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Management strategy evaluation for Greenland halibut (*Reinhardtius hippoglossoides*) in NAFO Subarea 2 and Divisions 3LKMNO

by

David C. M. Miller, Peter A. Shelton, Brian P. Healey, M. Joanne Morgan and William B. Brodie

Science Branch
Department of Fisheries and Oceans, Northwest Atlantic Fisheries Center
PO Box 5667, St John's
Newfoundland and Labrador A1C 5X1
Canada

Abstract

A rebuilding plan for the 2+3KLMNO Greenland halibut stock developed by NAFO Fisheries Commission has been in effect since 2003. Under the plan, *ad hoc* TAC reduction steps were specified to 2007. The most recent assessment of this stock indicates that the rebuilding plan has been ineffective in initiating any recovery. Fishing mortality continues to be far above Precautionary Approach reference levels and spawner biomass has continued to decline to very low levels. Management Strategy Evaluation provides a way of examining the performance of candidate management strategies with respect to rebuilding the stock. In particular, it allows the robustness of these strategies to be considered relative to alternative operating models of the "real world", for example the nature of the stock-recruit function for this stock. The analysis is carried out in FLR (Fisheries Libraries in R) environment, a new open source framework for the development and evaluation of management strategies. Results are provided for three simple management strategies – TAC status quo, F status quo and $F_{0.1}$ to illustrate the approach across a restricted reference set of operating models. A more comprehensive analysis would require broader input on an expanded set of operating models and the development of harvest control rules that incorporate PA reference points for this stock.

Key words: management strategy evaluation, operating model, fisheries management, management objectives, performance measures, stock-recruit, bootstrap, simulation

Introduction

The distribution of Greenland halibut in the Northwest Atlantic is continuous along the continental slope within NAFO Subareas 0, 1, 2 and 3 (Bowering and Brodie, 1995). An argument could be made to treat this entire distributional range as a single unit for stock assessment and management purposes. This is strengthened by the theory that most of the spawning occurs in the Davis Straight area (Bowering and Brodie, 1995). Smaller Greenland halibut fisheries also occur in the Gulf of St. Lawrence, in fjords off West Greenland and in Cumberland Sound, and may be on separate stocks. This paper introduces management strategy evaluation (MSE) for the 2+3KLMNO management unit, but could be expanded to include Subarea 0 and 1 if these are considered to be part of the same management unit at some point in the future. Alternatively, management strategies could be evaluated for robustness to population fragmentation through management unit boundaries.

The fishery for Greenland halibut in eastern Canada goes back to 1857 (Bowering and Brodie, 1995). Landings fluctuated between 250 and 1,000 t annually between 1916 and the early 1960s. The early fishery was conducted by longline and restricted to the deep channels in the bays. With the increase in factory freezer trawler activity in the offshore and the introduction of synthetic gillnets in the inshore, the nominal catches increased through the 1960s reaching a peak of about 37,000 t by 1969. Given that the stock was not under quota management and that much of the catch was processed at sea by factory freezer trawlers and factory mother ships, such as the Professor Baranov, capable of processing and freezing up to 100 tons of groundfish per day, the actual magnitude of fish dying from fishing operations must be assumed to be poorly known. It should also be noted that, while these nominal catches may seem modest compared to the equivalent data for northern cod over the same period, Greenland halibut is a slow growing, late-maturing, long-lived, deep-water species. Depending on the size of the stock and the actual catches, it is possible that fishing mortality was not sustainable during the late 1960s and early 1970s on Greenland halibut in the northwest Atlantic, consistent with the heavy overfishing occurring on other, better studied, groundfish stocks in the area at the time, such as cod, American plaice and yellowtail flounder. It is also clear that Greenland halibut was systematically overfished by gillnets in the deepwater bays around eastern Newfoundland in the late 1960s and early 1970s. This fishery eventually moved offshore in the 1980s, first to the mid-shore deepwater channels in Divs. 2J and 3K, and eventually to the deepwater slopes in SA 2+3.

Greenland halibut stock in Subarea 2 and Div. 3KL first came under TAC management by Canada in 1974. The TAC in this area increased from 35,000 t in 1980 to 55,000 t in 1981-84, 75,000 t in 1985, and 100,000 t in 1986-89. These increases in TACs were the result of research vessel survey estimates of stock biomass (in excess of 400,000 tons) which indicated presence of both high levels of fishable biomass as well as prospects of several better than average recruiting year-classes. The TACs were intended to apply to the entire stock area, and not just the portion in Canadian waters. After observing an estimated reduction in stock biomass from the late 1970s to the late 1980s in Subarea 2 and Div. 3KL of about 50%, the TAC was reduced to 50,000 t in 1990 and this level was maintained to 1993 despite further substantive declines in stock size throughout the normal range of observed historical stock distribution. The late 1980s-early 1990s coincided with a period of increased fishing effort in the regulatory area with the influx of about 40 Spanish factory freezer vessels displaced from Namibia. There was an increase in the violation of NAFO regulations over this period, including under-reporting and the use of illegal small mesh trawls. Although Scientific Council, in its deliberations during June 1993, could not advise on an appropriate catch level for 1994, the TAC was reduced to 25,000 tons by Canada in Subarea 2 and Divisions 3KL in consideration of low levels of stock size estimated for this area. It was intended that this TAC should include all catches in Subarea 2 and 3 for conservation purposes. Nevertheless, catches in the NAFO Regulatory area continued unregulated. In 1994, management of Greenland halibut in Subarea 2 and Div. 3KLMNO (note the change to include Div. 3MNO) became the responsibility of NAFO Fisheries Commission which imposed a TAC of 27,000 t for 1995. This level was maintained for 1996 and was proportioned throughout the management area in an attempt to reduce high concentrations of effort in localized areas. By 2003 the TAC had increased to 42,000 t.

The 2003 NAFO assessment (Darby *et al*., 2003) of Greenland halibut was a landmark event. There was a major downward revision relative to the previous assessment which had indicated a growing stock. This downward revision was based on an additional year of data and a change in the XSA formulation. Instead of a growing stock, it estimated that the exploitable biomass had decreased to the lowest level in the recorded time series and that fishing mortality was increasing and was double the level of $F_{0.1}$ (Darby *et al*., 2003). Projections showed that a continuation of the catch at the prevailing level would rapidly collapse the stock, and SC advised a reduction in TAC to 16,000 in 2004. NAFO Fisheries Commission responded by putting in place a fifteen year rebuilding plan with the objective of attaining a target of 140,000 tons exploitable (5+) biomass. TAC levels were set for 2004-2007 at 20 kt, 19 kt, 18.5 kt and 16 kt, respectively. The intention was that subsequent TACs would depend on rebuilding progress, but with a 15% cap on any year-to-year change. Thus 2007 is the last year of specified TAC reductions. These TAC steps have been implemented, but estimated catches have exceeded TACs by about 25%, fishing mortality has continued to increase, and biomass to decrease. The 2006 assessment found that average fishing mortality (ages 5-10) for 2005 was 0.63, over 2.5 times the F_{max} level and four times the $F_{0.1}$ level. Also, violations of NAFO regulations have continued, including miss-identification of catch from the NAFO regulatory area as Hatton Bank Greenland halibut (i.e. from the Northeast Atlantic). Shelton (2005a, 2005b) criticised the Fisheries Commission rebuilding plan for having no scientific basis and for not being submitted for scientific peer review. Shelton (2005a) concluded that the plan was considerably less cautious than one which would be specified under a Precautionary Approach. In addition, he found that the rebuilding was not robust to retrospective error in estimates of recruitment nor was it robust to alternative assessment methods. Shelton (2005b) concluded that, in order to be compliant with the Precautionary Approach, fishing mortality should be immediately reduced to below $F_{0.1}$. A variable-F rebuilding plan was described and subject to preliminary simulation testing in which fishing mortality is initially set at 0.5x$F_{0.1}$, but increases to $F_{0.1}$ as the stock rebuilds. This strategy outperformed alternative constant-F strategies in the simulation.

The Precautionary Approach has been adopted in principle by NAFO and Canada for the management of fish stocks in the Northwest Atlantic, but implementation has lagged (Shelton, 2007). Limited reference points have been suggested for some stocks. For example, B_{lim} for Divs. 3LNO yellowtail flounder is considered to be 30%B_{msy} and advice is provided on the basis of a 2/3F_{msy} harvest control rule. This advice has been followed in the recent past and the stock could be considered to be sustainably managed at the present time. The yellowtail management strategy does not specify how fishing mortality will change should the stock decline towards B_{lim}. For stocks for which there is an analytical assessment, NAFO Fisheries Commission makes the following standing requests for information from Scientific Council. As general reference points, the implications of fishing at $F_{0.1}$ and F_{current} in the next year and subsequent years should be evaluated. When spawner biomass reference points have been identified, short and medium term consequences should be identified for various exploitation rates (including no fishing) in terms of yield, stability in yield from year to year, and the risk or probability of maintaining the stock within, or moving it to, the Safe Zone. In order to consider the balance between risks and yield levels, each management strategy evaluation should provide risks and yields associated with various harvesting options in relation to B_{lim}, and F_{lim} and target F reference points selected by managers. Also, the present stock size and spawning stock size should be described in relation to those observed historically and those expected in the longer term under this range of options. Spawning stock biomass levels considered necessary for maintenance of sustained recruitment should be recommended for each stock. In those cases where present spawning stock size is a matter of scientific concern in relation to the continuing reproductive potential of the stock, management options should be offered that specifically respond to such concerns.

Although reference points have not been determined for SA 2+3KLMNO Greenland halibut, it seems that the present rebuilding strategy contradicts most of the principles for sustainable fisheries espoused above by NAFO. Fishing mortality is extremely high and spawner biomass is extremely low and declining. If precautionary approach reference points can be determined and accepted for the stock, then these could be incorporated in the development of a harvesting control rule which could be tested to determine if it performs in such a way that the risk of the stock falling outside the safe zone is relatively low and, for a depleted stock, the probability of rebuilding to the safe zone within a prescribed period of time is high.

Management strategy evaluation (MSE) is based on a time-proven approach of evaluating models through simulation before using them as a basis for decision-making. This approach gained increased prominence though the evaluation of management procedures by the International Whaling Commission and is described in Kirkwood and Smith (1996) and more recently in ICES by Kell *et al*. (2007) in the context of a new stock assessment environment in R-code called FLR (Fisheries Library in R). We work within the FLR environment in our MSE study of Greenland halibut. In this paper we scope out MSE in FLR for SA 2+3KLMNO Greenland halibut. We present a MSE structure for evaluating potential management strategies, identify the major inputs required to simulation-test a management strategy and identify the main areas of uncertainty. Finally, we present the results of a test run of this procedure evaluating two F-based strategies as an example of the type of results that can be expected. A thorough evaluation of management strategies is warranted for this stock in order to put in place a PA-compliant and robust sustainable management strategy that should result in the stock rapidly rebuilding to the Safe Zone and have a high probability of keeping the stock in the Safe Zone in the long-term.

Conceptual framework

The conceptual framework for Management Strategy Evaluation (MSE), adapted from Kell *et al.* (2007), comprises an operating model and a management procedure (Fig. 1). In this approach an "operating model" is constructed to simulate the fish stock and the fishery, and is conditioned on the available data to be a realistic representation. The operating model represents the "true" system and incorporates biological processes that make up the stock dynamics and fishery processes that result in the capture of fish. Conditioning of the operating model requires the estimation of parameters consistent with the data and hypotheses about how these were generated. These govern processes such as recruitment, growth, maturation and mortality with respect to stock dynamics, and selectivity at age with respect to the fishery. To implement MSE on the Greenland halibut stock, initial conditions for the population model are taken to be the most recent XSA estimates from the NAFO stock assessment (Healey and Mahé, 2006). The operating model represents the simulated "Real World" and is used to evaluate the performance of management procedures applied to a perceptions of this Real World – the "Perceived World", generated from the observed data and the fitted model. Performance statistics evaluate how well a particular management strategy is performing relative to other candidate strategies. The strategy can be implemented with implementation error, such as a TAC overrun, on the simulated real fishery, which in turn impacts the simulated real stock. This sequence is repeated many times over some planning horizon in order to evaluate alternative management strategies through the generation of distributions for the performance statistics. In the Greenland halibut implementation, data for catch, 5+ stock biomass, 10+ stock biomass, spawner biomass and average fishing mortality are collected. Strategies that are robust to the uncertainty with respect to falling into NAFO PA Zones 2-5 would be favoured under a PA approach, however specific PA reference points have not yet been accepted for this stock. Given that there may be a number of major hypotheses regarding the biology of the stock, for example, the appropriate recruitment function, a reference set of operating models is required that capture these hypotheses rather than only a single operating model. We present a limited reference set in the present analysis and apply the procedure on only one, but an expanded set should be considered in future work.

There are five key elements in the MSE approach (Smith *et al.*, 1999):

1. Management objectives,
2. Performance measures,
3. Alternative management strategies,
4. Simulation evaluation of alternative management strategy performance, and
5. Presenting the results to decision makers.

1. Management objectives

Clear management objectives are necessary before any evaluation of potential management strategies can be undertaken. General objectives, common to most fisheries stocks include a low risk of depletion of the stock while maintaining a reasonably high average annual catch (yield) and maximizing the stability of catches year to year. It is also preferable to have a management strategy that is robust to uncertainties in the dynamics of the population. With regards to the PA, a good management strategy should have a high probability of maintaining the stock within, or moving it to, the Safe Zone. Management objectives specific to the 2+3KLMNO Greenland halibut are specified under the rebuilding plan laid out by NAFO Fisheries Commission in 2003 (FC Doc 03/13): rebuild the stock to 140,000t exploitable (5+) biomass by 2018 while minimising the annual reduction in catch (no more than 15% change from year to year).

2. Performance measures

Performance measures need to be quantifiable statistics that can be used to directly compare the performance of each candidate management strategy in terms of the management objectives. These are needed in addition to descriptive statistics of the stock dynamics under a given management strategy. Based on the management objectives for 2+3KLMNO Greenland halibut these would include:

1. The probability of achieving 140,000t exploitable biomass in 2018 (risk profiles),
2. The ratio of exploitable biomass in 2018 to the current exploitable biomass as a measure of the growth of 5+ biomass (B_{2006}/B_{2018}),
3. The average catch/yield, and
4. The average annual variation in catch (AAV).

Other stock parameters reported include annual exploitable (5+) biomass, spawner stock biomass, recruitment, catch and *F* values (means or medians and percentiles).

3. Alternative management strategies

A risk-adverse management strategy should involve a decrease in *F* with decreasing biomass, in line with the PA. The past management of this stock has resulted in the exact opposite outcome – fishing mortality has tended to increase with decreasing stock size (Fig. 2). Management strategies that are compliant with the PA and thus provide for fishing mortality decreasing as stock size decreases would be preferred. However, given the absence of any PA reference points for this stock it is necessary to consider either simple F-based or TAC-based strategies.

4. Simulation testing

Simulation testing involves applying the alternative management strategies to an operating model constructed to simulate the fish stock and the fishery. The operating model is conditioned on the best available data and hypotheses on the dynamics of the stock. The operating model represents the Real World over the duration of the simulation and management strategies are applied based on data taken from this simulated Real World. A lot of uncertainty exists around the dynamics of the 2+3KLMNO Greenland halibut, so instead of a single representation of 'reality" it is advisable to consider many options encompassing most of the possibilities to deal with this uncertainty. A group of operating models each conditioned on different data or based on an alternative hypothesis of the stock dynamics or future trends in the fishery, is referred to as a reference set of operating models. In order to carry out a full management strategy evaluation, one need to examine each strategy under each operating model in the reference set. It is recommended that in the order of 100 simulations are run for each management strategy for each operating model (Rademeyer *et al*. 2007).

Conditioning of operating models requires consideration of the past system and initial starting point of the population, biological parameters of the stock, behavior of the fishery/fleet(s) and the level of uncertainty/error in the observation of the system.

Beginning at the initial starting point, numbers at age for ages 2 and up are projected using the basic equation for updating population size (equation 1). Natural mortality (M) and partial recruitment (PR) are specified by the operating model, while fishing mortality (F) depends on the harvest control rule (HCR) based on the management strategy being evaluated. Recruitment (numbers at age 1) is determined by the stock-recruit model applied in the operating model.

$$N_{a+1,y+1} = N_{a,y} \exp^{-(M+F\times PR_a)} \qquad (1)$$

Where: $N_{a,y}$ = numbers at age a in year y,
M = natural mortality,
F = fishing mortality,
PR_a = partial recruitment (selectivity) at age a.

Past system/starting point

The MSE procedure works by simulating stock dynamics (the Real World) and basing management decisions of the perception of this Real World. If the perception is derived based on an assessment model, it is necessary to have at least ten years of Real World data on which to base the assessment prior to the point from which one intends to evaluate management strategies. MSE can be used to evaluate strategies for a particular stock in terms of general ability to maintain a healthy stock or in terms of specific objectives for the current stock. The first case is a more philosophical approach under which the ideal management strategy would produce satisfactory results irrelevant of the condition of the stock (i.e. abundant, declining or collapsed). In such a case a variety of initial starting points may be generated in keeping with the stock structure and dynamics of the stock in question. The exploitable biomass target management objective for 2+3KLMNO Greenland halibut is specific to the stock as perceived through assessments at present. Therefore, to assess the ability of a management strategy to achieve this objective it is necessary to construct the past system and current starting point to be as close as possible to the real stock at this present time.

Important elements to that are needed to construct the past system/starting point include: age structure of the stock, stock abundance (numbers at age), fishery catch data (age disaggregated), weights at age, maturities at age and natural mortality. The age structure of the simulated stock should agree with the best hypotheses and data available for the stock. Numbers at age are best calculated by fitting available abundance indices through the preferred assessment model. The annual assessment of the 2+3KLMNO Greenland halibut stock has been based on Extended

Survivors Analysis (XSA; Shepherd, 1999) for a number of years (e.g. Healey and Mahé, 2006). Three survey series of age disaggregated abundance indices (mean numbers per tow, MNPT) are available:

1. EU 3M - a European Union summer survey in Div. 3M from 1995-2005, ages 1-12 (González Troncoso *et al.*, 2006).
2. Can 2J+3K autumn survey, Campelen trawl data from 1996-2005, ages 1 to 14 (Healey *et al*., 2006).
3. Can 3LNO spring survey, Campelen trawl data from 1996-2005, ages 1 to 8 (Healey *et al*., 2006).

To account for uncertainty around model fitting we have randomly resampled (bootstrapped) residuals from the 'best fit' XSA, generating new pseudo-abundance indices and refitting the XSA for each individual simulation. This method is fully described in Miller and Shelton (2007). Weight at age (1975 to present; Healey and Mahé, 2006) and maturity at age data (1966 to present; Morgan and Rideout, 2007) are available for this stock. Natural mortality is assumed to be 0.2 in current assessments. Biological evidence (age at maturity and growth rate) suggests that 0.1 may be a more realistic natural mortality value for this stock, this is discussed further below.

Biological inputs to the operating model

<u>Age structure</u>

The current XSA is age disaggregated up to age 13 with a 14+ plusgroup. Given that Greenland halibut mature at an old age (>10) and are slow growing, it is likely that they live well beyond age14. Fish have been caught that are older than 25 years but the apparent poor selectivity of fishery and survey gears for older fish means that an accurate estimate of the maximum age of Greenland halibut cannot be obtained. It is considered that creating a true population age disaggregated up to age 30 should adequately capture the age structure of the stock.

<u>Growth</u>

For cohorts 1971 to 1993 weight at age data (up to age 13) were taken from the inputs from the XSA in Healey and Mahé (2006). Given that only 5+ biomass and SSB are being computed, weights at age for ages 1 to 4 were set to null. Some length data for fish older than age 13 are available in the surveys. These were converted to weight using the length-weight relationship in Gundersen and Brodie (1999). Weights for older ages data were lumped across years and used to extend the age range for modeling purposes. A weight-based von Bertalanffy growth model was fit to the data available for younger and older ages, assuming that W_∞ = 13.5kg. The model was fit on a cohort by cohort basis and the parameters *k* and *B* were estimated:

$$W_a = W_\infty(1 - e^{-k(a-t_0)})^\beta \qquad (2)$$

The cohort weights at age curves are plotted in Fig. 3. The parameters, *k* and β were shown to be linearly related (Fig. 4). The *k* values were found to be normally distributed. The complete weight-at-age matrix for the true population (Table1) was constructed by inserting true data for all the years and ages when it was available (1975-2005, ages 5 to 13, light yellow). For all cohorts that had weight data for ages 5 to 13, the actual von Bertalanffy model fits (above) were used to project weights for ages 14 to 30 (dark yellow). For all other cohorts with missing data, *k* values were randomly sampled from the normal distribution of observed *k* values; and the corresponding β values were then calculated using the linear relationship between *k* and β (red).

<u>Maturation</u>

Parameter estimates for the slope (age effect) and intercept from models of maturity at age by cohort were taken for 1966-1994 cohorts from Morgan and Rideout (2007) and used to produce estimates of proportion mature at age:

$$g(\mu) = \log\left(\frac{\mu}{1-\mu}\right)$$

and μ $= \left(\frac{1}{1+\exp(-\eta)}\right) = \textit{proportion mature} \qquad (3)$

where: $\eta = \tau + \gamma A$, τ is an intercept, γ age effect, A is age.

The maturity-at-age matrix for the true population (Table 2) was constructed by using the equation above for all of the cohorts. For the 1966 to 1994 cohorts, parameters (slope and intercept) were taken from the fits of the model to actual data from each cohort (Fig. 5). For the remainder of the cohorts a double-Gaussian curve (Fig. 6) was fit to the observed distribution of slope values from the 1966 to 1994 cohorts and a slope value was randomly sampled from the double-Gaussian distribution of slope values. Once a slope value was selected, an intercept value was calculated using the linear relationship between slope and intercept (Fig. 7).

Natural mortality

Assuming von Bertalanffy growth parameters of L_{inf} = 220cm, K = 0.33, age at 50% maturity =13 and length at 50% maturity = 75 cm, it can be concluded, based on Beverton-Holt life history invariants (e.g. Jensen, 1996), that the appropriate value for natural mortality (M) is closer to 0.1 than the currently used value of 0.2. Thus sustainable fishing mortality levels would be around 10% of the biomass, following the rule-of-thumb that sustainable $F \approx M$. A range of M values could be examined by expanding the reference set of operating models to include a range in M.

Stock-recruit relationship

There is considerable uncertainty regarding the appropriate stock-recruit function for this stock. Primarily, defining the appropriate spawner stock biomass (SSB) is complicated. Greenland halibut is distributed continuously along the continental slope from within NAFO Subareas 0, 1, 2 and 3 (Bowering and Brodie, 1995). Hence it is possible that not all recruitment for the 2+3KLMNO Greenland halibut stock results from spawners located in this zone. Furthermore, Greenland halibut are late maturing fish with age at 50% maturity between 10 and 12 years (Morgan and Rideout, 2007). Age disaggregated data available for this stock only extends to age 13 with a 14+ plusgroup, suggesting that the majority of the mature stock is not adequately sampled. It appears that the selectivity of the fishery (and research surveys) for this stock is very low for the older ages, possibly due to older fish moving out of the fishing/stock area or into deeper waters beyond the reach of the nets. A further complication to defining a stock-recruit relationship is the uncertainty around what the potential unexploited biomass of this stock is. Greenland halibut are slow growing, late maturing and long lived fish and the fishery targets predominantly immature fish (ages 5 to 8). It is not fully known what the level of fishing pressure was on this stock during the early to mid 1900s, but these biological parameters and selectivities suggest that the stock may have been severely overfished prior to the earliest estimates of stock size, and that the unexploited biomass may be substantially larger than current estimates.

Given this large degree of uncertainty, and the importance of the stock-recruit relationship in MSE simulations, it is necessary to consider a number of possible stock-recruit models to ensure potential management strategies are robust to this uncertainty. A number methods are described below and shown in Fig. 8, although we do not advocate any of these as an ideal stock-recruit relationship. Best fits were all calculated by minimising the log sums of squares (SS). In all cases SSB (as calculated in equation 4) and recruitment data (n at age 1) data were obtained from the bootstrapped XSA at the start of each repetition of the operating model (years 1975 to 2005).

$$SSB = \sum_{a=1}^{14+} n_a . w_a . m_a \tag{4}$$

Where: n_a , w_a and m_a are numbers, weight and maturity at age a, respectively.

1. Ricker

The Ricker model would be consistent with a stock that has been somewhat overfished. This relationship provides the best fit to the latest assessment data.

2. Beverton and Holt - 0.9 steepness

Steepness is defined as the recruitment at 20% B_0 divided by the recruitment at B_0, where B_0 is the equilibrium biomass at $F = 0$. A steepness of 0.9 would be consistent with the life history parameters of this stock. Based on empirical data, a steepness of 0.9 would be at the high end of the range for flatfish and alternative values could be considered. Constraining a Beverton-Holt model to have a steepness of 0.9 would be consistent with a stock that has a very large maximum recruitment and that has been severely recruitment-overfished.

3. Recruit per spawner

Calculated as a straight line through the origin that best fits the all data points for SSB less than 12000t (to eliminate the extreme outliers). This constant recruitment rate model essentially simulates what would happen if the population always grows at its average recruitment rate over the range of biomass examined.

4. Constant recruitment

Calculated as the horizontal line (i.e. slope = 0) that best fits the SSB-Recruitment data. When error is added this method is equivalent to bootstrapping recruitment values from 1975-2005.

For all stock recruit models, error (log residuals) should be added. For each year a residual can be bootstrapped from the set of log model residuals and the model predicted recruitment was either multiplied or divided by the exponent of the residual (i.e. added or subtracted on the log scale).

Fisheries/Fleet dynamics

Selectivity/Partial recruitment

Partial recruitment (PR) for this stock is calculated by dividing each *F*-at-age by the maximum *F*-at-age for that year. This is then divided by the mean for ages 5-10. For the years 1975-2005 this is done for each individual year based on the XSA assessment and available catch data. This varies from run to run because the non-parametric bootstrap replicates of the XSA used to condition the operating model will differ slightly.

There are two aspects of PR that need to be considered. Firstly, because these PRs are based on the XSA, there are only values for ages 1-13. For the true population (likely to extend to age 30) the PR curve can either be assumed to be a flat-topped curve (i.e. PR for ages 14-30 = PR for age 13) or dome-shaped (i.e. decreasing after age 13). Few fish older than 20 are caught by the fishery and dropping PRs down to near 0 after age 20 would concur with this. Secondly, future trends in fishery selectivity at age may not be easy to predict. PR patterns going into the future for simulation can be taken as the mean over the last three years (i.e. *F*-at-age for each of the last three years standardized by dividing by the maximum *F* for that year; the mean standardized *F* for the three years is calculated and PR is computed as above). However, PR patterns may change as the age structure and abundance of the stock changes. Also, potential gear changes (e.g. reduction in net mesh size) could change selectivity.

Implementation error

Management implementation error, including TAC-overruns, is a serious problem with respect to the 2+3KLMNO Greenland halibut. Since the implementation of the rebuilding plan, reported catches have exceeded specified TACs by between 20 and 30%, averaging roughly 25%. This is a substantial overrun, given the current low biomass of the stock. The real overrun may potentially be even greater than this but is very difficult to estimate precisely. Implementation error is likely to vary depending on the availability of fish to the fishery and the level of TAC. To ensure the robustness of management strategies, it may be best to incorporate an overrun in catch ranging from 20% to as much as 40 or 50%.

Uncertainty/Error

MSE simulations can be run under different scenarios of uncertainty/error relating to the perception of the Real World stock. We have adopted the “POM” approach to management strategy evaluation described in the ICES COMFIE Report (ICES, 1997). P = Process error (e.g. variation in growth, maturation, recruitment, mortality, selectivity etc. not captured in the model); O = Observation error in the perception of the Real World such as the survey tuning indices; M = Model error (error associated with the XSA estimates of population size and fishing mortality). We evaluate the harvesting strategies sequentially, under P, PO and the full POM structures. In Fig. 1, P-level analysis is achieved by including Process error but applying the management strategy to the fishery as if there were perfect information (i.e. no Observation error and no Model estimation error). Process error is captured by running numerous simulations of the same operating model. PO-level analysis includes Process error and Observation error, but no Model error. POM-level analysis includes all three sources of error.

5. Reporting and Analysis of Simulation runs

Results of MSE simulations need to be presented in a clear and concise manner that managers/decision makers can easily interpret. When there is a large amount of uncertainty, the reference set of operating models can easily become excessive. It is important that a MSE is well planned so that only the most likely and influential sources of uncertainty are fully explored to keep the reference set manageable. Expert opinion may also be required to weight the various scenarios in order to determine the overall performance of each management strategy in the various models within the reference set. The robustness of management strategies to uncertainty, as well as their ability to achieve key management objectives while maintaining a healthy stock, needs to be presented in clear understandable manner so that the appropriate management strategy can be chosen.

Example MSE Application

A trial Greenland halibut MSE was run to illustrate the potential outputs using this method. In the absence of PA reference points for SA 2+3KLMNO for Greenland halibut, we evaluated two simpler standard management strategy options in this preliminary exercise – constant fishing mortality at the current (*status quo*) level (F_{sq}) and fishing at $F_{0.1}$. We are not advocating either of these as being the best strategies, but merely as simple examples to illustrate the Management Strategy Evaluation (MSE) approach in FLR. F_{sq} would be a risk-prone scenario with regard to stock rebuilding given the extremely high level of the current fishing mortality. $F_{0.1}$ would be a conservative scenario relative to the current rebuilding plan, representing a large decrease in fishing mortality and catch. For both strategies the TAC for 2006 was set as 18,500 t as specified by the rebuilding plan.

A single simple operating model was used. The simulated stock was age-disaggregated up to age 29 with a 30+ plusgroup. Numbers at age for each simulation were generated by running bootstrap replicate XSAs. A natural mortality (M) of 0.2 was used, in line with the current value used in the XSA assessment. Weights and maturities were generated as described above. New recruits for 2006-2018 were generated from the best fit Ricker stock-recruit model and randomly resampled residuals. With regards to the fishery, a flat-topped PR pattern was used (PR for 14+ equivalent to PR for age 13). PR values for 2006-2018 were made equal to the means for 2003-2005. No management implementation error (i.e. TAC overruns) was considered. While our application takes into account historical uncertainty in the form of Observation error through the bootstrap procedure, the forward simulation is strictly a Process error implementation, with no Observation error or Model error taken into account. Process error was generated by running the simulation for each management strategy 30 times.

The annual F values and corresponding catches for the two strategies are shown in Fig. 9. A sharp decrease in F is consistent with the TAC target of 18,500 t for 2006. Following that, F increases to the 2005 level under the F_{sq} strategy but decreases substantially under the $F_{0.1}$ strategy. Variation around the F levels is a result of both the bootstrap realization of the past observation error and process error into the future (e.g. level of recruitment from year to year, weights at age, proportion mature at age, etc.). The F_{sq} strategy yields consistently higher catches than the $F_{0.1}$ strategy, but shows little increase from 2007 to 2018. The $F_{0.1}$ strategy results in a significant catch decrease initially, but then catch consistently increases from year to year, almost to the level of the F_{sq} strategy by 2018.

The annual SSB, recruitment (age 1) and exploitable (5+) biomass are shown in Fig. 10. Under the F_{sq} strategy the SSB remains in a depressed state, decreasing slightly. In stark contrast, the SSB increases steadily and substantially under the $F_{0.1}$ strategy. It reaches approximately 80,000t, almost four times the highest on record. Population size would eventually stabilize as a result of negative density-dependent feedback in the Ricker model. Density-dependence can be seen clearly in the annual recruitment plot, where recruitment dips notably for SSB above 10,000t, the peak of the Ricker curve. Recruitment is largely unchanged under the F_{sq} strategy. The exploitable biomass shows a similar pattern to the SSB, though less marked. Because exploitable biomass comprises younger ages than SSB, the effect of density-dependent recruitment under the $F_{0.1}$ strategy can already be seen in the last couple of years. The rate of increase and approximate level of the peak in exploitable biomass under $F_{0.1}$ is fairly similar to the observed increase and peak in the late 1980s and early 1990s. While the Management objective of 140,000t exploitable biomass by 2018 is achieved under $F_{0.1}$, no recovery occurs under F_{sq} and the target is not achieved.

Plots of performance statistics are shown in Fig. 11. Under the $F_{0.1}$ strategy the exploitable biomass almost triples by 2018, while under the F_{sq} strategy it remains almost unchanged. The risk profiles show that the $F_{0.1}$ strategy achieved the exploitable biomass target for all 30 of the simulations (0% probability of not achieving the target) while the F_{sq} strategy failed for all 30 (100% probability of not achieving the target). However, fishing under F_{sq} yielded an average annual catch of 25,000t compared to only 17,000t under $F_{0.1}$. The average annual variation in catch was also lower under F_{sq} than $F_{0.1}$.

Evaluating which management strategy would be best for the stock depends on the management objectives, and the weightings applied to these. The results of this test implementation of the MSE are only for illustration. A far more comprehensive reference set of operating models, a full POM-error implementation, and a greater number of simulations per operating model would be required to more thoroughly evaluate these.

Discussion and conclusions

Although a full MSE implementation is required to decide on optimal management strategies for this stock, it seems likely that the present *ad hoc* TAC adjustments are sub-optimal and some form of *F*-based feedback control rule needs be implemented. This harvest control rule should be compliant with the NAFO PA framework and result in fishing mortality decreasing with stock size outside the Safe Zone. To be consistent with the United Nations Fish Stocks Agreement, F_{msy} should be considered as the default limit reference point. Performance statistics should include the risk of exceeding F_{lim} and falling below B_{lim}. The PA requires these risks to be low for any management strategy that is implemented (i.e. <10%). In the case of Greenland halibut this first requires the determination of a B_{lim}, acceptance of an F_{lim} and consideration of other biological reference points.

The rebuilding of the 2J+3KLMNO Greenland halibut stock will require a commitment to base management decisions on the best available scientific advice. Any rebuilding strategy would also have to be robust to uncertainties in stock biology and dynamics. There is considerable uncertainty in the dynamics of this stock, particularly with regards to the stock-recruit relationship and PR, both of which could have a substantial effect on the performance of the simulated management strategy. Progress in developing spawner biomass estimates for this stock based on maturity estimates (Morgan and Rideout, 2007) will assist in exploring robustness to alternative feasible stock-recruit models. F_{msy} depends on the choice of stock-recruit relationship in the operating model.

The simple example implementation illustrates the potential usefulness of the MSE in FLR for developing alternative management strategies and evaluating their performance across a reference set of operating models for the Greenland halibut stock. It should be noted that, while the capacity to carry out a full POM-error implementation MSE is needed, the poor performance of a management strategy at the P-error level would imply that further evaluation with the addition of O and M-level error may be unnecessary, since performance should not improve when more uncertainty is taken into account. The choice of the appropriate reference set of operating models is key and needs to be developed by a knowledgeable group of experts before any further management strategy evaluation takes place. Performance criteria need to be determined by fisheries managers and articulated through NAFO Fisheries Commission. Alternative management strategies need to be developed in collaboration with the fishing industry and fisheries managers. Further implementation of MSE for the 2+3KLMNO Greenland halibut stock is best achieved through a small working group with sufficient expertise to develop the operating model, apply alternative strategies and critically evaluate the inputs and the outputs.

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Table 1. Weights at age applied in the operating model. The light yellow area represents weight at age data derived from sampling the commercial catches, the bright yellow section represents extrapolations of weights to older ages based on cohorts with at least 8 years of weight data and the red section represents data generated from von Bertalanffy curves with randomly sampled parameters.

age	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1975	0	0	0	0	0.61	0.76	0.96	1.19	1.58	2.21	2.70	3.37	3.88	5.40	6.52	7.19	7.67	8.74	9.62	10.64	10.40	9.97	10.85	11.16	12.04	12.75	12.17	12.49	12.99	12.83
1976	0	0	0	0	0.61	0.76	0.96	1.19	1.58	2.21	2.70	3.37	3.88	5.49	6.19	7.34	7.93	8.34	9.38	10.19	11.13	10.86	10.39	11.22	11.50	12.31	12.95	12.39	12.68	13.14
1977	0	0	0	0	0.61	0.76	0.96	1.19	1.58	2.21	2.70	3.37	3.88	5.54	6.31	6.95	8.10	8.62	8.95	9.95	10.70	11.56	11.27	10.77	11.56	11.80	12.54	13.11	12.60	12.85
1978	0	0	0	0	0.61	0.76	0.96	1.19	1.58	2.21	2.70	3.37	3.88	5.72	6.37	7.09	7.67	8.80	9.25	9.52	10.46	11.15	11.93	11.62	11.12	11.85	12.06	12.75	13.25	12.77
1979	0	0	0	0	0.61	0.76	0.96	1.19	1.58	2.21	2.70	3.37	3.88	5.52	6.59	7.16	7.82	8.34	9.44	9.83	10.03	10.92	11.54	12.25	11.94	11.43	12.11	12.30	12.92	13.37
1980	0	0	0	0	0.51	0.66	0.87	1.05	1.15	1.26	1.57	2.71	3.12	5.25	6.35	7.41	7.90	8.51	8.95	10.01	10.34	10.50	11.32	11.89	12.52	12.21	11.70	12.35	12.50	13.07
1981	0	0	0	0	0.39	0.60	0.79	0.99	1.24	1.70	2.46	3.51	4.79	5.56	6.00	7.14	8.18	8.59	9.13	9.52	10.52	10.80	10.91	11.68	12.19	12.75	12.45	11.96	12.55	12.69
1982	0	0	0	0	0.53	0.68	0.89	1.13	1.40	1.79	2.38	3.47	4.51	5.66	6.39	6.71	7.88	8.89	9.22	9.70	10.03	10.98	11.21	11.28	11.99	12.45	12.95	12.66	12.18	12.73
1983	0	0	0	0	0.41	0.63	0.86	1.18	1.65	2.23	3.01	3.96	5.06	5.41	6.52	7.19	7.40	8.56	9.53	9.80	10.22	10.50	11.38	11.57	11.61	12.26	12.67	13.11	12.85	12.38
1984	0	0	0	0	0.38	0.58	0.83	1.10	1.46	1.94	2.63	3.49	4.49	5.91	6.21	7.34	7.93	8.04	9.19	10.10	10.31	10.68	10.91	11.73	11.89	11.91	12.50	12.86	13.25	13.00
1985	0	0	0	0	0.57	0.75	0.94	1.24	1.69	2.24	2.95	3.71	4.85	5.55	7.02	6.97	8.10	8.62	8.64	9.76	10.61	10.77	11.09	11.28	12.04	12.16	12.17	12.70	13.03	13.37
1986	0	0	0	0	0.35	0.58	0.81	1.10	1.58	2.12	2.89	3.89	4.95	5.68	6.53	8.05	7.69	8.80	9.25	9.19	10.28	11.06	11.18	11.46	11.61	12.31	12.41	12.39	12.88	13.17
1987	0	0	0	0	0.36	0.59	0.84	1.16	1.59	2.13	2.82	3.60	4.63	5.73	6.64	7.45	8.98	8.36	9.44	9.83	9.70	10.74	11.46	11.54	11.78	11.91	12.54	12.62	12.60	13.04
1988	0	0	0	0	0.36	0.57	0.81	1.16	1.66	2.22	3.01	3.93	5.09	5.52	6.67	7.55	8.30	9.80	8.98	10.01	10.34	10.16	11.15	11.81	11.86	12.06	12.17	12.75	12.81	12.77
1989	0	0	0	0	0.40	0.56	0.77	1.08	1.66	2.24	3.00	3.86	4.92	5.75	6.37	7.55	8.39	9.08	10.51	9.55	10.52	10.80	10.58	11.51	12.11	12.14	12.31	12.39	12.92	12.97
1990	0	0	0	0	0.34	0.55	0.77	1.12	1.61	2.17	2.85	3.73	4.69	5.71	6.65	7.18	8.37	9.15	9.78	11.11	10.06	10.98	11.21	10.95	11.83	12.38	12.38	12.53	12.60	13.07
1991	0	0	0	0	0.38	0.59	0.83	1.23	1.81	2.46	3.31	4.14	5.33	5.51	6.59	7.51	7.95	9.12	9.84	10.39	11.63	10.53	11.38	11.57	11.29	12.11	12.61	12.60	12.73	12.77
1992	0	0	0	0	0.43	0.58	0.79	1.23	1.82	2.46	3.12	3.97	5.10	6.02	6.33	7.43	8.30	8.65	9.79	10.44	10.93	12.06	10.94	11.73	11.89	11.60	12.36	12.80	12.79	12.89
1993	0	0	0	0	0.37	0.55	0.81	1.21	1.73	2.31	3.00	3.97	4.82	5.96	6.96	7.12	8.21	9.02	9.29	10.38	10.97	11.40	12.41	11.31	12.04	12.16	11.87	12.58	12.97	12.95
1994	0	0	0	0	0.33	0.51	0.79	1.18	1.70	2.27	2.99	3.77	4.88	5.71	6.87	7.85	7.86	8.92	9.68	9.88	10.90	11.42	11.80	12.71	11.64	12.31	12.41	12.12	12.77	13.12
1995	0	0	0	0	0.36	0.53	0.81	1.20	1.76	2.45	3.12	3.81	4.89	5.75	6.56	7.73	8.66	8.55	9.57	10.26	10.40	11.36	11.82	12.14	12.95	11.93	12.54	12.62	12.33	12.93
1996	0	0	0	0	0.36	0.54	0.83	1.27	1.80	2.48	3.15	3.86	4.95	5.60	6.60	7.36	8.52	9.40	9.18	10.15	10.77	10.86	11.75	12.16	12.44	13.14	12.19	12.75	12.81	12.53
1997	0	0	0	0	0.34	0.49	0.77	1.16	1.73	2.36	3.05	3.95	5.11	5.66	6.42	7.41	8.11	9.24	10.05	9.75	10.66	11.23	11.27	12.09	12.45	12.69	13.31	12.42	12.92	12.97
1998	0	0	0	0	0.37	0.54	0.81	1.20	1.75	2.35	3.10	4.01	5.13	5.82	6.49	7.20	8.16	8.79	9.89	10.62	10.27	11.11	11.62	11.63	12.38	12.69	12.90	13.44	12.62	13.07
1999	0	0	0	0	0.36	0.53	0.83	1.25	1.68	2.29	2.89	3.51	4.46	5.90	6.69	7.28	7.93	8.85	9.42	10.46	11.13	10.73	11.51	11.96	11.95	12.63	12.90	13.08	13.55	12.79
2000	0	0	0	0	0.35	0.52	0.79	1.19	1.77	2.28	2.90	3.65	4.49	5.36	6.77	7.51	8.02	8.60	9.48	9.99	10.96	11.56	11.14	11.86	12.26	12.23	12.84	13.08	13.23	13.63
2001	0	0	0	0	0.38	0.57	0.83	1.17	1.79	2.37	2.95	3.72	4.59	5.17	6.11	7.59	8.27	8.71	9.22	10.05	10.49	11.40	11.93	11.51	12.16	12.52	12.47	13.02	13.22	13.35
2002	0	0	0	0	0.37	0.56	0.84	1.19	1.76	2.28	2.90	3.58	4.41	5.27	5.89	6.83	8.35	8.97	9.33	9.78	10.55	10.94	11.78	12.25	11.83	12.42	12.74	12.68	13.18	13.35
2003	0	0	0	0	0.39	0.56	0.82	1.20	1.65	2.17	2.70	3.40	4.38	5.18	6.02	6.59	7.51	9.05	9.60	9.90	10.29	11.00	11.34	12.11	12.53	12.11	12.65	12.92	12.86	13.31
2004	0	0	0	0	0.38	0.54	0.81	1.20	1.63	2.15	2.73	3.54	4.38	5.12	5.92	6.75	7.26	8.15	9.68	10.17	10.40	10.75	11.40	11.69	12.39	12.76	12.36	12.85	13.08	13.02
2005	0	0	0	0	0.40	0.56	0.85	1.25	1.69	2.18	2.71	3.46	4.26	5.00	5.86	6.64	7.44	7.89	8.75	10.24	10.67	10.86	11.15	11.75	12.00	12.63	12.96	12.57	13.01	13.22
2006	0	0	0	0	0.50	0.56	0.75	1.04	1.62	2.30	3.00	3.85	5.00	4.94	5.70	6.58	7.32	8.09	8.48	9.30	10.74	11.12	11.26	11.51	12.05	12.27	12.84	13.12	12.76	13.16
2007	0	0	0	0	0.50	0.56	0.73	1.10	1.60	2.27	3.00	3.75	4.70	5.94	5.64	6.38	7.26	7.97	8.69	9.02	9.80	11.18	11.51	11.61	11.83	12.32	12.51	13.02	13.26	12.93
2008	0	0	0	0	0.51	0.55	0.74	1.08	1.61	2.34	3.04	3.75	4.52	5.56	6.85	6.31	7.03	7.90	8.56	9.24	9.52	10.25	11.56	11.85	11.93	12.10	12.55	12.71	13.17	13.38
2009	0	0	0	0	0.50	0.56	0.73	1.08	1.60	2.28	3.22	3.87	4.53	5.30	6.39	7.71	6.97	7.65	8.50	9.12	9.75	9.98	10.67	11.90	12.15	12.20	12.35	12.75	12.89	13.30
2010	0	0	0	0	0.50	0.55	0.75	1.07	1.60	2.28	3.05	4.19	4.73	5.31	6.06	7.19	8.50	7.58	8.22	9.05	9.63	10.22	10.40	11.04	12.19	12.41	12.44	12.56	12.92	13.04
2011	0	0	0	0	0.50	0.56	0.72	1.10	1.60	2.28	3.08	3.89	5.19	5.59	6.08	6.80	7.93	9.22	8.17	8.76	9.56	10.09	10.63	10.79	11.37	12.45	12.63	12.65	12.75	13.07
2012	0	0	0	0	0.51	0.55	0.73	1.06	1.61	2.29	3.07	3.95	4.77	6.18	6.43	6.82	7.49	8.62	9.86	8.71	9.26	10.03	10.51	11.01	11.13	11.67	12.67	12.83	12.83	12.92
2013	0	0	0	0	0.53	0.58	0.73	1.08	1.60	2.28	3.10	3.94	4.86	5.65	7.13	7.24	7.52	8.15	9.25	10.43	9.21	9.73	10.45	10.89	11.35	11.44	11.94	12.86	13.00	12.99
2014	0	0	0	0	0.52	0.67	0.78	1.07	1.60	2.30	3.05	3.99	4.84	5.76	6.50	8.02	7.99	8.17	8.75	9.83	10.94	9.68	10.15	10.84	11.24	11.65	11.72	12.18	13.02	13.14
2015	0	0	0	0	0.50	0.62	0.94	1.13	1.60	2.28	3.13	3.89	4.92	5.74	6.64	7.31	8.82	8.68	8.78	9.31	10.34	11.37	10.11	10.54	11.18	11.55	11.93	11.97	12.39	13.16
2016	0	0	0	0	0.50	0.55	0.85	1.33	1.64	2.29	3.08	4.04	4.77	5.84	6.61	7.47	8.07	9.55	9.31	9.34	9.82	10.80	11.76	10.50	10.89	11.50	11.82	12.17	12.20	12.58
2017	0	0	0	0	0.50	0.54	0.72	1.23	1.84	2.28	3.10	3.96	4.98	5.65	6.73	7.44	8.24	8.77	10.19	9.89	9.85	10.28	11.21	12.09	10.85	11.21	11.78	12.07	12.38	12.40
2018	0	0	0	0	0.51	0.55	0.70	1.06	1.73	2.42	3.01	3.99	4.87	5.92	6.50	7.57	8.21	8.95	9.41	10.75	10.40	10.31	10.70	11.57	12.37	11.17	11.50	12.03	12.29	12.57

Table 2. Maturity at age data applied in the operating model.

age	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1975	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.06	0.07	0.06	0.15	0.38	0.72	0.76	0.81	0.87	0.91	0.96	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1976	0.00	0.00	0.00	0.00	0.00	0.02	0.01	0.04	0.11	0.12	0.14	0.27	0.63	0.89	0.89	0.91	0.93	0.96	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1977	0.00	0.00	0.00	0.00	0.00	0.01	0.04	0.03	0.08	0.18	0.20	0.29	0.45	0.83	0.96	0.95	0.96	0.97	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1978	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.06	0.06	0.16	0.28	0.31	0.50	0.64	0.93	0.99	0.98	0.98	0.98	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1979	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.04	0.11	0.12	0.28	0.41	0.45	0.71	0.79	0.97	1.00	0.99	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1980	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.03	0.07	0.18	0.23	0.45	0.55	0.60	0.86	0.89	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1981	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.04	0.06	0.13	0.27	0.40	0.63	0.69	0.74	0.94	0.95	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1982	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.07	0.12	0.24	0.40	0.59	0.78	0.80	0.84	0.97	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1983	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.04	0.11	0.21	0.38	0.54	0.76	0.88	0.87	0.91	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1984	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.07	0.19	0.34	0.56	0.68	0.87	0.94	0.93	0.95	1.00	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1985	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.05	0.13	0.30	0.51	0.72	0.79	0.94	0.97	0.96	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1986	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.06	0.10	0.22	0.43	0.67	0.84	0.87	0.97	0.99	0.98	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1987	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.04	0.15	0.17	0.34	0.58	0.80	0.91	0.92	0.99	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1988	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.02	0.09	0.33	0.29	0.50	0.72	0.89	0.95	0.95	0.99	1.00	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1989	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.05	0.16	0.08	0.21	0.58	0.43	0.65	0.82	0.94	0.98	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1990	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.15	0.97	0.25	0.41	0.79	0.59	0.78	0.89	0.97	0.99	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1991	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.04	0.38	1.00	0.56	0.64	0.91	0.73	0.87	0.94	0.98	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1992	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.10	0.11	0.68	1.00	0.83	0.82	0.97	0.84	0.93	0.96	0.99	1.00	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1993	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.07	0.26	0.25	0.88	1.00	0.95	0.92	0.99	0.91	0.96	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1994	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.03	0.17	0.53	0.47	0.96	1.00	0.99	0.97	1.00	0.95	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1995	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.04	0.08	0.35	0.78	0.70	0.99	1.00	1.00	0.99	1.00	0.97	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1996	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.07	0.10	0.20	0.58	0.92	0.86	1.00	1.00	1.00	1.00	1.00	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1997	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.20	0.21	0.43	0.78	0.97	0.94	1.00	1.00	1.00	1.00	1.00	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1998	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.09	0.45	0.41	0.69	0.90	0.99	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1999	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.04	0.12	0.21	0.72	0.63	0.87	0.96	1.00	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2000	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.03	0.07	0.18	0.53	0.41	0.89	0.81	0.95	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2001	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.02	0.07	0.36	0.53	0.90	0.65	0.96	0.92	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2002	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.02	0.07	0.15	0.82	0.85	0.99	0.83	0.99	0.96	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2003	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.04	0.11	0.22	0.31	0.97	0.97	1.00	0.93	1.00	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2004	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.02	0.04	0.07	0.44	0.49	0.53	1.00	0.99	1.00	0.97	1.00	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2005	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.04	0.07	0.14	0.84	0.77	0.74	1.00	1.00	1.00	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2006	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.02	0.07	0.13	0.24	0.97	0.92	0.88	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2007	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.04	0.07	0.14	0.21	0.38	1.00	0.98	0.95	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2008	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.04	0.07	0.22	0.26	0.32	0.55	1.00	0.99	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2009	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.04	0.07	0.13	0.49	0.42	0.46	0.71	1.00	1.00	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2010	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.04	0.07	0.14	0.22	0.77	0.61	0.60	0.83	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2011	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.07	0.14	0.26	0.34	0.92	0.76	0.73	0.90	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2012	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.03	0.07	0.14	0.24	0.43	0.49	0.98	0.87	0.83	0.95	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2013	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.02	0.07	0.20	0.26	0.39	0.62	0.64	0.99	0.93	0.90	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2014	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.01	0.02	0.07	0.16	0.42	0.43	0.56	0.77	0.77	1.00	0.97	0.94	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2015	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.03	0.03	0.07	0.22	0.30	0.69	0.62	0.72	0.88	0.86	1.00	0.98	0.97	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2016	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.03	0.04	0.07	0.20	0.51	0.50	0.87	0.77	0.83	0.94	0.92	1.00	0.99	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2017	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.05	0.07	0.16	0.45	0.79	0.70	0.95	0.88	0.91	0.97	0.96	1.00	1.00	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2018	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.03	0.07	0.12	0.31	0.73	0.93	0.84	0.98	0.94	0.95	0.99	0.98	1.00	1.00	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00

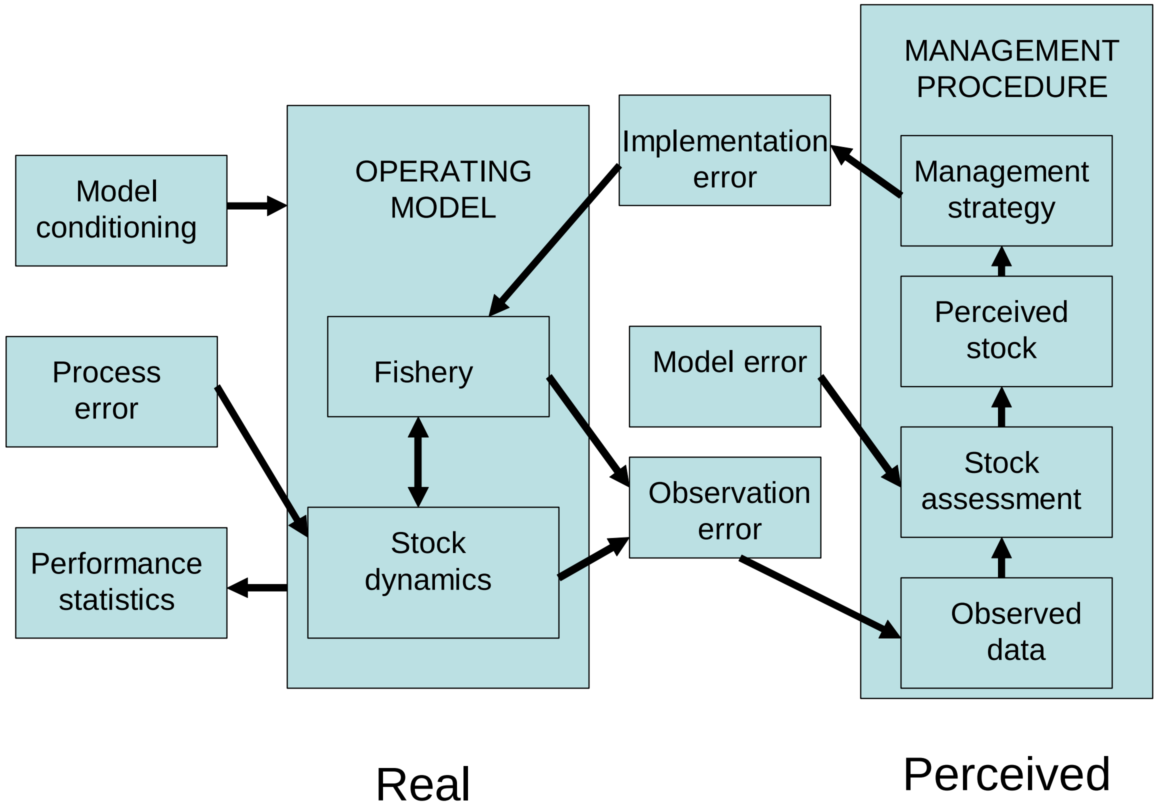


Fig. 1. Conceptual framework for Management Strategy Evaluation (MSE), adapted from Kell *et al.* (2007). The simulated "real" world is captured by the operating model. The management strategy is applied to the "perceived world" which is only known with error, either process error alone, process and observation error, or process, observation and model error.

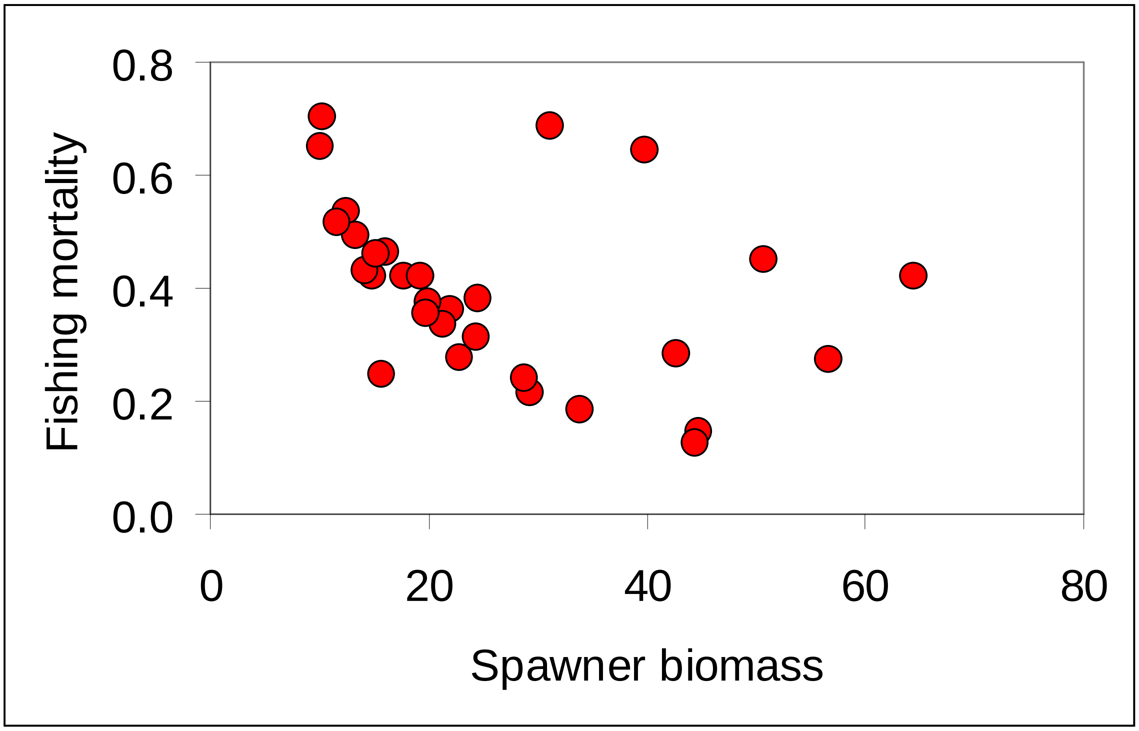


Fig. 2. Scatter plot of fishing mortality versus spawner biomass for SA 2+3KLMNO Greenland halibut from the 2006 assessment (Healey and Mahé, 2006). This is the exact opposite to the pattern required under the Precautionary Approach. Under the PA fishing mortality should decrease with decreasing SSB as the consequence of implementing an appropriate harvest control rule.

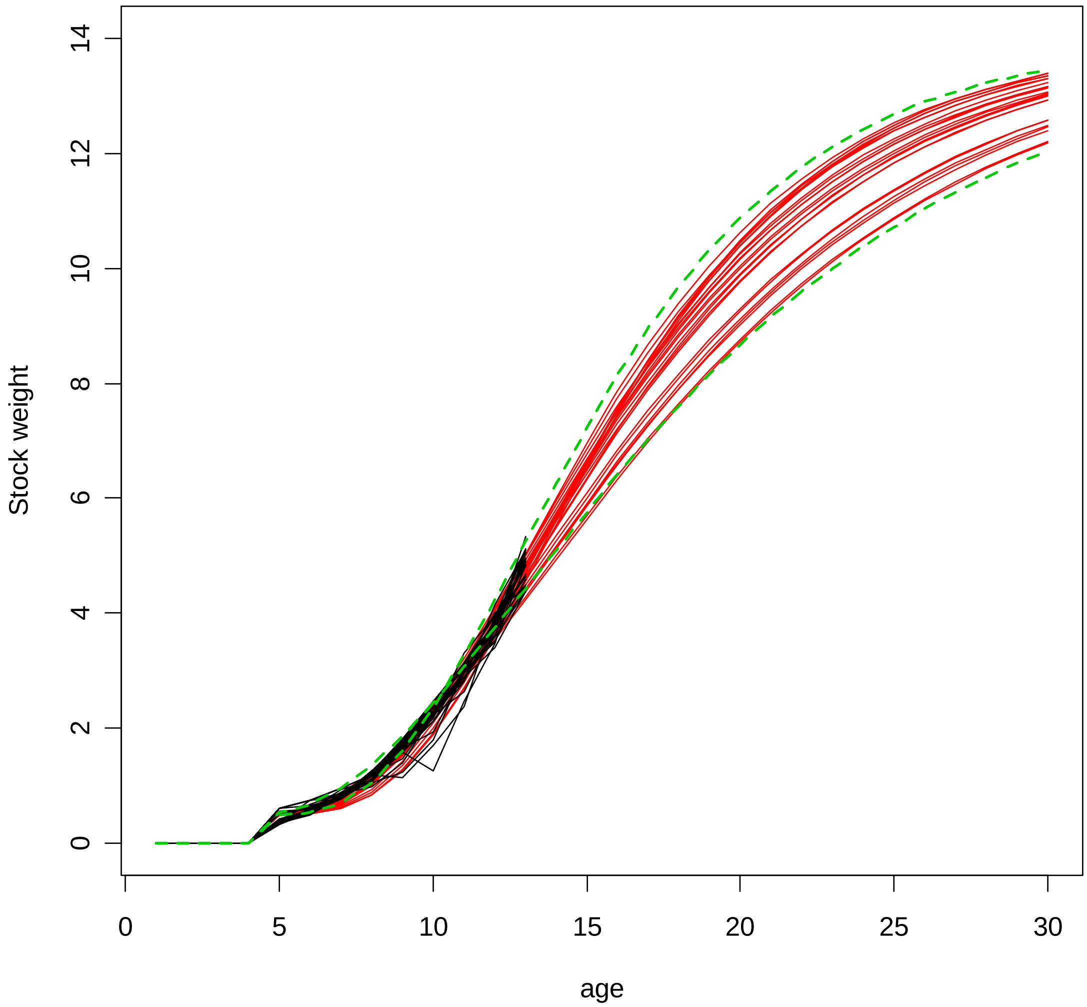


Fig. 3. Cohort weight-at-age curves used in the operating model for simulating the "true" population. Black lines represent observed data. Red lines represent von Bertalanffy curves fit to the observed weight-at-age data for each cohort. The dashed green lines show the curves that result from sampling the minimum (0.11) or maximum (0.185) k values from the distribution of *k* values.

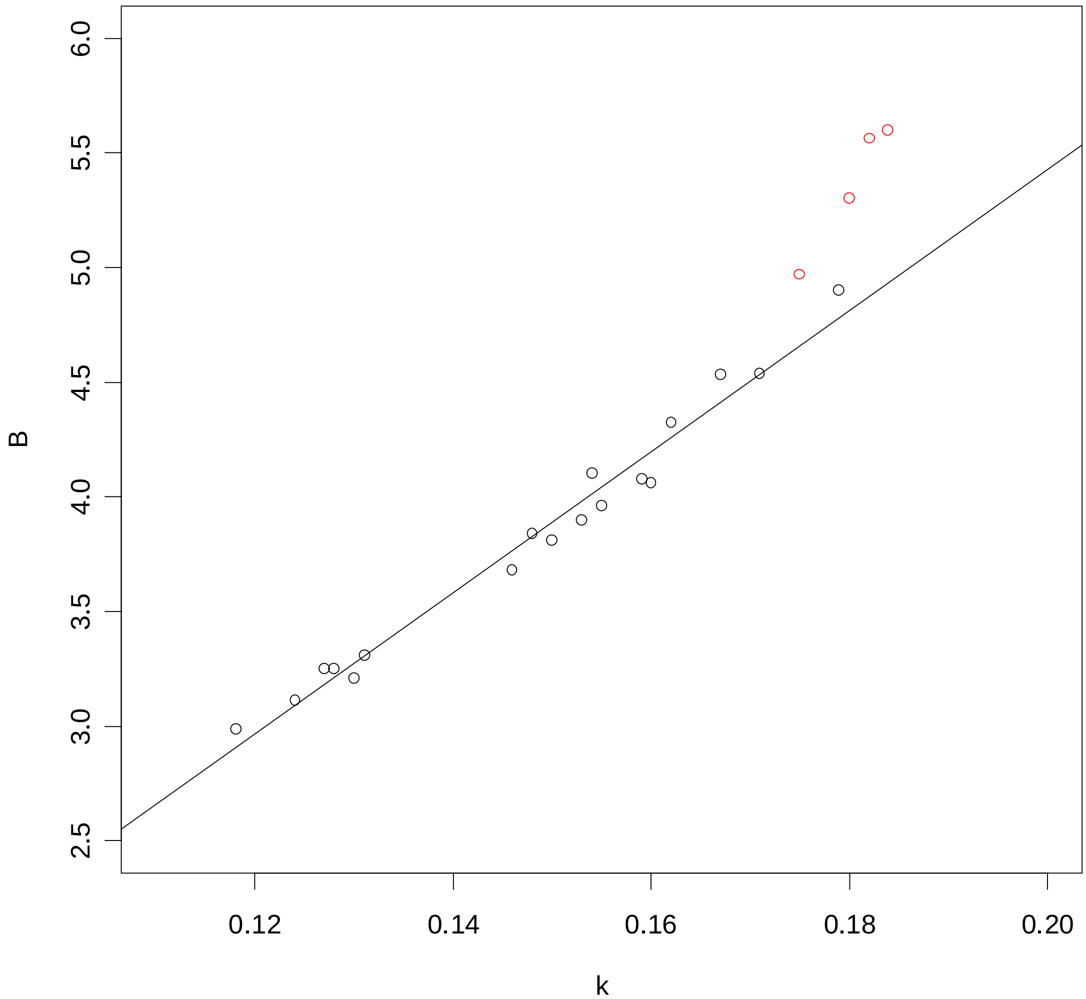


Fig. 4. Relationship between the parameters of the von Bertalanffy models fit to weight-at-age data for the 1971-1993 cohorts. The points in red (cohorts 1971-1974) were excluded for fitting the linear model (intercept = -0.72; slope = 30.70). The reason cohorts 1971-1974 were excluded is because the data suggest that weights decreasing from one age to the next in some cases.

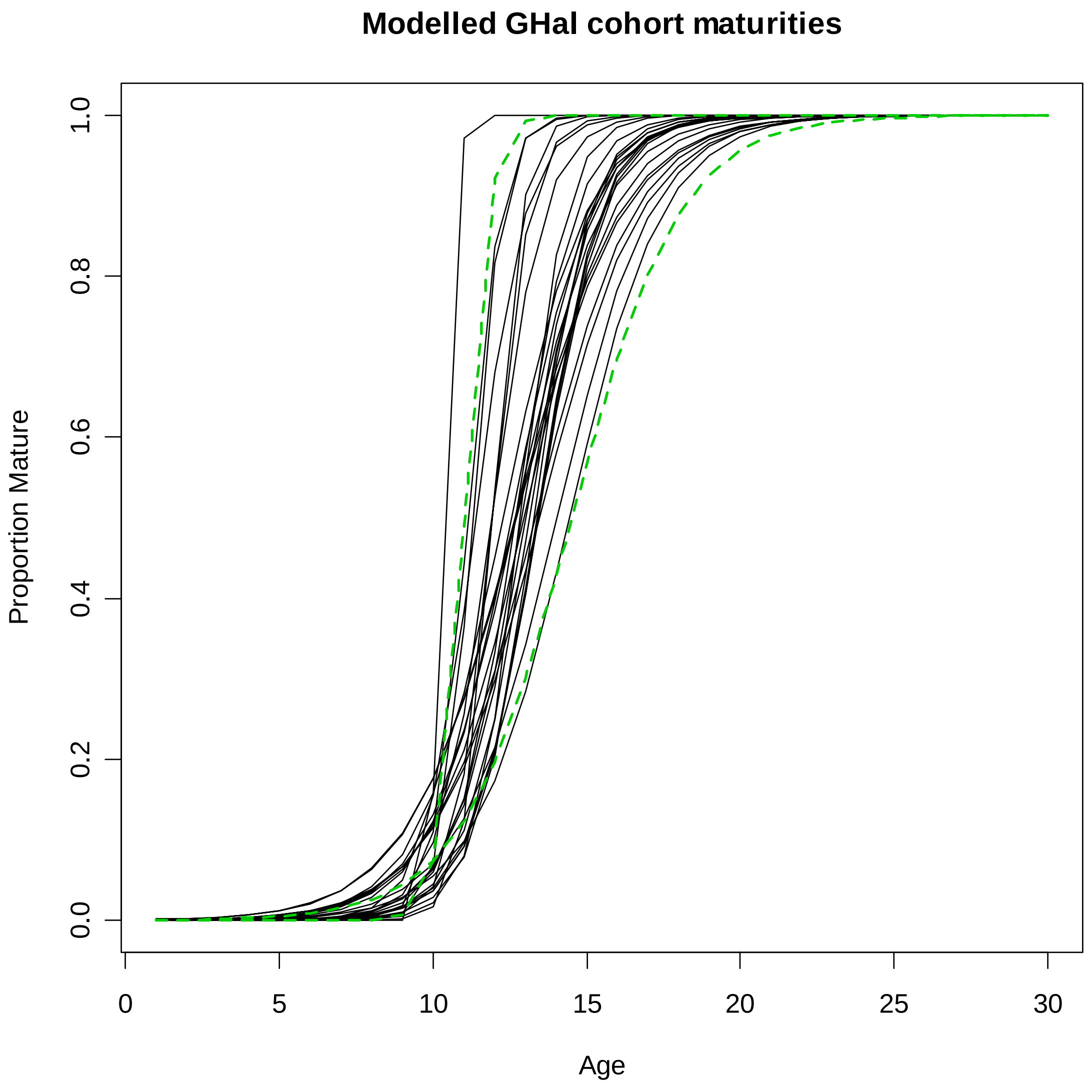


Fig. 5. Cohort maturity-at-age curves used in the true population. Black lines represent fits to the observed maturity at age cohorts for the 1966 to 1994 cohorts. The dashed green lines show the curves that result from sampling the minimum (0.56) or maximum (2.5) slope values from the distribution of slope values.

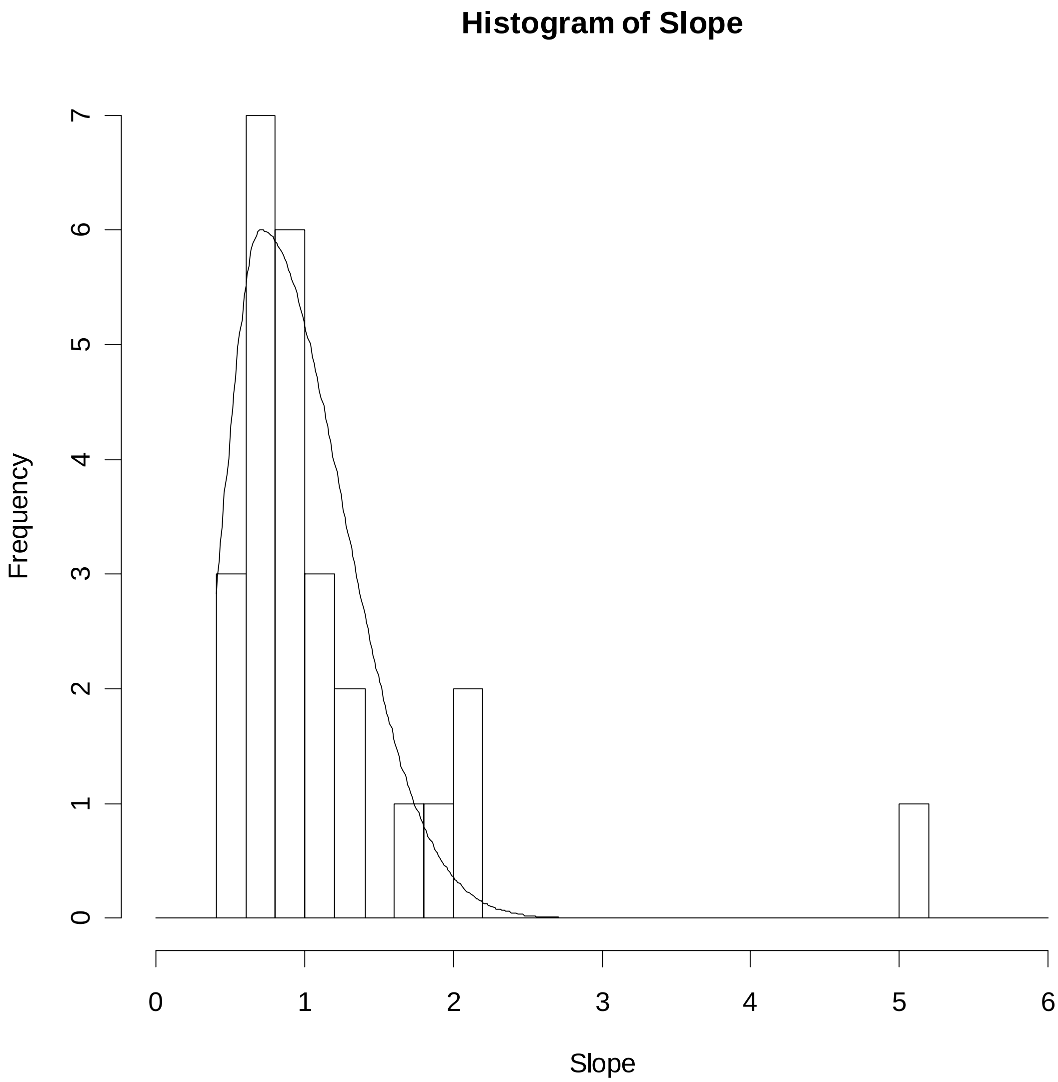


Fig. 6. Double-Gaussian curve fit to the distribution of slope values from the maturity models fit to the maturity-at-age data for the 1966-1994 cohorts.

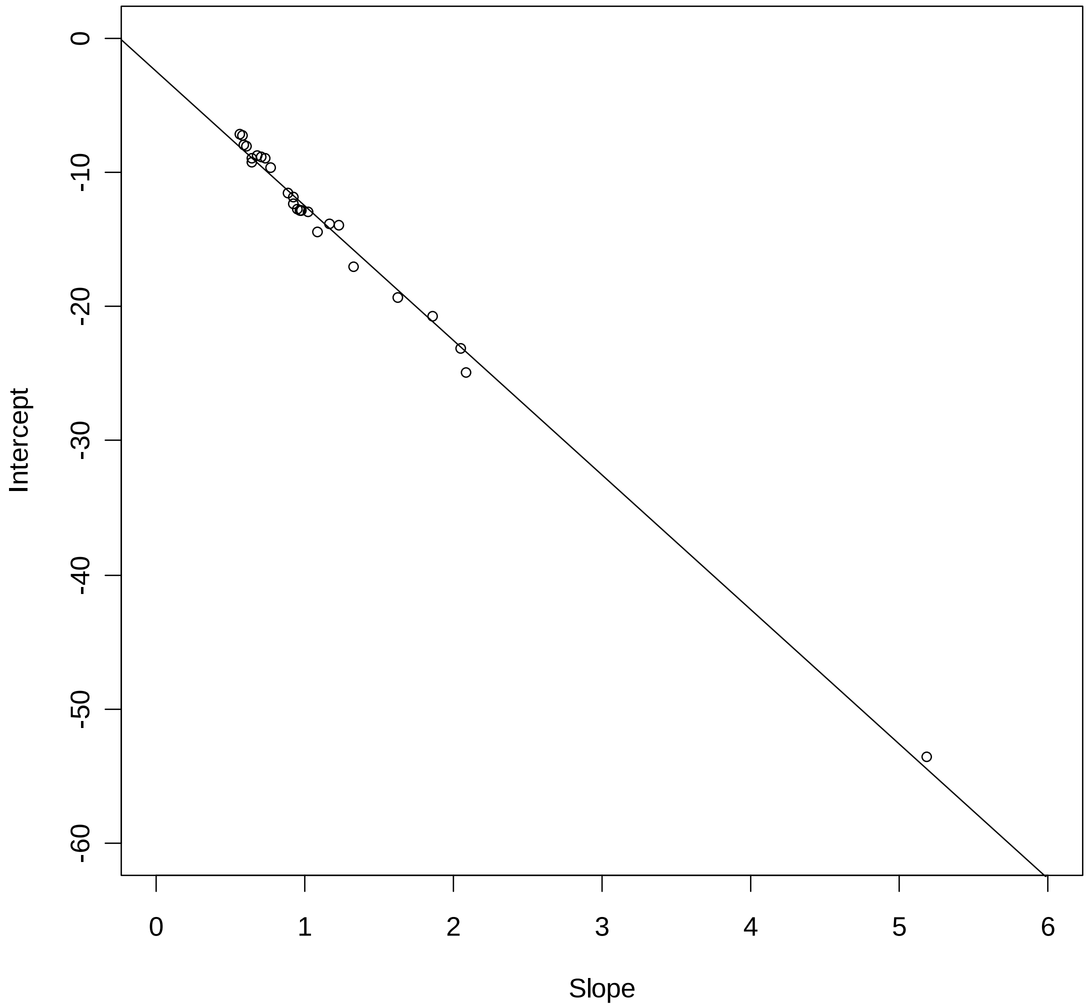


Fig. 7. Relationship between the parameters of the maturity models fit to maturity-at-age data for the 1966-1994 cohorts. (intercept = -2.52; slope = -10.00).

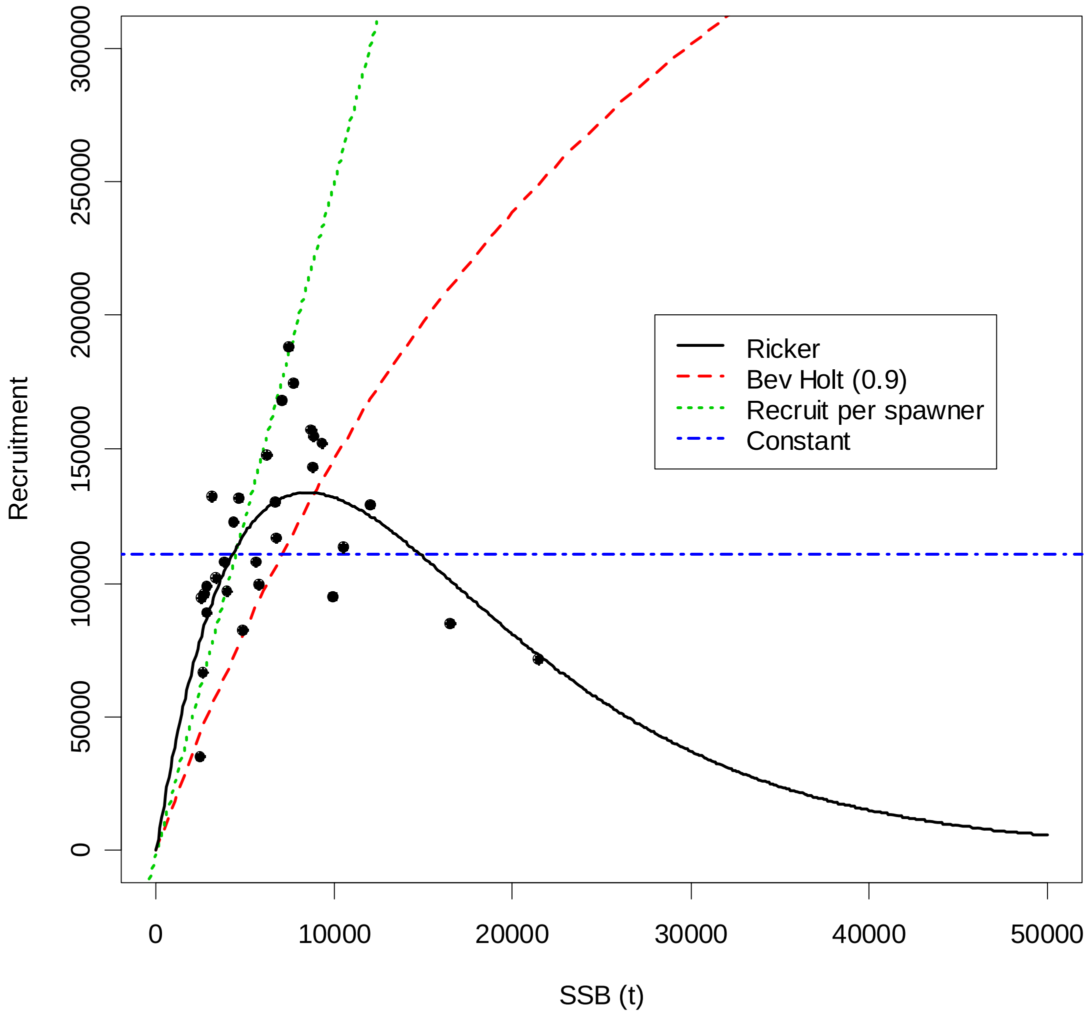


Fig. 8. The four stock recruit relationships considered for the true population in the operating model. Points indicate stock-recruit values from the 2006 XSA assessment.

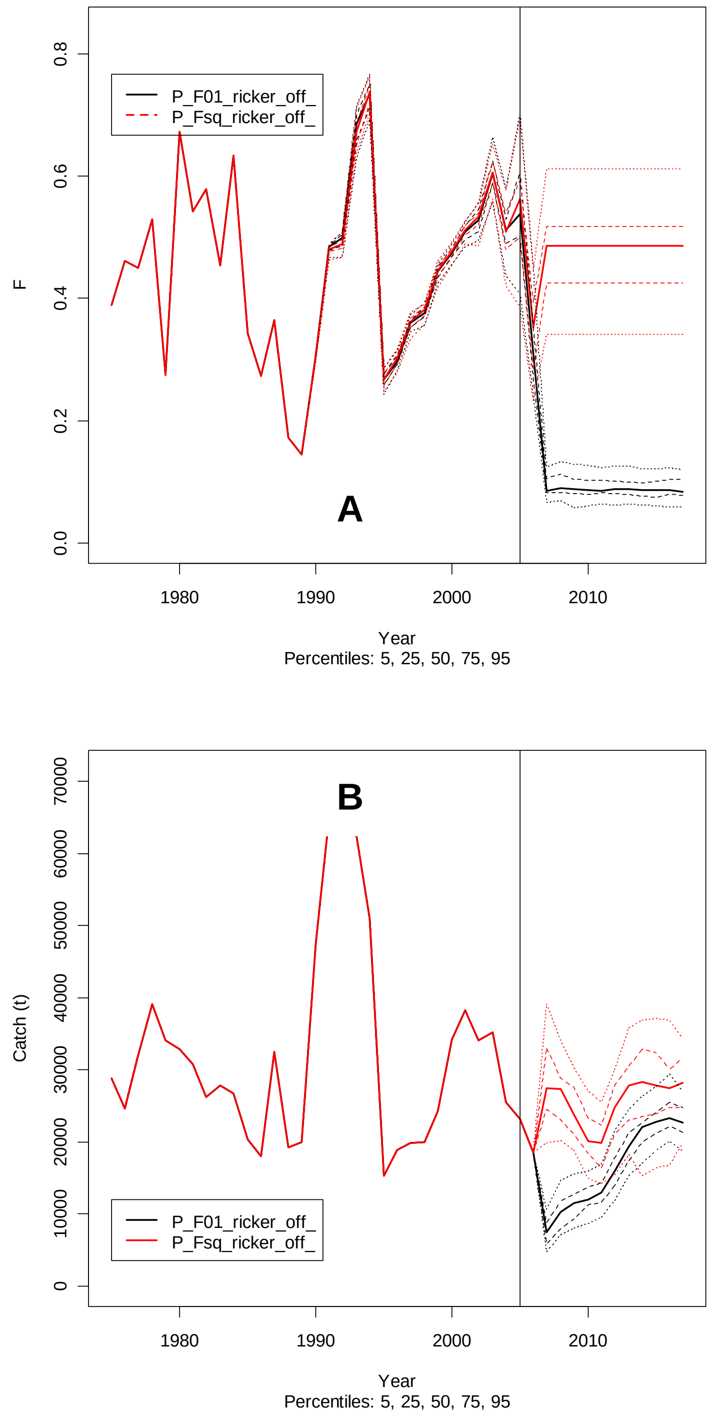
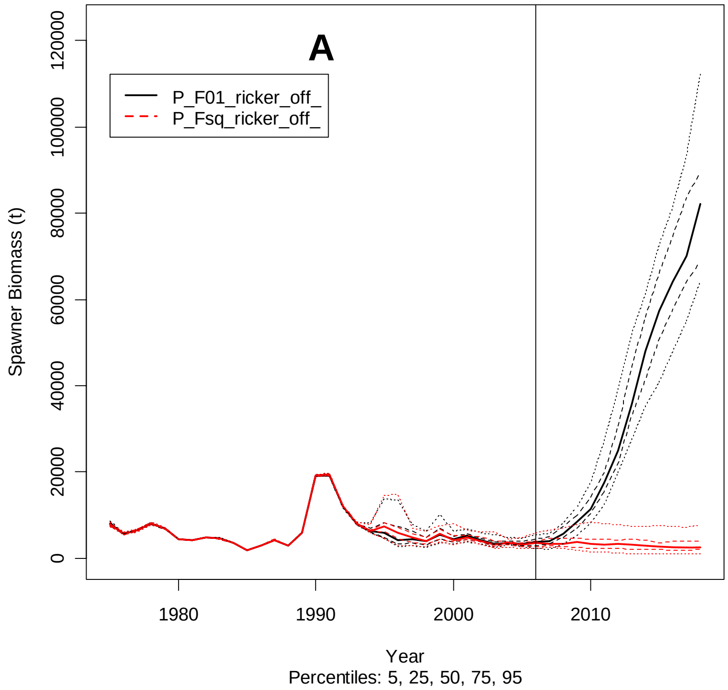
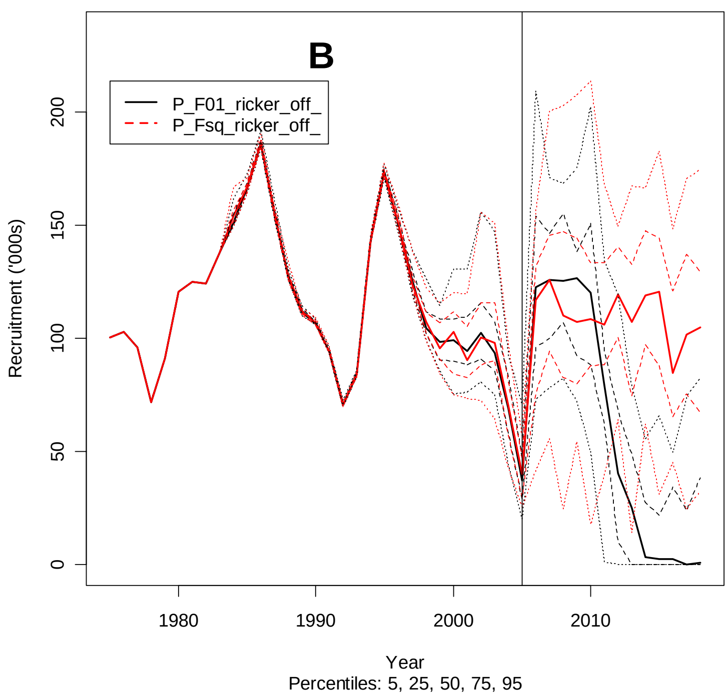


Fig. 9. Fishing mortality values (A) and corresponding catches under the two strategies ($F_{0.1}$= black, F_{sq} = red) considered in the Greenland halibut MSE. Solid lines represent the median of 30 simulations and the 5, 25, 75 and 95 percentiles are shown.


A
P_F01_ricker_off_
P_Fsq_ricker_off_
Spawner Biomass (t)
0
20000
40000
60000
80000
100000
120000
1980
1990
2000
2010
Year
Percentiles: 5, 25, 50, 75, 95


B
P_F01_ricker_off_
P_Fsq_ricker_off_
Recruitment ('000s)
0
50
100
150
200
1980
1990
2000
2010
Year
Percentiles: 5, 25, 50, 75, 95

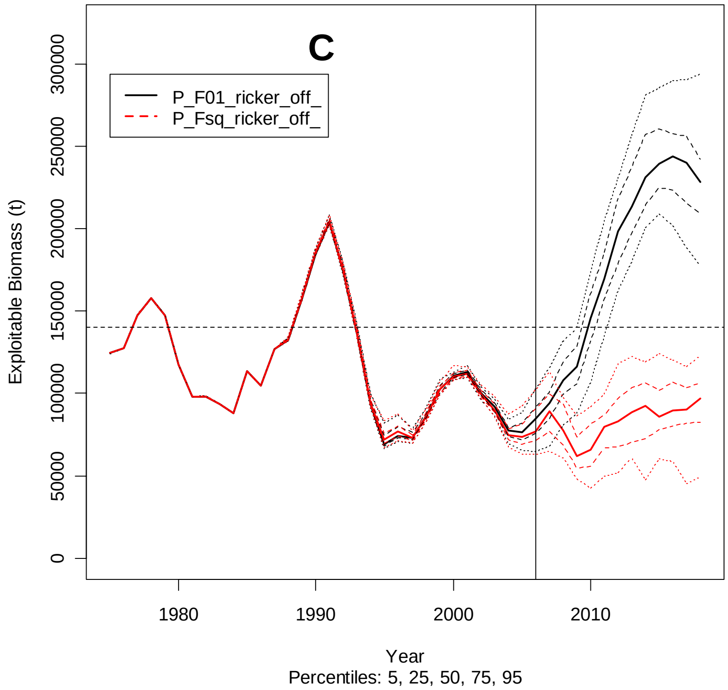
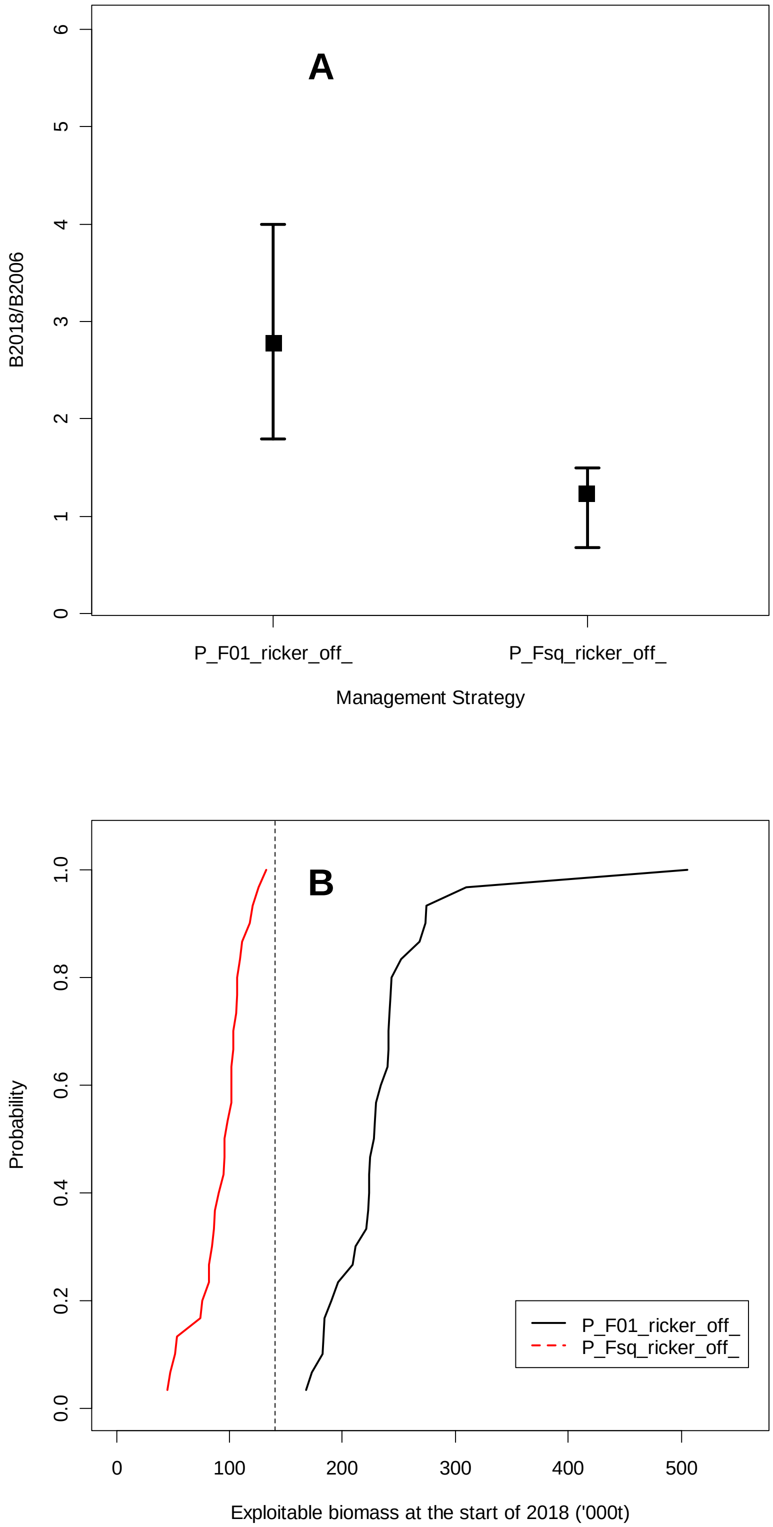
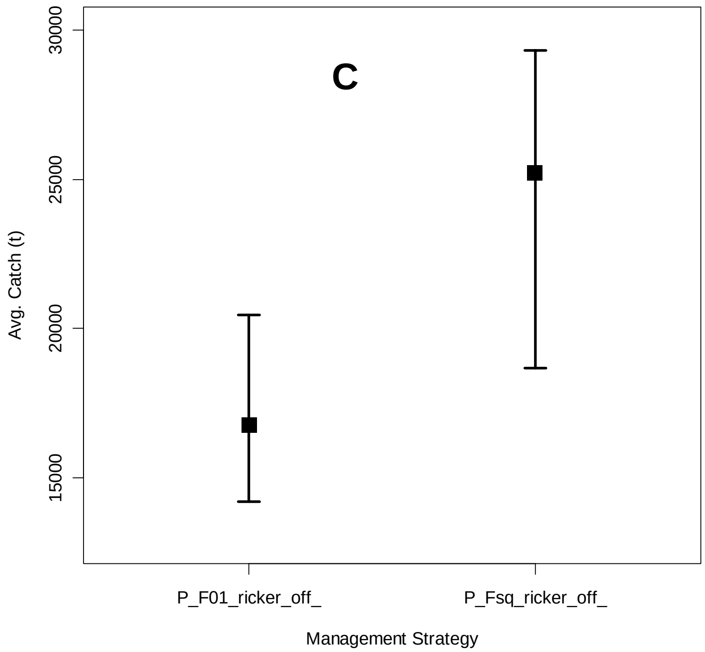


Fig. 10. Spawning stock biomass (A) and the resultant recruitment (B) and exploitable biomass (C) of the 2+3KLMNO Greenland halibut stock under the two strategies ($F_{0.1}$= black, F_{sq} = red) considered in the Greenland halibut MSE. The horizontal line represents the rebuilding plan target of 140,000t exploitable biomass. Solid lines represent the median of 30 simulations and the 5, 25, 75 and 95 percentiles are shown.


A
B2018/B2006
0
1
2
3
4
5
6
P_F01_ricker_off_
P_Fsq_ricker_off_
Management Strategy
B
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
100
200
300
400
500
Exploitable biomass at the start of 2018 ('000t)
P_F01_ricker_off_
P_Fsq_ricker_off_



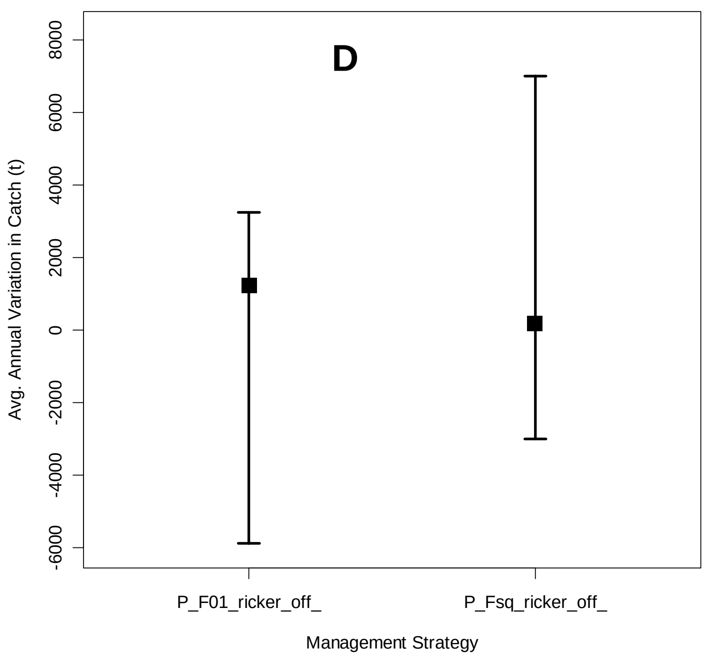


Fig 11. Performance statistics for the Greenland halibut MSE for the two strategies considered: the ratio of exploitable biomass at the start of 2018 to current exploitable biomass (A); risk profiles for potential exploitable biomass at the start of 2018 (B); average catch (C); and average annual variation in catch (D).