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Review and revamp of the SSM-based Management Strategy Evaluation for Greenland halibut stock in NAFO Subarea 2 and Divisions 3KLMNO

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Abstract

Detailed documentation of the 2017 management strategy evaluation (MSE) based on operating models from the state space stock assessment model (SSM) has not been available. This document is produced following an extensive review of the SSM-related code for the MSE. The work has made some updates to the original implementation and it presents documentation and results for the MSE.

Introduction

A Management Strategy Evaluation (MSE) of Greenland Halibut (*Reinhardtius hippoglossoides*) for NAFO Subarea 2 and Divisions 3KLMNO was undertaken in 2017.

An MSE is a simulation process with the following parts:

1. Operating model (OM)
    a. Biology and fishery model – describes the population dynamics and fisheries (simulates the real system—assumed true)
    b. Observation model – produces data with error (e.g. survey data) for the estimation model
    c. Implementation model – implements TAC decisions to calculate actual annual removals
2. Management Procedure (MP)
    a. Model based – estimation model fits to the data generated by the operating model

   b. Empirically-based rules are prescribed based on recent surveys, or other monitoring data-related outputs
3. Performance statistics (PS)
   a. Biomass based – short term or long term
   b. Catch or F based – short term or long term
   c. Others (conservation, utilization)

An MSE was performed in 2017 using a state-space model (SSM) and statistical-catch-at-age model (SCAA). An MSE was performed in 2017 using a state-space model (SSM) and statistical-catch-at-age model (SCAA). The MSE was developed with an abbreviated schedule and, after implementation, it became apparent that documentation was lacking for the SSM based MSE; one example highlighted by SC during the June 2019 meeting (NAFO, 2019) was that probability envelopes of projected indices used to investigate whether Exceptional Circumstances were occurring were not available from the SSM based MSE.

This document reviews the MSE that uses the SSM model to provide operating models. In the review process, we made a few updates. Here we provide documentation of the base case operating model for the SSM-based MSE.

For the base case OM of the MSE, the parameters from the SSM model are used to project the stock into the future. Three additional OMs (or alternate realities) were specified following an extensive selection process (NAFO, 2017a – June SC Report) to deal with structural uncertainties or implementation uncertainties. The four OMs are the (i) base case OM, (ii) low recruitment OM where the expected recruitment was reduced by 50% (prior to incorporating process error $N_{1,t} = \text{Lognormal}((\mu + \log(0.5)), \sigma^2)$) for the first 8 years (2019 to 2026 inclusive) of the simulation, (iii) OM with no plus group in the catch to model a fishery which mainly targets ages 5 to 9 (selectivity for plus group age 10+=0), and (iv) OM where the TAC is exceeded by 10% every year to allow for implementation error.

The MPs considered in this MSE are empirical rule based and are calculated by i) comparing current survey data to survey data in a reference period (target), ii) computing the trend in recent survey data (slope), and, iii) a combination of target and slope. Similar to OMs, previous extensive review within WG-RBMS (e.g. NAFO, 2017b) led to the selection of three rules that would be presented in the later sections. The performance of the MSE is based on the performance of simulations against biomass based (B_{MSY}) and F-based (F_{MSY}) performance statistics described in Varkey et al (2020).

Methods

The existing code for the SSM based MSE was reviewed in detail. A few changes were made during the process of review and the rectifications/changes are presented here (Box 1 for OM equations, Box 2 for MP equations):

1. Observation error: The original MSE passed perfect indices to the MPs. In the update we added observation error, as estimated in the SSM, to the indices used in the MPs.

2. Process error: The first year of the projection is taken from the last year of the assessment (SSM). The original SSM OMs assumed that the numbers at age for the first year of the

simulation period were known perfectly. For the revision, process error from SSM was added to the final-year estimates from the SSM. For all following years, the original MSE sampled the process errors from one of the previous years in the assessment (1975 to 2016). This method of sampling process is certainly defensible. However, a more robust approach that was used in the revision was to randomly sample process errors based on the standard deviation of the process error estimated when fitting the SSM to the historical data. The reason for this change is that we believe that this approach is a closer match to the structure and model parameter estimates than sampling all process error in the MSE simulations from the historical process error matrix from SSM.

3. MP: A misspecification of target indices used for the target based MP (***t***) was rectified (see Box 3 for illustration). The weighting for the slope based MP (***s***) was updated to use precision instead of variance. An indexing issue related to tracking the indices and passing these to the MPs in the beginning years of the simulation was rectified.

Box 1

Operating Model equations

1. Start projection from 2016 Numbers-at-age
   $N_{2016,a} = N_{2016,a}e^{\delta_a}$
   The earlier version started the MSE simulations without the error term.

2. For years 2017 to end of simulation generate Numbers at age
   a. Age 1 – recruits were sampled from a log-normal distribution using the mean and sd values estimated by the SSM,
   b. Age 2+ - follow cohort equation with age 10 as plus group. M=0.12. Previously process error was sampled by year from process error matrix from the SSM. Age 10 is a plus group.

$$N_{a,t} = \begin{cases} if\ a = 1 & N_{1,t} = \text{Lognormal}(\mu, \sigma^2) \\ if\ 10 > a > 1 & N_{a,t} = N_{a-1,t-1}e^{(-Z_{a-1,t-1}+\delta_{a-1,t-1})} \\ if\ a \geq 9 & N_{10+,t} = \sum_{a=9}^{10} N_{a,t-1}e^{(-Z_{a,t-1}+\delta_{a,t-1})} \end{cases}$$

3. F calculation
   a. Selectivity is sampled from one of last 10 years
   b. Weight at age sampled from last 10 years (same weights used for stock weights and catch weights)
   c. Selectivity and weight-at-age vector for 2016 are taken directly from SSM output for 2016.
   d. Selectivity calculated by scaling the fishing mortality estimates from SSM.
   $Sel_a = \frac{F_a}{\frac{\sum_{a=5}^{9} F_a}{5}}$

Box 1 contd:

F calculation contd.

e. For year 2016 to 2018
   i. TACs were specified (14799t, 14799t, 16500t). Previously, TAC for 2017 was slightly miss-specified (14997t)
   ii. Calculate corresponding F by minimizing the difference between proposed TAC and expected yield.
   iii. Calculate catch based on F:

$$C_{a,t} = \frac{F_{a,t}}{Z_{a,t}}(1 - e^{-Z_t})N_{a,t}$$

$$Y_t = \sum_{a=1}^{10} C_{a,t} * w_{a,t}$$

f. For years 2019 to 2037
   i. Calculate TAC based on MP (***t***, ***s***, or ***t+s***)
   ii. Apply same method as above to calculate F and catch

4. Calculation of index
   a. Perfect Index: $PI_{y,s} = \sum_{a=1}^{10} q_a N_a w_a$
      Previously this index was passed to calculation of the TAC using MPs
   b. Add observation error applied to index calculation. In the SSM model, the observation error standard deviations vary by age-group and survey.
      Index Numbers at age: $I_{a,y,s} = q_{a,y,s}\, N_{a,y}\, e^{-Z_{a,y}*t_s}\, e^{\sigma_{a,s}}$
      Index sum mean weight: $I_{y,s} = \sum_{a=1}^{10} I_{a,y,s} * w_a$

5. Index sum mean weight $I_{y,s}$ is passed to step 3fi. for the calculation of TACs.

6. For year 2016, observed survey indices were used:

Year	Canada Fall 2J3K	Canada Fall 3LNO	Canada Spring 3LNO	EU 3M 0-1400m	EU 3NO
2016	18.54	1.31	0.66	28.3	8.8

Box 2

Management Procedure equations

Under all MP rules, the maximum annual change (Δ) was limited to 10% during the MSE (Δ of 10% was final decision but other values were in mix earlier in the process).

$$\mathrm{TAC}_{t+1} = \begin{cases} \mathrm{TAC}_{t+1} & \mathrm{TAC}_t(1-\Delta_{down}) < \mathrm{TAC}_{t+1} < \mathrm{TAC}_t(1+\Delta_{up}) \\ \mathrm{TAC}_t(1-\Delta_{down}) & \mathrm{TAC}_{t+1} < \mathrm{TAC}_t(1-\Delta_{down}) \\ \mathrm{TAC}_t(1+\Delta_{up}) & \mathrm{TAC}_{t+1} > \mathrm{TAC}_t(1+\Delta_{up}) \end{cases}$$

1. Target based (***t***)

$$\mathrm{TAC}_{t+1} = \mathrm{TAC}_t\left(1+\gamma_{up/down}(J_t-1)\right)$$

$$J_t = \frac{\sum_{i=1}^{5}\frac{1}{(\sigma_i)^2}\frac{J_i^{current}}{J_i^{target}}}{\sum_{i=1}^{5}\frac{1}{(\sigma_i)^2}}$$

$$J_i^{current} = \frac{1}{q}\sum_{t'=t-q}^{t-1} I_i^{t'}$$

$$J_i^{target} = \alpha\frac{1}{5}\sum_{t'=2011}^{2015} I_i^{t'}$$

2. Slope based (***s***)

$$\mathrm{TAC}_{t+1} = \mathrm{TAC}_t\left(1+\lambda_{up/down}(m_t-X)\right)$$

$$\lambda = \begin{cases} 1.0 & m_t > 0 \\ 2.0 & m_t < 0 \end{cases}$$

$$m_t = \frac{\sum_{s=1}^{5}\frac{sl_{s,t}}{\sigma_s^2}}{\sum_{s=1}^{5}\frac{1}{\sigma_s^2}}$$

where, m_t is the weighted measure of the current (immediate past) trend in the survey indices. The weighting is on inverse variance for the surveys. The trend is calculated as the slope $sl_{s,t}$ of linear regression of previous five years of log unweighted survey indices $lnI_{s,t-5:t-1}$ against years *t-5:t-1* for each survey series. In the earlier version, the denominator in the calculation of m_t was the summation of variance instead of summation of inverse variance.

Box 2 contd..

Management Procedure equations

3. Combined (***t+s***)

In this case the TAC is calculated as the average between the previous two methods:

$$\mathrm{TAC}_{(y+1)} = \frac{\mathrm{TAC}_{(y+1)}^{target} + \mathrm{TAC}_{(y+1)}^{slope}}{2}$$

The values for the various parameters are obtained from NAFO SCS 19-20 pages 29-30. The weights used in the inverse variance weighting of survey indices are based on the SCAA.

Survey	σ_s
Canada Fall 2J3K	0.22
EU 3M 0-1400m	0.21
Canada Spring 3LNO	0.49
EU 3NO	0.38
Canada Fall 3LNO	0.26

Control parameter values for the MPs

TAC_{2018}	16 500 tonnes
γ	0.15
q	3
α	0.972
λ_{up}	1.00
λ_{down}	2.00
X	-0.0056
Δup	0.10
$\Delta down$	0.10

In the table above, 'q' indicates the number of years (3) from 'y-3' to 'y-1' that are used for the calculation of current indices for the MP (***t***). TAC. Missing survey values are treated as missing in the calculation of the rule. In such cases, q in the calculation of MP (***t***) is reduced according to the number of years of within the time-span for which survey data are available. This is important to note in the initial years of the TAC calculation in the MSE when the observed survey indices form part of the calculation of current indices.

Also note that when a TAC is set in year y for year y+1, indices will be available only upto year y-1. Therefore $J^{current}$ in MP(***t***) is based on years y-3:y-1 and slope calculation in MP(***s***) is based on years y-5:y-1.

Box 3

Miss-specification of target index: Predicted indices from SSM were averaged over surveys.

Year	Canada Fall 2J3K	Canada Fall 3LNO	Canada Spring 3LNO	EU Spring 3LNO	EU summer 3M	**Mean over Surveys**	**J target used**
2011	15.38	1.42	1.05	5.55	21.11	**8.90**	**8.65**
2012	17.20	1.61	1.18	5.96	22.62	**9.71**	**9.44**
2013	17.83	1.79	1.27	6.54	25.38	**10.56**	**10.27**
2014	16.46	1.60	1.05	6.65	26.77	**10.51**	**10.21**
2015	15.41	1.39	0.91	6.22	25.08	**9.80**	**9.53**

Corrected target index values based on observed indices. Table headers indicate survey names

Year	Canada Fall 2J3K	Canada Fall 3LNO	Canada Spring 3LNO	EU Spring 3LNO	EU summer 3M
2011	26.74	2.21	1.05	7.09	26.15
2012	23.50	1.71	1.94	7.37	19.20
2013	29.65	2.59	0.73	5.46	19.11
2014	33.34		0.66	6.24	23.92
2015	22.29	0.87		9.49	47.52
Mean over years	**27.10**	**1.84**	**1.10**	**7.13**	**27.18**
J target corrected	**26.34**	**1.79**	**1.06**	**6.93**	**26.42**

Results and Discussion

Results are presented in this report for the base case operating model and management procedure 'combined' (also referred to as 'combo'). Summaries of simulation outputs are presented in Figure 1 and Appendix A tables A1 to A8).

Performance statistics used for the evaluation of the MSE are presented in Table 1. The details of the calculation of the performance metrics are provided in Varkey et al (2020). In the SSM model (the base-case OM), recruitment is modelled with random effects and is therefore independent of stock size. Performance statistics are calculated as the expected F, yield, and biomass for ages 5 to 9 at equilibrium when fishing at F0.1. The F0.1 is used as a proxy for F_{MSY} here because the peak of F (i.e. Fmax) at maximum yield is not well defined. In the simulations conducted, the gain in yield in increasing F from $F_{0.1}$ to F_{max} is small compared to the loss in biomass. Further $F_{0.1}$ allows some allowance for the present SSM model assuming that recruitment is independent of spawning stock size. The MSE simulation runs passed all performance criteria (Table 2).

A comparison is presented of main output from the previous and current output from the MSE simulations (figure 2). Two main differences are noticeable. First, the addition of observation error

creates wider probability envelopes in the current simulation for all the survey indices. Second, it appears that in the earlier version, likely because the 'Jtarget' values were miss-specified (Box 3) for MP '***t***', the yields reached higher levels leading to a gradual decline in biomass. After the fix in 'Jtarget' values, biomass trends stabilize after 2030 and do not show a decline and this results in good performance of the MP in the base OM.

Acknowledgements

Thank you to Joanne Morgan for pointing us in the right directions in conducting this review.

References

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Figures

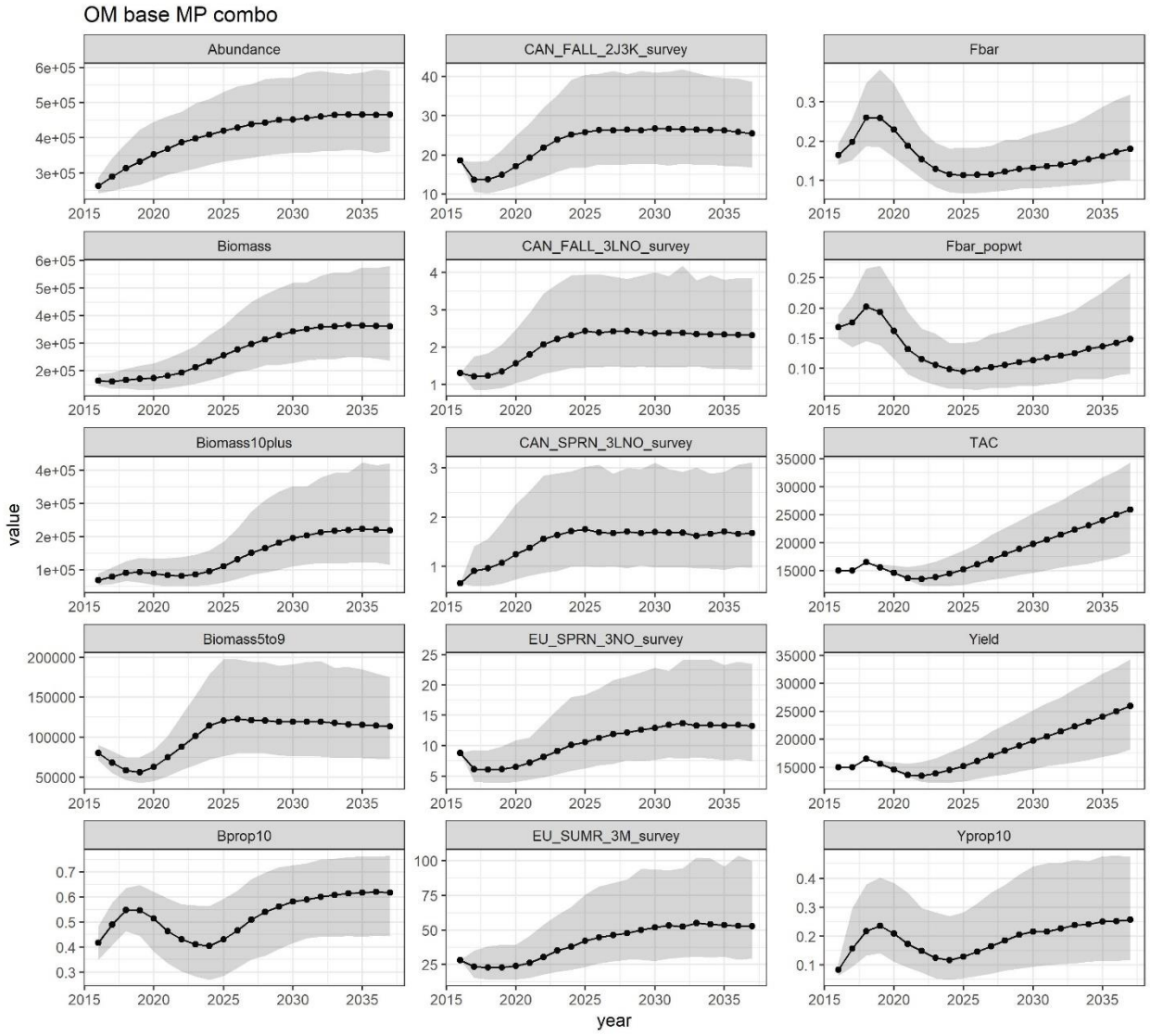

Figure 1. MSE simulation output from base case OM and MP combo (95% probability envelopes)

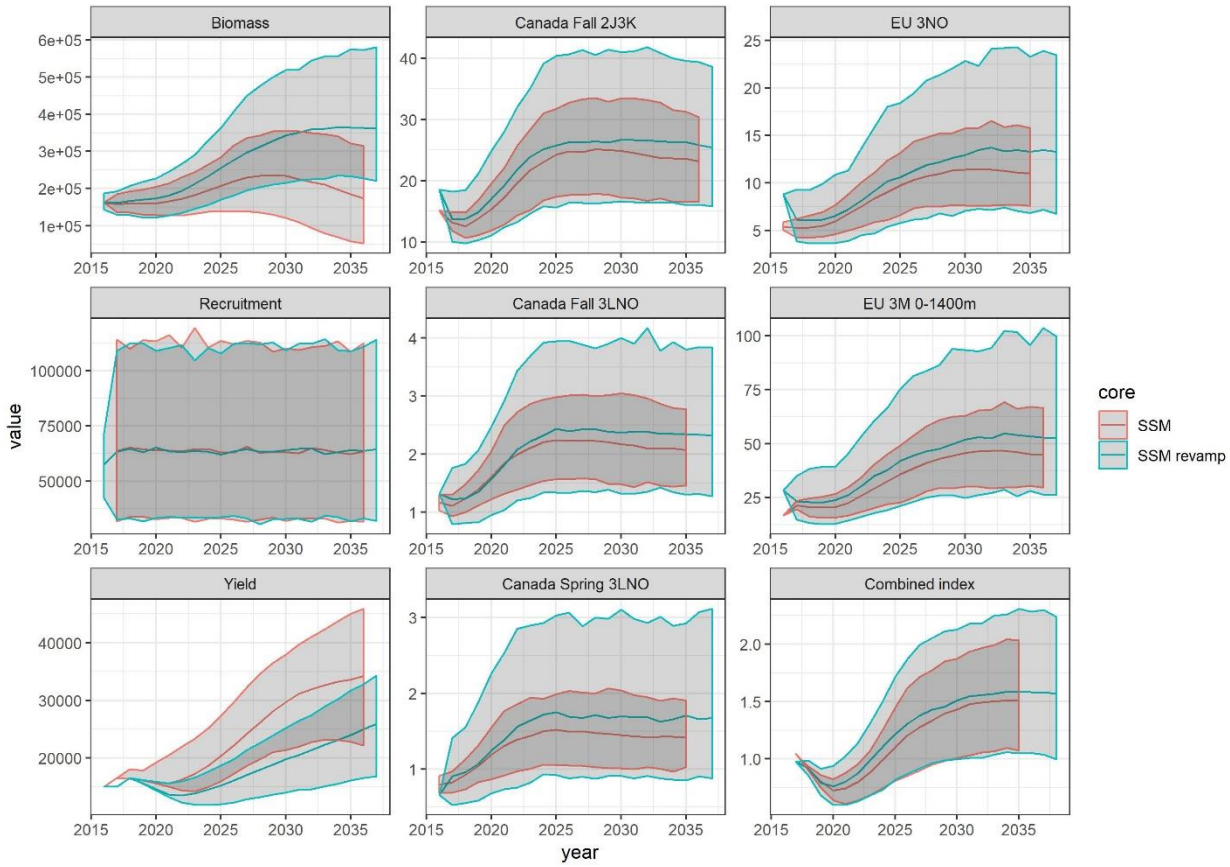

Figure 2. Comparison of key output from previous and revamped SSM-based MSE simulations (95% probability envelopes). Thank you to Paul Regular for providing me the envelopes for previous SSM-based simulations.

Tables

Table 1. Values of performance metrics considered for the base case OM

OM	FMSY	MSY(t)	B5-9MSY (t)
base	**0.363**	**25649**	**84464**

Table 2. Performance statistics for Base case OM and MP combo

Management objective	Perf. stats	metric	Median/ proportion	lower	upper
1. Restore to within a prescribed period of time or maintain at Bmsy	$B^{5\text{-}9}_{2037}/B^{5\text{-}9}_{msy}$	median (80%PI)	1.35	0.94	1.9
	$B^{5\text{-}9}_{2037} < B^{5\text{-}9}_{msy}$	Proportion <=0.5	0.14		
	$B^{5\text{-}9}_{2022} < 0.8B^{5\text{-}9}_{msy}$	Proportion <=0.25	0.13		
	$B^{5\text{-}9}_{2037} < 0.8B^{5\text{-}9}_{msy}$	Proportion <=0.25	0.03		
2. The risk of failure to meet the Bmsy target and interim biomass targets within a prescribed period of time should be kept moderately low	$B^{5\text{-}9}_{lowest}/B^{5\text{-}9}_{msy}$	median (80%PI)	0.64	0.52	0.76
	$B^{5\text{-}9}_{2022} < B^{5\text{-}9}_{2018}$	Proportion <W=0.25	0.07		
3. Low risk of exceeding F_{msy} (for each year y between 2018 to 2037, if more than 30% of the simulations had F5-9(y)>Fmsy, then count 1. i.e. maximum value for this metric is 20)	$(F_{2018\text{-}2037} > F_{msy})$ >0.3	Count	0		
	$B^{sp}_{2037}/B^{sp}_{2018}$	median (80%PI)	2.17	1.46	3.24

4. Very low risk of going below an established threshold (for each year y between 2018 to 2037, if more than 10% of the simulations had B5-9(y)<0.3*B5-9msy, then we count 1. I.e. maximum value for this metric is 20)					
	$B^{5\text{-}9}_{2037}/B^{5\text{-}9}_{2018}$	median (80%PI)	1.91	1.27	2.93
	($B^{5\text{-}9}_{2018\text{-}2037}$ <0.3$B^{5\text{-}9}_{msy}$) >0.1	Count	0		
	$B^{5\text{-}9}_{lowest}/B^{5\text{-}9}_{msy}$ <0.3	Proportion <=0.1	0		
5. Maximize yield in the short, medium and long term	avC: 2018-2020	median (80%PI)	15548	15480	15936
	avC: 2018-2037	median (80%PI)	18533	15828	21383
6. The risk of steep decline of stock biomass should be kept moderately low	$B^{5\text{-}9}_{2022}$ <0.75$B^{5\text{-}9}_{2018}$	Proportion	0		
7. Keep inter annual TAC variation below "an established threshold"	AAV: 2018-2037	median (80%PI)	5%	4%	6%
8. Proportion of the catch consisting of 10+ fish	average 2018-2037	median (80%PI)	0.21	0.18	0.25

Appendix A. Tables for MSE output probability envelopes for the base case OM and MP combo

Table A1. Biomass 5 to 9 envelopes

year	p50	p10	p90	p5	p95	p2.5	p97.5
2016	80539	73285	88315	71352	90395	69186	92823
2017	68273	58243	79249	55637	82890	53941	85491
2018	59072	49310	70772	46774	74894	45206	79047
2019	56414	45638	70511	42973	75363	41010	79891
2020	63097	48571	79123	45329	84008	42035	89754
2021	75001	56337	96431	51696	101821	48934	108914
2022	88341	64631	117209	59349	127277	55602	135228
2023	101780	71938	137466	65720	151954	60466	170671
2024	114406	80885	161018	72452	178420	65920	194849
2025	121084	85356	176856	76493	197502	71065	219354
2026	122975	86549	175689	79871	197586	74208	214998
2027	121376	87309	175322	79828	194409	74176	211392
2028	120885	85835	169692	80218	193405	72495	213318
2029	119380	85508	168422	77655	189208	71590	210011
2030	119254	83961	170596	76795	191120	69538	207203
2031	119223	84187	172465	76969	194058	70802	207597
2032	119588	83918	171182	75986	194734	71658	210951
2033	117935	83393	167493	74726	186869	70015	212103
2034	116078	82074	165487	74701	187908	69417	209367
2035	115576	82815	163614	74413	184732	68966	202910
2036	114750	80804	164654	73367	179341	67771	196170
2037	113896	79800	160226	72663	175266	66174	193930

Table A2 Fbar 5 to 9 envelopes

year	p50	p10	p90	p5	p95	p2.5	p97.5
2016	0.165	0.146	0.187	0.140	0.194	0.136	0.203
2017	0.198	0.160	0.243	0.152	0.258	0.143	0.268
2018	0.260	0.199	0.326	0.187	0.347	0.178	0.378
2019	0.258	0.198	0.349	0.184	0.382	0.172	0.405
2020	0.229	0.170	0.314	0.159	0.346	0.149	0.375
2021	0.188	0.141	0.257	0.132	0.283	0.123	0.304
2022	0.154	0.114	0.206	0.106	0.228	0.101	0.251
2023	0.129	0.093	0.180	0.083	0.196	0.076	0.213
2024	0.116	0.078	0.165	0.071	0.182	0.063	0.199
2025	0.114	0.076	0.166	0.068	0.185	0.062	0.195
2026	0.115	0.078	0.166	0.070	0.183	0.063	0.201
2027	0.116	0.081	0.170	0.072	0.188	0.064	0.203
2028	0.123	0.085	0.181	0.075	0.203	0.067	0.229
2029	0.130	0.087	0.186	0.080	0.205	0.072	0.226
2030	0.133	0.090	0.198	0.080	0.218	0.073	0.239
2031	0.137	0.092	0.207	0.083	0.227	0.076	0.240
2032	0.140	0.096	0.208	0.086	0.236	0.078	0.260
2033	0.147	0.101	0.221	0.088	0.247	0.082	0.268
2034	0.154	0.103	0.236	0.091	0.266	0.084	0.292
2035	0.162	0.105	0.254	0.094	0.287	0.084	0.324
2036	0.172	0.111	0.261	0.100	0.304	0.088	0.343
2037	0.181	0.117	0.286	0.102	0.318	0.093	0.355

Table A3. Survey envelopes: Canadian Fall 2J3K

year	p50	p10	p90	p5	p95	p2.5	p97.5
2016	18.54	18.54	18.54	18.54	18.54	18.54	18.54
2017	13.71	11.07	17.16	10.61	18.23	10.03	19.29
2018	13.81	10.91	17.33	10.20	18.49	9.77	19.64
2019	14.91	11.75	19.76	10.99	21.23	10.32	22.93
2020	17.09	12.97	22.90	11.99	24.90	11.12	26.42
2021	19.26	14.31	25.87	13.26	28.02	12.43	30.77
2022	21.82	15.66	29.43	14.35	32.05	13.24	34.37
2023	23.92	17.33	32.01	15.75	35.16	14.70	38.02
2024	25.17	18.54	35.82	16.86	39.12	15.83	42.41
2025	25.80	18.73	36.94	16.69	40.41	15.67	44.41

2026	26.34	19.20	37.38	17.56	40.68	16.44	45.35
2027	26.23	18.97	36.59	17.38	41.36	16.36	44.56
2028	26.48	19.44	36.49	17.61	40.57	16.33	44.45
2029	26.24	19.28	37.09	17.72	41.43	16.48	44.11
2030	26.72	19.07	37.63	17.74	40.99	16.67	44.57
2031	26.63	19.23	37.12	17.33	41.18	16.54	44.47
2032	26.59	19.28	37.32	17.84	41.81	16.48	45.27
2033	26.46	18.96	37.03	17.47	40.91	16.55	45.06
2034	26.34	18.95	36.61	17.61	40.00	16.46	44.24
2035	26.29	18.82	36.16	17.25	39.57	16.07	42.48
2036	25.86	18.90	36.14	17.13	39.40	16.13	41.86
2037	25.42	18.54	35.58	16.85	38.62	15.86	41.71

Table A4. Survey envelopes: Canadian Fall 3LNO

year	p50	p10	p90	p5	p95	p2.5	p97.5
2016	1.31	1.31	1.31	1.31	1.31	1.31	1.31
2017	1.22	0.92	1.60	0.86	1.76	0.79	1.88
2018	1.24	0.94	1.67	0.87	1.83	0.81	2.00
2019	1.35	0.98	1.89	0.90	2.07	0.83	2.25
2020	1.56	1.14	2.22	1.04	2.47	0.95	2.74
2021	1.81	1.25	2.65	1.15	2.91	1.03	3.12
2022	2.07	1.45	3.07	1.29	3.43	1.20	3.69
2023	2.22	1.50	3.29	1.36	3.69	1.24	4.12
2024	2.32	1.60	3.52	1.44	3.92	1.34	4.25
2025	2.44	1.63	3.55	1.45	3.94	1.34	4.31
2026	2.39	1.63	3.51	1.47	3.95	1.33	4.50
2027	2.43	1.64	3.53	1.50	3.89	1.37	4.31
2028	2.43	1.58	3.50	1.46	3.83	1.34	4.37
2029	2.39	1.66	3.52	1.49	3.90	1.39	4.27
2030	2.37	1.60	3.50	1.45	4.00	1.32	4.52
2031	2.39	1.65	3.52	1.46	3.90	1.32	4.26
2032	2.38	1.61	3.59	1.46	4.17	1.35	4.59
2033	2.35	1.66	3.40	1.50	3.78	1.42	4.27
2034	2.35	1.62	3.47	1.44	3.93	1.34	4.26
2035	2.34	1.61	3.39	1.42	3.80	1.30	4.22
2036	2.33	1.56	3.42	1.41	3.84	1.31	4.20
2037	2.32	1.58	3.36	1.40	3.84	1.27	4.22

Table A5. Survey envelopes: Canadian Spring 3LNO

year	p50	p10	p90	p5	p95	p2.5	p97.5
2016	0.66	0.66	0.66	0.66	0.66	0.66	0.66
2017	0.90	0.65	1.29	0.59	1.41	0.53	1.58
2018	0.96	0.67	1.42	0.60	1.56	0.56	1.68
2019	1.07	0.72	1.63	0.65	1.89	0.59	2.12
2020	1.25	0.83	2.00	0.73	2.26	0.68	2.44
2021	1.38	0.92	2.24	0.81	2.53	0.74	2.81
2022	1.56	0.98	2.52	0.87	2.85	0.76	3.16
2023	1.64	1.05	2.58	0.91	2.90	0.83	3.22
2024	1.72	1.10	2.63	1.00	2.93	0.93	3.32
2025	1.75	1.13	2.67	1.00	3.03	0.92	3.33
2026	1.69	1.12	2.72	0.98	3.07	0.88	3.43
2027	1.68	1.10	2.54	1.00	2.88	0.90	3.21
2028	1.71	1.09	2.67	0.96	3.00	0.87	3.35
2029	1.68	1.13	2.63	1.02	2.98	0.91	3.29
2030	1.70	1.13	2.71	0.98	3.11	0.91	3.29
2031	1.68	1.11	2.64	0.98	2.98	0.88	3.48
2032	1.69	1.09	2.64	0.99	2.93	0.91	3.26
2033	1.63	1.07	2.64	0.96	3.01	0.88	3.45
2034	1.66	1.09	2.55	0.95	2.89	0.86	3.23
2035	1.71	1.09	2.61	0.93	2.92	0.85	3.39
2036	1.66	1.10	2.63	0.99	3.07	0.91	3.40
2037	1.67	1.10	2.60	0.97	3.11	0.88	3.66

Table A6. Survey envelopes: EU Spring 3NO

year	p50	p10	p90	p5	p95	p2.5	p97.5
2016	8.80	8.80	8.80	8.80	8.80	8.80	8.80
2017	6.12	4.49	8.33	4.10	9.30	3.83	10.42
2018	6.04	4.35	8.41	3.91	9.24	3.64	10.03
2019	6.12	4.28	9.02	3.83	9.90	3.61	11.00
2020	6.51	4.36	9.70	4.02	10.86	3.67	11.78
2021	7.23	4.93	10.24	4.41	11.32	3.90	12.40
2022	8.16	5.39	12.22	4.76	13.65	4.50	15.40
2023	9.13	6.10	14.09	5.32	15.89	4.70	17.89
2024	10.16	6.62	15.60	5.86	18.02	5.37	20.00
2025	10.60	6.94	16.05	6.28	18.40	5.79	20.35
2026	11.27	7.47	17.17	6.77	19.40	6.11	22.80
2027	11.89	7.87	18.30	7.02	20.78	6.25	23.19
2028	12.18	8.45	19.39	7.61	21.36	6.77	24.00
2029	12.60	8.23	19.22	7.49	22.07	6.54	24.05
2030	12.92	8.51	19.96	7.68	22.85	7.05	24.40
2031	13.45	8.79	19.88	8.04	22.34	7.28	25.10
2032	13.71	8.79	20.74	7.82	24.10	7.13	26.37
2033	13.30	9.01	20.37	8.11	24.20	7.38	27.00
2034	13.46	8.89	20.99	7.89	24.27	7.04	27.81
2035	13.28	8.87	20.80	7.61	23.29	6.84	25.92
2036	13.44	8.79	20.85	7.76	23.89	7.17	26.73
2037	13.27	8.49	20.59	7.48	23.47	6.72	26.46

Table A7. Survey envelopes: EU Summer 3M

year	p50	p10	p90	p5	p95	p2.5	p97.5
2016	28.30	28.30	28.30	28.30	28.30	28.30	28.30
2017	23.40	17.18	32.40	15.47	35.13	14.76	39.17
2018	22.98	15.82	34.03	14.27	38.32	13.26	41.36
2019	22.80	15.59	34.28	14.09	39.30	12.66	42.61
2020	23.93	16.02	35.72	14.25	39.41	12.93	43.69
2021	26.29	17.12	40.47	15.43	45.59	14.37	49.83
2022	30.50	19.87	47.21	17.76	53.71	16.27	59.72
2023	35.15	22.14	54.22	19.88	60.84	17.95	67.51
2024	37.89	24.33	58.14	21.26	66.59	19.32	78.00
2025	42.08	27.36	65.99	23.22	75.45	21.20	86.75

2026	44.51	29.37	72.29	25.94	81.40	23.20	90.67
2027	46.41	30.64	74.49	27.46	83.87	25.09	92.41
2028	47.69	31.55	77.31	28.51	86.49	25.98	101.18
2029	49.86	32.04	79.88	28.52	94.07	26.21	101.16
2030	51.91	32.75	78.90	27.58	93.49	24.92	109.83
2031	53.13	33.46	82.66	29.27	92.92	26.17	101.86
2032	52.41	33.95	83.97	30.08	94.41	27.14	107.43
2033	54.77	34.95	89.22	30.68	102.34	28.65	113.20
2034	53.96	33.65	87.27	30.09	101.75	25.64	117.11
2035	53.41	34.26	85.87	30.67	95.72	28.11	107.10
2036	52.92	33.20	87.49	28.51	103.61	26.43	118.88
2037	52.76	33.28	85.26	29.43	99.81	26.14	111.82

Table A8. Survey envelopes: Combined survey index

year	p50	p10	p90	p5	p95	p2.5	p97.5
2016	0.98	0.98	0.98	0.98	0.98	0.98	0.98
2017	0.92	0.87	0.97	0.86	0.99	0.85	1.01
2018	0.79	0.71	0.89	0.70	0.91	0.68	0.94
2019	0.76	0.64	0.90	0.62	0.94	0.60	0.99
2020	0.80	0.67	0.97	0.63	1.02	0.60	1.08
2021	0.88	0.71	1.08	0.66	1.14	0.63	1.20
2022	0.99	0.77	1.24	0.73	1.31	0.68	1.38
2023	1.11	0.86	1.43	0.79	1.50	0.73	1.62
2024	1.22	0.93	1.61	0.86	1.72	0.82	1.86
2025	1.31	0.99	1.75	0.92	1.87	0.87	2.01
2026	1.38	1.05	1.84	0.98	2.00	0.92	2.12
2027	1.43	1.10	1.93	1.01	2.05	0.97	2.16
2028	1.45	1.15	1.98	1.04	2.11	0.99	2.26
2029	1.51	1.15	1.99	1.06	2.13	1.00	2.26
2030	1.54	1.15	2.02	1.08	2.18	1.01	2.32
2031	1.56	1.18	2.04	1.08	2.18	1.01	2.31
2032	1.57	1.20	2.09	1.11	2.25	1.04	2.35
2033	1.59	1.22	2.10	1.13	2.26	1.06	2.45
2034	1.58	1.22	2.12	1.12	2.31	1.05	2.51
2035	1.58	1.22	2.10	1.14	2.28	1.05	2.46
2036	1.58	1.21	2.08	1.11	2.30	1.04	2.45
2037	1.57	1.19	2.08	1.10	2.24	1.00	2.44
