Received: 30 November 2022 | Revised: 17 March 2023 | Accepted: 6 April 2023

DOI: 10.1111/fme.12629

ARTICLE

Fisheries Management and Ecology
WILEY

Adding to the mix – Challenges of mixed-fisheries management in the North Sea under climate change and technical interactions

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Funding information
Horizon 2020 Framework Programme, Grant/Award Number: 101000318 and 773713

Abstract

Technical interactions (multiple fleets fishing multiple species with various gears, as either target or bycatch), bycatch regulations through a landing obligation, and biological and economic effects of climate change, affecting fisheries yield and profits, provide a challenge for demersal mixed fisheries of the North Sea. A multi-stock, multi-fleet, bioeconomic model was used to understand management options under these combined influences. Scenarios considered climate change effects on recruitment of three main gadoid stocks (cod – *Gadus morhua*, saithe – *Pollachius virens*, whiting – *Merlangius merlangus*), possible future developments of fuel and fish prices, and strict implementation of a landing obligation. The latter leads to decreased yield and profits in the short term due to increased choke effects, mainly of North Sea cod, being influenced by climate-induced productivity changes. Allowing fishing above F_{MSY}, but within sustainable limits, or limiting year-to-year quota changes, could help buffer initial losses at the expense of decreased profits in the mid- to long-term. Economic performance of individual fleets was linked to their main target's stock status, cost structure, and fuel and fish prices. The results highlight a need to consider both biological and economic consequences of climate change in the management of mixed fisheries.

KEYWORDS
bioeconomic model, climate change, EU landing obligation, FLBEIA, Pretty Good Yield

1 | INTRODUCTION

The majority of fisheries worldwide are mixed fisheries, where multiple species are caught together by multiple fleets, summarised under the term "technical interactions" (Dolder et al., 2018; Ulrich et al., 2011). Managing these fisheries based on advice designed for single species is insufficient, as sustainable harvesting levels for one species could lead to overharvesting of other bycaught species. Still, management at the single-species level is the predominant strategy with the goal of acquiring maximum sustainable yield (MSY) through effort limitation or quota management. There is growing interest in creating management measures to try and deal with the "mixed-fisheries problem" (Briton et al., 2021; Dolder et al., 2018; Graham et al., 2007; Ulrich et al., 2017), as single species management cannot ensure the sustainable exploitation of all stocks involved. Climate change creates additional pressure through changes in stock productivity and spatial distribution, affecting yield and economic viability of fishers (Lam et al., 2016; Payne et al., 2021; Sumaila et al., 2011) that need to be taken into account when developing sustainable management plans for mixed fisheries (Lagarde et al., 2018).

The North Sea demersal fisheries are a representative example for mixed fisheries where a large variety of target and bycatch species are caught together. A wide range of stock status, influencing ranges in quotas and associated fishing effort, presents an additional challenge for managing demersal mixed fisheries in the North Sea. According to the latest assessment of the International Council for Exploration of the Sea (ICES, 2021a), some target stocks are outside biological safe limits (North Sea cod – *Gadus morhua* and saithe – *Pollachius virens*), whereas others are well above reference points (e.g. haddock – *Melanogrammus aeglefinus*, whiting – *Merlangius merlangus*) or were even at an all-time high for several subsequent years after 2010 (North Sea plaice – *Pleuronectes platessa*). The main management tool in the North Sea (next to technical measures like minimum landing sizes, design and use of gears, mesh size regulations and spatial measures) for all species controlled by a management plan are Total Allowable Catches (TACs), distributed using quotas among EU member states, the United Kingdom and Norway. Quotas became particularly crucial after full implementation of the landing obligation in 2019.

With the reform of the EU Common Fisheries Policy (CFP), the aim of the landing obligation was to create incentives to minimise, in particular, discarding of unwanted catches. Under the landing obligation, fishers need to land all regulated species, except those with exemptions, and count them against their quota, thereby leading to so-called choke effects (fisheries are forced to stop fishing once the first quota is exhausted) that have serious influence on fleet economics. This is one reason why compliance with the landing obligation is not perfect. Over recent years, the North Sea cod stock has consistently been the main choke species. Low TACs for cod and resulting cod avoidance measures largely determine current fisheries management in North Sea demersal mixed fisheries. To tackle this problem, the EU developed Multiannual Plans for management of mixed fisheries, based on utilisation of F_{MSY} ranges corresponding to F values around F_{MSY} leading to a pretty good yield (PGY). If stocks are healthy (SSB ≥ MSY $B_{trigger}$), fishing mortalities above F_{MSY} might be allowed, thereby creating more flexibility when setting TACs. Similarly, a long history in the fishing industry demands higher year-to-year stability in advised quotas, to reduce variability in landings and generate a stable profit (Cooke, 1999; Patterson & Résimont, 2007; Shephard, 1990).

Climate-induced changes in fish stock productivity represent an additional challenge for management and profitability of mixed fisheries. Changes in temperature and primary and secondary productivity within the North Sea coincided with decreased recruitment of stocks (Capuzzo et al., 2018). In a global analysis of historical temperature influences on productivity of 124 species in 38 ecoregions, the North Sea was an ecoregion with one of the strongest negative temperature effects, particularly on stocks from Gadidae and Ammodytidae families (Free et al., 2019). In particular, North Sea cod suffered from reduced recruitment since the late 1990s, which was linked to direct and indirect effects of elevated temperatures within the North Sea (Akimova et al., 2016; Beaugrand et al., 2003; Beaugrand & Kirby, 2010; Kühn et al., 2021; Nicolas et al., 2014; Olsen et al., 2011; Sguotti et al., 2020).

Integrating climate effects into fisheries management can provide necessary responsiveness to react to changes in productivity with the potential to allow sustainable harvesting even under negative effects of climate change (Bastardie et al., 2022). For North Sea cod, both mismanagement and climate change-related factors were responsible for the current low productivity regime (Brander, 2018; Engelhard et al., 2014). On a global scale, simulations showed that adapted fisheries management alone could successfully deal with productivity and distribution changes of stocks under climate change (Gaines et al., 2018). However, the authors assumed that all species can be fished at F_{MSY} sustainably, effectively ignoring situations, where stocks with differing productivity are caught together in a mixed fishery, like in the North Sea.

Parallel to changing productivity of stocks, development of international markets has drastically shaped the fishery. Future development of fish and fuel prices are both particularly important to profitability of a given fishery and are difficult to predict in the future. Fuel prices make up a substantial amount of variable costs, and the amount of fuel used is mainly dependent on technical characteristics of vessels and gears including their deployment (i.e. fishing speed), but also environmental conditions, target species, stock biomass and expertise of fishers (Parker et al., 2018; Parker & Tyedmers, 2015). Demersal trawl operations require particularly high fuel consumption compared to static gear or pelagic fishing operations.

This high dependency on the global oil market was felt by fisheries during past disruptions of oil prices during the Arab Oil Embargo in the 1970s and the 2007–2008 economic crisis (Cheilari et al., 2013). The future path of climate change and respective mitigation strategies, such as a tax on fossil fuels (Roll et al., 2022), reductions in fuel subsidies (Carvalho & Guillen, 2021), or shortage in fossil fuels, will potentially increase fuel costs for fishers and largely determine their economic performance. Similarly, future fish price development will be driven by multiple effects, such as dependency on international markets (Dahl & Oglend, 2014; Tveterås et al., 2012), consumer preferences for more sustainable or regionally caught fish (Claret et al., 2012; Menozzi et al., 2020), the role of the fishery in contributing to food security (Cojocaru et al., 2022; Rice & Garcia, 2011) and competition of wild fisheries with increasingly important aquaculture (Kobayashi et al., 2015).

With the combination of mixed-fisheries management under the landing obligation, faced with biological and economic effects of climate change, multiple future directions emerge that can be addressed in a systematic fashion through numerical simulations while concentrating on a few informative scenarios. Mixed-fisheries models have been implemented for the North Sea region, using the FLR Bio-Economic Impact Assessment (FLBEIA) model (Garcia et al., 2017) and Fleet and Fishery Forecast (Fcube) model (Ulrich et al., 2011) software, that incorporate technical interactions between stocks. However, climate change effects were often ignored or implemented through truncation of stock–recruit relationships to reflect current productivity (see Haltuch et al. (2019) for an overview), especially in single species management strategy evaluations (MSEs). Attempts to incorporate climatic effects into MSEs or assessment forecasts concentrate predominantly on biological effects on single stocks (Koul et al., 2021) or within a mixed-fisheries context (Lagarde et al., 2018), but rarely considered both biological and economic implications in a mixed-fisheries context (Hamon et al., 2021).

We extended the bioeconomic mixed-fisheries model FLBEIA for the North Sea to evaluate effects of climate change on recruitment of commercially important gadoids (cod, whiting and saithe) under two Representative Concentration Pathways (RCPs) describing future climate change, including a moderate (RCP4.5) and a high emission (RCP8.5) scenario, combined with fish and fuel price developments up to 2060. We evaluated the effects of management under a strict implementation of the landing obligation and simulated various harvest control rules (HCRs) within the PGY framework and an adapted HCR that limits year-to-year TAC changes for their potential to relax constraints imposed by the landing obligation, climate change and future economic developments. Because the exact path climate change and economic developments take is rather uncertain, we concentrate on simulating "possible futures" instead of accurate predictions – interpreting results in relative terms to derive general lessons for the demersal mixed fisheries of the North Sea.

2 | MATERIALS AND METHODS

2.1 | FLBEIA model of the North Sea demersal mixed fishery

2.1.1 | General model description

The mixed-fisheries model of the North Sea was defined using the procedure of WGMIXFISH (ICES, 2021a, 2022a), an ICES working group taking into account the consequences of technical interactions in multi-stock, multi-gear fisheries to inform management and advice. The model was expanded to include several additional stocks (European Agency for Small and Medium-sized Enterprises, 2021). The modelling framework is FLBEIA (Garcia et al., 2017), including 42 fleets (137 métiers, a group of fishing operations targeting similar species using similar gears in a similar area) and 24 stocks for North Sea mixed fisheries (Table 1). Stock dynamics were either age-based, biomass-based or fixed (no biological dynamics modelled).

2.1.2 | Model conditioning relying on the WGMIXFISH procedure

The model was conditioned with historical data up to 2018, to forecast future conditions thereafter. Stocks dynamics were based on assessments in 2019 (ICES, 2019), not including disruptions during the Covid-19 pandemic, which were hard to foresee ("black swan event") and considered non-representative for long-term dynamics (FAO, 2020; McNally, 2020; Mumtaz et al., 2021; Pititto et al., 2021). Also, the effects of the recent energy crisis were not considered, because data were not available. Fleets and métiers were parameterised based on work conducted during WGMIXFISH, which was valuable for defining fleets because it had information on vessel length, an important attribute of fishery segments in terms of their economic characteristics. Fleets were defined based on their country of origin (Belgium – BE, Denmark – DK, England – EN, France – FR, Germany – GE, the Netherlands – NL, Scotland – SC, Sweden – SW and Other – OTH), main gear employed (e.g. Static gear, Pelagic trawls, Danish seine, Otter trawl and Beam trawl) and vessel length (<10, 10–24, 24–40 and >40 m; Table S1). Within each fleet, further segmentation of métiers was based on main fishing operations, including gear (mesh size) and geographic area (ICES areas 3a20, 4a–c, 6a and 7d). Each métier was further parameterised in terms of catchability of each stock, which were used to predict changes in catch under changing effort and stock sizes (for further details, see Garcia et al. (2017) and Supplement T1 in the Appendix S1).

2.2 | Environmentally mediated stock recruitment relationships (EMSRRs)

2.2.1 | Framework for fitting EMSRRs

Environmentally mediated stock recruitment relationships for Cod (COD-NS), whiting (WHG-NS) and saithe (POK) were built using the framework of Kühn et al. (2021). The framework filters out meaningful environmental time series from large spatiotemporal environmental datasets and links these to recruitment in a semi-automatic way by simultaneously controlling for model fit and parsimony.

2.2.2 | Climate sensitivity of gadoids

We focused on the three gadoids because they exhibit sensitivities to climate change (e.g. negative effect of rising sea temperature on recruitment of North Sea cod; Akimova et al., 2016; Koul et al., 2021; Kühn et al., 2021; Olsen et al., 2011), although other stocks not considered here might be affected too. Haddock, another commercially important gadoid, was not modelled using EMSRRs due to its sporadic large recruitment events that could not be explained by environmental variables included in this study. For other North Sea gadoids, such as whiting and saithe, environmental influences on recruitment were unclear, although temperature may be a driver of productivity changes in these two stocks (Free et al., 2019). Correlative studies of temperature on whiting recruitment were inconclusive, with negative (Dippner, 1997), positive (Cook & Heath, 2005; Svendsen & Magnusson, 1992) and no effects (Lynam & Brierley, 2007) detected. For saithe, a positive effect of temperature (Cook & Heath, 2005;

TABLE 1 Stocks included in the North Sea mixed-fishery model: Scientific name – binominal nomenclature showing genus and species, stock code – ICES stock code, FAO – species code used by the FAO, ICES data category – determines the type of data and assessment available for the stock (1 – data rich with quantitative assessment, 2 – qualitative assessment, 3 – stocks, for which survey-based indices and assessment are available, 4 – stocks, for which only commercial catch data are available, 5 – data poor stocks, where only landings data are available, 6 – neglectable stocks caught primarily as bycatch), Stock dynamics – either age-based, biomass-based or fixed (no biological dynamics modelled), TAC – if stock is actively managed via a TAC, Extension – indicating for which stock an environmentally mediated stock recruitment relationship (EMSRR) was included, Model code – the stock code abbreviation used in the model.

Scientific name	ICES stock code	FAO	Common name	ICES data category	Stock dynamics	TAC	Extension	Model code
Gadus morhua	cod.27.47d20	COD	cod	1	Age	YES	EMSRR	COD-NS
Melanogrammus aeglefinus	had.27.46a20	HAD	haddock	1	Age	YES	–	HAD
Pollachius virens	pok.27.3a46	POK	saithe	1	Age	YES	EMSRR	POK
Solea solea	sol.27.4	SOL	sole	1	Age	YES	–	SOL-NS
Pleuronectes platessa	ple.27.420, ple.27.7d	PLE	plaice	1	Age	YES	–	PLE-NS PLE-EC
Merlangius merlangus	whg.27.47d	WHG	whiting	1	Age	YES	EMSRR	WHG-NS
Nephrops norvegicus	nep.fu.5, nep.fu.6, nep.fu.7, nep.fu.8 nep.fu.9 nep.fu.10 nep.fu.32 nep.fu.33 nep.fu.34, nep-IVnotFU	NEP	Norway lobster	Cat. 1 for FUs 6–9, Cat. 4 for other FUs	Fixed	YES	–	NEP5 NEP6 NEP7 NEP8 NEP9 NEP10 NEP32 NEP33 NEP34 NEPOTH-NS
Scophthalmus maximus	tur.27.4	TUR	turbot	1	Age	YES	–	TUR
Scophthalmus rhombus	bll.27.3a47de	BLL	brill	3	Biomass	YES	–	BLL
Glyptocephalus cynoglossus	wit.27.3a47d	WIT	witch flounder	1	Age	YES	–	WIT
Limanda limanda	dab.27.3a4	DAB	dab	3	Biomass	NO	–	DAB
Lophius budegassa, Lophius piscatorius	ang.27.3a46	ANF	anglerfish	3	Biomass	YES	–	ANF
Microstomus kitt	lem.27.3a47d	LEM	lemon sole	3	Biomass	YES	–	LEM
Molva molva	lin.27.3a4a6–91214	LIN	ling	3	Biomass	YES	–	LIN

Dippner, 1997; Svendsen et al., 1991) was no longer evident after addition of more recent data (Ottersen et al., 2013). For both stocks, currents may play an important effect on recruitment (Pécuchet et al., 2015; Pepin, 1990; Svendsen et al., 1991).

2.2.3 | Environmental datasets

Environmental data encompassed spatiotemporal fields of Sea Surface Temperature (SST) and salinity data from the AHOI dataset (Núñez-Riboni & Akimova, 2015) and eastward (u) and northward (v) velocity of surface current data from ORAS5 (Zuo et al., 2019) for the North Sea. These three environmental datasets were chosen due to their good spatial and temporal coverage to serve as proxies for changes in lower trophic levels (e.g. through match–mismatch dynamics; Asch et al., 2019; Beaugrand et al., 2003; Kristiansen et al., 2011), which are more limited in availability and spatiotemporal coverage.

2.2.4 | Pre-processing of environmental covariates and model fitting

Time series from seasonally averaged (DJF – December–January–February, MAM – March–April–May, JJA – June–July–August, SON – September–October–November) and annual (YR) spatiotemporal environmental fields were extracted using EOF analysis (i.e. temporal principal components, PCs), and significant PC scores were selected by the broken stick criterion (Table S2). The pool of potential covariates for each stock was passed to a multi-objective genetic search algorithm (NSGA-II; Deb et al., 2002) that allowed for identification of significant covariates by repeated ($n = 30$) fivefold cross-validation. The search was guided by an adapted fitness function ($2*RMSE_{test} - RMSE_{train}$) to identify models that performed equally well on training and test data sets, to act as an additional form of regularisation, similar to the idea a learning curve (Perlich, 2010).

Different types of EMSRR models for each stock (Ricker, Cushing, segmented regression) were compared using Pareto fronts (the output of the NSGA-II search, Figure S1a). A best compromise solution from the Pareto front, which balances model complexity and fit, was chosen using a twofold criterion. First, solutions should be significantly better than a solution of equal complexity, where the last added covariate was exchanged with a random noise variable. Second, solutions should be significantly better than a solution of lower complexity in the Pareto front, or the lower-order solution is preferred. Significance was tested using Monte Carlo simulations (2000 runs, different seed values for each simulation), and a solution was chosen when the median performance was outside the 95% confidence band of simulations with a random covariate (Figure S1b). Finalised EMSRRs were incorporated into FLBEIA using a framework introduced in the 2022 WGMIXFISH methods meeting (ICES, 2022b).

All other category 1 stocks were fit with segmented regression stock–recruitment relationships (SRRs) using the same span of historical years defined by respective ICES assessment benchmarks, and without additional environmental covariates. To account for uncertainty in the SRR, additional log-normal distributed noise was added to recruitment predictions with standard deviation derived from remaining residuals of the SRR. Because Haddock recruitment was characterised by sporadic large recruitment events that would be overestimated using a log-normal distribution, noise was generated from a truncated log-normal distribution that limited recruitment variability to 95% quantiles of the log-normal distribution.

2.3 | Economic parameterisation

2.3.1 | Preparation of the economic input data

Economic variables for fleets and métiers were defined using data available from the Scientific, Technical and Economic Committee for Fisheries (STECF), which are reported in the Annual Economic Report (AER; STECF, 2019). This data release included economic information (e.g. costs, revenue) for different fishing segments during 2009–2016 for FAO Area 27. Simulations used average values from 2014 to 2016 to condition economic parameters in the FLBEIA model for 2018. Due to differences in the level of fleet segmentation between STECF data and the FLBEIA model (ICES WGMIXFISH fleet definition), fleets could only be matched to the lowest level possible, not accounting for further métier segmentation of gear, mesh size and finer spatial-scale operations within the North Sea, because the data only specified aggregated information over the larger FAO Area 27. Also, as landing (monetary) values were only reported as aggregate, the STECF data may have contained species not considered in our model. To overcome this mismatch, the FLBEIA model was conditioned with the relative cost to revenue ratio to match the level of profitability reported for fleet segments in the STECF data (Supplement T2 in the Appendix S1). Therefore, final results of economic outcomes may be more appropriately interpreted in relative, rather than absolute, terms.

2.4 | Projections

2.4.1 | Climate projections

Regionalised climate projections for the North Sea

Future SST, salinity and ocean current projections (2019–2100) under climate change following the "Representative Concentration Pathways" (RCPs) (RCP4.5 and RCP8.5) were obtained from three independent runs of a dynamically downscaled version of the global climate model MPI-ESM (Max Planck Institute Earth System Model; Ilyina et al., 2013; Jungclaus et al., 2013), performed with a high-resolution version of the regionally coupled ocean–atmosphere climate system model MPIOM/REMO (Mathis et al., 2019; Mikolajewicz et al., 2005; Sein et al., 2015).

Preparation of climate projections for FLBEIA

Projections were bias corrected via the delta method (Maraun & Widmann, 2018), removing the monthly mean per grid-point in the mutual overlapping period (2006–2017) between historic observations and forecasts, to match the historical trend and minimise the offset to AHOI and ORAS5 datasets that have been used to identify significant environmental covariates for EMSRRs. Corrected spatio-temporal fields of SST, salinity and surface currents were then projected onto EOFs from historical data to obtain time series for the forecasted period as an average of all three MPIOM runs. For the estimation of the average stock development under projected change, a non-linear trend of each environmental time series was extracted using shape-constrained additive models (Pya, 2021; Pya & Wood, 2015) that were constrained to allow only monotonic increasing or decreasing trends.

To account for variability in covariates, 100 time series with the same variance as the three ensemble members were generated for each covariate, following either a Gaussian white noise process or an autoregressive first-order process (AR1) if the time series was autocorrelated (Figure S4). This approach was valid because variances of the time series did not exhibit significant long-term trends (not shown). Additional environmental time series for scenarios simulating current climate conditions (noCC) were generated by removing the fitted trend from the artificially generated time series for RCP4.5 and adding the offset from the RCP4.5 time series.

2.4.2 | Economic projections

CERES economic scenario projections

To project economic conditions (fuel price, fish price) into the future, we used scenarios defined within the EU-project CERES (Climate change and European aquatic RESources), Task 4.1, using the MAGNET model of Woltjer and Kuiper (2014). The EU-project CERES, funded under the Horizon 2020 programme during 2016–2020, had the goal to gain insight into the effects of climate change on European fish and shellfish resources and accompanying economic activities to inform EU Blue growth and climate policies (Peck et al., 2020). Scenarios were particularly suited for our application because they combined RCP scenarios used for bio-physical impacts of climate change, with "Shared Socio-Economic Pathways" (SSP), for future economic development, in a set of four likely perceptions of future conditions:

1. "Global Sustainability" (GS_RCP4.5_SSP1)
2. "Local Stewardship" (LS_RCP4.5_SSP2)
3. "National Enterprise" (NE_RCP8.5_SSP3)
4. "World Markets" (WM_RCP8.5_SSP5)

Each scenario has various political, economic, technological, environmental, biological and social assumptions that are described in Pinnegar et al. (2021), and the most important aspects for our study are shortly summarised here for brevity:

Under the "Global Sustainability" scenario, global sustainability is a key goal, limiting climate change to the lower RCP4.5 goal, and trying to ensure welfare by balancing economic, social, and environmental factors with a high level of trans-boundary cooperation. Factors such as smaller world population, better-managed fish stocks, cheaper source of fish meal and oil for aquaculture, and a higher competition of farmed versus wild fish lead to a lower increase in fish prices in "Global Sustainability" than other scenarios (Figure 1).

The "Local Stewardship" scenario, in contrast, represents a path where sustainability is achieved by small-scale regional means, with a strong focus on equity, social inclusion and democratic values. Similarly, under the "National Enterprise" scenario, governments behave "nationally," while trying to maximise welfare and employment in the fishing industry under lower trans-national cooperation. Fish prices are high to ensure national wellbeing and due to higher per capita consumption. Global warming is predicted to follow the RCP8.5 path, due to limited technological innovation and high reliance on fossil fuels, which leads to a high rate in fuel price increase.

The "World Markets" scenario is characterised by high demand of low-cost seafood (medium increase in fish prices), higher technological innovation due to international competition, lower taxes and a strong private sector. Global warming follows the RCP8.5 path, but the rate of fuel price increase is lower than under the "National Enterprise" scenario due to higher technological innovation. In general, fuel prices rise faster in "NE" and "WM" scenarios than lower warming "GS" and "LS" scenarios, which are assumed to be less reliant on energy from fossil fuels. Other non-fuel-related costs were adjusted for each scenario based on projected growth rates in Gross Domestic Product (GDP) by country (U.S. Department of Agriculture, 2020). Together, median variable costs rose 1.94% per year for "GS" and "WM," 1.95% for "LS" and 2.1% for "NE," with fixed-cost increases equal for all scenarios (1.37%; Figure 1).

Economic effects on the fishery as a whole and at the fleet level were evaluated in terms of profitability, defined as the ratio of net profits over revenues. Price volatility as a response to supply and demand was not considered in these scenarios and the FLBEIA model, by assuming that price changes on the world market would have a higher impact on long-term price developments than the current stock situation in the North Sea.

2.5 | Management

2.5.1 | The concept of Pretty Good Yield

The concept of PGY attempts to relax limits imposed by MSY while allowing more flexible management to achieve a broader set of biological and economic objectives (e.g. by reducing mixed-fisheries conflicts). While management at MSY implies that a single target fishing mortality, F_{MSY}, is used to set a TAC, when aiming at PGY (at least 95% of catch at MSY), a range of fishing mortality values around F_{MSY} can be used to set TACs (the F_{MSY} range, delimited by lower, F_{MSY}Lower, and upper, F_{MSY}Upper, limits).

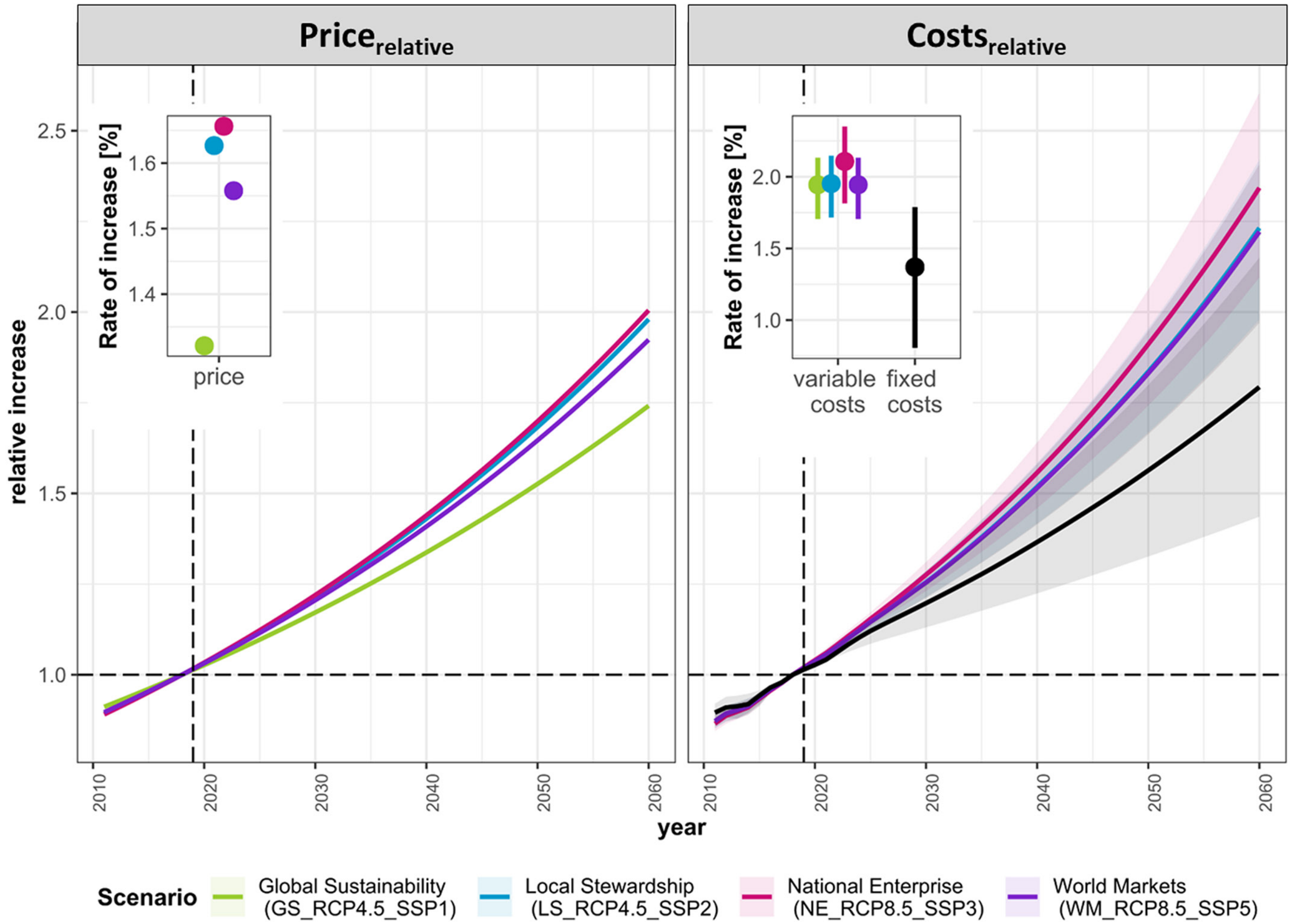

FIGURE 1 Relative increase in fish prices (left panel) and costs (right panel, fixed (black) and variable costs (coloured by scenario)) under four future scenarios described by Pinnegar et al. (2021), which differ in their assumed climate change trajectories and developments in fish and fuel prices: "Global Sustainability", "Local Stewardship," "National Enterprise" and "World Markets" summarised for all fleets (line: median, shaded bands/error bars: 5%–95% quantiles) from 2014 to 2060 to the reference level of 2018 (horizontal dashed line). Inset plots show percentage increases. The first simulation year (2019) is marked as vertical dashed line. Scenario codes in the legend (e.g. GS_RCP4.5_SSP1) denote the abbreviated scenario name (first letters), the representative climate change projection (RCP4.5/RCP8.5) and the shared-economic pathway (SSPs) the scenario corresponds to.

TABLE 2 Harvest control rules (HCR) and comprehensive description considered in the simulations.

HCR	Description
F_{MSY}	Fishing is allowed up to the single-species F_{MSY} as long as no choking effects occur
F_{MSY}Upper	If the stock is above MSY $B_{trigger}$, fishing is allowed up to the upper range of single-species F_{MSY} as defined by ICES and leading to at least 95% of MSY in the long term
F_{MSY}Lower	Fishing is only allowed up to the lower range of single-species F_{MSY} as defined by ICES and leading to at least 95% of MSY in the long term
F_{MSY}Stability	Same as F_{MSY} HCR, but year-to-year changes are limited to −20/+25% of the previous year's TAC

2.5.2 | Simulated harvest control rules

Harvest control rules (HCRs; Table 2) based on different target fishing mortality (F_{target}) were tested to evaluate the influence of management on fish stocks and economy of fleets and métiers, including F_{MSY}, F_{MSY}Lower and F_{MSY}Upper. Control rules build on the ICES advice HCR, where advised F is linearly reduced from F_{target} to 0 if the stock falls below MSY $B_{trigger}$ and equals F_{target} if the stock is above MSY $B_{trigger}$. To reduce variability in catch advice, we also implemented an HCR where interannual variation in the TAC was limited to +25/−20%, in combination with the ICES advice HCR. Setting asymmetric bounds (higher increase, than decrease) allowed similar responsiveness for decrease and increase, to ensure that TAC increases would result in the same level of yield after a series of subsequent reductions in TAC.

To simulate an enforced landing obligation, a given fleet's effort was stopped when its first quota was reached ("min" fleet control).

A baseline status-quo scenario was used for comparison, by fixing effort to status-quo effort irrespective of stock status ("fixed" fleet control). For simplicity, the observation model assumed perfect knowledge, with no uncertainty added to the perception of stocks. Short-term forecasts of recruitment within the management routine were based on averaging the preceding 3 years.

2.6 | Scenarios

Ecological and economic sustainability (and its limits) of North Sea demersal mixed fisheries were tested under climate change (RCP4.5 and RCP8.5) and management scenarios (RCP8.5) to derive strategies to balance short- and long-term effects on fisheries (Table 3). Simulations were run for the period 2019–2060, with 100 Monte Carlo iterations to account for variability from stock recruit relationships and climate projections.

2.7 | Software

Analysis used the programming language R version 4.0.2 (R Core Team, 2020) and FLBEIA version 1.15.6.15 (Garcia et al., 2017) building on the FLR framework (Kell et al., 2007).

3 | RESULTS

3.1 | EMSRRs

Segmented regression stock–recruit relationships provided better fits than Ricker and Cushing models for all three stocks (Figure S1a), with two environmental variables for cod, three for saithe and five for whiting. For cod, the dominant influence of temperature was identified ("SST.PC1_yrs.lag1"), followed by salinity in summer ("Salt.PC2_JJA.lag1"; Figure S5), with higher temperature and lower salinity being less favourable for recruitment. For whiting, recruitment was related to ocean currents in spring and summer ("Currents.PC1_MAM.lag0," "Currents.PC2_MAM.lag0," "Currents.PC2_JJA.lag0") and SST and salinity in winter ("SST.PC4_DJF.lag0," "Salt.PC3_DJF.lag0"). For whiting recruitment, winter salinity and dominant spring current signal (PC1) were most important, followed by SST, and the PC2 current in spring and summer. For saithe, recruitment was related only to currents (Figure S5). In particular, the dominant EOF mode of variation in the current field in summer ("Currents.PC1_JJA.lag2") was important for 1-year-olds, followed by currents in autumn in the birth year ("Currents.PC3_SON.lag3," "Currents.PC1_SON.lag3"; Figure S5). EMSRR models explained 0.45–0.67 of recruitment variation for all three species (Figure 2).

3.2 | Climate change

3.2.1 | Stock dynamics in response to climate change

Assuming the HCR with F_{MSY} as F_{target}, North Sea cod recruitment was most affected under climate change scenarios, which led to reduced recruitment under the more severe warming in RCP8.5 than in RCP4.5 and noCC (Figure 3). After a short recovery period, due to strict implementation of the landing obligation and maintenance of catches at or below advised TAC levels ("min" fleets control), recruitment of cod declined after 2025. whiting and saithe recruitment varied little among scenarios, because their most influential environmental variables (i.e. current signals) did not exhibit strong long-term trends in the forecasting period and did not differ markedly between the two warming scenarios until 2060 (Figure S4). Recruitment, SSB and catch of saithe were slightly higher under the

TABLE 3 Scenario overview, showing details of different model configurations in the FLBEIA North Sea model, the abbreviated scenario name, harvest control rule used (HCR), which fleet control was applied ("Min" – corresponding to a landing obligation and "Fixed" for status quo effort), the climate change scenario (projections under Relative Concentration Pathways RCP4.5 and RCP8.5 or current climate conditions) and the CERES (Peck et al., 2020) scenarios combining Relative Concentration Pathways (RCP) and Shared Socio-economic pathways (SSP) into a common projection of future socio-economic conditions (Global Sustainability, Local Stewardship, National Enterprise and World Markets). Deviations from the baseline run are marked in bold.

Scenario name	HCR	Fleet control	Climate change scenario	Economic projection
noCC	F_{MSY}	Min	**Current climate conditions**	None
WM_RCP8.5 (Baseline)	F_{MSY}	Min	RCP8.5	World Markets
NE_RCP8.5	F_{MSY}	Min	RCP8.5	**National Enterprise**
GS_RCP4.5	F_{MSY}	Min	**RCP4.5**	**Global Sustainability**
LS_RCP4.5	F_{MSY}	Min	**RCP4.5**	**Local Stewardship**
Status-quo effort	**None**	**Fixed**	RCP8.5	World Markets
F_{MSY}Lower	**F_{MSY}Lower**	Min	RCP8.5	World Markets
F_{MSY}Upper	**F_{MSY}Upper**	Min	RCP8.5	World Markets
F_{MSY}Stability	**F_{MSY}Stability**	Min	RCP8.5	World Markets

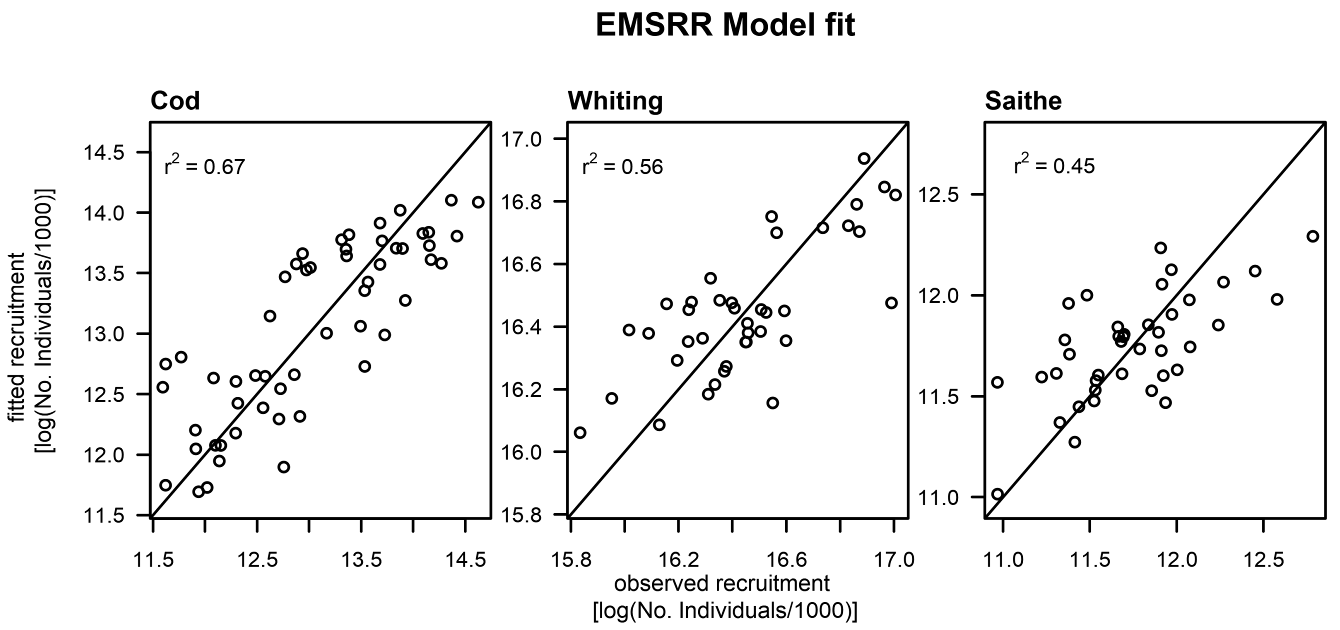

FIGURE 2 Fitted versus observed recruitment (log-scale) for the segmented regression EMSRR models for cod, whiting and saithe. Squared correlation (r^2) as a measure of fit is shown in the upper left corner.

more severe warming scenario RCP8.5, because of a slightly more favourable main current signal than the historical trend (Figure S4).

Stock sizes (SSB) and catches under the F_{MSY} HCR and a strict implementation of the landing obligation ("min" fleet control) recovered to equilibrium in the mid-term, except for cod, which declined in productivity after 2030 (compare RCP4.5/RCP8.5 runs with the noCC run in Figure 3). As a by-product of strict implementation of the landing obligation that led to historically low F values (Figure 3), stock biomasses for cod and saithe could increase above observed levels.

3.2.2 | Effects of climate change on economic viability of fleets

Using the F_{MSY} HCR with an enforced landing obligation, median profitability (net profits/revenues) of all fleets was highest for the "LS_RCP4.5" scenario, followed by two RCP8.5 scenarios, and lowest for the "GS_RCP4.5" scenario (Figure 4a). Differences in profitability between scenarios at the fleet level showed a more refined picture with some fleets being stronger influenced by catch composition, whereas profitability of others was largely driven by the future price development (Figure 4b,c). The cod stock suffered from reduced recruitment, which led to a stronger reduction in stock biomass, reduced catches and stronger choking effects on fishing effort under RCP8.5 than RCP4.5 (Figure 4b,c). Fleets that relied strongly on cod had a higher profitability under the "GS_RCP4.5" scenario than both RCP8.5 scenarios. Fleets less reliant on cod were driven by the development of fish prices that influenced revenues more than costs, and were more profitable under other scenarios with smaller differences between fish price and costs (Figure 4b,c) than "GS_RCP4.5," where fish prices increased at a slower rate than costs (Figure 1). "LS_RCP4.5" combined favourable price development with better stock condition for North Sea cod that led to the best performance for most fleets.

3.3 | Management

3.3.1 | Stock dynamics in response to different management

In the short term, catches dropped considerably due to the implementation of the landing obligation which allowed stocks to recover (Figure 5), in contrast to the status-quo effort scenario, which did not display such a drop due to the absence of choking effects. Under a landing obligation, lower Fs/TACs allowed stocks to recover faster towards higher biomass in early forecast years, although this was at the expense of a slower increase in catches (compare F_{MSY}Lower vs. F_{MSY}Upper in Figure 5). Allowing the TAC to vary only −20/+25% from year to year (F_{MSY}Stability) mitigated these initial losses in catch, but resulted in lower catches for most stocks than the F_{MSY} scenario in subsequent years, similar to catch levels of F_{MSY}Lower, before approaching levels comparable to F_{MSY} in the long term (Figure 5a). In the long term, management under different HCRs resulted in higher SSB under lower F_{target} (F_{MSY}Lower, F_{MSY}) than HCRs with higher target fishing pressure (F_{MSY}Upper, fixed effort) as stocks recovered to higher SSB equilibria. The status-quo effort scenario resulted in strong overfishing of all stocks, especially cod, which was fished to stock collapse by 2030 (Figure 5b).

Recruitment of age-based stocks differed less among different HCRs than climate change scenarios (Figure S6). For cod, recruitment differed marginally under F_{MSY} and PGY F (F_{MSY}Lower and F_{MSY}Upper) under different spawning stock sizes, with stronger

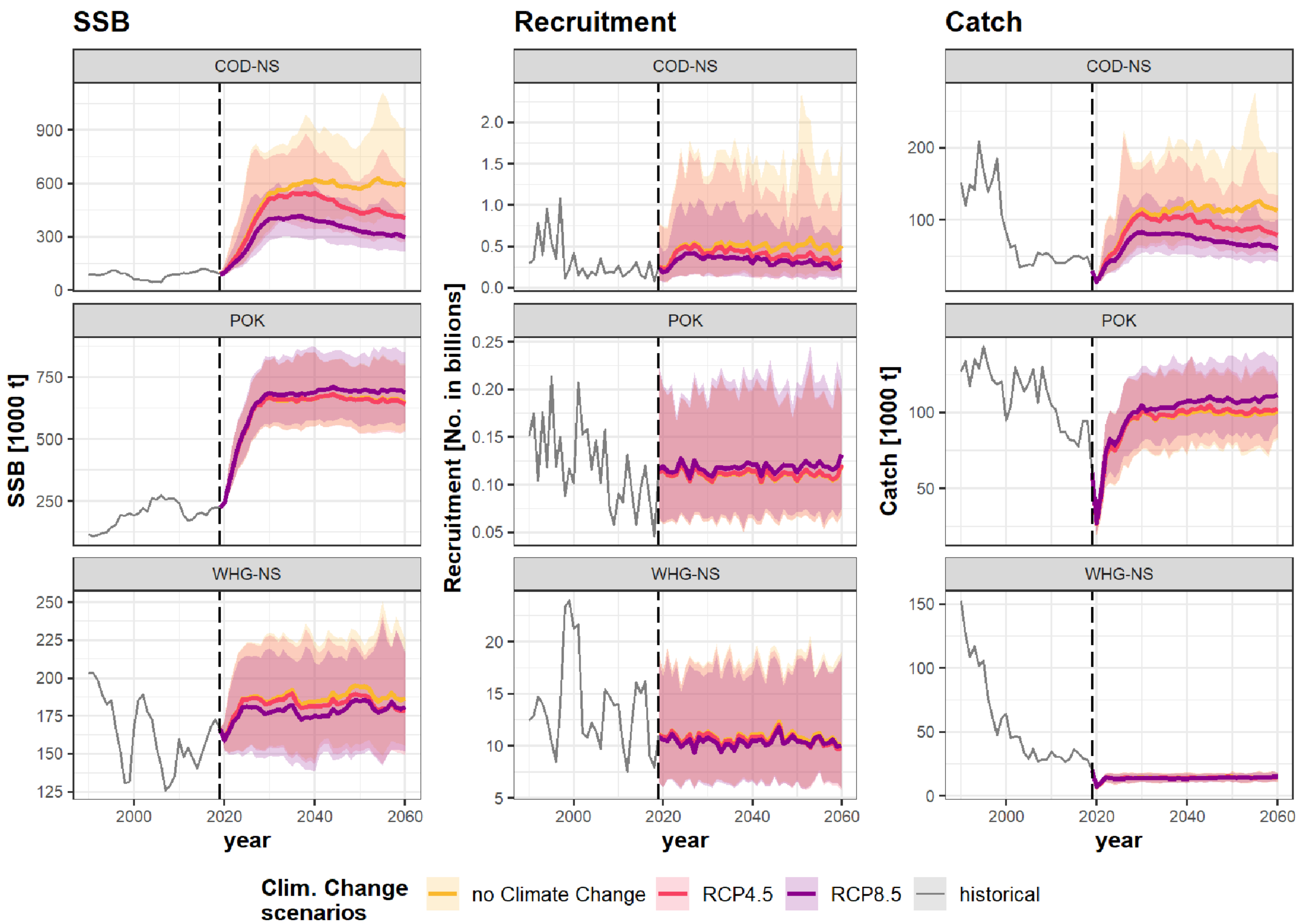

FIGURE 3 SSB, recruitment, catch and fishing mortality (columns from left to right) projections for cod (COD-NS), saithe (POK) and whiting (WHG-NS) stocks (rows), which are modelled with an environmental influence on recruitment for the period 2019 (dashed vertical line) to 2060. Trajectories (lines show median, shaded bands correspond to 5%–95% quantiles) are shown for a simulated "current climate conditions"-scenario (noCC, yellow), the RCP4.5 projection (pink) and the RCP8.5 projection (dark purple) under the F_{MSY} harvest control rule with an enforced landing obligation ("min"-scenario"). The historical time series from 1990 on (grey line) are shown for comparison. The level of the single-species target reference point F_{MSY} is shown as dashed horizontal line in the fishing mortality plot (right).

variation after 2040 and lowest recruitment under high fishing pressure (F_{MSY}Upper). Here, the environment (increase in the SST signal) largely dominated the pattern with decreasing recruitment after 2025. All stocks, except cod, were fished below their single-species F_{MSY} for all HCRs due to technical interactions and the landing obligation, in contrast to status-quo effort (Figure 5b). For cod, recruitment was above F_{MSY} under the F_{MSY}-HCR, related to the modelled management routine where 3-year average recruitment was used to inform the short-term forecast, which was slightly optimistic when recruitment decreased in climate change scenarios. Even if fleets were allowed to catch in the upper F_{MSY} range, most non-choking stocks were fished below their single-species F_{MSY} reference point (Figure 5b). Cod, the main choke species, was the only stock that was largely fished above their F_{MSY} reference point under the F_{MSY}Upper HCR (e.g. 1.2–2 times F_{MSY}).

Additionally, year-to-year variability in catches was high for all PGY HCRs under the landing obligation, but could be effectively reduced by the F_{MSY}Stability HCR (Figure S7). With stocks reaching equilibrium in the long term, year-to-year catch variability stabilised at 7%–12% median absolute deviation being higher under F_{MSY}Upper, followed by F_{MSY}, F_{MSY}Stability, and lowest for F_{MSY}Lower. The landing obligation resulted in rebuilding of stocks to levels considerably above B_{lim}, with higher SSB levels associated with HCRs advising lower fishing rates (Figure S8). In contrast, fishing under status-quo effort that allowed fleets to overshoot stock quota resulted in the lowest total biomass for all stocks combined and an increased risk of stocks falling under MSY $B_{trigger}$ (cod, whiting, haddock, eastern English Channel plaice, sole and turbot) and B_{lim} (cod, eastern English Channel plaice, sole and witch). For harvesting under F_{MSY}Upper, the risk of falling below MSY $B_{trigger}$ was increased for whiting for the whole simulation period and cod in the long term (Figure S8).

3.3.2 | Economic effects of management under the landing obligation

Catches and profit declined initially due to the implementation of the landing obligation in the F_{MSY} HCRs (Figure 5a). Short-term

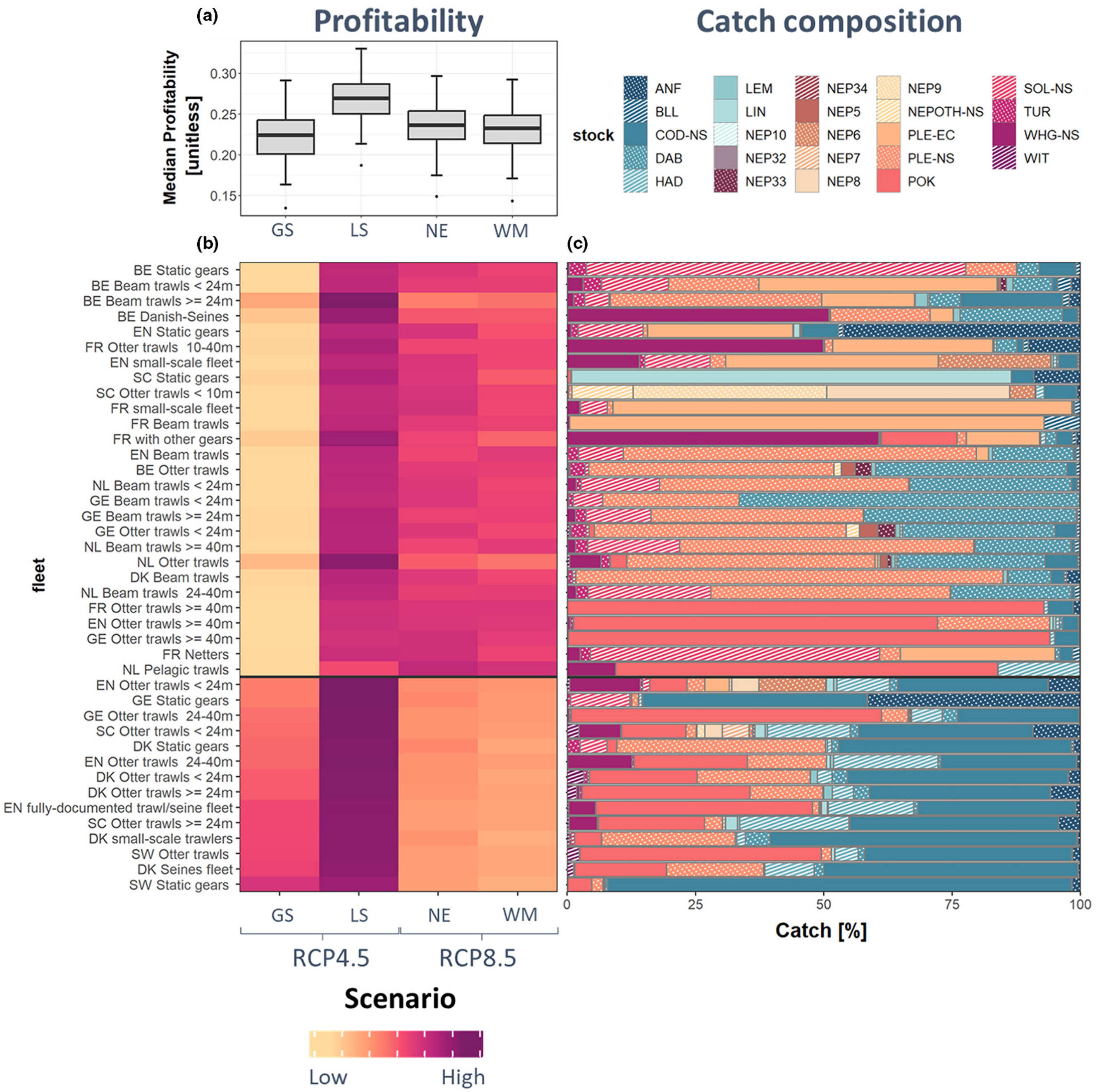

FIGURE 4 (a) Median profitability (over all fleets across iterations) by economic scenario (GS – Global sustainability, LS – Local Stewardship, NE – National Enterprise, WM – World Markets, scenarios are ordered from left to right based on accompanying climate projection RCP4.5 and RCP8.5) and (b) median profitability across iterations by fleet (heatmap colours represent scaled values across scenarios) per economic scenario for the period 2040–2060 in comparison to (c) the catch composition (stacked barplot, average catch of each stock (colours) in the RCP8.5 scenario 2040–2060) in percentage per fleet linking the economic effect of climate change with the catch of the fleets. Fleets below the black vertical line (plot b and c) are more profitable under both RCP4.5 – scenarios than under RCP8.5 and are characterised by a high percentage of cod in their catches (teal bars, left), whereas fleets above have a higher profitability under RCP8.5 compared to GS_RCP4.5 and lower catches of Cod. Fleet names show country (BE – Belgium, DK – Denmark, EN – England, FR – France, GE – Germany, NL – the Netherlands, SC – Scotland, SW – Sweden), main deployed gear and vessel length. Deviations to this naming convention occur if fleets were built by aggregating over various size classes and gears (for details see Table S1). Stock abbreviations: ANF – Anglerfish, BLL – Brill, COD-NS – North Sea cod, DAB – dab, HAD – haddock, LEM – lemon sole, LIN – Ling, NEP – Nephrops (with functional unit), PLE-EC – eastern English Channel plaice, PLE-NS – North Sea plaice, POK – saithe, SOL-NS – North Sea sole, TUR – turbot, WHG-NS – North Sea whiting, WIT – witch.

losses in the first 5 years could be compensated faster when fishing using the F_{MSY}Upper HCR compared to using the HCR with $F_{target} = F_{MSY}$ or F_{MSY}Lower, but at the expense of declining profitability in the mid-term until 2030. Maintaining interannual TAC changes within −20/+25% limits mitigated severe losses in catch and profit in the first 2 years after implementation of the

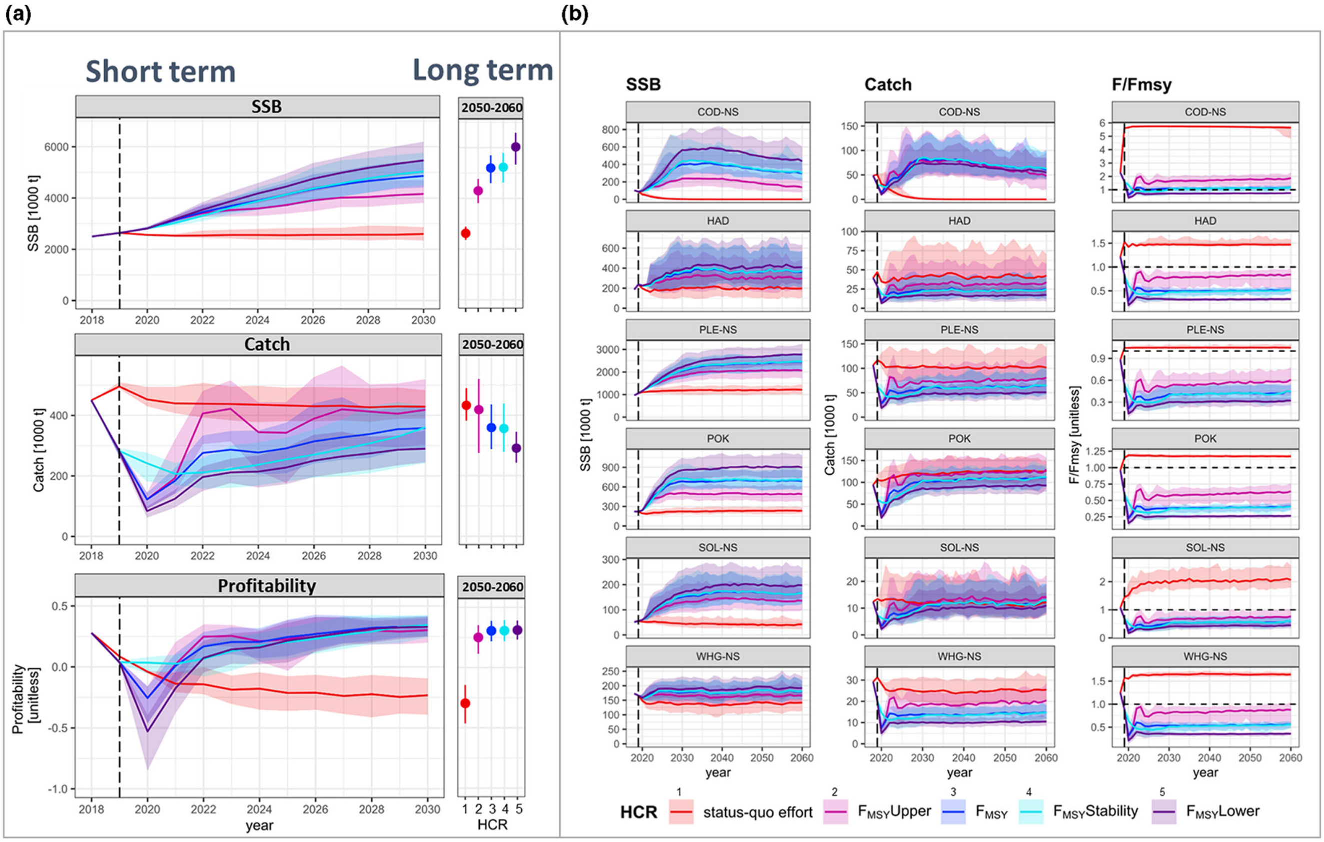

FIGURE 5 (a) Total SSB, total catch and total profitability summed across all stocks and fleets for the short term until 2030 (left) and long term summarised for the period 2050–2060 (right). (b) Detailed information on stock level from 2019 (dashed vertical line) to 2060 for SSB, Catch and fishing mortality in relation to their single-species F_{MSY} (F/F_{MSY}) for stocks with F_{MSY} ranges defined by ICES under the respective harvest control rule (HCR, coloured). The level of F_{MSY} is marked as horizontal dashed line in the F/F_{MSY} plot. Trajectories/Points correspond to the median, shaded bands/error bars to 5%–95% quantiles respectively. Stock abbreviations: COD-NS – North Sea cod, HAD – haddock, PLE-NS – North Sea plaice, POK – saithe, SOL-NS – North Sea sole, WHG-NS – North Sea whiting.

landing obligation by providing more stability in yield than fishing with a fixed fishing mortality target alone. However, recovery of stocks also slowed and therefore fell short in the mid-term to the level of F_{MSY}Lower, before approaching F_{MSY} HCR by 2030. The status-quo maintained high effort, but at the expense of low stock sizes, which reduced CPUE and profitability in the long-term. All other F_{MSY} HCRs allowed stocks to rebuild, while maintaining higher CPUE and profitability.

Profitability in the long-term (2051–2060) across all fleets was highest (under WM_RCP8.5) for the F_{MSY} HCR, followed by F_{MSY}Lower, F_{MSY}Upper and lowest for the fixed effort scenario (Figures 5a and 6a). For higher target fishing pressure (F_{MSY}Upper), variability in median profitability among fleets also increased (Figure 6a). In terms of long-term profitability, the F_{MSY}Stability was again equivalent to the F_{MSY} HCR. At the fleet level, the picture was more refined. Although most fleets had the highest or second highest profitability under the F_{MSY} HCR, some fleets performed better under F_{MSY}Lower and other fleets performed worse, with higher profitability under F_{MSY}Upper (Figure 6b). Fleets that greatly profited from fishing in the upper F_{MSY} range generated proportionally higher revenue, despite increasing costs (Figure S9a). This effect was mainly attributed to low variable costs that enabled higher profitability with higher fishing effort (Figure S9b). Also, compared to F_{MSY}, catches changed the most for this group, >25% more than under F_{MSY} (Figure S9b). In contrast, fleets with higher profitability under lower fishing pressure (F_{MSY}Lower) than the F_{MSY} scenario were those that had a lower fixed cost structure and relatively high variable costs per unit of effort than the rest of the fleets (Figure S9b). Although revenue decreased for most in this group due to overall lower catches compared to F_{MSY}, the better stock status and lower F allowed for a further reduction in effort that led to lower variable costs than under F_{MSY} (Figure S9b). For the two intermediate groups of fleets where F_{MSY} performed best, either the increase in catches could not outweigh costs under F_{MSY}Upper or the reduction in catches outweighed cost savings under F_{MSY}Lower (Figure S9b).

4 | DISCUSSION

A multitude of influences, ranging from management, climate effects on productivity, and economic developments, impact yield and profitability of fishing fleets operating in demersal mixed fisheries in the North Sea. Our model approach enabled for the first time a combined evaluation of these influences with respect to

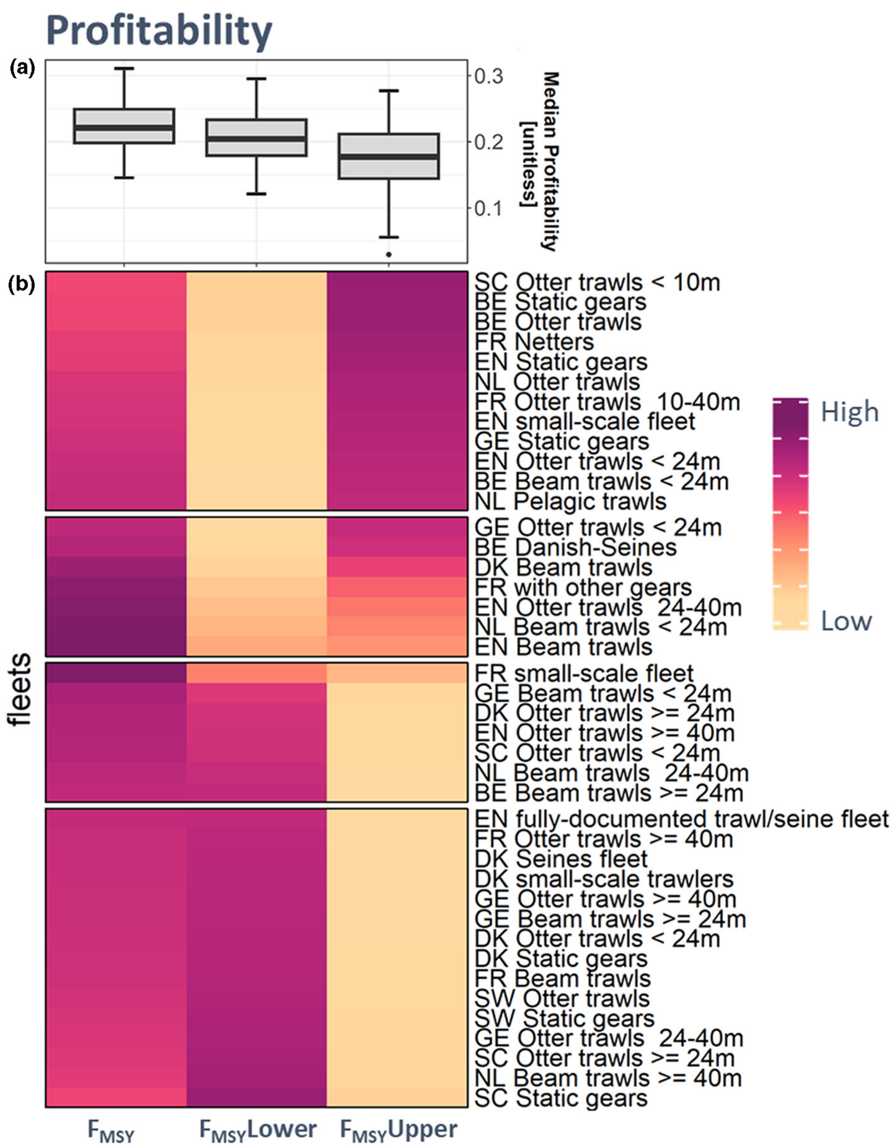

FIGURE 6 Comparison of the fleets' long-term median profitability (2051–2060) between the F_{MSY}, F_{MSY}Lower and F_{MSY}Upper scenarios: (a) Median profitability per scenario (over all fleets across iterations), (b) Profitability Heatmap (colours scaled by row with yellow and purple corresponding to low and high relative profitability between scenarios respectively) resolved at fleet level. Fleets were sorted into four groups (from top to bottom): 1. Fleets being more or equally profitable under F_{MSY}Upper than under F_{MSY} and least profitable under F_{MSY}Lower 2. Fleets being most profitable under F_{MSY}, followed by F_{MSY}Upper and F_{MSY}Lower. 3. Fleets being most profitable under F_{MSY}, followed by F_{MSY}Lower, and least profitable under F_{MSY}Upper. 4. Fleets being most profitable under F_{MSY}Lower, followed by F_{MSY}, and least profitable under F_{MSY}Upper. Fleet names show country (BE – Belgium, DK – Denmark, EN – England, FR – France, GE – Germany, NL – the Netherlands, SC – Scotland, SW – Sweden), main deployed gear and vessel length. Deviations to this naming convention occur if fleets were built by aggregating over various size classes and gears (for details see Table S1).

sustainable fisheries. A strict implementation of the landing obligation resulted in severe choking effects for fleets, especially by cod, which strongly reduced catch and profits in the first years after implementation. However, recovery of stocks is possible, even under simulated climate change effects for gadoid stocks, with HCR advised reductions in fishing pressure. Management within upper F_{MSY} ranges, as well as limiting year-to-year TAC changes, may overcome negative short-term effects in catch and profit for fishers, but only with trade-offs over the mid- to long-term. Declines in productivity due to reduced recruitment under climate change were visible for cod and less so for whiting and saithe. Reduced recruitment translated into economic effects for fleets catching cod, which were less profitable under the severe warming scenario RCP8.5. Fleets that relied less on cod profited from more favourable fish prices under RCP8.5. Management affected profitability of fleets differently, with fishing in the upper F_{MSY} range being more profitable for fleets with lower variable costs, compared to fishing in the lower F_{MSY} range, where fleets with high variable costs profited from increased stock biomass.

4.1 | Uncertainties and potential bias

Considering environmental drivers in the formulation of stock–recruit relationships allowed assessing long-term effects of climate change on mixed fisheries. However, environmental processes that explain historical recruitment might not be informative when projected in the long-term (e.g. for whiting and saithe in the model). This could be because environmental parameters have no strong pattern (e.g. trend) that influences stock dynamics or the scale on which an environmental parameter acts on stock recruitment dynamics (e.g. interannual) and was identified in the EMSRR is poorly resolved in the environmental forecast. For whiting and saithe, we could not identify a strong effect of climate change on productivity of stocks, although recent low recruitment of saithe suggests an environmental influence, such as a negative effect of temperature on productivity of those two stocks (Free et al., 2019).

Due to the low F under the "min"-scenario, stocks may be able to recover to very large biomass above of what was seen historically.

A lack of information from earlier, less-exploited periods, with potentially higher stock size, may hide important density-dependent changes other than those considered in stock–recruit relationships. This may include changes in natural mortality and growth (Rindorf et al., 2022) that we did not consider. Nevertheless, even if absolute stock levels are uncertain, evaluation of HCR performance relative to a baseline status-quo scenario allowed for insights into potential future directions of stock biomass development and yield under climate change.

Stock definitions may be revised in the future as more information on dynamics and sub-population spatial structure becomes available. Changes in stock productivity and shifts in distributions are expected for several other stocks caught in the demersal mixed fisheries of the North Sea (Dulvy et al., 2008; Engelhard et al., 2011; van Keeken et al., 2007), which were not considered in our model, so our results represent a possible direction, rather than an endpoint, for North Sea fleets. Effects of climate change on recruitment and spatial distribution are likely to affect productivity of stocks that lead to revision of MSY reference points, which are regularly updated during benchmark workshops for all stocks, including cod (ICES, 2015, 2021b). We did not consider updating reference points in response to climate change, so long-term scenarios lack a degree of management adaptation (e.g. a shift in response to these changes; Bastardie et al., 2022; Travers-Trolet et al., 2020). Additional effects could arise through changes in the distribution of stocks that are not currently included in the model, like hake, either intensifying or relaxing choking situations for different fisheries (Baudron & Fernandes, 2015). Furthermore, the increase in bycatch of southerly species moving into the North Sea (Beare et al., 2004; Lamine et al., 2022) could create new fishing opportunities that would make some fleets more profitable than previously thought.

Economic outcomes of simulations should be interpreted with caution due to shortcomings of matching AER data to the level of fleet segmentation in FLBEIA, and changes in fishing behaviour, decommissioning schemes, increased fuel efficiency, or technological investment of fleets, response of fishers to fuel and fish price volatility, and entry–exit strategies influencing economic performance, that we did not consider. Also, assumptions of fixed catchabilities, relative stability in catch composition and no dynamic quota swapping deviated from reality and would offer additional ways for fleets to avoid choking, thereby rendering them economically more profitable. Still, we think that the main relative pattern will hold and give insight into the performance of different HCRs under climate change and legislation of the landing obligation. Within the limits of model assumptions and large uncertainty around predicted values, our results highlight that both climate change effects on stock biology and development in economic variables need to be taken into account when judging future developments of fisheries. A fleet-by-fleet (or even métier by métier) consideration is needed in complex mixed fisheries in the North Sea to capture differences in developments of fishing fleets.

4.2 | The landing obligation as benefit and challenge

Implementation of the landing obligation is a challenge for demersal mixed fisheries. Compared to status-quo effort, scenarios with an enforced landing obligation led to substantially lower yield and profits for many fleets and métiers in the first few years after full implementation. However, after the first few years, landing obligation scenarios were more profitable than the status-quo effort scenario. In addition, the status-quo effort scenario failed to sustain SSB of several stocks above critical levels (MSY $B_{trigger}$, B_{lim}), so the landing obligation can be seen as an additional management measure to ensure sustainability. Alternative management scenarios that allow fishing in the upper F_{MSY}-range or limiting year-to-year TAC changes alleviated catch and profit losses shortly after implementation, albeit at the expense of higher year-to-year variability in catch and SSB (especially F_{MSY}Upper) or an extended period of reduced catch and profit in the medium-term (F_{MSY}Stability).

Management using HCRs alone did not entirely alleviate negative effects of a landing obligation, and incentives for improved selectivity in North Sea demersal fisheries using technical measures are needed to help fishers overcome decreased yield and profit during initial years. Implementing the current landing obligation with its many exemptions (but also deductions that account for discarding) under current selectivity patterns has a high chance of failure because it is against fisher's interests to accept lower yield and profit in the short-term. Current levels of compliance with the landing obligation also point in this direction, with unwanted catches still remaining high (COM, 2022).

4.3 | Climate change impacts

North Sea cod was the main choke species under all landing obligation scenarios, and climate change would likely intensify management problems caused by a reduced productivity of North Sea cod. Any successful management of demersal mixed fisheries will need a solution for this stock. Next to TAC management, technical measures to avoid unwanted bycatch of cod are important. Overall, climate change will likely negatively impact demersal mixed fisheries with the IPCC RCP 4.5 scenario having more moderate effects than the RCP 8.5 scenario.

The degree to which fleets are affected will strongly depend on future prices, cost structure, and stock status of their main target and bycatch species. Overall, fleets and métiers relying largely on cod will most likely experience decreased profitability due to climate change. Fleets targeting flatfish, for example, will be more affected by future prices and costs than increasing temperature. We only accounted for climate effects on a limited number of species (cod, whiting and saithe), although overall patterns are in line with a recent study of political, socio-economic and biological effects of projected CERES scenarios on the Dutch flatfish fishery (plaice, sole) in the

North Sea using a spatially explicit bio-economic model SIMFISH (Hamon et al., 2021). In that study, a sensitivity analysis revealed that fish and fuel prices were most influential on profitability of Dutch beam trawlers, rather than changes in the spatial distribution of stocks under climate change (Hamon et al., 2021).

4.4 | The importance of the right management strategy

Management based on F_{MSY} was the most promising long-term strategy compared to management strategies making use of F_{MSY} ranges. Our results indicated short-term benefits in yield and profitability of fishing in the upper F_{MSY} range for most fleets. In particular, effects of the landing obligation can be mediated in the first 5 years by relaxing choke situations until recovery to equilibrium. However, fishing consistently in the upper range could lead to overall loss and higher variability in profitability and yield, and to a higher risk of stocks being fished unsustainably (SSB below MSY $B_{trigger}$).

Management under F_{MSY}Lower resulted in slightly less-profitable fleets than fishing under F_{MSY}, which was somewhat counter-intuitive, given that F_{MSY}Lower would be expected to be closer to F_{MEY} (Maximum Economic Yield), due to decreased effort and costs for fleets. This counter-intuitive result is attributed to the large proportion of fixed costs for many fleets, although some fleets with lower fixed costs and higher variable costs were more profitable with the F_{MSY}Lower HCR. Stronger choking effects due to lower quotas negated benefits of increased stock sizes in mixed fishery multi-species simulations. Scenarios based on F_{MSY}Lower also led to larger losses in total catches than the F_{MSY} baseline scenario. In contrast, stocks could rebuild to higher biomass, with the benefit of reduced year-to-year variability in catches, due to less dependence on stochastic high recruitment, thereby illustrating a trade-off between conservation and economic or social objectives. In the face of climate change, however, having a larger stock biomass can enhance resilience against poor environmental conditions through genetic diversity and a healthy age structure (Mason et al., 2022).

In general, our results suggest that management has a greater influence on stocks than climate change. This might also be due to climate change effects being modelled for a limited number of stocks and only for recruitment processes, whereas effects could act on various other stages and processes within the life cycle. Still, our findings add to a growing body of literature (Beaugrand et al., 2022; Brander, 2018; Bryndum-Buchholz et al., 2021; Free et al., 2020; Gaines et al., 2018; Holsman et al., 2019) that emphasises the importance of adequate management to deal with climate change.

Although our results are uncertain, they illustrate the types of trade-offs of management strategies when evaluated in the context of mixed fisheries. For example, stronger choking effects under an F_{MSY}Lower scenario would be overlooked in a purely single-species approach.

4.5 | Management implications

We showed that management of mixed fisheries constituted both a great challenge for fishers in the short-term, but also had the potential to offset negative climate change effects for demersal North Sea stocks in the mid- to long-term future. In general, reductions in fishing effort have the potential of stock rebuilding in temperate regions (Cheung et al., 2022), allowing sustainable harvesting and increased profits in the mid- to long-term (Agnetta et al., 2022). Still, overcoming losses in profit and yield in the transitional period is crucial and requires adaptive compensatory measures (Agnetta et al., 2022). Management that allows for flexible advice within the F_{MSY} range or limits year-to-year TAC variability could, in part, address this issue under the landing obligation, however with some trade-offs. This result highlights the need for combining regional measures with those at the individual vessel level to reduce unwanted bycatch in mixed fisheries and sustain healthy fisheries under climate change. The role of technical measures (e.g. innovative gears or (semi-)closed areas) is of increasing interest to circumvent choke effects, but also to support the implementation of an ecosystem approach to fisheries management.

Our results illustrate that climate change intensifies the need for management to address the mixed fisheries perspective considering both the socio-economic and ecological dimensions to preserve the livelihood of fishers. Furthermore, the economic performance of fleets in the mixed fishery of the North Sea strongly depends on both stock status of individual (choking) stocks, and future fuel and fish prices. Even though future fuel costs are highly uncertain, our analysis highlighted the importance of fuel prices on profitability of fleets, which is partly decoupled from stock status. Our findings demonstrate the importance to gain insight of climate risk at fleet level (Payne et al., 2021), while also considering the dynamic effects of management under various bio-economic futures through simulations. This is of particular relevance for evaluating which fleets are the most vulnerable or have the highest potential to adapt to economic effects of climate change, e.g. via investing in less fuel-intensive technologies.

Our work demonstrates that incorporating environmental and economic information to management and MSE simulations in mixed fisheries adds a further dimension to understanding and decision making on which management measures perform best under climate change.

ACKNOWLEDGEMENTS

We thank Ismael Núñez-Riboni for helping to prepare the environmental projections and the people of the ICES WGMIXFISH group, who collated a large portion of input data relevant for the FLBEIA model. Additionally, we thank two anonymous reviewers and the editor for refining and scrutinising the article. Open Access funding enabled and organized by Projekt DEAL.

FUNDING INFORMATION

This research has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement numbers 773713 (PANDORA) and 101000318 (SEAwise).

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Kühn, B., Kempf, A., Brunel, T., Cole, H., Mathis, M., Sys, K., Trijoulet, V., Vermard, Y. & Taylor, M. (2023). Adding to the mix – Challenges of mixed-fisheries management in the North Sea under climate change and technical interactions. *Fisheries Management and Ecology*, *30*, 360–377. https://doi.org/10.1111/fme.12629