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Robustness of the Greenland Halibut MSE to different S/R functions and different Reproductive Potential indices

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Abstract

The objective of this document is to test whether the current HCR for Greenland halibut under the XSA Current Assessment View OM is robust to different stock recruitment assumptions and to different measures of Reproductive Potential (RP). We tested the HCR using alternative stock recruitment functions (Segmented Regression, Ricker and Ricker) with different RP indices which vary in the level of biological complexity. The RP indices used in increasing order of biological information were: Biomass 10+, SSBcohort, FSBcohort, FSByear and TEP. Understanding the basis of uncertainty in the S/R relationships is generally the most difficult outstanding problem in fisheries assessment and management and it is a key problem in the MSE. A Ricker stock recruitment function fitsthe Greenland halibut stock recruitment data better than the Segmented Regression for all the RP indices. The results show that the inclusion of more biological information when estimating Reproductive Potential does not improve the stock recruitment fit in either case (Segmented Regression and Ricker). The best fits in both cases were obtained in descending order with: 10+Biomass, SSBcohort, FSBcohort, TEP and FSByear. All the OMs based on the Segmented Regression have very similar results and seem to be robust to assumptions about Reproductive Potential.In the case of the OMs based on the Ricker stock recruitment function, all of them have a very low probability, less than 1%, of achieving the exploitable biomass objective. In the case of the OMs based on the modified Ricker function, all of them have a low probability of achieving the exploitable biomass objectivealthough the total biomass reaches maximum levels in all the OMs. The stock recruitment assumptions seem to have a big impact on the final results while the RP indices appear to have little impact.

1. Introduction

Determination of the reproductive potential (RP) of a population is an important aspect of fish stock assessment. The potential to produce recruits is a major component of population productivity and thus have a large impact on the level of exploitation that a population can sustain without collapse. Spawning stock biomass (SSB) is often used as

the measure of RP. However, SSB may not be the best metric of RP and predictor of recruitment produced (Morgan, 2008; Marshall *et al.*, 1998; Scott *et al.*, 2006; Marshall, 2009). This can be because the actual measure of SSB used is not adequate, with factors such as maturation assumed to be constant when in fact they often vary. It can also be because SSB itself does not capture the important dynamics of sex ratio and fecundity which play a role in recruitment (Marshall *et al.*, 2006; Morgan *et al.*, 2009).

The RP of a population should be taken into account when rules for determining appropriate levels of harvest are developed. Such rules can be tested using management strategy evaluation (MSE,Kell *et al.*, 2007). However, when conducting an MSE variation in RP may not be taken into account and/or SSB will be the measure of RP (Murua *et al.*, 2010). An example is the MSE that was conducted for the Greenland halibut (*Reinhardtius hippoglossoides*) stock on the Newfoundland shelf in the Northwest Atlantic (Miller *et al.*, 2008; Shelton and Miller, 2009). Greenland halibut is an important flatfish resource which has had catches in excess of 60 000 t (Healey *et al.*, 2010). The population declined to very low levels in the mid 1990s and a MSE was conducted to evaluate harvest control rules (HCR) to promote rebuilding while minimizing annual changes in total allowable catch (NAFO, 2010). This MSE did incorporate varying growth and maturation but it used only SSB as its measure of RP (Miller *et al.*, 2008). Thus it is not known if the adopted HCR is robust to different assumptions about RP.

Two sets of operating models – one conditioned by XSA and another conditioned by SCAA – using the same input were tested in the Greenland halibut MSE (NAFO WGMSE, 2010). All the OMs conditioned in the XSA assumed different Segmented Regressions functions:

- CAV Current Assessment View: M = 0.2, flat-topped PR, S/R Segmented Regression;
- LMV Lower M view: Same as CAV but it assumes M = 0.1;
- CAV_domed: Same as CAV, but with domed PR;
- CAV_varM: Same as CAV but M increases from 0.2 at age 10 to 0.4 at age 14 and it is constant at that level in older ages;
- CAV_dep: Same as CAV but Segmented Regression forced to have a maximum at the maximum observed recruitment and a slope equal to the best fit through the origin;
- LMV_dep: Same as CAV_dep but with M = 0.1.

CAV is most closely consistent with the 2010 NAFO Greenland halibut approved assessment model(Healey *et al.*, 2010).

The incorporation of more biological realism into indices of RP has been clearly shown to affect our perception of the status of populations (Morgan and Brattey, 2005; Morgan *et al.*, 2009; Marshall *et al.*, 2006). It can also improve estimation of recruitment (Murawski *et al.*, 2001; Kraus *et al.*, 2002; Marteinsdottir and Thorarinsson, 1998). However, this may depend on the stock being examined both because some populations have shown little trend in the variation in factors such as maturation and fecundity and/or because the data used to estimate alternative indices of RP are of poor quality or time series are lacking (Morgan *et al.*, 2011; Tomkiewicz *et al.*, 2003; DeOliveira *et al.*, 2006).

There have been few tests of whether HCR are robust to the inclusion of more biological realism into the measures of RP. DeOliveira *et al.*(2010) found that estimates of SSB and fishing mortality were biased if there was a trend in fecundity which was not taken into account in the model of realized fecundity used in the assessment of western horse mackerel (*Trachurus trachurus*). Murua *et al.*(2010) found that the HCR for European hake (*Merluccius merluccius*) was robust to the exclusion of more biological information in the indices of RP.

Our objective was to test whether the current HCR for Greenland halibut under the XSA Current Assessment View OM is robust to different stock recruitment assumptions and to different measures of RP. We test the HCR using alternative stock recruitment functions with different RP indices which vary in the level of biological complexity that is included.

This work builds upon work conducted under the project 'Analysis of Stock Reproductive Potential to promote sustainability of Greenland Halibut fishery' which was funded by the Canada-Spain Marine Collaboration program.

2. Material and methods

2.1. The simulation algorithm

The simulation algorithm used in this document is the same used in the development of the NAFO Greenland halibut Management Strategies Evaluation (Miller et al., 2007; Miller et al., 2008 and Shelton and Miller, 2009) adopted by the NAFO Fisheries Commission in 2010 (NAFO, 2010). The conceptual framework for Management Strategy Evaluation (MSE), adapted from Kell et al.(2007), comprises an operating model and a management strategy. The algorithm used in this work is divided intodifferent modules that simulate the various processes in the fisherysystem. The two main modules of the algorithm are the operatingmodel (OM) which simulates the 'real or true system' (i.e.the biological population and the fishery, their interaction and theimplementation of the management advice) and the Management Procedure (MP)modelwhich simulates the management strategy (Figure 1). This simulational gorithm explicitly or implicitly acknowledges different sources of uncertainty in both the "real" system and the management strategies (Francis and Shotton, 1997; Kell et al., 2007; Rosenberg and Restrepo, 1994). The real biologicalpopulation and fishery are projected, in yearly time steps, using theOM and the MPis applied annually to produce the managementadvice for the next year. The advice obtained within the MP for acertain year constrains the behavior of the fleets in the next year. The Greenland halibut MSE takes into account historical uncertainty in the form of observation error through an XSA bootstrap procedure (Miller and Shelton, 2007), giving a distribution of initial population sizes and age compositions. Process error (variation in weights at age, proportions mature at age, partialrecruitment at age and number of recruits) was also taken into account. No management implementation error (i.e. TAC over/under-runs) wasconsidered from 2010.

2.1.1. The initial population

Theinitial random population is generated based on the 2010 NAFO approved assessment carried out with the XSA(Healey *et al.*, 2010) but replacing the observed abundance indices by a set of 500 bootstrapped abundance indices. To generate the random abundance indices for each bootstrap iteration, from the approved XSA a nonparametric bootstrap resampling within each age and index was conducted (Miller and Shelton, 2007).

The current XSA structure used to assess this stock includes ages 1 to 13 with a 14+ plus age group. XSA methodology predicted numbers in the plus group based on theannual catch in the plus group and the assumption that *F*-at-age for the plus group is the same as the *F*-at-age for thelast age before the plus group (Darby and Flatman, 1994). This method was considered unreasonable for the Greenland halibut stock given that survivorship to the plus group is high under reduced fishing mortality, and was replaced by an *F*-based dynamicpool method (Miller *et al.*, 2008).

TheGreenland halibut specimens mature at an old age (>10) and are slow growing, it is likely that they live well beyond age 14.Given that almostall of the fish are mature by age 20 and that most of the reproductive potential is included in the 14+, it was decided expand the "true" population in the OM to be agedisaggregated up to age 20 (age 20+ as plus group). The plus group numbers for each year estimated with the dynamic pool method were then expanded out to age 20+ based onassumption about the PR (selectivity to the commercial fishery) for the older ages equal to that of age 12.Natural mortality was assumed constant for all ages and years and equals to 0.2. The weights at age for years 1975 to 2009 were taken from the XSA inputs (based oncommercial catch data) in Healey *et al.* (2010). Some length data for fish older than age 13 are available from research surveys. These were converted to weight using the length-weight relationship in Gundersen and Brodie (1999).

2.1.2. The operating models

The Operating Models (OMs) tested in this document are based on three different Stock/Recruitment (S/R) relationships: One of the OMuses the Segmented Regression, the second oneuses the Rickerstock-recruit model. This last model led to the recruitment at high values of reproductive potential (RP) indices being very low causing extremefluctuations at high stock size as a result of strong compensation in the Ricker model. Therefore, a modified Ricker stock-recruit OM was implemented. In this modified Ricker model the recruitment does not decline below a specified level at high indices of reproductive potential. The modified Ricker curve setsas the recruitment for estimates of RP above the maximum historically observed level of the index the recruitment estimated by the Ricker function for the maximum observed RP value plus error. These scenarios cover the uncertainty about the recruitment levels depending on the level of the different RP indices. The Segmented Regression assumes constant recruitment from some level of RP indices. Ricker function assumes the decrease of recruitment for high levels of RP indices due to compensation effect and the modified Ricker function assumes certain degree of compensation but for levels

of RP indices never observed assumes a more or less constant recruitment.Similar to Shelton and Miller (2009) the OM based on the Segmented Regressionwas called Current Assessment View (*CAV*), the OM based on the Ricker function was called *CAV_Ric* and the OM based on the modified Ricker model was called *CAV_mRic*. *CAV* is most closely consistent with the NAFO Greenland halibut acceptedassessment model and is the same XSA CAV OM tested in the Greenland halibut MSE.

In all OMsthe Partial Recruitment (PR) is assumed to be flat-topped for ages older than 12. TheseOMs consist of an age-structured biological population and single fishery inducing fishing mortality during the harvestingprocess. EachOM starts in 2010 and for this year the population numbers of age 2 and older are calculated using the numbers and fishing mortalities obtained in the generation of the initial population while the recruits at age 1 are estimated using the different S/R relationshipsdescribed abovewith a lognormal multiplicative random error with autocorrelation.TheS/R relationships were fitted using thenumbers at age 1 in the initial population and the different RP indices for the period 1975-2006in each of the iterations. In subsequent years, given the matrix ofnumbers-at-age of the previous years, the population numbers arecarried forward using the exponential survival equation. Natural mortality was assumed constant for all ages and years and equals to 0.2. It was applied an implementation error only in 2010:Theapproved TAC for 2010 is known (16000 t), it is assumed that in 2010the catch level will be the TAC plus the observed TAC overrun in the period 2004-2009. The catchability of the fishery in the projected years isresampled from the catchability observed in the period 1997-2006. Weights for projected years were resampled by year (all ages), from the period 2000 to 2009.

2.1.3. Indices of reproductive potential

Data on maturity, sex ratio and fecundity were collected from Canadian research vessel bottom trawl surveys conducted in the fall from 1978 to 2010. Survey data from Div. 2J and 3K only were used as these areas had the most consistent coverage of the deep water areas inhabited by Greenland halibut.

Maturities were determined macroscopically; however, there are some uncertainties with the classification scheme that has been used and maturity at age is likely over estimated (Rideout *et al.*, 2012). It is not possible to retroactively correct the maturity staging and so these are the best data available at this time for estimating maturity at age. In addition, starting in the early 1990's the frequency of older/larger fish declined substantially meaning that there are few data from adults, probably increasing the variability in the estimates of maturity at age, and possibly sex ratio.

Proportion mature at age was estimated by cohort or by year, using generalized linear models with a logit link function and binomial error. Age was treated as a continuous variable since in general it is not possible for there to be a lower proportion of adults at age a+1 than at age a (Morgan and Colbourne, 1999). For cohorts where there was no significant model fit to the data, the average of estimates from adjacent cohorts (or years) or of the three closest cohorts (or years) were used. All ages were used in the fitting. Maturation occurs as a cohort ages and so estimation by cohort is the more biologically sound approach and this was the approach used in most of the RP indices. However, the earliest and latest cohorts in a time series generally do not have sufficient representation across age to allow for model fit. So to avoid this problem one index of RP (FSByear, see below) used maturities estimated on an annual basis.

Sex ratio (proportion female) at age was also estimated using generalized linear models with a logit link function and binomial error. These models had the form sex ratio =age + cohort, where age and cohort were both class variables. In this case age was treated as a class variable since there is no a priori reason to believe that sex ratio would change continuously across age (Morgan and Brattey, 2005). Ages 3 to 14 were used in the model fitting and only ages for a cohort with at least 5 observations were used in the fitting. Sample sizes for a cohort ranged from 753 to 1527. Sufficient data were available to fit the model to cohorts from 1969 to 2001.

Fecundity data were limited. A fecundity/length relationship based on data collected in 1976-77 (Bowering, 1980) was used for those years. For 1980 unpublished data were used and for the other years a combination of all of these data was used. The relationships were:

- For 1976-1977: F=0.0623(Length3.082)
- For 1980: F= 0.0018(Length3.8263)
- For all other years: F=0.01064(Length3.454)

The fecundity length relationships were applied to mean length at age to produce egg production at age. The lengths at age used were the beginning of the year estimates from the assessment. However, they were for sexes combined and so could deviate from true female weight or length. Fecundity is determined mostly by size so age was not included in the modeling (Lambert *et al.*, 2003).

These estimates of maturity, sex ratio and fecundity were used along with the weights and numbers at age to produce five different Reproductive Potential (RP) indices test the robustness of the currentHCR for Greenland halibut to different assumptions about indices of reproductive potential. The different RP indices were:

SSBcohort.Stock Spawning Biomass using maturity ogives estimated by cohort applied to the total biomass. Where *Nay* is the population number-at-age *a* in year *y*, *Way* the weight-at-age *a* in year *y*, *May* is the proportion mature-at-age *a* in year *y*. The age range is 5-20. This index is the NAFO approved RP measure for this stock.

$$SSBcohort = \sum_{a=i}^{j} Nay * Way * May$$

B10+. Is the biomass for ages more than 9 years old as proxy of SSB.

$$B10+=\sum_{a=10}^{20} Nay * Way$$

FSBcohort. Female Spawning Biomass estimated using maturity ogives estimated by cohort applied to female biomass. Where *Ray* is the proportion of females-at-age *a*in year *y*.

$$FSBcohort = \sum_{a=i}^{j} Nay * Way * May * Ray$$

FSByear. Female Spawning Biomass estimated using maturity ogives estimated by year applied to female biomass.

$$FSByear = \sum_{a=i}^{j} Nay * Way * May * Ray$$

TEP. Total Egg Production, incorporating a proxy for realized fecundity-at-age. Where Eay is the egg production atage a in year ycalculated as described above.

$$TEP = \sum_{a=i}^{J} Nay * May * Ray * Eay$$

2.1.4. The management procedure

TheMSwasfirst applied in 2010 and led to the first TAC advice for 2011based on the Harvest Control Rule (HCR) approved by the Fisheries Commission in 2010 (NAFO, 2010). The same HCR is applied every year up to 2030. The MP model is divided in twosteps: (i) the observation model which simulates the data collection (the surveys indices) (ii) the management decision model which uses a HCR based on the surveys indices to derive managementadvice. In the observation model the abundance indices are generated with a multiplicative random error assuming a linear relationship between catchability and abundance-at-age. The TAC for year y+1 is set based on the survey indices observed in the period y-5toy-1 with the following HCR based on a simple TAC adjustment strategy that uses the change in perceived status of the stock (from research surveys) to adjust the TAC:

TAC
$$_{y+1}$$
 = TAC $_{y}(1 + \lambda x \text{ slope})$

Where: slope = average slope of log-linear regression lines fit to the last five years of each biomass index (equally weighted). The biomass indices are: the Canadian Fall, the Canadian spring and the EU Flemish Cap to1400 m. surveys.

 λ = an adjustment variable to ensure that the relative change in TAC is greater than the perceived relative decline in stock size. The λ values are: 2 if the slope is negative and 1 if the slope is positive.

The TAC from 2011 onwards shall not be set at levels beyond 5% less or greater than the TAC of the preceding year. To apply this HCR for estimating the first TAC for 2011, the TAC of 2010 was set at 17500 t.

2.1.5. Management objectives

We used the following four Performance Targets that we used in the Greenland halibut MSE conducted by NAFO (NAFO FC, 2010):

- 1) The probability of the decline of 25% or more in terms of exploitable biomass from 2011 to2016 is kept at 10% or lower.
- 2) a) The probability of annual TAC variation of greater than 15% is kept at 25% or lower and
 - b) The probability of variation of TAC more than 25% over any period of 3 years should bekept at 25% or lower.

If the conditions a) and b) are not met, then an alternate performance target should beconsidered as follows:

c) The TAC should not be below 10 000 t for the period 2011-2015 in any one year with aprobability of 25% on a year by year basis.

3) The magnitude of the average TAC in the short, medium and long term should be maximized.

4) The probability of failure to meet or exceed a milestone within a prescribed period of time should be kept at 25% or lower. Milestone means the average exploitable biomass for the period 1985-1999 to be compared with the exploitable biomass in 2031.

The performance target 2 was cover with the final approved MSE HCR in September 2010: "*The TAC from 2011 onwards shall not be set at levels beyond 5% less or greater than the TAC of the preceding year*". This requirement included in the final HCR addresses thetarget 2 by which the TAC cannot vary more than 15%. The recovery target for the exploitable biomass was established as the mean exploitable biomass for ages 5 to 9 in the period 1985-1999.

2.1.6. Performance Statistics

Performance statistics allow the evaluation of the success of the proposed HCR across a set of OMs relative to target objectives.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. Performance statistics need to address both fishery related objectives and those that are stock-conservation related. In this document we defined the following Performance Statistics to measure the achievement of the management targets in the different OM:

- 1. The probability of exploitable biomass in 2016 should be higher than the exploitable biomass in 2011. The exploitable biomass is defined asages 5 to 9 biomass.
- 2. Measure the magnitude of the average TAC in the short (2015), medium (2020) and long term (2030).
- 3. The probability of exploitable biomass in 2031 should be more than the target exploitable biomass.
- 4. The probability of the annual F_{bar} should be more than the annual F_{max} .

The first three PSs measured the management targets set in the approved Greenland halibut MSE. In this study a fourth PS is included related to fishing mortality, although there are currently no precautionary approach fishing mortality reference points for this stock. The annual probability of the F beinggreater than the annually estimated F_{max} was calculated. F_{max} is normally used as proxy of F_{lim} in many NAFO stocks.

2.2. The parameterization or conditioning of the operating model

2.2.1. The projection

In each scenario of RP indices, the biological population and fisherywere projected until 2030 and for 500 iterations. Thus, thelast management process is run in 2030 and the last 'perceived'population is obtained for 2031.In the projection of the "true" biological population, weights for projected years were resampled by year (all ages) from the period 2000 to 2009. Sex-ratio is assumed constant and equal to that observed in 2011 and maturity and fecundity were assumed constant and equal to the last year available information: maturity by cohort 2018, by year 2011 and fecundity 2010. Natural mortality in the projections was assumed 0.2. The catchability of the fishery in the projected years isresampled from the catchability observed in the period 1997-2006. The RP, based on the different RP indicesdescribedabove, determined the number of recruits for the simulated population in the next year class using the S/R models. Foreach of the RP indices, S/R relationships were fitted using the Segmented Regression, the Ricker and the modified Ricker models of the initial random population between 1975-2006 for 500 iterations. The parameters and associated errors obtained from fitting the S/R relationships were used in each of the iterations to estimate the recruitment. In the observation model, the catchability and the errors of the abundance indices were equal to those obtained in the generation of the initial population and the catch-at-age matrix was taken directly from the fishery without error.

3. Results

3.1. Biological variables by age

Variation in maturity at age was evident both when estimated by year and by cohort (Figure2). However, estimates by cohort show a clear pattern over time with cohorts from the 1980's on generally maturing at a younger age than those of the 1970's, while there is little or no pattern over time in the estimates by year. There was a trend to increasing proportion female over time, although most of the change was in age classes at which very few females are mature. Fecundity has also varied over time, with some trend to lower fecundity since about 2000. Since fecundity data are limited, much of the change in fecundity actually reflects changes in mean length at age.

The range of variability of each of the biological inputs at age is shown in Figure 3. The proportion female at age is more or less constant around 0.5 till age 7. Proportion females then clearly increases from age 8 till age 12 and for older ages the proportion of females is almost 1. This reflects differential longevity and probably growth, maturity and mortality pattern between females and males. The variability in the proportion female is very low for all ages. The mature proportion at age estimated by cohort and by year is quite similar, being almost zero for ages younger than 10, and increasing to one by about age 18. The major difference between them is that the ogive estimated by year has a bigger variation at age than that the estimated by cohort. The fecundity at age presents a clear increasing trend from age 5 onwards. This is the result of the increase in fecundity with length. The variability by age is quite low till age 15 and increase from age 16 till 20.

3.2. Reproductive Potential indices by year

Trends in RP indices calculated to age 14+ and age 20+ show some differences. The 14+ RP indices are lower than the 20+ indices (Figure 4). All RP indices calculated to 14+ show similar trends except the 10+ index, which does not show the same decrease in the late 1980's shown by the other indices. In the case of the 20+ RP indices, all the trends are quite similar except the FSByear, which shows much more variability in the early part of the time series than the other indices. The SSBcohort and FSBcohort are very similar because most of the mature females are older than 13 years, where the proportions of females are almost 1, so that the inclusion of sex ratio does not result in much change in SSBcohort. These RP indices have a maximum in 1992 while the 10+ maximum appears in 1991.

3.3. Stock recruitment relationships

The fitsof the Segmented Regression to all the RP indices are very similar except the FSByear where the slope of the regression below the break point is much steeper so themaximum recruitment is reached at lower levels than the other indices (Figure 5). For all indices their level at the start of the projection (2010) is greater than the Segmented Regression break point ("b" parameter). For the Ricker S/R all the indices show a very similar fit with a strong compensationeffect (Figure 6). The maximum observed level of RP gives a very low recruitmentcompare with the observed recruitments. The levels of all RPs at the start of the projection are close to those that produces the maximum recruitment.

Based on the Mean Absolute Error (MAE) and the Akaike information criterion (AIC),10+ biomass, SSBcohort and FSBcohort indices have a better fit to thedata by the Ricker function. In the TEP and FSByear cases the Segmented Regression and Ricker AIC and MAE values are very similar. In bothSegmented Regression and Ricker the bestfits were to the 10+ index followed by SSBcohort, FSBcohort, TEP and FSByear indices. The last two RP indices have very similar AIC and MAE values (Table 1).

Table 2 presents the deterministic values and the 5%, 50% and 95% percentiles of the S/R relationship parameters. The uncertainty around the median of the parameters seems to be quite small. In the Segmented Regression cases, except forFSByear, the deterministic values of the "a" parameter are smaller than the estimated median and for the "b" parameter the deterministic estimations are bigger than the median. For the Ricker cases both parameters have deterministic values that are bigger than the estimated median except for TEP.

3.4. Stochastic results of the different Reproductive Potential (RP) indices under different Operating Models

3.4.1 Operating Models based on the Segmented Regression (CAV)

All RP indices have similar results in their mediansfor biomass, fishing mortality, catches and recruitmentshowing very similar trajectories (Figure 7). Biomass5+in the projected years shows a clear increasing trend reaching maximum values around 350000 t in the last year (2031) in all cases. All the RP scenarios showan increase in exploitable biomass (5-9) in the short term (2011-2016) reaching the exploitable biomass objective, mean exploitable biomass of the period 1985-1999, in 2031 (Table 3). The probability of the 2016 biomass being higher than the 2011 biomass (PS 1) is very highfor all the RP indices. For 10+ biomass, SSBcohort, FSBcohort and TEP it is more than 99% and for FSByear it is more than 98%. The probability of reaching the exploitable biomass objective in 2031 (PS 3) is very high for all RP indices more than 99%. Theexploitable biomass (5-9) time series shows an increasing trend from 2012to 2018 and since then is more or less stable around 130000-135000 t in all RP scenarios.

Fishing mortality shows a decreasing trend from2012 to2018 and after that is quite stable around 0.1 in all the scenarios under this stock recruitment assumption. The probability thatthe annual F ismore than the annual F_{max} (PS4) is less than 1% in all projected years for all the RP indices (Table 4).All the RP indices scenarios have very similar catch results: in the short term the mean catch isaround 16000 t, in the medium term around 19000 t and in the long term around 21000 t (Figure 8). Catch time series showa slight increase until2024 with stability around 25000 t annually after this year.

The biomass dynamics in projected years is determined by the stock recruitment function assumed to calculate the recruitment in these years. The OMs based on the Segmented Regressionfunction assume constant recruitment from some level of the RP indices. This level of RP is estimated by the "b" parameter of the Segmented Regression function. Recruitment in all projected years is quite constant in all cases (Figure 7) and is around 120000 recruits as the maximum recruitment estimated for all indices of RP. This stability is the result of all RP indices in allprojected years arelargerthan the "b" parameter.

3.4.2. Operating Models based on the Ricker stock recruitment function (CAV_Ric)

All the RP indices medians based on maturity ogives estimated by cohort oryear under this OM have very similar results for biomass, fishing mortality, catch and recruitment (Figure 9). The 10+ RP index results areslightly differentwhile the TEP index has quite different results than the others. The 5+ biomass in the projected years for all RP indices except TEP shows a clear increasing trend reaching a maximum around 250000 t in 2023 for the scenarios based on maturity ogives and around 275000 t in 2025 in the 10+ case. From then until 2031, biomass 5+ decreased to 100000 t in the maturity ogives cases and to 175000 t in the 10+ scenario. In the TEP case the 5+ biomass decreases to almost zero in 2020 and increases slightly in the last three years of projections. These trends are similar for the exploitable biomass (5-9). The probability thatthe 2016 exploitable biomass (5-9) is higherthan the 2011 biomass (PS 1) is for all the RP indices very high, more than 99%, except for the TEP RP index where this probability is only 20% (Table 3). The probability of reaching the exploitable biomass (5-9) time series show an increasing trend from2012 to2019 and then decrease toalmost zero in 2031 in all the scenarios except TEP. In the TEP case the exploitable biomass decrease starts in 2014 and reaches almost zero in 2020-2028 before starting to increase.

Fishing mortality in all the scenarios except TEP shows a slight decreasing trend from2012 until2026 and after shows a slight increase to2031 where is around 0.2 (Figure 9). In the TEP case, F_{bar} increases from 0.2 in 2012 to1.4 in 2023 and is stable at this level until2028 after which decreasesto0.8 by 2031. The probability of the annual F being more than the annual F_{max} (PS4) in the 10+ case is less than 1% in all projected years (Table 4). In the SSBcohort, FSBcohort and FSByear scenarios it is less than 5% in almost all years, except the last projected year where it is 7%, 10% and 5%. In the TEP case it is less than 1% in the short term (until2017), starts to increase in the medium term period from 2018-2021 and from then to2031 in all years is higher than 70%. All the RP indices scenarios have a very similar mean catch results in the short termat 16000 t (Figure 10). In the medium term the 10+, FSBcohort and FSByear catches are around 19000 t, for SSBcohort around 18000 t and for TEP 14000 t. The mean catch in the long term period for 10+ biomass is around 19000 t, for FSBcohort, FSBcohort and FSByear 18000 t and for the TEP RP index scenario is only 12000 t. Catch time series show a slight increase to2024 followed by a slight decrease to2031 where they are around 15000 t for all the scenarios except TEP. Catch in the TEP case decreasestoalmost zero in 2024 and presents anincrease from 2029reaching about 10000 t in 2031.

In the Ricker case the S/R function assumes that recruitment increases with increasing RP indexto a maximum recruitment followed by a decline in recruitment with further increase in RP. For Greenland halibut this model led to the recruitment at high values of RP being very low causing extreme fluctuations at high stock size as a result of strong compensation. In all the scenarios except TEP, the recruitment in the projected years increaseduntil 2014, where the maximum recruitment level was reached, and then decreased to almost zero in 2023 as a result of large RP indices. This large decline in recruitments is the cause of the drop in5+ and exploitable biomass. In the TEP case the maximum recruitment level is reached in the first year of the projection and the drop to nearzero recruits happens much earlier in 2014. This causes the decline in biomass before the other scenarios.

3.4.3. Operating Models based on the modified Ricker stock recruitment function (CAV_mRic)

As in the Ricker OMs, the RP SSBcohort, FSBcohort and FSByearmedians based on the maturity ogives (cohort and year) under the modified Ricker functionhave very similar results for biomass, fishing mortality, catch and recruitment. The 10+ RP index has slightly different results from the previous ones and the TEP index has quite different results from the others (Figure 11). The 5+ biomass in the projected years for all RP indices except TEP shows a clear increasing trend reachingamaximum around 250000 t in 2025 for the scenarios based on maturity ogives and around 275000 t in the 10+ case. From then to2031 biomass 5+ is more or less stable in all the ogive scenarios with aslight decrease in the 10+ to 250000 t. In the TEP case the 5+ biomass shows a more or less constant increase until 2031 when itreaches values around 200000 t. All the RP scenarios showan increase in exploitable biomass (5-9) in the short term (2011-2016) except the TEP index. The probability of the 2016 biomass beingmore than the 2011 biomass (PS 1) is very highfor all the RP indices at more than 99% except for TEP where this probability is 82% (Table 3). The probability of reaching the exploitable biomass objective in 2031 (PS 3) is very low for all RP indices under the modified Ricker function (Table 3). It isless than 5% for the 10+ biomass and TEP scenarios, less than 10% in the SSBcohort and FSBcohort cases and less than 20% in the FSByearscenario.The exploitable biomass time series (5-9) for all the cases except TEP shows an increasing trend from 2012 to 2019 reaching levels around 135000 t.After 2019 exploitable biomass decreased to around 95000 t in2025, remaining stable at these levels until 2031 in the ogive RP cases. The 10+ RP case showed a decrease from 2019 to a level of 80000 t in 2031. In the TEP case the exploitable biomass shows an increase to 2018 and after remains more or less stable at levels around 90000 t.

Fishing mortality shows a slight decreasing trend from2012 ($F_{bar}=0.2$) to2031($F_{bar}=0.1$) in all the scenarios. The probability of the annual F_{bar} being more than the annual F_{max} (PS4) is less than 1% in all the scenarios from 2012 (Table 4).All the RP indices scenarios in the short term have a very similar mean catch results at 16000 t (Figure 12). In the medium term the 10+, SSBcohort, FSBcohort and FSByear catches are around 19000 t and for TEP case they are 17000 t. The mean catch in the long term period for 10+, SSBcohort, FSBcohort and FSByear biomass is around 19000 t and for TEP RP index is around 18000 t.Catch inall the scenarios shows a slight increase until2023 with levels around 21000 t and after shows a decline until 2031 withlevels around 18000 t.

In themodified Ricker model used here recruitment does not decline below a specified level at high indices of RP. The modified Ricker curve sets for estimates of RP above the maximum historically observed level of the index the recruitment estimated by the Ricker function for the maximum observed RP value plus error. Theprojected RP indices reach the maximum observed RP level at different times resulting in constant recruitment beginning at different years in the projection period. In the scenarios based on maturity ogives (SSBcohort, FSBcohort and FSByear), recruitment in the projected years only increasesuntil2012, withamaximum recruitment level around

135000.After this, recruitment decreases of 90000 in 2021 remaining at this level for the rest of the projection period. The decline in recruitment for the 10+ index from 2012 is more moderate up to 2018 but after this recruitment drops to level around 73000 in 2023. In the TEP case the recruitment level is more or less constant for the entire projected period at 85000 recruits.

4. Discussion

The XSA Current Assessment View (CAV) operating model tested during the Greenland halibut MSE assumed the Segmented Regression S/R function, constant natural mortality (M=0.2) and a flat top PR for ages 12 and older. This OM was run with the maturity ogive estimated by cohort. The objective of the study was to test whether the current HCR for Greenland halibut under XSA CAV OM is robust to different stock recruitment assumptions and to different measures of RP.

The MSE simulated "true" versus "perceived" population for different scenarios and allowed to test the management system performance in relation to the inclusion of alternative S/R functions and different reproductive potential indices. We tested the HCR using alternative S/R functions (Segmented Regression, Ricker and modified Ricker) with different RP indices which vary in the level of biological complexity. The RP indices used in increasing order of biological information were: Biomass 10+, SSBcohort, FSBcohort, FSByear and TEP.

The results (Figure 4) show that for stocks for which most of their reproductive potential is included in the plus group, as is the case for Greenland halibut, the estimation of the abundance of the plus group can have big impact when estimating the RP of the stock. The method used by XSA and the F-based dynamic pool method to calculate the plus group resulted in indices of RP that differed both in level and trend.

Understanding the basis of uncertainty in the S/R relationships is generally the most difficult outstanding problem in fisheries assessment and management (Hilborn and Walters, 1992) and it is key problem in the MSE. Ricker S/R function fits better than the Segmented Regression the Greenland halibut stock recruitment data for all the RP indices (Table 1). It was clearly better for Biomass 10+, SSBcohort and FSBcohort. All the XSA OM tested during the Greenland halibut MSE were based on the Segmented Regression function. Some XSA OM based on the Ricker function should be included since the data appear to show some degree of compensation at high levels of the RP indices.

The results show that for Greenland halibut data the inclusion of more biological information when estimating the reproductive potential does not improved the S/Rfit in both cases (Segmented Regression and Ricker). The best fits in both cases were obtained in descending order with: 10+Biomass, SSBcohort, FSBcohort, TEP and FSByear. The CAV tested in the Greenland halibut MSE was based on the SSBcohort which had the second best fit. These results are similar to those found by Marshall *et al.*(2006), Morgan (2008) and Murua *et al.* (2010), who showed that alternative and more complex RP indices did not always significantly improve the S/R relationship.

All the OMs based on the Segmented Regression have very similar results (Figure 7) and seem to be robust to assumptions about reproductive potential. All the OMs based on different RP indices under this scenario reach the objective for the exploitable biomass (5-9) with a very high probability (Table 3) and with levels the F less than F_{max} . These results are similar to those obtained for CAV OM during the MSE process and is seems that the RP indices have no a major impact in the final results for Biomass and F.

In the case of the OMs based on the Ricker S/R function, all the OMs have a very low probability, less than 1%, of achieving the exploitable biomass objective. The main reason for this failure is that inpart of the projected period all of the RP indices reach high levels that produce a drop in recruitment to levels close to zero, causing a large decrease in the exploitable biomass (5-9) levels. Total biomass (+5)decrease is much smaller, except in the TEP OM, due to a considerable increase in spawning biomass that it is not accessible to the trawl gear used in this fishery. In the Ricker TEP OM both biomass, total and exploitable, decrease to very low levels because the RP index is very high during all projected years.

In the case of the OMs based on the modified Ricker function, all the OMs have a low probability of achieving the exploitable biomass objectivealthough the total biomass reaches maximum levels in all the OMs. The main reason for this failure is that the recruitment level assumed for RP indices higher than the maximum observed RP indices is

not enough to reach the exploitable biomass objective. Most of the biomass increase is not accessible to the trawl gear.

The results for the Ricker based OMs pose a problem for the provision of advice. The data clearly seem to be Ricker in nature, with a decline in recruitment at high levels of RP. This leads to low biomass and seems to indicate that the population should not be allowed to increase above the level of maximum recruitment. However, this could prove to be a dangerous objective if the S/R function is not really a Ricker. In fact, the better fit of the Ricker to the data is driven mainly by 3 or 4 stock recruit pairs at high stock size. It would be prudent to proceed cautiously until the shape of the S/R function is confirmed.

Within a given stock recruit assumption all the RP indices analyzed have very similar results except for TEP in the Ricker and modified Ricker. There was however, a major impact of stock recruitment assumptions. The results are different inter the stock recruitment assumptions. So, the stock recruitment assumptions have a big impact in the final results while the RP indices appear to have little impact.

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 Table 1.- Segmented Regression and Ricker deterministic estimated parameters values as well as the Mean Absolute Error (MAE) and the AkaikeInformation Criterion (AIC) for the analyzed RP indices.

SegmentedRegression											
	a b AIC MAE										
10+	7.4211	17123	-68.98	0.1940							
SSBcohort	24.091	5179	-67.10	0.2010							
FSBcohort	26.706	4723	-62.61	0.2171							
ТЕР	0.0037545	32311000	-58.97	0.2295							
FSByear	65.385	1789	-56.61	0.2236							

Ricker								
	а	b	AIC	MAE				
10+	1.28E+01	3.34E-05	-82.87	0.1660				
SSBcohort	4.41E+01	1.16E-04	-74.97	0.1890				
FSBcohort	4.40E+01	1.16E-04	-71.20	0.1964				
ТЕР	0.005293	1.4422E-08	-57.43	0.2283				
FSByear	5.00E+01	1.25E-04	-57.46	0.2322				

 Table 2.- Segmented Regression and Ricker deterministic and the 5%, 50% and 95% percentiles of the estimated parameters values.

SegmentedRegression											
	а	5%	50%	95%	b	5%	50%	95%			
10+	7.421	6.762	7.467	9.068	17123	13545	16941	18791			
SSBcohort	24.091	22.173	26.233	34.331	5179	3576	4644	5608			
FSBcohort	26.706	25.697	29.536	38.152	4723	3118	4222	4921			
ТЕР	0.00375	0.00354	0.00421	0.00509	32311000	23259857	28770605	34531810			
FSByear	65.385	40.335	62.646	68.398	1789	1719	1868	3006			
				Rick	er						
	а	5%	50%	95%	b	5%	50%	95%			
10+	12.78	11.22	12.10	13.08	3.34E-05	3.05E-05	3.24E-05	3.44E-05			
SSBcohort	44.08	35.16	39.33	45.78	1.16E-04	9.58E-05	1.07E-04	1.21E-04			
FSBcohort	44.03	39.02	42.80	48.44	1.16E-04	1.02E-04	1.14E-04	1.25E-04			
ТЕР	0.0053	0.0050	0.0055	0.0062	1.4422E-08	1.31E-08	1.46E-08	1.72E-08			
FSByear	50.01	39.99	44.35	50.89	1.25E-04	1.01E-04	1.14E-04	1.28E-04			

Table 3.-Probability of exploitable biomass in 2016 will be higher than the exploitable biomass in 2011 (PS 1) and the probability of exploitable biomass in 2031 will be more than the target exploitable biomass (PS 3) for 10+ biomass, SSBcohort, FSBcohort, FSByear and TEP Reproductive Potential indices under the Segmented Regression, Ricker and modified Ricker S/R functions.

PS 1	10+	SSBcohort	FSBcohort	FSByear	TEP
SR	1.00	1.00	0.99	0.98	0.99
Ricker	1.00	1.00	1.00	1.00	0.20
RickerModified	1.00	1.00	1.00	0.99	0.82
PS 3	10+	SSBcohort	FSBcohort	FSByear	TEP
PS 3 SR	10 + 1.00	SSBcohort 1.00	FSBcohort 0.99	FSByear 0.99	TEP 0.99
PS 3 SR Ricker	10+ 1.00 0.00	SSBcohort 1.00 0.00	FSBcohort 0.99 0.00	FSByear 0.99 0.00	TEP 0.99 0.00

Table 4. Probability of the annual F_{bar} (5-10) will be higher than the annual F_{max} (PS 4) in the projected years for the different Operating Models.

	CAV					CAV_Ric				CAV_mRic					
Year	10+	SSBcohort	FSBcohort	TEP	FSByear	10+	SSBcohort	FSBcohort	TEP	FSByear	10+	SSBcohort	FSBcohort	TEP	FSByear
2010	0.04	0.05	0.04	0.03	0.04	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.03
2011	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
2012	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2013	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2014	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2015	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2016	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2017	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2018	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00
2019	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.00
2020	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.23	0.00	0.00	0.00	0.00	0.00	0.00
2021	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.51	0.00	0.00	0.00	0.00	0.00	0.00
2022	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.80	0.00	0.00	0.00	0.00	0.00	0.00
2023	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.94	0.00	0.00	0.00	0.00	0.00	0.00
2024	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.98	0.00	0.00	0.00	0.00	0.00	0.00
2025	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
2026	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
2027	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
2028	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
2029	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.96	0.00	0.00	0.00	0.00	0.00	0.00
2030	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.04	0.88	0.01	0.00	0.00	0.00	0.00	0.00
2031	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.10	0.73	0.05	0.00	0.00	0.00	0.00	0.00



Figure 1 (From NAFO SCR 07/58).- Conceptual framework for Management Strategy Evaluation (MSE), adapted from Kell*et al.* (2007).



Figure 2.-Trends over time in biological inputs to the indices of Reproductive Potential. Age at 50% maturity estimated by cohort and year (along with 95% confidence limits), proportion female for ages 10 and 11 and number of eggs produced in thousands for age 12.



Figure 3.-Maturity estimated by cohort, maturity estimated by year, female sex ratio and fecundity by age box plot.



Figure 4.-Reproductive Potential indices for ages 1 to 14+ as were calculated in the 2010 assessment and for 1 to 20+ estimated by the dynamic pool method: 10+ biomass (10+), spawning stock biomass SSB estimated by cohort (SSBcohort), female spawning biomass FSB estimated by cohort (FSBcohort), total egg production (TEP) and female spawning biomass SSB estimated by year (FSByear).



Figure 5.-Deterministic Segmented Regression S/R fit for the different Reproductive Potential indices. Vertical line shows the 2010 PR index level.



Figure 6.-Deterministic Ricker S/R fit for the different Reproductive Potential indices. Vertical line shows the 2010 PR index level.



Figure 7.-Median values of the time series for the 5+ biomass, exploitable biomass (5-9), F_{bar}(5-10), catches, the normal(0,1) standardized RP indices and the recruitment for the 10+ biomass, SSBcohort, FSBcohort, Total Egg Production (TEP) and FSByear RP indices used in the Segmented Regression.



Figure 8.-Box plot for short, medium and long term expected yield of the different PR indices under the Segmented Regression function.



Figure 9.-Median values of the time series for the 5+ biomass, exploitable biomass (5-9), F_{bar}(5-10), catches, the normal(0,1) standardized RP indices and the recruitment for the 10+ biomass, SSBcohort, FSBcohort, Total Egg Production (TEP) and FSByear RP indices used in the Ricker S/R function.



Figure 10.-Box plot for short, medium and long term expected yield of the different PR indices under the Ricker function.



Figure 11.-Median values of the time series for the 5+ biomass, exploitable biomass (5-9), $F_{bar}(5-10)$, catches, the normal(0,1) standardized RP indices and the recruitment for the 10+ biomass, SSBcohort, FSBcohort, Total Egg Production (TEP) and FSByear RP indices used in the modified Ricker S/R function.



Figure 12.-Box plot for short, medium and long term expected yield of the different PR indices under the modified Ricker function.