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Reconciling single-species TACs in the North Sea demersal fisheries using the Fcube mixed-fisheries advice framework

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Abstract :

Single-species management is a cause of discarding in mixed fisheries, because individual management objectives may not be consistent with each other and the species are caught simultaneously in relatively unselective fishing operations. As such, the total allowable catch (TAC) of one species may be exhausted before the TAC of another, leading to catches of valuable fish that cannot be landed legally. This important issue is, however, usually not quantified and not accounted for in traditional management advice. A simple approach using traditional catch and effort information was developed, estimating catch potentials for distinct fleets (groups of vessels) and métiers (type of activity), and hence quantifying the risks of over- and underquota utilization for the various stocks. This method, named Fcube (Fleet and Fisheries Forecast), was applied successfully to international demersal fisheries in the North Sea and shaped into the advice framework. The substantial overquota catches of North Sea cod likely under the current fisheries regimes are quantified, and it is estimated that the single-species management targets for North Sea cod cannot be achieved unless substantial reductions in TACs of all other stocks and corresponding effort reductions are applied.

Keywords : advice ; demersal ; effort ; Fcube ; mixed fisheries ; North Sea ; TACs

1. Introduction

A common fishery management measure is to impose limits on the amount of fish that can be removed and landed from a given stock. These limits are typically specified as annual Total Allowable Catches (TACs). As a management measure, a TAC assumes a correspondence between the management action (the TAC) and what it is intended to achieve (typically a specified level of fishing mortality. Implicitly, this assumes that the level of fishing activity will adapt to the quota available for a particular stock, and thus will lead to the targeted fishing mortality level. The simplest link is to assume that vessels will stop catching a given species once their quota for that species is exhausted. This assumption may be valid for simple, single stock, fisheries, but it is much less likely to hold true for complex, multi-species, multi-gear fisheries, where fleets are given a set of different fishing opportunities for the various stocks. Indeed, the highly complex nature of many European fisheries has been a major contributory factor to the limited success of TAC management in this context, as different catch limits for the various stocks may lead to imperfect implementation of the single-species TAC through incentives for misreporting, high-grading and discarding, which then undermine the basis for data collection and stock assessment (Penas, 2007; Rijnsdorp *et al.*, 2007; EC, 2009b).

The recent history of the demersal fisheries in the North Sea provides a useful illustration of the problems of using TACs to manage mixed fisheries. Around 2005 the North Sea cod stock was at a very low level while the stock of haddock, which is to a large extent caught together with cod, was at its highest biomass in thirty years (ICES, 2009b). In these circumstances, if single-species TACs are set with no consideration of the status of the other stocks caught in the same fishery, fishers are faced with a dilemma when the quota for cod is exhausted: stop fishing and underutilize the quota for haddock, or continue fishing and discard or illegally land overquota cod. When they choose the latter option the cod TAC does not achieve its intended conservation objective. Moreover, the reliability of the assessment of the cod stock is jeopardized because the catch data on which it is based tend to become more uncertain due to discarding or unreported landings (Reeves and Pastoors, 2007; Hamon *et al.*, 2007).

One approach to make TACs more effective as a management measure in mixed fisheries like those of the North Sea would be to account for the technical interactions that arise when multiple fleets use different gears to target different combinations of target species in the same area, and to incorporate these effects into scientific advice on fisheries management. The MTAC approach (Vinther *et al.*, 2004) was developed to use information on technical interactions alongside biological information from stock assessments, in order to estimate mixed-species TACs. These were intended to be consistent across species in terms of the amount of effort they implied. In principle, this approach should improve the link between catch opportunities and the resulting activity. However, MTAC did not prove to be robust and flexible enough in practice to become a standard operational tool for mixed-fisheries advice, and there were also problems with data availability (STECF 2004; ICES 2006). Subsequently, attempts have been made to develop a simpler and more robust approach to mixed-fisheries advice, more tailored to the data available and sufficiently flexible to address a wider range of mixed-fisheries issues (ICES, 2006). This led to an innovative approach to mixed-fisheries modelling, referred to as Fcube (from Fleet and Fishery Forecast) which is described here.

The model was initiated within the larger development of the multi-fleet, multi-species bioeconomic simulation framework TEMAS (Sparre, 2003; Ulrich *et al.*, 2007; Andersen *et al.*, 2010), where forecast simulations of stocks and fleet dynamics are performed in order to evaluate the consequences of various management scenarios. Various modelling hypotheses can be tested, in order to best capture future effort allocation schemes under changing TAC conditions. The Fcube method was developed from these hypotheses as a stand-alone approach to provide short-term mixed-fisheries advice.

The objective of this paper is thus to describe the Fcube model and how it addresses mixed-fisheries issues in a simple, flexible and operational manner directly applicable to most fisheries. We present a number of applications using the North Sea demersal fisheries as a case study. An earlier version of the framework and its economic extension was already described by Hoff *et al.* (2010), but this current paper documents a more in-depth investigation of the model outcomes, and a comprehensive analysis of the implications for the North Sea fisheries management and scientific advice framework.

Central to the Fcube model is the explicit representation of both fishing vessels and their activity, where the former are described in terms of fleets, or fleet segments, and the latter is incorporated through assigning each individual trip by a vessel to a specific métier. Various approaches have been used for identifying métiers and, to a lesser extent, fleets, but for operational use it is desirable that the categorisations used are consistent with existing data collection programmes. In the European context, the latter are structured according to the Commission of the European Community's Data Collection Framework (DCF; EC, 2008). This gives the following definitions which we adopt here*: A Fleet segment* is a group of vessels with the same length class and predominant fishing gear during the year. Vessels may have different fishing activities during the reference period, but will generally be assigned to only one fleet segment. *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.

2. Material and methods

2.1. The Fcube model

The basis of the model is to estimate the potential future levels of effort by fleet corresponding to the fishing opportunities (TACs by stock and/or effort allocations by fleet) available to that fleet, based on how the fleet distributes its effort across its métiers, and the catchability of each of these métiers. This level of effort is in return used 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 average *Fbar (F)* levels and catch compositions by fleet and métier in tonnage only. However, the model could be easily modified to include selectivity data by fleet and métier, provided that the sum of catch-at-age by fleet and métier is equal to the total catch-at-age used in the stock assessment.

Partial fishing mortality *F* and catchability *q* by fleet *Fl*, métier *m* and stock *St* from observed catches *C,* effort *E* and assessed fishing mortality *F* are estimated for year *Y* :

$$F(Fl,m,St,Y) = F(St,Y) * \frac{C(Fl,m,St,Y)}{Ctot(St,Y)} \quad (1)$$

$$q(Fl,m,St.Y) = \frac{F(Fl,m,St,Y)}{E(Fl,m,Y)} \quad (2)$$

To estimate values for $q(Fl,m,St,Y+1)$ at year *Y+1* an average over a number of recent years can be used. Alternatively, the user may choose to vary the value of *q*, if evidence exists of e.g. significant technical creep.

The observed distribution of effort by fleet across métiers is:

$$Effshare(Fl,m,Y) = \frac{E(Fl,m,Y)}{E(Fl,Y)} \quad (3)$$

As with catchability, the simplest approach to the forecast effort distribution $Effshare(Fl,m,Y+1)$ would be to estimate it from an average of past observed effort allocation. This would reflect 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 some restrictions on the amount of effort spent in each métier. Alternatively, a more complex approach such as a behaviour algorithm could be used if available (Andersen *et al.*, 2010), or full flexibility in the effort allocation could be envisaged via consideration of economic optimisation (Hoff *et al.*, 2010).

These variables are then used for the forecast estimates of catchability by stock for each fleet. This catchability cannot be directly estimated from observed data, as it is linked to the flexibility of the fleet.

While catchability by métier is assumed to be measurable and linked to the type of fishing, the resulting catchability by fleet varies with the time spent in each métier. The catchability of a fleet is thus equal to the average catchability by métier weighted by the proportion of effort spent in each métier for the fleet:

$$q(Fl,St,Y+1) = \sum_m q(Fl,m,St,Y+1) * Effshare(Fl,m,Y+1) \quad (4)$$

A TAC is usually set in order to achieve a specific fishing mortality. It might be a particular short-term target, such as F_{MSY}, or specific reduction in F as part of a long-term management plan (LTMP). This intended F is converted into forecast effort by fleet. This step introduces the concept of "Stock-dependent fleet effort", which is the effort corresponding to a certain partial fishing mortality on a given stock, disregarding all other activities of the fleet. The total intended (or targeted) fishing mortality $F_{target}(St,Y+1)$, usually coming from a management plan target or a TAC, is first divided across fleet segments (partial fishing mortalities) through coefficients of relative fishing mortality by fleet. These coefficients are fixed quota shares estimated from observed landings. How these are estimated may need to reflect the mechanisms in place to derive fleet quota shares from overall TACs, but the simplest approach is thus to estimate these from observed mean proportions of landings by fleet (as in Equation (1)). The resultant partial fishing mortalities are subsequently used for estimating the stock-dependent fleet effort:

$$F(Fl,St,Y+1) = F_{target}(St,Y+1) * QuotaShare(Fl,St) \quad (5)$$

$$E(Fl,St,Y+1) = \frac{F(Fl,St,Y+1)}{q(Fl,St,Y+1)} \quad (6)$$

The final input required is the effort by each fleet during the forecast year. 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. Rather than assuming a single set of fleet efforts, the approach used in practice with Fcube has been to investigate a number of different scenarios about fleet activity during the forecast period. The user can thus explore the outcomes of a number of options or rules about fleet behaviour (e.g. continue fishing after some quotas are exhausted) or management scenarios (e.g. all fisheries are stopped when the quota of a particular stock is reached).

$$E(Fl,Y) = rule(E(Fl,St1,Y), E(Fl,St2,Y), \ldots) \quad (7)$$

For example, if one assumes that fishers continue fishing until the last quota is exhausted, effort by fleet will be set at the maximum across stock-dependent effort by fleet, i.e.:

$$E(Fl,Y+1) = MAX_{St}[E(Fl,St1,Y+1), E(Fl,St2,Y+1), \ldots] \quad (8)$$

As a contrast, a more conservative option would be to assume that the fleets would stop fishing when the first quota is exhausted, and thus would set their effort at the minimum across stocks. Alternatively, management plans for a particular stock could be explored, with the fleets setting their effort at the level for this stock etc. Different rules could also be applied for the various fleets. These options are further developed in the application below.

Finally, this resulting effort by fleet is distributed across métiers, and corresponding partial fishing mortality is estimated.

$$E(Fl,m,Y+1) = E(Fl,Y+1) * Effshare(Fl,m,Y+1) \quad (9)$$

$$F(Fl,m,St,Y+1) = q(Fl,m,St,Y+1) * E(Fl,m,Y+1) \quad (10)$$

Partial fishing mortalities are summed by stock, and these new $F_{Fcube}(St,Y+1)$ are used in standard forecast procedures instead of the initial $F_{target}(St,Y+1)$ used in the single-species short-term advice. Corresponding landings are estimated and compared with the single-species TAC.

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).

2.2. Fcube implementation for North Sea demersal fisheries

Details of the main target species and stocks in the demersal fisheries of the North Sea are given in Table 1. The fisheries are highly international in nature, with the seven countries that have a North Sea coastline all having established fisheries in the area. The main gears in use are towed gears such as trawls and beam trawls with various mesh sizes, though there is also some usage of static gears including gill and trammel nets and longlines (STECF, 2008b). Annual stock assessments are available for all these target fish stocks (ICES, 2009b), and these provide the basis for annual TACs which have historically been the main management measure for these stocks. Single-stock LTMPs with specific harvest control rules are in place for cod, haddock, saithe, plaice and sole (Table 2). Since 2003, restrictions on fishing effort have also applied to demersal fisheries in the North Sea, mainly in relation to the cod recovery plan (EC, 2004; Horwood *et al.*, 2006; STECF 2008b).

The situation for the highly targeted crustacean *Nephrops norvegicus* is complex, as they are considered as eight discrete stocks (or Functional Units, FU) within the North Sea area. Only four of these are routinely assessed. These are FUs 6-9 covering the stocks along the UK coastline (Table 1), which are assessed using underwater video surveys. A TAC is in place for North Sea *Nephrops*, but this applies to the whole area rather than individual FUs.

Data by fleet and métier for the North Sea were obtained from the national fisheries institutes of Belgium, Denmark, England, the Netherlands, Norway and Scotland. Data covered the period 2003-2008. Discard data were available for some fleet segments and included as estimates of discards ratios. To ensure compatibility with available economic data, the fleet definitions used were based on EC (2004) and EC (2001). Depending on this, some fleets were further broken down by vessel length categories but not all. The definition of demersal métiers in the North Sea does not in practice follow a single established nomenclature (Ulrich *et al.*, 2009). In the present case, the métiers were defined on the basis of the gear and mesh categories from the cod recovery plan (EC, 2009a).

In order to reduce the number of categories, an aggregation threshold, established through trial and error was used to determine ‘major’ métiers. A métier catching on average at least 1% of the total catches of at least one of the stocks considered was classified as major. All remaining ‘minor’ métiers were then aggregated by fleet into an “Other” métier (OTH). Further, all minor fleets (i.e. those where all effort was allocated to the “OTH” métier), were aggregated into a single “OTH” fleet.

Since relevant effort data are not systematically available for all catch declarations (e.g. for vessels under ten meters), the catch (landings plus discards) data that could be allocated to the fleets represented only a proportion of the total catches for the stocks as estimated in the relevant stock assessments, and the difference needed to be accounted for to cover all sources of mortality. For landings, the coverage for most stocks was usually high (over 80%), and the difference between summed fleet landings and stock landings were accounted for by pooling them into the OTH fleet. The cod stock represented a special case, as the cod assessment procedure is the only one estimating “unallocated removals”, implying that catch estimates are higher than the sum of landings and discards (ICES 2009b). Therefore the sum of catches by fleet represented only 50% of the estimated catches. Instead of allocating this large difference in catches to the OTH fleet, it was decided to raise the catches of all fleets to the level of total (allocated plus unallocated) removals, as assumed in the single-stock forecast (ICES, 2009b). This approach may nevertheless lead to some distortion of the perception of fleet catchability. Work is currently ongoing to improve input data and stock assessment for North Sea cod (ICES, 2011), and the Fcube procedures will be updated to maintain consistency with the single-stock procedure. For discards, the coverage was not as good (around 50%), likely due to the fragmentation of discards samples over several fleet and métier categories which could affect the raising estimates. In the absence of additional information the remaining difference was also pooled in the discards data of the OTH fleet,although this could also lead to some distortion of the catchability estimates.

After aggregation, the final dataset used contained 26 fleets (plus the OTH fleet) from eight countries, from 2003 to 2008. These fleets engaged in between one and six different métiers each, resulting in 70 combinations of fleet*métier (Table 3). The main fleets in terms of total effort and landings for the stocks listed above are the Scottish trawlers (mainly catching demersal roundfish and *Nephrops*), the Dutch beam trawlers (mainly catching flatfish) and the Norwegian trawlers (mainly catching saithe).

The Fcube model was applied to these data, including the six demersal stocks and the four *Nephrops* FU with assessment data. The four other *Nephrops* FU (FU 5, 10, 32 and 33) without independent abundance estimates, were not included here, although they could eventually be linked to the assessed FUs in the final advisory framework (ICES, 2009a). Catch targets by *Nephrops* FU were approximated by sharing the total North Sea TAC over the various FUs using historical proportions of realised catch. The conditioning of the Fcube model with regards to assumptions on future trends in catchability and effort share by métier was based on visual inspection of historical trends using grid plots as well as tests of linear regression of log(catchability) with time. In most cases, historical catchability and effort share estimates fluctuated without trends over the time series, and a standard three-years average was thus used in the projections. When a significant ($p<0.05$) trend was detected, data for the final year was used instead.

2.3. Model runs

2.3.1. Testing and sensitivity analyses

A number of sensitivity analyses had earlier been performed before finalising the Fcube model setup for the North Sea and other implementations (ICES, 2008, Hille Ris Lambers *et al.*, 2009, Garcia *et al.*, 2009). These aimed at testing the sensitivity of the model outcomes to a number of issues, including e.g. the use of alternative fleets and métiers definitions and aggregation thresholds; the use of an alternative effort measure, or the effect of removing some stocks from the database. From the results of these analyses it was concluded that the model outputs were largely insensitive to such variability in the input data. The main sources of uncertainties were also investigated, which showed that the highest uncertainty was linked to the projection of the stock itself, similarly to single-stock forecasts (Garcia *et al.*, 2009). The second largest source of uncertainty was the variability of the catchability by métier parameters. The model was accordingly modified to be able to run on a stochastic basis including uncertainty in the main parameters to derive confidence intervals. The Fcube model was demonstrated to be fairly robust also to this source of uncertainty, with a decrease of the propagation of the uncertainty into model outcomes (Hille Ris Lambers *et al.*, 2009). The 'hindcast' runs presented below also formed a major component of the model testing.

2.3.2. One-year forecast

The Fcube model was applied to the North Sea data in a variety of ways. For the basic understanding of the method, a one-year Fcube projection was first performed, analysing the potential mixed-fisheries interactions for 2009 under a number of scenarios described below. The single-species target F by stock for 2009 [$F_{target}(St,Y+1)$ in Equation (5)] were set equal to the landings component of the F in the intermediate year used in the single-stock short-term forecast (these forecasts are hereon referred to as the "Baseline"). These targets were F reductions of 25%, 11% and 5% for cod, haddock and saithe respectively, with no F reduction targets specified for plaice, sole and whiting. These 2009 targets are to a large extent defined by the LTMPs in place for the relevant stocks (ICES, 2009c). Here the term "landings" refers to the proportion of catches above the minimum landing size that can be potentially landed, based on the historical landings/discards ratios by fleet and stock included in the inputs; but it is not necessarily equal to the legal landings, i.e. the TAC.

Consistently with common procedures in the advice provided by the International Council for the Exploration of the Sea (ICES), only deterministic short-term forecasts were performed, with the same settings as used by ICES (2009b) with regards to mean weight at age, mean selectivity at age, discard ratio (usually 3 years-average) and recruitment assumptions (usually a geometric mean estimate). The results were compared with the 2009 landings assumptions from the Baseline, based on the stock assessment results. The one-year forecasts for the different scenarios provided alternative sets of plausible levels of F by stock in 2009 ($F_{Fcube}(St,Y+1)$) accounting for mixed-fisheries interactions. The following Fcube scenarios were simulated:

"**max**". the underlying assumption is that the fleets continue fishing until their last quota is exhausted. The difference between the estimated landings and the actual TAC for the other stocks is considered as overquota catches.

"**min**". the underlying assumption is the opposite to the "max" scenario, i.e. the fleets stop fishing as soon as their first quota is exhausted, and, as a result do not take the whole of their quota for the other stocks.

"**cod**" : The underlying assumption is that the fleets stop fishing as soon as their cod quota is exhausted, regardless of other stocks.

"**val**" : This represents a very simple proxy computed with regards to revenue. The underlying assumption is that the global effort of each fleet is influenced by the monetary value each fleet can get from its quota shares across stocks. The quota value is used as a weighting factor of the estimated effort necessary to catch each quota share. As with other parameters, the simplest approach to the forecast quota value is to take the average over recent years of the relative value of landings by species and fleet *L(Fl,St,Y)*. The final level of effort is set at the level of this weighted mean [Equation (11)]. This is not a true economic proxy, rather it reflects the situation that a vessel is more likely to continue fishing if it has quota left for high value species than if the remaining quota is for low value species.

$$QuotaValue(Fl,St,Y) = \frac{L(Fl,St,Y) * Price(Fl,St,Y)}{\sum_{St} L(Fl,St,Y) * Price(Fl,St,Y)}$$

$$E(Fl,Y+1) = \sum_{St} E(Fl,St,Y+1) * QuotaValue(Fl,St,Y+1) \quad (11)$$

"**sq_E**" : The effort is simply set as constant compared to the previous years.

2.3.3. Two-year forecast

Typically, single-stock TAC advice is based on a two-years short-term forecast, as stock assessment data do not include the current year (referred to as the "intermediate year") in the forecast. Therefore, the Fcube model was adjusted to work on a two-years flow as such:

The new 2009 $F_{Fcube}(St,Y+1)$ values by stock derived from the one-year forecast were used as input for the intermediate year in single-stock forecasts, instead of the values used for the single-stock advice. Then the stocks were projected one more year, using the same settings for 2010 as in the Baseline Run. The aim was to derive single-stock TAC advice for 2010 following single-stock management plans but accounting for mixed-fisheries interactions in 2009.

Finally, the same Fcube scenarios as for 2009 were applied again in 2010 (i.e. a "max" scenario was applied in 2010 on the results of the "max" scenario in 2009, etc). In this way both differences in recommended TACs for 2010 resulting from different scenarios and an estimate of the cumulative difference between TAC and realised catches over two years could be calculated.

2.3.4. Hindcasting

In addition to the exploratory sensitivity analyses summarised above, hindcasting exercises were performed to test the suitability of the various Fcube scenarios to predict the observed levels of effort by fleets. This serves to evaluate whether one particular scenario could be considered a likely proxy for future effort level by fleet in the projections. Hindcasting was performed by sequentially removing one year from the database, performing one-year projections similarly to the one-year forecast above, and then comparing the forecasted effort by fleet with the actual observation in the removed year. Hindcasting projections thus covered the years 2004 to 2008, using the actual observed landings by stocks as a proxy for the TAC target (instead of the true TAC to avoid issues of actual TAC not being entirely consistent with reproducible single-stock forecasts).

3. Results

3.1. One-year forecast

For each fleet, striking differences occurred with regards to the estimated amount of effort necessary to catch the respective landings share for the various stocks in 2009 (Figure 1). Only the values corresponding to the fish stocks are displayed for illustration, but similar values were also estimated for each of the four *Nephrops* FUs. This figure underlines the relative inconsistencies of the target *F*s at the fleet level. Whiting and saithe were often the stocks with the highest corresponding effort for most fleets, indicating them to be the species with the least restrictive target *F*. On the other hand, cod and haddock were those corresponding with the smallest effort, indicating more restrictive targets. These discrepancies also varied from fleet to fleet, indicating that each fleet has its own set of incentives in terms of quota share, and no single pattern could be determined.

The results illustrated in Figure 1 translated into the resulting effort by fleet expendable under the different Fcube scenarios (Figure 2), which could vary dramatically between scenarios. While the “max” effort was often substantially higher than the effort implied by the other scenarios, it was the closest to the observed effort in 2008 for a number of fleets (“sq_E” scenario), including the important Scottish and English trawlers. For many other fleets, the effort estimated in the “val” scenario remained around the range of the observed effort in 2008. For many of the demersal otter trawler fleets, the “val” estimate is also relatively close to the “cod” estimate, indicating cod is still a key source of revenue for the fleet in spite of decreased recent TACs compared to historically.

The results at stock level once partial *F*s were summed are shown in Figure 3 and Table 4. It is to be noted that for cod, plaice, sole and whiting, the single-species forecast assumptions used by ICES (2009b) following LTMP guidelines and assumed here as Baseline implied higher expected landings for 2009 than the actual TAC.

The results provide estimates of the potential overquota landings or overshooting of the Baseline assumptions. In the “sq_E” scenario, estimated landings of cod and haddock exceed the Baseline estimates by 29% and 58% respectively, while whiting landings estimates were 13% below the Baseline. In the “val” scenario, the estimated landings in excess of the Baseline were 12% and 20% for cod and haddock respectively, while they were 23% below the Baseline for whiting.

On the contrary, the “cod” scenario, which complies with the 25% reduction in cod *F* in 2009 required by the management plan, implied strong reductions of landings for plaice, sole, saithe and whiting (15%, 20%, 23% and 31% respectively with regards to the Baseline; 9%, 13%, 39% and 24% respectively with regards to the TAC 2009), while haddock landings were close to the Baseline. This suggests the implications of the haddock and cod management plans were consistent with each other for 2009, while the other management plans were not consistent with these.

3.2. Two-year forecast

The full overview of the runs up to 2010 is given in Table 4, and in Figure 4 in relative numbers. Let us follow the “max” scenario for easier understanding. The Baseline assumption, leading to landings of 41.2 kt of cod in 2009 (corresponding to the 25% reduction in *F* from the management plan), resulted in 38.7 kt in 2010 following another 10% reduction. But under the “max” scenario, assuming that all fleets would fish until the full amount of their least restrictive quota is exhausted (usually saithe or whiting), 2009 cod landings would be 64.4 kt, i.e. 55% more than assumed in the Baseline. If this were the case, the resultant lower stock size at the start of 2010 (37.3 kt instead of 64.4 kt), would imply a lower TAC advice for 2010 of 27.7 kt in order to comply with the 35% reduction in *F* in 2010 required by the LTMP, i.e. a reduction of 29% compared with the single-species advice. If again we assumed the “max” scenario in 2010 also, then the potential cod landings would be estimated at 46.9 kt, i.e. only 20% above the initial single-stock Baseline but up to 68% above the landings corresponding to the LTMP if it had been adjusted for increased catches in 2009. And while the single-stock advice estimated a SSB for cod of 73.3 kt by 2011 under full compliance with the LTMP, the extreme “max” Fcube scenario applied to 2009 and 2010 estimated SSB in 2011 as low as 18.4 kt.

In contrast to cod, the advised 2010 TACs for most other stocks that would follow from applying the relevant LTMP are generally not sensitive to the scenario used for 2009. This results from an element of the relevant management plans that constrains annual changes in TACs to a specified percentage in either direction, usually +/-15% from year to year.

3.3. Hindcasting

As the only sensitivity analysis presented, the hindcasting exercises compared the observed effort with the predicted ones under the various scenarios for the years 2004-2008 (Figure 5). For most fleets and years, the observed effort was within the range predicted by the “min” and “max” scenarios. The size of this range varied across fleets and years, without a clear pattern. For most of the large fleets though, the range was smaller in 2008 than in previous years, suggesting that the single-species TACs may have been more consistent with each other this year than before. However, the effort predicted by the “max” scenario was in most cases much higher than the observed effort, whereas the estimates from the “min” scenario were much lower. Therefore neither of these two extreme hypotheses (that the fleets stop fishing when their first or their last quota is exhausted) is a likely proxy for actual behaviour, and the truth lies in between. Indeed, and although this cannot be generalised to all fleets and years, the effort levels estimated by the “val” scenario were usually closer to the observed effort than the extreme “min” and “max” scenarios.

4. Discussion

The application of the Fcube approach to the North Sea demersal fisheries presented here has demonstrated the sensitivity of forecast results to a plausible range of scenarios of fleet activity during the intermediate year. In effect, these Fcube scenarios look at the implications of the single-species advice in a mixed-fishery context. Each effort scenario implies a different outcome, in terms of the state of each stock, at the start of the TAC year. In most cases however, single-species LTMPs are used to derive TACs for these stocks. These include a component which restricts annual changes in TAC to within specified bounds. Within the current context this means that in most cases the TACs implied for 2010 do not change with the effort scenario assumed for 2009. The main exception to this is cod, where the management plan requires a specified reduction in fishing mortality in 2010. Given its current status relative to limit reference points (ICES, 2009b) cod is the species of greatest conservation concern within the North Sea demersal fishery. The constraints on annual changes in TAC in the existing single-species management plans offer improved stability of catching opportunities for the fishing industry but this seems to come at the expense of an increased risk to the cod stock. This could be addressed in the short term by introducing additional measures to ensure that the cod TAC is not exceeded, but in the longer term it would be desirable to develop a single management plan for all species in the mixed fishery. As a comparison, management through “weak-stock” considerations (Hilborn *et al.*, 2004), where protection is afforded to individual stocks, and those stocks with the lowest quotas can markedly influence how the overall fishery is prosecuted, is implemented in New England and in Alaska. US Fishers now refer to the stocks having low quotas as "choke" stocks because once the quota for any of these stocks is reached, then fishing in an area may cease altogether, or restrictive trip limits may be implemented, or other types of controls on fishing may take effect. This corresponds exactly to the “cod” scenario, as in the “min” scenario the stock minimizing the effort may not be the same across all fleets. Other Interesting mixed-fisheries approaches could be drawn from e.g. New Zealand (Marchal *et al.*, 2009) and the Faroe Islands (Baudron *et al.*, 2010). In this context, the Fcube approach could be used to investigate trade-offs and robust harvest control rules in a longer-term perspective by including these into mixed-fisheries management strategies evaluations such as those used by Hamon *et al.* (2007), Mackinson *et al.* (2009) or Baudron *et al.* (2010). Many of the problems with using TACs as a management measure arise because TACs limit landings rather than total catches. Approaches to address this are also currently underway through the development of e.g. “fully-documented fisheries” (Dalskov and Kindt-Larsen, 2009)

Traditionally, biological analyses and advice have focused on fish stocks, with some incidental consideration of the métiers (also referred to as fisheries), in the context of how various gears and mesh size may impact on the fish stocks (Reeves *et al.*, 2008). In contrast, economic advice has usually considered only the fleet, with the main focus being on the vessel’s profitability (STECF, 2008a; Frost *et al.*, 2009). While modelling approaches combining both fleets and métiers in an integrated framework are not new (e.g. Laurec *et al.*, 1991; Ulrich *et al.*, 2002), the wide recognition of the need to consider both concepts as distinct but complementary approaches in the management sphere has emerged only recently (EC, 2008); and these two concepts are the cornerstone of the Fcube approach.

Among the scenarios considered here, only the “val” scenario has a specific economic component. The utility of the “val” scenario lies in its computational simplicity, and because it provides a proxy for revenue-based behaviour within the bounds of the “min” and “max” scenarios, which the hindcasting indicated were unlikely to occur in reality. However, the validity and utility of the “val” scenario in a real economic perspective can be challenged, since it does not take into account the actual costs linked to the uptake of the quota share and thus does not properly address the hypothesis of profit maximisation. Therefore, these analyses should be complemented by further investigations of the effect of such profit maximisation, as was done by Hoff *et al.* (2010). Their results suggest that provided enough flexibility to switch across métiers within a fleet, the optimum effort for profit maximisation may lie well below the levels estimated by the “max” and “val” scenarios. However, given the current strict effort limitations by métier currently in place in the North Sea, it is unlikely that the fleets may have such flexibility and may thus operate in an economically suboptimal way.

Earlier sensitivity analyses (Hille Ris Lambers *et al.*, 2009, Garcia *et al.*, 2009) had contributed to increased knowledge of the model behaviour and confidence in the robustness of the approach, and had shaped the setup of the final runs presented here. One main issue encountered is the uncertainty in the catchability estimates, which is obviously inherent to any model linking fishing effort with fishing mortality. These weak linkages are of major importance for mixed-fisheries management (van Oostenbrugge *et al.*, 2008; Marchal *et al.*, 2006; Baudron *et al.*, 2010). However, stochastic simulations had shown that standard deviation in Fcube outputs was lower than the standard deviation of input catchability parameters (Hille Ris Lambers *et al.*, 2009). Fcube input parameters of catchability and effort share are directly correlated, being both estimated from the partial *F* and total effort by fleet. This implies that departures from one of these parameters due to alternative hypotheses will be compensated by the other parameter in the calculations. This makes intuitive sense, since if the catchability is higher than expected the TAC of a stock will be taken up more quickly, therefore requiring a lower amount of effort, and *vice versa*. Secondly, individual variations by fleets are also smoothed when being pooled with other fleets at the regional level. Finally, uncertainty in effort and catchability is further smoothed out when translating fleets’ effort into catches by stock, because of the non-linear relationships between catches and fishing mortality. This robustness

contributes to strengthening the confidence that the Fcube approach can be used to deliver operational and robust mixed-fisheries advice.

Fcube has been developed as a simple model for complex fisheries. In the North Sea case investigated here, even after the aggregation of minor fleets and métiers, the data set still includes data for 70 fleet*métier combinations catching differing quantities of ten different stocks. The Fcube runs support the conclusion of Andersen *et al.* (2010) that each fleet may react differently based on its own set of incentives in terms of quota share, and regardless of the behaviour of other fleets. This illustrates the high complexity of the North Sea demersal fisheries and hence the need to account for this complexity in their management.

The Fcube framework builds on simple computations of some key processes of the fishing activity. The assumptions used are simple and transparent, and the model can be conditioned on routinely available logbook information. The underlying approach is the recognition that fisher behaviour and flexibility is a key factor to consider in mixed-fisheries management, but also that this human behaviour is too complex to be easily captured and modelled on a routine basis, even at the level of the individual trip and fishing vessel. A fine-scale simulation of the actual fishing strategies of the fleets can be implemented at some regional scale (Andersen *et al.*, 2010; Marchal *et al.*, 2009), but this requires substantial analyses and a number of assumptions to condition the model, and as such its use as a routine advice model at the same level as a single-stock assessment model would not be a simple task. It is in this latter context that the Fcube approach is now being adopted for routine advisory use (ICES 2009a; 2010).

The Fcube model represents a flexible intermediate stage between the single-stock forecasts and more complex models such as MTAC (Vinther *et al.*, 2004). By proceeding with scenarios rather than optimization, and with only a few additional parameters compared to the traditional single-stock

approach, the Fcube model works at the level of the "broad picture", extracting simple proxies that are indicative of large trends. Optimization could nevertheless still be performed using the FcubEcon module described in Hoff *et al.* (2010). The Fcube model was also observed to be consistent with the established rule of relative stability which fixes the quota shares between countries (ICES, 2009a). Preliminary trials were also performed in more data poor areas: ICES Sub-areas VII and VIII where many stocks' assessments do not have accepted forecast procedures (Garcia *et al.*, 2009) and the Mediterranean, where there are no TACs and little biological information is available but effort limitations are in place (Maravelias *et al.*, 2011). In this area, useful recommendations on effort management could however be issued based on a few simple but plausible hypotheses.
In conclusion, the Fcube approach is compatible with standard stock assessment and advice frameworks, and we believe that it has potential for application to mixed fisheries in other areas. This would also help to promote fleet- and métier-based approaches to fisheries management and thus help to bridge the gap between the traditional single-species approach and a more comprehensive ecosystem approach (Reeves and Ulrich, 2007; Ulrich *et al.*, 2008).

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Tables

Table 1. Species and stocks included in the North Sea Fcube runs. Values are mean price at first sale averaged over 2002-2005. The range is the minimum and maximum values across different nations.

Species	Code	Stock	Value, €/kg
Cod, Gadus morhua	COD	North Sea, Skagerrak and Eastern Channel	1.53 – 2.21
Haddock, Melanogrammus aeglefinus	HAD	North Sea and Skagerrak	0.94 – 1.29
Whiting, Merlangius merlangus	WHG	North Sea and Eastern Channel	0.61 – 1.04
Saithe, Pollachius virens	POK	North Sea, Skagerrak, West of Scotland and Rockall	0.53 – 1.00
Plaice, Pleuronectes platessa	PLE	North Sea	1.84 -2.01
Sole, Solea solea	SOL	North Sea	9.01 – 10.28
Norway Lobster, Nephrops norvegicus	NEP6	FU6, Farn Deeps	3.81
Norway Lobster, *N. norvegicus*	NEP7	FU7, Fladen Ground	3.81 – 7.26
Norway Lobster, *N. norvegicus*	NEP8	FU8, Firth of Forth	3.81
Norway Lobster, *N. norvegicus*	NEP9	FU9, Moray Firth	3.81

Table 2. Overview of target *F*, *F* settings used for the intermediate year and the harvest control rules (based on management plans except for whiting) applied to single-stock ICES advice. In this application the current year is assumed to be 2009 and 2010 is the year for which the management measures are to be set. Assessment estimates are available up to and including 2008.

Stock	Target *F*	Basis for ICES advice2010	Expected landings 2009	TAC 2010
Cod	0.4	*F*(2009=0.75**F*(2008), *F*(2010)=0.65**F*(2008), 20% limit in TAC change in 2010 (EU management plan – EC 1342/2008)	41900	40300 (incl. all catches)
Haddock	0.3	In 2009 the TAC was assumed to have been caught; 15% limit in TAC change in 2010 (EU and Norway management plan)	44700	38000
Plaice	0.3	*F*(2010)=0.9* *F*(2009), 15% limit in TAC change in 2010 (EU management plan – EC 676/2007)	59500	63800
Sole	0.2	*F*(2010)=0.9* *F*(2009), 15% limit in TAC change in 2010 (EU management plan – EC 676/2007)	15140	14100
Saithe	0.3	15 % limit in TAC change in 2010 (EU and Norway management plan)	110000	118000
Whiting		SSB in 2011 should not be lower than SSB in 2009	19000	7400

Table 3. Final fleet and métier categories used in the mixed-fishery analysis, with 2008 effort (in 10^3 kWdays) and total landings (in tonnes) for the considered stocks. Métier names are consistent with the cod long-term management plan (Council Regulation (EC) 43/2009) : TR1=Otter Trawl and Demersal seine with mesh size >=100 mm, TR2= Otter Trawl and Demersal seine with mesh size 70-99 mm, TR3= Otter Trawl and Demersal seine with mesh size 16-31 mm, BT1=Beam Trawl with mesh size >120 mm, BT2 =Beam trawl with mesh size 80-119 mm, GN1=Gillnets, GT1=Trammel nets, LL1=Longlines, OTH=Others. 4, 3AN and 7D refer to the ICES area (North Sea, Skagerrak and English Channel respectively).

fleet	metier	effort	landings
BE_Beam	BT1.4	944	2009
	BT2.4	3246	3909
	OTH	2922	500
DK_Beam	BT1.4	232	683
	OTH	212	37
DK_DSeine	OTH	435	1046
	TR1.4	274	2162
DK_Otter<24	OTH	328	239
	TR1.3AN	421	2361
	TR1.4	815	3947
	TR2.3AN	2099	8633
	TR2.4	188	373
DK_Otter>24	OTH	984	139
	otter.3AN	966	690
	TR1.3AN	316	2217
	TR1.4	2721	9009
	TR2.3AN	313	1760
	TR2.4	484	792
DK_Otter40+	OTH	3284	425
	TR3.4	438	189
DK_Static<24	GN1.3AN	372	4275
	GN1.4	884	5221
	GT1.4	95	493
	OTH	56	299
EN_Beam>24	BT1.4	218	609
	BT2.4	1946	3831
	OTH	453	107
EN_Otter<24	OTH	456	486
	TR1.4	860	3294
	TR2.4	1547	2600
EN_Otter>24	TR1.4	808	2613
	TR2.4	747	1031
EN_Static	GN1.4	522	979
	OTH	5275	834
OTH_OTH	OTH	1000	14292
FR_Otter	OTH	71	8

	TR1.4	2801	16588
	TR2.4	1270	2157
	TR2.7D	7433	3408
FR_Static	GT1.4	433	795
	OTH	1530	25
GE_Beam	BT2.4	1464	1216
	OTH	6259	75
GE_DSeine	OTH	34	83
	TR1.4	176	2680
GE_Otter	TR1.3AN	156	1721
	TR1.4	1397	16285
	TR2.4	457	1282
NL_Beam<24	BT2.4	946	1798
	OTH	29	88
NL_Beam24-40	BT2.4	3091	3934
	OTH	51	9
NL_Beam40+	BT1.4	324	539
	BT2.4	18438	22618
	OTH	118	27
NL_Otter	TR1.4	770	1942
	TR2.4	1177	2429
NO_Beam	BT1.4	39	63
	BT2.4	103	161
NO_Otter	OTH	1006	1133
	TR1.4	5988	51659
SC_Beam>24	BT1.4	69	170
	BT2.4	1349	2756
SC_DSeine	TR1.4	1291	8853
SC_Otter<12	OTH	20	18
	TR2.4	752	1489
SC_Otter>24	TR1.4	7501	34336
	TR2.4	1288	2178
SC_Otter12-24	OTH	116	8
	TR1.4	3364	11869
	TR2.4	7297	18455

Table 4 .Results of the two-year forecast. Actual estimates are obtained by applying identical scenarios two years in a row. Authorised landings and estimated SSB are obtained by applying the basis of single-stock ICES advice for 2010 after Fcube scenarios in 2009. Baseline run represents the single-stock forecast. *Fmult* for a given year is given relative to *F* in 2008. Landings and SSB in kt. See text for more explanation.

			COD	HAD	PLE	POK	SOL	WHG	NEP6	NEP7	NEP8	NEP9
Fbar	2009	baseline	0.59	0.22	0.25	0.29	0.34	0.47	0.1	0.09	0.24	0.17
	2010	baseline	0.51	0.32	0.24	0.34	0.3	0.19	0.08	0.09	0.14	0.14
Actual Fmult	2009	baseline	0.75	0.89	1	0.95	1	1	1.22	1.22	1.22	1.22
		min	0.67	0.86	0.74	0.58	0.73	0.54	1.22	0.63	0.66	0.65
		max	1.47	1.99	1.95	1.51	2.04	1.20	2.47	1.28	1.34	1.32
		cod	0.75	0.98	0.81	0.80	0.81	0.71	1.45	0.76	0.79	0.78
		val	0.89	1.15	1.00	0.91	0.98	0.80	1.58	1.06	1.13	1.11
		sq_E	1.08	1.52	1.00	1.01	0.95	0.91	1.83	1.16	1.22	1.20
	2010	baseline	0.65	1.29	0.98	1.13	0.90	0.42	1.00	1.30	0.68	1.00
		min	0.61	0.77	0.66	0.55	0.63	0.49	1.00	0.53	0.54	0.53
		max	1.82	2.43	2.97	1.49	3.42	1.50	2.99	1.49	1.57	1.54
		cod	0.65	0.85	0.70	0.71	0.71	0.65	1.26	0.66	0.69	0.67
		val	0.91	1.27	0.95	1.01	0.90	0.86	1.49	1.07	1.13	1.11
		sq_E	1.08	1.52	1.00	1.01	0.95	0.91	1.83	1.16	1.22	1.20
Actual landings potential	2009	baseline	41.2	44.6	59.6	110.1	15.1	21.3	1.6	15.4	2.8	1.7
		min	37.7	43.2	45.6	72.2	11.6	12.4	1.6	8.0	1.5	0.9
		max	64.4	86.7	105.2	160.0	26.4	24.9	3.2	16.2	3.1	1.9
		cod	41.2	48.8	49.2	95.2	12.6	15.9	1.9	9.6	1.8	1.1
		val	46.8	55.8	59.4	106.8	14.9	17.6	2.0	13.4	2.6	1.6
		sq_E	53.4	70.4	59.7	116.1	14.5	19.7	2.3	14.7	2.8	1.7
	2010	baseline	38.7	37.9	63.8	118.2	14.1	9.3	1.3	16.4	1.6	1.4
		min	38.8	24.0	47.4	70.6	11.1	12.2	1.3	6.6	1.2	0.7
		max	46.9	49.4	127.9	125.2	28.8	26.5	3.8	18.8	3.6	2.2
		cod	38.7	25.6	49.5	83.1	12.1	15.0	1.6	8.3	1.6	1.0

		val	45.0	35.1	62.2	108.9	14.2	18.8	1.9	13.5	2.6	1.6
		sq_E	44.8	37.6	65.3	105.5	15.0	19.1	2.3	14.7	2.8	1.7
Authorised landings	2010	min	40.9	37.9	63.8	118.2	11.9	26.6	1.3	16.4	1.6	1.4
appliying the basis		max	27.7	37.9	61.8	118.2	16.1	16.9	1.3	16.4	1.6	1.4
For ICES advice		cod	38.7	37.9	63.8	118.2	12.4	23.8	1.3	16.4	1.6	1.4
in 2010		val	35.2	37.9	63.8	118.2	14.0	22.5	1.3	16.4	1.6	1.4
		sq_E	31.1	37.9	63.8	118.2	13.7	20.8	1.3	16.4	1.6	1.4
Actual SSB	2009	baseline	59.6	223.9	388.1	263.4	37.7	93.8				
	2010	baseline	64.4	195.1	442.3	234.5	37.7	89.0				
		min	68.6	196.7	467.0	269.4	41.0	100.3				
		max	37.3	149.1	362.9	189.6	27.2	84.6				
		cod	64.4	190.5	460.5	248.2	40.1	95.8				
		val	57.8	182.9	442.6	237.6	37.9	93.7				
		sq_E	50.1	166.8	442.0	229.0	38.3	91.0				
	2011	baseline	73.2	166.5	488.4	212.3	39.6	93.8				
		min	80.2	183.5	549.3	294.3	45.9	99.0				
		max	18.4	107.1	276.4	157.3	15.2	68.2				
		cod	73.2	175.5	537.1	259.0	44.1	91.7				
		val	54.2	157.2	491.6	223.9	39.8	85.2				
		sq_E	41.7	138.3	485.5	217.5	39.4	82.6				
SSB estimated	2011	min	77.4	168.0	521.9	250.8	45.2	93.8				
appliying the basis		max	41.2	119.8	385.2	163.2	26.9	93.8				
For ICES advice		cod	73.2	161.8	513.1	227.4	43.8	93.8				
in 2010		val	66.4	154.1	488.9	215.6	40.1	93.8				
		sq_E	58.5	137.9	488.0	206.3	40.6	93.8				

Figures

Figure 1. One-year forecast Fcube estimates of effort by fleet corresponding to the individual "quota share" (or partial Ftarget) by fish stock in 2009, relative to 2008. Columns truncated at value of 2. Fleet OTH_OTH not shown.

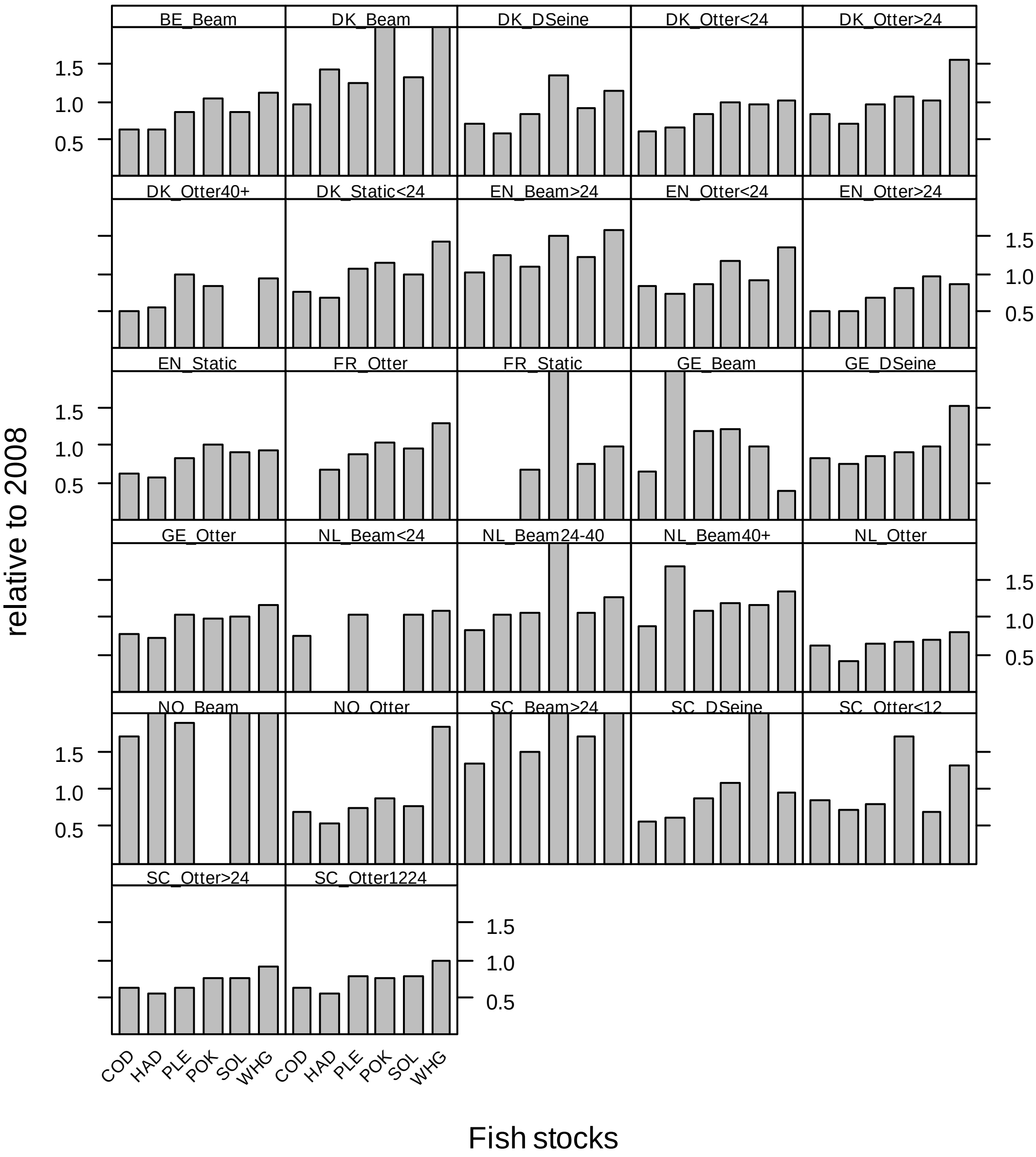

Figure 2. One-year forecast Fcube estimates of effort by fleet for the various scenarios in 2009, relative to 2008. Columns truncated at value of 2. Fleet OTH_OTH not shown.

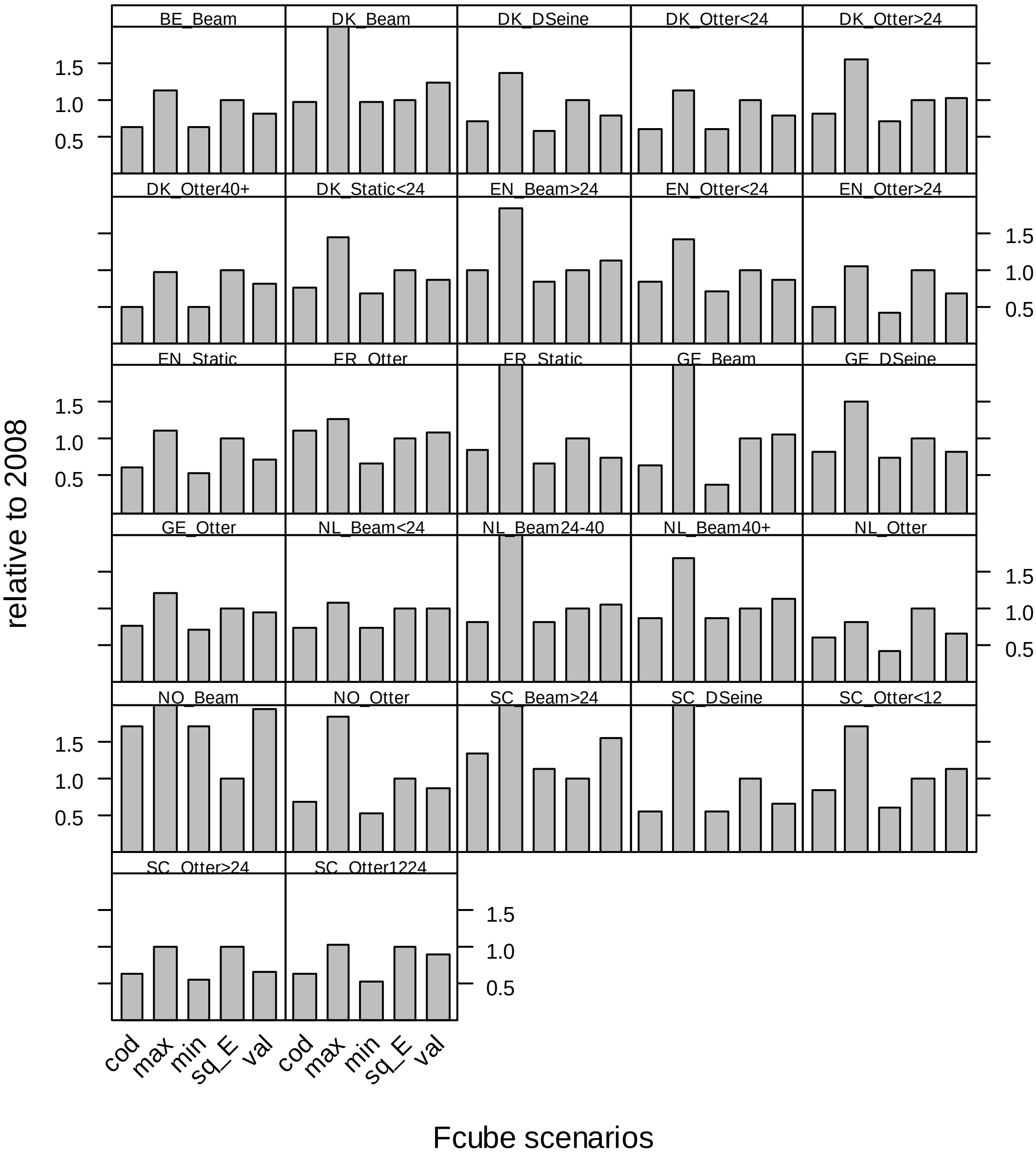

Figure 3. One-year forecast Fcube landings estimates by stock for the various scenarios in 2009. Straight lines are the Baseline estimates (landings estimates in the intermediate year in the single-stock forecast). NEP6-9 baseline is not labelled as it is almost equal to WHG baseline.

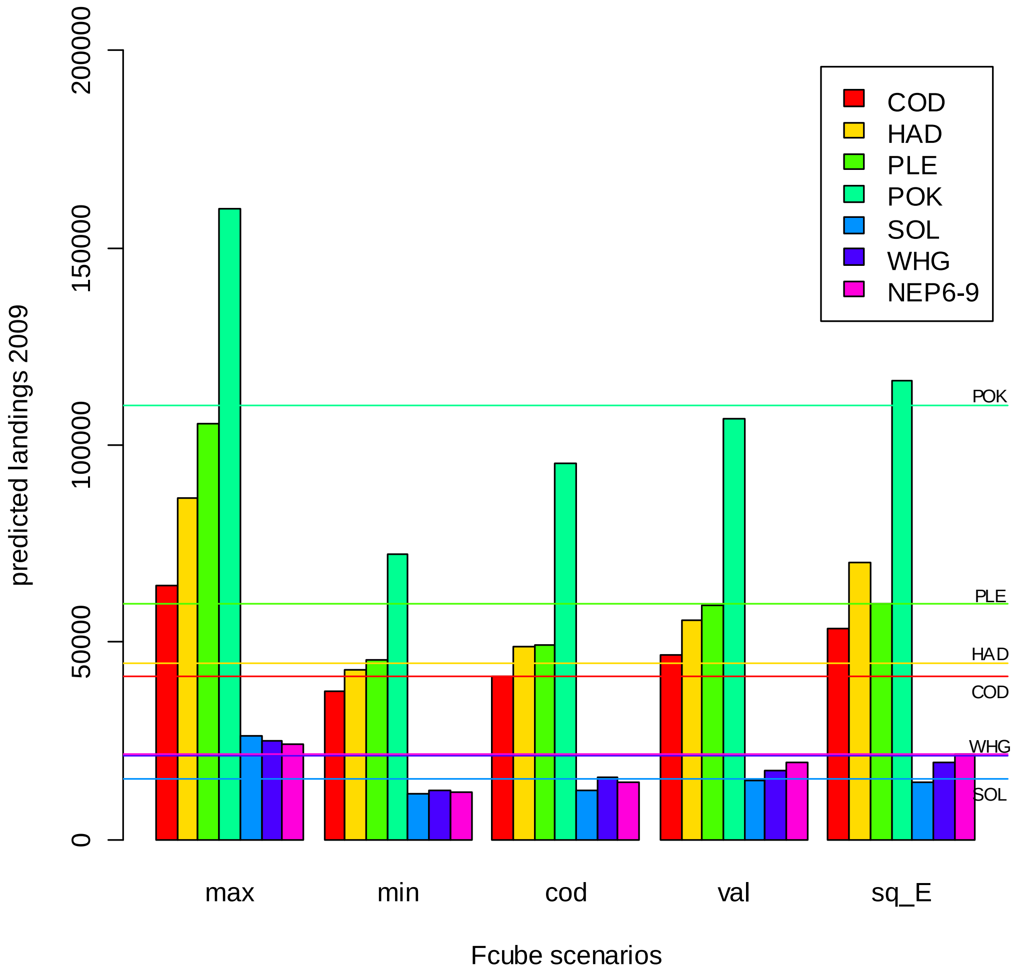

Figure 4. Results of Fcube two-years forecast relative to baseline for the fish stocks under various Fcube scenarios (“cod” – open square, “min” - triangle point down, “max” - triangle point up, “val” – cross and “sq_E” – filled diamond). *F*mult is relative to *F* in 2008.

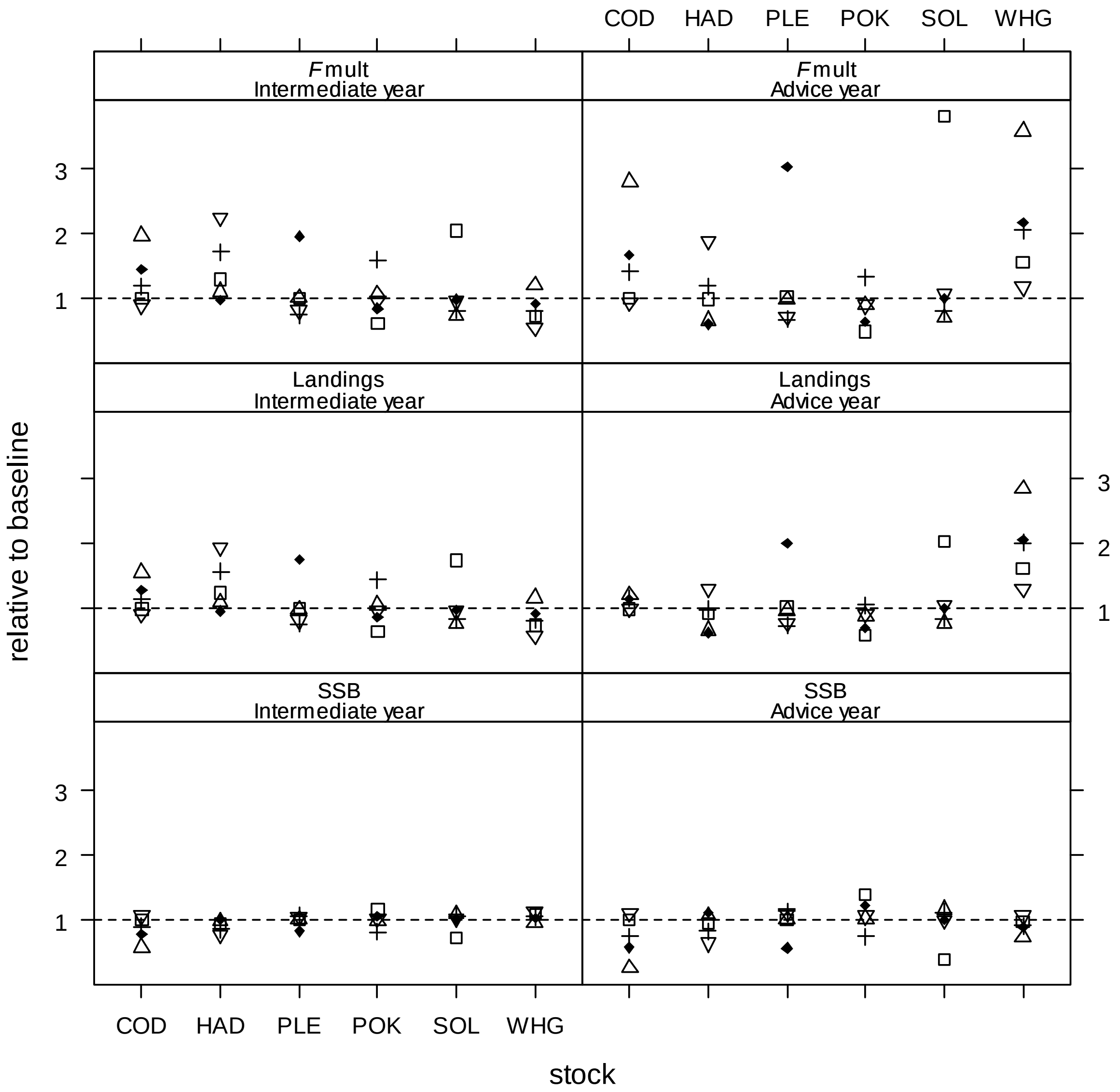

Figure 5. Hindcasting of the effort by fleet and year projected under various Fcube scenarios (“min” - triangle point down, “max” - triangle point up and “val” - cross) compared to the observed effort (black diamond). Within each fleet panel, the highest effort estimate across scenarios and years is set to 1 and all other effort values are expressed relative to this maximum.. Fleet “OTH_OTH” not shown.