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

EASME/EMFF/2020/3.2.6 - Lot1/SC07

EASME/EMFF/2020/3.2.6 - Lot2/SC08

Final Report

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LIST OF ABBREVIATIONS

Term	Description
AER	Annual Economic Report
AMO	Atlantic Multidecadal Oscillation
AMOC	Atlantic Meridional Overturning Circulation
BER	Break-even Revenue Ratio
BFT	Bluefin Tuna
Blim	Limit Biomass
B_{MSY}	Biomass Maximum Sustainable Yield
$B_{trigger}$	Biomass Trigger (Value of spawning stock biomass (SSB) that triggers a specific management action)
CFP	Common Fisheries Policy
CINEA	European Climate, Infrastructure and Environment Executive Agency
CPUE	Catch Per Unit Effort
CPUF	Catch Per Unit Fuel
CV	Coefficient of Variation
DCF/DCR	Data Collection Framework / Data Collection Rules
DFN	Drift/Fixed Net
DG MARE	Directorate General Maritime Affairs and Fisheries
DRB	Dredges
DTS	Demersal Trawl and Seines
ECA	Emission Control Area
EEOI	Energy Efficiency Operational Index
EEZ	Exclusive Economic Zone
EFF	European Fisheries Fund
EFTP	European Fishing Technology Platform
EKE	Eddy Kinetic Energy
EMFAF	European Maritime Fisheries and Aquaculture Fund
EMFF	European Maritime and Fisheries Fund
EwE	Ecopath with Ecosim
F	Fishing Mortality
FAD	Fish Aggregating Device
FAO	Food and Agriculture Organization of the United Nations
FDI	Fisheries Dependent Information
FLBEIA	Bio-Economic Impact Assessment using FLR
FLR	Fisheries Library in R
FMSY	Maximum rate of fishing mortality
FPO	Pots and Traps
FUI	Fuel Use Intensity
GAM	Generalised Additive Modelling

Term	Description
GCFM	General Fisheries Commission for the Mediterranean
GCM	Global Climate Models
GES	Good Environmental Status
GHG	Greenhouse Gas
GLM	General Linear Model
GSA	Geographic Sub-area
GVA	Gross Added Value
HCR	Harvest Control Rule
HOK	Hooks
ICCAT	International Commission for the Conservation of Atlantic Tunas
ICEEF	Information Collection on Energy Efficiency for Fisheries
ICES	International Council for the Exploration of the Sea
ICES WKREF	ICES Report of the Workshop on Limit and Target Reference Points
ICESJMS	ICES Journal of Marine Science
ICV	Interannual Catch Variability
IEA	Integrated Ecosystem Assessment
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre
LO	Landing Obligation
LPUE	Landings Per Unit Effort
M	Natural Mortality
MARPOL	International Convention for the Prevention of Pollution from Ships
MEPC	Marine Environment Protection Committee
MGO	Mobile Gears Others
MGP	Multiple Passive Gears
MICE	Models of Intermediate Complexity for Ecosystem
MLD	Mixed Layer Depth
MPI-ESM	Max Planck Institute Earth System Model
MPIOM	Max Planck Institute Ocean Model
MSE	Maximum Strategy Evaluation
MSVPA	Multispecies Virtual Population Analysis
MSY	Maximum Sustainable Yield
M_{SY} $B_{trigger}$	Maximum Sustainable Yield Biomass Trigger (The lower bound of spawning-stock biomass fluctuation when fished at the maximum rate of fishing mortality)
NAOw	North Atlantic Oscillation Winter Index
NEA	Northeast Atlantic
NLD	The Netherlands
NOSCCA	North Sea Region Climate Change Assessment
NoV	Number of Active Vessels

Term	Description
NOx	Nitrogen Oxides
NPM	Net Profit Margin
NPV	Net Present Value
NVA/FTE	Net Value Added Per Full-Time Equivalent
PCA	Principal Component Analysis
PG	Passive Gears
PGO	Passive Gears Others
PGP	Multiple Passive Gears
PMP	Multiple Passive and Mobile Gears
PP	Primary Productivity
PS	Purse Seine
PSU	Practical Salinity Unit
RCP	Representative Concentration Pathway
RFMO	Regional Fisheries Management Organisation
RMSE	Root Mean Square Error
RoFTA	Return on Fixed Tangible Assets
SAM	Stock Assessment Model
SDG	Sustainable Development Goal
SEEMP	Ship Energy Efficiency Management Plan
SMHI	Swedish Meteorological and Hydrological Institute
SOx	Sulphur Oxides
SRR	Stock-recruitment Relationship
SSB	Spawning Stock Biomass
SST	Sea Surface Temperature
STECF	Scientific, Technical and Economic Committee for Fisheries
TAC	Total Allowable Catch
TBB	Beam Trawl
VBGF	von Bertalanffy Growth Function
VMS	Vessel Monitoring System
VPUF	Value Per Unit Fuel
VUR	Vessel Utilisation Ratio
WCPFC	Western and Central Pacific Fisheries Commission
WeMO	Western Mediterranean Oscillation
WGBFAS	Baltic Fisheries Assessment Working Group
WGIAB	Working Group on Integrated Assessments of the Baltic Sea
WGMIXFISH	Working Group on Mixed Fisheries
WGSAM	Working Group on Multispecies Assessment Methods
WKFISHDISH	Report of the Working Group on Fish Distribution Shifts
YFT	Yellowfin Tuna

ABSTRACT

This study has shown that the EU fisheries assessed here are resilient to the impact of climate-driven short-term stresses, provided that the management of such fisheries is based on sound scientific advice. Resilience to long term-trends in climate change can be improved by flexible, adaptive management. Managing fisheries at Maximum Sustainable Yield with fishing mortalities set in the lower range when stocks are affected by short-term stress reduces the impact on the exploited stocks and buffer against risks. Non-compliance with quotas with higher than intended fishing mortality combined with climate change effects pushes the stocks levels outside levels that safeguard the reproductive capability of the stock. The role of species interactions in the ecosystem is an important predictor of resilience, though marine populations almost always return to an initial state and not to a new equilibrium as long as no significant changes would affect the biological features of individual species in the food webs.

At the fleet level, bioeconomic models showed that using flexible management with lower than Maximum Sustainable Yield targets improves stock resilience, at the cost of reducing catch in the short term. A high resource resilience would not necessarily lead to fleet resilience nor to the use of less fuel, as other economic factors come into play. The way forward is, therefore, to continue a dynamic, adaptive management to cope with the changing conditions induced by climate change in EU Waters.

Fuel consumption may be affected by stock development and changes in technologies. Collection of high-resolution vessel data may show that fuel use depends on fishing techniques. In parallel, energy-efficient technologies already exist. Implementing them would require improving the uptake of innovations, including demonstrating to stakeholders the potentials for increased catch rates. The transition towards reducing fuel consumption would need to be supported by the setup of EU regulatory instruments.

EXECUTIVE SUMMARY

This specific contract focused on the role of climate change in impacting the sustainability of EU fisheries stocks and the fishing industry that rely on such stocks. Within this, this project modelled the **impact of short-term, climate-driven stress on important EU fish stocks, associated with climate change, and their resilience to 2030** was determined. This study also investigated whether the current management regimes in place were robust to such stresses. The study then attempted to determine **patterns in fuel consumption,** and therefore emissions of greenhouse gases (GHG), between Member State fleets (between years and metiers), to identify the drivers that may influence reduction of fuel use, while also determining how fuel use and **changes in stocks development may impact fuel use intensity (litre fuel consumed per kg landed, FUI) and change in technologies may impact fuel and catch efficiency (fuel or catch per unit effort, CPUE) and possibly contribute to the fuel-use reduction for important EU stocks**. Lastly, the technological changes that may positively impact GHG emissions from the EU fishery fleet were surveyed and discussed, with the most innovative solutions to reducing GHG emissions identified.

Our projections show that recovery to biomass management targets (i.e., maximum sustainable yield (MSY) $B_{trigger}$, B_{MSY}) is **not always achieved by 2030** – in most cases, not because of the shock itself, but because of the adverse long term climate effects of future climate change impeding a full recovery (e.g., for North Sea herring, Baltic Sea and North Sea cod).

We found that **healthy** and **well-assessed stocks are highly resilient.** Stocks in a poor state will suffer from a more extended period at risk even if future prospects are positive. For example, because of their current low levels, North Sea cod and Mediterranean hake will take longer to recover when impacted by a shock.

It is apparent that **resilience to short term shocks is modified by long-term climate effects.** Hence, the long-term climate effects result in **a delay** in stock recovery; for example, for the cod stock to return to safe biological limits. For North Sea herring, for which the implementation of the effect of temperature results in a rapid decline in recruitment level – under Intergovernmental Panel on Climate Change Representative Concentration Pathway (IPCC RCP)4.5 and IPCC RCP8.5 projections – this detrimental effect of climate change acts in conjunction with the effect of the shock to prevent the herring stock from recovering to its initial state. Long-term climate change trend does not appear to significantly affect stock resilience for other North Sea stocks.

The simulation study showed that **short-lived species are more impacted but recover more quickly** if stock recruitment returns to normal. Short-lived species, such as sprat and anchovy (Baltic Sea, North Sea, Black Sea case studies) have a short reaction time to short-term shocks, and the maximum amplitude is often reached the year after the shock. However, this recovery is conditional on the assumptions made in the models regarding how recruitment would return to a regular regime after a shock.

Bioeconomic models showed that **using lower fishing mortality and adaptive management improves resilience** and makes a buffer against shocks **but at the cost of reducing short-term catches**. If using the target Maximum Sustainable Yield fishing mortality (Fmsy) range is permitted in the EU multiannual plans to buffer against the possible losses induced by technical interactions between fleets and biological interactions between stocks, using target fishing mortality in the lower bound (Fmsy_low) is shown to reduce the amplitude of the impact of the climate-driven shock on stocks, thereby leading to a faster recovery. In the case of North Sea herring, using a Fmsy in the lower bound (F_{MSY}_low) management target prevents the stock from going down rapidly and maintains it at a higher level, which reduces the risk of exiting the safe limits. Using Fmsy_low for mackerel cancelled the risk of a Spawning Stock Biomass to go below the Limit Reference Point (SSB<Blim) and significantly increased the recovery rate, which is beneficial for ensuring **long-term economic return from higher catch levels**.

Non-compliance with quotas or not following the advised quotas would usually lead to application of fishing mortality that is higher than intended (i.e., higher than F_{MSY}). Such mismatch would create uncertainties in future stock assessment and would cumulate badly with the climate-induced stress and augment the risk for stocks exiting the safe limits for exploitation.

By testing with best available ecosystem models**, we tested the role of species interactions in the ecosystem.** When accounting for species interactions in the ecosystem, with the ecosystem models deployed for this study and for the short term shock scenarios tested, marine exploited and non-exploited populations almost always return to an initial state and the ecosystem proprieties are not modified on the long term. A short-term shock on the recruitment of a given species generally had little impact on the other species. Heatwave events in the North Sea and the Celtic Sea could lead to instantaneous effects, contrary to shocks affecting reproduction, which cascades through the ecosystem's trophic interactions.

We showed that, as expected, fishing fleets with low profitability will not be resilient to shocks. More importantly, as illustrated by the case study on Dutch flatfish (sole and plaice) or the Baltic Sea fisheries, **a high resource resilience does not necessarily lead to financial resilience, nor to the use of less fuel**. If models include a spatial component, it is shown that fuel consumption could increase over the 10 years because of the change in distribution of the target species (e.g., plaice in the Southern North Sea moving into deeper waters). The Baltic case illustrated that **likely dominating compensatory/rebound effects from stocks in better shape may prevent fuel saving**. If fuel saving occurs, it is possible that more time could be spent at sea or fishing could be redirected towards areas that become attractive when fuel use is less limiting, which are undesirable side-effects.

Climate change is expected to increase the frequency and magnitude of extreme climatic events. This study found **no apparent preparation within the fishing sector for likely climate-induced degradation of infrastructure.** Indeed, responses from ship owners, fishers, gear manufacturers, and producer organisations revealed that these actors had no specific or immediate concern about the potential effects of climate change on their infrastructure.

We assessed that **the current management framework could be challenged to ensure the resilience of EU marine living resources and fisheries.** While changes in the ecosystem are occurring at a grand scale, resource resilience is somewhat at odds with such change. For example, if stock abundance changes at the local level as a result of a geographical redistribution of fish, it is still uncertain how severe this needs to be before current local conservation measures become ineffective. The way forward is to continue to implement the **ecosystem approach to fisheries management** (EAFM) in Europe, to better understand and cope with the changing conditions. This study identifies the need for **enabling a dynamic, adaptive management framework**.

The simulation work conducted in this study indicates that, overall, the **fisheries system is resilient to the impact of climate-driven short-term stress, provided that management has been based on sound advice** and has been followed for the years preceding the shocks. The current management targets should lead to large enough stocks with a diverse age structure, ensuring their resilience to short-term shocks such as recruitment failure or high mortality episodes.

Resilience can also be improved by flexible, adaptive management. Using the F_{MSY} ranges to **decrease fishing mortality when stocks are affected by short-term stress** offers flexibility to reduce the impact on the exploited stocks. This, however, requires that shocks be detected soon enough, either by detecting the environmental anomalies that trigger them (assuming the factors that drive population dynamics are well understood), or by monitoring the earlier reactions of the stock (e.g., through scientific surveys on population recruitment strength).

For the management advice to remain accurate, there is a need for adaptive management to **regularly re-evaluate management and biological reference points** to make sure they are in tune with the current levels of productivity of the stocks. The general practice (e.g. in ICES) is to re-estimate reference points at each benchmark assessments, which generally occur on a five-year cycle. This timescale seems appropriate, as it matches the management system, avoids erratic changes in the designation of stock status, and provides some stability in planning horizons for fisheries. When calculating these reference points, there should be systematic verification that using the agreed management points would allow for stock recovery in case of short-term shock (e.g., a recruitment failure). It is also key **to understand the linkages between stock productivity and climate**, identify changes in productivity and make the correct assumptions for future productivity when estimating reference points.

It is not possible to apply the Data Collection Framework/Data Collection Rules (DCR/DCF) data and draw conclusions on fuel efficiency of the fleet segments at such a high level of data aggregation. This is largely due to high levels of inter-annual variation within each Member State Scientific, Technical and Economic Committee for Fisheries (STECF) Annual Economic Report data, wholly associated with methodological differences in how DCF and DCR data are collected, reducing the likelihood of finding consistent trends in fuel consumption.

Despite these data-related restrictions, we have been able to compare fuel and catch efficiencies of Member States fleets in a few cases. For example, in the case of the Danish fleets and the Dutch flatfish fleet, where more detailed data is available, it is possible to provide information on historical development of fuel and catch efficiencies. Finer national fleet-segmented data can also contribute to the **assessment via the application of bio-economic models to show how these fuel and catch efficiencies may develop**. The flatfish fleet is an example of where analysis of technical improvements was possible. It is shown that the ban on Dutch pulse trawlers has removed some potential for improving fuel efficiency and has proved a missed opportunity to limit adverse effects on bottom habitats in this area because beam trawling with conventional, heavier gear may be more damaging for the seafloor, all other variables being equal (e.g. habitat type visited, deployed effort, and area extent swept).

Fuel use is shown to be highly dependent on the fishing techniques used, some techniques being less fuel intense than other for the same target assemblage of species. Fuel consumption will also depend on a range of factors at the individual vessel level. The most appropriate way of determining fuel consumption, and subsequent systematic analysis, would be via the development of a monitoring system within vessels.

We have identified and listed potential **energy-efficient technologies** based on three categories: (i) technologies to improve vessel structure and on board equipment (‘Vessel’); (ii) strategies to improve the fishing in operation (‘Strategy’); (iii) fishing gear-related technologies to reduce fuel consumption (‘Gear’) completed with the setup of EU regulatory instruments (‘Regulation’). We present in detail a suite of actions undertaken for reducing fuel consumption in Dutch **beam trawl fisheries**. For **otter board trawls and midwater trawls**, the modification of gears to reduce the drag of the nets is one of the most investigated solutions by the stakeholders in fisheries. Hence, improvements include modifying otter trawls with new netting designs, materials and net modifications, modifications for semi-pelagic doors, innovative doors and lighter materials, or efforts to raise the doors from the seabed. If many or most of these modifications are applied to a bottom otter trawl, energy savings of up to 40% and increased catches are possible. We also discuss the feasibility of substitution of single otter trawls with less-fuel-intense types of gear.

We have identified **barriers when implementing energy-efficient solutions**. We found that a limited number of solutions are transferred to the fishing sector from research, likely due to little knowledge transfer on the technologies and because not all proposed solutions in the scientific literature are applicable. It was identified that there might be barriers to innovation uptake, and not all solutions are suitable for all types of fisheries. There is also a lack of collaborative work with and among end users; fishers lack data for developing accurate technological knowledge, for which training courses are needed; skippers may be less concerned than the vessel owner re improving fuel efficiency; investment costs may slow down implementation; new technologies can be ineligible for the current scheme of public funding; and regulations may sometimes limit the opportunities for improvements supported by the EU.

We investigated regulation, management, and market **strategies to boost energy efficiency in the fishing sector**. The CFP includes provisions for EU Member States concerning incentives for energy-efficient vessels. The European Maritime Fisheries and Aquaculture Fund (EMFAF) has financial support for on-board investments for energy efficiency. We list relevant management instruments for reducing fuel-use intensity (the ratio of fuel use to catch volume) including **instruments that would reduce fuel use** (such as taxation based on performance in saving fuel, fuel tax, restricting engine power, restricting gear, improving fish stocks, fish quota systems, increased fuel price, eco-certification, reducing effort, improving skippers' skills, and rewarding skippers for implementing good practice), or, **instruments that would increase catch rates,** reduce bycatch and therefore decrease fuel intensity. We also present a suite of **recommendations** for reducing fisheries' GHG emissions via technical, regulatory and management means, reiterating the need for **fuel monitoring tools on-board vessels** to collect adequately resolved and sufficiently representative data to align research needs with policy ambition.

RÉSUMÉ

Cette étude a montré que les pêcheries de l'UE sont résilientes à l'impact des stress à court terme induits par le climat, à condition que la gestion des pêcheries soit basée sur des avis scientifiques solides. La résilience aux tendances à long terme du changement climatique peut également être améliorée par une gestion flexible et adaptative. L'utilisation de la pression de la pêche au Rendement Maximal Durable (FMSY) pour réduire la mortalité par pêche lorsque les stocks sont affectés par un stress à court terme réduit l'impact sur les stocks exploités. Le non-respect des quotas scientifiquement conseillés avec une mortalité par pêche plus élevée que prévu combiné aux effets du changement climatique, pousse les niveaux des stocks hors des niveaux préservant la capacité de reproduction tout en maximisant le rendement. Les interactions entre les espèces dans l'écosystème est un prédicteur important de la résilience, bien que les populations marines reviennent presque toujours à l´état initial et non à un nouvel équilibre.

Au niveau de la flotte, les modèles bioéconomiques ont montré que l'utilisation d'une gestion adaptative avec des objectifs inférieurs à FMSY améliore la résilience des stocks, au prix d'une réduction des captures à court terme. Une résilience élevée des ressources ne conduirait pas nécessairement à la résilience des flottilles de pêche ni à la moindre utilisation de carburant, car d'autres facteurs économiques entrent en jeu. La voie à suivre consiste donc à poursuivre une gestion dynamique et adaptative des pêcheries pour faire face aux conditions environnementales changeantes induites par le changement climatique dans les eaux de l'UE.

La consommation de carburant peut être affectée par l'évolution des stocks de pêche et l'évolution des technologies. La collecte de données finement détaillées sur les navires démontre que la consommation de carburant dépend des techniques de pêche. En parallèle, des technologies à haute efficacité énergétique existent déjà. Leur mise en œuvre nécessiterait d'améliorer l'adoption des innovations par les parties prenantes, notamment si elles conduisent à de meilleurs taux de capture. La transition vers la réduction de la consommation de carburant devrait être soutenue par la mise en place d'instruments réglementaires de l'UE.

RÉSUMÉ ANALYTIQUE

Ce contrat spécifique a étudié le rôle du changement climatique quant à son impact sur la durabilité des stocks halieutiques de l'UE et sur l'industrie de la pêche qui dépend de ces stocks. Dans ce cadre, ce projet a modélisé **les impacts du stress climatique à court terme sur d'importants stocks halieutiques de l'UE, associés au changement climatique, et la résilience de ces stocks à l´horizon 2030** a été déterminée. Cette étude a également examiné si les mesures de gestion en place étaient robustes à de telles contraintes. L'étude a ensuite tenté de déterminer les **schémas de consommation de carburant**, et donc les émissions de gaz à effet de serre (GES), pour les flottes des États membres (entre les années et les métiers), afin d'identifier les facteurs qui peuvent influencer la réduction de la consommation de carburant, y compris comment l'utilisation de carburant et les **changements dans le développement des stocks peuvent avoir un impact sur l'intensité de l'utilisation de carburant (litre de carburant consommé par kg débarqué, FUI), et comment les changements dans les technologies peuvent avoir un impact sur l'efficacité du carburant et des captures (carburant ou capture par unité d'effort, CPUE) pour éventuellement contribuer à la réduction de la dépense énergétique sur les stocks importants de l'UE.** Enfin, les changements technologiques susceptibles de réduire émissions de GES de la flotte de pêche de l'UE ont été étudiés et discutés, les solutions les plus innovantes pour réduire les émissions de GES ayant été identifiées.

Nos projections montrent que le rétablissement aux objectifs de gestion de la biomasse halieutique (c'est-à-dire, le rendement maximal durable (MSY), le $B_{trigger}$, le B_{MSY}) **n'est pas toujours atteint d'ici 2030** - dans la plupart des cas, non pas à cause du choc lui-même, mais à cause de l'effet négatif à long terme du changement climatique futur qui empêche un rétablissement complet (par exemple, pour le hareng de la mer du Nord, le cabillaud de la mer Baltique et de la mer du Nord).

Nous avons constaté que les stocks **sains** et **bien évalués sont très résilients.** Les stocks en mauvaise santé souffriront d'une période à risque plus longue, même si les perspectives d'avenir sont positives sous le changement climatique. Par exemple, en raison de leurs faibles niveaux actuels, le cabillaud de la mer du Nord et le merlu de la Méditerranée pourraient mettre plus de temps à se rétablir lorsqu'ils seront touchés par un choc.

Il est évident que la **résilience aux chocs à court terme est modifiée par les effets climatiques à long terme.** Par conséquent, les effets climatiques à long terme entraînent un **délai supplémentaire** pour la reconstitution des stocks**, par exemple** pour le retour du stock de cabillaud aux limites biologiques de sécurité. Pour le hareng de la mer du Nord, pour lequel la mise en œuvre de l’effet de la température entraîne une baisse rapide du niveau de recrutement – dans le cadre des projections du Groupe d'experts intergouvernemental sur l'évolution du climat (IPCC RCP)4.5 et RCP8.5 du GIEC – cet effet néfaste du changement climatique agit en conjonction avec l’effet du choc pour empêcher le stock de hareng de retrouver son état initial. La tendance au changement climatique à long terme ne semble pas affecter de manière significative la résilience des autres stocks de la mer du Nord.

Les simulations ont montré que les **espèces à courte durée de vie sont plus touchées mais se rétablissent plus rapidement** si le recrutement des stocks revient à la normale. Les espèces à espérance de vie courte, telles que le sprat et l'anchois (études de cas de la mer Baltique, de la mer du Nord et de la mer Noire) ont un temps de réaction court aux chocs à court terme, et l'amplitude maximale est souvent atteinte l'année suivant le choc. Cependant, cette reprise est conditionnée par les hypothèses énoncées dans les modèles concernant la manière dont le recrutement reviendrait à un régime régulier après un choc.

Les modèles bioéconomiques ont montré que **l’utilisation d’une mortalité par pêche plus faible et d’une gestion adaptative des pêches améliore la résilience** et constitue un tampon contre les chocs**, mais au prix d’une réduction des captures à**

court terme. Si l'utilisation de la fourchette cible de mortalité par pêche à rendement maximal durable (F_{MSY}) est autorisée dans les plans pluriannuels de l'UE pour amortir les pertes éventuelles induites par les interactions techniques entre les flottes et les interactions biologiques entre les stocks, il est démontré que l'utilisation de la taux cibles de mortalité par pêche dans la limite inférieure (F_{MSY}_low) réduit l'amplitude de l'impact du choc climatique sur les stocks, conduisant ainsi à une récupération plus rapide. Dans le cas du hareng de la mer du Nord, l'utilisation d'un objectif de gestion F_{MSY} dans la limite inférieure (F_{MSY}_low) empêche le stock de baisser rapidement et le maintient à un niveau plus élevé, ce qui réduit le risque de sortie des limites de sécurité. L'utilisation de F_{MSY}_low pour le maquereau a annulé le risque que la biomasse du stock reproducteur passe en dessous du point de référence limite (SSB<Blim) et a augmenté de manière significative le taux de récupération, ce qui est bénéfique pour garantir le **retour économique à long terme de niveaux de capture plus élevés**.

Le non-respect des quotas ou le non-respect des quotas conseillés conduirait généralement à l'application d'une mortalité par pêche plus élevée que prévu (c'est-à-dire supérieure à F_{MSY}). Un tel décalage créerait des incertitudes dans l'évaluation future des stocks et se cumulerait mal avec le stress induit par le climat et augmenterait le risque que les stocks sortent des limites de sécurité pour l'exploitation.

En utilisant les meilleurs modèles écosystémiques disponibles, **nous avons testé le rôle des interactions entre espèces au sein de l'écosystème.** Lors de la prise en compte des interactions entre les espèces dans l'écosystème, avec les modèles écosystémiques déployés pour cette étude et pour les scénarios de choc à court terme testés, les populations marines exploitées et non exploitées reviennent presque toujours à un état initial et sans non plus modifier les propriétés de l'écosystème à long terme. Un choc à court terme sur le recrutement d'une espèce donnée n´a généralement que peu d'impact sur les autres espèces. Les épisodes de canicule en mer du Nord et en mer Celtique pourraient avoir des effets instantanés, contrairement aux chocs affectant la reproduction, qui se répercutent le long des interactions trophiques au sein de l'écosystème.

Nous avons montré que, comme prévu, les flottes de pêche à faible rentabilité ne seront pas résilientes aux chocs. Plus important encore, comme l'illustre l'étude de cas sur les poissons plats en Hollande (sole et plie) ou les pêcheries de la mer Baltique, **une résilience élevée des ressources ne conduit pas nécessairement à une résilience financière, ni à la moindre utilisation de carburant.** Si les modèles incluent une composante spatiale, il est démontré que la consommation de carburant pourrait augmenter au cours des 10 années à venir en raison du changement de distribution spatiale des espèces cibles (par exemple, la plie du sud de la mer du Nord se déplaçant vers des eaux plus profondes). Le cas de la Baltique a montré que les **effets compensatoires/de rebond comme la conséquence de stocks en meilleur santé pourrait empêcher les économies de carburant en valeur absolue**. En effet, si des économies de carburant se produisent, il est possible que plus de temps soit passé en mer ou que la pêche soit réorientée vers des zones qui deviennent attrayantes lorsque la consommation de carburant est moins limitative.

Le changement climatique devrait augmenter la fréquence et l'ampleur des événements climatiques extrêmes. Cette étude **n'a trouvé aucune préparation apparente du secteur de la pêche à une probable dégradation des infrastructures induite par le changement climatique.** En effet, les réponses des armateurs, des pêcheurs, des fabricants d'engins de pêche et des organisations de producteurs ont révélé que ces acteurs n'avaient aucune préoccupation spécifique ou immédiate quant aux effets potentiels du changement climatique sur leurs infrastructures.

Nous avons évalué que **le cadre de gestion actuel pourrait être remis en question pour garantir la résilience des ressources marines vivantes et de la pêche de l'UE.** Alors que les changements dans l'écosystème se produisent à grande échelle, la résilience des ressources est quelque peu en contradiction avec l'un et l'autre. Par exemple, si l'abondance des stocks change au niveau local à la suite d'une redistribution géographique des poissons, on ne sait toujours pas quelle doit être l'ampleur de ce changement avant que les mesures actuelles de conservation locales ne deviennent inefficaces. La voie à suivre consiste à poursuivre la mise en œuvre de **l'approche écosystémique de la gestion de la pêche** (EAFM) en Europe, afin de mieux comprendre et de mieux faire face aux conditions changeantes. Cette étude identifie la nécessité de **mettre en place un cadre de gestion dynamique et adaptatif.**

Le travail de simulation effectué dans le cadre de la présente étude indique que, dans **l'ensemble, le système de pêche est résilient à l'impact du** stress à court terme causé par le climat, à **condition que la gestion suive les avis scientifiques** pendant les années précédant les chocs. Les objectifs de gestion des ressources halieutique devraient conduire à des stocks suffisamment importants avec une structure d'âge diversifiée, garantissant leur résilience aux chocs à court terme tels que l'échec du recrutement ou les épisodes de mortalité élevés.

La résilience peut également être améliorée par une gestion flexible et adaptative. L'utilisation des fourchettes de F_{MSY} pour **diminuer la mortalité par pêche lorsque les stocks sont affectés par un stress à court terme** réduit l'impact sur les stocks exploités. Cela exige toutefois que les chocs soient détectés assez tôt, soit en détectant les anomalies environnementales qui les déclenchent (en supposant que les facteurs qui déterminent la dynamique des populations sont bien compris), soit en analysant les réactions passées des stocks à ces anomalies (par exemple, par des enquêtes scientifiques sur la force de recrutement de la population).

Pour que les avis scientifiques restent précis, il est nécessaire de **réévaluer régulièrement les points de référence biologiques et de gestion** pour s'assurer qu'ils sont en phase avec les niveaux actuels de productivité des stocks. La pratique générale (par exemple au CIEM) consiste à réestimer les points de référence sur un cycle de cinq ans. Ce calendrier correspond au système de gestion, évite des changements erratiques dans la désignation de l'état des stocks et offre une certaine stabilité dans les horizons de planification des pêches. Lors du calcul de ces points de référence, il convient de vérifier systématiquement que l'utilisation des points de gestion convenus permettrait la reconstitution du stock en cas de choc à court terme (par exemple, un échec du recrutement). Il est également essentiel **de comprendre les liens entre la productivité des stocks et le climat, d'identifier** les changements de productivité et de faire les hypothèses correctes pour la productivité future lors de l'estimation des points de référence.

Il n'est pas possible d'appliquer les données du Data Collection Framework/Data Collection Rules (DCR/DCF) et de tirer des conclusions sur l'efficacité énergétique des flottilles de pêche européenne à un niveau aussi élevé d'agrégation de données. Cela s'explique en grande partie par les niveaux élevés de variation interannuelle relevées dans le rapport économique annuel du Comité scientifique, technique et économique de la pêche (CSTEP) de chaque État membre, entièrement associées à des différences méthodologiques dans la manière dont les données DCF et DCR sont collectées, ce qui réduit la probabilité de trouver des tendances cohérentes dans la consommation de carburant.

Malgré ces restrictions liées aux données, nous avons pu comparer les États membres dans quelques cas. Par exemple, dans le cas des flottilles danoises et de la flottille néerlandaise ciblant les poissons plats, où des données plus détaillées sont disponibles, il est possible de fournir des informations sur l'évolution historique de l'efficacité énergétique. Des données nationales plus fines par flottille peuvent également contribuer à l'**évaluation, au sein de modèles bioéconomiques, et montrer comment ce rendement énergétique pourrait évoluer**. La flottille ciblant les poissons plats en Mer du Nord est un exemple où l'analyse des améliorations techniques a été possible. Il est démontré que l'interdiction des chalutiers électriques a éliminé certaines possibilités d'amélioration de l'efficacité énergétique et s'est avérée une occasion manquée dans la limitation des effets néfastes du chalutage sur les habitats de fond dans cette zone, vu que le chalutage à perche avec des engins conventionnels plus lourds peut être plus dommageable pour le fond marin, toutes les autres variables étant égales (par exemple, le type d’habitat visité, l’effort déployé et l’étendue de la zone balayée).

L'utilisation de carburant s'avère fortement dépendante des techniques de pêche utilisées, certaines techniques étant moins gourmandes en carburant que d'autres pour le même assemblage cible d'espèces. La consommation de carburant dépend également d'une série de facteurs à l´échelle du bateau. La manière la plus appropriée de déterminer la consommation de carburant, et de procéder à une analyse systématique ultérieure, sera d´équiper les bateaux de pêche avec un système de mesure de consommation à bord.

L´étude identifie et répertorie les **technologies** potentielles d'**efficacité énergétique** en se basant sur trois catégories : (i) les technologies visant à améliorer la structure du navire et l'équipement à bord ("Bateau") ; (ii) les stratégies visant à améliorer la pêche en cours d'opération ("Stratégie") ; (iii) les technologies liées aux engins de pêche visant à réduire la consommation de carburant ("Engin") complétées par la mise en place d'instruments réglementaires de l'UE ("Règlement"). Nous présentons en détail une série d'actions entreprises pour réduire la consommation de carburant dans **les pêcheries néerlandaises au chalut à perche**. Pour **les chaluts à panneaux et les chaluts pélagiques**, la modification des engins pour réduire la traînée des filets est l'une des solutions les plus étudiées par les acteurs de la pêche. Par conséquent, les améliorations comprennent la modification des chaluts à panneaux avec de nouveaux modèles de filets, des matériaux et des modifications de filets, des modifications pour les panneaux semi-pélagiques, des panneaux innovantes et des matériaux plus légers, ou des efforts pour soulever les panneaux du fond marin. Des économies d’énergie allant jusqu’à 40 % et une augmentation des captures est possible si un grand nombre ou la plupart de ces modifications sont appliquées à un chalut de fond. Nous discutons également de la possibilité de remplacer les chaluts à panneaux simples par des types d'engins consommant moins de carburant.

La présente étude identifie des **obstacles lors de la mise en œuvre de solutions écoénergétiques**. Nous avons constaté qu'un nombre limité de solutions sont transférées au secteur de la pêche à partir de la Recherche scientifique, probablement en raison du manque de transfert de connaissances sur ces technologies ou lorsque certaines solutions proposées ne sont pas viables ou adaptées à tous les types de pêche. Il y a également un manque de collaboration avec et entre les utilisateurs finaux ; les pêcheurs manquent de données pour développer des connaissances technologiques précises, pour lesquelles des formations sont nécessaires ; les capitaines peuvent être moins concernés que le propriétaire du bateau pour l'amélioration de l'efficacité énergétique ; les coûts d'investissement et de conversion peuvent ralentir la mise en œuvre ; les nouvelles technologies peuvent être inéligibles au système actuel de financement public ; et les réglementations soutenues par l'UE peuvent parfois limiter les possibilités d'améliorations.

L´étude rappelle la réglementation, la gestion et les **stratégies de marché actuelles pour stimuler l'efficacité énergétique dans le secteur de la pêche**. La Politique Commune des Pêches de l´UE comprend des dispositions destinées aux États membres de l’UE concernant les incitations en faveur des navires économes en énergie. Le Fonds européen pour les affaires maritimes, la pêche et l'aquaculture (FEAMP) bénéficie d’un soutien financier pour les investissements à bord en faveur de l’efficacité énergétique. Nous énumérons les instruments de gestion pertinents pour réduire l'intensité de l'utilisation de carburant (le rapport entre l'utilisation de carburant et le volume des captures), y compris les **instruments qui réduiraient l'utilisation de carburant** (tels que la taxation basée sur les performances en matière d'économie de carburant, la taxe sur le carburant, la limitation de la puissance des moteurs, l'amélioration des stocks halieutiques, les systèmes de quotas, l'augmentation du prix du carburant, l'écocertification, la réduction de l'effort de pêche, l'amélioration des compétences des capitaines de navire et l´incitation au déploiement des bonnes pratiques en matière énergétique), ou les **instruments qui augmenteraient les taux de capture,** réduiraient les prises accessoires et diminueraient donc l'intensité de l'utilisation de carburant. Nous présentons également une série de recommandations visant à réduire les **émissions** de GES du secteur de la pêche par des moyens techniques, réglementaires et de gestion, réitérant la nécessité de **disposer d’outils de surveillance et de mesure de la consommation du carburant à bord des navires** pour recueillir des données suffisamment fines et représentatives pour aligner les besoins de la recherche scientifique à l’ambition politique.

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1 INTRODUCTION

This study evaluates opportunities for reducing the carbon footprint of the marine wild capture sector managed under the current Common Fisheries Policy (CFP), while maintaining the viability, sustainability and resilience of this sector in face of climate change as a stress factor acting on the European Union (EU) fishing system. This work is vital as large environmental change adds to ecosystem variability and fishing impacts on the marine ecosystems, weakening marine ecosystem productivity and ultimately impacting fishing opportunities or affecting their spatial distributions. The work takes place in the context of an increasingly changing global environment, for which there is a need to understand the energy dependence, and therefore emission of carbon dioxide (CO_2) of EU fisheries.

Within this contract, a literature review and simulation studies have been used to get a good understanding of the climate effects on fisheries and identify opportunities to reverse possible declining trends in fisheries stocks induced by ongoing large-scale climate change, including the potential risk of short-term climate-change-induced stresses on such stocks. This work benefits from insights obtained by applying fit-for-purpose state-of-the-art fisheries simulation studies to document the likely future impacts of climate change, and the performance and robustness of fishing strategies to resist stress under the current CFP management. Here, the study evaluated the preparedness of fisheries to resource, ecosystem, fishing-related infrastructure and financial/economic shocks. Included in our evaluation is how the development and use of fuel-efficient practices and low impact fishing, in coherence with environmental policies and environmental targets on reduction of CO_2 emission, may further improve the sustainability of EU fisheries.

In a first part, the study assessed the resilience of the fisheries systems as a series of seven regional case studies[1] to short-term, climate-driven stress, and investigates whether the current management regimes in place are robust to such stresses. The study first collated knowledge in understanding the environmental drivers that influence the development of important European commercial fisheries. The aim was to identify robust relationships that could form the basis to formulate assumptions in assessing long-term trends in stock viability, while also understanding the impacts of climate-induced short-term shocks on stocks. This knowledge was key to enable the design of plausible scenarios for understanding future stock trends under the current management framework. Secondly, simulation studies have been carried out to evaluate the resilience of the resource, the ecosystems, and the fishing sector to long-term change and climate-induced stress or anomalies.

Long term climatic changes were covered with a "most likely" and "worst-case" scenarios based on the assumption that future climate change would conform with the IPCC scenarios RCP 4.5 and RCP 8.5, while the "worst case" also included short-term environmentally driven stresses induced by climate change. Management options included those applying TAC setting rules within the range allowed under the EU CFP multiannual management plans (EU-MAPs)[2], in place for demersal mixed fisheries in the North Sea, Baltic Sea and Celtic Sea (including Atlantic EU western waters). For the International Commission for the Conservation of Atlantic Tunas (ICCAT), which provide management advice for tropical tuna being examined in the EU Atlantic western waters, advice is based on the Kobe

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[1] Case studies within the Baltic Sea, North Sea, EU Atlantic western waters and EU Outermost Regions, and within the Mediterranean Sea and the Black Sea.

[2] Regulation (EU) 2019/472 of the European Parliament and of the Council of 19 March 2019 establishing a multiannual plan for stocks fished in the Western Waters and adjacent waters, and for fisheries exploiting those stocks, amending Regulations (EU) 2016/1139 and (EU) 2018/973, and repealing Council Regulations (EC) No 811/2004, (EC) No 2166/2005, (EC) No 388/2006, (EC) No 509/2007 and (EC) No 1300/2008
Regulation (EU) 2018/973 of the European Parliament and of the Council of 4 July 2018 establishing a multiannual plan for demersal stocks in the North Sea and the fisheries exploiting those stocks, specifying details of the implementation of the landing obligation in the North Sea and repealing Council Regulations (EC) No 676/2007 and (EC) No 1342/2008
Regulation (EU) 2019/1022 of the European Parliament and of the Council of 20 June 2019 establishing a multiannual plan for the fisheries exploiting demersal stocks in the western Mediterranean Sea and amending Regulation (EU) No 508/2014
Regulation (EU) 2016/1139 of the European Parliament and of the Council of 6 July 2016 establishing a multiannual plan for the stocks of cod, herring and sprat in the Baltic Sea and the fisheries exploiting those stocks, amending Council Regulation (EC) No 2187/2005 and repealing Council Regulation (EC) No 1098/2007

framework, where the main objective is to keep the stock above BMSY and F below FMSY. Lastly, for both the eastern and western Mediterranean, the General Fisheries Commission for the Mediterranean (GCFM) and SGMED management is based on using F0.1 as proxy for FMSY.

In a second part, the study examined the fuel use in EU fisheries as a first step for supporting climate resilience with informed strategies. the levels of fuel-use intensity (catch (kg), per litre of fuel) of the various fleets operating in the EU waters were examined. Fuel intensity levels were analysed at the aggregated fleet-segmentation level shared among EU Member States by analysing EU Data Collection Framework (DCF) data and a 2002-2018 time series of fuel use for different EU fisheries. A pilot study was undertaken to estimate fuel-use intensity and catch efficiency based on more finely resolved data. Historical fuel use was also assessed against historical stock development to measure how influential the recovery of EU stocks is for reducing the fuel use. To project the fuel use forward in changing conditions, a simulation study analysed scenarios of fuel consumption further by applying bio-economic models on selected case studies capable of modelling resource dynamics together with fishing effort spent at sea, which varies with catch rates, catch quotas levels, and links to fuel use.

In a third and final part, based on a literature review of the scientific and technical literature, including previous projects in the field, the study provided a range of technological solutions to reduce fuel use. A questionnaire to experts and stakeholders was launched, and the outcomes complement the findings of the review work, and identified some of the practical or regulatory barriers to overcome when promoting and supporting better energy efficiency and their uptake by the marine wild capture sector.

2 RESILIENCE TO THE EFFECTS OF CLIMATE CHANGE

Understanding the impacts of climate change on fisheries involves assessing long-term trends in climate variability and short-term anomalies associated with more frequent extreme weather conditions. Over the long term, changes in fisheries ecosystems are unavoidable, and adaptive harvest rules that respond to available biomass can help provide large benefits under both static and changing climates (Gaines *et al.* 2018). Such adaptive harvest rules allow for updates in target, threshold and limit reference points, as changes in stock productivity are detected.

By definition, extreme climate events are hard to predict. Therefore, adaptation to short-term climatic shocks can only be achieved by implementing fisheries management that contributes to building both ecological and economic resilience. Ecological resilience is defined as the capacity of a system to absorb disturbance and reorganise while undergoing change so as to still retain the same essential function, structure, identity, and feedback (Bahri *et al.* 2021). In parallel, economic (i.e., macroeconomic) resilience has two components: (i) instantaneous resilience, which is the ability to limit the magnitude of immediate production loss for a given amount of asset loss, and (ii) dynamic resilience, which is the ability to reconstruct and recover (Hallegatte, 2014). Therefore, to be resilient, a system must resist damage and recover quickly from stochastic disturbances. Within this study, we focused on understanding the ecological and economic resilience of EU fisheries.

2.1 Definition of scenarios on climate change effects to test resilience

In this study, resilience is investigated using simulations based numerical models representing the main features of the system under study (fish stock, other biological component of the ecosystem, fishing fleets) - for this we focus on using a range of case studies to cover the major fisheries within the EU. The models used where for the most part already available before this study and were developed for a range of purposes (scientific advice, impact assessment study, scientific research). The first step to this study consisted in extending these models so that the effect of future climate change can be incorporated. This first required, first, that for each species in each case study, the key linkages between population dynamics and climate dependent environmental variables were identified. This section presents the outcome of a literature review on the linkages between fish stocks and the environment, on the role of climate as a driver of the productivity in fish stocks and on the future environmental variability in the different case study regions that is expected from future climate change. This information is then used to formulate scenarios for the simulation period in each region studied. These scenarios - combining an assumption on the effect of future (long-term) climate change and an assumption on the nature of the short-term shocks - are presented in this section. The outcome of the literature reviews and the complete list of assumptions made in the definition of the scenarios are presented for each case study region in Annex 1, Annex 2, Annex 3, Annex 4, Annex 5, Annex 6 and Annex 7. The following section provides a summary of these annexes.

2.1.1 Climate and fisheries: biological mechanisms impacted, drivers of productivity and future environmental changes

The literature review gathered information on the potential linkages between the different fish stocks included in the case studies and changes in their environment. The aim was to identify relationships in the impact of environmental change that could form the basis for formulating assumptions about long-term trends in stock viability, and to help provide an understanding of the impacts on the resilience of EU stocks to climate-induced short-term shocks.

Three main questions were identified from the literature search to evaluate whether current management strategies are impacted by environmental variation and, therefore, also by global climate change, namely:

1. What are the known environmental drivers for the stocks (used in the case studies) fished by the EU fleet that would affect biological function (e.g., recruitment, growth, maturation, mortality) and ecological structure (e.g., spatial distribution)? This will provide information on how biological parameters may change in the future and so should be included in simulation to assess the robustness of management strategies.
2. Is there evidence for climate-driven long-term (multidecadal) changes in stock productivity or distribution, or the overall ecosystem? This will inform the magnitude and the direction of the changes that can be expected under future climate change.
3. Are there documented examples where short-term environmental shocks affect those stocks? This is needed to make assumptions on the nature and magnitude of the short-term shocks to be simulated.

What are the known environmental drivers for the stocks fished by the EU fleet that would affect biological function (e.g., recruitment, growth, maturation, mortality) and ecological structure?

The highest number of references were found for stock-recruitment-environment relationships, which also covered the largest range of species, with references found for almost all the species included in models (Table 2) for all case studies. Amongst these references, the majority dealt with **temperature effects on stocks**: direct effects on, for example, larvae physiology; and indirect effects through, for example, changes in plankton community abundance and species composition.

At the regional level, in the Baltic Sea, **fish population recruitment** was substantially structured by salinity and oxygen (or larger oceanic features influencing these parameters), while river runoff and wind were also cited regularly as important parameters impacting stock structure. In the North Sea, successful recruitment was associated with high abundance and species composition of zooplankton, as well as strong oceanic circulation. Within the Atlantic, the highly migratory Atlantic tuna stocks had little fisheries-independent data or biological information available, with comparatively little known about inter-annual variation in growth, maturity and natural mortality, and trophic interactions. In comparison, in the Mediterranean and the Celtic Sea, exploited stock recruitment was highly impacted by local oceanography (i.e., productivity) and species interactions.

The main **environmental factor affecting body growth** was temperature, although food availability and (intraspecific or interspecific) competition for food was also referred to as an important driver, especially in the Baltic Sea. **Sexual maturation** was mainly linked to the environment through the environmental effects on body growth, and only a few references reported a direct influence of temperature on maturity. The majority of references focusing on **natural mortality** discussed environmentally driven changes in predator abundance (especially in the Baltic Sea), while changes in the ecosystem (affecting dissolved oxygen concentration and prey abundances) influenced natural mortality in the Baltic and Mediterranean Sea. Lastly, temperature was found to increase natural mortality throughout regions, as it increased the sensitivity to increasing ocean acidification, while generating extreme weather conditions (e.g., cold winters).

Is there evidence for climate-driven long-term changes in drivers that impact stocks?

In the **North Sea**, the trend in sea surface temperature (SST) (or climate indices associated with this long-term trend, such as the Atlantic Multidecadal Oscillation (AMO)) was identified as the main source of change in fish stock productivity (although the magnitude of the effect was species-specific). An increase in temperature has also caused a northward shift and a deepening in species distribution (although some stocks have extended their distribution southwards as a result of the beneficial effects of milder winters). Changes in species composition at different trophic levels have also affected fish stocks. For example, changes in zooplankton communities have affected the success of a range of species (mainly at the larval stage), while saithe populations have been impacted by increasing abundance of hake associated with the warming waters.

In the **Baltic Sea**, the main driver of long-term change has been the frequency of water inflow from the North Sea, affecting dissolved oxygen and water salinity conditions. This has affected the extent of Eastern cod spawning grounds, with consequences on stock-recruitment success. Changes in cod abundance, through predation, have had a direct effect on forage fish species (e.g., sprat and herring).

In the **Black Sea**, warmer winters have impacted migration routes of anchovy, while climate-driven changes in zooplankton (e.g., production, species composition) have had a major influence on fish stocks.

In **Atlantic western waters**, variation in the AMO and the Atlantic Meridional Overturning Circulation (AMOC), resulting in impacts to phytoplankton and zooplankton abundance (Wu *et al.* 2020) have likely reduced the recruitment, growth rates and abundance (as well as increased mortality) of tropical tuna. Future projections based on global climate models indicated that ocean temperatures in the North Atlantic will experience an increase of ~2 °C by the end of the 21st century, with a simultaneous 25% reduction in the strength of the AMO. The AMOC is the primary ocean circulation system in the Atlantic Ocean, contributing to the flow of warm, higher salinity water in the upper layers of the water column and associated heat transport from the South Atlantic and tropical North Atlantic to the subpolar and polar North Atlantic (Schmittner *et al.* 2005). In addition, according to the most recent climate models, global average tropical cyclone intensity is expected to increase by 2–11%, while the frequency of cyclone occurrence is expected to decrease by 6–34% (Knutson *et al.* 2010). This means that the frequency of more intense and damaging tropical storms and hurricanes is projected to increase globally (Biasutti *et al.* 2012).

In western Mediterranean Sea waters, hake and red mullet are impacted by environmental effects that involve the combination of large-scale and short-scale drivers that can have different and even contrasting impacts on the same species in adjacent management areas. For hake, years with high convection and anomalous strong formation of waters in intermediate depth in the Gulf of Lion forced by winter wind-driven vertical mixing cause strong mortality events and recruitment failures in this management area (Hidalgo *et al.* 2019). By contrast, the same hydroclimatic process increases the flux of nutrient-rich waters flowing southwards and the general biological productivity of the Balearic Sea (Monserrat *et al.* 2008, Balbín *et al.* 2013), which in turn favours recruitment in the Balearic Islands (Massutí *et al.* 2008). A similar pattern is seen for red mullet, and there is a strong environmental effect on survival from juveniles to adults (from age two to three). This is consistent with studies on red mullet showing a positive influence of increased SST anomalies (Levi *et al.* 2003). There is also an environmental influence in the western Mediterranean on growth, as years with high convection, and anomalously strong formation of intermediate waters in the Gulf of Lion forced by winter wind-driven vertical mixing (Monserrat *et al.* 2008, Balbín *et al.* 2014), trigger reductions in growth of red mullet.

In **eastern Mediterranean Sea waters** for European anchovy and sardine, stock dynamics are largely defined by bottom-up factors (Peck *et al.* 2013). Specifically, riverine inputs, advection and eddies, salinity, temperature, and prey quantity and quality are all associated with stock success. Within this region, large-scale climatic variability has also been shown to impact stock success (Stergiou *et al.* 2016; van Beveren *et al.* 2016; CERES, 2018a; Tsikliras *et al.* 2019), with climate fluctuations and large climatic phenomena (AMO, Western Mediterranean Oscillation (WeMO)) linked to landings of small pelagics (Stergiou *et al.* 2016). Increases in sea temperature above an optimum has been reported to negatively affect small pelagic species growth rate (Katara *et al.* 2011).

In the **Celtic Sea** there are correlations between large-scale climatic indicators, temperature, primary and secondary productivity, and fish recruitment of the species assessed within this work (Bentley *et al.* 2021). In detail, there are negative correlations between the North Atlantic Oscillation winter index (NAOw) and large zooplankton abundance, and between the AMO and recruitment of cod (*Gadus morhua*) and whiting (*Merlangius merlangus*).

Are there documented examples where short-term environmental shocks affecting those stocks?

The literature review also looked for documented cases where short-term environmental stresses impacted fish stocks. However, **only a few references** were found, and they were not necessarily linked to stresses related to climate change. The stresses ranged from the effect of storms, anomalies in hydrological conditions and toxic algal bloom. These stresses mainly had negative effects, except in severe winters in the North Sea that resulted in extremely high recruitments of flatfish.

2.1.2 Future changes in the environment between the different case studies

The scenarios for the simulations are based on two different assumptions for future climate change. The 'most likely' and 'worst-case' scenarios were based on the assumption that future climate change would conform with the Intergovernmental Panel on Climate Change Representative Concentration Pathway (IPCC RCP) IPCC scenarios RCP4.5 and IPCC RCP RCP8.5, respectively. In order to make assumptions on the implication of these climatic scenarios for fish stocks, it was first necessary to determine how the marine environment in the regions covered by the case studies is affected by climate change, and the projections for the future under the **two selected IPCC scenarios**. To do so, each case study reviewed the available work in which (bio)physical oceanographic models, forced by a regional climatic model, produced projections for the main environmental factors in the marine environment over the 21st century.

The main conclusions for the case studies are presented below, with the complete list of assumptions made in the scenarios listed in the tables of the case study reports presented in Annex 1, Annex 2, Annex 3, Annex 4, Annex 5, Annex 6 and Annex 7. It should be noted that in all case studies there is hardly any difference between the projections done under the RCP4.5 and RCP8.5 by 2030, the time horizon for this study. The magnitude of the changes expected for the next 10 years is also very small, often much smaller than the interannual variations in the projections from these models. Because preliminary studies have shown that the difference of RCP4.5 compared to RCP8.5 appears only beyond the 10-year horizon, we have prolonged the simulations for a longer time horizon wherever the modelling tool makes this possible.

- **Baltic Sea environmental projections**

The projections indicate an increase in mean annual SST of 1 °C and 2 °C by 2100, for the RCP4.5 and RCP8.5 scenarios, respectively. Such changes will be more pronounced in the northern coastal area. Warmer temperatures will also increase river runoff through increased precipitation, resulting in coastal salinity decreasing by ~ 0.4 and 1.2 practical salinity units (psu) in RCP4.5 and RCP8.5, respectively.

- **North Sea environmental projections**

The projections indicate an increase of 1 °C and 2 °C in mean annual SST by 2100, for the RCP4.5 and RCP8.5 scenarios, respectively. This warming will occur over the entire North Sea, although this will be more pronounced in coastal areas. Primary production will also likely decline. Lastly, some areas will show marked reductions in primary production (predominantly within northern regions) while only a slight increase in production is expected in coastal areas.

- **Black Sea environmental projections**

The only available projections in the Black Sea are based on scenarios published in the 4th IPCC assessment report (AR4, dating from 2007[3]). These indicate an increase in average SST by 2100 of between 2 °C and 4 °C (depending on the models used) for the IPCC RCP8.5 scenario. No information is available for the RCP4.5 scenario. Model projections also indicate a decrease of 10% in primary production and zooplankton biomass by 2100, especially in the southwestern Black Sea.

- **Mediterranean Sea (both eastern and western) environmental projections**

Atmospheric circulation changes in the Mediterranean are expected to increase SST substantially (though this is predicted to be more substantial in the western than eastern Mediterranean). Such changes in the SST are expected to impact oxygen levels, with less dissolved oxygen available, and increase the stratified vertical structure. Such changes in the water column structure are expected to result in reduced availability of nutrients, reducing the growth of phytoplankton and therefore zooplankton; in correlation, the abundance of chlorophyll-a has decreased since the early 2000s and is expected to keep decreasing. Particularly, for the western Mediterranean, highly predictable climate change processes including warming, increasing heatwaves or changes in the river's runoff have been reported over the whole sub-basin (e.g., Adloff *et al.* 2015, Darmaraki *et al.* 2019), with events becoming more stronger under RCP4.5 and RCP8.5 than RCP2.6. At regional scale, however, the most important drivers affecting fishing resources go far beyond warming and are, in general, hardly predictable (Hidalgo *et al.* 2018). Changes in the vertical mixing affecting primary production regimes (Macias *et al.* 2015, 2018), thermohaline circulation and local hydrography (Ser-Giacomi *et al.* 2020), or the strength of winter weather events (Gaertner *et al.* 2018) are critical drivers for the spatiotemporal dynamics of the western Mediterranean fish stocks.

In the eastern Mediterranean (N. Aegean Sea) model, SST was found to significantly affect the communities during the hindcast period and was therefore used as a driver for climate scenarios following the methodology of Bentley *et al.* (2017) and Serpetti *et al.* (2017). SST data for the model area were obtained from the CMIP5 (Coupled Model Intercomparison Project Phase 5) scenario runs; the MPI-ESM-LR model (Giorgetta *et al.* 2013) was chosen as giving a better representation of the ensemble (CERES 2018b). An increase in temperature has been already observed during the hindcast period and continues after 2020 in both RCP scenarios. The SST predictions between RCP 4.5 and 8.5 diverge more after 2050 when the temperature increase slows down in the RCP 4.5 contrary to RCP 8.5. Average temperature in the 2046-2050 period increases by 0.65°C in RCP 4.5 and by 0.94°C in RCP 8.5 compared to that in 2020.

- **Celtic Sea environmental projections**

In the future the Irish Sea will be warmer during all seasons. The warming will be stored largely in the surface layer of the water column, leading to strengthened stratification (Olbert *et al.* 2012). The IPCC projects ocean warming throughout the 21st century, with models predicting the Irish Sea will experience a maximum sea surface temperature of 11.6 °C under RCP4.5 and a maximum of 13.7 °C under RCP8.5 (temperature maxima taken from the mean trend of RCP model sets) (Poloczanska *et al.* 2018). Given that the retrospective ecosystem dynamics of the Irish Sea were impacted by changes in temperature (Free *et al.* 2019; Bentley *et al.* 2020), it is highly likely that future ocean warming will impact stock production, ecosystem structure, and fishing opportunities. Climate scenarios for the Irish Sea case study were simulated using future sea surface temperature projections from the IPCC following the methods of Bentley *et al.* (2017) and Serpetti *et al.* (2017). As in Serpetti *et al.* (2017), climate projections for RCP4.5 and RCP8.5 were extracted for the model area (ICES division 7a)[4].

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[3] https://www.ipcc.ch/report/ar4/wg1/

[4] http://climexp.knmi.nl/plot_atlas_form.py

- **Atlantic western waters environmental projections**

A further reduction in the AMOC is expected, but it is very unlikely that the AMOC will undergo an abrupt transition or collapse in the 21st century. There is also significant evidence to suggest that Atlantic subtropical regions, dominated by net evaporation, are likely to become more saline, while ongoing substantial and increased warming of surface waters is expected.

2.1.3 Defining plausible, ecosystem-coherent environmental scenarios

A key step towards assessing ecological and economic resilience in EU fisheries has been to define plausible scenarios for the future effects of climate change on fish stocks. As stated above, **climate change involves long-term effects** (e.g., gradual change in the physical marine environment) **and short-term anomalies** (i.e., more frequent extreme weather conditions or increased variability). Both aspects of climate variability represent different threats for fisheries. Long-term climatic changes may lead to inappropriate management rules being applied (e.g., reference points, allocation keys), as stock productivity and distribution change. Since there is currently no framework to anticipate these changes and take account of them in fisheries advice, management usually reacts to such changes with a delay, representing the first threat for fisheries resilience. In comparison, short-term environmentally driven stresses could have a sudden negative impact on fish stocks and ecosystems, bringing them into states where their recovery is jeopardized. The chance of recovery (or resilience to such stresses) may be further influenced by the long-term effects of climactic changes.

Therefore, within this study it has been important to **simulate different scenarios** to examine the magnitude of future long-term climate change, as well as the nature and frequency of short-term stresses. The number of possible scenarios is only restricted by computing time, especially as each environmental scenario needs to be run for different management options. Hence, this study investigated resilience for three scenarios, each composed of an assumption on long-term effects and a hypothesis on the short-term shock.

1. In the first climate scenario, **'status quo'** (also referred to as "base case" in the annexes for some case studies), it is assumed that no change will occur in the future, neither in the long term nor in the short term. This scenario establishes the baseline for how resilient the system is under the current CFP management, according to the rules laid out in the CFP. This is in the hypothetical absence of any future environmental change, given the current state of the different fish stocks and ecosystems.
2. The second climate scenario, named **'most likely'**, assumes that future changes in climate would conform to an intermediate IPCC scenario. This scenario is based on RCP4.5, which corresponds to CO_2 emissions increasing up to, and then declining after, 2045. In combination with this long-term trend, it is assumed that a single shock will affect the system. In order to be able to assess resilience by 2030, it was decided to impose this shock in the first year of the simulation.
3. The third climate scenario, **'worst-case'**, assumes a more pessimistic long-term climate trend, based on the IPCC scenarios RCP8.5, in which greenhouse gas emissions increase throughout the 21st century. In addition to the first shock, a second shock is applied in the second year of simulation.

An approach was agreed to ensure that the definition of scenarios was done in a **consistent manner across case studies** and geographic regions. The general approach consisted of: (i) identifying the biological aspects (e.g., reproduction, growth, distribution) impacted by environmental factors; (ii) inspection of predictions from physical oceanographic models forced by the IPCC scenario, to determine which factors from the marine environment would be affected by climate change; and, based on (i) and (ii), (iii) the formulation and inclusion of assumptions into the different models. The main conclusions for the different case studies are presented below, with the complete list of assumptions made in the scenarios presented in Annex 1, Annex 2, Annex 3, Annex 4, Annex 5, Annex 6 and Annex 7.

2.1.4 Assumptions for comparing between scenarios

Below we provide a synopsis of the assumptions that have been made to compare modelling scenarios.

The **environmental scenarios** for each simulation undertaken within this work correspond to a combination of a scenario on the long-term effects of climate change, and a scenario for the short-term shocks. In almost all simulation frameworks, it was decided to implement long-term environmental changes on recruitment. The main approach consisted of fitting stock-recruitment models in which the key environmental factor identified in the literature review was used as a covariate in the model.

Different assumptions were made for future animal body **growth** as well, though for a smaller number of stocks. In some instances, a growth model with the influence of temperature was developed, either based on fitting a von Bertalanffy model with parameters influenced by temperature (e.g., North Sea herring model), or more simply making assumptions on future changes in the von Bertalanffy parameters (e.g., Baltic Sea DISPLACE).

Assumptions were also made for future **changes in spatial distribution** in a smaller number of frameworks i.e., the spatially explicit models (SIMFISH and DISPLACE), while other models implement a possible change in spatial distribution by modifying the fleet catchability for certain species in certain areas (i.e., bio-economic impact assessment using Fisheries Library in R (FLBEIA) in the North Sea).

Because of the differences between the models, it was necessary to define different sets of **model-specific assumptions** even if the same assumptions were used across models as much as possible. In the North Sea case study, the Fisheries Library in R (FLR)-based models (SIMFISH and FLBEIA) and the multispecies Ecopath with Ecosim (EwE) model used mostly similar assumptions (although the shape of the stock-recruitment relationship – Ricker vs Beverton-Holt – could differ between EwE and the FLR models).

The assumptions made for the **effect of short-term shocks were defined pragmatically** since little information was found in the literature to base the effects on observed effects. For most simulation platforms modelling recruitment explicitly, a recruitment failure is the most evident short-term shock effect. Depending on the scenario, either one or two consecutive recruitment failures were implemented at the start of the simulations. For the ecosystem models in which temperature plays a role in different functional relationships (e.g., EwE in the southern North Sea, or Atlantis model in the Baltic Sea), scenarios were also made for the heatwave (i.e., a strong positive temperature anomaly impacting the whole ecosystem for a short period of time). The basis for simulating heatwaves was either environmental conditions observed during past heatwaves, or more arbitrarily, the average temperature conditions which are expected to prevail in the long-term (i.e., by 2100).

Finally, for each environmental scenario, simulations were run for two different management scenarios, corresponding to using a Ftarget at either F_{MSY} or at F_{MSY_lower} (lower bound of the F_{MSY} range). For some stocks, the F_{MSY} ranges are already used as management targets (e.g. for the stocks included in the EU Multi-Annual plans). For other stocks (e.g. stocks managed in the context of international agreements, as North Sea herring or mackerel), the F_{MSY} ranges are not used for management (and sometimes not defined, as for North Sea herring), but there performance as candidate alternative management target was tested here. Moreover, the stocks exploited in the Med are managed with a target F of F0.1 which is intended to be a lower estimate of FMSY, while in tuna stocks the F target is commonly set to be less than FMSY as the objective is to keep biomass> BMSY and F<FMSY.

2.2 Simulation tools and measures of resilience

2.2.1 Resource resilience

Resource resilience was defined by the ability for fish stocks to remain above biomass limits (Blim) and thresholds at which productivity is impaired, and rebuild, in a timely manner, to levels that correspond to management targets (the lower bound of spawning-stock biomass fluctuation when fished at the maximum rate of fishing mortality: MSY $B_{trigger}$ in the International Council for the Exploration of the Sea (ICES) and B_{MSY} in other regional fisheries management organisations (RFMOs), Figure 1). The aim is to test whether, under a given management option, stocks remain at levels at which exploitation is still possible (above limits) and are still able to reach levels at which exploitation is optimal (e.g., maximum sustainable yield (MSY)).

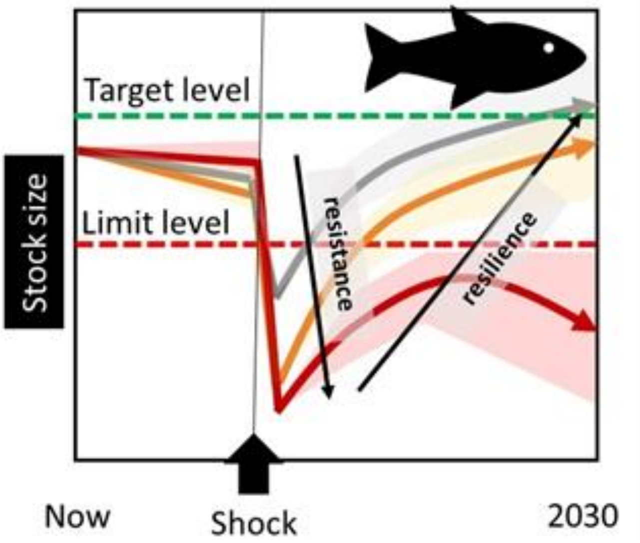


Figure 1 Resource resilience is described as the ability of a stock to recover from a shock, knowing that resistance is described as the ability for the resource to remain unchanged when being subjected to disturbances. Depending on the initial conditions, the fisheries management applied, and the shock encountered, some paths are expected to be more resilient than others.

To measure resource resilience, a series of indicators were used, that describe, first, the magnitude of the impact of the shock (or resistance) and, second, the dynamics of the recovery (resilience). These indicators are based on the relevant metrics to describe stock size (spawning stock biomass (SSB), exploitable biomass, etc.) (

Table 1).

Table 1 Preliminary list of indicators to describe resource resilience

Indicators of resource resilience		
Resistance (ability to withstand the perturbation)		
Amplitude	Minimum stock level reached after the shock compared to initial level	SSBmin/SSByear shock
Responsiveness	Number of years between the	YearSSbmin – Yearshock

Indicators of resource resilience		
	shock and the minimum observed stock level	
Biological risk	Probability (P) of SSB falling below safe biological limits (B_{lim} for ICES, 40% of B_{MSY} elsewhere)	Max(P(SSB<Blim))
Resilience (ability to recover from the perturbation)		
Recovery rate	Probability that stock level is at MSY target level (MSY $B_{trigger}$ for ICES, B_{MSY} elsewhere) or above in 2030	p(SSB2030>=B_{target})
Recovery speed	Number of years to reach stock levels corresponding to MSY	YearSSB>=B_{target} – Yearshock

Resource resilience was tested in single stock simulation models, ranging from simple multi-annual forecasts, full feedback MSEs, to ecosystem models (the latter described in section 2.2.2). The list of the models used specifically for resource resilience, and details of how the scenarios on climate change and short-term shocks were implemented are provided (Table 2). Note that simulation models that were applied to study other aspects of resilience (ecological or economic) also involved simulating future stock development, and were also used to provide insight into resource resilience.

Table 2 List of simulation models applied to test resource resilience

Model type	Stocks included	Population dynamics	Model specificities	Long-term climate effect	Short-term shock
Northeast Atlantic (NEA) mackerel					
Forecast in FLR without feedback	NEA mackerel	Abundance at age	Historical estimates based on a single stock assessment Uncertainty on starting conditions taken into account	Distribution: climate- and density-dependent regulated geographic distribution indirectly modelled through a relationship between catch per country and area and stock size Recruitment: negative trend on recruitment stochastic deviations with a slope set arbitrarily Growth: density dependent	Recruitment: poor recruitment based on lowest observed values
North Sea herring					
Full feedback MSE	Autumn-spawning herring	Abundance at age		Recruitment: fitted stock-recruitment model with temperature as covariate, using projections from climate/ocean model for future years Growth: von Bertalanffy model with parameters influenced by temperature	Recruitment: poor recruitment based on lowest observed values
North Sea sprat					
MSE (short-cut approach)		Abundance at age	In addition to current stock abundances, scenarios were also run with starting values corresponding to the lowest, median and maximum stock size in the assessed period	None	Recruitment: based on lowest observed values

Model type	Stocks included	Population dynamics	Model specificities	Long-term climate effect	Short-term shock
Western Mediterranean					
Forecast in FLR without feedback	Hake, red mullet	Abundance at age	Historical estimates based on a single stock assessment Projections conditioned ad hoc Empirical estimates of growth and maturity	Natural mortality (M): status quo, trend (25 % linear increase from 2020 to 2070), regime shift (25 % increase after and including 2020) Growth: status quo; trend (25 % linear increase from 2020 to 2070) Stock recruitment relationship: status quo; trend (25 % decrease from 2020 to 2070)	50 % increase in M in first year of projection
Atlantic tropical tuna					
Forecast in FLR without feedback	Bigeye and yellowfin tuna	Spatially disaggregated seasonal model with sub-cohorts spawning in each quarter with different biological parameters and stock-recruitment relationships (SRRs)	Multiple scenarios based on an assessment grid reflecting the main uncertainties in steepness of the SRR, natural mortality, recruitment variability and relative data weighting Growth based on a single growth curve. Projections based on recommended catch to achieve MSY, and the current catch levels	Status quo as in historical assessment Trend in M and growth: increase from 2020 onwards Trend in virgin biomass: decrease from 2020 onwards	150 % increase in season two for sub-cohort 2 in 2020
North Sea demersal mixed fisheries					
FLBEIA	Main (influenced by climate): cod, haddock, plaice, saithe, sole, whiting Auxiliary (not influenced by climate):	Abundance at age	Uses catch and effort data from 41 fleets (141 metiers) to model mixed fisheries interactions Assumes that fleets do not overshoot any of their quotas	Recruitment: cod, plaice, saithe and whiting Fitted stock-recruitment model with environmental covariates using projections from climate/ocean model for future years	Decreased recruitment for cod, plaice, saithe, sole, whiting implemented in separate runs Defined as 5 % percentile of the deviations from

Model type	Stocks included	Population dynamics	Model specificities	Long-term climate effect	Short-term shock
	anglerfish, brill, dab, lemon sole, lingue, turbot, witch				the smoothed recruitment time series For haddock: absence of recruitment spike for 10 years
Baltic Sea stocks					
GADGET	Cod, herring, sprat	Multi-species age–length based	GADGET is also fitted to data for the past period, giving similar but slightly different basis than given by single stock assessments	Deviations from future predicted recruitment (stock-recruitment model) are influenced by reproductive volume (cod), summer SST (herring, sprat) Future environmental condition based on projections from climate/ocean model with two scenarios for future nutrient upload	Poor recruitment based on lowest observed historically First shock in 2020. Second shock in a random year

2.2.2 Ecosystem resilience

Ecosystem resilience is defined by the capacity of an ecosystem to absorb disturbance and reorganise while undergoing change to still retain essentially the same broad function, structure, identity and feedback (stability and compensatory effects, Figure 2).

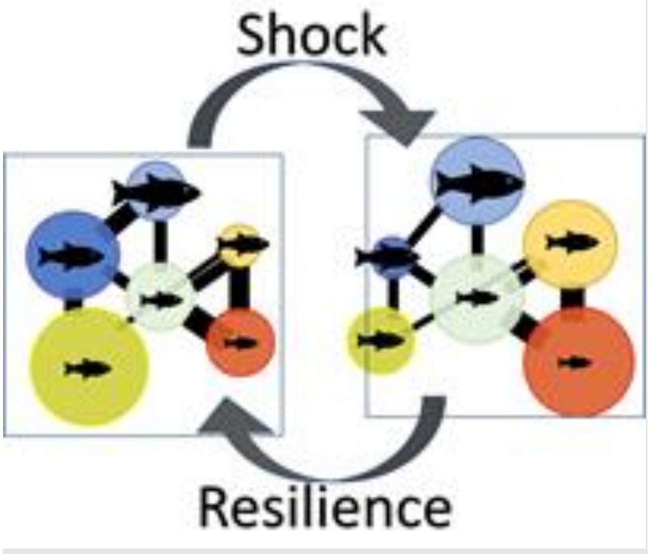


Figure 2 Ecosystem resilience will be defined by the capacity of an ecosystem to resist and absorb disturbance and return to pre-disturbed state (i.e., maintaining the same trophodynamics including similar levels in relative species abundances or biomasses (the relative size of the bubbles), and production-to-biomass ratio (the thickness of the trophic links)).

A number of indicators are used to describe the ecological characteristics of the ecosystem (indicators 1 to 3 in Table 3). Where not already provided by the models, these indicators were calculated on the output of the simulations. Where possible, these indicators were common across case studies to help in synthesizing the results. Ecological resilience was measured using metrics quantifying the temporal dynamics of these ecological indicators after the system had been exposed to a shock (Table 3).

Table 4 provides a list of the models used to simulate the reaction of the whole ecosystem and how they were configured to implement short-term shocks combined with long-term effects of climate change.

Table 3 Indicators to describe ecosystem resilience

Indicators of ecological resilience		
1	Demersal-Pelagic ratio	*Indicative of changes in the ecosystem in terms of relative importance of the pelagic vs. demersal components*
2	Biodiversity indices (i.e., Pielou's J) indicators	*Indicative of both the species richness (number of species) and the species evenness (balance in the distribution of abundance across the species).*
3	Bray–Curtis dissimilarity among ecosystem states	*Measure the difference in abundance distributed over species between two different states of a same ecosystem*

4a, b	Mean trophic level of catch, mean trophic level of community	*Indicative of the distribution of the biomass in the ecosystem in term of trophic level*
Resistance		
Amplitude	Comparison between the indicator minimum level after the shock and its estimated initial level	1, 2, 3
Responsiveness	Number of years between the shock and the minimum level reached by the indicator	1, 2
Risk	Probability of the indicator falling below a reference level (i.e., good environmental status (GES) if available, or equivalent)	1, 2
Resilience		
Recovery time	Number of years before the indicator reaches the level it would have had in the absence a shock	1, 2

Table 4 List of simulation models applied to test ecosystem resilience

Model type	Stocks included	Population dynamics	Model specificities	Long-term climate effect	Short-term shock
Southern North Sea					
EwE	Cod, whiting, haddock, herring, plaice, sole, shrimp		Ecopath model represents the state of the ecosystem in 1991, thereafter fitted to data for 1991–2010 with Ecosim	Effect of temperature on food consumption rates, via trapezoidal tolerance range per functional group, using future SST projections from ocean-climate model	Shocks tested using a gradient approach (simulations run for a range of shock amplitudes): – heatwave (temperature max 15 °C) impacting all components of the ecosystem, – poor recruitment (up to 90% reduction) for cod, herring and plaice) – bottom-up effect testing a range of increase or decrease rates in primary production
Black Sea ecosystem					
EwE	37 trophic groups (14 commercial fish species)		EwE model fitted on data up to 2016	Forcing on either primary production on phytoplankton groups or food consumption rates of fish (sprat or anchovy) by SST	Inducing a 50% reduction in the consumption rate of sprat or anchovy, in order to illustrate a negative effect of a thermal shock (one or two consecutive years)
Baltic Sea ecosystem					
Atlantis	30 biological functional groups, which include: mammals, seabirds, pelagic fish, demersal fish, benthic invertebrates, commercial benthos, pelagic invertebrates, benthic primary producers, pelagic	Age-structured for the vertebrate groups	Three-dimensional, spatially explicit end-to-end ecosystem	Physiological processes (consumption, growth, mortality, reproduction) are affected by temperature Future environment based on ocean-climate model projections under RCP4.5 and RCP8.5	Poor recruitment: 50% decrease in cod, sprat, herring recruitment, tested separately Mass mortality for cod: no cod recruitment in the future Heat wave: one episode of high temperature affecting

Model type	Stocks included	Population dynamics	Model specificities	Long-term climate effect	Short-term shock
	primary producers, bacteria, detritus groups				physiological response in all groups
Celtic Sea					
EwE	Cod, whiting, haddock, herring, plaice, sole, shrimp		Ecopath model represents the state of the ecosystem in 1991, thereafter fitted to data for 1991–2010 with Ecosim	Effect of temperature on consumption rates, via trapezoidal tolerance range per functional group, using future SST projections from ocean-climate model	Shocks tested using a gradient approach (simulations run for a range of shock amplitudes): – heatwave (temperature max 15 °C) impacting all components of the ecosystem, – poor recruitment (up to 90% reduction) for cod, herring and plaice) – bottom-up effect testing a range of increase or decrease rates in primary production
Aegean					
EwE	40 functional groups (one phytoplankton, four zooplankton, nine benthic/demersal invertebrates, 21 fish, three charismatics, detritus, discards) with emphasis on anchovy and sardine for the current work		Ecopath model represents the ecosystem in 1993, fitted to data for 1993–2020 with Ecosim	Effect of temperature on consumption rates for 28 groups, via Gaussian-like tolerance range per functional group, using future SST projections from ocean-climate model	– Primary production shock, simulated by modifying primary production anomaly values for one year – Gelatinous plankton shock, simulated by forcing the biomass of the respective functional groups included in the model for one year – combination of the two scenarios (primary production + jellyfish)

2.2.3 Economic resilience

The economic resilience of fishing fleets was defined as their ability to withstand short-term economic stresses caused by the effect of short-term adverse climatic events on fish stocks (Figure 3). This work therefore focused, in addition to the biological component, on the fisheries economic aspects, by modelling costs and earnings and applying risk analysis to measure the risk to attain negative economic results along with possible short-term financial/economic stresses.

The economic resilience was defined as the ability to withstand short-term economic stresses (measured as the capacity of a suite of indicators to return to the average path followed by the baseline shock-free scenario trajectories). A range of metrics were calculated to quantify economic resilience based on the trends in simulated economic variables (

Table 5). In addition, bio-economic models were used to assess economic resilience (Table 6).

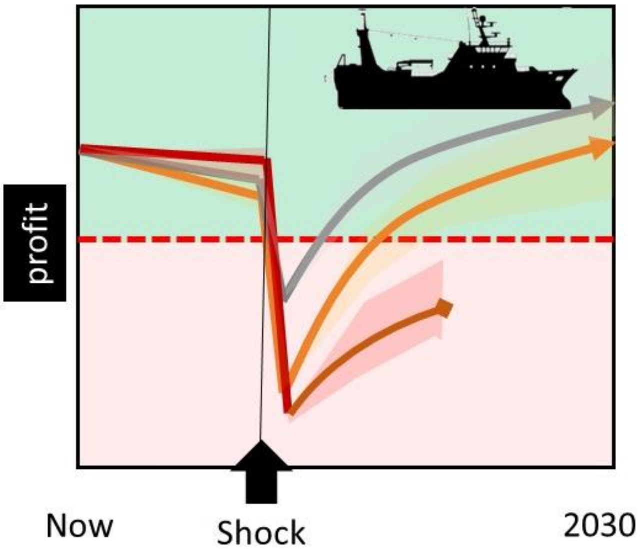


Figure 3 Fishing fleet economic resilience

Table 5 Indicators of economic resilience (expressed as probability P of exceeding a baseline value) based on a set of economic indicators used in Europe to monitor the EU fleets.

Indicators of economic resilience		
Break-even revenue ratio (BER)	Does the revenue cover the operating costs and salaries?	P(BER>=BER_baseline)
Gross value added (GVA)	What is the contribution of the fishing activity to the national economy?	P(GVA>=GVA_baseline)
Net value added per full-time equivalent (NVA/FTE)	What is the labor productivity?	P(NVA/FTE>=NVA/FTE_baseline)
Net profit margin	What is the resource productivity measured as the economic performance of the fleet?	P(NetProfitM>=NetProfitM _baseline)

Indicators of economic resilience		
Return on fixed tangible assets (RoFTA)	What is the capital productivity? Is the long-term profitability of the fishing fleet segment larger than other available investment?	P(RoFTA>=RoFTA_baseline)
Number of active vessels (NoV)	What is the number of vessels active in the segment?	P(NoV>=NoV_baseline)
Vessel utilisation Ratio (VUR)	What proportion of the capacity in the segment is used?	P(VUR>=VUR_baseline)

Table 6 List of simulation models applied to test economic resilience

Model type	Stocks included	Population dynamics	Model specificities	Long-term climate effect	Short-term shock
Baltic Sea fisheries					
DISPLACE	Cod, plaice, herring, sprat (several stocks per species)	Spatial population age and length based	Simulates the movement of individual fishing vessel agents Includes trophic interactions	Multipliers applied to parameters for the stock-recruitment and growth functions (arbitrarily set)	Mortality episode: 20 % increase in M for cod herring and sprat Spatial distribution: 10 % range contraction
North Sea flatfish fishery					
SIMFISH	North Sea sole and plaice (shrimps included but not affected by climate)	Spatially explicit fleet and fish stocks dynamics	Fisher behaviour is simulated based on optimal effort allocation, spatially and by metier, according to a set of constraints (quota, information on fishing grounds, effort, etc.)	Stock-recruitment model with temperature as covariate for plaice (same as FLBEIA) Changes in distribution for both stocks based on prediction from spatial modelling under RCP4.5 or RCP8.5 assumptions	Decreased recruitment for sole and plaice. Defined as 5 % percentile of the deviations from the smoothed recruitment time series
Bay of Biscay anchovy					
FLBEIA	Anchovy	Numbers at age by semester	Historical estimates based on a single stock assessment	Recruitment: fitted Ricker stock-recruitment model with changes in the slope parameter in time related to the expected	Decreased recruitment: implemented decreasing the recruitment for 2021 to the 10 % of

Model type	Stocks included	Population dynamics	Model specificities	Long-term climate effect	Short-term shock
				enhancement due to climate change Growth: a decreasing trend on weights at age of individuals is applied Mortality: natural mortality is modified with decreasing trend on age zero individuals The effect on recruitment and on growth are combined	the expected recruitment according to the stock recruitment model and for a second random year in the pessimistic scenario

2.3 Synthesis of the results

This section presents a condensed summary of the results of the case studies conducted in this study to investigate resource, ecological and economic resilience. The full description of the work carried out and detailed results from the simulations are provided in Annexes.

2.5.1. Resource resilience

Baltic Sea fisheries - GADGET multispecies multifleet model (Annex 8)
Summary of the results: The shocks accentuate the initial drop (due to recent low recruitment, Figure 4) in cod SSB, but only slightly reduce the chance of recovery to above MSY Btrigger by 2030, which is low in all scenarios (10 % to 32 %). Herring is highly resilient to the shocks, which have only a mild, short-term effect. Sprat is less resilient, as shocks have a larger and longer lasting impact. However, both pelagic stocks are well above MSY Btrigger in all simulations. For the three stocks, the effect on future dynamics is larger (positive for cod, negative for sprat and herring) when future changes in nutrient loads are included in the environmental projections (in addition to warming). For herring and sprat, applying Fmsy or Fmsy_lower also results in large differences in future trajectories, but does not affect much resilience to the short-term shocks.

Stock	Scenario	Long-term development without shock	Resilience	Remarks
Cod				
	Status Quo	Not presented in the annex		
	Most likely	Cod stock is well under MSY $B_{trigger}$ at the start of the simulations and is expected to decline to 45 % of SSB2019 in 2022 and increase	SSB drops to 28 % of SSB2019, three years after the shock, with a 90 % chance of getting below MSY $B_{trigger}$ and 27 % of being above MSY $B_{trigger}$ by 2030	In this case study, the second shock occurs in a random year. The amplitude is largest when the second shock occurs just after the first

Stock	Scenario	Long-term development without shock	Resilience	Remarks
		afterwards to roughly 28 % chance of SSB>MSY $B_{trigger}$ in 2030		Cod dynamics is not affected by the two pelagic stocks Managing based on F_{MSY} or F_{MSY} lower makes little difference to the resilience
	Worst case	22 % chance of SSB>MSY $B_{trigger}$ in 2030	SSB drops to 27 % (but for replicates down to 17 %) of starting conditions three years after the first shock, with a 96 % chance of getting below MSY Btrigger and 17.5 % of being above MSY $B_{trigger}$ by 2030	
Herring				
	status Quo	Not presented in the annex		
	Most likely	Stock increase until 2024 (marginally when managed based on F_{MSY}, but with a larger magnitude when managed based on F_{MSY}_lower), and then decreases until the end of the 2030s to increase again until 2045	Minor drop in SSB 3.5 years after the shock. Small risk of SSB<MSY $B_{trigger}$ in 2030 (8 % and 2 % when managed based on F_{MSY} and F_{MSY}_low respectively) but this is the same as without shock	The long-term stock levels are much lower (150ktons) when changes in nutrient load occur in addition to sea-water warming
	Worst case	Similar to 'most likely', with slightly higher biomasses in 2050	Similar to 'most likely'	
Sprat				
	status Quo	Not presented in the annex		
	Most likely	Increase in the short term to 1.9mt and 2.3 mtons in 2028 (when managed either on the basis of F_{MSY} or F_{MSY}_low, respectively) and then fluctuates round this level	Shock delays the increase in SSB, stock remains above MSY $B_{trigger}$ with very high probability	
	Worst case	Similar to 'most likely', with maximum in 2029 at 2.1 mtons and 2.6 mtons	Similar to 'most likely', although stock trajectory takes longer to recover to the	

Stock	Scenario	Long-term development without shock	Resilience	Remarks
			trajectory without shock	

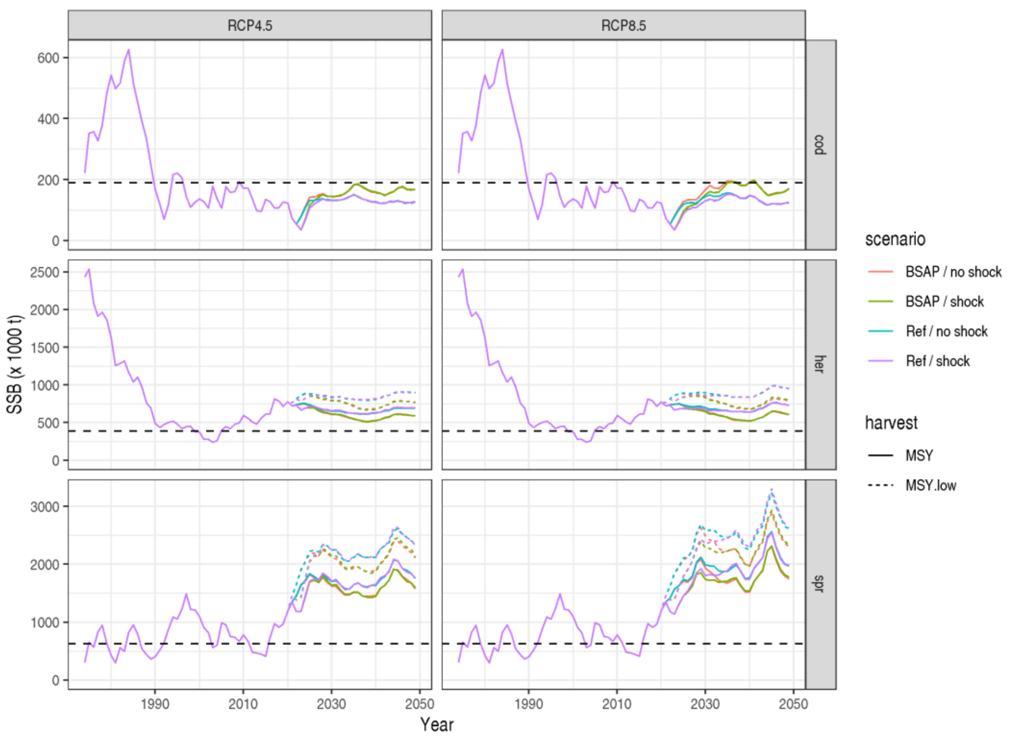


Figure 4 Projection of future SSB (50 % percentile of distribution) for Baltic Sea cod, herring and sprat from the GADGET model for the most likely (RCP4.5, left panels) and worst case (RCP8.5, right panels) scenarios, with and without shocks (1 poor recruitment for 'most likely', 2 for 'worst case'), for two levels of fishing mortality, and for two scenarios for future environmental changes (reference Ref: warming only, BSAP Baltic Sea Action Plan: includes reduction in nutrient load)

North Sea demersal mixed fisheries (Annex 10)

Summary of the results: Under the assumption that no fishing fleet overshoots its quota for any of the stocks, cod is the stock that limits the effort for most of the fleets in the simulations because of its current low stock size. The choking effect of cod is such that the fishing mortality on most stocks is very low. In the absence of shocks, all stocks increase under the three climate scenarios, although to much lower biomasses in the case of the worst-case scenario (Figure 5). In all cases, stocks are well above MSY $B_{trigger}$ (the two stocks that were below recover quickly).

When the shock (poor recruitment) were implemented separately on each stock, this caused a temporary decline in the biomass of the corresponding stock, which did not affect the stocks' capacity to recover to safe SSB levels under all scenarios, and any delays caused by the shock were relatively short-term (all stocks above MSY $B_{trigger}$ by 2030). Recruitment shock on cod had small consequences for the other stocks as it amplified the choking effect of cod (induced by the Landing Obligation) and therefore results in a roughly 10 % lower catch and therefore larger SSB (maximum 5 %) for the other stock (except in the first years of simulation, where the opposite is observed).

Stock	Scenario	Long-term development without shock	Resilience	Remarks
Cod				
	Status quo	SSB increases until 2030 and stabilises afterward at nearly 400kt (when $F_{target}=F_{MSY}$) and 520 kt (when $F_{target}=F_{MSY}$_low). SSB above MSY $B_{trigger}$ in the first years of simulation		
	Most likely	Similar to 'base case'	No stock decline after the shock, only a delayed recovery (max difference is SSB 17% lower than with no shock observed on the third year after shock)	The shock on cod also affects the other stocks: – First years: poor 2019 recruitment means a higher F has to be applied to catch the 2020 quotas (not simulated, but data). This results in catches for all stocks in 2020 higher than without shock, and biomass lower (although less than 5 %) in the first five years – Then: cod stock being smaller with shock than without, F is lower and stock levels in long term are above their trajectories without shock
	Worst case	SSB increases until 2030 and stabilises afterwards at nearly 300kt (when $F_{target}=F_{MSY}$) and 400kt (when F_{target} $=F_{MSY}$_low). SSB above MSY $B_{trigger}$ in the first years of simulation	No stock decline after the shock, only delayed recovery (max difference is SSB 28 % lower than with no shock observed on the third year after shock)	
Haddock				
	Status quo	Stock increases until 2030 to 400 kt and 450 kt (for F_{target} at F_{MSY} and at F_{MSY}_low respectively), always above MSY $B_{trigger}$		
	Most likely	No long-term climate effect for this stock	No shock for this scenario	
	Worst case	No long-term climate effect for this stock	No decline after the shock, the stock remains stable at levels above MSY $B_{trigger}$ over	Shock here is defined as absence of recruitment spike in the first 10 years

Stock	Scenario	Long-term development without shock	Resilience	Remarks
			the first 10 years, and then increases	No effect on resilience of the F_{target} used
Plaice				
	Status quo	The SSB increases continuously without reaching any plateau (to 2.3mt and 2.5mt in 2035 with F_{target} set at F_{MSY} and F_{MSY}_lower respectively). Well above MSY $B_{trigger}$		
	Most likely	Very similar to 'base case', only marginally lower SSB	No decline after the shock, the stock has similar trajectory to that seen with no shock (4 % lower)	Shocks have little effect because the stock is very healthy at the start of the simulation and absence of poor recruitment(55 % of prediction from stock-recruitment model)
	Worst case	Very similar to most likely, only marginally lower SSB	No decline after the shock, the stock has similar trajectory to that seen with no shock (9 % lower)	
Sole				
	Status quo	The SSB increases continuously without reaching any plateau (to 150kt and 180kt in 2035 with F_{target} set at F_{MSY} and F_{MSY}_lower respectively). Well above MSY $B_{trigger}$		
	Most likely	Same as 'base case'	SSB does not decrease after the shock, but remains constant for one year before increasing, but with a delay compared to non-shock trajectory (max annual difference of -17 % two years after the shock)	Sole is the stock for which the magnitude of the recruitment shock is the largest (27 % of prediction from stock-recruitment model) No long-term climate effect for this stock, therefore 'most likely' and 'worst case' scenarios without shock is identical
	Worst case	Same as 'base case'	SSB does not decrease after the shocks, but remains constant for two years before increasing, but with a delay compared to non-shock trajectory (max annual difference of	

Stock	Scenario	Long-term development without shock	Resilience	Remarks
			-30 % 2 years after the second shock)	
Saithe				
	Status quo	Stock increases until 2027 and then decreases to levels similar to current levels by 2035, remaining well above MSY $B_{trigger}$ (maximum SSB is around 700kt and 800kt with F_{target} set at F_{MSY} and F_{MSY}_lower respectively)		This stock has a Ricker stock-recruitment model implying strong density dependence. The period of high biomass around 2026-2027 leads to a decrease in recruitment, which explains the decrease in SSB in the second part of the simulation
	Most likely	Same as ‘base case’	No decrease in stock size following the shock, but a delay of about one year compared to the trajectory with shock (max annual difference of -16 % 2.6 years after the second shock)	For this stock, the influence of long-term climate change on recruitment is weak, therefore trajectories without shock are similar in all scenarios
	Worst case	Same as ‘base case’	No decrease in stock size following the shock, but a delay of about 32 years compared to the trajectory with shock (maximum annual difference of -30 % three years after the second shock)	
Whiting				
	Status quo	Stock increases until 2026 and reaches a plateau at 275kt and 290kt (with F_{target} set at F_{MSY} and F_{MSY}_lower respectively). After 2021, the stock is above MSY $B_{trigger}$		
	Most likely	Similar to ‘base case’	Decrease in the year following the shock and then trajectory similar to non-shock scenario, with a delay afterwards (maximum 10 % lower, two years after the	Choice of F_{target} (F_{MSY} or F_{MSY}_low) has little impact on the dynamics shortly after the shock

Stock	Scenario	Long-term development without shock	Resilience	Remarks
			shock). Stock above MSY $B_{trigger}$ after 2022	
	Worst case	Similar to 'base case'	Decrease in the year following the shock and then trajectory similar to non-shock scenario, with a delay afterwards (maximum 17 % lower, three years after the shock). Stock above MSY $B_{trigger}$ after 2023	

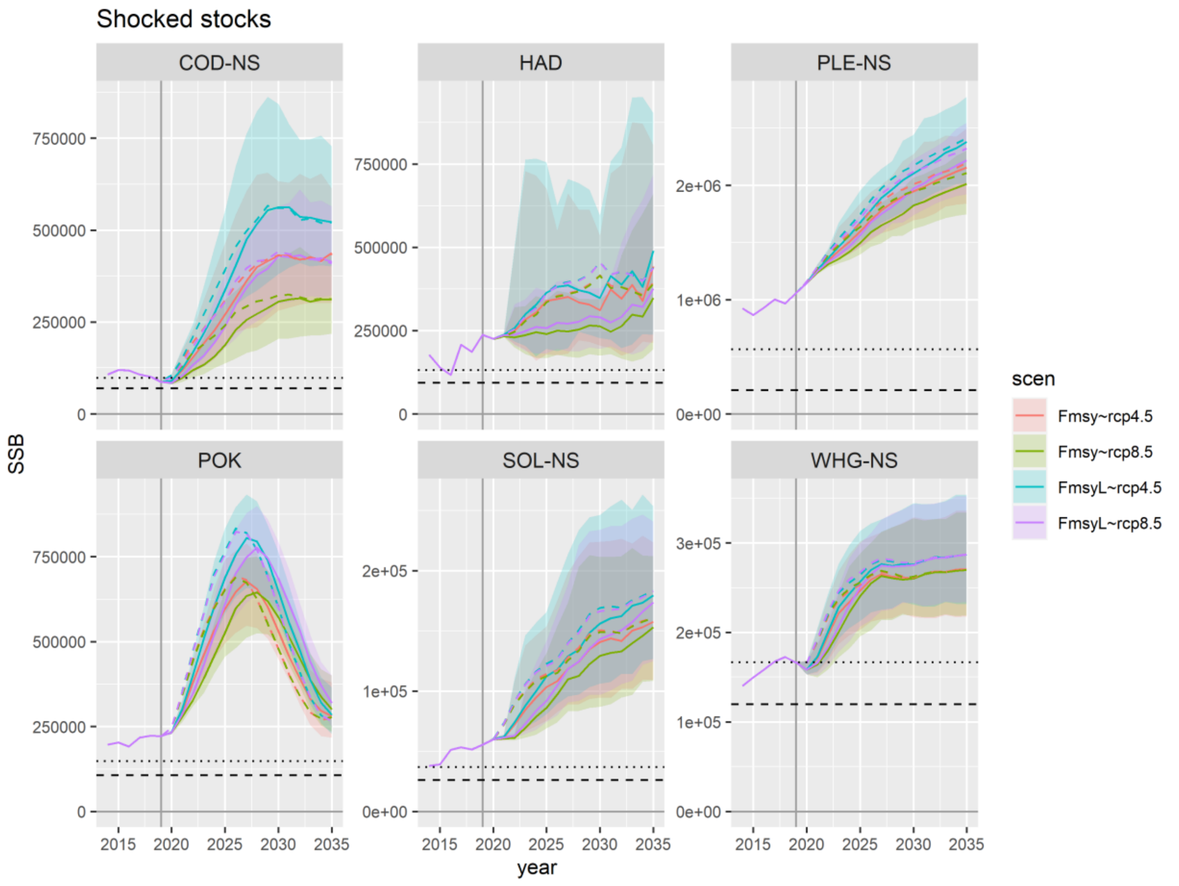


Figure 5 Spawning stock biomass (SSB in tons) by stock (North Sea cod COD-NS, haddock HAD, and plaice PLE-NS), climate change projection, and target F under scenarios with recruitment shock to COD-NS (combinations of RCP scenarios and F target at Fmsy or FmsyL i.e., Fmsy lower bound range). Solid grey reference lines indicate zero (horizontal) and the starting projection year (2019). Horizontal black lines denote $B_{trigger}$ (dotted) and B_{lim} (dashed) reference points for each stock. For each scenario ('scen'), shaded and coloured areas show the 5 % and 95 % quantiles and solid coloured lines show the median of all runs (n=100). Dashed coloured lines show the respective median of scenarios without shocks. Scenario ID format is Harvest Control Rule (HCR)~(Climate Change) CC.

North Sea herring (Annex 10)
Summary of the results: Simulations with climate change show a decline in SSB related to a lower level of recruitment (Figure 6). Under the current F_{MSY}, this leads to high biological risk (Figure 7). Risk is greatly reduced if a more conservative estimate of F_{MSY} is used. The occurrence of a single shock accelerates the decline, but does not increase risk substantially. The occurrence of two shocks results in a dip in the SSB trajectory, with a corresponding increase in the biological risk. In both cases the risk can be reduced to lower levels (<20 %) if the more conservative F_{MSY} estimate is used.

Stock	Scenario	Long-term development without shock	Stock resilience to short-term shock	Remarks
North Sea herring				
	Status quo	Increase in SSB followed by a decrease in the short term, and then stable at around 1.5mt after 2023		No F_{MSY}_low available Two alternative management options (based on different F_{MSY} estimation methods) are tested: – highRef (less conservative): Higher F_{target}/lower trigger point – lowRef (more conservative): lower F_{target}, higher trigger point
	Most likely	SSB declines after 2023 to around B_{lim} (874kt) in 2027 (highRef) or around 1.2mt (lowRef) and is stable thereafter. With highRef, there is a high probability of the stock being below MSY $B_{trigger}$ and even below B_{lim} in 2030. The risk is reduced, but remains high with lowRef	Shock accelerates the decline in SSB, but does not increase biological risk. The probability of recovery above MSY $B_{trigger}$ is low, but mainly because of the long-term trend in the stock	
	Worst case	SSB declines to just above 1mt (highRef) and 1.3mt (lowRef) in	Two successive shocks result in a deep in the SSB	For this case study, the temperature projections for RCP8.5 are higher than for RCP4.5 for the period covered by the simulations. This explains the larger SSB for this scenario

Stock	Scenario	Long-term development without shock	Stock resilience to short-term shock	Remarks
		2027, with some oscillations afterwards	(reached in 2026), leading to an increased biological risk (especially for highRef)	

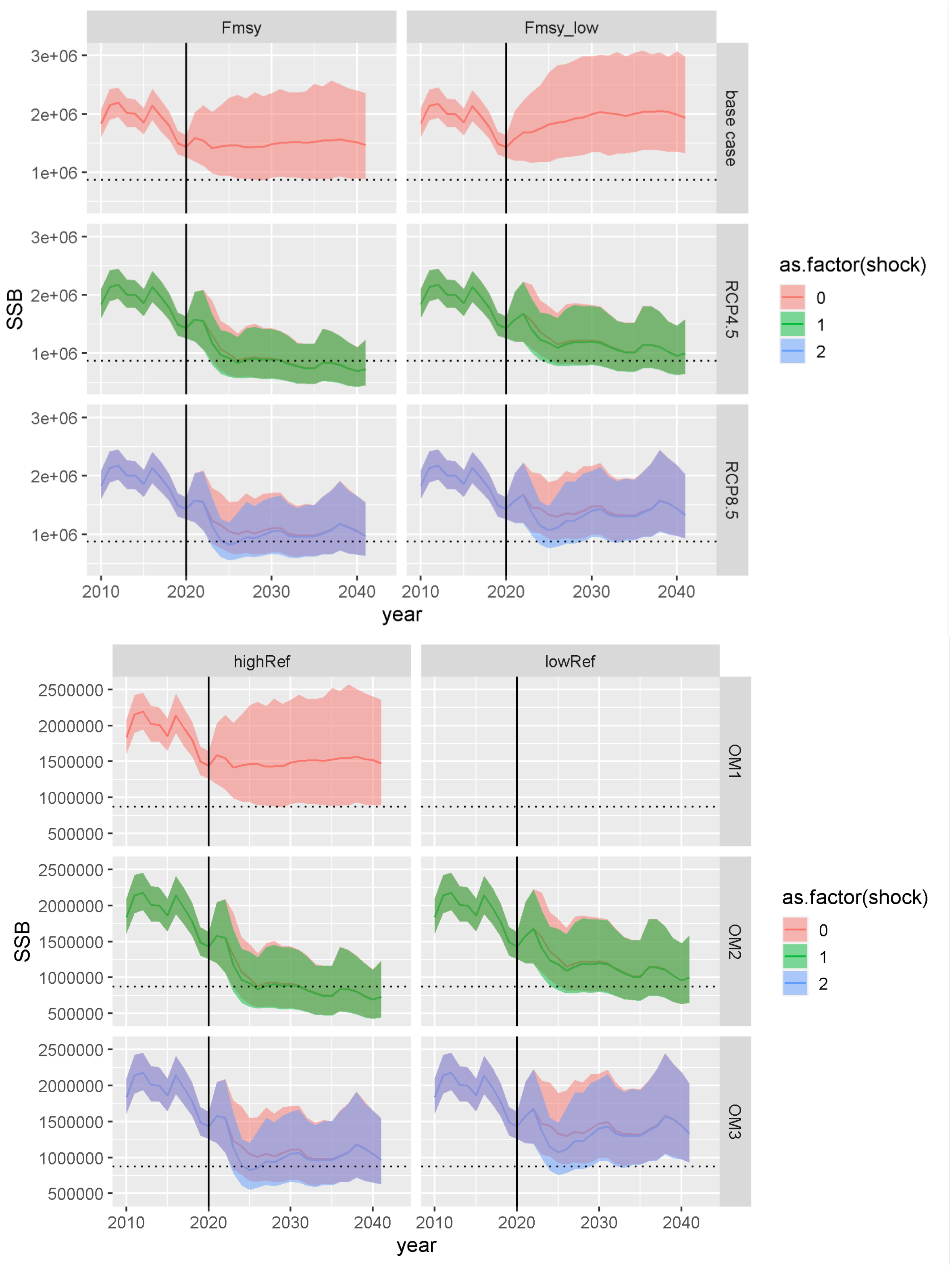
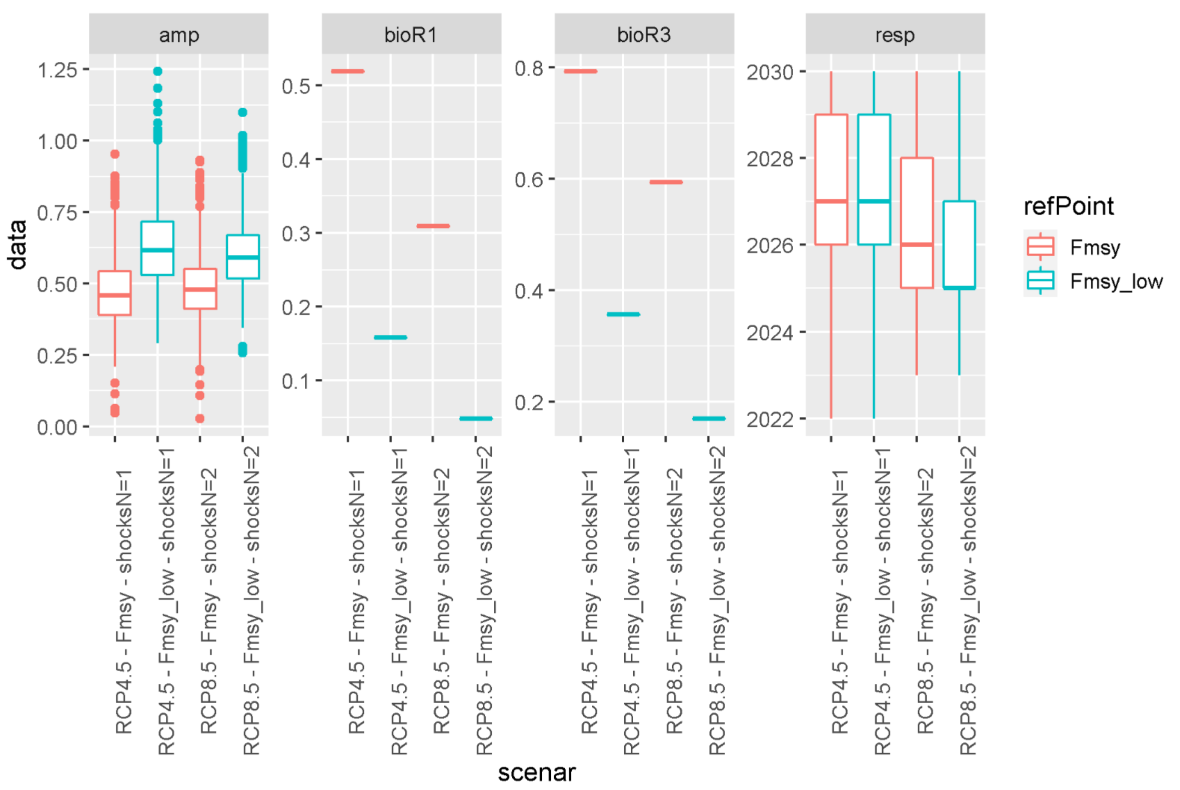


Figure 6 Simulated SSB (tons) trajectories for North Sea herring under two different fishing mortality targets and for different climate scenarios.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bioR1
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resp
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scenar
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Fmsy
Fmsy_low
RCP4.5 - Fmsy - shocksN=1
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RCP8.5 - Fmsy - shocksN=2
RCP8.5 - Fmsy_low - shocksN=2
0.00
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0.50
0.75
1.00
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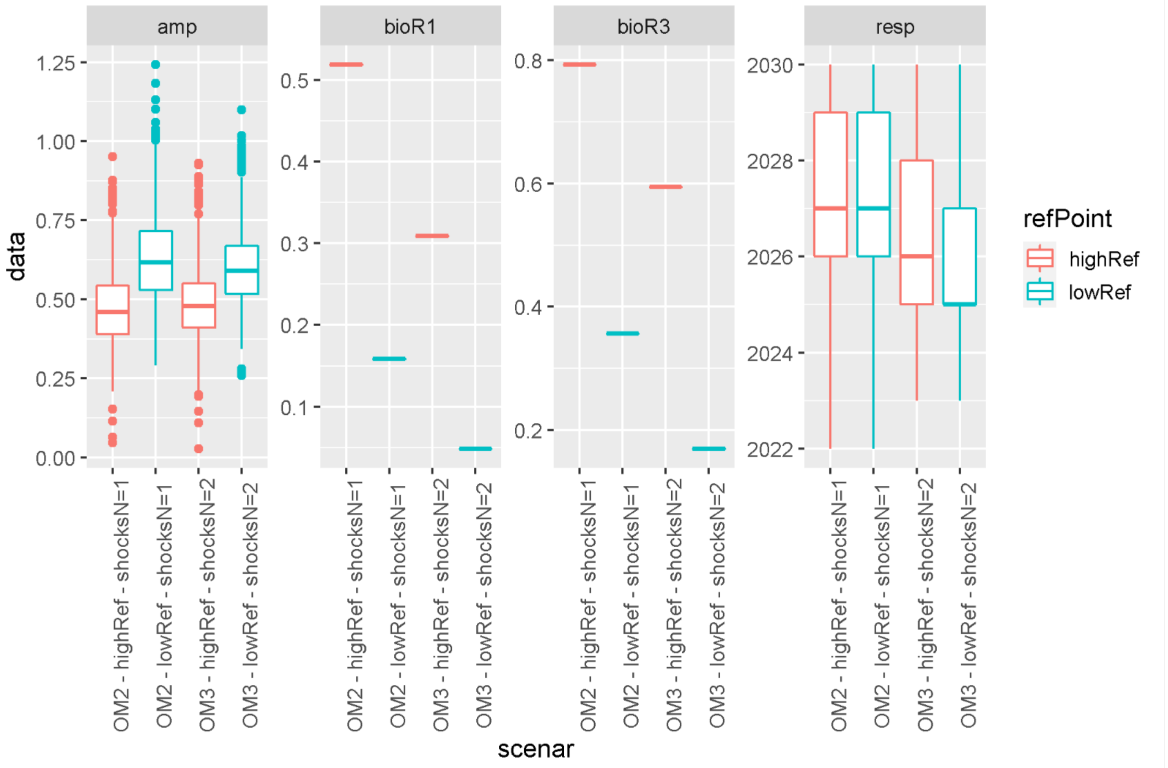
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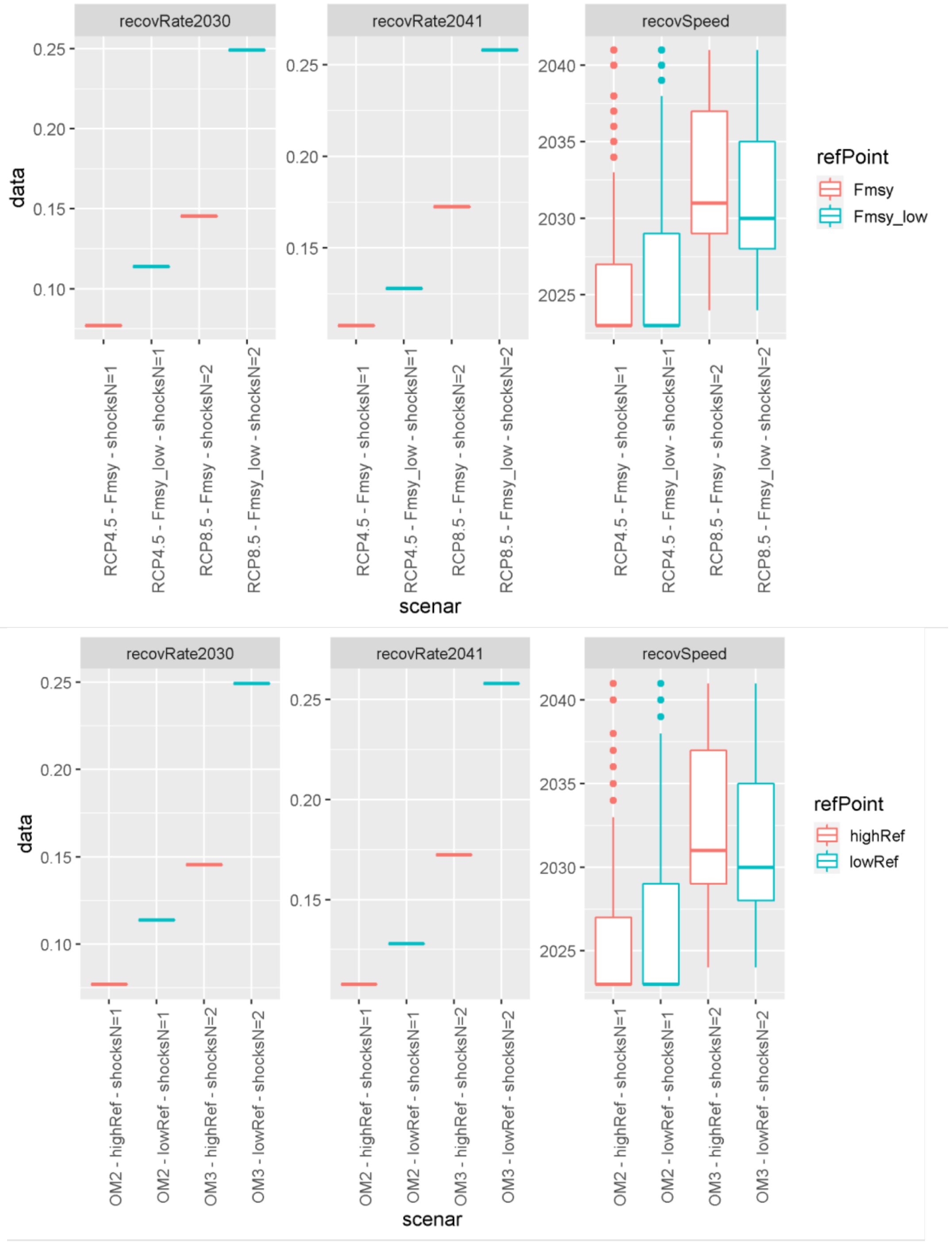

Figure 7 Indicators of resistance and resilience for North sea herring. Amp: amplitude, bioR3: probability of SSB falling below Blim; resp: responsiveness; recoRate 2030 and 2041: recovery rate by 2030 and 2041; recovSpeed: recovery speed

Northeast Atlantic mackerel (Annex 11)

Summary of the results: Because of its current high level, the mackerel stock is resilient for both the ‘most likely’ and ’worst case’ scenarios (Figure 8, Figure 9). Recovery is only partial by 2030, but (almost) full recovery is achieved by 2058. However, the stock does go through a period of increased biological risk ($p(SSB<B_{lim})>5$ % when managed based on F_{MSY}. This is not the case when managed based on F_{MSY}_lower. Resilience could also be improved if there were an international TAC sharing agreement.

Stock	Scenario	Long-term development without shock	Stock resilience to short-term shock	Remarks
NEA mackerel	Status quo	Stock decreases in the short term and stabilises at 2.8mt and 3.7mt (for F_{MSY} and F_{MSY}_lower based management respectively)		Non-compliance with MSY advice results in F_{bar} higher than F_{target} by 0.02–0.03
	Most likely	Stock decreases in the short term and stabilises at 2.5mt and 3.4mt (for F_{MSY} and F_{MSY}_lower based management respectively)	F_{MSY} target: SSB drops to 55% eight years after the shock, p(SSB>=MSY $B_{trigger}$) is 60 % in 2030 and 96 % at least one year between 2030 and 2058 F_{MSY}_low target: SSB drops to 70 % eight years after the shock, p(SSB>=MSY $B_{trigger}$) is 94 % by 2030 and 100 % at least one year between 2030 and 2058	The shock brings the stock down to levels that are close to equilibrium corresponding to F_{MSY} and F_{MSY}low. Therefore, there is no recovery phase. At these levels the stock oscillates around MSY Btrigger
	Worst case	Stock decreases in the short term and stabilises at 2.3mt and 3.1mt (for F_{MSY} and F_{MSY}_lower based management respectively)	$F_{MSY\ target}$: SSB drops to 47% seven years after the second shock, p(SSB>=MSY $B_{trigger}$) is 40 % in 2030 and 96 % at least one year between 2030 and 2058 Fmsy_low target: SSB drops to 60 % seven years after the second shock p(SSB>=MSY $B_{trigger}$) is 84 % by 2030 and 100 % at least one year between 2030 and 2058	After the shock, there is an initial recovery, but SSB then declines again due to long-term productivity decrease

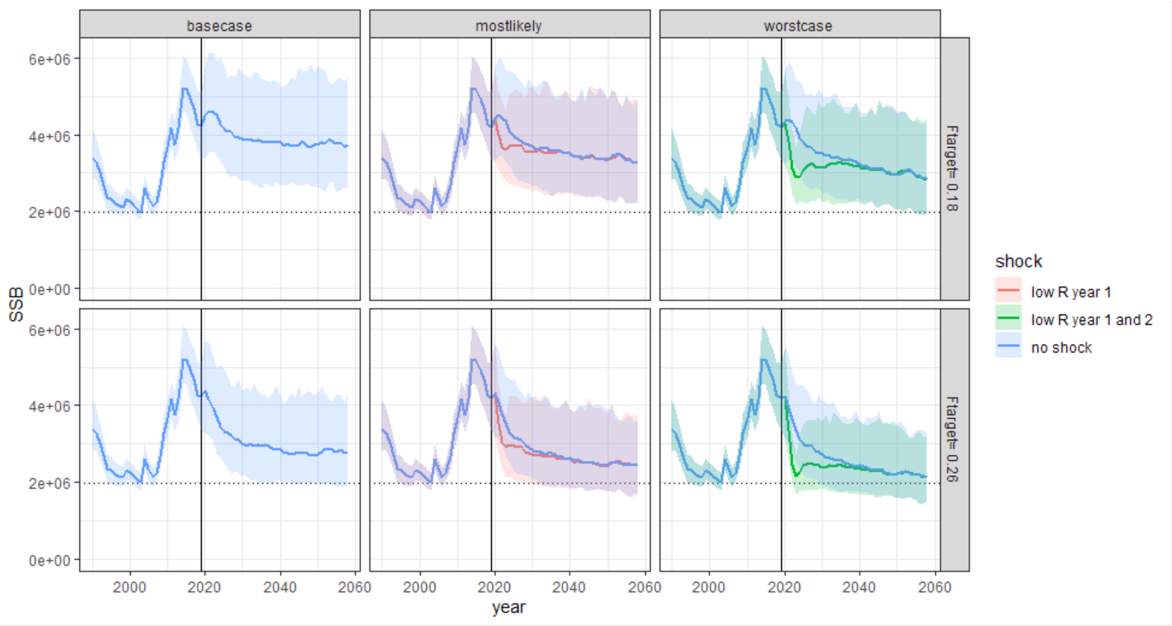

Figure 8 NEA mackerel: simulated mackerel SSB (in thousand tons) for the three scenarios ('base case', 'most likely', and 'worst case') on long-term effects of climate change (columns) and for target fishing mortality set at 0.18 (F_{MSY}_lower) and at 0.26 (F_{MSY}). The colours depict the different scenarios for the short-term shocks, the horizontal dotted line represents B_{lim} and the vertical black line shows the starting year of the simulations

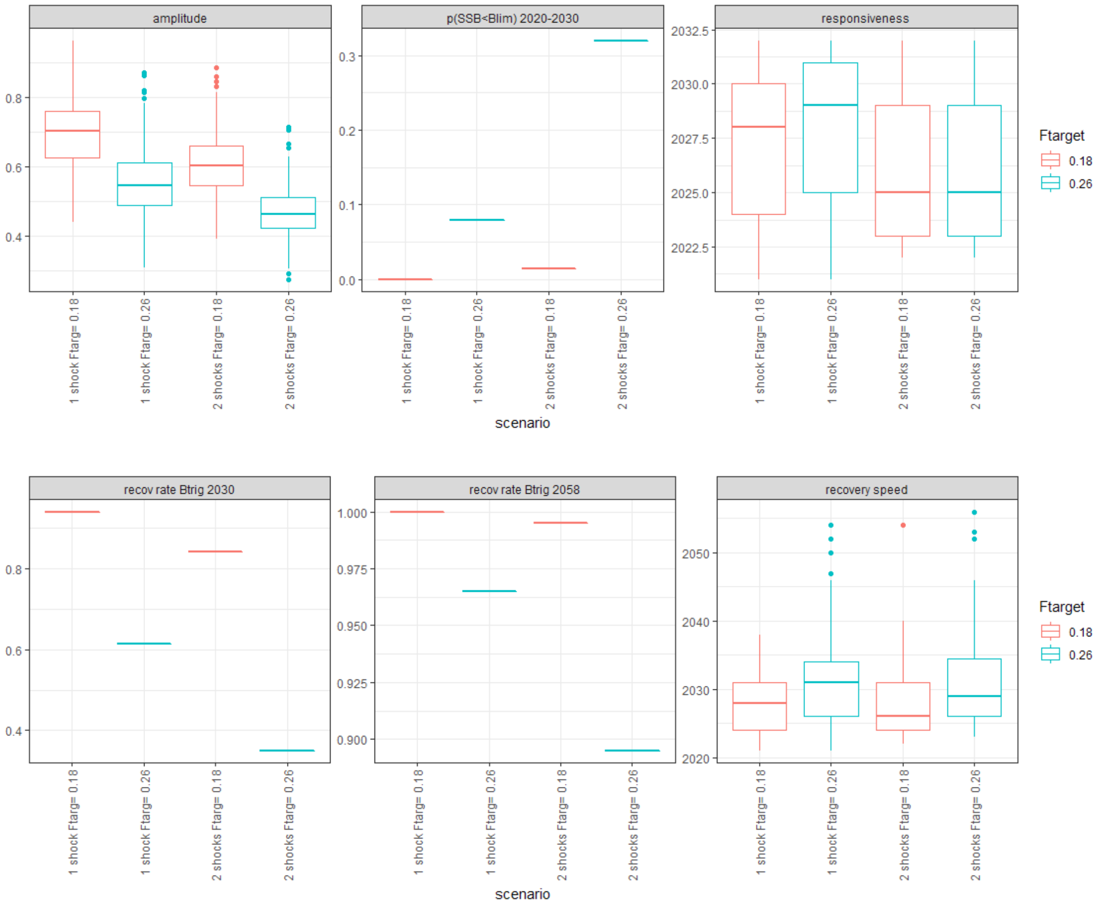

Figure 9 Indicators of stock resilience following a short-term shock for the different scenarios.

North Sea sprat (Annex 12)

Summary of the results: Sprat is a short-lived species and has a quick reaction to a bad recruitment episode (reaches a minimum the year after the shock and recovers two or three years later, Figure 10, Figure 11). The stock is at an increased biological risk (p(SSB<B_{lim})>5 %) in the years following the shock. Applying a lower fishing mortality (60 % of F_{cap} was lowest tested value) reduces the risk, which, however, remains well above 5 %. The SSB in 2030 had a similar distribution for all cases (four starting conditions, with and without shocks), but scenarios with poorer initial stock level had to go through a period of increased biological risk.

Stock	Scenario	Long-term development without shock	Stock resilience to short-term shock	Remarks
North Sea sprat	Status quo	Applying F_{cap} (current basis for advice), SSB decreases by 5 % over the simulation period, and p(SSB<B_{lim})>5 % after 2023		Other assumptions on stock status in 2021 were also investigated

Stock	Scenario	Long-term development without shock	Stock resilience to short-term shock	Remarks
	Shock	The SSB declines by roughly 50 % in the year following the shock and recovers after two years	Increase p(SSB<B_{lim}) to max 45 % for about five years, no difference with non-shock scenario in 2030	No long-term climate effect incorporated, only one shock in 2022

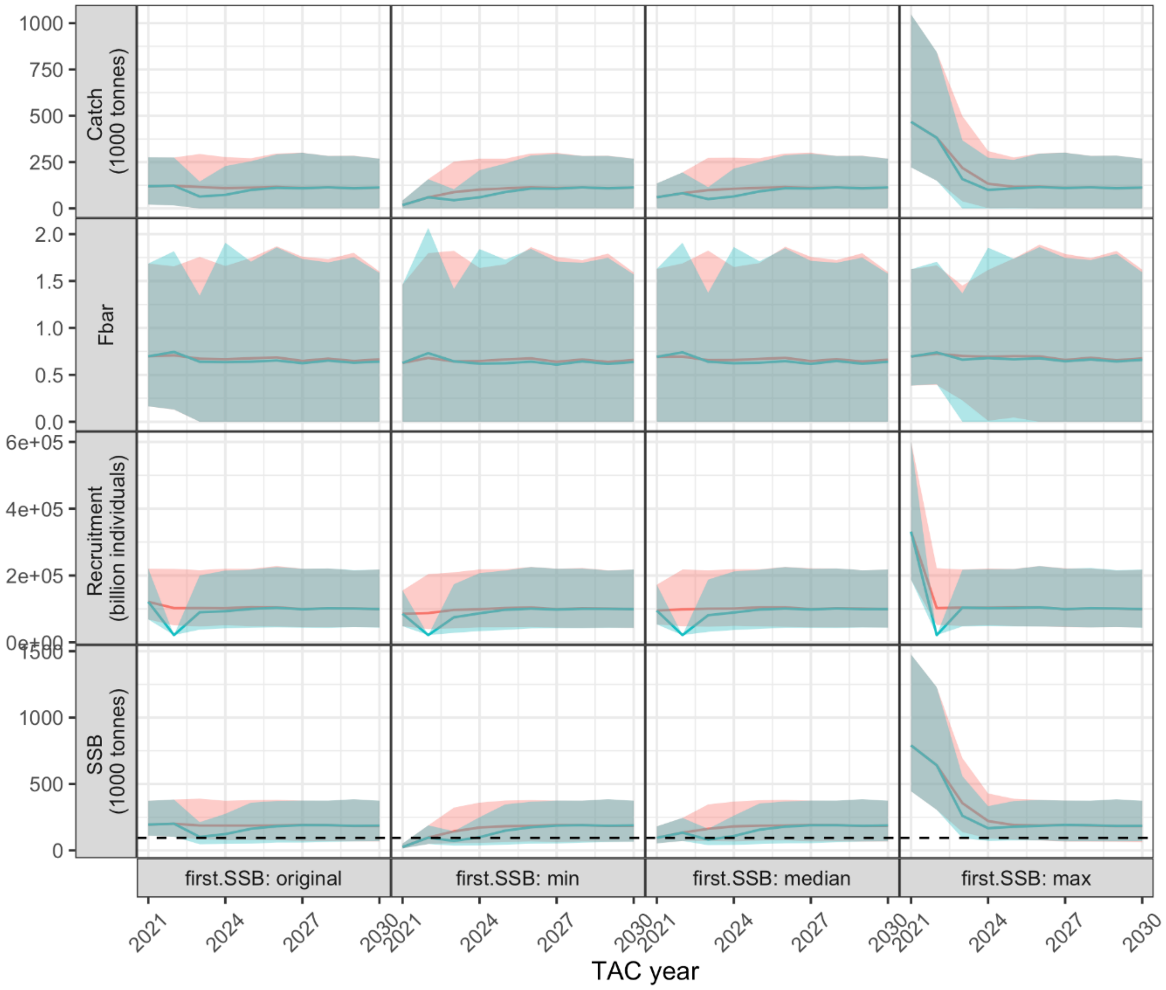

Figure 10 Simulated stock development in MSE. Each panel shows the 0.05, 0.5, and 0.95 quantiles of 1000 replicate simulation trials in one scenario. Red: low recruitment in 2022, blue: no shock. The column corresponds to different starting conditions (original: population abundances in 2021 from stock assessment, min, media and min: population abundances for the year's corresponding to the minimum, median and maximum SSB in the assessment period. Fishing mortality in the simulations is based on the HCR of the real NS sprat fishery which is an escapement strategy with Fcap of 0.69. The horizontal line in SSB is Blim

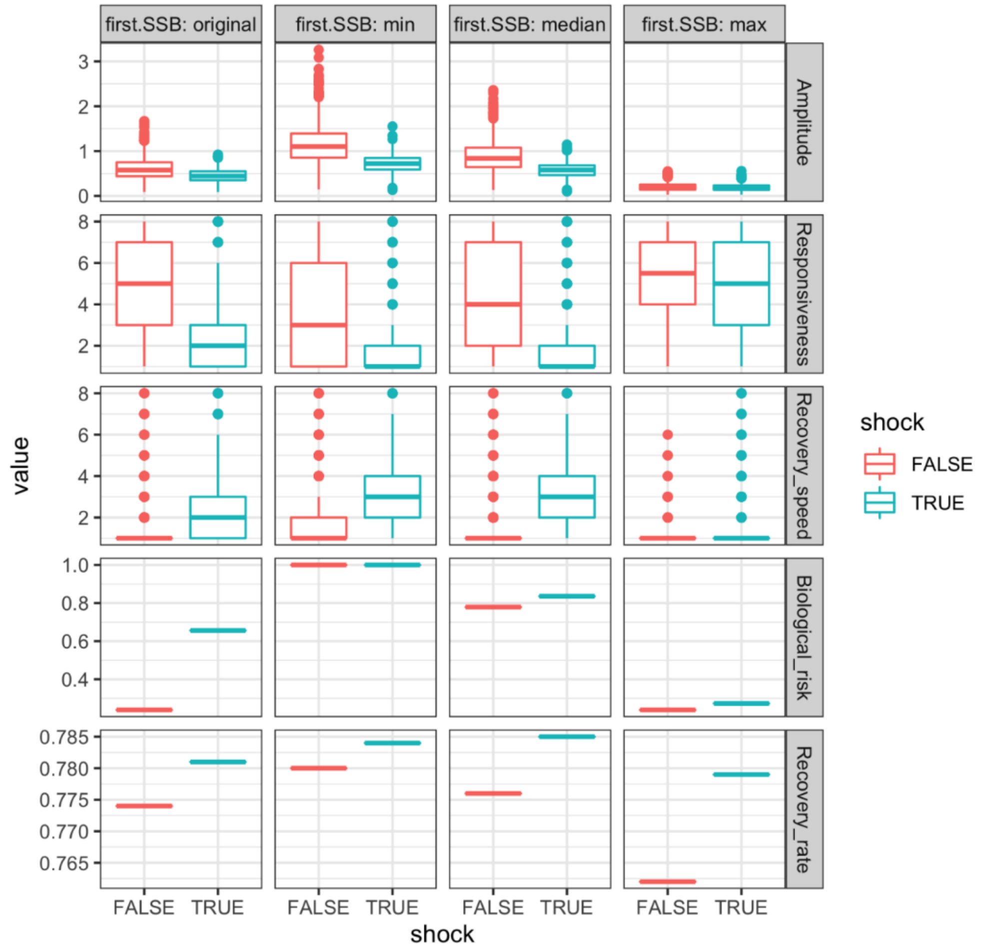

Figure 11 Indicators of resilience for North Sea sprat

Western Mediterranean red mullet and hake stocks (Annex 13)

Summary of the results: The red mullet stock was from geographic sub-area (GSA) 6 that is associated with the central and northern Spanish Mediterranean coast. The hake stock is within a combination of GSAs (1, 5, 6 and 7) from the Alboran Sea to the Gulf Lion, but mainly represents the dynamics of central and northern Spanish Mediterranean coast (GSA 6) and Gulf of Lion (GSA 7) stocks.

For both stocks, projections were performed for $F_{0.1}$ and $F_{statusquo}$, taken as the recent three-year average. In the projections, recruitment was assumed to follow a Beverton-Holt stock recruitment relationship with a steepness of 0.75 and uncertainty was modelled by recruitment deviates to be log normally distributed with a coefficient of variation (CV) of 30 %. Climate change scenarios were considered for natural mortality and the stock recruitment relationship, and compared to ‘status quo’ (i.e., future parameters were the same as their historical values). These were: M Trend 25 % linear increase from 2020 to 2070); M regime shift 25 % change in 2020; growth trend 25 % increase from 2020 to 2070; and stock recruitment relationship trend 25 % decrease from 2020 to 2070.

The resilience indicators are summarised in Figure 12, all quantities are reported as shocked relative to unshocked levels. Unlike for ICES, MSY $B_{trigger}$ is not defined; therefore, 40 %B_{MSY} was used as the limit reference point. The metrics are: A) minimum stock level reached after the shock compared to initial level; B) number of years between the shock and the minimum observed stock level; C) probability of SSB falling below 40 % of B_{MSY}; D) probability that stock level is at or above B_{MSY} in 2030; and E) number of years to reach B_{MSY}.

Stock	Scenario	Long-term development	With Shock
Red mullet	Status quo	The outcomes for fishing at $F_{0.1}$, and F_{SQ} are similar. There is about a 60 % reduction in the level of the stock (panel A) in the year following the shock (panel B). While the probability of falling below 40 %B_{MSY} is low The probability that stock level is at or above B_{MSY} in 2030 (panel D) is reduced if there is a shock of 60 %; While the number of years to reach B_{MSY} is about the same (Panel E)	The stock and yield will be reduced by about 25 %, and will recover to the unshocked level by 2030
	Trend in Growth and SRR (columns)	These had little effect as a comparison across columns showed that there was little difference to the status quo results	The effect of the shock is similar to the status quo status quo M scenario
	Trend or M regime shift in M (rows)	The biggest effect was seen for the regime shift in M. The results for the trend were similar to those in growth and SRR If there were a regime shift, the stock would not achieve B_{MSY} in 2070 and have 100 % chance of being below 40 %B_{MSY}	The shock has less effect than the regime shift
Hake	Status quo	The reduction in the stock is around 65 %, it is slightly lower if fishing is at $F_{current}$ (Panel A) The biggest reduction in the stock is seen in 2022 (panel B) The other metrics are similar, apart from the number of years to reach B_{MSY} because this is not achieved if fishing is maintained at the current level	
	Trend in growth and SRR (columns)	Results are similar to the status quo assumptions	
	Trend or M regime shift in M (rows)	The initial effects of a shock are similar. However, in the long term, the stock will not achieve B_{MSY} and have a high probability of being below 40 %B_{MSY}	

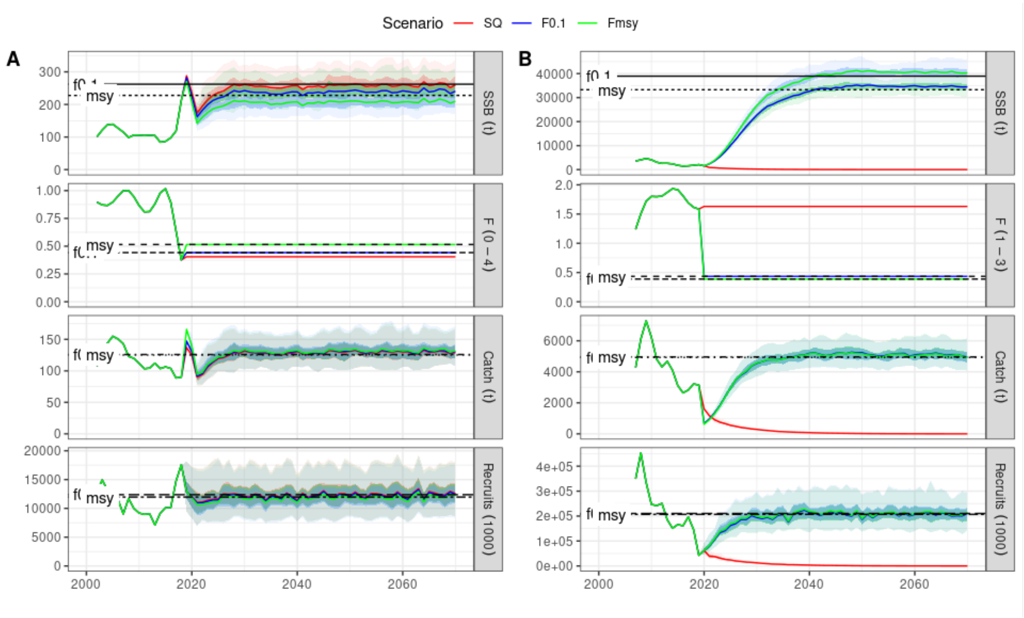

Figure 12 Comparison of projections at $F_{current}$, $F_{0.1}$ and F_{MSY} for no climate change or shocks for A) red mullet, B) hake

Atlantic tropical bigeye and yellowfin tuna (Annex 14)

As well as simulating a shock, due to an increase in M of 150 % in 2020 for sub-unit 2 in quarter 2, projections were run for three long-term scenarios corresponding to i) status quo (no change in future parameters), ii) positive trends in natural mortality (M) and growth for 2020 onwards, and iii) a negative trend in virgin biomass from 2020 onwards (Figure 13).

Currently catches for both stocks exceed the level that would ensure the stock would achieve BMSY in the long-term, based on the advice of the ICCAT scientific committee. Therefore, two catch scenarios were run, based on current catch levels and the level recommended to keep the stock at or above BMSY. The recommended and current catches were 65K and 75K for bigeye and 110K and 135K for yellowfin respectively.

Both stocks are currently below BMSY, and all stocks and sub-stocks only recover to BMSY if there is a shock if there are no climatic effects. The shock had a major impact in the short term because catches were not reduced, as they would be under an F management scenario. If there was a shock, and the recommended catches were exceeded then time to recover increased (and for most sub-stocks did not occur within 50 years), and some sub-stocks collapsed. For the carrying capacity scenario (K) similar behaviour was seen but recovery time was longer and more sub-stocks collapsed. For the change in M all stocks collapsed.

Stock	Scenario	Long-term development	With shock	Remarks
Bigeye	Status quo	The stock only attains the B_{MSY} level in the long term if catches are as recommended by ICCAT, and not the current catches	The shock has an effect in the medium term, reducing the stock For stock-unit 1 and with a shock and current catches	The impact varies by stock unit, and assessment scenario. However, the trends are the same

Stock	Scenario	Long-term development	With shock	Remarks
			there is a high probability of falling below the limit reference point 40 %B_{MSY}	
	Trend in K	A trend in K results in a large reduction in SSB relative to B_{MSY} at current catch levels. If catch is at the recommended level, the decline is less, but at best the stock is at 80 % of B_{MSY} in the medium term	The shock has a big effect in the medium and long term	
	Trend M	A trend in M has a large impact in the medium and short terms, reducing SSB to below 40 % of B_{MSY}	With or without a shock, the stock collapses	
Yellowfin	Status quo	The stock only attains the B_{MSY} level in the long term if catches are as recommended by ICCAT, and not the current catches	The shock has an effect in the medium term, reducing the stock	The impact varies by stock unit and assessment scenario. However, the trends are the same
	Trend in K	A trend in K results in a longer time for stocks to recover after a shock	The shock has a big effect in the medium and the long term if the current catch level is maintained	
	Trend in M	A trend in M has a large impact in the medium and short term, reducing SSB to below 40 % of B_{MSY}	With or without a shock the stock collapses	

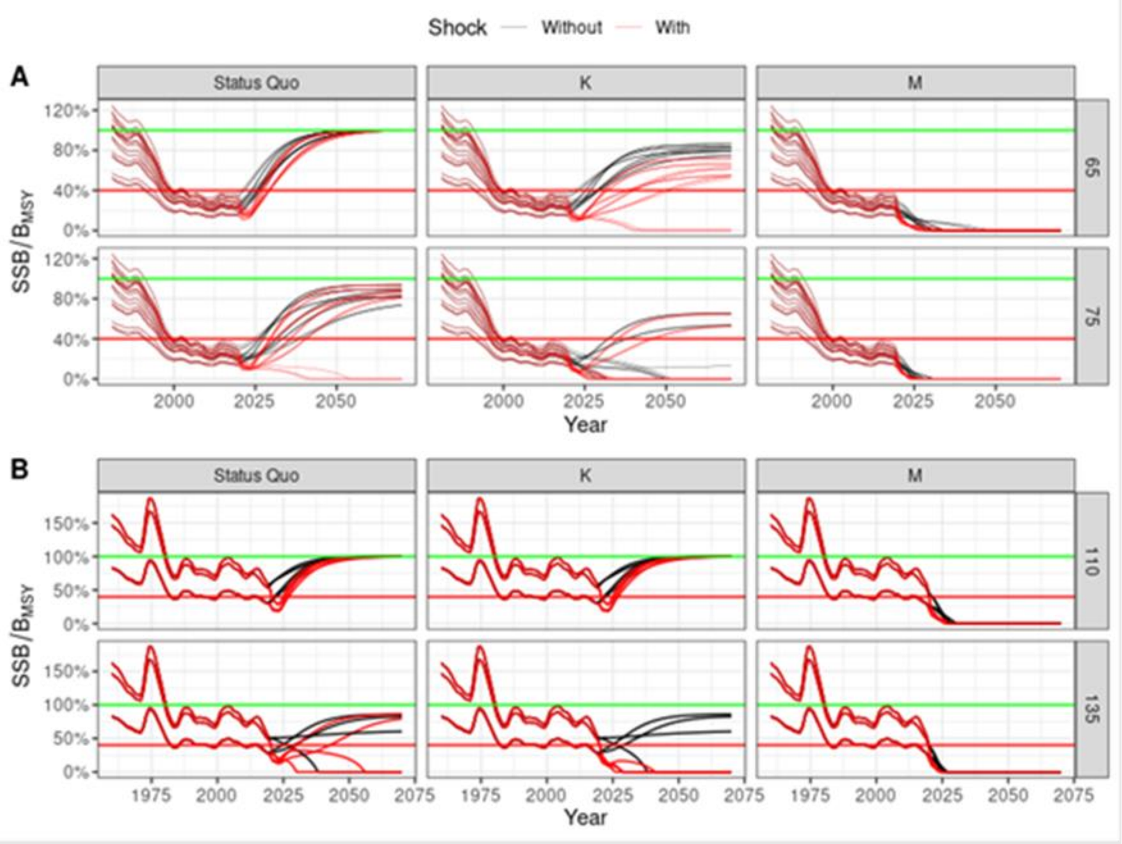

Figure 13 Time series, for stock unit 2, of SSB relative to the long-term realised SSB under the recommended catch and Status Quo scenario, lines are for the different assessment scenarios; A) bigeye, B) yellowfin.

2.3.1 Ecological resilience

Baltic Sea ecosystem - Atlantis model (Annex 15)
Summary of the results: The shock scenario tested for the Baltic Sea ecosystem were relatively mild (50 % decrease in recruitment in one or two consecutive years) and overall had only a minimal impact on the stocks (8 % amplitude at most, Figure 14) with little repercussion on other species groups. The recovery rate of the short-term shocks is usually around 11 years for a one-year shock and 12 years for a two-year shock.

Scenario	Stock developments	Ecological resilience
Cod: poor recruitment	Only small difference compared to status quo with (max 3 % lower for cod, four years after the shock) No impact on other commercial stocks Small negative impact on harbour porpoise (<1 % lower than baseline)	Minimal change in demersal/pelagic ratio (-2 % maximum with two shocks)
Herring: poor recruitment	Small effect of the shock on herring (4 % and 8 % lower than status quo with one and two shocks respectively) No impact on other commercial stocks Small negative impact on harbour porpoise, seal and birds (<2 % lower than baseline)	Minimal change in demersal/pelagic ratio (+2 %)

Scenario	Stock developments	Ecological resilience
Sprat: poor recruitment	Small effect of the shock on herring (4 % and 8 % lower than status quo with one and two shocks respectively) Minor negative effect on cod and herring (<1 % difference with status quo) and on seals and birds (<2 % max difference) Minor positive effect on copepods (max 2 % higher than without shock)	Small increase in demersal/pelagic ratio (up to 8 % with two shocks, return to initial after 12 years)

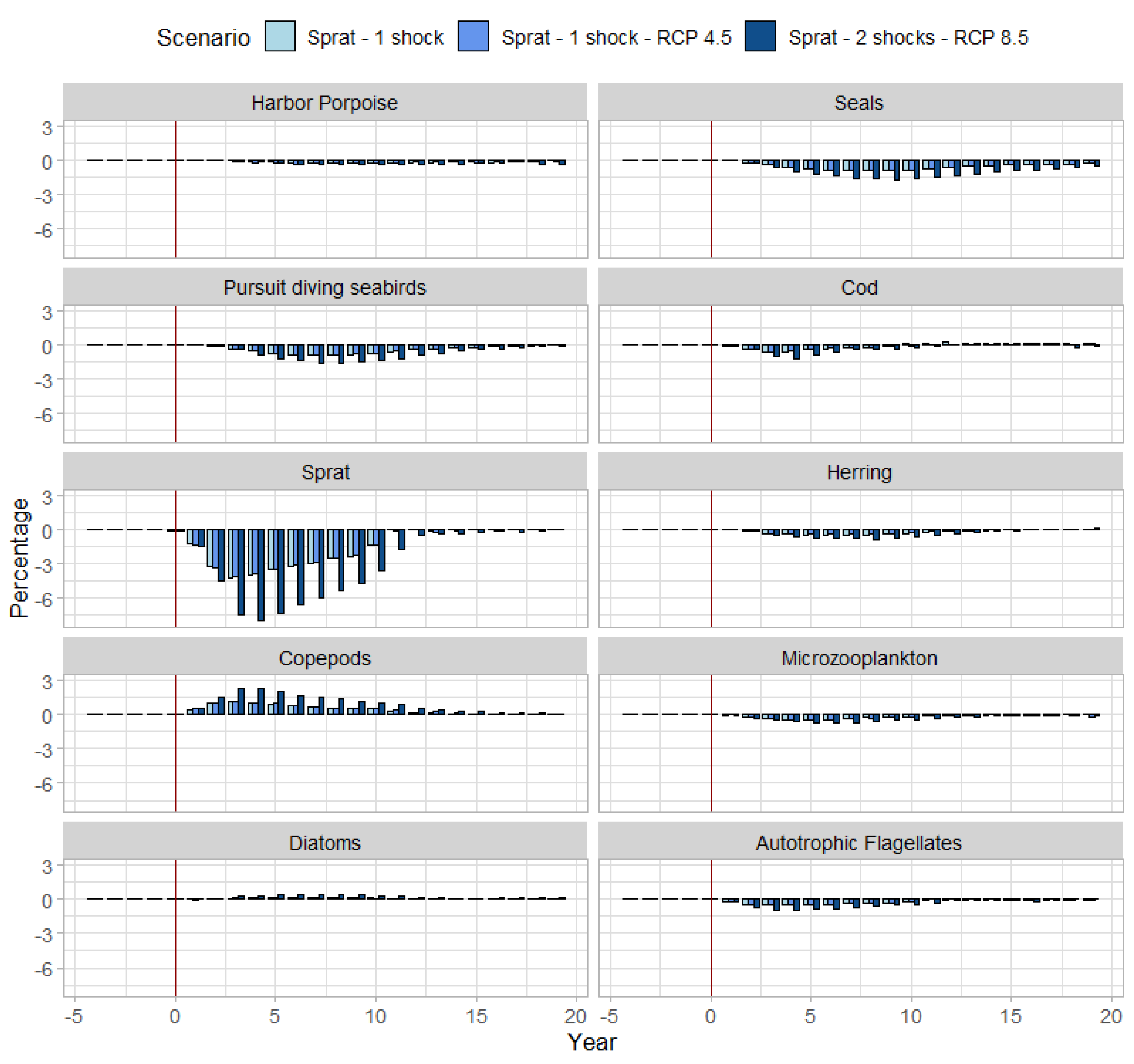

Figure 14 Shock scenarios for sprat of −50 % recruitment compared to the baseline. The y-axis shows the relative change in percent compared to the status quo scenario (no shock or long-term effects). Results are presented for: one shock at the beginning of the simulation period for present climate (light blue); one shock and RCP4.5 (mid blue); and for two consecutive shocks and RCP8.5 (dark blue). Results are shown for a selection of functional groups according to the objectives and focus of the study

Southern North Sea - Ecopath with Ecosim (Annex 16)
Summary of the results: The different types of shocks did not lead to a long-term change in the ecosystem, or an entire regime shift. Indicators showed that the ecosystem returns to its original state at the latest by the end of the long-term projection (figures 19 and 20). Responsiveness revealed that impacts on the entire ecosystem, such as a heatwave, leads to an instantaneous reaction, while shocks in recruitment need to cascade through the ecosystem prior to inducing a change in ecosystem indicators that reflect the majority of the ecosystem. Shocks to lower trophic productivity had the most profound impact on commercial stock biomass and ecosystem structure and function. Reducing or stopping fishing buffered the impact of the heatwave shock, but this effect was small (Figure 15, Figure 16).

Scenario	Stock developments	Ecological resilience
RCP4.5 vs RCP8.5	Differences start to appear after 2050. Cod biomass decreases from just under 150kt around 2015, to just above 140kt in the long term. Herring is stable at around 1.2mt. Plaice is stable at around 1.35mt	Resilience to a given type of shock not influence by long-term climate scenario
One shock vs two shocks	Effects on stocks and indicators in the same direction, but larger amplitude and reaction time with two shocks	
Heatwave	Cod biomass decreases (by 15 %) followed after five years by strong increase exceeding biomass in baseline. Herring biomass increases by 40 %; return to baseline after five years. Plaice decreases by 10 % and recovers within five years	Small impact on mean trophic level and diversity index, and increase in demersal/pelagic ratio with fast recovery (< five years). Small impact on BC dissimilarity (5 %) with long recovery time
Poor recruitment	Cod recruitment failure resulted in a 20 % decrease in cod, recovering in less than 10 years, but had negligible effects on other stocks	Very minor impact on ecosystem indicators
	Herring recruitment failure lead of an 8 % decrease in herring biomass (recovered after eight years) and a minor increase in cod	Minor impact on ecosystem, except a small short-term increase in demersal/pelagic ratio
	Plaice recruitment failure lead of an 8 % decrease in herring biomass (recovered after six years) and a minor increase in cod	As for herring recruitment failure
Shock on lower trophic levels	Increased primary production leads to an increase of cod, plaice and herring by 100%, 50% and 200%, returning to base line after 20 years for cod and 10 years for the 2 other stocks.	Strong decrease in demersal/pelagic ratio, and increase in increase in dissimilarity, returning to original values after 20 years
	Decreased primary production results in near collapse for herring, and -50 % and -40 % for cod and plaice, with long recovery time for cod and herring (>2060)	Strong increase in demersal/pelagic ratio, and increase in dissimilarity, returning to original values after 20 and eight years respectively
		Minor changes in indicators

Scenario	Stock developments	Ecological resilience
	Benthos mortality had a negligible impact	

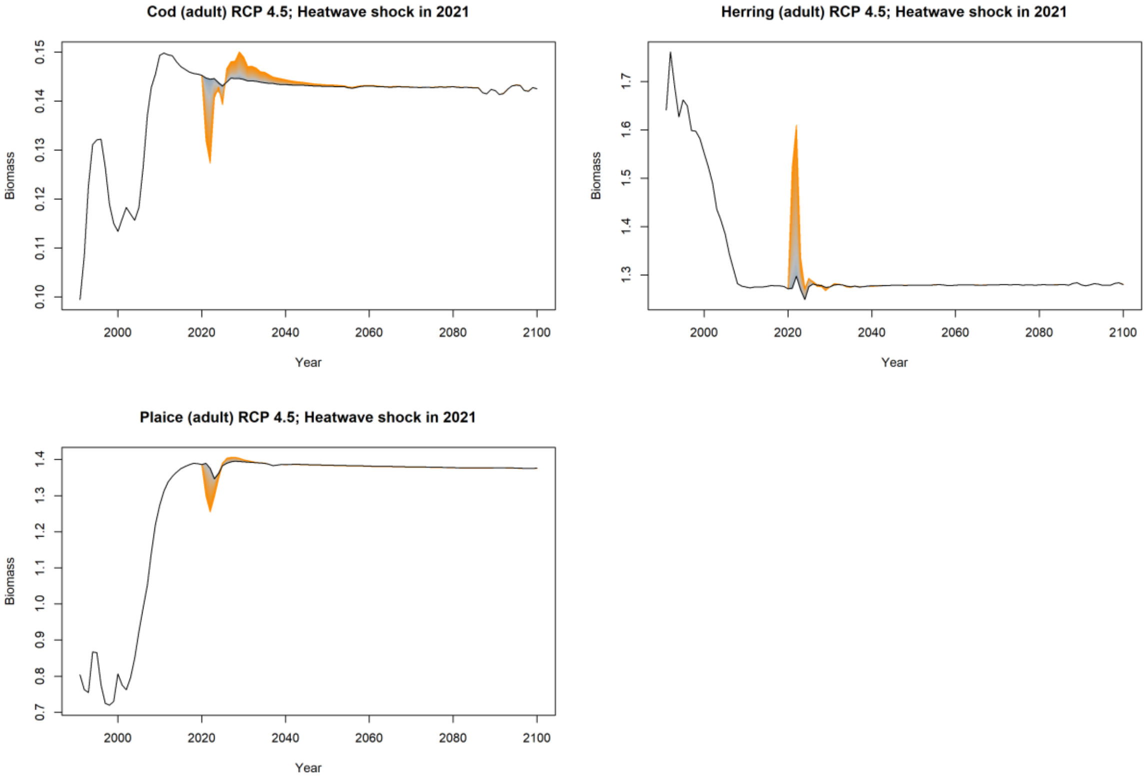

Figure 15 Cod, plaice and herring biomass trajectory for the scenario based on RCP4.5 and a heatwave occurring in 2021 (‘status quo’ fishing effort). The colour gradient indicates the reaction to a range of amplitudes for the shock.

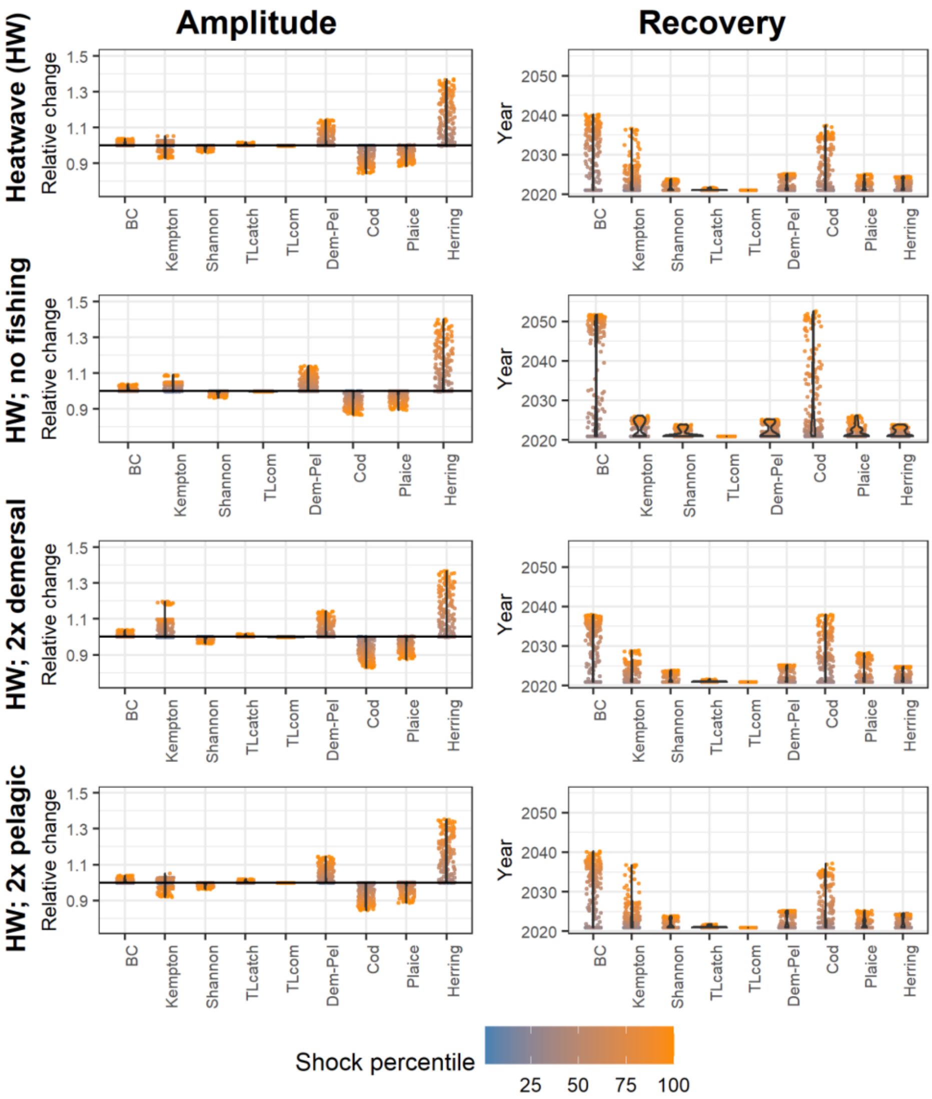

Figure 16 Changes in biomass and indicator values for the ecosystem in the southern part of the North Sea. Fishing regimes displayed are: business as usual, no fishing effort, double demersal fishing effort, and double pelagic fishing effort. 207 heatwaves were simulated from the baseline temperature in 2021 (10.87 °C, 0 percentile) to 15 °C (100 percentile) at increments of 0.02 °C. Amplitude illustrates the maximum biomass deviation from the base scenario (no shock); recovery illustrates the number of years taken for the biomass to return to the level of the base scenario (i.e., where it would have been in the absence of a system shock)

Irish Sea Ecopath with Ecosim (Annex 16)

Summary of the results: The Irish Sea case study showed similar results to the Southern North Sea case study. The different types of shocks did not lead to a long-term change in the ecosystem, or an entire regime shift. Indicators showed that the ecosystem returns to its original state at the latest by the end of the long-term projection (Figure 17, Figure 18). Responsiveness revealed that impacts on the entire ecosystem, such as a heatwave, leads to an instantaneous reaction. Recruitment shocks had limited impacts on ecosystem structure. Shocks to lower trophic productivity had the most profound impacts on commercial stock biomass and ecosystem structure and function. Reducing or stopping fishing buffered the impact of the heatwave shock and impacted the recovery time of stocks. Stocks recovered faster following shocks with reduced fishing. The gradient approach used in this case study also identified tipping-points/non-linearity in stock and indicator response to shock magnitude.

Scenario	Stock developments	Ecological resilience
RCP4.5 vs RCP8.5	Differences start to appear after 2050. Cod and herring biomasses are more negatively impacted under RCP8.5 whereas haddock and Nephrops benefited from the reduced predation mortality.	Resilience to a given type of shock not influence by long-term climate scenario
One shock vs two shocks	Effects on stocks and indicators in the same direction, but larger amplitude and reaction time with two shocks	
Heatwave	Negative heatwave responses were seen for the biomass of cod (-40%), herring (-20%), and whiting (-20%) under the highest amplitude heatwave tested (15°C). Haddock and Nephrops biomass increased due to reduced predation mortality. The impact was mediated by fishing pressure, with reduced fishing reducing stock recovery time.	Small impact on mean trophic level and diversity index, and increase in demersal/pelagic ratio with fast recovery (< five years).
Poor recruitment	Cod recruitment failure resulted in a 20 % decrease in cod, recovering in less than 10 years. Reduced cod led to 5% increase in other stocks due to reduced predation. Whiting recruitment failure led of a 30 % decrease in herring biomass (recovered after 12 years). Haddock recruitment failure led to an initial increase in SSB, but higher amplitudes led to a decrease of 15% (recovered after six years) and a minor increase in Nephrops. Plaice recruitment failure led to 10% decrease in plaice biomass (recovery in 16 years).	Very minor impact on ecosystem indicators Minor impact on ecosystem, except a small short-term increase in demersal/pelagic ratio with cod recruitment failure.
Shock on lower trophic levels	Increased primary production leads to an increase of all key commercial stocks (cod: 50%; haddock: 50%; herring: 125%; Nephrops: 75%; plaice: 25%; sole: 25%; whiting: 125%). Stock recovery spanned between 10 and 20 years. Decreased primary production resulted in biomass declines for all stocks (cod: 40%; haddock: 40%; herring: 70%; Nephrops: 40%; plaice: 25%; sole: 40%; whiting: 60%). Benthos mortality had a negative impact on cod (-5%), haddock (-10%), Nephrops (-15%) and plaice (-2.5%). Sole and whiting had slight positive responses.	Non-linear response in demersal/pelagic ratio due to growth time of pelagic and demersal communities in response to PP increase magnitude. Strong increase in demersal/pelagic ratio (>50%), and increase in dissimilarity, returning to original values after 16 and 13 years respectively. Minor changes in indicators, slight increase in dissimilarity and decrease in demersal/pelagic ratio and biodiversity indicators.

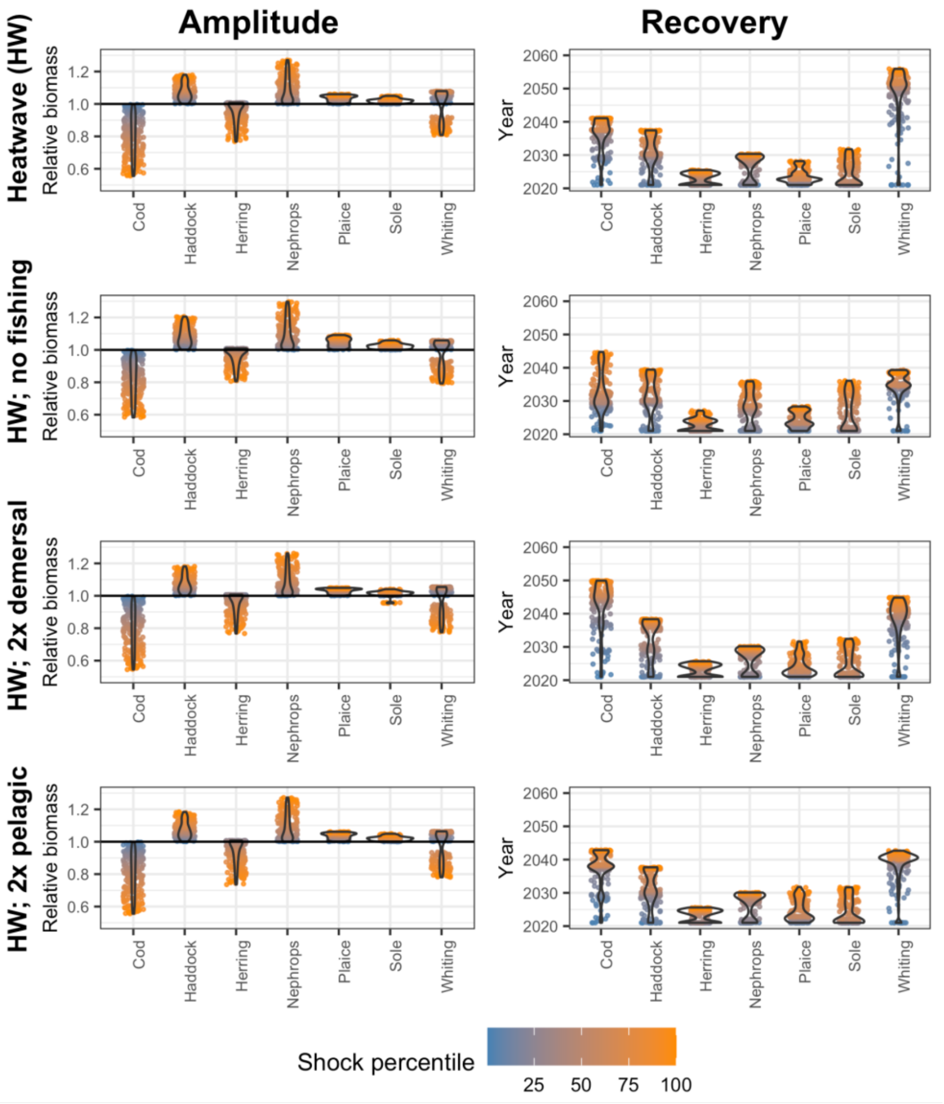

Figure 17 Distributions of biomass responses for commercial stocks from the Irish Sea following heatwave shocks under alternate fishing strategies: business as usual, no fishing effort, double demersal fishing effort, and double pelagic fishing effort. A set of 206 heatwaves were simulated from the baseline temperature in 2021 (10.88°C, 0 percentile) to 15°C (100 percentile) at increments of 0.02°C. Amplitude illustrates the maximum biomass deviation from the base scenario (no shock); recovery illustrates the number of years taken for the biomass to return to the level of the base scenario (i.e., where it would have been in the absence of a system shock)

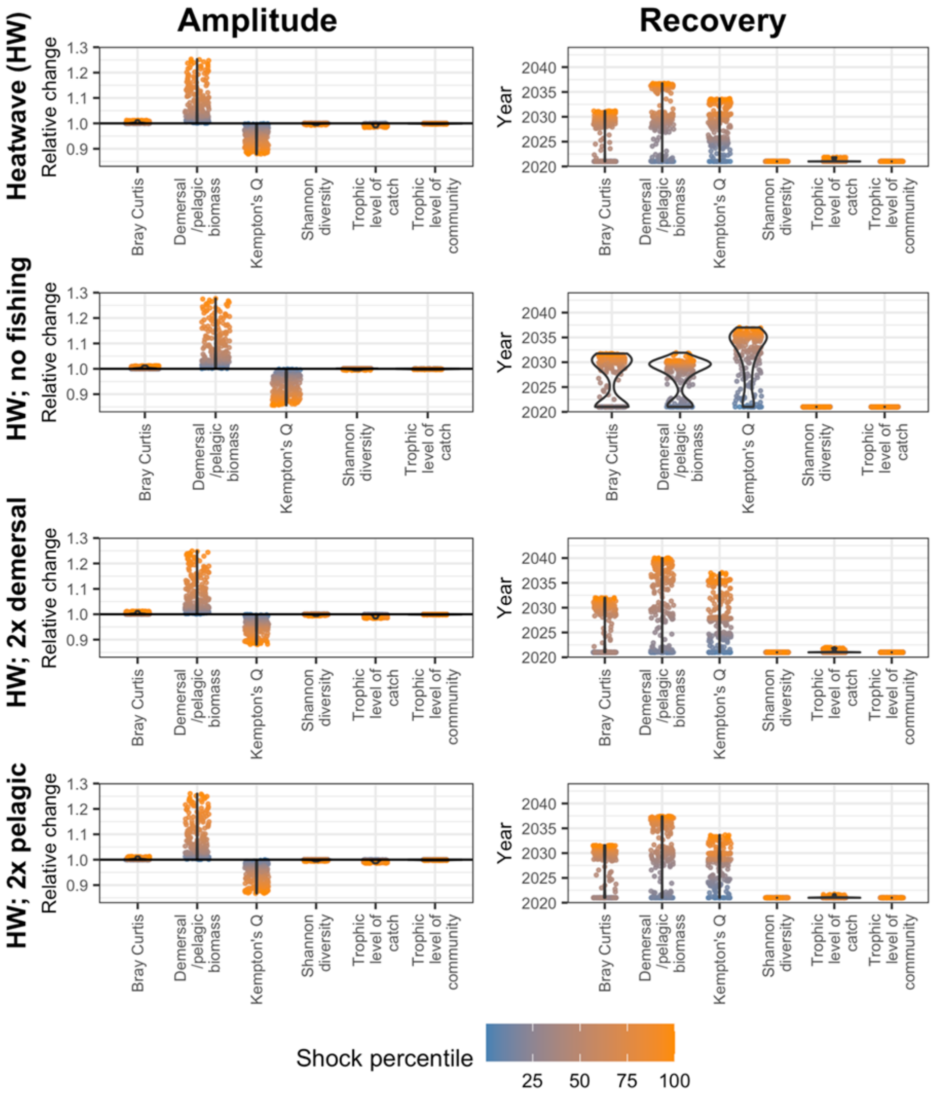

Figure 18 Distributions of Irish Sea ecosystem indicator responses to heatwave shocks under alternate fishing strategies: business as usual, no fishing effort, double demersal fishing effort, and double pelagic fishing effort. A set of 206 heatwaves were simulated from the baseline temperature in 2021 (10.88°C, 0 percentile) to 15°C (100 percentile) at increments of 0.02°C. Amplitude illustrates the maximum indicator deviation from the base scenario (no shock); recovery illustrates the number of years taken for the indicator to return to the level of the base scenario (i.e., where it would have been in the absence of a system shock).

Black Sea Ecosystem Ecopath with Ecosim (Annex 17)

Summary of the results: The two main scenarios tested for the long-term effect of climate change had almost opposite effects. An increased consumption rate for sprat induced by warmer sea surface temperature is beneficial for sprat and negative for its competitor, anchovy. The effect on anchovy then affects other fish species negatively. The opposite is observed, but with larger amplitude, when the consumption rate of anchovy is affected (Figure 19).

When shocks occur (50 % lower consumption rate for either of these two species), an immediate response of the two planktivorous fish species is observed, followed by a cascading effect on other species. Recovery is also faster for the species directly affected by the shocks or closely linked to them, and can take significantly longer for other species. In some scenarios (two shocks affecting anchovy), a number of stocks settle into a new equilibrium and never recover to pre-shock levels.

Black Sea Ecosystem Ecopath with Ecosim (Annex 17)
The effect of long-term change in primary production were also investigated but were found to have a relatively small effect.

scenario	Stock developments	Ecological resilience
Status quo (F_{sq}, 130 % of F_{sq} or F_{MSY})	Fish stock biomasses are lower for 130 % of F_{sq} than for F_{sq}, and in both cases reach equilibrium quickly. Biomasses are higher for F_{MSY} (most of the time much lower than F_{sq}), and keep increasing for most stocks. Sprat (and alien comb-jelly and its predator *Beroe ovata*) have an opposite pattern as they suffer from the increase of anchovy (competitor and dominant planktivorous species)	When fished at F_{MSY}, the demersal/pelagic ratio and biodiversity index increase
Increasing primary production	The effect on the biomass of fish is small except for bluefish and red mullet (positive in both cases species). No shock tested	Negligible effect
SST effect on sprat consumption rate and short-term shock	Positive effect on sprat and negative on anchovy, leading to different cascading effect on predatory fish (positive for turbot, negative for bonito, bluefish and dogfish)	Shocks (punctual 50 % decrease in consumption by sprat) leads to a 50 % decrease in sprat, but a moderate increase in other fish species (especially anchovy and bonito). The effect on sprat is immediate, but is delayed by up to seven years for predatory fish. Recovery times range from 15 years for sprat, to 40 years for turbot and red mullet, while dogfish never returns to its original state
SST effect on anchovy consumption rate and short-term shock	Positive effect on anchovy, negatively impacting sprat and positively affecting all other fish species	Shocks (punctual 50 % decrease in consumption by anchovy) leads to up to 80 % decrease in anchovy, and 70 % to 130 % increase sprat. Bonito and dogfish are negatively impacted (up to 80 % decrease) and horse mackerel and whiting are positively affected (+50 %). Impact is largest after one to three years for anchovy, sprat and bonito), but takes up to six to 10 years for other species. Recovery takes 10 to 15 years but some species do not return to their initial state (bluefish, turbot, dogfish, red mullet)

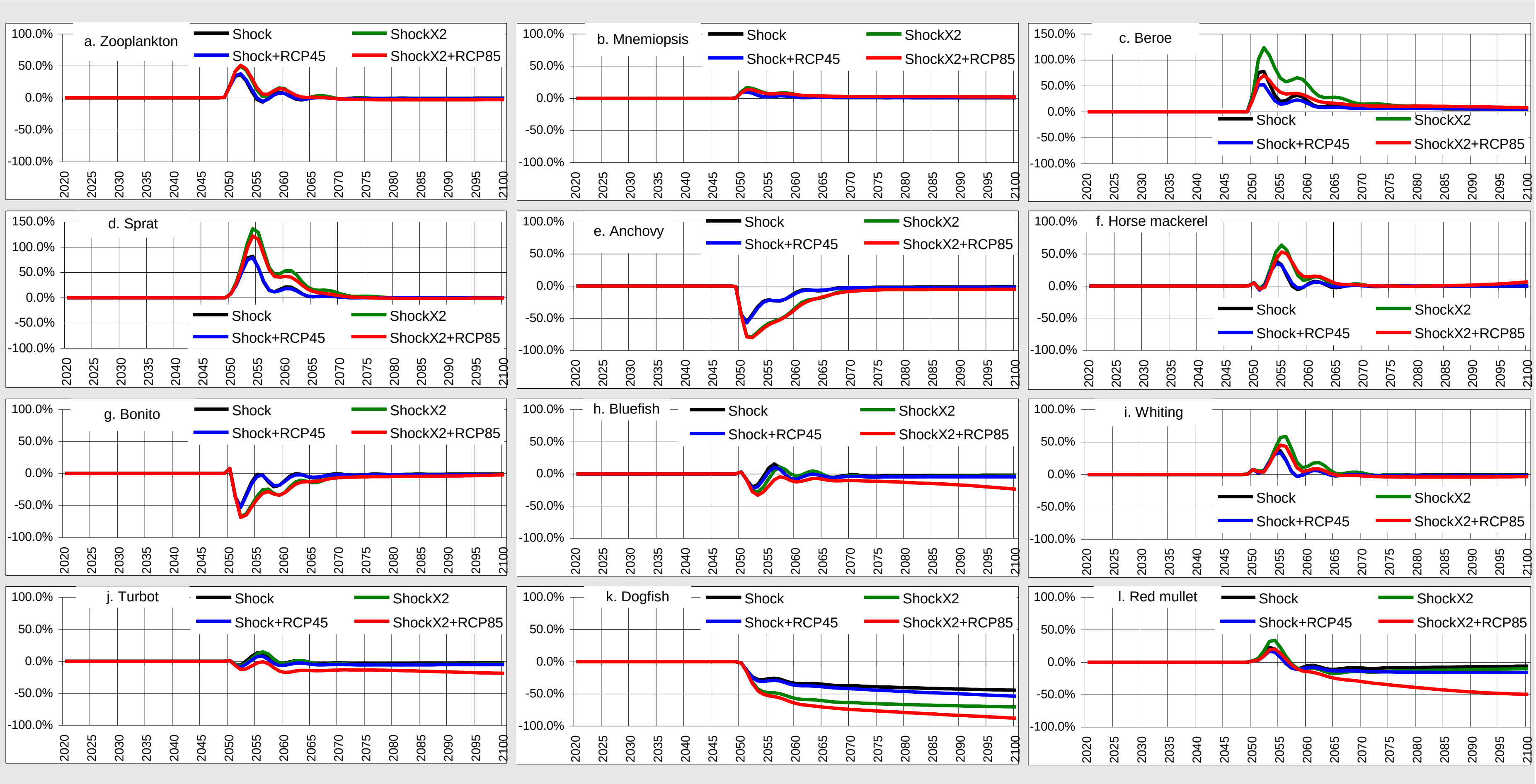

Figure 19 Effect of a short-term shock on anchovy on the biomass of different species (percentage of their biomass without shock). Shock: 50 % reduction of anchovy biomass in 2050; shockX2: 50 % reduction of anchovy biomass in 2050 and 2051. In shock+RCP4.5 and shockX2+RCP8.5 scenarios long-term effects on ecosystem productivity are added to the first two scenarios

North Aegean Sea Ecopath with Ecosim (Annex 18)
Summary of the results: The most severe effects in terms of amplitude and recovery time were observed for the combined Gelatinous plankton and Primary Production (PP) shock, followed by the PP shock alone and the Gelatinous plankton shock alone. Almost all ecosystem indicators returned to their baseline trajectories after the shocks, either in the short (within 3-4 years) or in the long term (after more than a decade), with few exceptions. In all three climate scenarios considered, indicators showed similar responses after the shocks in terms of amplitude, responsiveness and recovery time. Fishing at optimum levels moderated the amplitude and/or recovery time of several indicators, and was especially beneficial for sardine, substantially reducing or even eliminating the amplitude of the shocks as well as shortening the recovery time.

Scenario	Stock developments	Ecological resilience
Stable SST vs RCP4.5 vs RCP8.5	Increasing temperature favoured anchovy in the long term, however in the short term (shocks) there were only slightly more moderate effects than under stable temperature. Sardine biomass declined under RCP4.5 and even more under RCP8.5 in the long term, while recovery time from shocks delayed more under increasing temperature.	Almost all ecosystem indicators returned to their baseline trajectories in all climate scenarios. The demersal/ pelagic ratio and the diversity indicators (Kempton's Q, Shannon) were negatively impacted by SST warming, contrary to TLco and TLc which seemed unaffected
Decrease in Primary Production	Sardine: 44% decrease; recovered after 7 years. Anchovy: 29% decrease; recovered after 3 years.	Intermediate overall impact, with highest effect on Kempton's Q (-30%) and higher impact on TL than the other shocks; slow recovery time (min 4 years for TLc, max 14 years for Kempton's Q)
Increase in Gelatinous plankton	Sardine: 15% decrease; recovered after 6 years. Anchovy: 16% decrease; recovered after 4 years.	Low effect on TL; 12-20% change in the other indicators; more delayed responsiveness (compared to other shocks) as shock propagates in the food web; recovery depends on indicator, usually within few years (max 10)
Combined shocks (decrease in Primary Production and increase of Gelatinous plankton	Sardine: 59% decrease; recovered after 8 years. Anchovy: 53% decrease; recovered after 4 years.	Low effect on TL, higher on Demersal/Pelagic ratio (37%) and >25% on the rest; relatively slow recovery (min 4 years for TLco, max 13 years for Kempton's Q)
Fishing at optimum level (F/Z<0.4) for sardine and anchovy	Sardine: biomass stabilized at much higher level and shocks had a more moderate impact when fished sustainably. Anchovy: no substantial effect (slightly worse forecasts due to competition with sardine)	Minor effects on ecosystem resilience

2.3.2 Economic resilience

North Sea flatfish fishery SIMFISH (Annex 19)

Summary of the results: The flatfish fishery profitability is expected to decrease to initial states after having to switch back from pulse trawl to conventional beam trawl gear. Given these lower levels of profitability, the fleets heavily dependent on flatfish are more vulnerable to recruitment shocks. Economic indicators show large decrease two years after the shocks, around the time the weak population year-classes are recruited in 2023 (Figure 20, Figure 21). Continued lower economic performances lead to vessels exiting the fishing fleets starting in 2025 (larger beam trawlers) and in 2027 (medium-sized beam trawlers). The decrease of fishing capacity led to lower fixed costs and allowed the rest of the fleet to improve its economic profitability. The economic indicators seem to oscillate around the baseline as a result of a feedback loop, with entry-exit of vessels (economic situation improves, the fleet grows again leading to a worse economic situation and possibly a new exit of vessels). By 2030 the fleets still have not recovered from the shock in the 'most likely' scenario. The 'worst case' scenario shows the oscillations with a largest amplitude.

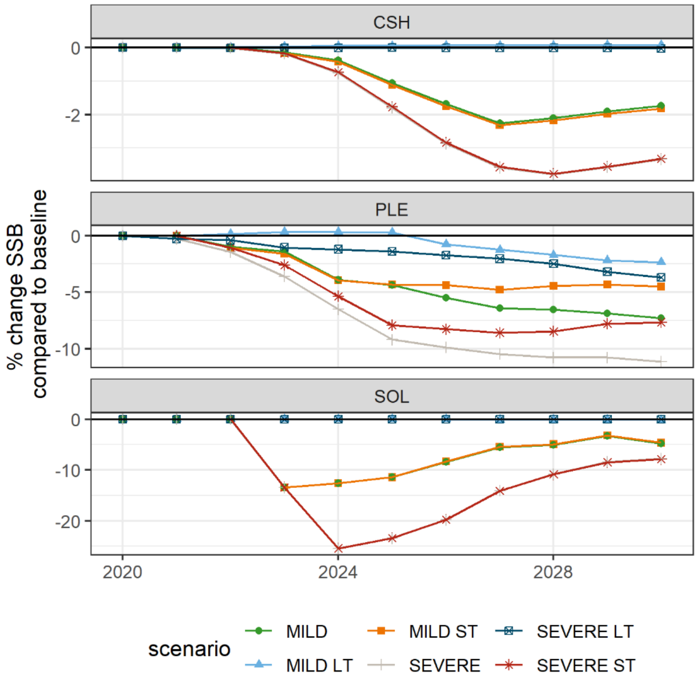

Figure 20 Simulated biomass change relative to the baseline for shrimp (CSH), plaice (PLE) and sole (SOL) for the biological shocks (ST) and long-term changes (LT), mild and severe

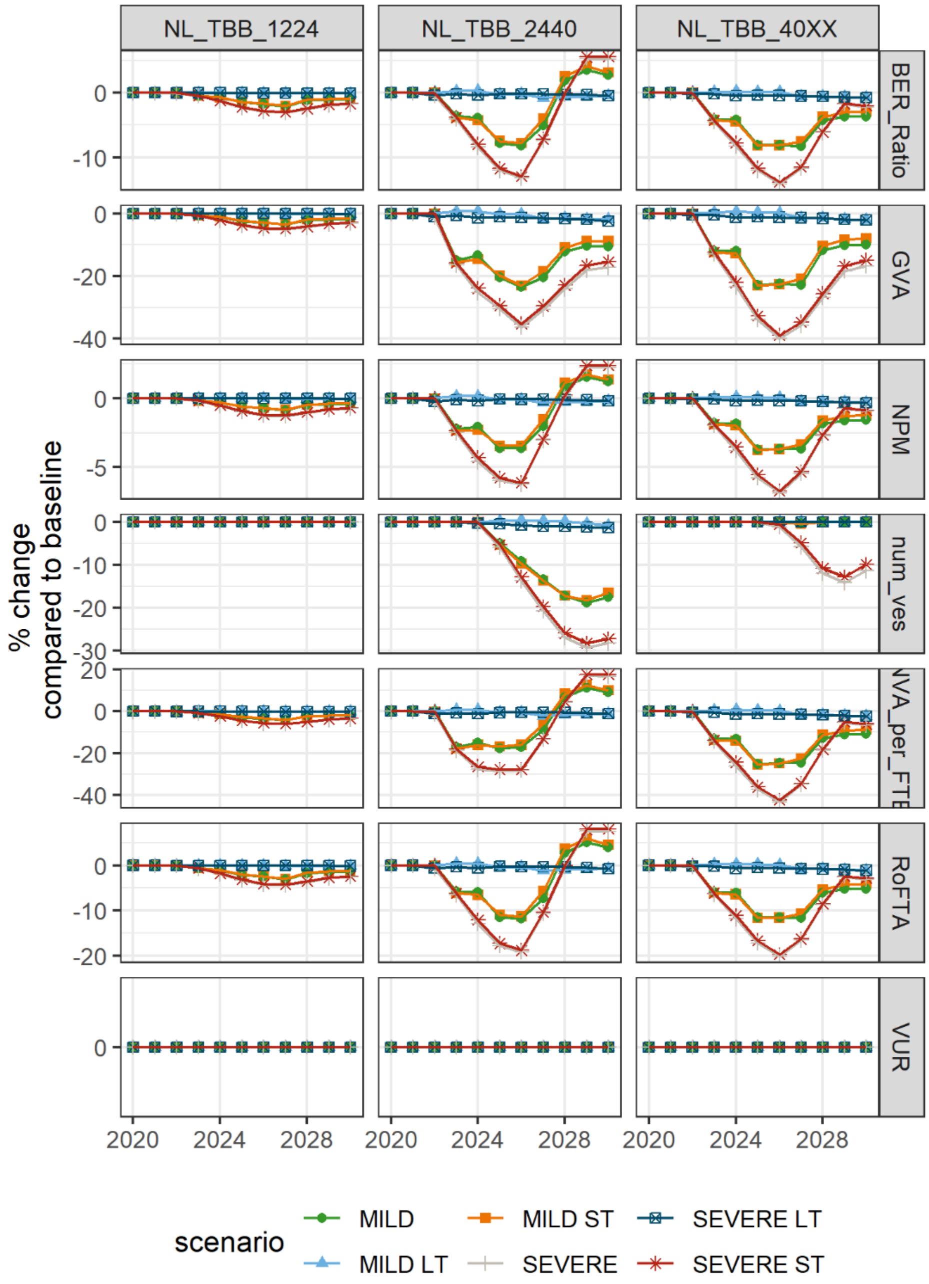

Figure 21 Economic indicators of the simulated Dutch flatfish fleet relative to the baseline: Break-even revenue ratio (BER), gross value added (GVA), net value added per full-time equivalent (NVA/FTE), net profit margin (NPM), return on fixed tangible assets (RoFTA), number of active vessels (num_ves), vessel utilisation ratio (VUR). Scenarios: MILD=most likely (RCP4.5 combined with one shock), SEVERE=worst case (RCP8.5 combined with two shocks). LT: only long-term effect; ST, only shock

Spatial bioeconomic modelling of the Baltic Sea fisheries with DISPLACE (Annex 20)

Summary of the results: The effect of a higher natural mortality episode results in a notably lower revenue for the fleets (Figure 22). This impact of the shock on revenue for fleets using bottom-contacting gears is much smaller when management is based on F_{MSY}_lower.

A range contraction has a long-lasting negative effect on the revenue of the fleets because of the loss of fishing ground for smaller-scale fisheries. This has a generally positive effect on the stocks from a passive protection.

Scenario	Stock developments	Economic indicators
Baseline	Exploited at F_{MSY}, most stocks have an increasing SSB except cod Kattegat, herring central Baltic and sprat, which decline. Applying F_{MSY}_lower makes little difference	Applying F_{MSY}_low leads in midterm to larger cod stock than when applying F_{MSY}, and reduces the choking effect of these stocks, allowing for larger overall income (10 % more for bottom-contacting gears)
RCP8.5 and mortality event	Without shock, Eastern Baltic cod shows a strong decrease (increasing with no climate change), with a faster decrease for central Baltic herring. Gulf of Riga and Gulf of Bothnia herring both increase quickly and to higher levels With shock, faster stock decline for the central Baltic herring and sprat, delayed increase of herring stocks	Without shock: even larger fleet revenue (NPV ca. >20 %) and energy efficiency (ca. >10 %), from higher landings on Baltic cod seeing its overall abundance decreasing. Shock: adversely impacting the fleet income and the energy efficiency, unless the F_{MSY}-lower strategy is applied
RCP8.5 and geographical range contraction	Eastern Baltic and North Sea cod remain stable (vs increase in baseline). Is beneficial to herring and plaice stocks, and delays the reduction of sprat because of reduced access to fishing grounds	Economic income and energy efficiency are strongly affected, with a loss of more than 20 %. This results from limiting landings realised on west cod (COD.2224), east cod (COD.2532), and flatfish for passive gears, and Kattegat herring (HER.3a22) and Baltic herring (HER.2532) for active gears

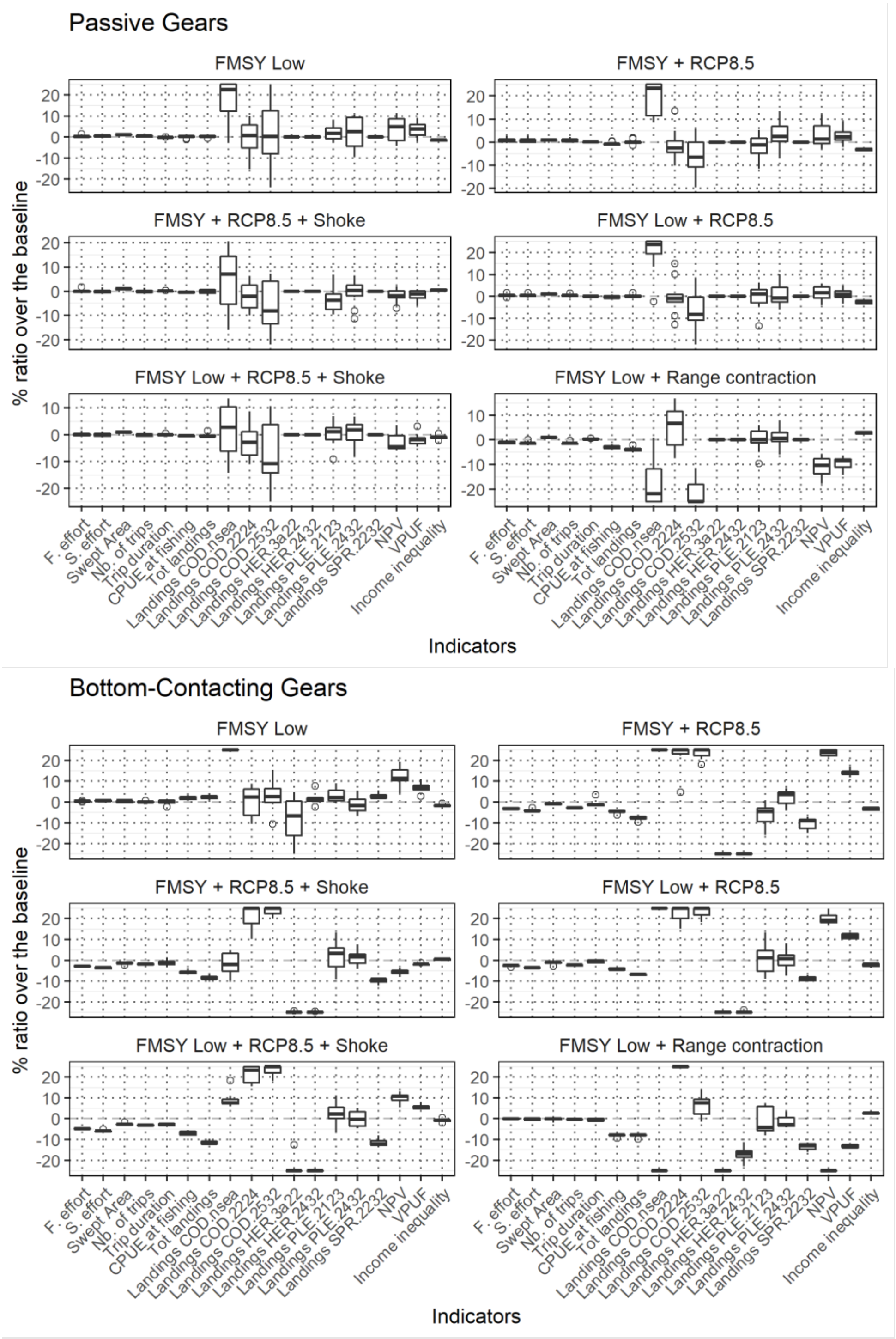

Figure 22 Fleet indicators integrating the differences to baseline (i.e., the FMSY-strategy alone) over the entire simulation period for selected scenarios. Indicators: fishing effort, steaming effort, swept area, number of trips, trip duration, CPUE at fishing, landed kg, net present value (NPV), value per unit of fuel (VPUF), and income inequality

Bay of Biscay anchovy (Annex 21)

Summary of the results: Under the current management plan for the anchovy stock in Bay of Biscay, using the agreed harvest control rule, 'most likely' scenarios result in SSB levels that are in median well above Blim for all tested climate effects in the short term (10 years of projection). The probability for being below Blim for all these cases is <5 %. For the 'worst case' scenarios, none of the tested climate effects leads to median SSB levels below Blim in the short term. However, the probabilities of below Blim are above 5 % when a decreasing trend in the survival of age zero individuals is applied or when two punctual decrements on recruitment are applied (Figure 23, Figure 24).

When shocks are incorporated to the tested climate effects the resulting stock status in the long term is similar, the stock reaches the same SSB levels as when no short-term shocks are applied for all climate effects. However, in the short term, applying the shock results in lower SSB median levels in all cases and in the worst-case scenarios the probability to be below Blim is >0.05. More years are needed for stabilization when these shocks are applied.

The relative income indicator with respect to the last historical year's computed median income shows a similar trend to the SSB, obtaining relative income levels around 50 % of the median income in 2020 for the most extreme scenario. The prices vary depending on the weight at age, which increases the effects in the climate scenarios assuming a decreasing weight-at-age trend with time.

Stock	Scenario	Long-term development	Resilience	Economic indicators
Anchovy	Status quo	After some very high SSB values in the last years of the historical series, because of the conditioning on mean values, the stock stabilises around recent-period mean values of approximately 110kt, well above B_{lim} (21kt)	The probability of being below B_{lim} is lower than 5 % throughout the projection period	Catches oscillate around the maximum allowed by the agreed HCR and the income does not show changes throughout the projection period
	Punctual decrement on recruitment Most likely	This effect results in a large SSB reduction in the first year. It is able to recover to values near the status quo by 2030	Has a big effect in the very short term (five years) but not in the medium and long term	Total catches decrease during the first years. They reach maximum values by 2040. The relative income decreases to half of the income for the 'worst case' scenario in the very short term. However, it recovers to the reference value in the long term for both scenarios
	Punctual decrement on recruitment Worst case	This effect results in a large SSB reduction in the first years. The median SSB in 2030 is 40 % lower in comparison with the status quo. Able to recover to these values by 2040	Has a big effect in the very term (10 years) and in the medium term, but not in the long term. The probability of being below B_{lim} in the short term is >5 %	
	Decreasing trend in age 0 survival Most likely	This effect results in a gradual decrease of the SSB for the short and long term, stabilising at around a 73 % of median SSB level in the 'status quo' scenario	The effect in the short term is kept in the long term. The probability of being below B_{lim} in the short term is <5 %, but this is not the case in the long term	Total catches decrease gradually and stabilise in the long term. The relative income stabilises around a 75 % of the 2020 median income for the 'most likely' scenario, but decreases to 50 % for the 'worst case' scenario
	Decreasing trend in age 0 survival Worst case	This effect results in a gradual decrease of the SSB for the short and long term, stabilising at around a 55 % of median SSB level in the 'status quo' scenario	The effect in the short term is kept in the long term. The probability of being below B_{lim} in the short and long term is >5 %	

Stock	Scenario	Long-term development	Resilience	Economic indicators
	Decreasing trend in weights at age Most likely	This effect results in a gradual decrease of the SSB for the short and long term, stabilising at around a 55 % of median SSB level in the 'status quo' scenario by 2040	The effect in the short term is increased in the long term. The probability of being below B_{lim} in the short term is <5 %, but this is not the case in the long term	Total catches decrease gradually and stabilise in the long term (although not for the 'worst case' scenario, which keeps decreasing until recurrent fishery closures occur) The relative income stabilises at around 55 % of the 2020 median income for the 'most likely' scenario in the long term. In the short term both scenarios present a 75 % relative income
	Decreasing trend in weights at age Worst case	This effect results in a gradual decrease of the SSB for the short and long term, stabilising at around a 10 % of median SSB level in the 'status quo' scenario by 2055	The effect in the short term is increased in the long term. The probability of being below B_{lim} in the short term is <5 %. In the long term, this probability exceeds 70 %, with the median SSB values below B_{lim} from 2045	
	Increasing trend on recruitment Most likely	This effect results in a gradual increase of the SSB for the short and long term, stabilising at around a 145 % of median SSB level in the 'status quo' scenario by 2035	The effect in the short term is kept in the long term. The probability of being below B_{lim} in the short and long term is <5 %	Total catches are at maximum values, resulting in a median relative income of 115 % throughout the projection period
	Increasing trend on recruitment Worst case	This effect results in a gradual increase of the SSB for the short and long term, stabilising at around a 180 % of median SSB level in the 'status quo' scenario by 2035	The effect in the short term is kept in the long term. The probability of being below B_{lim} in the short and long term is <5 %	
	Increasing trend on recruitment + decreasing weights at age	This combined scenario results in a stock status similar to that seen in the 'status quo' scenario, stabilising at around 110kt as median SSB	The probability of being below B_{lim} is lower than 5 %, throughout the projection period	Total catches decrease slightly and stabilise for the 'most likely' scenario (although not for the 'worst case' scenario, which keeps decreasing). The relative income is 80 % of the 2020 income for the

Stock	Scenario	Long-term development	Resilience	Economic indicators
	Most likely			'most likely' scenario and <50 % in the worst case scenario
	Increasing trend on recruitment + decreasing weights at age Worst case	In the short term, his combined scenario results in a stock status similar to that seen in the 'status quo' scenario. In the long term, the decreasing weights lead to a decrease in SSB, stabilising at around a 40 % of median SSB level in the status quo scenario by 2055	The effect in the short term is increased in the long term. The probability of being below B_{lim} in the short term is <5 %, but this is not the case in the long term	

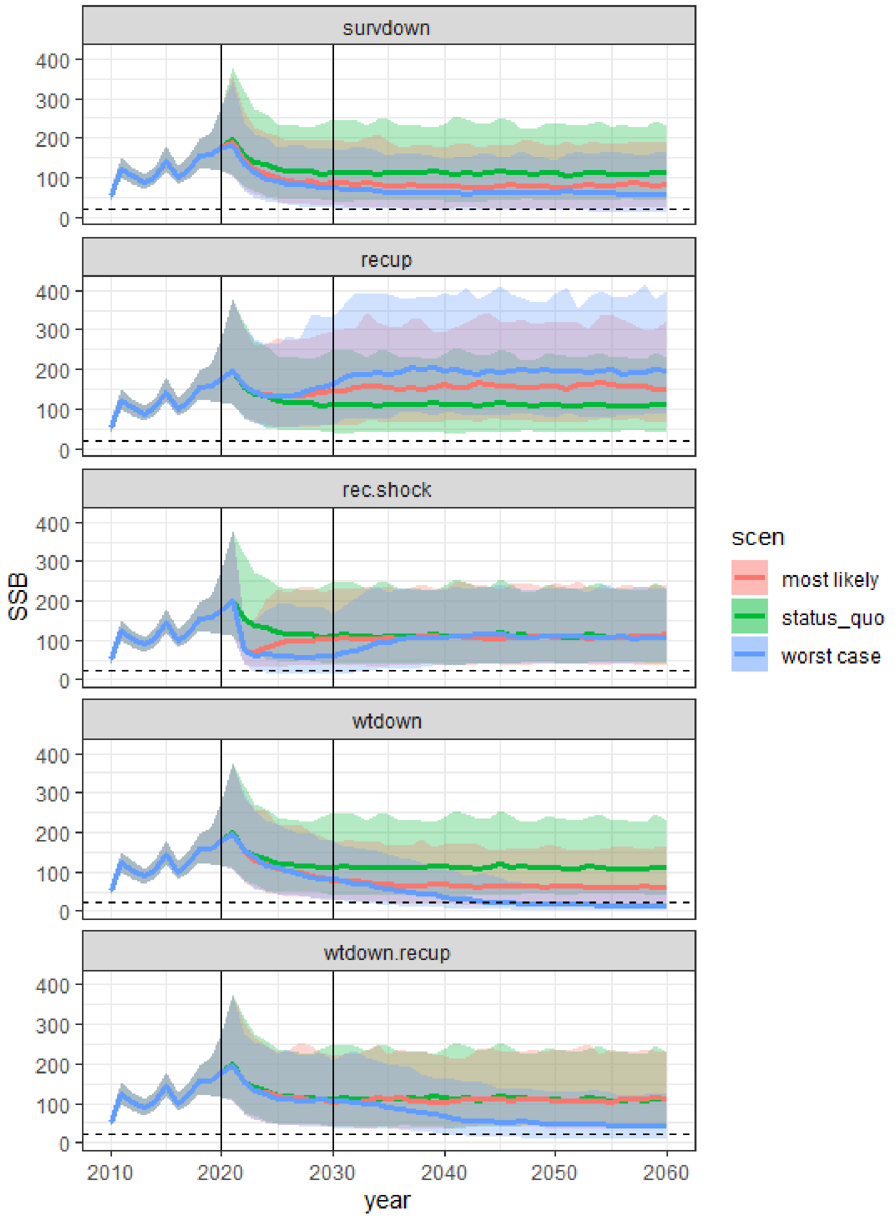

Figure 23 Spawning stock biomass (SSB in tons) by climate change effects and scenarios. Solid vertical black lines indicate the starting projection year (2021) and the 10-year time horizon (2030). Horizontal dashed lines denote B_{lim} reference point. For each scenario ('scen'), shaded and coloured areas show the 5 % and 95 % quantiles and solid coloured lines show the median of all runs (n=500). *survdown* stands for the dressing trend in age 0 survival, *recup* stands for increasing trend in recruitment, *rec.shock* stands for punctual decrement on recruitment, *wtdown* stands for decreasing trend on weights at age, *wtdown.recup* stands for the combination the most likely scenario for *recup* with the two scenarios for *wtdown.*

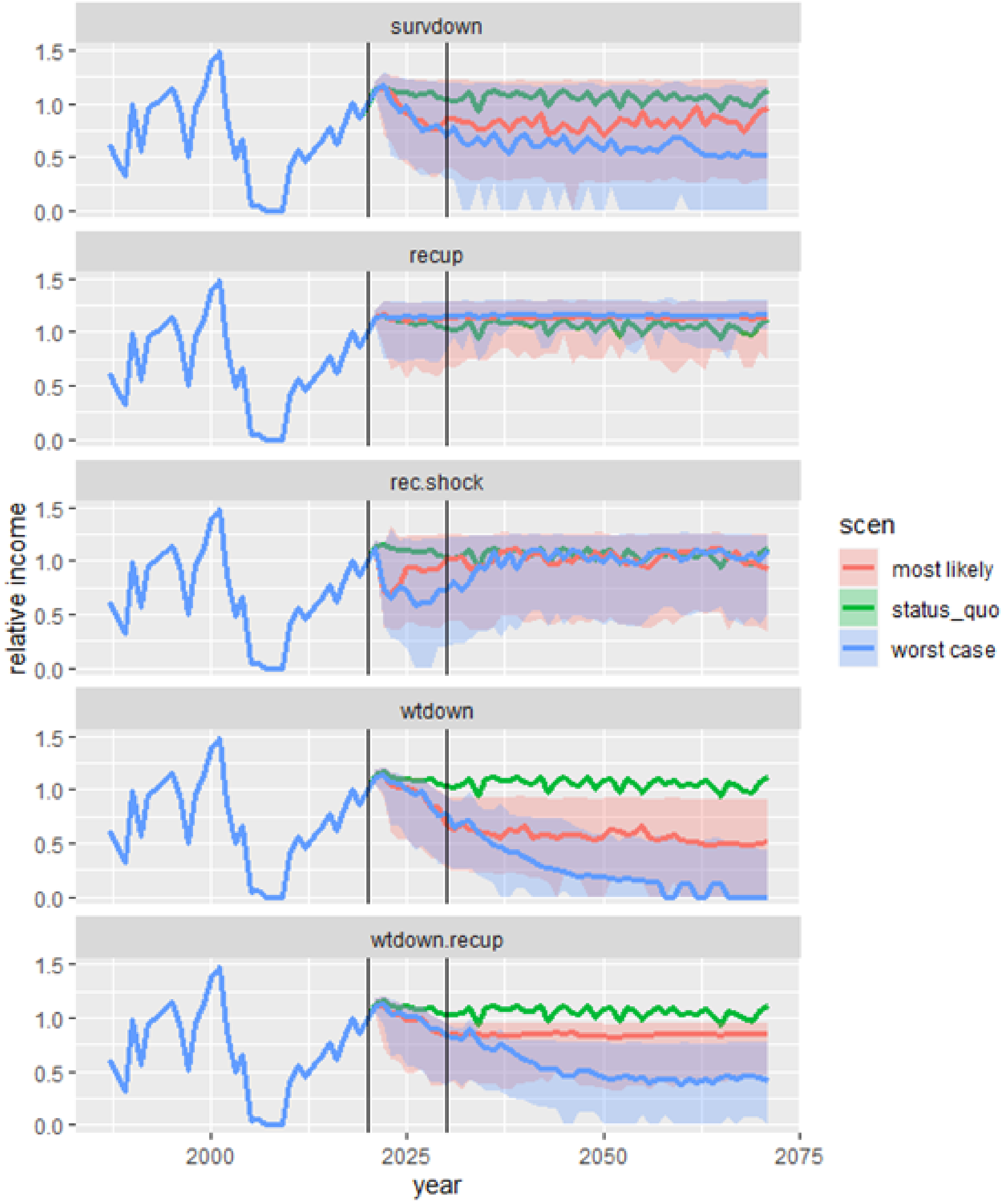

Figure 24 Relative income (computed as the ratio of the computed income in each iteration and the median income from the 'status quo' scenario in 2020) by climate change effects and scenarios. Solid vertical black lines indicate the starting projection year (2021) and the 10-year time horizon (2030). Horizontal dashed lines denote B_{lim} reference points. For each scenario ('scen'), shaded and coloured areas show the 5 % and 95 % quantiles and solid coloured lines show the median of all runs (n = 500). *survdown* stands for the dressing trend in age 0 survival, *recup* stands for increasing trend in recruitment, *rec.shock* stands for punctual decrement on recruitment, *wtdown* stands for decreasing trend on weights at age, *wtdown.recup* stands for the combination of the most likely scenario for *recup* with the two scenarios for *wtdown.*

2.4 Capacity of governance mechanisms to improve resilience

Climate change is affecting fish stock productivity and causes changes in their geographical distribution (Baudron et al. 2020). These changes both affect the fishing fleets, fishing strategies as well as the (instruments and governance of) the EU fisheries management system under the CFP. The effect of climate change on fish stocks poses some challenges for the fishing fleets when the carrying capacity of the seas to provide resource can be lowered and the resource resilience can be jeopardized, or fleets' c profitability is at risk, and fleets imbalanced, affecting their economic resilience.

A review of the main challenges for the fleets and the governance mechanisms, including current management measures, is presented in Annex 22. This study also analysed how the current governance system can facilitate the implementation of flexible, precautionary measures identified for optimal fishing strategies in the face of climate change.Hence, the governance system could promote more flexibility in the quota management system, where there might be more use of swapping quotas between countries, as long as there are some quotas to swap, and of transferring quotas across regions within a country quotas portfolio.

Below is a list of the main challenges (see also Bastardie *et al.* 2021), which CFP instruments are impacted, and how they can be modified to become fit for purpose (**Table 7**), while the potential actions to enhance resilience within the current or a reformed CFP governance are provided (**Table 8**).

Table 7 Towards renewed or adapted CFP instruments to fit the new challenges induced by climate change stresses

Climate-induced stresses	Challenges	Impacted current CFP instruments	CFP instruments to deploy/adapt
Changing fishing patterns	Maladaptation to the new situation, imbalanced fleets	• Total allowable catch (TAC) and quotas • Technical measures (landing sizes and selectivity requirements) • Bilateral agreements	• Annual TACs, quotas and current minimum conservation reference sizes (MCRSs) defined in the EU Technical Measures Regulation (EC, 2019) may need adjustment to new carrying capacity • Fishing rights would need to adjust to the available fishing opportunities with quota swapping and via the bilateral agreements negotiated every year with non-EU fleets • Continue the regionalization (CFP Art. 18) for adapting the governance structure, besides EU level generic measures, to decentralized, regionalized measures based on sound scientific advice and stakeholder anticipation
Transition towards a new climate-aware fisheries management	Barriers to transition (path dependencies, costs, social acceptance)	• Grandfathering (i.e., allocation based on historical landings) • Prevailing technical measures (EU, 2019)	• Flexible quota allocation (e.g., individual fishing quotes (ITQs) or at least an easier system to exchange quota between companies of two MS)

Climate-induced stresses	Challenges	Impacted current CFP instruments	CFP instruments to deploy/adapt
			• Promote investment in new gears • Adapt the landing obligation to limit the risk in multi-species fishery of choke species "on the move" (i.e. with a shifting spatial distribution compared to historical ranges)

Table 8 Potentials for resilience within the current or a reformed CFP governance

Actions	Entities	Potential for resilience	Obstacles
Anticipate the change	Fishing fleet	• High profitability	• Overcapitalisation and overfishing impairing profitability
	CFP governance	• Dynamic management (e.g., update biological reference points regularly) • Ecosystem approach to fisheries management (EAFM) (e.g., account for supporting ecosystem services)	• A demanding scientific knowledge acquisition and the need for a detailed, robust, and shared understanding of the marine ecosystems' dynamics by all relevant stakeholders • Moving targets (e.g., fluctuating quotas) making future profit uncertain • "Relative stability" principle
Response to change	Fishing fleet	• Adapt to local circumstances • Follow the stocks	• Additional effort to reach the fishing grounds • Crossing jurisdictions • Mismatched opportunities with species assemblage (e.g., risk for choke species)
	CFP governance	• Redesign of the principle of relative stability, or quota swapping and quota transfers	• Inertia of historical rights (path dependency)
	Common market organisation (CMO)	• Stimulate demand through marketing strategies and informative campaigns • Producer Organisations (POs) have the potential to adapt EU fisheries to the new context of resource availability and evolving market conditions	• Consumer habits may impose a barrier for trade of newly abundant resources

2.5 Discussion

Resource, ecological and economic resilience

This study aimed to evaluate the resilience to climate change of fisheries management frameworks. Climate change involves **both long-term trends due to changes in ecosystems and short-term anomalies** due to more frequent extreme weather conditions. By definition, extreme events are hard to predict. Therefore, adaptation to short-term climatic shocks requires implementing management systems that contribute to building both long-term ecological and short-term economic resilience. To be resilient, a system must resist damage and recover quickly from stochastic disturbances. We therefore modelled short-term shocks for the fish stocks and evaluated the consequences, i.e., the time taken for the stock to recover to the unshocked state. Because an exploited stock does not evolve in isolation, we also looked at the resilience of the ecosystem, the fisheries and governance structures.

Resilience by 2030

Recovery to biomass management targets (i.e., MSY $B_{trigger}$, B_{MSY}) was **not always achieved by 2030**. When recovery was not achieved, it was most often not due to the shock itself, but to an adverse effect of future climate change, impeding a full recovery (e.g., for North Sea herring, Baltic Sea and North Sea cod). In some case studies, e**xcessive fishing mortality** was also responsible for this non-recovery to biomass targets. The cause was either the use of a **non-appropriate management target** (e.g., F_{MSY} for North Sea sprat - estimated in 2018- appears to be non-precautionary when the simulation model is based on the 2021), or a scientific advice not being followed (Mediterranean hake, and Atlantic bigeye and yellowfin tunas).

While stocks did not always recover to management targets, in most case studies, **they fully recovered from the shock itself by 2030** (i.e., stock trajectory after shock converged to the trajectory without shock). Only in the 'worst-case' scenario when two successive shocks occurred, was recovery occasionally observed only after 2030. In the case of the highly migratory tuna stocks, where seasonal sub-stocks were modelled, at the current catch levels (which are greater than that recommended by the scientific committee), some sub-stocks collapsed when a shock occurred.

The **shocks can affect species with a time lag as a result of cascading effects in ecosystem models**. In the Baltic Sea case study, this did not seem to result in a prolonged impact of the shocks on the ecosystem, primarily because the impact on the affected species was already weak. In the North and Irish Sea, shocks affecting a single species (e.g., poor recruitment) also affect the directly impacted stocks and with no consequences after 2030. Only in the case of shocks that affect the whole ecosystems (heatwave or deficit of primary production) can full recovery happen later than 2030.

Healthy and well-assessed stocks are highly resilient.

A number of stocks in the case studies are in good condition at the start of the simulation when the shocks are applied. This is the case for North Sea flatfish, which are well above MSY $B_{trigger}$ and are expected to increase and be highly resilient to short-term shocks. This is also the case for mackerel. Despite the sum TACs declared unilaterally by the different fishing parties not being aligned with the scientific advice and the unfavourable long-term effect of climate, the mackerel stock is highly resilient to shock because of its current large stock size. **Some other stocks are not in good condition at the start**. Hence, in the Mediterranean, red mullet is close to the biomass target while hake is overfished at the start of the present evaluation. Also, catches for Atlantic tropical tuna are currently exceeding the advice, and bigeye tuna was overfished at the start of the simulations.

Stocks in a poor state (even if future prospects are positive) will suffer from a more extended period at risk. Because of their current low levels, North Sea cod and Mediterranean hake will take longer to recover when impacted by a shock. Similarly, in the case of western Baltic cod that is currently declining due to poor recent year classes, the occurrence of additional poor year classes (in the shock scenarios) will lead to a further decline in the stock and a considerable delay for its recovery to safe biological limits.

Large stock biomass often comes with a diverse age composition, while depleted stocks usually have an age composition truncated towards younger ages. Through the accumulation of the biomass in numerous age classes, **a balanced age structure provides a buffering capacity to the stock**, dampening the effect of poor recruitment and improving resistance (Brunel and Piet, 2013). This study also showed that, in addition to stock size, the exploitation pattern applied (i.e., the fishing mortality-at-age that directly influences the stock's age composition) has a crucial role in resilience. An exploitation pattern aiming at maximising the catch, by letting the cohort grow and fishing it when it reaches its maximum biomass, would result in truncated age structures, which will affect the stock more quickly if a recruitment failure occurs but could recover faster. On the other hand, strategies aiming at maintaining a healthy age structure by protecting older fish, or balancing the harvesting (Law et al, 2012), will **likely improve resistance to shocks but would lead to slower recovery** as rebuilding to initial SSB levels would require several cohorts to grow and join the pool of mature, fecund fish. In addition, because many life-history processes such as maturation, fecundity, and reproductive success are size-dependent, a change in size structure can affect the reproductive potential of stocks, sustainability, and recovery potential. In this context, the EU Marine Strategy Framework Directive (MSFD) Descriptor 3, evaluates whether "Populations of all commercially exploited fish and shellfish are within safe biological limits, exhibiting a population age and size distribution that is indicative of a healthy stock.".

However, **it is a challenge to get a robust stock assessment as soon as the natural mortality or the stock-recruitment relationship changes**, since these are by nature difficult to estimate. Hence, for Mediterranean hake, the effect of the shock was secondary to whether overexploitation occurred or a recovery plan was implemented. Some management targets are proven to be resilient to the shock scenario (e.g., Fishing at $F_{0.1}$). However, implementing such strategy is not as simple as assumed in the simulation as it will require some additional measures to manage fleet capacity and define reference points to monitor the stock relative to targets and limits. The ICES Report of the Workshop on Limit and Target Reference Points (WKREF) showed that if biological parameters such as growth and maturity vary, then recalculating reference points using a recent average would likely increase the resilience.

Even if some advisory bodies such as ICCAT does update assessments regularly (e.g., every three years) and changes reference points accordingly, **the effect of overfishing due to higher than recommended catches would be detrimental**. For example, for tropical tuna, the projections were made for two catch projections: the recommended (i.e., MSY) and the current catch levels. For yellowfin and bigeye, even with shock, fishing at the recommended level did not result in stock collapse for any of the scenarios. However, if the catch was maintained at the current (non-recommended) level, stock collapse was shown for some stock components after the shock. The shock also had a long-term effect if catches were at the current level and there had been changes in carrying capacity or natural mortality. Hence, it appears that advice based on long-term catch projections, as performed by ICCAT, are not robust to either short-term shocks or trends in difficult-to-estimate quantities such as natural mortality or carrying capacity.

Is resilience to short term shocks modified by long-term climate effects?

In North Sea cod (Annex 11), for the 'worst-case' scenario, the impact of longer-term climate effects is already visible in the relatively short term (compared to the 'status quo' and 'most likely' scenarios). The **long-term climate effects result in an additional delay** for the cod stock to return to safe biological limits. For North Sea herring, for which the implementation of the effect of temperature results in a rapid decline in recruitment level (both under RCP4.5 and RCP8.5 projections), this detrimental effect of climate change acts in conjunction with the effect of the shock to prevent the herring stock from recovering to its initial state.

Long-term climate change effects in the North Atlantic Ocean do not appear to affect significantly stock resilience for other stocks as it was shown **less determining than other factors, such as the level of fishing mortality applied in the North Atlantic Ocean**. For mackerel, for example, trajectories within a short-term horizon (<2030) are similar in all scenarios without shock. The impact of the shock is mainly influenced by exploitation level and shock intensity.

To evaluate the impact of non-stationarity on target reference points for the ICCAT and Mediterranean case studies, trends in productivity due to changes in recruitment, natural mortality and growth were also simulated in addition to shocks modelled as one-off increases in natural mortality M. It was found generally that **a change in natural mortality had the greatest effect**, which is an issue as a change in M is more challenging to measure than a change in weight at age or fecundity at age. For example, significant changes are seen in the recent SSB and F estimates for red mullet (even if currently estimated to be around F_{MSY}, and SSB is above B_{MSY}). This may be a sign of an inaccurate stock assessment, resulting from an underlying change in natural mortality or other biological parameters such as recruitment or stock distribution and fishery operations, all of which are likely affected under climate change.

Short-lived species are more impacted but recover more quickly if recruitment returns to normal

Short-lived species, such as sprat and anchovy (Baltic, North Sea, Black Sea case study) **have a short reaction time to the short-term shocks** (the maximum amplitude often reaches the year after the shock). Although in all case studies these stocks recover quickly, this recovery is really conditional to the assumptions made in the model that recruitment following the shocks return to a regular regime. In contrast, the persistence of a low recruitment period would quickly put these stocks in danger. Also, the stocks would be more vulnerable to any inaccurate management (either due to imprecisions in stock assessments or scientific advice not being followed). It is observed that longer-lived stocks (e.g., herring in the North Sea or Baltic Sea) have a higher resistance to the shock but a lower resilience (i.e., recovery takes longer).

Using lower fishing mortality and adaptative management improves resilience but at the cost of reducing short-term catches

Using F_{MSY}_low as a management target instead of F_{MSY} is beneficial for resilience. A lower fishing mortality imposed to the stock reduces the amplitude of the impact of the shock, thereby leading to a faster recovery. In the case of North Sea herring, using a F_{MSY}_low management target prevents the stock from going down rapidly and maintains it at a higher level, which reduces the risk of exiting the safe limits. Using F_{MSY}_low for mackerel reduced the risk of SSB<B_{lim} to 0 and significantly increased the recovery rate to MSY $B_{trigger}$.

For these stocks, **substantially lower catches come with improved resilience from using F_{MSY}_lower in the first years following the shock**. After a few years, using F_{MSY}_lower would pay off to the fleets, as it would lead to larger stocks, allowing them to sustain similar to higher catches during the rebuilding phase than when using F_{MSY}. For stocks that are currently in a good state and for which future conditions could lead to a further increase in stock size, i.e., for the Baltic Sea herring and sprat, there is little to be gained by using F_{MSY}_lower. The higher resilience (which is already high) would not justify the short-term loss in catches.

Simulations of **heatwave shocks** in combination with different fishing intensities in the North Sea and the Irish Sea revealed for both ecosystems that reducing or stopping fishing activities buffered the impact of the heatwave shock. This effect was small in both ecosystem models but likely reflects the reduced mortality experienced by the stocks plus the capacity for stocks with larger SSBs to recover faster. Adaptive management approaches may thus dampen the initial impact of heatwave shocks and facilitate faster stock recovery. Shocks to benthic biomass were also shown to propagate through the food web and reduce the biomasses of multiple key stocks. Alternative, low-impact fishing techniques may prevent the prevalence and severity of such future shocks while minimising the impact on important supportive and regulating habitats (e.g., essential fish habitats, carbon sinks).

The only case where there was no benefit in using F_{MSY}_low was highlighted in the North Sea mixed fisheries simulations. The fishing effort, in this case, is mainly determined by the quotas on cod, while cod is limiting the North Sea mixed demersal fisheries with a low stock level. The MSY range for cod that can be used to give advice is also very narrow (because the stock is on the sliding slope of the MSY advice rule).

Compliance

Non-compliance with proper exhausting the quotas or not following the advised TAC and quotas would most of the time lead to **fishing mortality applied that is higher than intended** (i.e., F_{MSY}). In the mackerel example, the MSY $B_{trigger}$ is defined assuming no implementation error (i.e., that TACs are set equal to scientific advice). Under this assumption, there should be a maximum 5 % change of SSB<MSY $B_{trigger}$ (definition of MSY Btrigger). In the simulations here, the scientific advice is not followed, which, even without climate impacts, led to actual fishing mortality much higher than the F_{MSY}, and subsequently a high risk of exceeding safe biological limits. Such mismanagement induced by non-compliance to the established TAC and quotas or not following the scientific advice reduces stock resilience.

However, **full compliance with fishing quotas in the North Sea demersal mixed fisheries results in highly resilient stocks**. Provided that all fleets limit their effort to the effort needed to catch their reduced quota by a choking effect of cod, this effort limitation led in the simulations to a fast stock increase softening the exploitation pressure. ICES typically uses such a full-compliance scenario mixed fisheries working group to illustrate the fleet behaviour the regulation expects, i.e., stop fishing as soon as the quota on the limiting stock is exhausted (so-called 'Effort min.' scenario), which contrasts with the scenario assuming that fleets continue catching for exhausting their quotas. Both scenarios are generally considered as defining the extremes of a spectrum. In reality, the fleet may continue fishing given the many specific fisheries exemptions to the EU landing obligation.

Species interactions in the ecosystem

When accounting for species interactions in the ecosystem, with the ecosystem models deployed for this study and for the short-term shock scenarios tested, marine exploited and non-exploited populations almost always return to an initial state and the ecosystem proprieties are not modified on the long term. A short-term shock on the recruitment of a given species generally had little impact on the other species. In the Baltic Sea, the largest impact observed was a maximum 8 % biomass decline in the stock affected, with some minor short-term consequences for other species through trophic interactions. Effects were similar in the ecosystem simulations for the North Sea and the Irish Sea. **Heatwave events in the North Sea and the Celtic Sea could lead to instantaneous effects, contrary to shocks affecting reproduction, which cascade through the ecosystem's trophic interactions**. The near-time responses to shocks were similar regardless of RCP4.5 or RCP8.5 long-term projections. Such shocks have not been found to lead to a long-term change in the ecosystem. However, shocks to lower trophic levels had the most profound impact, affecting productivity and subsequently the commercial stock biomass, ecosystem structure and function. Such an impact highlights the need for including possible productivity change when developing advice based on single-species modelling work. Those findings confirm the previous investigation on the southern North Sea and Irish Sea ecosystems identified as highly sensitive to secondary and primary production (Stäbler *et al.* 2019; Bentley *et al.* 2020).

In the **Aegean Sea**, among the three shock scenarios considered, the most severe effects in amplitude and recovery time were observed for the combined shock on gelatinous plankton and primary productivity (PP) shock on primary production, followed by the primary production shock alone and the gelatinous plankton shock alone, as revealed by most indicators. In the case of the Mean Trophic Level indicators, the gelatinous plankton and PP shocks led the indicators in opposite directions. **In all climate scenarios considered, almost all ecosystem indicators returned to their baseline trajectories** within three to four years or in the long term (after more than a decade), with few exceptions, denoting a relatively resilient system that can recover after abrupt changes. The long-term effect of climate projections was indicator-specific; the demersal/pelagic ratio, the biodiversity indicators and sardine biomass were negatively impacted by warmer sea surface temperature, contrary to the trophic level index, which seemed unaffected. Besides this, anchovy biomass seemed to be favoured by climate change. However, in the short term, there were no critical differences in the amplitude, responsiveness and/or recovery time of the indicators after the same shocks in different climate projections; few exceptions were observed, e.g., the recovery time of the diversity indicators was generally longer in RCP4.5 and RCP8.5 compared to stable sea surface temperature. In many shocks, fishing at optimum levels moderated the amplitude and/or recovery time of the indicators, even though fishing changes were limited only to reducing the fishing mortality of sardine. Resource resilience was also high for anchovy, which could fully recover within three or four years, while recovery for sardine was slower, possibly because it is fished at levels higher than F_{MSY} at the period that the shocks were applied. Fishing at optimum levels had a very positive effect on sardine, substantially reducing or even eliminating the amplitude of the shocks and shortening the recovery time. At the same time, this had no adverse effect on anchovy, a sardine’s competitor, for which no change in fishing mortality was applied. Since different responses are observed among indicators, the combined use of several indicators provides a more holistic view of the effects of possible shocks on the ecosystem and fisheries resources.

In the **Black Sea** case study, however, in the most extreme scenarios **the long-term trajectory after shock of some stocks did not converge to the trajectory without shock**. If the Black Sea is at the forefront of a regime shift is unclear at this stage. Indeed, documented cases of long-lasting changes in ecosystem state, or regime shifts, are generally observed as a consequence of longer-term changes in the environment and not from a single perturbation. Earlier **regime shifts** observed in the North Sea ecosystem were, for example, triggered by a shift in salinity and weather conditions (1979 regime shift) or a shift in temperature and weather condition (1988 regime shift, Weijerman *et al.* 2005). Likewise, changes in deep water salinity and oxygen conditions triggered a regime shift in the Baltic Sea ecosystem in the late 1980s (Möllmann et al, 2009). The common cause for these regime shifts was a large-scale change in the climate, materialised by a switch from negative to a positive phase in the NAO (Alheit *et al.* 2005).

Fishing fleets with low profitability will not be resilient to shocks

As illustrated by the case study on Dutch flatfish (sole and plaice) fisheries, **a high resource resilience does not necessarily lead to good financial resilience**. In this case study, the low resilience of the Dutch beam trawler fleet is mainly the result of diminished profitability resulting from the obligation to switch back from the pulse trawl to the conventional tickler chain beam trawl, with lower catch rates and generating higher costs. The positive development of the sole stock, without climate-induced shock, is necessary for the fleets to increase their profit. By delaying this increase, a short-term shock on sole recruitment results in maintaining degraded economic performances leading eventually to vessels exiting the fishery.

No apparent preparation of the fishing sector to climate-induced degradation of infrastructures

Climate change is expected to increase the frequency and magnitude of extreme climatic events, which could damage the fishing-related infrastructures (vessels, ports, landing sites, markets) of the fishing fleets. Fishing sector stakeholders were consulted to investigate the possible threats for infrastructure resilience and the potential measures taken by the industry to mitigate these effects. A total of 12 answers mainly filled in by ship owners, fishers, gear manufacturers, and producer organisations revealed that they had no specific concern about the potential effects of climate change. When climate effects were mentioned, the main concern was its effect on the fish, namely its distribution, migration and seasonality. Invasive species were also mentioned. When the risks linked to bad weather were mentioned, these related to the limitation of the fishing days, while acknowledging that extreme events are usually well predicted by weather forecasts. There was no mention of a specific material impact on infrastructure or mention of any proactive actions taken to secure infrastructure against climate-induced risks.

Can the current management framework ensure the resilience of EU marine living resources and fisheries?

While changes in the ecosystem are occurring at a grand scale, resource resilience is somewhat at odds with these changes. For example, if at the local level, stock abundance changes because of a geographical redistribution of fish, how severe does this need to be before current local conservation measures (e.g., the plaice box) become inadequate?

The key question is whether scientific advice, as discussed above, is still adequate to achieve the objectives of the CFP in applying the precautionary approach and reaching MSY. Namely ensuring a stock fluctuates around or is maintained above BMSY, achieving optimal long-term yields, while avoiding risk for stock collapse with high probability. The CFP provides a comprehensive framework for management at the stock level. An issue lies with the entry of new species into the system, especially when it concerns changes in distribution or invasive species. Another issue is the change in the respective balance of key species in the marine ecosystems. Both issues can potentially affect the trophodynamics of marine ecosystems and promote different set of species with diverging commercial interests. In order to face ecosystem effects and implement an EAFM under these changing conditions, there is **a need for a dynamic, i.e., adaptive, management framework**, and integrated to bridge the historical divide between fisheries and environmental managements.

The most crucial factor that needs to be considered is that today, although the marine ecosystem is always dynamic and in flux, the management system has to become more adaptive and perhaps develop from a (single) species-oriented framework towards an adaptive regional fisheries-oriented framework (see Borges & Penas Lado 2019 for the necessity to change to a multi-species management framework due to the EU landing obligation). In this framework, the **balance between regional fishing capacity and** fishing **opportunities** are leading. The framework should be adaptive from a management perspective to reflect the fleets' fishing reality. The relative stability principle gives the MS and fishers little room for adjustments of quota distribution for individual fishers/vessels. A discussed option which would have severe consequences on the MS quota shares would be the introduction of pan-European tradable fishing rights, allowing stock management at TAC levels and fishers to adjust their local catch opportunities by trading in fishing rights across Europe (for those regional seas working with TACs). However, a look at the ownership of vessels in the EU reveals that then huge parts of the quota of a MS would be fished by vessels operating from other MS (today independent of ownership only a national vessel can fish on a national quota). As such a change would unlikely be adopted within the EU (MS would basically give up their resource use rights in their EEZ which were initially translated into quota shares at EU level in 1982), **a more realistic option is to use the existing quota swapping between Member States to also reflect the actual presence of species in regional and local waters.**

Updating reference points in a changing environment

The management procedure should ideally encompass **a set up for regular update of reference points to be adaptive and simulation tested with HCRs using MSE**, that consider trends, variability, and reference points. The ecological resilience analysis highlighted the importance of including changes in stock and ecosystem productivity when developing single-species advice. The ICES and Mediterranean $F_{0.1}$ framework are based on reference points and forecasts that assume future biological parameters based on the recent period are constant in the future. In the ICCAT assessments, used to provide advice, historical parameters such as growth and natural mortality are assumed not to vary over time. However, changes in dynamic ecosystems are unavoidable, and adaptive harvest rules, i.e., that respond to available biomass, have been shown to provide benefits under both static and changing climates (Gaines *et al.* 2018). For example, by updating target, threshold and limit reference points as changes in stock productivity are detected.

Even without climate change, reference points are time-varying, as they depend on growth, maturity, and natural mortality-at-age and the stock-recruitment relationship, all of which may vary due to environmental or other processes. In some assessments, e.g., ICES, body mass and maturity are estimated from empirical data. However, in tropical tunas, where data are harder to collect, these come from a growth curve that does not vary by year. While natural mortality is difficult to estimate, and so in ICES stock assessments may be derived from minimum or intermediate complexity (MICE) models under a variety of assumptions, while in the Mediterranean and ICCAT it is derived from life-history theory or assumed not to vary by age, and held fixed across years. The key is to ensure that advice is robust, i.e., that despite uncertainty it can still meet management objectives such as achieving MSY and avoiding stock collapse. The way to ensure robustness of advice is to conduct Management Strategy Evaluations (MSE) and include scenarios related to variations in productivity, e.g., based on the scenarios considered above for Mediterranean and Tuna stocks

If biological parameters vary, this implies that, as stated by ICES WKCHANGE, biological reference points should be **re-estimated** regularly. The general practice is to re-estimate reference points **at** each **benchmark assessments**, which generally occur on a five-year cycle. This timescale seems appropriate, as it matches the management system, avoids erratic changes (‘whipsaw’) in the designation of stock status, and provides some stability in planning horizons for fisheries. A problem with regularly changing reference points is that they may simply be varying randomly without trend. Which is more likely for species with short-generation times. In which case if a biomass target reference point is reduced for a recovering stock then this may mean that a stock “recovers” even though no change in stock biomass occurs. Risks are also asymmetric, as incorrectly increasing catches may result in overfishing resulting long-term, while incorrectly reducing catches may result in under-fishing which can be corrected as soon as an increase in stock biomass is identified. It is unlikely that a single generic advice framework can be applied across all life histories, and management should instead be linked to life-history traits, and in particular, the nature of the time series of stock metrics (Fischer *et al.* 2020)

To provide catch advice requires conducting forecasts, which generally assumes that the future biology will be similar to a recent period. ICES WKREF showed that forecast skill declined with the distance from the initial conditions (i.e., last years of the assessment). After three to five years, ICES predictions performed poorly. This again reinforces the concept that biological reference points need to be re-estimated regularly at benchmark assessments and that **short-term forecasts should not exceed three years**.

There are two main approaches when trying to include scenarios related to evaluate the robustness of scientific advice to climate change and environmental variability when conditioning simulation (i.e., operating) models when conducting MSE, either to **include the mechanistic relationship** between the environment and stock dynamics **or to take an empirical approach and examine possible broad scenarios**. Punt *et al.* (2014) found that modifying management strategies to include environmental factors does not improve the ability to achieve management goals much, if at all, and only if the mechanism that drive the system is well known. They concluded that until the skill of stock projection models improves, it is more appropriate to consider the implications of plausible broad forecasts related to how biological parameters may change in the future as a way to assess the robustness of management strategies, rather than attempting specific predictions.

Limitations

The literature review conducted in this study highlighted that, although some aspects of the biology of most stocks were found to be linked to environmental factors, there was a lack of a robust statistical model to describe these linkages. For lack of well-established relationships with climate in some case studies, **ad hoc assumptions were made on the magnitude of the changes expected for the different environmental scenarios tested**. Likewise, very little information was available on the effect of potential short-term shock, and shock scenarios (nature and magnitude of the shocks) were also defined arbitrarily. Therefore, this work should be viewed as a theoretical exercise. The result of the simulations should be considered for scenario comparison purposes and not as likely projections of the future state of this stock.

A key concept is resource resilience, defined by the ability for fish stocks to remain above biomass limits and thresholds at which productivity is impaired and rebuild, in a timely manner, to levels that correspond to management targets. This requires the definition of single-species reference points, such as B_{lim}, B_{pa}, MSY $B_{trigger}$, and $F_{0.1}$. These require estimates of weights, fecundity and natural mortality at age and the selection pattern of the fisheries. B_{lim}, B_{pa} and MSY $B_{trigger}$ also require a stock recruit relationship to be assumed or estimated.

The robustness of the reference points and the management system in which they are used depends on **assumptions about the stability of biological processes**. However, whether the biological parameters changed as a result of density dependence, the evolutionary effect of fishing, or the environment is questionable. M is a key parameter (that) which cannot be observed but instead is derived based on various assumptions and models. These models must be validated to provide robust and credible advice (Saltelli *et al.* 2020). This requires assessing whether it is plausible that a system equivalent to the model generated the data (Thygesen *et al.* 2017). Validation using empirical data plays a vital role in sustainability science (Eker *et al.* 2018). This is a reason for using management strategies evaluation, a form of exploratory modelling, where there is significant uncertainty (Bankes, 1992). MSE should be used to evaluate the robustness of current management strategies to climate change. For instance, is simply changing the set of years used to define reference points robust, or are some forms of reference point more robust than others, e.g., F_{01} versus F_{MSY}?

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

In the light of an increasing demand to integrate ecosystem information into fisheries management, the results presented in this study showed the importance of accounting for trophic effects in management considerations. **Combining tactical single-species advice with strategic ecosystem information could enhance advice** for single stocks or mixed fisheries (Howell *et al.* 2021). For example, the use of an ecosystem-based fishing mortality reference point (FECO) (Bentley *et al.* 2021) has recently been adopted into advice by ICES, and work is ongoing to establish how it will be used in practice. The FECO approach uses strategic ecosystem information, such as that delivered by this report, to advise thresholds, within the ‘pretty-good yield’ ranges (Hilborn, 2010; Rindorf *et al.* 2017) that make the foundation of the precautionary FMSY ranges used in EU multiannual plans, as flexible targets to minimise cumulative impacts of fishing and environmental change, and provide a buffer against the risk of an unexpected reduction in productivity.

2.6 Conclusions

The simulation work conducted in this study indicates that, overall, the **fisheries system is resilient to the impact of short-term stress, provided that management has been based on sound scientific advice and has been followed for the years preceding the shocks**. The current management targets should lead to large enough stocks with a diverse age structure, ensuring their resilience to short-term shocks such as recruitment failure or high mortality episodes.

Recovery to management targets following short-term, climate-driven stress is not always achieved by 2030. Healthy and well-assessed stocks were found to be highly resilient to climate shocks, while climate shocks impacted more short-lived species, though those stocks could recover more quickly. **Resilience can also be improved by adaptative management**. Using the F_{MSY} ranges to lower fishing mortality when stocks are affected by short-term stress reduces the impact on the exploited stock. This, however, requires that shocks be detected soon enough, either by detecting the environmental anomalies that trigger them (assuming the linkages are understood), or by monitoring the earlier reactions of the stock (e.g., through surveys on population recruitment strength).

For the management advice to remain accurate, there is a **need to regularly re-evaluate management reference points** to make sure they are in tune with the current levels of productivity of the stocks. When calculating these reference points, there should be systematic verification that using the agreed management points would allow for stock recovery in case of short-term shock (i.e., recruitment failure). It is also key to understand the linkages between stock productivity and climate, identify changes in productivity and make the correct assumptions for future productivity when estimating reference points.

The framework should be adaptive from a management perspective to reflect the fleets' fishing reality. Resource resilience does not equate financial/economic resilience as the **inevitable losses induced by** climate-driven **shocks** on the marine resource **can provoke some fisheries to become unprofitable**. In addition to this, the relative stability principle in EU gives the MS and fishers little room for adjustments of quota distribution for individual fishers/vessels to be able to adapt (properly) to shocks. Hence, **adapting the fishing capacity to local circumstances, or alternatively follow the stocks movements**, would also require to use the flexible tools provided by the EU CFP (e.g. the quota swapping system between two states for a given area, or the quota transfer within a MS across areas) to compensate for the imbalance of the fishing capacity with the fishing opportunities the climate change effects could induce, and possibly redesign current national quota distribution within MS, with flexible resource allocation through the backup of the producer organisations, including influencing the demand for seafood with marketing strategies.

3 EXAMINING FISHING STRATEGIES FOR IMPROVING ENERGY USE EFFICIENCY

The aim of the study was to evaluate how fishing strategies that rebuild stocks may (i) improve energy use and efficiency, (ii) decrease fisheries highly dependent on fuel use, and (iii) increase their profitability along with stable yields. Overall, this part of the study was to determine the drivers of fuel consumption within the EU fisheries.

Within this study, fleet segment level economic data was utilised (hereafter 'economic fleet segment') as provided by the EU Member States under the annual Fleet Economic data call (i.e., the Scientific, Technical and Economic Committee for Fisheries (STECF) Annual Economic Report (AER) data call), and further reconstructed and examined historical energy use in capture fishing activities for all Member States (Annex 23). Such reconstruction should enable identifying **patterns in fuel use**, and if patterns were apparent, try to determine the driving forces for such trends. Such a pattern could be stock dynamics and we compare for a few important fleet segments the development of fuel intensity and efficiency with the development of stocks of target species (e.g., North Sea flatfish fishery).

Annual fuel use intensity was obtained from the datasets (**litres of fuel per kg of fish landed**) and fuel efficiency (**litres of fuel per day at sea**) for EU economic fleet segments, by year and fishing activity. In addition, catch efficiency (**kg of fish landed per day at sea**), per metier and fleet size was obtained. All data was sourced from the EU Data Collection Regulation (DCR) and the EU Data Collection Framework (DCF, 2008 onwards). From these three parameters (fuel use intensity, fuel efficiency and catch efficiency), we examined how energy consumption had varied across the available time period for each available combination of metier and vessel size at the Member State level.

For some Member States, the data available allowed retrieving a time series of fuel use intensity and efficiency **between 2002 and 2018**, while the most consistent data related to each fishery's catch efficiency was available for the period 2013–2018 (Figure 25). This analysis show that beam trawlers and demersal trawlers are the most fuel intensive gears, while the purse seiners, the pelagic trawlers and some passive gears (PG) are the

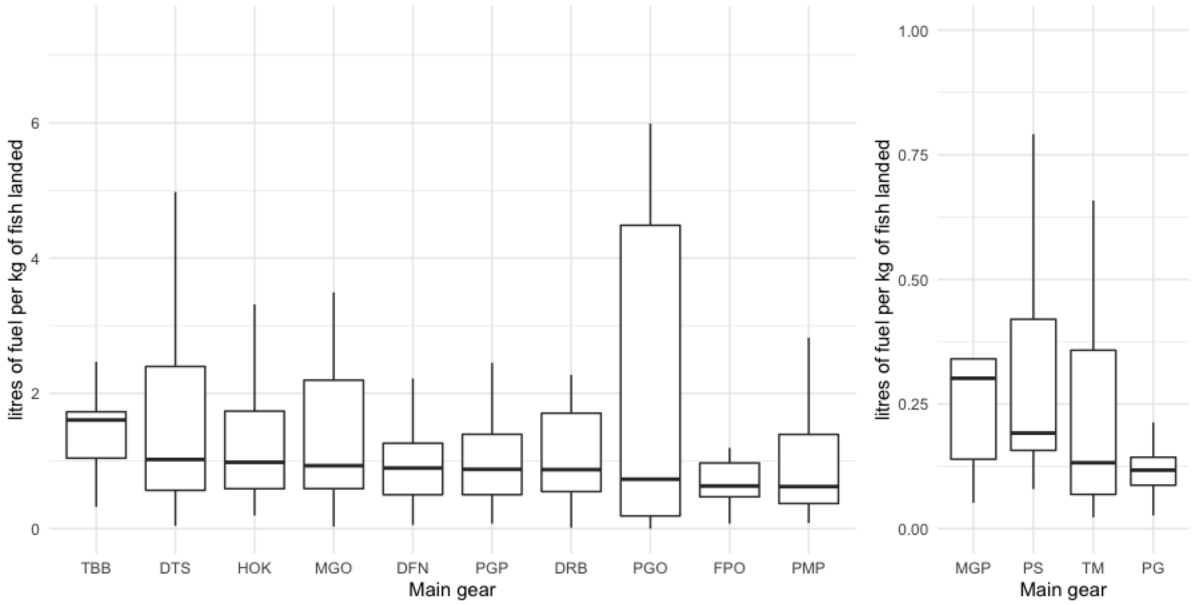

Figure 25 Fuel use intensity ranges in the EU fleet between 2016 and 2018 (DFN: Drift and/or fixed netters, DRB: Dredges, DTS: Demersal Trawls and Seines, FPO: pots and traps, HOK: Hooks, MGO: Other active gear, MGP: Polyvalent active gear only, PG: Passive gears vessels <12m, PGO: Other passive gear, PGP: Polyvalent passive gear only, PMP: Active and passive gear, TBB: Beam trawlers, PS: Purse seiners, TM: Pelagic trawls)

3.1 Results of the analyses of trends for economic fleet segments

The indicator values were calculated for all MS and fleet segment for which data is available. To illustrate some of the results the segments were grouped to show the trends for similar fleet segments from different MS. The fleet segments where then also grouped for fishing gear groups (e.g., hooks (HOK) or demersal trawlers (DTS). The following list of gears are used in the DCF economic data collection (STECF 2021a) (

Table 9)

Table 9 Fishing Technologies – DCF categories

Acronym	**Category description**
DFN	Drift and/or fixed netters
DRB	Dredgers
DTS	Demersal trawlers and/or demersal seiners
FPO	Vessels using pots and/or traps
HOK	Vessels using hooks
MGO	Vessel using other active gears
MGP	Vessels using polyvalent active gears only
PG	Vessels using passive gears only for vessels < 12m
PGO	Vessels using other passive gears

Acronym	Category description
PGP	Vessels using polyvalent passive gears only
PMP	Vessels using active and passive gears
PS	Purse seiners
TM	Pelagic trawlers
TBB	Beam trawlers

3.1.1 North Sea beam trawls (TBB)

Figure 26 shows for the North Sea beam trawlers that **the fuel efficiency in the North Sea is relatively stable, except for two Dutch segments** (NLD NAO TBB2440 and NLD NAO TBB40XX[5]) .

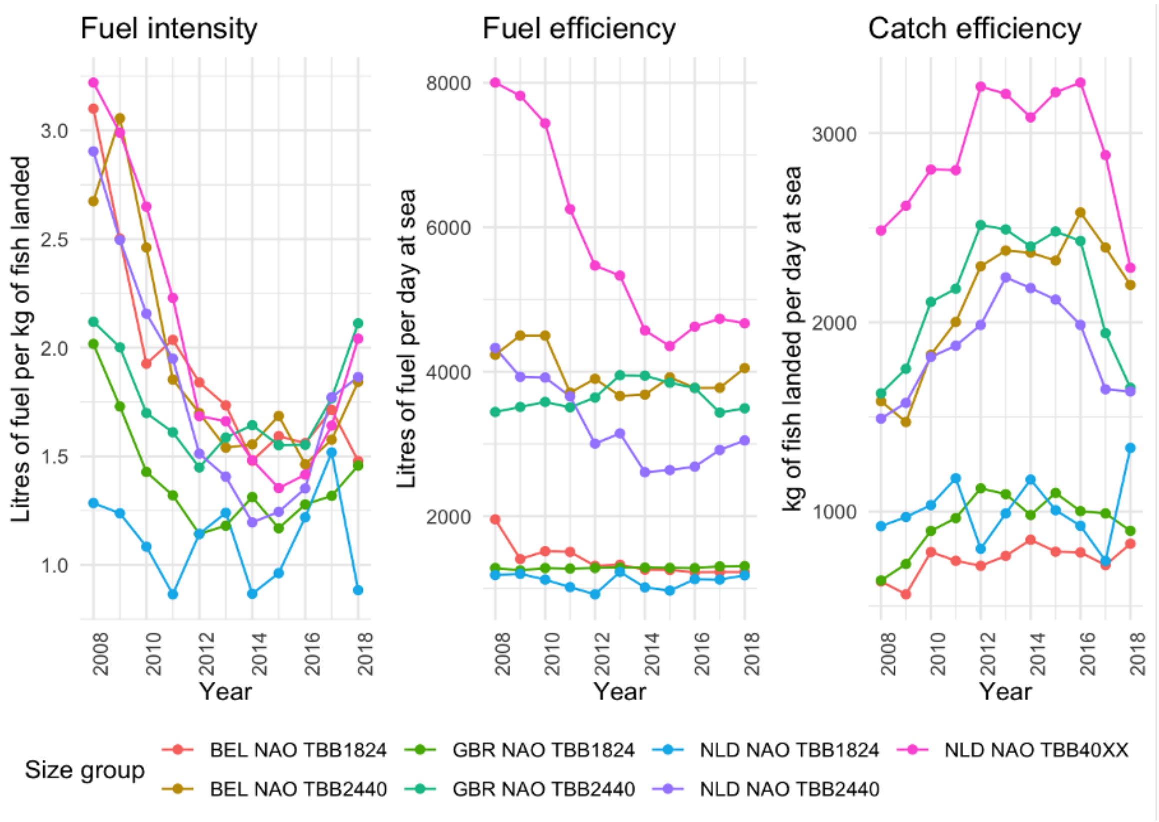

Figure 26 Fuel intensity for selected beam trawlers in the North Sea

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[5] NLD (Netherlands) NAO (catch area) TBB (Beam Trawler) 2440 (24 to 40m length overall); 40XX (40 to >40 m LOA)

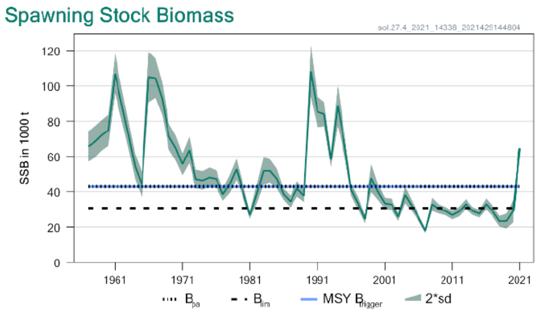

Figure 27 SSB Sole and Plaice North Sea (ICES 2021a)

The main target species for the beam trawl fleet segments are sole with plaice as bycatch for many vessels. The stock was relatively stable around Blim between 2006-2018 (Figure 27). **The observed reduction in fuel use intensity has, therefore, to do with other factors than improvement in stock size** (e.g., improved catch efficiency independent of stock size).

These two segments (NLD NAO TBB2440 and NLD NAO TBB40XX) experienced a decrease in daily fuel consumption between 2008 and 2014 along with being more fuel efficient, which may coincide with the introduction of outrigger trawl techniques and pulse trawling. Overall, catch efficiency of the most of EU beam trawl segments show a similar trend over the period 2008-2018, with an increase in catch rates (LPUE) between 2008 and 2012, followed by a decrease between 2013 and 2018. In overall, the catch efficiency increase seems to link to targeted stock status in better shape (Figure 28).

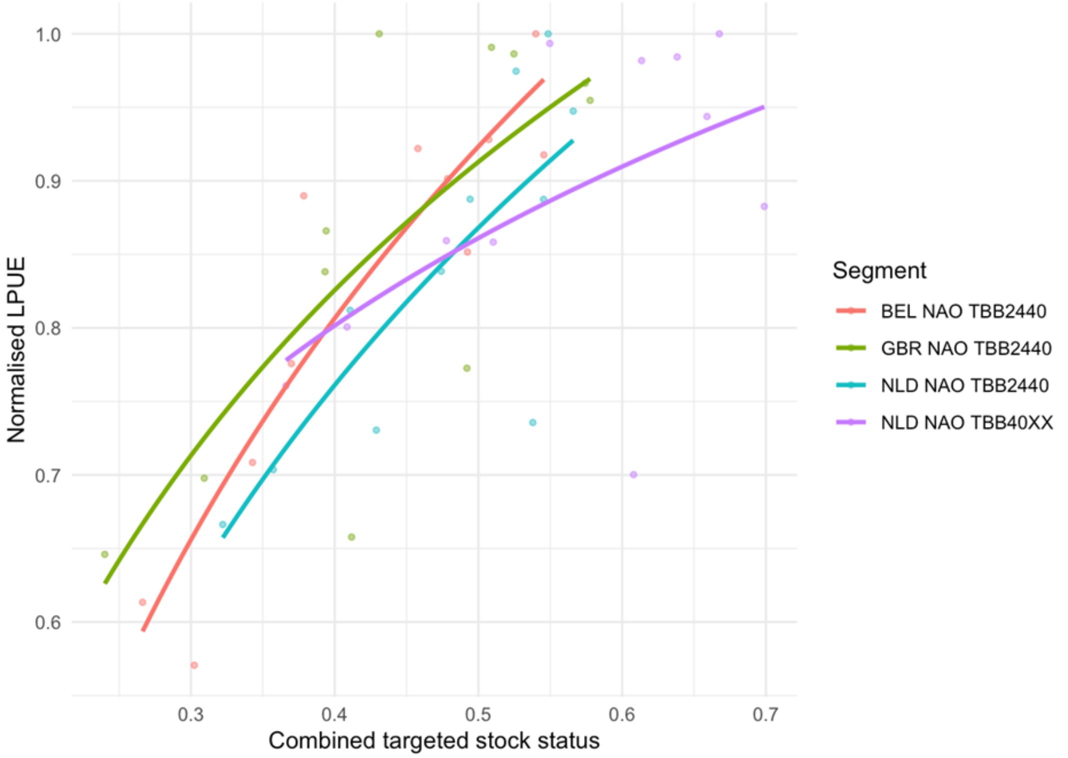

Figure 28 Relationship between the Combined targeted stock status and the normalised LPUE for North Sea beam trawlers (TBB) (see Annexe for detail of the calculation of the indicators). The relationship is only calculated for segments landing more than 50% (in volume) of species from stock evaluated by the ICES.

3.1.2 Demersal trawls Mediterranean (DTS)

For the some of the demersal trawl segments in the Mediterranean Sea the data shows much higher fuel intensity than other areas, and a lot fluctuation in fuel use intensity and fuel efficiency. In the last years of the time series catch efficiency increased for all segments (Figure 29).

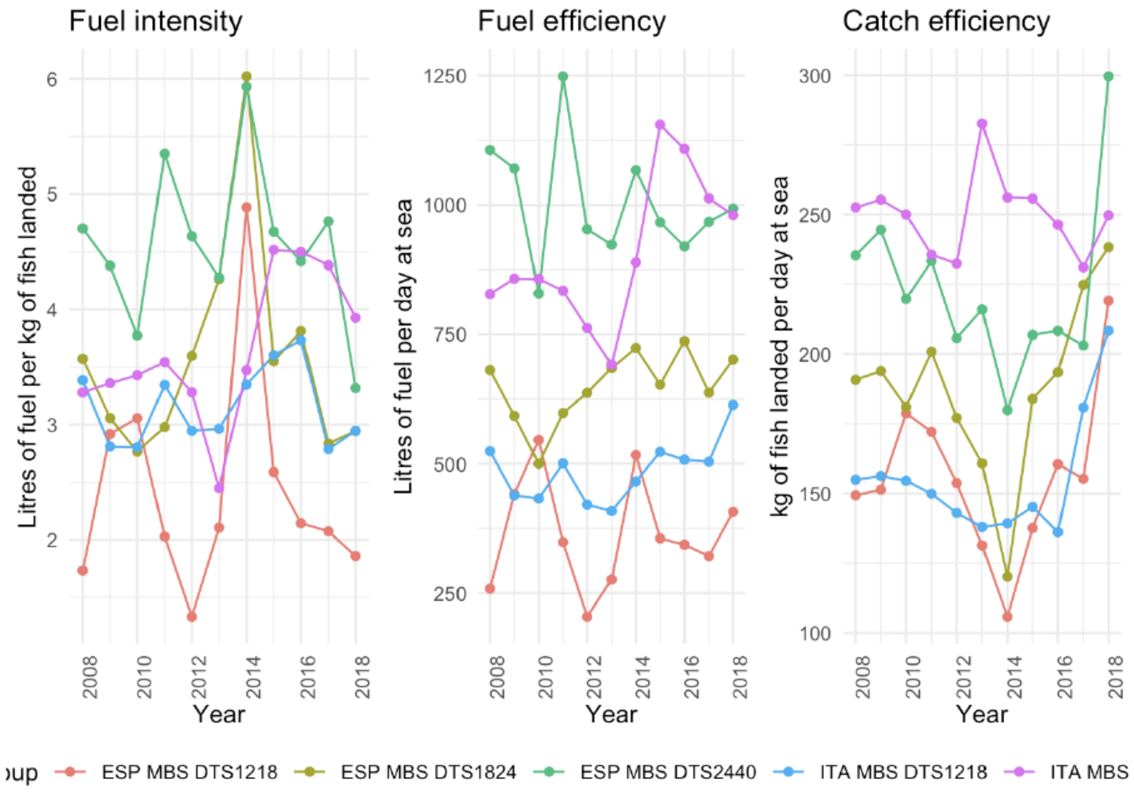

Figure 29 Fuel intensity for selected demersal trawlers in the Mediterranean Sea

This unclear trend for fuel intensity cannot be linked to any stock development at the level of data aggregation available for this study. The average F/Fmsy in the Central and West Med. stayed far above the target at 1 over this time period (STECF 2021), a stability that might explain the absence of a clear link and trend in fuel use. Besides this, the unclear trend in fuel efficiency could not be linked to any technical development for these segments (Figure 30).

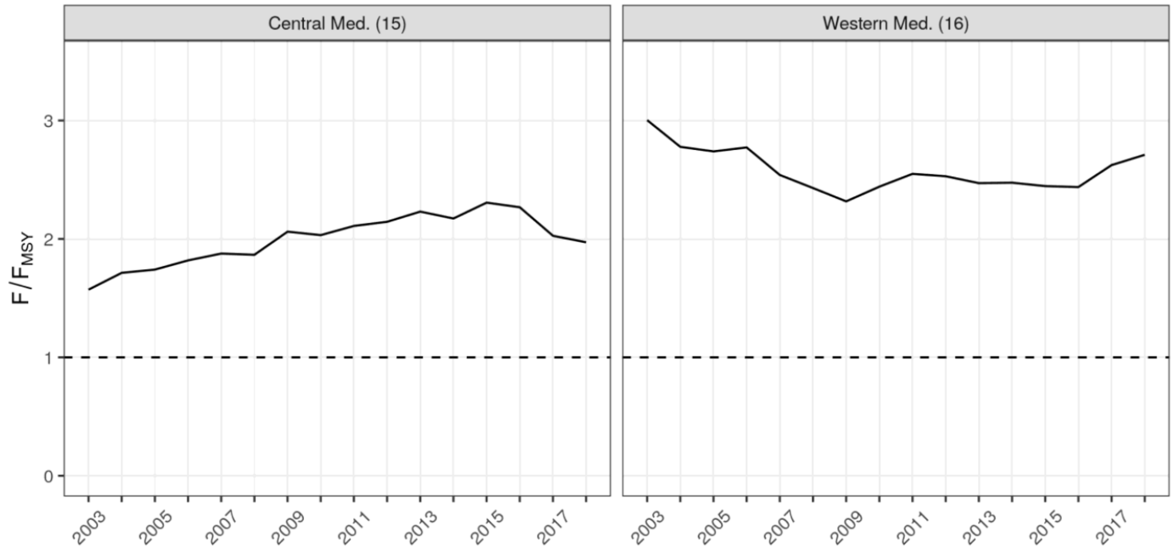

Figure 30 Trend in F/Fmsy in the Central and Western Mediterranean Sea (STECF 2021a, p. 62)

3.1.3 Demersal trawlers over 40 m North-East Atlantic (DTS)

For the three selected fleet segments (Figure 31) the fuel intensity decreased for many years. The fuel efficiency indicator is not showing a clear trend for all segments. While for the French segment fuel use per day at sea decreased over several years, there is not such a clear trend for the fleet segments from the UK and Portugal.

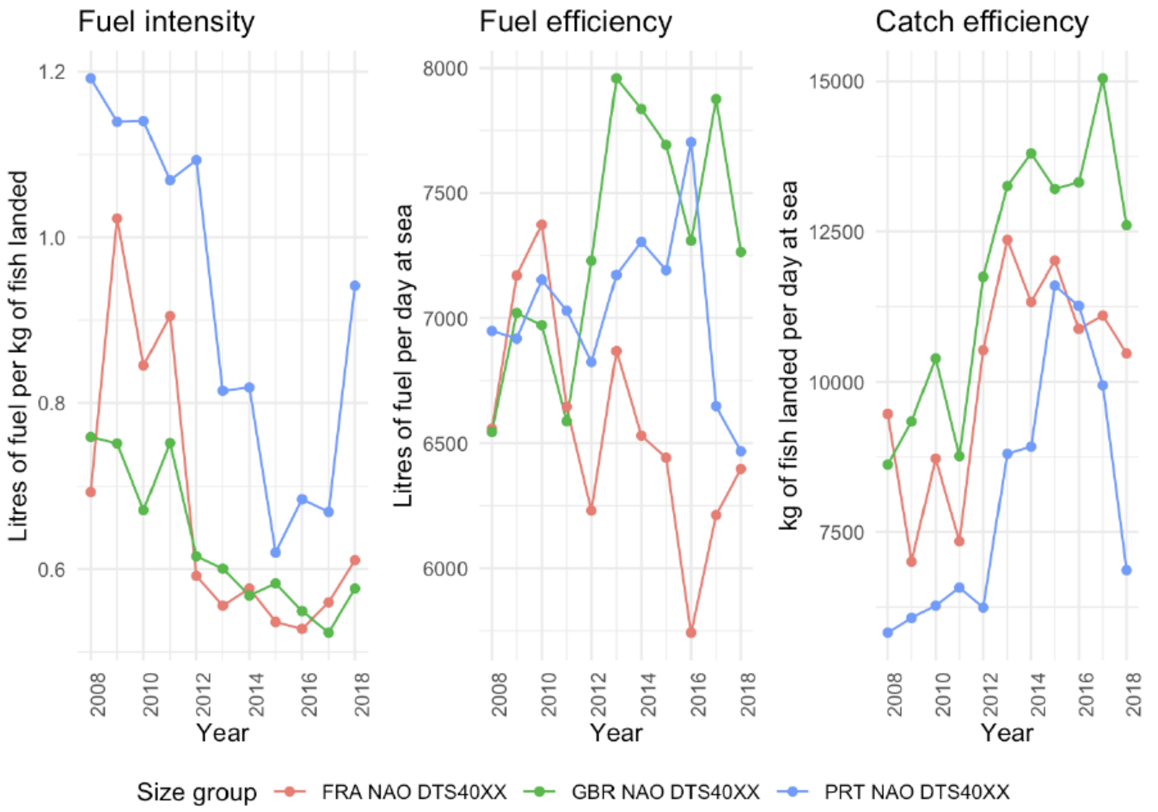

Figure 31 Fuel intensity for selected demersal trawlers above 40 m in the Northeast Atlantic

There was a general trend in FAO Area 27 for an improvement in stocks since 2003 with now F/Fmsy is overall near 1 (Figure 32). **This concomitant reduction of fuel use intensity, increase in catch efficiency, and the F/FMSY indicator would be a sign that the favourable stock developments are accompanied by less fuel intense fishing,** also resulting from higher catch rates (Figure 33). However, the large demersal trawlers fish a variety of species in the Northeast Atlantic with different trends and fluctuations in available quota. In addition to this, if the reduction in fuel use intensity or the catch efficiency result from or is the actual origin of the wished stock development is still not clear.

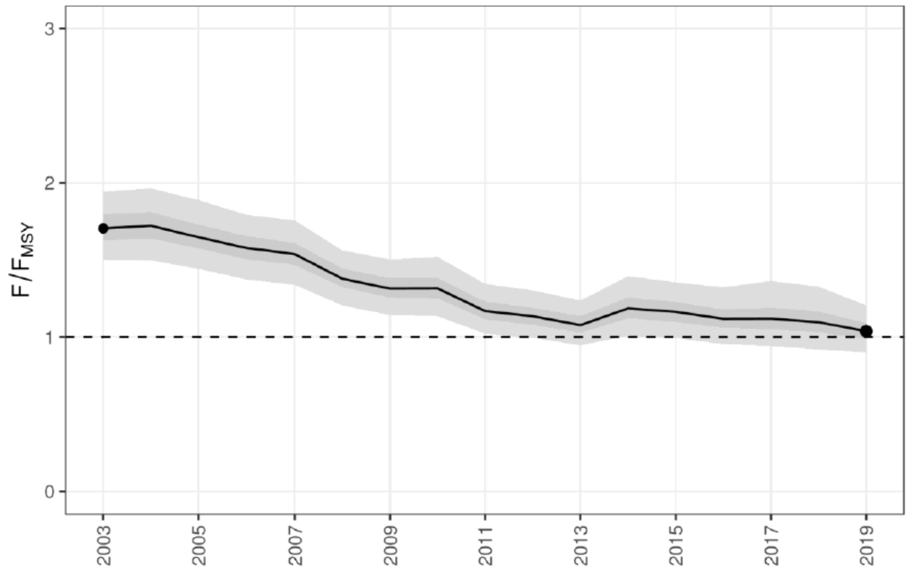

Figure 32 Trend in F/Fmsy in FAO Area 27 (STECF 2021a, p. 44)

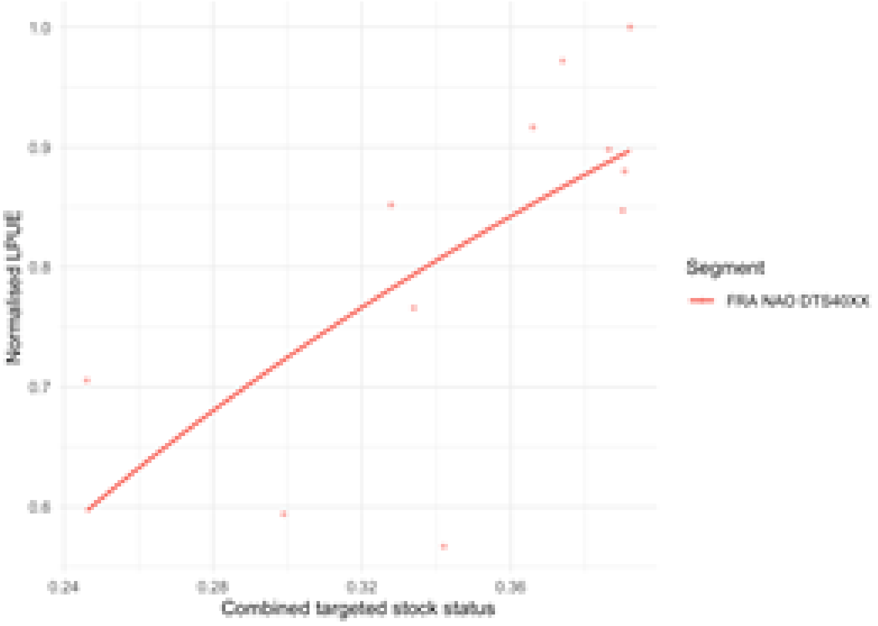

Figure 33 Relationship between the Combined targeted stock status and the normalised LPUE for North Sea demersal trawlers or seiners (DTS) (see Annexe for detail of the calculation of the indicators). The relationship is only calculated for segments landing more than 50% (in volume) of species from stock evaluated by the ICES.

3.1.4 Pelagic trawler Baltic Sea (TM)

For pelagic trawlers in the Baltic Sea the fuel use intensity is much lower than for other segments. The trend for most fleet segments is quite stable for fuel efficiency while more fluctuating for fuel intensity. The catch efficiency increased slightly over the last years of the time series (Figure 34).

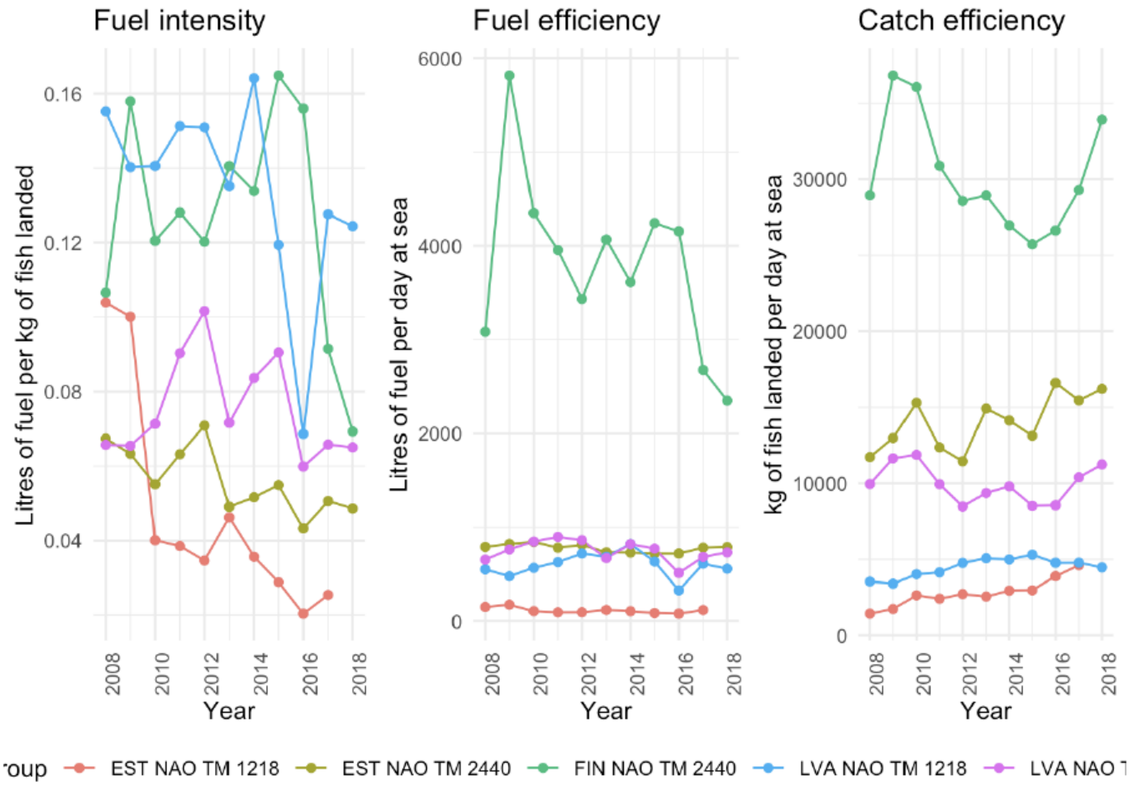

Figure 34 Fuel intensity for selected pelagic trawl segments in the Baltic Sea

The F/Fmsy indicator decreased for the Baltic Sea since 2003 but there are still several stocks where the indicator is above 1 (Figure 35).

The sprat stock in the Baltic Sea was above BMSYtrigger since the 1990 while the herring stocks in the eastern Baltic Sea were slightly below and above MSYBtrigger since the mid of the 1990ies with currently slightly over Blim. This fluctuation in stock size could be a reason why also the fuel intensity indicator fluctuates. Beside this, as the fuel efficiency is found stable, there are no apparent changes in gear technology that would link to a change in fuel efficiency during that time period, except for maybe Finish large Pelagic trawlers. For the other segments, better catch efficiency would link to better targeted stock status (Figure 36).

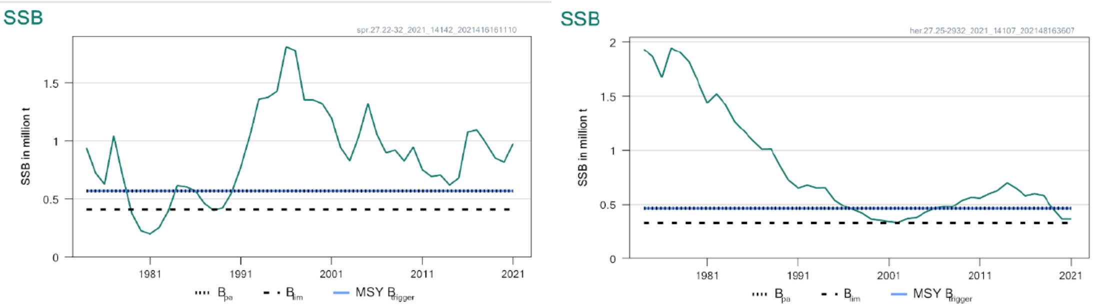

Figure 35 Sprat stock Baltic Sea (left) and Herring stocks in area 25-32 (incl. Gulf of Riga) (ICES 2021b)

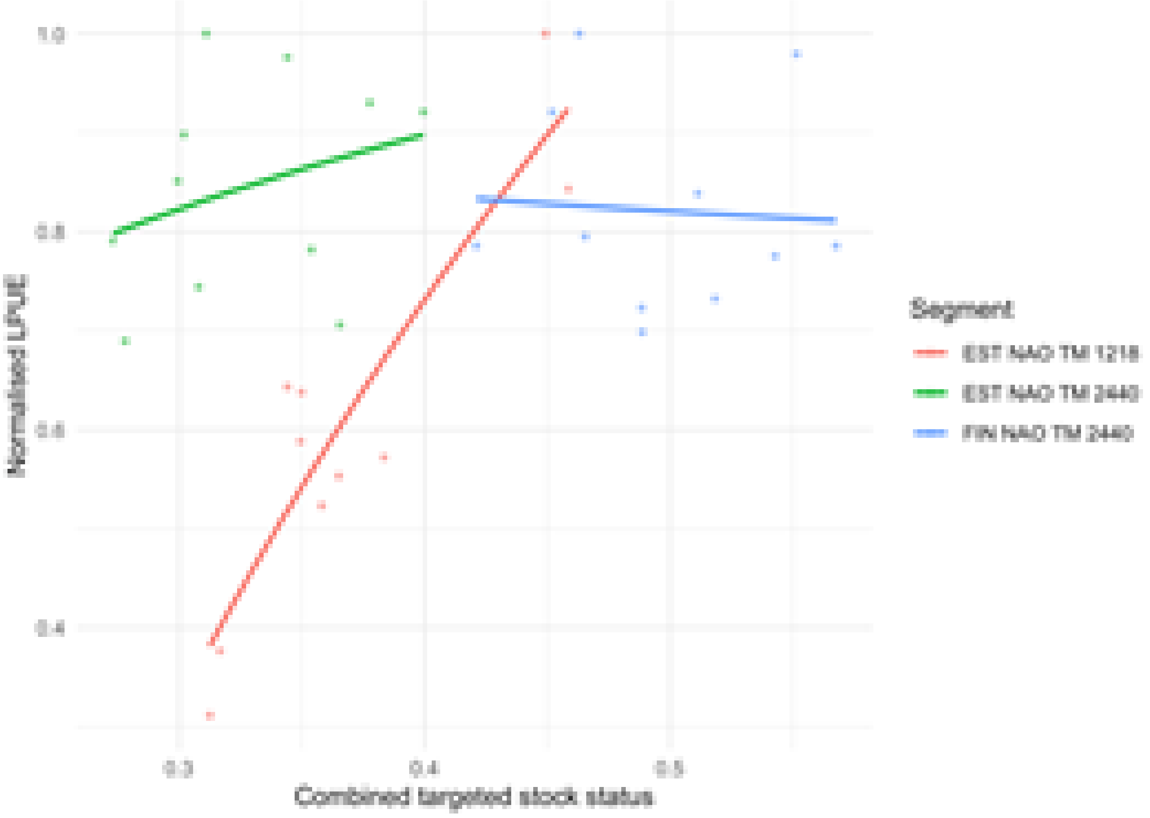

Figure 36 Relationship between the Combined targeted stock status and the normalised LPUE for Baltic Sea pelagic trawlers (TM). The relationship is only calculated for segments landing more than 50% (in volume) of species from stock evaluated by the ICES.

3.1.5 Pelagic trawls Northeast Atlantic (TM)

For the pelagic trawlers the fuel intensity indicator is relatively flat for most of the segments with higher fluctuation at the beginning for the French NAO TM1824 segment. Fuel efficiency show a more fluctuating and unstable trend with a decreasing trend in fuel use per day at sea for the French segment (TM1824) while increasing trend for the Irish segment (TM40XX) for several years. The indicator is stable for the other segments (Figure 37).

The **fuel intensity of pelagic trawlers is not surprisingly much lower than the fuel intensity for demersal trawl segments** given the very large volume of catch these fisheries are used to land. The trend in the F/Fmsy indicator for stocks in FAO Area 27 (Figure 37) is decreasing and nearly 1 today, which would support the fact that the fuel use intensity appears quite disconnected from the stock developments for the pelagic fisheries in this area, while the catch efficiency could have increased along with an increase in the combined targeted stock status (Figure 38).

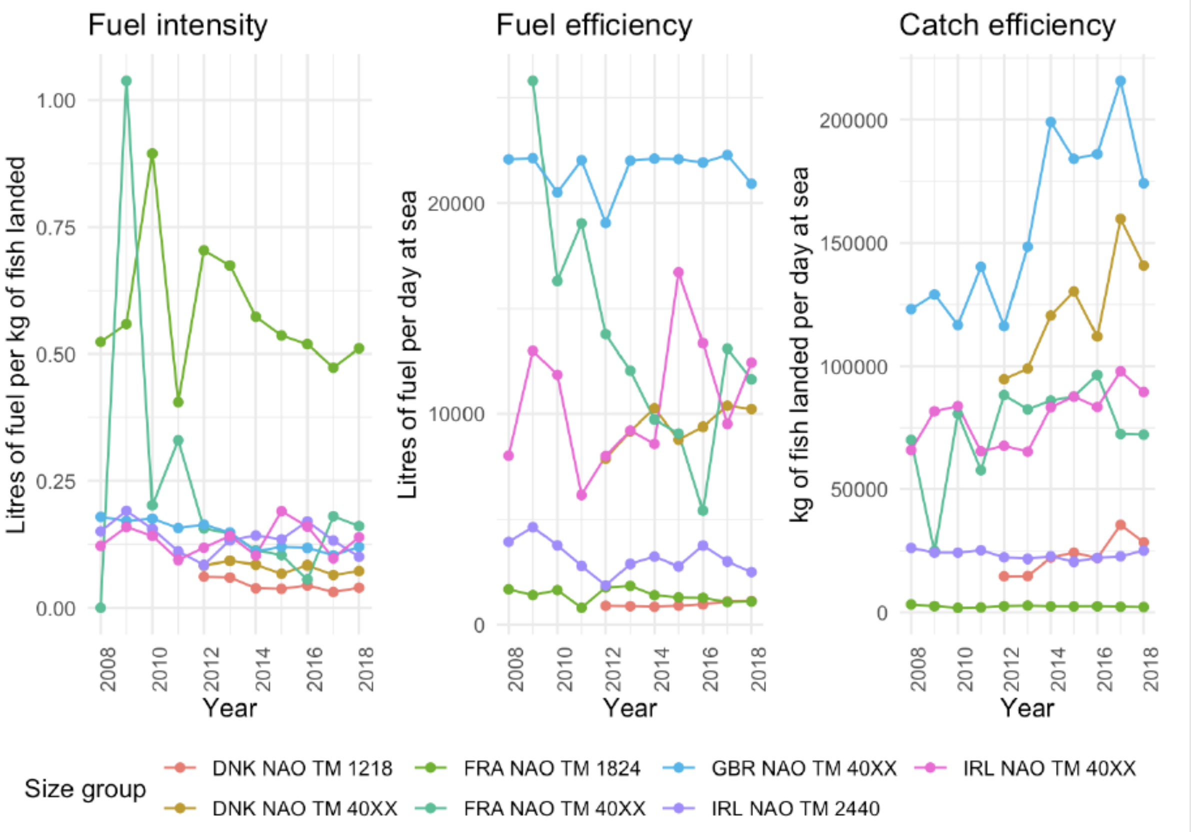

Figure 37 Fuel intensity for selected pelagic trawl segments in the Northeast Atlantic

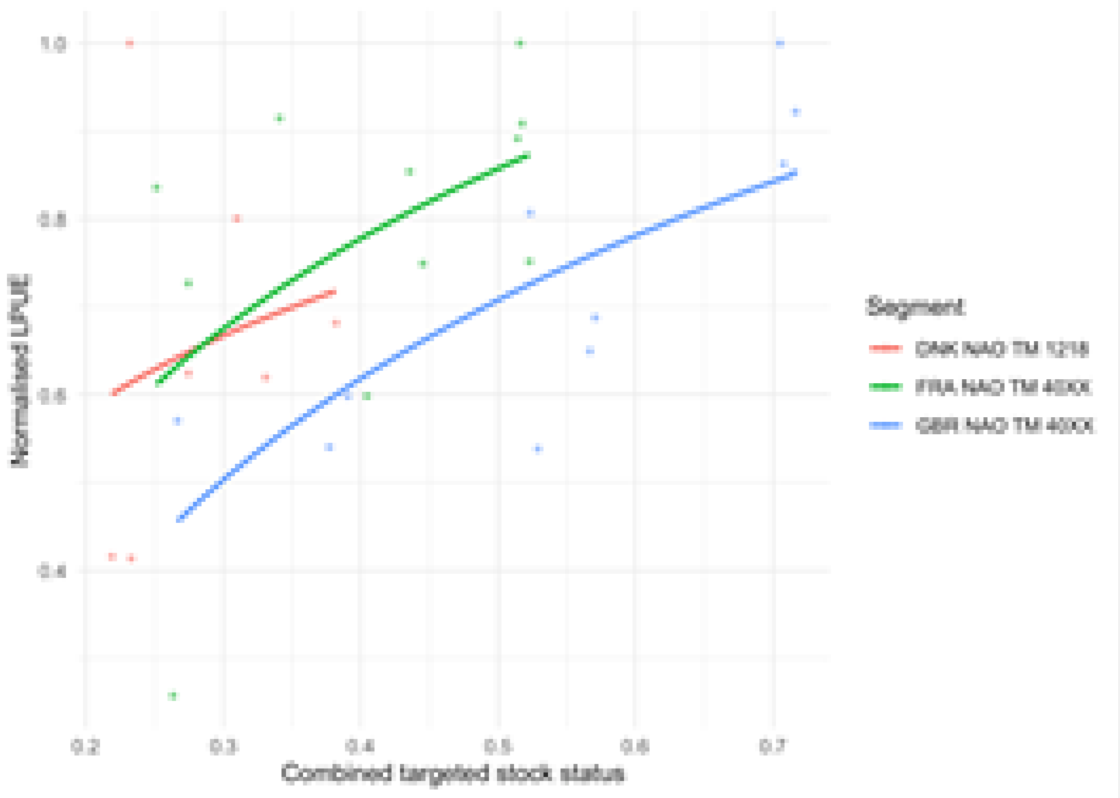

Figure 38 Relationship between the combined targeted stock status and the normalised LPUE for North Sea pelagic trawlers (TM) (see Annex 23 for detail of the calculation of the indicators). The relationship is only calculated for segments landing more than 50% (in volume) of species from stock evaluated by the ICES.

3.1.6 Across segments

The profiles allowed also to estimate the ranges of fuel use intensity for the different EU fishing fleets. These ranges confirm that fuel intensity ranges for bottom trawls and several static gears are very similar among large vessels, as reported in previous studies, and that the least fuel intensity is achieved by segments using midwater trawls and purse seine.

Active demersal segments have generally a slightly higher fuel use than midwater trawls (TM) and passive gears (PG) segments. The overall look at the different fishing gears seems also to indicate that if very small vessels using passive gears (PG) are less fuel intense, some small-scale coastal fisheries (PGO) are not necessary more fuel efficient than larger vessels, especially the vessels searching for the pelagic species. This seems a bit counterintuitive as the small vessels are fishing close to shore and often with passive gears. The reason for that could be that the CPUE is lower, the large vessels with pelagic trawls are able to catch a large number of fish with relatively low fuel input.

STECF has analysed the methodology of **total factor productivity (TFP)** in the AER 2020 to compare the performance of smaller and larger vessels (STECF 2020, p. 39 ff.). With the TFP we can analyse productivity of labour, capital and energy in the production process. Capital and energy were analysed as close complements as the energy consumption is correlated to the invested capital (in the vessel itself with its characteristics like hull design or engine power and this is correlated to the fuel necessary to run the vessel) and can hardly be changed in the short term. A vessel is usually operated for some time before there will be investments on board, e.g., more fuel-efficient engines.

The TFP is expressed in relative terms and therefore unitless. The production is calculated as an aggregation of labour remuneration, capital remuneration and energy expenditure. The inputs also aggregated in one value (Capital, Labour, Energy). The TFP is then interpreted as the ratio of the output value aggregate to the input value aggregate. Analysing the ratio of one to the other results in a TFP index (Da Rocha *et al.* 2019). From a TFP perspective the small-scale fleet was more efficient in the use of their input factors than the large-scale fleet in two areas (NAO and MBS). On average the small-scale fleet generates more output per unit of input compared to larger vessels (

Table 10**)**.

Table 10 Total Factor Productivity Levels in real terms for two areas (STECF 2020) i.e., North Atlantic Ocean (NAO) and Mediterranean (MBS) large scale fishing (LSF), split for demersal target species vs pelagic, and small-scale fishing (SSCF).

Area	**NAO**			**MBS**		
Fleet categories	LSF		SSCF	LSF		SSCF
Fisheries	Demersal	Pelagic	all	Demersal	Pelagic	all
TFP	2,05	2,03	4,02	1,71	1,80	2,12

The number of small-scale vessels is, however, decreasing in many countries of the EU (STECF 2021b) as higher economic efficiency (i.e., higher TFP) may not translate into a better economic situation if the profit level of the individual fishers may be too low to stay in business for long. Nevertheless, small-scale vessels seem to be more productive and that could be good reason to **look into possibilities to improve economic performance of the small-scale vessels** in the long run, which **would go hand to hand with the use of more fuel-efficient technologies** on board to reduce the energy expenditure.

Limitations

The results presented above on the fuel intensity, fuel efficiency and catch efficiency have to interpreted with caution. Importantly, **none of the three data sources (DCR, DCF and FDI) constitutes a direct measurement of fuel consumption**. Contrarily to other physical characteristics describing the activity of fishing vessels (physical characteristics, effort, catch), fuel consumption is always estimated by segments or sub-segments. Moreover, some Member States have adjusted their estimation procedures, modifying the way fuel consumption is calculated without re-estimating previous years. Hence, time series may present interannual variations that are not linked to technical change or change in fishing patterns.

For an improvement of the information on fuel consumption gathering of data on fuel consumption at the vessel level would need daily reporting by a significant sample of the fleet in each Member State. Some projects are currently pushing for the implementation of fuel meters on-board fishing vessels (e.g., Amarée in France), but these projects do not cover the entire fleet, nor are they geared towards data collection. This has several implications on the quality of the data:

- Fuel consumption is **estimated at the economic segment level on an annual basis**. Evaluating the fuel consumption at the metier level (level 5 or 6) is currently not possible and would need modifications in the way economic data is collected and

methodological developments to define a commonly accepted disaggregation methodology.
- **Several methods are used to estimate fuel consumption**: direct surveys (although questions may vary from one Member State to another), economic approximations based on annual fuel costs, estimation based on physical characteristics. Mixing estimation methods lessens the ability to generate comparable estimations.
- Fuel consumption per day at sea is highly **dependent on the physical characteristics of the fishing vessel** (hull design and engine system) and on the metiers performed by the vessel. For most EU vessels, these characteristics are stable from one year to the next at the segment level.
- Moreover, some Member states have not submitted the relevant data for some years, creating gaps in the time series. These gaps have long been identified by the STECF, but only few of have been filled over the years.

There are **a range of sources of greenhouse gas** (GHG) emissions on fishing vessels, such as **refrigerant leaks**, **packaging**, **ice making** or **bait**. Some standards also consider the **GHG emissions associated with the construction of the fishing vessel** (notably the Norwegian standard). These additional sources of GHG emissions are not covered in the calculations performed in this project. It is therefore not possible to assess the total GHG emissions of the production stage through the public data currently available. Parker (2012) notes that most of the projects looking at GHG emissions of fishing vessels integrate information of non-fuel-related GHG emissions with a high level of uncertainty attached.

For each Member State, a specific profile of fuel use and catch was created (available online)[6] to present how the fuel-use indicators differed for each economic fleet segment within each Member State.

The main conclusion of the analysis is that **the level of precision in the DCF and DCR data is not sufficient to identify the diffuse adoption of technological innovations by fishing vessels**. The temporary introduction of pulse trawling by Dutch beamers is the only example for which the effect of innovation may be observed in the data collected at the European level. Other innovations that may have been adopted by EU fishing vessels cannot be linked to fuel efficiency gains, notably because the granularity and the quality of the fuel consumption data are not sufficient to conduct such analysis.

To further the understanding, and support the analysis of DCF and DCR data, in determining fuel consumption of vessels and the overall landings of those vessels, a stakeholder engagement was utilised to query overall fuel consumption and landings per vessel. There was a very low answer rate (five questionnaires returned) to further our understanding of fuel consumption rates across fisheries, with the responses potentially showing that fuel use intensity may not differ substantially between bottom trawls and static gear (e.g., longlines, pots). Importantly, this engagement shows that asking for fuel consumption via questionnaires is not likely to provide substantial and rigorous information. It is, however, one of the most common methods used in current EU data collection to estimate fuel consumption. The most appropriate way of determining fuel consumption, and being able to analyse in a systematic way, would be through **developing a monitoring system within vessels**.

3.2 Danish pilot study

To provide a further analysis of whether there are any potential patterns in fuel use associated with EU capture fisheries, a specific **pilot case study looking at the Danish fishery** is provided (see full details in Annex 24, Bastardie *et al.* in press). Within this work, as found for the majority of fisheries within Europe, interannual variation in fuel use

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[6] https://data.sakana-consultants.com/CINEA_fuel/

intensity was the most substantial pattern apparent, with no particular trend in fuel use intensity over the period 2005-2019. Despite this, there was **substantial differences in fuel use (and also intensity) between different fishing techniques**. For example, fuel use intensity is relatively low for dredge fishing on mussels, but very high in comparison for a range of crustacean fisheries (northern shrimp PRA, *Nephrops norvegicus*, *Crangon crangon*); this type of fishing has relatively high fuel use intensity, as there is a low level of return (i.e., biomass) against the amount of fuel used. Nevertheless, such high fuel use is balanced against the high economic return for such fisheries. Importantly, if an absolute value for fuel consumption is utilised, those economic fleet segments targeting pelagic species show the highest fuel use, as pelagic species, being geographically spread over an extended and offshore area, require the deployment of large fishing vessels. However, fuel use intensity for pelagic fisheries is low, i.e., lower than bottom trawling for demersal fish and shellfish resource. This is because fuel use intensity is determined by litres of fuel per unit of catch kg, and the pelagic fleet is landing a huge volume compared to any other fisheries.

3.3 Potential impacts of a changing climate and higher fuel-efficient techniques on fuel consumption

Although there seem to be no major patterns in fuel use consumption detected across the majority of the EU capture fisheries, there is a need to understand further **how resource efficiency may be impacted by future changes in climate and alternative stock developments with change in catchability**. Therefore, three bio-economic models were applied to assess the effect of changes in stock levels on fuel consumption under different climate change scenarios (full details of methods provided in Annex 25). **The models assumed that an increased catch rate (CPUE) would mean lower fuel usage per kg of fish and vice versa**. All results are presented for model runs until 2060 for FLBEIA, until 2030 for SIMFISH and DISPLACE. We present the results here focusing on cod and plaice for the North Sea and international mixed fisheries in the Baltic Sea.

3.3.1 Cod – FLBEIA

For all climate scenarios (None: prolonging the environmental conditions from today; RCP4.5: climate scenario from the IPCC with lower temperature increase; RCP8.5: climate scenario from the IPCC with higher temperature increase) and three of the HCRs (F_{MSY}: the fleet is fishing at the F_{MSY} level; F_{MSY}H: the fleet is fishing at the upper F_{MSY} level from the F_{MSY} ranges; F_{MSY}L: the fleet is fishing at the lower F_{MSY} level from the F_{MSY} ranges) cod stocks show increases after 2020, though for the fixed effort HCR (i.e., the fleet is always fishing at this effort level) the stock collapses (Figure 39a). After a sharp increase at the beginning for all HCR scenarios, **the stock decreases for RCP4.5 and RCP8.5 scenarios, with the sharpest decrease for RCP8.5.** In addition, fishing effort stays flat after 2025, and only decreases dramatically in the RCP8.5/F_{MSY}H scenario after 2050 (Figure 39a). This stems from the fact that cod drops below $B_{trigger}$, and thus the target F must be scaled down according to the ICES HCR. As long as F_{MSY} is the target, the effort is relatively constant.

In terms of effort, for the two economic fleet segments for otter trawl (Denmark and Germany), in the RCP8.5 scenario for the F_{MSY}H HRC there was a decrease in effort at the beginning of the time period (between 2020 and 2025) (Figure 39b, c). Such drop in effort is the result of limited availability of cod associated with the **choke effect of cod** (i.e., because of regulations associated with the landing obligation) and the full implementation of the discard ban. Such reduced effort then changes with increased stock abundance after 2025, staying relatively stable across the full model run. Such stability in effort is likely associated with the fleet having to stop fishing when cod quota is reached (i.e., min. assumption in the model).

As a proxy of the quantity of fuel that would be required to catch the quotas, the change in SSB and effort can be translated into change in CPUE (Figure 39d, e); an increasing

CPUE would mean lower fuel usage per kg of fish and vice versa. For both economic fleet segments of otter trawls (Denmark, Germany) the CPUE increases at the beginning of the modelling run, and then stays flat across the majority of climate and HRC scenarios, although in some cases (especially RCP8.5) the CPUE decreases. Such **patterns show that at the beginning of the time period the fleet can improve its efficiency by catching the same amount of fish with a potential for lower fuel usage**. Later, especially for the $F_{MSY}H$ and RCP8.5 scenarios, CPUE decreases, which would result in an increasing use of fuel per kg fish. This is, however, only true if vessel characteristics do not change over this period (e.g., fuel efficiency associated with changes in hull design). Over a 40-year period (as modelled within this work) it is expected that new vessels/motors that are more fuel efficient will be introduced into the fleet.

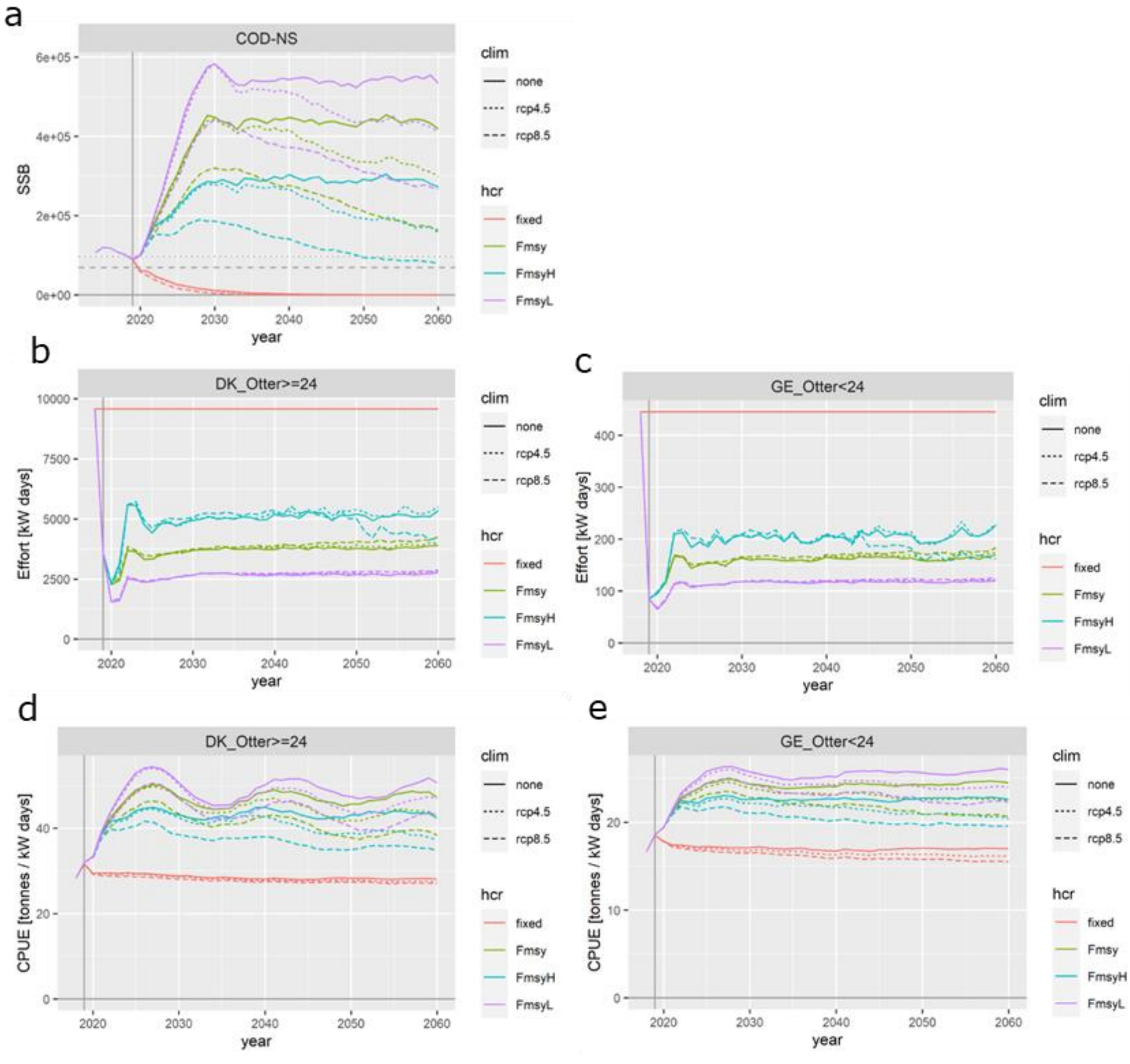

Figure 39 Simulated indicators including a. SSB (in tonnes) for cod 2020–2060; b. effort (kW days) for Danish otter trawls above 24m 2020–2060; c. effort for German otter trawls below 24m 2020–2060; d. CPUE for Danish otter trawls above 24m 2020–2060; e. CPUE of German otter trawls below 24m 2020–2060

3.3.2 Plaice – FLBEIA

For the North Sea plaice fishery, all scenarios show that the stock is increasing, with the lowest rate of increase under the fixed-effort scenario (Figure 40a). Effort in the plaice fishery (which is focused solely on beam trawlers) at the beginning of the period fluctuates much more than for otter trawlers, and is relatively constant after 2030 (Figure 40b).

Interestingly, despite F_{MSY}H HCR showing the highest effort, stock levels stay well above MSY $B_{trigger}$. The initial increase in SSB under the modelled scenarios have a positive impact on CPUE, likely resulting from decreased fuel usage per kg of fish. However, **the CPUE decreased over time, especially for the RCP8.5 scenario with the potential for greater fuel usage** in an attempt to catch the same amount of fish (Figure 40c).

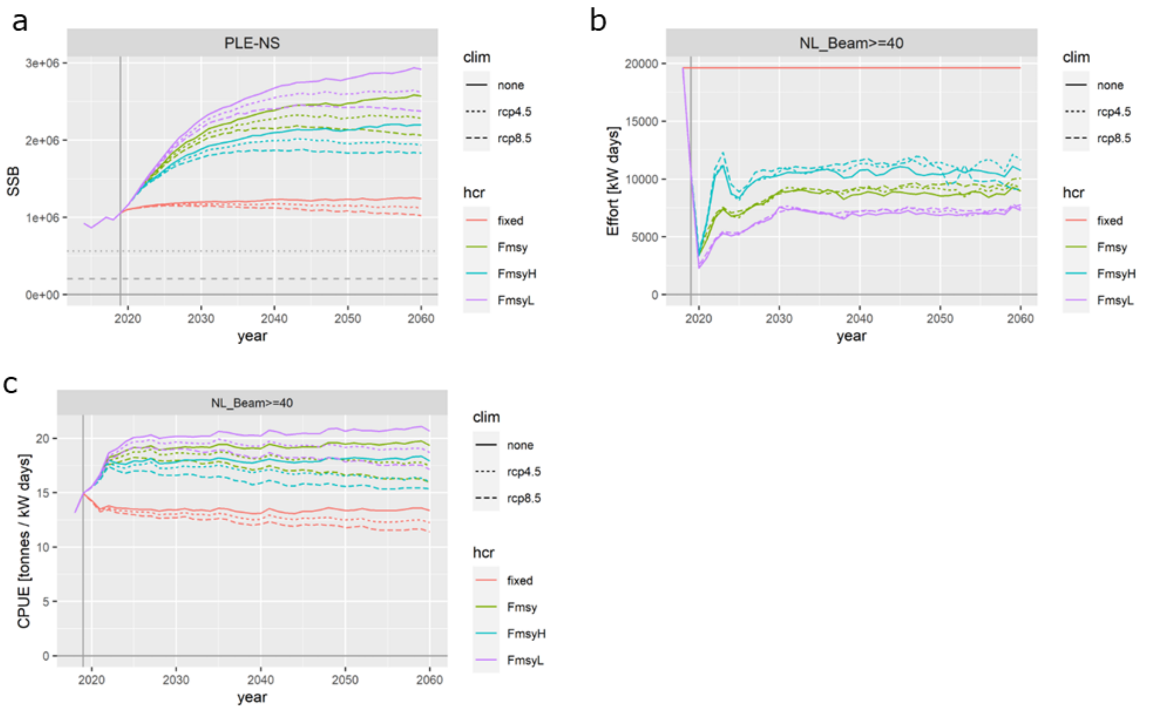

Figure 40 a. SSB of plaice 2020–2060; b. Effort Netherlands beam trawlers above 40m 2020–2060; c. CPUE Netherlands beam trawlers above 40m 2020–2060

3.3.3 SIMFISH – Dutch Flatfish fisheries

For the base scenario, because of the ban on pulse trawling, effort decreases rapidly, while the increase in fuel costs results in the profit of the three segments decreasing substantially over the time period (Figure 41a). For example, the economic fleet segment NL_TBB_2440 has an increase and then substantial loss during the first years of the timeline. In line with this, in the simulation, when examining fuel consumption per kg of landings, the **ban on pulse trawling led to a substantial increase in fuel consumption** (Figure 41b). There is also a decreasing trend in fuel consumption when looking at the scenario analyses (Figure 41c), although these calculations may also include possible changes in effort distribution over the 10-year period. For the base scenario, possibly as a result of change in effort distribution and changes in recruitment, fuel consumption increases.

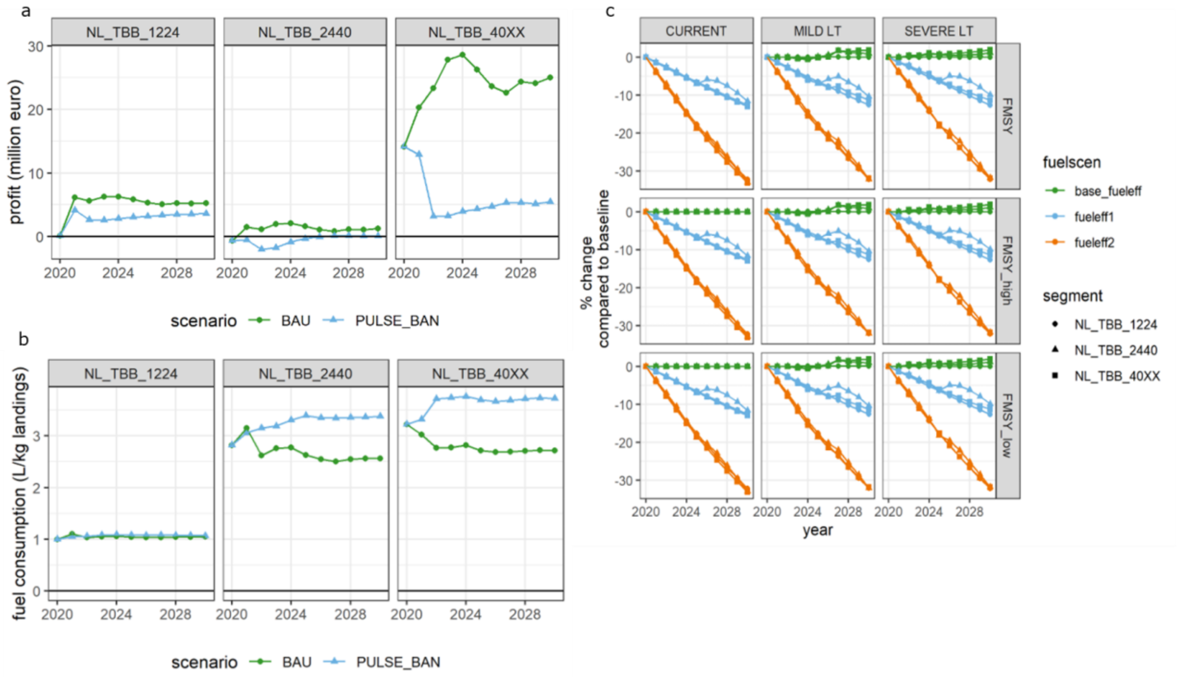

Figure 41 a. profit for the business as usual (BAU) compared to the PULSE_BAN scenario; b. fuel consumption per kg landings; c. scenario analyses including the fuel-efficiency scenarios

The SIMFISH model (Bartelings *et al.* 2015) runs include a spatial component contrary to the FLBEIA runs. Therefore, fuel consumption increases slightly over the 10 years because of the change in distribution of plaice in the Southern North Sea (the stock moves into deeper waters).

3.3.4 DISPLACE – International mixed Baltic fisheries

In the simulations, vessels assumed to save fuel when towing (e.g., from limiting the hydrodynamic drag required to tow the gear in contact with the bottom, or assuming less fuel-intense gear specification for midwater pelagic trawls) led to better development of anticipated revenue from fishing (Figure 42). Such a result would hold as long as the overwhelming effect of the 'effort max' scenario is not considered ('Effort max' is a scenario for which a fleet does not stop fishing as soon as its limiting quota is exhausted), leading to long-term economic loss on average

Besides the direct effect on reducing fuel costs, more fuel-efficient fishing has a marked indirect impact on **west Baltic cod and plaice** by increasing stock abundance and subsequent TACs as a result of **higher catch rates and lower operating costs releasing the pressure on those stocks**. Given the nature of the model, this change is likely the result of a change in spatial effort allocation, possibly towards more distant fishing grounds that are now becoming more attractive when fuel is less limiting the expected profit on zones – a determining factor for vessels when selecting where to fish.

Hence, the simulation shows no apparent link of stock developments with the energy-use intensity apart from saving on costs that benefit the economy of fishing. There are **likely dominating compensatory/rebound effects that prevent saving fuel from stocks in better shape**. However, a possible indirect effect on fished stocks levels arises from saving energy costs, which result from more time spent at sea. In addition, some redirection of fishing effort toward areas that become attractive when fuel use is less limiting is a possible undesirable side effect.

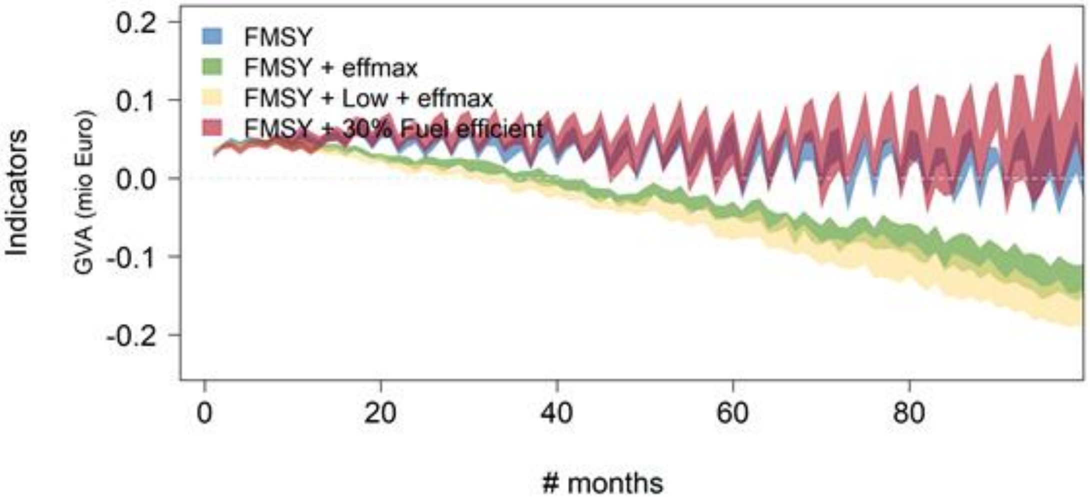

Figure 42 Monthly GVA calculated as a monthly average per vessel from all vessels fishing in the Baltic Sea combined for a selection of scenarios comparing a combination of F_{MSY}, F_{MSY} lower, 'effort min', 'effort max', or assuming a reduction of fuel use per unit of fishing effort of 20 %, in the absence of climate change effect

3.4 Conclusions

It was shown that the fuel use intensity is larger in the Mediterranean than in the North East Atlantic fisheries, but also depend on fisheries where the pelagic fisheries have one of the lowest fuel use intensities. Only a few trends have been found out making difficult to relate to any underlying stock developments. A few cases have also shown an increase in fuel efficiency that would possibly relate to a change in technologies, which are the Dutch Beam trawling, or the possible Finish pelagic trawling for herring in the Baltic Sea. As the data analyses revealed, **it is however not accurate to apply the DCR/DCF data and draw conclusions on the fuel efficiency of the fleet segments** at such a high level of data aggregation. Limitations also result from the way data is collected, which was found far too variable to allow the comparison between Member States (see Annexe on Task 2 methods). Only in a few cases, for example, the Danish fleets or the Dutch flatfish fleet where more detailed data is available, was it possible to provide information on the historical development of fuel efficiency. Nevertheless, finer national fleet-segmented data **with the application of bio-economic models** also contribute to **assessing how the fuel efficiency may develop**. The flatfish fleet is an example of where the analysis of technical improvements was possible. It is shown that the ban on Dutch pulse trawlers has removed some potential for improving the fuel efficiency. The ban may also have proved a missed opportunity to limit the adverse effects on bottom habitats in this area because beam trawling with conventional, heavier gear may be more damaging for the seafloor, all other variables being equal.

3.5 Recommendations

Develop and inform a monitoring programme collecting accurate data on fuel consumption at the vessel level for daily reporting by a significant sample of the fleet in each Member State. Direct measurements of fuel use (and maybe GHG emissions) during fishing operations may be possible by installing fuel loggers' on-board vessels completed via mandatory reporting in, for example, logbooks as a simple but quite significant step forward, besides conducting regular energy audits. Some projects are currently pushing for the implementation of fuel meters on-board fishing vessels (e.g., Amarée in France, data collection performed by AZTI), but these projects are not covering the entire Member State fleet, nor are they geared towards data collection. Development in intelligent fuel meters may help close the data gaps by allowing fuel consumption to be reported automatically without the need for vessel owners and skippers to transmit the data.

Support and extend research project-based investigation with bioeconomic models to anticipate the effects of management measures on reducing fuel use in fisheries, especially identifying reduction potentials when switching fishing techniques, and risk for compensatory/rebound effects that may prevent saving fuel from stocks development towards recovery.

4 REDUCING EMISSIONS OF GREENHOUSE GASES FROM FISHING BY TECHNICAL MEANS

Information and data are needed to assess the potential of European fisheries for reducing their GHG emissions by technical, regulatory, and management means. Hence, **desk studies** have been undertaken to review the scientific and technical literature for data on energy efficiency in the marine capture sector, including screening previous projects in the field (see details of all outcomes Annex 26, methods used for literature review Annex 27 and the stakeholder engagement questionnaire, Annex 28). Scientific partners from the consortium and external European stakeholders were also consulted via a **questionnaire survey** to collect their views on implemented strategies across Europe.

4.1 Categorisation of energy-efficient technologies

Potential energy-efficient technologies were listed based on in-house knowledge and grouped in four categories. The list was further amended after the completion of the literature review and stakeholders’ consultation. The four categories are as follows (Table 11):

Vessel: Technologies to improve vessel structure and on-board equipment such as hull and propeller improvements, improved propulsion and auxiliary engines, improved fuel performance, LED lighting, alternative refrigerants, and assisted fishing.

Strategy: Strategies to improve the fishing in operation such as route optimisation, on-board fuel control and monitoring, and slow steaming.

Gear: Fishing gear technologies to reduce fuel consumption, such as new netting and gear designs that reduce drag, fishing gears that improve catch efficiency.

Regulatory and management measures: Measures that would improve energy efficiency by regulatory or management means.

Table 11 Exhaustive classification of energy-efficiency measures adopted on-board fishing vessels.

Category	Target	Subcategories
Vessel	Drag force reduction (hull)	Hull improvements: • Improved hull designs • Ducted rudders • Addition of a bulb • Use of stabiliser fins • Antifouling coatings and cleaning • Polyester covering of hull to reduce friction
		Improved propulsion and auxiliary engines:

Category	Target	Subcategories
	Fuel consumption and GHG emissions	• Improved propulsion system (engines, gearbox, propellers) • Renewable energy (for propulsion and on-board consumers) • Improved maintenance • Heat-recovery systems • Magnetic devices • Frequency converters • Shore power / shore supply of electricity
		Energy-consuming machinery: • Shift from mechanical-hydraulic consumers to electric consumers on-board • LED lighting • Alternative refrigerants for cooling system
		Improved fuel performance • Alternative fuels • Additives
Strategy	Route optimisation	Route optimisation (based on metocean data): • Slow steaming, speed optimisation • Autopilot • Fishing-zone prediction systems • Route-planning systems, route optimisation
		Change of fishing ground: • Change the fishing ground based on the catch and changing the return day
	Energy consumption control and management	On-board control and monitoring: • Energy audits • On-board energy-monitoring devices and operative advice
Gear	Drag-force reduction (gear)	New netting designs: • New or improved designs (including mouth opening, net shape, wings) • Alternative materials (Dyneema™) • Different mesh size, types of knots, panel cuttings
		Operational improvement: • Electronically controlled gears
		New gear designs: • Change from demersal to semi-pelagic trawling doors • Alternative designs of trawl doors, trawl net, Sumwing • Ground gear • Alternative ropes (helix ropes) • Sledges
	Fishing gear change	From active to passive: • Gear change: from trawl to gillnet

Category	Target	Subcategories
		Within active: • Gear change: from mid-water trawl to purse seine • Gear change: from bottom trawl to pulse trawling • Change the number of rigs from single trawling • Assisted fishing
	Catchability	Improve catchability: • Selective fishing: LED lighting and selective gears • Technology to increase catch efficiency

The fuel consumption and GHG emissions from fisheries increased significantly with the reliance on **larger vessels, more powerful engines, use of additional technologies** for gear operation, on-board processing, refrigeration and ancillary services, and the search for previously unharvested species and new fishing grounds. On-board a vessel, fuel (mainly marine diesel oil) is burnt by main and auxiliary engines (MEPC, 2020). The energy produced is used to propel the vessel or to power the on-board energy consumers. However, GHG emissions, are directly linked to the fuel consumption and the use of refrigerants in the on-board cooling systems. Therefore, a reduction of GHG emissions of fisheries can be driven by different means, such as reducing the fuel consumption, using alternative fuels or refrigerants with less GHG emissions, or by increasing the catch for the same amount of fuel consumed.

Several terms are commonly used to refer to energy efficiency, some are interchangeably used (see various metric definitions in Annex 26). **Fuel use intensity** (FUI) expressed in litres of fuel burned per tonne of live weight landings is the metric most commonly used. FUI is encouraged as a proxy for management effectiveness (Parker and Tyedmers, 2015) as it is widely used to address energy efficiency in fisheries research.

The review highlighted that the factors that affect the fuel consumption and energy efficiency of fisheries can be classified as human, biological, technological and political, and include the target species, status of the stock, fish quotas, quota allocation policies, harvesting methods, distance to the fishing ground, fleet age, skipper effect, sale system and fuel cost, technical regulations and spatial and temporal limitation of fisheries, structural policies, and the availability of fuel subsidies/taxes (Jafarzadeh *et al.* 2016; Sala *et al.* 2012; Villasante *et al.* 2022). While there is broad agreement on the factors, there is **still debate on which aspects should be prioritised to make fishing more efficient**. Some authors suggest that using energy-saving technologies and strategies should be a short-term solution, whereas the improvement of the stocks should be the long-term solution (Jafarzadeh *et al.* 2016; Parker and Tyedmers, 2015).

Stakeholders' participation and **viewpoints** showed that scientific respondents tended to respond with solutions that focused on experimental measures, whereas commercial stakeholders highlighted successful measures. A total of 108 energy-saving measures were proposed across three categories: 'vessel', 'strategy' and 'gear'. Passive fisheries prioritised improvements to the 'vessel' category (N=24) with some strategic measures (N=2). Pelagic fisheries focused on both the 'vessel' (N=8) and the 'strategy' category (N=4), as did generic measures (N=10). Bottom trawl fisheries included measures for all categories and were the only gear type that included 'gear' as a category (Nvessel=18, Nstrategy=11, Ngear=31).

Efforts to reduce fuel-consumption, costs and emissions in fisheries need to be **tailored to the nature of individual fisheries** (Parker *et al.* 2017); however, solutions are often presented as one-fits-all solutions, even the potential savings are reported as a whole, and little insights are given into whether the savings are applicable to all fisheries or to a certain activity mode (e.g., steaming or fishing). In fact, defining a vessel's energy (or fuel consumption) and activity patterns ([7]) are key to the ability to propose tailored solutions (Basurko *et al.* 2013) and energy audits are seen as the means to obtain this information (Basurko *et al.* 2013; Thomas *et al.* 2010).

The **energy-use pattern is highly related to whether the fishery employs passive or active fishing gears**. In particular, active fisheries that require towing a gear, such as **trawlers or Danish seines**, tend to consume most of their fuel during the fishing mode. Hence, measures designed to reduce fuel consumption while fishing are most cost-efficient. There are many publications devoted to reducing the drag in trawling fisheries in comparison to actions undertaken to improve other measures related to the 'vessel' or 'strategy' categories. In contrast, **purse seiners and pole and liners**, which target migratory pelagic species, spend much of their time and effort sailing to the fishing grounds or finding fish. This translates into higher fuel consumption spent during the steaming stage; hence, measures such as route optimisation and slow steaming appear the most suitable for this type of fishery.

4.1.1 Bottom trawl fisheries

Vessel-related measures included improvements to the (1) hull, (2) propulsion, and (3) engine. Alternative energy systems like solar or wind energy supply or improved fuel performance using additives were rarely mentioned, and, if so, were not seen as additional energy supplies for machinery other than that used for than propulsion. Hull improvements related to **optimised hull shape, a bulbous bow and cleaning of the hull**. Propulsion improvements included a **ducted propeller, controllable pitch and propeller diameter**. Engine improvements related to engine maintenance and technology, such as using modern technology, an **electronic controller of the fuel pump** and engines with low-energy specifications.

Strategy improvements in bottom trawl fisheries focused on adjustments of steaming speed (steaming at slower speed), on training skippers to use the engine optimally, on promoting the use of fuel-monitoring systems, on autopilot installations, on using trawl geometry electronics and on fishing in accordance with waves and currents. Improvements were perceived both as experimental and operational, depending on the fishery (small-scale vs large-scale) and the group of respondents (scientific vs commercial).

Gear improvements were dominated by means to reduce the drag force using new netting or gear designs. Solutions to reduce energy use in **beam trawl fisheries** focused mainly on new gear designs, such as the replacement of the beam by a Sumwing, the **replacement of trawl shoes** by roller wheels and the use of lighter chains. The replacement of conventional beam trawls by pulse trawls and gear change options were also proposed. All of these improvements are implemented. One solution was mentioned related to using Dyneema^{TM} netting, but this improvement was not perceived as ready for implementation. In **bottom otter trawl fisheries**, the use of new netting designs was mentioned more frequently (N=7), but its implementation level varied according to the way reduced drag was achieved. The use of larger meshes was discussed as possible measure (e.g., in wings and front belly of the trawl), whereas the use of low-drag netting material (e.g., Dyneema^{TM}) and new netting configurations were considered experimental. New gear designs were also frequently mentioned to improve energy use in bottom otter trawl fisheries, with a major focus on improvement of the otter boards. **Reducing the hydrodynamic drag of otter boards by lifting them off the seabed** was seen as the main solution. The success rate of improved

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(7)7 Energy pattern is the energy consumed by main and auxiliary engines whilst the vessel is engaged in different activities during the fishing trip (e.g., steaming, finding fish, fishing, in port during a fishing trip); activity pattern is time spent per trip at each of the above-mentioned activities.

otter board designs was seen both as experimental and fully operational. The use of electronic equipment to monitor operational characteristics of the trawl and the trawl doors was mentioned as well.

4.1.2 Passive gear fisheries

Energy-saving strategic solutions were provided by respondents from Greece and Sweden. Swedish solutions related to the energy supply from the shore and to **replacing the engine**, whereas Greek solutions varied between solutions that were operational and those that had a low success rate.

Vessel-based operational solutions included the use of an **autopilot**, optimisation of engine speed, cleaning the hull, changing wooden vessels to vessels with polyester hulls, the installation of a refrigerator and using photovoltaic panels. Improvements with a low success rate related to changes in propulsion systems, such as the use of hybrid engines, replacement of engines, and kites to aid propulsion.

4.1.3 Pelagic fisheries

Vessel-related measures to improve energy efficiency include the **replacement** of the engine, replacement of diesel to gas or electric power supply, hull design and shore power supply.

Strategic measures related to **improving fish-finding capacity, steaming speed and real-time monitoring** of fuel use.

4.1.4 Generic measures

Some measures were not attributed to a specific fishery. Those included the use of **energy-saving equipment for processes other than fishing**, e.g., LED lighting, and the use of electric instead of mechanical-hydraulic power supplies. Other potential improvements were the use of **fuel-monitoring systems**, reducing steaming speed, the skipper’s mind-set (e.g., slow steaming irrespective of fuel prices), and maintenance of the hull and propulsion systems.

4.1.5 Technological measures for energy efficiency

A wide variety of technologies was discussed (41 solutions) in the scientific and grey literature; however, stakeholders only mentioned the application of 50 % (commercial stakeholders) or 36 % of the solutions (scientific stakeholders). Therefore, it was found that only a limited number of solutions are transferred to the fishing sector from research, likely due to **limited knowledge transfer** on the technologies, and because not all proposed solutions in scientific literature are applicable. It was identified that there might be **barriers to innovation uptake**, and not all solutions are suitable for all types of fisheries. Furthermore, the information flow among different stakeholders (scientific, policy-makers and fishers) might not be fluid enough, which may induce a **lack of trust towards innovations**.

Improving hull design, propulsion systems and associated maintenance, application of slow steaming and on-board monitoring, and using alternative designs of door, trawl net, ground gear or even changing from demersal trawl gears to more pelagic ones to reduce the drag are shown as **suitable solutions** by all consulted stakeholders (Table 12). Some solutions are proposed by the scientific community and the grey literature but are not reflected by commercial stakeholders (Table 12); as seen in the case of the use of LED lighting on-board. In addition, two solutions discussed by commercial stakeholders as suitable options to improve energy efficiency – covering the hull with polyester to reduce friction, and the installation of an autopilot – are not discussed by scientists, as scientists assume they are already included in the more modernised fleets (Actions for improvement listed in Table 12 are described in detail in Annex 26..

4.1.6 Technological measures to improve VESSEL energy efficiency

Actions relate to efforts to reduce the drag and vessel consumption with:

- **Vessel hull improvements**, including: hull designs, ducted rudders, addition of a bulbous bow, use of stabiliser fins and other anti-roll systems that are part of hull appendages, antifouling coating, polyester covering of hull for reducing the friction with water.
- **Fuel consumption and GHG emissions**, including: improved propulsion system, engine simulation models, ducted propeller, controllable pitch propeller, propeller gear box, hybrid propulsion (diesel + electric + batteries), renewable energy for propulsion, renewable energy for on-board consumers, improved maintenance, heat-recovery systems, magnetic devices as fuel treatment, frequency converters to control speed of induction motors, shore power/shore supply of electricity, shift from mechanical-hydraulic to electric consumers on-board.
- **Energy-consuming machinery**, including: LED lighting, alternative refrigerants for cooling systems.
- **Improved fuel performance**, including: alternative fuels, liquefied natural gas (LNG), waste oils from recycled waste, additives, autopilot selecting an economical navigation speed.

4.1.7 Technological measures to improve STRATEGY energy efficiency

Actions relate to effort for finding strategies to optimise fuel use, as follows:

- **Navigation route,** including: slow steaming, route planning system for route optimisation.
- **Energy-consumption control and management**, including: on-board control and monitoring, energy audits for detailed scan of energy flows, on-board energy-monitoring devices and operative advice.

4.1.8 Technological measures to improve GEAR energy efficiency

Contact drag of the gear components depends on their weight, geometry, the type of sediment on which they are towed and whether they are rolling or not. Actions relate to effort for improving fishing gears to reduce the total gear drag as follows:

- **Investigating the relationship of hydrodynamic drag with towing speed** and the surface area of gear components. Developments in the fishing gear may reduce fuel consumption to a maximum of 20 % by modifying bottom trawls (EC, 2006). Substitution of conventional gears with innovative ones may reduce fuel consumption further (by up to 50 %) but comes with other considerations related to legislation relating to the new gear (e.g., pulse trawl fisheries).

A suite of actions undertaken for reducing fuel consumption in **Dutch Beam trawl fisheries** is presented in Annex 26. These actions concern modifications to reduce the drag resistance of the beam trawl gear, including: netting modifications e.g., replacement of traditional nylon netting, modifications to the beam trawl configuration, and replacement of trawl shoes with rolling wheels. The 2008 fuel crisis also stimulated research whereby the cylindrical beam was replaced by a hydrofoil wing, called the ‘Sumwing’ or the ‘pulsewing’ when it is used in combination with the pulse trawl (Figure 43). This also induced research into developing alternative non-electrical catch stimuli water jets, and alternative electrical catch stimulus-pulse trawl, replacing the conventional beam trawl with outrigger trawl, or switching to other active or passive fisheries: twin rig otter trawl, Danish seining, fly-shooting or set nets. Since the recent prohibition of pulse trawling, the Dutch beam trawl fishing industry is investigating alternative solutions to improve energy efficiency via gear-related measures.

Figure 43 Top panels: rolling wheels assist trawl shoes to reduce drag in chain mat beam trawl fisheries, lower left panel pulsewing, lower right panel: Sumwing with tickler chains (© top left: Z36 Sophie 2021[8], © other pictures ILVO)

For **otter board trawls and midwater trawls**, the found literature offered a variety of modifications that can reduce fuel consumption. A suite of actions undertaken for reducing drag resistance and therefore fuel consumption in bottom otter trawl fisheries is presented in Annex 26. Otter trawls are common throughout Europe and fish a variety of species, the most common being demersal fish such as cod and whiting, *Nephrops*, shrimps, cuttlefish and squid. Total drag of bottom otter trawls can be broken down into the drag of the interacting components, which shows the gear components that contribute the most to the total drag and fuel consumption. The highest gain in improvement of energy efficiency will thus be gained by looking at trawl netting followed by otter boards and ground gear.

These **improvements include modifying otter trawls** with new netting designs, materials and net modifications, door modifications for semi-pelagic doors, innovative doors and lighter materials, or efforts to raise the doors from the seabed, or warp modification, or ground gear, rope and line modifications, e.g. by optimising the length and weight of the ropes and ground gear, reducing the sweep length and optimising the bridles and warps, using assisted fishing devices, or complete setup modifications that combine many of the earlier mentioned modifications in one fishing vessel. Optimising the ropes and ground gear can reduce fuel consumption significantly, although it is often difficult for fishermen to actually fish optimally with the gear. Adding sensors and adjustable doors to the package can circumvent this problem leading to fuel reductions, as demonstrated in flume tanks and models. If many or most of these modifications are applied to a bottom otter trawl, **energy savings of up to 40 % can be result, alongside increased catches**. Alternating from a single rig to a multi-rig also shows potential to reduce fuel use: the triple rig is most promising. Literature offered proof for a potential switch from otter trawling to seine netting.

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[8] Z36 Sophie, 2021. https://www.facebook.com/z39sophie/photos/ pcb.443406432668511 9/4434059530018932 (visited on 17 November 2021).

Substitution of single otter trawls with less fuel-intense types of gear is also presented in Annex 26: changing the single otter trawl to a different gear type can bring major changes in drag, fuel use and catch. This change can be made to be a different type of otter trawl deployment, such as pair trawling (Figure 44) or multi-rig trawls, but it can also constitute a whole different metier, such as gill netting or seine fishing. Also, pair-trawling is more energy-efficient than single-vessel trawling, mainly because there is no need for trawl doors. Changing from bottom otter trawl to semi-pelagic trawls reduces fuel use and has advantages for the environment, although for some fisheries this can mean changed catch composition and/or reduced catch.

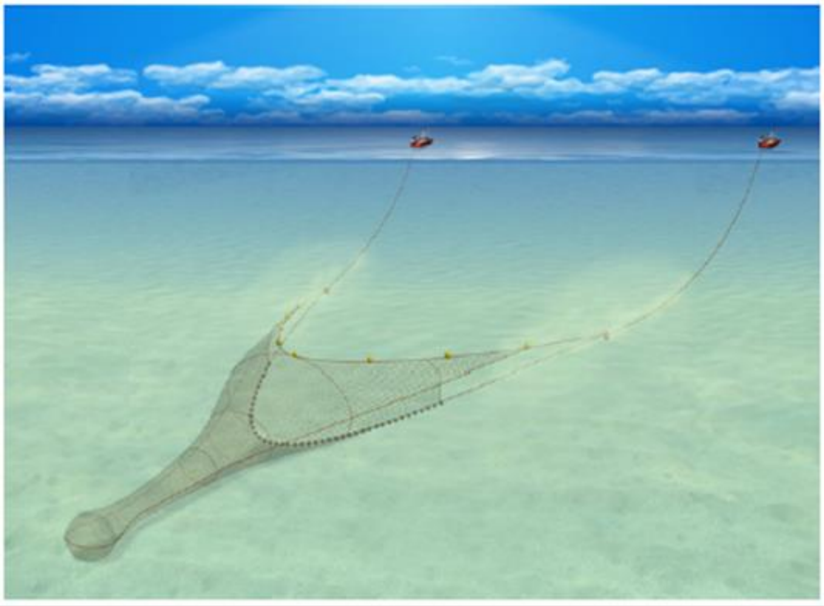

Figure 44 Pair trawl where there is no need for doors as the ships take up the function. Image obtained from www.seafish.org on 24/11/21

There is also a suite of actions undertaken for **reducing drag resistance** and therefore fuel consumption in midwater trawl fisheries is presented in Annex 26, which includes new netting designs, materials and net modifications, e.g., with hexagonal meshes, helix ropes for achieving the same mouth opening as conventional trawls, but with reduced door size.

Catchability can be improved by means that increase the catch efficiency or by using more selective gears and technologies. Most of the modifications that have been discussed above, although primarily designed to reduce fuel, also induced catchability changes by being more selective or increasing the catch of the target species in bottom trawling fisheries. These include use of LED lights, e.g., for pots targeting cod as a way to increase catchability, use of selective gears, or technologies to increase catch efficiency such as fish aggregating devices (FADs) when properly and sustainably managed. It goes without saying that the application of catchability improving technologies require proper and sustainable management upon their introduction.

Table 12 Energy-efficient technology usage reported in the scientific and grey literature and by consulted stakeholders (S: scientific reports, G: grey literature, CQ: questionnaires to commercial fishers, SQ: questionnaires to scientists)

Category	Target	Sub-categories	Source of information*				% fuel-saving potential**	Source
			S	G	CQ	SQ		
Vessel	Drag force reduction (hull)	Hull and propeller improvements						
		Improved hull designs	🟦	🟥	🟨	🟩	3–20	Notti and Sala, 2014; Basurko *et al.* 2013; Sala *et al.* 2012; Sala *et al.* 2011; Thomas *et al.* 2010
		Use of rudders		🟥			5	Sala *et al.* 2012; van Marlen, 2009
		Addition of a bulb	🟦	🟥		🟩	6–30	Notti and Sala, 2014; Basurko *et al.* 2013; Thomas *et al.* 2010; van Marlen, 2009; EC, 2006
		Use of stabiliser fins	🟦				2 (in drag)	Thomas *et al.* 2010
		Use of stern post					11 (antifouling) 0.8–5 (hull cleaning)	Notti *et al.* 2019; Thomas *et al.* 2010; van Marlen, 2009
		Antifouling coatings and cleaning	🟦	🟥	🟨		26	
		Polyester covering of hull to reduce friction			🟨		3–20	Notti and Sala, 2014; Basurko *et al.* 2013; Sala *et al.* 2012; Sala *et al.* 2011; Thomas *et al.* 2010
	Fuel consumption and GHG emissions	Improved propulsion and auxiliary engines						
		Improved propulsion system	🟦	🟥	🟨	🟩	5–100	Bastos *et al.* 2021; Tadros *et al.* 2020; Jaurola *et al.* 2020; Gabrielii and Jafarzadeh, 2020; Notti and Sala, 2014; Basurko *et al.* 2013; Sala *et al.* 2012; Sala *et al.* 2011; Thomas *et al.* 2010; van Marlen, 2009; EC, 2006
		Renewable energy (sail-assisted propulsion)	🟦	🟥			5–25	Schau *et al.* 2009; van Marlen, 2009; Ziegler and Hansson, 2003; Bose and MacGregor, 1987; Amble, 1985

Category	Target	Sub-categories	Source of information*				% fuel-saving potential**	Source
			S	G	CQ	SQ		
		Renewable energy (for onboard consumers)		🟥	🟨		***	Gabrielii and Jafarzadeh, 2020
		Improved maintenance (predictive maintenance)	🟦	🟥	🟨	🟩	3–8	Basurko *et al.* 2013; van Marlen, 2009
		Heat-recovery systems	🟦	🟥			5–10	Gabrielii and Jafarzadeh, 2020; Palomba *et al.* 2017; Notti and Sala, 2014; Wang and Wang, 2005
		Magnetic devices	🟦	🟥			2–6	Gabiña *et al.* 2016a; Notti and Sala, 2014
		Frequency converters	🟦	🟥			9.1–25	Lee and Hsu, 2015; Notti and Sala, 2014; Basurko *et al.* 2013
		Shore power/shore supply of electricity		🟥	🟨		90–100 (consumption in port)	Gabrielii and Jafarzadeh, 2020
		Shift from mechanical-hydraulic consumers to electric consumers on-board		🟥	🟨	🟩	10–15	Gabrielii and Jafarzadeh, 2020; Notti and Sala, 2014; Sala *et al.* 2012
		Energy-consuming machinery						
		LED lighting	🟦	🟥		🟩	26–55	Basurko *et al.* 2013; Sala *et al.* 2012; Thomas *et al.* 2010
		Alternative refrigerants for cooling system	🟦				50 (in electricity)	Sandison *et al.* 2021; Ziegler *et al.* 2013
		Improved fuel performance						
		Alternative fuels	🟦	🟥			1.2 (1.9% for CO_2 reduction)	Gabrielii and Jafarzadeh, 2020; Gabiña *et al.* 2019; Uriondo *et al.* 2018; Jafarzadeh *et al.* 2017; Gabiña *et al.* 2016b; Thomas *et al.* 2010; Schau *et al.* 2009; Goldsworthy, 2009
		Additives	🟦		🟨		–	Hsieh *et al.* 2009

Category	Target	Sub-categories	Source of information*				% fuel-saving potential**	Source
			S	G	CQ	SQ		
		Autopilot			🟨		3	
Strategy	Route optimisation	Route optimization (based on metocean data)						
		Slow steaming, speed optimisation	🟦	🟥	🟨	🟩	15–59	Chang *et al.* 2016; Basurko *et al.* 2013; Sala *et al.* 2011; van Marlen, 2009; Parente *et al.* 2008; EC, 2006; Latorre, 2001
		Route-planning systems, route optimisation	🟦				****	Granado *et al.* 2021; Groba *et al.* 2020; Chang *et al.* 2016
		Change of fishing ground						
		Change the fishing ground based on the catch and changing the return day	🟦		🟨		****	Bastardie *et al.* 2010
	Energy consumption control and management	On-board control and monitoring						
		Energy audits	🟦	🟥			***	Basurko *et al.* 2022; Basurko *et al.* 2013; Sala *et al.* 2012; Sala *et al.* 2011; Thomas et al, 2010
		On-board energy-monitoring devices and operative advice	🟦	🟥	🟨	🟩	3–15	Notti and Sala, 2014; Basurko *et al.* 2013; Sala *et al.* 2011; van Marlen, 2009; EC, 2006; Latorre 2001
Gear	Drag-force reduction (gear)	New netting designs						
		New or improved designs	🟦	🟥	🟨	🟩	17–22	ICES, 2020b; Lee *et al.* 2018; Balash *et al.* 2015; Notti and Sala, 2014; Hansen *et al.* 2013; Sala *et al.* 2012; Sala *et al.* 2011; van Marlen, 2009; Priour 2009, Parente *et al.* 2008; EC, 2006
		Alternative materials (Dyneema$^{\text{TM}}$)	🟦	🟥	🟨	🟩	2–40	ICES, 2020b; Lee *et al.* 2018; Balash *et al.* 2015; Notti and Sala, 2014; Hansen *et al.* 2013; Sala *et al.* 2012; van Marlen, 2009; EC, 2006

Category	Target	Sub-categories	Source of information*				% fuel-saving potential**	Source
			S	G	CQ	SQ		
		Different mesh size, types of knots, panel cuttings	🟦	🟥	🟨		25–27	Lee *et al.* 2018; Hansen *et al.* 2013; Khaled *et al.* 2012; Sala *et al.* 2012; Sala *et al.* 2011; van Marlen, 2009; Parente *et al.* 2008; EC, 2006
		Operational improvement						
		Electronically controlled gears		🟥	🟨	🟩	>15	ICES, 2020a
		New gear designs						
		Change from demersal to semi pelagic trawling doors	🟦	🟥	🟨	🟩	1.6–19	ICES, 2020b; Lee *et al.* 2018; Guijarro *et al.* 2017; Notti and Sala, 2014; Basurko *et al.* 2013; Hansen *et al.* 2013; EC, 2006
		Alternative designs of trawl doors, trawl net, Sumwing	🟦	🟥	🟨	🟩	4.5–20	ICES, 2020b; Lee *et al.* 2018; Notti and Sala, 2014; Sala *et al.* 2012; Priour 2009; van Marlen, 2009; EC, 2006
		Ground gear	🟦	🟥	🟨	🟩	***	ICES, 2020b; Larsen *et al.* 2018; van Marlen, 2009
		Alternative ropes (helix ropes)	🟦	🟥			***	Kebede *et al.* 2020; ICES, 2020b; Sistiaga *et al.* 2015; van Marlen, 2009;
		Sledges	🟦	🟥			****	Kaykac *et al.* 2017; van Marlen, 2009
	Fishing-gear change	From active to passive						
		Gear change: change from trawl to gillnet		🟥			****	van Marlen, 2009
		Within active						
		Gear change: change from mid-water trawl to purse seine	🟦	🟥			5–25	Parker and Tyedmers, 2015; Driscoll and Tyedmers, 2010; van Marlen, 2009

Category	Target	Sub-categories	Source of information*				% fuel-saving potential**	Source
			S	G	CQ	SQ		
		Gear change: pulse trawling	🟦	🟥		🟩	35–54	Batsleer *et al.* 2016; van Marlen *et al.* 2014; Taal and Klok, 2014; Sala *et al.* 2012; van Marlen, 2009; EC, 2006
		Change the number of rigs from single trawling	🟦	🟥			10–30	Broadhurst *et al.* 2013; EC, 2006; van Marlen, 2009; Ziegler and Hansson, 2003
		Assisted fishing		🟥			****	Sala *et al.* 2012
	Catchability and reduced mortality	Improve catchability and reduce mortality						
		Selective fishing: LED lighting	🟦				****	Kuo and Shen, 2018; An *et al.* 2017; Bryhn *et al.* 2014; Matsushita *et al.* 2012; Yamashita *et al.* 2012
		Selective fishing: use of selective gears	🟦	🟥			8–25	ICES, 2020b; Jørgensen *et al.* 2017; Ziegler and Hornborg, 2014; Hornborg *et al.* 2012; van Marlen, 2009
		Technology to increase catch efficiency	🟦		🟨		****	Chassot *et al.* 2021

*Savings are reported for several measures together; ** Fuel-saving Potential: only the cases reporting a fuel saving by one technology is included. Those citing savings by several measures are excluded. The ranges reported consider different TRLs; *** In grey literature, no quantitative data is presented about the reduction; **** The potential for saving is mentioned but no quantitative data are shown.

4.2 Regulation, management, and market strategies to boost energy efficiency in the fishing sector

4.2.1 Incentives set up for energy efficiency in the marine sector in current EU regulations

The International Maritime Organization (IMO) is the principal regulatory institution for the energy efficiency of shipping sector, including the fishing sector. Exhaust emissions and energy efficiency are covered by the Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL) 73/78 Convention (International Convention for the Prevention of Pollution from Ships) (

Table 13). See full details of methods used to assess literature on energy efficiency, Annex 28.

Table 13 IMO regulations for emissions in shipping and fishing (from Gabrielii and Jafarzadeh, 2020).

Emissions	Regulations	Comments
Sulphur oxides (SOx)	In 2020, 0.5 % sulphur content of the fuel (for the whole world). 0.1 % sulphur content Emission Control Area (ECA) zones	ECA zones: Baltic and North Seas, USA Canada, US Caribbean Sea Inclusion of Mediterranean and Norwegian west coast is under discussion
Nitrogen oxides (NOx)	Updated: for Europe, applies TIER III standard (developed in 2016 in US waters) limiting to 2g/kWh NOx for 2021 in Baltic and North Sea areas, for any vessel with 130kW engine output	Outdated: Reduction of 80 % from TIER I standard (developed in 2000, that limited to 10g/kWh NOx for 2021) and 75 % from TIER II standard (developed in 2011 that limited to 8g/kWh NOx for 2021)
Carbon dioxide (CO_2)	Ship Energy Efficiency Management Plan (SEEMP) for vessels >400GT Energy Efficiency Operational Index (EEOI) as a measure of fuel efficiency of a ship operation	$EEOI_F = \frac{\sum_j FC_j C_{Fj}}{m_{fish} D} \quad [gCO_2/t_{fish} nm]$
	GHG emissions reduction targets: 50 % by 2050 compared to 2008 level	For example, Norway: reduction of 40 % by 2030

Sulphur oxides content is directly related to the type of fuel in use and depends on the fuel suppliers. **Nitrogen oxides** are directly related to the engine type and the age of the engine. Therefore, there is a requirement for the engine manufacture brands to adapt their engines to the new rules (now, TIER III). **Carbon dioxide emission** is related to the energy efficiency of vessels. For that, the Ship Energy Efficiency Management Plan (SEEMP) is applied for vessels of 400GT or greater. SEEMP is a plan to establish a way to improve energy efficiency with operational measures. EEOI is an index used to monitor and measure the fuel efficiency of single vessels. Fuel consumption is directly related to CO_2 emission (9). The index is obtained by measuring the total fuel consumption (converted to CO_2 emission) per geographical distance, and cargo carried. In the case of fishing vessels, the cargo is considered as the fish caught (EEOI = tn_CO_2 / nm·tn_fish). The equation is shown in

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9 IMO, Report of the Marine Environment Protection Committee on its 59th Session, 2009.

Table 13, where FC is the total fuel consumption, CF is the conversion factor from fuel to CO_2 in mass units, D is the distance travelled in nautical miles, and m is the mass of fish caught and carried during the fishing trip.

As an example, regulations of

Table 13 are currently applied in **Norway's fisheries** (Gabrielii and Jafarzadeh, 2020) as follows.

- In distant waters, fishing vessels are exempt from sulphur tax, but in coastal waters (within 250 miles), from 2020 a tax on anything exceeding 0.05 % sulphur weight content (NOK0.1355 for every 0.01 %) applies.
- There is a 'NOx Agreement 2018–2025' including shipping and fishing. From 2020, the NOx tax is 22.7NOK/kg NOx emitted. In addition, there is a NOx fund (16.5NOK/kg NOx) to support potential technologies and retrofits to achieve the agreement.
- Norway has committed to reducing its total CO_2 emissions by 40 % by 2030. Following this environmental target, a fishing organisation has self-committed to reduce its CO_2 emissions from its fishing fleet by 40 % by 2030, compared to levels in 2005.

Even if energy efficiency is not an explicit objective of the CFP (EU Regulation 1380/2013), **the CFP's first objective is "Promoting environmentally sustainable, resource-efficient, innovative, competitive and knowledge-based fisheries", which implicitly includes energy efficiency** as one of the goals. In addition, CFP article 17 includes provisions for EU Member States concerning incentives to energy-efficient vessels when it comes to the distribution of fishing opportunities.

The European Maritime and Fisheries Fund 2014–2020 (**EMFF**), EU regulation 508/2013, aims align with the Europe 2020 Strategy and includes energy efficiency as one eligible action. The EMFF makes provisions for the eligibility of actions to improve energy efficiency through **modernisation of main and auxiliary engines**, while prioritising small-scale fisheries through access to financing, and makes provisions to motivate larger operators to reduce engine power. Article 41 of the EMFF regulation outlines the broad eligible actions for mitigation of climate change that encompass investment on equipment on board to reduce the emission of pollutants, and improvement of gears, energy audits and improvements in vessel propulsions and hull design to reduce energy consumption. Article 41 also establishes the conditions for replacement or modernisation of engines in relation to the size of the vessel and establishes more favourable conditions for vessels below 12m. Article 43 includes provisions for energy efficiency, environmental protection, and improvement of safety and working conditions in land infrastructure, such as ports, shelters and auction halls. The **EMFF co-funded research & development projects and private initiatives to improve the design of more selective gears** that could reduce unwanted catches, reduce fishing effort, and consequently reduce fuel use. The EMFF also provides means for developers to propose gear designs that reduce towing resistance and thus diminish fuel consumption.

In July 2021, the new European Maritime, Fisheries and Aquaculture Fund (**EMFAF**) entered into force ([10]). The EMFAF includes some changes re energy efficiency, such as **financial support for investments on board vessel for energy efficiency**, or improved working and safety conditions, even if the individual gross tonnage of the vessel increases, as long as this does not lead to an increase in the Member States' overall fishing

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[10] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021R1139&from=EN10 https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021R1139&from=EN

capacity. The EMFAF is committed to the United Nations 2030 Agenda for Sustainable Development, which includes conservation and sustainable use of oceans as one of its 17 Sustainable Development Goals (SDGs): "Conserve and sustainably use the oceans, seas, and marine resources for sustainable development" (SDG 14). This is aligned with the **European Green Deal** (11), which is the roadmap for EU climate and environmental policies. The Farm to Fork Strategy of this deal will tackle climate change, protect the environment, and preserve biodiversity. The Commission's proposals for the EMFAF are to devote at least 30 % to climate action.

Energy efficiency also arises as a factor to be considered in the context of **the EU Landing Obligation (LO)**, which was one of the most important regulatory breakthroughs in the 2013 EU CFP. In an LO context, it is convenient for fishing fleets to become more energy-efficient to compensate for fishing opportunities loss induced by landing low (or no) marketable fish. The size of vessels may also have implications on fuel consumption under the LO. Fitzpatrick *et al.* (2019) consider that small-scale boats and smaller trawlers may incur higher costs because of the requirements to store unwanted fish. Fishers are obliged to make more trips to land all fish and then return to the fish spot to continue working and searching for more profitable fish. The higher costs associated with the LO conditions, such as extra work to sort out fish on board, higher use of ice and increased fuel consumption require improvements in selectivity to reduce the number of unwanted fish, or the use of more energy-efficient equipment to reduce variable costs.

On the road to decarbonising of Europe's economy to achieve climate neutrality by 2050, the Commission adopted **the 'Fit for 55' package in July 2021**[12]. It consists of a set of legislative proposals to make the EU's climate, energy, land use, transport and taxation policies fit for reaching the European Green Deal's objective of reducing greenhouse gas emissions by at least 55% by 2030, in comparison to 1990 levels.

The proposals presented in the package are all connected and complementary. They combine: application of emissions trading to new sectors, such as the shipping sector, and a tightening of the existing EU Emissions Trading System; increased use of renewable energy; greater energy efficiency; a faster roll-out of low emission transport modes and the infrastructure and fuels to support them; an alignment of taxation policies with the European Green Deal objectives; measures to prevent carbon leakage; and tools to preserve and grow our natural carbon sinks. The link to Fishing and shipping is made by the following specific proposals:

- **The EU Emissions Trading System (ETS)** defined in (COM(2021)551)[13] puts a price on carbon and lowers the cap on emissions from certain economic sectors every year. The Commission has proposed to include shipping emissions for the first time in the EU ETS. Shipping companies should monitor and report their aggregated emissions data from maritime transport activities at company level in accordance with the rules laid down in Regulation (EU) 2015/757. However, the rules for Monitoring, Reporting and Validation (MRV) only apply to large emitters (> 5000 GT ships going to and coming from Union ports) and does not include fishing vessels at present.

- **European Taxation Directive (ETD)** (COM(2021)559[14], repealing Directive

  2014/94/EU): A revision of the Energy Taxation Directive proposes to align the taxation of energy products (such as fuels) with EU energy and climate policies. These objectives will be achieved by: (1) promoting clean technologies, such as shore-side electricity provided to vessels while at berth in ports, that can be exempt from taxation; (2) eliminating incentives or exemption for fossil fuel; (3) setting the

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(11)11 https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52019DC0640&from=EN

[12] https://www.europarl.europa.eu/legislative-train/theme-a-european-green-deal/package-fit-for-55

[13] COM(2021)551: https://ec.europa.eu/transparency/documents-register/detail?ref=COM(2021)551&lang=en

[14] COM(2021)559: https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A52021PC0559

taxation based on energy content instead of volume, therefore encouraging the take-up of electricity and alternative fuels (renewable hydrogen, synthetic fuels, advanced biofuels, etc.); and (4) introducing a ranking of the fuels according to their environmental performance. Specifically for fishing vessels, the minimum levels of taxation should be applied to fuel use. And to provide an incentive to their use, sustainable alternative fuels (including sustainable biofuels and biogas, low-carbon fuels, advanced sustainable biofuels and biogas, and renewable fuels of non-biological origin) and electricity would have a taxation rate of zero for ten years.

- **Use of renewable and low-carbon fuels in maritime transport Regulation** ((COM(2021)562[15] proposal to amend Directive 2009/16/EC): The 'FuelEU Maritime' initiative aims to increase the production and the uptake of sustainable maritime fuels and zero-emission technologies for the maritime sector by setting a maximum limit on the GHG content of energy used by ships calling at European ports. This is fully in line with the initial strategy on the reduction of GHG emissions from ships adopted by the IMO in 2018, where the IMO includes promoting the uptake of alternative low-carbon and zero-carbon fuels and providing shore-side electricity as short-term measures. This initiative focuses on highest emitters (ships > 5000GT) and fishing vessels are currently not covered by this initiative.

- **The Alternative Fuels Infrastructure Regulation** (COM(2021)559[16], repealing Directive 2014/94/EU)aims to promote the deployment of alternative fuels by setting obligations to provide the infrastructure to supply the demand of sustainable alternative (renewable and low carbon) fuels. Member States are obliged to set up national policy frameworks to establish markets for alternative fuels and ensure that an appropriate number of publicly accessible recharging and refuelling points are available. For the maritime sector, this is translated in ships having access to shore-side electricity or decarbonised gases (i.e., bio-LNG and synthetic gaseous fuels (e-gas) supply in major ports.

4.2.2 Reported regulatory or management drivers to boost energy efficiency

Fuel costs and **catch volume** are important for the **profitability of fishing operations**. Fishers are more likely to play a role in minimising fuel costs while maximising catch volume; policymakers and managers can aim at reducing the fuel-use intensity by providing market-based instruments to promote i) fuel-use reduction and ii) increase in fishing opportunities.

For point (i), scientific and grey literature and stakeholders identify that in order to reduce fuel-use intensity (the ratio of fuel use over the catch volume), relevant management instruments for first **reducing the fuel use** should first include the following (Table 14).

- **Taxation based on performance in saving fuel**, by changing fuel and emission taxation for emission quotas: currently, the debate is whether the shipping sector should be included in the emissions trading system (Wissner and Defour, 2021). Despite the fact that fishing (according to the IMO (2020)) contributes 4 % of total shipping (17) GHG emissions, in similar proportion to RoPax ferries and cruise ships together, several things have to be overcome before fishing can be considered in any carbon emission quota system, e.g. EU policy should strive to include all ship types including fishing vessels in accordance with the polluter-pays principle or the EU Monitoring, Reporting and Verification regulation (Wissner and Defour, 2021).

- **NOx fund**, as in Norway: with the entry of NOx caps as a result of The Gothenburg protocol, Norway established a NOx tax for domestic shipping and fishing in 2007. NOx tax does not apply to high-seas fishing (Borrello *et al.* 2013). The NOx tax

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15 COM(2021)562: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0562
16 COM(2021)559: https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A52021PC0559
17 Total shipping understood as international, domestic, and fishing (IMO 2020).

evolved into NOx fund resulting from the NOx agreement between the government and 15 business associations, including the Norwegian Fishermen's association). As part of the agreement, the involved parties pay a smaller amount to the NOx fund instead of the tax when emission-reducing measures are implemented. The fund supports NOx reducing measures in addition to covering administrative costs (Jafarzadeh *et al.* 2016, 2017).

- **Fuel tax**: the application of fuel tax or changing the current fuel taxation system may motivate fishers to be more energy efficient (Guillen *et al.* 2016; Thrane, 2006; Thomas *et al.* 2010). However, some authors suggest that providing exemption from taxes as a subsidy might justify a lower fuel efficiency and would slow down the adjustments to increase energy efficiency (Parker and Tyedmers, 2015; Ziegler and Hornborg, 2014). In Norway, in addition to the NOx fund, Norwegian fisheries are exempt from different taxes related to fuel consumption. Norwegian vessels operating in the exclusive economic zone (EEZ) are reimbursed for fuel and CO_2 taxes (Jafarzadeh *et al.* 2016); vessels buy taxed fuel, and the CO_2 tax is reimbursed by a government agency (Isaksen *et al.* 2015). Like NOx fund, fuel and CO_2 tax revenues go to a fund that financially supports investment in emissions-reducing measures aboard vessels (Isaksen *et al.* 2015).

- **Harmonisation of fuel taxes amongst nations**: some vessels are fuelling in neighbouring countries with more flexible fuel taxes; hence an international harmonisation of fuel taxes among nations is recommended by some researchers to generate funds to invest in energy efficiency measures (Isaksen *et al.* 2015).

- **Restrictions by regulation on pull power, engine power**: these restrictions should be revised with time as new technologies and more efficient engines are available in the market to improve the overall energy efficiency and not necessarily increase catching capacity. The consulted stakeholders have also highlighted this by stating that although they showed proactivity in being more efficient by being willing to change their engine for a more efficient one, funds such as the EMFF exclude such changes because they increase catching capacity. However, the new engines could be more fuel efficient, smaller, require less maintenance and be more adapted to the operational need and power usage of vessel (Thomas *et al.* 2010). This information could be easily obtained via an energy audit of the vessel.

- **Gear restriction**: Driscoll and Tyedmers (2010) modelled the potential effect of the entry into force of two fisheries management decisions on fuel use and GHG emissions in the New England fishery (US) for Atlantic herring (*Clupea harengus*). They observed that a dramatic reduction in fuel consumption could be achieved from gear restriction in the New England Atlantic herring (*Clupea harengus*) fishery by replacing trawls with less fuel-intensive purse seine gear.

- **Fisheries management system/modelling**: Efficiency of fisheries may be improved by adding concerns for energy efficiency to political goals (Jafarzadeh *et al.* 2016), for example, by management to reduce fishing pressure as part of climate change policies. Management decisions can have long-term effects on fleet structure and dynamics, and their performance regarding fuel use and GHG emissions. The use of energy-efficiency indices in fisheries management or modelling can provide information on how to improve energy efficiency in fisheries. Fuel-use intensity can act as a rough proxy for management effectiveness (Parker and Tyedmers, 2015). Others suggested the use of fuel-consumption indicators, such as litres of fuel consumed per day, as an additional input into the fisheries management system (Ziegler and Hornborg, 2014) or in mixed fisheries management plans by enumerating potential economic consequences and behavioural adaptations in response to management measures (Davie *et al.* 2014).

- **Improvement in fish stocks**: Improved stocks may lead to higher fish quotas and therefore more energy-efficient fisheries, although the CPUE is not directly proportional to biomass (Hornborg and Smith, 2020). The potential for reducing fuel use in this way might be larger than that obtained from technological improvements (Ziegler and Hornborg, 2014). Considering fuel efficiency in setting reference points for target stock biomass in fisheries has also been suggested as a way to include energy efficiency in fisheries management.

- **Fish quota systems**: as a fish quota is set to balance with fish abundance and availability, installing a quota system might have been one of the main reasons for the improvements in energy efficiency in several single-species fisheries, e.g., Norway, Sweden (Jafarzadeh *et al.* 2016; Parker and Tyedmers, 2015; Sala *et al.* 2012). Improving energy efficiency would result from covering more fisheries with quotas whenever possible (Sala *et al.* 2012) or reducing the quotas of less fuel-efficient fisheries (Thrane, 2004).

- **Increased fuel price**: the recent episodes of fuel price increase (Cheilari *et al.* 2013) were decoupled from the fish price, which has remained relatively stable because of the price-setting power of seafood buyers. Although fishers tend to negotiate fuel price at fishery level (Jafarzadeh *et al.* 2016; Schau *et al.* 2009), they are the ones absorbing the increased costs, which ends up affecting their profitability, security and recruitment (Abernethy *et al.* 2010). However, several studies have stated that fuel price and energy-efficiency practices are not strongly correlated (Parker *et al.* 2017; Jafarzadeh *et al.* 2016). Nevertheless, Dutch beam trawlers have reduced their towing and steaming speed with considerable results (0–40 % fuel saving by reducing speed by up to 14 %) (Poos *et al.* 2013). Danish fishers confirmed in a survey that they are inclined to reduce their fuel consumption when fuel price is high (Ziegler and Hornborg, 2014). Other fisheries, such as Danish netters, are not pressured by high fuel prices and netters instead try to optimise their economic efficiency by targeting high-priced fish, which may lead to a higher effort by searching for a bonus from landing a high quality of fish rather than quantity (Bastardie *et al.* 2013). Large fuel-intensive vessels base their decisions on fish price only, while small-scale vessels usually consider other flexible factors, e.g., the potential for a large catch, weather, previous knowledge and experience, and the distance to/from port, which affect the number and duration of trips and the fuel consumption (Bastardie *et al.* 2013).

- **Monitoring of sustainability certifications**: Chassot *et al.* (2021) observed that sustainable fishery certification should include indicators related to energy efficiency as part of the criteria. This is in line with the IMO’s energy-efficiency indicators, which establish scores for each vessel and performance. This could enable the provision of incentives to certain fisheries that fish most efficiently (Ziegler and Hornborg, 2014).

- **Promote the use of certain gears**: the change from mid-water trawl to purse seine for Atlantic herring (Parker and Tyedmers, 2015), from beam trawl for flatfish to pulse trawl (Batsleer *et al.* 2016; van Marlen *et al.* 2014; Soetaert *et al.* 2015) or from bottom trawls to semi-pelagic trawls (Lee *et al.* 2018; Sistiaga *et al.* 2015) have been presented in the literature as solutions to promote energy efficiency in different fisheries, with fuel savings of 66 %, 37–49 % and 37 % respectively.

- **Promote reducing fishing effort**: Guijarro *et al.* (2017) demonstrated that by reducing the fishing effort (reduction in the weekly activity of the vessels, from 68 h discontinuous (from 12 h/day for 5 days/week to 46 h continuous), not only did they obtain similar landings, but it also served to save fuel and improve the life quality of the crew. Bastardie *et al.* (2010) modelled the effects of different effort-allocation scenarios and despite fuel savings observed when fishers dedicated effort to closer-to-harbour fishing grounds, the gain obtained from the fuel savings was not enough to compensate the overall loss in landing value from lower CPUE.

- **Promote improved skipper skills**: skipper effect can be defined as the 'ability of a skipper to locate high fish densities and to harvest them' (Marchal *et al.* 2006), resulting in different catch performances among vessels (Bastardie *et al.* 2010; Ruttan and Tyedmers, 2007). Fishers' tactics and choices (where and when to fish) are based on a combination of economic and environmental factors as well as a balance between total catch rate and catch efficiency, and skipper experience, education and age, and this influences the fuel performance (Parker *et al.* 2017; Oliveira *et al.* 2016).

- **Promote skipper ownership of vessels**: while some authors confirm that proactivity towards energy efficiency is related to vessel size (Parker *et al.* 2018), others associate the proactivity with the skipper's skills and fishing abilities (Basurko *et al.* 2013) and their level of acceptance of innovation. Vessel owners are likely to use less fuel than company skippers (Abernethy *et al.* 2010), and this has also been observed in Basque coastal purse seine and artisanal vessels (Basurko *et al.* 2013). In the case of tropical freezer purse seiners, catch volume and fuel use are two indicators used to assess the utility of a skipper by the firm; however, skippers usually try to maximise the number of tonnes fished per hour rather than reduction of fuel cost (Groba *et al.* 2020).

- **Promote proactivity**: possible reluctance to apply fuel-saving practices and technologies may arise from the lack of methodological approach to monitoring energy performances (Notti and Sala, 2014), the limited shared information regarding technologies and innovations, the information not reaching fishers (as reflected by the stakeholders consulted), or the preferences to approved technologies instead of opting for innovations. Large vessels could be more proactive as they are usually more fuel dependent (Parker *et al.* 2018), or because large vessels can target higher catch rates by accessing better fishing locations or fishing for longer periods (Ziegler *et al.* 2016).

- **Promote the inclusion of fisheries in global emission databases or carbon emission quota systems**: global exhaust emissions from fisheries were reported for the first time by the IMO in the 4th IMO GHG study in 2020 (Faber *et al.* 2020). This delay in including fishing in the reporting derived from a lack of understanding among key agents of the need to regulate emissions from fishing. Accounting for fishing as part of shipping's emissions (shipping considered as international and domestic shipping, and fishing) has been a push forward to regulating GHG emissions from fisheries and putting fisheries in line with IMO's energy-efficiency indicators. In 2020, fisheries emitted 40.7 million tonnes of GHG emissions by consuming 12.86 million tonnes of fuel, 4 % of overall shipping emissions (MEPC, 2020).

- **Use ecolabelling to influence consumer demand for fish**: sustainable fishing eco-labels allow consumers to make informed choices when purchasing seafood. However, energy efficiency, fuel consumption and carbon footprint indicators are currently excluded from the certification process and therefore not reported. Several authors suggest that the inclusion of such indicators could help promote energy-efficiency practices within fisheries (Chassot *et al.* 2021; Schau *et al.* 2009). This bottom-up approach is one of the instruments currently applied in shipping through the Poseidon Principles ([18]) (framework for assessing and disclosing the climate alignment of ship finance portfolios), where banks committed to decarbonisation goals provide 'green' credits to shipowners who ask for loans to finance their investment and demonstrate their commitment to decarbonisation, which is measured by the carbon-intensity metric (derived from fuel consumption, distance travelled, deadweight tonnage at summer draught).

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(18)18 https://www.poseidonprinciples.org/

- **Promote fishing methods/skippers that apply efficient practices**: providing subsidies or rewards to energy-efficient fishing methods or fisheries can be a way of promoting sustainable fisheries (Schau *et al.* 2009). No example has been found in the literature nor was such a practice mentioned in the stakeholder reports.

For point (ii), scientific and grey literature and stakeholders identify that, for reducing fuel-use intensity (ratio of fuel use over the catch volume), relevant management instruments for **increasing the catch** include the following.

- **Increase catch rates**: Vessel buyback schemes could help some fisheries to remove licences and increase the catch rates for the remaining vessels, e.g., as seen in the rock lobster fishery of South Australia or northern prawn fishery of Australia (Parker *et al.* 2017). Likewise, changing fishing limits from maximum sustainable yield to maximum economic yield while increasing or removing the limit on pot numbers have been proposed for Australian rock lobster fisheries as a way to reduce fuel consumption (Farmery *et al.* 2014). Other strategies are linked to increasing the stock biomass and availability (Jafarzadeh *et al.* 2016; Parker and Tyedmers, 2015; Ziegler and Hornborg, 2014).

- **Reduce bycatch**: e.g., with a Landing Obligation for incentivising operators for being more selective: Selectivity and the skipper skills and fishing practice can also affect the catchability for the same effort and fishing gear, and therefore limit the fraction of unmarketable catch in the overall catch. This would improve the energy efficiency even if unmarketable catch is usually not used to calculate fuel-use intensity.

Table 14 Energy-efficient regulatory and management measures proposed in the scientific and grey literature and by consulted stakeholders

Category	Target	Subcategories	Source of information*				Source
			S	G	CQ	SQ	
Regulatory or management measures by decision-makers (not fishers)	Reduce fuel consumption (focus on the numerator of the FUI indicator, L fuel/t catch)	Taxation based on performance					
		Changes in fuel and emission taxation	🟦				Jafarzadeh *et al.* 2017; Jafarzadeh *et al.* 2016; Parker and Tyedmers, 2015; Ziegler and Hornborg 2014; Thomas *et al.* 2010; Sumaila *et al.* 2008; Thrane, 2006; Thrane, 2004
		Harmonisation of fuel taxes amongst nations	🟦				Isaksen *et al.* 2015
		Restrictions by regulation					
		Restrictions on pull power, engine power	🟦				Thomas *et al.* 2010; Thrane, 2004
		Gear restriction	🟦				Driscoll and Tyedmers, 2010; Thrane, 2006
		Inclusion of fuel or carbon footprint or FUI scores in:					
		Fisheries-management system/modelling	🟦				Parker and Tyedmers, 2015; Davie *et al.* 2014; Ziegler and Hornborg, 2014; Driscoll and Tyedmers, 2010
		Fish quota system	🟦				Thrane, 2004
		Political goals	🟦				Jafarzadeh *et al.* 2016
		Improvement in fish stocks	🟦				Jafarzadeh *et al.* 2016
		Imposition of fuel and emission taxes	🟦				Thrane, 2004
		Monitoring of sustainability certifications	🟦				Chassot *et al.* 2021

Category	Target	Subcategories	Source of information*				Source
			S	G	CQ	SQ	
		Allocation of subsidies to fuel-efficiency fisheries	🟦	🟥			Jafarzadeh *et al.* 2016; EC, 2006
		Promotion of:					
		Certain gears	🟦				Batsleer *et al.* 2016; Parker and Tyedmers, 2015
		Reducing fishing effort	🟦	🟥		🟩	Guijarro *et al.* 2017; EC, 2006
		Improvement of skipper skills	🟦			🟩	Ziegler *et al.* 2018; Parker *et al.* 2017; Basurko *et al.* 2013; Bastardie *et al.* 2010; Ruttan and Tyedmers, 2007; Ziegler and Hansson, 2003
		Agreements on fuel price between suppliers and fisheries	🟦				Jafarzadeh *et al.* 2016
		Inclusion of fisheries in global emission databases or carbon-emission quota systems	🟦				Guillen *et al.* 2016; Coello *et al.* 2015
		Consumers					
		Consumer demands for more specific fuel data for fish purchased, eco-labelling	🟦				Schau *et al.* 2009; Thrane, 2006
		Fuel subsidies or incentives					
		To fuel efficient fishing methods	🟦	🟥			Thomas *et al.* 2010; Thrane, 2006; EC, 2006; Thrane, 2004;
		To fishers based on fuel efficiency, not catch alone	🟦				Groba *et al.* 2020; Basurko *et al.* 2013; Abernethy *et al.* 2010
		To invest in energy-efficiency strategies	🟦				Isaksen *et al.* 2015; Thrane 2004

Category	Target	Subcategories	Source of information*				Source
			S	G	CQ	SQ	
	Increasing the t catch (focus on the denominator of the FUI indicator, L fuel/t catch)	Improving the CPUE					
		Improve stock biomass (fish abundance and availability)	🟦				Jafarzadeh *et al.* 2016; Parker and Tyedmers, 2004; Ziegler and Hornborg, 2014
		Better allocation of quotas or higher quotas	🟦				Thrane, 2004
		Changing of fishing limits from maximum sustainable yield to maximum economic yield (e.g., rock lobster)	🟦				Farmery *et al.* 2014
		Boat buyback schemes	🟦	🟥			Parker *et al.* 2015; Pascoe *et al.* 2012; Hua and Wu, 2011; Sloan and Crosthwaite, 2007; EC, 2006
		Discard ban					
		Reduce bycatch by being more selective	🟦				Batsleer *et al.* 2016

* More than one measure, ** No information about the reduction, ***No quantitative data found

4.2.3 Barriers when implementing energy-efficient solutions

The **lack of collaborative work with end users** was identified as one of the main barriers, both in technological transfer and in development of new technologies and strategies (Jafarzadeh *et al.* 2014). The extent of this lack of sharing among end users stems from the nature of individual fisheries, because the relative roles of technology, behaviour and management vary (Parker *et al.* 2017).

Fishers lack data for developing accurate technological knowledge for helping their decision-making. For example, there are not enough datasets of the engine load profile for different vessel types, nor on the engine size and the age and type of the engine. This hampers the estimation of resulting emissions from standardised data (Ziegler and Hansson, 2003). There is a lack of information about existing potential technologies that would suit each vessel, as well as on the most environmentally friendly gears.

Even when end users have the information, **training courses are needed** to educate the crew on complex technologies. Low proactivity is also identified as a barrier, along with a general suspicion and reluctance towards accepting innovations (Notti *et al.* 2014), or when **the skipper is less concerned than the vessel owner**. The skipper may be more oriented to fishing and not toward trying new technologies whenever the current ones work just fine. Unlike other sectors, the fishing industry is exempt from global shipping emissions inventories such as the IMO's Greenhouse Gas Studies (Coello *et al.* 2015). For instance, certain fisheries operating in Norway are free of environmental Tax (CO2 and NOx tax), which is therefore not triggering effort for improving energy efficiency.

Investment costs may slow down implementation of new technologies/actions, mainly in the small-scale fishing sector that usually has a lower turnover. High-strength netting material or other types of efficient gear are usually more expensive than traditional counterpart gears. For example, sails have been rejected as a complementary aid for navigation because of the cost of the implementation, even though the use of sails would reduce fuel use.

Covering the cost for the implementation of **new technologies with public funding was found ineligible** for the Operational Plan for Fisheries and Sea (2014-2020 and beyond) or other funds (European Fisheries Fund (EFF) and EMFF). This includes replacing an existing engine with a low-consumption new-technology engine. Subsidy of innovative gears (Action 4.1.20 for the 'Energy efficiency and mitigation of climate change, investments on vessels, control systems of energy efficiency, alternative propulsion systems and hull design'), has not been approved – even though such measures would reduce fuel use and possibly reduce the negative impacts of trawling. Even if some end-users were able to obtain funding, the impediment is that the purchase must be made in advance, and taking a loan likely implies a lengthy procedure and interest payments.

In addition, stakeholders have identified current regulations as one of the main barriers for the uptake of new technologies, as **regulations could limit the opportunities for improvements supported by the EU**. For instance, adding a bulb to the vessel or replacing the engine are possible actions that would reduce the fuel use, but these changes would result in an increase of the gross tonnage and engine power, which is prohibited by the current CFP regulation. Another technical limitation mentioned and induced by the regulation related to the 'kW/fishing effort' cap requirement. Gas or battery/electric engines are heavier and larger than counterpart diesel engines, thus, a kW increase of the cap would be needed for a switch. Some end users and stakeholders consider that fuel subsidies or any empowering capacity change could bring a risk of delaying adaption to growing costs and contribute to unsustainable fishing practices.

Stakeholders stated that the main reason behind searching for energy-efficient measures was high fuel price (Table 15). Commercial stakeholders further underlined that having subsidies available for that helped. Also, the commercial stakeholders pointed out that

having measures proven by scientific testing is a driver for uptake, while the scientific community argued that the uptake of energy-efficient technologies would result mainly from proofs of increased catch efficiency.

In contrast, the reasons for ceasing use of energy-efficient technologies were related to the fact that stakeholders mainly preferred to work with known technology; and sometimes also because the contract for subsidy was finished, or because the technology required more input from fishers to operate it.

Table 15 Reasons to start using energy-efficiency technology

Reasons to start using a technology	Surveyed stakeholders	
	Commercial (%)	Scientific (%)
Fuel price/Fuel cost	48	60
Subsidies	19	7
Environmental awareness	5	10
Improved working environment	14	10
Regulatory limitation	5	0
Scientific tests	10	0
Catch efficiency	0	10
Improved public image	0	3

4.3 Recommendations for reducing fisheries' GHG emissions by technical, regulatory and management means

Ocean literacy is needed amongst stakeholders (fishing sector, scientists, engineers and policymakers) to improve knowledge transfer, stimulate proactivity, and facilitate funding of tailored energy-efficiency solutions for the fishing sector.

It is of utmost importance to intensify the **stakeholder dialogue** (policymakers, fishing associations and researchers) and the IMO, to ensure the fishing industry's alignment with IMO's targets. The fishing industry needs clarification on how to achieve decarbonisation targets – 'target of zero GHG' by 2050 – including common indicators, reporting, emission inventories. Fisheries science and vessel engineering dialogue is required to encourage the uptake of fuel-saving technologies tailored to fishing vessels and specific fisheries.

The most feasible or beneficial energy-efficiency measure depends on the characteristics of the vessel, fishery and gear. Therefore, a **tailored approach** should be adopted when promoting the implementation of energy-efficiency measures.

Specific energy-efficiency improvements of the fishing sector are best developed in a **regional context**: applying energy-efficient international policies seems to be detrimental for regional/local policies, because the exhaust emissions are mainly emitted in coastal or near-coastal areas. National governments should play a more important role to regulate emissions.

The way **subsidies or incentives** are given should be reviewed. Providing subsidies to energy-efficient vessels or fishing methods, or individual skippers (giving incentive to those skippers that consider other variables to the catch) should be considered, also to those investing in energy-efficient strategies.

Energy efficiency should be an aspect embedded in fisheries management, e.g., through **redistributing quota shares** towards more fuel-efficient fisheries and vessels.

International harmonisation of fuel taxes among nations would prevent refuelling in neighbouring countries with lower taxes and enable better control of emissions and fuel consumption.

Fuel-monitoring tools on board vessels, monitoring programmes and subsequent evaluation of fuel use would increase awareness of individual fishers towards the need for reducing fuel use (e.g., slower steaming speeds helped fishers save fuel during the fuel crisis), and would also facilitate large-scale monitoring and reporting of disaggregated fuel-use data.

Monitoring programmes require data with a sufficient degree of detail to facilitate understanding of fuel use and potential for improvement. Examples of monitoring data may include:

a. Engine and vessel characteristics relevant to fuel use. These parameters only change over large time scales (years).
b. Detailed description of the gear in logbooks. Gear parameters could change at trip level.

Encourage the **reporting of energy-saving technologies individually** and not combined/aggregated with others, to facilitate the transfer of information and knowledge-gain amongst stakeholders on the respective merits of individual solutions.

Stimulate the transitional change when improving towards energy efficiency in fisheries with the help of **financial (**national**) resources for covering for costly conversion**.

Promote **usage of energy-saving gears**, and for otter trawls, focus on nets and doors because most reduction can be gained on those aspects. Furthermore, adding sensors on the gear (or integrated to the gear) can greatly optimise the fishing operation and reduce fuel usage.

Promote a bottom-up approach by informing consumers with **scoring of fisheries depending on criteria for sustainability that would also account for the relative carbon footprint** of the harvesting phase.

Promote **pilot studies** of implementation of measures on board fishing vessels while ensuring a common reporting methodology (homogenisation of indicators and protocols to measure energy efficiency).

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