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Original article

Data, analyses, and models to support the implementation of ecosystem-based fisheries management in the North Sea

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Abstract

The theoretical foundation of ecosystem-based fisheries management (EBFM) is well-established, emphasizing the need to balance ecological, economic, and social objectives. In contrast, the actual implementation of EBFM has been challenging due to diverse and often conflicting objectives, as well as the complexity of marine ecosystems. Using the demersal mixed fisheries in the North Sea as case study, a working example is delivered how data, analyses, and models available for the North Sea region can be combined to get a comprehensive picture of the performance of management strategies under EBFM. Climate and ecological effects on the stocks as well as impacts of fisheries on the ecosystem and food webs were specifically addressed next to the economic and social performance of management decisions. The traditional set of indicators used to measure the performance of fisheries management was extended to deal with a wide range of objectives related to the European Common Fisheries Policy, the Marine Strategy Framework Directive as well as global objectives such as reducing CO_2 footprints. Results indicate that under climate change a sustainable exploitation of demersal stocks is possible under a maximum sustainable yield (MSY) approach in combination with a landing obligation. However, negative impacts on socio-economic objectives could only be partly mitigated. A reduction of fishing effort below levels of the status-quo option led to many win–win situations for both ecological and socio-economic indicators, however, only up to a certain effort reduction beyond which trade-offs between ecological and socio-economic performance became apparent. Despite large parameter and structural uncertainties, the example framework provided in this study enables target-oriented discussions with stakeholders and may help to identify technical measures needed to resolve trade-offs preventing current fisheries management from reaching a ‘sweet-spot’ under EBFM. The study provides evidence that the key to successful EBFM is to maximize wanted catches per unit of effort, while reducing unwanted bycatch and keeping the environmental footprint to an acceptable low level without too severe social and economic hardships. Our results demonstrate that data and models can be successfully integrated, but making EBFM operational will depend on modern governance structures that can handle such integrated products.

Keywords EBFM, management strategy evaluation, mixed fisheries, ecological indicators, socio-economic indicators

Introduction

Ecosystem-based fisheries management (EBFM) represents a paradigm shift from traditional single-species management approaches, aiming to sustain healthy marine ecosystems and the sustainable use of fishery resources (Link 2002, Pikitch et al. 2004). EBFM incorporates the relevant complex interactions within marine ecosystems, including predator–prey relationships or environmental drivers to stock production and considers the broader impacts of fisheries beyond the target species, such as bycatch of endangered, threatened, and protected (ETP) species or physical impacts on the seafloor and associated benthic communities. EBFM also acknowledges human dimensions of sustainability relating to economic, socio-cultural, and institutional performance (Hornborg et al. 2019) and emphasizes the need to balance ecological, economic, and social objectives to achieve long-term sustainability (Patrick and Link 2015, Doyen et al. 2017, Marshall et al. 2017). Efforts to implement ecosystem approaches to fisheries management and EBFM, as well as the necessary research to underpin them, have increased in recent years

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(Jennings and Rice 2011, Pedreschi et al. 2023, Link 2025). However, the use of EBFM approaches in advice products are less common (Skern-Mauritzen et al. 2015, Trochta et al. 2018, Karp et al. 2023, Link 2025).

An EBFM-based framework combining available data and tools to test the impact of fisheries management strategies in a holistic and quantitative way is often still missing in tactical and strategic advice (Skern-Mauritzen et al. 2015, de Moor 2023), although examples of some level of ecosystem analyses and modeling to advance EBFM do exist (Townsend et al. 2019). The application of management strategy evaluations (MSEs) provides thereby a promising framework (Punt et al. 2014, Kaplan et al. 2021, de Moor et al. 2022). MSEs can support the identification of win–win situations and trade-offs between different EBFM-related objectives to enable target-oriented discussions on potential solutions that account for the impacts of both fisheries and environmental changes. However, MSEs have been primarily focused on single stocks (Thorpe and De Oliveira 2019, Karp et al. 2023), challenging their application in an EBFM context. Complicating matters further, the inherent differences in the many goals and aspects related to EBFM hinders the development of a one-type-fits-all model. Instead, combinations of different models, analyses and data may be used to provide a holistic evaluation of management strategies in support of the implementation of EBFM.

Demersal mixed fisheries are especially complex to manage. Multiple species with different life-history traits and stock status must be considered simultaneously, leading to so called choke effects where fishing effort must stop when the fishing opportunities for the first species are exhausted [under total allowable catch (TAC) management] or allowed fishing effort is determined by the weakest stock (under effort management). This potentially leads to substantial losses in revenues and socio-economic performance (Sun et al. 2023). The situation is further complicated under climate change as some species and stocks suffer from lower productivity, while others are either not or positively affected (Kühn et al. 2023). The demersal mixed fisheries in the North Sea are a typical example of this. They cover a wide range of main target species (ICES WGMIXFISH 2025), including gadoids such as Atlantic cod (*Gadus morhua)* , whiting (*Merlangius merlangus*), haddock (*Melanogrammus aeglefinus*), and saithe (*Pollachius virens*), flatfish such as European plaice (*Pleuronectes platessa)* and Common sole (*Solea solea)* , as well as crustaceans, such as Nephrops (*Nephrops norvegicus*). These stocks are managed by reference points indicating their status, such as fishing pressure (F) at maximum sustainable yield (MSY) and spawning stock biomass (SSB) above critical levels, which are rooted in both the EU Common Fisheries Policy (CFP; EU et al. 2013) and the Marine Strategy Framework Directive (MSFD; EU et al. 2008). The status of these stocks, in relation to agreed reference points, has varied greatly in recent years (ICES WGNSSK 2025) . For example, while cod has been overfished in relation to F_{MSY} and the SSB has been outside safe biological limits for several years, the SSB of plaice, haddock and whiting currently show healthy stock status and are fished well below F_{MSY}.

In addition to the complications arising from mixing of species during the fishing process, demersal mixed fisheries negatively impact ecosystems beyond the extraction of single species. A wide variety of gears is used in the North Sea demersal mixed fisheries ranging from beam and otter trawls to seines and passive gears like gill nets and pots (ICES WGMIXFISH 2025). All of these gears have their own challenges in relation to EBFM objectives: Some negatively impact the sea floor integrity (MSFD, EU 2008), while the fishing process leads to potential unintentional bycatch of ETP species. A seabed impact assessment of mobile bottom-contacting gears showed that otter trawling for crustaceans has the highest total seabed impact in the North Sea, followed by otter trawling for demersal fish and beam trawling for flatfish and fly-shooting (Rijnsdorp et al. 2020). Beam trawling for brown shrimps, otter trawling for industrial fish like sandeels, and dredging for molluscs have the lowest overall seabed impact. Passive gears like gill and trammel nets have a low bottom impact, but lead to bycatch of seabirds and marine mammals such as harbour porpoise (*Phocoena phocoena*; Larsen et al. 2021, ICES Bycatch 2024). In a food web context, stocks of top-predator demersal fish, such as cod and saithe have been greatly reduced in the North Sea in past decades (Kühn et al. 2023, ICES WGSAM 2021) and the proportion of large fish remains below set thresholds (Lynam and Piet 2023).

The economic performance of EU fleets fishing in the North Sea (all fisheries, not only demersal mixed fisheries) increased between 2013 and 2016 but subsequently gross value added and net profit declined and reached the lowest point since 2013 in 2022 (STECF 2024). Further, employment has reduced in recent years (STECF 2024). The deterioration in the socio-economic performance has been caused to a large extent by societal events, such as Brexit, the COVID-19 pandemic, and increasing fuel prices. To ensure that decision makers trying to implement EBFM can choose management strategies on an informed basis, the impacts of the various management measures must first be predicted.

In this study, we provide a working example how available data, analyses, and models can be combined to compare the performance of alternative management strategies within an EBFM approach using the demersal mixed fisheries in the North Sea as case study. We specifically include climate and ecological effects on the stocks as well as impacts of fisheries on the ecosystem and food webs and the economic and social performance of management decisions. For this, we used models ranging from bio-economic mixed fisheries MSE models to full ecosystem models for estimating indicators dealing with a wide range of ecological, economic, and social objectives related to the CFP and MSFD as well as global objectives such as minimizing CO_2 footprints [Regulation (EU) 2021/1119]. Model predictions were linked via 'common currencies', such as fishing effort or landings by fleet and métier to analyses of relative benthic state (RBS) and landings by harbour information as a proxy for the contributions of fishing to coastal communities. As this is a first step, the example framework does not address the question of how fishing patterns could be further optimized to attain EBFM objectives. We highlight win–win situations as well as trade-offs between different EBFM-related objectives to allow for a targeted discussion on the shortcomings of current management and potential merits of adapted approaches.

Material and methods

Framework to test the impact of management strategies

A framework was developed and applied that links various available data, analyses, and models to deliver a holistic picture on the impacts of potential management strategies for the demersal

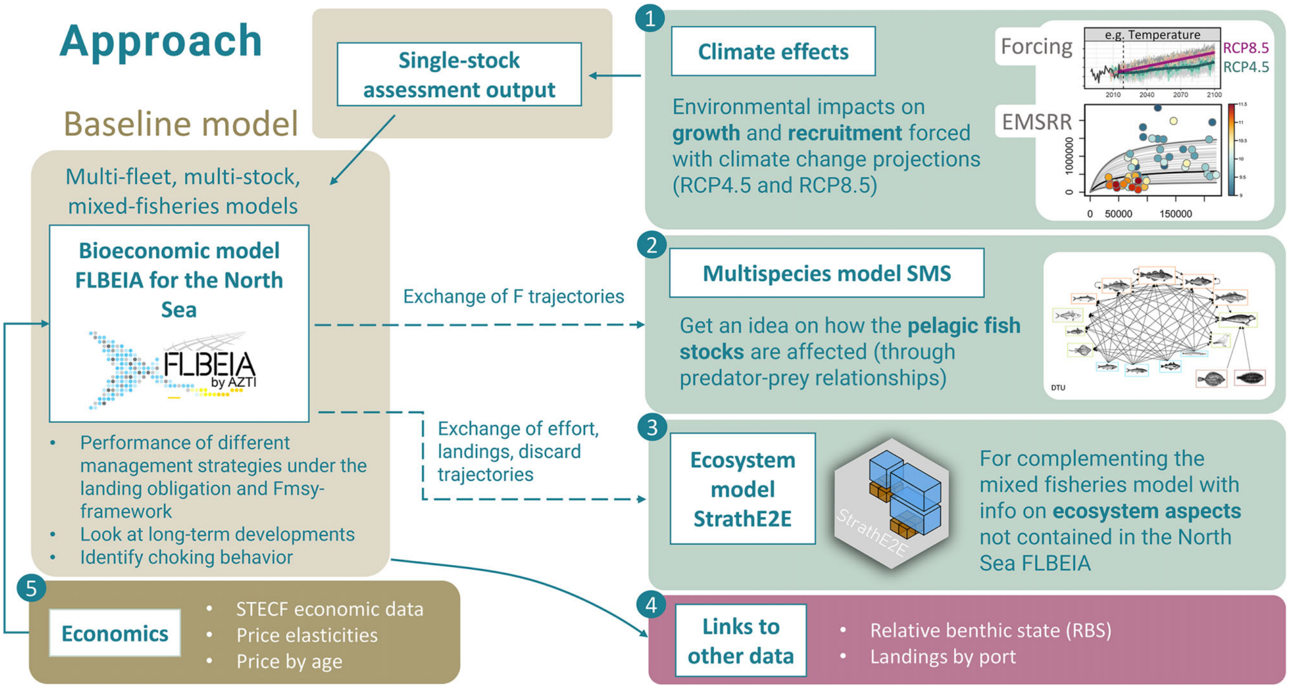

Figure 1 Applied framework for linking data, models, and analyses. Abbreviations used in the graphic: RCP—relative concentration pathway, EMSRR—environmentally mediated stock recruitment relationship, and STECF—Scientific, Technical, and Economic Committee for Fisheries.

mixed fisheries in the North Sea (Fig. 1). Each of the models and analyses applied had its own strengths and weaknesses (Table 1) and a holistic evaluation of management options was possible by the combination of these approaches. The models and analyses covered different species and ecosystem components (Table 2). No model was able to estimate all indicators; instead, the strength of each model was utilized to cover a broad range of indicators (Table 3).

Parameterized with outputs from benchmarked ICES single species assessments and adapted to be able to consider environmental effects on recruitment and growth (Fig. 1), central CFP indicators (e.g. probability to fall below B_{lim}) could be derived from the bio-economic model FLBEIA (Garcia et al. 2017). Socio-economic CFP indicators (e.g. revenues and wages) were estimated based on the FLBEIA outputs in combination with data from annual economic reports (AER; STECF 2022) of the Scientific, Technical, and Economic Committee for Fisheries (STECF). To derive MSFD-related indicators (e.g. forage fish indicator, by-catch of marine mammals, or seabirds), predicted fishing effort, fishing mortality, and catch trajectories from FLBEIA made it possible to establish links with the multispecies model SMS (Lewy and Vinther 2004) and the ecosystem model StrathE2E (Heath 2012, Heath et al. 2020). The predicted trajectories from FLBEIA were also used as link to detailed analysis on benthic impact and impact on fishing harbours.

In more detail, the bio-economic mixed fisheries model FLBEIA was used as a base model to simulate the North Sea demersal mixed fisheries in an MSE context. The model was conditioned with historical data up to 2021 (i.e. catch and effort data from 2021 and assessment time series with stock specific starting year and 2021 as last assessment year), and forecasted using future conditions thereafter. Stock dynamics were based on relevant assessments conducted by the International Council for the Exploration of the Sea (ICES) in 2022 (ICES WGNSSK 2022). Fleets and métiers were parameterized as detailed in ICES WGMIXFISH (2022) and used as basis for the 2022 ICES advice on mixed fisheries considerations. This base model was extended by environmentally mediated stock recruitment relationships (EMSRRs) and environmental-driven growth relationships to consider the influence of environmental changes on stock productivity (see Fig. 1: '1—climate effects'). The environmental factors influencing recruitment were identified with the help of a machine learning framework based on Kühn et al. (2021) and the predictive power of EMSRRs was tested by cross validation. Only EMSRRs improving the predictive power over standard SRRs were implemented in the FLBEIA simulations. Similarly, growth models with explicit environmental effects were only included if the predictive capability on a holdout-set was improved over a naive model (mean weight-at-age). For further details see Annex A in the Supplementary material.

Forecasted F-trajectories and EMSRRs for demersal stocks from FLBEIA predictions informed the stochastic multispecies model, SMS, which was parameterized by the ICES multi species working group in 2020 (ICES WGSAM 2021) to provide natural mortality estimates for single species assessments of important commercial stocks in the North Sea (see Fig. 1: '2—multispecies model SMS'). SMS estimated the predation impact on forage fish like sandeel (*Ammodytes* spp.), sprat (*Sprattus sprattus*), and herring (*Clupea harengus*) under the different fishing strategies (see description of scenarios below) for gadoid predators and allowed for the evaluation of forage fish stock trajectories in relation to indicator thresholds under established management approaches as well as climate change scenarios. While for demersal stocks annual fishing mortality per year, stock and scenario was used directly from the FLBEIA predictions, for the pelagic stocks herring and mackerel fishing mortalities were calculated dynamically by year within SMS following the ICES MSY approach (ICES 2023a). For the short-lived species sandeel, sprat and Norway pout an

Table 1 Main strength and weakness of the models and analyses applied.

Model or analysis	Type of model	Strength	Weakness
Bio-Economic Impact Assessment using FLR (FLBEIA)	Bio-economic mixed fisheries simulation model	Detailed simulation of technical interactions in mixed fisheries based on benchmarked ICES single stock assessments Economic submodel MSE type simulations Fleet/metier-specific catchability profiles and predictions of fishing effort by fleet and metier	No dynamic biological interactions between stocks Constant catchabilities
Stochastic Multispecies model (SMS)	Stochastic multispecies model	Estimation of predation mortalities for commercially important fish stocks Covers main parts of the North Sea food web	No simulation of fleets and metiers, only F by species/stock
Strathclyde End to End ecosystem model (StrathE2E)	End to end model	Includes output from hydrodynamic model(s) to consider changes in nutrient cycling Covers the whole ecosystem Simulates main types of fleets separately	Aggregated in guilds, no species Deterministic simulations Fleet aggregation quite coarse
Analyses on RBS	Specific analysis focusing on fishing impact on benthic habitats	Spatially explicit representation of fishing impact by Benthis metier on benthic communities at ecosystem scale Quantitative data-driven indicator, also suitable for data-poor situations	Risk-based pressure indicator, not a dynamic state assessment No biological interactions Focused on total biomass only (e.g. not diversity or ecosystem functioning)

'escapement strategy' was applied where the TAC is set such that a minimum biomass is left (escaped) after the fishery has taken place and fishing mortality stays below an upper limit called F_{cap}. Further details can be found in the Supplementary material under Annex B.

Fishing effort by fleet and métier simulated by FLBEIA were transferred into the ecosystem model StrathE2E (see Fig. 1: '3—ecosystem model StrathE2E'). StrathE2E represents the full ecosystem with 26 guilds spanning bio-geochemistry through phytoplankton, zooplankton, benthos, and fish, to birds, pinnipeds, and cetaceans, each presented in nitrogen units, and the full trophic connectivity between them. All fishing activity in StrathE2E is represented by 12 métiers, which can be parameterized to represent the full range of fishing methods in terms of catching power, guild selectivity, seabed abrasion, discarding, and processing-at-sea rates. The starting point for each StrathE2E run was a baseline model driven by 2003–2013 monthly resolution mean annual cycles of environmental data (temperature, ocean boundary nutrient concentrations, river inflows and nutrients, and boundary hydrodynamic inflows) and fishing métier activity rates, and fitted to a database of corresponding ecosystem measures (e.g. guild annual production and biomass data). Each scenario run (see scenario descriptions below) projected forwards from 2014 to 2060 with the baseline annual métier activity rates scaled to the corresponding FLBEIA métier effort, and year-specific annual cycles of environmental driving data extracted from the quarter-degree global physical–biogeochemical model NEMO-MEDUSA assuming RCP8.5 emissions (Yool et al. 2015). This linkage allowed evaluations of the predicted changes in FLBEIA fishing effort by fleet and métier on the wider ecosystem (e.g. ecosystem mean trophic level, Fogarty index, and bycatches of seabirds, cetaceans, and pinnipeds) and offered the possibility to test bottom-up effects resulting from climate change induced alterations in nutrient cycling and primary production. For further details see Annex C in the Supplementary material.

Fishing effort by fleet and metier was also used to establish a link between FLBEIA predictions and analyses on RBS (see Fig. 1: '4—links to other data'). RBS is based on an equilibrium solution of the logistic population growth model and represents the state of the benthic community biomass relative to its carrying capacity (B/K) (Ellis et al. 2014, Pitcher et al. 2016). RBS decreases as fishing intensity (F) and depletion rate per trawl pass (d) increase relative to the intrinsic biomass recovery rate (r), following: $RBS = \frac{B}{K} = 1 - \frac{F\,d}{r}$.

Fishing intensity was estimated by metier as the annual swept area ratio, while depletion rates were derived from a meta-analysis of experimental trawling impact studies and vary by gear and sediment type (Rijnsdorp et al. 2020, Pitcher et al. 2022). Recovery rates increase with decreasing benthic longevity (Hiddink et al. 2019). The RBS value ranges between zero (strong negative impact) and one (undisturbed). Benthic impact was assessed following the population dynamics methods used in the EU project

Table 2 Species/stocks as well as fleets and metiers covered in the models and analyses applied. For more details see Annexes A–E in the supplementary material.

Model name	Spatial extent	Species/stocks included	Fleets/metiers/fisheries included
Bio-Economic Impact Assessment using FLR (FLBEIA)	ICES areas 4, 7d, 3a20, and 6a for stocks extending to 6a (cod, saithe, and haddock)	Cod, whiting, haddock, saithe, plaice (4; 7d), sole (4; 7d), turbot, witch, Nephrops Functional Units (5,6,7,8,9,10,32,33,34,IV not in FU)	Demersal fleets and metiers (46 national fleets and 152 metiers)
Strathclyde End to End ecosystem model (StrathE2E)	North Sea (ICES subarea 4)	26 guilds: Nutrients (4), detritus (6), primary producers (2), Zooplankton (6), benthos (2), fish (3: planktivorous, migratory, demersal), seabirds (1), and mammals (2)	12 fleets/metiers covering the entirety of fishing activity, harvesting nine guilds (carnivorous zooplankton, suspension/deposit feeding benthos, carnivore/scavenge feeding benthos, planktivorous, demersal and migratory fish, birds, and pinnipeds and cetaceans)
Stochastic Multispecies model (SMS)	ICES area 4	Cod, haddock, saithe, whiting, hake, plaice, sole, herring, sprat, sandeel, Norway pout, mackerel, horse mackerel, seals, harbour porpoise, grey gurnard, starry ray, and 8 bird species.	None (fishing mortality by species/stock)
Analysis on RBS	ICES areas 4 and 7d	Infaunal and smaller epifaunal biomass of the macrobenthic community, as sampled from grabs and boxcorers	Benthic metiers (*Nephrops* otter trawls, whitefish otter trawls, flatfish-directed beam trawls, Danish seines, and fly-shooters; see Eigaard et al. 2016, Rijnsdorp et al. 2020)

SEAwise (Van Hoey et al. 2023) and the ICES Advice on spatial trade-off analysis between reducing the extent of mobile bottom-contacting gear disturbance to seabed habitats and potential costs to fisheries (ICES WKD6STAKE 2024). The sensitivity layers (i.e. longevity distribution) were constant in time. The methodological guidelines are well established by the ICES Working Group on Fisheries Benthic Impact and Trade-offs (ICES WGFBIT 2021, ICES WGFBIT 2022, ICES WGFBIT 2023). For further details see the Supplementary material under Annex D.

The socio-economic submodel of FLBEIA (see Fig. 1: '5—economics') was parameterized using STECF data from the AER (STECF 2022). Revenues (value of landings) and the costs of fishing (i.e. fixed, variable, and crew share costs) could be fully considered in the evaluation of management strategies. Due to differences in the aggregation level for fleets and metiers between the STECF economic data and the FLBEIA model (ICES WGMIXFISH 2022 fleet definitions), fleets could only be matched to the lowest aggregation level possible. STECF data also contain species not considered in the FLBEIA model. To overcome this mismatch, the FLBEIA model was conditioned with the relative costs to revenue ratio to match the level of profitability reported for fleet segments in the STECF data. With this concession, the final results of the economic outcomes may be more appropriately interpreted in relative terms between scenarios rather than absolute terms. FLBEIA predictions of landings and revenues by species were additionally linked to landings by harbour information from the ICES regional database and estimation system (ICES RDBES) to provide a proxy for the impact on local communities on land (see Fig. 1: '4—links to other data'). Further details can be found in the Supplementary material under Annex E.

Indicators selected

Following consultations with members of the North Sea Advisory Council (Rindorf et al. 2023), indicators of both ecological and human wellbeing were identified for CFP, MSFD as well as global objectives and used to assess the effects of tested scenarios (Table 3). The indicators covered different scales from single stocks to whole ecosystem metrics and were chosen to be representative for the main types of objectives mentioned in the respective regulations and consultations. For each indicator it was decided which model or analysis delivered the right level of detail (e.g. age distribution by stock available in FLBEIA vs. functional groups covering the whole ecosystem in StrathE2E). Only some indicators had targets and limits that have been agreed upon by the scientific community and/or political committees. For indicators without agreed thresholds, scenarios were ranked relative to each other based on the desired direction of change.

For each indicator, the averages over the prediction years 2055–2060 (i.e. 6-year period as suggested by the most recent MSFD guidelines; European Commission 2022) were calculated under each scenario. In this study, we focused on the long-term implications between 2055 and 2060 to be less dependent on the starting conditions and to highlight the impacts of further climate driven changes to be expected over the next decades.

Table 3 Set of indicators used to evaluate the performance of scenarios against CFP, MSFD as well as global objectives.

Type of objective	Indicator	Model/analysis used	Targets or limits available?	Comments
CFP ecological	Proportion of stocks fished at or below F_{MSY}	FLBEIA	Yes	Also relevant for MSFD descriptor 3 (commercial fish and shellfish). F_{MSY} values available from ICES advice. F_{MSY} is the fishing mortality rate leading to MSY.
	Proportion of stocks with <5% probability to fall below B_{lim}	FLBEIA	Yes	Also relevant for MSFD descriptor 3 (commercial fish and shellfish), B_{lim} values available from ICES advice. Below B_{lim} recruitment may be impaired and the probability of a stock collapse increases.
CFP socio-economic	Landings (average of yearly sums across fleets/metiers)	FLBEIA	No (the higher the better)	
	Discards (average of yearly sums across fleets/metiers)	FLBEIA	No (the lower the better)	
	Revenues (average of yearly sums across fleets/metiers)	FLBEIA	No (the higher the better)	Revenue = landings × fish price
	Gross value added (average of yearly sums across fleets/metiers)	FLBEIA	No (the higher the better)	Gross value added (GVA) = income from landings + other income—energy costs—repair costs—other variable costs—nonvariable costs (STECF 2021)
	Wages (average of yearly sums across fleets/metiers)	FLBEIA	No (the higher the better)	Wages = crewshare × revenue
	Proportion of harbours with an increase in landings of ≥10% compared to the base year/first year of the simulation (Port Winner Index)	FLBEIA and link to the ICES regional database and estimation system (RDBES)	No (the higher the better)	Landing harbour as link to communities and industry on land
	Fishing effort (yearly sums across fleets/metiers)	FLBEIA	No (the lower the better)	The same landings at a lower fishing effort improves the economic performance. Lower fishing effort is also beneficial for MSFD-related indicators.

Table 3 Continued

Type of objective	Indicator	Model/analysis used	Targets or limits available?	Comments
MSFD-related indicators (further descriptor 3 indicators are included under CFP indicators)	Mean trophic level	StrathE2E	No (the higher the better)	Mean trophic level in the ecosystem (annual average biomass-weighted mean of individual guild trophic levels spanning the whole food web). Relevant for MSFD descriptor D4 (Food webs)
	Average stock age	FLBEIA	No (the higher the better)	Average stock age (ASA) across stocks in the model. Relevant for MSFD descriptor 3 (Commercial fish and shellfish).
	Large fish indicator (LFI) for commercially important demersal fish	FLBEIA	No (the higher the better)	Examples of size-based indicators applied for fish include the large fish indicator (LFI). The LFI relies on the estimation of the size of a 'large fish' to be estimated separately by guild and region, and the indicator is therefore not directly comparable between regions but may provide useful results within a region. For the North Sea often the threshold of 40 cm (Greenstreet et al. 2010) is used for demersal fish. Relevant for MSFD descriptor 4 (Food webs).
	Forage fish stocks with biomass above 1/3 of the maximum observed biomass in the time series	SMS	Yes	Cury et al. (2011) identified a threshold in prey (fish and krill, termed 'forage fish') abundance below which seabirds experience consistently reduced and more variable productivity. This response was common to all 7 ecosystems and 14 bird species examined within the Atlantic, Pacific, and Southern Oceans. The threshold approximated one-third of the maximum prey biomass observed in long-term studies. This provides an indicator of the minimal forage fish biomass needed to sustain seabird productivity over the long term. Relevant for MSFD descriptors 1 (Marine biodiversity) and descriptor 4 (Food webs)
	Bycatch of pinnipeds, birds, and cetaceans	StrathE2E, FLBEIA (for harbour porpoise only)	Partly (for some species in the North Sea; the lower the better)	Biological extraction of, or mortality/injury to, wild species (by commercial and recreational fishing and other activities). Relevant for MSFD descriptor 1 (Marine biodiversity).

Table 3 Continued

Type of objective	Indicator	Model/analysis used	Targets or limits available?	Comments
	Swept area ratio (SAR)	StrathE2E	No	Swept area ratio given by the sum over all metiers, of activity rates (s m^{-2} y^{-1}) times the metier-specific seabed area sweeping rates (m^2 s^{-1}; Eigaard et al. 2016). Relevant for MSFD descriptor 6 (Sea bed integrity)
	% Area with RBS <0.8 or 0.9 for each broad MSFD broad habitat type	RBS analysis linked to FLBEIA effort predictions	Yes for % area, no for RBS threshold	There are no official agreed thresholds for habitat quality, though there is a limit for the habitat extent that may be impaired [25% of the area of each of the MSFD broad habitat types can be impaired, i.e. 75% needs to be in good environmental status (GES)]. GES habitat quality can be defined as an RBS above 0.8 as potential candidate for favourable RBS conditions following WKBENTH2 (ICES 2022). However, also 0.9 could be an option for policy makers and was tested as alternative. Relevant for MSFD descriptor D6 (sea bed integrity).
Global indicators	CO_2 per landed kg of fish	FLBEIA	No (the lower the better)	Efficiency in providing food per CO_2 footprint. Relevant in relation to e.g. the EU climate law [Regulation (EU) 2021/1119] or Paris Agreement (2016).
	Ratio of fisheries catches to primary production (Fogarty index in Link and Watson 2019)	StrathE2E	Yes	On the basis of simple trophic transfer calculations, the Fogarty index of catches relative to primary production (PP) ranges from 0.1‰ to 3‰ according to Link and Watson (2019). This is suggestive of reasonable limits to catch potential and hence a possible threshold. Given worldwide catches of 0.1 to 0.42 Gt year − 1 would imply an expected ratio of catch to PP of 0.22‰–0.92‰, suggesting a possible "Not to Exceed" threshold around one. Even an extreme estimate of catches near 1 Gt per year would result in a value of 2.2‰ (~2.5‰).

Scenarios tested

The ICES approach to achieving MSY across a range of species life histories and degrees of data richness (ICES 2023a) is central for providing advice on fishing opportunities in the North Sea. In addition to the ICES MSY approach, sustainable F_{MSY} ranges were considered delivering at least 95% of the maximum yield [Pretty Good Yield (PGY)] as mentioned in the multiannual plan (MAP; EU 2018) for the North Sea demersal fisheries. As a further important management measure, landing obligations (i.e. discard bans) exist for EU, UK, and Norwegian waters of the North Sea.

Three management scenarios mimicking potential management approaches were compared:

a) A 'Status-quo' effort/F scenario (status-quo): The effort by fleet and metier is set to year 2021 and held constant during the simulation. The year 2021 was chosen, because it was the latest available data year and several fleets exhibited clear positive or negative effort trends before 2021 next to major structural changes caused e.g. by Brexit. This is the baseline scenario assuming no effective changes in management from the status-quo.
b) A 'min' scenario (FMSY-Min): The ICES MSY advice rule is applied with F_{MSY} as target for each stock and fleets and metiers have to stop when their first quota is exhausted. The scenario implies a strict implementation of the landing obligation.
c) A 'pretty good yield' (PGY) scenario (PGY-Min) using a default of F_{MSY} as target combined with established fishing mortality ranges from the EU MAP for demersal fisheries. Under certain constraints, F_{MSY} was replaced by fishing at the 'F_{MSY} upper' level (F_{MSY_upper} indicates the upper limit of sustainable fishing mortalities delivering at least 95% of the maximum yield). Fishing mortalities up to F_{MSY_upper} were allowed when stocks are in good status; i.e. above MSY $B_{trigger}$ at the beginning of the advice year. In addition, a buffer to year-to-year advice variability was introduced for stocks in good status, such that TACs are limited to max ± 20% from one year to the next, but limited to TACs associated with F_{MSY_upper}. The scenario is somewhat more flexible due to the use of the upper F_{MSY} range, possibly alleviating some choking behaviour when most-limiting stocks are in good status.

The impact of climate change on indicators was tested by combining the three management scenarios with three climate change scenarios: current ('no climate change', current conditions held constant), RCP4.5 [Intermediate Representative Concentration Pathway (RCP) where climate policies limit and achieve stabilization of greenhouse gas concentrations leading to a radiative forcing of 4.5 W m^{-2} by 2100] and RCP8.5 (Worst case RCP where high emissions of greenhouse gases continue in the absence of climate change policies leading to a radiative forcing of 8.5 W m^{-2} by 2100). This resulted in a total of nine scenarios.

While the impact of climate change was implemented in all three used models, the processes of simulating climate change effects differed between models dependent on their focus (Table 4). Details on how the time series of environmental variables were derived and implemented in each model and scenario can be found in the Supplementary material under Annexes A–C.

Model predictions of fishing effort by fleet and métier were linked to RBS analyses to test the impact on seafloor integrity and benthic communities (see Table 3). Two RBS thresholds for negative seabed impact were considered, namely 0.8 and 0.9 (ICES 2022). These two scenarios provided information on how political agreements on the definition of negative seabed impact thresholds may influence the frame in which the demersal mixed fisheries have to operate in the future.

Results

The combination of available data, models, and analyses allowed for a holistic impact assessment of current management approaches for mixed demersal fisheries covering many aspects relevant for EBFM in the North Sea. The central set of ecological and socio-economic indicators related to the CFP were supplemented by information on MSFD relevant indicators (Fig. 2, Table 3) including the impact on forage fish and thereby seabirds relying on them as source for food (Fig. 5) as well as RBS of broad MSFD habitat types (Fig. 6). The different sets of indicators were analysed separately and in combination to derive an overall picture on win–win and trade-off situation of the three management approaches tested (Fig. 7).

Ecological and socio-economic CFP indicators

Results were analysed relative to the status-quo scenario (fishing effort level in 2021) under current climate conditions and therefore give an impression on what might be expected under management scenarios and further climate change (Fig. 2). CFP-related indicators (averages 2055–2060) were largely driven by the applied management strategies amplified or buffered by effects from climate change (Fig. 2). In the scenarios with a strict implementation of the landing obligation (FMSY-Min and PGY-Min), fishing pressure was strongly reduced (on average well below F_{MSY}) due to choking effects compared to the status-quo effort scenario, where on average stocks were fished above F_{msy} (Fig. 3). Only in the status-quo effort scenario some stocks were fished above F_{MSY} (not shown). Several stocks were at risk of being harvested unsustainably (i.e. >5% risk of falling below Blim) in the status-quo effort scenarios, while this was no longer the case in the FMSY-Min and PGY-Min scenarios under all tested climate change assumptions (Fig. 2).

Climate change strongly reduced the yield from the system (Fig. 2), largely driven by negative effects of temperature on cod and saithe recruitment (see under Annex A in the Supplementary material). Lower predicted stock sizes for cod and saithe and associated lower catches per unit of effort (CPUEs) under RCP4.5 and RCP8.5 led to overall lower landings (food security), lower economic outcomes [gross value added (GVA) , lower number of ports gaining > 10% compared to 2021] as well as lower wages compared to the simulations under current climate conditions (Fig. 2). When comparing to the status-quo scenario, the two landing obligation scenarios were able to mitigate the negative climate change effects on e.g. landings to some extent and at lower levels of discards as positive side effect. In contrast, fishing effort was only influenced by the type of management strategy, but hardly by climate change (Fig. 2). This was due to the fact that the limiting (choking) stocks were the same among the different climate scenarios. While stock sizes have differed by climate scenario, their

Table 4 Implementation of climate change effects in each model.

Model name	Climate change impact simulated on…	Implementation of effects
FLBEIA	Recruitment and growth	Recruitment was simulated with environmentally mediated stock recruitment functions (EMSRRs) that proved to have a higher predictive power compared to standard SRRs. EMSRRS took into account changes in temperature, salinity, and currents for the gadoid stocks cod, saithe, and whiting as well as for plaice as flatfish stock. Growth models were incorporated for cod and haddock taking into account an explicit effect of temperature and salinity, providing an improvement over a prediction of weight with a length-at-age model without an environmental effect.
SMS	Recruitment	See above for FLBEIA
StrathE2E	Entire ecosystem driven by global biogeochemical climate change models	Temperature affects the feeding rates and metabolism of all living guilds in the model. In addition, the model is driven by geographic boundary influxes of dissolved nutrients and suspended organic particulate matter which affect primary production and nutrient flows within the model domain.

overall acceptable stock status resulted in the same advised fishing mortality in the long-term. Since effort and fishing mortality are proportional and scaled by catchability, the assumption of constant catchabilities over time resulted finally in similar fishing effort to achieve the advised fishing mortalities independent of the assumed climate trajectories.

Looking at the GVA as well as wages across fleets showed economic and social gains in scenarios with a strict implementation of the landing obligation compared to the status-quo scenario, although climate change effects could only partly be mitigated (Fig. 2). However, the strictest implementation of the MSY concept and of the landing obligation (FMSY-Min scenario), led to lower performance in economic and social indicators compared to the more flexible PGY-Min scenario (Fig. 2). The PGY-Min scenario represented a potential compromise of the options tested.

MSFD-related and global indicators

A strict implementation of the landing obligation and interpretation of the MSY concept (FMSY-Min) provided the largest improvement of MSFD and global indicators because it led to the lowest fishing effort among the three tested harvest strategies (Fig. 2). PGY-Min showed intermediate results for MSFD and global indicators, which were slightly worse than in the FMSY-Min scenario, but showed still large improvements compared to the status-quo effort scenario.

With climate change leading to a decline in some stocks and therefore declining CPUEs, the average carbon footprint (emissions from fishing vessels) per kg fish landed increased with the severity of climate change trajectories next to expected changes with the amount of fishing effort in the three management scenarios (Fig. 2). Although stock recovery and accompanying shifts in age distributions (see Average Stock Age indicator in Fig. 2) under the landing obligation scenarios helped to improve LFI for North Sea demersal fish included in FLBEIA, only under current climate conditions could a potential threshold of 0.3 discussed in Greenstreet et al. (2010) be reached (Fig. S1 in Annex G of the Supplementary material). Under continued climate change (RCP4.5 and RCP8.5) the LFI did not reach 0.25 even under the low exploitation FMSY-Min scenario. This is a consequence of cod and saithe being negatively influenced by climate change in the model overruling the positive effects of lower fishing effort in the two landing obligation scenarios.

The bycatch of harbour porpoise was assumed proportional to the effort of specific gears in the FLBEIA model. Therefore, the amount of bycatch followed the general effort levels in the scenarios and there was not much difference between the climate change scenarios (Fig. 2). In contrast, StrathE2E predicted substantially less bycatch of cetaceans, pinnipeds, and seabirds under RCP8.5 compared to the scenario under current climate conditions. This was caused by predicted declines in primary production under RCP8.5 cascading through the whole food web (Fig. 4). Resulting lower biomass of marine mammals and seabirds finally led to less individuals being bycaught per km^2 at similar fishing effort levels. Such a dynamic change in biomass was not implemented in FLBEIA for harbour porpoise. This highlights that some structural differences between FLBEIA and StrathE2E may lead to seemingly contradictory outcomes, and also that changes in indicators in an apparently desirable direction from a conservation perspective might not always be caused by positive developments. A similar example is the Fogarty index in StrathE2E where, under RCP8.5, less catches are predicted per primary production due to stronger decreasing biomass in higher trophic levels compared to decreasing primary production (Fig. 4).

Because of predation, the stock sizes of the small pelagic forage fish predicted in the SMS model (Fig. 5) and planktivorous fish in StrathE2E (Fig. 4) were influenced via cascading effects through the food web by the choice of management scenario implemented for gadoids in FLBEIA and climate change scenarios impacting their productivity. Despite varying predation pressure, the applied escapement harvest strategy for sandeel and sprat as well as the

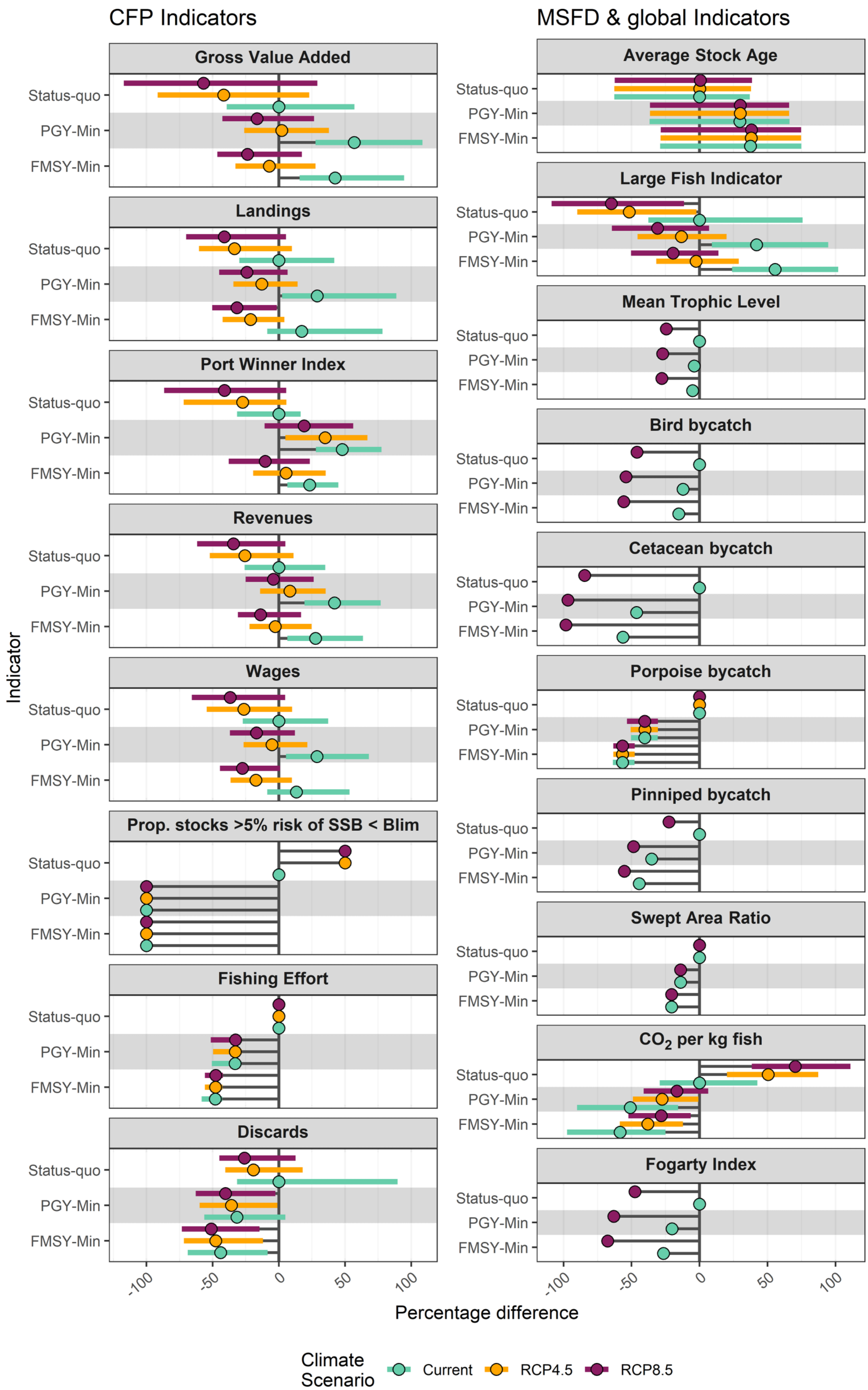

Figure 2 Outcomes for CFP as well as MSFD and global indicators (average 2055–2060) by management and climate change scenario relative to the status-quo effort scenario under current climate conditions (median set to zero). Points indicate the median and colored horizontal lines the 2.5%–97.5% quantiles, respectively. For Indicators derived from StrathE2E no uncertainties were predicted and indicators are available for the Current and RCP8.5 climate change scenarios only. The horizontal grey lines were included to ease the visual interpretation only. See Table 3 for descriptions of indicators. Indicators are ordered in the direction of desired change. Please note that some indicators mentioned in Table 3 are treated in the text only or are shown in Figs 5 and 6.

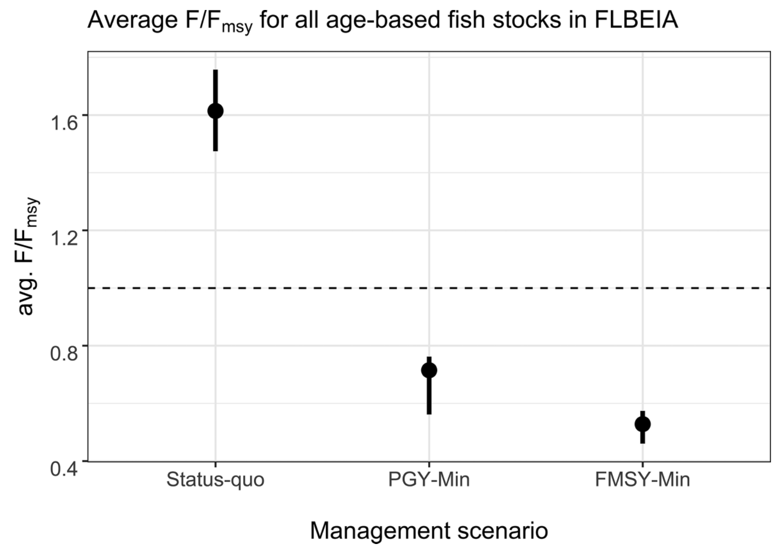

Figure 3 Ratio of fishing mortality (F) by management scenario relative to fishing mortality providing maximum sustainable yield (FMSY) and averaged over the time period 2055–2060, across climate scenarios and the 10 age-based demersal stocks (without Nephrops) in the FLBEIA model. Points indicate the median and vertical lines the 2.5%–97.5% quantiles, respectively.

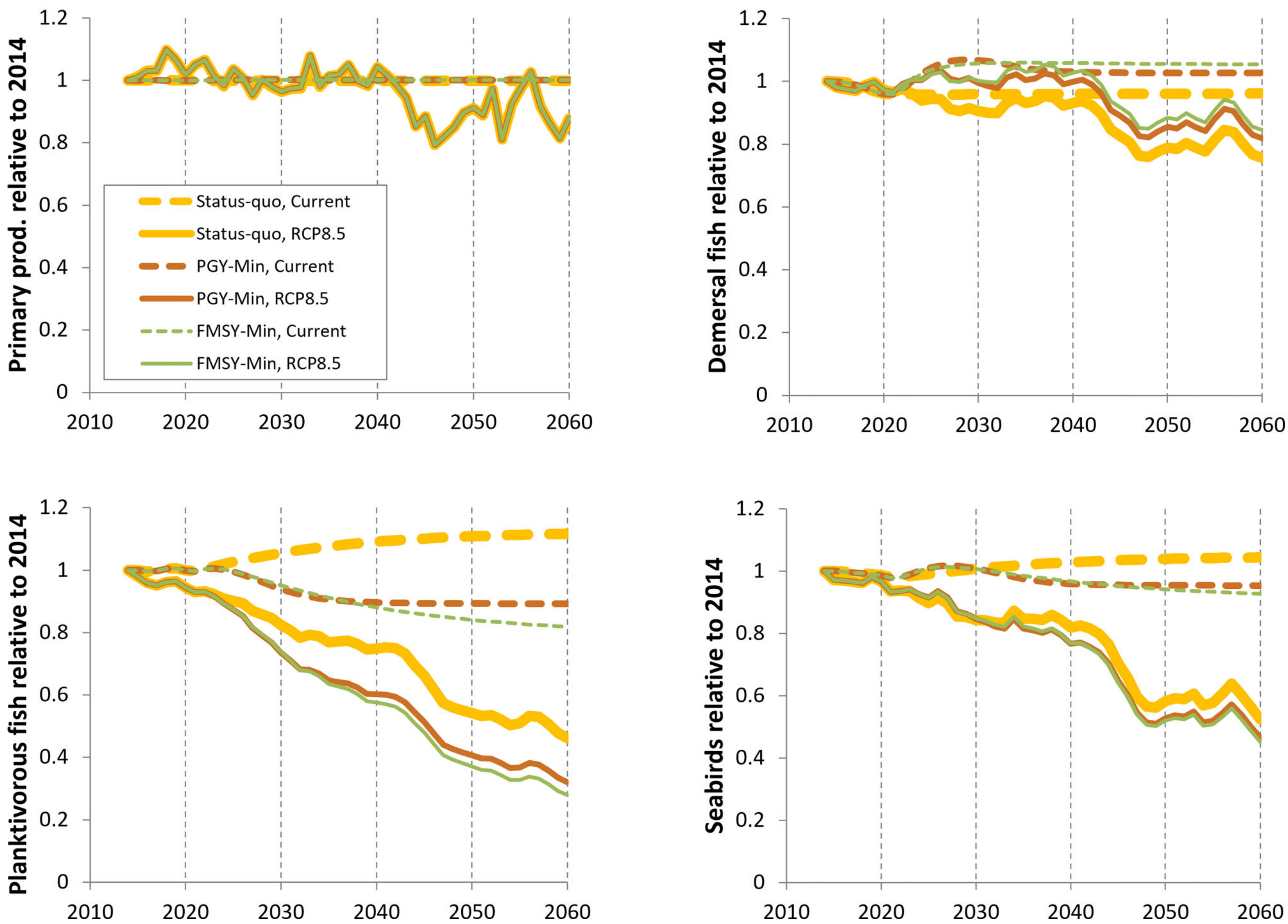

Figure 4 StrathE2E predictions of climate change effects on primary production and follow up effects cascading through the food web. Trajectories are shown for three management scenarios (status-quo, FMSY-Min, and PGY-Min) under Current and RCP8.5 climate conditions.

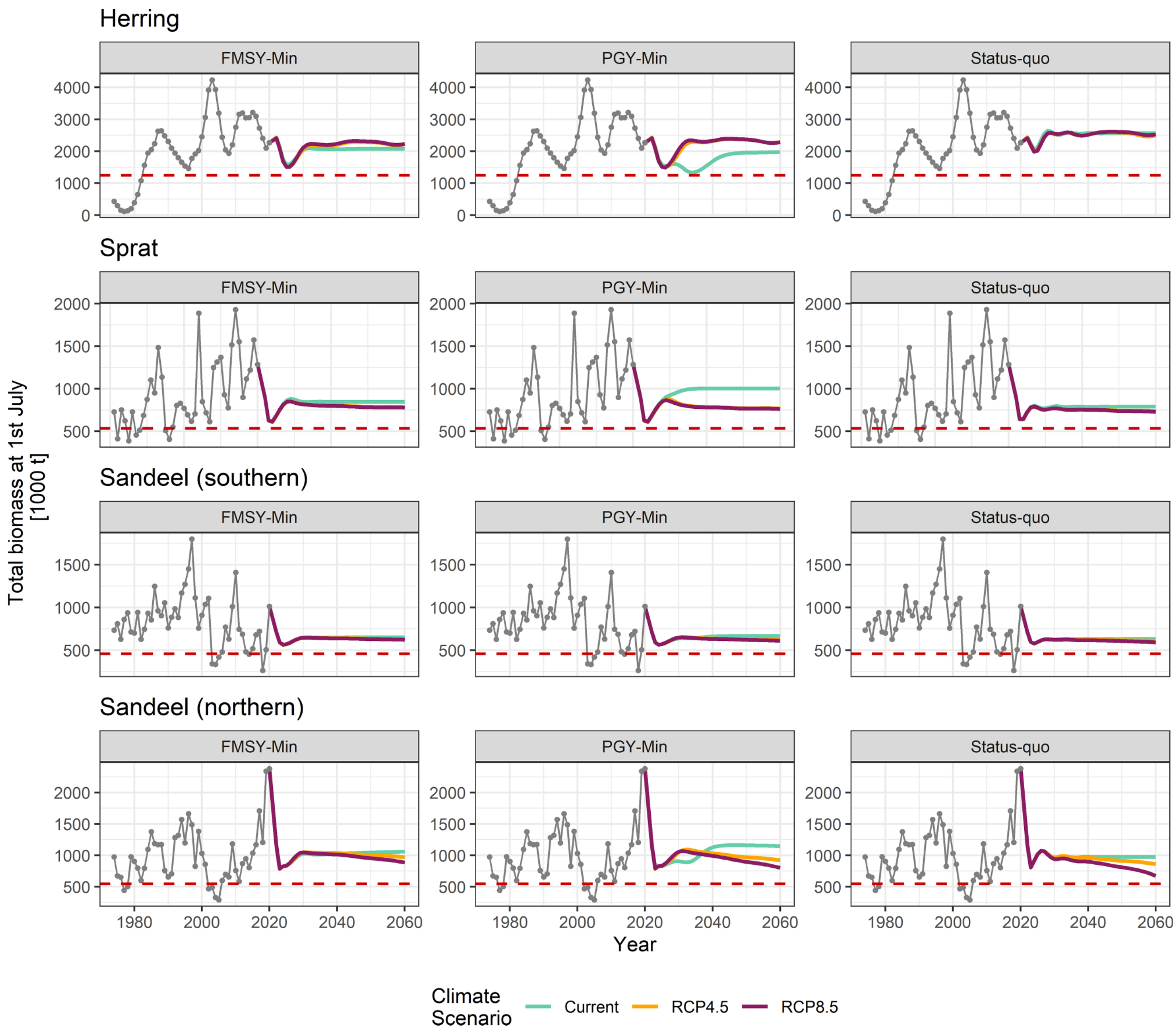

Figure 5 Total biomass (1st of July) trajectories for forage fish predicted by the stochastic multispecies model SMS under each management (status-quo, PGY-Min, and FMSY-Min) and climate (current, RCP4.5, and RCP8.5) scenario. The broken horizontal red line indicates one third of the 95th percentile of historical total biomasses at 1st July used as forage fish indicator threshold. Grey lines with dots show results from the model hindcast, while coloured lines show results from the prediction time period.

MSY approach used for herring in SMS was able to keep stocks relatively stable in the long-term. Changes in predation pressure were buffered by the yield that can be taken from the forage fish stocks under the tested management strategies (Fig. S2 in Annex G of the Supplementary material). Regarding the "one third for the bird" indicator (see Table 3), total stock biomasses of important forage fish for birds (herring, sandeel, and sprat) larger than the 'one-third for the bird' threshold in all scenarios (Fig. 5). This is partly due to the SMS forecast using a deterministic stock–recruitment relationship. Therefore, on average the indicator threshold was not reached. This does not mean that it is not possible to fall below the threshold in one or the other year when uncertainties in stock dynamics are considered.

Under the assumption that Good Environmental Status (GES) for benthic habitats is achieved if <25% of the habitat area are below 0.8 as RBS threshold (see Table 3), the effort by metier in the FMSY-Min and PGY-Min scenarios led to GES for all MSFD broad habitat types in the long-term (Fig. 6). In contrast, even under the strict FMSY-Min scenario, it was not possible to recover all habitat types to GES if 0.9 was used as RBS threshold. High fishing effort of e.g. *Nephrops* otter trawlers in offshore circalittoral mud and other mobile fisheries in circalittoral mud turned out to be the most problematic habitat types despite their relatively low sensitivity. Climate change had hardly any effect on the outcomes because of the assumed constant catchabilities, which leads to similar fishing effort in each of the climate scenarios (see above). In addition, the benthic sensitivity layers behind RBS calculations were not subject to climate change.

Win–win situations and trade-offs

The strict application of the landing obligation in combination with MSY or PGY management leads to many win–win situations (in a sense that indicators codevelop in the desired direction,

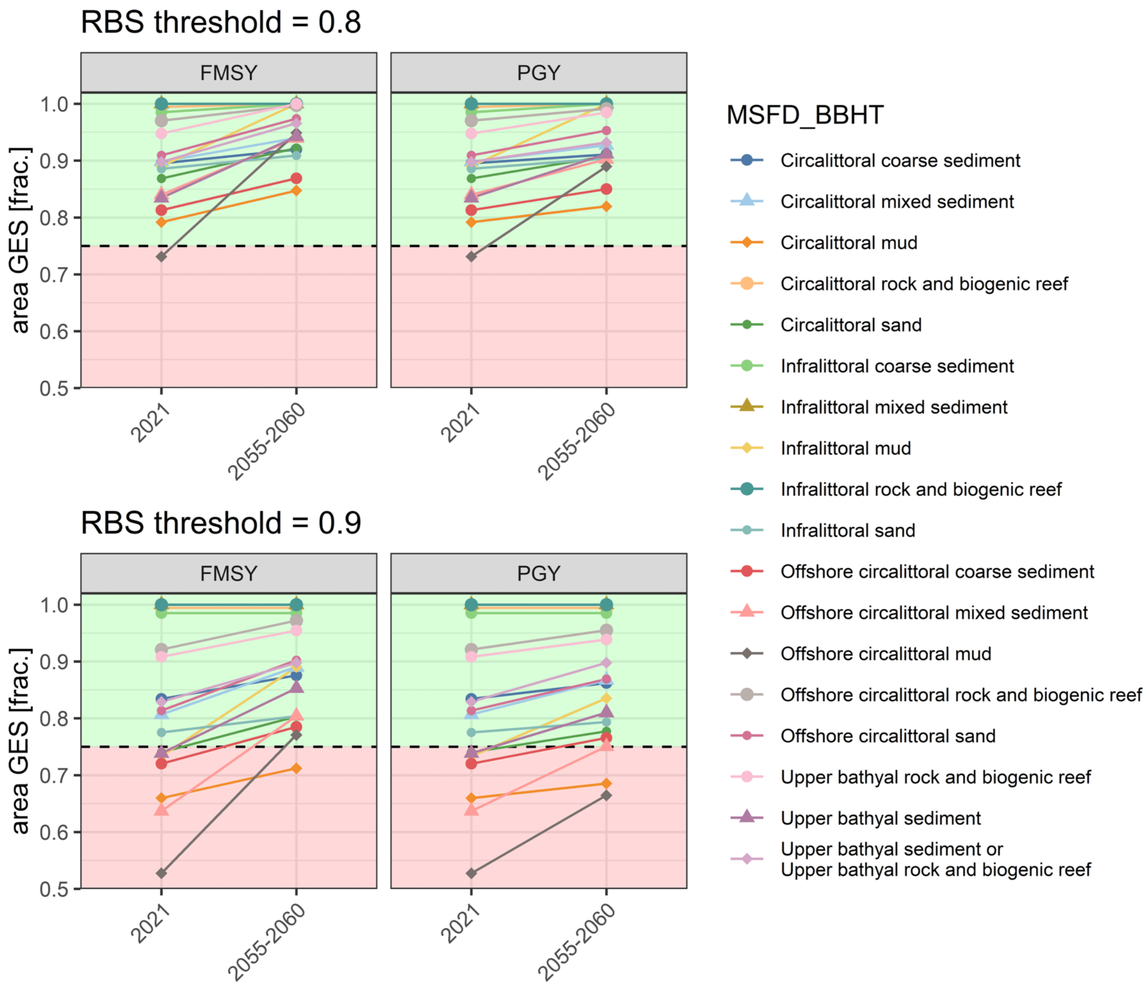

Figure 6 Fraction of each MSFD broad habitat type (BBHT) above a certain RBS threshold. To reach GES >75% of the area of each MSFD BBHT must be above the respective RBS threshold. The 2021 situation also reflects the status-quo effort scenario. For each habitat type, results from the Current, RCP4.5, and RCP8.5 climate scenarios are nearly identical and therefore results are shown for the Current scenario only.

represented by positive correlations in Fig. 7). In comparison to the status-quo effort scenario, this includes also socio-economic indicators highlighting that reducing fishing effort below levels oberved in 2021 is not only beneficial for MSFD-related indicators. Overall, the stronger the positive correlations in Fig. 7, the more straightforward are management decisions. Weaker correlations warrant a careful interpretation (see below) and negative correlations ask for careful considerations between different objectives.

When looking closer between status-quo effort, FMSY-Min and PGY-Min outcomes, the correlations especially between ecological and socio-economic indicators are not linear over the whole range of tested effort/F and the strength of correlations is determined mainly by the difference between the status-quo and the two landing obligation scenarios (Fig. 7). Quite often CFP-related socio-economic indicators performed better under PGY-Min (with effort levels slightly higher compared to FMSY-Min) than under FMSY-Min (Fig. 2), which indicates that there are turning points for fishing effort where win–win situations between CFP- and MSFD-related indicators turn into trade-offs as fishing effort and fishing mortalities decline. PGY-Min performed better in terms of CFP-related indicators, such as landings and catch, revenues, GVA, and number of ports that win >10% in landings, but trading off to some extent against MSFD-related indicators such as slightly higher bycatch of cetaceans, seabirds and pinnipeds, lower proportion of large fish (LFI indicator) and a slightly higher Fogarty index indicating ecosystem overfishing, and swept area ratio (Fig. 7). A typical example for such a change from win–win to a trade-off situation between CFP- and MSFD-related indicators is the correlation between porpoise bycatch and GVA in Fig. 7. The yellow dots (PGY-Min) show a higher GVA than the light blue dots (FMSY-Min) at a certain climate change scenario, but the yellow dots indicate a less desirable bycatch level compared to the light blue dots. However, both scenarios clearly lead to more desirable outcomes compared to the status-quo scenario (red dots) in both dimensions.

Next to trade-offs between the FMSY-Min and PGY-Min scenario, indicators from StrathE2E for bycatch of cetaceans, pinnipeds, and birds as well as the Fogarty index often showed negative correlations (indication of trade-offs) with other indicators. In these cases, the climate change effect under RCP8.5 overruled the benefits from management strategies with lower fishing effort in StrathE2E (Fig. 2). For example, the discards for cetaceans

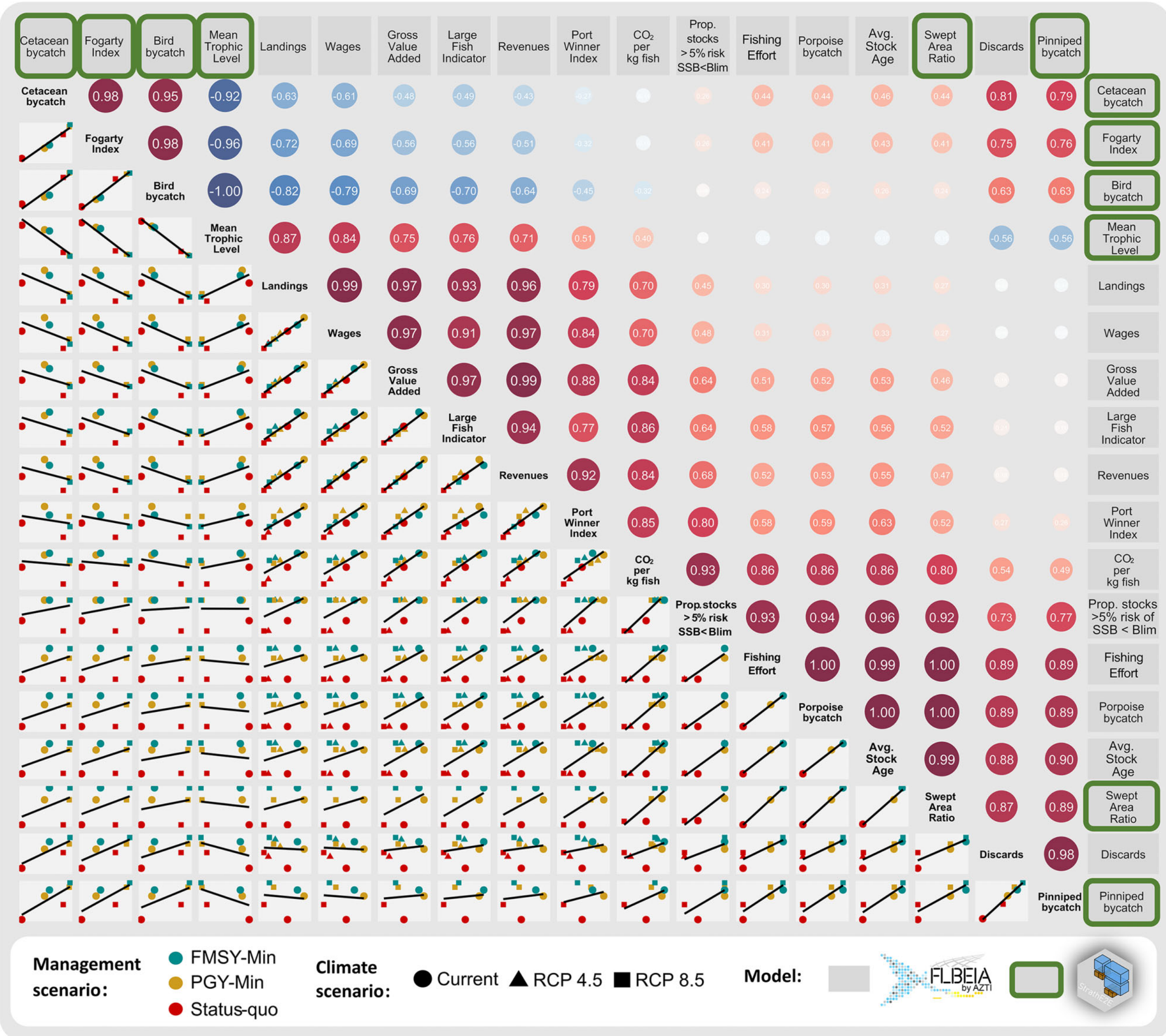

Figure 7 Pairwise correlations between indicators (average 2055–2060) across management and climate change scenarios. Indicators were transformed (multiplication with −1 for indicators where lower values indicate improvement). Therefore, positive correlations indicate win–win situations and negative correlations indicate trade-offs. Order of indicators is determined by the angle of the eigenvectors. See Table 3 for descriptions of indicators.

declined substantially under RCP8.5 and therefore developed in the desired direction although the cause (decline of biomass due to lower productivity under climate change) was not desirable. At the same time, many socio-economic indicators evolved in an undesired direction (declined) under RCP8.5 in FLBEIA compared to the scenario under current climate conditions. This finally leads to a negative correlation between both indicators (Fig. 7), although it is not a trade-off caused by the tested management strategies. FLBEIA does not simulate harbour porpoise biomass dynamically and therefore outcomes for harbour porpoise bycatch are driven by the effort levels in the three management scenarios rather than changes in harbour porpoise biomass (Fig. 2). As many socio-economic indicators benefited from lower fishing effort levels compared to status-quo in FLBEIA, positive correlations are frequent (Fig. 7). This highlights that the interpretation of win–win and trade-offs requires a good understanding of modelled processes and structures, differences between models and the modelled causes of the outcomes.

Discussion

This study demonstrates how available data, analysis, and models may be combined to overcome shortcomings of individual approaches in covering EBFM related aspects, providing a holistic evaluation of management strategies. Results highlighted that even for complex demersal mixed fisheries, the current single-species MSY approach and the landing obligation are potential instruments to achieve multiple EBFM-related objectives or at least advance in the desired direction. The applied models show that a sustainable exploitation of stocks is possible even when considering consequences of future climate change, although negative impacts on socio-economic objectives could only be partly mitigated. A reduction in fishing effort below levels in the status-quo option was beneficial for both ecological and socio-economic indicators, however, only up to a certain point beyond which trade-offs between ecological and socio-economic performance occurred. The main challenge under EBFM remains to find a 'sweet-spot', where both ecological and socio-economic indicators reach acceptable levels at the same time. In this study, management based on a PGY concept within the legal constraints of a landing obligation provided an option for compromise. The example framework for the evaluation of management strategies provides a basis for target-oriented discussions with stakeholders and can help to reveal additional management measures needed to resolve trade-offs preventing current fisheries management from reaching a 'sweet-spot' under EBFM.

Framework structure, indicators, and sources of uncertainty

The combination of available information and tools provided a clear improvement from standard single species/stock MSE simulations to a greater focus on ecological and economic aspects and, to a lesser extent, socio-cultural implications. The approach of linking predicted landings by fleet and metier to specific ports enables more detailed analyses on the development of fishing communities in future studies. The data available from the ICES RDBES allow for the identification of each port's dependencies on certain stocks, and thereby the evaluation of the impact of management strategies on their associated processing industries, land-based infrastructure, and consequences for coastal regions. This study is a first demonstration of linking the output of large-scale bioeconomic fishery models to more regional social and economic impacts on land, a current methodological gap in EBFM research, and missing link between natural and social sciences (Kraan et al. 2025).

All models used were peer reviewed and, in the cases of the North Sea FLBEIA and SMS, the methods and parameterizations were based on benchmarks or key-runs conducted within ICES (ICES IBP MIXFISH 2021, ICES WGSAM 2021). Nevertheless, results indicate substantial parameter uncertainties (Fig. 2) sometimes overlapping to a large degree between scenarios. This highlights that the differences between scenario outcomes were not always significant, and their ranking in relation to indicator outcomes may be subject to change in more extreme cases.

RBS is one of the selected candidate indicators for assessing the habitat quality under MSFD descriptor 6, because of its responsiveness to trawling. RBS was previously used in a special request advice for the European Commission (ICES 2024b), and is pursued as candidate indicator for setting quality thresholds for seafloor habitats under the MSFD (ICES 2025a,b). This study used RBS as main benthic indicator because of its potential as European-wide risk assessment framework (Hiddink et al. 2026), though we acknowledge the recommendation of using both an indicator relying on biological traits, and a diversity-based indicator (Van Dendere et al. 2024, Raicevich et al. 2025). The study provided a proof of concept for the integration of benthic indicators with mixed fisheries assessments, while integration of benthic indicators and their thresholds is ongoing.

Parameter estimates for RBS were deterministically inferred for the assessed metiers, although we recognize that Monte Carlo approaches similar to Khedri et al. (2025) would be useful to quantify uncertainties for input parameters and metiers. Under the equilibrium assumption of the logistic population dynamics model, RBS scales linearly with fishing intensity, a constant metier-specific depletion ratio and the spatially resolved recovery rates (Ellis et al. 2014, Pitcher et al. 2016). RBS was estimated for the tested scenarios under static fishing distribution patterns observed in 2021, which facilitated the integration with modelling results from the other components of the framework. The integration with other models allowed us to assess trade-offs with total landings and GVA as was presented in the special EU advice request to ICES (ICES 2024b), but to also evaluate effects on other ecosystem indicators and stock-specific changes under climate and fisheries management scenarios. Future studies may focus more on the impact of changes in the spatial distribution of fishing grounds due to MPAs, offshore windfarms and closed areas by using spatially explicit modelling tools next to RBS analyses with altered fishing distribution patterns.

The short-cut MSE setup in FLBEIA focused on uncertainties originating from the environment propagated through the stock–recruitment relationship as well as other biological parameters like growth or maturity. This may potentially underrepresents sources of uncertainty (e.g. in the observation submodel or the assessment part) (e.g. Punt et al. 2014). Since uncertainties can be additive, this has the potential to influence some of the indicator outcomes, particularly whether the 5% risk threshold to fall below B_{lim} is reached for certain stocks. Linking assessment models and forecasts within the MSE loop (i.e. full feedback loop) would have further merits, however, run-time of each iteration would have increased drastically given the many stocks implemented in the North Sea FLBEIA model. The example framework does also not follow approaches where e.g. complex ecosystem models are used as operating model trying to cover all relevant aspects in one model (e.g. Lucey et al. 2021). The linking of existing models and analysis via effort or catch trajectories allowed the reuse of available approaches and led to a manageable complexity with a focus on the strength of each individual approach. As drawback, the linking of models was sometimes challenging because of different aggregation levels for fleets and metiers and certain behavior/emergent properties may have been overlooked compared to an approach integrating all processes into one complex operating model like Atlantis (Perryman et al. 2023).

The structural uncertainty was sometimes high between models as evidenced in the differences between FLBEIA and StrathE2E caused by a constant (FLBEIA) or dynamic (StrathE2E) treatment of marine mammal biomass under climate change. The bottom-up forcing in StrathE2E via changes in nutrient cycling impacting all guilds at the same time was profoundly different from the top-down focused parameterizations of FLBEIA and SMS, although in these models climate change effects on the productivity of stocks has been incorporated via EMSRRs. Different model assumptions like steady-state conditions in the beginning (StrathE2E) or not (FLBEIA, SMS) can also lead to differences in predicted trajectories, although the ranking of management scenarios was overall robust in terms of overall reactions to different effort levels in MSFD and global indicators (see Fig. 2). Such structural uncertainties demonstrate the strength of linking different models as this uncovered uncertainty is not visible in a one model MSE approach.

The study focuses on 'traditional' commercially important species. Stakeholders like the North Sea Advisory Council (NSAC) were very interested during consultations (Travers-Trolet et al. 2025) in the question whether 'new' resources such as squid and cuttlefish (Sulanke et al. 2025) can at least partially compensate observed and predicted losses from 'traditional' species. The appearance of new species could also lead to even more losses if they act as predators of commercially important fish species (Oesterwind and Piatkowski 2023). However, this is difficult to predict, particularly because assessments are currently missing for such species. Actual revenues in the North Sea region still originate mainly from the boreal and lusitanean species already included in the models (e.g. sole, whiting, and sprat; Travers-Trolet et al. 2025). However, the proportion of e.g. cephalopods in revenues is increasing in the North Sea area (2023: ∼1% in Skagerrak and Kattegat, 3% in the North Sea, and 20% in the English Channel; Travers-Trolet et al. 2025) and an update of the analyses may be needed once the magnitude of catch levels that can be sustained by such 'new' resources becomes evident.

From a computational and logistic perspective, implementing, conditioning, and running three different models and additional analyses as done for this study, would be expensive if done from scratch. Here lies the strength of the applied framework. By making this a team-effort and building on already existing models each developed by their respective experts and institutes, one could save time and resources to answer EBFM-related questions.

However, using alternative models or parameterizations in the framework may change results to some extent because of structural and parameter uncertainties. For example, the assumption of constant catchabilities in FLBEIA is used by default in ICES (ICES IBP MIXFISH 2021). However, alternative assumptions would change relationships between effort, catch, and fishing mortality to some extent. Another example is the use of a Holling Type II functional feeding response in SMS determining the relationship between prey abundance and predation mortality (ICES WGSAM 2021). Therefore, to achieve more robust consclusions, we analysed the scenarios mainly relative to each other for strategic management and not in absolute terms. Organisations like ICES decide in peer review in benchmark type settings on the exact parameterizations and type of models to be used together with stakeholders. Processes applied in the Irish Sea with a series of workshops (e.g. ICES WKIrish5 2019) or in the USA (Townsend et al. 2019) may serve as illustrative examples. Similarly, workshops for benthic impacts have been held in interaction with stakeholders (e.g. ICES WKD6STAKE 2024), although these were focused on management of benthic impacts only, and did not include the integration with fisheries objectives such as reaching MSY.

Implications for fisheries management in the North Sea

In the past two decades, overall fishing pressure has been reduced towards levels, which are on average compatible with MSY (STECF 2025). However, nearly one-third of the stocks remained overfished in relation to F_{MSY} in 2023. Results from this study suggest that the effort levels used as status-quo scenario (from year 2021) are suboptimal. Lowering fishing effort compared to the status-quo option through the strict implementation of MSY-related advice rules in combination with a landing obligation ensured not only a sustainable exploitation of stocks, but had benefits for MSFD-related and global indicators like CO_2 footprints and improved socio-economic indicators to a certain degree. Therefore, management based on MSY in combination with measures like the landing obligation may have to be reinvestigated in an EBFM context. Choke effects (fishing fleets stop when their first quota is exhausted) under the landing obligation were one of the main reasons why fishing effort declined in the scenarios (∼−50% under the FMSY-Min scenario; Fig. 2) compared to the status-quo option. In the short-term, such choke effects are a serious concern for fishers, because they lead to substantial losses in yield in the first years (Kühn et al. 2023, Prellezo and Villasante 2022). This loss in yield is hypothesized as reason for noncompliance of fishers with the landing obligation, and is shown by the relatively unchanged levels of discard rates since the implementation of the landing obligation (Davie et al. 2025). Only in the long-term, a strict implementation of the landing obligation under the assumption of fisher compliance and sufficient control led to many win–win situations under EBFM as simulated in this study. Fishing on average well below F_{MSY} had its merits for improving socio-economic indicators, but only up to a certain point (PGY-Min more desirable than FMSY-Min in this aspect). To reach a situation where stocks are fished closer to F_{MSY} and to lower choke effects under the landing obligation, species and size selectivity need to be improved via technical measures [e.g. innovative gears, spatial (real-time) closures]. Lowering choke effects (i.e. in the short-term) would be beneficial for socio-economic objectives, however, it also means higher fishing effort levels in turn negatively influencing the status of MSFD-related indicators as long as technical measures cannot reduce e.g. the bycatch of sensitive species or the impact on benthic habitats at the same time. This highlights direct and indirect effects on the EBFM trade-off space under current fishing patterns. It also shows the limits of what changes in overall effort levels or fishing mortalities can do to resolve trade-offs. Either technical measures are able to improve fishing patterns and lower the impact of fishing on ecosystem components or political decisions are needed to reach consensus among the interests of different stakeholder groups. Like in this study, combining available data, analyses and models is an important step to allow for informed decisions by managers. While this study deals with the overall challenges of EBFM in the North Sea, detailed results from e.g. FLBEIA would also allow more specific discussions on certain stock and fishing metier combinations (ICES WGMIXFISH 2025).

Climate change was identified as important external factor influencing the fate of fish stocks, marine mammals, ecological indictors like LFI as well socio-economic indicators. The North Sea is rapidly warming (Mohamed et al. 2025) and substantial changes in the food web have been observed in terms of species composition and spatial distribution of stocks (Perry et al. 2005, Dulvy et al. 2008, Rutterford et al. 2023, Gordó-Vilaseca et al. 2024). Cold-temperate species with the North Sea defining the southern limit of their distribution area (e.g. cod and saithe) were negatively impacted, whereas warm-temperate stocks [e.g. sprat, northern hake (*Merluccius merluccius*)] may benefit (Kjesbu et al. 2021). Observed and predicted decreases in primary production under climate change (e.g. Kwiatkowski et al. 2020, Sandø et al. 2024, Silsbe et al. 2025; projections from StrathE2E in this study) highlight concerns about the productivity of marine systems in general. Therefore, climate change may lead to new or worsened choke effects because of shifts in spatial distributions and changes in species' productivity. Fisheries management must adapt expectations for what can be sustainably fished and what economic and social gains can be expected under the different climate change trajectories. While yield is likely to decrease, fisheries management can try to improve the resilience of stocks by lowering fishing pressure (Bastardie et al. 2023). Nevertheless, biomass reference points or other thresholds (e.g. LFI) may have to be adapted to avoid unachievable goals, which can weaken the credibility of the management system and potentially lead to less commitment (Gary et al. 2017). Overall, climate change was an important driver in the North Sea that has to be considered from assessments and reference points up to governance structures to be able to deal with a fast-changing environment.

Setting thresholds and limits is an ongoing task for many MSFD indicators (European Commission 2022). While there are some targets and limits defined by e.g. OSPAR (e.g. bycatch of seals and harbour porpoise in the North Sea; Taylor et al. 2023), the thresholds defining GES for sea floor integrity or food webs are still under debate. In this study the 'one-third for the birds'-indicator (Cury et al. 2011) was chosen as potential candidate to ensure sufficient forage fish biomass. The LFI is another potential food web indicator. For seafloor integrity, the approach developed in ICES based on RBS (ICES 2024b, ICES WKBENTH2 2022) has been followed, but will require updates for implementation using ongoing developments for setting quality thresholds for seafloor habitats under the MSFD (ICES 2025a,b). The fate of demersal mixed fisheries will be influenced by RBS thresholds to a larger extent and e.g. a threshold of 0.9 for RBS would likely lead to a need for additional technical measures (e.g. closed areas) to protect problematic benthic habitats, such as offshore circalittoral mud identified in this study. Otherwise, model results indicate that even major effort reductions as simulated in the FMSY-Min scenario could be insufficient under current fishing patterns to reach GES for all habitats under such a threshold. However, stronger effort reductions than in the FMSY-Min scenario would increase the trade-offs with socio-economic indicators according to model results. This example highlights the ability of the example framework to fuel informed discussions among stakeholders about necessary management decisions not only on management strategies, but also the other way around when evaluating the impact of decisions on MSFD indicators and thresholds on the fishing industry.

Outlook

This study demonstrated how science can inform managers and stakeholders on win–win and trade-offs situations under EBFM, although with certain parameter and structural uncertainties. In the current advice system in ICES as main advisory body in the North Sea region, the different aspects of EBFM are often still treated in isolation. While there are ecosystem overviews (e.g. ICES 2024a), fisheries overviews including mixed fisheries considerations (e.g. ICES 2025c), special request advice on MSFD implementation (e.g. ICES 2024b) next to recurrent advice on single stock fishing opportunities (e.g. ICES 2023a), the integration of these different advice products and aspects and their linkage to management objectives and actions within and across legal mandates and management bodies remains a challenge, not only in ICES, but worldwide (Harvey et al. 2025). This study provides an example of how improved integration of EBFM aspects may be possible when evaluating EBFM-ready management strategies, but also when setting up an EBFM indicator framework for recurrent advice. It should be mentioned that establishing links between data, analyses, and models was a challenge. Each model and data product has been developed independently. This makes it more difficult to derive necessary linkages and increases the need for assumptions to overcome e.g. different aggregation levels (e.g. between so called Benthis metiers used to derive RBS and a much more disaggregated fleet and metier resolution in FLBEIA) . The development and standardization of data products and models in a more integrated approach with EBFM as explicit objective would be beneficial to support a holistic evaluation of management strategies in the future. Model ensembles may also be a way forward to better cover the extent of structural and parameter uncertainties, but also to exploit the strength of different modelling approaches in a more objective way (Spence et al. 2023).

Next to science, legal and political frameworks often treat different aspects of EBFM in isolation. For example, implementation of the CFP occurs at EU-level, while MSFD is implemented at national level. Both are two distinct regulations that are harmonized with each other by definition. However, results of this study indicate potential trade-offs between CFP and MSFD objectives when reducing fishing effort beyond a certain level. The next step for policy makers would thus be to develop an EBFM governance framework that allows for a transdisciplinary platform where win–win and tradeoff situations can be considered and discussed among stakeholders to find consensus. Like demonstrated in this study, scenario analyses and a more integrated advice may provide an important input for discussions and informed political decisions.

The results provide evidence that the key to successful implementation of EBFM is efficient fishery management maximizing wanted CPUE, while reducing unwanted bycatch and keeping the environmental footprint to an acceptable low level without too severe social and economic hardships. Technical measures are important elements for improvements in the EBFM trade-off space. Reasons for the current low uptake of e.g. innovative gears within the ICES area are not well understood and can be related to political, economic, social, technological, environmental, and legal factors (ICES 2023b). In addition to innovative gears, the prohibition of specific fishing techniques (e.g. bottom trawling) in fit-for-purpose areas can limit e.g. juvenile catches, the risk of incidental bycatch, or the degradation of specific benthic habitats (Bastardie et al. 2025). However, redistributing fishing effort without reducing overall effort and catches may negate intended overall (inside and outside MPAs) benefits or can even be overall damaging at least in the short-term (Püts et al. 2023, Bastardie et al. 2025). Short-term economic losses on specific fishing fleets and uncertain gains in the long-term are further potential downsides. Overall, this highlights that a better understanding of the impacts of technical measure solutions is needed. This study focused on benefits that can be achieved by scaling fishing pressure and effort based on certain harvest control rules under current observed fishing patterns and fishing impact on the ecosystem. The complementary optimization and evaluation of fishing patterns and impacts via technical measures is a key priority for future extensions of the example framework provided in this study.

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Supplementary material

Supplementary material is available at *ICES Journal of Marine Science* online.

Conflict of interest

The authors have no conflicts of interest to declare.

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Data availability

The code used for the analyses and model outputs can be made available on request.

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