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

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Abstract :

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 FMSY that would allow for more flexibility in management targets. This article investigates the potential of FMSY 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 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 multi-level 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 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 operationalised into multi-annual 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 an 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 log-books, so the only estimates for it has 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 fifteen years. Fisheries targeting North Sea haddock (*Melanogrammus aeglefinus*), have contributed to a decline of 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 incentivise cod avoidance in the latter half of the decade, such as Catch Quota Management with Fully Documented Fisheries (Needle *et al.*, 2015; van Helmond *et al.*, 2015; Ulrich *et al.*, 2015) and Real-Time Closures (Holmes *et al.*, 2011; Little *et al.*, 2014).

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, 2015c), 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 though start showing 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, 2013).

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: the achievement of an exploitation rate consistent with Maximum Sustainable Yield (F_{MSY}) at the latest by 2020 for all stocks; the establishment of regional mixed-fisheries multi-annual plans; and the 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 five years without additional effort reductions and/or major changes in current fishing practices.

Recognising 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 to use 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 multi-dimensional area rather than a point estimate. The International Council for the Exploration of the Sea (ICES, 2015b,f) 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 (2015b) 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, 2015c,d,e). 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; Gourget *et al.*, 2016).

Material and Methods

FCube modelling framework

The FCube model (Ulrich *et al.*, 2011; see also in the Appendix) 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, 2015e). 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, 2015c). 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 to 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 one 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, 2015c, see also in the Appendix). The "Min" option is the most conservative scenario, forecasting the underutilization of other stocks compared to 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 are 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 & Punt, 1999) tool, with or without technical interactions (ICES, 2014; STECF, 2015b; see also in the Appendix). 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 (realised) 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 realised fishing mortality by stock is modified to account for implementation error in the form of over – or underquota fishing mortality, according to the various FCube options ("Min", "Max" or "Value"). This new vector of realised fishing mortality is then used to project the stocks in the operating model.

In this study, an optimisation 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 maximising a given objective function ("what‟s best") rather than the usual ("what if") set-up of FCube (ICES, 2015d, see also in the Appendix). The aim was to search the vector of fishing mortality by stock within the F_{MSY} ranges that would minimise 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, 2015c). The optimisation was performed using a genetic algorithm, which is well suited for multi-objective problems and could easily be plugged onto the FCube script.

Data and conditioning

The MSE-extended FCube model presented here only involve medium-term projections for five North Sea stocks with full analytical assessment: Cod in the North Sea, Skagerrak and Eastern Channel

(COD); Haddock in the North Sea, Skagerrak and West of Scotland (HAD); Saithe *Pollachius virens* in the North Sea, Skagerrak, Kattegat and West of Scotland (POK); Sole *Solea solea* in the North Sea (SOL); Plaice *Pleuronectes platessa* in the North Sea (PLE). North Sea whiting was not included as 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, 2015e). The stock recruitment relationships used in the MSE are consistent with those used to derive F_{MSY} ranges (ICES, 2015f), 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 (2015b) (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 short-term impact of the annual management advice. All runs presented assume a full implementation of the landings obligation i.e. all catches are landed from 2016 on, without changes of the catchability and selectivity patterns (ICES, 2015d; STECF, 2015b).

Analyses

Four evaluation aspects were analysed (summarised 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 (2015d) 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, 2015e)).

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 optimisation module was used to identify which vector of target fishing mortalities in 2016 within the MSY ranges would minimise the mixed-fisheries imbalance, in the deterministic short-term forecast setup as used in ICES (2015c). 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, 2015b; STECF, 2015b). In particular, the consequences of applying TACs based on F_{MSY} point estimate in 2016 is compared with those resulting from the F_{optim} values.

Results

Medium-term performance of single-stocks 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 (2015b) which considered large fluctuations across several generations. The risk of falling below MSY $B_{trigger}$ is also very high for these two stocks (around 40% in 2020), implying increased inter-annual 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.

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 of 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 optimisation 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, 2015c), 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 optimised 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. In consequence 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 to 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 optimised 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, and therefore it is likely that the actual F will be below F_{MSY} in 2016.

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 in the law (Article 9 in EU 2013). Scientific evidence has accumulated since the seventies to show that MSY is inherently variable and difficult to define, not only due to multi-species and mixed-fisheries interactions (Mackinson *et al.* 2009; Thorpe *et al.* In review), but even in the narrow single-stock approach (Larkin, 1977; Mace, 2001), where the productivity and the 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, Mumford, *et al.*, submitted), 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 of 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 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 on whether the proper incentives will be activated towards more selective fishing or not (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 overquota 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 TACs setting. The basic idea of this regional mixed-fisheries approach is to avoid the situations where the 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 overquota 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 (Thorpe *et al,* In review). 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 asymmetrised 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 (2015b). While ICES (2015b) 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 (2015f), 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 the next years, in order to prevent undesirable increases of fishing mortality if productivity is below average or deviate from the long term assumptions. This highlights also 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 (Kempf *et al.* 2016.; Mackinson *et al.* 2009), 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, the uncertainty on 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 prioritised 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 formalise and operationalise this approach in an objective and pragmatic manner, generically applicable to other complex mixed-multispecies fisheries.

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Stock	LTMP target	F_{MSY}	MSY F_{upper}	MSY F_{lower}	F2014	MSY $B_{trigger}$	B_{lim}
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 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 2015b), biomass reference points and current fishing mortality from the latest assessment (ICES 2015g)

Analysis type	Simulation type	Projected years	iterations	HCRs	Number of FCube runs
Performance of single-stock HCR	Medium term stochastic MSE without technical interactions	30 years	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 years	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	Optimisation of 2016 fishing opportunities	2 years	1	MSY ranges	1 (Optim = minimised difference between Max and Min)
Impact Assessment	Impact in 2016 of different HCR	2 years	1	F_{MSY}	1 (Value)
				F_{optim}	1 (Value)

Table 2. Summary of the various analyses and runs performed

HCR	sq-E	current LTMP				MSY F_{lower}				F_{MSY}				MSY F_{upper}				2014
Stock		SS	Max	Min	Value	SS	Max	Min	Value	SS	Max	Min	Value	SS	Max	Min	Value	
COD	91005	93804	87817	38411	87617	72754	87848	59911	77345	86211	91249	76360	89058	91872	83639	81422	93075	45266
HAD	197482	107913	252288	66341	140445	187659	181113	93749	132500	230545	214066	131553	171737	261704	244841	148286	205801	46317
PLE	145173	161334	161722	45147	148340	120118	127409	64588	101612	146332	153319	80897	133540	163515	157065	86350	156931	133623
POK	130459	112750	132538	57867	121766	108755	131481	96085	109030	134381	139456	111186	129980	138472	129230	114488	136344	75176
SOL	18496	16734	18241	7103	18329	12957	17127	8576	14367	17040	18555	9364	17596	19033	17778	9598	18692	12758
Total	582615	492535	652606	214869	516497	502243	544978	322909	434854	614509	616645	409360	541911	674596	632553	440144	610843	313140
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

Table 3 – Median catch 2020 by stock for different target F, with or without FCube technical interactions included. Sq-E : scenario of constant fishing effort at 2014 level. SS : single-stock projection without technical interactions. Max, Min, Value : FCube options. Catch 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.

Stock	Value	F_{MSY}	F_{upper}	F_{lower}	LTMP	F_{optim}
COD	F 2016	0.327	0.486	0.218	0.33	0.411
COD	catches 2016	47907	66761	33406	48270	58128
COD	SSB 2017	176835	155878	193217	176427	165421
HAD	F 2016	0.37	0.52	0.25	0.37	0.27
HAD	catches 2016	75273	99814	53361	75683	57248
HAD	SSB 2017	194152	170175	215992	195109	212090
PLE	F 2016	0.19	0.27	0.13	0.293	0.149
PLE	catches 2016	148906	204667	104502	220074	118565
PLE	SSB 2017	1026413	970244	1071238	954750	1057032
POK	F 2016	0.278	0.373	0.173	0.298	0.36
POK	catches 2016	65285	83782	42953	68600	81360
POK	SSB 2017	174417	157669	194832	168129	159853
SOL	F 2016	0.2	0.37	0.11	0.2	0.286
SOL	catches 2016	12804	21534	7419	12834	17420
SOL	SSB 2017	53920	45057	59410	54027	49226

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

List of Figures

BE = Belgium, DK = Denmark, EN = England, FR = France, GE = Germany, NL = Netherlands, NO = Norway, SC = Scotland, SW = Sweden.

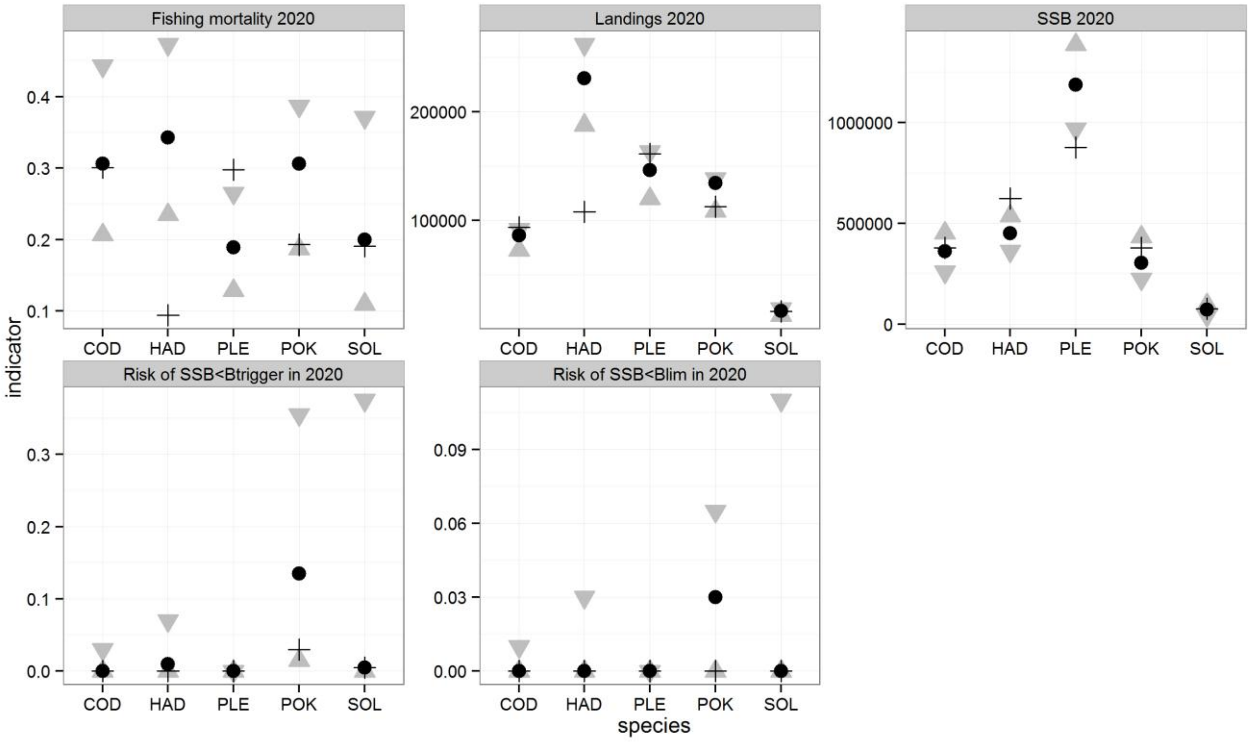

Figure 1. Diagnostics in 2020, single-stock MSE without technical interactions. Median values of fishing mortality, landings and SSB, and risk of falling below MSY $B_{trigger}$ and B_{lim}. Black circle: F_{MSY}. Downward triangle: MSY F_{upper}. Upward triangle: MSY F_{lower}. Cross: current LTMP. Scales differ between Figure 1 and Figure 2

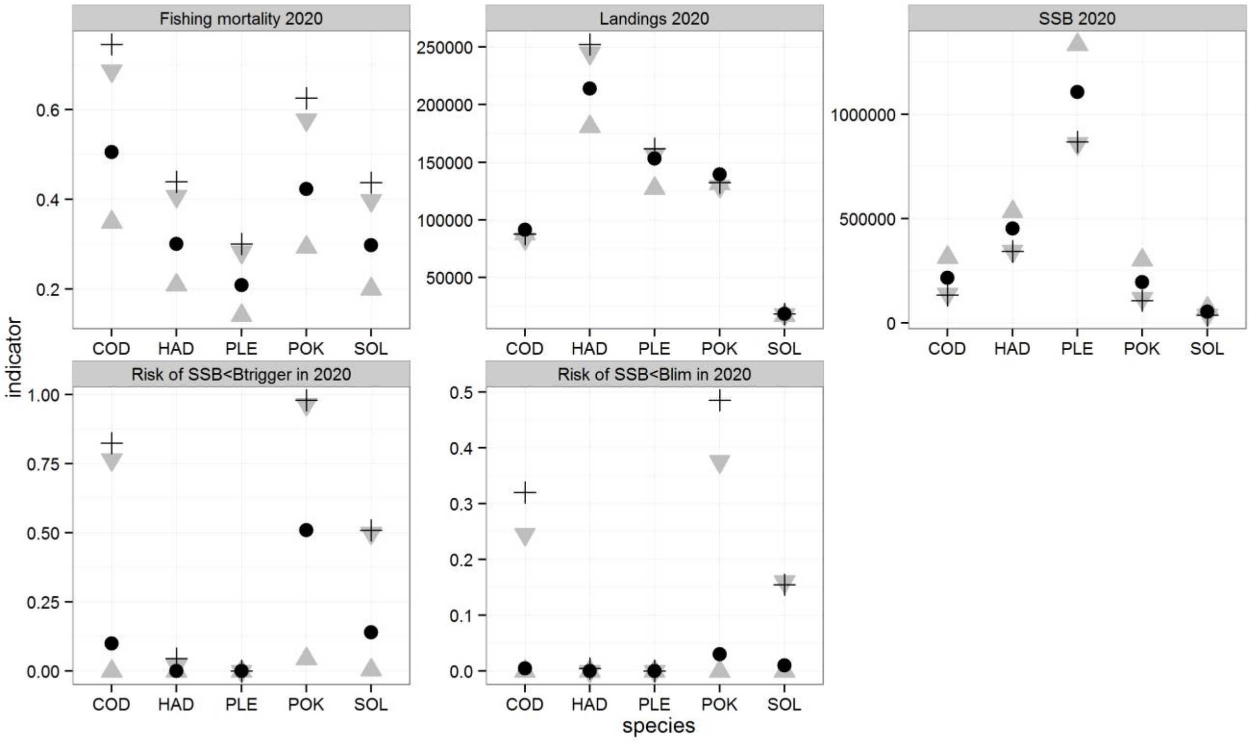

Figure 2. Diagnostics in 2020, single-stock MSE with FCube Max technical interactions assuming an imperfect implementation of the landing obligation and that all quotas are fished out. Black circle: F_{MSY}. Downward triangle: MSY F_{upper}. Upward triangle: MSY F_{lower}. Cross: current LTMP. Scales differ between Figure 1 and Figure 2

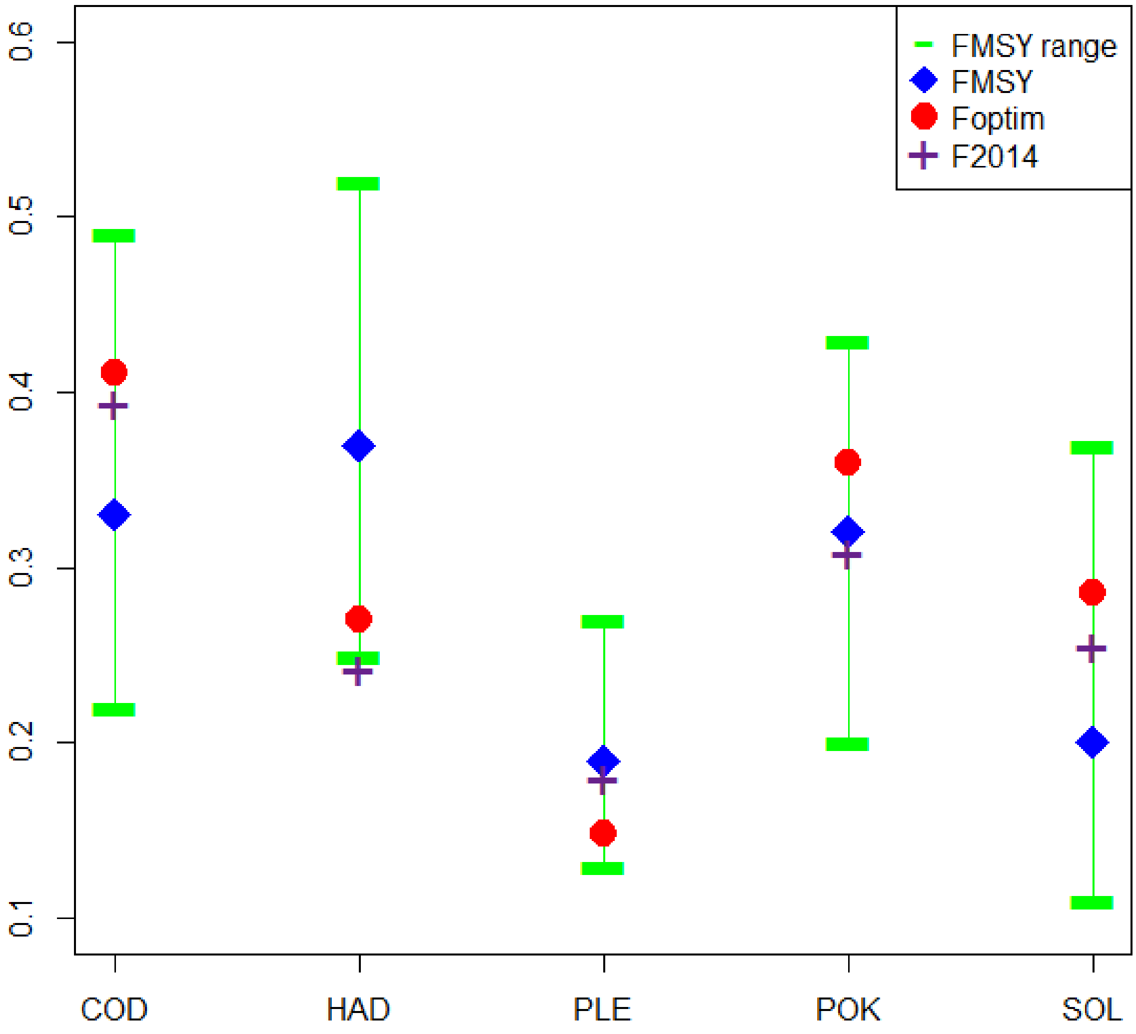

Figure 3. Fishing mortality by stock: F_{MSY}, F_{MSY} ranges, F_{2014} and F_{optim} in 2016.

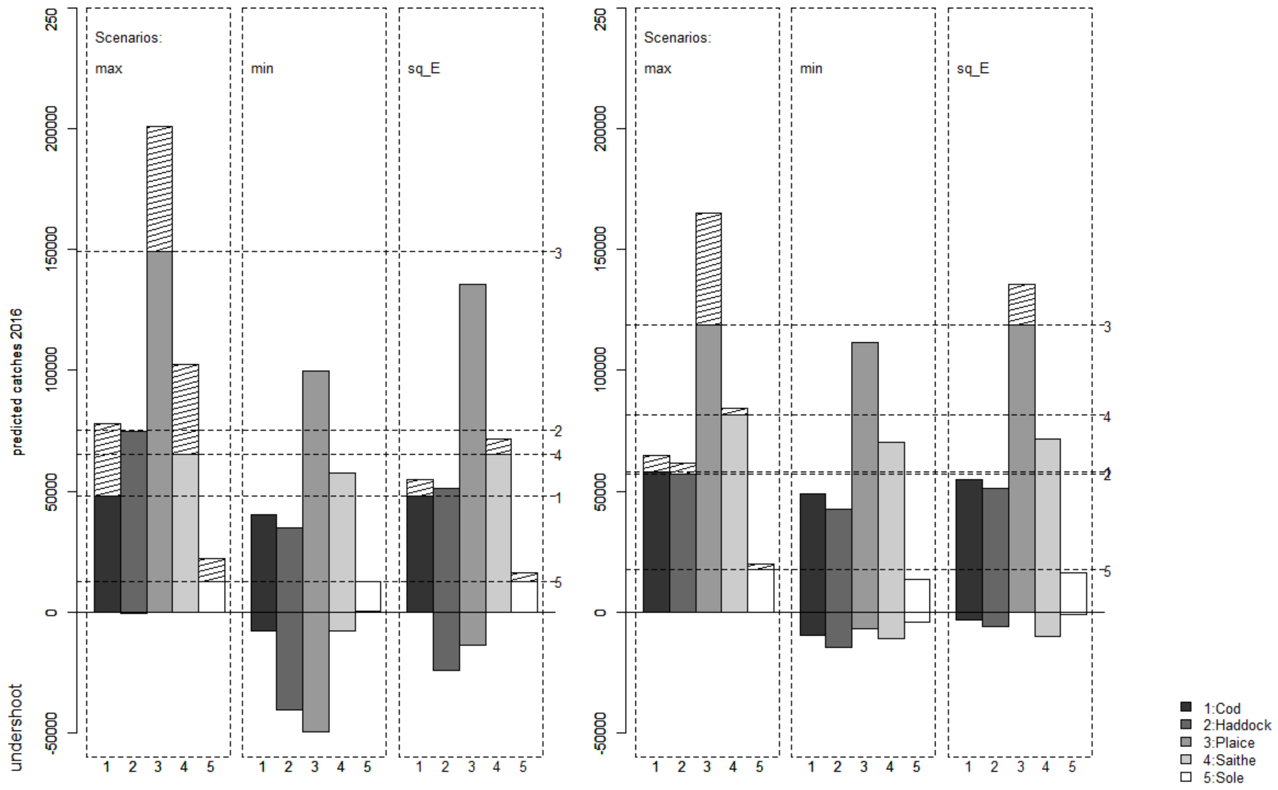

Figure 4. North Sea mixed fisheries projections for 2016, following standard display as in ICES (2015c). FCube options Max, Min and Status-Quo effort at 2014 level. Left F_{MSY} target. Right: F_{optim} target. Estimates of potential catches (in tonnes) by stock and by scenario. Horizontal lines correspond 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 to 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.

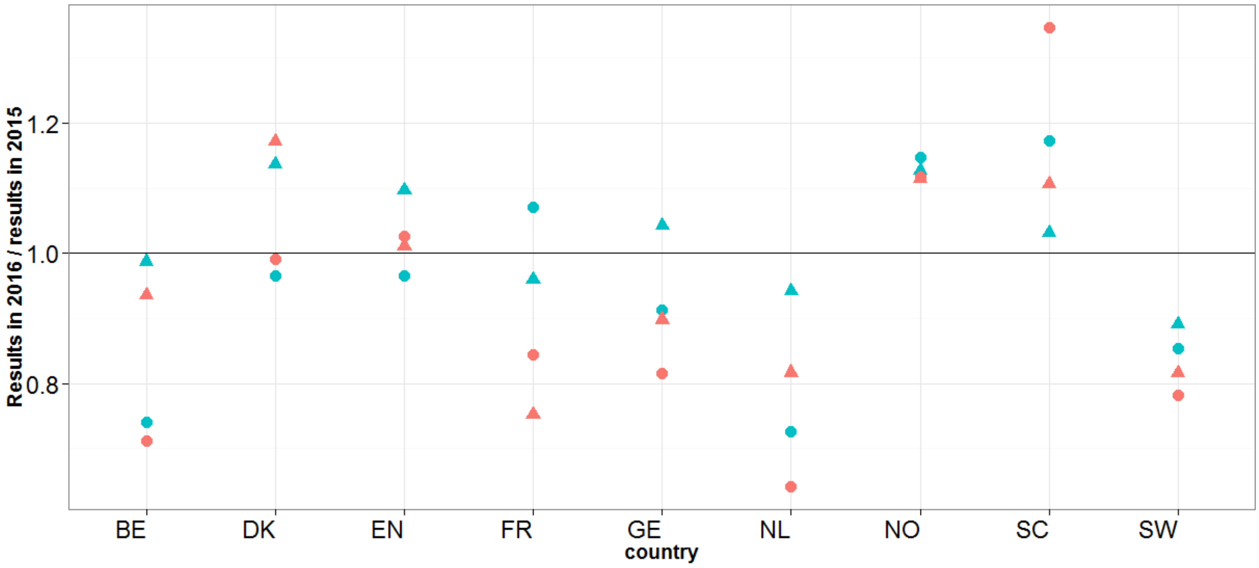

Figure 5. Impact of the alternative target F (Red: F_{MSY} target. Blue : F_{optim} target) in 2016 on the potential landings (dots) and effort (triangles) of all fleets by country (Scotland displayed separately from England), compared to the projected 2015 level (with effort in 2015= = effort in 2014),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

Appendix

The implementation of FCube is based on partition of fishing effort and catch into those of fleets and métiers. Their definition is based on those of the EC's Data Collection Framework

- ***A Fleet*** is a group of vessels with the same physical characteristics and predominant fishing gear during the year.
- ***A Métier*** is a group of fishing operations targeting a similar (assemblage of) species, using similar gear, during the same period of the year and/or within the same area and which are characterized by a similar exploitation pattern.

The basis of the model is to estimate for each fleet potential future levels of effort corresponding to the fishing opportunities, i.e. total allowable catches (TACs) by stock and/or effort allocations by fleet, available to that fleet. The effort levels are based on how the fleet distributes its effort across its métiers, and the catchabilities (across all stocks considered) of each of these métiers. The effort levels are used in turn to estimate landings and catches by fleet and stock, using standard forecasting procedures. In the current implementation, the analysis is performed assuming identical selectivity at age across métiers due to limitations of the available data. Therefore calculations are conducted using total annual fishing mortality $F_{\mathrm{t}}(y,s)$, fishing effort $E(\mathrm{y},f,m)$, and catches $C(\mathrm{y},f,m,s)$ by year *y*, fleet *f*, metier m, and stock s. The annual total fishing mortality $F_{\mathrm{t}}(y,s)$ is taken from stock assessment reports. The final year for which $F_{\mathrm{t}}(y,s)$ is available is denoted by *Y*. The catches enter into the model as overall tonnage, that can be split into landings $L(\mathrm{y},f,m,s)$ and discards $D(\mathrm{y},f,m,s)$.

Partial fishing mortality $F_{\mathrm{p}}(y,f,m,s)$ in year *y* for fleet *f*, métier *m*, and stock *s* is calculated from total fishing mortality and observed catches by multiplying the total fishing mortality by the fraction of the catches per fleet and metier to the total catches,

$$F_{\mathrm{p}}(y,f,m,s) = F_{\mathrm{t}}(y,s) * \frac{C(\mathrm{y},f,m,s)}{\sum_{f,m} C(\mathrm{y},f,m,s)} \quad . \qquad \text{Eq. (1)}$$

Once the partial fishing mortality is calculated, catchability $q(y,f,m,s)$ per year, fleet, metier, and stock can be calculated from the partial fishing mortality and fishing effort per year, fleet, and metier,

$$q(y,f,m,s) = F_{\mathrm{p}}(\mathrm{y},f,m,s)/E(\mathrm{y},f,m)\,. \qquad \text{Eq. (2)}$$

This catchability has two components, a landing component and a discard component. The selectivity $S(y,f,m,s)$ is defined as the ratio of the landings over the catches, ranging between 0 and 1,

$$S(y,f,m,s) = \frac{L(y,f,m,s)}{C(y,f,m,s)} \qquad \text{Eq. (3)}$$

The observed effort share $\kappa(y,f,m)$ of each of the métiers within each of the fleets is calculated as

$$\kappa(y,f,m) = E(\mathrm{y},f,m)/\sum_m E(\mathrm{y},f,m). \qquad \text{Eq. (4)}$$

Forecasting

Catchability and selectivity in future years (e.g. *Y*+1) must be specified. The default options are either assumed to be equal to the catchability in the final year, such that $q(Y+1,f,m,s) = q(Y,f,m,s)$ or an average over a number of recent years. But alternative options can be used, for example if catchability is known to have technical creep or density dependency. In the present study the value of the most recent data year was used.

The effort shares in future years (e.g. $\kappa(Y+1,f,m)$) can likewise be taken from the most recent data year or estimated from an average of a number of recent years, reflecting the assumption that fleets contain vessels that cannot switch freely from one métier to another, or that the management system, such as the effort regime in place in the North Sea (EC, 2004), imposes restrictions on the amount of effort spent in each métier. The present, North Sea based study, allocates effort shares according to the most recent data year. More complex approaches, such as a behavioural algorithms (e.g. Andersen *et al.*, 2010, Batsleer et al. 2015), or economic optimisation (Hoff *et al.*, 2010) are potentially possible.

For each stock, a stock by stock target future fishing mortality $F_{\mathrm{t}}(Y+1,s)$ usually coming from a management plan target or a TAC, is taken as an input parameter. The stock target fishing mortality is divided across fleets (i.e. a target partial fishing mortality for each fleet is determined) using a historic quota share $\lambda(y,f,s)$ that is calculated as

$$\lambda(y,f,s)=\frac{\sum_m L(\mathrm{y},f,m,s)}{\sum_{f,m} L(\mathrm{y},f,m,s)}. \qquad \text{Eq. (5)}$$

The quota shares are thus estimated from observed landings, and like catchability can be assumed to be equal to the most recent quota share such that $\lambda(Y+1,f,s)=\lambda(Y,f,s)$. Alternatively, quota shares may need to reflect specific TAC allocation mechanisms, but the simplest approach, as used in this study, is to estimate them from observed mean proportions of landings by fleet. The target future fishing effort by stock can then be calculated using the target overall fishing mortality, the quota share for each fleet, the catchability per fleet and metier, and the effort shares of the metiers within the fleets,

$$E_{\mathrm{t}}(Y+1,f,s)=\frac{F_{\mathrm{t}}(Y+1,s)*\lambda(Y+1,f,s)}{\sum_m(q(Y+1,f,m,s)*S(y,f,m,s)*\kappa(Y+1,f,m))}. \qquad \text{Eq. (6)}$$

If FCube is used to derive a mixed-fisheries short-term forecasts, the analyses are performed during the year Y+1, in order to produce advice for the TAC year (*Y*+2). Consistently with single-stock forecast which by generally applies the status quo F in the intermediate year (F(*Y*+1)=F(*Y*)), the model is applied with status quo effort in Y+1 (E(*Y*+1)=E(*Y*)) and the equations above would be applied for the TAC year *Y*+2.

Scenarios

It is unlikely that the effort corresponding to each single-species TAC will be the same within fleets, and it is equally possible that factors other than catching opportunities could influence the amount of effort exerted by a given fleet. The effort per fleet and metier in year *Y*+1 must therefore be determined by a rule about fleet behaviour (e.g. continue fishing after some quotas are exhausted) or connected with a management scenario (e.g. all fisheries are stopped when the quota of a particular stock is reached). This is captured in a set of rules. Simple rules are e.g. that each fleet stops fishing when the most constraining quota is exhausted,

$$E_{\min}(Y+1,f,m)=\min_s[\mathrm{E_t(Y{+}1,\,f,s)}]\,\kappa(y,f,m), \qquad \text{Eq. (7)}$$

or when fishing stops after the least constraining quota is exhausted,

$$E_{\max}(Y+1,f,m)=\max_s[E_{\mathrm{t}}(\mathrm{Y}+1,f,s)]\,\kappa(y,f,m). \qquad \text{Eq. (8)}$$

As a final step, the corresponding forecasts of partial fishing mortalities by métier can be estimated, for instance if "min" scenario is assumed:

$$F_{\mathrm{p}}(Y+1,f,m,s) = q(Y+1,f,m,s)\, E_{\mathrm{min}}(Y+1,f,m). \qquad \text{Eq. (9)}$$

Partial fishing mortalities are summed by stock, and these fishing mortalities are used in standard forecast procedures instead of the initial $F_{\mathrm{t}}(Y+1,s)$ used in the single-species short-term advice. The FCube model has been coded in R (R Development Core Team, 2008), as part of the FLR framework (Kell *et al.*, 2007, www.flr-project.org). This forecast based on the fishing mortalities under the different scenarios also yield the forecasted catches using age structured population dynamics under the different scenarios (e.g. $C_{\mathrm{min}}(Y+1,f,m,s), C_{\mathrm{max}}(Y+1,f,m,s)$).

FCube as part of a stochastic MSE

Management Strategy Evaluations (Butterworth & Punt 1999) project stocks into the future while including a feedback loop. Hence they simulate a management procedure where a harvest control rule (HCR) is used to determine an allowed harvest, e.g. by means of a TAC in each projected year. This is generally done based on a perception of the state of the stock, the fishing mortality, and a short-term forecast. The true (realised) fishing mortality can differ from the target (intended) mortality because of stochastic variation in stock related variables (e.g. the stock-recruitment relationship, growth, natural mortality) and/or errors in observation and implementation. The forward projections are repeated allowing the probability of achieving specified objectives (a level of stock biomass or fishing mortality) to be determined.

The harvest control rule in the FCube MSE implementation annually sets TACs based on the goal of achieving mean fishing mortality consistent with maximum sustainable yield (MSY). The basis for any of the fishing mortalities $F_{\mathrm{t}}(y,s)$ in the future is thus the F_{MSY} estimate provided by ICES. However, the harvest control rule also follows the "ICES advice sliding rule", i.e. the target fishing mortality for a species is reduced if the spawning stock biomass *B*(Y,*s*) for a given year for that species falls below a trigger level associated with MSY, $B_{\mathrm{t}}(s)$, such that

$$F_{\mathrm{t}}(Y+1,s) = \begin{cases} F_{MSY}(s), & B(Y,s) \geq B_{\mathrm{t}}(s) \\ F_{MSY}(s) * B(Y,s)/B_{\mathrm{t}}(s), & B(Y,s) < B_{\mathrm{t}}(s) \end{cases}. \qquad \text{Eq. (10)}$$

Stochastic variation is introduced through variability of future recruitment: for each species recruitments are drawn using the standard deviation of residuals from the fitted stock-recruit relationship. In the current study a "Hockey Stick" segmented regression model on the entire time series of annual recruitment was used to estimate the stock recruitment relationships (ICES, 2015a). Future recruitment $R(Y+1,s)$in year *Y*+1 is

$$R(Y+1,s) = \begin{cases} \alpha(s)B(Y,s) * \mathrm{e}^{N(0,\sigma(s))}, & B(Y,s) \leq \beta(s) \\ \alpha(s)\beta(s) * \mathrm{e}^{N(0,\sigma(s))}, & B(Y,s) > \beta(s) \end{cases}, \qquad \text{Eq. (11)}$$

where $N(0,\sigma(s))$is a draw from a normal distribution, centered around zero, with standard deviation equal to the species specific standard deviation of residuals from the fit to the historic data.

To estimate $\alpha(s)$ and $\beta(s)$ are estimated from the historic observations of spawning stock biomass and recruitment. The exception was for North Sea cod where only the recent low recruitments (since 1988) are used as in the ICES stock assessment (ICES, 2015b). In the current implementation there is no estimation error in catches, and no assessment error, i.e. there is an assumption of perfect knowledge about the status of the stock. To prevent excessive computing time demands, other potential sources of parameter uncertainty (e.g. in weight at age, selectivity, discard ratio) were also omitted. Growth and selectivity parameters for all stocks were fixed at the 2012-2014 average.

All runs assumed perfect implementation of the landings obligation, i.e. that all catches are landed from 2016 on, but without changes of the selectivity patterns. The MSE was run with 200 iterations over a 30 year period.

FCube with optimisation

The optimisation procedure finds, for the set of stocks considered in the study, the target fishing mortalities to be used to set the TAC in the advice year Y+1 which lead to minimum the incompatibilities between the resulting TACs. The magnitude of these incompatibilities was described by the differences, stock by stock, in the catches between the **max** scenario (where, in order to use all fishing opportunities, the TAC is overshot for most species) and the **min** scenario (where, in order not to overshoot any TAC, fishing opportunities are lost for most of the stocks).

Therefore, the values to be optimised were the target fishing mortalities for year *Y*+1, $F_{\mathrm{t}}(Y+1,s)$ which were constrained to be within the F_{MSY} ranges of each species. The objective function to minimise was the squared difference (in tonnes) of catches in year *Y*+1 for all stocks for the Fcube scenario “max” and “min” respectively:

$$\sum_s\left(\sum_{f,m} C_{\max}(Y+1,f,m,s) - \sum_{f,m} C_{\min}(Y+1,f,m,s)\right)^2. \qquad \text{Eq. (12)}$$

The optimisation was carried out using a genetic algorithm (the function rbga() from the R package genalg). This optimiser works by mimicking a natural selection process. Initially a number (in this study 30) of sets of candidate fishing mortality values (one per stock) were chosen and the corresponding single species TACs calculated. For each set FCube was run and the objective function calculated. Once evaluated, only the best performing candidates (here 6) were kept to generate, by recombination and occasionally mutation, a new generation of 30 candidate sets. With each iteration, the overall performance of the population of fishing mortality sets improved until the algorithm converged according to a set tolerance. The best performing set of $F_{\mathrm{t}}(Y+1,s)$ values of the last generation was returned as the output of the optimisation.

Because of computing time requirements the optimiser was not integrated into the stochastic MSE. Instead the analysis was performed using the deterministic short-term forecast configuration of FCube.

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