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GREENLAND HALIBUT STOCK ASSESSMENT & MANAGEMENT STRATEGY EVALUATION

Instituto Español de Oceanografía Centro Oceanográfico de Vigo

Vigo, Spain – 3-7 April, 2017

Contents

Scientific Council Greenland Halibut Meeting Participants

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Front row: Mónica Mandado Alonso, Carsten Hvingel, Margaret Treble, Diana González-Troncoso, Brian Healey (co-chair), Adriana Nogueira Gassent, Puri Fernandez

Missing from photo: Katherine Sosebee (co-chair), Dayna Bell MacCallum

GREENLAND HALIBUT STOCK ASSESSMENT & MANAGEMENT STRATEGY EVALUATION

Vigo, Spain – 3-7 April, 2017

1. Opening of the meeting

The Scientific Council met in Vigo, Spain to discuss Greenland halibut Management Strategy Evaluation. The meeting was attended by representatives from Canada, the EU (Portugal & Spain), Japan, Norway, Greenland, Russia and the USA. In addition, three expert external reviewers also participated in the meeting. The full participants list is included as Appendix II.

The meeting was co-chaired by the SC Chair, Kathy Sosebee (USA) and SC vice-chair Brian Healey (CAN). The SC coordinator was appointed as rapporteur.

2. Scope

The Fisheries Commission (FC) of the Northwest Atlantic Fisheries Organization (NAFO) revised a timeline for the Greenland halibut assessment and MSE review in September 2016 (Annex 7 of FC 16-20). In this timeline, a meeting of the Scientific Council was scheduled for April 2017. For this meeting, the FC requested the SC to conduct an assessment through 2015, give feedback of the performance of the existing management strategy, and reach an agreement on a final set of data to be used for the current MSE. At this meeting the SC was to provide both an internal and an external peer review of the stock assessment for **Greenland halibut in 2+3KLMNO** (*Reinhardtius hippoglossoides* (Walbaum, 1792)).

i) Requirements for external reviewers

The chairs welcomed the invited external reviewers (Carmen Fernandez - ICES, Ana Parma - Centro para el Estudio de Sistemas Marinos, Argentina, and Mark Terceiro - NOAA) to the meeting and expressed gratitude for their availability to contribute to the work of SC. The role and function of the external reviewers were presented to the meeting by the co-chairs and were discussed in plenary:

- Review the background materials and reports prior to and during the review meeting.
- Attend and participate in the review meeting which will consist of presentations by various members of the SC as well as any additional work conducted during the meeting. Reviewers may ask for additional runs of models and are encouraged to do so.
- During the meeting, additional questions that were not in the Terms of Reference but that are directly related to the assessments may be raised.
- The external reviewers will be asked to give feedback during the meeting about the assessment as well as the meeting format and function.

ii) Specific Terms of Reference for the Greenland halibut Assessment

1. Develop an assessment model following Appendix I. A, if possible
2. Give feedback on the existing management strategy, including identification of possible deficiencies/areas for improvement (i.e. lessons learned)
3. Agreement on final data set/input data to be applied in the MSE
4. Directions from WG on Risk-based Management Strategies
5. Review results from available operating models
6. Discuss elements of other possible operating models to be developed prior to June SC meeting
7. Develop advice for RBMS re quantification of objectives/performance criteria and constraints

8. Specify MP[1] "trials", including operating model variants to be fit, projection specifications, observation models for future generated data, and performance statistics (initial quantification of objectives)
9. Possibly give guidance for development of Candidate Management Strategies and/or HCRs

3. Introductory presentations

i) Recommendations from the WG-RBMS meeting

The co-chair of joint Fisheries Commission-Scientific Council Working Group on Risk-Based Management Strategies (WG-RBMS) presented the report of the meeting held 07-09 February 2017 at the NEAFC Headquarters in London, UK. This report is now finalized and published as FC-SC Doc. 17-02.

ii) Review of previous WebEx Meetings.

A series of preparatory meetings of SC were held by WebEx on October 26 2016, January 9 and February 25 2017 to discuss *inter alia* the data sets to be used in developing the MSE operating models. The conclusions of those meetings are summarized below.

Surveys

A variety of survey indices is available for consideration, although none covers the entire distribution of the stock. These surveys (with depth and period included below) are:

- EU3M 0-700m 1995-2003 age 1-12 (mainly July)
- EU3M 0-1400m 2004-2015 age 1-13 (mainly July) (also available split into 0-700 and 700-1400)
- Canadian fall 0-1450m 2J3K 1996-2015 age 1-13 (mainly October-December)
- Canadian spring 3LNO 0-730m 1996-2014 age 1-8 (mainly late April to end June)
- EU Spain summer 3L 0-1450m 2006-2015 age 1-14+ (mainly August)
- EU Spain spring 3NO 0-1450m 1997-2015 age 1-14+ (May or June, timing shifted to June in 2004)
- Canadian fall 3LNO 0-730 m 1996-2015 age 0-9 (mainly September-December)

A number of analyses were conducted to investigate the internal consistency of each of these surveys as well as to examine consistency across surveys.

The best internal consistency from one age to the next (log numbers) was for Canadian fall 2J3K (all ages correlated with the age before), Canadian fall 3LNO (only indices at age 2 through to age 3 in the following year; (hereafter written age 2-3, etc.)age 2-3 not significantly correlated, this index was only examined to age 9 because there were very few fish older than this in the series), Canadian spring 3LNO (only age 1-2 not correlated) and EU Spain 3NO (only age 1-2 not correlated). Internal consistency seems relatively poor for EU Spain 3L, with 1-2, 2-3, 3-4, 4-5 and 8-9 all not being significantly correlated. The EU 3M 0-700 was intermediate with 4 of 9 comparisons not being significant (2-3, 7-8, 8-9, 9-10) and for EU 3M 0-1400 with 3 of 9 comparisons being non-significant (5-6, 6-7, 9-10).

Surveys were compared to each other through the estimation of relative year class strength using ages 2-5. Surveys which extend to the mid-1990s have highly correlated estimates of relative year class strength. When time series are started in the late 1990's or early 2000's there are few significant correlations between estimates of relative year class strength. This is partly due to the lack of strong signal and the shortness of the time series. However, there is one potentially important point to note from these comparisons for the later years. The pattern in year class strength from the EU3M 0-1400m survey (initiated in 2004) is very different from all of the other survey indices. XSA analyses presented in 2011 (SC report page 206) detected a strong trend in the residuals for ages 1-4 from this survey and found that model fit was much improved if these data were excluded.

[1] MP refers to Management Procedure, which here reflects the same as intended by "Management Strategies and/or HCRs in point 9 below.

Correlations among surveys for each age were also evaluated: see Table 1.

Table 1. Number of significant correlations (at the p=0.05 level) for each age-specific index with other surveys of the same age.

Age	Can 2J3K	EU 3NO	EU 3L	EU 3M 1400	EU 3M 700	Can 3LNO	Can 3LNO Fall	Total
1	2	2		2	2	2	2	12
2	3	2		1	2	2	2	12
3	3	5	1	2	3	5	2	21
4	4	4		1	5	4	4	22
5	4	4	1	1	6	4	4	24
6	2	1			2	4	3	12
7	2	2	1	3	2	3	3	16
8	3	3	2	3	1	4	2	18
9	3	5	1	1		3	3	16
Total	26	28	6	14	23	31	25	

The EU Spain 3L survey had a very low number of significant correlations with other surveys (6), as did the EU 3M 0-1400 (14) survey. The other surveys (Canadian fall 2J3K, EU Spain 3NO, EU 3M 0-700, Canadian spring 3LNO and Canadian fall 3LNO) all had a larger or similar number of significant correlations.

Ages 1, 2 and 6 have a very low number of significant correlations (12), which means that the information for these ages are inconsistent between surveys. Ages 7 to 9 have an intermediate number of significant correlations (16-18) while ages 3-5 have quite high number of significant correlations (21-24). The available survey information does not seem to be consistent for ages 1, 2 and 6, and has an intermediate consistency for ages 7-9, while consistency is good for ages 3-5. This means that the most important ages in the commercial catch (5-10) have a low or intermediate consistency across surveys. The short length of the time series for some of the surveys impacts these results.

Comparison among surveys was also conducted based on mean weight per tow (i.e. age independent). In this case there are three pairs of surveys with a significant correlation index (Canadian Spring/EU 3M 0-700, EU 3M 0-1400/EU Spain 3L and EU 3M 0-1400/EU Spain 3NO). All the other correlations are quite low and in many cases negative. Therefore, inconsistencies exist among surveys on an age aggregated basis as well as in the indices at age.

Consistent with previous studies on the available survey data for this stock, it is clear that there are inconsistencies among and within surveys. However, it is not clear which surveys (if any) should be excluded from consideration. A set of candidate groupings of surveys was proposed as a starting point. Final data selection will depend on model diagnostics.

It was agreed that all candidate operating models should include, as a minimum, the data series listed in Table 2.

Table 2. Survey data sets considered for estimation of population size for Greenland Halibut in SA 2 + Divs. 3KLMNO.

	Base	O1	O2	O3
Fall 2J3K	1996-2015	1996-2015	1996-2015	1996-2015
Spring 3LNO	1996-2014	1996-2014	1996-2014	1996-2014
EU 3M 0-700	1995-2003	1995-2015	1995-2015	1995-2003
EU 3M 0-1400	2004-2015			2004-2015
EU 3M 700-1400		2004-2015	2004-2015	
EU Spain 3L		2006-2015		
EU Spain 3NO		1997-2015	1997-2015	1997-2015
Fall 3LNO		1996-2015	1996-2015	1996-2015

It was decided that a split of the age range for the EU 3M survey could be considered so that EU 3M 0-700 would be taken to reflect ages 1-5 and EU 3M 700-1400 ages 6 and above, if such a split was considered to be warranted.

Natural mortality

Under-ageing the oldest fish in the population can have appreciable impacts on assessments. Several studies have indicated that, as a result of ageing error, natural mortality (M) for fish populations may be underestimated when using whole otoliths to determine age. Using M = 4.22/t_{max} (where t_{max}=maximum age in years) as a rule of thumb (Hewitt and Hoenig, 2005), and assuming a maximum age of 35 (Dwyer et al. 2016), yields an estimate of 0.13 for M, which is comparable to the 0.15 from Gregg et al. (2006) using thin-sectioned otoliths stained with aniline blue, and the 0.12 from Treble et al. (2008). Cooper et al. (2007) independently concluded that M was about 0.12 for the same stock of Greenland halibut using the relationship with gonadosomatic index (GSI).

Models should include a base case that is similar to the last accepted assessment, including the same survey/age combinations, an M=0.2 and a 14+ group. This will aid in comparison of models. Natural mortality in most model runs (other than the base case) should have an M=0.12.

Age range in the assessment

The traditional method of reading whole left otoliths used in past assessments for SA2+3KLMNO Greenland halibut underestimates growth and longevity and was found to be invalid for fish that are 10 years of age or older (ICES 2011). The Workshop on Age Reading of Greenland halibut 2 (WKARGH2) met in Reykjavik, Iceland on 22-26 August, 2016 (ICES 2017) to examine two other age estimation methods for this population: the frozen whole right otolith (viewed with transmitted light) and thin-sectioned left otolith (viewed with reflected light). New information was presented at the meeting which confirmed the full or partial validation of both methods. A comparison of methods using the WebGR (an online exchange system for comparing age estimates from images) occurred prior to the meeting and indicated some bias between these methods, and low precision (between methods CV of approximately 15%), but generally this difference was felt to be acceptable (ICES 2017). It was recommended that both methods be used to provide age estimates for assessments with the caveat that either an ageing error matrix (AEM) or a growth curve should be used to account for the uncertainty in the age estimation (within method CVs of approximately 10%) (ICES 2017). Thin-section ages indicate longevity of about 35 years and that Greenland halibut are slower growing and longer lived than ages indicated from the traditional whole otolith method (Dwyer *et al*. 2016, Treble *et al*. 2008, Gregg *et al.* 2006).

Work published by Dwyer *et al.* (2016) compared age estimates between the traditional method of reading whole left otoliths and thin-sectioned left otoliths which indicated bias between these two methods does not occur until age 10, after which ages estimated from whole left otoliths underestimate the true age of Greenland halibut by 40% on average. More recently, twenty samples were added to the bomb radiocarbon validation analysis to determine whether whole otoliths gave an accurate age for smaller fish. In general, most fish <60 cm were aged correctly using the whole otolith method. Overall it was concluded that whole otoliths are generally accurate for fish up to age 9, and beyond that thin-sections provide more accurate ages for the Northwest Atlantic stock of Greenland halibut (Dwyer *et al*. 2016 and ICES 2017).

iii) Catch

Catch estimates for 2+3KLMNO Greenland halibut were not available over 2011-15, preventing an assessment of the stock during that period. During the June Scientific Council meeting in 2016, a method for computing catch was agreed that utilized effort estimates calculated from VMS data and catch rates (CPUE) derived from Scientific Observer data. When Scientific Observer data were not available during 2011-14, catch rates would be calculated from average rates over a previous, representative period when Scientific Observer data were available. However, testing revealed large differences among effort calculations from VMS, logbook and observer data that could not be explained. It was further acknowledged that the selection criterion used to enumerate VMS effort led to an overestimate as it included 100% of the time vessels spent within a set speed range, which would capture some portion of activities outside of bottom trawling (e.g. vessel turning, net deployment or retrieval, riding out poor weather, etc). Therefore, the VMS effort data were not used to estimate catch.

Catch estimates for 2011 to 2014 applied CPUE or effort data originating from sources that differed among countries. While both EU-Portugal and EU-Spain used Scientific Observer data collected during 2007-2010 to estimate mean catch rates, EU-Portugal used effort data from Statlant 21B whereas EU-Spain used NAFO Observer effort data. Russia estimated catch by modelling their observer CPUE data (2008-2015) and derived effort from logbooks. The Canadian otter trawl fleet fished almost entirely within the Canadian EEZ. For this fleet, catch was estimated from modelled CPUE (2005-2015) from observer data which was adjusted to reflect logbook effort data. There are insufficient observer data to model catch rates in double or triple trawls so reported landings were taken as catch. Reported landings from Canadian gillnets were accepted as catch as there have been substantial changes to the fishery (recent practice of baiting gillnets) and management regulations (a period of gradual change in the mesh sizes permitted at various depth ranges) that are not captured in logbook data, precluding an estimation procedure that could account for these changes.

The catch estimation method for 2015 differed from the previous four years and was established by the ad-hoc FC/SC WG on Catch Reporting. Daily catch record data were compiled by the NAFO Secretariat to estimate catch in the NRA during 2015. For Canada, reported landings by both the otter trawl and gillnet fleets within its EEZ were accepted as catch.

The TACs and estimated catches (using the procedures above) are shown in Table 3. Catch ranged from 20-25 Kt over 2011-2014 but decreased to 15Kt in 2015. Over 2011-2014, catch exceeded the TAC by an average of 38.5% except during 2015 when the values were similar (2% below TAC).

Table 3. Catch and TAC (1000t) for Greenland halibut in subarea 2+3KLMNO during 2011-2015.

	2011	2012	2013	2014	2015
TAC	17.2	16.3	15.5	15.4	15.6
Catch	25.0	23.0	20.0	21.4	15.3

A full description of catch estimation for various countries as well as the procedure for constructing the catch-at-age over 2011-2016 will be provided in an SCR document that is currently in preparation.

iv) Catch-at-age

Computation of catch and weight at age was conducted as in the past, with Canadian age length keys applied to available length frequency data as a result of ageing inconsistencies between the institutes providing age interpretations for this species. Ages 7 and 8 dominated the catches during 2011 to 2015, similar to the previous decade. Weights at age were generally stable over the entire time-series, although there was a slight dip for older ages (10+) in the mid-late 2000s. Overall the sum of the products of catch numbers-at-age and the corresponding weights-at-age ranged from 0.99 to 1.02 of the total catch reported over 2011 to 2015.

v) Overview of available data and biological features.

Greenland halibut are a deep-water circumpolar species that are relatively slow growing and long-lived (maximum age of about 35 years). Several contextual aspects relating to both Greenland halibut biology and data sources were tabled to establish the basis for discussion during the remainder of the meeting, and in particular to help orient the external reviewers regarding the implications of multiple issues for both stock assessment modelling and management strategy evaluation.

There is no single survey series which covers the range of this resource or even the spatial extent of the fishing activity. There has been extensive comparative analysis of the available surveys and their concordance (or lack thereof). Tagging experiments indicate that Greenland Halibut can be highly mobile and suggest that additional research is needed to understand the existing survey results better. Age determination of the species is exceedingly difficult and recent research has shown that ages beyond 9 years old cannot be reliably determined.

Information on the fishery, the history of catch estimation and appreciable changes in fishery performance (CPUE) were also presented, with discussion on how some recent changes should inform future selectivity patterns that should and/or could be employed in any management strategy evaluation.

4. Performance of existing management strategy

The Fisheries Commission requests the Scientific Council to implement the steps of the work plan relevant to the SC for progression of the Greenland halibut Management Strategy Evaluation Review (FC Working Paper 16-11 Rev. 2 adopted at the NAFO 2016 annual meeting). Step IV of that plan includes:

2) Give feedback on the existing management strategy, including identification of possible deficiencies/areas for improvement (i.e. lessons learned)

Scientific Council responded:

The evaluation of the performance of a medium to long term harvest strategy after six years is obviously difficult. The primary direct indicators of resource status – the survey indices of abundance – fell within the bounds forecast with few exceptions. SC noted that the 5% downward constraint on the change in TAC was applied in 4 out of the 6 years that advice was given according to the rule. However a serious concern is that the agreed annual catch estimates (which have only very recently become available) were appreciably above the TACs output in terms of the strategy (by an average of 39% over 2011-2014) which means that exceptional circumstances were occurring. SC recommends that the revision of the strategy includes:

- consideration of systematic differences between TAC provided by the harvest control rule and removals
- limitations imposed by inter-annual constraints on TAC variability
- specification of the HCR calculation to be performed in the event of missing survey data.

In the previous MSE for Greenland halibut, several indicators were defined to determine if 'exceptional circumstances' were occurring. These indicators can give guidance on the performance of the HCR.

The "primary indicators" used to determine if exceptional circumstances were occurring were catch and surveys. The observed values are compared to the simulated distributions from both SCAA-based operating models and XSA-based operating models. If the observed values are outside of the 90% confidence interval (i.e. outside 5th-95th percentiles) from the simulations presented to WGMSE during September 2010, then SC shall advise FC that exceptional circumstances are occurring.

On an annual basis, the SC advised on the survey primary indicator over 2012-2016 (exceptional circumstances were not defined during the 2011 meeting as distributions from the MSE OM were not available at that time). For the three surveys that comprise the input data to the HCR, the observed values were compared with composite distributions of simulated surveys for both SCAA-based and XSA-based operating models (Figure 1). The Canadian spring 3LNO survey in 2015 had insufficient coverage to be considered representative of the Greenland halibut population, and the 2015 value was not used in the calculation of the HCR or for determination of exceptional circumstances. Out of the 34 comparisons possible over three surveys, two sets of operating models and 6 years (5 years in the case of the Canadian spring 3LNO survey), there were 4 for which the observed survey index was above the 95th percentile. These were the Canadian spring 3LNO 2010 for the SCAA operating models, Canadian fall 2J3K 2011 for the XSA operating models and in 2014 for the SCAA operating models, and, EU Flemish Cap survey in 2015 for the XSA operating models. Surveys above the 95th percentiles do not constitute a conservation concern. There were also two cases (Canadian Spring 3LNO for the XSA operating models in 2013 and 2014), for which the observed survey index was below the 5th percentile. The fact that one of the surveys in 2013 and in 2014 is below the simulated distributions of one suite of operating models is a conservation concern.

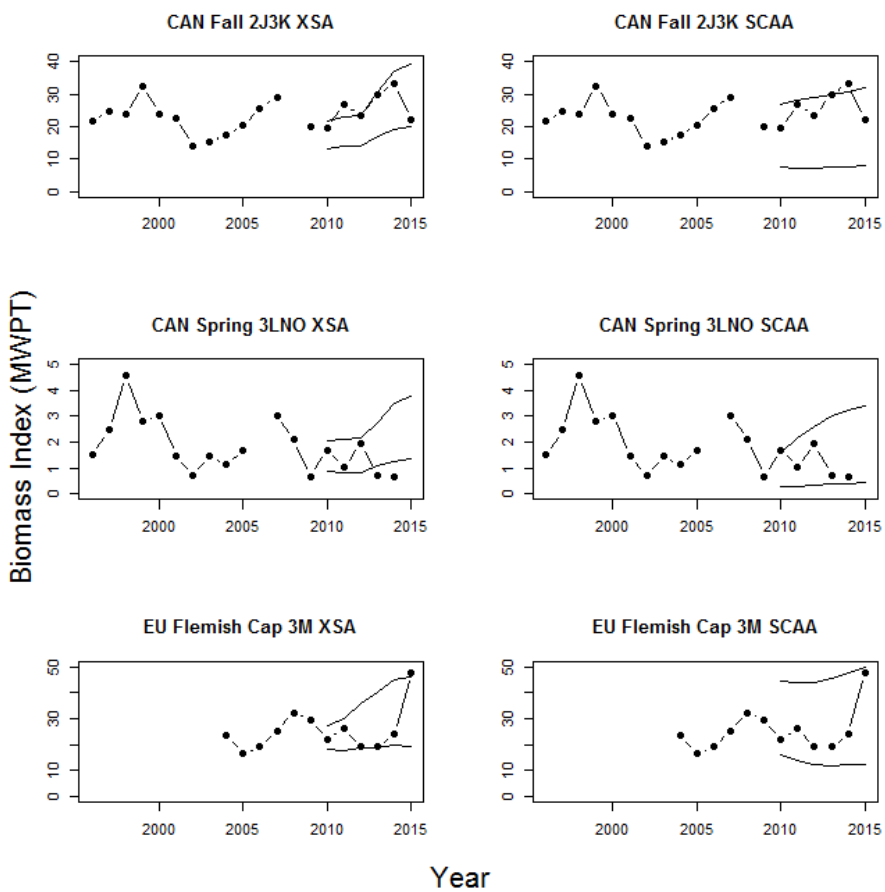


Fig 1. Observed surveys (lines with dots) and upper and lower 90% confidence intervals of surveys simulated (solid lines) in the MSE for Greenland Halibut in Subarea 2 + Divisions 3KLMNO. The panels on the left give the simulated surveys from the XSA operating models and on the right from the SCAA operating models

STACFIS catch estimates for 2011-2015 were not available until September 2016. Therefore the SC could not annually compare observed catches to the simulated distributions, and was unable to determine if exceptional circumstances were occurring with respect to this indicator before then. The SC notes the management strategy for Greenland halibut assumed that the simulated catches would exactly equal the TACs generated from the HCR. Newly available estimates of catch indicate that catch estimates and TACs often differed considerably. The estimated catch was above the 95th percentile of simulated catch in all years for both sets of OM except for 2015 for the XSA OM. This means that exceptional circumstances occurred in every year from 2010 to 2015.

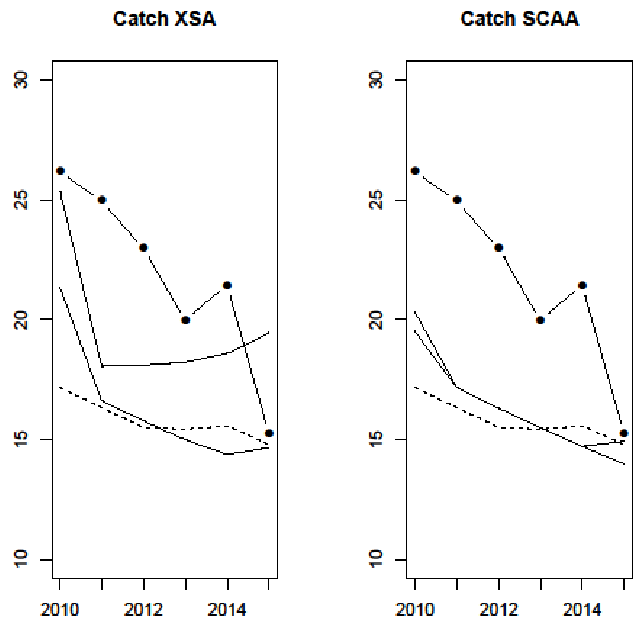


Fig 2. Estimated catch (lines with dots) and upper and lower 90% confidence intervals of catch simulated (solid lines) in the MSE for Greenland Halibut in Subarea 2 + Divisions 3KLMNO. The dashed line gives the TAC. The panel on the left gives the simulated surveys from the XSA operating models and on the right from the SCAA operating models.

When exceptional circumstances are occurring there are five secondary indicators which should be considered:

1 Data Gaps. Data gaps occurred in the survey series used in the HCR. The Canadian fall 2J3K survey in 2008 and Canadian spring 3LNO survey in 2006 and 2015 had insufficient coverage to be considered representative of the Greenland halibut population. These values were not used in the calculation of the TAC from the HCR. Any new HCR developed should include specification of the calculation to be performed in the event of missing data points as this was not explicitly documented in the previous MSE.

2 Biological Parameters: Natural mortality, maturity at age, weights at age. There is no new information on natural mortality. Since the last MSE it has been determined that the method used to determine maturity is inaccurate and maturities have not been updated. This would have impacted estimates of SSB and recruits generated from that biomass in the previous MSE study.

There were many instances where the observed weights at age over 2010-2015 were outside of 90% of the weights used in the MSE. However, in most cases the weights were greater than those used in the MSE and should not constitute a conservation concern. Indicators 3 to 5 (recruitment, fishing mortality and exploitable biomass) could not be evaluated in terms of the HCR performance. A full examination of these indicators would require an update of all operating models and these were not all available to SC. Updated estimates of stock size from various methods are presented in section 6.

5. Assessment models considered:

i) XSA

Extended Survivors Analysis (XSA) (Shepherd 1999, Darby and Flatman 1994) was used as the basis of assessments of Greenland halibut from 2000 to 2010. In addition, the Management Strategy Evaluation (MSE) conducted in 2009/2010 used XSA as one of two estimation models to develop operating models. The last accepted assessment using XSA was conducted during the 2010 Scientific Council meeting (Healey et al., 2010), and conclusions of stock status based on that model indicated that the estimated 5+ biomass remained well below the long-term average, that all recent year classes were relatively weak and that projections indicated a further decline in biomass. The XSA diagnostics showed problems in the model fit and there were concerns about using the associated assessment to provide management advice based on these diagnostics and other issues with residuals.

In the current meeting the XSA runs were not carried out as a possible basis for the provision of inputs to the Greenland halibut MSE, but rather to provide a contextual link between the previous accepted stock assessment and an updated run using the available data. In addition, there were runs carried out to determine the effect of lowering the plus group from 14+ to 10+ and also to supply a lower value of natural mortality (M). Those presenting this work felt that other methods, which include modelling uncertainty in the catch, were superior to and preferred over catch-at-age without error approaches and that further assessment development should focus on these approaches rather than further XSA work.

Four model runs were carried out. The first run had the same data series and model settings as the last accepted assessment (Healey and Mahé, 2010), but was updated with catch and survey data to 2015 (Run 1). The XSA settings were mostly unchanged in all further work and not optimized for best fit/performance in each case. The subsequent runs were conducted to explore sensitivity to i) a change in the plus-group age and ii) reducing the imput value of natural mortality. Run 2 used the same data inputs as Run 1, except for ageing data only up to age 9 (and catch at age with a 10+ group instead of 14+) based on known ageing bias after age 9. The third run was carried out using the same data as for Run 1, except M was assumed to be 0.12. Run 4 was similar to Run 2, but with M assumed to be 0.12. Again, this was conducted based on higher estimates of longevity of Greenland halibut (Cooper et al., 2007) and consistent with SC WebEx discussions earlier this year.

As in the last full assessment, XSA diagnostics revealed serious issues with model fit for all of the runs explored similar to the findings of the 2010 assessment. Standard errors of the log-scale survey catchability parameters, as in 2010, exceeded 0.5 at most of the survey-ages. Values in excess of 0.5 are indicative of problems with that age for the fleet (Darby and Flatman, 1994). Residual patterns indicated year and cohort effects, with larger residuals at some of the early ages (e.g. for the EU-3M 1400 survey, ages 1-3 residuals are particularly high).

Retrospective patterns for biomass estimates seem slightly improved in the current analysis, but recruitment estimates show revisions that are substantial.

Lowering the plus group from 14 to 10 did not have an effect on the most recent estimates of biomass, but in the earliest part of the time series there were higher estimates of biomass in the analysis with the 10+ group, and these estimates were more variable. Lowering the natural mortality rate from 0.2 to 0.12 had the expected effect of lowering estimates of biomass and recruits, thereby increasing estimates of fishing mortality.

ii) SCAA

SCR Doc. 17/02 provided results for baseline assessments and a number of variants using SCAA (Statistical-Catch-at-Age) methodology, which was described in detail in an Appendix to the document. Recent trends in abundance were quite similar across the variants. However small changes to assumptions could result in very different magnitudes and trends in biomass over 1975-2000. The precision of these last estimates was very poor by comparison with those from recent years. MSY estimates were generally in the vicinity of 25 000 mt.

Following consideration of these results and experimenting with further sensitivities, at the current meeting SC agreed to the following variations of assumptions and choices made for the SCR Doc. 17/02 baseline to provide an initial revised SCAA baseline assessment. The key changes made and the reasons for them were as follows:

- Fix the Beverton-Holt stock-recruitment function steepness at h = 0.8 instead of 0.9. The available data were unable to provide a precise estimate of this parameter through the assessment model fit, so a central value for flatfish from the RAM Legacy database was selected.
- Fix natural mortality M at 0.12 instead of 0.2 and recruitment variability σ_R at 0.4 rather than 0.2. These values were considered more realistic biologically.

- Fix the downweighting of CAA data in the log likelihood relative to survey indices of abundance, w_{CAA}, to 0.2 rather than 0.1. This removed a serious lack of fit to the age-structure information for the EU 0-700 series at the expense of increasing the variance of the residuals for this and the Canadian fall series; this trade-off was considered appropriate as these larger variances were in any case more in line with what might be expected and the original evident overfitting of the EU 0-700 series was avoided.
- Change the Punt-Kennedy form of the log likelihood (Punt and Kennedy, 1997) for the CAA data to the "sqrt(p)" form, as this was considered likely to be more robust to possible outlier inputs.
- The commercial selectivity blocks, initially three in number, were increased to first six specified on the basis of known changes in the fishery, and then combined to four blocks as the selectivities for certain of the new blocks differed only very slightly.
- Instead of commencing in 1975, the start date was taken back to 1960, allowing a penalty to be imposed to ensure that the starting numbers-at-age vector differed little from that at pre-exploitation equilibrium, as little catch had been taken before 1960.

Results for the resultant initial revised baseline are shown in Fig. 3.

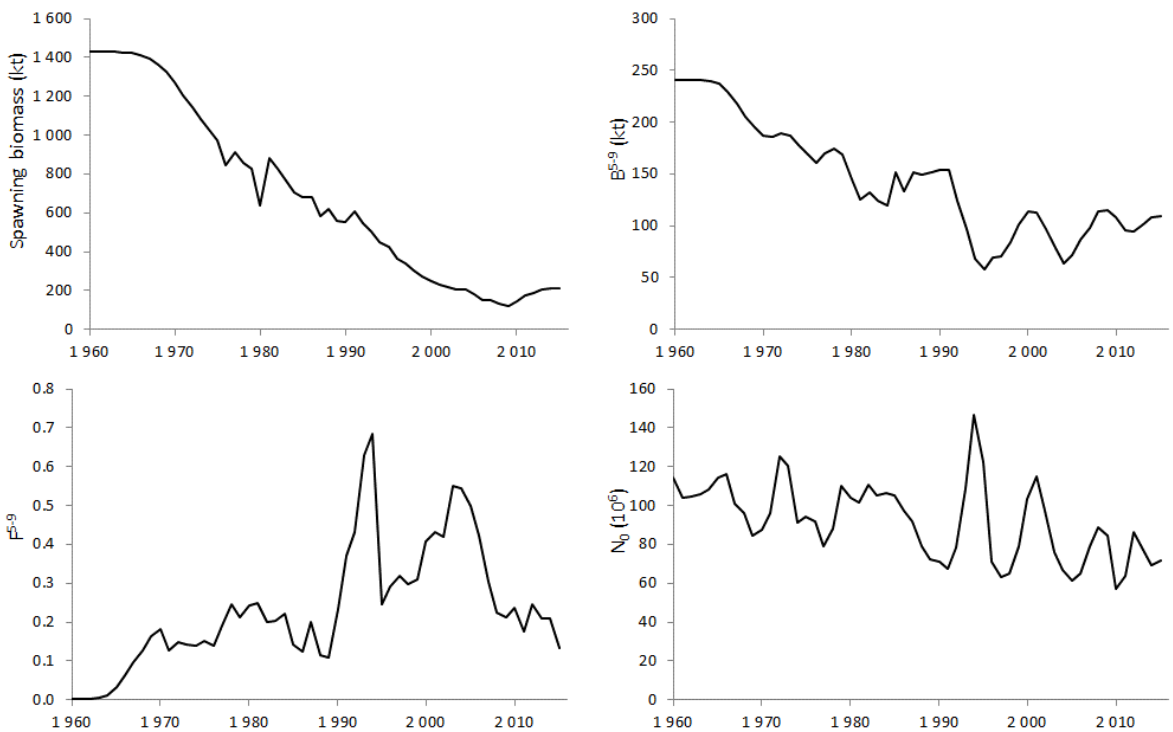


Fig. 3. Trajectories of spawning and B5-9 biomass, ages 5 to 9 average fishing mortality and recruitment for the SCAA proposed new baseline (NBf).

iii) SAM-style Model

A variation of the state-space assessment models developed by Nielsen and Berg (2014) and Cadigan (2015) was presented. The core of this model is similar to other age-structured assessment models since the population dynamics involve a basic cohort model with a plus group. Likewise, observations from trawl survey data and catch statistics are used to estimate parameters of the population dynamics model. A key distinction from other assessment models, however, is that a state-space model attempts to differentiate variation stemming from natural processes (process error; e.g. natural mortality, immigration, emigration) from variation stemming from survey and fishery observations (observation error; e.g. sampling error). This model also attempts to account for correlation in fishing mortality rates across ages and years such that fish of similar ages from similar time periods are assumed to have experienced similar fishing mortality rates. Finally, recruitment was simply assumed to be random as initial study indicated there was little evidence of a stock-recruitment relationship.

Two formulations of the SAM-style model were developed and tested: 1) a standard whole-stock model (denoted M1), and 2) an experimental quasi-spatial variant (S1). The latter – and the determination of how to structure the spatial dynamics of the population - was motivated by apparent conflicts/lack-of-fit in the survey data. Specifically, trends in stock size in the Flemish Cap (FC) area seem different from those observed in the NL shelf (NS) region. This suggests that there may be important spatial differences that are not incorporated into M1, potentially decreasing its reliability as an assessment of the stock as a whole. The lack of reliability may depend on changes in the relative magnitude of the NS and FC stock components. The new quasi-spatial model formulation attempts to address this issue in a simple way. While this model still treats the stock as a whole in terms of modelling recruitment and mortality rates, it allows a proportion of the stock to move from one region to another. In discussion it was noted that the choice of the spatial disaggregation (NS vs FC) was not biologically based but rather entirely guided by the statistical fit of the M1 model.

Though conceptually simple, state-space models have been notoriously difficult to fit due to the numerical challenge of splitting process and observation error. However, recent advances in estimation tools such as Template Model Builder (Kristensen et al. 2016) have facilitated the fitting of state-space models that require few user supplied parameters. Parameter estimates are largely data driven. The model presented assumed a value of natural mortality (M = 0.12 for the base case) and an assumed level of variation between reported landings and their model predicted values (CV = 0.1 for the base case).

Following substantial discussion it was agreed that the M1 (whole-stock model) would be pursued further to develop operating models. It was noted however that the quasi-spatial variant may hold promise for future work. Participants encouraged research which explored other spatial separation beyond that described above. Results from the base case run (for M1) are presented in Figure 4. One alternate formulation was tested along with dozens of tests of variations of data and parameter input; details are presented in Regular et al. (2017) along with a detailed description of the SAM-style model.

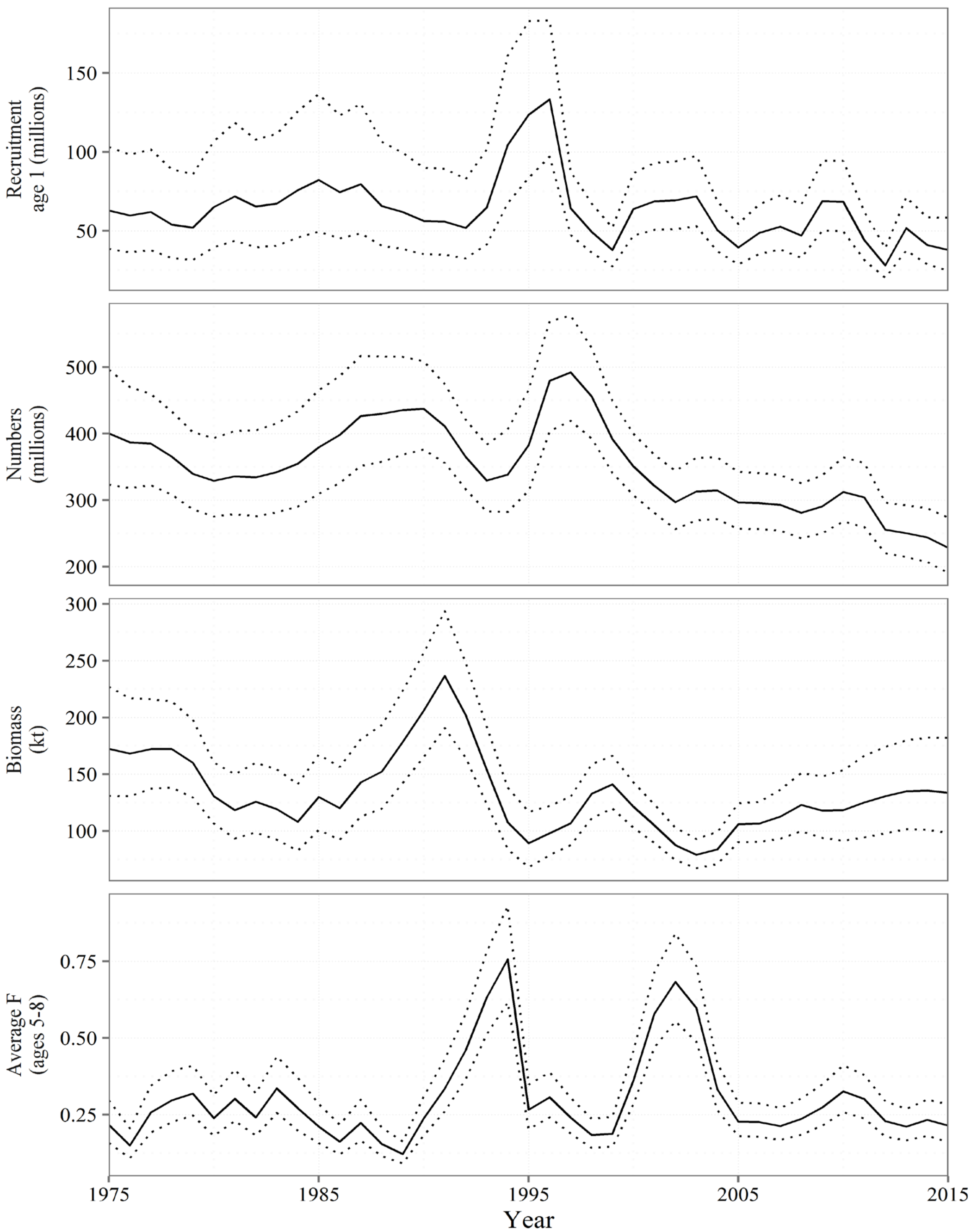


Fig. 4. Estimates of recruitment, numbers, total biomass, and average F, with 95% confidence intervals, from base case model run (M1_O3) of the SAM-style model.

iv) Surplus Production Models in a Bayesian Framework

A series of different formulations of surplus production models in a Bayesian framework were run. The different model formulations varied in choice of survey data and priors on K and r.

Model formulations that included all surveys (Option 1) led to unreasonably large estimates of r unless a very informative prior was used. Model formulations using the surveys from the last accepted assessment (in some cases with EU 3M survey split into shallow and deep) had lower process error and more reasonable estimates of r. These model formulations estimated MSY to be in the order of 37 000 t, F_{msy} to be about 0.19 and K to be around 400 000 t.

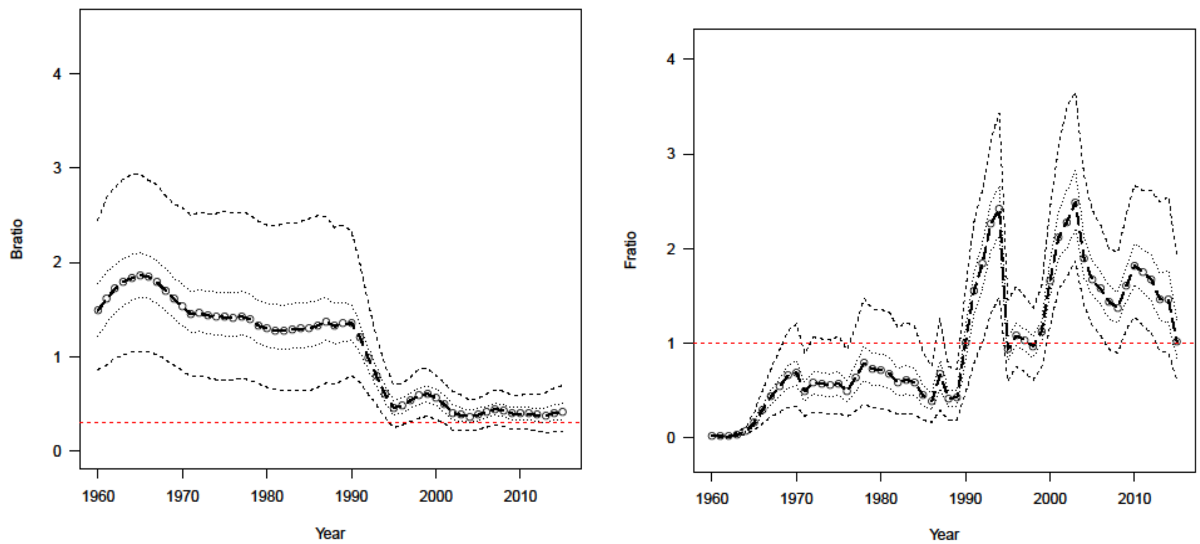


Fig. 5. Ratio of biomass to B_{msy} (B ratio; left panel) and fishing mortality to F_{msy} (F ratio; right) from the surplus production model for Greenland halibut in SA2+3KLMNO with the best diagnostics. 50th and 95th credible intervals are also shown. The horizontal line is 30% B_{msy}.

All formulations showed biomass to have declined in the early to mid 1990's and recent biomass to be in the order of 40-50% of B_{msy}. At least some of the operating models in the MSE should be consistent with this view of the population trajectory.

An additional point agreed during discussion was that a full set of computer code (including uncompiled source code) for all population models tabled would be made available on the SharePoint for all models tested. This code will be held by the Secretariat on the SharePoint, and made available for non-commercial use.

6. Comparison of assessment model results

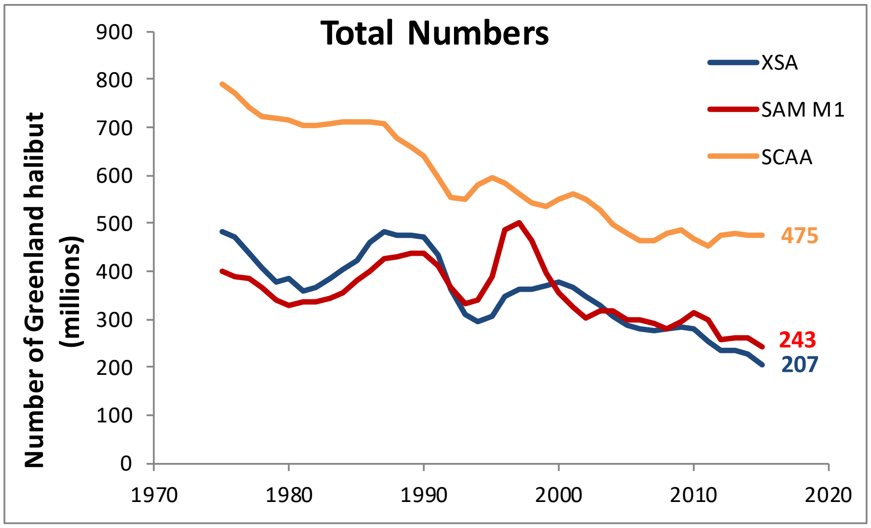
After considering individual model results and sensitivity to various specifications within each model, discussion turned to the need to develop a suite of operating models for use in the MSE. In order to determine if it was necessary to continue using multiple estimation methods in future MSE analysis, a comparison of model results was presented to compare estimated population size and structure. If the estimated population size and age-structure were sufficiently similar, one estimation method could be used to provide the 'starting point' for subsequent MSE work.

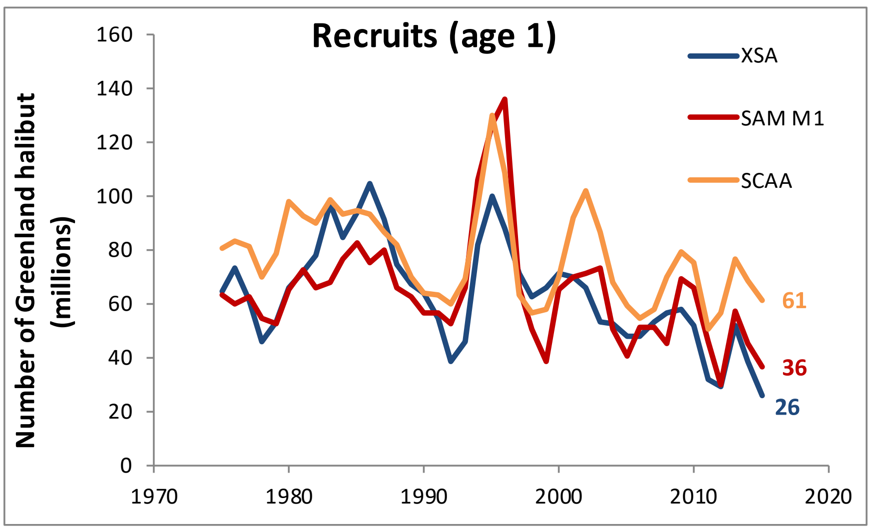
Retrospective patterns for biomass estimates seem slightly improved in the current analysis, but recruitment estimates show revisions that are substantial.

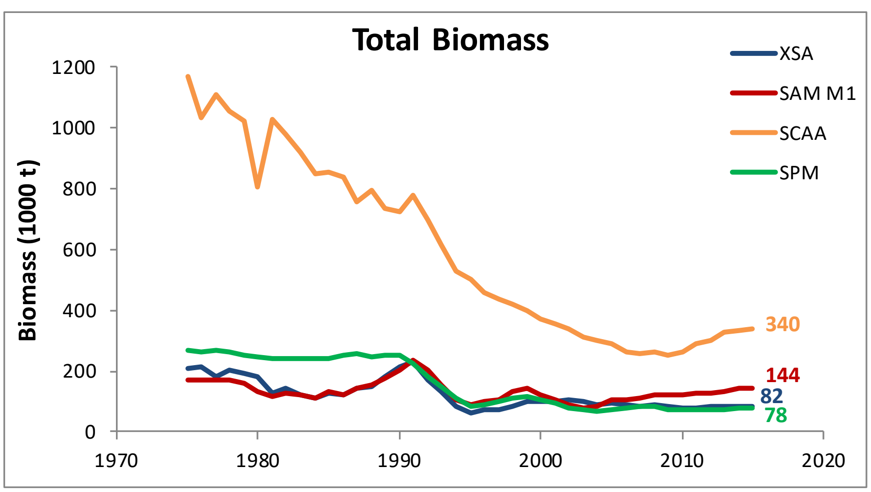
Results from a representative case from each of the following models presented during the meeting were compared:

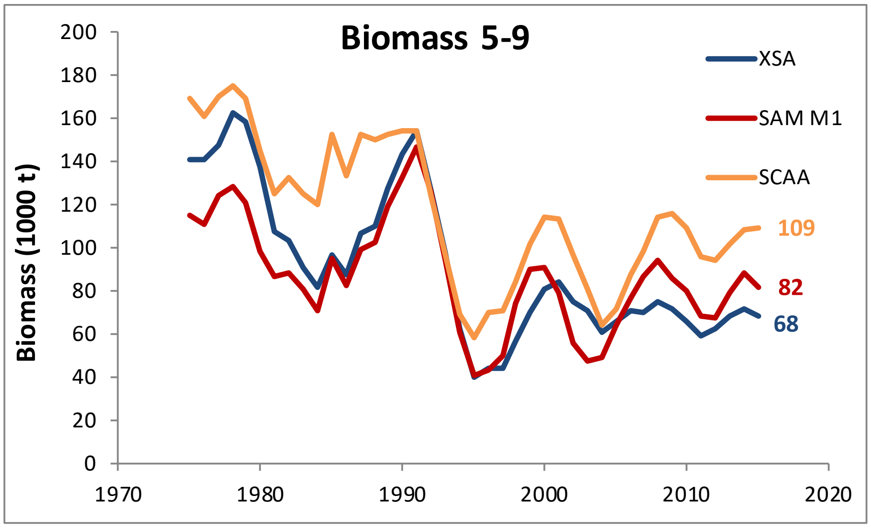
- Surplus production model (SPM)
- Statistical-Catch-at-Age (SCAA) model
- SAM-style state space model, and
- XSA model.

The model results indicated that the scale of the XSA, SAM, and SPM were in greater agreement than that of the SCAA. Trends in recruitment, exploitable biomass (ages 5-9 aggregated) and fishing mortality (averaged over ages 5-9) show general agreement. The main source of the difference in estimated total population size (abundance and biomass) between the SCAA and XSA or SAM is within the plus group. The SCAA results indicate a considerably larger population within the plus group, and this comprises a much larger fraction of the total stock size over time. For this stock, it is important to note that the scale of the plus group aged population is poorly defined by the available data. Hence the biomass within the plus group is mostly 'cryptic biomass' in that it is sampled at a relatively low rate compared to younger ages, i.e. it is largely unavailable to commercial fisheries and fisheries independent surveys.


Total Numbers
Number of Greenland halibut (millions)
900
800
700
600
500
400
300
200
100
0
1970
1980
1990
2000
2010
2020
XSA
SAM M1
SCAA
475
243
207


Recruits (age 1)
Number of Greenland halibut (millions)
160
140
120
100
80
60
40
20
0
1970
1980
1990
2000
2010
2020
XSA
SAM M1
SCAA
61
36
26


Total Biomass
Biomass (1000 t)
1200
1000
800
600
400
200
0
1970
1980
1990
2000
2010
2020
XSA
SAM M1
SCAA
SPM
340
144
82
78



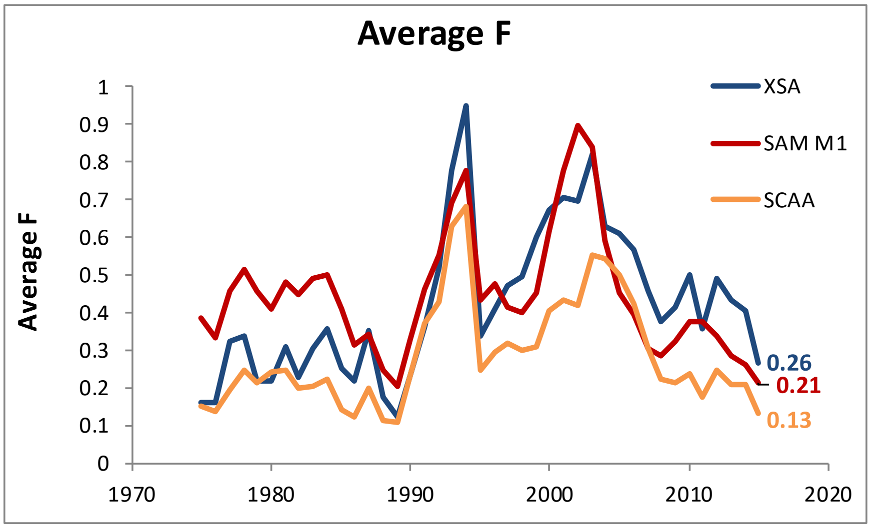


Fig. 6. Comparison of estimates of Total Numbers, Recruits (age 1), Total Biomass, Exploitable Biomass (ages 5-9 aggregated), and average fishing mortality from XSA, SAM, SCAA and (for total biomass only) SPM.

Although these differences are large in magnitude, the **SC agreed** that if subsequent MSE includes operating models in which the forecasted yield does not rely on the plus group biomass, then the impact of these differences are substantially reduced, and the robustness of any proposed harvest rule will be enhanced. Thus, MSE testing must include operating models with zero (or virtually nil) selectivity on the 10+ group. This was considered imperative in light of recent changes in the fisheries selectivity induced by reduced catches from larger mesh gillnets within the Canadian EEZ, i.e. lowering current selectivity of older ages.

Throughout the meeting, there was discussion on the quality of fit for all models, and it was noted that all had various residual / lack of fit issues probably arising from the poor quality and consistency of the input data. In addition, this finding was consistent with that of XSA results from the 2010 SC assessment.

7. Review results from available operating models to determine a baseline case for SCAA and SAM-style models

A number of robustness/sensitivity analyses were conducted on both the SCAA model as well as the SAM-style model to arrive at preliminary base cases for each. These trials were not run across all potential variants of the survey data set. Additionally, this item was discussed in the context of development of the trials to be used to test candidate Management Procedures, and consequently included considerations related to projecting into the future, as well as variations in the assessments considered above, to provide the basis for Operating Models for this testing.

This item comprised a majority of the meeting time, as there were many model results available for review, and considerable time was spent comparing the impact of each variant on both model diagnostics as well as the estimated quantities. A full description of these robustness trials can be found in Appendix I.

8. Develop advice for RBMS re quantification of objectives/performance criteria and constraints

The SC debated suitable options for potential metrics that could become performance statistics to measure the ability of a given harvest control rule to accomplish the specified management objectives, or, to provide desirable outcomes for 'trade-off' objectives.

NAFO/FC-SC Doc. 17-02 lists the following general management objectives:

1. Restore to within a *prescribed period of time* or maintain at B_{msy}
2. The risk of failure to meet the B_{msy} target and interim biomass targets within a *prescribed period of time* should be kept moderately low
3. Low risk of exceeding F_{msy}
4. Very Low risk of going below an established threshold (e.g. B_{lim}* or B_{lim} proxy)
5. Maximize yield in the short, medium and long term
6. The risk of steep decline of stock biomass should be kept moderately low
7. Keep inter annual TAC variation below established thresholds

A number of mathematical expressions (Performance Statistics) are proposed by the SC to capture these objectives:

(a) B_{2022}/B_{2018}, B_{2027}/B_{2018} and B_{2037}/B_{2018}, where B_y is the biomass in year y;

(b) B_{lowest}/B, where B_{lowest} is the lowest biomass during evaluation period (2018-2037);

(c) B_{lowest}/B_{min}, where B_{min} is the lowest biomass during the assessment period (1975-2015);

(d) B/B_{target}, where B_{target} is pre-defined recovery target biomass, for which the average value over the period 1975 to 1999 for the assessment/operating model concerned will be used for the moment pending further discussions;

(e) B_{2037}/B_{MSY} where B_{MSY} is the biomass when maximum sustainable yield is achieved;

(f) F_{2022}/F_{MSY} and F_{2027}/F_{MSY} F_{2037}/F_{MSY} where F_{MSY} is the fishing mortality rate needed to achieve maximum sustainable yield.

In each of them, population can be measured as total numbers (N_y^{tot}), total biomass (B_y^{tot}), exploitable numbers (ages 5 – 9) (N_y^{5-9}), exploitable biomass (B_y^{5-9}), survey index (B_y^i) or spawning biomass (B_y^{sp}), (though with primary focus on exploitable biomass for P_{target}) where:

$$N_y^{tot} = \sum_{a=0}^{m} N_{y,a} \quad (1)$$

$$B_y^{tot} = \sum_{a=0}^{m} w_{y,a}^{st} N_{y,a} \quad (2)$$

$$N_y^{5-9} = \sum_{a=5}^{9} N_{y,a} \quad (3)$$

$B_y^{5-9} = \sum_{a=5}^{9} w_{y,a}^{mid} N_{y,a}$ (4)

$B_y^{i} = \sum_{a=0}^{m} w_{y,a}^{i} S_a^i N_{y,a} e^{-Z_{y,a}T^i/12}$ (5)

$B_y^{sp} = \sum_{a=1}^{m} f_a \, w_{y,a}^{strt} N_{y,a}$ (6)

The fishing mortality rate refers to the annual average of fishing mortality across ages 5-9.

The catch-related objectives can be captured by:

(g) (Average) annual catch over short, medium and long terms:

$C_{2018}, C_{2019}, C_{2020}, \sum_{y=2018}^{2022} C_y/5, \sum_{y=2018}^{2027} C_y/10, \sum_{y=2018}^{2037} C_y/20$

(h) Average annual variation in catch over short and long terms:

$AAV_{2018-2022} = \frac{1}{5}\sum_{y=2018}^{2022} |C_y - C_{y-1}|/C_{y-1}$ and

$AAV_{2018-2037} = \frac{1}{20}\sum_{y=2018}^{2037} |C_y - C_{y-1}|/C_{y-1}$

$P > 15\%$ being the proportion of years during the projection period where $\frac{|C_y - C_{y-1}|}{C_{y-1}} > 0.15$. Catch constraints as part of the control rule or as a performance statistic to be determined.

(i) $F_{highest}/F_{msy}$, where $F_{highest}$ is the highest F during each evaluation period (2018-2022, 2023-2027 and 2028-2037);

Management Objectives	**Performance Statistics which may be relevant to scoring performance of Objectives**	**Example Performance Targets**
Restore to within a *prescribed period of time* or maintain at B_{msy}	See item e) above, (but noting the 'prescribed period' has not been set).	
The risk of failure to meet the B_{msy} target and interim biomass targets within a *prescribed period of time* should be kept moderately low	It was suggested results would be required in order to determine appropriate reference period, though the merits of this approach were debated.	
Low risk of exceeding F_{msy}	See item i) above.	
Very low risk of going below an established threshold [e.g. B_{lim} or B_{lim} proxy].	No limit threshold has been defined	
Maximize yield in the short, medium and long term	See item g) above.	
The risk of steep decline of stock biomass should be kept moderately low	See item a) above. (over only initial 5 year period). Definition of "steep decline" needs consideration.	
Keep inter annual TAC variation below "an established threshold"	See item h) above	

9. Specify MP "trials", including operating model variants to be fit, projection specifications, observation models for future generated data, and performance statistics (initial quantification of objectives)

As a result of time constraints, there was little discussion of this item at the meeting but all agreed that development of model free HCRs should be the first step (as was recommended by RBMS in February 2017).

The SC referred to the RBMS request from February 2017, "In the April 2017 stock assessment meeting, it would be helpful if SC could consider how the risk concept should be applied e.g. should performance relative to targets be assessed at the level of individual operating models or against a (possibly weighted) average of all models". There was again little time for discussion on this consideration. This request will be discussed again in June 2017 meeting of SC when the full suite of operating models (OM) will be better defined. At this moment, there was only the base case OM defined and a series of OM candidates for further discussion.

In regard to the calculation of risk, there was again little discussion on the specifics. Nevertheless, the SC notes the recommendation made by RBMS in 2015 (NAFO FC/SC Doc. 15/02) to calculate the risk in the 3M Cod case:

> *b. An HCR which meets management objectives 1 (very low risk of breaching Blim) and 2 (low risk of overfishing) within five years, and within ten years, with:*
>
> > *i. risk calculated for each year in the time series*
> >
> > *ii. risk calculated for the end of the periods (final year)*
> >
> > *iii. risk averaged over the periods*

There were differences of opinion on this recommendation and its applicability to the GHL MSE, but there was no time to clarify the concerns. This will have to be revisited (RBMS April and/or SC June) in order to develop appropriate risk measures for performance statistics in the GHL case or to provide more general guidance. It was noted that lower risk thresholds may be advisable for stock sustainability metrics compared to fishery trade-offs.

10. External Reviewer Perspectives

Immediately prior to the close of the meeting, the three invited external experts each provided their perspectives of the work undertaken so far on Greenland halibut assessment modelling and the technical elements underpinning the ongoing management strategy evaluation. Below is a summary of the main points highlighted:

- Arriving at a 'best assessment' appears very difficult in this case given the unusually large number of basic questions on species biology and input data. This contributes to the high uncertainty around the scale of the resource.
- Pace of this process is problematic and seems rushed.
- Meeting and entire process thus far is very well done particularly considering the compressed timeline.
- The current timeline will perhaps not allow the most appropriate decision to be made (insufficient time to consider all of the relevant technical and management detail).
- Support the SC decision to move forward with both SAM and SCAA.
- Plausibility weighting of operating models can be very informative but can also be very difficult to determine/agree.
- Concern over discrepancy in scale of model estimates between SCAA and SAM. How will this impact results when a common level of removals are compared across methods within an MSE?

11. Conclusions

The co-chairs thanked meeting participants for their contributions, particularly recognizing those participants who produced extensive model results prior to and during the meeting. Further, the SC

acknowledged the three external experts and their constructive input and review which added much value to the process. SC also extended its thanks to IEO for hosting the meeting and to those who assisted with the meeting logistics.

It was noted that the meeting struggled to fully complete most of its tasks and the SC remains concerned about the time available to complete the work. During this meeting, several important technical issues received limited time to allow debate and review. The report was not able to be completed by the close of the meeting and it was agreed that it would be completed by correspondence as soon as possible.

The SC agreed to continue to follow the work plan outlined in FC Doc 16/17, but reiterates the possibility that additional time beyond September 2017 may be required to allow sufficient time to debate and implement the technical details which are at the core of a complex simulation process.

The meeting was adjourned at 1400h.

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APPENDIX I. DETAILS OF OPERATING MODELS & PROJECTION PROCEDURES TO BE CONSIDERED

Discussions on this topic developed from the specifications of the SCAA assessment provided in SCR Doc. 17/02 and proposed details of projections provided in SCR Doc. 17/03. The material below specifies amendments and extensions to those details.

Variations to the Baseline SCAA assessment

1) Relative weighting of CAA data in log likelihood w_{CAA}: baseline: 0.2; variants 0.1 and 0.5
2) Recruitment variability σ_R: baseline 0.4; variant 0.6
3) Natural mortality M: baseline 0.12; variant 0.2
4) Increase M with age; variants with higher values for M for the 14+ group (e.g. 0.5)
5) Stock-recruitment steepness h: baseline 0.8; variants 0.7 and 0.9
6) Annual catch uncertainty σ_C: baseline 0.1; variant 0.2
7) Form of CAA log likelihood: baseline sqrt(p); variant Punt-Kennedy
8) Survey choices: baseline past choice set; variant the O3 set
9) Update of baseline assessment to include further data available by June 2017
10) Alternative selectivities
    a) Descending limb: normal to negative exponential and "fourth-power" normal for commercial selectivity
    b) Split the last commercial block and/or change the final commercial selectivity form to remove the systematic residual pattern for 10+ group in commercial CAA proportions over the last few years
    c) Force less doming of the EU 0-1400 survey
11) Sensitivity to the method used for estimating the 1960 starting $N(y,a)$ vector
12) Changing survey selectivity over time: baseline no change; variants to be advised on the basis of any such indications from XSA or SAM-style assessments

Variations to the Baseline SAM-style assessment

1. Input data set (combinations of survey series previously defined in webex)
2. Process error variance profiling
3. Assumed level of natural mortality
4. Plus-group age
5. Recruitment modeled as a random vs. random-walk process
6. Assumed level of variation around landing estimates
7. Catchability at age

Projections: general

1) Autocorrelation in future recruitment residuals of 0.5 (as indicated by the baseline SCAA assessment)
2) Use Hessian to develop a multivariate normal basis to generate variability in the starting $N(y,a)$ vector; if the Hessian is not obtained even given convergence, default to the Hessian for the corresponding baseline assessment

Projection variations

1) Alternative selectivities: commercial selectivity for projections taken to be the one which differs most from that for most recent block
2) Higher/lower starting numbers at age by 20%
3) Future catches are 30% greater than the corresponding intended TAC
4) Alternative choices for surveys used for Management Procedures: baseline and O3 sets, with differential weighting amongst members of the set to be considered

Mimicking XSA and SAM-style assessments

At minimum the results of these assessments are to be reflected amongst the trials by having the SCAA assessment and/or the projection specifications mimic their results

1) Alternative starting (1960 or 1975) biomasses or $N(y,a)$ vectors to start projections – note that these projections must preserve the multivariate normal variance structure for the uncertainty in these estimates, together with the estimates values of catchability and selectivity for the surveys and selectivity for the last commercial block
2) Process error in future dynamics for SAM-style assessments – add random error to $M(y,a)$ with the variance structure indicated by SAM-style assessment

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