ICES Journal of Marine Science, 62: 1104–1117 (2005)
doi:10.1016/j.icesjms.2005.05.005

Evaluation of multiple management objectives for Northeast Atlantic flatfish stocks: sustainability vs. stability of yield

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Kell, L. T., Pastoors, M. A., Scott, R. D., Smith, M. T., Van Beek, F. A., O'Brien, C. M., and Pilling, G. M. 2005. Evaluation of multiple management objectives for Northeast Atlantic flatfish stocks: sustainability vs. stability of yield. – ICES Journal of Marine Science, 62: 1104–1117.

This paper describes a simulation study that evaluated the ICES scientific advisory process used to recommend total allowable catches (TACs) for flatfish stocks. Particular emphasis is given to examining the effects on stock biomass, yield and stability of constraining interannual variation in TACs. A "management strategy evaluation" approach is used where an operating model is used to represent the underlying reality, and pseudo data are generated for use within a management procedure. The management procedure comprises a stock assessment that uses data to estimate parameters of interest and a decision rule to derive TAC recommendations for the following year. Bounds on TAC of between 20% and 40% have little effect on yields or stability, while a 10% bound on TAC can affect the ability to achieve management targets and result in low-frequency cycling in the stock. In the short term, performance is highly dependent on current stock status but bounds have less effect if the stock is close to equilibrium for a target fishing mortality (F). In addition, it was shown that current ICES biomass and fishing mortality reference points are not always consistent, and several are clearly inappropriate. Importantly, including realistic sources and levels of uncertainty can result in far from optimal management outcomes based on the current procedures. Results also conflicted with expert opinion, in suggesting that management based on a fixed F regime could result in relatively stable yields despite fluctuations in year-class strength and that the management feedback process itself is implicated in causing fluctuations in the system due to significant time-lags in this process. We therefore emphasize that providing more precise population estimates or developing harvest control rules alone will not necessarily help in achieving management objectives, rather management procedures that are robust to uncertainty and tuned to meet management objectives need to be developed. Operating models in these simulations were constrained to be based on existing ICES methods and perceptions of stock dynamics, but we recommend that, in future, operating models that represent the best available understanding of the actual system dynamics be used to evaluate models and rules considered for application.

Keywords: ABC, allowable biological catch, evaluation, fisheries management strategies, harvest, mathematical models, plaice, simulation, sole, TAC, total allowable catch.

Received 6 June 2004; accepted 7 May 2005.

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Introduction

Advice on the management of flatfish stocks in the Northeast Atlantic is provided by the Advisory Committee on Fisheries Management (ACFM) of the International Council for the Exploration of the Sea (ICES). The main objectives for the management of these stocks are to ensure that spawning-stock biomass (SSB) remains above a threshold at which recruitment may be impaired, and that fishing mortality remains below a threshold level that would drive the stock below the biomass threshold. The thresholds are often referred to as limit values (i.e. F_{lim} and B_{lim} for the fishing mortality and biomass limits, respectively). In recognition of the uncertainties in stock estimates and in

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an attempt to apply the precautionary approach, precautionary reference points (i.e. pa-values, F_{pa} and B_{pa}) have also been defined, which trigger management action before the thresholds are reached.

Management advice is based on an estimate of an allowable biological catch (ABC) that corresponds to a level of fishing mortality that will ensure that SSB remains above or recovers to the precautionary biomass level. However, such advice can lead to substantial interannual variations in ABCs and hence in the recommended total allowable catch (TAC), because of fluctuations in recruitment and uncertainties in the stock assessments. It might also be expected that variations in ABCs would be even larger when exploitation levels are high, because the incoming recruitment is then the main determinant of stock development (COM, 2000). The fishing industry has repeatedly pointed to their difficulties in adjusting to large fluctuations in TAC between years. On the other hand, stability in TACs could threaten the sustainability of fishery resources unless TACs were set very conservatively. Therefore, this study was conducted on behalf of the European Commission (i.e. the body with responsibility for management) to evaluate the trade-offs between sustainability and yield for strategies, based upon the current advisory framework, that restrict interannual variability in TACs for the main flatfish stocks in the ICES area. These stocks were plaice in the Skagerrak/Kattegat, the Irish Sea, the North Sea, and the eastern English Channel, and sole stocks in the North Sea, Irish Sea, and Eastern Channel.

A simulation approach, as pioneered by the IWC (Hammond and Donovan, in press), was used to evaluate the alternative management strategies (Kell *et al.*, 1999). The framework considered uncertainty in the dynamics of stocks and their fisheries, as well as our ability to monitor and manage them. The "true" stock and fishery dynamics are represented as the *operating model*, from which simulated data were sampled (*observation model*). The data were used within an *assessment procedure* to assess the status of the stock and, depending on the perception of the stock, management controls were applied within the *management procedure* to the fishery and fed back into the operating model. Performance statistics were used to evaluate the behaviour of the operating model. The operating models were conditioned on the recent ICES perceptions of the stock dynamics.

Material and methods

The simulation framework models both the "true" and the "perceived" systems (Figure 1). The "true" system represents plausible alternative hypotheses about the dynamics of the stocks and fisheries, and the "perceived" system represents the assumptions and methods used to provide scientific advice. The complexity of the system to be managed and the interactions between system components (e.g. as a consequence of delays between collecting data, assessing system status, and implementing management actions) makes simulation an important means of evaluating the relative importance of various components to the overall success of management of the resource (de la Mare, 1998; Holt, 1998; Kell *et al.*, 2005).

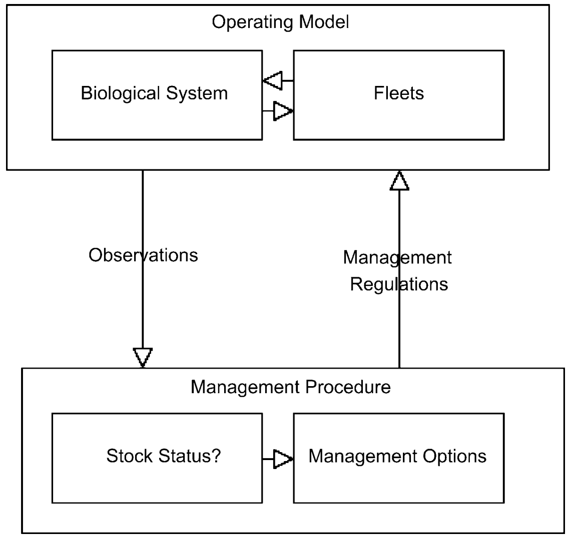

Figure 1. Conceptual diagram of the management evaluation framework.

Both the true state of stocks and our knowledge of their dynamics are generally more uncertain than indicated by stock assessments (c.f. Simonoff, 2003). Using a simulation framework allows the perceived system to be based on different assumptions from those made within the stock assessment process. This allows the robustness of alternative scientific advisory frameworks to be tested against the dynamics of fish stocks, our ability to monitor them, and to implement appropriate management regulations. The framework explicitly incorporates the sources of uncertainty categorized by Rosenberg and Restrepo (1994): process error caused by natural variation in dynamic processes (e.g. recruitment, natural mortality), measurement error (generated when collecting observations from a population), estimation error that arises from trying to model the dynamic processes, model error (as the model used in the assessment procedure will never capture the true complexity of the dynamics), and implementation error (as management actions are never implemented perfectly).

The true stock and fishery dynamics are represented as the operating model, and from this, simulated data are sampled in the observation model. These sampled data are used within a simulated management procedure, in which management actions for the fishery are set and implemented. The management actions are then fed back into the operating model. The management procedure in our implementation consists of an assessment procedure that is used to determine stock status relative to biological reference points. Performance statistics from the operating model are used to evaluate the performance of the management procedures for alternative plausible hypotheses about the system dynamics (in this case limited to assumptions about stock and recruitment).

Operating model

The operating model consisted of a simulated population, conditioned upon the ICES assessments in 2000 (ICES, 2001a, b, c). The population model was age-structured. Numbers-at-age were projected down a cohort (see Equations (1)–(6) in the Appendix), and recruitment was derived from a stock-recruitment relationship (see Equations (7a, b and c) in the Appendix). The simulated population consisted of three parts: the distant past, the recent past (the 5 years prior to the last assessed year, i.e. 1995–1999), and the future (a period of 30 years from the date of the last assessment year). Selection pattern in the recent past and future was modelled as a random variable, with expected values and residuals obtained from a lowess smoother (Cleveland, 1979) with a span of 0.75. Variability was modelled by bootstrapping the residuals to the smoothed fit. Alternative hypotheses about resource dynamics were modelled through different assumptions about the stock-recruitment relationship. Process error was modelled by the uncertainty in mass-at-age, selection pattern-at-age, and recruitment.

The objective of the study was a limited reform of the present system (i.e. interannual bounds on TACs), rather than a radical overhaul. The operating model in the distant past therefore corresponded to assumptions made and parameters estimated by ICES, and all values were deterministic. In the recent past, expected recruitment was obtained from the stock-recruitment curve, but realised recruitment had the same residual value as the recruitment in the original ICES fit. In this way, autocorrelation in the period 1995–1999 was preserved. For the future, the relationship between stock and recruitment was modelled as a random variable, assuming the same stock-recruitment relationship as used in the recent past.

Selection pattern-, proportion mature-, and mass-at-age by stock are presented in Figure 2. Selection pattern and stock mass-at-age were derived from a lowess smoother (span = 0.75). ICES Working Group values for proportion mature-at-age were used and were constant over years. As there was little additional information on natural mortality, values were deterministic, and took the same values as used by ICES.

As stock-recruitment data do not always yield information on the appropriate functional form to adopt for the relationship between stock and recruitment, five alternative functional forms were explored in the operating model:

(i) the relationship assumed by the relevant working group;
(ii) a two-line model as proposed by Butterworth and Bergh (1993, also termed a hockey stick model by Barrowman and Myers, 2000) – (see Equation (7b) in the Appendix);
(iii) a two-line model including the first-order autoregressive process, AR(1);
(iv) a Beverton and Holt (1957) model;
(v) a Beverton and Holt (1957) model including the first-order autoregressive process, AR(1).

All models were fitted assuming that recruitment had a lognormal distribution.

In the case of the Beverton and Holt model, the parameters were constrained to ensure a biologically meaningful parameterization, and α and β were re-parameterized as steepness (τ) and virgin biomass (γ; Francis, 1992). Steepness is the fraction of the virgin recruitment ($R\gamma$) that is expected when SSB has been reduced to 20% of its maximum, i.e. $R = \tau R\gamma$ when $SSB = \gamma/5$. As it was not possible independently to estimate a value of steepness for each stock, a common value of steepness (0.9) was chosen that minimized the residual variance across all stocks. Figure 3 shows the fitted stock and recruitment models, and compares them with estimates derived by ICES.

Expected equilibrium yields as a function of SSB (Kell and Bromley, 2004) were calculated to compare the observed relationships between yield and SSB with the theoretical expectations (Figure 4). The values of F_{MSY}, MSY, B_{MSY}, and MSY:B_{MSY} derived from the Beverton and Holt stock-recruitment relationship are compared with B_{lim} and B_{pa} in Table 1.

Management procedure

The management procedure is the combination of a particular data collection regime, a stock assessment methodology, and a harvest control rule (and implementation regime).

Data collection

Mass-at-age and landings-at-age were sampled from the operating model. Observation errors were derived from the EMAS project (evaluation of market sampling strategies for a number of commercially exploited stocks in the North Sea; ICES, 2001e), which investigated sampling error in the estimates of international landings compositions and mass-at-age. North Sea plaice was the only flatfish stock investigated in EMAS, but it was assumed that the mean–variance relationships and between age correlations for all stocks were similar (see Equations (16) and (17) in the Appendix). Natural mortality-at-age and maturity-at-age were assumed constant between years, and corresponded to values used in the most recent ICES Working Group.

Stock assessment methodology

The single-species stock assessment method XSA (eXtended Survivors Analysis; Shepherd, 1999) was used throughout the study. XSA is a calibrated variant of virtual

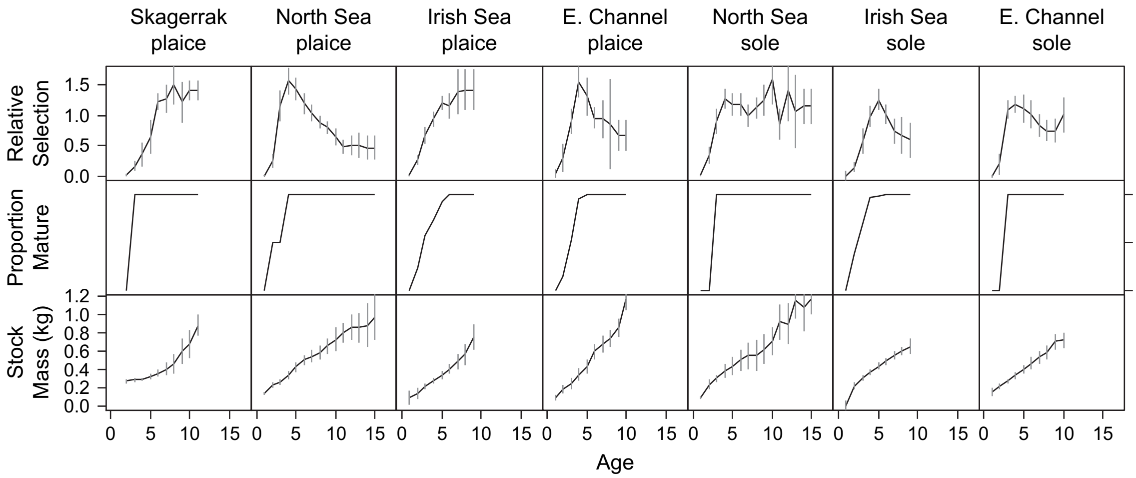

Figure 2. Selection, maturity, and stock mass-at-age assumed in future components of the operating model. Error bars show $\pm$ 1 s.d.

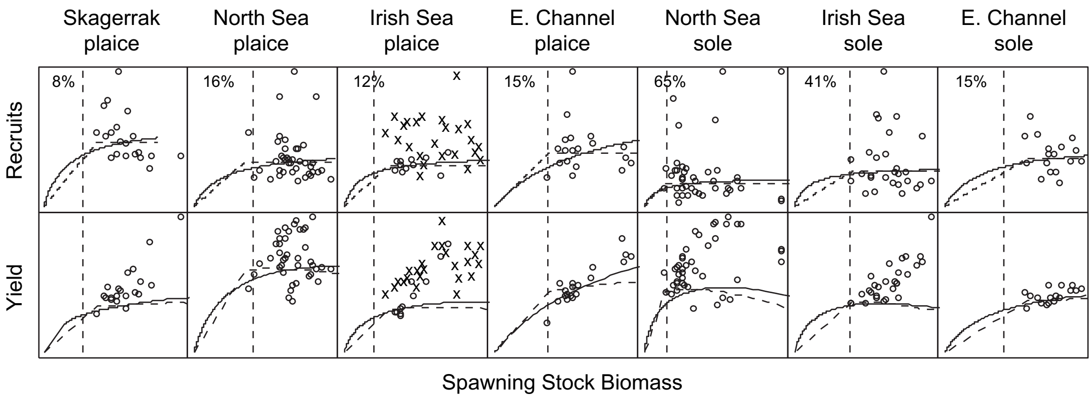

Figure 3. ICES estimates of recruits and yield plotted against spawning-stock biomass. Expected values are also shown for Beverton and Holt (solid) and Butterworth and Bergh (dashed) stock-recruitment relationships. The axes show spawning-stock biomass, recruitment, and yield, from 0 to the maximum value by stock. CVs of recruitment residuals are indicated.

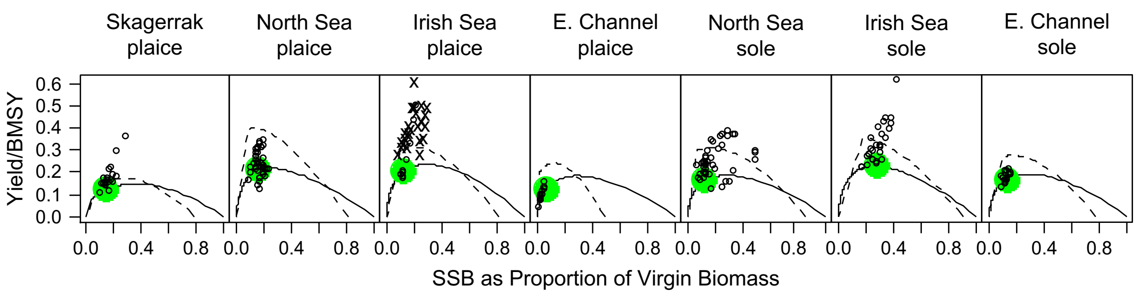

Figure 4. Estimates of relative yield (yield over spawning-stock biomass at MSY) plotted against SSB, expressed as a proportion of virgin biomass. Superimposed are the expected yield−SSB curves for Beverton and Holt (solid) and Butterworth and Bergh (dashed) stock-recruitment relationships. The grey area indicates the expected yield and SSB for F_{pa} assuming a Beverton and Holt stock-recruitment relationship. Points indicated by crosses indicate data that were not used to fit the stock-recruitment relationship.

Table 1. Values of F_{MSY}, MSY, B_{MSY}, and MSY:B_{MSY} derived from the Beverton and Holt stock-recruitment relationship, together with B_{lim} and B_{pa}.

Parameter	Skagerrak plaice	North Sea plaice	Irish Sea plaice	Eastern Channel plaice	North Sea sole	Irish Sea sole	Eastern Channel sole
F_{MSY}	0.16	0.19	0.18	0.15	0.15	0.29	0.17
MSY	12 849	115 519	2 318	13 505	17 595	1 169	4 699
B_{MSY}	96 636	630 462	10 607	88 533	107 702	5 292	27 055
MSY:B_{MSY} (%)	13	18	22	15	16	22	17
B_{lim}	Not defined	210 000	Not defined	5 600	25 000	2 800	Not defined
B_{pa}	24 000	300 000	3 100	8 000	35 000	3 800	8 000

population analysis (VPA). The method re-creates a stock's historical population structure from the catch-at-age matrix. Recruitment estimates of the survivors after the last year of data were replaced using calibrated regression estimates of survivors (RCT3; Shepherd, 1997), where this analysis was carried out by the ICES Working Group. All options in the assessment procedure matched the assumptions used by ICES. These settings were maintained for the future analytical period. This is contrary to the practice of ICES Working Groups, which tend to make small changes to the way assessments are run each year.

Catch per unit effort (cpue) data were used to calibrate the assessment model. For each stock, the data corresponded to those used by ICES. For the future period, they were generated from the true numbers-at-age in the operating model by assuming catchability to be a lognormal random variable, with parameters taken from the ICES assessments. The CVs used by age, survey, series, and stock are shown in Figure 5. These include measurement error (attributable to sampling), process error (as biological processes may change, the distribution of a stock with respect to the spatial distribution of fishing effort), and estimation error (as these quantities are derived from XSA).

The estimation errors associated with the ICES assessments (i.e. XSA) are summarized in Figures 6 and 7. Values are scaled to B_{lim} for SSB and to F_{pa} for F. The box-and-whisker plots represent the uncertainty derived from XSA estimates of the expected values and CVs of numbers and fishing mortality-at-age in the final data year.

Harvest control rule

The objective of the simulations was to reduce fishing mortality to the target fishing mortality level (see experimental treatments). The allowable biological catch (ABC) was derived from a "short-term projection". Numbers-at-age were projected through the year of assessment (for which total catch data are not yet available). *Status quo* exploitation pattern and mass-at-age were set as the mean of the last 3 years. A projection based on a fixed fishing mortality was then made in the following year, to estimate the ABC. The quota or TAC corresponded to the ABC, except if it differed from the previous year's TAC by an amount greater than pre-specified limits (the "TAC bounds"); i.e.

If $ABC_{t+1} > TAC_t \times (1+\alpha)$, then
$TAC_{t+1} = TAC_t \times (1+\alpha)$;
Else, if $ABC_{t+1} < TAC_t \times (1-\alpha)$, then
$TAC_{t+1} = TAC_t \times (1-\alpha)$;
Otherwise,
$TAC_{t+1} = ABC_{t+1}$;

where α is the bound on the annual fluctuation in TAC.

If the target fishing mortality was smaller than the current fishing mortality at the start of the future period, an initial transition period was implemented, where fishing mortality was progressively reduced by 50% each year until the target level was reached. There was no transition period if the target mortality was greater than the current fishing mortality.

The simulated yield in the future was assumed to equate to the TAC set by the management procedure (i.e. no implementation error). Fishing mortality was constrained so that in any year, both the annual increase and absolute level were never more than twice those that had been observed historically. If this constraint were applicable, the TAC would not be taken in that year. In the recent past, yield was as estimated by the ICES Working Groups. The fishery was modelled as a single fishing fleet, with stochastic noise on the selection-at-age.

Experimental treatments

Experimental treatments were set up in terms of target fishing mortalities and bounds on the interannual variability in TACs. These were compared with a base case in which there were no bounds on interannual variation.

In terms of target fishing mortality, the target values evaluated for each stock (Table 2) spanned the lowest value of the standard reference points F_{pa}, F_{max}, or $F_{0.1}$ to 1.2

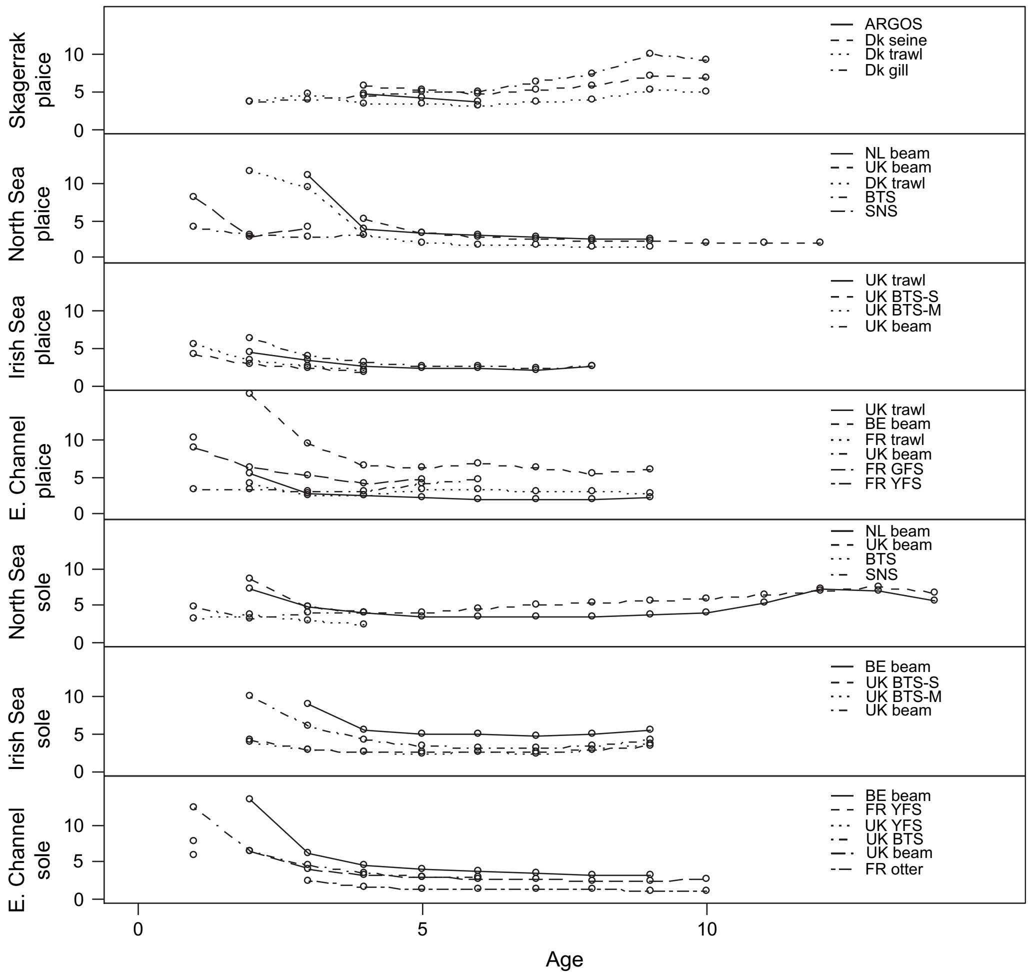

Figure 5. CVs of catchability-at-age for cpue series, derived from 2001 ICES stock assessments.

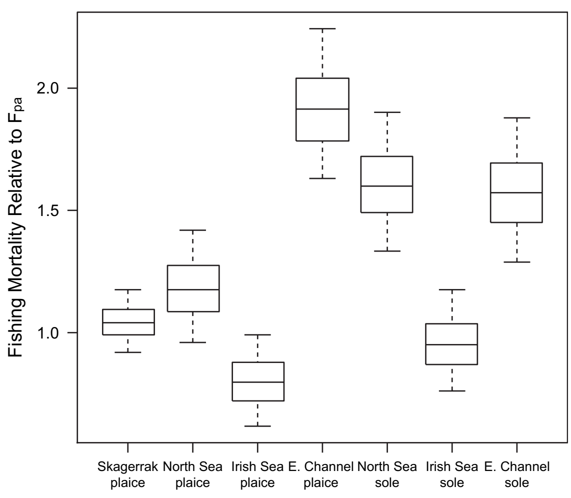

Figure 6. Median F values at start of simulations (2000) relative to F_{pa} by stock. Boxes show 25th and 75th percentiles, and whiskers 5th and 95th percentiles.

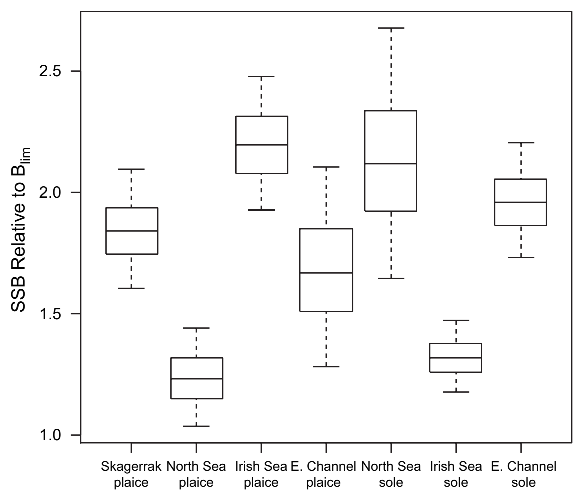

Figure 7. Median values of spawning-stock biomass at the start of simulations (2000), relative to B_{lim} by stock. Boxes show 25th and 75th percentiles, and whiskers 5th and 95th percentiles.

Table 2. Target Fs used in evaluations.

Skagerrak plaice	North Sea plaice	North Sea sole	Irish Sea plaice	Irish Sea sole	Eastern Channel plaice	Eastern Channel sole
0.1	0.2	0.2	0.1	0.2	0.1	0.1
0.275	0.275	0.3	0.1875	0.275	0.275	0.2
0.45	0.3 (F_{pa})	0.4 (F_{pa})	0.275	0.3 (F_{pa})	0.45 (F_{pa})	0.3
0.625	0.355	0.5	0.3625	0.35	0.625	0.4 (F_{pa})
0.73 (F_{pa})	0.42	0.6	0.45 (F_{pa})	0.425	0.8	0.5
0.8	0.5	—	—	0.5	—	—

times $F_{1997-1999}$ or F_{pa}, whichever was the highest. Five different F levels were investigated for each stock, chosen at equal intervals, plus F_{pa} if the value of this reference point was not included as one of the five levels.

In terms of TAC bounds, the imposed bounds on interannual variability in TACs were 10%, 20%, 30%, and 40%, and were symmetric.

In addition, treatments were carried out that corresponded to the (unrealistic) assumption of a perfect assessment of stock status (i.e. no measurement error, estimation error, or model error), which is the implicit assumption of ICES Stock Assessment Working Groups. This allowed examination of the effect of assessment procedures on the results of management evaluations.

Performance statistics

Performance or summary statistics from the operating model were used to evaluate effects of reductions in interannual variability in yield, and on the trade-off between expected yield and the risk of the stock falling below B_{lim}. The main summary statistics were therefore:

(i) the probability of SSB falling below B_{lim};
(ii) the mean yield.

The summary statistics were monitored in the short, medium, and long term.

Results

The effect of constraining interannual variability in TACs for different levels of fishing mortality, averaged over all stock-recruitment relationships, is summarized in Figure 8. The expected yields and SSB (Figure 8a and b, respectively) relative to the long-term yields and SSBs are summarized for a fishing mortality of F_{pa}, with no bounds on TACs in the short (2001−2005), medium (2006−2015), or long term (2016−2030).

In the short term, the behaviour of stocks depends upon the initial stock status relative to the yield and SSB implied by the treatment fishing mortalities. In the medium to long term, as the equilibrium point is approached, initial conditions have less of an effect. Where contours are vertical, TAC bounds have little effect, for example in the two Channel stocks. This indicates that expected yields and SSB in both the short and long term are driven largely by target fishing mortality. In other stocks, the strong effects of limiting TAC variability can be seen clearly by the strong horizontal or diagonal contours, e.g. North Sea plaice and Irish Sea sole. Therefore, TAC constraints initially prevent F being reduced, so SSB is driven down. Note that the effects of limiting interannual TAC variability are mostly observed in the short term; the long-term effects of these limitations are substantially less.

The dynamic behaviour for an exploitation rate equivalent to F_{pa} is shown in Figure 9 by stock and for the different interannual TAC constraints. Although the evaluations were performed for a variety of assumptions about the stock-recruitment relationships in the operating model, similar behavioural responses were seen. The results for the stock-recruitment relationship used by ICES to provide advice on TACs are therefore presented. The trajectories are expected to converge on the equilibrium value in an anti-clockwise direction, at the rate of change and direction indicated by the vectors (Kell *et al.*, 2005). The further the point is from the equilibrium curve, the greater will be the annual change in SSB and yield, as indicated by the vectors. Biological reference points are superimposed on the graph. Although the equilibrium SSB−yield curves are all similar in shape, there is considerable variation in the positions of the biomass reference points, the relative distance between them (i.e. the precautionary level), and the expected SSB for F_{pa}. This shows that both limit and precautionary reference points, as chosen by ICES, are not consistent within or between stocks, and in the case of Irish Sea sole (where fishing at F_{pa} would drive the stock to a SSB below B_{pa}), clearly inappropriate.

As expected for all stocks, the equilibrium values of SSB and yield are approached in an oscillating fashion. The effect of limiting interannual TAC variability is mostly observed in the case of the strongest bound (10%). Although the equilibrium SSB and yield curves are similar for the stocks considered, the behaviour of the simulations

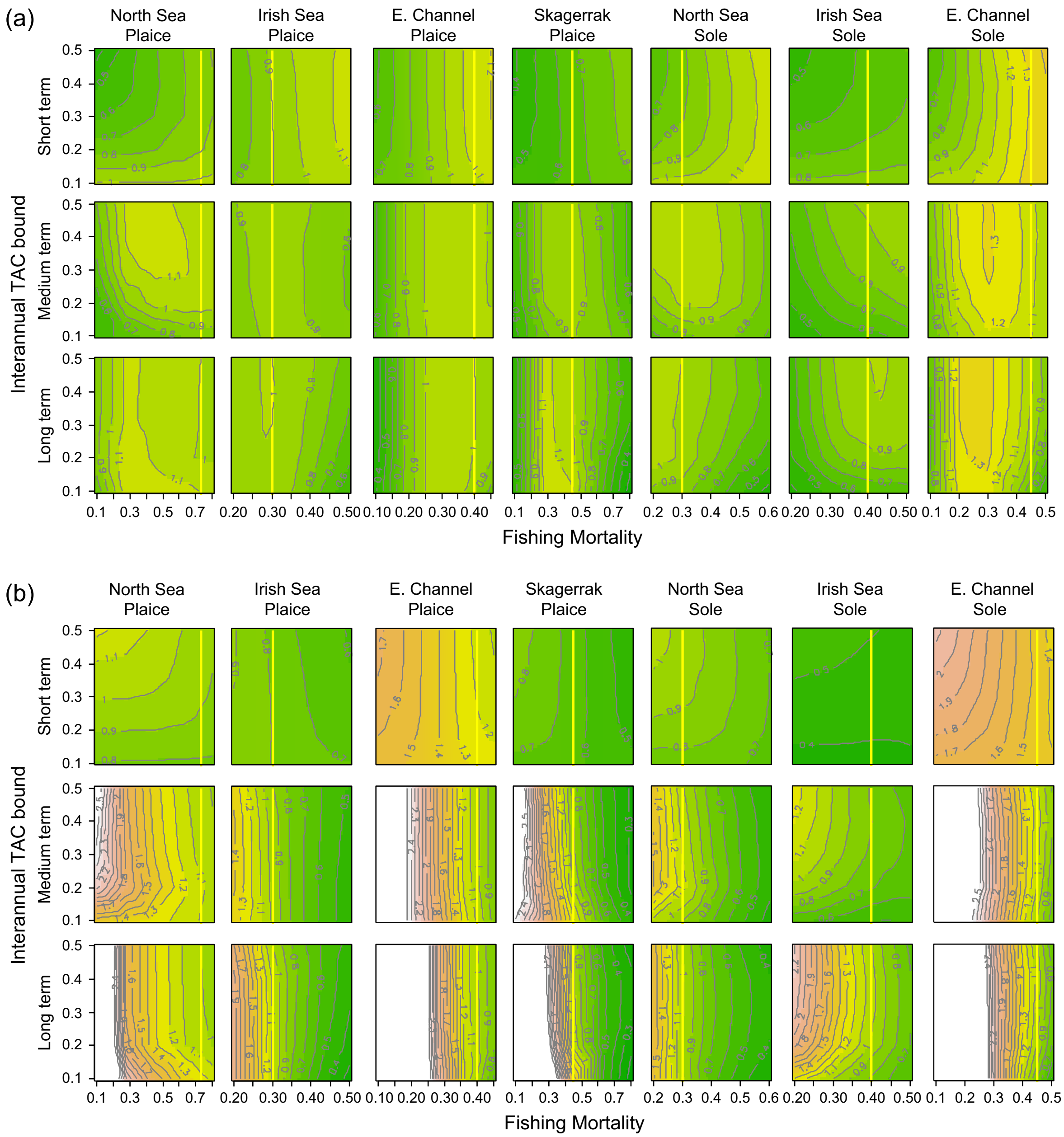

Figure 8. Contour plots of (a) expected yields and (b) expected spawning-stock biomasses, in the short (2001−2005), medium (2006−2015), and long term (2016−2030) for different combinations of fishing mortalities (x-axis) and TAC bounds (y-axis). Expected yield values are relative to the long-term yield for a fishing mortality of F_{pa}, with no bounds on TACs.

is quite different. The trajectories of Irish Sea plaice and Eastern Channel sole converge on the target point in a relatively short period of time. Skagerrak plaice and North Sea plaice do not converge to the equilibrium value, but to a point nearby. North Sea sole exhibits strong cycles and Irish Sea sole does not converge on the target at all, because the yield is always below the equilibrium level, so SSB continues to increase. The latter behaviour is due to the failure of the XSA assessment to converge.

To determine whether the observed behaviour was due to assumptions in the operating model or due to behaviour of the management procedure, simulations were conducted where the fishing mortality in the operating model was actually F_{pa}, rather than being set via a TAC, i.e. there was no assessment or stock projection in the management procedure. Results are presented in Figure 10 for two indicative stocks. In the absence of estimation and measurement error, the expected yield and SSB converge

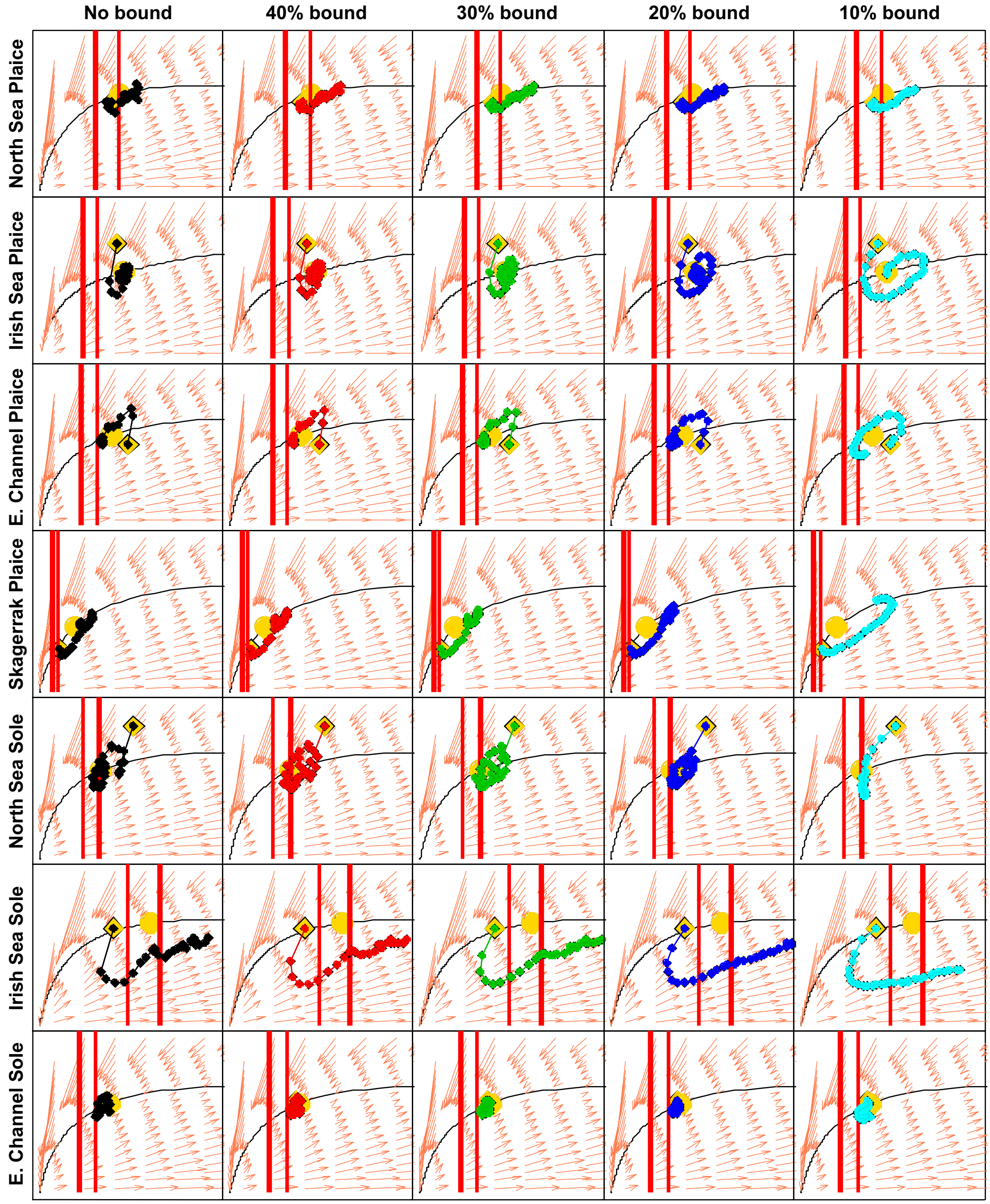

Figure 9. Curves of equilibrium yield against spawning-stock biomass for all stocks and for different bounds on interannual variation in TACs (including no bounds) under the assumption of a Beverton and Holt stock-recruitment relationship. Simulated trajectories for 30 years are also shown. The dots represent the midpoints of the distribution each year. The yellow diamond shows the starting position and the yellow circle the implied target (equilibrium value). Vectors show the expected direction and rate of change in yield and SSB for perturbations from the equilibrium. Vertical lines represent B_{lim} (thick) and B_{pa} (thin), respectively.

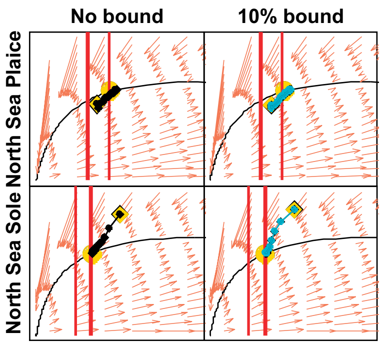

Figure 10. Curves of expected yield against spawning-stock biomass for North Sea plaice and sole under a fixed F (equal to F_{pa}) scenario, without implementation error and for two different bounds on interannual TAC variation: no bound and a 10% bound.

quickly to the equilibrium values. Only in the case of a 10% bound on interannual variation in TACs is there still some oscillating behaviour. This demonstrates that the oscillation is mostly a result of the management procedure, rather than operating model assumptions, and that it is important to include the management procedure within management strategy evaluations. When the management procedure was included (Figure 8), the dynamic behaviour of the stocks and fisheries in terms of yield and SSB could not be predicted from the biological assumptions alone or from the simulations based upon a target fishing mortality (i.e. without feedback from the management procedure to the operating model).

When fishing mortalities are set using a management procedure that includes stock assessment and forecasts, bounding interannual variability in TACs results in an increased tendency for stocks to cycle anti-clockwise around the equilibrium value. Low-frequency oscillations occur as a result of lags between being able to detect changes in a stock, implement the management measure, and obtain a response from the stock. If a stock is already near its equilibrium value, bounds on TACs have little effect (e.g. North Sea plaice).

Figure 11 shows the average annual variation in yield for different levels of fishing mortality for Irish Sea plaice and North Sea sole, two stocks that illustrate the range of behaviours seen. Fishing mortality is set directly (i.e. there is no management procedure), so only process error attributable to growth, selectivity, or catchability-at-age, and recruitment is modelled. Panels in the first row show variation attributable to growth and selectivity, those in the second row to variability in recruitment, and those in the third row to both processes combined. The expected interannual variation in yield is around 10% for both stocks when all processes are combined, the same as the most restrictive TAC bound, so explaining why interannual bounds had little effect when the management procedure was not simulated. It had been argued by "experts" prior to these simulation experiments that largest variations in yields were to be expected at high fishing mortalities where variability in biomass will be determined by year-class strength (COM, 2000). Although that may be the case for North Sea sole, in which recruitment variability was the highest of all the study stocks with a CV of 65%, it was not the case for Irish Sea plaice, with a CV of 14%, in which greater variations in yields result at the highest and lowest fishing mortalities, and variations in growth selection and catchability-at-age dominate. Also, the two sources are not additive: variation appears to be dominated by one or other of the processes.

Discussion

At the request of managers, the study evaluated the trade-offs between yield, stability of yield, and sustainability of the stock, when limiting the interannual variability in TACs set by the ICES scientific advice framework for flatfish stocks. The request constrained the study within the current framework, because the strategies evaluated simply set bounds on the relative interannual increase or decrease in TACs as set by the current system.

Within the range of interannual TAC bounds examined, those between 20% and 40% had little effect on either yields or sustainability. In general, interannual variability seen in actual flatfish TACs has been about 10−20%, with occasional larger changes. However, applying a 10% bound to interannual TAC variation, within the simulations, affected the ability to achieve management targets, and could also result in low-frequency cycling in the stock. This meant that, while interannual variability was constrained, the actual range of TACs seen over the longer term could still be wide.

The effect of bounds on interannual yields in the short term was strongly dependent on the status of the stock at the start of the simulation. If the stock was within safe biological limits, strong limitations on TAC variability kept the stock high. However, narrow bounds such as 10% eliminated the possibility of large reductions in TAC, and could result in a delay in achieving management targets when the stock was in a recovery scenario and TAC levels were too high. Bounds had less effect once the stock had reached equilibrium for a target F.

The results also indicated that large fluctuations in yields and effort could result from the management procedure itself (i.e. in data collection, stock assessment, and the management framework). Simply trying to cap the fluctuations in TACs does not therefore address the root cause of the problem, the management procedure. This is because the current management procedure is a feedback process in which there are important time-lags between the collection of data, performing the stock assessment, implementing

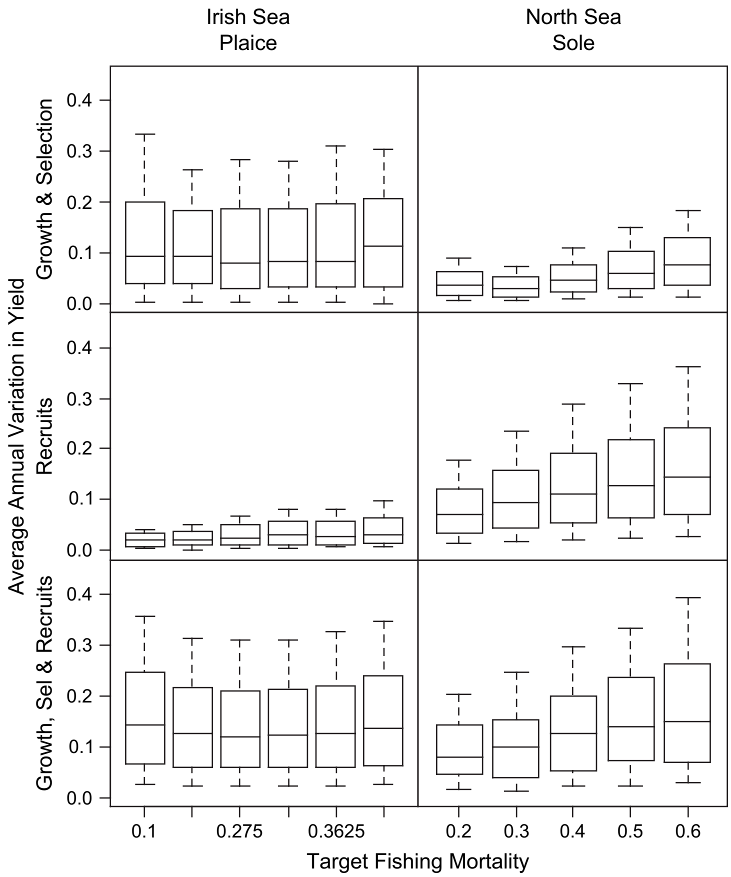

Figure 11. Average annual variation in simulated yield of two plaice stocks in ICES Subdivisions IIIa, IV, VIIa, and VIId at different fixed levels of target fishing mortality, without implementation error. Boxes show median, 25th, and 75th percentiles, and whiskers show 5th and 95th percentiles.

management advice, and detecting the effect of a given management action, and then re-starting the cycle. If it was possible to ensure directly that fishing mortality was constant, rather than indirectly through a management procedure based upon TACs aligned on a target fishing mortality, the result would be relatively stable TACs for flatfish, as can be seen from a comparison of Figure 10 with Figure 9. This appears to conflict with expert opinion that a constant effort regime will result in yield fluctuations as a consequence of different year-class strengths (COM, 2000).

In our simulations, we found that the highest variations in yields were not necessarily at the highest fishing mortalities, but could also be at moderate fishing mortalities. For example, Figure 11 shows that, for Irish Sea plaice, there is greater variability in yields at both the lower and higher fishing mortalities. This was also contrary to expert opinion that high fishing mortalities lead to high fluctuations in catch possibilities from year to year.

The ICES scientific advice framework is based upon defining limits for SSB and fishing mortality. B_{lim} corresponds to a biomass level below which recruitment is impaired or stock dynamics are unknown, and F_{lim} corresponds to a fishing mortality above which the stocks would be driven below the biomass limit. Avoiding these limits is institutionalized by defining precautionary reference points (B_{pa} and F_{pa}) as thresholds that allow for uncertainty in estimating stock status. The biological reference points used in this framework are generally derived from equilibrium assumptions (ICES, 2001d). However, inspection of the expected dynamics across stocks (as given by the equilibrium curves) showed that biomass and fishing mortality reference points were sometimes inconsistently chosen between and even within stocks, and did not appear to reflect differences in stock dynamics. For example, the biomass reference points B_{lim} and B_{pa} for Skagerrak plaice are set at a level where productivity of the stock is already severely impaired, whereas for Irish Sea sole they are set at a level well before any impairment is expected. The choices of fishing mortality and biomass reference points are often also inconsistent within stocks. For example, in the case of Irish Sea sole, a fishing mortality of F_{pa} results in an expected biomass below B_{pa}. It is also known that fish stocks can fluctuate extensively over a large range of spatial and temporal scales independently of human exploitation (e.g. Hjort, 1914; Cushing and Dickson, 1976). This may result in the productivity of stocks, and hence their biological reference points, changing over time, a possibility not considered here but potentially important especially with respect to environmental changes.

Similar inconsistencies in biological reference points have already been noted for the main ICES roundfish stocks (Kell *et al.*, 2005). Combined, these studies strongly indicate that the methodology and/or its application to set limit and precautionary reference points is not consistent.

This study was based on the methods currently used by ICES to provide advice. We simulated the data collection, the assessment process, and the harvest control rule as a management procedure, then tested this using an operating model that represented the hypothesized dynamics of the stocks. Even though the operating models were conditioned on the same data and assumptions used by ICES, the outcomes when explicitly modelling the management procedure were very different from those predicted by ICES Working Groups.

These results, and those of a companion study performed for the main ICES roundfish stocks (Kell *et al.*, 2005), indicated that the inclusion of more realistic sources and levels of uncertainty could produce management outcomes that are far from the objectives for both flatfish and roundfish. The results deviate substantially from those obtained in the current ICES approach, which is based upon stock assessment and projections without feedback. We believe that these differences may be caused by the fact that the ICES approach does not reflect the true uncertainty encountered when managing stocks, and therefore does not provide realistic levels of risk.

A risk-analysis framework consistent with the precautionary approach requires a comprehensive consideration of uncertainty. The use of simple stock projections, in which it is assumed that the assessments represent the true dynamics, that process error is limited to variability about a stock-recruitment relationship, and where management regulations are implemented without error, ignores important sources of uncertainty, and assumptions may be violated. It is also implicitly assumed that TACs are implemented without error, and that exploitation in single-species fisheries occurs where landings correspond to catches (e.g. no discarding or misreporting). However, plaice and sole are caught in mixed fisheries, and discarding and highgrading may take place to comply with TACs and minimum landing sizes. Furthermore, there is migration across stock boundaries (Kell *et al.*, 2004) and considerable variability in biological processes (Kell and Bromley, 2004). These aspects could invalidate estimated uncertainties in the simple stock projections carried out by ICES.

The simulations indicate that there is no need to change TACs rapidly in response to a latest annual assessment, because bounds on TAC do not have a negative effect in general. A simpler assessment method that is able to pick up overall trends in the stocks may be sufficient when used within a suitable management framework. We emphasize here that better management is not necessarily achieved through better stock assessments; even if stock status is known perfectly in our simulated management procedure, stocks may still crash at fishing levels that standard stochastic projections would suggest were safe. This is because the time-lags in the management system can still cause mismatches between TACs and the actual stock sizes.

In conclusion scientists have a role in defining limit reference points based upon biological models, the definition of precautionary reference points depends on defining an acceptable level of risk, and is a management decision that also depends upon the properties of the management procedure. Management strategies and assessment methods must be considered part of the same procedure, where the interactions between the monitoring regime, estimation of current stock status and biological reference points, and management controls are explicitly recognized. The management procedure simulation approach used in this study and that of Kell *et al.* (2005) therefore provides a powerful tool for the examination of the performance of candidate management strategies. Management simulations should be used as part of a dynamic process involving dialogue between scientists, managers, and stakeholders. Candidate management procedures formulated by relevant management bodies or stakeholders should be simulation-tested by specialists for a range of plausible assumptions about the true dynamics of the resources, against pre-agreed objectives (IWC, 1992; McAllister *et al.*, 1999).

Acknowledgements

This paper was prepared with funding support provided by the Commission of the European Communities Directorate General for Fisheries (DG XIV) under contract (MATACS, Analysis of possibilities of limiting the annual fluctuations in TACs, Reference No. FISH-2000-02-01). The UK's Department for Food, Environment and Rural Affairs (Defra) provided funding support (under contracts MF0316 and MF0322) to five authors (LTK, RDS, MTS, CMO'B, and GMP). Scientific editing by Pierre Pepin and Andy Payne, editors of the journal is gratefully acknowledged.

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Appendix

Equations and symbols used in the simulation framework.

Equations		
Population dynamics	$N_{a+1,y+1} = N_{a,y}\, e^{-Z_{a,y}}$	(1)
	$N_{p,y} = N_{p-1,y-1}\, e^{-Z_{p-1,y-1}} + N_{p,y}\, e^{-Z_{p,y-1}}$	(2)
	$N_{r,y} = f(B_{y-r})$	(3)
Mortality rates	$Z_{a,y} = F_{a,y} + D_{a,y} + M_{a,y}$	(4)
	$F_{a,y} = \sum_{i=1}^{f} P_{i,a,y} S_{i,a,y} E_{i,y}$	(5a)
	$D_{a,y} = \sum_{i=1}^{f} (1 - P_{i,a,y}) S_{i,a,y} E_{i,y}$	(5b)
Catch equation	$C_{f,a,y} = N_{a,y} \frac{F_{f,a,y}}{Z_{f,a,y}} (1 - e^{-Z_{a,y}})$	(6)
Stock-recruitment relationships		
Beverton and Holt	$N_{r,y} = \frac{B_{y-r}}{\alpha B_{y-r} + \beta}$	(7a)
Butterworth and Bergh	$N_{r,y} = \begin{cases} B_{y-r} \geq \alpha : \alpha B_{y-r} \\ B_{y-r} < \alpha : \alpha\beta \end{cases}$	(7b)

Recruitment residuals	$N_{r,y} = f(B_{y-r})\, e^{\varepsilon_y - \sigma^2/2}$ $\varepsilon_{y+1} = \rho\varepsilon_y + \eta_{y+1}$ $\eta_y \sim N(0, \sigma_\eta^2)$ $\sigma^2 = \ln(CV^2 + 1)$ $\sigma_\eta^2 = (1-\rho^2)\sigma^2$	(7c)
Derivation of effort	$\sum^{age} C_{f,a,y} W_{f,a,y} - Y_{f,y} = 0$	(8)
Catch per unit effort models	$U'_{f,a,y} = q_{f,a} N_{a,y}$	(9)
	$U'_{f,a,y} = \dfrac{U_{f,a,y}}{A_{f,a,y}}$	(10)
	$A_{f,a,y} = \dfrac{(e^{-\alpha_f Z_{a,y}} - e^{-\beta_f Z_{a,y}})}{(\beta_f - \alpha_f) Z_{a,y}}$	(11)
	$U'_{f,a,y} = q_{f,a} N_{a,y} \gamma\, e^{N(0,\varphi^2) - \varphi^2/2}$	(12)
Selectivity	$S_{f,y} = MVN\left(\mu_f \cdot \sum_f\right)$	(13)
Yield	$Y_{f,y} = \sum_{i=r}^{a} C_{f,i,y} W_{f,i,y}$	(14)
SSB	$B_y = \sum_{i=r}^{p} N_{i,y} W_{i,y} O_{i,y}$	(15)
Observation error Catch-at-age	$C_{a,y} = MVN(\kappa, \Lambda)$	(16)
Variance in catch-at-age	$\kappa_{a,y} = \alpha N_{a,y}^{\beta}$	(17)

There was a linear relationship between log(variance) and log(mean) for catch numbers-at-age. Therefore, variances were estimated from catch numbers based on this observed relationship instead of assuming constant CV. There was also a linear relationship between the CV of catch numbers and weights-at-age. This appeared reasonable as weights were calculated from a length–weight relationship in which numbers-at-length were used in estimating the condition factor.

Symbols used in equations.

Parameter	Definition
$N_{a,y}$	Numbers of fish of age a at the start of year y
$M_{a,y}$	Natural mortality-at-age a in year y
$F_{a,y}$	Fishing mortality-at-age a in year y
$F_{f,a,y}$	Partial fishing mortality of fleet f at age a in year y
$D_{a,y}$	Discard mortality-at-age a in year y
$Z_{a,y}$	Total mortality-at-age a in year y
$S_{f,a,y}$	Selection pattern for fleet f at age a in year y
$P_{f,a,y}$	Proportion of catch retained for fleet f at age a in year y
$C_{f,a,y}$	Catch in numbers of fleet f at age a in year y
r	Age at first recruitment to the fishery
p	Age of the plus group
B_y	Spawning-stock biomass in year y
α,β	Model parameters
$W_{a,y}$	Mass-at-age a in year y in the stock
$W_{f,a,y}$	Mass-at-age a in year y in catch of fleet f
$O_{a,y}$	Proportion mature-at-age a in year y
$Y_{f,y}$	Total catch mass of all ages of fish in year y by fleet f
$U_{a,y}$	Cpue of age a in year y
$U'_{a,y}$	Cpue of age a adjusted to start of year y
$q_{f,a}$	Catchability, relationship between cpue and numbers-at-age a for tuning index f
γ	Relationship between catchability and abundance
α_f	Start of the period of fishing in cpue series f
β_f	End of the fishing period cpue series f
ϵ_y	Recruitment residual in year y
σ	Standard error of recruitment residuals
ρ	Autocorrelation of recruitment residuals
η_y	Recruitment innovation in year y
σ_η	Standard error of recruitment residual innovations η_{year}
μ_f	Expected selectivity vector
Σ_f	Covariance matrix used in selectivity modelling
ν_f	Expected mass-at-age in the stock
Ψ_f	Covariance between the ratio of stock to catch mass-at-ages
Ω_f	Covariance between mass-at-ages in the stock
κ	Variance numbers-at-ages in the sampled catch
Λ	Covariance between numbers-at-ages in the sampled catch
φ	Standard error of cpue residuals
MVN	Multivariate normal