**ICES CM 2008 / O:13**
**Governmental quality and risk management**

# Risk management within an RFMO – The case of Greenland halibut and NAFO

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Abstract

In 2003 NAFO Fisheries Commission established a fifteen year rebuilding plan for Greenland halibut (*Reinhardtius hippoglossoides*), a valuable straddling stock off the east coast of Canada, following a period of declining biomass and increasing fishing mortality. The rebuilding plan was, however, *ad hoc*, developed without consultation with NAFO Scientific Council and has been strongly criticized for being risk-prone and inconsistent with the Precautionary Approach. This criticism has been borne out by subsequent assessments of the stock that have shown that fishing mortality increased under the rebuilding plan to over 2.5 times $F_{max}$ and four times $F_{0.1}$. The development of the rebuilding plan reflects how NAFO has traditionally worked - mainly behind closed doors, making selective use of scientific advice and arriving at decisions on TACs and other regulations though a process that is not always transparent. At the NAFO meeting in 2005 a renewed commitment was made to rebuild the Greenland halibut stock based on scientific principles and the Precautionary Approach. This encouraged NAFO Scientific Council to form a study group to evaluate rebuilding options for the stock using a management strategy evaluation approach, utilizing the open-source FLR environment. This is a transparent approach, necessitating involvement from all stakeholders, which aims to find rebuilding strategies that are robust to risk and uncertainty. We report on progress of the study group, describing how a WIKI was used to encourage participation and how a review meeting in Vigo in February 2008 which included scientists, fisheries managers and industry has been instrumental in guiding the approach.

Keywords: Fisheries management, risk, management strategy evaluation, FLR, transparent governance, recovery strategies, stock rebuilding

## Introduction

NAFO (Northwest Atlantic Fisheries Organization) is an inter-governmental regional fisheries management organization (RFMO) founded in 1979 under the Convention on Future Multilateral Cooperation in the Northwest Atlantic Fisheries. NAFO's objective is the sustainable use of fishery resources in the Northwest Atlantic, in particular optimum utilization, rational management, and conservation (NAFO 2004; NAFO GC, 2007). However, of the 19 stocks regulated by NAFO, 10 are currently under moratoria with regard to directed fishing.

Annual requests for specific scientific advice by Fisheries Commission (FC) are addressed by Scientific Council (SC) based on formal, peer reviewed stock assessments. The requests for advice from FC have changed over time. Routine requests have for a number of years included advice on the implications of fishing at $F_{0.1}$, $F$ status quo ($F_{sq}$) and $F_{max}$. Starting in 1996 FC began to request scientific advice in the context of the 1995 UN Fish Stocks

Agreement (UNFSA). Specifically, information on Precautionary Approach (PA) limit and target reference points and associated estimates of medium term risk was requested to "assist the Commission in developing the management strategies" as described in the UNFSA (NAFO FC, 2007). Because of uncertainties in the assessment, including estimation of a stock-recruit relationship, SC felt that reference points could not be reliably estimated for the 2+3KLMNO Greenland halibut (*Reinhardtius hippoglossoides*) stock. However, risk was quantified in terms of the probability of $F$ exceeding $F_{sq}$ under different Total Allowable Catch (TAC) options.

Although stock assessments in 2000 and 2001 were fairly optimistic and indicated a recovering population following a decline in the mid-1990s, the 2002 assessment was unable to provide quantitative estimates due to the poor fit to the model and the 2003 assessment, based on a revised assessment model, gave a much more pessimistic view of the status of the stock (Darby *et al.*, 2003). Stochastic medium-term stock projections suggested that reducing $F$ from the prevailing level (0.44) to $F_{0.1}$ (0.16) or even to $F_{max}$ (0.28) would result in a recovery of the exploitable biomass to the estimated previous low level (1995-97; about 90kt) by 2007. Stochastic projections indicated that there was a high probability that keeping the TAC at the current level (34-38kt) would result in high mortality rates that exceed those of the early-1990s (>0.6). SC recommended a reduction in the TAC to 16 kt which, although maintaining $F_{sq}$, but would have exceeded $F_{max}$. A reduction to 7 kt would have been consistent with $F_{0.1}$ at the time.

FC rejected the 2003 SC TAC advice to immediately reduce the TAC to 16 kt and instead came up with a 15-year rebuilding plan of its own with the objective of attaining a target of 140kt exploitable (5+) biomass by the beginning of 2019 (NAFO FC, 2003). The plan specified *ad hoc* step-wise reductions in TAC for the period 2004-2007 to 20 kt, 19 kt, 18.5 kt and 16 kt, respectively. The intention was that subsequent TACs would depend on rebuilding progress, but with a 15% cap on any year-to-year change.

In 2004 SC evaluated the rebuilding plan and concluded that although initially the 5+ exploitable biomass would remain stable at a low level and $F$ would remain high (~0.60), there was a high probability that biomass would increase in 2007 and 2008 and that fishing mortality would decline by about 50%. However, there was a low probability of achieving the rebuilding plan target by the end of 2018. By restricting itself to only commenting on the rebuilding plan, SC lost out on an opportunity to put forward science-based alternatives more in keeping with the Precautionary Approach adopted in principle by NAFO.

Shelton (2005a, 2005b) criticized the FC rebuilding plan for having no scientific basis and for not being subject to scientific peer review. Shelton (2005a) concluded that the plan was considerably less cautious than one which would be specified under a Precautionary Approach and it was neither robust to retrospective error in estimates of recruitment nor robust to alternative assessment methods. Shelton (2005b) suggested that $F$ should be immediately reduced 0.5x $F_{0.1}$ or less in accordance with general principles of the UNFSA for a stock below $B_{lim}$, and warned that unless immediate conservation steps were taken it would seem highly likely that this fishery would, in only a few years, join a number of other NAFO managed groundfish stocks in being relegated to by-catch fishery status. He used stochastic simulation to evaluate a quasi-PA compliant harvest control rule:

$$F = \begin{cases} 0.5 \times F_{0.1} & if \quad B \leq B_{\lim} \\ 0.8 \times F_{0.1} & if \quad B_{\lim} < B \leq B_{MSY} \\ F_{0.1} & if \quad B_{MSY} < B \end{cases}$$

As proxies for the reference points he proposed:
$B_{lim}$ = $B_{recov}$ = 5+ biomass in 1997 (about 80 kt). This is the biomass from which the stock previously sustained a rapid recovery;
$B_{MSY}$ = the FC rebuilding target: 5+ biomass corresponding to a relatively stable period of reasonably high catches (about 140 kt);
$F_{lim}$ = $F_{max}$ = 0.24;

$F_{buf} = F_{0.1} = 0.14$.

Shelton (2005b) suggested that this strategy provided a good balance between initial rapid rebuilding and medium term average catch, and would also go some way towards meeting PA requirements specified under UNFSA. Healey and Mahé (2005) also evaluated the FC rebuilding plan and concluded that, under the plan, projected average fishing mortality would decrease and 5+ biomass would slowly increase. However, they concluded that prospects for rebuilding the stock to the recovery target by the beginning of 2019 were low and that $F$ was expected to remain above $F_{max}$. Although SC supported the conclusion that prospects for rebuilding under the FC plan were poor, no alternative PA-based advice or alternative rebuilding strategy was recommended in 2005.

In the 2006 assessment (Healey and Mahé, 2006) it was noted that recent catches had exceeded the TACs by up to 27% and advised that in all projection scenarios, the 2009 exploitable biomass would remain well below the target level of biomass specified in the FC rebuilding plan. The 2007 assessment (Healey and Mahé, 2007) found that average fishing mortality for 2006 was 0.59, over two times the $F_{max}$ level (0.26) and four times the $F_{0.1}$ level (0.14). Thus, although FC rebuilding plan TAC reduction steps have been implemented, fishing mortality has continued to increase and biomass had continued to decrease (Healey and Mahé, 2007). Also, it was noted that violations of NAFO regulations had continued. Canadian inspections of vessels in the regulatory area provide evidence of miss-identification of catch from the NAFO regulatory area as Hatton Bank Greenland halibut (i.e. from the Northeast Atlantic) and various other forms of under-reporting. The 2007 SC assessment evaluated a number of management options including $F_{0.1}$, $F_{sq}$, a fixed 16 kt TAC and TACs decreasing from 16 kt by 15% annually to 2011. The scientific advice from SC was that fishing mortality should be reduced to a level not higher than $F_{0.1}$, or alternatively, catches over the next four years should be reduced by 15% annually from the 2007 TAC of 16 kt. FC ignored this advice and decided to retain the 2008 TAC at 16 kt (i.e. a TAC with a projected $F > F_{max}$).

## Management by reference points and risk

Although NAFO adopted the PA in 2004 as outlined in the 1995 UNFSA, initial emphasis has been on pilot studies on yellowtail flounder in 3LNO and shrimp in 3M, two stocks that are at high stock size for which fishing poses no immediate threat. The door was however open for SC to provide PA advice on the overfished Greenland halibut stock in terms of reference points and risk, but SC continued to find that it was unable to determine appropriate stock-size reference points and quantify the associated risk. Recently, evidence has been assembled to demonstrate that a stock-recruit relationship does exist for this stock (Morgan *et al.*, 2008) which could increase the support for developing reference points. Commentary from SC, both within the formal assessment and in ancillary SCR documents, that the rebuilding plan was failing, did not appear to have had any significant impact on FC. It is an open question whether or not SC advice would have had greater impact had provisional reference points been adopted and had short term and medium term risk relative to these reference points been provided.

Critics of management by reference points and risk suggest that estimates of current stock size can be very uncertain, the appropriateness of selected reference points is often questionable (Hilborn, 2002), and that projections commonly ignore structural or model uncertainty (Butterworth, 2008). There is also a statistical issue of basing decisions on low risk of serious harm when the tails of distributions may be particularly poorly determined. Together, these shortcomings reduce the usefulness of management by reference points and risk in decision-making. Then there is also the question of how an RFMO like NAFO may interpret and apply estimates of risk. Where scientific advice from SC has included risk in the past, for example a high risk of projected $F$ exceeding $F_{sq}$ or a low probability of the rebuilding plan actually working, the reaction by FC appears to have been limited. Although in principle the PA approach has been adopted by NAFO, there is no specific commitment by NAFO to ensure that management is consistent with a low risk of serious harm or a high probability of rapid rebuilding of a depleted stock. A cynic could suggest that the current approach to risk management is to acknowledge that the scientific assessments are very uncertain while in comparison the impact of any TAC reductions on the fishery are quite certain, and then to adopt a risk-prone management action in the hope that the stock is either in much better state than suggested by the scientific assessments, or that some favorable event will occur such as a string of good year-classes.

Management decisions emanating from FC with respect to Greenland halibut thus far appear to be largely *ad hoc*, and because the decision making process is neither public nor transparent, there is no way of determining how far scientific advice penetrates the decision-making process and reasons for it not being followed. Consequently there is only limited opportunity for SC to learn to be more effective in providing future advice. In fact, since the introduction of the rebuilding plan, SC has been mute with regard to suggesting any alternatives prior to the 2007 assessment. It is anticipated that there will be reluctance on the part of the NAFO decision making process to be weaned off the current *ad hoc* decision-making approach. It provides the maximum flexibility and the least transparency. It thus maximizes the opportunity to make deals behind closed doors which may relate to varied factors such as compliance, indirect economic benefits, etc. On the other hand, it provides no defense against accusations of unsustainable fisheries management practices that contravene the spirit and intent of the UNFSA. While this may not be major pressure right now, there is increasing societal awareness of the need to mange fisheries sustainably for long-term public good and a growing demand for accountability and governance reform, perhaps particularly with respect to RFMOs who are expected to lead the way and set the bar higher than might be the case for individual nations for whom short-term political agendas dominate.

Initial attempts by NAFO SC to encourage FC to implement a PA reference point-risk framework in the mid to late 1990s received a lukewarm reception on the basis that it was too rigid and prescriptive. A Proposal for a more flexible framework for general application of PA on NAFO Stocks (Shelton et al., 2003) fared no better. A combination of low acceptability by managers and inherent unresolved scientific problems with management by reference points and risk suggests that an alternative approach to risk management in RFMOs may be required.

## Choosing a robust management strategy

Although formal management strategy evaluation (MSE) has been around for more than 20 years in the context of management of whales and other species (IWC, 1989; Butterworth and Punt, 1999), application to marine fish has gained increased impetus recently through evidence of a number of apparent successes (Butterworth and Rademeyer, 2005; Plagányi *et al.*, 2007) and the development of an open-source R-based environment for developing and implementing MSE (FLR; Kell *et al*., 2007). MSE has the advantages over management by reference points and risk in that the emphasis is on finding management strategies that are robust with regard to uncertainty regarding the dynamics of the stock and current stock status rather than the almost impossible task of trying to estimate the risk associated with annual TAC options. MSE also provides a more participatory environment for decision-makers as will be described below.

An initial application of MSE to 2+3KLMNO Greenland halibut using FLR (Miller *et al.*, 2007) indicated that a project of this magnitude required input from a range of experts in order to be successful. This led to the establishment of an open-access Wiki site in mid-2007 which became the virtual hub for the project. This was followed up by a NAFO Study Group meeting in Vigo Spain in February 2008 (NAFO SC, 2008) which solidified much of the progress achieved through the Wiki site. Input to both the Wiki and the SG meeting was received from industry members, fisheries managers and scientific experts – a somewhat unique occurrence within NAFO. Further consultation is envisaged with representative ENGOs. The revised analysis (Miller *et al.*, 2008) provides results for 5 management strategies applied to a reference set of 4 operating models (OMs), generating 8 performance statistics. The complete OM reference set that has been identified for 2+3KLMNO Greenland halibut comprises 20 OMs reflecting the large amount of uncertainty associated with the biology, population dynamics and current status for this stock. Although there may be some redundancy in this set, evaluation of management strategies against the remaining 16 OMs is ongoing. Only two OMs are used as examples in this paper.

Development of the reference set of operating models is primarily the concern of scientists and the details of how a management strategy is evaluated, while open and transparent, should not be of paramount concern to decision-makers. Their challenge is to agree on the important performance statistics and to suggest management strategies they would like to see evaluated. They also need to consider how they will treat the results in arriving at a decision regarding an appropriate management strategy that is robust to the inherent uncertainties. The performance statistics should embody the range of management objectives for the stock in the short, medium and long-term. For the Greenland halibut MSE we have identified 8 initial performance statistics for consideration based on suggestions by industry, managers and scientists – more can be added:

i. Annual Average Variation (AAV) in catch
ii. $C$/MSY
iii. $B/B_{recov}$
iv. $B/B_{MSY}$
v. $F/F_{MSY}$
vi. Average catch
vii. CV on $F$
viii. Age in catch

We divided these on the basis of whether or not the performance statistic represents a risk tolerance (i, iii, iv, v) or a tradeoff (ii, vi, vii, viii). Management strategies need first to meet prescribed risk tolerances before they would qualify to be considered further with regard to the tradeoffs in performance statistics. For risk tolerance performance statistics, a reference level, risk threshold need to be specified by decision-makers for short, medium and long-term time horizons. Some risk tolerance statistics may perform a dual role in terms of tradeoff statistics. In deciding on a management strategy, decision makers have considerable flexibility in terms of considering which trade-offs are more acceptable.

In theory it would be possible to develop some overall weighted sum of performance measures and choose the management strategy that has the highest score across all OMs in the reference set. This "find the winner" approach is, however, not advocated as an initial step. Instead, the approach of "*satisficing*" be adopted. This is a decision-making strategy which attempts to meet criteria for adequacy, rather than to identify an optimal solution. Under this approach, FC would be presented with a number of strategies that perform adequately with respect to risk tolerance performance statistics. Clearly, MSs that don't meet PA criteria for low risk of serious harm and that have low probability of rebuilding the stock should not be considered "adequate".

Guidance on the reference levels for risk tolerance statistics (Table 1) can come from a variety of sources. For (i), industry has expressed the desire that the annual absolute variation in catch should not exceed 15%. FC could thus perhaps consider specifying $P \leq 50\%$ of AAV>15% as a reasonable risk tolerance for short-, medium- and long-term. For (iii), FC has specified that it wants to rebuild to $B_{recov}$ (average exploitable biomass 1975-99; 140kt in the base XSA) by 2019 (medium-term). Thus FC could consider specifying $P \leq 10\%$ of $B/B_{recov}<1$ in the medium-term and $P \leq 5\%$ of $B/B_{recov}<1$ in the long-term (2030). For (iv) the UNFSA considers $B_{MSY}$ to be a target and thus $P \leq 50\%$ of $B/B_{MSY}<1$ might be considered appropriate in the long-term (i.e. for a fully rebuilt stock). Under the UNFSA, $F_{MSY}$ is considered a limit, so that $P \leq 10\%$ of $F/F_{MSY}>1$ may be considered appropriate in the short-, medium- and long-term. This process requires the decision-makers to explicitly document their tolerance levels and degree of risk-averseness or risk-proneness across a range of statistics, and to consider how these differ depending on the length of the time horizon, i.e. short-term risk vs. longer term risk.

There are some clear expectations with regard to trade-off statistics. For example, in the short to medium term faster recovery will be a tradeoff against higher average catch. High average catch will trade off against AAV and CV in *F*. These tradeoffs can be provided in graphical or tabular form for decision-makers to evaluate as part of the process of arriving at an "adequate" and acceptable management strategy.

In addition to the performance statistics, a number of descriptive statistics are useful for comparing how OM populations behave under different MSs. We consider exploitable biomass, spawning stock biomass, recruitment, mean fishing mortality, mean catch and mean exploitable age.

Five management strategies have been proposed in the Greenland halibut study thus far in consultation with industry, managers and scientists (Miller *et al.*, 2008):

i. $F_{sq}$ strategy (Fsq) – the stock is fished at the same fishing mortality as in the previous year. i.e. in each year y, *F* from the previous year, $F_{y-1}$, is converted to a TAC for year *y*+1, based on stock projections to the start of year *y*+1. This is recalculated each year, so *F* will vary over time. Given the current high level of *F*, this is a heavy fishing strategy.

ii. Precautionary Approach strategy (PA) - this is a simplified PA implementation. *F* is determined depending on how current SSB relates to *β*, the breakpoint in a segmented regression curve fit to the S-R data:

$$F = \begin{cases} 0.5 \times F_{0.1} & if \quad SSB \le \frac{\beta}{2} \\ \frac{SSB}{\beta} \times F_{0.1} & if \quad \frac{\beta}{2} < SSB \le \beta \\ F_{0.1} & if \quad \beta < SSB \end{cases}$$

iii. Model-free, index-based TAC adjustment strategy (ModFree) - a simple TAC adjustment strategy that uses the change in perceived status of the stock (directly from research surveys) to adjust the TAC accordingly:

$$TAC_y = TAC_{y-1} \times \left(1 + \lambda \times slope\right)$$

where: *slope* = average slope of log-linear regression lines fit to the last five years of each index (equally weighted), λ = an adjustment variable to ensure that the relative change in TAC is greater than the perceived relative change in stock size (i.e. $\lambda > 1$, therefore allowing the strategy to stabilize the stock size through positive feedback).

Various $\lambda$ values >1 were tested in deterministic simulations and a value of 1.25 was selected (allowed for adequate adjustment of the TAC without having excessively large fluctuations from year to year). In addition to this a constraint was made limiting the new TAC to a minimum of 25% of the previous TAC (to prevent setting negative TACs in the case of extremely steep stock declines).

iv. Fisheries Commission Rebuilding Plan Model- (FCMod) – this strategy was designed to comply as closely as possible to the conditions laid out by the FC rebuilding plan i.e. stability for the fishery is considered important, therefore no large TAC changes are allowed. The basic strategy is the same as the model-free strategy except this is a model-based strategy where: *slope* is the slope of log-linear regression line fit to the last five years of exploitable (5+) biomass according to the latest XSA assessment (years *y*-4 to *y*-1 from the XSA and year *y* projected based on the previous year's TAC). $\lambda$ =1.5. The TAC from 2008 is constrained to be within 15% less or greater than the TAC of the preceding year. TACs are only changed every second year to increase stability to the fishing industry. Note that, while this strategy attempts to address some of the aspects of the FC rebuilding plan, the actual FC plan specifies arbitrary *ad hoc* TAC reduction steps and does not adopt a feedback harvest control rule of the kind explored here. It cannot therefore be subject to MSE without some modification.

v. Half $F_{0.1}$ strategy (HalfF01) – $F$ is immediately reduced to the $0.5*F_{0.1}$ and retained at this level. This conservative strategy could be considered justifiable by some given the large uncertainties associated with the size and dynamics of the Greenland halibut stock. Note that $F_{0.1}$ is re-estimated every year in the simulation so it will vary over time.

## The MSE Procedure and Operating Models

The MSE simulation procedure works by projecting numbers at age into the future from an initial starting point using a standard equation for updating population size (Equation 3). Natural mortality ($M$) and partial recruitment ($PR$) are specified by the operating model, while fishing mortality ($F$) depends on the harvest control rule (HCR) defined within the management strategy being evaluated.

$$N_{a+1,y+1} = N_{a,y} e^{-(M + F_y \times PR_a)} \tag{3}$$

Where: $N_{a,y}$ = numbers at age $a$ in year $y$,
$M$ = natural mortality constant across all ages and years,
$F_y$ = fishing mortality in year $y$,
$PR_a$ = partial recruitment (selectivity) at age $a$.

Recruitment (numbers at age 1) is determined by the stock-recruit function applied within the operating model. There is a large degree of uncertainty about the stock-recruit relationship in 2J+3KLMNO Greenland halibut. A number of possible stock-recruit functions are considered in the full reference set of OMs for this stock to ensure potential management strategies are robust to this major source of uncertainty (Miller *et al*., 2008). For this analysis a simple segmented regression model is used, with constant recruitment above the breakpoint ($\beta$) and recruitment declining linearly ($\alpha$) to zero below the breakpoint. It thus defines a recruitment-overfishing threshold. Estimates of current spawning stock biomass are below the breakpoint indicating recruitment-overfishing is occurring.

Conditioning of operating models requires consideration of the past system and initial starting point of the population, biological parameters of the stock (stock-recruit curve, maturity and weight/growth), behavior of the fishery/fleet(s) and the level of uncertainty/error in the observation of the system and estimation of stock parameters. There is substantial uncertainty around the dynamics and current state of the 2+3KLMNO Greenland halibut stock. Miller *et al.* (2008) described a full reference set of 20 operating models (OMs) covering a broad range of possible "realities". These operating models are distinguished by: starting point (historical numbers at age arising from the indices chosen for the assessment), stock-recruit function, $M$ and the shape in commercial PR (selectivity) after age 13. However, we have only analyzed the performance of MSs against two of these OMs in the current paper. These results are not considered an adequate evaluation of possible management strategies for Greenland halibut; our aim here to illustrate how the MSE result can be used in selecting viable MSs based on the two example OMs.

The assessment of 2+3KLMNO Greenland halibut is based on an XSA (eXtended Survivors Analysis; Shepherd, 1999). Three research vessel survey series of age disaggregated abundance indices (mean numbers per tow, MNPT) are used to tune the XSA (González Troncoso *et al.*, 2006; Healey, 2007). The Greenland halibut MSE takes into account historical uncertainty in the form of observation error through an XSA bootstrap procedure (Miller and Shelton, 2007), giving a distribution of initial population sizes and age compositions. Process error (variation in weights at age, proportions mature at age, partial recruitment at age and number of recruits) was generated by running the simulation for each management strategy 100 times. No management implementation error (i.e. TAC over/under-runs) was considered.

The factor distinguishing the two operating models in this analysis is natural mortality (*M*). The current assessment model assumes *M*=0.2. However, given von Bertalanffy growth parameters for the best fit to survey length at age data of $L_{inf}$ = 220cm, *K* = 0.33, age at 50% maturity =13 and length at 50% maturity = 75 cm, it can be concluded, based on Beverton-Holt life history invariants (e.g. Jensen, 1996), that the appropriate value for natural mortality (*M*) is closer to 0.1 than the currently used value of 0.2. Thus, $F_{msy}$ would be around 10% of the biomass, following the rule-of-thumb that $F_{msy} \approx M$. Two *M* values were therefore examined, 0.1 (OM 2) and 0.2 (OM 4), to account for uncertainty.

Future trends in fishery selectivity at age may not be easy to predict. PR patterns going into the future for these simulations are simply resampled with replacement from the recent period (1996 to 2004), thought to be the most representative period for current fishery dynamics. PR patterns may change as the age structure and abundance of the stock changes. Also, potential gear changes (e.g. reduction in net mesh size) could change selectivity. These refinements could be built into future versions of the OMs should analyses be presented in support of such relationships.

To evaluate each management strategy, stochastic MSE simulations are run taking into account uncertainty/error relating to the dynamics and perception of the Real World stock. Under the "POM" approach to management strategy evaluation described in the ICES COMFIE Report (ICES, 1997), three kinds of error are considered, process error, observation error and model error. Process error arises from variation in growth, maturation, recruitment, mortality, and selectivity between each stochastic simulation (*n* = 100). Observation error in the perception of the Real World is achieved by applying index residuals from the initial XSA, used to create the population, to add error to the actual population numbers (see Miller et al., 2008 for more details). Model error results from imperfect XSA estimates of population size and fishing mortality. Model estimates cancel out observation error to some extent by 'smoothing' over the error from each of the three indices used (each of which contain observation error). However, further error can result from model biases and incorrect assumptions or constraints used in the model (e.g. *M*, shrinkage of *F* in the final years, etc.).

## Example results

Example results from the MSE are presented to demonstrate the different behaviors of the two OMs and to show how performance statistics could be used to evaluate risk tolerances and tradeoffs in order to select an appropriate MS from among the candidates. Differences in *F* generated by the different MSs translate into a range of catch values that in turn impact upon the recovery or decline of the stock under both OMs (Figs. 1 and 2). Under both OMs, exploitable biomass increases over time for all MSs except Fsq. However, under OM 2 only the HalfF01 MS achieves the rebuilding target of 140 kt by the beginning of 2019. Under OM 4 the rebuilding target is achieved by all MSs except for Fsq. Under OM 2, SSB increases to above historic levels after some fluctuation for the PA and HalfF01 strategies while under OM 4 the increase in SSB is substantial for all strategies except Fsq. Recruitment levels increase rapidly to fluctuate near the maximum level of the stock-recruit function with the exception of the Fsq strategy. Under OM 2, mean *F* is controlled at moderate levels to 2019 under ModFree, PA, FCMod and HalfF01 strategies while in the longer term the ModFree and FCMod strategies show higher probability of elevated values of *F* occurring. Under OM 4, mean *F* declines rapidly to low levels for all strategies except Fsq. With the exception of the Fsq strategy, all strategies result in increasing catches over time under both OMs, although not exceeding the historic catch peak, even under OM 4. Under the PA and HalfF01 there is a considerable decrease in catch in the short term. This is compensated for by higher catches in the longer term under OM 4 but not under OM2. Mean exploitable age in the population shows some improvement under all MSs except Fsq, the improvement being more substantial in the case of OM4.

It is clear that the projections of the stock are highly sensitive to *M*. Better rates of recovery of exploitable biomass and SSB occur under OM 4. Average age increases notably by the end of the rebuilding plan for all MSs, creating a large biomass of fish that are less accessible to the fishery (due to lower PR at older ages), leading to sustained high, increasing exploitable biomass levels, large SSB and consequently strong recruitment feeding into the stock. The current annual assessment assumes $M$=0.2, while biological attributes suggest that it may be lower for this stock. It seems resolving this issue should be a high priority.

The Fsq strategy allows the greatest average catch (>20kt) in the short term while collapsing the stock. The ModFree and FCMod strategies maintain catch levels only slightly lower than recent observed catches. The PA and HalfF01 strategies result in substantial initial decreases in catch to around 5kt. Over the length of the rebuilding plan period (2019) and into the longer term (2030), the average catch allowed by the Fsq strategy decreases steadily as the stock declines. The initial high F values for the Fsq strategy crashes the stock in OM 2. The low F strategies (PA and HalfF01) offer the best prospects for recovery with both exploitable and spawner biomass rapidly increasing from the period of implementation.

The descriptive statistics also show that in practice, the Fsq strategy leads to increasing *F*s which would seem counter-intuitive. The explanation is that TACs in this strategy are set based on projections of stock size in the year after the XSA assessment is done. Shrinkage of *F* in the XSA leads to an underestimation of an increasing stock and conversely an overestimation of a declining stock. The stock declines in the initial simulation period, but because the TAC is based on the perceived view which shows less decline, the actual *F* inflicted on the stock is higher. In reality, the combination of the XSA perception of the stock, shrinkage within the XSA and the two year lag between data (up to year y-1 used to fit the model) and the setting of the TAC (based on projections to year y+1) renders the implementation of *F*-based strategies somewhat problematical. For example, in the case of the FCMod strategy, the perceived view of the stock (i.e. the XSA estimate of exploitable biomass for each year) is slightly higher than the true population in the short term because shrinkage of *F* results in a lower estimated *F* in from the assessment model than actually occurs in reality in the first few years. This leads to higher TAC being set than the HCR would specify if the true population was known without error. In contrast, the PA replicates have a much tighter distribution. The perceived view, which exaggerates the fluctuations in the true population, initially underestimates stock size, resulting in very low catches in the short term. This allows the stock to recover rapidly and in turn leads to increased catch. The impact of shrinkage and the lag effect in assessments appear to be important aspects worthy of further consideration in the context of MSE.

Risk tolerance performance statistics are summarized in Table 1. The four "satisficing" performance statistics considered are AAV%, $B/B_{recov}$, $B/B_{msy}$ and $F/F_{msy}$. For each performance statistic, the tolerance level is given as well as the acceptable risk associated with it (probability of achieving the tolerance level). The performance statistics values given for each MS under each OM are the values from the stochastic simulations that correspond to the risk level required. If these values meet or exceed the tolerance level requirements, the strategy is considered to be successful and is denoted in bold. There are 2 short term (2010), 3 rebuilding plan/medium term (2019) and 4 long term (2030) "satisficing" requirements. In the totals columns, the percentage of these targets that are met is given. The last column gives the overall "satisficing" percentage score for each MS across both OMs. Ideally, a strategy would be considered adequate if it met all of the risk tolerances (i.e. 100% score) across all of the OMs.

Although none of the management strategies achieve a 100% score, FCMod and ModFree strategies score the highest (78%). They meet all of the AAV requirements. These strategies also lower *F* below the FMSY level. But, while they achieve the stock rebuilding targets in OM 4, they fail to meet the recovery targets at any stage under OM 2. The PA and HalfF01 strategies score the next highest (61% and 67%, respectively). These two strategies have lower scores because of high AAV values over all terms. However, they are the most successful strategies in terms of stock rebuilding, with HalfF01 being the only strategy that meets all the risk tolerances over both OMs. With a low score of 22%, Fsq is clearly a poor strategy by any account.

Box and whiskers plots for the "satisficing" performance statistics for the five MSs under each of the two OMs are shown in Figs. 3-5, corresponding to short, medium and long term. In the short term (2010, Fig 3) there is very little difference between OMs. AAV in Catch is only high for the PA and HalfF01 strategies as these two produce a substantial initial decrease in *F* and hence catch. The quicker recovery observed under OM 4 (Fig. 2) is evident, with respect to all MSs except Fsq, exceeding the rebuilding target by 2019.

Because of the higher catches in the short term, the Fsq strategy eventually leads to a stock collapse and hence the reduction in Recov. Ratio and B/Bmsy as well as the considerable reduction in catch seen in the long term. Fishing mortality under the Fsq is the highest compared to Fmsy. Only the HalfF01 and PA strategies lead to substantial rebuilding in stock size in the long term under OM 2. While both achieve a B/Bmsy ratio of greater than 1, only HalfF01 achieves the rebuilding target by the end of the rebuilding plan under both OMs. While the ModFree and FCMod strategies are unlikely to collapse the stock by keeping catches high, neither lead to any real recovery of the stock either. Recov. Ratio and B/Bmsy show similar patterns as would be expected. However, OM 4 has greater Bmsy levels and hence more recovery is required for stocks to reach Bmsy in these OMs.

The Fsq strategy is clearly not a viable way to manage this stock although it has often been resorted to by NAFO FC as a default strategy. It fails to achieve the rebuilding target, long term sustainability is not achieved and, ultimately, it leads to large annual reductions in TAC. Both the model-free and FC model-based results have varied results. While the concept of MSE is relatively new to NAFO, experience elsewhere has indicated that model-free management strategies may have a higher degree of acceptability to fisheries managers and industry than those based estimates from models and may perform as well or better than model based strategies (Butterworth, in press). Increased acceptability is mainly related to simplicity and transparency. However, this current analysis shows that the large amount of observation error associated with the Greenland halibut stock translates into variability in possible recovery outcomes. The FCMod strategy, which is based on the XSA perception of stock which has a large amount of associated error, also leads to considerable variability in outcomes. In the case of the FCMod strategy, this is exacerbated by the less frequent adjusting of TACs (i.e. adding to the reaction lag) in this strategy, hence the even broader range of possible outcomes. The failure of these two strategies to allow reasonably recovery of the stock under OM 2 in both the rebuilding plan period and the longer term, albeit primarily due to error in the perception of the stock, deems them unsuitable for the management of the stock, despite the consistency in TAC they allow from year to year.

None of the strategies are 100% adequate according to the risk tolerance criteria set down. It is therefore necessary to look at trade-offs in performance statistics associated with each strategy across both OMs for the three time horizons to assess which strategies might be more preferable (Figs. 6 and 7). Fsq can be ruled out at this stage. ModFree and FCMod strategies maintain similar average catch levels and keep AAV relatively low, particularly for the FCMod strategy which only changes the TAC every two years. The PA and HalfF01 strategies produce increasingly higher levels of catch as the stock recovers, with the PA strategy having the greatest Avg Catch over all three time periods. This however coincides with a high AAV in catch, particularly for the HalfF01 strategy (due to initial large decreases in TAC and subsequent large increases in TAC as the stock recovers). In the present evaluation, only HalfF01 and PA strategies achieved the desired exploitable biomass target level by the end of the rebuilding plan in both OMs, although FCMod results just makes it to a median Recov. Ratio of 1 in the longer term. While none of the strategies are entirely adequate, decision makers might find the trajectories of the stock in phase space, as indicated by the arrows, useful. In this sense, a strategy that is heading the stock in the right direction with respect to a performance statistic is more desirable than an strategy that is having the reverse effect.

The mean age of the catch (Fig. 7) can have important economic implications if size-based pricing exists. Mean age fluctuates more under low *F* strategies than observed in the past.

Not surprisingly, the average age caught increases most in OM 4, where the lower *M* leads to greater survival to the older ages. In OM 2, mean age remains between 6 and 9 years, covering the peak selectivity of the fishery but below the age of 50% maturation.

The example application given here is considerably circumscribed relative to the full MSE for Greenland halibut proposed in Miller *et al*. (2008). The intention for the full analysis is to create a flat file with performance statistics percentiles for the three time horizons, short, medium and long-term for all OM-MS combinations. This file could then be perused using a simple R-script that would recognize whether the statistic is designated as a risk tolerance that has to be met or as a tradeoff statistic to be evaluated once an adequate subset of MSs have been arrived at. The script would return the MSs that are found to be adequate across all risk tolerances and then carry out the required tradeoff analysis.

## Conclusions

By evaluating MSs across multiple OMs the risk of choosing an MS that will, in reality, result in an adverse outcome is reduced. Although the outcome for only two OMs is explored here to illustrate the approach, it is clear that for this stock the considerable uncertainty that exists will make it difficult for decision makers to find an MS that is robust in terms of meeting the risk tolerances. The indication is that an acceptable MS would have to be quite conservative, similar to the HalfF01 strategy. Resolving the uncertainty around *M* and obtaining more or better survey indices in the future might reduce the uncertainty within the reference set of operating models and less conservative management strategies might then be shown to meet the risk tolerance criteria specified here. The reference set of OMs should thus be periodically updated as the scientific information improves in the future.

A number of descriptive statistics, allowing an understanding of the stock dynamics under different OM-MS combinations can be developed by scientists. However, performance criteria are largely the domain of the stakeholders, both the fishing industry and representatives of broader segments of society, such as ENGOs. This process needs to be informed by national and RFMO policies on sustainable fisheries, and guided by legally binding agreements such as UNFSA and voluntary undertakings such as the FAO Code of Conduct for Responsible Fisheries. We have suggested a range of both industry-focused and conservation-focused performance statistics based on input from industry, scientists and fisheries managers obtained through the Wiki and at the Vigo SG meeting. It is intended that ENGOs be informally engaged to provide feedback on whether or not additional performance statistics are desired to meet conservation objectives.

It should also be noted that the risk tolerance criteria that are specified in this paper are arbitrary and for example only. Further input from decision-makers will be required to decide on tolerance levels and risk. At present, a recovery ratio of >1 by 2019 and an annual average variation in TAC of <15% are the only rebuilding plan conditions that have been provided by FC. The current analysis indicated that it will be difficult to simultaneous achieve both. B/Bmsy and F/Fmsy have been added as additional performance statistics based on the need for fisheries management to meet the UNFSA criteria with respect to the PA.

In addition to obtaining more specific technical guidance from decision makers on tolerances, risks and tradeoffs, there is also the need to more broadly engage NAFO on whether or not it is prepared to replace the current largely *ad hoc* decision making approach with a prescribed management strategy approach incorporating a harvest control rule that has been demonstrated through MSE to perform adequately in terms of specified performance statistics. We consider that major selling points include the flexibility allowed FC to suggest alternative harvest control rules, define thresholds and risk tolerances and the opportunity to evaluate trade offs. There is also the considerable international caché that society would afforded the RFMO should it make the bold step of actually implementing sustainable fishery management practices rather than just talking about them. We are optimistic that sound reason will prevail.

## References


BUTTERWORTH, D.S. 2008. Why Fisheries Reference Points Miss the Point. *American Fisheries Society Symposium*. No. 49, vol. 1: 215-222.

BUTTERWORTH, D.S. (in press). Some lessons from implementing management procedures, in Fisheries for global welfare and environment, memorial book for the 5th World Fisheries Congress in Japan, October, 2008, Yokohama. TERRAPUB: Tokyo, Japan.

BUTTERWORTH, D.S. and A.E. PUNT. 1999. Experiences in the evaluation and implementation of management procedures. *ICES Journal of Marine Science*, **56**: 985–998.

BUTTERWORTH, D.S. and R.A. RADEMEYER. 2005. Sustainable management initiatives for the southern African hake fisheries over recent years. *Bulletin of Marine Science*, **76**: 287–319.

DARBY, C.D., W.R. BOWERING, and J.-C. MAHÉ. 2003. An Assessment of Stock Status of the Greenland Halibut Resource in NAFO Subarea 2 and Divisions 3KLMNO Based on Extended Survivors Analysis with Short and Medium-term projections of Future Stock Development. *NAFO SCR Doc*., No. 03/64, Ser. No. N4883.

GONZÁLEZ TRONCOSO, D., J.M. CASAS, and F. SABORIDO-REY. 2006. Results from bottom trawl survey on Flemish Cap of July-August 2005. *NAFO SCR Doc*., No. 16, Ser. No. N5231.

HEALEY, B.P. 2007. Greenland halibut (*Reinhardtius hippoglossoides*) in NAFO Subarea 2 and Divisions 3LKMNO: stock trends based on annual Canadian research vessel survey results during 1978-2006. *NAFO SCR Doc.*, No. 07/45, Ser. No. N 5397.

HEALEY, B.P. and J.-C. MAHÉ. 2005. An Assessment of Greenland Halibut in Subarea 2 + Divisions 3KLMNO, with Projections under the Fisheries Commission Rebuilding Plan. *NAFO SCR Doc.,* No. 05/63, Ser. No. N5149.

HEALEY, B.P. and J.-C. MAHÉ. 2006. An Assessment of Greenland Halibut (*Reinhardtius hippoglossoides*) in NAFO Subarea 2 and Divisions 3KLMNO. *NAFO SCR Doc.,* No. 06/51, Ser. No. N5281.

HEALEY, B.P. and J.-C. MAHÉ. 2007. An Assessment of Greenland Halibut (*Reinhardtius hippoglossoides*) in NAFO Subarea 2 and Divisions 3KLMNO. *NAFO SCR Doc.,* No. 07/53, Ser. No. N5405.

HILBORN, R. 2002. The Dark Side of Reference Points. *Bulletin of Marine Science*. **70**(2): 403-408.

ICES 1997. Report of the Comprehensive Fishery Evaluation Working Group (COMFIE). ICES CM 1997/Assess: 15.

IWC. 1989. Comprehensive assessment workshop on management procedures. In The Comprehensive Assessment of Whale Stocks: the Early Years. *Reports of the International Whaling Commission*, Special Issue, **11**: 29–44.

JENSEN, A..J. 1996. Beverton and Holt life history invariants result from optimal trade-off of reproduction and survival. *Can. J. Fish. Aquat. Sci.* **53**: 820-822.

KELL, L.T., I. MOSQUEIRA, P. GROSJEAN, J-M. FROMENTIN, D. GARCIA, R. HILLARY, E. JARDIM, S. MARDLE, M.A. PASTOORS, J.J. POOS, F. SCOTT and R.D. SCOTT. 2007. FLR: an open-source framework for the evaluation and development of management strategies. *ICES J. Mar. Sci.* **64**(4): 640-646.

MILLER, D.C.M. and P.A. SHELTON. 2007. A nonparametric bootstrap of the 2006 XSA assessment for Greenland Halibut (*Reinhardtius hippoglossoides*) in NAFO Subarea 2 + Divisions 3KLMNO using Fisheries Libraries in R (FLR). *NAFO SCR Doc*., No. 07/59, Ser. No. N5411.

MILLER, D.C.M., P.A. SHELTON, B.P. HEALEY, W.B. BRODIE, M.J. MORGAN, D.S. BUTTERWORTH, R. ALPOIM, D. GONZÁLEZ, F. GONZÁLEZ, C. FERNANDEZ, J. IANELLI, J-C. MAHÉ, I. MOSQUEIRA, R. SCOTT and A. VAZQUEZ. 2008. Management strategy evaluation for Greenland halibut (*Reinhardtius hippoglossoides*) in NAFO Subarea 2 and Divisions 3LKMNO. *NAFO SCR Doc*., No. 08/25, Ser. No. N5225.

MILLER, D.C.M., P.A. SHELTON, B.P. HEALEY, M.J. MORGAN and W.B. BRODIE. 2007. Management strategy evaluation for Greenland halibut (*Reinhardtius hippoglossoides*) in NAFO Subarea 2 and Divisions 3LKMNO. *NAFO SCR Doc*., No. 07/58, Ser. No. N5410.

MORGAN, M.J., P.A. SHELTON, D.C.M. MILLER and B.P. HEALEY. 2008. Is there any evidence of a stock recruit relationship for Greenland halibut in Subarea 2 + Div. 3KLMNO? *NAFO SCR Doc*., No. 08/46, Ser. No. N5548.

NAFO. 2004. Convention on Future Multilateral Cooperation in the Northwest Atlantic Fisheries. ISBN 0-9698167-1-5.

NAFO FC. 2003. NAFO Rebuilding Plan for the stock of Greenland Halibut in Subarea 2 and Divisions 3KLMNO. *NAFO FC Doc.*, No. 03/13, Ser. No. N4904.

NAFO FC. 2007. Fisheries Commission's Request For Scientific Advice On Management In 2009 Of Certain Stocks In Subareas 2, 3 and 4**.** *NAFO FC Doc.*, No. 06/21, Ser. No. N5448.

NAFO GC. 2007. Amendment to the Convention on Future Multilateral Cooperation in the Northwest Atlantic Fisheries (Annex 17). *NAFO GC Doc*., No. 07/04.

NAFO SC. 2008. Report of NAFO Scientific Council Study Group on Rebuilding Strategies for Greenland halibut. *NAFO SCS Doc*. No. 08/13, Ser. No N5518.

PLAGÁNYI, É. E., R.A. RADEMEYER, D.S. BUTTERWORTH, C.L. CUNNINGHAM and S.J. JOHNSTON. 2007. Making management procedures operational — innovations implemented in South Africa. *ICES Journal of Marine Science*, **64**: 626–632.

SHELTON, P.A. 2005a. Does the rebuilding plan for Greenland halibut in Subarea 2 and Divisions 3KLMNO have a scientific basis and is it on track? *NAFO SCR Doc*., No. 05/10, Ser. No. N5089.

SHELTON, P.A. 2005b. A PA-compliant rebuilding plan for Subarea 2+ Divisions 3KLMNO Greenland halibut based on the 2005 NAFO assessment. *NAFO SCR Doc*., No. 05/71, Ser. No. N5165.

SHELTON, P.A., P.M. MACE, W.B. BRODIE and J.-C. MAHÉ. 2003. A Proposal for a More Flexible Framework for Implementing the Precautionary Approach on NAFO Stocks. *NAFO SCR Doc.,* No. 03/58, Ser. No. N4876.

SHEPHERD, J. G. 1999. Extended survivors analysis: An improved method for the analysis of catch-at-age data and abundance indices *ICES J. Mar. Sci*., 56(5): 584-591.

Table 1. Risk tolerance performance statistics for the Greenland halibut 2J3KLMNO stock: values and risk limits in the short-, medium- and long-term. The performance statistics values given for each MS under each OM are the values from the stochastic simulations that correspond to the risk level required. If these values meet or exceed the tolerance level requirements, the strategy is considered to be adequate and is denoted in bold. In the totals columns, the percentage of these targets that are met is given. The last column gives the overall "satisficing" percentage score for each MS across both OMs. Ideally, a strategy would be considered adequate if it met all of the risk tolerances (i.e. 100% score) across all of the OMs. None of the strategies achieve this.

| | | Performance Statistic | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **AAV (%)** | | | ***B*/*B*$_{recov}$** | | ***B*/*B*$_{MSY}$** | ***F*/*F*$_{MSY}$** | | | **Total** | | | | |
| Term: | | ST | MT | LT | MT | LT | LT | ST | MT | LT | ST | MT | LT | All | |
| Tolerance: | | <15 | <15 | <15 | >1 | >1 | >1 | <1 | <1 | <1 | % | % | % | % | |
| Risk (*P*): | | 50% | 50% | 50% | 10% | 5% | 50% | 10% | 10% | 10% | (/2) | (/3) | (/4) | (/11) | |
| MS | OM | | | | | | | | | | | | | | |
| **Fsq** | 2 | **5.7** | 22.7 | 30.3 | 0 | 0 | 0 | 2.39 | 3.54 | 1.48 | 50 | 0 | 0 | 11 | **22%** |
| | 4 | **8.8** | 20 | 21.5 | 0.05 | 0.54 | 0.4 | 4.35 | **0.62** | **0.26** | 50 | 33 | 25 | 33 | |
| **ModFree** | 2 | **3.8** | **10** | **10.5** | 0.41 | 0.01 | 0.37 | **0.95** | **0.93** | **0.57** | 100 | 67 | 50 | 67 | **78%** |
| | 4 | **7.4** | **12.2** | **10.3** | **1.66** | **5.88** | **2.37** | 1.33 | **0.39** | **0.13** | 50 | 100 | 100 | 89 | |
| **PA** | 2 | 35.7 | 31.8 | 24 | 0.71 | **1.53** | **1.62** | **0.15** | **0.79** | **0.6** | 50 | 33 | 75 | 56 | **61%** |
| | 4 | 38.8 | 33.8 | 24.7 | **1.97** | **1.88** | **1.24** | **0.24** | **0.78** | **0.71** | 50 | 67 | 75 | 67 | |
| **FCMod** | 2 | **3** | **2.9** | **4.5** | 0.27 | 0 | 0.97 | **0.76** | **0.64** | **0.55** | 100 | 67 | 50 | 67 | **78%** |
| | 4 | **3** | **3.3** | **4.1** | **1.05** | **5.49** | **2.15** | 1.37 | **0.46** | **0.19** | 50 | 100 | 100 | 89 | |
| **HalfF01** | 2 | 46.6 | 74.3 | 46.3 | **1.24** | **2.57** | **2.69** | **0.05** | **0.42** | **0.21** | 50 | 67 | 75 | 67 | **67%** |
| | 4 | 50.2 | 85.2 | 50.1 | **2.95** | **6.36** | **2.41** | **0.07** | **0.44** | **0.2** | 50 | 67 | 75 | 67 | |

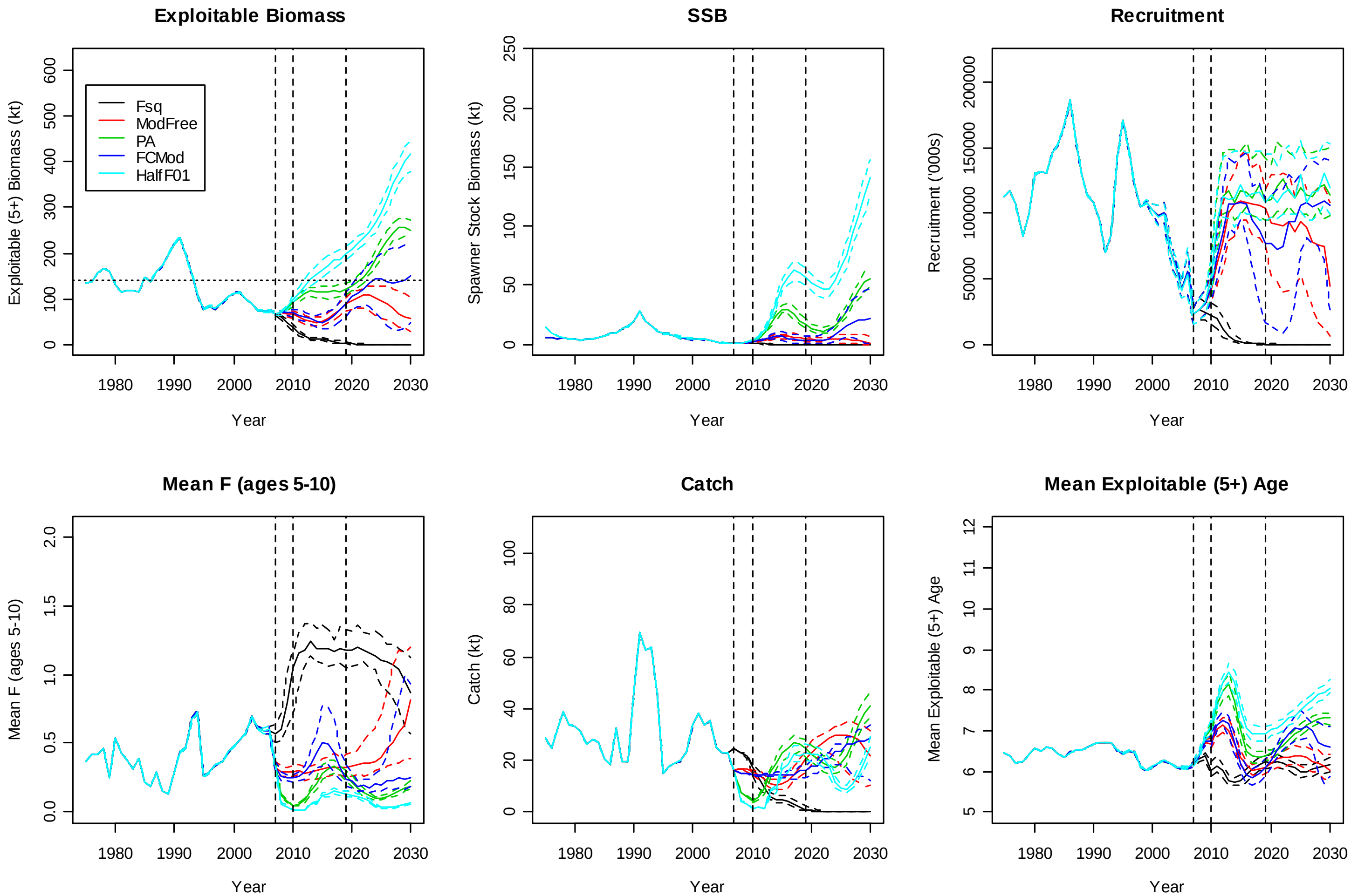


Fig. 1. Descriptive statistics from the stochastic simulations (100 runs) for the five Management Strategies under Operating Model 2 ($M$ = 0.2). Solid lines represent the median value, dashed lines show the 25 and 75 percentiles. Vertical broken lines represent the three time horizons of concern, short, medium and long term.

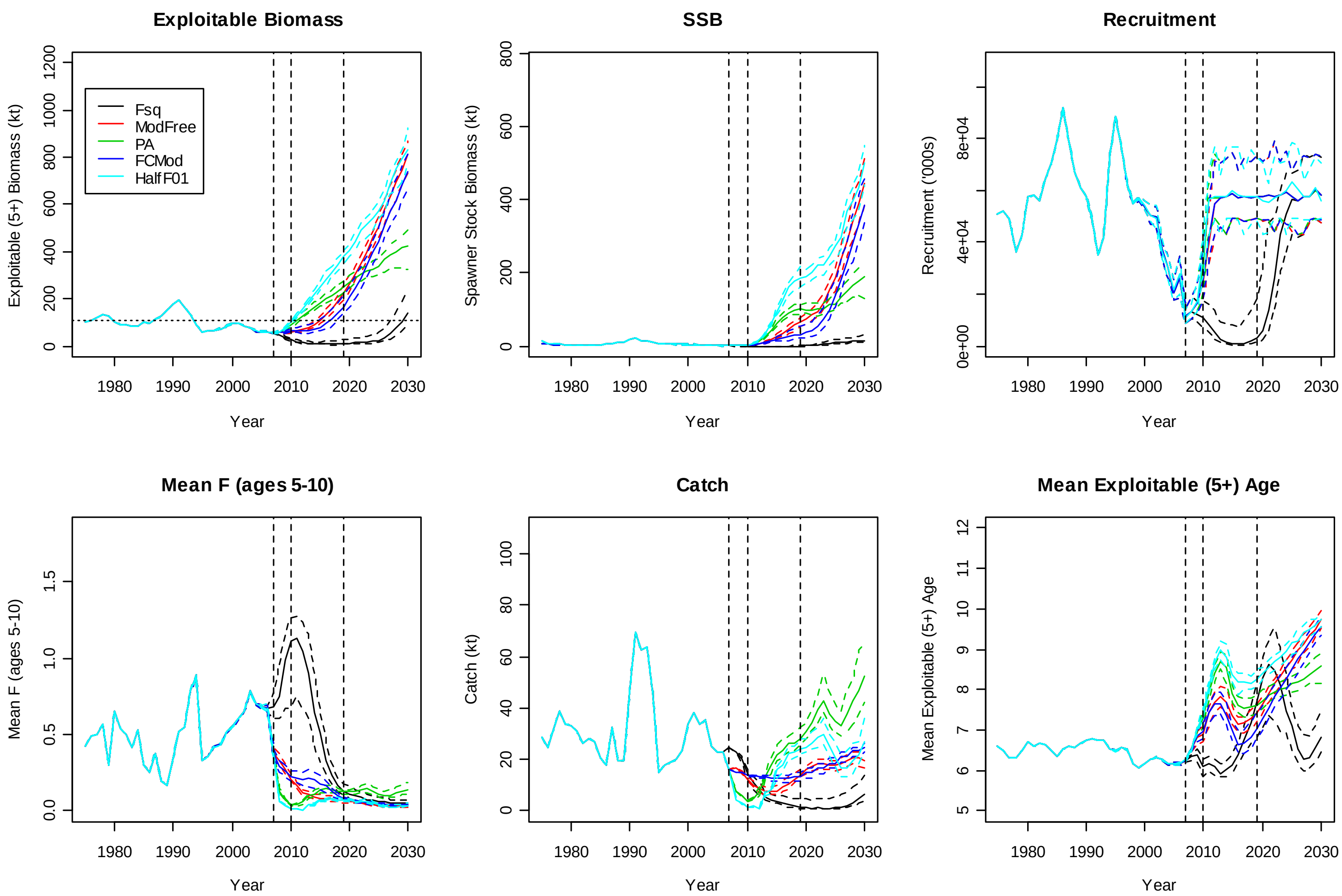


Fig. 2. Descriptive statistics from the stochastic simulations (100 runs) for the five Management Strategies under Operating Model 4 ($M$ = 0.1). Solid lines represent the median value, dashed lines show the 25 and 75 percentiles. Vertical broken lines represent the three time horizons of concern, short, medium and long term.

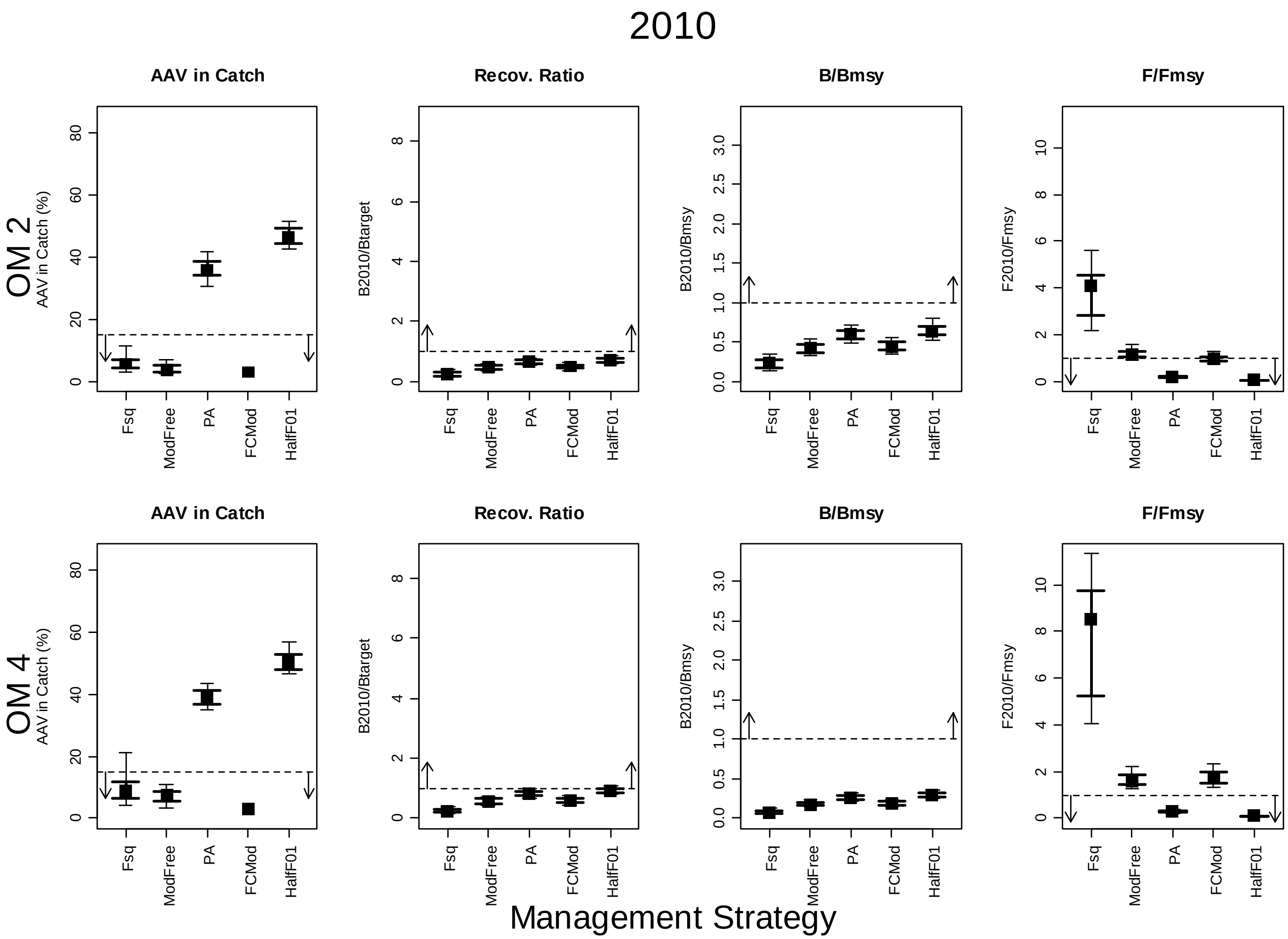


Fig. 3. Risk tolerance performance statistics for the five Management Strategies, short term – 2010. Boxes represent the medians and whiskers show the 5, 25, 75 and 95 percentiles. Horizontal broken lines indicate the desired tolerance level with arrows indicating whether it is desirable to be above or below this level.

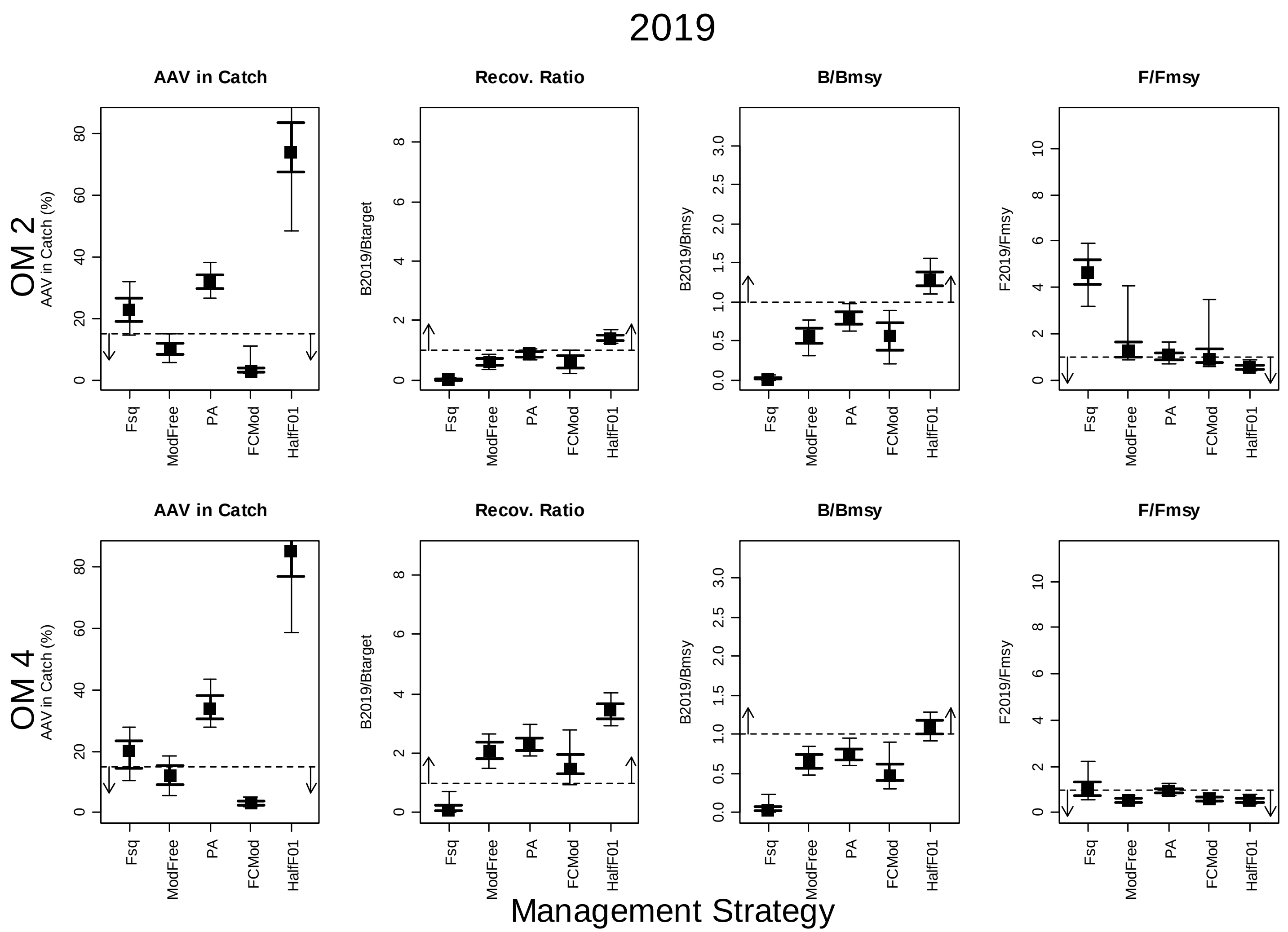


Fig. 4. Risk tolerance performance statistics for the five Management Strategies, rebuilding plan period – 2019. Boxes represent the medians and whiskers show the 5, 25, 75 and 95 percentiles. Horizontal broken lines indicate the desired tolerance level with arrows indicating whether it is desirable to be above or below this level.

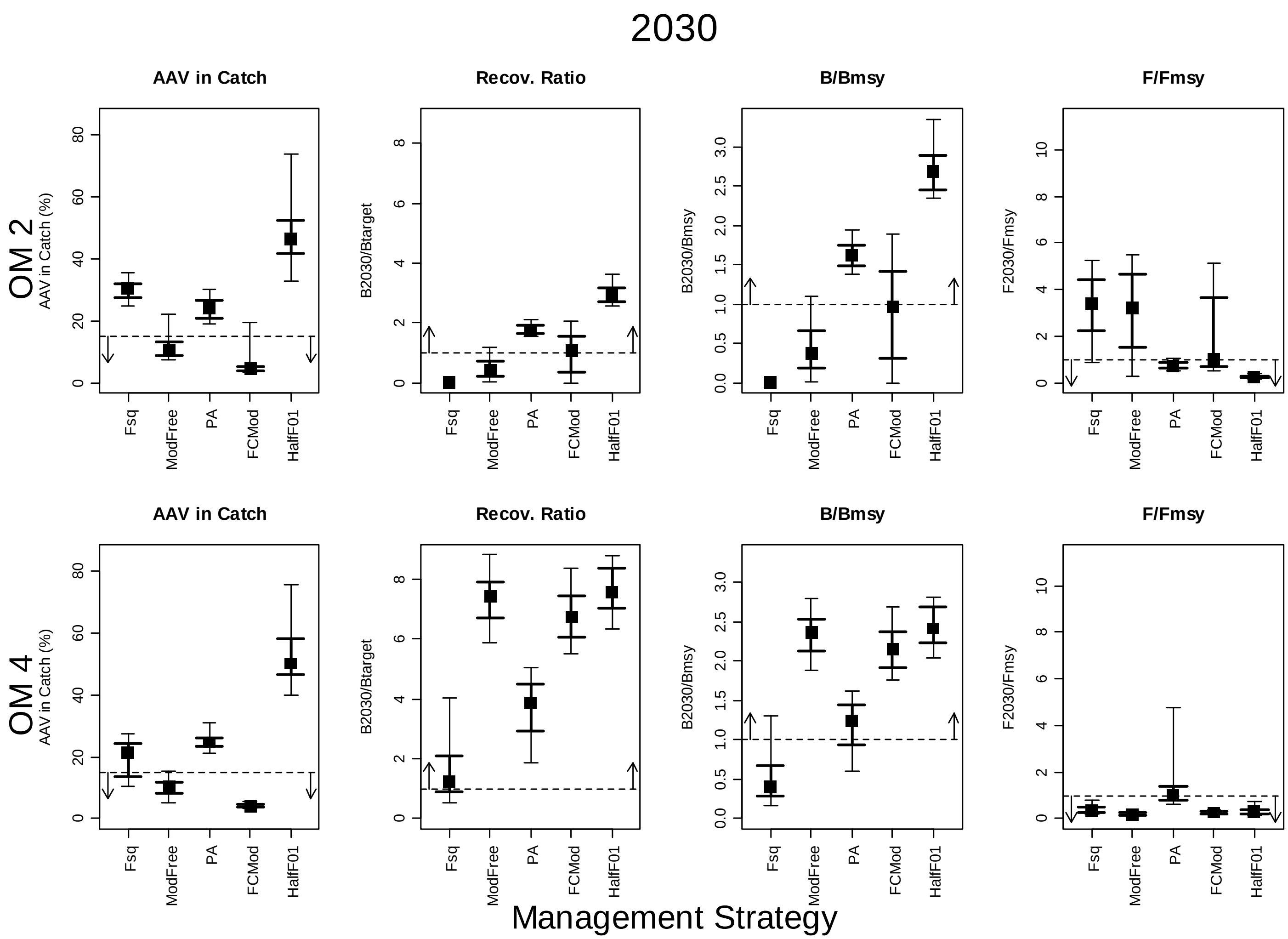


Fig. 5. Risk tolerance performance statistics for the five Management Strategies, long term – 2030. Boxes represent the medians and whiskers show the 5, 25, 75 and 95 percentiles. Horizontal broken lines indicate the desired tolerance level with arrows indicating whether it is desirable to be above or below this level.

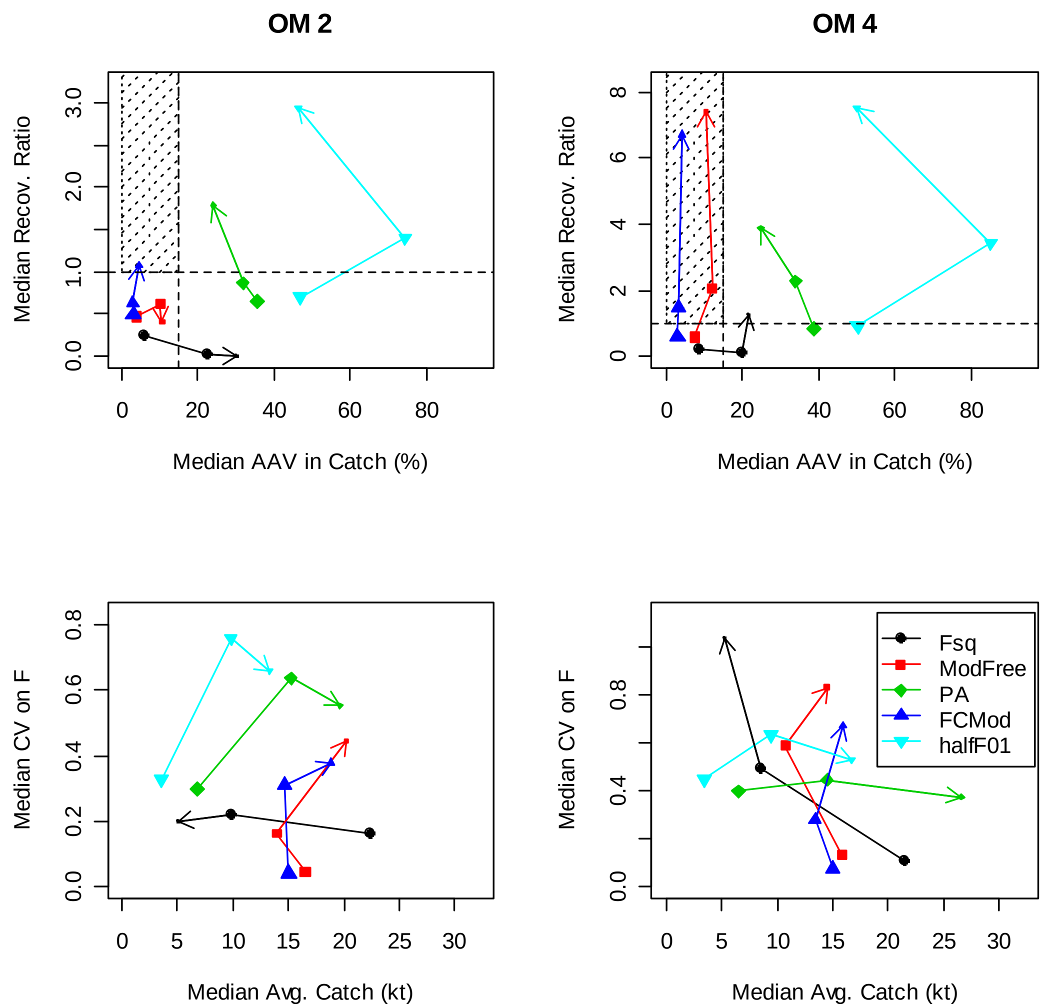


Fig. 6. Plots of performance statistics for examining trade offs among the 5 MSs under the two OMs. The lines join short, medium and long term outcomes with the arrows indicating the direction of the time sequence. The shaded area in the top panels indicates the desired medium term outcome reflected by the FC rebuilding plan.

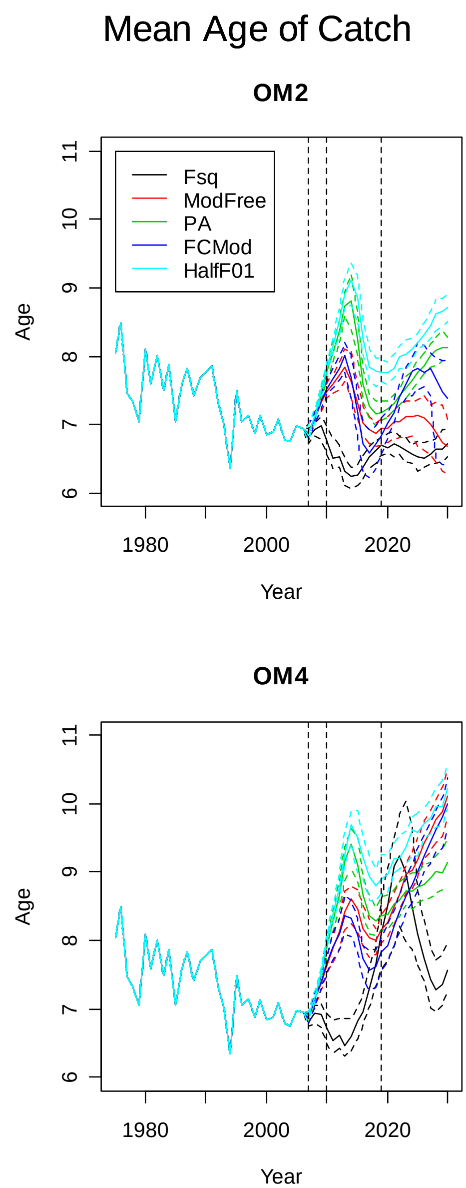


Fig. 7. Mean age of catch for the range of MSs under the two OMs.