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Robust management strategies for rebuilding and sustaining the NAFO Subarea 2 and Divs. 3KLMNO Greenland halibut fishery

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Abstract

Management Strategy Evaluation is applied to the Subarea 2+Divs. 3KLMNO Greenland halibut stock as an aid to decision-making by NAFO Fisheries Commission. Alternative management strategies are evaluated against a range of operating models reflecting alternative possible realities. A number of performance criteria were developed in order to quantify management objectives. Some of these are based on industry considerations with regard to catch and catch stability and others relate to the rebuilding, stock conservation and sustainability. Performance statistics were divided into two types - those that are imperative and require "satisficing", and those that are not imperative, but are useful in evaluating the trade offs. Robust feedback harvest control rules, either based on survey data directly or on the XSA, show the most promise. Two successful management strategies incorporating feedback harvest control rules are proposed for further consideration in the management of this stock.

Key words: management strategy evaluation, operating model, fisheries management, harvest control rules, management objectives, performance statistics, satisficing, trade offs, risk

Introduction

A three year study to develop and undertake a Management Strategy Evaluation (MSE) for Greenland halibut in NAFO Areas 2+3KLMNO was initiated in 2007. Preliminary analyses were presented at the June 2007 NAFO Scientific Council (SC) Meeting (Miller *et al.* 2007). Based on these preliminary findings SC considered the approach promising enough to strike a Study Group on Rebuilding Strategies for Greenland halibut (Chair: Bill Brodie, Canada) to further the development of an MSE for this stock. The study group met in Vigo, Spain February 21-23, 2008 to review progress on the Greenland halibut MSE and to provide guidance for further work. Participants included scientists, fisheries managers and industry from the NAFO community and three invited independent experts (Doug Butterworth, South Africa; Jim Ianelli, US; and Rob Scott, UK) funded by NAFO. A full report of the Vigo meeting is available (NAFO 2008). The Vigo meeting was preceded by online interactions and preparations among this group through the medium of a Wiki site. Following the Vigo meeting a multi-authored revised MSE report was prepared and presented to the June 2008 SC meeting incorporating a number of modifications proposed in the Vigo meeting (Miller *et al.* 2008). SC endorsed both the Vigo meeting report and the follow-up MSE work. The Chair of SC undertook to report on the progress of the Greenland halibut MSE to NAFO Fisheries Commission (FC) during presentation of scientific advice at the Annual Meeting in September

2008, and to seek an endorsement from FC to consider implementing this kind of approach in the future management of the stock.

The present research document describes further work carried out on the reference set of operation models. It then reviews the final list of management strategies (MSs) that are evaluated based on recommendations from fisheries managers and industry made at the Vigo workshop. The bulk of this document deals with reviewing the results from the MSE, translation of these results into performance statistics and a description of how performance statistics might be used in decision-making by FC. Although fully described in Miller *et al.* (2008), a detailed flow chart in included in Appendix 1 to illustrate the steps involved in the Greenland halibut MSE (Fig. A1.1). Appendix 1 also contains details of how to run the MSE R code. The code is available on request from the authors.

Modifications to the reference set of operating models

Some modifications to the reference set of operating models (OMs) described in Miller *et al.* (2008) have been carried out. Initially a reference set of 20 OMs were specified and the results from four of these are described in Miller *et al.* (2008). Certain OMs were removed to eliminate redundancy and others were added to examine alternative hypotheses. In the current version of the MSE, the reference set consists of 12 OMs, conditioned on the June 2008 XSA assessment (Healey and Mahé 2008). Eight of these OMs are considered for a full evaluation of MSE results:

CAV - Current Assessment View. *CAV* is most closely consistent with the current assessment model and is similar to *OM2* in Miller *et al.* (2008). Thus *M* is assumed to be 0.2 and the PR is assumed to be flat-topped. Recruitment is modeled by a segmented regression.
LMV - Lower *M* View. Same as *CAV* but it assumes *M*=0.1. This is considered to be more in keeping with the life history traits of Greenland halibut.
CAV_domed - *CAV*, PR declines for older ages. Same as *CAV* but partial recruitment to the fishery decreases exponentially after age 14, i.e. a domed PR.
CAV_varM - *CAV*, higher *M* for older ages. Same as *CAV* but *M* increases from the base level of 0.2 starting at age 10 and reaching 0.4 by age 14, after which it is constant. This is an attempt to account for the limited evidence of older fish in the surveys and catches compared to model estimates (cryptic biomass).
CAV_dep - *CAV*, Depleted Seg Reg. Same as *CAV* but instead of modeling recruitment with the best fit segmented regression, we constrained the segmented regression model to have a maximum recruitment equal to the maximum observed recruitment, and a slope that is the best fit (SS) line through the origin. This S-R mode would be consistent with a stock that has a large maximum recruitment and that has been severely recruitment-overfished.
LMV_dep - *LMV*, Depleted Seg Reg. Same as *CAV_dep* but with *M*=0.1.
CAV_mRic - *CAV*, Modified Ricker. Same as *CAV* but with a best fit Ricker stock-recruit model modified to decrease the amount of density dependence compared to a standard Ricker model fit to the data. See details below.
LMV_mRic - *LMV*, Modified Ricker. Same as *CAV_mRic* but with *M*=0.1.

CAV, *LMV*, *CAV_domed*, *CAV_dep* and *LMV_dep* correspond to operating models already described in Miller *et al.* (2008). The *CAV* OM is considered to be the base case OM, due to its close agreement with the currently accepted NAFO scientific assessment, and *LMV* is considered to be the next most logical alternative hypothesis regarding stock dynamics. For display purposes, most results are plotted from these two OMs (this has no bearing on the validity of the other OMs). Figures of equilibrium analysis results showing the biological characteristics and dynamics of the stock are presented in Appendix 3 for each of these eight operating models (Figs. A3.1-8).

It was recommended at the Vigo Study Group meeting that commercial CPUE be incorporated in the conditioning of one or more operating models to create a historical and current version of the stock more in line with industry perceptions. It was however pointed out that the Fall RV and EU survey data for commercial size fish shows a similar trend to commercial CPUE information. The attempt to create a more optimistic view of the stock by applying commercial CPUE as a tuning index in the XSA did not produce a great improvement in recent historical exploitable or spawner biomass (Miller *et al.* 2008). Further, no CPUE indices for the fishery have been accepted by NAFO SC. Based on these considerations and further discussion at the June 2008 SC meeting, operating models conditioned on commercial CPUE data have therefore been dropped from the reference set.

CAV and *LMV* were modified to include implementation error to examine the impact of the large TAC overrun that is occurring. Currently this is set as a random uniform distribution between 10% and 40% TAC overrun:

CAV_IE - Current assessment view with implementation error. Same as *CAV* but includes implementation error.

LMV_IE - Lower *M* View with implementation error. Same as *LMV* but includes implementation error.

Implementation error models do not represent different OMs and should not be used in the evaluation of performance statistics for alternative MSs. Implementation error may mask the relative merits of alternative management strategies and these OMs should only be used to assess the dangers of overrunning TACs by comparing results to the corresponding OM not including implementation error. It should be noted that managers could take implementation error into account by setting TACs lower than those prescribed by particular management strategy.

Two OMs using best-fit Ricker stock recruit models were run:

CAV_ric - *CAV*, Ricker. Same as *CAV* but with a best fit Ricker stock-recruit model rather than a segmented regression.

LMV_ric - *LMV*, Ricker. Same as *CAV_ric* but with M=0.1.

These models lead to recruitment at B_0 being very low as a result of strong compensation, causing extreme fluctuations at high stock size as a result of strong compensation in the Ricker stock recruit model. To counteract this effect, modified Ricker stock-recruit models, *CAV_mRic* and *LMV_mRic* were introduced in which recruitment at high stock size does not decline below a specified level. The Modified Ricker curve sets a minimum recruitment level to the right of the peak recruitment (Rec_0). The value of 20% recruitment at F=0 ($20\%Rec_0$) is calculated from the original Ricker curve. Then by assuming a new steepness value (h), and fixing $20\%Rec_0$, the new Rec_0 value can be calculated as $20\%Rec_0/h$. In this way the Ricker parameters remain the same (importantly the slope at the origin) but the decrease in recruitment with increasing SSB is limited. Values for x can reasonably range from three to five. In this case a value of 3.4 is used.

Provision is made for the weighting of OMs for in the reference set. However, given that OMs should only be included within the reference set if they are considered to be a viable representation of stock dynamics and status, a base-case scenario of equal weightings for all OMs is used in the current analysis.

Modifications to set of management strategies

Seven candidate Management Strategies (MSs) are considered, some of which are modified from those presented in Miller *et al.* (2008). All of the strategies considered in this MSE set Total Allowable Catches (TACs) for year y+1, in year y, using data up to year y-1 (as is done in practice). To implement strategies which are F-based, the stock is projected forward to the beginning of year y+1 using available data including the TAC set in year y. The F value for year y+1 is then converted to a TAC using the projected numbers at age at the beginning of year $y+1$ and three-year geometric means of commercial selectivity (PR) and weight at age for y-1 to y-3. For both deterministic and stochastic simulations, the TAC is caught exactly (excluding the implementation error runs), unless there is not enough exploitable biomass to support such a TAC, in which case an F_{cap} value of 1.73 is applied (this equates to approximately 85% of available fish being caught). A minimum catch of 2 kt is set for all strategies.

To illustrate a range of potential strategies and how they can be assessed using MSE, seven management strategies were applied in stochastic analyses:

CC_16 - Constant Catch (16kt)
This strategy incorporates no feedback, setting a TAC of 16kt every year regardless of stock size or indices. This strategy is consistent with recent FC decisions not to lower the TAC below 16kt despite the current low perceived

stock levels and continued TAC overruns in recent years. This MS is considered as the base case MS for presenting differences between OMs.

Fsq - F status quo strategy
This is an *F*-based strategy. 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 as a consequence of error in the stochastic model. Given the current high level of *F*, this is a heavy fishing strategy.

hF01 - Half $F_{0.1}$ strategy
Under this fixed *F* strategy, fishing mortality is immediately reduced to half of $F_{0.1}$ and retained at this level.

PA - Precautionary Approach style strategy
This is a variable *F*-based strategy. It constitutes a simplified PA implementation based on the breakpoint in segmented regression as a reference point. In this case, the value of *F* is determined depending on how current SSB relates to the estimated (not the true) *beta* (β), the breakpoint in the segmented regression curve:

$$F_{y+1} = \begin{cases} 0.5 \times F_{0.1} & if \quad SSB_{y+1} \leq \dfrac{\beta}{2} \\ \dfrac{SSB_{y+1}}{\beta} \times F_{0.1} & if \quad \dfrac{\beta}{2} < SSB_{y+1} \leq \beta \\ F_{0.1} & if \quad \beta < SSB_{y+1} \end{cases} \tag{1}$$

modFree - Model-free, index-based TAC adjustment strategy
This is a variable TAC-based strategy. It constitutes a simple TAC adjustment strategy that uses the change in perceived status of the stock (from research surveys) to adjust the TAC according to:

$$TAC_{y+1} = TAC_y \times \left(1 + \lambda \times slope\right) \tag{2}$$

Where:

slope = unweighted average slope of log-linear regression lines fit to the last five years of each index (all ages combined), i.e. *y*-5 to *y*-1

λ = an adjustment variable for the relative change in TAC to the perceived change in stock size

Various λ values were examined in deterministic simulations and a value of 1.25 was selected in the case of a declining stock (allows for adequate adjustment of the TAC without having excessively large fluctuations from year to year) and a value of 1 in the case of an increasing stock. $\lambda > 1$ is required in the case of a perceived decline in stock size (*slope*<0) but this value of λ could hamper stock recovery in the case of a perceived increase in stock size (*slope*>0). A variable λ approach with $\lambda<1$ when *slope*>0 will allow for more rapid recovery of the stock.

rbPlan - Model-based TAC adjustment strategy
This strategy was designed to address some of the aspects of 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:

a) *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 years TAC – done automatically in the XSA).
b) λ =1.5 for *slope*<1 and λ =1 for *slope*>1. A larger value of λ is used in this strategy compared to the *modFree* strategy because adjustments to the TAC are made less regularly.
c) TAC adjustments from 2008 onwards are constrained to be ≤15% from *y* to *y*+1
d) TACs are only adjusted every second year.

Note that, while this strategy attempts to address some of the aspects of the FC rebuilding plan, the current FC plan specifies arbitrary *ad hoc* TAC setting and does not specify a feedback harvest control rule of the kind explored here.

Bfrac - Biomass fraction TAC adjustment strategy
For this strategy TAC_{y+1} is set based on TAC_y from the previous year and the perceived exploitable biomass for the beginning of the fishing year B_{y+1}:

$$TAC_{y+1} = (1-\lambda)\mu B_{y+1} + \lambda TAC_y \qquad (3)$$

Where:

B_{y+1} = the projected exploitable (5+) biomass for the start of year y+1
μ = the proportion of B_{y+1} used to adjust the TAC
λ = a stabilising parameter (between 0 and 1) for the change in TAC

A μ value of 0.15 was chosen by examining the ratio of yield to equilibrium biomass at F_{MSY} (~20%) and $F_{0.1}$ (~12%). The higher the value of λ, the greater the stability in TAC from year to year (λ=1 implies no change, λ=0 implies fully dependent on the perceived biomass level). A λ value of 0.5 was chosen (equal weighting to perceived biomass and previous TAC). Note that under this approach it would be equally valid to apply an alternative MS based on an average biomass value over a number of previous years.

A number of other "rebuilding plan" strategies were also considered (see Miller *et al*. 2008). These were designed to get the population to reach the rebuilding plan target or an equilibrium at the target within a specific period of time. However, technical difficulties with the versions of R and FLR libraries being run have hampered the successful implementation of these strategies thus far. Further work should be considered to address these kinds of strategies.

Performance statistics

Performance Statistics (PSs) are a quantification of the management objectives for the fishery. They can be used to evaluate how well a particular management strategy is performing relative to other candidate strategies across a range of conservation and fishery related performance measures. Within an MSE, application of an MS is repeated many times over the management time horizon in order to explore the impact of the various sources of uncertainty included in the operating model and hence to generate distributions of values for each performance statistic. Management strategies that are robust to uncertainties are preferred because of their generally higher performance across the reference set of operating models. Performance statistics need to address both fishery related objectives and those that are stock-conservation related.

We divide performance statistics into two kinds – "satisficing" statistics that address imperative performance measures and "trade-off" statistics that address important but not necessarily imperative measures of performance. "Satisficing" (a portmanteau of "satisfy" and "suffice") is defined as follows[1]:

> *"A decision-making strategy which attempts to meet criteria for adequacy, rather than to identify an optimal solution. A satisficing strategy may often be (near) optimal if the costs of the decision-making process itself, such as the cost of obtaining complete information, are considered in the outcome calculus."*

Satisficing statistics identify required thresholds and associated risks that have to be met for an MS to be considered to be adequate. These are usually critical criteria, and failure to meet these targets is considered to be detrimental to the viability of the fishery. Those MSs that pass this first level of performance evaluation can be subject to further evaluation of the trade-offs between the different performance statistics across MSs when applied to the range of OMs. Some satisficing performance statistics may perform a dual role in terms of being used as trade-off statistics as well. Decision-makers have considerable flexibility in terms of specifying the threshold levels and acceptable risks for satisficing statistics and in using judgment when considering which trade-

[1] "Satisficing," in *Wikipedia: The Free Encyclopedia*; (Wikimedia Foundation Inc., updated August 2008) [encyclopedia on-line]; available from http://en.wikipedia.org/wiki/Satisficing; Internet; retrieved 12 June 2009.

offs are more acceptable than others. 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. Also, higher average catch will trade off against low annual average variation in catch. We considered three terms over which to evaluate performance statistics: short (3 years) medium (to 2019) and long term (to 2030).

It is important to recognize that in the MSE approach taken here, the Precautionary Approach reference points required under the NAFO PA framework, B_{buf}, B_{lim} and F_{lim}, are considered in terms of performance statistics evaluated against the "true" simulated state of the stock relative to the "true" estimates of, for example, 80%B_{MSY}, 40%B_{MSY} and F_{MSY} respectively. Perceived PA reference points are therefore not estimated from the simulated data to be used to trigger harvest control rules within the MSs, contrary to the traditional approach generally advocated in PA-based fisheries management.

In order to analyse the results of the MSE we set thresholds and acceptable risks for the satisficing statistics and choose percentile levels at which to evaluate trade-off statistics, depending on where we think the emphasis is likely to be. Thresholds, acceptable risks and percentile choices are all open for alteration by decision-makers and could form the basis for a structured discussion and negotiation process.

Satisficing statistics
Seven satisficing PSs were chosen for the Greenland halibut MSE analysis: one fishery stability related PS, one catch related PS and five resource conservation/rebuilding related PSs. The details of these PSs, including type (see Punt *et al.* 2005), terms, thresholds, allowable risks and weightings are presented in Table 1. If a satisficing condition is met (i.e. a performance statistic threshold achieved within the allowable risk level), it is said to be "satisficed".

Under fishery stability, annual average variation (year-on-year) in catch (AAV) was emphasised as an imperative fishing performance statistic by industry at the 2008 Vigo workshop. Industry felt strongly that AAV should have a threshold of <0.15 with an allowable risk of this not being met of 50% in the short, medium and long-term. A higher AAV threshold or a higher risk would severely impact industry operations. Under catch, it was considered imperative to ensure that the minimum catch since the inception of the MS should be greater than a threshold 3kt (a catch below this would likely lead to the economic extinction of the fishery) with an allowable risk of this not being met of 15%. This would allow a bycatch of Greenland halibut in fisheries directed at other species. With respect to resource considerations, four performance statistics are considered imperative related to internationally accepted target and limit reference points under the Precautionary Approach and the United Nations Fish Stocks Agreement, FAO Code of Conduct for Responsible Fisheries and the FAO Guidelines or the Precautionary Approach (Shelton and Sinclair 2008). The threshold of the ratio of current 5+ biomass to biomass at MSY was set at >1 for the long-term and the acceptable risk of this not occurring was chosen as 50%. This reflects the PA requirement to rebuild the stock to B_{MSY} in the long term and then have it fluctuate at this level. The threshold for the ratio of current 5+ biomass to 40% of B_{MSY} was set at >1 for the long-term with an acceptable risk of this not occurring of 5%. This reflects the requirement that there should be a low risk of the biomass falling below the limit reference point. The threshold of the ratio of current fishing mortality to the fishing mortality at MSY was set as <1.2 in the medium-term and <1 in the long-term, in both terms with an acceptable risk of 25%. This gives a step-wise requirement for reducing fishing mortality and reflects the PA requirement that F_{MSY} should be considered a minimum standard for the fishing mortality limit reference point. The risk level of 25% reflects somewhat more flexibility than that associated with the biomass limit reference point risk (5% in the long-term) given that F may exceed F_{MSY} on a healthy stock for a couple of years without serious impact. In addition to the ratio of the F to F_{MSY} measured at the end of the medium and long-terms, the ratio of the average F to F_{MSY} since the inception of the MS for both medium and long-terms was considered to be a further imperative PS to be satisficed. This gives additional emphasis to what has occurred over the time period rather than just at the end of the period. Thresholds of <1.2 for the medium term and <1 for the long-term were adopted for the average F to F_{MSY} ratio since the inception with acceptable risk levels of 25% in both cases. In addition to PA reference points, NAFO FC has specified a rebuilding plan target of 140kt exploitable (5+) biomass by the beginning of 2019 under the current assessment and this target, in a relative sense (i.e. will change depending on the OM), was also considered imperative. The performance statistic adopted is the ratio of current exploitable biomass to the target. A threshold of greater than 0.8 and an allowable risk of 50% were considered acceptable for the medium-term and a threshold of greater than 1 and a risk of 25% were considered for the long-term.

For any given term, satisficing PSs have a threshold value and an associated risk level (percentage chance of failure). Each MS is allocated a satisficing "score" according to its performance across all satisficing PSs for each OM, as well as a total score for the whole reference set of OMs. The score is calculated as the percentage of thresholds met within the allowable risk level. An adequate ("successful") MS will achieve a score of 100% for each OM in the reference set, and therefore 100% overall. Sub-scores can also be calculated as the percentage success for each individual type or term. In addition to the total score, the "raw" satisficing results can be presented in two ways: as the actual PS values for the MS at the given risk level (i.e. the value at the percentile corresponding to the risk level) or as the percentile of the MS that corresponds to the given threshold (i.e. the probability of failing to meet the threshold). In the case of the former, if the value is greater or less than (depending on the preference) the threshold, the MS can be adjudged to have passed or failed the satisficing criteria. In the case of the later, if the associated risk is less than the allowable risk, the MS is deemed to have passed the satisficing criteria. Given that a successful management strategy would need to achieve the thresholds set by all satisficing PSs, weightings for satisficing performance statistics is not advised although there is provision to do this in the MSE code. In the situation where none of the MSs satisfice all the imperative PSs that have been specified, it would be necessary for fisheries managers to consider revising the MSs or if necessary, reassess the feasibility of their objectives. In the case of failure, examining the satisficing scores by type or term would be useful for assessing the areas of weakness and may be useful in order to re-tune or revise an MS to make it adequate or to change the objectives.

Trade-off statistics

Fourteen trade-off performance statistics were selected, with some of the satisficing statistics doing "double-duty" as both trade-off statistics and satisficing statistics. The details of these PSs, including terms, percentiles examined, preferred values and PS weightings are presented in Table 2. In some instances, two percentile values of interest are identified. For example, it was considered that both the median and the 10th percentile of the ratio of biomass to the biomass at MSY (B:Bmsy) is of interest in the long-term. The logic being that the center of the distribution should be high, but it is also important that the lower tail of the distribution should be high as well. For the medium-term, the lower percentile of interest for B:Bmsy is set at the 5th percentile, reflecting greater tolerance for the probability of low biomass in the initial rebuilding period. For average catch (avgCatch), three percentiles are identified, 5% ("guaranteed"), 50% (expected), 95% (potential). A target (preferred value) is set for each performance statistic. In addition to this a "preference" is specified for the preferred position in relation to the target. "Low" implies a value as low as possible without being less than the specified target, whereas "high" implies a value as high as possible without exceeding the target (a target of infinity equates to "the higher the better").

A number of the trade-off performance statistics are considered relevant to both resource and catch outcomes. For example, the ratio of fishing mortality to the fishing mortality at MSY ($F:F_{MSY}$) has relevance in terms of the resource – whether or not overfishing is taking place, as well as relevance in terms of catch – low ratio should imply high catch rates and the need to utilize less effort for the same amount of catch, thereby increasing the profitability of the fishery. Note that the same performance statistic can have what appears to be contradictory impact on the evaluation, depending on whether it is being examined in the context of the resource or the catch. For example, the ratio of the catch to the maximum sustainable yield (C:MSY), if low is good for the resource, but if high is good in terms of the benefit to the fishery.

Selection of trade-off performance statistics, the terms over which they are to be evaluated, the percentiles of interest, the preference for a low or high value, the target for this value and the weight assigned to each statistic, are all open for alteration by as part of the decision-making process. However, it is important that this be carried out in an objective manner *a priori*, rather than manipulated iteratively to achieve a particular outcome. For trade-offs, weightings should reflect priorities for the management of the stock. In the absence of clearly specified management objectives, in the current evaluation values were selected such that resource specific PSs had the same weighting as the fishery stability and catch PSs combined (a "base-case" scenario for weightings). Weightings cover the range of 0.2 (low) to 1.5 (high). For resource PSs, greater weighting is given to long term performance, while stability and catch PSs weightings are spread more evenly across all time horizons. Weightings for the trade-off statistics over the three time periods are summarized in Table 3.

Trade-off scores were calculated for each MS according to PSs performance across all OMs in the reference set. Scores are calculated as follows for each trade-off PS:

1. For trade off PSs with specific target values (e.g. a value of 1, instead of "as low/high as possible"), an MS gets a score of 1 if it meets or exceeds the target.
2. Unless all MSs meet or exceed the target, the poorest performing MS is allocated a score of 0.
3. The "best" performing MS allocated a score of 1.
4. The remaining MSs receive scores ranging from 0 to 1 according to where their PS value lie within the range from "worst" to "best"/target

$$TOscore_{ms,ps} = \begin{cases} 1 & if \quad PS_{ms} \succ PS_{tar} \\ 1 & if \quad PS_{ms} = \max(PS_{RS}) \\ 0 & if \quad PS_{ms} = \min(PS_{RS}) \\ \dfrac{PS_{ms}}{range(PS_{RS})} & otherwise \end{cases} \tag{4}$$

Where:

$TOscore_{ms,\,ps}$ = the trade off score of MS *ms* for PS *ps*
PS_{ms} = the PS value for MS *ms*
PS_{RS} = the set of PS values for all MSs across the reference set of OMs
$\succ PS_{tar}$ = the PS value meets or exceeds the requirements of the PS target
$range(PS_{RS}) = \min[\max(PS_{RS})\text{-}\min(PS_{RS}),\ abs(\max(PS_{RS})\text{-}PS_{tar}) \vee abs(PS_{tar}\text{-}\min(PS_{RS}))]$
(note: $\vee$ denotes "or")

The total score is then calculated as the weighted average of the scores for each PS.

These scores reflect the relative performance of an MS in relation to the other MSs and range from a value of 0 ("worse" than every other MS for every trade off PS) to 1 ("better" than every other MS for every trade off PS). Because these are relative scores, an MS may have a different score depending on which set of MSs are being compared. The MS that gets the highest score is considered most acceptable MS out of the candidates being considered according to the *a priori* selection of trade off PSs, specification of targets and the importance placed on each PS (weighting).

Descriptive statistics

In addition to satisficing and trade-off statistics, a number of descriptive statistics may be useful: exploitable (5+) biomass, Spawner Stock Biomass (SSB), recruitment, fishing mortality (*F*) and total catch. In addition, the mean age of fish older than 5 (exploitable biomass, to eliminate the effect of recruitment fluctuation on mean age calculations) was also calculated. Descriptive statistics can be useful in understanding the behaviors of the alternative OMs under the same MS, for example in terms of potential rate of recovery, sensitivity to changes in TAC and *F* and stock-recruit dynamics.

Results

The range of alternative realities expressed by the set of OMs is demonstrated under the constant catch MS (*CC_16*) in Fig. 1. All scenarios yield a recovering stock in the long-term. The three lower *M* OMs, *LMV*, *LMV_mRic* and *LMV_dep*, increase rapidly to high levels, aided by quicker initial recovery. *LMV_dep* performs best because it has a higher maximum possible recruitment than the other lower *LMV* OMs. *CAV_mRic* shows rapid initial growth as a result of elevated recruitment, but this begins to level off after about 2020 as recruitment declines as a result of compensation. Differences in the maximum recruitment achieved under the different OM structures is considerable. The OMs with segmented regression stock-recruit relationships, and the *LMV_dep* OM, all reach achieve SSBs greater than β (the breakpoint in the curve, i.e. reach the recruitment plateau) within ten years and thereafter the mean recruitment remains around this level. The *CAV_dep* OM SSB takes longer to recover above *beta* due to slower initial recovery and a greater level of recovery required (α is less steep than that of the regular segmented regression stock recruit relationship and β is greater). Hence recruitment for this OM fluctuates more as slight changes in SSB shift the position of the stock up or down the slope of the segmented regression curve. Fishing mortality under the OMs showing recovery (the *LMV* OMs) drops to low levels by 2020. For the remaining OMs *F* fluctuates around a value of about 0.4 and the mean catch for these OMs drops slightly below 16kt. This is because a small proportion of the runs collapse the stock or decimate it enough such that a TAC of 16kt can not be fished. The projected mean age of the population increases notably for the *LMV* OMs and the *CAV_mRic* OM.

The satisficing scores for all the MSs are given in Table 4 by type and term for each OM and overall (see Tables A2.1 and A2.2 in Appendix 2 for more detailed value and risk level results). A score of 100 means that an MS achieved the defined threshold value at the allowable risk level for each satisficing statistic for the given term, type or overall. Figs. 2 and 3 display these results graphically for OMs *CAV* and *LMV*. For these plots an adequately performing MS would have values within the shaded areas, according to the allowable risk, for all PSs.

CC_16 performs surprisingly well, meeting all of the stability and short-term goals but failing to meet medium and long term catch and resource thresholds. *CC_16* meets the satisficing criteria under those OMs in which rebuilding is rapid as a result of assumptions regarding low *M* or high initial recruitment (i.e. *CAV_mRic*). However, this MS fails badly under the other OM scenarios in the medium and long term and an overall score of 68% means this is an inadequate management strategy for the stock. *Fsq* performs the poorest of all the MSs considered, only meeting two thirds of the stability criteria and none of the catch and resource goals, clearly not meeting the satisficing criteria across any of the OMs for an overall score of 20%. The *hF01* and *PA* MSs perform similarly, both failing to meet short term objectives but improving in the medium and long terms across most, but not all OMs. Neither, in particular *hF01*, meets the stability criteria required. Both perform poorer in terms of resource building on the *LMV* OMs, probably because *F* is estimated, and TAC calculated based on the current assessment that assumes a higher *M*. Hence these two MSs fail due to a lack of stability and robustness to uncertainty, mainly about *M* and its effect on stock dynamics. *Bfrac* is a fairly simple feedback control strategy and it might have been expected that it would perform better than it did. It failed to satisfy the stability requirements and had mixed results with regard to the resource requirements. It performed reasonably well with regards to three of the four *CAV* versions of the OM. It is possible that this MS could be tuned to perform better. By adjusting the value of λ, the stabilising parameter, the stability requirements could be met. However, to allow enough recovery of the stock, particularly in the *LMV* OMs, it is likely that a larger decrease in TAC would initially be required. The remaining MSs, *modFree* and <u>*rbPlan*</u>, meet all the satisficing criteria for all OMs and are therefore both adequate MSs worthy of further consideration in terms of performance with regard to trade-off statistics.

The descriptive results of the two adequate MSs on the *CAV* and *LMV* OMs are plotted in Figs. 4 and 5, respectively. Both have very similar trajectories: catch is lowered initially then starts to increase slowly after about 5 years (*rbPlan* eventually has higher catch), thereby significantly lowering *F* and allowing the stock to rebuild (and fish to reach older ages). The main difference between the two is a slightly greater decrease in catch initially under the *modFree* strategy that allows for a more rapid decline in *F* and hence greater recovery in the long term. When implementation error is included (Figs. 6, 7, 8 and 9) both MSs perform significantly worse. While collapse of the stock is prevented, recovery of the stock is significantly reduced. When implementation error is considered, the *modFree* MS performs better than the *rbPlan* MS, most likely because of the lower initial catches this MS sets, allowing for *F* to continue to decrease, while *F* remains high under the *rbPlan*. This suggests that the *modFree* MS is more robust to implementation error.

The trade off between catch and recovery is illustrated in Fig. 10. An initial reduction in catch is necessary for rebuilding (because these MSs pass the satisficing criteria this reduction is within acceptable range), but thereafter catch can increase steadily while still allowing the stock to rebuild. Catch decreases more under the *modFree* MS, but this allows for greater recovery in the long term. The *rbPlan* allows less recovery but higher catch in the short and long terms, although slightly less catch in the medium term. Both MSs head in the right direction in relation to F:F_{MSY} and B:B_{MSY} (Fig. 11). The stock is depleted so even though F is less than F_{MSY} (in *CAV*, not *LMV*), a reduction in F is still required to allow recovery to B_{MSY} within the specified time horizons. Both MSs allow the required recovery by initially reducing F substantially. This in turn translates into significant biomass growth.

The close similarity of the performance of the *modFree* and <u>*rbPlan*</u> results makes it difficult to choose the "best" MS. We therefore turn to the trade-off scores based on the predetermined weightings of performance criteria in order to select the best MS for the management of the stock. The trade-off results are presented in Table 5 and

Fig. 12 for all seven MSs. However, the focus is on the two adequate MSs, *modFree* and *rbPlan*. The other MSs are unacceptable because they perform poorly with regards to the critical thresholds set by the satisficing PSs. Overall, *modFree* scores slightly higher than *rbPlan*, but they are very similar across terms. *ModFree* scores higher in terms of resource conservation/rebuilding at the cost of less fishery stability and slight lower catches than the *rbPlan*. The "crazy pie" plots illustrating these trade-off scores (Fig. 12) clearly show the inadequacy of the *Fsq* strategy. The small "pie" size shows that this strategy performs poorly for all trade off types. *CC_16* has the best stability performance, but performs poorly on the other trade-off statistics. While *hF01* clearly does well in terms of resource recovery, this strategy performs poorly on the stability trade-off statistics. *PA* and *Bfrac* perform similarly in terms of high catch and mediocre stability but *Bfrac* performs better on the resource trade-off statistics. Of the two adequate strategies, *rbPlan* appears to be a more rounded strategy (pie slices nearly equal), but according to the trade off statistics and weights we have chosen, emphasizing resource recovery, the *modFree* is rated as the most suitable strategy.

Discussion

Our results suggest that there is considerable scope for rebuilding the NAFO 2+3KLMNO Greenland halibut stock under all OM scenarios in the long-term. While some sacrifices have to be made in terms of forgoing catch in the short term, this is compensated by a stable fishery on a healthy rebuilt resource generating reasonable yields in the medium to long-term. Successful strategies require a prescribed feedback harvest control rule that responds to the perceived status of the stock and that is robust to uncertainty. Although we could not simulate the current *ad hoc* approach being implemented by FC, based on empirical experience on other groundfish stocks, such as northern cod, it will be ineffective in achieving objectives, will not be robust to uncertainties, and will perform poorly relative to well designed feedback harvest control rules of the kind considered in this study.

Although a number of the management strategies examined have the potential to rebuild the stock, we found that only two strategies had 100% success rates in meeting all satisficing performance statistics across short, medium and long term for all operating models – *modFree* and *rbPlan*. These two strategies react to relative changes in perceived stock size and are therefore robust to uncertainty about absolute stock size. They are similar to management strategies in use elsewhere. For example Icelandic cod was managed by a similar harvest control rule for a number of years (ICES 2008):

$$TAC_{y+1} = 0.25(\frac{B_y + B_{y+1}}{2}) \qquad (5)$$

where B is the biomass of fish aged four and older from a statistical catch at age model. ICES has considered this harvest control rule to be consistent with the precautionary approach provided the implementation error is minimal.

Further evaluation of trade-off statistics with respect to *rbPlan* and *modFree* gave fairly similar results, with *modFree* outcompeting *rbPlan* to a slight degree. *rbPlan* performs better in terms of stability and catch while *modFree* performs better in terms of resource related performance statistics. *rbPlan* requires an XSA estimate of the exploitable biomass, whereas *modFree* is applied directly to the recent trend in the survey series and the TAC in the previous year. The effectiveness of the *modFree* strategy suggests that a model-based assessment of this stock may not be required on a regular basis to achieve a sustainably managed fishery. Instead a model-based assessment could be carried out periodically and used to re-condition the reference set of operating models and re-run the MSE, if necessary, to ensure that the selected management strategy is still the best.

With the introduction of the Precautionary Approach as best practice for dealing with uncertainty in fisheries management, there has tended to be an emphasis on HCRs that reduce fishing mortality on a declining stock in a prescribed manner based on the relative state of the biomass with respect to target, buffer and limit reference points. For example, the NAFO PA framework specifies that when the stock is in the Cautionary Zone, "the closer the current or projected biomass is to B_{lim}, the lower F_{target} must be to ensure that biomass remains above B_{lim}" (NAFO 2003). The evaluation of MSs for Greenland halibut in this study has taken a different approach, with the exception of the *PA* MS. Instead of adjusting fishing mortality based on the perceived state of the stock relative to the perceived value of a reference point, feedback harvest control rules are developed which respond to the perceived state of the stock (either from an analytical assessment or from the indices themselves) and then these rules are evaluated for robustness to the simulated uncertainty by examining the "known" (simulated) state of the stock relative to the "known" (simulated) reference point values to determine risks of not meeting targets and transgressing limits.

Although *modFree* and *rbPlan* respond well to relative changes in perceived stock size, they do not have the capacity to react to changes in observation error. For example, if one of the three surveys deteriorates or is terminated, this could increase the uncertainty in status as inferred directly from the survey trends or from an XSA tuned with survey data. The harvest control rule will be insensitive to this change. The management strategy is evaluated against the historical uncertainty estimated from the XSA used to condition the OM. To do this indices of stock abundance are created by using index residuals from the initial XSA, used to create the population, to add error to the actual population numbers. Consequently, if there is thought to be a change observation error, then it would be necessary to redo the MSE. In practice, the more uncertain the assessment the more conservative the MS has to be to meet resource conservation performance statistics. Similarly, if there are changes in process error (e.g. range of weights at age departs from historical range) or models error (e.g. *M* assumptions, stock-recruit assumptions) such that the modeled range in the OM reference set appears to no longer be reflective of the range of possible realities, then the MSE would have to be updated. A decision was made, in consultation with participants in the 2008 Vigo Study Group meeting not to include autocorrelation in the process error, even though exploratory analysis had shown that this may exist. The logic was that this should first be further researched, documented and peer reviewed, before being considered. While this is considered an appropriate approach, it should be pointed out that ignoring autocorrelation in the process error could under-estimate the risk associated with the current analyses and should be a consideration in further MSE developments for this stock. Provided none of the above sources of uncertainty show significant changes from historical ranges, both *rbPlan* and *modFree* should be considered to provide robust management strategies worthy of further consideration by FC in the management of this stock.

The range of operating models applied in this MSE should be such that they reflect the range of likely "realities" that could exist with regard to the Greenland halibut stock. The degree to which this has been achieved has to be subjectively evaluated. The Greenland halibut MSE has been designed in such a way that different OMs could be given plausibility weightings. In this application all OMs that have been retained in the analysis have been given equal weighting. We suggest that OM weightings should only be included if they can be determined objectively and *a priori* (i.e. based on data-driven analyses), and this is often not possible. For example, assigning weights to OMs with differing assumptions of *M* or PR for older ages cannot easily be accomplished objectively at this time. The two-step approach of satisficing followed by trade-off analysis removes the need for weighted OMs in selecting adequate MSs. For an MS to satisfice the required conditions, it is necessary that it meets <u>all</u> the performance criteria across <u>all</u> OMs, not just a combined weighted average performance. In this way, inadequate MSs are removed from further consideration before the trade-off analysis is done. At this point all MSs being considered perform suitably over the entire reference set and therefore weighting of the alternative scenarios should not be necessary. A further benefit of this two step approach is that many MSs can be considered without producing an excessively large set of trade off values to compare. If too many MSs satisfice the criteria, it may be necessary to raise the bar with regards to what is considered "adequate" performance.

There are some OM possibilities that have not been explored. For example, it is assumed that the 2+3KLMNO stock represents a closed population with no immigration or emigration. The expanding fishery for Greenland halibut to the north of the stock in Subareas 0 and 1 is therefore not factored into the study. Should it be established that there is a connection between the two stocks then this would be an important consideration in future studies. For example, there could be a combined MSE carried out for the combined northern and southern stocks in which spatial considerations are included in the OMs both with respect to the generation of the tuning indices and in the dynamics of the fishery.

Given the life history of Greenland halibut – slow growing, late maturing and presumably reasonably long lived (age 20+), together with the current observed truncated age structure and small biomass estimates, all of the operating models assume a currently depleted stock in need of considerable rebuilding to B_{MSY}. Although it seems unlikely that this perception is incorrect, it is feasible that new information or analysis could provide a different view. Because all the OMs assume a depleted starting population, the successful MSs result in considerable rebuilding in the long-term. For example, *modFree* results in a 50th percentile of the ratio B:B_{MSY} in the range of

1.75 to 5.18 under different OMs (mostly around 2.5). Recall that in the "true" simulated population in the OMs, the age is disaggregated up to age 20 with age 20+ being a plus group (Miller *et al.* 2008). Much of this biomass accumulates in the older ages. In the MSE, PR patterns for each year going into the future for the simulation runs are resampled from the recent period and therefore do not result in catches of older fish (Miller *et al.* 2008). These PR patterns could change in the future as the age structure and abundance of the stock changes and fishing gear selectivity is modified to access these ages. As noted in Miller *et al.* (2008) these refinements could be built into future versions of the OMs should analyses be presented in support of this. Similarly, ages beyond the current range reflected by the tuning indices are not used in the simulation of the perceived stock. So, while it may be considered that *modFree* or *rbPlan* over-rebuild the stocks with regard to B_{MSY}, and under-fish with regard to F_{MSY}, this biomass is considered to be unavailable to both the fishery and the surveys (i.e. it is cryptic biomass). It is assumed that adaptive changes to the management of this stock will be made once such an accumulation of older biomass in a rebuilding stock has been verified.

We adopted an approach in which the OMs are conditioned on variants of the current XSA assessment of the stock. Merits of this approach vs. a bottom-up life history and fishery dynamics based OM approach need further consideration. At one end of the spectrum a single generic OM could be constructed that allows for a wide range in life history and population dynamics (model uncertainty) together with realistic but assumed CVs on process error and observation error. A large number of samples from such a model would be required to explore the full range of possible behaviors against which the candidate MSs have to be tested. Alternatively, individual OMs can be developed that make alternative model assumptions, and then process error and observation error can be explored around these models (the concept of a reference set of operating models; Rademeyer *et al.* 2007). We considered it most expedient to develop the reference set of OMs in the form of variants around the current XSA and treatment of the stock-recruit curve. This allowed us to be able to properly condition the OMs on the available age disaggregated data for the tuning indices and the available catch.

Potential changes in the future behaviour of the fish and fishery or the stock structure, as well as possible ecosystem changes, necessitate the occasional review of the MSs and the MSE process. For example fishery selectivity patterns may change with new gear or a difference in the age structure of the stock. Likewise a shift in oceanographic conditions could lead to changes in weight or maturity at age and could affect stock-recruit relationships. Every 3 to 5 years the MSE reference set should be reviewed to ensure it still encompasses the range of possibilities suggested by all available data. Should this not be the case, candidate MSs should be re-evaluated against an expanded (or even contracted) reference set to assess whether or not changes need to be made to the accepted MS.

Computationally, the generation of observation error through an XSA bootstrap procedure (Miller and Shelton 2007) in which we randomly resampled bootstrapped residuals with replacement from the "best fit" XSA (within age and index), to generate new pseudo-abundance indices to which the XSA was refitted for each individual simulation, may be considered daunting by some and could be difficult to explain to managers and decision-makers. We consider it the best approach to have taken in this case, but alternative simpler procedures could also be examined.

Over the period of this three-year study an attempt was made to engage both fisheries managers and industry as partners in the management strategy evaluation exercise. This was only partly successful. The Vigo Workshop (NAFO 2008) brought together scientists (both NAFO and independent), fisheries managers and industry and significant contributions were made by all three groups. However, the response by Fisheries Commission in September 2008 to an SC proposal to endorse the MSE approach in the management of 2+3LMNO Greenland halibut, and thereby pave the way for further input, particularly with regard to the performance statistics and the acceptable levels of risk, was not encouraging. Consequently a number of decisions related to the quantification of the objectives through the development of performance statistics, percentiles of interest and allowable risk had to be made independently by the authors, guided by similar studies elsewhere and considerations of international best practice. It could therefore be argued that these choices do not necessarily reflect the perceptions and desires of Fisheries Commission. Should guidance be forthcoming, these could be changed within the current MSE without redoing the whole analysis.

Whether or not this particular management strategy evaluation is going to have further life within NAFO, it is time that Fisheries Commission became explicit in terms of what it wants to achieve with regard to management objectives within the Regulatory Area. In addition, a predetermined rule-based approach should replace the current *ad hoc* approach to setting the annual TAC. The lack of explicit, quantifiable management objectives and the current *ad hoc* approach to managing wild capture fisheries by NAFO is outdated (Shelton 2007). Precautionary approach target and limit reference points need to be established in relative terms with respect to B_{MSY} and F_{MSY} for each stock, acceptable risk levels need to be determined and harvest control rules need to be developed and tested through simulation to ensure that they have a reasonable probability of meeting the targets while avoiding the limits. Depleted stocks need to be placed under predetermined management strategies in which there is a reasonable probability of rebuilding to B_{MSY} or above within a reasonably short period of time. These actions have to be prescribed and transparent. Progress needs to be monitored and reported in a public manner at regular intervals.

The United Nations Fish Stocks Agreement, the FAO Code of Conduct for Responsible Fisheries and the 2002 World Summit on Sustainable Development (WSSD, Johannesburg 2002) all require a much higher standard of fisheries management practice than is currently the case within NAFO. Approaches such as MSE provide a considered, explicit and participatory approach to adopting a predetermined management strategy that can meet PA requirements, rebuild depleted fisheries such as Greenland halibut, and achieve sustainable fisheries and ensure sustainably managed fisheries for long-term public good. Such approaches and should be encouraged and embraced by NAFO.

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Table 1. Satisficing performance statistics used in the analysis of the Greenland halibut MSE. ST = short term (2011), MT = medium term (2019) and LT = long term (2030).

PS Name	Description	Type	Term	Threshold	Risk (%)
AAV	Annual Average Variation (year-on-year) in catch since inception of MS	Stability	ST MT LT	<0.15 <0.15 <0.15	50 50 50
B:Btarget	Ratio of 5+ biomass to the recovery plan target biomass	Resource	MT LT	>0.8 >1	50 25
B:Bmsy	Ratio of 5+ biomass to biomass at MSY	Resource	LT	>1	50
B:40Bmsy	Ratio of 5+ biomass to 40% of biomass at MSY	Resource	LT	>1	5
F:Fmsy	Ratio of *F* to *F* at MSY	Resource	MT LT	<1.2 <1	25 25
avgF:Fmsy	Average ratio of *F* to *F* at MSY since inception of MS.	Resource	MT LT	<1.2 <1	25 25
minCatch	Minimum catch since inception of MS	Catch	LT	>3	15

Table 2. Trade off performance statistics used in the analysis of the Greenland halibut MSE. **ST** = short term (2011), **MT** = medium term (2019) and **LT** = long term (2030). **Perc** = percentile value used and **Pref** = preference (low, high or specific value). Types: 'Cat' = Catch, 'Sta' = Stability and 'Res' = Resource. Targets: 'Inf' = infinity, i.e. the higher the better.

PS Name	Description	Type	Term	Perc	Pref	Target	wt	Tot. wt. (/26)
AAV	Annual Average Variation (year-on-year) in catch since inception of MS	Sta	ST	50	L	0	1	**3**
			MT	50	L	0	1	
			LT	50	L	0	1	
maxCatch Change	Maximum change in catch since inception of MS	Sta	LT	50	L	0	1	**1**
B:Bmsy	Ratio of 5+ biomass to biomass at MSY	Res	MT	50	H	Inf	0.5	**4**
				5	H	Inf	1	
			LT	50	H	Inf	1	
				10	H	Inf	1.5	
F:Fmsy	Ratio of *F* to *F* at MSY	Res	ST	50	L	0	0.5	**3**
			MT	50	L	0	0.5	
			LT	50	L	0	0.5	
		Cat	ST	50	L	1	0.5	
			MT	50	L	1	0.5	
			LT	50	L	1	0.5	
avgF:Fmsy	Average ratio of *F* to *F* at MSY since inception of MS	Res	ST	50	L	0	0.5	**3**
			MT	50	L	0	0.5	
			LT	50	L	0	0.5	
		Cat	ST	50	L	1	0.5	
			MT	50	L	1	0.5	
			LT	50	L	1	0.5	
CVF	Co-efficient of variation on *F* since inception of MS	Sta	ST	50	L	0	0.33	**1**
			MT	50	L	0	0.33	
			LT	50	L	0	0.34	
C:MSY	Ratio of Catch to MSY	Res	LT	50	L	1	0.5	**1**
		Cat	LT	50	H	1	0.5	
avgC:MSY	Average ratio of catch to MSY since inception of MS	Res	LT	50	L	1	0.5	**1**
		Cat	LT	50	H	1	0.5	
avgCatch	Average catch since inception of MS	Cat	ST	5	H	Inf	0.3	**3**
				50	H	Inf	0.5	
				95	H	Inf	0.2	
			MT	5	H	Inf	0.3	
				50	H	Inf	0.5	
				95	H	Inf	0.2	
			LT	5	H	Inf	0.3	
				50	H	Inf	0.5	
				95	H	Inf	0.2	

Table 2. *cont*.

PS Name	Description	Type	Term	Perc	Pref	Target	wt	Tot. wt. (/26)
catchAge	Average age in the catch	Cat	ST	50	H	Inf	0.33	**1**
			MT	50	H	Inf	0.33	
			LT	50	H	Inf	0.34	
recovRate	Number of years until 5+ biomass exceeds B_{MSY}	Res	LT	50	L	0	1	**1**
rebuildRate	Number of years until 5+ biomass exceeds the rebuilding plan target	Res	LT	50	L	0	1	**1**
SSB	Spawner stock biomass (indication of reproductive potential)	Res	MT	50	H	Inf	1	**2**
			LT	50	H	Inf	1	
meanExpAge	Mean age in the stock	Res	MT	50	H	Inf	0.5	**1**
			LT	50	H	Inf	0.5	

Table 3. Breakdown of weight allocations for trade off performance statistics (by number and weight).

PSs:	Trade Off							
Term:	ST		MT		LT		Tot	
PS Type	#	**wt**	#	**wt**	#	**wt**	#	**wt**
Catch (Cat)	6	**2.33**	6	**2.33**	8	**3.34**	20	**8**
Fishery Stability (Sta)	2	**1.33**	2	**1.33**	3	**2.34**	7	**5**
Resource Conservation/ Rebuilding (Res)	2	**1**	6	**4**	10	**8**	18	**13**

Table 4. Satisficing success (%) for each of the seven management strategies by performance statistic type and term (short, medium and long) and overall.

			PS Type			PS Term			
MS	**OM**	**wt**	**Stability**	**Catch**	**Resource**	**ST**	**MT**	**LT**	**Overall**
CC_16	***CAV***	**1**	100	0	17	100	33	33	40
	LMV	**1**	100	100	67	100	83	75	80
	CAV_domed	**1**	100	0	25	100	50	33	45
	CAV_varM	**1**	100	0	50	100	67	50	60
	CAV_dep	**1**	100	0	25	100	50	33	45
	LMV_dep	**1**	100	100	67	100	83	75	80
	CAV_mRic	**1**	100	100	100	100	100	100	100
	LMV_mRic	**1**	100	100	83	100	100	83	90
	ALL		**100**	**50**	**54**	**100**	**71**	**60**	**68**
Fsq	***CAV***	**1**	67	0	0	0	33	17	20
	LMV	**1**	67	0	0	0	33	17	20
	CAV_domed	**1**	67	0	0	0	33	17	20
	CAV_varM	**1**	67	0	0	0	33	17	20
	CAV_dep	**1**	67	0	0	0	33	17	20
	LMV_dep	**1**	67	0	0	0	33	17	20
	CAV_mRic	**1**	67	0	0	0	33	17	20
	LMV_mRic	**1**	67	0	0	0	33	17	20
	ALL		**67**	**0**	**0**	**0**	**33**	**17**	**20**
hF01	***CAV***	**1**	0	100	100	0	67	83	70
	LMV	**1**	0	100	67	0	67	50	50
	CAV_domed	**1**	0	100	100	0	67	83	70
	CAV_varM	**1**	33	100	100	0	67	100	80
	CAV_dep	**1**	0	100	100	0	67	83	70
	LMV_dep	**1**	0	100	75	0	67	58	55
	CAV_mRic	**1**	0	100	67	0	67	50	50
	LMV_mRic	**1**	0	100	100	0	67	83	70
	ALL		**4**	**100**	**89**	**0**	**67**	**74**	**64**

Table 4. *cont*.

MS	OM	wt	PS Type: Stability	PS Type: Catch	PS Type: Resource	PS Term: ST	PS Term: MT	PS Term: LT	Overall
PA	***CAV***	**1**	67	100	100	0	100	100	90
	LMV	**1**	0	100	17	0	33	17	20
	CAV_domed	**1**	33	100	100	0	67	100	80
	CAV_varM	**1**	67	100	100	0	100	100	90
	CAV_dep	**1**	33	100	100	0	67	100	80
	LMV_dep	**1**	0	100	17	0	33	17	20
	CAV_mRic	**1**	67	100	67	0	100	67	70
	LMV_mRic	**1**	0	100	42	0	67	25	35
	ALL		**33**	**100**	**68**	**0**	**71**	**66**	**61**
modFree	***CAV***	**1**	100	100	100	100	100	100	100
	LMV	**1**	100	100	100	100	100	100	100
	CAV_domed	**1**	100	100	100	100	100	100	100
	CAV_varM	**1**	100	100	100	100	100	100	100
	CAV_dep	**1**	100	100	100	100	100	100	100
	LMV_dep	**1**	100	100	100	100	100	100	100
	CAV_mRic	**1**	100	100	100	100	100	100	100
	LMV_mRic	**1**	100	100	100	100	100	100	100
	ALL		**100**	**100**	**100**	**100**	**100**	**100**	**100**
rbPlan	***CAV***	**1**	100	100	100	100	100	100	100
	LMV	**1**	100	100	100	100	100	100	100
	CAV_domed	**1**	100	100	100	100	100	100	100
	CAV_varM	**1**	100	100	100	100	100	100	100
	CAV_dep	**1**	100	100	100	100	100	100	100
	LMV_dep	**1**	100	100	100	100	100	100	100
	CAV_mRic	**1**	100	100	100	100	100	100	100
	LMV_mRic	**1**	100	100	100	100	100	100	100
	ALL		**100**	**100**	**100**	**100**	**100**	**100**	**100**
Bfrac	***CAV***	**1**	33	100	100	0	67	100	80
	LMV	**1**	33	100	33	0	67	33	40
	CAV_domed	**1**	33	100	100	0	67	100	80
	CAV_varM	**1**	67	100	100	0	100	100	90
	CAV_dep	**1**	33	100	100	0	67	100	80
	LMV_dep	**1**	0	100	33	0	67	17	30
	CAV_mRic	**1**	33	100	50	0	67	50	50
	LMV_mRic	**1**	33	100	42	0	67	42	45
	ALL		**33**	**100**	**70**	**0**	**71**	**68**	**62**

Table 5. Trade-off value score for each of the seven management strategies by performance statistic type and term (short, medium and long) and overall. Scores are a relative comparison of candidate MSs ranging from 0 (the worst of all MSs) to 1 (the best MS or, for PSs with a specific target, achieves required target).

			PS Type			PS Term			
MS	**OM**	**wt**	**Stability**	**Catch**	**Resource**	**ST**	**MT**	**LT**	**Overall**
CC_16	***CAV***	**1**	0.82	0.67	0.39	0.71	0.51	0.53	0.56
	LMV	**1**	0.90	0.59	0.51	0.73	0.55	0.60	0.61
	CAV_domed	**1**	0.82	0.70	0.41	0.74	0.52	0.55	0.58
	CAV_varM	**1**	0.82	0.70	0.39	0.75	0.54	0.52	0.57
	CAV_dep	**1**	0.84	0.67	0.36	0.75	0.50	0.51	0.55
	LMV_dep	**1**	0.88	0.57	0.54	0.73	0.53	0.62	0.62
	CAV_mRic	**1**	0.83	0.72	0.60	0.77	0.60	0.70	0.68
	LMV_mRic	**1**	0.88	0.66	0.60	0.83	0.55	0.69	0.67
	ALL		**0.85**	**0.66**	**0.48**	**0.75**	**0.54**	**0.59**	**0.60**
Fsq	***CAV***	**1**	0.51	0.21	0.08	0.37	0.18	0.15	0.20
	LMV	**1**	0.51	0.18	0.09	0.37	0.14	0.18	0.20
	CAV_domed	**1**	0.49	0.22	0.08	0.37	0.19	0.15	0.20
	CAV_varM	**1**	0.47	0.22	0.08	0.37	0.19	0.14	0.20
	CAV_dep	**1**	0.52	0.19	0.08	0.37	0.18	0.15	0.20
	LMV_dep	**1**	0.51	0.18	0.10	0.37	0.12	0.19	0.20
	CAV_mRic	**1**	0.56	0.27	0.08	0.37	0.22	0.19	0.23
	LMV_mRic	**1**	0.54	0.24	0.10	0.37	0.14	0.23	0.23
	ALL		**0.51**	**0.22**	**0.08**	**0.37**	**0.17**	**0.17**	**0.21**
hF01	***CAV***	**1**	0.16	0.58	0.96	0.53	0.73	0.72	0.69
	LMV	**1**	0.14	0.62	0.79	0.53	0.76	0.55	0.61
	CAV_domed	**1**	0.15	0.57	0.98	0.53	0.73	0.72	0.69
	CAV_varM	**1**	0.16	0.56	1.00	0.53	0.73	0.74	0.70
	CAV_dep	**1**	0.16	0.58	0.95	0.53	0.73	0.71	0.68
	LMV_dep	**1**	0.14	0.62	0.79	0.53	0.75	0.56	0.61
	CAV_mRic	**1**	0.14	0.49	0.83	0.53	0.73	0.54	0.59
	LMV_mRic	**1**	0.16	0.59	0.78	0.53	0.75	0.55	0.60
	ALL		**0.15**	**0.58**	**0.88**	**0.53**	**0.74**	**0.64**	**0.65**

Table 5. *cont*.

MS	OM	wt	PS Type: Stability	PS Type: Catch	PS Type: Resource	PE Term: ST	PE Term: MT	PE Term: LT	Overall
PA	***CAV***	**1**	0.45	0.73	0.57	0.67	0.63	0.55	0.60
	LMV	**1**	0.41	0.66	0.41	0.68	0.60	0.35	0.49
	CAV_domed	**1**	0.44	0.74	0.60	0.66	0.64	0.57	0.61
	CAV_varM	**1**	0.46	0.74	0.58	0.68	0.62	0.57	0.61
	CAV_dep	**1**	0.45	0.75	0.58	0.69	0.63	0.57	0.61
	LMV_dep	**1**	0.43	0.67	0.40	0.69	0.62	0.35	0.49
	CAV_mRic	**1**	0.46	0.74	0.48	0.68	0.63	0.47	0.55
	LMV_mRic	**1**	0.37	0.74	0.42	0.69	0.62	0.39	0.51
	ALL		**0.43**	**0.72**	**0.50**	**0.68**	**0.62**	**0.48**	**0.56**
modFree	***CAV***	**1**	0.60	0.65	0.84	0.75	0.64	0.78	0.74
	LMV	**1**	0.62	0.59	0.91	0.72	0.67	0.82	0.75
	CAV_domed	**1**	0.62	0.66	0.83	0.74	0.67	0.77	0.74
	CAV_varM	**1**	0.60	0.66	0.82	0.74	0.66	0.77	0.73
	CAV_dep	**1**	0.58	0.65	0.83	0.74	0.65	0.77	0.73
	LMV_dep	**1**	0.58	0.59	0.84	0.72	0.65	0.74	0.71
	CAV_mRic	**1**	0.55	0.61	0.80	0.76	0.69	0.68	0.70
	LMV_mRic	**1**	0.57	0.57	0.82	0.77	0.64	0.70	0.69
	ALL		**0.59**	**0.62**	**0.84**	**0.74**	**0.66**	**0.75**	**0.72**
rbPlan	***CAV***	**1**	0.70	0.69	0.74	0.76	0.64	0.74	0.72
	LMV	**1**	0.72	0.60	0.80	0.73	0.64	0.76	0.72
	CAV_domed	**1**	0.70	0.69	0.73	0.76	0.63	0.74	0.71
	CAV_varM	**1**	0.71	0.71	0.70	0.76	0.65	0.72	0.70
	CAV_dep	**1**	0.69	0.67	0.76	0.76	0.62	0.76	0.72
	LMV_dep	**1**	0.71	0.58	0.79	0.73	0.62	0.75	0.71
	CAV_mRic	**1**	0.71	0.70	0.67	0.76	0.66	0.67	0.69
	LMV_mRic	**1**	0.71	0.63	0.73	0.79	0.63	0.70	0.70
	ALL		**0.71**	**0.66**	**0.74**	**0.76**	**0.64**	**0.73**	**0.71**
Bfrac	***CAV***	**1**	0.42	0.71	0.71	0.62	0.68	0.65	0.65
	LMV	**1**	0.33	0.65	0.50	0.63	0.71	0.36	0.51
	CAV_domed	**1**	0.43	0.73	0.72	0.62	0.69	0.66	0.66
	CAV_varM	**1**	0.41	0.72	0.74	0.62	0.66	0.69	0.67
	CAV_dep	**1**	0.43	0.72	0.71	0.63	0.67	0.66	0.66
	LMV_dep	**1**	0.30	0.64	0.48	0.63	0.71	0.33	0.49
	CAV_mRic	**1**	0.42	0.69	0.59	0.63	0.70	0.51	0.59
	LMV_mRic	**1**	0.33	0.64	0.55	0.63	0.71	0.41	0.54
	ALL		**0.38**	**0.69**	**0.62**	**0.63**	**0.69**	**0.54**	**0.60**

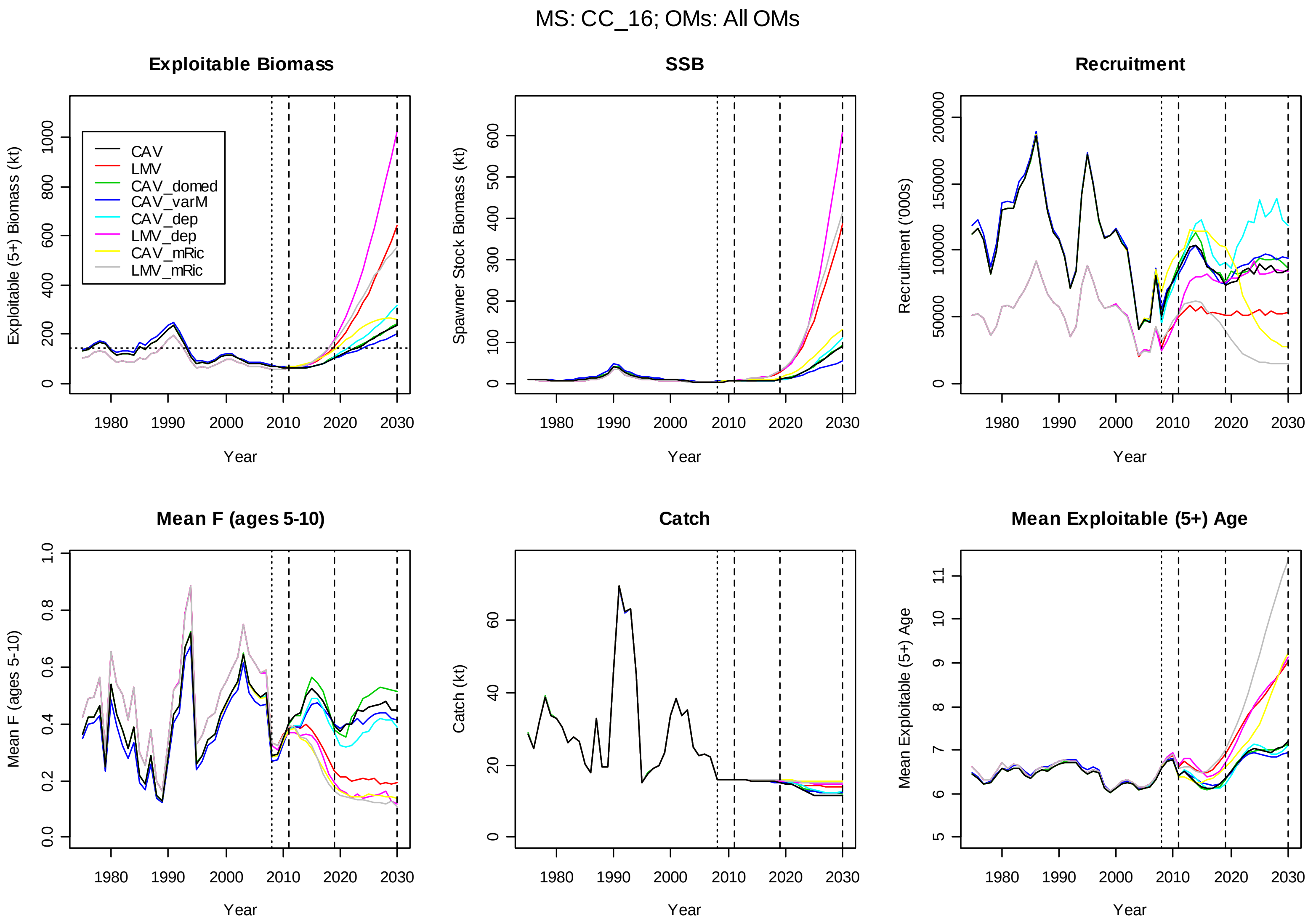

Fig. 1. Descriptive statistics from the stochastic simulations (100 runs) of the *CC_16* (constant catch 16kt) management strategy for each operating model in the reference set. Mean values are plotted.

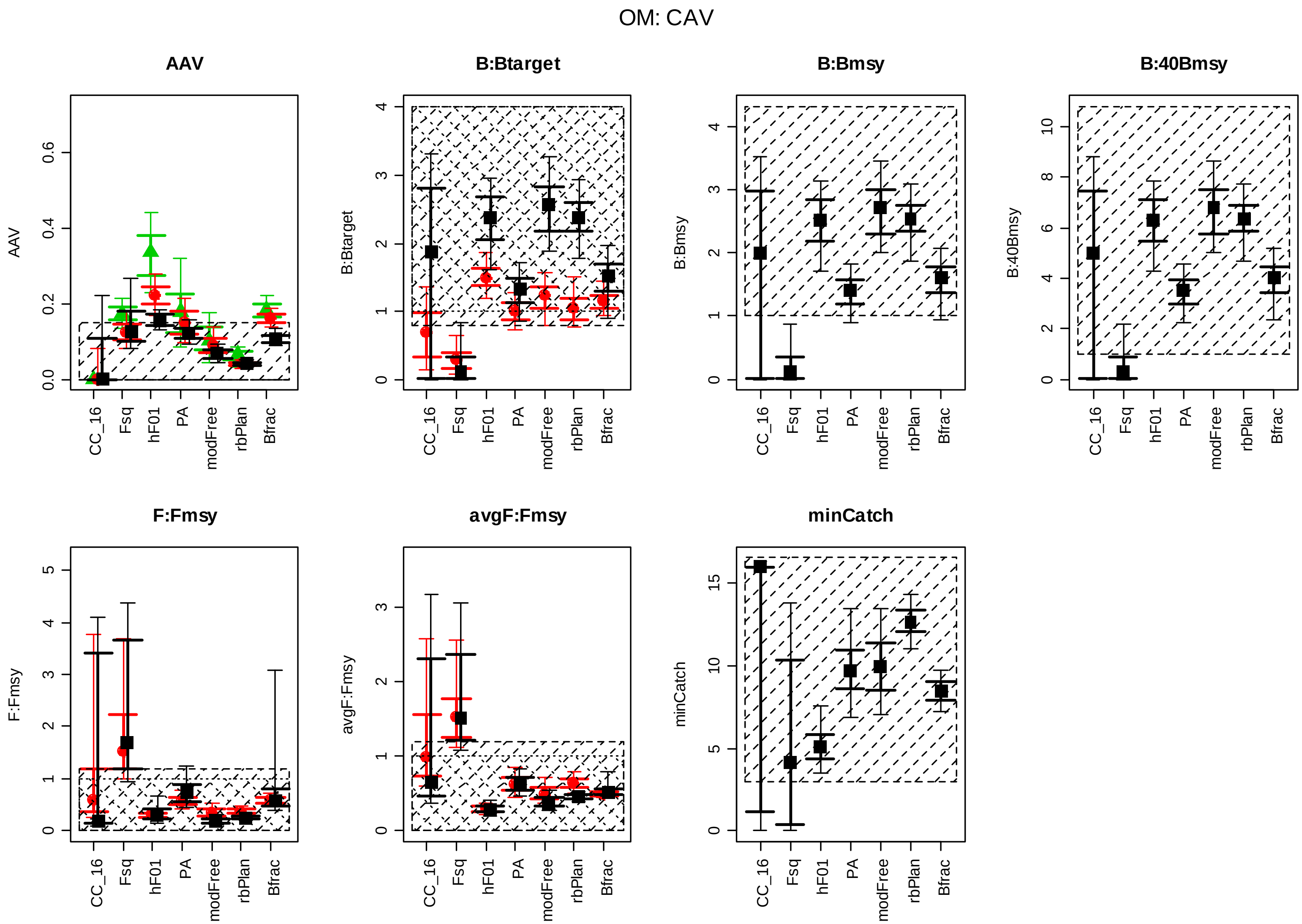

Fig. 2. Satisficing performance statistic results for all management strategies, *CAV* (current assessment view) operating model. Medians, 25/75 and 5/95 percentiles shown. Shaded areas represent satisfactory zones (i.e. within the required threshold). For multiple thresholds, right facing shading shows the medium term threshold, and left facing shows the long term threshold. Terms: ▲(green) = short, ● (red) =medium, ■ (black) =long.

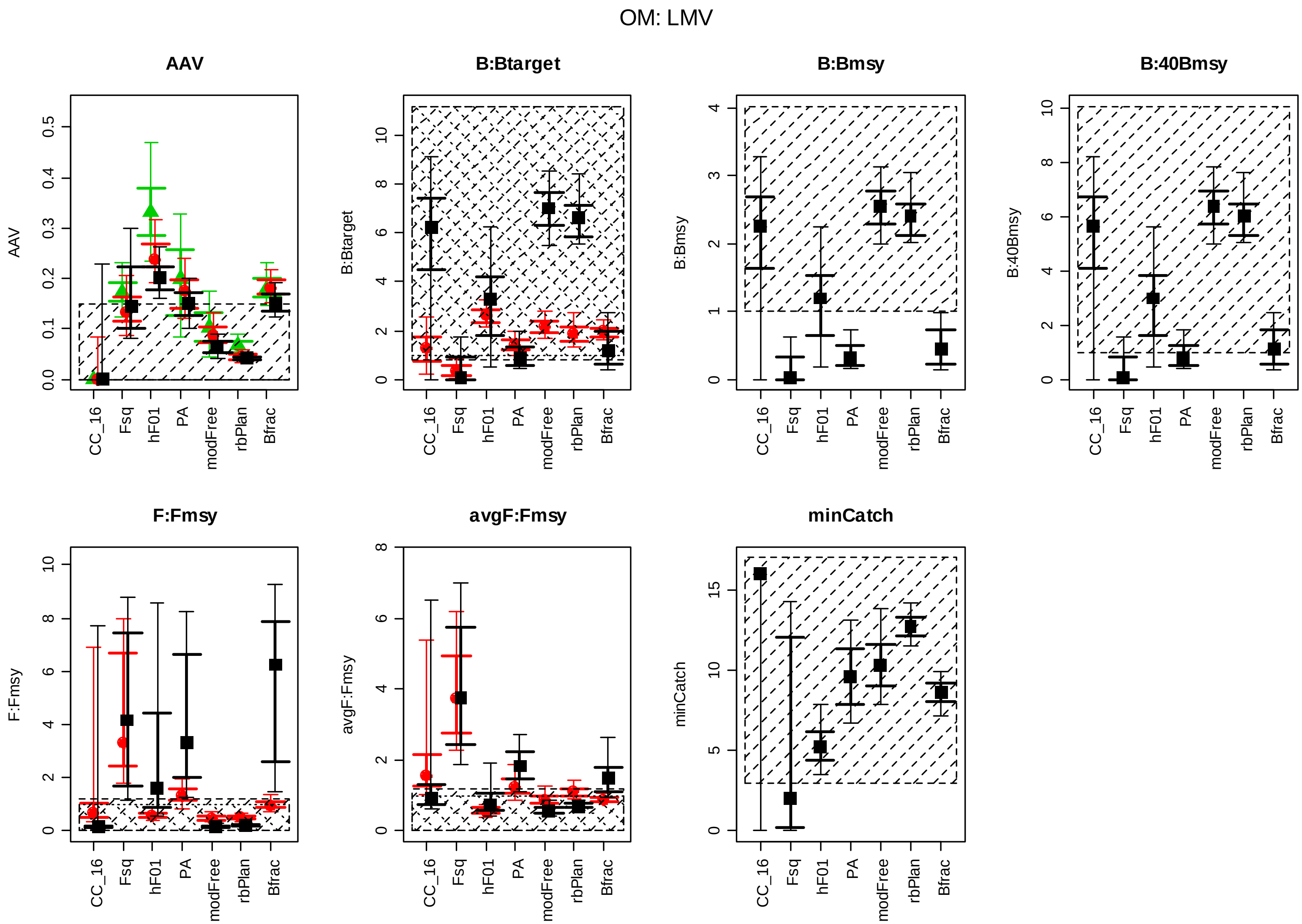

Fig. 3. Satisficing performance statistic results for all management strategies, *LMV* (low mortality view) operating model. Medians, 25/75 and 5/95 percentiles shown. Shaded areas represent satisfactory zones (i.e. within the required threshold). For multiple thresholds, right facing shading shows the medium term threshold, and left facing shows the long term threshold. Terms: ▲(green) = short, ● (red) =medium, ■ (black) =long.

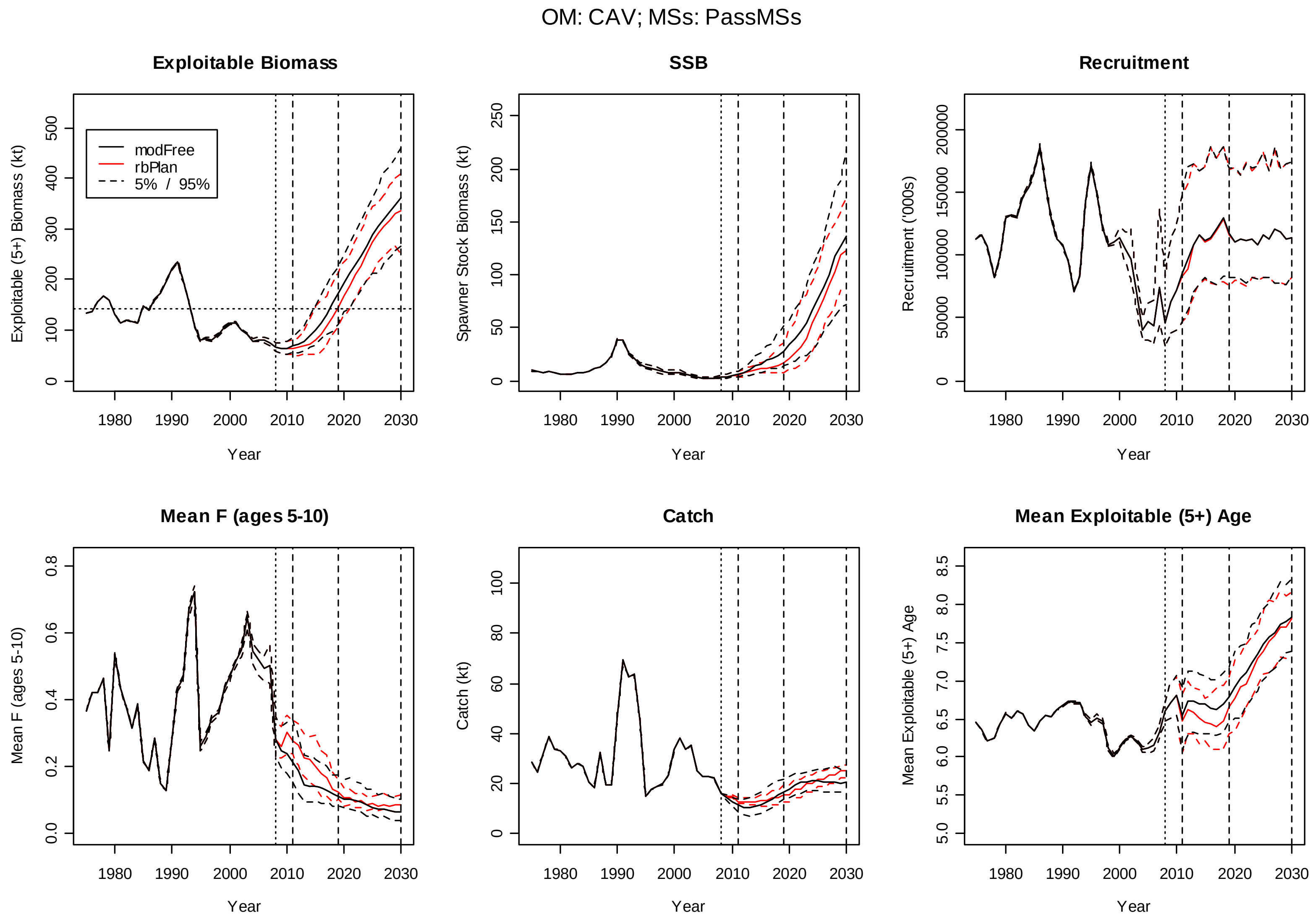

Fig. 4. Descriptive statistics from the stochastic simulations (100 runs) for the two successful Management Strategies (*modFree* and *rbPlan*) in the *CAV* operating model. Solid lines represent the median value, dashed lines show the 5 and 95 percentiles.

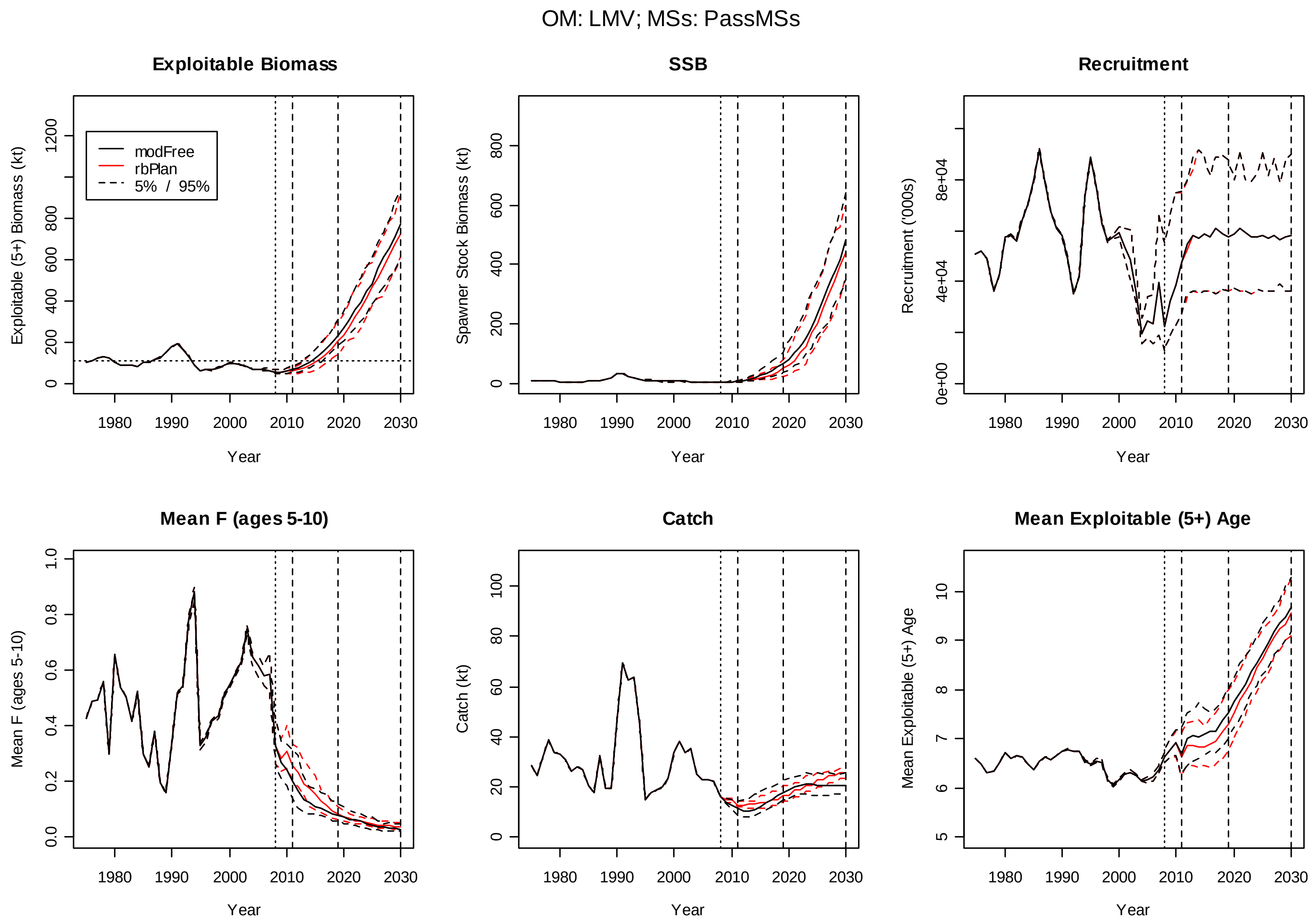

Fig. 5. Descriptive statistics from the stochastic simulations (100 runs) for the two successful Management Strategies (*modFree* and *rbPlan*) in the *LMV* operating model. Solid lines represent the median value, dashed lines show the 5 and 95 percentiles.

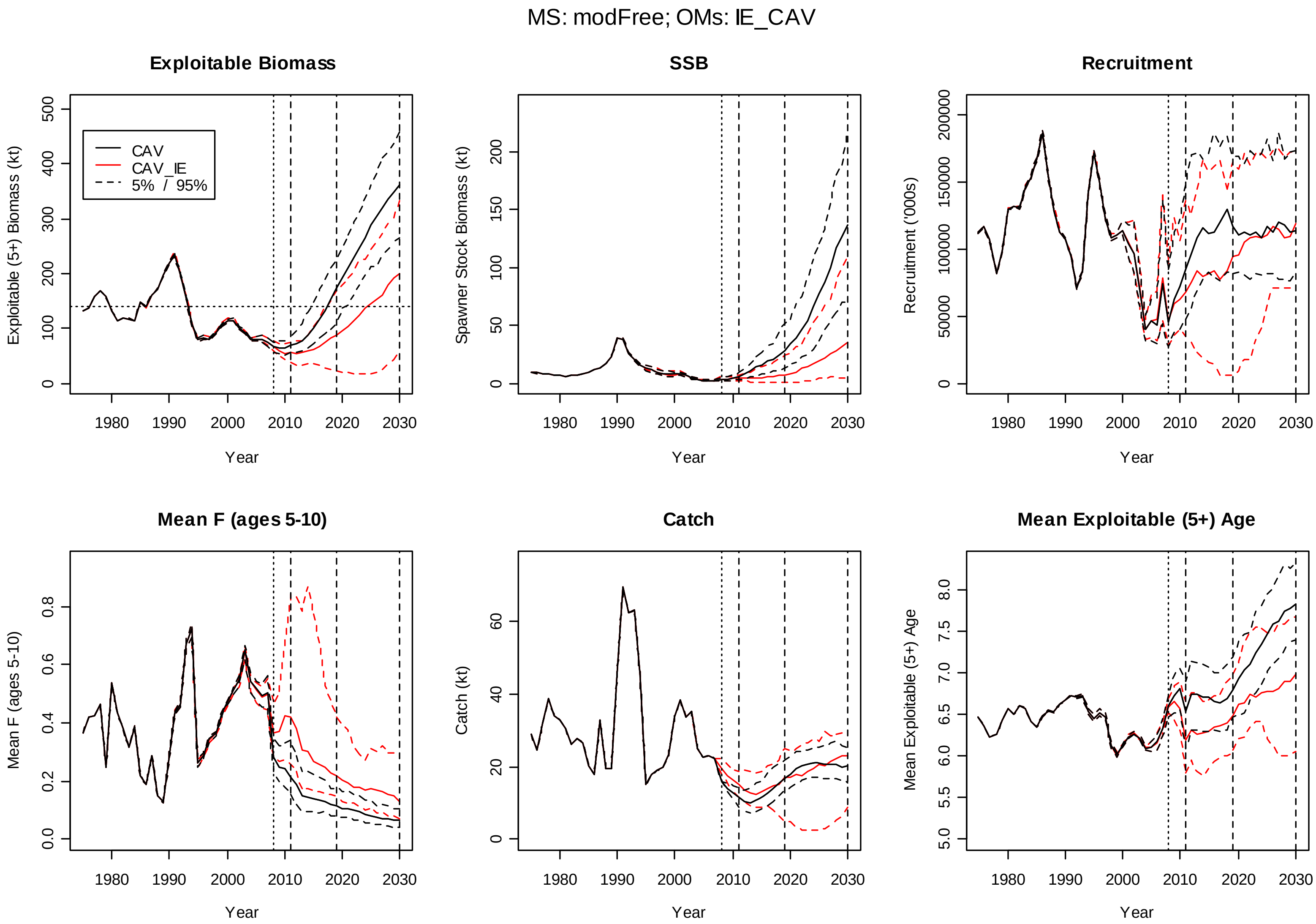

Fig. 6. Descriptive statistics from the stochastic simulations (100 runs) for the *modFree* Management Strategy with and without implementation error (random uniform 10-40%) in the *CAV* operating model. Solid lines represent the median value, dashed lines show the 5 and 95 percentiles.

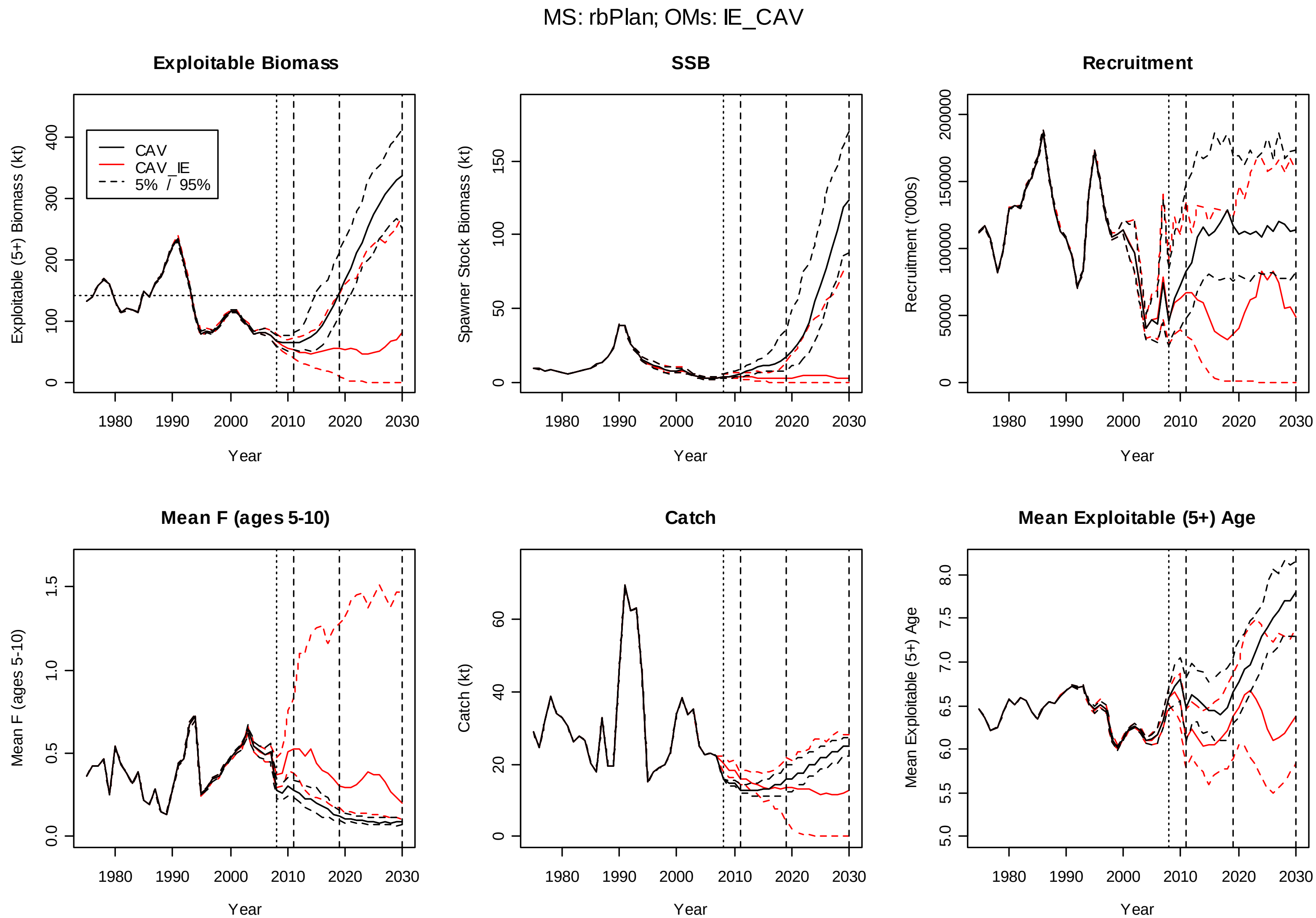

Fig. 7. Descriptive statistics from the stochastic simulations (100 runs) for the *rbPlan* Management Strategy with and without implementation error (random uniform 10-40%) in the *CAV* operating model. Solid lines represent the median value, dashed lines show the 5 and 95 percentiles.

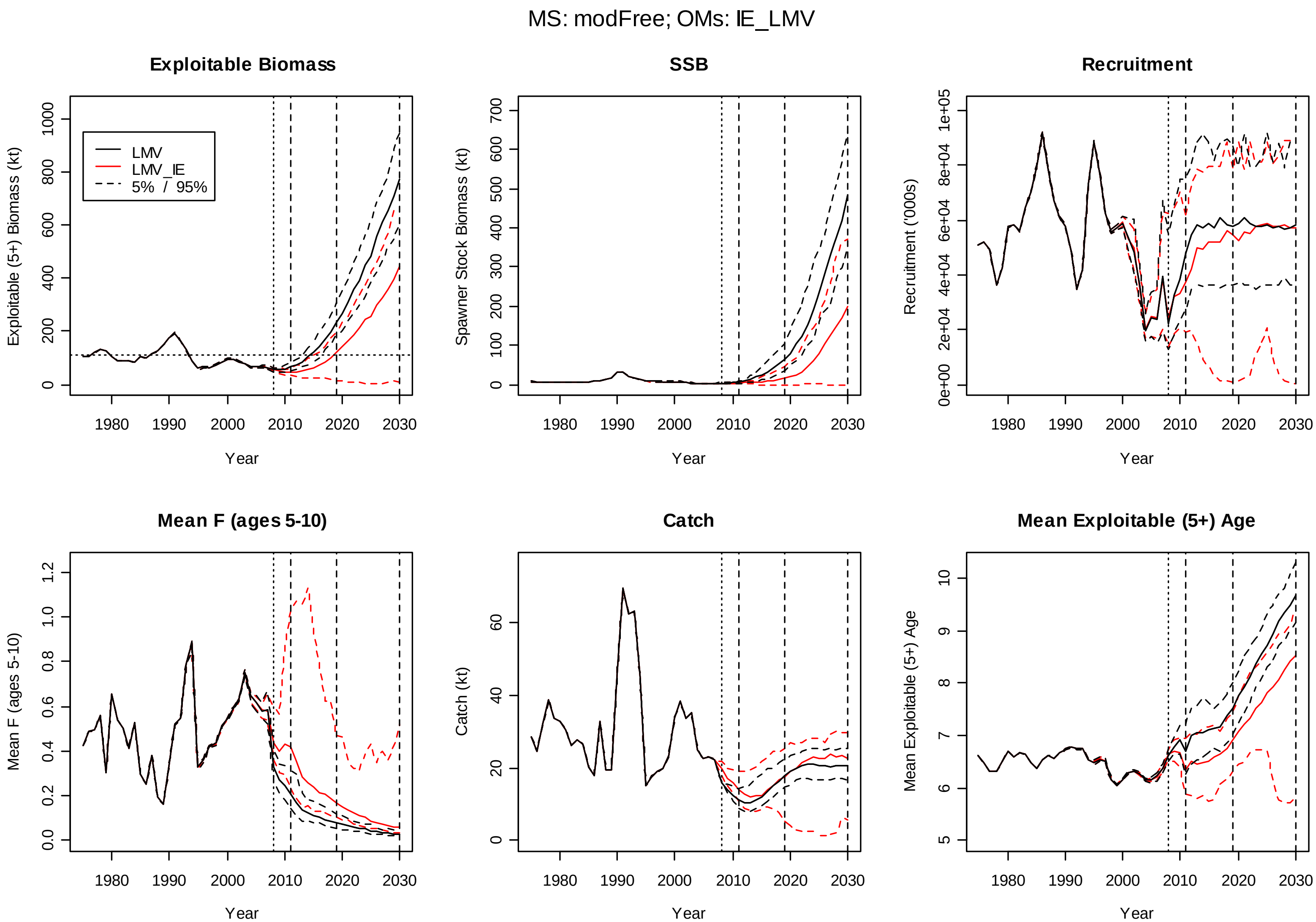

Fig. 8. Descriptive statistics from the stochastic simulations (100 runs) for the *modFree* Management Strategy with and without implementation error (random uniform 10-40%) in the *LMV* operating model. Solid lines represent the median value, dashed lines show the 5 and 95 percentiles.

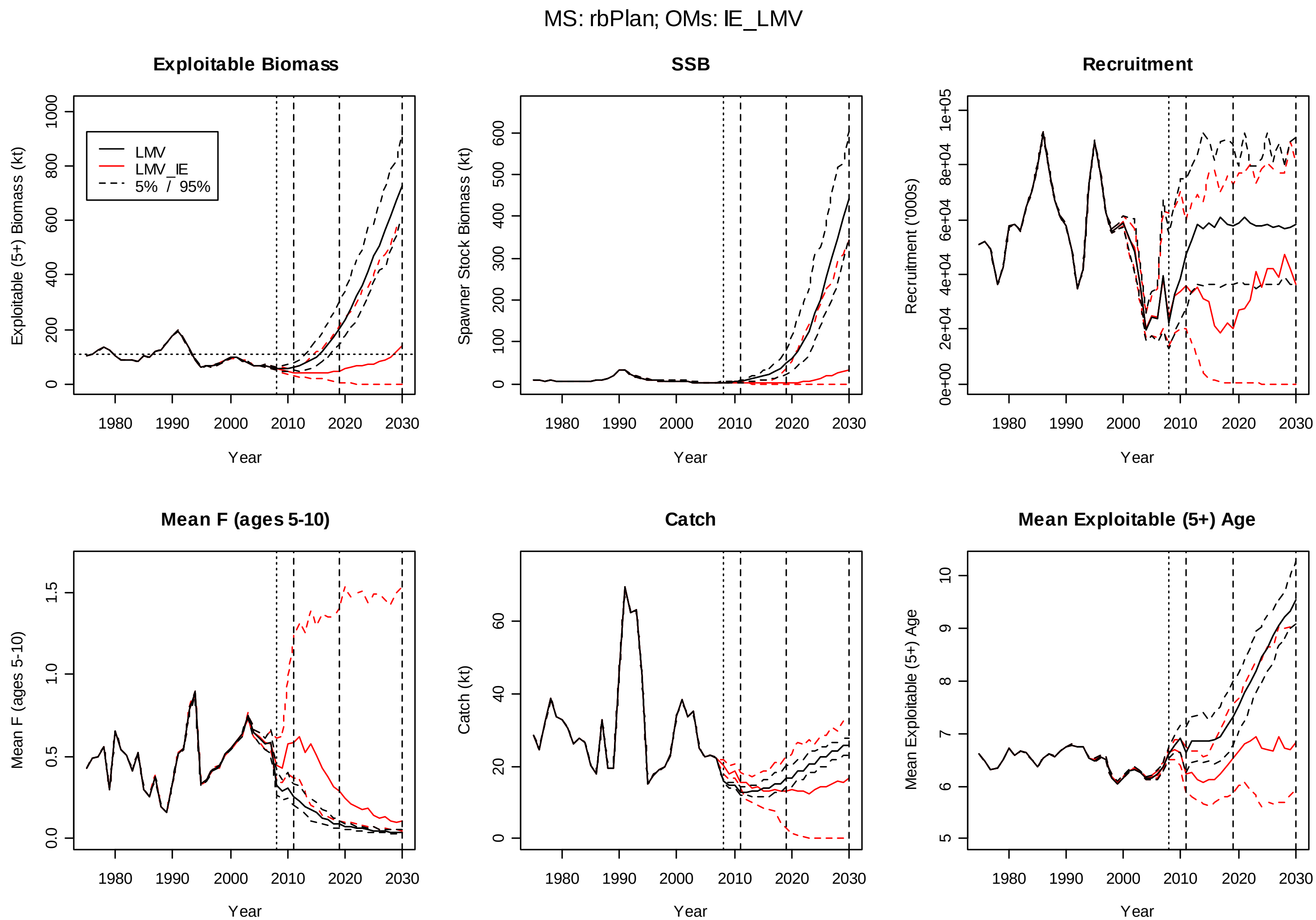

Fig. 9. Descriptive statistics from the stochastic simulations (100 runs) for the *rbPlan* Management Strategy with and without implementation error (random uniform 10-40%) in the *LMV* operating model. Solid lines represent the median value, dashed lines show the 5 and 95 percentiles.

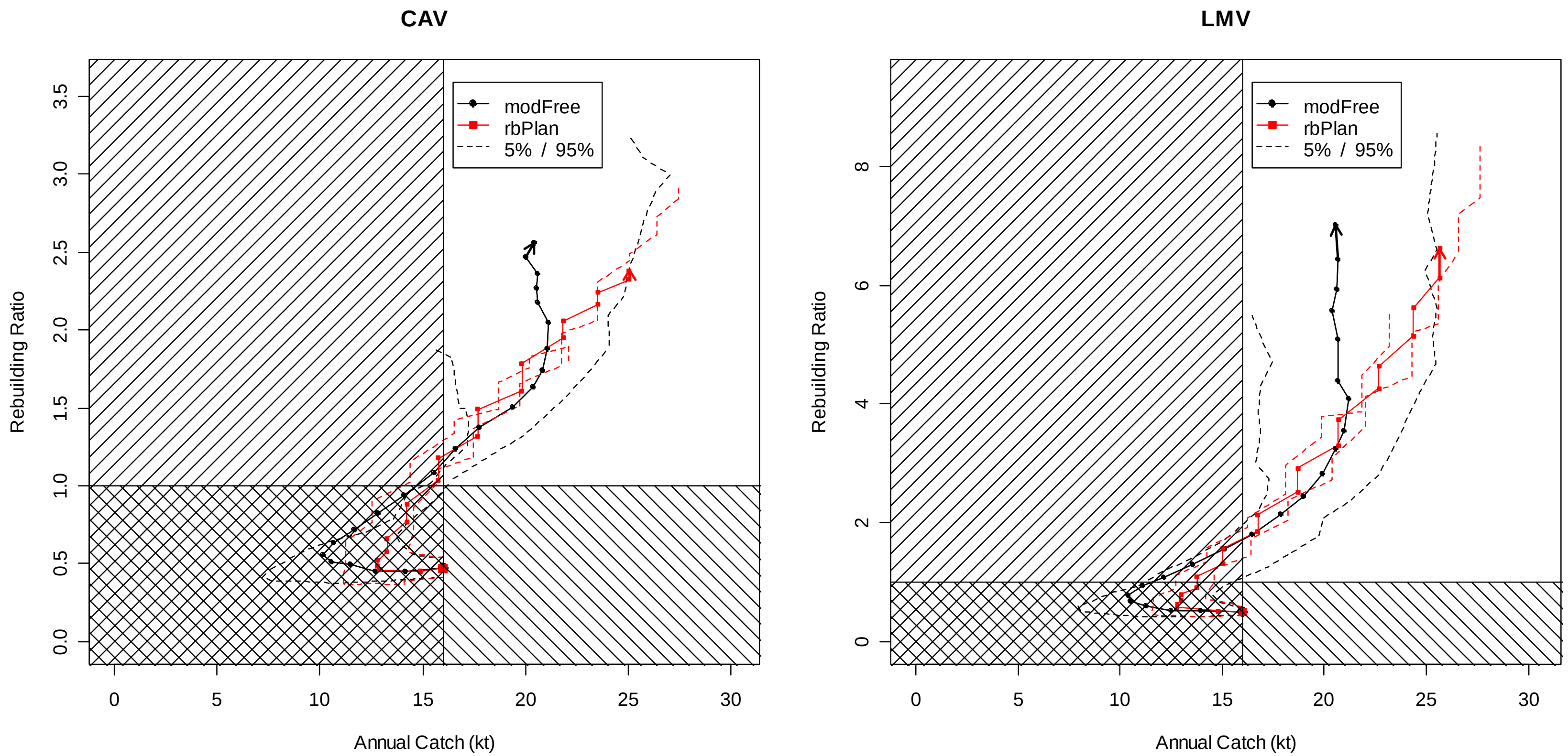

Fig. 10. Trajectories of annual catch vs. stock rebuilding from 2009 (first year of management strategy applied TAC) until 2030 for the *modFree* and *rbPlan* management strategies (*CAV* and *LMV* operating models). The shaded areas represent less than 16kt (catch status quo) and below rebuilding target, respectively. Medians and 5/95 percentiles shown.

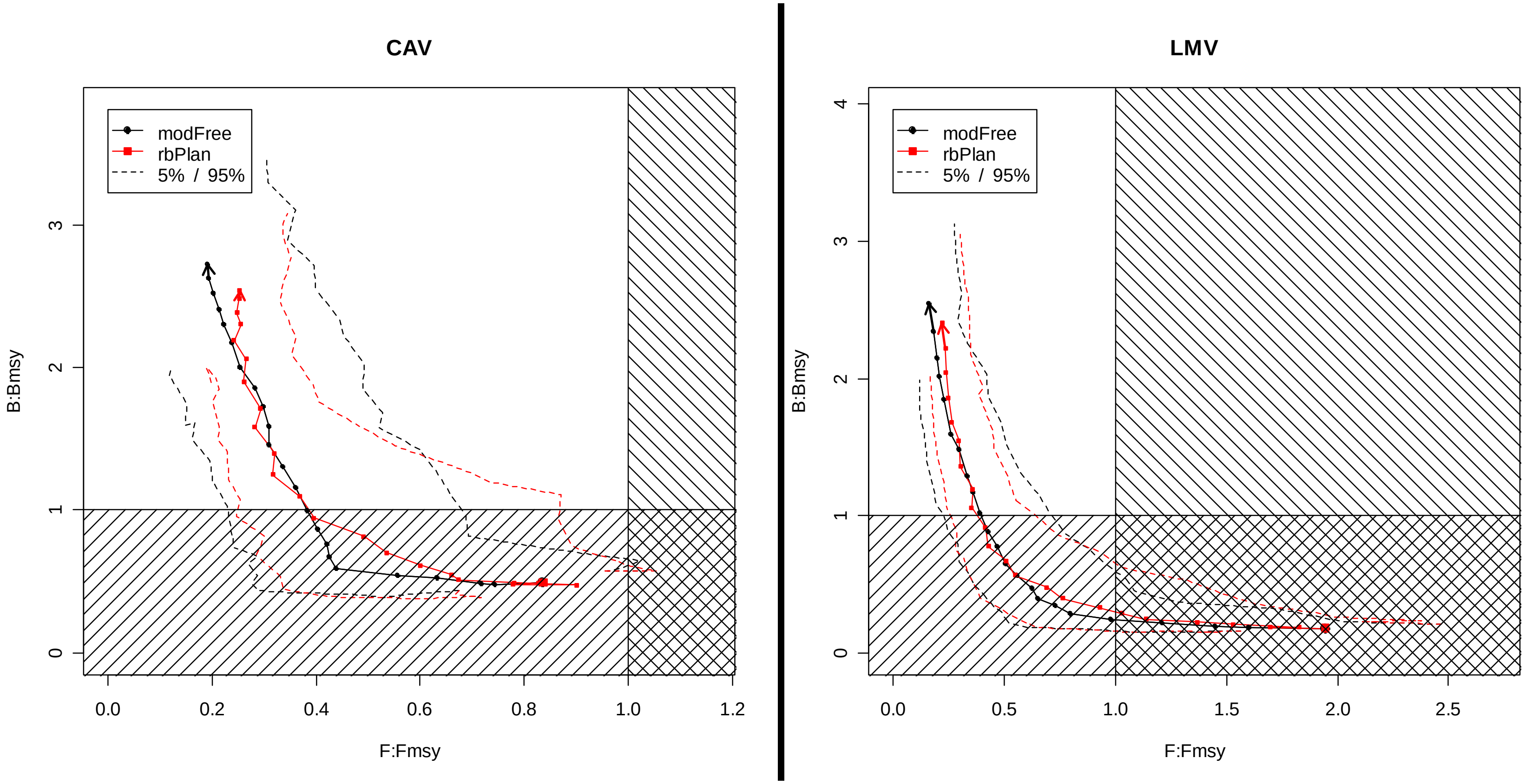

Fig. 11. Trajectories of the ratio of $F{:}F_{MSY}$ vs. $B{:}B_{MSY}$ from 2009 (first year of a management strategy applied TAC) until 2030 for the *modFree* and *rbPlan* management strategies (*CAV* and *LMV* operating models). The shaded areas represent 'overfished' (stock below B_{MSY}, right shading) and overfishing (F above F_{MSY}, left shading). Medians and 5/95 percentiles shown.

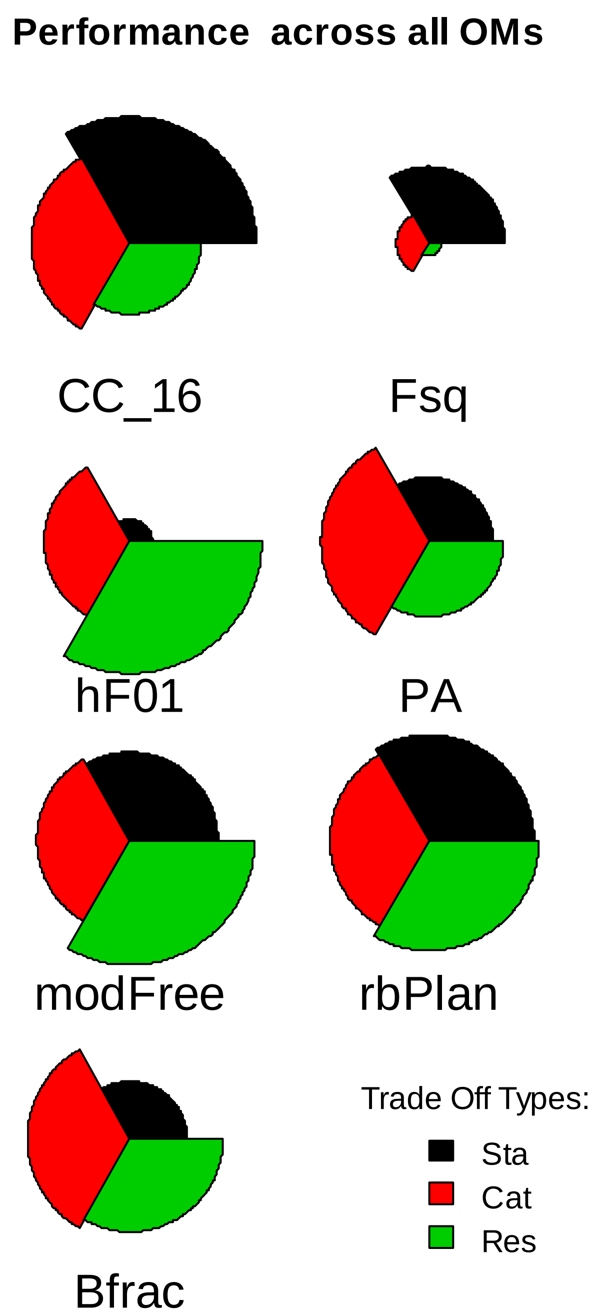

Fig. 12. 'Crazy pie plots' (modified spider plots) of the trade-off score by type for all seven management strategies, for all operating models (equal weighting). Scores are relative comparisons between MSs: the larger the pie segment for a particular type, the better the performance relative to the other management strategies (or targets, if they existed for the trade off performance statistic). Types: fishery stability ('Sta', black); catch ('Cat', red) and resource conservation/rebuilding ('Res', green).

Appendix 1: Overview of technical details of the MSE process

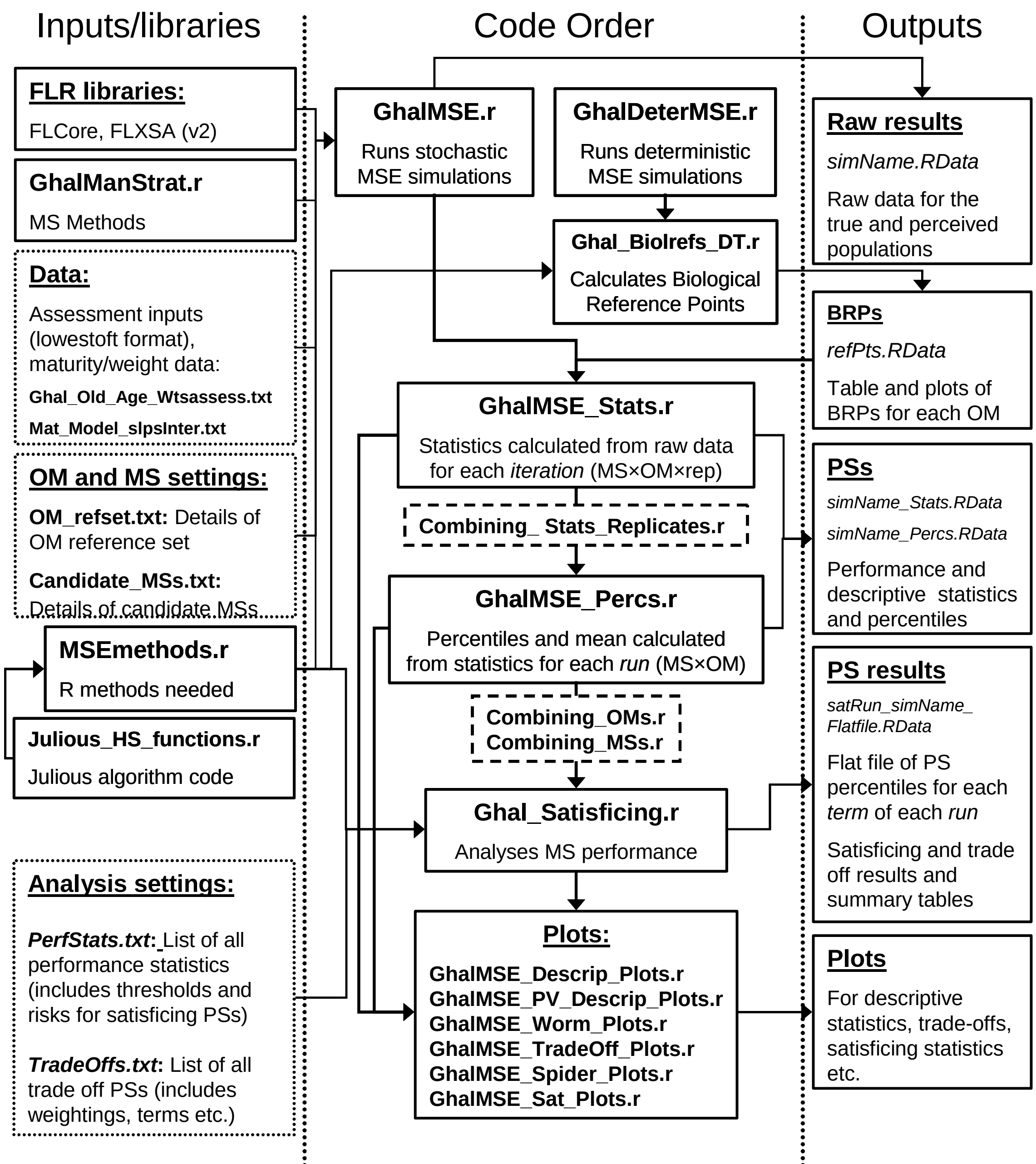

Fig. A1.1. Flowchart of the inputs, R routines (code files) and outputs for the Greenland halibut MSE.

Data for GhalMSE.r

In subfolder named for the assessment year (e.g. 2008):
Assessment data (indices, stock weights etc.) in Lowestoft format .txt files.
In 'MSE' subfolder:
'Mat Model slpsInter.txt': Maturity parameters (from Morgan and Rideout cohort model).
'GhalOldAgeWts2008.txt': Weight at age for the assessment plusgroup age and older (from 'GhalWAA_for_14+.xls').

Note: inputs (e.g. for the OM reference set and candidate management strategies) are contained in an excel file entitled "Ghal Data Input.xls"

FLR libraries

Works on R v2.7.1
FLCore v2.0
FLXSA v1.99-6
FLAssess v1.99-6 (not essential at this point – i.e. not actually used for current code, may be needed depending on what OMs or MSs are added).

Description of routines and instructions for running an MSE

<u>GhalDeterMSE.r</u>
Performs deterministic (no process error) simulations. Useful in evaluating OMs and MSs (or fine-tuning MSs) before running full stochastic simulations.

Useful to have a 'standard'/'base-case' OM and MS to compare alternative MSs and OMs, respectively. For Greenland halibut, the *CAV* OM and the *CC_16* MS are considered the base-cases scenarios.

<u>GhalDeterMSE_Stats.r</u>
Calculates statistics for deterministic runs.

<u>GhalDeterMSE_Plots_*x*.r</u>
_grp.r = A group of six descriptive statistics that can be plotted by OM or MS
_single.r = Various statistics plots that can be done for any OM*MS combinations
_PV.r = Plots for the perceived view of the simulations (if the assessment was run each year). The 'retro' perceived population plot is useful for looking at how well the assessment model is performing through time.

<u>GhalMSE.r</u>

Performs stochastic (process, observation and model error) simulations.

MSE simulation settings:
pathGhalMS: Single path for the directory where "Ghal MSE Package.zip" was unpacked (This directory should contain the folder "Ghal MSE Package"). Do not change any of the sub-folder names.
e.g. pathGhalMSE <- "C:\\Documents and Settings\\millerdcm\\Desktop\\"

chooseOMs: Select operating models (as numbered in the " Ghal Data Input.xls").
e.g. chooseOMs <- c(10)

chooseMSs: Select management strategies (as numbered in the " Ghal Data Input.xls").
e.g. chooseMSs <- c(1:7)

errorLevel : Level of error - #"P" (process error only) or "POM" (process, observation and model error). Note: constant TAC MSs or any MS that does not set the TAC based on model or index inputs DO NOT need to be run under "POM" error.

e.g. errorLevel <- "POM"

TPrep : Number of replicates. 100 is suitable for final runs, at least 20 are required to calculate PS percentiles down to the 5^{th} or 95^{th} percentile.
e.g. TPrep <- 100

assess: Current assessment year
e.g. assess<- 2008

simName: Name for workspace file to be saved as once the simulation is complete
e.g. simName <- test

- Each OM*MS*rep combination = an 'iteration'.
- Each OM*MS combination = a 'run'

i.e. a 'run' is a combination of iterations.

Any additional OMs or MSs need to be defined in this code in the matrices *OM* and *MS* (in file "Ghal data input.xls").

If simulations fail due to an error:
If only running a single OM, then check what 'rp' the failure occurred on (by typing this in the R window) and re-run the 'Replicate loop' only (start and finish of this are noted in the file), starting from replicate 'rp' instead of 1. i.e. replace: "for (rp in 1:TPrep)" with: "for (rp in *x*:TPrep)", where *x* in the 'rp' that the error occurred on.

If running multiple OMs, then check what 'om' the failure occurred on and re-run the 'Operating Model loop' only (start and finish of this are noted in the file), starting from replicate 'om' instead of 1.

You will need to manually save the workspace (or run the "save.image" line at the end) to save the results.

Ghal_biolrefs_DT.r
Run one MS for all OMs using GhalDeterMSE.r . Using the resultant output, Ghal_biolrefs_DT.r will produce a file called refPts.rData containing biological reference points for each OM.
Need to set *rmData* to 'T', run the whole code and then manually save *refPts.r* (workspace with only the matrix refPts) in the MSE output subfolder.

GhalManStrat.r
Methods for calculating TACs.
Fixed TAC MSs do not require methods.
All MS methods have options for perfect information ("P" error only) or "POM" error input. i.e. based on Biol or model/index, respectively.
The MSE can be applied the MS every 2 or 3 years instead of annually.

Methods:
1. "FsqMS": *F* status quo - *F* strategy with TAC set based on last year's *F*
2. "FbasedMS": Set the TAC based on a given *F*
3. "surTACMS": Model free variable TAC strategy with TAC adjusted according to the slope of index values in recent times (5yrs)
4. "PAMS": XSA-based PA rule with *F* determined based on the current SSB in relation to beta
5. "RBMS": XSA-based rebuilding plan TAC adjustment strategy. TAC is adjusted depending on the perceived exploitable biomass trend for the recent period (last five years including current year projection). TAC changes are limited to 15% either way.
6. "Bfrac": Model free variable TAC strategy with TAC adjusted according to the slope of index values in recent times (5yrs)

MSEMethods.r
Sources code from '**Julious_HS_functions.r**'.
Contains the following methods (although not all are currently used):
1. "replaceNegative": Replaces negative values need to be replaced with NA (for XSA analysis)
2. "naResid": Replaces (makes NA) 'strange' residuals generated by FLXSA for cases where the index = "NA"
3. "EUPR": Calculates partial recruitment (PR) for each year of a FL stock object, or a recent period average
4. "Fcalc": F0.1 and Fmax Calculator
5. "SPR": Calculates the spawner per recruit
6. "Fcrash": Calculates the *F* value, at a given *M* value and stock recruit relationship, above which a stock will crash
7. "SSB0": Calculates the equilibrium biomass at a given fishing mortality (default f=0), a given *M* value and stock recruit relationship
8. "steepness": Calculates the steepness of a stock-recruit relationship, at a given *M* value.
9. "RPS": Calculates the recruit per spawner as the slope of the straight through the origin that minimises the sum of log residuals, given a set of SSB values and corresponding Recruitment values
10. "depSegRegRatio" version A - based on ratio to max Rec or max SSB: Calculates the segmented regression stock recruit relationship under the assumption that the current stock has "collapsed" (by making an assumption based on Rec)
11. "depSegRegSSB" version B - based on ratio to SSB0: Calculates the sgemented regression stock recruit relationship under the assumption that the current stock has "collapsed" (by making an assumption based on SSB)
12. "modRicker": Calculates a 'breakpoint' on the ricker curve beyond which (>SSB) a minimum recruitment level is set ('asymptote')
13. "expPlusGrp" - linear PR decline: Converts stock numbers in a plusgroup to numbers over a range of ages beyond the plusgroup given *F* and *M* values
14. "expPlusGrpExp" - exponential PR decline: Converts stock numbers in a plusgroup to numbers over a range of ages beyond the plusgroup given *F* and *M* values
15. "replacePG": Replaces plusgroup numbers in an FLStock quant with numbers from a dynamic pool model by:
1. "DP": making an assumptions about how *F* in the plusgroup relates to *F* in the previous age
or 2. "PAC": using catch numbers and Pope's approximation instead of *F*
16. "FTAC": Converts a *F* value to an TAC value given a set of PRs
17. "JulAlg": Calculates the best fit parameters for a segmented regression stock recruit relationship using the Julious Algorithm (Julious_HS_functions.r)
18. "percData": Fills in percentile values in the MSE flat file from the relevant (PS) data quants.
19. "riskThreshold": Fills in PS weighting, risk, Threshold and AorB (above or below) values from the PS matrix into the MSE flat file at the relevant rows.
20. "passCheck": Compares Thresholds and Risks against the percentiles of PSs for each row of the flat file (with satisficing weight >0) and determines pass or fail..
21. "summSatTable": Creates a summary table of the satisficing PS results.
22. "satSuccRate": Creates a table of the satisficing success rate of MSs.
23. "summTOTable": Creates a summary table of the trade off PS results (values or ranks).
24. "5": Creates a summary table of the MS trade off scores (using values) or an overall rank (using ranks).

PlotMethods.r
Extra methods not currently used.

GhalMSE_Stats.r
Calculates performance and descriptive statistic values for each iteration.

Combining Stats Replicates.r
Combines workspaces with replicates of the same OMs and MSs.

Combining OMs.r / Combining MSs.r
Combines workspaces with additonal OMs or MSs

Output form GhalMSE.r

Data is stored in FLR quants. Each "iteration" (sixth dimension of the quants) is a replicate of an MS applied to an operating model (therefore total iterations (noIt) = *TPrep***numOM***numMS*).

GH.biol.data: the "True Population" through time (stock number, weights, maturities)

GH.stock.PV.yr.data: the “Perceived View” or the population through time (stores the final year from each years assessment i.e. the perceived view each year).

SR.data: stock recruit parameters (for *PA* MS only)

msTAC.data: MS specified TAC (recommended by MS - may differ from that actually caught if over-run or too few fish exist)

catch.data: catch at age

F.data: mean *F* ages 5-10

Appendix 2: Complete satisficing performance statistic results

Table A2.1. Satisficing performance statistic values at the corresponding risk levels for each of the seven management strategies on each operating model. **bold** = passes satisficing condition (i.e. value achieved at the risk level meets or exceeds the threshold requirement). All OMs have equal weighting.

	PS Name:	AAV			B:Btarget		B:Bmsy	B:40Bmsy	F:Fmsy		avgF:Fmsy		minCatch
	Type:		Sta		Res		Res	Res	Res		Res		Cat
	Term:	ST	MT	LT	MT	LT	LT	LT	MT	LT	MT	LT	LT
	Threshold:		<0.15		>0.8	>1	>1	>1	<1.2	<1	<1.2	<1	>3
	Risk (%):	50	50	50	50	25	50	5	25	25	25	25	15
	Wt:	1	1	1	1	1	1	1	0.5	0.5	0.5	0.5	1
MS	**OM**												
CC_16	*CAV*	**0.00**	**0.00**	**0.00**	0.69	0.02	**1.99**	0.00	**1.20**	3.40	1.56	2.32	0.15
	LMV	**0.00**	**0.00**	**0.00**	**1.30**	**4.50**	**2.26**	0.00	**1.04**	**0.20**	2.17	1.32	**14.62**
	CAV_domed	**0.00**	**0.00**	**0.00**	0.71	0.05	**2.43**	0.00	**0.99**	1.61	1.25	1.27	0.42
	CAV_varM	**0.00**	**0.00**	**0.00**	0.65	0.02	**1.86**	0.00	**0.78**	**0.80**	**0.97**	**0.91**	0.04
	CAV_dep	**0.00**	**0.00**	**0.00**	0.69	0.18	**1.57**	0.00	**1.10**	2.65	1.42	1.66	0.47
	LMV_dep	**0.00**	**0.00**	**0.00**	**1.63**	**7.87**	**2.28**	0.00	**0.79**	**0.12**	1.98	1.12	**16.00**
	CAV_mRic	**0.00**	**0.00**	**0.00**	**1.00**	**1.50**	**1.95**	**1.08**	**0.40**	**0.21**	**0.77**	**0.49**	**16.00**
	LMV_mRic	**0.00**	**0.00**	**0.00**	**1.56**	**4.33**	**5.19**	0.12	**0.27**	**0.07**	**0.64**	**0.37**	**16.00**
Fsq	*CAV*	0.17	**0.12**	**0.13**	0.29	0.01	0.11	0.00	2.24	3.65	1.77	2.36	0.12
	LMV	0.17	**0.13**	**0.15**	0.31	0.00	0.03	0.00	6.68	7.45	4.93	5.75	0.10
	CAV_domed	0.18	**0.13**	**0.13**	0.29	0.02	0.13	0.00	1.80	3.85	1.58	1.93	0.31
	CAV_varM	0.17	**0.13**	**0.13**	0.27	0.01	0.08	0.00	1.74	3.23	1.43	1.94	0.13
	CAV_dep	0.18	**0.13**	**0.13**	0.28	0.01	0.07	0.00	2.14	3.39	1.79	2.34	0.13
	LMV_dep	0.17	**0.13**	**0.14**	0.38	0.00	0.03	0.00	5.52	6.92	4.48	5.65	0.07
	CAV_mRic	0.17	**0.12**	**0.11**	0.42	0.07	0.28	0.02	1.55	2.01	1.36	1.57	2.00
	LMV_mRic	0.17	**0.13**	**0.12**	0.40	0.01	0.29	0.00	1.81	2.39	1.55	1.92	0.18

Table A2.1 *cont.*

MS	OM	AAV			B:Btarget		B:Bmsy	B:40Bmsy	F:Fmsy		avgF:Fmsy		minCatch
	PS Name:	**AAV**			**B:Btarget**		**B:Bmsy**	**B:40Bmsy**	**F:Fmsy**		**avgF:Fmsy**		**minCatch**
	Type:	**Sta**			**Res**		**Res**	**Res**	**Res**		**Res**		**Cat**
	Term:	**ST**	**MT**	**LT**	**MT**	**LT**	**LT**	**LT**	**MT**	**LT**	**MT**	**LT**	**LT**
	Threshold:		**<0.15**		**>0.8**	**>1**	**>1**	**>1**	**<1.2**	**<1**	**<1.2**	**<1**	**>3**
	Risk (%):	**50**	**50**	**50**	**50**	**25**	**50**	**5**	**25**	**25**	**25**	**25**	**15**
	Wt:	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**0.5**	**0.5**	**0.5**	**0.5**	**1**
MS	**OM**												
hF01	***CAV***	0.33	0.22	0.16	**1.49**	**2.04**	**2.52**	**4.29**	**0.35**	**0.42**	**0.33**	**0.34**	**4.02**
	LMV	0.33	0.24	0.20	**2.63**	**1.79**	**1.19**	0.48	**0.68**	4.43	**0.65**	1.07	**3.91**
	CAV_domed	0.32	0.22	0.16	**1.50**	**2.17**	**2.80**	**5.01**	**0.32**	**0.40**	**0.29**	**0.30**	**4.08**
	CAV_varM	0.30	0.21	0.14	**1.28**	**1.82**	**2.69**	**5.32**	**0.30**	**0.27**	**0.28**	**0.27**	**4.49**
	CAV_dep	0.33	0.24	0.17	**1.69**	**2.61**	**2.06**	**3.57**	**0.35**	**0.44**	**0.34**	**0.36**	**4.26**
	LMV_dep	0.32	0.26	0.21	**3.11**	**2.96**	**1.08**	0.64	**0.68**	3.70	**0.63**	**0.98**	**3.93**
	CAV_mRic	0.32	0.21	0.17	**1.46**	0.68	0.86	**1.41**	**0.28**	**0.32**	**0.28**	**0.29**	**4.05**
	LMV_mRic	0.33	0.24	0.18	**2.60**	**1.39**	**1.98**	**1.13**	**0.24**	**0.47**	**0.22**	**0.27**	**3.75**
PA	***CAV***	0.18	**0.15**	**0.12**	**1.01**	**1.12**	**1.41**	**2.27**	**0.65**	**0.90**	**0.71**	**0.71**	**7.68**
	LMV	0.20	0.18	**0.15**	**1.42**	0.55	0.31	0.40	1.56	6.61	1.47	**2.23**	**7.46**
	CAV_domed	0.20	**0.15**	**0.12**	**1.04**	**1.11**	**1.57**	**2.58**	**0.58**	**0.79**	**0.61**	**0.62**	**7.45**
	CAV_varM	**0.15**	**0.13**	**0.11**	**0.86**	**1.07**	**1.57**	**2.57**	**0.50**	**0.60**	**0.59**	**0.57**	**8.74**
	CAV_dep	0.17	0.16	**0.13**	**1.12**	**1.38**	**1.25**	**1.75**	**0.66**	**0.88**	**0.72**	**0.74**	**7.98**
	LMV_dep	0.17	0.19	0.16	**1.78**	0.89	0.31	0.36	1.54	5.46	1.45	2.19	**7.73**
	CAV_mRic	0.18	**0.15**	**0.12**	**1.04**	0.63	0.79	**1.13**	**0.54**	**0.73**	**0.58**	**0.60**	**7.97**
	LMV_mRic	0.19	0.17	0.15	**1.45**	0.18	0.42	0.31	**0.55**	2.17	**0.51**	**0.83**	**5.10**
modFree	***CAV***	**0.10**	**0.09**	**0.07**	**1.24**	**2.17**	**2.72**	**4.99**	**0.41**	**0.23**	**0.58**	**0.44**	**7.92**
	LMV	**0.10**	**0.09**	**0.06**	**2.14**	**6.33**	**2.55**	**4.98**	**0.55**	**0.21**	**1.00**	**0.65**	**8.57**
	CAV_domed	**0.10**	**0.09**	**0.07**	**1.21**	**2.19**	**2.96**	**5.33**	**0.39**	**0.24**	**0.54**	**0.41**	**8.11**
	CAV_varM	**0.09**	**0.08**	**0.06**	**1.06**	**1.74**	**2.54**	**4.86**	**0.36**	**0.24**	**0.46**	**0.37**	**8.45**
	CAV_dep	**0.10**	**0.11**	**0.08**	**1.31**	**3.05**	**2.29**	**4.70**	**0.46**	**0.23**	**0.58**	**0.45**	**7.90**
	LMV_dep	**0.10**	**0.11**	**0.08**	**2.51**	**8.19**	**2.30**	**3.83**	**0.58**	**0.23**	**1.02**	**0.68**	**8.33**
	CAV_mRic	**0.09**	**0.07**	**0.10**	**1.28**	**1.52**	**1.75**	**3.39**	**0.32**	**0.06**	**0.48**	**0.33**	**3.03**
	LMV_mRic	**0.09**	**0.07**	**0.10**	**2.18**	**4.48**	**5.18**	**10.21**	**0.20**	**0.02**	**0.37**	**0.22**	**3.64**

Table A2.1. *cont.*

	PS Name:	AAV			B:Btarget		B:Bmsy	B:40Bmsy	F:Fmsy		avgF:Fmsy		minCatch
	Type:		Sta		Res		Res	Res	Res		Res		Cat
	Term:	ST	MT	LT	MT	LT	LT	LT	MT	LT	MT	LT	LT
	Threshold:		<0.15		>0.8	>1	>1	>1	<1.2	<1	<1.2	<1	>3
	Risk (%):	50	50	50	50	25	50	5	25	25	25	25	15
	Wt:	1	1	1	1	1	1	1	0.5	0.5	0.5	0.5	1
MS	**OM**												
rbPlan	*CAV*	**0.07**	**0.04**	**0.04**	**1.04**	**2.19**	**2.54**	**4.70**	**0.42**	**0.29**	**0.71**	**0.49**	**11.54**
	LMV	**0.07**	**0.05**	**0.04**	**1.86**	**5.82**	**2.40**	**5.05**	**0.55**	**0.25**	**1.19**	**0.76**	**11.99**
	CAV_domed	**0.07**	**0.04**	**0.04**	**1.06**	**2.20**	**2.82**	**5.75**	**0.37**	**0.28**	**0.63**	**0.44**	**11.66**
	CAV_varM	**0.06**	**0.04**	**0.04**	**0.89**	**1.59**	**2.32**	**4.47**	**0.40**	**0.29**	**0.59**	**0.44**	**12.00**
	CAV_dep	**0.07**	**0.04**	**0.05**	**1.13**	**3.12**	**2.49**	**4.39**	**0.43**	**0.22**	**0.70**	**0.46**	**11.88**
	LMV_dep	**0.06**	**0.05**	**0.05**	**2.20**	**8.83**	**2.31**	**4.74**	**0.50**	**0.20**	**1.16**	**0.71**	**11.96**
	CAV_mRic	**0.06**	**0.05**	**0.04**	**1.25**	**1.06**	**1.30**	**2.18**	**0.31**	**0.44**	**0.52**	**0.40**	**12.20**
	LMV_mRic	**0.07**	**0.05**	**0.04**	**2.10**	**3.77**	**4.21**	**7.11**	**0.18**	**0.11**	**0.40**	**0.26**	**12.03**
Bfrac	*CAV*	0.18	0.16	**0.11**	**1.14**	**1.30**	**1.62**	**2.38**	**0.64**	**0.80**	**0.52**	**0.57**	**7.58**
	LMV	0.18	0.18	**0.15**	**1.95**	0.62	0.44	0.36	**1.08**	7.89	**0.96**	1.79	**7.61**
	CAV_domed	0.18	0.16	**0.10**	**1.15**	**1.36**	**1.75**	**3.18**	**0.57**	**0.70**	**0.47**	**0.52**	**7.70**
	CAV_varM	0.17	**0.15**	**0.10**	**0.98**	**1.30**	**1.95**	**3.77**	**0.56**	**0.46**	**0.45**	**0.45**	**7.80**
	CAV_dep	0.18	0.17	**0.11**	**1.32**	**1.80**	**1.47**	**2.43**	**0.64**	**0.82**	**0.53**	**0.56**	**8.03**
	LMV_dep	0.18	0.20	0.17	**2.24**	0.87	0.35	0.37	**1.13**	7.82	**0.96**	1.96	**7.60**
	CAV_mRic	0.18	0.16	**0.12**	**1.18**	0.35	0.52	0.52	**0.52**	**0.90**	**0.43**	**0.55**	**7.81**
	LMV_mRic	0.18	0.18	**0.13**	**2.02**	0.19	0.57	0.29	**0.34**	2.56	**0.32**	**0.63**	**7.23**

Table A2.2. Percentile levels (probability of meeting or exceeding the given value) corresponding to the satisficing performance statistic threshold values for each of the seven management strategies on each operating model. **bold** = passes satisficing condition (i.e. percentile values is less than the allowable risk level). All OMs have equal weighting.

	PS Name:	**AAV**			**B:Btarget**		**B:Bmsy**	**B:40Bmsy**	**F:Fmsy**		**avgF:Fmsy**		**minCatch**
	Type:	**Sta**			**Res**		**Res**	**Res**	**Res**		**Res**		**Cat**
	Term:	**ST**	**MT**	**LT**	**MT**	**LT**	**LT**	**LT**	**MT**	**LT**	**MT**	**LT**	**LT**
	Threshold:	**<0.15**			**>0.8**	**>1**	**>1**	**>1**	**<1.2**	**<1**	**<1.2**	**<1**	**>3**
	Risk (%):	**50**	**50**	**50**	**50**	**25**	**50**	**5**	**25**	**25**	**25**	**25**	**15**
	Wt:	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**0.5**	**0.5**	**0.5**	**0.5**	**1**
MS	**OM**												
CC_16	***CAV***	**0**	**5**	**20**	75	50	**50**	50	**50**	50	50	50	50
	LMV	**0**	**5**	**15**	**50**	**15**	**20**	15	**25**	**15**	80	50	**15**
	CAV_domed	**0**	**5**	**15**	75	50	**50**	50	**20**	50	50	50	50
	CAV_varM	**0**	**5**	**20**	75	50	**50**	50	**25**	**25**	**20**	**25**	50
	CAV_dep	**0**	**5**	**20**	75	50	**50**	50	**25**	50	50	50	25
	LMV_dep	**0**	**5**	**10**	**20**	**15**	**20**	15	**20**	**10**	75	50	**10**
	CAV_mRic	**0**	**0**	**5**	**50**	**10**	**10**	**5**	**5**	**5**	**5**	**5**	**5**
	LMV_mRic	**0**	**5**	**5**	**15**	**10**	**10**	10	**5**	**10**	**10**	**10**	**5**
Fsq	***CAV***	85	**25**	**50**	100	100	100	80	75	95	90	100	50
	LMV	85	**50**	**50**	95	80	100	90	100	100	100	100	75
	CAV_domed	85	**20**	**50**	100	100	100	80	75	90	75	100	50
	CAV_varM	80	**20**	**50**	100	100	100	90	75	90	75	90	50
	CAV_dep	80	**25**	**50**	100	100	100	95	80	85	90	100	50
	LMV_dep	80	**50**	**50**	90	75	100	80	100	100	100	100	75
	CAV_mRic	75	**10**	**15**	100	100	100	75	75	75	75	90	25
	LMV_mRic	80	**50**	**50**	90	75	75	75	50	50	50	75	50

Table A2.2 *cont.*

	PS Name:	AAV			B:Btarget		B:Bmsy	B:40Bmsy	F:Fmsy		avgF:Fmsy		minCatch
	Type:	Sta			Res		Res	Res	Res		Res		Cat
	Term:	ST	MT	LT	MT	LT	LT	LT	MT	LT	MT	LT	LT
	Threshold:		<0.15		>0.8	>1	>1	>1	<1.2	<1	<1.2	<1	>3
	Risk (%):	50	50	50	50	25	50	5	25	25	25	25	15
	Wt:	1	1	1	1	1	1	1	0.5	0.5	0.5	0.5	1
MS	OM												
hF01	*CAV*	100	100	75	0	0	0	0	0	5	0	0	5
	LMV	100	100	100	0	15	50	20	0	75	0	50	5
	CAV_domed	100	100	75	0	0	0	0	0	5	0	0	5
	CAV_varM	100	100	50	0	0	0	0	0	0	0	0	0
	CAV_dep	100	100	80	0	0	5	0	0	5	0	0	5
	LMV_dep	100	100	100	0	5	50	15	0	75	0	25	5
	CAV_mRic	100	100	80	0	75	75	5	0	5	0	0	5
	LMV_mRic	100	100	100	0	15	20	5	0	15	0	0	5
PA	*CAV*	75	50	10	20	25	15	0	0	15	0	0	0
	LMV	75	75	75	5	75	100	75	75	100	75	100	0
	CAV_domed	75	75	15	10	15	5	0	0	10	0	0	0
	CAV_varM	75	50	5	25	20	5	0	0	5	0	0	0
	CAV_dep	75	75	50	5	5	50	0	0	20	0	0	0
	LMV_dep	75	85	75	0	50	100	75	75	100	75	100	0
	CAV_mRic	75	50	10	5	90	85	5	0	10	0	5	0
	LMV_mRic	75	75	75	5	85	85	50	5	75	5	5	5
modFree	*CAV*	20	5	0	10	0	0	0	0	0	0	0	0
	LMV	15	5	0	0	0	0	0	0	0	10	0	0
	CAV_domed	15	5	0	5	0	0	0	0	0	0	0	0
	CAV_varM	10	0	0	15	0	0	0	0	0	0	0	0
	CAV_dep	15	10	0	5	0	0	0	0	0	0	0	0
	LMV_dep	20	15	0	0	0	0	0	5	0	10	5	0
	CAV_mRic	5	0	0	0	0	0	0	0	0	0	0	15
	LMV_mRic	10	5	0	0	0	0	0	0	0	0	0	5

Table A2.2 *cont.*

	PS Name:	AAV			B:Btarget		B:Bmsy	B:40Bmsy	F:Fmsy		avgF:Fmsy		minCatch
	Type:	Sta			Res		Res	Res	Res		Res		Cat
	Term:	ST	MT	LT	MT	LT	LT	LT	MT	LT	MT	LT	LT
	Threshold:		<0.15		>0.8	>1	>1	>1	<1.2	<1	<1.2	<1	>3
	Risk (%):	50	50	50	50	25	50	5	25	25	25	25	15
	Wt:	1	1	1	1	1	1	1	0.5	0.5	0.5	0.5	1
MS	**OM**												
rbPlan	***CAV***	**0**	**0**	**0**	**15**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	LMV	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**25**	**5**	**0**
	CAV_domed	**0**	**0**	**0**	**10**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	CAV_varM	**0**	**0**	**0**	**50**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	CAV_dep	**0**	**0**	**0**	**15**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	LMV_dep	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**20**	**5**	**0**
	CAV_mRic	**0**	**0**	**0**	**5**	**20**	**20**	**0**	**0**	**0**	**0**	**0**	**0**
	LMV_mRic	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Bfrac	***CAV***	95	75	**5**	**5**	**10**	**10**	**0**	**0**	**15**	**0**	**5**	**0**
	LMV	95	100	**50**	**0**	50	100	50	**20**	100	**5**	90	**0**
	CAV_domed	95	75	**0**	**0**	**5**	**5**	**0**	**0**	**10**	**0**	**0**	**0**
	CAV_varM	85	**50**	**0**	**10**	**5**	**0**	**0**	**0**	**5**	**0**	**0**	**0**
	CAV_dep	95	80	**5**	**0**	**0**	**10**	**0**	**0**	**20**	**0**	**0**	**0**
	LMV_dep	90	100	80	**0**	50	95	75	**15**	100	**0**	90	**0**
	CAV_mRic	90	75	**5**	**5**	100	100	50	**0**	**25**	**0**	**5**	**0**
	LMV_mRic	95	100	**50**	**0**	75	75	50	**0**	75	**0**	**0**	**0**

Appendix 3: Biological reference points for the operating models in the MSE reference set

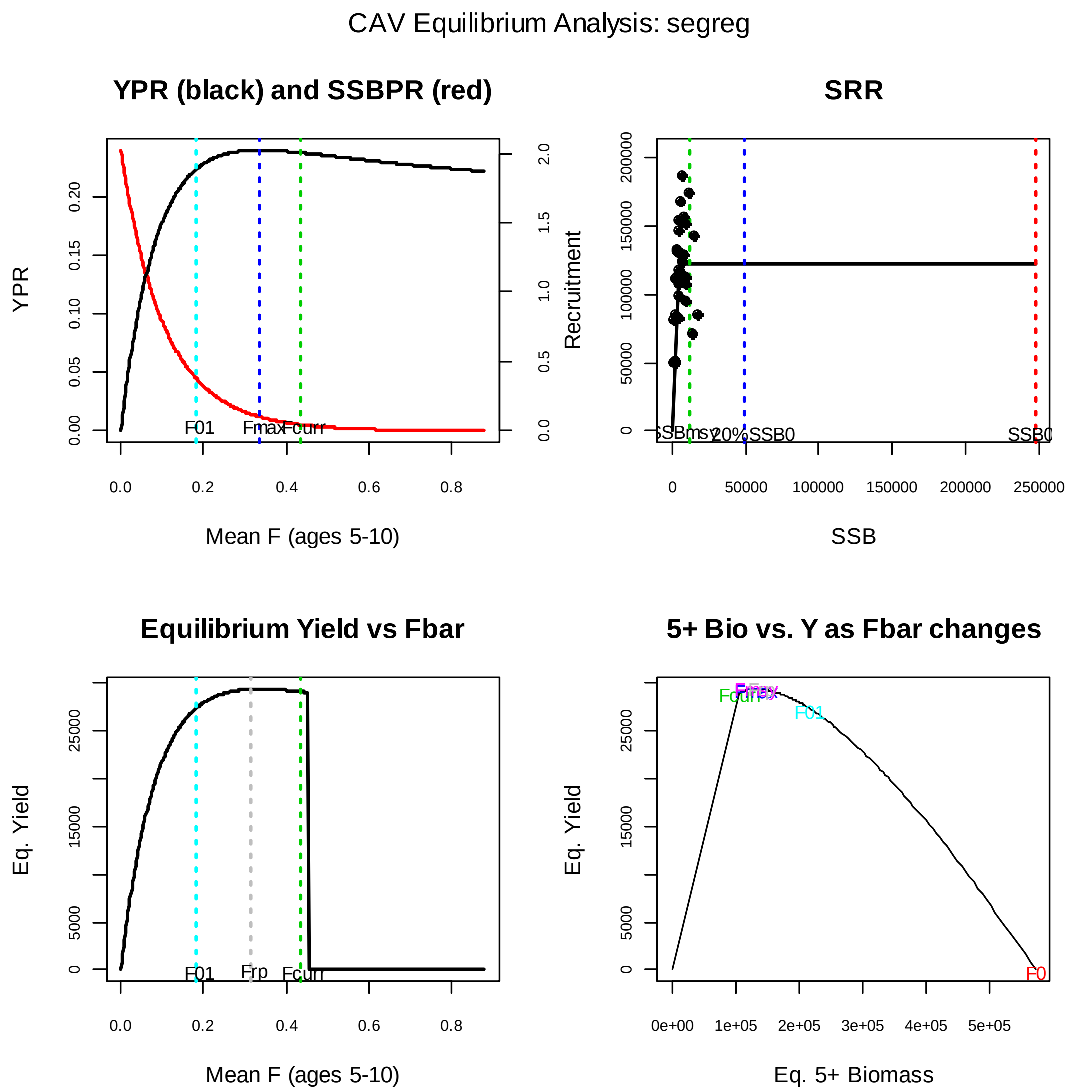

Fig. A3.1. Equilibrium analysis showing the biological characteristics and stock dynamics for the *CAV* operating model. Recruitment is generated using a segmented regression stock-recruit relationship (SRR).

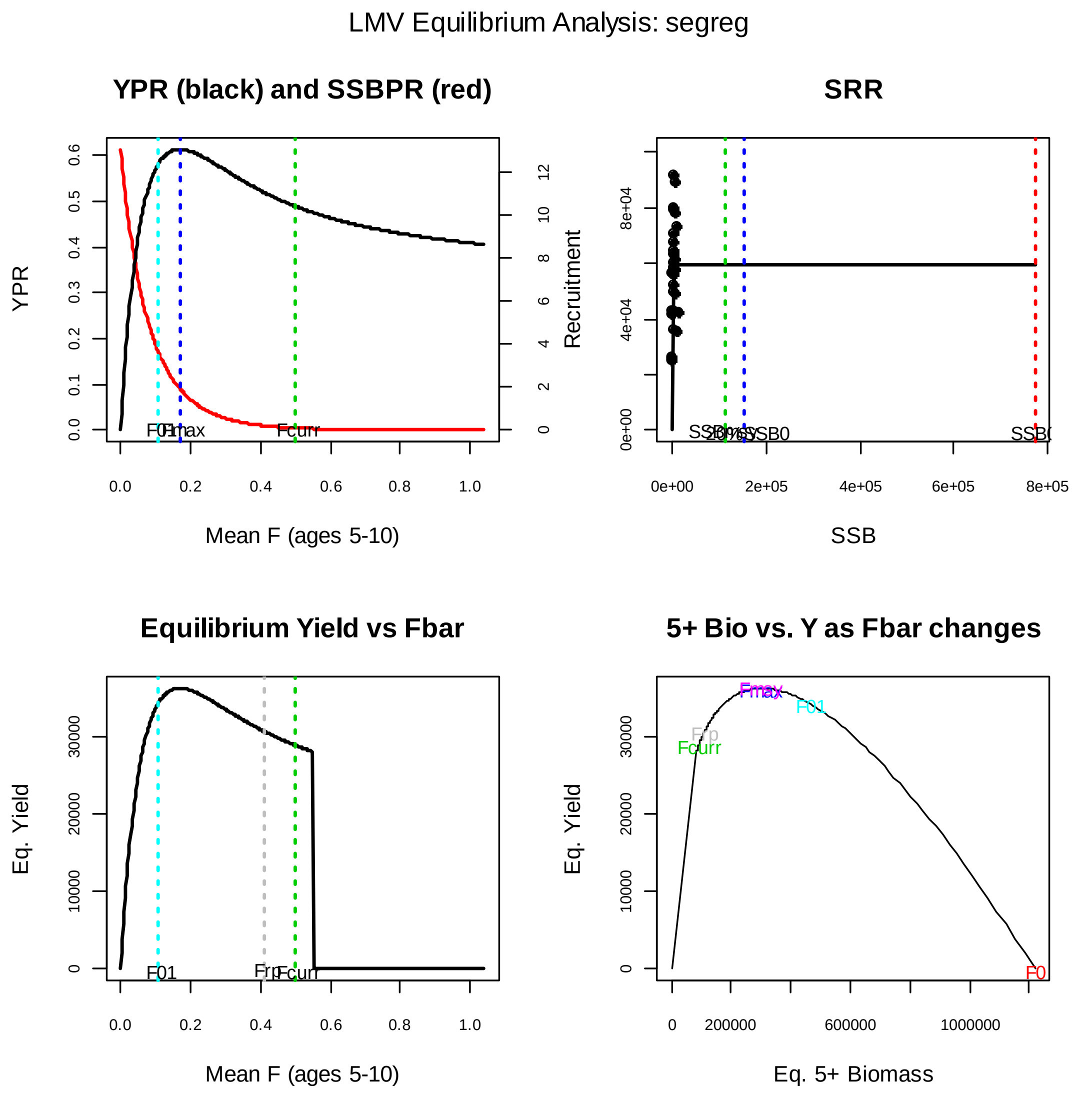

Fig. A3.2. Equilibrium analysis showing the biological characteristics and stock dynamics for the *LMV* operating model. Recruitment is generated using a segmented regression stock-recruit relationship (SRR).

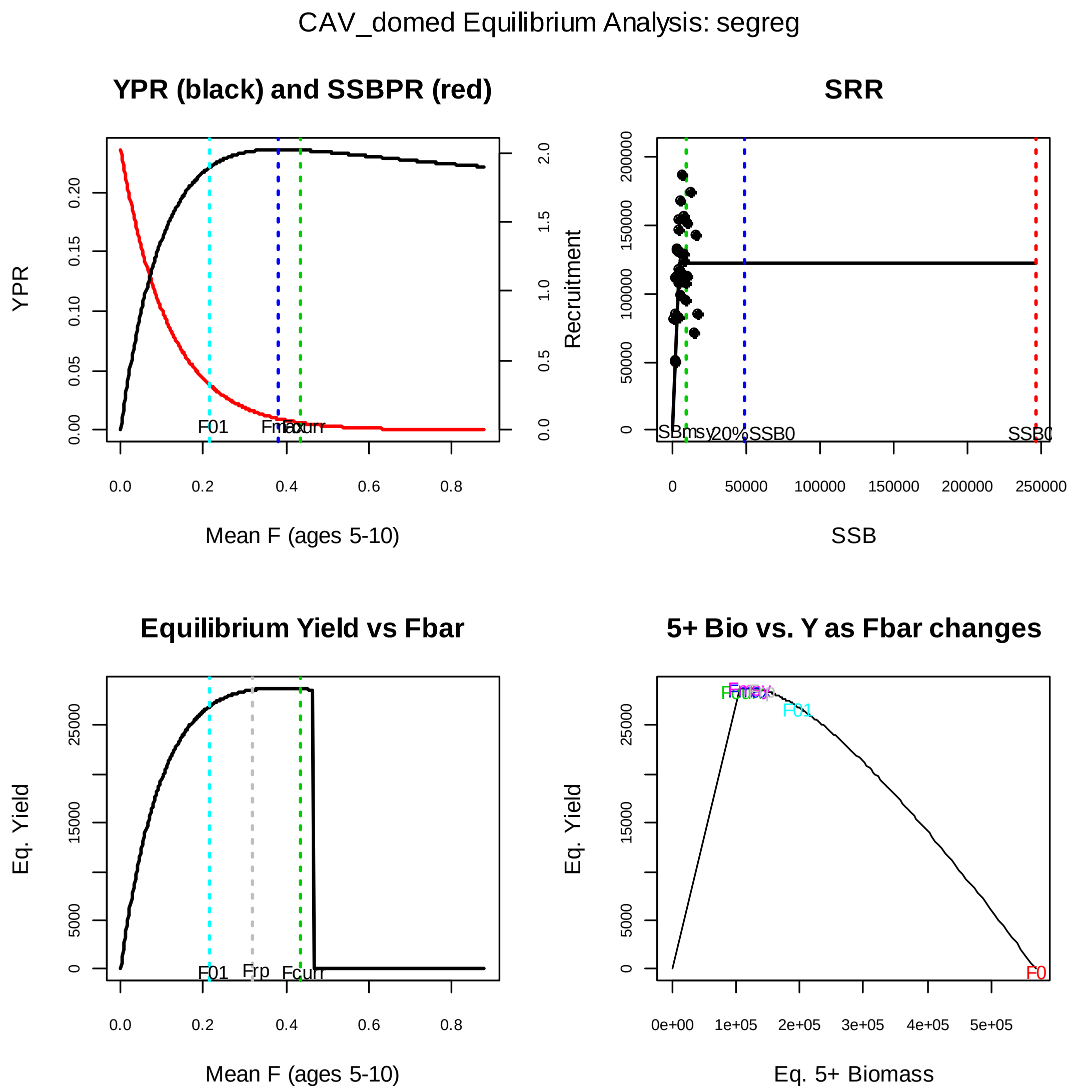

Fig. A3.3. Equilibrium analysis showing the biological characteristics and stock dynamics for the *CAV_domed* operating model. Recruitment is generated using a segmented regression stock-recruit relationship (SRR).

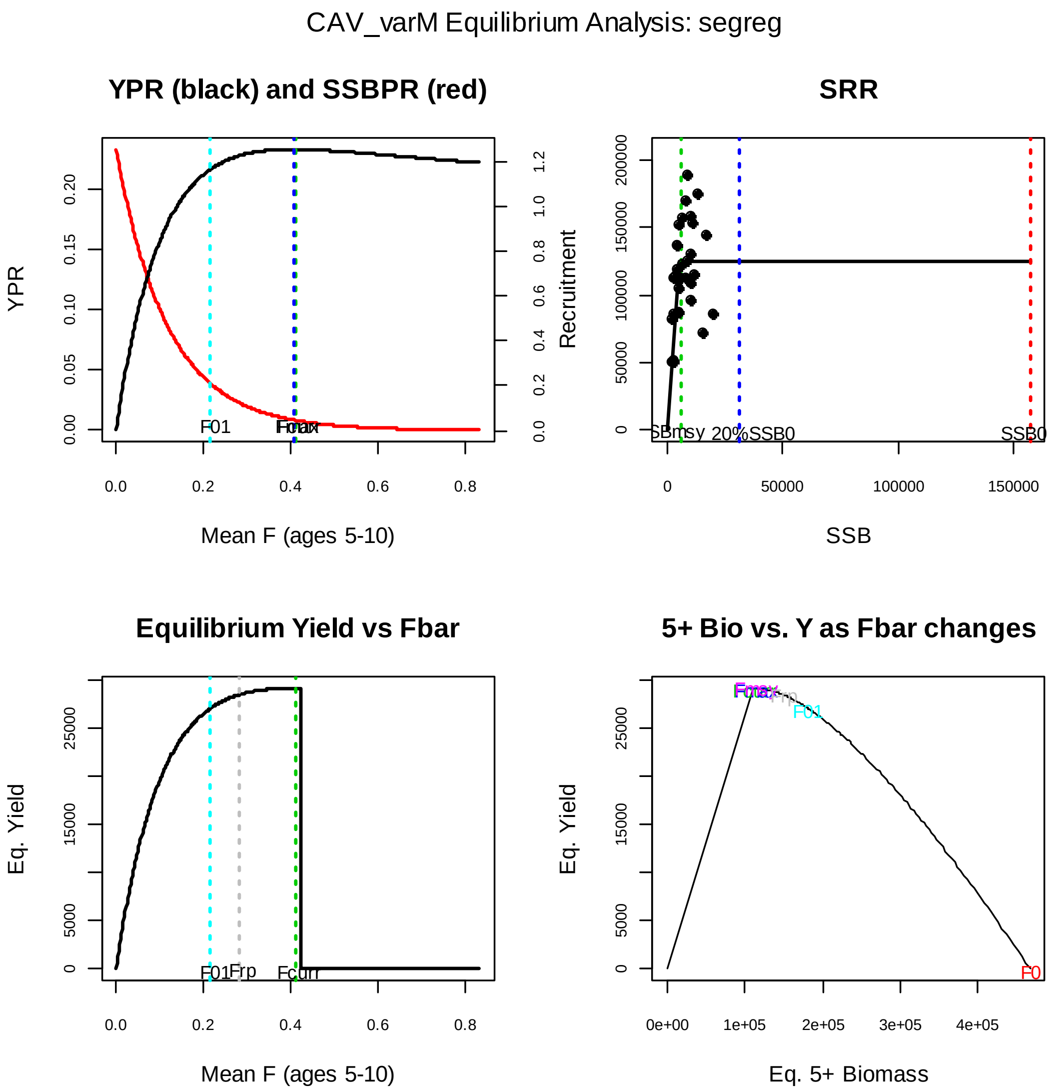

Fig. A3.4. Equilibrium analysis showing the biological characteristics and stock dynamics for the *CAV_varM* operating model. Recruitment is generated using a segmented regression stock-recruit relationship (SRR).

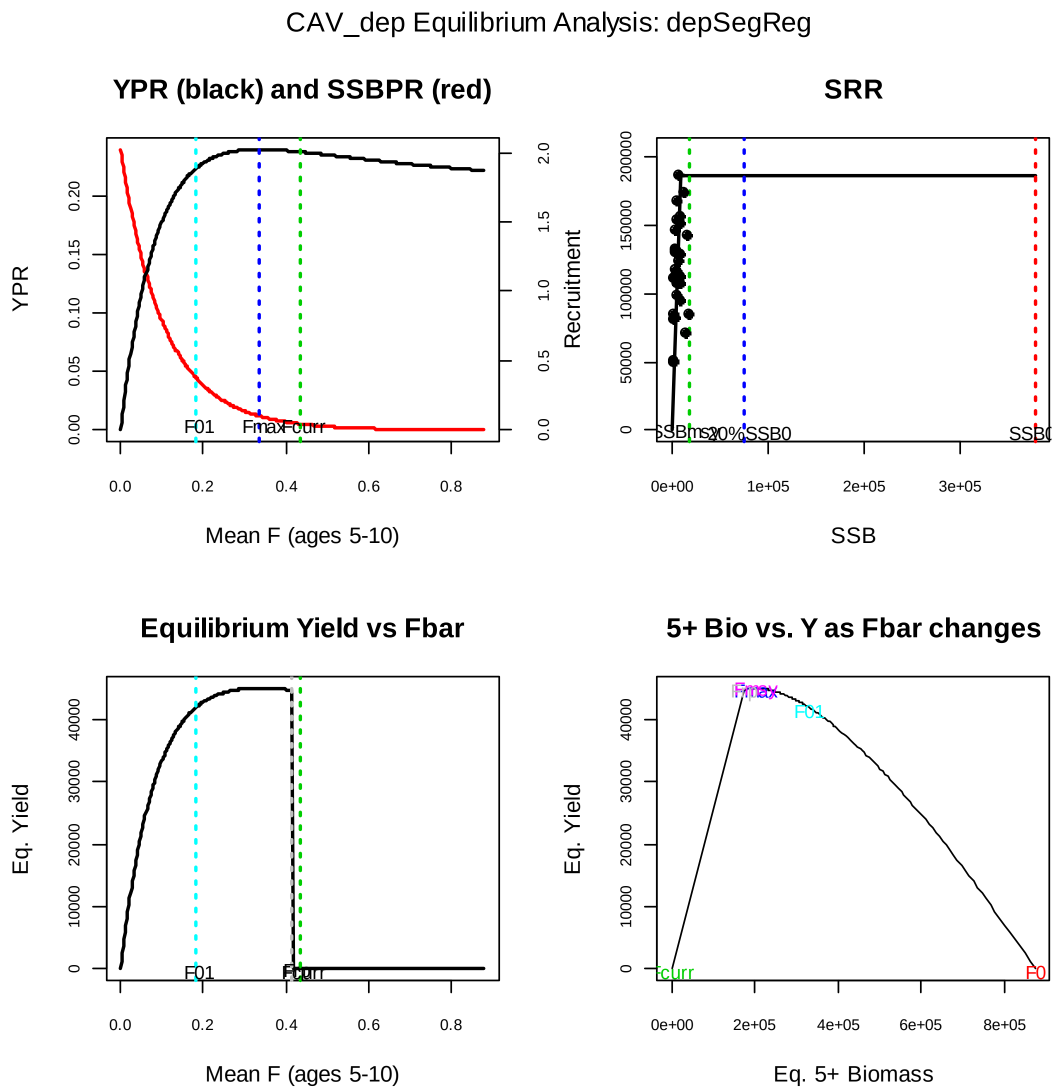

Fig. A3.5. Equilibrium analysis showing the biological characteristics and stock dynamics for the *CAV_dep* operating model. Recruitment is generated using a segmented regression stock-recruit relationship (SRR).

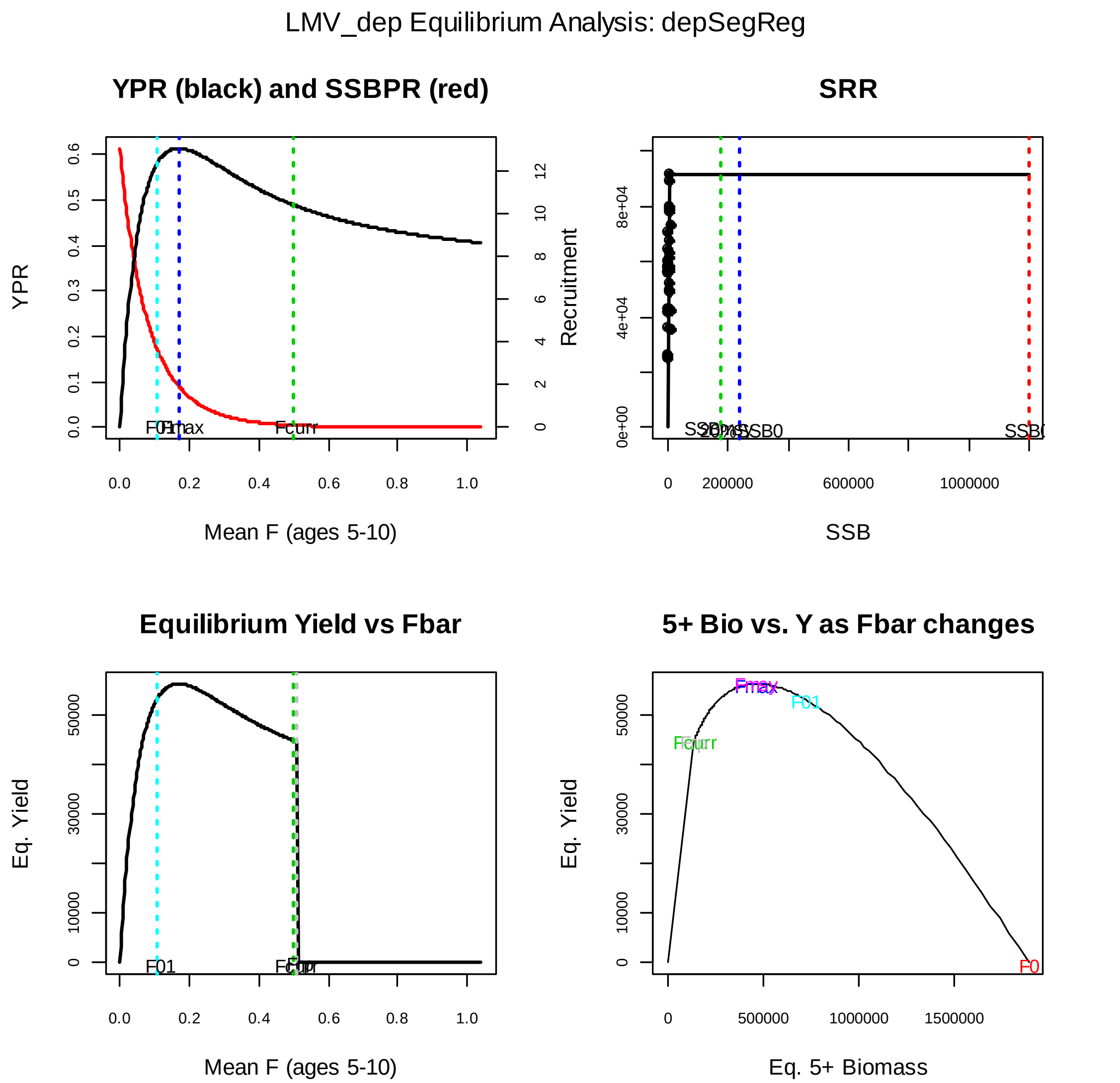

Fig. A3.6. Equilibrium analysis showing the biological characteristics and stock dynamics for the *LMV_dep* operating model. Recruitment is generated using a segmented regression stock-recruit relationship (SRR).

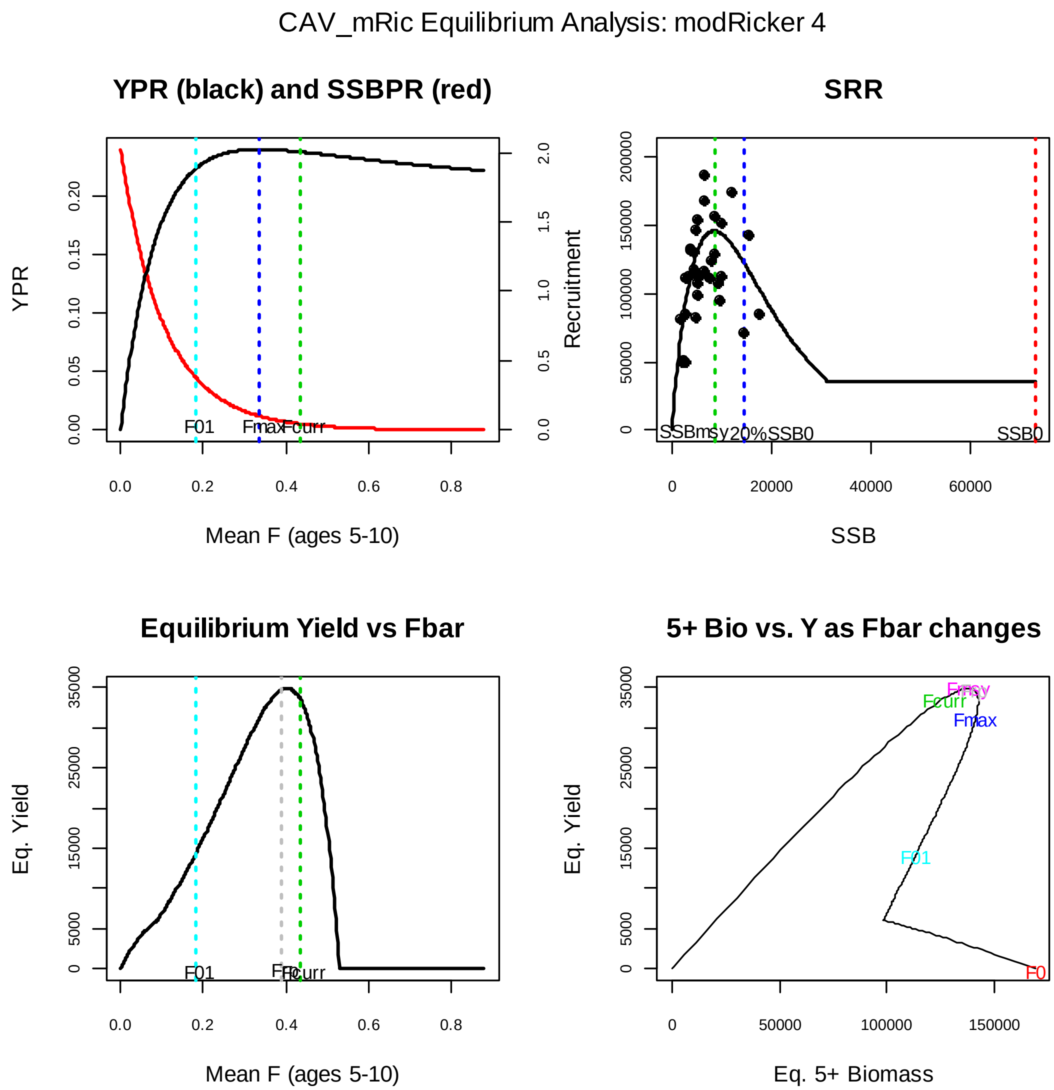

Fig. A3.7. Equilibrium analysis showing the biological characteristics and stock dynamics for the *CAV_mRic* operating model. Recruitment is generated using a segmented regression stock-recruit relationship (SRR).

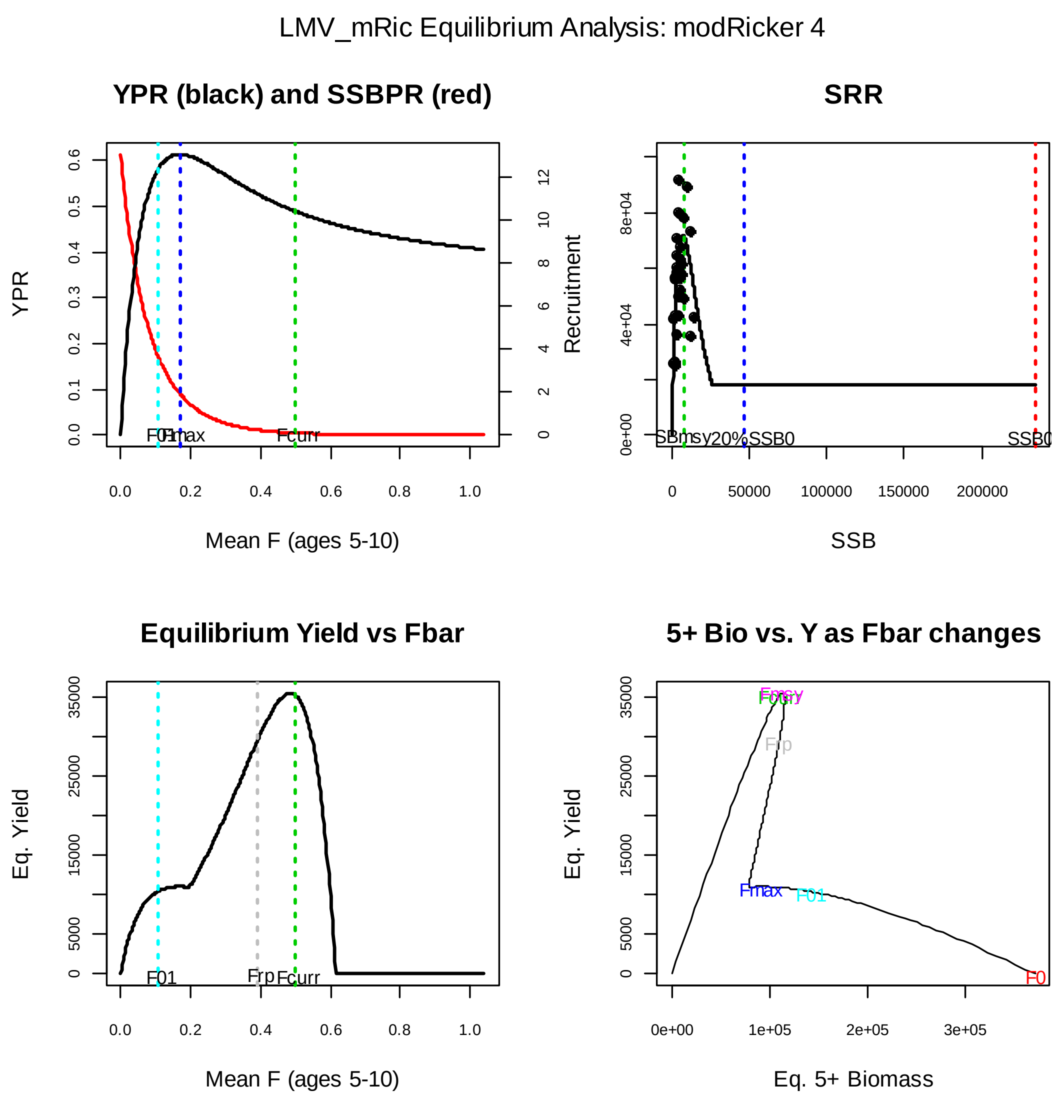

Fig. A3.8. Equilibrium analysis showing the biological characteristics and stock dynamics for the *LMV_mRic* operating model. Recruitment is generated using a segmented regression stock-recruit relationship (SRR).