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Achieving maximum sustainable yield in mixed fisheries: a management approach for the North Sea demersal fisheries

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Achieving single species maximum sustainable yield (MSY) in complex and dynamic fisheries targeting multiple species (mixed fisheries) is challenging because achieving the objective for one species may mean missing the objective for another. The North Sea mixed fisheries are a representative example of an issue that is generic across most demersal fisheries worldwide, with the diversity of species and fisheries inducing numerous biological and technical interactions. Building on a rich knowledge base for the understanding and quantification of these interactions, new approaches have emerged. Recent paths towards operationalizing MSY at the regional scale have suggested the expansion of the concept into a desirable area of "pretty good yield", implemented through a range around F_{MSY} that would allow for more flexibility in management targets. This article investigates the potential of F_{MSY} ranges to combine long-term single-stock targets with flexible, short-term, mixed-fisheries management requirements applied to the main North Sea demersal stocks. It is shown that sustained fishing at the upper bound of the range may lead to unacceptable risks when technical interactions occur. An objective method is suggested that provides an optimal set of fishing mortality within the range, minimizing the risk of total allowable catch mismatches among stocks captured within mixed fisheries, and addressing explicitly the trade-offs between the most and least productive stocks.

Keywords: choke species, Common Fisheries Policy, fleet modelling, FMSY ranges, landing obligation, management plan, pretty good yield.

Introduction

Achieving maximum sustainable yield (MSY) from mixed fisheries, where stocks of different productivity are caught together, remains a major challenge in demersal fisheries worldwide. Although the Common Fisheries Policy (CFP) of the European Union (EU) has its own specificities due to its complex multilevel jurisdiction (Holden, 1994), its development since 1983 has been shaped by similar management goals as other advanced fisheries management systems (Marchal *et al.*, 2016), and it faces many similar challenges, not least those linked to mixed fisheries (Hilborn *et al.*, 2012).

The main management instrument within the CFP is the setting of annual single-stock total allowable catches (TACs) which limit the tonnage to be landed for each stock. Since 2002

[Framework Regulation (EC) No 2371/2002], decisions on TACs have been increasingly based on long-term considerations, reducing annual political battles over the setting of TACs by providing a framework under which stock sustainability and quota stability for fishers are jointly considered. This has been operationalized in multiannual or long-term management plans (MAPs or LTMPs) and in recovery plans for stocks outside safe biological limits. Such plans contain the goals for management of stocks, typically expressed in terms of fishing mortality and/or targeted stock size. How to attain these goals is defined in the plans by a harvest control rule (HCR), which translates the scientific estimates of the stock's status into annual TAC advice. Additional measures, such as area closures or changes to fishing gear, are sometimes included as well. In 2015, many important stocks in the North Sea were managed by means of a LTMP.

However, while single-stock LTMPs have contributed to the recovery of European stocks to varying degrees (STECF, 2015a), other conflicts have appeared. The most serious arises from mixed-fisheries interactions, when several stocks with different productivity and catchability are caught together. In such cases, a reduction in TAC resulting from a single-stock HCR may not lead to the expected reduction in fishing mortality and biomass recovery if fisheries continue to catch (but not land) the overexploited stock while targeting healthier stocks (Gillis *et al.*, 1995; Batsleer *et al.*, 2015). This over-catch has, until now, been legally discarded and is not reported in logbooks, so the only estimates for it have come from scientific observers.

The mixed demersal roundfish fisheries in the North Sea are a good example of mixed-fisheries interactions, which has contributed to shaping the evolution of the CFP over the last 15 years. Fisheries targeting North Sea haddock (*Melanogrammus aeglefinus*) have contributed to a decline in the North Sea cod (*Gadus morhua*) stock, and discards increased as the cod quota were reduced (Bannister, 2004). Indeed, the annual fishing mortality of these two stocks is highly correlated, especially in the recent period ($\rho = 0.82$, $p < 0.01$ for the years 2000–2014; data from ICES, 2015a). Despite emergency measures in 2001 followed by a recovery plan for cod in 2004, the situation continued to deteriorate. This triggered a range of innovative management initiatives to incentivize cod avoidance in the latter half of the decade, such as catch quota management with fully documented fisheries (Needle *et al.*, 2015; Ulrich *et al.*, 2015; van Helmond *et al.*, 2015) and real-time closures (Holmes *et al.*, 2011; Little *et al.*, 2015).

On the scientific side, new tools to quantify and monitor mixed-fisheries interactions were also developed. In particular, the Fcube approach (fleets and fisheries forecast, Ulrich *et al.*, 2011) has delivered mixed-fisheries considerations as part of the annual ICES advice since 2009 (ICES, 2015b), measuring the inconsistencies across the different single-stock TAC advice for the following year when stocks are caught together by the same fleets. Until now, these considerations did not aim to provide a single-best, mixed-fisheries TAC advice, but to raise managers' awareness of the potential TAC mismatches at the regional level, where severe limitations on fishing imposed by shortage of quota for one stock (also called "choke-species" effects) could lead to over-quota discarding, and thereby to fishing mortalities higher than those intended in the single-stock management objectives. But while the mechanisms creating over-quota discards became increasingly understood, no regional integrated management solutions were yet introduced. Rather, a more stringent management plan for North Sea cod was implemented in 2008 [Council Regulation (EC) No1342/2008]. The plan's HCR stipulated large fishing mortality reductions and commensurate effort reductions. These stringent measures, however, did not achieve the required reduction in fishing mortality during the first years of implementation (Kraak *et al.*, 2013). The fishing industry strongly opposed effort reductions, and discard mortality remained high. In 2012, the North Sea cod stock did, however, begin to show signs of recovery, which led to a situation where stock biomass and catch rates were increasing while the legally binding HCR called for further TAC and effort reductions. Between 2013 and 2015, the HCR-based TAC advice has been rejected every year after long and conflictual negotiations. In the meantime, NGOs and the civil society have expressed increasing concerns about the high quota-induced discards and the insufficient recovery of the cod stock (Borges, 2015).

This situation in the North Sea has influenced the 2013 reform of the CFP (EU, 2013), calling for a more integrated and ecosystem-based approach to management. The 2013 reform sets three important strategic objectives: (i) achievement of an exploitation rate consistent with maximum sustainable yield (F_{MSY}) at the latest by 2020 for all stocks; (ii) establishment of regional mixed-fisheries multiannual plans; and (iii) ending of discarding practices under the so-called landing obligation. Clearly though, these three objectives may seem inconsistent or even contradictory if the mixed fisheries are highly dependent on an overexploited stock with low productivity, as illustrated here with the North Sea cod stock. In such cases, it seems unlikely to achieve all three objectives within 5 years without additional effort reductions and/or major changes in current fishing practices.

Recognizing this fundamental mixed-fisheries issue, new approaches have emerged out of intense political, institutional, and scientific activity (Kempf *et al.*, 2016). A task force (EU, 2014) comprising the three main EU institutions (EU Commission, EU Parliament, and EU Council of Fisheries Ministers) suggested using ranges of or around F_{MSY} as flexible targets for the regional management plans rather than prescriptive HCRs (STECF, 2015b), thus considering MSY as a desirable multidimensional area rather than a point estimate. The International Council for the Exploration of the Sea (ICES, 2015c, d) was then requested to provide precautionary estimates of fishing mortality delivering up to 95% of the maximum yield, an approach close to the United States concept of optimum yield (Patrick and Link, 2015) or of "pretty good yield" (Hilborn, 2010; Rindorf *et al.*, 2016). Two reference points were estimated for each stock, which define the range of F with high yields and low risk of severe stock depletion, MSY F_{lower} and MSY F_{upper}. Notwithstanding, ICES (2015c) advised that sustained fishing with values above F_{MSY} would have adverse consequences, including lower biomass and more variable fishing opportunities.

The objectives of the present study are to evaluate the ability of using F_{MSY} ranges to diminish the conflict between MSY management of single stocks and the possibility to deliver operational regional management based on mixed-fisheries considerations. The present study thus extends the approach that has been followed by ICES using Fcube since 2009 (ICES, 2015b, e, f). While the results are illustrated here on the North Sea case, this approach to mixed-fisheries MSY is clearly of much broader interest as similar choke-species issues are encountered in many other demersal fisheries worldwide (e.g. Hilborn *et al.*, 2012; Guillen *et al.*, 2013; Gourguet *et al.*, 2016).

Material and methods

Fcube modelling framework

The Fcube model (Ulrich *et al.*, 2011; see also the Supplementary Data) builds on modular FLR (Fisheries Library in R) objects and functions for the modelling of fisheries (Kell *et al.*, 2007), with additional methods specifically developed for providing mixed-fisheries projections (ICES, 2015f). Input data are a vector of target fishing mortality by stock, as well as historical data of stock assessments, effort, and catch by fleet and fishing activity (métier). The standard output is the estimation of potential catches above or below the annual single-stock forecasts across a range of effort scenarios (ICES, 2015b). Considering that understanding and modelling fishers' behaviour is still a major challenge in fisheries management (Andersen *et al.*, 2010; Fulton *et al.*, 2011), Fcube has been developed as an envelope modelling approach contrasting extreme effort scenarios driven by the most and least limiting TAC for each fleet, rather than relying on the putative prediction of future fishing effort. The model builds on a fairly simple idea: the target fishing mortality for each stock can be translated into an equivalent level of fishing effort for each fleet–stock combination ("effort-by-stock"), assuming unchanged patterns of effort and catchability across metiers compared with the current situation (i.e. fishers would engage in the same metiers in the same relative proportions as before, and metiers would induce the same fishing mortality on stocks per unit of effort). Since each fleet can only have one unique amount of total effort over 1 year, various effort scenarios are contrasted. For example, for each fleet, fishing would stop when the catch for any one stock is taken ("Min" option) (Ulrich *et al.*, 2011; ICES, 2015b, see also the Supplementary Data). The "Min" option is the most conservative scenario, forecasting the underutilization of other stocks compared with their single-stock management objectives (F_{MSY} or LTMP target). Conversely, the "Max" option estimates catches above the single-stock fishing opportunities of most stocks if fleets would stop fishing when all catch shares are taken. Neither of these two options is considered entirely plausible under the current management framework where discarding is allowed. Rather, they frame the range of potential outcomes considering the fleet's decision options. An intermediate option is the "Value" option. This scenario accounts for the economic importance of each stock for each fleet, assuming that fleets might be more inclined to continue fishing until their most valuable quotas are exhausted. The effort by fleet is equal to the average of the efforts required to catch the fleet's stock shares, weighted by the relative importance of that stock for that fleet (in value). Although the validity of this proxy in an economic perspective has been questioned (Hoff *et al.*, 2010), this scenario is a convenient and computationally simple intermediate between the "Min" and the "Max" options in the absence of an accurate behaviour algorithm predicting future effort by fleet. It has also historically predicted effort levels reasonably close to the observed effort (Ulrich *et al.*, 2011).

Fcube was initially developed for deterministic mixed-fisheries, short-term forecasts of the catch levels resulting from any chosen scenario, but the model has been here extended to operate as a stochastic medium-term, management strategies evaluation (MSE, Butterworth and Punt, 1999) tool, with or without technical interactions (ICES, 2014; STECF, 2015b; see also the Supplementary Data). Parallel single-stock MSEs using standard FLR functions simulate the management procedure (HCR) where a TAC is defined every year based on a short-term forecast, mimicking the actual conditions of management advice where the true (realized) fishing mortality can differ from the target (intended) mortality (ICES, 2013). Uncertainty is introduced through variability of future recruitment. To limit computer time demands, additional sources of uncertainty such as observation, assessment, and implementation errors are not considered here, but they are optional plugs-in to the model. When technical interactions are not included, the projections are independent for each stock, and the Fcube module is not activated. When technical interactions are implemented, the vector of realized fishing mortality by stock is modified to account for implementation error in the form of over- or under-quota fishing mortality, according to the various Fcube options ("Min", "Max", or "Value"). This new vector of realized fishing mortality is then used to project the stocks in the operating model.

In this study, an optimization process was also developed that can, so far, be applied for a single-year, deterministic, short-term forecast. It identifies the set of fishing mortality by stock maximizing a given objective function ("what's best") rather than the usual ("what if") setup of Fcube (ICES, 2015e, see also the Supplementary Data). The aim was to search the vector of fishing mortality by stock within the F_{MSY} ranges that would minimize the mixed-fisheries imbalance. Here, the imbalance is defined as the catch difference between the Fcube Min and Max options (measured as the sum across stocks of squared differences in total tonnes), but other objective functions could be defined or constraints introduced. Imbalance is thus apprehended here in a management sense, referring to mismatches between the various single-stock TAC advice. Strong imbalance is interpreted as an increased risk of tensions within the fishing industry, of poorer implementation of management objectives, and of postponed recovery of the most exploited stocks (Kraak *et al.*, 2013; ICES, 2015b). The optimization was performed using a genetic algorithm, which is well suited for multiobjective problems and could easily be plugged onto the Fcube script.

Data and conditioning

The MSE-extended Fcube model presented here only involves medium-term projections for five North Sea stocks with full analytical assessment: (i) cod in the North Sea, Skagerrak, and Eastern Channel (COD); (ii) haddock in the North Sea, Skagerrak, and West of Scotland (HAD); (iii) saithe (*Pollachius virens*) in the North Sea, Skagerrak, Kattegat, and West of Scotland (POK); (iv) sole (*Solea solea*) in the North Sea (SOL); and (v) plaice (*Pleuronectes platessa*) in the North Sea (PLE). North Sea whiting (*Merlangius merlangus*) was not included because no reference point and MSY ranges have been defined for this stock (ICES, 2015b). The model is conditioned on the 2015 assessments and forecasts (ICES, 2015a) and the 2014 international catch and effort data by fleet and metier (ICES, 2015f). The stock–recruitment relationships used in the MSE are consistent with those used to derive F_{MSY} ranges (ICES, 2015d), using a "hockey stick" segmented regression model fitted on the entire time series, except for North Sea cod, where only the recent low recruitments (since 1988) are used as in ICES (2015a). Growth and selectivity parameters are fixed at the 2012–2014 average. The F_{MSY} ranges were taken from ICES (2015c) (Table 1).

The MSE presented here was run with 200 iterations over a 30-year period, but the main focus of the results presented is the

Table 1. Current target from the long-term management plan (LTMP), F_{MSY}, MSY F_{upper}, MSY F_{lower} for the five North Sea demersal stocks (ICES, 2015c), biomass reference points, and fishing mortality from the assessment (ICES, 2015g).

Stock	LTMP target	F_{MSY}	MSY F_{upper}	MSY F_{lower}	F_{2014}	MSY $B_{trigger}$ (t)	B_{lim} (t)
Cod	0.4	0.33	0.49	0.22	0.39	165 000	118 000
Haddock	0.3	0.37	0.52	0.25	0.24	88 000	63 000
Plaice	0.3	0.19	0.27	0.13	0.18	230 000	160 000
Saithe	0.3	0.32	0.43	0.20	0.30	200 000	106 000
Sole	0.2	0.2	0.37	0.11	0.25	37 000	25 000

Table 2. Summary of the various analyses and runs performed.

Analysis type	Simulation type	Projected years	No. of iterations	HCRs	Number of Fcube runs
Performance of single-stock HCR	Medium-term stochastic MSE without technical interactions	30	200	Current LTMP	1 (single-stock MSE)
				F_{MSY}	1 (single-stock MSE)
				MSY F_{lower}	1 (single-stock MSE)
				MSY F_{upper}	1 (single-stock MSE)
Robustness of HCR to mixed fisheries implementation error	Medium-term stochastic MSE with technical interactions	30	200	Constant effort	1 (all stocks together)
				Current LTMP	3 (Max, Min, Value)
				F_{MSY}	3 (Max, Min, Value)
				MSY F_{lower}	3 (Max, Min, Value)
				MSY F_{upper}	3 (Max, Min, Value)
Minimum imbalance	Optimization of 2016 fishing opportunities	2	1	MSY ranges	1 (Optim=minimized difference between Max and Min)
Impact assessment	Impact in 2016 of different HCR	2	1	F_{MSY}	1 (Value)
				F_{optim}	1 (Value)

short-term impact of the annual management advice. All runs presented assume a full implementation of the landing obligation, i.e. all catches are landed from 2016 on without changes of the catchability and selectivity patterns (ICES, 2015e; STECF, 2015b).

Analyses

Four evaluation aspects were analysed (summarized in Table 2):

(1) *Performance* of the different single-stock HCR without accounting for technical interactions. These runs are used as a baseline, and they also evaluate the short- and medium-term outcomes of the MSY ranges using the MSE, in comparison with the long-term outcomes estimated by ICES (2015e) using a different methodology. Four HCRs were compared for the five stocks: F_{MSY}, MSY F_{upper}, MSY F_{lower}, [all three with the ICES advice sliding rule, where the F target decreases linearly below MSY $B_{trigger}$ (ICES, 2015g)], and current single-stock management plans [LTMP, including the respective sliding rules where appropriate (ICES, 2015f)].

(2) *Robustness* of these four HCRs to mixed-fisheries implementation error, where the true catches for each stock differ from the expected catches due to quota over- or under-shoots. For each HCR, three Fcube options were run (“Min”, “Max”, “Value”). In addition, a run was performed fixing fishing effort at its 2014 level (“Sq_E”), thus assuming constant fishing mortality. The outcomes of this analysis are compared for the level of imbalance and risk in the system under different target fishing mortalities.

(3) *Minimum imbalance.* The optimization module was used to identify which vector of target fishing mortalities in 2016 within the MSY ranges would minimize the mixed-fisheries imbalance in the deterministic short-term forecast setup as used in ICES (2015b). In this forecast, the fleets' effort in the intermediate year (2015) is set at its 2014 value, and the Fcube options are only applied for 2016. The resulting vector of fishing mortalities is referred to as F_{optim}.

(4) *Impact assessment* of the different HCR on stocks and fleets accounting for technical interactions, performed using the “Value” Fcube scenario with the same forecast setup as above (ICES, 2015c; STECF, 2015b). In particular, the consequences of applying TACs based on the F_{MSY} point estimate in 2016 is compared with those resulting from the F_{optim} values.

Results

Medium-term performance of single-stock HCRs

The current LTMP targets and HCR bear low risks for all stocks (Figure 1). But they are not fully consistent with the CFP objectives, leading to fishing mortalities sometimes higher and sometimes lower than F_{MSY}.

Using the MSY F_{upper} mortality values in our medium-term MSE appeared potentially risky, mainly for sole and saithe, with more than 5% risk to fall below B_{lim} in 2020. This is higher than the risk identified in the long-term stochastic projections from ICES (2015c) which considered large fluctuations across several generations. The risk of falling below MSY $B_{trigger}$ is also very high for these two stocks (ca. 40% in 2020), implying increased interannual variability in the advised fishing opportunities including frequent TAC reductions to rebuild the stock above MSY $B_{trigger}$, and higher dependency of the biomass on incoming year classes.

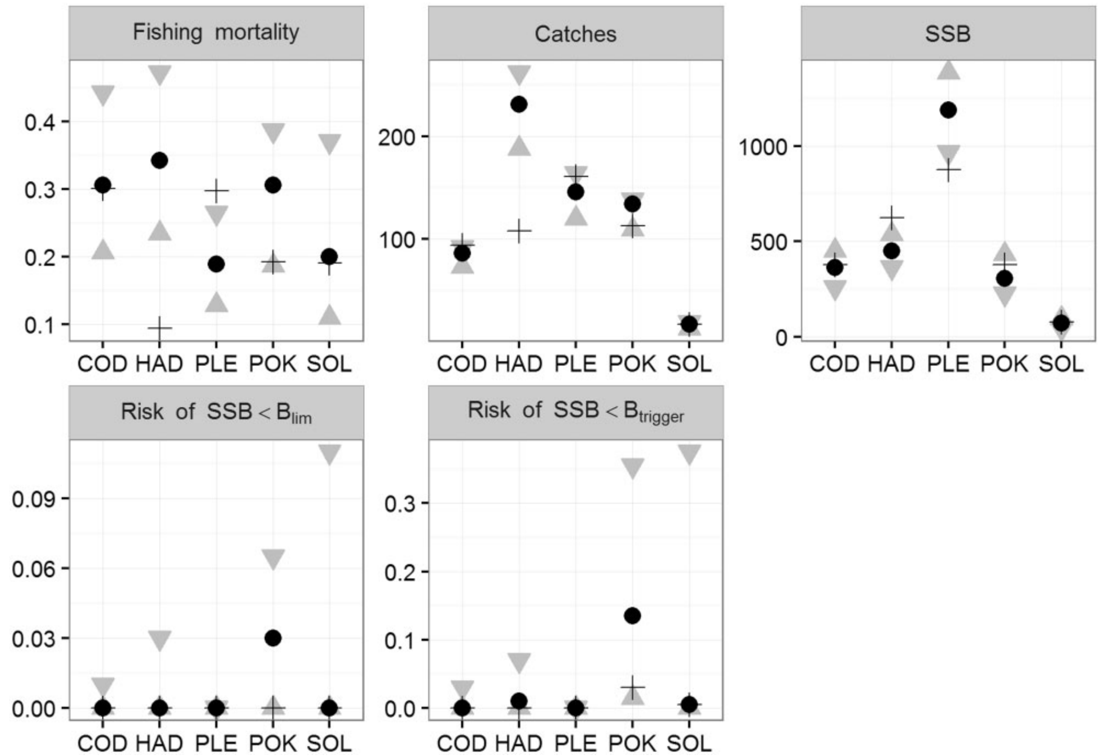

Figure 1. Diagnostics in 2020 by stock, single-stock MSE without technical interactions. Median values of fishing mortality, catches ('000 t), and SSB ('000 t), and risk of falling below MSY B_{trigger} and B_{lim}. Black circle: F_{MSY}. Downward triangle: MSY F_{upper}. Upward triangle: MSY F_{lower}. Cross: current LTMP. Scales differ between Figures 1 and 2. COD, cod; HAD, haddock; PLE, plaice; POK, saithe; SOL, sole.

In accordance with the "pretty good yield" concept, it is observed that, for most stocks except haddock, landings levels in 2020 are fairly similar across the range of fishing mortality targets, but arising from large differences in the underlying biomass (Figure 1).

Medium-term robustness of the single-stock HCR to mixed-fisheries implementation error

The robustness of the HCR is primarily investigated by inspecting the worst case "Max" option. In these simulations, high effort increases lead to increases in fishing mortality for all stocks except the least limiting ones, such as plaice and haddock (Figure 2). Interestingly, the risk to the stocks is higher with the current set of LTMP HCR than with MSY F_{upper}. This result arises from the fact that plaice is the least limiting stock for many fleets, and is also the only stock for which MSY F_{upper} is lower than the current LTMP target, so fishing effort for all fleets catching plaice is comparatively higher with the LTMP target, thus inducing higher fishing mortality for all other stocks. In comparison, setting the target at F_{MSY} is robust to mixed-fisheries interactions, as the risk of falling fall below B_{lim} remains low for all stocks, even in the "Max" option.

When the F_{MSY} point estimate is used as a management target, the results obtained from the Fcube scenarios "Max" and, to a lesser extent, also "Value" are close to those obtained with the "*status quo* effort" ("Sq_E") option (Table 3). Indeed, many options provide fairly similar yield. In 2020, most scenarios display a total yield within [−20, +10]% of the sum of the single-stock projections at F_{MSY} (Table 3), which itself is almost twice the level of 2014 catches for these five stocks. This means that for any of the considered targets, preventing short-term increases in fishing mortality would largely pay off within a few years through increased landings from larger stocks.

Minimum imbalance within the MSY ranges

The optimization algorithm converged rapidly to reach a stable solution. The optimal fishing mortality values obtained (Figure 3) were close to the lower bound of the F_{MSY} range for haddock and plaice, while they were higher than the F_{MSY} value for cod, saithe, and sole, approximately halfway between F_{MSY} and MSY F_{upper}. It is noticeable that the 2016 F_{optim} values were fairly close to current (2014) fishing mortalities. This is in accordance with the latest mixed fisheries advice (ICES, 2015b), which underlined that the North Sea fisheries were in better balance in 2014 than in the previous decade, with cod no longer estimated to be the most limiting stock.

The Fcube model was run again to compare the single-stock advice based on either the F_{MSY} point estimates or F_{optim} (Figure 4). The differences in the 2016 single-stock advice (horizontal lines on Figure 4) are direct consequences of the different vectors of target fishing mortality (Table 4, columns 3 and 7). Projections based on the optimized F values resulted in larger TACs for cod, saithe, and sole and smaller TACs for plaice and haddock. Plaice is the least limiting stock, inducing the largest effort to fully catch the TAC. With F_{optim}, the "effort-by-stock" required for catching the plaice TAC became smaller, while the effort needed to take the TACs for cod, saithe, and sole became larger. Consequently, the overall TAC overshoot in the "Max" scenario was smaller than for the single-species F_{MSY} point estimate projection. Conversely, in the "Min" scenario, the limiting TAC (for sole) became higher, and the largest TACs became reduced, leading to the overall magnitude of the TAC under-consumption being reduced. The overall difference in the predicted 2016 catches between the "Max" and "Min" scenarios is thus much smaller when the single-species TACs are given based on the F_{optim} values, reflecting a balance between the most and the least productive stocks. Incidentally, the "Min" option returned less quota undershoot than with a constant effort at 2014 level, indicating very little risk of a "choke" effect of a given stock compared with the current situation of the fishery.

Short-term impact assessment of the different management scenarios on stocks and fleets

The potential effect of using the optimized F values within the F_{MSY} range rather than the F_{MSY} point estimate in 2016 were investigated, using the Fcube "Value" scenario (Figure 5). For most countries, the outcomes in 2016 would be within 20% of the 2015 levels (with effort in 2015 assumed equal to 2014 in the short-term forecast), and F_{optim} would lead to slightly higher catches than with F_{MSY}. For haddock, both F_{optim} and F_{MSY} are greater than the most recently assessed F (Figure 3) and with F_{MSY} higher than F_{optim}. The impact of the higher (target) Fs in 2016 can be seen in the results for Scotland being above 1, as haddock forms a large proportion of the national fleet catch (Figure 5). For plaice, F_{optim} is lower than F_{MSY} and the most recently assessed F; therefore, the effect of changing to F_{optim} is negative for fleets catching plaice. However, this impact assessment assumes full uptake of TACs, which has not happened for North Sea plaice since 2010; therefore, it is likely that the actual F will be below F_{MSY} in 2016.

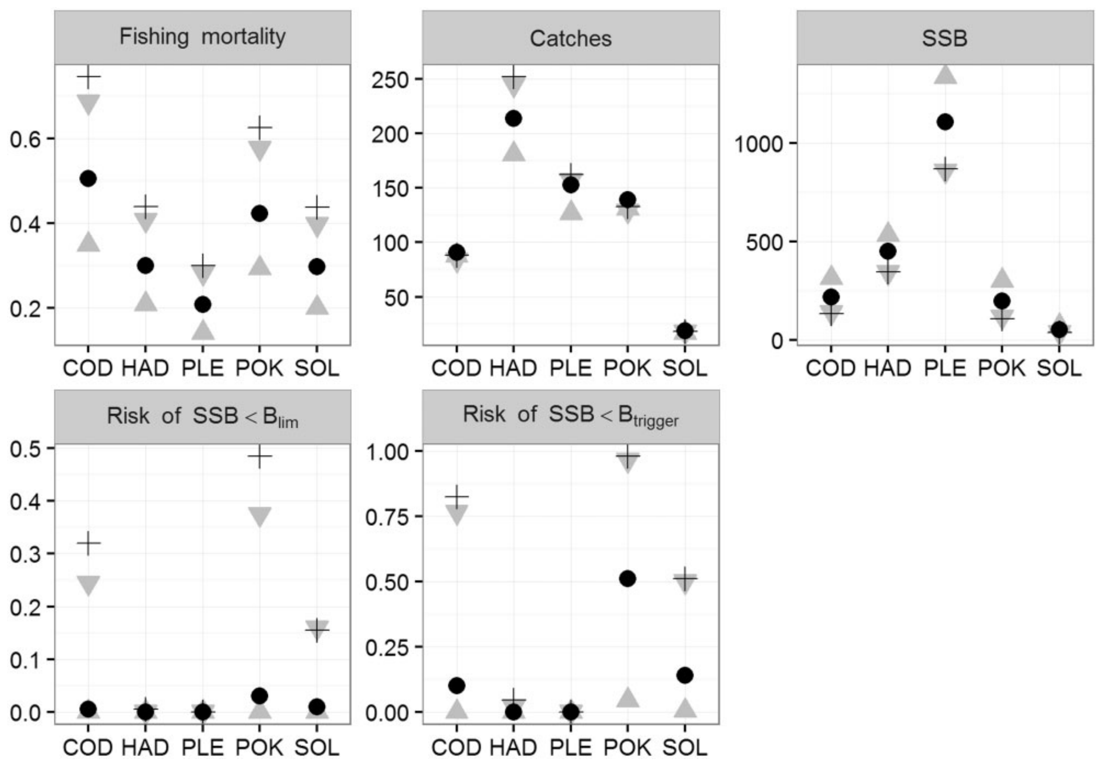

Figure 2. Diagnostics in 2020 by stock, single-stock MSE with Fcube Max technical interactions assuming an imperfect implementation of the landing obligation and that all quotas are fished out. Catches and SSB in '000 t. Black circle: F_{MSY}. Downward triangle: MSY F_{upper}. Upward triangle: MSY F_{lower}. Cross: current LTMP. Scales differ between Figures 1 and 2. COD, cod; HAD, haddock; PLE, plaice; POK, saithe; SOL, sole.

Table 3. Median catch (tonnes) 2020 by stock for different target F, with or without Fcube technical interactions included.

HCR		Current LTMP				MSY F_{lower}				F_{MSY}				MSY F_{upper}				
Stock	Sq-E	SS	Max	Min	Value	SS	Max	Min	Value	SS	Max	Min	Value	SS	Max	Min	Value	2014
Cod	91 005	93 804	87 817	38 411	87 617	72 754	87 848	59 911	77 345	86 211	91 249	76 360	89 058	91 872	83 639	81 422	93 075	45 266
Haddock	197 482	107 913	252 288	66 341	140 445	187 659	181 113	93 749	132 500	230 545	214 066	131 553	171 737	261 704	244 841	148 286	205 801	46 317
Plaice	145 173	161 334	161 722	45 147	148 340	120 118	127 409	64 588	101 612	146 332	153 319	80 897	133 540	163 515	157 065	86 350	156 931	133 623
Saithe	130 459	112 750	132 538	57 867	121 766	108 755	131 481	96 085	109 030	134 381	139 456	111 186	129 980	138 472	129 230	114 488	136 344	75 176
Sole	18 496	16 734	18 241	7 103	18 329	12 957	17 127	8 576	14367	17 040	18 555	9 364	17 596	19 033	17 778	9 598	18 692	12 758
Total	582 615	492 535	652 606	214 869	516 497	502 243	544 978	322 909	434854	614 509	616 645	409 360	541 911	674 596	632 553	440 144	610 843	313 140
Ratio to baseline	0.95	0.80	1.06	0.35	0.84	0.82	0.89	0.53	0.71	1.00	1.00	0.67	0.88	1.10	1.03	0.72	0.99	0.51

Sq-E, scenario of constant fishing effort at 2014 level; SS, single-stock projection without technical interactions; Max, Min, Value, Fcube options. Catches in 2014 are also displayed. The last line is the ratio between total landings by column and the total landings for the single-stock F_{MSY} scenario.

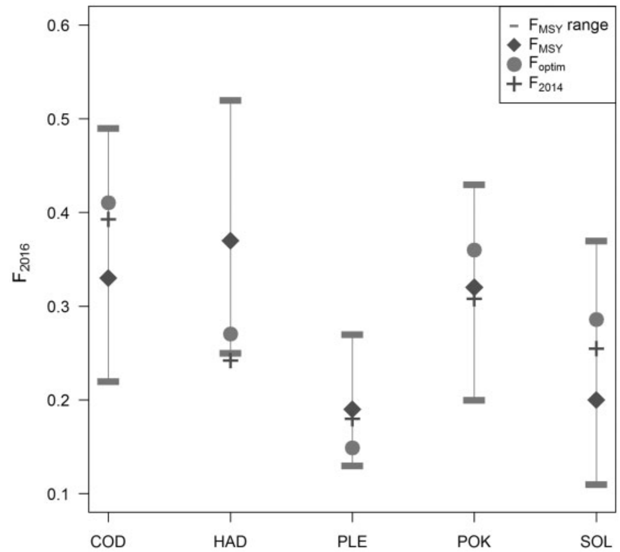

Figure 3. Fishing mortality by stock: F_{MSY}, F_{MSY} ranges, F_{2014}, and F_{optim} in 2016. COD, cod; HAD, haddock; PLE, plaice; POK, saithe; SOL, sole.

Discussion

The work presented here is the outcome of a process developed over several years, where scientists, managers, and stakeholders have together matured new conceptual thinking on the design of mixed-fisheries management plans (STECF, 2015b; Kempf *et al.*, 2016). This new thinking has been shaped by the various institutional, legal, and social constraints within the European fisheries management system, which are more complex than in other regions in the world (Marchal *et al.*, 2016). MSY is the overall objective stated in the basic regulation, but the need to account for mixed fisheries and ecosystem interactions is also written into the law (Article 9 in EU, 2013). Scientific evidence has accumulated since the 1970s to show that MSY is inherently variable and difficult to define, not only due to multispecies and mixed-fisheries interactions (Mackinson *et al.*, 2009), but even in the narrow single-stock approach (Larkin, 1977; Mace, 2001), where productivity and growth of fish populations are constantly changing. In addition, the agreement between the Council of Ministers and the EU Parliament resulted in the removal of binding harvest control rules in order to maintain some room for political flexibility in the annual TAC negotiations (EU, 2014). As a consequence, identifying ranges of fishing mortality around F_{MSY} has emerged as a pragmatic fisheries management approach integrating these institutional and ecological constraints (Rindorf *et al.*, 2016), potentially allowing some flexibility in decision-making within the framework of MSY and the precautionary objectives (STECF, 2015b). The present work is intended to inform this debate on the potential challenges, risks, and opportunities for moving along this path and hopefully to contribute to informed decision-making for the management plans in development.

In banning discards, the European institutions hope to trigger bottom–up mechanisms of adaptation through changes in fishing

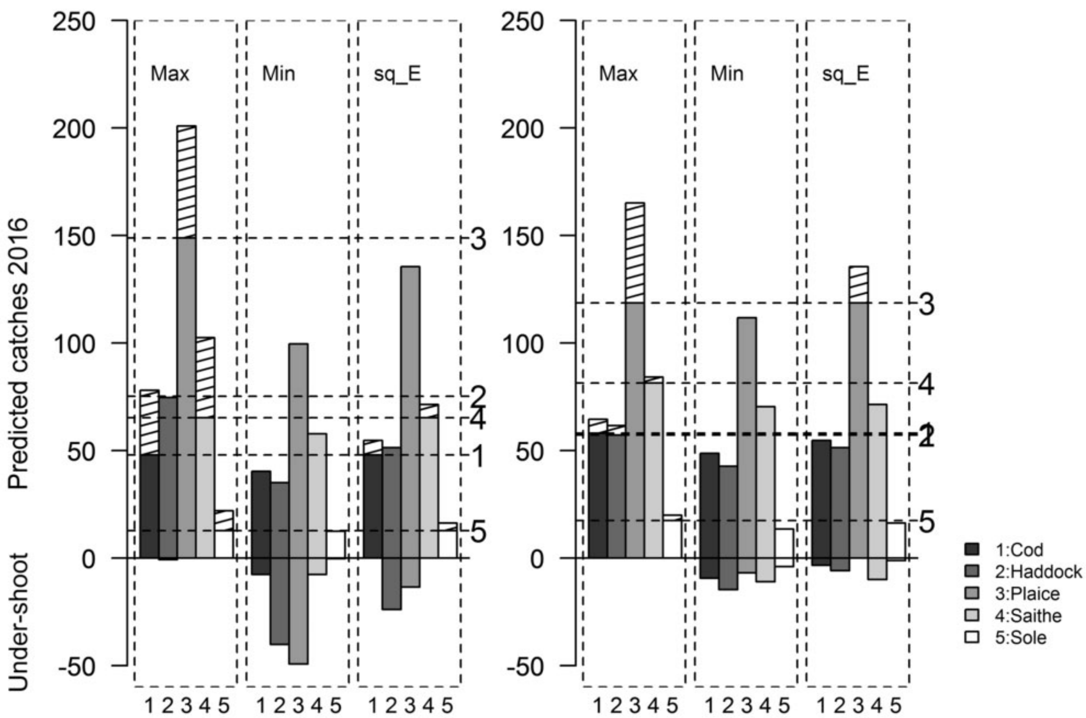

Figure 4. North Sea mixed-fisheries projections for 2016 following standard display as in (ICES, 2015b). Fcube options Max, Min, and Status Quo effort at 2014 level. Left: F_{MSY} target. Right: F_{optim} target. Estimates of potential catches (in tonnes) by stock and by scenario. Horizontal lines correspond to the single-stock projection with the given target, with each number corresponding to a stock. Bars below the value of zero show undershoot (compared with single-stock) where catches are predicted to be lower when applying the Fcube option. Hatched columns represent catches in overshoot of the single-stock projection.

Table 4. Outcomes of short-term forecast for different HCR in 2016.

Stock	Value	F_{MSY}	F_{upper}	F_{lower}	LTMP	F_{optim}
Cod	*F* 2016	0.327	0.486	0.218	0.33	0.411
	Catches 2016	47 907	66 761	33 406	48 270	58 128
	SSB 2017	176 835	155 878	193 217	176 427	165 421
Haddock	*F* 2016	0.37	0.52	0.25	0.37	0.27
	Catches 2016	75 273	99 814	53 361	75 683	57 248
	SSB 2017	194 152	170 175	215 992	195 109	212 090
Plaice	*F* 2016	0.19	0.27	0.13	0.293	0.149
	Catches 2016	148 906	204 667	104 502	220 074	118 565
	SSB 2017	1 026 413	970 244	1 071 238	954 750	1 057 032
Saithe	*F* 2016	0.278	0.373	0.173	0.298	0.36
	Catches 2016	65 285	83 782	42 953	68 600	81 360
	SSB 2017	174 417	157 669	194 832	168 129	159 853
Sole	*F* 2016	0.2	0.37	0.11	0.2	0.286
	Catches 2016	12 804	21 534	7 419	12 834	17 420
	SSB 2017	53 920	45 057	59 410	54 027	49 226

Catches and SSB in tonnes.

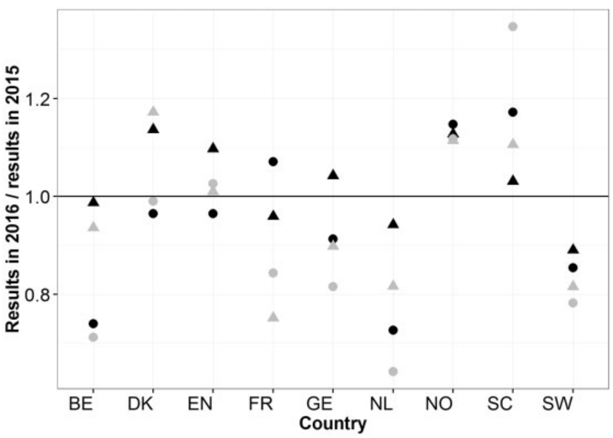

Figure 5. Impact of the alternative target *F* (Grey: F_{MSY} target. Black: F_{optim} target) in 2016 on the potential landings (dots) and effort (triangles) of all fleets by country (Scotland displayed separately from England), compared with the projected 2015 level (with effort in 2015 = effort in 2014), using Fcube "Value" scenario. BE, Belgium; DK, Denmark; EN, England; FR, France; GE, Germany; NL, Netherlands; NO, Norway; SC, Scotland; SW, Sweden.

practices and uptake of more selective gears by the fishing industry. However, the paths that this adaptation will take are still uncertain at present, depending whether the proper incentives will be activated towards more selective fishing (Condie *et al.*, 2014; Sigurðardóttir *et al.*, 2015; de Vos *et al.*, 2016). Before this adaptation has fully taken place, it is possible that discarding will continue to take place illegally and unreported under the limited capacity of control. Therefore, it is also necessary to develop top–down mechanisms addressing the factors that lead to over-quota discarding in order to relax some of the sources of pressure. The ideas presented here have explored operational options to reconcile single-stock management objectives in the mixed-fisheries context. These are mainly useful when one or more important commercial stocks are less productive and require managers to make important trade-offs between conservation and exploitation of healthier stocks. Here, we suggest that applying annual sets of cohesive TACs defined within the range may build a path towards progressively achieving fishing mortality objectives by improving the governance around the setting of TACs. The basic idea of this regional mixed-fisheries approach is to avoid situations where TAC increases for one stock and decreases for another stock if these are caught together. Such a situation has prevailed for a long time in the North Sea because of the poor status of the cod stock, triggering the development of the approach presented here. In 2015, though, the situation had become more balanced, with many stocks now exploited at fishing mortality close to F_{MSY} and within the MSY ranges (ICES, 2015a). This may be a consequence of the management initiatives launched to avoid cod catches, although it is very difficult to demonstrate any sort of causal relationship (Holmes *et al.*, 2011). In a perfectly balanced situation, F_{optim} and F_{MSY} would be the same. If the system was strongly out of balance, the F_{optim} values would be returned at the limits of the F_{MSY} ranges, at the upper limit for the more overexploited stocks, and at the lower limit for the healthier stock(s).

MSY ranges are a controversial concept. On the one hand, the ranges may provide an explicit precautionary bound for political negotiations within the CFP framework. On the other hand, the major caveat of providing ranges for fishing mortality as an operational management target is the risk that managers and stakeholders may systematically and blindly set TACs at the upper limit of the range of the advice for each stock. This may occasionally satisfy short-term, socio-economic goals. However, such a strategy would maintain higher fishing pressure on all stocks, slowing or reversing the recovery of the least productive stocks, thus prolonging the period where these stocks may limit the entire fishery. Furthermore, this would not solve the imbalance problem. The same inconsistencies and drivers of over-quota discarding that exist with F_{MSY} point estimates would still prevail, though now at lower biomass and higher fishing levels, which ultimately lead to greater ecosystem risk in the long-term with little benefit in terms of additional yield. F_{MSY} may remain the primary reference point for single-stock fishing opportunities, but the ranges would be best used by managers as a flexible buffer to reduce the annual imbalance effects and enhance compliance and controllability. The approach presented here is independent of the actual definition of MSY ranges, and could be applied to any defined interval. Ultimately, the concept of ranges could be extended and potentially asymmetrized to include other ecological and economic considerations (Rindorf *et al.*, 2016).

The MSE results obtained here were, in this sense, more pessimistic than the outcomes of ICES (2015c). While ICES (2015c) identified MSY F_{upper} as having a low risk to the biomass in the long-term, we obtained much higher risks in the short- and medium-term for some stocks. The scope, assumptions, and incorporation of uncertainty differ between the present MSE and the model (called EqSim) used by ICES (2015d), so it is difficult at this stage to ascertain what is causing this difference and which of these models capture the most likely outcome. But this highlights the need for caution against the use of MSY F_{upper} as a management target, even more so when technical interactions occur. Particular attention should be paid to mixed-fisheries stocks in subsequent years in order to prevent undesirable increases in fishing mortality if productivity is below average or deviates from the long-term assumptions. This also highlights the uncertainties linked with any projection model, especially when complex interactions occur. There are many assumptions which may lead to quite different outcomes on what is the optimum target and how to get there (Mackinson *et al.*, 2009; Kempf *et al.*, 2016), and this problem is generic to any mixed-fisheries model. Above all, the likely future changes in fishers' behaviour and fishing patterns will always remain the largest unknown (Fulton *et al.*, 2011). The medium-term results presented here included only a limited set of uncertainty and variability. Adding other sources may not affect the general patterns, but would affect the perception of risks. In particular, uncertainty regarding future fleets' catchability has been highlighted as another important parameter to include in future projections (Iriondo *et al.*, 2012).

Ultimately, this reinforces the idea that avoiding risks ("staying away from where we do not want to be") should be prioritized over achieving a given optimum ("being where it is exactly best") (Degnbol, 2015; Hilborn *et al.*, 2015). The emergent thinking around what could be appropriate and applicable management targets and limits for the demersal fisheries in the North Sea shall be seen as an attempt to formalize and operationalize this approach in an objective and pragmatic manner, generically applicable to other complex mixed-multispecies fisheries.

Supplementary data

The Supplementary material available at the *ICESJMS* online version of this article includes additional information on the Fcube model, forecasting, scenarios, Fcube as part of a stochastic MSE, and Fcube with optimization.

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