Northwest Atlantic Fisheries Organization

Serial No. N7492 **NAFO SCR Doc. 24/001REV**

SCIENTIFIC COUNCIL MEETING–2024

Results for Greenland Halibut Candidate Management Procedure Trials for the final SCAA Reference Set trials

(Update to NAFO SCR Doc. 24/01[1])

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Summary

The existing MP is slightly adjusted (one survey replaced and survey weights adjusted), and then retuned to meet the updated recovery target of median exploitable biomass equal to Bmsy by 2044 for the Base Case SCAA operating model. This requires a downward adjustment of 3.7% to the existing MP formula for the TAC. This target is generally closely achieved across a wide range of robustness tests agreed at the January 2024 Scientific Council meeting.

Key words: Greenland halibut; management procedure; retuning; robustness trials; SCAA

Introduction

This paper reports results of the Candidate Management Procedure (CMP) trials for the updated SCAA-based baseline (OM1) and robustness trials (OM2 to OM14 - see Table 1). Butterworth and Rademeyer (2023) give methods and results for the earlier first application of this process.

The CMP considered has been tuned to meet the updated recovery target of median exploitable biomass equal to Bmsy by 2044 for the Base Case SCAA operating model. In addition, results are shown for a zero future catch (C=0) scenario to illustrate bounds on the extent of stock recovery which is possible.

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[1] This document is near identical to that presented to the January 2024 Scientific Counsil meeting. A key change is the renumbering of the robustness tests to match that in the SC report. Important additions include results for OM5a, OM5b robustness tests and an updated hockey-stick robustness test (OM2), as agreed at that SC meeting.

Methodology Applied

The set of Trials:

The set of trials (Operating Models – OMs) are as specified during the January 2024 SC meeting. These are sorted into three plausibility levels (High, Intermediate and Low).

In the previous paper, the hockey-stick OM used the hockey-stick stock-recruit function for the projections only. This was a first approximation only; in this paper, for self-consistency, the OM has been reconditioned fitting to a hockey-stick stock-recruit curve in the past as well. Some results comparing OM1 and OM2 are given in Appendix C.

The CMP

The MP selected in 2017 is modified as follows:

1) The Canadian 3LNO spring survey is not used anymore to compute the TAC.
2) The EU 3L survey is now included to compute the TAC.
3) The weights given to each survey in the MP TAC formula, computed from the variances of the fits estimated to the survey data, are taken from the updated Base Case (see Table 2).
4) The MP is further modified as follows: $TAC_{y+1} = \mu TAC_{y+1}^{MP17*}$ where TAC_{y+1}^{MP17*} is the TAC in year y+1 computed using the 2017 MP modified by 1)-3) above, and μ is a tuning parameter.

This new CMP is named **CMPts.**

The projection methodology

The projection methodology applied is set out in Appendix B.

Because of a change in survey vessels for the Canadian RV surveys, results for these surveys are generated assuming random error in the relative catchability change (the calibration factor estimate), i.e., equation B10 is modified as follows:

$$I_y^i = q^i B_y^i e^{\varepsilon_y^i} e^{\vartheta^i} \qquad (1)$$

with

ϑ^i being the random error of the relative q change, generated from its distribution $\vartheta^i \sim N(\rho_B; \varepsilon)$ once for each 20-year replicate, remaining the same for each year in that replicate. The values for ρ_B and ε are survey specific and are given in Table 3.

Results

The revised tuning parameters for CMPts, to achieve the recovery target of Bmsy for the exploitable biomass component of the resource by 2044, are given in Table 4

The performance measures, as described in the April 2023 WG-RBMS Meeting report (NAFO, 2023), are given in **Table 5** for all OMs under zero catch and CMPts, with some of the performance measures compared graphically in **Figure 1**.

Medians and lower 10%iles for projected catch, spawning and exploitable biomass (both relative to B_{MSY}) and F/F_{MSY} (for which the upper 10%iles are plotted instead of lower 10%iles) are compared under CMPts for all OMs in **Figures 2a-c**.

Worm plots showing individual trajectories as well as 80% probability envelopes are given in **Figure 3** for catch, spawning and exploitable biomass, and F/F_{MSY} for the baseline OM (OM1) under CMPts.

Discussion

The following points merit noting:

- The retuning requires setting TACs 3.7% lower than would previously have been the case.
- Under the Base Case, future catches are expected to increase slowly in median terms.
- Having a hockey-stick stock-recruit relationship (OM2) results in a more positive view of the resource, with future catches slightly higher than for the Base Case and spawning biomass well above the MSY level by 2044. (This follows from B_{MSY} for OM2 in terms of spawning biomass being appreciably lower than for the Base Case – see Table C1.)
- OM3(Lorenzen *M*) results in lower future catches and little impact on biomass trajectories.
- Including future random error in M (OM4 and OM6) results in lower future TACs but does not impact biomass trajectories much.
- As anticipated, OM5a and OM5b (with bias in the survey conversion factors) have little impact on the results.
- OM7 (zero selectivity on plus group) has little impact on the results compared to the base case OM1.
- Under OM8 (less doming in commercial selectivities), current biomass is estimated to be further below the MSY level than under the Base Case, but this biomass still increases into the future.
- The CMP reacts appropriately in OM9 (lower starting N(2022) values) by setting lower TACs initially.
- OM10 (lower recruitment in the next 8 years) is the test with the greatest impact on future trajectories. The CMP reacts appropriately by reducing the TAC in sufficient time to compensate and for the resource to recover.
- Assuming senescence (OM11) results in a more positive view of the resource, with future catches slightly higher than for the Base Case and biomass well above the MSY level.
- OM12 (higher *M* in the next 8 years) is the other test with a large impact on future trajectories. Again, the CMP reacts appropriately by reducing the TAC in sufficient time to compensate and see eventual resource recovery.
- As to be expected, projected biomass is slightly lower than for the base case for OM13 (110% TAC in the future).
- OM14 (excluding the EU Spain 3L and Canada Autumn 3LNO survey series for 8 years) has little impact on the performance of the CMP.
- The new statistic on the risk of exceeding Fmsy, which now excludes instances where the biomass is not low, gives notably lower counts than was the case before this exclusion (see Table 5).
- Some of the desired performance criteria cannot be met, even under an immediate closure of the fishery.

References

NAFO. 2023. Report of the NAFO Joint Commission-Scientific Council Working Group on Risk-Based Management Strategies (WG-RBMS) Meeting. 18-19 April 2023, Halifax, Nova Scotia.

Rademeyer RA and Butterworth DS. 2023. Updated SCAA Base Case Assessment and sensitivities. NAFO SCR Doc. 23/043

Table 1 List of OMs with a short description and plausibility level accorded to each.

OM	**Name**	**Description**	**Plausibility**
1	Base Case		High
2	Hockey-stick stock-recruit relationship	Use a hockey-stick S/R relationship. (Requires reconditioning)	High
3	Assume allometric natural mortality	Assume that M follows an allometric shape (i.e., Lorenzen M), where Ma = 0.12 * WAA ^ -0.305. (Requires reconditioning)	High
4	Include future random error in natural mortality	Base Case in the past, including future random error in $M_{y,a}$ with variance of the error as indicated by the SSM, which has a process error variance estimate of 0.16	High
5a	Assume provisional conversion factors are biased	Increase the true conversion factor by 10% for Canadian 2J3K and 3LNO indices.	High
5b	Assume the 3LNO Fall survey conversion factor is biased	Increase the true conversion factor by 10% for Canadian 3LNO index.	High
6	Increase the variance in natural mortality for younger ages	Base Case in the past, increase the variance of $M_{y,a}$ for age groups 1 to 10 by multiplicative amounts that decrease linearly with age from 2 for age 1 to 1 for age 10. Keep the variance of 0.16 for still higher ages	Intermediate
7	Zero selectivity on plus-group	Base Case in the past, with future commercial selectivity on ages 10 and above taken to be zero	Intermediate
8	Decrease the doming in the commercial selectivities	Decrease the doming in the commercial selectivities, by fixing the parameter values for the right side (higher ages) half-normal to double their values for the Base Case OM, so that commercial selectivity decreases at higher ages at half its previously-estimated rate	Intermediate
9	Decrease starting values N(2022, a) by 10% for all ages a	Base Case in the past, decreasing starting values $N_{2022,a}$ by 10% for all ages a, to allow for a possible decrease in abundance while some surveys were not conducted	Intermediate
10	8 years with recruitment halved	Base Case in the past, with the first 8 years of projected recruitment taken as 50% of those predicted by stock-recruit relationship	Low
11	Assume senescence	Assume senescence: M increases from 0.12 for age 9 to 0.5 for ages 10+. (Requires reconditioning)	Low
12	8 years with increased natural mortality	Assume that M increases from 0.12 to 0.2 in the first 8 years of the projections	Low
13	Catch = 110% TAC	Base Case in the past, with all future catch taken as 110% of TAC recommended by CMP.	Low
14	8 years with limited survey data from 3LNO	Repeat baseline OM but, at the start of the projections, exclude the EU-Spain 3L series and Canada Autumn 3LNO surveys for 8 years from 2022 to 2029.	Low

Table 2. Variances (shown as standard deviations of log residuals) of the survey data series about the expected abundance trend from the updated SCAA base case OM, and the related weights and weight ratios given to each survey in the MP TAC formula as in 2017 and now in 2023.

	σ_i		$w_i=1/\sigma_i^2$		w_i ratios	
	2017	2023	2017	2023	2017	2023
Can 2J3K autumn	0.222	0.230	20.300	18.962	0.294	0.274
Can 3LNO spring	0.488	-	4.200	-	0.061	-
Can 3LNO autumn	0.257	0.254	15.140	15.495	0.220	0.224
EU 3M 0-1400m	0.211	0.299	22.400	11.191	0.325	0.162
EU 3L	-	0.239	-	17.464	-	0.252
EU 3NO	0.381	0.405	6.900	6.099	0.100	0.088

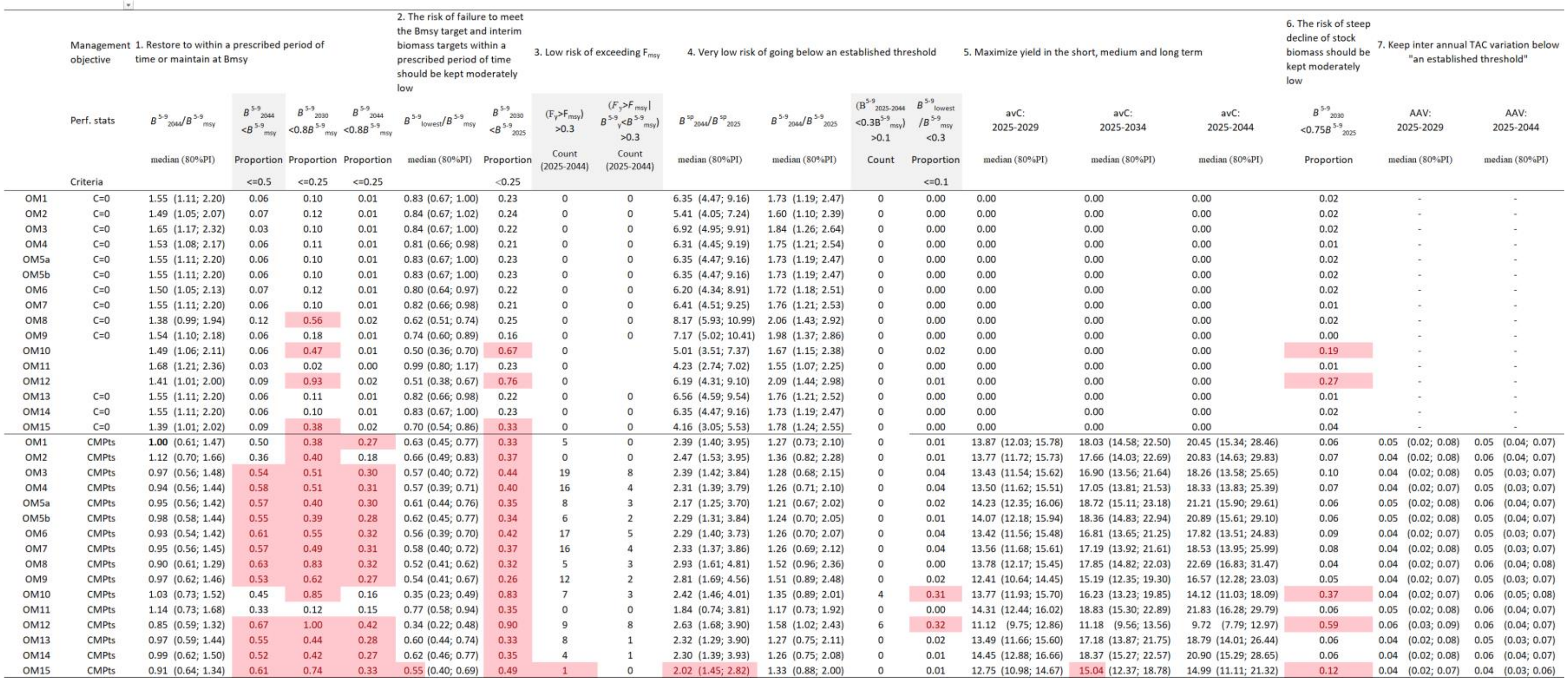
Table 3. Biomass based conversion for mean weight per tow (MWPT) and standard error of estimated conversion factor.

	ρ_B	ε
Can 2J3K autumn	0.9191	0.0394
Can 3LNO autumn	1.1122	0.0645

Table 4. Tuning parameters for the CMPs considered here. The parameter that is adjusted to achieve a median biomass equal to Bmsy for the exploitable component of the resource biomass in 2044, rather than being pre-fixed, is shown in **bold.**

	μ	γ	α	λ_{up}	λ_{down}	X	Δ_{up}	Δ_{down}
C=0		-	-	-	-	-	-	-
CMPts	**0.9630**	0.15	0.9720	1.00	2.00	-0.0056	0.1	0.1

Table 5. Performance measures for zero catch and CMPts for the different OMs; the pink highlights show instances where a desired performance criterion specified during the April WG-RBMS meeting (NAFO, 2023) has not been met. A value shown in **bold** indicates that the tuning parameter m was adjusted to achieve that result for that OM/CMP combination. A second column under the "low risk of exceeding Fmsy" has now been included to report a new statistic added recently.



	Management objective	1. Restore to within a prescribed period of time or maintain at Bmsy				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		3. Low risk of exceeding F_{msy}		4. Very low risk of going below an established threshold				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 "an established threshold"	
	Perf. stats	$B^{5-9}_{2044}/B^{5-9}_{msy}$	$B^{5-9}_{2044}<B^{5-9}_{msy}$	$B^{5-9}_{2030}<0.8B^{5-9}_{msy}$	$B^{5-9}_{2044}<0.8B^{5-9}_{msy}$	$B^{5-9}_{lowest}/B^{5-9}_{msy}$	$B^{5-9}_{2030}<B^{5-9}_{2025}$	$(F_y>F_{msy})>0.3$	$(F_y>F_{msy}\mid B^{5-9}_y<B^{5-9}_{msy})>0.3$	$B^{sp}_{2044}/B^{sp}_{2025}$	$B^{5-9}_{2044}/B^{5-9}_{2025}$	$(B^{5-9}_{2025-2044}<0.3B^{5-9}_{msy})>0.1$	$B^{5-9}_{lowest}/B^{5-9}_{msy}<0.3$	avC: 2025-2029	avC: 2025-2034	avC: 2025-2044	$B^{5-9}_{2030}<0.75B^{5-9}_{2025}$	AAV: 2025-2029	AAV: 2025-2044
		median (80%PI)	Proportion	Proportion	Proportion	median (80%PI)	Proportion	Count (2025-2044)	Count (2025-2044)	median (80%PI)	median (80%PI)	Count	Proportion	median (80%PI)	median (80%PI)	median (80%PI)	Proportion	median (80%PI)	median (80%PI)
	Criteria		<=0.5	<=0.25	<=0.25		<0.25						<=0.1						
OM1	C=0	1.55 (1.11; 2.20)	0.06	0.10	0.01	0.83 (0.67; 1.00)	0.23	0	0	6.35 (4.47; 9.16)	1.73 (1.19; 2.47)	0	0.00	0.00	0.00	0.00	0.02	-	-
OM2	C=0	1.49 (1.05; 2.07)	0.07	0.12	0.01	0.84 (0.67; 1.02)	0.24	0	0	5.41 (4.05; 7.24)	1.60 (1.10; 2.39)	0	0.00	0.00	0.00	0.00	0.02	-	-
OM3	C=0	1.65 (1.17; 2.32)	0.03	0.10	0.01	0.84 (0.67; 1.00)	0.22	0	0	6.92 (4.95; 9.91)	1.84 (1.26; 2.64)	0	0.00	0.00	0.00	0.00	0.02	-	-
OM4	C=0	1.53 (1.08; 2.17)	0.06	0.11	0.01	0.81 (0.66; 0.98)	0.21	0	0	6.31 (4.45; 9.19)	1.75 (1.21; 2.54)	0	0.00	0.00	0.00	0.00	0.01	-	-
OM5a	C=0	1.55 (1.11; 2.20)	0.06	0.10	0.01	0.83 (0.67; 1.00)	0.23	0	0	6.35 (4.47; 9.16)	1.73 (1.19; 2.47)	0	0.00	0.00	0.00	0.00	0.02	-	-
OM5b	C=0	1.55 (1.11; 2.20)	0.06	0.10	0.01	0.83 (0.67; 1.00)	0.23	0	0	6.35 (4.47; 9.16)	1.73 (1.19; 2.47)	0	0.00	0.00	0.00	0.00	0.02	-	-
OM6	C=0	1.50 (1.05; 2.13)	0.07	0.12	0.01	0.80 (0.64; 0.97)	0.22	0	0	6.20 (4.34; 8.91)	1.72 (1.18; 2.51)	0	0.00	0.00	0.00	0.00	0.02	-	-
OM7	C=0	1.55 (1.11; 2.20)	0.06	0.10	0.01	0.82 (0.66; 0.98)	0.21	0	0	6.41 (4.51; 9.25)	1.76 (1.21; 2.53)	0	0.00	0.00	0.00	0.00	0.01	-	-
OM8	C=0	1.38 (0.99; 1.94)	0.12	0.56	0.02	0.62 (0.51; 0.74)	0.25	0	0	8.17 (5.93; 10.99)	2.06 (1.43; 2.92)	0	0.00	0.00	0.00	0.00	0.02	-	-
OM9	C=0	1.54 (1.10; 2.18)	0.06	0.18	0.01	0.74 (0.60; 0.89)	0.16	0	0	7.17 (5.02; 10.41)	1.98 (1.37; 2.86)	0	0.00	0.00	0.00	0.00	0.00	-	-
OM10		1.49 (1.06; 2.11)	0.06	0.47	0.01	0.50 (0.36; 0.70)	0.67	0		5.01 (3.51; 7.37)	1.67 (1.15; 2.38)	0	0.02	0.00	0.00	0.00	0.19	-	-
OM11		1.68 (1.21; 2.36)	0.03	0.02	0.00	0.99 (0.80; 1.17)	0.23	0		4.23 (2.74; 7.02)	1.55 (1.07; 2.25)	0	0.00	0.00	0.00	0.00	0.01	-	-
OM12		1.41 (1.01; 2.00)	0.09	0.93	0.02	0.51 (0.38; 0.67)	0.76	0		6.19 (4.31; 9.10)	2.09 (1.44; 2.98)	0	0.01	0.00	0.00	0.00	0.27	-	-
OM13	C=0	1.55 (1.11; 2.20)	0.06	0.11	0.01	0.82 (0.66; 0.98)	0.22	0	0	6.56 (4.59; 9.54)	1.76 (1.21; 2.52)	0	0.00	0.00	0.00	0.00	0.01	-	-
OM14	C=0	1.55 (1.11; 2.20)	0.06	0.10	0.01	0.83 (0.67; 1.00)	0.23	0	0	6.35 (4.47; 9.16)	1.73 (1.19; 2.47)	0	0.00	0.00	0.00	0.00	0.02	-	-
OM15	C=0	1.39 (1.01; 2.02)	0.09	0.38	0.02	0.70 (0.54; 0.86)	0.33	0	0	4.16 (3.05; 5.53)	1.78 (1.24; 2.55)	0	0.00	0.00	0.00	0.00	0.04	-	-
OM1	CMPts	**1.00** (0.61; 1.47)	0.50	0.38	0.27	0.63 (0.45; 0.77)	0.33	5	0	2.39 (1.40; 3.95)	1.27 (0.73; 2.10)	0	0.01	13.87 (12.03; 15.78)	18.03 (14.58; 22.50)	20.45 (15.34; 28.46)	0.06	0.05 (0.02; 0.08)	0.05 (0.04; 0.07)
OM2	CMPts	1.12 (0.70; 1.66)	0.36	0.40	0.18	0.66 (0.49; 0.83)	0.37	0	0	2.47 (1.53; 3.95)	1.36 (0.82; 2.28)	0	0.01	13.77 (11.72; 15.73)	17.66 (14.03; 22.69)	20.83 (14.63; 29.83)	0.07	0.04 (0.02; 0.08)	0.06 (0.04; 0.07)
OM3	CMPts	0.97 (0.56; 1.48)	0.54	0.51	0.30	0.57 (0.40; 0.72)	0.44	19	8	2.39 (1.42; 3.84)	1.28 (0.68; 2.15)	0	0.04	13.43 (11.54; 15.62)	16.90 (13.56; 21.64)	18.26 (13.58; 25.65)	0.10	0.04 (0.02; 0.08)	0.05 (0.03; 0.07)
OM4	CMPts	0.94 (0.56; 1.44)	0.58	0.51	0.31	0.57 (0.39; 0.71)	0.40	16	4	2.31 (1.39; 3.79)	1.26 (0.71; 2.10)	0	0.04	13.50 (11.62; 15.51)	17.05 (13.81; 21.53)	18.33 (13.83; 25.39)	0.07	0.04 (0.02; 0.07)	0.05 (0.03; 0.07)
OM5a	CMPts	0.95 (0.56; 1.42)	0.57	0.40	0.30	0.61 (0.44; 0.76)	0.35	8	3	2.17 (1.25; 3.70)	1.21 (0.67; 2.02)	0	0.02	14.23 (12.35; 16.06)	18.72 (15.11; 23.18)	21.21 (15.90; 29.61)	0.06	0.05 (0.02; 0.08)	0.06 (0.04; 0.07)
OM5b	CMPts	0.98 (0.58; 1.44)	0.55	0.39	0.28	0.62 (0.45; 0.77)	0.34	6	2	2.29 (1.31; 3.84)	1.24 (0.70; 2.05)	0	0.01	14.07 (12.18; 15.94)	18.36 (14.83; 22.94)	20.89 (15.61; 29.10)	0.06	0.05 (0.02; 0.08)	0.05 (0.04; 0.07)
OM6	CMPts	0.93 (0.54; 1.42)	0.61	0.55	0.32	0.56 (0.39; 0.70)	0.42	17	5	2.29 (1.40; 3.73)	1.26 (0.70; 2.07)	0	0.04	13.42 (11.56; 15.48)	16.81 (13.65; 21.25)	17.82 (13.51; 24.83)	0.09	0.04 (0.02; 0.07)	0.05 (0.03; 0.07)
OM7	CMPts	0.95 (0.56; 1.45)	0.57	0.49	0.31	0.58 (0.40; 0.72)	0.37	16	4	2.33 (1.37; 3.86)	1.26 (0.69; 2.12)	0	0.04	13.56 (11.68; 15.61)	17.19 (13.92; 21.61)	18.53 (13.95; 25.99)	0.08	0.04 (0.02; 0.08)	0.05 (0.03; 0.07)
OM8	CMPts	0.90 (0.61; 1.29)	0.63	0.83	0.32	0.52 (0.41; 0.62)	0.32	5	3	2.93 (1.61; 4.81)	1.52 (0.96; 2.36)	0	0.00	13.78 (12.17; 15.45)	17.85 (14.82; 22.03)	22.69 (16.83; 31.47)	0.04	0.04 (0.02; 0.07)	0.06 (0.04; 0.08)
OM9	CMPts	0.97 (0.62; 1.46)	0.53	0.62	0.27	0.54 (0.41; 0.67)	0.26	12	2	2.81 (1.69; 4.56)	1.51 (0.89; 2.48)	0	0.02	12.41 (10.64; 14.45)	15.19 (12.35; 19.30)	16.57 (12.28; 23.03)	0.05	0.04 (0.02; 0.07)	0.05 (0.03; 0.07)
OM10	CMPts	1.03 (0.73; 1.52)	0.45	0.85	0.16	0.35 (0.23; 0.49)	0.83	7	3	2.42 (1.46; 4.01)	1.35 (0.89; 2.01)	4	0.31	13.77 (11.93; 15.70)	16.23 (13.23; 19.85)	14.12 (11.03; 18.09)	0.37	0.04 (0.02; 0.07)	0.06 (0.05; 0.08)
OM11	CMPts	1.14 (0.73; 1.68)	0.33	0.12	0.15	0.77 (0.58; 0.94)	0.35	0	0	1.84 (0.74; 3.81)	1.17 (0.73; 1.92)	0	0.00	14.31 (12.44; 16.02)	18.83 (15.30; 22.89)	21.83 (16.28; 29.79)	0.06	0.05 (0.02; 0.08)	0.06 (0.04; 0.07)
OM12	CMPts	0.85 (0.59; 1.32)	0.67	1.00	0.42	0.34 (0.22; 0.48)	0.90	9	8	2.63 (1.68; 3.90)	1.58 (1.02; 2.43)	6	0.32	11.12 (9.75; 12.86)	11.18 (9.56; 13.56)	9.72 (7.79; 12.97)	0.59	0.06 (0.03; 0.09)	0.06 (0.04; 0.07)
OM13	CMPts	0.97 (0.59; 1.44)	0.55	0.44	0.28	0.60 (0.44; 0.74)	0.33	8	1	2.32 (1.29; 3.90)	1.27 (0.75; 2.11)	0	0.02	13.49 (11.66; 15.60)	17.18 (13.87; 21.75)	18.79 (14.01; 26.44)	0.06	0.04 (0.02; 0.08)	0.05 (0.03; 0.07)
OM14	CMPts	0.99 (0.62; 1.50)	0.52	0.42	0.27	0.62 (0.46; 0.77)	0.35	4	1	2.30 (1.39; 3.93)	1.26 (0.75; 2.08)	0	0.01	14.45 (12.88; 16.66)	18.37 (15.27; 22.57)	20.90 (15.29; 28.65)	0.06	0.04 (0.02; 0.08)	0.06 (0.04; 0.07)
OM15	CMPts	0.91 (0.64; 1.34)	0.61	0.74	0.33	0.55 (0.40; 0.69)	0.49	1	0	2.02 (1.45; 2.82)	1.33 (0.88; 2.00)	0	0.01	12.75 (10.98; 14.67)	15.04 (12.37; 18.78)	14.99 (11.11; 21.32)	0.12	0.04 (0.02; 0.07)	0.04 (0.03; 0.06)

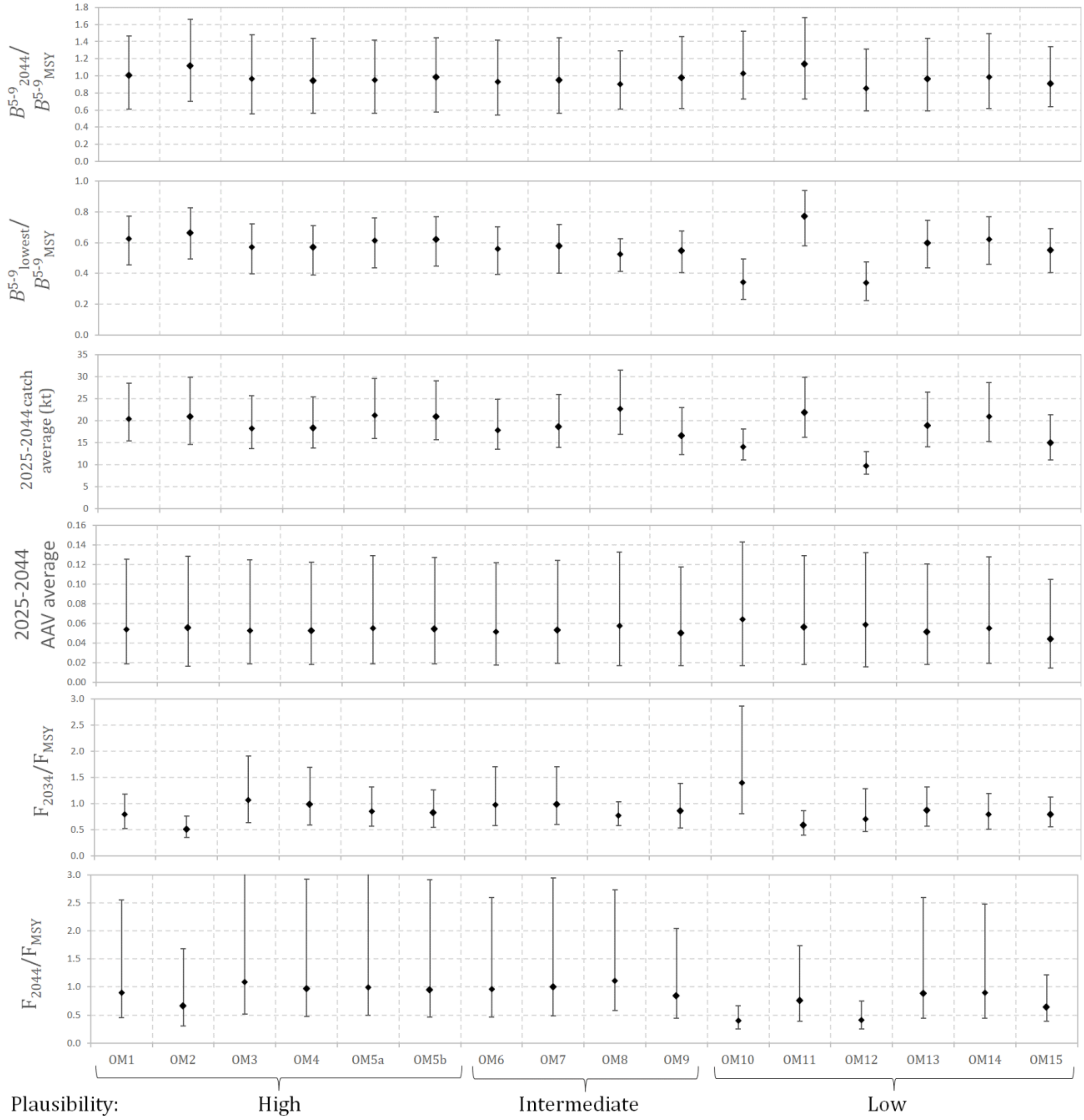


Figure 1. Projected median and 80% PIs for a series of performance statistics for each OM under CMPts.

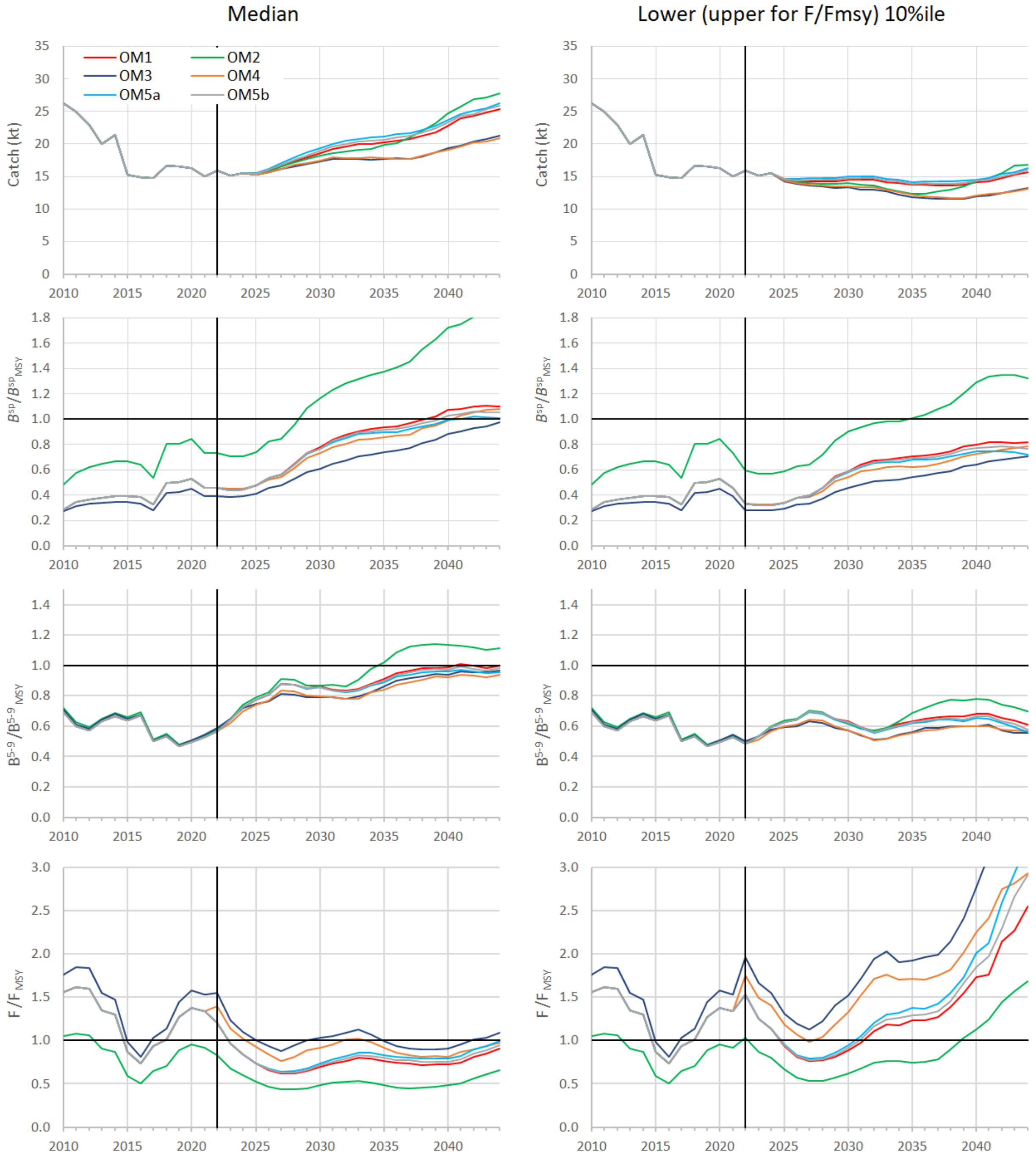


Figure 2a. Projected median and lower 10%iles for catch, spawning and exploitable biomass (both relative to B_{MSY}) and F/F_{MSY} (the upper 10%iles are plotted instead of lower 10%iles) for **OM1** and the high plausibility OMs: **OM2 to OM5b** under CMPts.

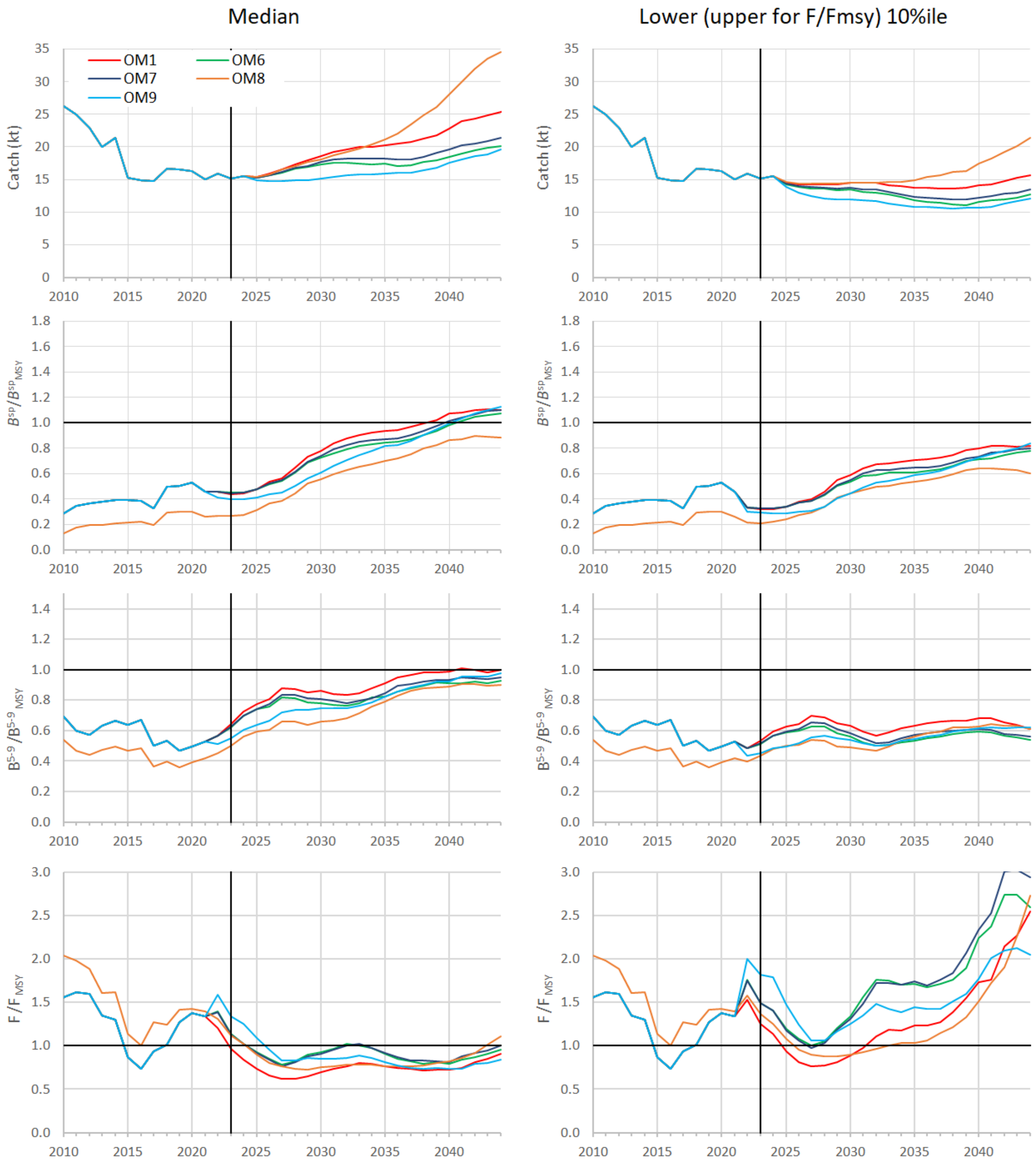


Figure 2b. Projected median and lower 10%iles for catch, spawning and exploitable biomass (both relative to B_{MSY}) and F/F_{MSY} (the upper 10%iles are plotted instead of lower 10%iles) for **OM1** and intermediate plausibility OMs: **OM6 to OM9** under CMPts.

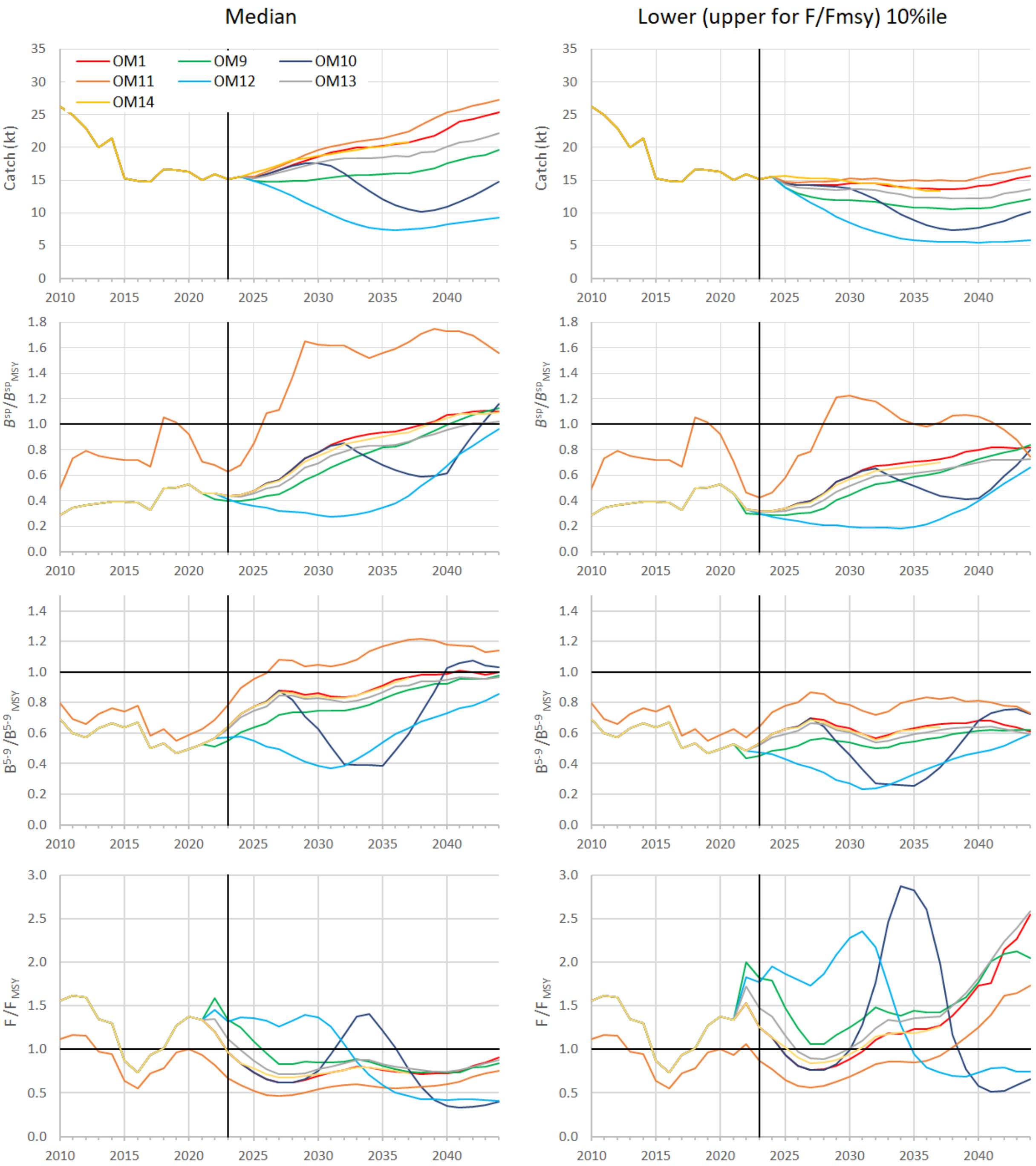


Figure 2c. Projected median and lower 10%iles for catch, spawning and exploitable biomass (both relative to B_{MSY}) and F/F_{MSY} (the upper 10%iles are plotted instead of lower 10%iles) for **OM1** and low plausibility OMs: **OM10 to 14** under CMPts.

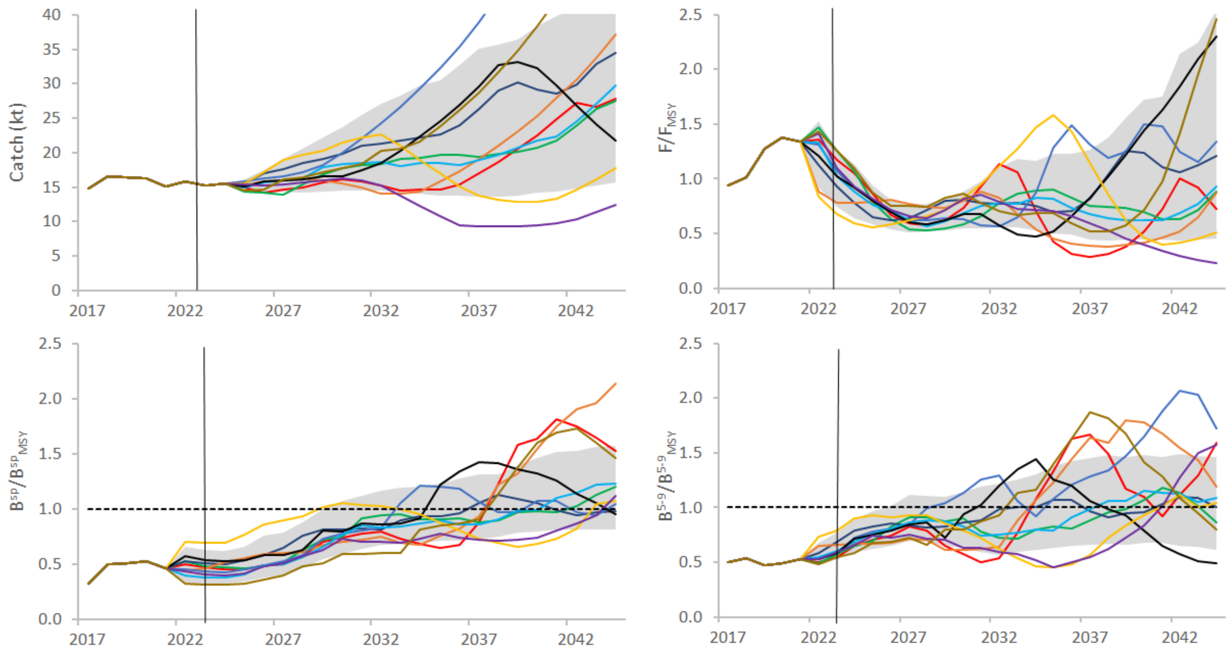


Figure 3. “Worm” plots showing individual trajectories as well as the 80% probability envelopes (grey shading) for catch, fishing mortality relative to F_{MSY}, and spawning and exploitable biomass (both relative to B_{MSY}), for the baseline OM (OM1) under CMPts.

Appendix A: The CMPs

The CMPs considered here are a combination of target based, slope based:

$$TAC_{y+1} = \left(TAC_{y+1}^{target} + TAC_{y+1}^{slope}\right)/2 \qquad \text{(A1)}$$

Target based part:

$$TAC_{y+1}^{target} = TAC_y\left(1 + \gamma\left(J_y - 1\right)\right) \qquad \text{(A2)}$$

where

TAC_y is the TAC recommended for year y,

γ is the "response strength" tuning parameter

J_y is a composite measure of the immediate past level in the abundance indices that are available to use for calculations for year *y*; for this base case CMP five series have been used, with *i* = 1, 2, 3, 4 and 5 corresponding respectively to Canada Fall 2J3K, EU 3M 0-1400m, EU 3L, EU 3NO and Canada Fall 3LNO:

$$J_y = \sum_{i=1}^{5} \frac{1}{(\sigma^i)^2} \frac{J_{curr,y}^i}{J_{target}^i} \Big/ \sum_{i=1}^{5} \frac{1}{(\sigma^i)^2} \qquad \text{(A3)}$$

with

$(\sigma^i)^2$ being the estimated variance for index *i* (estimated in the model fitting procedure, see **Table 1**)

$$J_{curr,y}^i = \frac{1}{q}\sum_{y'=y-q}^{y-1} I_{y'}^i \qquad \text{(A4)}$$

$$J_{target}^i = \alpha\frac{1}{5}\sum_{y'=2011}^{2015} I_{y'}^i \quad \text{(where } \alpha \text{ is a control/tuning parameter for the CMP)} \qquad \text{(A5)}$$

Note the assumption that when a TAC is set in year *y* for year *y*+1, indices will not at that time yet be available for the current year *y*.

Slope based part:

$$TAC_{y+1}^{slope} = TAC_y\left[1 + \lambda_{up/down}\left(s_y - X\right)\right] \qquad \text{(A6)}$$

where

$\lambda_{up/down}$ and X are tuning parameters,

s_y is a measure of the immediate past trend in the survey-based abundance indices, computed by linearly regressing lnI_y^i vs year y' for $y' = y - 5$ to $y' = y - 1$, for each of the five surveys considered, with

$$s_y = \sum_{i=1}^{5} \frac{1}{(\sigma^i)^2} s_y \Big/ \sum_{i=1}^{5} \frac{1}{(\sigma^i)^2} \qquad \text{(A7)}$$

with the standard error of the residuals of the observed compared to model-predicted logarithm of survey index *i* (σ^i) estimated in the operating model.

Each year these TAC_{y+1}^{target} and TAC_{y+1}^{slope} are evaluated according to each rule separately, and then an arithmetic average is taken before applying the constraints below.

Constraints on the maximum allowable annual change in TAC are then applied, viz.:

if $TAC_{y+1} > TAC_y\left(1 + \Delta_{up}\right)$ then $TAC_{y+1} = TAC_y\left(1 + \Delta_{up}\right)$ (A8) and

if $TAC_{y+1} < TAC_y\left(1 - \Delta_{down}\right)$ then $TAC_{y+1} = TAC_y\left(1 - \Delta_{down}\right)$ (A9)

Tuning parameter values for the final CMP presented in this paper are given in **Table 3**.

Appendix B: Projection methodology

Projections into the future under a specific Candidate Management Procedure (CMP) are evaluated using the following steps.

Step 1: Begin-year numbers at age

The components of the numbers-at-age vector at the start of 2022 ($N_{2022,a}$: $a = 0,\dots, m$) are obtained from the MLEs for an assessment of the resource. Error is included for all ages to allow for estimation imprecision in the assessment through use of the Hessian to provide a variance-covariance matrix, i.e.:

$$N_{2022,a} \rightarrow N_{2022,a} e^{\varepsilon_a}$$

where ε_a is generated from the variance-covariance matrix. (B1)

Step 2: Catch

These numbers-at-age are projected one year forward at a time given a catch for the year concerned.

For 2022 and 2023 the actual 2022 catch and the 2023 TAC respectively are assumed:

$$C_{2022} = 14864 \text{ t} \tag{B2a}$$

$$C_{2023} = 15156 \text{ t} \tag{B2b}$$

From 2024 onwards:

C_y is as specified by the CMP.

This requires specification of how the catch is disaggregated by age to obtain $C_{y,a}$, and how future recruitments are specified.

Step 3: Catch-at-age (by number)

The $C_{y,a}$ values are obtained under the assumption that the commercial selectivity function estimated for the last period (2000 to 2021) continues in the future. F_y[2] is solved iteratively to achieve that the annual catch by mass:

$$C_y = \sum_{a=0}^{m} w_{y,a}^{mid} N_{y,a} S_{y,a} F_y \left(1 - e^{-Z_{y,a}}\right) / Z_{y,a} \tag{B3}$$

where $w_{y,a}^{mid}$ is taken as the average of the last 10 years (2012-2021) weight-at-age vectors, and hence that:

$$C_{y,a} = N_{y,a} S_{y,a} F_y \left(1 - e^{-Z_{y,a}}\right) / Z_{y,a} \tag{B4}$$

The numbers-at-age can then be computed for the beginning of the following year (y+1):

$$N_{y+1,0} = R_{y+1} \tag{B5}$$

$$N_{y+1,a+1} = N_{y,a} e^{-Z_{y,a}} \quad \text{for } 0 \le a \le m-2 \tag{B6}$$

$$N_{y+1,m} = N_{y,m-1} e^{-Z_{y,m-1}} + N_{y,m} e^{-Z_{y,m}} \tag{B7}$$

The plus-group m is 14.

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[2] An upper bound of 5 is imposed on fishing mortality.

Step 4: Recruitment

Future recruitments for the baseline and sensitivity SCAA operating models are provided by a Beverton-Holt stock-recruitment relationship:

$$R_y = \frac{4hR_0B_y^{sp}}{b_0(1-h)+(5h-1)B_y^{sp}}e^{\left(\varphi_y-(\sigma_R)^2/2\right)} \tag{B8}$$

Log-normal fluctuations are introduced by generating φ_y factors which also take account of autocorrelation:

$$\varphi_y = \rho\varphi_{y-1} + \sqrt{1-\rho^2}\lambda_y$$

with λ_y from $N(0,(\sigma_R)^2)$ where ⍰$_R$ is input (0.4) and ρ is fixed at 0.5 (based on results from the baseline assessment).

b_0 is as estimated for that Operating Model. For the baseline SCAA, h is fixed (0.8).

$$B_y^{sp} = \sum_{a=1}^{m} f_a\, w_{y,a}^{strt} N_{y,a} \tag{B9}$$

where $w_{y,a}^{strt}$ is taken to be the average of the last 10 years (2012-2021) weight-at-age vectors.

Step5:

The information obtained in Step 1 is used to generate values of the abundance indices I_{2022}^i (in terms of biomass or of numbers), and similarly for following years. The EU survey is assumed to continue sampling the 0-1400m depth zone. Indices of abundance in future years will not be exactly proportional to true abundance, as they are subject to observation error. Log-normal observation error is therefore added to the expected value of the abundance index evaluated, i.e.:

$$I_y^i = q^iB_y^ie^{\varepsilon_y^i} \tag{B10}$$

with

ε_y^i from $N(0,(\sigma^i)^2)$

where

B_y^i is the biomass available to the survey:

$$B_y^i = \sum_{a=0}^{m} w_{y,a}^i S_a^i N_{y,a} e^{-Z_{y,a}T^i/12} \tag{B11}$$

The survey selectivities are assumed to remain unchanged over the projection period.

The constant of proportionality q^i and residual standard deviation σ^i are as were estimated directly in the associated assessment.

For 2022, the following survey results are input: 13.492 MWPT for EU 3M and 10.284 MWPT for EU 3LNO, with no results available for the Canadian surveys, which were therefore taken as missing for the calcutations.

Step 6:

Given the new survey indices I_y^i compute TAC_{y+1} using the CMP (aside from the fixed values assumed for 2022 to 2023).

Step 7:

Steps 1-6 are repeated for each future year in turn for as long a period as desired, and at the end of that period the performance of the CMP under review is assessed by considering statistics such as the average catch taken over the period and the final spawning biomass of the resource.

Appendix C: OM2 conditioning results

Table C1 provides the results, with Hessian-based CVs, for the OM1 and OM2. Figure C1 compares results for OM1 with OM2.

Table C1. Results from fits of the Base Case (OM1) and the OM with a hockey-stick SR relationship (OM2). Hessian-based CVs are shown in parentheses. Values shown in **bold** are fixed on input. B5-9 is the biomass of fish aged 5 to 9.

	OM1 (Base Case)		OM2 (Hockey-stick)	
'-lnL:overall	-583.75		-582.65	
	-lnL: index	-lnL: CAA	-lnL: index	-lnL: CAA
Can. Fall 2J3K	-1.31	-79.75	-1.72	-80.03
EU 3M 0-700m	0.99	-34.37	0.65	-33.98
EU 3M 0-1400m	3.80	-55.21	3.90	-55.33
Can. Spring 3LNO	14.83	-53.64	14.76	-53.57
EU 3L	-0.18	-49.63	0.49	-49.47
EU 3NO	12.36	-77.67	12.25	-77.29
Can. Fall 3LNO	1.17	-70.60	0.74	-70.59
Commercial		-119.79		-118.65
'-lnL:RecRes	7.32		8.04	
-lnL:CatchPen	-82.06		-82.84	
h	**0.80**		-	
M	**0.12**		**0.12**	
ϑ	0.00	-	0.00	-
K^{sp}	726	(0.07)	695	(0.08)
B^{sp}_{1975}	492	(0.14)	461	(0.16)
B^{sp}_{2016}	65	(0.30)	89	(0.17)
B^{sp}_{2021}	77	(0.28)	102	(0.18)
B^{sp}_{2016}/K^{sp}	0.09	(0.31)	0.13	(0.19)
B^{sp}_{2021}/K^{sp}	0.11	(0.29)	0.15	(0.20)
$B^{sp}_{2016}/B^{sp}_{1975}$	0.13	(0.33)	0.19	(0.23)
$B^{sp}_{2021}/B^{sp}_{1975}$	0.16	(0.31)	0.22	(0.24)
$B^{5\text{-}9}_{1975}$	157	(0.18)	151	(0.19)
$B^{5\text{-}9}_{2016}$	82	(0.11)	90	(0.10)
$B^{5\text{-}9}_{2021}$	65	(0.14)	70	(0.14)
$B^{5\text{-}9}_{2016}/B^{5\text{-}9}_{1975}$	0.52	(0.20)	0.60	(0.22)
$B^{5\text{-}9}_{2021}/B^{5\text{-}9}_{1975}$	0.41	(0.22)	0.46	(0.24)
B^{sp}_{MSY}	169	(0.19)	48	(0.21)
$B^{5\text{-}9}_{MSY}$	123	(0.09)	108	(0.09)
	σ index	σ CAA	σ index	σ CAA
Can. Fall 2J3K	0.23	0.06	0.23	0.06
EU 3M 0-700m	0.27	0.05	0.26	0.06
EU 3M 0-1400m	0.30	0.05	0.30	0.05
Can. Spring 3LNO	0.49	0.09	0.49	0.09
EU 3L	0.24	0.09	0.25	0.09
EU 3NO	0.40	0.09	0.40	0.09
Can. Fall 3LNO	0.25	0.09	0.25	0.09
Commercial		0.07		0.07

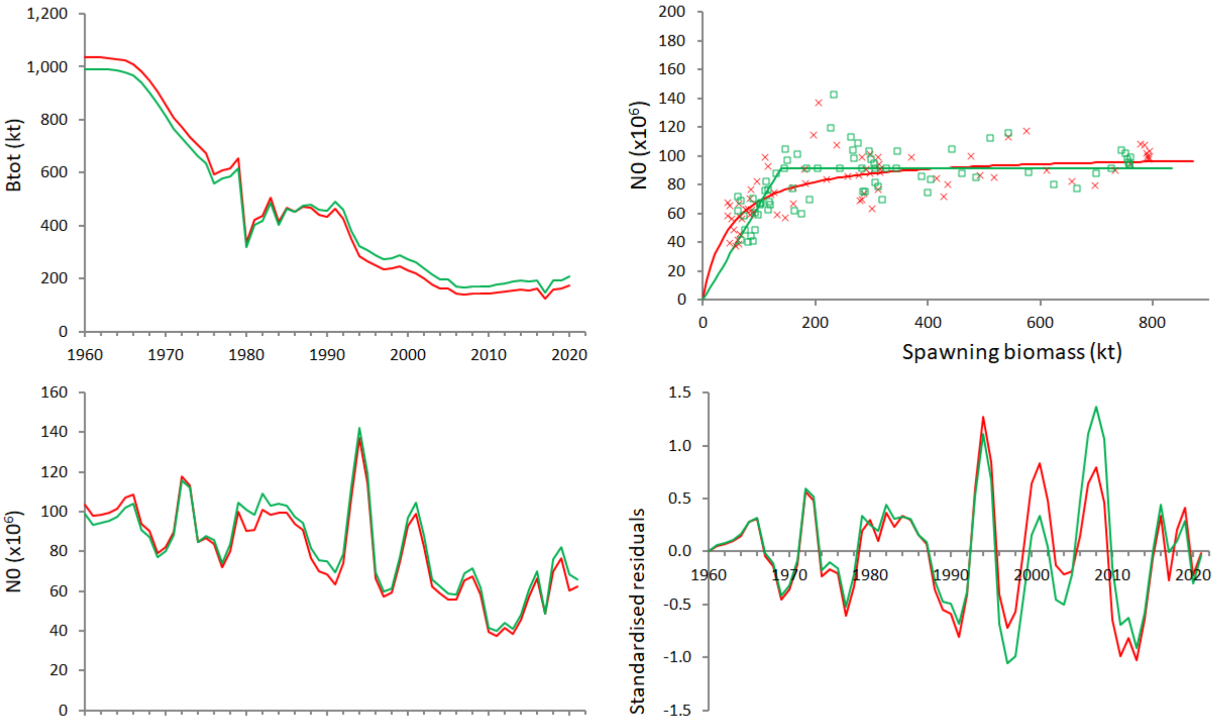

Figure C1. Results for Base Case (OM1, in red) and OM2 (hockey-stick) (in green). The stock-recruitment plot shows the Beverton-Holt and hockey-stick curves estimated.