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An evaluation of the implicit management procedure used for some ICES roundfish stocks

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This paper describes a simulation study that evaluated the performance of the scientific advisory process used by ICES to recommend total allowable catches (TACs) for roundfish stocks. A "management strategy evaluation" approach is used, involving development of an operating model to represent the underlying reality, and an observation model to generate pseudo data that are then used within a management procedure. The management procedure comprises an assessment that uses data to estimate parameters of interest and a decision rule to derive TAC recommendations for the following year. There are two important results: including realistic sources and levels of uncertainty can result in far from optimal management outcomes based on the current procedures; and current ICES biomass and fishing mortality reference points are not always consistent, and several are clearly inappropriate. This is because the types of projection used by ICES do not incorporate important lags between assessing stock status and implementing management measures, and they also ignore important sources of uncertainty about the actual dynamics, as well as our ability to collect data and implement management regulations (i.e. model, measurement, and implementation error, respectively). The simulation approach also showed that better management is not necessarily going to be achieved by improving the assessment, because even with a perfect assessment (where the simulated working group knew stock status perfectly), stocks may crash at fishing levels that standard stochastic projections would suggest were safe. It is proposed 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. These operating models should capture the plausible range of characteristics of the underlying dynamics, but not necessarily model their full complexity. In general, they will be more complex than those used by assessment working groups, so developing management procedures that are robust to a broad range of uncertainty. However, the models and rules used as part of the management procedure should be simpler than those used at present.

Keywords: cod, haddock, hake, harvest strategies, management, population modelling, saithe, simulation, TAC, whiting.

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Introduction

The current framework for providing total allowable catch (TAC) advice for roundfish within the ICES convention area is based on catch forecasts derived for multiples of current fishing mortality. Advice is based on "precautionary" reference points that trigger action intended to ensure that limit (or threshold) reference points, both fishing-mortality-rate and biomass-based, are not exceeded (ICES, 2001a). The aim is to ensure that advice is consistent with the precautionary approach, as embodied in the Code of Conduct for Responsible Fisheries and the Agreement for the Implementation of the Provisions of the United Nations Convention of the Law of the Sea of 10 December 1982 relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish stocks (Doulman, 1995).

There is no formal management procedure within ICES of the type developed but not yet implemented by the International Whaling Commission (IWC, 1993), where monitoring, assessment, and management regimes are pre-agreed. There is, however, an implicit procedure because the precautionary approach framework used by ICES is intended to ensure that stocks and fisheries remain within safe biological limits. For example, the ICES Advisory Committee on Fishery Management (ACFM; ICES, 2001a) bases its advice on ensuring that "there should be a high probability that (i) the spawning-stock biomass is above the threshold where recruitment is impaired, and that (ii) the fishing mortality is below that which will drive the spawning stock to the biomass threshold. The biomass threshold is defined as B_{lim} (lim stands for limit) and the fishing mortality threshold as F_{lim}." In practice, owing to uncertainty in estimating F_{lim}, a fishing mortality level below F_{lim} (i.e. F_{pa}, the fishing mortality precautionary approach reference point) is chosen with the intention that B_{lim} be avoided with a high probability. ICES also applies a "buffer zone" for biomass by setting a higher spawning biomass reference point B_{pa} (the biomass precautionary approach reference point) at which management action is triggered.

Fournier and Warburton (1989) recommended the evaluation of management procedures as a part of any integrated fisheries management system. Recently, Sainsbury *et al.* (2000) applied such an approach for meeting ecosystem objectives, and Punt *et al.* (2002) described an application for management of Australia's south east fishery.

The success of a management procedure depends upon the interactions between the monitoring regime, stock assessment procedures, choice of biological reference points, and management options, rather than each in isolation (Butterworth and Bergh, 1993; Butterworth *et al.*, 1997; Kirkwood, 1997; Cochrane *et al.*, 1998; De Oliveira and Butterworth, 2004). Therefore, for the purpose of this work, a simulation framework was used to evaluate the performance of the current management procedure implicit in the ICES advice for Northeast Atlantic roundfish stocks. This framework is able to consider uncertainty in the dynamics of stocks and their fisheries, as well as our ability to monitor and manage them.

In this study, the performance of the ICES management procedure is compared for the main roundfish stocks: North Sea cod, haddock, saithe and whiting, northern and southern Atlantic hake, and eastern and western Baltic cod. Management is based upon a specified fishing mortality, achieved by setting a total allowable catch (TAC). The performance of the current assessment procedures and impacts on stock dynamics and on yields from the fisheries are evaluated within the framework.

Material and methods

Simulation framework

The simulation framework (Kell *et al.*, 1999) used to investigate the response of fishery systems to management, models both "true" (i.e. plausible hypotheses about system dynamics) and "perceived" systems (methods used in practice to collect observations, to assess current status, and to define reference points used in management; Figure 1). The approach requires computer simulation of the stocks and fisheries to be managed, as well as of the assessment and management procedures.

The "true" stock and fishery dynamics are represented as the *operating model*, from which simulated data are sampled (*observation model*). In this example, the data are used within an *assessment procedure* to assess the status of the stock and, depending on the perception of the stock, management controls are applied within the *management procedure* to the fishery and fed back into the operating model. Performance statistics are used to evaluate the behaviour of the operating model.

The equations used in the operating model and in the management procedure are shown in the Appendix.

The framework includes a variety of sources of uncertainty, as categorized by Rosenberg and Restrepo (1994). These include *process error* attributable to natural variation in dynamic processes (e.g. recruitment, somatic growth, natural mortality), *measurement error* (generated when collecting observations from a population), *estimation error* that arises from trying to model the dynamic process (during the assessment process), *model error* (because the model used in the assessment procedure will never capture the true complexity of the dynamics), and *implementation error* (because management actions are never implemented perfectly).

The simulation framework allows the operating model (i.e. the "true" system) to be based on different assumptions from those made within the assessment and management procedures, so allows candidate management procedures to be tested against alternative hypotheses about stock and fishery dynamics. This difference allows the robustness of candidate management strategies to uncertainties in our knowledge of the system to be evaluated before implementation. It also allows the *interactions* between system components to be evaluated, and provides an integrated

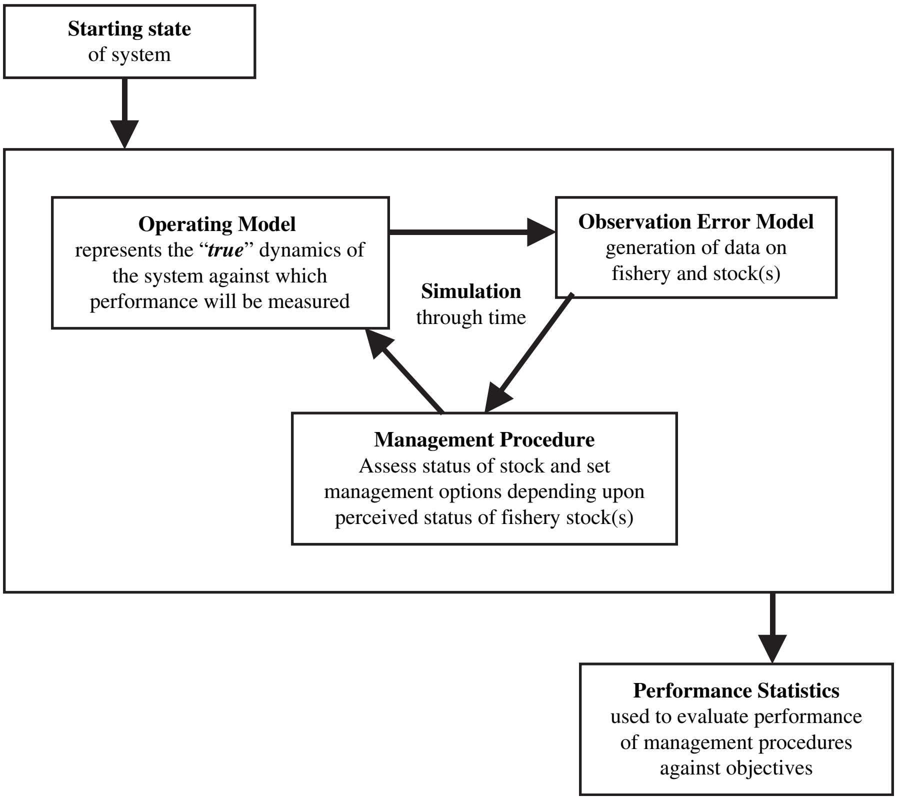

Figure 1. Conceptual framework.

means of evaluating the relative importance of these components to the overall success of management of the resource (Wilimovsky, 1985; De la Mare, 1998; Holt, 1998).

In this study, however, it was assumed that the ICES assessment represented the "true" dynamics, so the operating model for each stock was based upon the analysis performed by ICES. Robustness testing of the management strategies to uncertainty about resource dynamics was limited to an evaluation of the importance of the assumed relationship between recruitment and stock.

Operating model

The operating model consisted of a simulated population, conditioned upon the 2001 ICES assessments (ICES, 2001b−d). Prior to 2001, the historical component of the operating model and the starting state of the system correspond to the ICES assessment. The management procedure starts in 2001, and is then run for 30 years, i.e. the future component. In the historical component, parameters were those estimated or used by ICES, and all values were deterministic, apart from the numbers at age in 2000, which were lognormal random variables with expected values and CVs estimated by the working group. This ensured consistency of simulated biomass, reference points, and stock-recruitment relationship with current perceptions. In the future component, recruitment was modelled by a stochastic stock-recruitment relationship and selectivity; mass- and catchability-at-age were modelled as random variables. Constant values of natural mortality and maturity-at-age were used.

For each stock other than whiting and haddock, a single fishery was modelled. In the case of whiting and haddock, industrial (i.e. non human consumption) fisheries were also included. Where discards were included in the ICES assessment (i.e. North Sea whiting and haddock), the operating model also included estimates of discards in both the historical and future periods. The historical fishing mortality-at-age was as estimated by ICES, and for the future, selectivity-at-age was modelled as random variables, where expected selectivity-at-age was equal to the expected value in the last year (2000), as given by a lowess smoother (span = 0.75), and variability was modelled by bootstrapping the residuals to the smoothed fit.

In the operating model, historical mass-at-age corresponds to values used by ICES. For the projections, masses-at-age were modelled as random variables, with expected values equal to the smoothed values in the last year (2000). Variability was modelled by bootstrapping the residuals to the smoothed fit. No trends in growth were modelled for any of the stocks, for consistency with current ICES advice. For stocks other than North Sea haddock and whiting (for which discard data were available and catch masses were modelled explicitly), if mass-at-age in the catch differed from that in the stock, then the ratio between the two was calculated. Values were then smoothed within an age, and the expected ratios in the last year were used to model the future ratios. In the case of the stock masses-at-age, year-class effects were included by also modelling autocorrelation within a cohort. Historical catch-at-age was taken from the appropriate working group report.

Yield taken by the fishery corresponded to the total allowable catch (TAC), as set by the management procedure. However, to prevent unrealistic fishing mortalities being generated, fishing mortality was constrained so that, in any year, the average fishing mortality was never more than 2.5. If fishing mortality was constrained, the TAC was not reached. Historical catches were as reported to ICES, even though they may not have been accurate.

To evaluate the robustness of the management procedures to the assumed stock dynamics, three Ricker stock-recruitment relationships (SRR) were included in the operating model for each stock: (i) Ricker with lognormal errors; (ii) Ricker with autocorrelation and lognormal errors; (iii) Ricker with a "pessimistic" value of the slope-at-the-origin, set equal to the 25th percentile of the Ricker with lognormal errors.

A Ricker functional form was chosen because recruitment declines at bigger population sizes and because it is commonly assumed to be most appropriate for gadoids (Garrod and Jones, 1974; Jakobsen, 1996).

The management procedure

A management procedure combines a particular sampling regime and stock assessment technique, with appropriate harvest control rules and their implementation. The management procedure evaluated in this study corresponds to the *de facto* assessment methodology and ACFM advice.

The observation model simulates the sampling regime, to generate data from the operating model for use in an assessment. These data simulate the commercial catch-at-age matrix, and research vessel survey results are used to generate time-series of abundance estimates.

Catch-at-age – Catch-at-age was sampled without error and bias from the operating model.

Mass-at-age – Mass-at-age was sampled without error and bias from the operating model.

Historical stock estimation – A single assessment method, extended survivors analysis (XSA; Darby and Flatman, 1994; Shepherd, 1999) based upon virtual population analysis (VPA), was used throughout this study. XSA is an implementation of sequential population analysis (Doubleday, 1981) that recreates a stock's historical population structure from the catch-at-age matrix and abundance indices.

Biological parameters – Natural mortality- and maturity-at-age varied with age but were held constant over years, and corresponded to values used by the 2001 working group.

Catch per unit effort (cpue) – This was used to calibrate the XSA in the assessment procedure and generate "best estimates" of terminal populations. A single cpue fleet that covered all age classes in the population was constructed, assuming the relationship given in the Appendix, and a CV of 30% (an average value for the fleets studied). The results of limited simulations showed that the performances of multiple and single fleet assessments were broadly comparable.

Setting TACs – An annual TAC was set equal to the allowable biological catch (ABC), in accordance with the management procedure and precautionary F value.

Given the XSA result in each year a "short-term projection" was performed, using the same methodology as the relevant ICES Working Group, to estimate the ABC. Numbers-at-age were projected through the year of the assessment (for which total catch data are not yet available), assuming fishing mortality-at-age was equal to the estimate in the previous year. A projection based on a fixed fishing mortality was then made in the following year to estimate the ABC. Exploitation pattern and masses-at-age for the forecast were assumed equal to the mean of the estimates from the last 3 years. Natural mortality- and maturity-at-age were the same as values assumed in the assessment.

TACs were set with the objective of reducing fishing mortality immediately from the current level to F_{pa}, unless the intended fishing mortality was less than half the current fishing mortality estimated from the XSA. In the latter case, fishing mortality was reduced in two steps; F was reduced to 50% of the current F in the next year, and then to the intended fishing mortality in the second year.

Experimental treatments

As the intention was to compare the implicit ICES management procedure across stocks, for consistency, a fishing mortality corresponding to F_{pa} was evaluated for each stock (Table 1), i.e. a constant F strategy. In the case of southern and northern hake and eastern and western Baltic cod, F_{pa} incidentally corresponded to a fishing mortality level that appears to be close to that which provides the maximum equilibrium yield, although this was not the case for the North Sea stocks.

In addition, two treatments were examined to understand the effect of including the full management procedure in the simulations. (i) A projection for 30 years where F_{pa} was implemented without error in each year, equivalent to ICES medium-term projection. (ii) Current stock status is known perfectly within the management procedure, i.e. the same as the management procedure, but based upon a perfect assessment rather than XSA outputs. For each treatment, Monte Carlo simulations were performed 100 times.

Table 1. Fishing mortality corresponding to F_{pa}, and relevant F_{bar} for 2000, where F_{bar} is the average fishing mortality for reference ages used by ICES for each stock.

	Cod North Sea	Haddock North Sea	Whiting North Sea	Saithe North Sea	Hake Southern	Hake Northern	Cod Baltic 22–24	Cod Baltic 25–32
F_{pa}	0.65	0.64	0.61	0.40	0.27	0.20	0.60	0.16
F_{bar}	0.83	0.92	0.45	0.29	0.27	0.31	1.15	1.00

Results

In Figures 2 and 3, results are presented for the Ricker model with lognormal errors as an example of the dynamic behaviour of the system. The results were similar for the other stock-recruit relationship treatments (Kell *et al.*, 2003).

In Figure 2, the expected equilibrium yields and SSBs for a particular fishing mortality are shown by the equilibrium curve, based upon the Ricker stock-recruitment relationship (Kell and Bromley, 2004). The corresponding simulation trajectories of the median catch and SSB from 2001 to 2030, where TACs were set to achieve F_{pa}, are shown. Dots on those trajectories represent the SSB position at the start of each year and the catch taken in the year. Arrows indicate the direction and rate of change in yield and SSB if the fishing mortality is perturbed from equilibrium to the level that would give the expected yield at the start of the arrow in 1 year; shorter and longer arrows represent combinations of catch and stock status that are close to or some distance away from the equilibrium curve.

In practice, the equilibrium curves also provide biological reference points. Fishing mortality and biomass reference points are not always set consistently (Figure 2). The relative locations of the vertical lines representing B_{pa} and B_{lim} vary between species. For example, for North Sea whiting, they lie near the SSB at which maximum yield is achieved; for other species they lie closer to the level of stock collapse. More importantly, the relative position of the reference point F_{pa} also varies with respect to B_{pa} and B_{lim}. For example, in the case of North Sea saithe, F_{pa} was chosen as the 5th percentile of F_{loss} (Cook, 1998), while B_{pa} was chosen from the plot of recruits against SSB as the level of SSB below which recruitment was impaired. However, the target SSB implied by a fishing mortality of F_{pa} lies below B_{pa} and close to B_{lim}.

Initial responses of the trajectories are defined by current stock status relative to target fishing mortality, i.e. the implied position of the target fishing mortality on the equilibrium yield–SSB curve. All trajectories have to converge (in expectation) on the equilibrium yield–SSB curve, but bias in the management procedure may mean that the target fishing mortality is not achieved. Also, the equilibrium curves ignore the stochastic dynamics. For example, recruitment of western Baltic cod is highly variable, with a CV of 70%. Combined with the responsiveness of that stock, this results in a highly variable trajectory. Indeed, only in the case of southern hake does the trajectory of simulated yield and SSB come close to the target point. For western and eastern Baltic cod, and northern and southern hake, trajectories end to the right of the implied target (higher SSBs achieved). For North Sea cod, haddock, saithe and whiting, however, trajectories end at lower SSBs than implied by the target, and for the first three of these species, end below the biomass limit reference point level.

Figure 3 shows a comparison between the simple treatment where stock status is known perfectly and a fishing mortality of F_{pa} is achieved without error in each year, and treatments where a TAC is set to achieve a fishing mortality of F_{pa} (both where the stock status is known perfectly or the stock assessed using XSA), for North Sea cod and northern hake. The Figure presents expected trajectories for each period along with the individual realizations of the 100 simulations for 2005, 2015, and 2030, when fishing at F_{pa}.

In the cases of the working group medium-term projection (fishing mortality is equal to F_{pa}) and perfect assessment (stock status known perfectly, and TAC set to achieve F_{pa}), the random variability is similar in the short, medium, and longer terms. When stock status is estimated using XSA, variability increases. An important difference, however, is seen in terms of bias (i.e. whether the trajectory converges on the target point) and the rate at which the stock moves towards the target point.

For North Sea cod, a simple projection would predict that, in the short term, the stock would recover above B_{lim} with a high probability, then converge on the equilibrium point in the medium term. It also has a high probability of being above B_{lim} and B_{pa} in the long term, and the stock remains at the equilibrium point. However, in the case where feedback is modelled in the short to medium term, in some realizations the stock is below B_{lim}. When the assessment process (both bias and random variation) is also included, in many instances the stock appeared to collapse in the short term. In the medium to long term, the stock does not converge on the target point.

For northern hake, the working group assumptions again suggest that the stock would converge on the equilibrium point in the medium term, and stay there in the longer term. When feedback is included, the stock takes longer to recover, because in the medium term there is still a high probability of the stock being below B_{lim}. In the longer term, the stock has

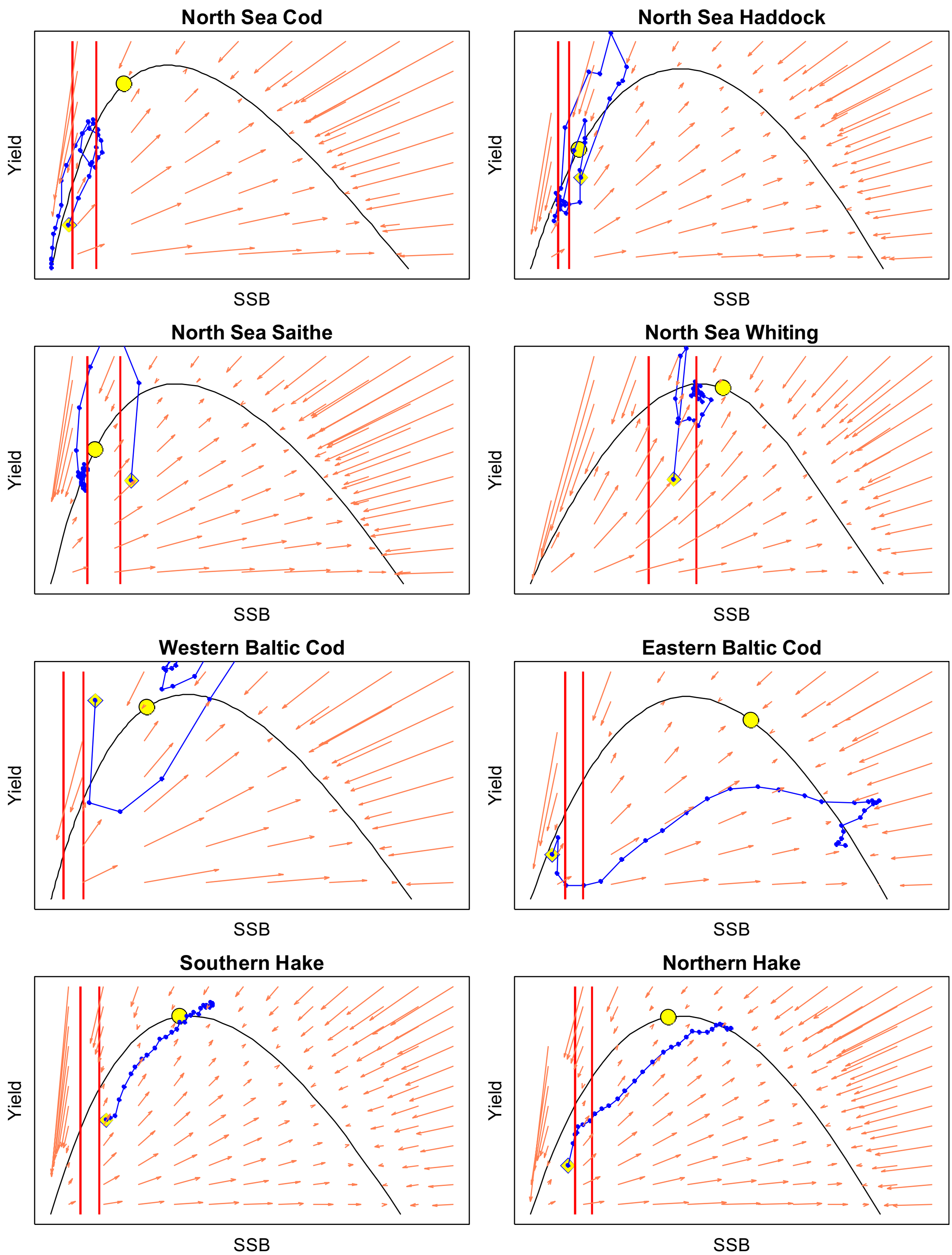

Figure 2. Equilibrium yield–SSB curves for each study species with vectors showing the expected direction and rate of change in yield and SSB for a perturbation from equilibrium. Simulated trajectories for 30 years (2001–2030) are also shown (median values from 100 simulations). The vertical lines represent B_{lim} (to the left) and B_{pa} (to the right), the yellow diamond shows the starting position and the yellow circle the position at the implied target (F_{pa}).

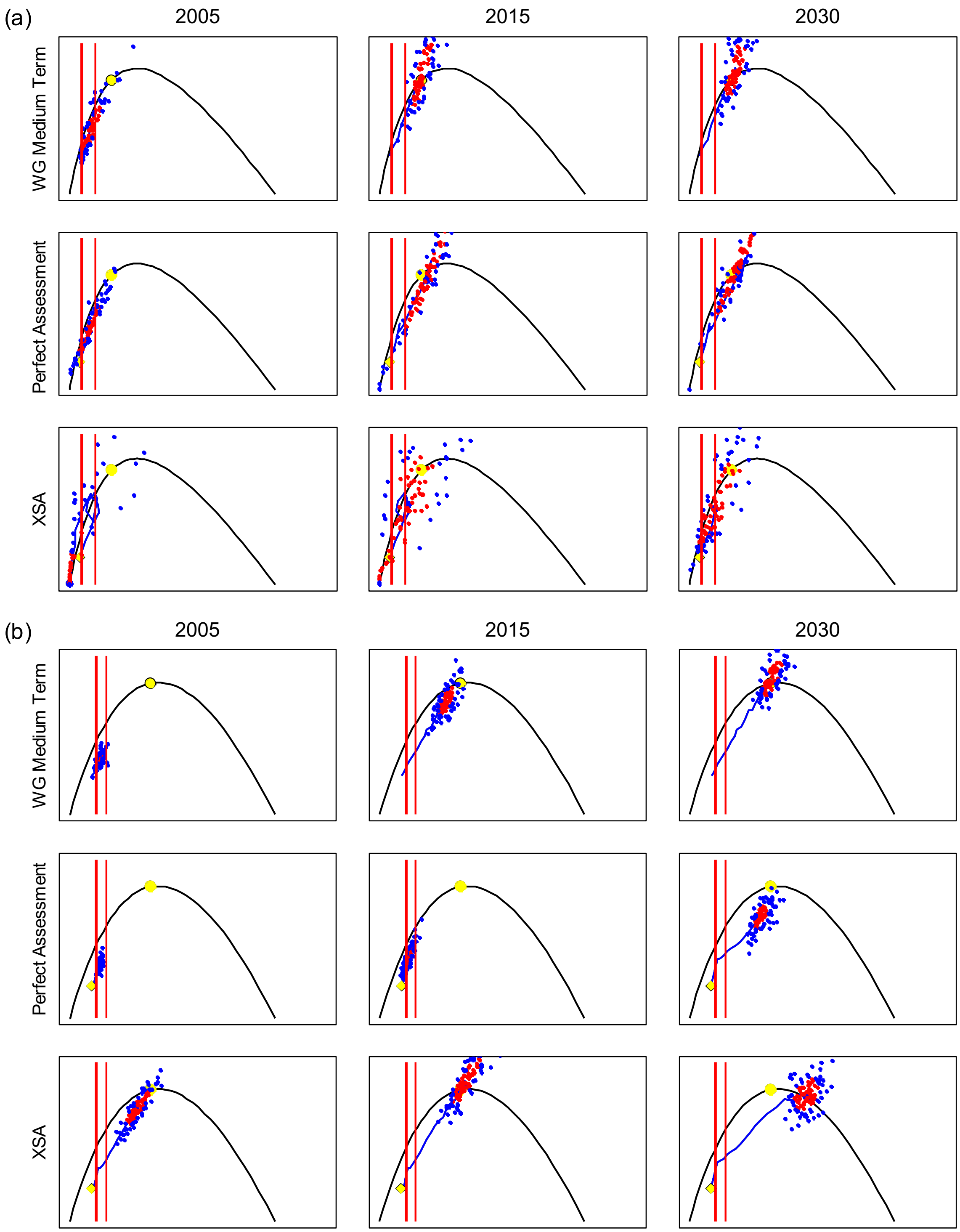

Figure 3. (a) North Sea cod and (b) northern hake simulations for TACs aligned on a target fishing mortality of F_{pa}, where the yellow circle represents the target on the equilibrium yield−SSB curve. The vertical red line to the left represents B_{lim} and that to the right B_{pa}, and red dots the 50th bi-variate percentile. Simulations are for three time periods using a simple ICES medium-term style projection, the management procedure with a perfect assessment, or the management procedure with an XSA assessment. (b) Northern Hake simulations for TACs aligned on a target fishing mortality of F_{pa}.

not achieved the target. Although the uncertainty is greater, when assessment uncertainty is included recovery is achieved in the medium term, but in the longer term the stock does not reach the expected point on the equilibrium curve because the biomass exceeds the expected value. These results illustrate the importance of including uncertainty attributable to assessment and management when evaluating the performance of management procedures.

Discussion

The management simulations described in this paper differed from the standard ICES approach used to recommend TACs (which is essentially based upon an assessment and short-term deterministic projection) because they modelled both the "true" and observed systems, and explicitly considered the interactions between the various system components. The simulations therefore enable us to evaluate the properties of management procedures with respect to the intrinsic properties of the systems, and importantly enhance our ability to monitor, assess, and control them.

Although the equilibrium curves for the study species were similar, the relative biomass reference points and the expected values of SSB were frequently different. The choice of fishing mortality and minimum stock levels results from ICES interpretation of the precautionary approach. This leads to the definition of fishing mortality and biomass reference points that are intended to prevent overfishing and to trigger recovery plans when a stock is overfished, respectively. Although fishing mortality and biomass reference points were originally intended to be independent, a fishing mortality level implies a corresponding biomass level. For example, in the case of saithe, a fishing mortality of 0.40 (i.e. the F_{pa} level) would drive the stock to B_{lim}. The choices of biomass and target reference points have not always been consistent. When considering the dynamics in a full feedback model, with reference to the trajectories, the average SSB attained in the long term is not equal to the target. For example, in the case of North Sea cod, the expected SSB falls below the limit biomass level (B_{lim}) even at a fishing mortality of F_{pa}.

This study has performed an evaluation of the current limit reference points and management system under comparatively ideal circumstances. It has demonstrated that the medium-term projections used by ICES to test management procedures and to set reference points are based on simplistic assumptions, and are unlikely to work as intended because, when feedback was included, the implicit ICES management procedure performed poorly. The performance of management could not have been predicted from an examination of the stock data or assumptions alone. This is because the assessment and management process includes important time-lags between the monitoring, assessment, and control processes. For example, 2001 catch data are only available in 2002, when they are used in an assessment to set a TAC for 2003. The effect of TAC management in 2003 will be on the SSB at the start of 2004. However, any effect can only be detected first in 2005, when the 2004 data are available. This results in a 5-year lag between deciding upon management and detecting its effectiveness, although actually determining the effectiveness of any management action will require even more time because estimates from VPA are more uncertain in the most recent period. If these lags are modelled, the results generated may be very different from those derived by ICES. In an extreme case, as seen for North Sea cod, traditional stochastic medium-term methodology does not identify a collapse in the stock as a result. The actual probability of falling below B_{lim} associated with F_{pa} may therefore be different from that assumed by the working groups. This is despite the fact that important sources of uncertainty were not included in the current simulations, e.g. non-compliance with management and subsequent catches above the TAC, and misreporting of the true catch. This will have significant effects on both the perception of the stock, and hence TACs and actual yields from the fisheries. The study also did not examine the influence of structural uncertainty, such as spatial effects, more realistic biology, carrying capacity changes (and hence non-stationarity in reference points) or biological or technical interactions.

The management procedure simulation approach used in this study provides a powerful tool for the examination of the performance of candidate management strategies. Clearly, better management is not necessarily going to be achieved by attempting to improve the assessment of historical stock status, because even where the simulated working group knew stock status perfectly, stocks crashed at fishing levels that standard stochastic projections would suggest were safe. This illustrates the importance of considering management strategies and assessment methods as 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.

It is proposed that future management procedures be rigorously tested with respect to pre-agreed objectives, using operating models that represent the best available understanding of the actual system dynamics. The objective is then to develop simple management procedures that are robust to a broad range of uncertainty. The operating models used to test the performance of the models and rules considered for application will, in general, be far more complex than those used by assessment working groups, but they should capture the plausible range of characteristics of the underlying dynamics, though not necessarily model their full complexity. Such an approach has been applied by the IWC (1993) to test the potential future performance of alternative proposals for new whaling management procedures, and in other instances also (e.g. Kell *et al.*, 1999; McAllister *et al.*, 1999).

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Appendix

Equations and symbols used in the 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)
	$F_{a,y} = \sum_{i=1}^{f} P_{i,a,y}S_{i,a,y}E_{i,y}$	(5)
	$D_{a,y} = \sum_{i=1}^{f} (1 - P_{i,a,y})S_{i,a,y}E_{i,y}$	(5a)
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		
Ricker	$N_{r,y} = \alpha B_{y-r}e^{-\beta B_{y-r}}$	(7)
Recruitment residuals	$N_{r,y} = f(B_{y-r})e^{\epsilon_y - \sigma^2/2}$ $\epsilon_{y+1} = \rho\epsilon_y + \eta_{y+1}$ $\eta_y \sim N(0, \sigma_\eta^2)$ $\sigma^2 = \ln(CV^2 + 1)$ $\sigma_\eta^2 = (1 - \rho^2)\sigma^2$	(8)
Effort (E) derived by solving	$\sum_a C_{f,a,y}W_{f,a,y} - Y_{f,y} = 0$	(9)
Catch per unit effort models	$U'_{f,a,y} = q_{f,a}N_{a,y}$	(10)
	$U'_{f,a,y} = \frac{U_{f,a,y}}{A_{f,a,y}}$	(11)
	$A_{f,a,y} = \frac{(e^{-\alpha_f Z_{a,y}} - e^{-\beta_f Z_{a,y}})}{(\beta_f - \alpha_f)Z_{a,y}}$	(12)
	$U'_{f,a,y} = q_{f,a}N_{a,y}\gamma e^{N(0,\varphi^2) - \varphi^2/2}$	(13)
Selectivity	$U_{f,y} = MVN\left(\mu_f, \sum_f\right)$	(14)
Mass-at-age	$W_{f,y} = MVN(\nu_f, \Omega_f)$	(15)
Yield	$Y_{f,y} = \sum_{i=r}^{a} C_{f,i,y}W_{f,i,y}$	(16)
SSB	$B_y = \sum_{i=r}^{p} N_{i,y}W_{i,y}O_{i,y}$	(17)

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	Stock-recruitment model parameters
$W_{a,y}$	Mass-at-age 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
$Y_{f,y}$	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	Auto-correlation 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 masses-at-ages in the stock
φ	Standard error of cpue residuals
MVN	Multivariate normal
$E_{f,y}$	Effort of fleet f in year y