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LIMITING INTER-ANNUAL VARIATION IN TOTAL ALLOWABLE CATCH STRATEGIES. AN APPLICATION TO ICES ROUNDFISH STOCKS

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ABSTRACT

This study evaluated through simulation management strategy that stabilise catch levels by setting bounds on the inter-annual variability in Total Allowable Catches (TACs). An integrated modelling approach was used, which modelled both the ‘real’ and observed systems and the interactions between all system components. The modelling framework therefore allowed evaluation of the robustness of candidate management strategies to both the intrinsic properties of the systems, and the ability to observe, monitor, assess and control them. Strategies were evaluated in terms of level of risk (measured as the probability of spawning stock biomass falling below the biomass limit reference level for the stock) and cumulative yield.

The simulation approach used provides a powerful tool for the examination of the performance of candidate management strategies. It has shown that better management is not necessarily going to be achieved by improving the assessement, since 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. Also explicitly modelling the assessment process can result in quite different outcomes than those predicted by the simple projection traditionally used by stock assessment working groups. This is because the simple projection assumes that the status of the stock in the current year is known without error and that the target fishing mortality can be achieved without error. However, in practice the assessment is based on last years data and the effect of any management measure on SSB is only manifest, following the implementation of the quota, at the end of the following year.

The choice of target and fishing mortality levels and minimum stock levels results from ICES interpretation of the precautionary approach. This lead to the definition of fishing mortality and biomass reference points that are intended to prevent over-fishing 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. In the case of saithe a fishing mortality of 0.40 (i.e. the $\boldsymbol{F_{PA}}$ level) would drive the stock to $\boldsymbol{B_{lim}}$, suggesting that the choice of biomass and target reference points are not consistent for this stock.

Keywords: population modelling; cod, haddock, whiting, saithe, hake, TAC, simulation, management, evaluation, Harvest strategies.

INTRODUCTION

The current framework for providing advice for roundfish within the ICES convention area is based on total allowable catches (TACs) derived from multiples of current fishing mortality. Management is based on reference points that trigger action to ensure that limit reference points (both fishing mortality rate and biomass based) are not exceeded (ICES, 2001a). The objective is to ensure that advice is consistent with the precautionary approach, as embodied in the Code of Conduct for Responsible Fisheries (United Nations, 1995b) 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 (United Nations, 1995ac).

However, the fishing industry has repeatedly pointed to the difficulties created by wide annual fluctuations in TACs resulting from the current system. Experts have countered that total stability is impossible due to natural fluctuations in stocks, particularly in recruitment. Consequently, any attempts to maintain TACs at a constant level could threaten the sustainability of fishery resources, at odds with the precautionary approach, unless TACs were set at a very conservative level. Experts have also pointed out that even if it were possible to reduce annual fluctuations in TACs, it would be impossible to stabilise catches and exploitation levels (and thus fishing effort) at the same time and that compromises would therefore be necessary. Finally, they have stressed that stocks vary even more from one year to the next when exploitation levels are high (Kell et al., 2002, MATES EU/FISH/2001/2).

A simulation framework, that explicitly considered and incorporated uncertainty in the dynamics of stocks and their fisheries and our ability to monitor and manage them, was therefore used to evaluate the performance of candidate management strategies that reduce inter-annual variations in TACs. This approached allowed the trade-offs between yield and the risk of stock collapse to be considered. Strategies are defined by a specific target fishing mortality and limits on annual fluctuations in the total allowable catch ('TAC bounds'). The study stocks were the main roundfish stocks, North Sea Cod, Haddock, Saithe and Whiting, Northern and Southern Atlantic Hake, and Eastern and Western Baltic Cod.. The impacts of these management strategies on the yields obtained from the fisheries and the risk to the stocks were evaluated.

MATERIAL AND METHODS

The simulation framework (Kell et al 1999a, 1999b, 2001, 2002, 2003) used to investigate the response of fishery systems to management models both the “real” and “perceived” systems (observed data, assessment of current status and reference points used to guide management). The framework allows the management strategies to be tested against both the intrinsic properties of natural systems and our ability to understand and monitor them. It also allows the interactions between system components to be evaluated and provides an integrated way to evaluate the relative importance of these components to the overall success of management (Wilimovsky, 1985; De la Mare 1998; Holt 1998).

The approach requires computer simulations of the system to be managed as well as of the assessment and management procedures. The “real” stock and fishery dynamics are represented as the **operating model**, from which simulated data are sampled. These data are used within a **management procedure** to assess the status of the stock and, depending on the perception of the stock, management controls are applied to the fishery and fed-back into the operating model. Performance statistics are used to explain the behaviour of the operating model. This makes it possible to evaluate the consequences of alternative management strategies before implementation (see figure 1).

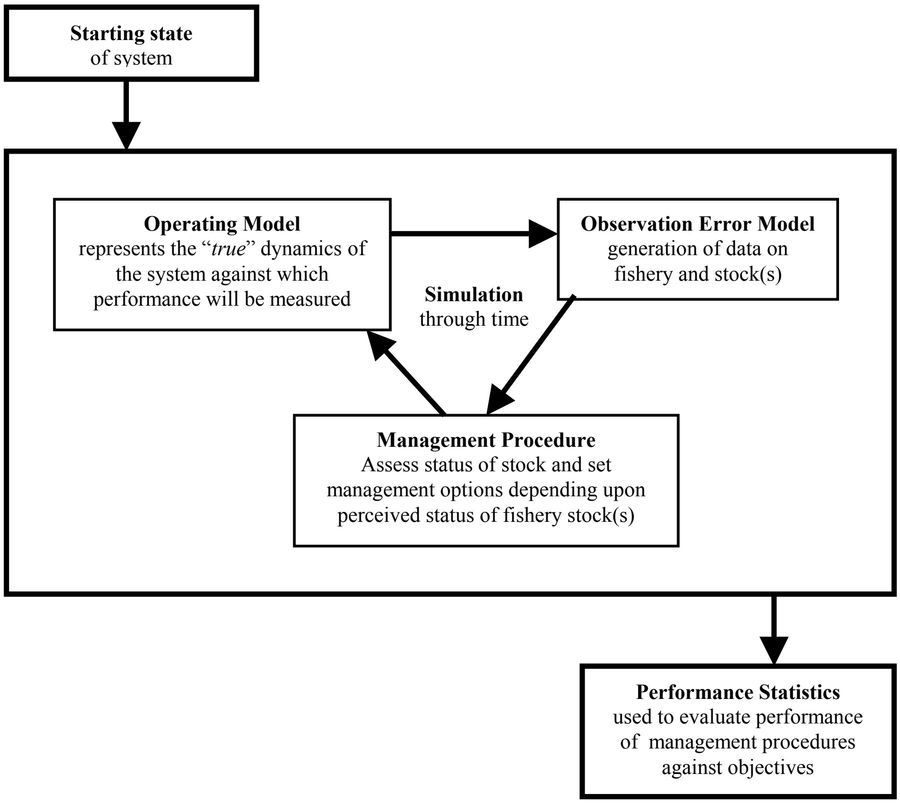

Figure 1: Conceptual framework

The framework acknowledges the presence of a variety of sources of uncertainty as categorised by Restrepo and Rosenberg (1995). These include, ***process error*** due 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*** (since the model used in the assessment procedure will never capture the true complexity of the dynamics) and ***implementation error*** since management actions are never implemented perfectly.

THE OPERATING MODEL

The operating model consisted of a simulated population comprising historic and future parts. In the past, the system corresponded to the assumptions and the population estimates made by the most recent ICES assessment working group. The future part extended for a period of 30 years from the date of the last assessment and the starting state of the system corresponded to the perception of the 2001 ICES Working Group. Parameters were those estimated by the relevant ICES working groups, and all values were deterministic, apart from the population status in 2000. Although working group practice does change between years, the future assessments were performed in the same way as the last assessment (ICES, 2001b, 2001c, 2001d). The starting state for simulations into the future was therefore directly comparable to the (year 2000) perception of the working group. Uncertainty was added to population numbers in 2000 using the CVs for number-at-age estimated by the working group.

The true states of stocks are generally more uncertain than indicated by stock assessment, due to using incorrect models or data. The simulation framework allows the operating model (i.e. the true system) to be based on different assumptions than those made within the management procedure. This difference allowed the robustness of candidate management strategies to uncertainties in our knowledge of the system to be evaluated. In this study, however, it was assumed that the ICES WG assessment was correct, and the operating model for each stock was based upon the analysis performed by the relevant working group. 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 abundance and alternative plausible hypotheses about discarding practices.

In the future projections, selectivity, weight, maturity and catchability-at-age were modelled as random variables. In addition, if discards were included in the ICES assessment, the operating model also included discarding (i.e. North Sea whiting and haddock). The relationship between stock and recruitment was modelled as a Ricker stock recruitment relationship, but with three parameterisations derived from fits made with three different assumptions about the relationship, and lognormal errors. Yield taken by the fishery corresponded to the total allowable catch, as set by the management procedure. However, to prevent unrealistic fishing mortalities being generated, fishing mortality was constrained so that, in any year, the absolute level was never more than 2.5. If fishing mortality was constrained, the TAC was not taken. In the past, yield was as reported to the working group.

For each stock, there was one main target fishery, corresponding to a single human consumption fleet. The historic fishing mortality level was taken from the Working Group and in the future, selectivities-at-age were modelled as random variables, where expected selectivity-at-age was equal to the smoothed values in the last year (2000). Variability in selectivity (i.e. process error) was modelled by bootstrapping the residuals to the smoothed fit. In addition, for North Sea whiting and haddock, discarding and industrial fisheries were also modelled as these were included in the ICES assessment (ICES, 2001b).

For each stock, biological and fishery parameters were taken from the current practice of the relevant ICES working groups, to ensure consistency of simulated biomass, reference points and stock-recruitment relationship with current perceptions. Three stock recruitment relationships (SRR) were modelled in the operating model for each stock:

1. Ricker with lognormal errors
2. Ricker with autocorrelation and lognormal errors
3. Ricker with a “pessimistic” value of the slope-at-the-origin set equal to the 25th percentile of the standard Ricker

Deterministic values of natural mortality and maturity-at-age were as used by the working groups.

Weights-at-age in the past correspond to those used by the working group. In the future projections, weights-at-age were modelled as random variables. No trends in growth were modelled for any of the stocks to ensure consistency with current advice. For stocks other than North Sea haddock and whiting (for which discard data were available and catch weights were explicitly modelled), if weights-at-age in the catch differed from those in the stock then the ratios between the two were calculated. These were then smoothed within an age and the expected ratios in the last year were used to model the future ratios. Uncertainty, corresponding to natural variability in growth (i.e. process error), was modelled by bootstrapping residuals to the smoothed fits. In the case of the stock weights, significant year-class effects were included by also modelling autocorrelation within a cohort. The age composition of historic landings was taken from the appropriate working group report to model catch-at-age. Future catch-at-age was derived from equation 6 (see appendix).

THE MANAGEMENT PROCEDURE

The management procedure combines a particular sampling regime and stock assessment technique with appropriate control rules and their implementation. The management procedure corresponded to the *de facto* assessment methodology used by the most recent relevant ICES working group.

The sampling regime as modelled by the "*Observation Error Model*" generates data from the operating model for use in the management procedure. The data correspond to the commercial catch data and research vessel surveys used to generate time series of abundance estimates

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

Weight-at-age – Weights-at-age were sampled without error and bias from the operating model.

Catch per unit effort – CPUE was used to calibrate the XSA in the management procedure. A single series that covered all the age ranges in the population was constructed, assuming the relationship given in equations 14 to 18 (see appendix). A single tuning fleet was used, whose CPUE was proportional to population size with a CV of 30% (an average value for the fleets studied). The results of limited simulations examining the performance of multiple and single fleet assessments were comparable.

Historical stock estimation – A single assessment method eXtended Survivors Analysis (XSA, Darby & 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 re-creates a stock's historical population structure from the catch-at-age matrix and abundance indices.

Biological parameters – Natural mortality- and maturity-at-age did not vary between years, and corresponded to the values used in the most recent working group.

Projection – A "short-term projection" was performed, using the same methodology as the most recent relevant working group, to estimate the allowable biological catch (ABC). Numbers-at-age were projected through the "current year" (for which total catch data were not yet available), assuming fishing mortality was equal to the value in the previous year for all stocks. A projection based on the target fishing mortality was then made in the following year to estimate the ABC. The status quo exploitation pattern and weights-at-age were equal to the mean of the last three years values. Natural mortality and maturity-at-age were the same as values assumed in the assessment.

Setting TACs – The TAC was set on an annual basis equal to the ABC, unless the ABC differed from last year's TAC by an amount greater than given limits (the TAC bounds).

If $\boldsymbol{ABC_{t+1}} > \boldsymbol{TAC_t} \times (1 + \boldsymbol{\alpha})$ then $\boldsymbol{TAC_{t+1}} = \boldsymbol{TAC_t} \times (1 + \boldsymbol{\alpha})$

Else if $\boldsymbol{ABC_{t+1}} < \boldsymbol{TAC_t} \times (1 - \boldsymbol{\alpha})$ then $\boldsymbol{TAC_{t+1}} = \boldsymbol{TAC_t} \times (1 - \boldsymbol{\alpha})$

Otherwise $\boldsymbol{TAC_{t+1}} = \boldsymbol{ABC_{t+1}}$,

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

If the current fishing mortality was greater than the target fishing mortality, 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 current fishing mortality.

EXPERIMENTAL TREATMENTS

The precautionary approach framework used by ICES is intended to ensure that stocks and fisheries remain within safe biological limits and the ICES Advisory Committee on Fishery Management [ACFM] (ICES, 2001) bases it advice on ensuring that "*there should be a high probability that 1) the spawning stock biomass is above the threshold where recruitment is impaired and that 2) the fishing mortality is below that which will drive the spawning stock to the biomass threshold. The biomass threshold is defined as* $\boldsymbol{B_{lim}}$ *(lim stands for limit) and the fishing mortality threshold as* $\boldsymbol{F_{lim}}$*.*" In practice, due to uncertainty in estimating $\boldsymbol{F_{lim}}$ a fishing mortality level below $\boldsymbol{F_{lim}}$ (i.e. $\boldsymbol{F_{PA}}$) is chosen to ensure that $\boldsymbol{B_{lim}}$ is avoided with a high probability. The effect of applying inter-annual bounds on catch limits was therefore investigated for a management strategy based upon $\boldsymbol{F_{PA}}$.

Fishing mortalities corresponding to $\boldsymbol{F_{PA}}$ were evaluated for each stock. In the case of Southern and Northern hake and Eastern and Western Baltic cod, $\boldsymbol{F_{PA}}$ also corresponds to a fishing mortality level that attempts to achieve optimum yield, although this is not the case for the North Sea stocks.

Table 1 Fishing mortality management treatments.

	Cod N. Sea	*Haddock N. Sea*	*Whiting N. Sea*	*Saithe N. Sea*	*Hake Southern*	*Hake Northern*	*Cod Baltic 22-24*	*Cod Baltic 25-32*
$\boldsymbol{F_{PA}}$	0.65	0.64	0.61	0.25	0.27	0.20	0.60	0.16

Limits on the annual fluctuations in TACs – Symmetric bounds of 10%, 20%, 30% and 40% were investigated. In addition, a base case was included, corresponding to no bounds on inter-annual change.

RESULTS

In figures 2, 3, and 4 results are presented for the WG Ricker model as an example of the dynamic behaviour of the system. In figure 5 the results are averaged over all three stock recruitment relationships.

In figure 2, the equilibrium yield-SSB curve based upon the working group Ricker stock recruitment relationship for each species is shown. The dot on the equilibrium curve represents the point on the curve corresponding to the target level fishing mortality and the vertical lines represent $\boldsymbol{B_{PA}}$ and $\boldsymbol{B_{LIM}}$ respectively. 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. The arrows indicate the direction and rate at which a stock will respond to management; shorter and longer arrows represent stocks that are less or more responsive to changes in effort. The simulation trajectories corresponding to median yield and SSB from 2000 to 2030 where no TAC bounds were applied and fishing mortality was at $\boldsymbol{F_{pa}}$ are also shown. Dots on this trajectory represent the position at the start of each year. The expected yields and SSBs for a particular fishing mortality are shown by the deterministic equilibrium curve, which in practice is also the basis for deriving biological reference points. However, the actual realised yields and SSBs may be different because of the stochastic dynamics or because of the difference between the target fishing mortality and actual fishing mortality.

Cod stocks can be seen to be much more responsive that the hake stocks, whilst haddock and whiting are somewhere between the two. Initial responses 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. For stocks currently being overfished (those where the initial point is above the curve), a target fishing mortality of $\boldsymbol{F_{PA}}$ would imply a reduction in fishing effort and therefore a rebuilding phase.

The trajectories will not necessarily converge on the equilibrium curve, since 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 this stock, this results in a highly variable trajectory. Historical variability in yield of the Eastern Baltic cod is highest of the eight species looked at, possibly a result of productivity and carrying capacity changes which were not explicitly modelled since a constant stock and recruitment relationship was assumed. Where there is such a potential for regime shifts with corresponding changes in stock productivity it would be sensible to consider their impact on the candidate management strategies.

Figure 3 compares the case based upon the working group Ricker stock recruitment relationship where there are no inter-annual TAC bounds to cases where a 40, 30, 20 or 10% bound was imposed. Again the equilibrium curve, biomass limits and implied target of the fishing mortality level, $\boldsymbol{F_{PA}}$ are shown. Factors of interest when considering the effect of bounding the inter-annual variability of TACs are the level of bound at which an effect is seen and the magnitude of changes in yield and SSB.

Inter-annual TAC bounds have little effect on Southern hake and only a small effect for North Sea saithe and whiting. For Western and Eastern Baltic cod and North Sea cod and haddock, large variation in SSB and yields are seen. For Eastern Baltic cod, any bound less than 10% and for North Sea cod any bound less than 20% have little effect.

An example of the difference in outcomes due to the working group assumptions and a more complete treatment of uncertainty is given in figure 3 for North Sea cod and Northern hake, which shows expected trajectories along with the individual realisations for 2005, 2015 and 2030, for management strategies based upon setting quotas where fishing mortality is aligned at $\boldsymbol{F_{PA}}$.

Three types of simulations are presented:

- Working group projections (as used by ICES assessment working groups), with no feedback and where stock status is assumed to be known perfectly
- with feedback but stock status is known perfectly
- with feedback and where the stock is assessed using XSA

In the cases of the WG projection and where the stock status is known perfectly, the random variability is similar in the short-, medium- and longer terms. When stock status is estimated using XSA, the variability increases. An important difference, however, is seen in terms of bias (i.e. does the trajectory converge on the target point) and the rate at which the stock moves towards the target point.

For North Sea cod, a working group projection would predict that in the short-term the stock will recover above $\boldsymbol{B_{lim}}$ with a high probability and then converge on the equilibrium point in the medium-term. It also has a high probability of being above $\boldsymbol{B_{lim}}$ and $\boldsymbol{B_{pa}}$ 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 realisations the stock is below $\boldsymbol{B_{lim}}$. However when the assessment uncertainty (both bias and random variation) is also included, in the short-term the stock collapses. In the medium to long-term the stock never converges on the target point.

For Northern hake, again the working group assumptions 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 as in the medium-term there is still a high probability of the stock being below ***Blim***. In the longer-term, the stock has not achieved the target. When assessment uncertainty is included, although the uncertainty is greater ironically recovery is achieved in the medium-term, though in the longer-term the stock does not achieve the target point, as the biomass exceeds the target. These results illustrate the importance of including uncertainty due to assessment and management.

Given the stochasticity and uncertainty in the trajectory for an individual simulation run, there is a need to look at the risk inherent in management actions. These are examined as the risk of falling below limit reference points or the probability of achieving a target reference points based upon biomass. The effect of inter-annual TACs bounds on a $\boldsymbol{F_{pa}/B_{LIM}}$ strategy (i.e. one based on maintaining a stock above a biomass threshold by maintaining a constant fishing mortality) is summarised in figure 5.

The first column of plots in figure 5 explores the probability of maintaining the stock biomass above ***Blim***.

The SSBs of North Sea haddock, saithe, whiting, Western Baltic cod and Southern Hake are currently above $\boldsymbol{B_{lim}}$ with a high probability. In the case of Southern Hake, bounds on TACs have a minimal effect. For North Sea whiting and Western Baltic cod, there is a slight effect but the probability of being above $\boldsymbol{B_{lim}}$ remains about 80%. North Sea haddock shows no effect in the short-term, but in the medium-term the stricter the bound the greater is the probability of being above $\boldsymbol{B_{lim}}$, although there is some evidence of cyclical behaviour. Similarly in the case of North Sea saithe, bounds have no effect in the short-term but do show an effect in the medium to long-term; the stricter the bound the greater is the probability of falling below $\boldsymbol{B_{lim}}$.

North Sea cod was initially below $\boldsymbol{B_{lim}}$ with a probability of about 40%. The stock initially recovers but then declines in the medium-term. The stricter the TAC bound applied for this species, the longer the stock remains above $\boldsymbol{B_{lim}}$ with a high probability. However in the long-term the probability declines to 20% regardless of the bound.

Eastern Baltic cod and Northern Hake were both initially below $\boldsymbol{B_{lim}}$ with a high probability. Both stocks recover in the short-term and in the case of Northern hake a bound appears to hasten recovery slightly.

The second column of plots evaluates the power of the stock assessment, i.e. whether the stock assessment can correctly detect when the stock is above or below $\boldsymbol{B_{lim}}$ (i.e whether the stock assessment in the perceived system gets it right as opposed to the perception that it has).

i.e. $$P(\hat{S} > B_{Lim} | S > B_{Lim}) + P(\hat{S} < B_{Lim} | S < B_{Lim})$$

where $\hat{S}$ is the estimated stock biomass and S the actual value.

For North sea cod, haddock, saithe, whiting and Western Baltic cod, the power is around 80% to 90%, however it is noticeable that the power declines when the probability that SSB exceeds $\boldsymbol{B_{lim}}$ changes. For the other stocks during the recovery phase the power is generally lower (e.g. Eastern Baltic cod).

The third and fourth columns of figure 4 evaluate the effect of TAC bounds on a strategy based on target reference points that attempt to achieve an optimum yield level rather than to avoid a biomass limit. The third column evaluates the effect of inter-annual TAC bounds on the probability of actually achieving the biomass target implied by a fishing mortality level that aims to optimise the yield of the fishery (e.g. approximating to the $\boldsymbol{F_{MSY}}$ and $\boldsymbol{B_{MSY}}$ levels).

Only North Sea Haddock is currently near the target biomass (it has a 50% probability of being above the target level); the remaining stocks are all below the target biomass. A 10% bound in nearly all cases causes the target biomass to be reached sooner than cases with less strict bounds, basically because recent yields are relatively low. This is not the case in the Baltic cod stocks where the 10% bound on TAC variation.

The fourth column of plots evaluates the power to detect where the actual biomass is relative to the target level,

i.e. $$P(\hat{S} > B_{Target} | S > B_{Target}) + P(\hat{S} < B_{Target} | S < B_{Target})$$

For North Sea cod, haddock, saithe and whiting and Western Baltic cod, the power is relatively high throughout the simulation period. Power does fluctuate and appears to be correlated with change in the stock biomass; as a stock declines the power to detect the decline also falls. For Eastern Baltic cod stocks and the two Hake stocks, as the stock recovers, the power to detect that change diminishes. In those cases the stock assessment fails to identify the recovery.

The final column shows the cumulative yield over the 30-year period. For the hake stocks and whiting the bounds have no effect. For saithe, a 10% bound has an effect in the long-term whilst for North Sea cod and haddock, a 10% bound has an effect in the short- to medium term. For the Baltic cod stocks, the stricter the bound the lower is the yield in the short-, medium- and long-terms.

DISCUSSION

The study evaluated management strategies that reduce the inter-annual variation in TACs and in particular examined the trade-offs between yield and risk to the stock. The study was not intended to provide tactical advice on what actual target fishing mortalities or quota levels should be. The approach therefore differed from the standard ICES working group approach used to set TACs and to define safe biological limits (which is essentially based upon an assessment and short-term projection) since it modelled both the "real" and observed systems and explicitly considered the interactions between the various system components. It was therefore able to evaluate the properties of the candidate management strategies with respect to the intrinsic properties of the systems and importantly our ability to monitor, assess and control them.

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 quota for 2003. The effect of quota management in 2003 will be on the SSB at the start of 2004. However, any effect can only be first detected in 2005 when the 2004 data are available. Since the greatest uncertainty in the assessment is found in the recent year, the 2004 assessment of stock status will be the most uncertain. This importantly 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 since 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 stock assessment working groups.

A comparison of management strategies based on a "*working group projection*", "*perfect assessment*" or the "*management procedure*" showed that assessment/management performed more poorly than is currently assumed by stock assessment working groups when providing advice to managers. The simple projection assumes that the status of the stock in the current year is known without error, and target fishing mortality can be achieved without error. As a result of the lag explained above, this is unlikely. In an extreme case, as seen for North Sea cod with a target fishing mortality of 1.0, traditional stochastic medium term methodology does not identify a collapse in the stock as a result.

The risk levels associated with $\boldsymbol{F_{PA}}$ may therefore be different from that assumed by the working groups. This was despite the fact that important sources of uncertainty were not included, for example non-compliance with management and subsequent catches over-quota, and misreporting of the true catch. This will have significant effects on both the perception of the stock, and hence quotas and actual yields from the fisheries. The study also did not examine the influence of structural uncertainty, such as spatial effects, more realistic biology or biological or technical interactions.

The benefits of TAC bounds are dependent on the current status of the stock. There is a difference between an $\boldsymbol{F_{PA}}$ strategy for stocks that are currently below $\boldsymbol{B_{lim}}$ and/or $\boldsymbol{B_{pa}}$ and those above those levels. Therefore rebuilding mode strategies, and those aimed at maintaining the stock above prescribed limits (i.e. steady state mode) should be considered separately.

If the stock is currently below $\boldsymbol{B_{lim}}$ (Northern North East Atlantic hake, Southern North East Atlantic hake, Eastern Baltic cod, Western Baltic cod, and North Sea cod, whiting and haddock) the short-term consequences of adopting a particular management strategy depend on whether current fishing mortality is above or below a level that would cause the stock to recover. When an $\boldsymbol{F_{PA}}$ strategy means that catches need to be reduced, SSB will tend to increase. TAC bounds will limit the rate at which catches can be cut, so that the rate of recovery is reduced, potentially increasing the risk of the stock falling below $\boldsymbol{B_{LIM}}$. If TACs are currently set greater than the replacement level then inter-annual TAC bounds result in an increased risk to the stock. Under rebuilding plans, therefore, TAC bounds of the type evaluated are inappropriate. Asymmetric bounds may be appropriate, for example on a recovering stock, where fishing mortality has been reduced, increasing quotas are unlikely to be as harmful as in the case of a stock where fishing mortality is still high

In some cases (e.g. North Sea haddock) recent strong recruitment may mean that recovery occurs in the short term, irrespective of any management action, although in the longer-term the stock is likely to decline at the current level of fishing mortality.

Symmetric TAC bounds of the level examined during the current study may therefore only be appropriate when a stock has recovered, but as pointed out above the consequences of bounds on increases in TACs and those on decrease will be different and will depend on the status of the stock and management objectives.

The biology of the stock had significant impacts on the performance of management incorporating TAC bounds. For example, hake stocks responded slowly to imposed management measures compared to the gadoid stocks, for which it was possible to get large increases or decreases in biomass in a relatively short time. This is likely to be related to the older age at first (or at full) maturity of hake and illustrates the importance of considering the specific biology of stock in their management

In the presence of TAC bounds, management was less responsive to fluctuations resulting from large recruitment events, such as those seen for haddock in the North Sea. If such good recruitments followed a period of low stock levels, yield would be forgone as TACs could not be increased sufficiently fast to benefit from the increased abundance resulting from good recruitment. Although not presented, results were robust to the assumed stock-recruitment relationship, at least within the range of the data seen historically.

Examination of the historical variations in yield in the study stocks indicate that the variations have generally been small, in the region of the lowest level of inter-annual variations explored in the simulations (figure 6). The largest changes have generally occurred during the period of the recovery plans, where large decreases have been made in TACs.

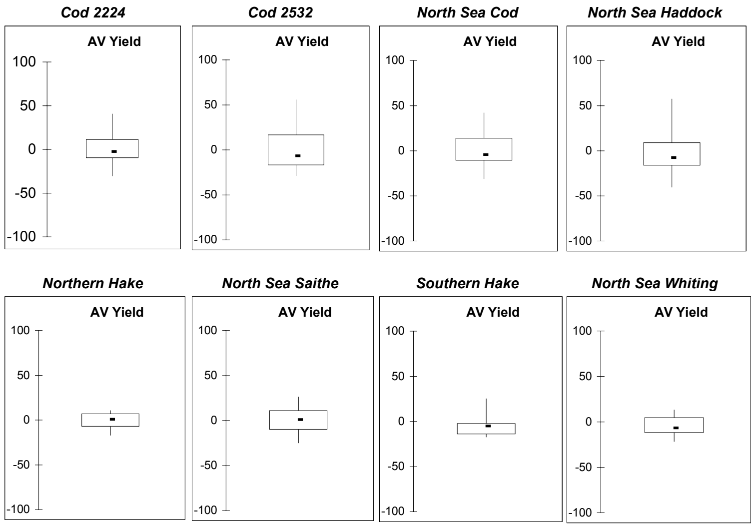

Figure 6. A comparison of historical variability in TACs, boxes represent the inter-quartile range and whisker the 5 to 95 percentiles.

The management strategy simulation approach used in this study provides a powerful tool for the examination of the performance of candidate management strategies. It has shown that better management is not necessarily going to be achieved by attempting to improve the assessment of the historical stock status, since 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. This illustrates the importance of considering management strategies and assessment methods as being part of the same procedure, where the interactions between the monitoring regime, estimation of current stock status and biological references points and the management controls are explicitly recognised.

Explicitly modelling the assessment process can result in quite different outcomes than those predicted by the simple projection traditionally used by the working group. This is because the simple projection assumes that the status of the stock in the current year is known without error and that the target fishing mortality can be achieved without error. However, in practice the assessment is based on last years data and the effect of any management measure on SSB is only manifest, although not detectable, following the implementation of the quota, at the end of the following year. This means that there are important lags in our ability to assess a stock take management action and assess it's effect.

The choice of target and fishing mortality levels and minimum stock levels results from ICES interpretation of the precautionary approach. This lead to the definition of fishing mortality and biomass reference points that are intended to prevent over-fishing 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. In the case of saithe a fishing mortality of 0.40 (i.e. the $\boldsymbol{F_{PA}}$ level) would drive the stock to $\boldsymbol{B_{lim}}$, suggesting that the choice of biomass and target reference points are not consistent for this stock.

While inter-annual TAC bounds may confer benefits on fisheries where the stocks are in certain states, their use must be closely monitored to ensure sufficient management flexibility remains to take action under the changing conditions encountered by fish stocks.

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APPENDIX

The equations and symbols used in the framework are listed in tables 4.1 & 4.2.

Table 4.1 Equations

Population dynamics

$$N_{age+1,year+1} = N_{age,year}\exp\{-Z_{age,year}\} \tag{1.}$$

$$N_{plusgrp,year+1} = N_{plusgrp-1,year-1}\exp\{-Z_{plusgrp-1,year-1}\} + N_{plusgrp,year}\exp\{-Z_{plusgrp,year}\} \tag{2.}$$

$$N_{r,year} = f(SSB_{year-r}) \tag{3.}$$

Mortality rates

$$Z_{age,year} = F_{age,year} + M_{age,year} \tag{4.}$$

$$F_{age,year} = \sum^{fleet} S_{landing,fleet,age,year}Effort_{fleet,year} \tag{5.}$$

$$D_{age,year} = \sum^{fleet} S_{discarding,fleet,age,year}Effort_{fleet,year} \tag{5a}$$

Catch equation

$$C_{fleet,age,year} = N_{age,year}\frac{F_{fleet,age,year}}{Z_{age,year}}(1-\exp(-Z_{age,year})) \tag{6.}$$

$$Z = F_{age,\ year} + D_{age,\ year} + M_{age,\ year}$$

Stock recruitment relationships

Butterworth-Bergh

$$N_{r,year} = \begin{cases} SSB_{year-r} \geq B_{loss} & : \overline{R} \\ SSB_{year-r} < B_{loss} & : \overline{R}\ SSB_{year-r} / B_{loss} \end{cases} \tag{7.}$$

Shepherd

$$N_{r,year} = \frac{\alpha SSB_{year-r}}{1 + (SSB/\beta)^{\gamma-1}} \tag{8.}$$

Ricker

$$N_{r,year} = \alpha SSB_{year-r}\exp(-\beta SSB_{year-r}) \tag{9.}$$

Beverton Holt recruitment

$$N_{r,year} = \frac{SSB_{year-r}}{\alpha SSB_{year-r} + \beta} \tag{10.}$$

Saila-Lorda

$$N_{r,year} = \alpha S^{\gamma}_{year-r}\exp(-\beta S_{year-r}) \tag{11.}$$

Recruitment residuals

$$N_{r,year} = f(SSB_{year-r})\exp(\varepsilon_{year} - \sigma^2/2) \tag{12.}$$

$$\varepsilon_{year+1} = \rho\varepsilon_{year} + \eta_{year+1}$$

$$\eta_{year} \sim N(0, \sigma^2_{\eta}).$$

$$\sigma^2 = \ln(\mathrm{CV}^2 + 1)$$

$$\sigma^2_{\eta} = (1-\rho^2)\sigma^2$$

Derivation of effort

$$\sum^{age} C_{fleet,age,year}CWt_{fleet,age,year} - Yield_{fleet,year} = 0 \tag{13.}$$

Catch per unit effort models

$$U'_{fleet,age,year} = q_{fleet,age}N_{age,year} \tag{14.}$$

$$U'_{fleet,age,year} = q_{fleet,age}\,N_{age,year}{}^{\gamma} \tag{15.}$$

Table 4.1 Equations

	$U'_{fleet,age,year} = \dfrac{U_{fleet,age,year}}{A_{fleet,age,year}}$	16.
	$A_{fleet,age,year} = \dfrac{\left(\exp(-\alpha_{fleet} Z_{age,year}) - \exp(\beta_{fleet} Z_{age,year})\right)}{\left(\beta_{fleet} - \alpha_{fleet}\right) Z_{age,year}}$	17.
	$U'_{fleet,age,year} = q_{fleet,age} \, N_{age,year}{}^{\gamma} e^{N(0,\varphi^2)-\frac{\varphi^2}{2}}$	18.
Selectivity	$S_{fleet,year} \sim MVN(\mu_{fleet}, \Sigma_{fleet})$	19.
Weight-at-age	$SWt_{fleet,year} \sim MVN(\nu_{fleet}, \Omega_{fleet})$ $CWt_{fleet,year} \sim MVN(SWt_{fleet,year}, \Psi_{fleet})$	20.
Yield	$Yield_{fleet,year} = \sum^{age} C_{fleet,age,year} CWt_{fleet,age,year}$	21.
SSB	$SSB_{year} = \sum^{age} N_{age,year} SWt_{age,year} Mat_{age,year}$	22.

Table 4.2. Symbols used in equations

Parameter	Definition
$N_{age,year}$	Numbers of fish by age and year
$M_{age,year}$	Natural mortality by age and year
$Z_{age,year}$	Total mortality by age and year
$F_{age,year}$.	Fishing mortality by age and year
$F_{fleet,age,year}$	Fishing mortality by fleet, age and year
$D_{age,\ year}$	Discard mortality by age and year
r	Age at first recruitment to the fishery
PlusGrp	Age of the plus group.
SSB_{year}	Spawning stock biomass
$Effort_{fleet,year}$	Annual component of mortality, essentially fishing effort.
$S_{\mathrm{type,\ fleet,age,year}}$	Selectivity by type, fleet, age and year
$C_{fleet,age,year}$	The catch by fleet, age and year
α, β, γ	Stock-recruitment model parameters.
R_{λ}	Recruitment at virgin spawning stock biomass
τ	An index of steepness of the stock recruitment curve. Defined as recruitment at 20% virgin spawning stock biomass ($\lambda/5$) divided by the recruitment at virgin spawning stock biomass (R_{λ}).
λ.	Virgin spawning stock biomass
	Relationship between α,β,and τ and λ for Beverton-Holt: $\alpha = \dfrac{(SSB\ /\ R)_{F=0} - \beta}{\gamma}$

Table 4.2. Symbols used in equations

	$\beta = \frac{(SSB \;/\; R)_{F=0}(1-\tau)}{4\tau}$.
$\overline{R}$	Mean recruitment
$SWt_{fleet,year}$	Weight-at-age in the stock
$CWt_{fleet,\ year}$	Weight-at-age in the catch
$Yield_{fleet,\ year}$	Total catch weight from all ages of fish
γ	A parameter used in CPUE modelling that controls the relationship between CPUE and abundance.
$U_{age,year}$	CPUE by age and year.
$U'_{age,year}$	CPUE by age and year.
$q_{fleet,age}$	Catchability
$A_{fleet,ageyear}$	Averaging factor used in CPUE modelling
α_{fleet}.	Start of the period of fishing in this fleet
β_{fleet}.	End of the fishing period for the given fleet
ε_{year}	Recruitment residual in the given year
σ	Standard error of recruitment residuals
ρ.	Auto-correlation in recruitment residuals.
η_{year}	Innovations in the recruitment residual time series
σ_{η}	Standard error of recruitment residual innovations η_{year}
μ_{fleet}	Expected selectivity vector
Σ_{fleet}	Covariance matrix used in selectivity modelling
ν_{fleet}	Expected weight-at-age in the stock
Ψ_{fleet}	Covariance between the ratio of stock to catch weights-at-age
Ω_{fleet}	Covariance between weights-at-age in the stock
φ	Standard error of CPUE residuals

Figure 2. . Equilibrium yield-SSB curves with vectors showing the expected direction and rate of change in yield and SSB for perturbation from equilibrium. Simulated trajectories for 30 years are also shown for the case where there are no inter-annual bounds on TACs, The vertical lines represent $\boldsymbol{B_{lim}}$ and $\boldsymbol{B_{PA}}$ respectively, the yellow diamond shows the starting position and the yellow circle the implied target.

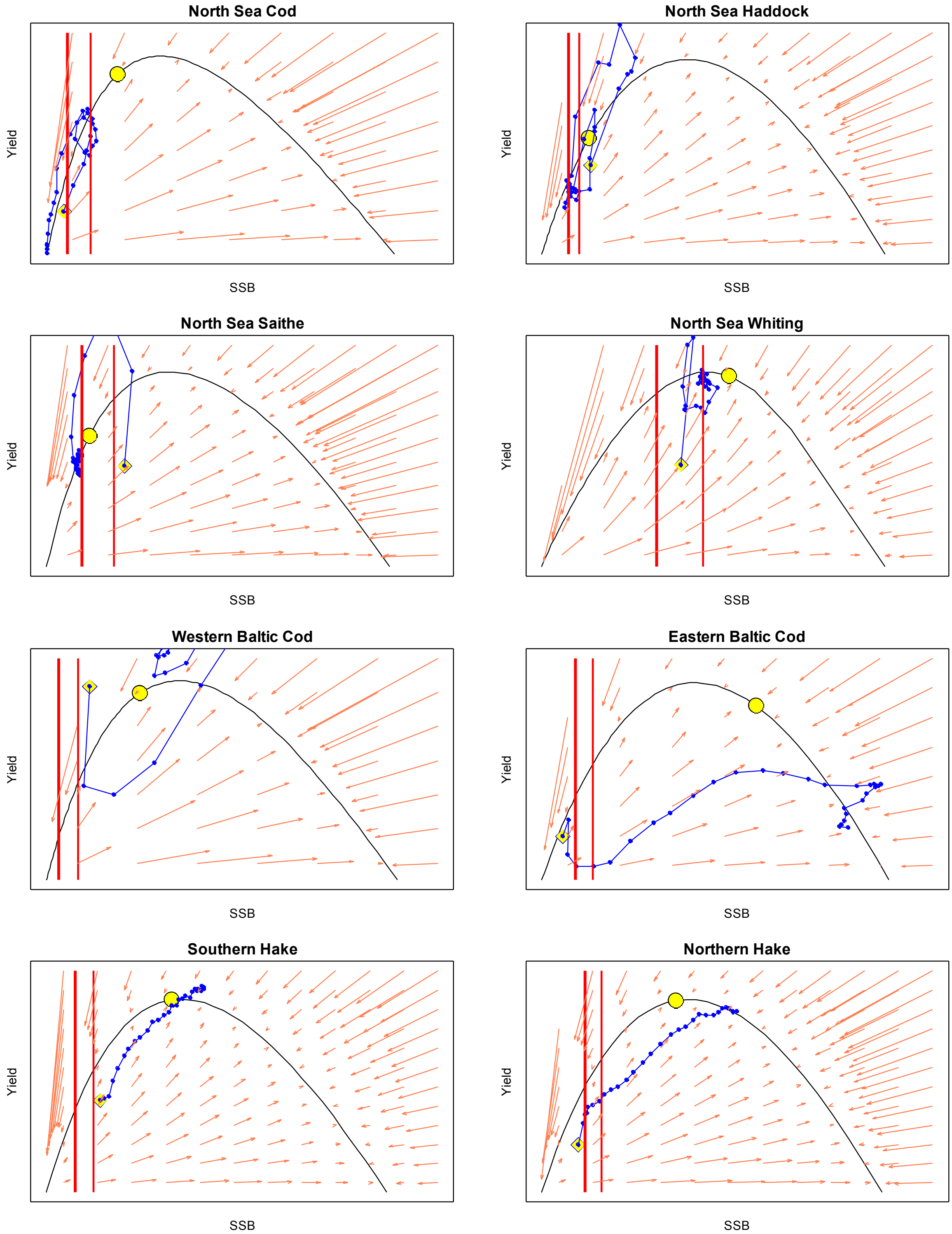

Figure 3. . Equilibrium yield-SSB curves with simulated trajectories for 30 years for no (cyan), 40% (blue) , 30% (green) , 20% (red) and 10% (black) on inter-annual TACs, The vertical limes represent $\boldsymbol{B_{lim}}$ and $\boldsymbol{B_{PA}}$ respectively, the yellow diamond shows the starting position and the yellow circle the implied target.

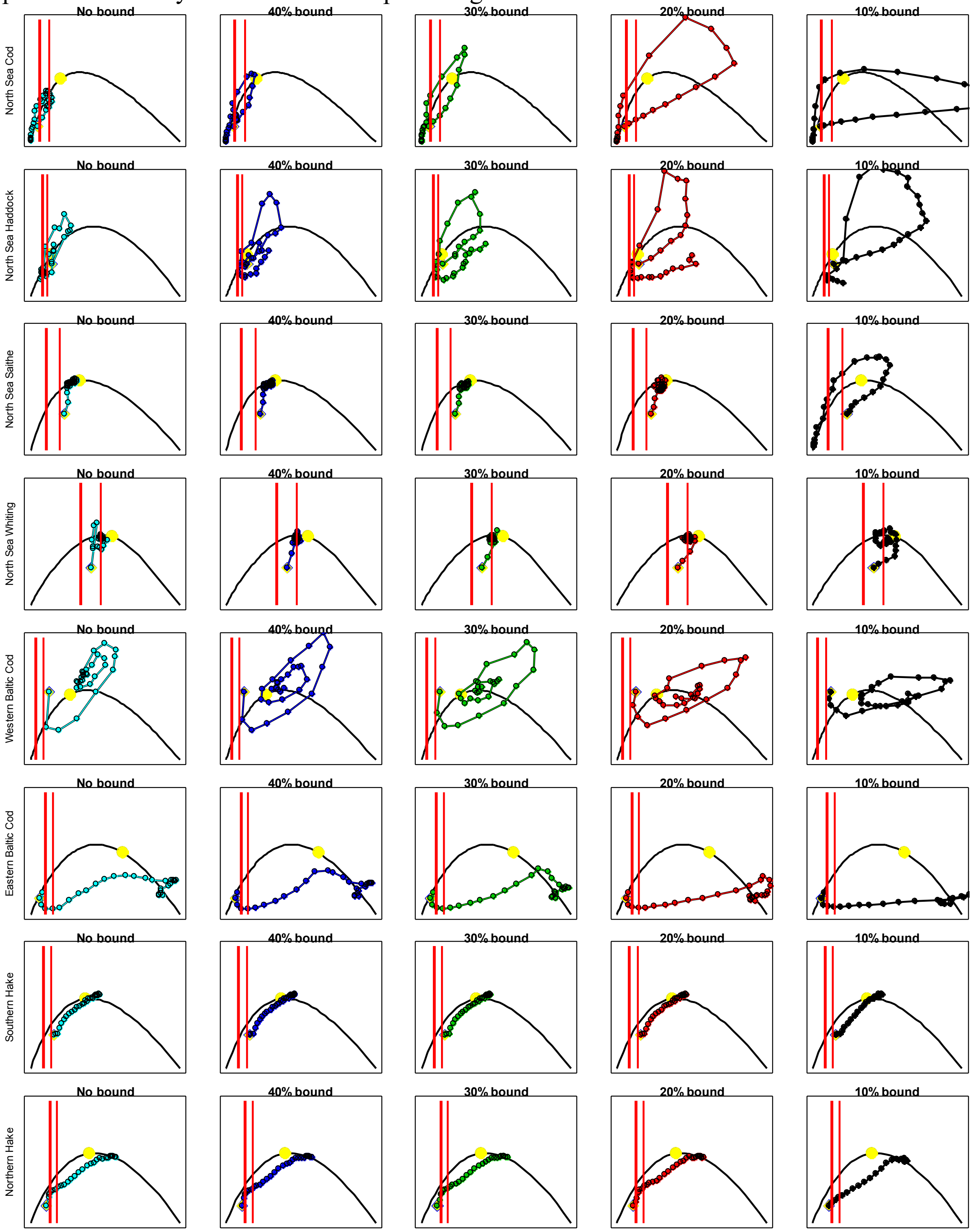

Figure 4a. North Sea cod simulations for TACs aligned on a target fishing mortaility of F_{PA}, where the yellow circle represents the target on the equilibrium yield-SSB curve. Red vertical lines represent B_{Lim} and B_{PA} respectively, red dots represent the 50th bi-variate percentile. Simulations are for three time periods and a simple projection, feedback with a perfect assessment and feedback with an assessment.

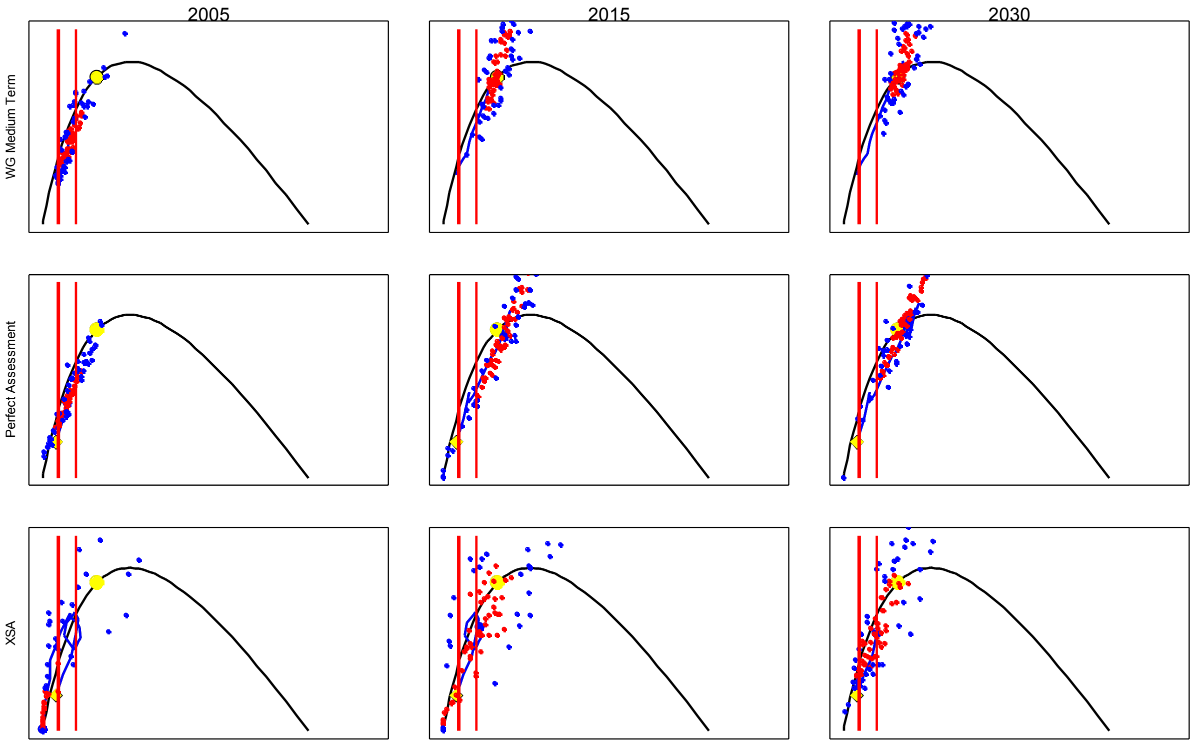

Figure 4b. Northern Hake simulations.

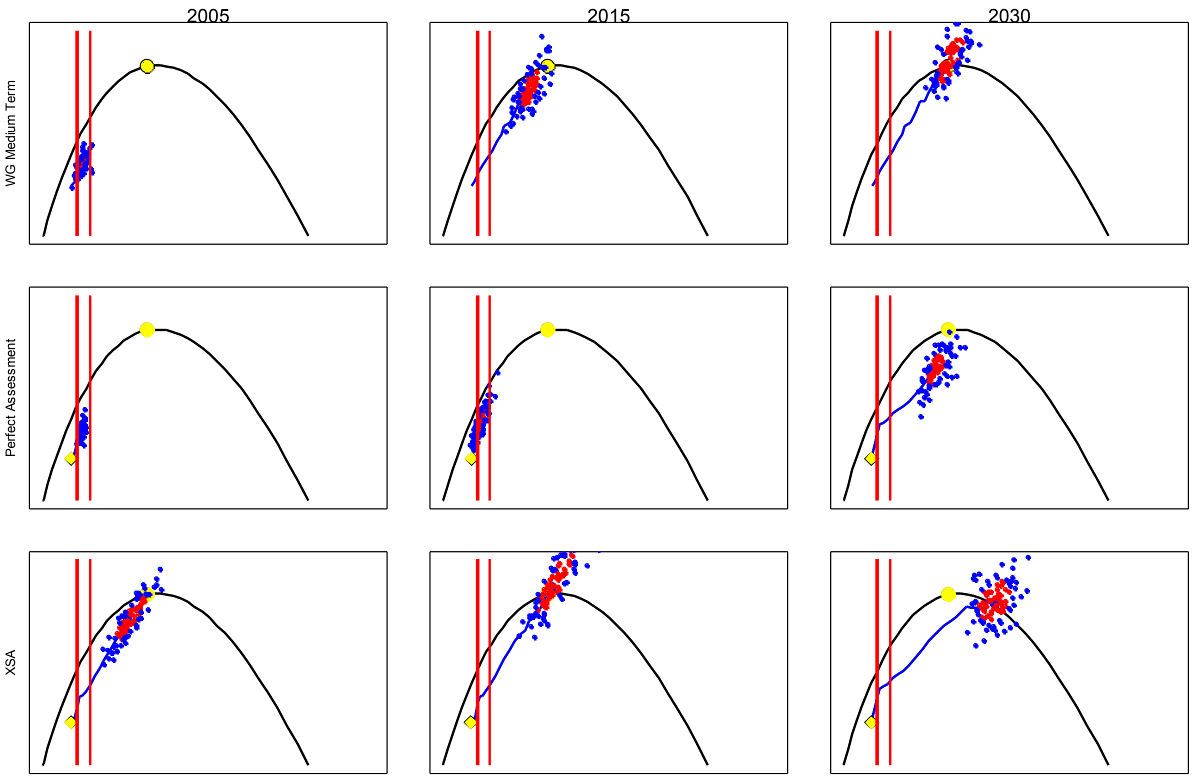

Figure 5. A comparison of the probabilities of falling below $\boldsymbol{B_{lim}}$ and $\boldsymbol{B_{Target}}$ (the point on the equilibrium curve corresponding to the given fishing mortality level), the power of determining actual stock biomass relative to $\boldsymbol{B_{lim}}$ and $\boldsymbol{B_{Target}}$ and the cumulative yield for the different inter-annual bound levels. The different inter-annual TAC bound levels are shown, 10% (black), 20% (red), 30% (green), 40% (blue) and none (cyan).