95% CI 922-3325) when not including the unrepresentative data) (ICES 2021b). The lower estimate of bycatch estimated in the North Sea, 1627 individuals (95% CI 921-3325), only slightly exceeds the threshold while the higher estimate, 5929 individuals (95% CI 3176-10739), exceeds the threshold significantly.

Harbour porpoise in Irish and adjacent waters

Bycatch rates for harbour porpoise for the Celtic Seas Ecoregion can also be found in the latest WGBYC report (ICES 2022d). However, the recent report from the ICES Workshop on Estimation of Mortality of Marine Mammals Due to Bycatch (WKMOMA) gives a more detailed breakdown by OSPAR assessment unit and also gives the corresponding mPBR threshold estimates for those areas (which make up most of Celtic seas Ecoregion) (Fig. 3, Table 5)(ICES 2021b) .

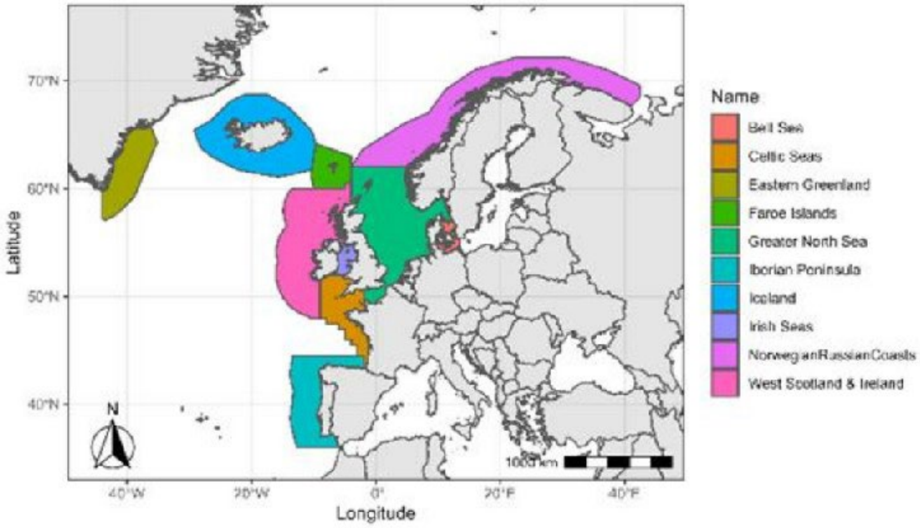

Figure 3: OSPAR assessment units for bycatch of harbour porpoise. From WKMOMA (ICES 2021b).

Table 5. Reported monitoring effort (days at sea, DaS) and bycatch rate (no. of animals per day) for harbour porpoise from 2005 - 2021, as well as the OSPAR mPBR from WKMOMA. Metiers reported are those where bycatch was observed.

Assessment area	*Metier*	*DaS*	*No. of animals*	*Rate*	*OSPAR mPBR threshold*
Celtic seas	GND	332.10	9	0.03	43
	GNS	5271.35	94	0.02	
	GTR	4418.67	83	0.02	
	OTB	11252.86	5	0.0004	
	OTT	6835.26	3	0.0004	
	PTM	1413.05	4	0.003	
Irish Seas	GNS	58.7	1	0.02	34
West of Scotland and Ireland	GNS	641.33	2	0.003	78
	GTR	24	2	0.08	
	OTB	7537.3	1	0.0001	

Readers should be aware that total bycatch estimates (no. of animals) in a given year may be much higher than those in the table above. Bycatch numbers in the table are only those associated with the observed DaS. In the WKMOMA report, bycatch estimates for 2020 are reported and compared to the mPBR. For example, estimated bycatch of harbour porpoises in the Celtic Seas assessment unit for 2020 was 738 (284-2240) animals. The mPBR set by OSPAR for that assessment unit was 43 animals and estimated bycatch is therefore much higher than the threshold.

Pinnipeds

Grey seal in the North Sea

The grey seal *Halichoerus grypus* has a cold temperate to sub-Arctic distribution in North Atlantic waters over the continental shelf (Hall & Russell 2018). In the northeast Atlantic population is concentrated around the UK and Ireland but is also found around Iceland, the Faroe Islands, and along the European mainland coast from the Kola Peninsula south to southern Norway, and from Denmark to Brittany in France. The Baltic Sea subpopulation is confined to the Baltic Sea (Hall & Russell 2018).

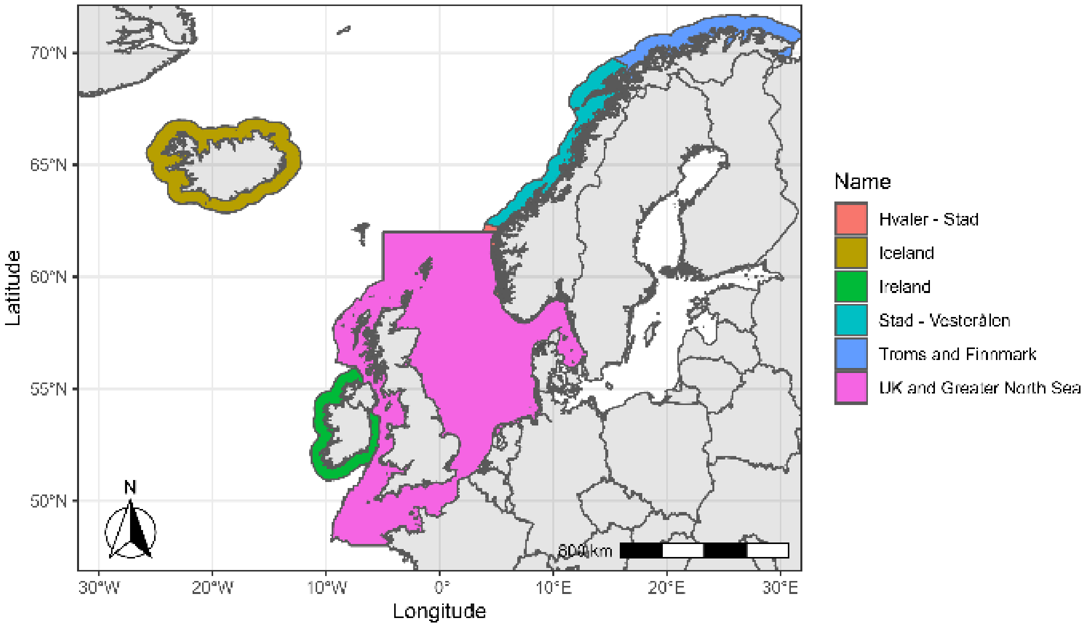

Figure 4: OSPAR assessment units for grey seal. From WKMOMA (ICES 2021b).

For the grey seal several assessment units have been defined (Fig. 4); however, anthropogenic removal thresholds could only be estimated for the Greater North Sea. In this case, conventional PBR was applied, but setting Rmax= 0.12, the default value for pinnipeds (Wade 1998). Unlike with common dolphin and harbor porpoise, Fr=1 was used because grey seals in the Greater North Sea are increasing throughout the region (Bowen 2016). A Fr of 1 has also been used in the UK for setting PBR limits (Thompson et al. 2021) and is justified when populations are well studied and biases in population estimates are negligible or when populations are known to be at optimum level or increasing.

Grey seals are not monitored in a consistent way throughout the North Sea which means deriving Nmin based on the 20th percentile of the best abundance estimate was not feasible. The following approach to calculate Nmin was therefore taken, using a combination of count data:

1) August survey counts scaled to population size from the UK (2016-2019)
2) Moult counts from France, Netherlands and Wadden Sea (2019/2020)

Counts from Belgium, Sweden and Norway were not included in this example; but there are very few seals within the OSPAR region II in these countries. This approach resulted in an Nmin of 126,956 animals (ICES, *in prep*). When applying these values in equation 1, an anthropogenic removal limit of 7,617 individuals was obtained (Table 6).

Table 6. *Bycatch thresholds estimated through PBR approach. Parameters needed to estimate the thresholds are also included as well as the organisms and/or the studies that apply them.*

Species	*Method*	*N*	*Nmin*	*Rmax*	*Fr*	*Threshold*	*Organization*	*Reference*
North Sea	PBR	---	126,956	0.12	1	7617	OSPAR	ICES (2021b)

**Total population estimate was not provided.*

According to the data presented in the latest Working Group on Bycatch of Protected Species for the 2017-2021 period (WGBYC; ICES 2022d), grey seal in the greater North Sea, is caught, although in different rates, in gillnets (GNS) and trammel nets (GTR), midwater otter trawls (OTM), bottom otter trawls (OTB) and beam trawls (TBB) (Table 7).

Bycatch rates for these metiers were estimated using the number of animals recorded bycaught divided by days at sea observed. The number of bycaught animals and days at sea observed were aggregated by ICES Ecoregion and Métier Level 4 (rates based on less than 50 days at sea observed should be taken with caution). Confidence intervals around the bycatch rates were estimated assuming a binomial distribution (ICES 2022d).

Table 7. *Grey seal bycatch rates (no. of animals per day) and 95% confidence intervals around the rates provided for the North Sea by métier level 4 over the 2017-2021 period. Days at Sea (Das) refers to observed effort while coverage (not always available) refers to the % of days observed respect to total effort.*

Ecoregion	**Metier**	**DaS**	**Coverage (%)**	**No. of animals**	**Rate**	**CI5-CI95**
North Sea	GNS	8170	--	11	0.0013	0.0007-0.002
	GTR	641	--	8	0.012	0.006-0.02
	TBB	1526	--	1	0.00065	0-0.0019
	OTB	4194	--	1	0.00023	0-0.00071
	OTM	694	--	23	0.033	0.021-0.044

Note that those bycatch numbers are only associated with the observed DaS. The overall bycatch estimates for grey seal in the Great North Sea assessment unit was 2229 individuals (95% CI 1598-3199) based on bycatch events from 2015-2020 and raised with effort data from 2020 (ICES 2021b).

This estimate is considerably lower than the PBR threshold set by OSPAR of 7617 grey seals in the Great North Sea.

Seabirds

Northern fulmar and Northern gannet in Irish waters

Population estimates of Irish colonies of Northern fulmar *Fulmarus glacialis* and Northern gannet *Morus bassanus* were taken from a reasonably recent National Parks and Wildlife Service (NPWS) report (Cummins et al. 2019). Surveys were conducted between 2015-2018 for fulmar and 2013-2014 for gannet. It should be noted that there have been more recent more recent surveys and results of these are expected to be published later this year. Other sources of seabird population estimates were also considered, primarily those from the ObSERVE report. ObSERVE survey estimates are for offshore seabirds so are likely to be underestimates of population size, however these estimates may be useful in the future if looking at a more specific area (i.e. the specific area coverage of the EWE model) (Rogan et al. 2018).

Life history parameters (adult survival/mortality and age at first breeding) for both species were obtained from two different sources to account for uncertainty in the estimates. The first source was “Birds of the World” by the Cornell Lab of Ornithology (Mallory et al. 2020, Mowbray 2020), with the exception of fulmar age at first breeding (Robinson 2005). The second source was a list of seabird life history parameters collated by (Bird et al. 2020).

The **BLT** is the recommended method from BirdLife International for seabirds and is theoretically the most simple of the two methodologies, where the BLT is 1% of an adult population’s annual mortality, N is the number of the population and m is the annual mortality of adults in the population (BirdLife International 2019).

$$BLT = \frac{Nm}{100} \tag{3}$$

This method is inherently very conservative by design. In their pilot assessment OSPAR propose applying this method to species on the “OSPAR List of Threatened and/or Declining Species and Habitats” (OSPAR Agreement 2008-06) and state that the method is an approximation of zero bycatch, which acknowledges that there will still be a small number of incidental mortalities (Dierschke 2022). Birdlife International justify this approach in a similar context, whilst also stating that threshold values should only be used to determine “Good Environmental Status” and not as a limit to trigger management of the impact of fisheries (BirdLife International 2019).

Table 8. Population estimates, adult mortality estimates and BirdLife International Threshold (BLT) range for two seabird species in Ireland. The BLT range (no. of birds, rounded down to the nearest integer) was calculated using the two differing adult mortality values for each species.

SPECIES	*POPULATION ESTIMATE*	*M (CORNELL)*	*M (BIRD ET AL. 2020)*	*BLT*
FULMAR	65798	0.012	0.03	7 - 19
GANNET	95892	0.08	0.06	57 - 76

PBR is a method that has been commonly used for marine mammals and in many cases seabirds as well. In the case of seabirds, previous studies have defined Nmin as the lower boundary of the breeding population estimate within a 60% confidence interval (Dillingham & Fletcher 2008, Marchowski 2022). In order to estimate Nmin a coefficient of variation is needed for population estimates. These were not available from the NPWS report, however there were brief summaries on the confidence in the estimates (medium for fulmar and high for gannet) within the report and CVs (0.3 for fulmar and 0.1 for gannet) were decided upon based on this.

By changing the level of f used in the PBR formula the user can in theory determine whether to maintain a population at or above the maximum net productivity level or reduce the time to recovery, with 0.1 giving the most conservative threshold (Wade 1998). For a useful summary of factors to take into account when selecting an f value readers should see Dillingham and Fletcher (2008).

Obtaining a value for Rmax can be problematic, however using the relationship with population growth rate (λmax) a value be estimated. Population growth rate (λmax￼￼.

$$\lambda_{max} = e^{\left[\left(\alpha + \frac{s}{\lambda_{max} - s}\right)^{-1}\right]} \tag{4}$$

$$R_{max} =| \lambda_{max} - 1 \tag{5}$$

Equation 4 can be solved numerically to give λmax and in turn R max (equation 5)

Table 9. *Population estimates (N), lower boundary of the breeding population estimate within a 60% confidence interval (Nmin), adult survival (s), age at first breeding (α) and maximum net recruitment rate (Rmax) for Irish colonies of fulmar and gannet. Rmax values were calculated using equations 5 and 6 with s and α values.*

			Cornell			Bird et al. (2020)		
Species								
Fulmar	65798	51419	0.986	9	0.035	0.97	8.5	0.049
Gannet	95892	88185	0.92	5.5	0.098	0.94	4	0.111

Table 10. *Potential Biological Removal (PBR) threshold values for two seabird species in Ireland. PBRs were estimated from two different sources of life history parameters and five levels of recovery factor (f).*

		PBR	
Species	**f**	**Cornell**	**Bird et al. (2020)**
Fulmar	0.1	90	127
	0.2	179	254
	0.3	269	382
	0.4	359	509
	0.5	448	636

Gannet	0.1	434	490
	0.2	867	979
	0.3	1301	1469
	0.4	1735	1959
	0.5	2169	2449

Whilst the above PBR thresholds are estimated for the Irish breeding population of fulmar and gannet, bycatch rates for these two species of seabird can only be found for the wider Celtic Seas ecoregion and not solely Irish waters or the specific area the Celtic Sea EWE model covers (ICES 2022d).

Table 11: *Bycatch rates (no. of animals per day), 95% confidence intervals, observed days at sea (DaS) and observed number of animals as bycatch for each relevant metier for northern fulmar and northern gannet in the Celtic Seas Ecoregion as collated by in the WGBYC 2022 report (ICES, 2022). DaS are round to 2 d.p., rate and C.I.s are to 3 s.f.*

Species	Metier	DaS	No. of animals	Rate	C.I.5	C.I.95
Fulmar	LLS	179.75	12	0.0668	0.0389	0.100
Gannet	LLS	179.75	14	0.0779	0.0445	0.111
	PTB	29.47	2	0.0678	0	0.169
	OTB	3848.74	17	0.00442	0.00286	0.00625
	PTM	332.53	1	0.00301	0	0.00902
	TBB	1091.60	2	0.00183	0	0.00458

Balearic shearwater in the Mediterranean Sea and Western Waters

The Balearic shearwater *Puffinus mauretanicus* is the most threatened seabird in Europe and listed as "Critically Endangered" (Birdlife International 2023). The species breeds exclusively at the Balearic Islands, but migrates to the Northeast Atlantic during the non-breeding season (late spring-early summer) presumably to exploit highly rich productive areas (Pérez-Roda et al. 2017).

For the PBR calculation, we used, as with cetaceans, the 20th percentile of the distribution of population size following Genovart et al. (2016). The population size was estimated based on coastal migrations counts (Arroyo et al. 2016) and ranged between 23780 and 26535 individuals (minimum value was taken here). Rmax = 0.101 (λ_{max}-1) was used and Fr=0.1, conservative value typical for endangered species (Genovart et al. 2016). As a result, a PBR of 101 individuals was obtained (Table 12).

Table 12. Bycatch thresholds estimated through PBR approach. Parameters needed to estimate the thresholds are also included as well as the organisms and/or studies that apply them.

Species	*Method*	*N*	*Nmin*	*Rmax*	*Fr*	*Threshold*	*Organization*	*Reference*
Balearic shearwater	PBR	23780	19965	0.101	0.1	101	--	Genovart et al. (2016)

In the Mediterranean, the species mainly interacts with pelagic longline (LLD) (Genovart et al. 2016); in the Atlantic, acording to the data presented in the latest Working Group on Bycatch of Protected Species for the 2017-2021 period (WGBYC; ICES 2022d), the species is also caught in bottom otter trawls (OTB), gillnets (GNS), trammel nets (GTR) and set longlines (LLS) (Table 13).

Bycatch rates for these metiers were estimated using the number of animals recorded bycaught divided by days at sea observed. The number of bycaught animals and days at sea observed were aggregated by ICES Ecoregion and Métier Level 4. Confidence intervals around the bycatch rates were estimated assuming a Poisson distribution using the function qpois in R. Poisson distribution was selected rather than binomial, after an analysis conducted in 2020 investigating which error distribution was the most suitable for data in the WGBYC database.

Table 13. Balearic shearwater bycatch rates (no. of animals per day) and 95% confidence intervals around the rates provided by métier level 4 for 2017-2021 period (pooled). Days at Sea (Das) refers to observed effort while coverage (not always available) refers to the % of days observed respect to total effort.

Region	*Metier*	*DaS*	*Coverage*	*No. of animals*	*Rate*	*CI5-CI95*
	GTR	1730	--	5	0.002	0.001-0.005

Bay of Biscay and Iberian Coast	GNS	2875	--	4	0.001	0.0003-0.002
	OTB	1637	--	2	0.001	0-0.003
	LLS	364	--	1	0.002	0-0.008
Western Mediterranean Sea	LLD	2110	--	33	0.033	0.021-0.046

Current WKBYC bycatch data, and the fact that bycatch in artisanal fisheries is rarely monitored, do not allow inferring total bycatch numbers from extrapolations of these data (ICES 2022d). However, the estimated bycatch rate of about half of the mortality detected in Genovart et al. (2016) confirms that current fishery impact is unsustainable and that should be reduced urgently to avoid extinction.

Reptiles

Loggerhead turtle in the Mediterranean Sea

The loggerhead turtle *Caretta caretta* is the most abundant sea turtle species in the Mediterranean. It frequents the entire marine area of the Mediterranean, with high occurrence reported in the oceanic zones of the westernmost part of the basin (from the Alboran Sea to the Balearic Islands), the Strait of Sicily, and the Ionian Sea (Casale & Margaritoulis 2010). Its Mediterranean population is recognized as regional management unit, and it is subject to several anthropogenic threats, including incidental capture in fishing gear (Casale 2011), despite being listed as Least Concern by the IUCN.

The size and demographic structure of sea turtle populations are commonly unknown, and until recently, only the number of adult females nesting annually in the Mediterranean had been estimated (Broderick et al. 2002). Under such circumstances, Curtis and Moore (2013) developed the Reproductive Value Loss Limit (RVLL), a maximum bycatch estimation approach which uses reproductive value equivalents in place of the number of individuals.

In the last years, however, new attempts to estimate the population size of sea turtles have arisen, enabling the application of PBR. Casale and Heppell (2016), for example, estimated the population of the Mediterranean loggerhead turtle through a stationary age distribution model. By assuming a sexual maturity age of 21 years, they estimated a population of 1,197,087 (95% CI: 805,658 -1,732,675) individuals for the whole basin. In 2022, DiMatteo et al. (2022) applied species distribution models to the data collected between 2003 and 2018 on aerial and ship surveys, estimating a total abundance of 1,201,845 (CV=0.22; 95% CI: 838,864-1,548,280) turtles.

For the PBR calculation, we have applied the latest abundance estimate (DiMatteo et al. 2022), as it also provides a confidence interval value. As recovery factor, we will assume the default value, which is used when the species is threatened or has unknown status. For the productivity rate we will use the same as in Casale and Heppell (2016) (Table 14).

Table 14. Bycatch thresholds estimated through PBR approach. Parameters needed to estimate the thresholds are also included as well as the organisms/studies that apply them.

Species	*Method*	*N*	*Nmin*	*Rmax*	*Fr*	*Threshold*	*Organization/ Reference*
Loggerhead turtle	PBR	1,201,845	1,003,541	0.064	0.5	16057	Adapted from Casale and Heppell (2016)

According to the data presented in the latest Working Group on Bycatch of Protected Species for the 2017-2021 period (WGBYC; ICES 2022d), loggerhead turtle in the Mediterranean is caught in longlines (LLD), midwater pair trawls (PTM), bottom otter trawls (OTB), otter twin trawls (OTT), trammel nets (GTR) and purse seiners (PS) (Table 15).

Bycatch rates for these metiers were estimated using the number of animals recorded bycaught divided by days at sea observed. The number of bycaught animals and days at sea observed were aggregated by ICES Ecoregion and Métier Level 4 (rates based on less than 50 days at sea observed should be taken with caution). Confidence intervals around the bycatch rates were estimated assuming a Poisson distribution using the function qpois in R. Poisson distribution was selected rather than binomial, after an analysis conducted in 2020 investigating which error distribution was the most suitable for data in the WGBYC database.

Table 15. *Loggerhead turtle bycatch rates (no. of animals per day) and 95% confidence intervals around the rates provided for the Mediterranean basin by métier level 4 for 2017-2021 period (pooled). Days at Sea (Das) refers to observed effort while coverage (not always available) refers to the % of days observed respect to total effort.*

Region	*Metier*	*Das*	*Total effort in days*	*Coverage (%)*	*No. of animals*	*rate*	*CI5-CI95*
Adriatic Sea	LLD	167	2389	6.9	15	0.089	0.053-0.131
Western Mediterranean		2110	24679	8.5	46	0.042	0.029-0.057
Adriatic Sea	PTM	988	10532	9.3	67	0.067	0.054-0.081
Adriatic Sea	OTB	464	130920	0.3	20	0.043	0.028-0.060
Aegean-Levantine Sea		544	--	--	3	0.005	0.001-0.011
Western Mediterranean		2842	301564	0.9	3	0.001	0.0003-0.002
Western Mediterranean	OTT	455	130773	0.3	2	0.004	0-0.010
Aegean-Levantine Sea	GTR	1392	--	--	1	0.0007	0-0.002
Adriatic Sea	PS	362	23601	1.5	21	0.058	0.038-0.080
Ionian Sea and the Central		35	--	--	0	0	0

Note that those bycatch numbers are only associated with the observed DaS. In The Adriatic Sea data from four métiers (PTM, LLD, PS, OTB) were available with reported bycatch of loggerhead turtles but only two of those métiers (LLD and PS) were suitable for calculations of bycatch estimates. The total annual estimate of bycatch in drifting longlines (LLD) was between 129-315 turtles, while the estimate in purse seines (PS) was between 913 -1891 turtles. Therefore, for the Adriatic Sea, the total minimum bycatch for LLD and PS only is between 1042 and 2206 turtles annually (although high bycatch rates for loggerhead turtles are known to occur in OTB and PTM)(ICES 2022d).

In the western Mediterranean three métiers (OTB, LLD, OTT) reported bycatch of loggerhead sea turtles but only two of those métiers (OTB and OTT) were suitable for calculations of bycatch estimates. The estimate for otter bottom trawl (OTB) was between 106-637 turtles annually, while the estimate in otter twin (or multi-rig) trawla (OTT) was between 0 and 1437 turtles. In the Western Mediterranean, therefore, the total minimum bycatch estimate is between 106 and 2074 turtles annually(ICES 2022d). By summing both estimates, the total amount of bycaught turtles would be between 1148-4280.

Fish

Spurdog in Northeast Atlantic and adjacent waters

The Spurdog *Squalus acanthias* has a cosmopolitan distribution in boreal and temperate waters of the Atlantic and Pacific Oceans. In the Northeast Atlantic, spurdog is distributed widely in shelf seas and occurs from Iceland and the Barents Sea southwards to Northwest Africa and the Mediterranean Sea, although it is most common north of the Bay of Biscay (Ebert et al. 2013).

They are a slow-growing, late-maturing species, and have low fecundity (Hammond & Ellis 2004). These K-strategy life history traits, along with this species' high susceptibility to fishing gear make the spurdog highly vulnerable to overfishing (McCully et al. 2013). This vulnerability has been demonstrated in the Northeast Atlantic, where spurdog biomass has declined by more than 90% due to commercial fishing (Hammond & Ellis 2004). This magnitude of depletion was used to list it as "Critically Engandered" according to the Red List criteria of the International Union for Conservation of Nature (IUCN), although current estimates of depletion suggest an IUCN listing of "Endangered"(De Oliveira et al. 2013).

Spatial management of the remaining NE Atlantic population has been hampered because spurdog is generally considered a highly mobile species, and this population is thought to be a single, large, stock unit, undertaking large-scale seasonal movements (Vince 1991). In 2021 the stock of the Northeast Atlantic and adjacent waters (subareas 1-10,12 and 14) was benchmarked (ICES 2021a). There was a substantial improvement in data available for the stock assessment and improved catch information since 2005 (ICES 2022b).

Table 16. Maximum catches of spurdog that should not be exceeded for 2023 and 2024 when the MSY approach is applied, as well as the organization/studies that apply or recommend this approach.

SPECIES	*METHOD*	*YEAR*	*THRESHOLD*	*ORGANIZATION*	*REFERENCE*
SPURDOG	MSY	2023	17353	ICES	ICES (2022b)
	MSY	2024	17855		

ICES advice suggest that when the MSY approach is applied, catches in 2023 and 2024 should be no more than 17 353 tonnes and 17 855 tonnes, respectively (Table 16) (ICES 2022b). In 2021, 1178 tonnes of spurdog were caught (Table 17); 639 tonnes were discards, while 539 tonnes were landings, coming from nets mainly (ICES 2022b). Currently, fishing pressure on the stock is below HR_{MSY}, and spawning-stock size is above MSY $B_{trigger}$, B_{pa}, and B_{lim} (ICES 2022b).

Table 17. Spurdog catch distribution by fleet in 2021 as estimated by ICES for the Northeast Atlantic

Total catch	Landings				Discards
1178 tonnes	Nets 88%	Bottom trawl 5%	Hooks and lines 6%	Other gears 1%	639 tonnes
	539 tonnes				

Bycatch rates are only available for greater North Sea (within the Northeast Atlantic), and only for one metier in latest Working Group on Bycatch of Protected Species (Table 18) (WGBYC; ICES

2022d). Because data on fish species were not consistently submitted to WGBYC in previous years, only 2021 data were used for fish of bycatch relevance (ICES 2022d). That is why days at sea (Das) are so low. Furthermore, rates based on less than 50 days at sea observed should be avoided or at least taken with caution (ICES 2022d).

Table 18. *Spurdog bycatch rates (no. of animals per day) and 95% confidence intervals around the rates provided by métier level 4 for 2021. Days at Sea (Das) refers to observed effort while coverage (not always available) refers to the % of days observed respect to total effort.*

Region	*Metier*	*Das*	*Coverage*	*No. of animals*	*rate*	*CI5-CI95*
Greater North Sea	GNS	29	--	3	0.103	0.034-0.206

Additional bycatch rates, with a higher number of observed days, can be found in the Working Group on Bycatch of Protected Species of 2020 (ICES 2020a), although these are provided by metier 3 and ICES area (Table 19).

Table 19. *Spurdog bycatch rates (no. of animals per day) derived from the ICES WGBYC data call for 2018 data. Numbers are provided by métier level 3, region and ICES area. Days at Sea (Das) refers to observed effort while coverage refers to the % of days observed respect to total effort. When rates for more than one metier are given in the same region, mean rate is also provided.*

Region	*ICES Area*	*Metier 3*	*Das*	*Total effort in days*	*Coverage (%)*	*No. of animals*	*Rate*	*Mean rate*
Bay of Biscay and Iberian Coast	27.8.a	Bottom trawls	581.48	22051	2.63	4	0.007	-
	27.8.a	Nets	145.86	10421.11	1.39	3	0.021	0.013±0.010
	27.8.b	Nets	172.34	7279.98	2.36	1	0.006	
Celtic Sea	27.6.a	Bottom trawls	259.15	23117.75	1.12	102	0.212	0.357±0.722
	27.7.a	Bottom trawls	339.43	15029.09	2.26	619	1.824	
	27.7.f	Bottom trawls	120.87	11138.26	1.08	2	0.017	
	27.7.h	Bottom trawls	860.62	11591.21	7.42	25	0.029	
	27.7.g	Bottom trawls	477.18	24146.81	1.98	84	0.176	
	27.7.j	Bottom trawls	312.84	11512.01	2.72	14	0.045	

	27.6.a	Longlines	49	2805.17	1.75	2	0.041	-
	27.6.a	Pelagic trawls	124	2300.53	5.39	3	0.024	-
	27.7.a	Nets	5	353.19	1.41	7	1.4	1.802±2.467
	27.7.f	Nets	66	2695.08	2.45	17	0.258	
	27.7.g	Nets	63	2302.47	2.73	423	1.27	
	27.7.h	Nets	29.58	1168.51	2.53	180	6.08	
	27.7.j	Nets	175	3200.80	5.47	1	0.006	
Greater North Sea	27.4.a	Bottom trawls	347.95	41430.55	0.83	3	0.009	0.014±0.009
	27.7.d	Bottom trawls	217.46	28150.30	0.77	2	0.009	
	27.7.e	Bottom trawls	439.13	31665.05	1.38	37	0.025	
	27.4.a	Longlines	58	4955.80	1.17	1	0.017	0.285±0.341
	27.4.c	Longlines	2	259.31	0.77	1	0.50	
	27.4.a	Pelagic trawls	68	2022.07	3.36	13	0.191	-
	27.7.e	Nets	164.52	11442.16	1.44	758	1.629	-

Undulate rate in English Channel

The members of the Superorder Batoidea are widely distributed throughout the Northeast Atlantic Ocean and the Mediterranean Sea (Ebert & Dando 2020) and are exploited by commercial fisheries as target and by-catch species. Generally recognized as K-selected species, they are characterized by slow growth, late sexual maturity, low fecundity and long life, limiting their population's capacity to recover from overfishing (Villagra et al. 2022).

Among the rays fished in European waters, the undulate ray *Raja undulata* is of major concern given its current high discard rate in most northeast Atlantic commercial coastal fisheries. In fact, it is listed as "Endangered" according to the Red List criteria of the International Union for Conservation of Nature (IUCN). Fishing of this species was first prohibited in December 2009 (EC 43/2009) before being assigned a zero total allowable catch (TAC) in December 2013. A small TAC (25 t) for undulate ray was introduced in ICES Division 8 in 2015 and increased to 30 t in 2018 (Morfin et al. 2019).

In 2022, the stock was benchmarked for English Channel (divisions 7d-e) (ICES 2022a). Whereas total biomass was considered during the benchmark, ICES assessment and advice is based only on exploitable biomass (individuals ≥ 50 cm total length)(ICES 2022c).

For this stock, ICES advises that when the MSY approach is applied, landings in 2023 and 2024 should be no more than 4836 and 4675 tonnes respectively (Table 20).

Table 20 Maximum catches of undulate ray that should not be exceeded for 2023 and 2024 for undulate ray when the MSY approach is applied, as well as the organization/studies that apply or recommend this approach.

SPECIES	*METHOD*	*YEAR*	*THRESHOLD*	*ORGANIZATION*	*REFERENCE*
UNDULATE RAY	MSY	2023	4836	ICES	ICES (2022c)
	MSY	2024	4675		

In 2021, 2959 tonnes of undulate ray were caught (Table 21); a small part, 205 tonnes, were landings that come from bottom trawls and nets mainly, while the biggest part, 2754 tonnes, were discards (ICES 2022c). In this species, acoustic tracking revealed that at least the 49% of the rays survived discarding (Morfin et al. 2019). Currently, fishing pressure on the stock is below HR_{MSY}, and spawning-stock size is above MSY $B_{trigger}$, B_{pa}, and B_{lim} (ICES 2022c).

Table 21. Undulate ray catch distribution by fleet in 2021 as estimated by ICES for English Channel

Total catch	Landings					Discards
2959 tonnes	Beam trawl 6%	Bottom trawl 56%	Nets 28%	Lines 1%	Other gears 1%	2754 tonnes
	205 tonnes					

Bycatch rates are only available for greater North Sea in in latest Working Group on Bycatch of Protected Species (Table 22) (WGBYC; ICES 2022d). Because data on fish species were not consistently submitted to WGBYC in previous years, only 2021 data were used for fish of bycatch relevance (ICES 2022d). That is why days at sea (Das) are so low. Furthermore, rates based on less than 50 days at sea observed should be avoid or at least taken with caution (ICES 2022d).

Table 22. *Undulate ray bycatch rates (no. of animals per day) and 95% confidence intervals around the rates provided for the Mediterranean basin by métier level 4 for 2021. Days at Sea (Das) refers to observed effort while coverage (not always available) refers to the % of days observed respect to total effort.*

Region	*Metier*	*Das*	*Coverage*	*No. of animals*	*rate*	*CI5-CI95*
Greater North Sea	GTR	13	--	55	4.230	3.307-5.153
	TBB	95	--	48	0.506	0.390-0.633
	GNS	27	--	11	0.407	0.222-0.629

Additional bycatch rates, with a higher number of observed days, can be found in the Working Group on Bycatch of Protected Species of 2020 (ICES 2020a), although these are provided by metier 3 and ICES area (Table 23).

Table 23. *Undulate ray bycatch rates (no. of animals per day) derived from the ICES WGBYC data call for 2018 data. Numbers are provided by métier level 3, region and ICES area. Days at Sea (Das) refers to observed effort while coverage refers to the % of days observed respect to total effort. When rates for more than one metier are given in the same region, mean rate is also provided.*

Region	*ICES Area*	*Metier 3*	*Das*	*Total effort in days*	*Coverage (%)*	*No. of animals*	*Rate*	*Mean rate*
Bay of Biscay and Iberian Coast	27.8.a	Bottom trawls	581.48	22051	2.63	37	0.064	0.125±0.092
	27.8.b	Bottom trawls	41.88	10759.01	0.39	11	0.263	
	27.8.c	Bottom trawls	94	11049.86	0.85	7	0.074	
	27.9.a	Bottom trawls	149	50861.49	0.29	15	0.101	
	27.8.a	Nets	145.86	10421.11	1.39	64	0.439	0.916±0.674
	27.8.b	Nets	172.34	7279.98	2.36	240	1.393	
	27.8.b	Longlines	11.63	2813.75	0.41	3	0.258	-
Celtic Sea	27.7.f	Nets	66	2695.08	2.45	1	0.015	0.126±0.156

	27.7.h	Nets	29.58	1168.51	2.53	7	0.237	
	27.7.h	Bottom trawls	860.62	11591.21	7.42	2	0.002	-
Greater North Sea	27.7.d	Bottom trawls	217.46	28150.30	0.77	69	0.317	0.235±0.115
	27.7.e	Bottom trawls	439.13	31665.05	1.38	67	0.153	
	27.7.d	Nets	131	11816.96	1.11	129	0.985	0.510±0.671
	27.7.e	Nets	164.52	11442.16	1.44	6	0.036	
	27.7.d	Pelagic trawls	55.81	1006.72	5.54	24	0.430	0.232±0.185
	27.7.d	Seines	9.78	3365.50	0.29	2	0.205	
	27.7.e	Dredges	16	10038.48	0.16	1	0.063	

Longnose spurdod in the Mediterranean

The longnose spurdog, *Squalus blainville* is a demersal shark inhabiting depths to about 700 m, extending from tropical to temperate waters of the Atlantic, Pacific, and Indian Oceans, including the Mediterranean and the Black Sea (Compagno et al. 2005). In the Mediterranean Sea, *S. blainville* is a usually taken as bycatch in bottom trawling and long line vessels, and then marketed for human consumption; however official records of its landings are not available. Indeed, the IUCN categorizes it as Data Deficient (DD) (Dulvy et al. 2016), because of the paucity of information regarding the abundance, distribution and biological traits of the species. However, there is growing concern over the extent of shark catches in the Mediterranean, as their K-selected life-history characteristics make them intrinsically vulnerable to fishing pressure (Dulvy et al. 2016). The longnose spurdog presents a low growth rate and a long life span (> 10 years) (Marouani et al. 2012, Kousteni & Megalofonou 2015), low fecundity and great length at first maturity (Kousteni & Megalofonou 2011, Marouani et al. 2012, Anastasopoulou et al. 2017, Donnaloia et al. 2022)

The size and demographic structure of longnose spurdog populations are poorly known. Thus, to estimate the population size we used the MEDITS survey density index (Spedicato et al. 2019) from data collected within 11 years (2009-2019) in South Adriatic Sea (GSA18, Fig. 5), and between 2014 and 2021 in the eastern Ionian Sea (GSA20, Fig. 6). In GSA 18 the last two years were excluded because in those surveys the areas (east part of South Adriatic) where this species is more present were not sampled. In order to obtain the number of longnose spurdog population in each area, the average density index was estimated. In GSA18, the average density index was 5.38 ind/km^2 and the average population size 156,075 shark specimens. In GSA20, the average index was calculated based on the hauls (presence and absence in the area) for a total of 6 years of surveys. The estimation was 38.04 ind/km^2 and the population size 639,948 individuals (Table 24).

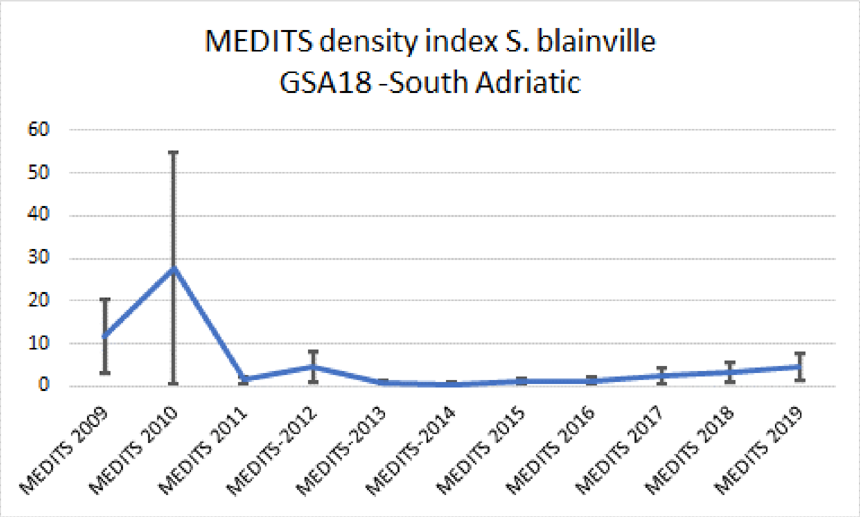

Figure 5 – Medits survey density index for S. blainville in south Adriatic Sea (GSA 18)

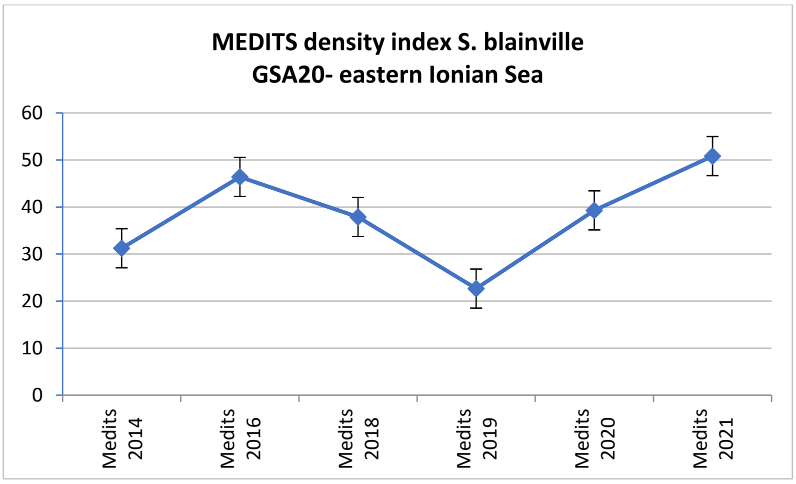

Figure 6 – Medits survey density index for S. blainville in the eastern Ionian Sea (GSA 20)

For the PBR calculation, we applied the mean abundance estimation per year considering the 20th percentile of the 11 years in GSA18 (Nmin= 33,564), whereas the hauls were taken into account for 6 years in GSA20 (Nmin= 525,275). As a recovery factor, Fr was set at 0.5 as default, which is used for threatened species or with unknown status. For the productivity rate (*Rmax*) we used the average value calculated for another species of the same genus (*Squalus acanthias*), from two areas of the Atlantic Ocean (Cortés 2016) (Table 24).

Table 24. *Bycatch thresholds estimated through PBR approach. Parameters needed to estimate the thresholds are also included as well as the organisms and/or studies that apply them.*

Species/Population	*Method*	*N*	*Nmin*	*Rmax*	*Fr*	*Threshold*	*Organization*
Longnose spurdog GSA 18	PBR	156,075	33,564	0.057	0.5	478	--
Longnose spurdog GSA 20	PBR	639,948	525,275	0.057	0.5	7,485	--

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9. Document Information

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Deliverable	N°	D6.7	Title	Consistency of existing targets and limits for indicators in an ecosystem context
Work Package	N°	6	Title	Evaluation of fisheries management strategies in an ecosystem context
Work Package Leader	Dorleta García			
Work Participants	Kempf, A., Taylor, M., Kühn, B., Brown, E., Trijoulet, V., Vinther, M., Girardin, R., Savina-Rolland, M., Lehuta, S., Halouani, G., Robert, M., Woillez, M., Mahevas, S., Travers, M., Andres, M., Garcia, D., Ibaibarriaga, L., Sánchez-Maroño, S., Astarloa Diaz, A., Batts, L., Reid, D., Bitetto, I., Spedicato, M.-T., Romagnoni, G., Giannoulaki, M., Sgardeli, V., Tsoukali, S., Liontakis, A., Vassilopoulou, C., Millar, S., Depestele, J., van Hoey, G., Piet, G., Hamon, K., Kraan, M., Smout. S., Ransijn, J., Thorpe, R., Lynam, C., Bluemel, J., Voss, R., Ojaveer, H., Hommik, K., Melia, P., Gascuel, D., Potier, M., Ustups, D., Plikss, M., Heath, M., Poos, J.-J., Binch, L., and Rindorf, A.			

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