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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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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.

Introduction

A common fishery management measure is to impose limits on the quantity 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 will lead to the targeted level of fishing mortality. 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, multigear 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 contributing factor to the limited success of TAC management in this context, because different catch limits for the various stocks may lead to imperfect implementation of the single-species TAC through incentives for misreporting, highgrading 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 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 (*Gadus morhua*) stock was at a very low level, whereas the stock of haddock (*Melanogrammus aeglefinus*), which is to a large extent caught together with cod, was at its highest biomass in 30 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 as a result of discarding or non-reporting of landings (Hamon *et al.*, 2007; Reeves and Pastoors, 2007).

One approach to making TACs more effective as a management measure in mixed fisheries such as 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 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 development of the multi-fleet, multispecies bioeconomic simulation framework TEMAS (Sparre, 2003; Ulrich *et al.*, 2007; Andersen *et al.*, 2010), where forecast simulations of stocks and fleet dynamics are performed to evaluate the consequences of various management scenarios. Various modelling hypotheses can be tested 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 providing short-term, mixed-fisheries advice.

The objective of this paper is 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 described by Hoff *et al.* (2010), but this paper documents a more in-depth investigation of the model outcomes, and a comprehensive analysis of the implications for North Sea fisheries management and the scientific advisory 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 categorizations 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 (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.

Material and methods

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, as a consequence of limitations in the available data. Therefore, calculations are conducted using average F (Fbar) levels and catch compositions by fleet and métier in tonnage only. However, the model could be modified easily to include selectivity data by fleet and métier, if 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:

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

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

To estimate the values for $q(\mathrm{Fl}, m, \mathrm{St}, Y+1)$ 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, for instance, significant technical creep.

The observed distribution of effort by fleet across métiers is

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

As with catchability, the simplest approach to the forecast effort distribution $\mathrm{Effshare}(\mathrm{Fl}, m, Y+1)$ 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 optimization (Hoff *et al.*, 2010).

These variables are then used for the forecast estimates of catchability by stock for each fleet. This catchability cannot be estimated directly from observed data, because it is linked to the flexibility of the fleet. Although 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 therefore equal to the average catchability by métier weighted by the proportion of effort spent in each métier for the fleet:

$$q(\mathrm{Fl}, \mathrm{St}, Y+1) = \sum_m q(\mathrm{Fl}, m, \mathrm{St}, Y+1) \times \mathrm{Effshare}(\mathrm{Fl}, m, Y+1). \quad (4)$$

A TAC is usually set to achieve a specific fishing mortality. It might be a particular short-term target, such as F_{MSY}, or a 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 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:

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

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

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 therefore 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):

$$E(\mathrm{Fl}, Y+1) = \mathrm{rule}(E(\mathrm{Fl, St1}, Y+1), E(\mathrm{Fl, St2}, Y+1), \ldots). \quad (7)$$

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.

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

As a contrast, a more conservative option would be to assume that the fleets would stop fishing when the first quota is exhausted, so 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 that 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:

$$E(\mathrm{Fl}, m, Y+1) = E(\mathrm{Fl}, Y+1) \times \mathrm{Effshare}(\mathrm{Fl}, m, Y+1), \quad (9)$$

$$F(\mathrm{Fl}, m, \mathrm{St}, Y+1) = q(\mathrm{Fl}, m, \mathrm{St}, Y+1) \times E(\mathrm{Fl}, m, Y+1). \quad (10)$$

Partial fishing mortalities are summed by stock, and these new F_{Fcube} (St,$Y+1$) values are used in standard forecasting procedures instead of the initial F_{target} (St,$Y+1$) values used in 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).

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 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, although there is also some use of static gears such as gillnets, trammelnets, 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 that 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 (*Pollachius virens*), plaice (*Pleuronectes platessa*), and sole (*Solea solea*; 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, because it is considered as eight discrete stocks (or functional units, FUs) within the North Sea area, and only four 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 (BE), Denmark (DK), England (EN), France (FR), Germany (GE), the Netherlands (NL), Norway (NO), and Scotland (SC). Data covered the period 2003–2008. Discard data were available for some fleet segments and included as estimates of discard ratios. To ensure compatibility with available economic data, the fleet definitions used were based on EC (2001, 2004). Depending on this, some, but not all, fleets were further broken down by vessel length category. 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 based on the gear and mesh categories from the cod recovery plan (EC, 2009a).

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

Table 1. Species and stocks included in the North Sea Fcube runs, the values being mean price at first sale averaged over the years 2002–2005 and the range of minimum and maximum values across different nations.

Species	Code	Stock	Value (€ kg^{-1})
Cod	COD	North Sea, Skagerrak, and eastern Channel	1.53–2.21
Haddock	HAD	North Sea and Skagerrak	0.94–1.29
Whiting	WHG	North Sea and eastern Channel	0.61–1.04
Saithe	POK	North Sea, Skagerrak, West of Scotland, and Rockall	0.53–1.00
Plaice	PLE	North Sea	1.84–2.01
Sole	SOL	North Sea	9.01–10.28
Nephrops norvegicus	NEP6	FU6, Farn Deeps	3.81
N. norvegicus	NEP7	FU7, Fladen Ground	3.81–7.26
N. norvegicus	NEP8	FU8, Firth of Forth	3.81
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, with the current year assumed to be 2009 and 2010 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 advice 2010	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)	41 900	40 300 (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)	44 700	38 000
Plaice	0.3	*F*(2010) = 0.9 *F*(2009), 15% limit in TAC change in 2010 (EU management plan—EC 676/2007)	59 500	63 800
Sole	0.2	*F*(2010) = 0.9 *F*(2009), 15% limit in TAC change in 2010 (EU management plan—EC 676/2007)	15 140	14 100
Saithe	0.3	15% limit on TAC change in 2010 (EU and Norway management plan)	110 000	118 000
Whiting		Spawning-stock biomass (SSB) in 2011 should not be lower than SSB in 2009	19 000	7 400

catches of at least one of the stocks considered was classified as a major one. All remaining minor métiers were then aggregated by fleet into an "Other" (OTH) métier. Further, all minor fleets, i.e. those where all effort was allocated to the OTH métier, were aggregated into a single "OTH" fleet.

As relevant effort data are not systematically available for all catch declarations, e.g. for vessels <10 m), 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 (>80%), and the difference between summed fleet landings and stock landings was accounted for by pooling them into the OTH fleet. The cod stock represented a special case, because 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 just 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 (~50%), likely because of the fragmentation of discard 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 discard data of the OTH fleet, although this may also lead to some distortion of 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 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 Scottish trawlers (mainly catching demersal roundfish and *Nephrops*), Dutch beam trawlers (mainly catching flatfish), and Norwegian trawlers (mainly catching saithe).

The Fcube model was applied to these data, including the six demersal stocks and the four *Nephrops* FUs with assessment data. The four other *Nephrops* FUs (FUs 5, 10, 32, and 33) without independent abundance estimates were not included, 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 realized catch. The conditioning of the Fcube model about assumptions on future trends in catchability and effort share by métier was based on visual inspection of historical trends, using grid plots and tests of linear regression of log(catchability) with time. Usually, historical catchability and effort-share estimates fluctuated without trend over the time-series, and a standard 3-year average was therefore used in the projections. When a significant ($p < 0.05$) trend was detected, data for the final year were used instead.

Model runs

Testing and sensitivity analyses

Several sensitivity analyses had earlier been performed before finalizing the Fcube model setup for the North Sea and other implementations (ICES, 2008; Garcia *et al.*, 2009; Hille Ris Lambers *et al.*, 2009). These aimed at testing the sensitivity of the model outcomes to a number of issues, including the use of alternative fleet and métier 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 revealed that the greatest uncertainty was linked to the projection of the stock itself, similar 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 fairly robust also to that source of uncertainty, with a decrease in 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.

One-year forecast

The Fcube model was applied to North Sea data in a variety of ways. For the basic understanding of the method, a 1-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 [$F_{\text{target}}(\text{St}, Y + 1)$ in Equation (5)] were set equal to the landings component of the *F* in the intermediate year used in the single-stock, short-term

Table 3. Final fleet and métier categories used in the mixed-fishery analysis, with 2008 effort and total landings for the stocks considered.

Fleet	Métier	Effort (thousand kW-days)	Landings (t)
BE_Beam	BT1.4	944	2 009
	BT2.4	3 246	3 909
	OTH	2 922	500
DK_Beam	BT1.4	232	683
	OTH	212	37
DK_DSeine	OTH	435	1 046
	TR1.4	274	2 162
DK_Otter <24	OTH	328	239
	TR1.3AN	421	2 361
	TR1.4	815	3 947
	TR2.3AN	2 099	8 633
	TR2.4	188	373
DK_Otter >24	OTH	984	139
	otter.3AN	966	690
	TR1.3AN	316	2 217
	TR1.4	2 721	9 009
	TR2.3AN	313	1 760
	TR2.4	484	792
DK_Otter40+	OTH	3 284	425
	TR3.4	438	189
DK_Static <24	GN1.3AN	372	4 275
	GN1.4	884	5 221
	GT1.4	95	493
	OTH	56	299
EN_Beam >24	BT1.4	218	609
	BT2.4	1 946	3 831
	OTH	453	107
EN_Otter <24	OTH	456	486
	TR1.4	860	3 294
	TR2.4	1 547	2 600
EN_Otter >24	TR1.4	808	2 613
	TR2.4	747	1 031
EN_Static	GN1.4	522	979
	OTH	5 275	834
OTH_OTH	OTH	1 000	14 292
FR_Otter	OTH	71	8
	TR1.4	2 801	16 588
	TR2.4	1 270	2 157
	TR2.7D	7 433	3 408
FR_Static	GT1.4	433	795
	OTH	1 530	25
GE_Beam	BT2.4	1 464	1 216
	OTH	6 259	75
GE_DSeine	OTH	34	83
	TR1.4	176	2 680
GE_Otter	TR1.3AN	156	1 721
	TR1.4	1 397	16 285
	TR2.4	457	1 282
NL_Beam <24	BT2.4	946	1 798
	OTH	29	88
NL_Beam24-40	BT2.4	3 091	3 934
	OTH	51	9
NL_Beam40+	BT1.4	324	539
	BT2.4	18 438	22 618
	OTH	118	27
NL_Otter	TR1.4	770	1 942
	TR2.4	1 177	2 429
NO_Beam	BT1.4	39	63
	BT2.4	103	161
NO_Otter	OTH	1 006	1 133
	TR1.4	5 988	51 659
SC_Beam >24	BT1.4	69	170
	BT2.4	1 349	2 756
SC_DSeine	TR1.4	1 291	8 853
SC_Otter <12	OTH	20	18
	TR2.4	752	1 489
SC_Otter >24	TR1.4	7 501	34 336
	TR2.4	1 288	2 178
SC_Otter12-24	OTH	116	8
	TR1.4	3 364	11 869
	TR2.4	7 297	18 455

Métier names are consistent with the cod LTMP [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, trammelnets; LL1, longlines; OTH, others. 4, 3AN and 7D refer to the ICES Area (North Sea, Skagerrak, and English Channel, respectively).

forecast (these forecasts are hereafter 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, or whiting (*Merlangius merlangus*). 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 landed (potentially), based on the historical landings/discards ratios by fleet and stock included in the inputs, but they are not necessarily equal to the legal landings, i.e. the TAC.

Consistent with common procedures in the advice provided by ICES, only deterministic short-term forecasts were performed, with the same settings used by ICES (2009b) in terms of mean weight-at-age, mean selectivity-at-age, discard ratio (usually 3-year averages), and recruitment assumptions (usually a geometric mean estimate). The results were compared with the 2009 landings assumptions from the baseline, based on the results of the stock assessments. The 1-year forecasts for the different scenarios provided alternative sets of plausible levels of F by stock in 2009 [$F_{\mathrm{Fcube}}(\mathrm{St}, Y+1)$] accounting for mixed-fisheries interactions. The Fcube scenarios simulated are listed below.

(i) "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.

(ii) "min"—the underlying assumption is 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.

(iii) "cod"—the underlying assumption is that the fleets stop fishing as soon as their cod quota is exhausted, regardless of quota for other stocks.

(iv) "val"—this represents a very simple proxy computed about revenue. The underlying assumption is that the global effort of each fleet is influenced by the monetary value each fleet

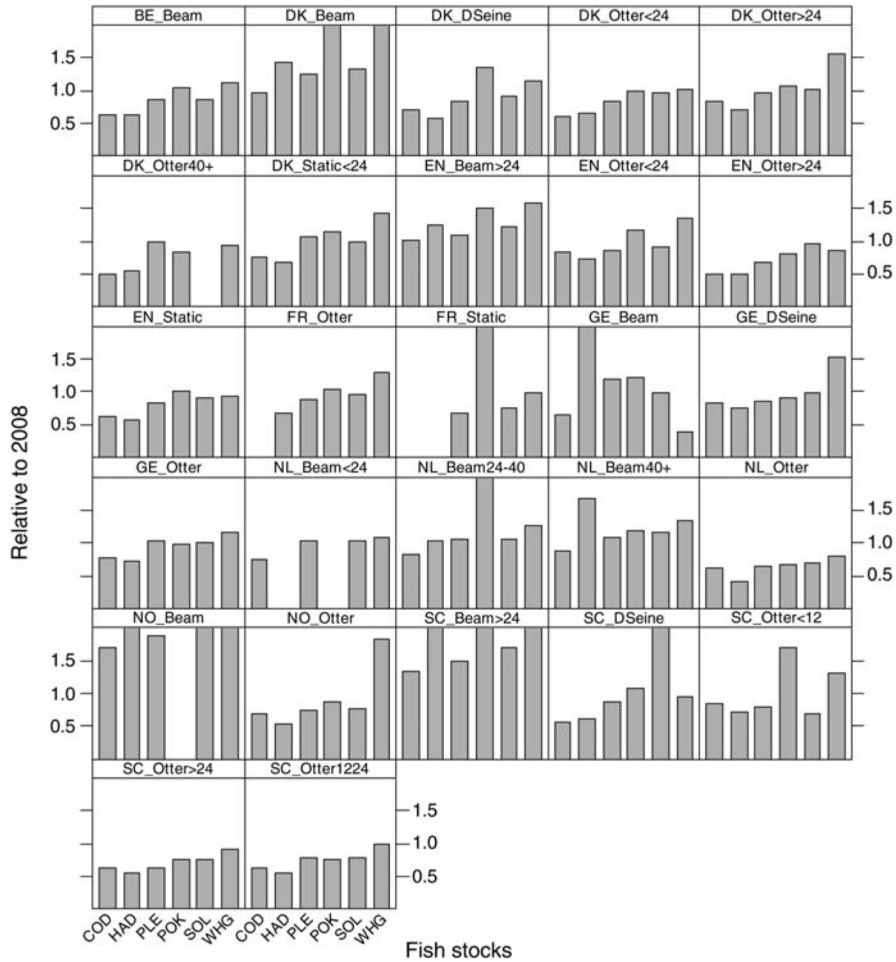

Figure 1. One-year forecast Fcube estimates of effort by fleet corresponding to the individual quota share (or partial F_{target}) by fish stock in 2009, relative to 2008. Columns are truncated at a value of 2. Fleet OTH_OTH not shown.

can obtain 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, $L(\text{Fl,St},Y)$. The final level of effort is set at the level of this weighted mean [Equation (12)]. This is not a true economic proxy, but rather 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:

$$\text{Quota Value}(\text{Fl, St}, Y) = \frac{L(\text{Fl, St}, Y) * \text{Pr ice}(\text{Fl, St}, Y)}{\sum_{\text{St}} L(\text{Fl, St}, Y) * \text{Pr ice}(\text{Fl, St}, Y)}, \tag{11}$$

$$E(\text{Fl}, Y+1) = \sum_{\text{St}} E(\text{Fl, St}, Y+1) \times \text{Quota Value}(\text{Fl, St}, Y+1). \tag{12}$$

(v) "sq_E" —the effort is simply set as constant relative to previous years.

Two-year forecast

Typically, single-stock TAC advice is based on a 2-year, short-term forecast, because 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 2-year flow. The new 2009 $F_{\text{Fcube}}(\text{St},Y+1)$ values by stock derived from the 1-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 for 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, differences in the recommended TACs for 2010 resulting from different scenarios and an estimate of the cumulative difference between TAC and realized catches over 2 years could be calculated.

Hindcasting

In addition to the exploratory sensitivity analyses summarized above, hindcasting exercises were performed to test the suitability

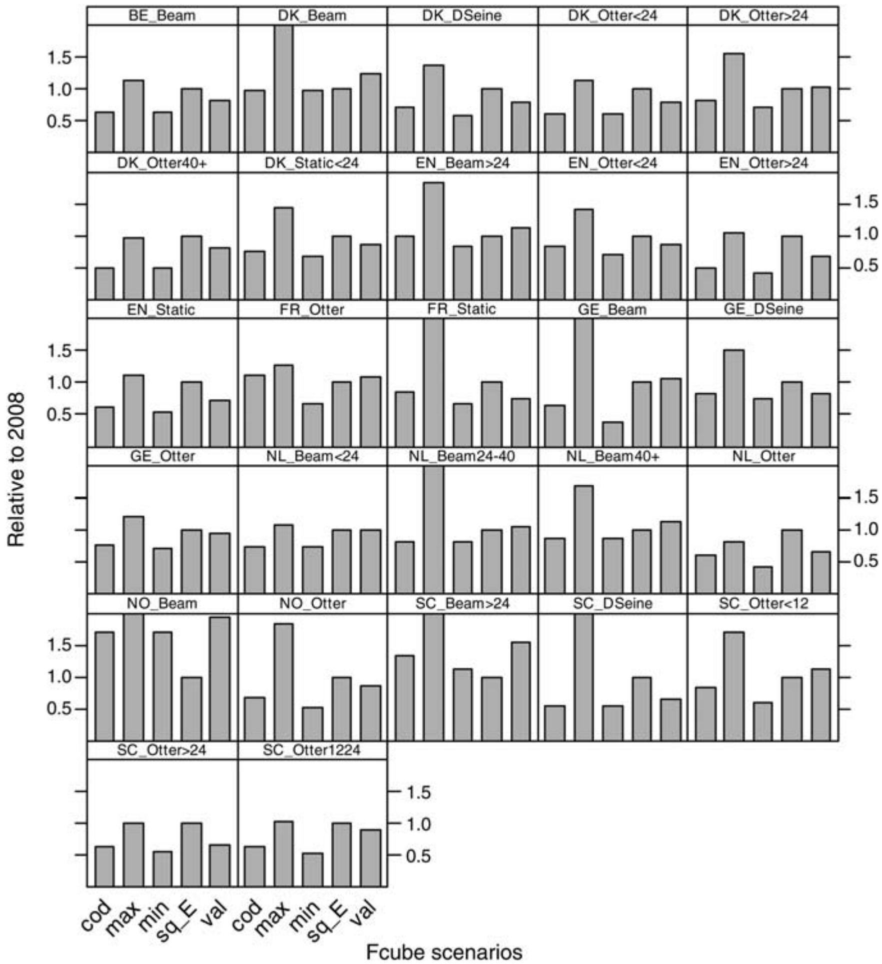

Figure 2. One-year forecast Fcube estimates of effort by fleet for the various scenarios in 2009, relative to 2008. Columns are truncated at a value of 2. Fleet OTH_OTH not shown.

of the various Fcube scenarios to predicting the observed levels of effort by fleets. This served 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 1 year from the database, performing 1-year projections as for the 1-year forecast above, then comparing the forecast effort by fleet with the actual observation in the removed year. Hindcasting projections therefore covered the years 2004–2008, using the actual observed landings by stocks as a proxy for the TAC target (instead of the true TAC, to preclude issues of actual TAC not being entirely consistent with reproducible single-stock forecasts).

Results

One-year forecast

For each fleet, there were striking differences about 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. The figure illustrates 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 to the least effort, indicating more-restrictive targets. These discrepancies also varied from fleet to fleet, demonstrating that each fleet had 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. Whereas the "max" effort was often substantially greater 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 was also relatively close to the "cod" estimate, indicating that cod is still a key source of revenue for the fleet despite decreased recent TACs compared with historical ones.

The results at stock level once partial *F*s were summed are shown in Figure 3 and Table 4. Note that for cod, plaice, sole, and whiting, the single-species forecast assumptions used by

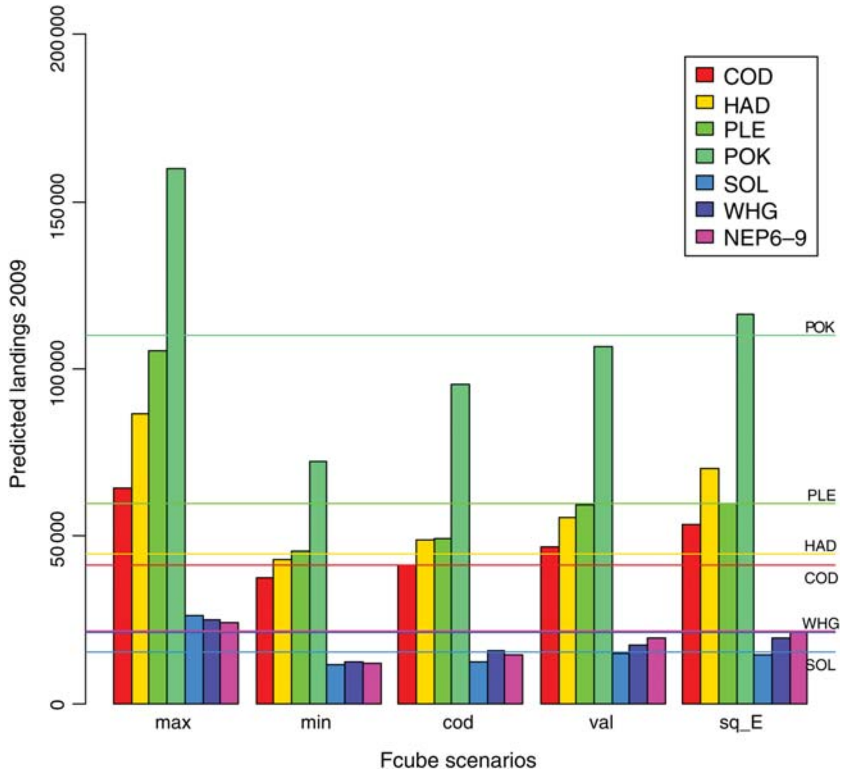

Figure 3. One-year forecast Fcube landings estimates by stock for the various scenarios in 2009. Straight lines are the baseline estimates (landings estimates in the intermediate year in the single-stock forecast). The NEP6–9 baseline is not labelled because it is almost equal to the WHG baseline.

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 exceeded the baseline estimates by 29 and 58%, respectively, whereas whiting landings estimates were 13% below the baseline. In the "val" scenario, the estimated landings above the baseline were 12 and 20% for cod and haddock, respectively, whereas they were 23% below the baseline for whiting.

In contrast, the cod scenario, which complies with the 25% reduction in cod *F* in 2009 required by the management plan, implied strong reductions in landings for plaice, sole, saithe, and whiting (15, 20, 23, and 31%, respectively, with regard to the baseline, and 9, 13, 39, and 24%, respectively, with regard to TAC 2009), whereas haddock landings were close to the baseline. This suggests that the haddock and cod management plans were consistent with each other for 2009, but that the other management plans were not consistent with these.

Two-year forecast

The full overview of the runs up to 2010 is given in Table 4, and in Figure 4 in relative numbers. Following 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. However, under the "max" scenario, assuming that all fleets would fish until the full amount of their least restrictive quota was 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 rather than 64.4 kt) would imply a lower TAC advice for 2010 of 27.7 kt 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 an estimated 46.9 kt, i.e. just 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. Also, whereas the single-stock advice estimated an 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 the 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 were 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 $\pm 15\%$ from year to year.

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 extent of this range varied across fleets and years, without a clear pattern. For most of the

Table 4. Results of the 2-year forecast, with actual estimates obtained by applying identical scenarios 2 years in a row.

Variable	Year	Scenario	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
Authorized landings applying the basis for ICES advice in 2010	2010	min	40.9	37.9	63.8	118.2	11.9	26.6	1.3	16.4	1.6	1.4
		max	27.7	37.9	61.8	118.2	16.1	16.9	1.3	16.4	1.6	1.4
		cod	38.7	37.9	63.8	118.2	12.4	23.8	1.3	16.4	1.6	1.4
		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 applying the basis for ICES advice in 2010	2011	min	77.4	168.0	521.9	250.8	45.2	93.8				
		max	41.2	119.8	385.2	163.2	26.9	93.8				
		cod	73.2	161.8	513.1	227.4	43.8	93.8				
		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				

Authorized landings and estimated SSB are obtained by applying the basis of single-stock ICES advice for 2010 after Fcube scenarios in 2009. The baseline run represents the single-stock forecast. Fmult for a given year is given relative to *F* in 2008. Landings and SSB in kilotonnes. See text for full explanation.

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 that year than before. However, the effort predicted by the "max" scenario was usually 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 real behaviour, and the truth likely lies in between. Indeed, and although this cannot be generalized 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.

Discussion

Application of the Fcube approach to the North Sea demersal fisheries as 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 single-species advice in a mixed-fishery context. Each effort scenario implies a different outcome, in terms of the

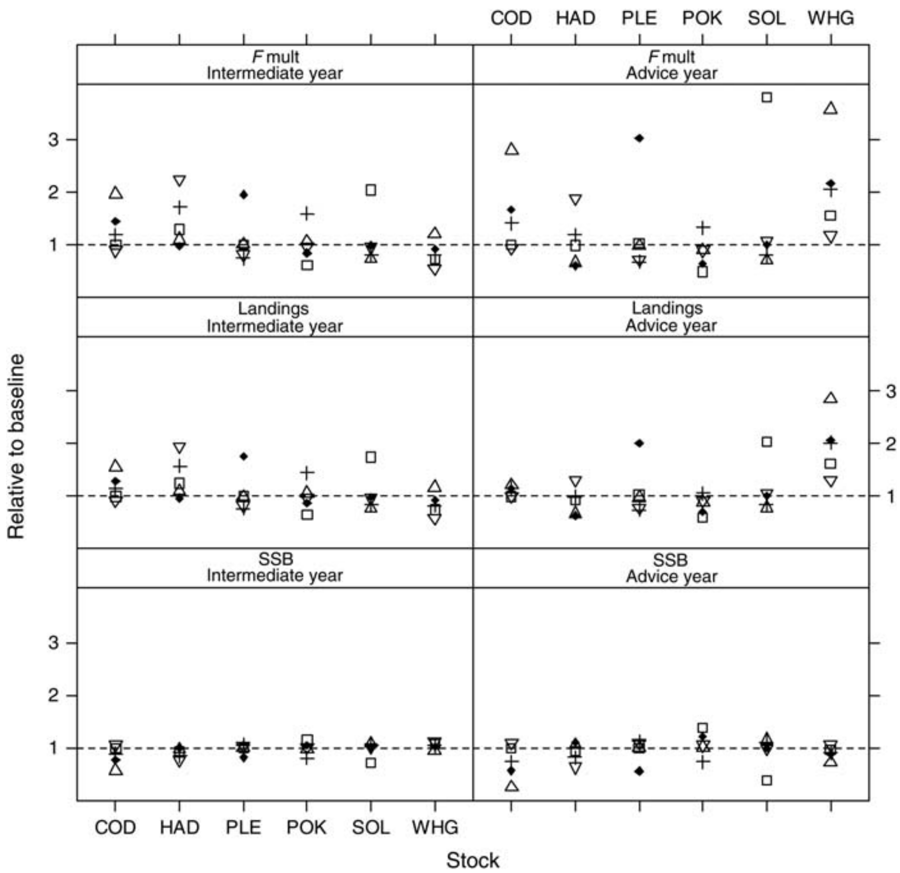

Figure 4. Results of the Fcube 2-year forecast relative to baseline for the fish stocks under various Fcube scenarios ("cod", open squares; "min", inverted triangles; "max", triangles; "val", crosses; "sq_E", filled diamonds). Fmult is relative to *F* in 2008.

state of each stock, at the start of the TAC year. Usually, 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 usually, 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 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 an 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 here, because in the "min" scenario, the stock minimizing the effort may not be the same across all fleets. Other interesting mixed-fisheries approaches may be drawn from, *inter alia*, 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 strategy 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, for example, of "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 affect 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). Whereas 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

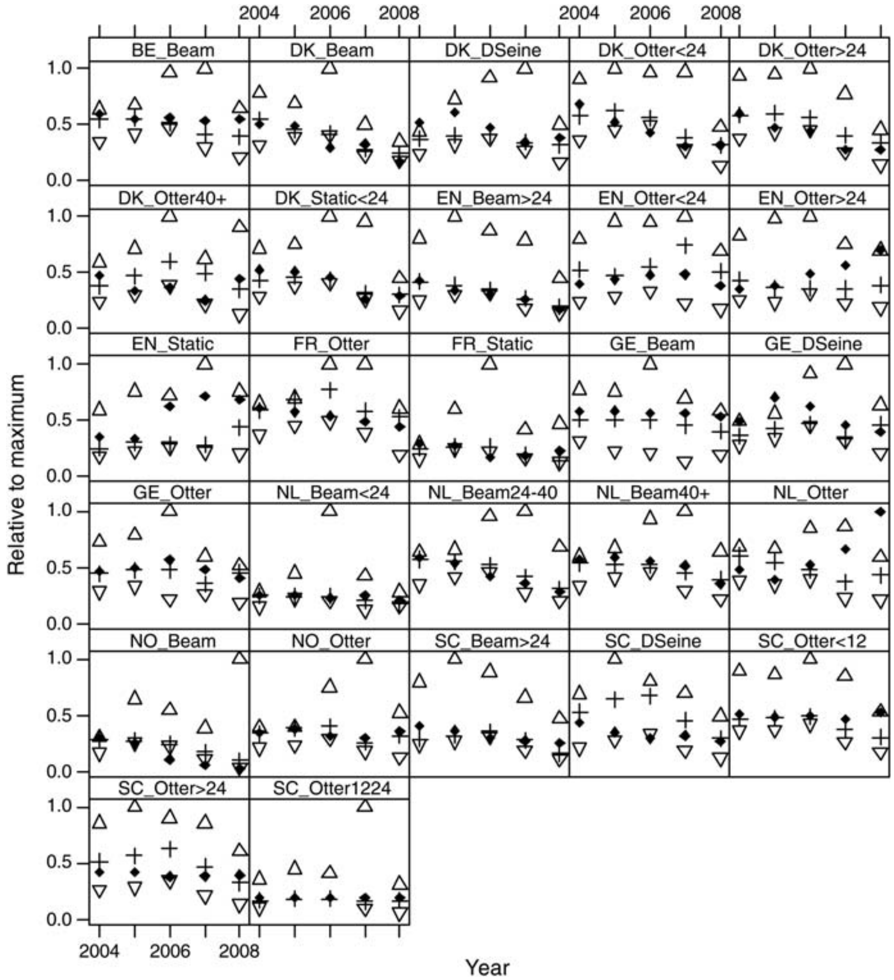

Figure 5. Hindcasting of the effort by fleet and year projected under various Fcube scenarios ("min", inverted triangles; "max", triangles; "val", crosses) compared with observed effort (filled diamonds). Within each fleet panel, the highest effort estimate across scenarios and years is set to 1 and all other effort values expressed relative to this maximum. Fleet "OTH_OTH" not shown.

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 arise in reality. However, the validity and utility of the "val" scenario in a real economic perspective can be challenged, because it does not take into account the actual costs linked to the uptake of the quota share, so does not effectively address the hypothesis of profit maximization. Hence, these analyses should be complemented by further investigations of the effect of such profit maximization, as done by Hoff *et al.* (2010), whose results suggest that provided there is sufficient flexibility to switch across métiers within a fleet, the optimum effort for profit maximization 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, so they are probably operating in an economically suboptimal manner.

Earlier sensitivity analyses (Garcia *et al.*, 2009; Hille Ris Lambers *et al.*, 2009) contributed to increased knowledge of model behaviour and confidence in the robustness of the approach, and shaped the setup of the final runs presented here. One main issue encountered is the uncertainty in 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 (Marchal *et al.*, 2006; van Oostenbrugge *et al.*, 2008; Baudron *et al.*, 2010). However, stochastic simulations showed that the standard deviation in Fcube outputs was less 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, both being estimated from the partial F and total effort by fleet. This implies that departures from one of these parameters as a consequence of alternative hypotheses will be compensated for by the other parameter in the calculations. This is intuitive, because if the catchability is higher than expected, the TAC of a stock will be taken up more quickly, requiring less effort, and *vice versa*. Moreover, individual variations by fleets are also smoothed when being pooled with other fleets at a regional level. Finally, uncertainty in effort and catchability is further smoothed out when translating fleet effort into catches by stock, because of the non-linear relationships between catches and fishing mortality. This robustness contributes to strengthening 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 dataset still includes information 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 complexity of North Sea demersal fisheries and the need to account for this complexity in their management.

The Fcube framework builds on simple computations of some key processes of 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 such human behaviour is too complex to be captured and modelled on a routine basis, even at the level of individual trip and fishing vessel. A fine-scale simulation of actual fishing strategies of fleets can be implemented at a regional scale (Marchal *et al.*, 2009; Andersen *et al.*, 2010), 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 simple. 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 single-stock forecasts and more-complex models such as MTAC (Vinther *et al.*, 2004). By proceeding with scenarios rather than optimization, and with just a few additional parameters compared with 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 quota shares between countries (ICES, 2009a). Preliminary trials were also performed in more data-poor areas: ICES Subareas VII and VIII where many stock 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.*, in press). In this area, useful recommendations on effort management can be issued based on a few simple but plausible hypotheses.

To conclude, 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 therefore 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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