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Results for Initial Candidate Management Procedure Testing for Greenland Halibut

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Summary

A number of target-based Candidate Management Procedures (CMPs) are applied to the full set of SCAA-based Operating Models (OMs) and robustness tests for Greenland halibut. These target-based rules are shown to outperform similar slope-based rules, especially in terms of lower inter-annual TAC changes, in achieving the same target of a resource at its MSY level in terms of median exploitable biomass in 20 years (2037). Four CMPs seem to reasonably capture the range from which a final MP might be selected. These have 2018 starting TACs of 15 000 or 20 000t, and are tuned to achieve the target exploitable biomass in 2037 at its MSY level for the baseline OM (OM0) or for Rob15 which assumes future under-reporting of catches at a level similar to the recent past. All four meet the agreed primary depletion probability criterion related to falling below $0.3B_{MSY}$. The higher initial TAC choice results in a smaller increase in spawning biomass. Performance is generally robust for the tuning based on the baseline OM0, except for greater depletion under Rob15. If this level of under-reporting is considered a reasonable possibility, a more conservative tuning level (i.e. a higher value of the tuning parameter α) than that for OM0 should be considered when choosing the final MP.

Introduction

The Statistical Catch-at-Age (SCAA) methodology for the assessment of Greenland halibut was set out in Rademeyer and Butterworth (2017a). Following discussion at the April Scientific Council (SC) meeting held in Vigo (NAFO 2017a), certain changes were agreed for a baseline assessment which provides the baseline Operating Model (OM) – OM0 - for Candidate Management Procedure (CMP) testing. This methodology is set out in Appendix A.

Rademeyer and Butterworth (2017b) set out the suggested specifications for future projections for the halibut resource, together with procedures for generating future data, for use in testing CMPs. Again certain changes were agreed at the Vigo SC meeting (NAFO 2017a), and the final specifications are set out in Appendix B, together with a list of the variants of the baseline OM0 for CMP testing which were agreed in Vigo.

This paper reports the results of these tests for a number of CMPs, as set out below.

Methods

<u>The SCAA Reference Set</u>

To reduce the number of OMs for which full results needed to be reported, initial tests were run of the previous "central CMP" (Rademeyer and Butterworth, 2017c) for all the OMs. The following OMs were then selected for inclusion in a restricted Reference Set of OMs, based upon their showing performances which were distinctly different from that for OM0:

1) OM0: The baseline
2) OM2b: Alternative steepness parameter (baseline: *h*=0.8): *h*=0.9
3) OM5a: Alternative CAA -lnL weighting (baseline: Wcaa=0.2): Wcaa=0.1
4) OM6a: Alternative σ_R value (baseline: σ_R =0.4): σ_R =0.6
5) Rob10a: Current (2016) numbers: 1.2 baseline estimates
6) OM12b: EU survey selectivity shape: Force less doming
7) Rob13: Poor future recruitment (5 years of half the recruitment predicted under the stock-recruit curve, starting from 2018), projecting from OM0
8) Rob14: Commercial selectivity for projections which differs most from that for the most recent block, projecting from OM0.
9) Rob15: Future catches 30% greater than TAC, projecting from OM0
10) Rob16: Process error in future dynamics (random error on $M_{y,a}$ with variance as indicated by the SAM-style model), projecting from OM0
11) Rob17: Zero selectivity on 10+ in the future (so that forecast yield does not rely on the plus group biomass), projecting from OM0.

<u>The CMPs</u>

The primary CMPs considered here are target based:

$$TAC_{y+1} = TAC_y \left(1 + \gamma_{up/down}(J_y - 1)\right) \qquad (1)$$

where

TAC_y is the TAC recommended for year *y*,

γ_{up} and γ_{down} are "response strength" tuning parameters (γ_{down} if $J_y < 1$ and γ_{up} if $J_y \geq 1$)

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 three series have been used, with *i* = 1, 2 and 3 corresponding respectively to Canada Fall 2J3K, EU 3M 0-1400m and Canada Spring 3LNO:

$$J_y = \sum_{i=1}^{3} \frac{1}{(\sigma^i)^2} \frac{J_{curr}^i}{J_{target}^i} \Big/ \sum_{i=1}^{3} \frac{1}{(\sigma^i)^2} \tag{2}$$

with

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

$$J_{curr}^i = \frac{1}{q} \sum_{y'=y-q}^{y-1} I_{y'}^i \tag{3}$$

$$J_{target}^i = \alpha \frac{1}{5} \sum_{y'=2011}^{2015} I_{y'}^i \qquad \text{(where } \alpha \text{ is a control/tuning parameter on the CMP)}^{[1]} \tag{4}$$

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.

Constraints on the maximum allowable annual change in TAC can be applied, viz.:

$$\text{if } TAC_{y+1} > TAC_y(1 + \Delta_{up}) \text{ then } TAC_{y+1} = TAC_y(1 + \Delta_{up}) \tag{5}$$

and

$$\text{if } TAC_{y+1} < TAC_y(1 - \Delta_{down}) \text{ then } TAC_{y+1} = TAC_y(1 - \Delta_{down}) \tag{6}$$

An initial selection for a series of tuning parameters has been made by the authors following investigations of their effect. This is used for all four CMPs presented in this main text (see Appendix C for results for some variations of these choices):

a. Interannual constraints on TAC: $\Delta_{up} = \Delta_{up} = 0.1$ i.e. 10%;
b. Number of years over which to average the survey indices: q=3; and
c. The response strength tuning parameters: $\gamma_{up/down} = 0.05$.

The four CMPs presented here are:

1. CMP1: Tuned (by selecting an appropriate ⍰ value – see equation (4)) so that the median $B_{2037}^{5-9}/B_{MSY}^{5-9} = 1$ for the baseline OM0; the initial (2018) TAC is fixed at 15 000t;
2. CMP1ic20: As CMP1 above, but with the TAC in 2018 fixed at 20 000t;
3. CMP2: Tuned so that the median $B_{2037}^{5-9}/B_{MSY}^{5-9} = 1$ for Rob15, one of the more pessimistic robustness tests, and with the initial TAC set as in 1; the TAC in 2018 is fixed at 15 000t;
4. CMP2ic20: As CMP2 above, but with the TAC in 2018 fixed at 20 000t.

[1] If an index value is not available for one of these years, it is omitted from the average.

Results[2]

Medians and lower 5%iles for projected catch, spawning and exploitable biomass are compared for each OM in the Reference Set under each of the four CMPs in Figure 1. The corresponding performance measures, as agreed at the April RBMS meeting in Falmouth (NAFO 2017b), are given in Table 1, with some of the performance measures compared graphically in Figure 2. Note in Table 1 that sometimes when the median $B^{5-9}_{2037}/B^{5-9}_{MSY}$ has been tuned to 1, the corresponding proportion less than 0.5 is not exactly equal to 0.50 – this simply reflects rounding errors in the tuning for which α was evaluated correct to the nearest 0.01. Table 2 compares the negative log likelihood values for the fits of the various OMs considered (as an aid to later contrast their relative plausibilities).

Appendix C considers the combination of CMP1 applied the baseline OM (OM0) and shows results for varying the values of the control parameters and the form of this CMP.

Appendix D provides a listing of the full set of OMs/robustness tests, and gives results for their performances under CMP1.

Appendix E shows the primary trajectories (catch, biomass and F) resulting from the application of CMP1 to OM0 in the form of worm plots (10 trajectories and shaded 90% probability envelopes are plotted).

Appendix F contrasts results for two forms of variants of CMP1 applied to the baseline OM0:

i) changing the starting TAC in 2018 (and including results for C=0 – a fishery closure – simply to indicate a bound on the range of possibilities); and

ii) changing the tuning parameter α to cover two further cases than CMP1 and CMP2: first to a value intermediate between that for these two CMPs (CMP1.5), and then to a value which achieves one of the criteria suggested by the Falmouth meeting (NAFO 2017b) that the probability that $B^{5-9}_{2022} < B^{5-9}_{2018}$ is equal 0.25.

Tuning parameter values for each of the CMPs presented in this paper are given in Appendix G.

Discussion

This section first summarises changes made to the OMs and projections in the light of discussions at the April meeting of the SC in Vigo (NAFO 2017a), and incorporated in Appendices A and B.

[2] Subsequent to the meeting at which this document was presented, a glitch was found in the projection code used to provide the results. Appendix H compares some results in the main text following with those with this glitch corrected. These changes are generally in the direction to be expected (given that the glitch involved larger starting numbers-at-age values for the projections than appropriate) and are not great, the largest relating to a smaller lowest exploitable biomass, a greater recovery of spawning biomass in the longer term, lower average annual catches in the longer term, and less average inter-annual TAC variability. These changes would not be of particular consequence to the differences in results presented for different OMs or CMPs and the associated inferences.

It then proceeds to highlight key results amongst those reported, and their implications. In most instances the clearest indications of these features of the results are provided by the graphical comparisons of distributions of key performance statistics in the form used for Figure 2. Results in Appendices C to G are discussed first, and then those in the main text.

Appendix A

The SCAA methodology is described in Appendix A. The changes made to the baseline "StartA" in Rademeyer and Butterworth (2017a) to provide the baseline OM (OM0) used here are:

- h=0.8;
- [illegible]$_R$=0.4;
- [illegible]
- Start in 1960 with specifications for the initial numbers-at-age vector;
- The "sqrt(p)" approach for the commercial and survey catch-at-age negative log-likelihood;
- Maximum data plus group of 10+ (model plus group remains 14+);
- Weight-at-age for 10+ applies to all older fish;
- Survey timing T^i modified;
- Flat selectivity for the plus group for the EU surveys;
- W_{CAA}=0.2;
- Commercial selectivity periods: 1960-1989, 1990-1995, 1996-2003 and 2004+

Appendix B

Appendix B gives the projection specifications. The main changes from Rademeyer and Butterworth (2017b) are:

- Error in the 2016 numbers-at-age is generated from the estimated variance-covariance matrix;
- Addition of autocorrelation in the recruitment residuals.

Appendix C

Five forms of changes to the control parameters and form of CMP1 results in the following changes to performance:

i) If the surveys are not inverse variance weighted in constructing the composite abundance index, there is a marginal increase in the range of average annual catches to be anticipated.

ii) Changing from a target- to a slope-based harvest control rule restricts flexibility, as changing tuning parameters cannot realise a full range of possible final (2037) median exploitable biomass levels. The average annual TAC variability (AAV) increases considerably, and the range of average annual catches to be expected also increases.

iii) Modifying the maximum extent to which the TAC can change each year to values that are higher than 10% has little impact, especially because given the value chosen for the control parameter γ (0.05), TAC changes are very seldom that large anyway. Reducing this limit to 5% does not compromise performance for OM0, and leads to a smaller range of the average annual catch to be anticipated, and reduces the upper end of the range of F values expected.

iv) Increasing the value of γ from 0.05 to 0.10 admits lower 5%ile values for both exploitable and spawning biomasses, and increases AAV. In contrast reducing the value to 0.03 has little impact beyond a slight reduction in the range of the annual average catch to be expected.

v) Increasing the number of years over which survey averages are taken above 3 has a marginal impact only: AAV increases and the range of the annual average catch decreases slightly.

In summary, perhaps the clearest outcome from these comparisons is the very obvious improvement in performance of the target-based compared to the slope-based control rules. There seems little case to change the other control parameter values selected, except perhaps to consider reducing the maximum inter-annual TAC change allowed to below 10%.

Appendix D

Results for the Reference Set of OMs are discussed below, so comments here are confined to the other OMs not included in that set. A general impression is that CMP1 performance is hardly changed from that for OM0 for these other OMs. The one exception is Rob10b, for which all the numbers-at-age in the population vector used to start the projections are reduced by 20%. Not surprisingly future annual average catches are less, as is AAV.

Appendix E

The worm plots shown for the application of CMP1 to OM0 serve to show that plots of median and 90% probability envelope “trajectories” can give a misguided impression of the true extent of trajectory variability. In particular both biomass and F trajectories can vary quite markedly towards the end of the 20-year projection period, but catch trends are steadier.

Appendix F

Increasing the starting (2018) TAC has little impact on the exploitable biomass, but the average annual catch also increases with a concomitant decrease in the extent of growth in the spawning biomass. The upper bound on F also drops.

As the tuning parameter α is increased, there is the expected trade-off between greater biomass increase and less catch. If α is increased sufficiently to meet the suggested criterion that the probability that $B_{2022}^{5-9} < B_{2018}^{5-9}$ is equal 0.25 (CMP3), F is greatly reduced, but the average annual catch is reduced by some 8 600t compared to what would be anticipated under CMP1, Given this considerable cost to catch performance, the need for this low a probability for a five-year reduction in exploitable biomass would seem to merit re-consideration.

Appendix G

The values of the tuning parameter α for most of the CMPs listed are close to 1, i.e. a target for the composite biomass index which is close to its 2011-2015 average. However α (and hence this target) is appreciably larger if the starting TAC in 2018 is 25 000t or if CMP3 is applied.

General

A notable feature of Table 1 of the main text is that the criterion of a probability that $B^{5-9}_{2022} < B^{5-9}_{2018}$ is less than 0.25 is not satisfied for any of the four CMPs considered in that Table for any of the Reference Set OMs. The discussion above indicates the cost in reduced catch that achieving this objective would entail. In contrast the key criterion that the probability that $B^{5-9} < 0.3\, B^{5-9}_{MSY}$ is less than 0.1 is met in every case except for OM6a for the OM0-based tuning, and the failure there is only marginal (a 0.12 probability) – furthermore reasons given below suggest that greater biomass variability for this greater-recruitment-variability OM should not be of too great a concern.

Figure 2 shows that there are six instances where conservation performance (in terms of the risk of reducing biomass to a low level) is notably worse than for the baseline OM0:

1) OM2b: Alternative steepness parameter (baseline: *h*=0.8): *h*=0.9
2) OM6a: Alternative σ_R value (baseline: σ_R =0.4): σ_R =0.6
3) Rob10a: Current (2016) numbers: 1.2 baseline estimates
4) OM12b: EU survey selectivity shape: Force less doming
5) Rob13: Poor future recruitment (5 years of half the recruitment predicted under the stock-recruit curve, starting from 2018), projecting from OM0
6) Rob15: Future catches 30% greater than TAC, projecting from OM0

The acceptability or otherwise of, for example, CMP1 as the MP to be adopted hinges on how these OMs/robustness tests are to be considered, especially by way of their plausibility compared to the baseline OM0. Two seem of less pertinence in this context:

2) OM6a: Alternative σ_R value (baseline: σ_R =0.4): σ_R =0.6 – if there is greater recruitment variability, one expects greater variation in biomass and also a greater resilience of the resource to the biomass decreasing to low levels.

5) Rob13: Poor future recruitment (5 years of half the recruitment predicted under the stock-recruit curve, starting from 2018), projecting from OM0 – a lower final biomass is not unexpected in these circumstances, but what is important is that the CMPs secure biomass recovery after the downturn caused by these poor recruitments.

For the other four:

1) OM2b: Alternative steepness parameter (baseline: *h*=0.8): *h*=0.9 – a steepness of 0.9 is very high, so that this scenario would seem to be of less plausibility.

3) Rob10a: Current (2016) numbers: 1.2 baseline estimates – this test is overly pessimistic, as it does not adjust for the fact that higher starting numbers-at-age imply higher recent recruitment and hence higher predicted recruitments in the future from the stock-recruitment curve; however, this has not been taken into account in the computations.

4) OM12b: EU survey selectivity shape: Force less doming – Table 2 reports a considerably worse negative log likelihood for this variant, suggesting it to be of less plausibility.

6) Rob15: Future catches 30% greater than the TAC, projecting from OM0 – while TAC overruns of this magnitude have occurred in the past, the question does arise of how plausible it is that they might re-occur to this extent in the future.

Ideally the selection amongst the CMPs should be based on some average over the OMs where there is down-weighting in some sense if certain OMs are too "similar" or if they are less plausible. Performance of the OMs not included in the Reference Set (RS) is sufficiently similar to that under OM0 that any plausibility they might be assigned is not going to impact averaged performance. Of the four included in the RS that are listed above, three would not seem to rate that highly in terms of plausibility relative to the baseline OM0. The possible "exception" is Rob15 which addresses TAC overruns.

Conclusions

The four CMPs for which results are reported in the main text all meet the primary deletion probability criterion related to $0.3B_{MSY}$ that was agreed in Falmouth (NAFO 2017b), and would seem to reasonably capture the range from which a final MP might be selected. These are four target-based CMPs which have 2018 starting TACs of 15 000 or 20 000t, and are tuned to result in an exploitable biomass equal in median terms in 2037 to its MSY level for the baseline OM (OM0) or for Rob15 which assumes future under-reporting of catches.

The tuning level aside, these CMPs produce reasonably robust performance across the alternative OMs/robustness tests considered, and show little sensitivity to other variations of the control parameters of the harvest control rule of equation (1) (except that this target-based rule clearly outperforms a comparable slope-based rule). The only major difference arising from starting with a 20 000t TAC from 2018 rather than one of 15 000t is a lesser increase in spawning biomass even though the exploitable biomass reaches its MSY level for both cases. There might be concerns about some instances of highish F values towards the end of the 20-year projection period, but any MP adopted at this time would certainly be reviewed and modified before the end of such a longish period.

The key choice remaining would then seem to be the tuning level, or rather which OM (or combination of OMs) should be used to tuned to provide the target median exploitable biomass at the MSY level after 20 years (i.e. in 2037). In most respects, robustness of results to OM variation, or the relatively lower plausibility of alternative OMs, suggest that basing tuning on OM0 would be a reasonable choice. The exception is Rob15, which assumes a level of TAC under-reporting in the future comparable to that estimated for the recent past. If this is considered a reasonable possibility, a more conservative tuning level (i.e. ahigher α value) than that for OM0 should be considered when choosing the final MP.

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Table 1: Performance measures for the four CMPs for each OM in the Reference Set; the pink highlights show instances where desired performance criterion specified by the Falmouth RBMS meeting (NAFO 2017a) has not been met. Values shown in **bold** indicate that the tuning parameter α was adjusted to achieve that result for that OM/CMP.

	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	$B^{5\text{-}9}_{2037}/B^{5\text{-}9}_{msy}$	$B^{5\text{-}9}_{2037}<B^{5\text{-}9}_{msy}$	$B^{5\text{-}9}_{2037}<0.8B^{5\text{-}9}_{msy}$	$B^{5\text{-}9}_{lowest}/B^{5\text{-}9}_{msy}$	$B^{5\text{-}9}_{2022}<B^{5\text{-}9}_{2018}$		$(F_{2018\text{-}2037}>F_{msy})>0.3$	$B^{sp}_{2037}/B^{sp}_{2018}$	$B^{5\text{-}9}_{2037}/B^{5\text{-}9}_{2018}$	$(B^{5\text{-}9}_{2018\text{-}2037}<0.3B^{5\text{-}9}_{msy})>0.1$	$B^{5\text{-}9}_{lowest}/B^{5\text{-}9}_{msy}<0.3$	avC: 2018-2020	avC: 2018-2037	$B^{5\text{-}9}_{2037}<0.75B^{5\text{-}9}_{2018}$		AAV: 2018-2037
		median (90%PI)	Proportion	Proportion	median (90%PI)	Proportion		Count	median (90%PI)	median (90%PI)	Count	Proportion	median (90%PI)	median (90%PI)	Proportion		median (90%PI)
	Criteria		<=0.5	<=0.25		<Ω	Ω					<=0.1			<β	β	
CMP1	OM0	**1.00** (0.45; 1.83)	0.49	0.22	0.81 (0.42; 1.07)	0.31	0.25	5	1.35 (0.56; 2.53)	0.89 (0.35; 1.59)	0	0.00	15.39 (15.10; 15.81)	21.85 (17.36; 29.02)	0.02	0.25	3.64 (1.38; 6.50)
	OM2b	0.87 (0.29; 1.60)	0.65	0.41	0.75 (0.28; 1.09)	0.27	0.25	7	1.24 (0.38; 3.18)	0.74 (0.22; 1.62)	0	0.06	15.50 (15.14; 16.07)	24.71 (19.05; 32.10)	0.01	0.25	4.73 (2.18; 10.41)
	OM5a	1.15 (0.63; 2.04)	0.29	0.11	0.93 (0.56; 1.32)	0.33	0.25	0	1.03 (0.43; 1.97)	0.82 (0.36; 1.58)	0	0.00	15.44 (15.09; 15.96)	21.33 (16.71; 29.23)	0.02	0.25	3.17 (1.16; 6.25)
	OM6a	0.87 (0.31; 2.19)	0.59	0.41	0.61 (0.21; 0.91)	0.30	0.25	8	1.46 (0.61; 3.55)	0.93 (0.26; 2.15)	0	0.08	15.38 (15.11; 15.80)	22.72 (17.17; 31.49)	0.04	0.23	4.07 (1.30; 8.49)
	Rob10a	0.75 (0.21; 1.57)	0.71	0.56	0.66 (0.21; 1.13)	0.37	0.25	10	0.82 (0.42; 1.65)	0.43 (0.12; 1.05)	1	0.12	15.84 (15.42; 16.38)	30.13 (22.46; 38.32)	0.02	0.25	5.65 (3.19; 8.05)
	OM12b	0.66 (0.28; 1.30)	0.82	0.64	0.56 (0.24; 0.77)	0.31	0.25	10	1.31 (0.56; 3.03)	0.82 (0.32; 1.76)	0	0.10	15.44 (15.14; 15.87)	25.54 (19.47; 32.17)	0.01	0.17	5.71 (2.49; 10.56)
	Rob13	1.04 (0.52; 1.86)	0.43	0.14	0.52 (0.29; 0.89)	0.42	0.25	6	1.11 (0.41; 2.29)	0.93 (0.40; 1.61)	0	0.05	15.39 (15.10; 15.81)	19.53 (16.07; 25.30)	0.03	0.25	2.45 (0.98; 4.92)
	Rob14	1.03 (0.54; 1.87)	0.42	0.15	0.83 (0.50; 1.07)	0.33	0.25	3	1.44 (0.64; 2.63)	0.91 (0.42; 1.61)	0	0.00	15.39 (15.10; 15.81)	22.24 (17.53; 29.48)	0.02	0.25	3.82 (1.48; 6.65)
	Rob15	0.82 (0.33; 1.63)	0.68	0.46	0.69 (0.26; 0.99)	0.33	0.25	11	0.97 (0.42; 2.05)	0.78 (0.26; 1.48)	0	0.06	15.37 (15.08; 15.78)	20.14 (16.32; 26.34)	0.02	0.25	2.81 (0.81; 6.36)
	Rob16	1.00 (0.47; 1.80)	0.50	0.25	0.80 (0.44; 1.07)	0.33	0.25	5	1.32 (0.56; 2.54)	0.88 (0.35; 1.60)	0	0.00	15.39 (15.10; 15.81)	21.70 (17.35; 28.45)	0.02	0.25	3.48 (1.31; 6.28)
	Rob17	0.99 (0.39; 1.81)	0.52	0.30	0.78 (0.35; 1.08)	0.32	0.25	7	1.23 (0.52; 2.40)	0.84 (0.28; 1.56)	0	0.02	15.39 (15.10; 15.80)	21.25 (17.00; 27.98)	0.02	0.25	3.27 (1.14; 6.19)
CMP1ic20	OM0	**1.00** (0.51; 1.88)	0.49	0.18	0.78 (0.43; 1.05)	0.39	0.25	7	1.19 (0.51; 2.43)	0.91 (0.35; 1.58)	0	0.01	20.20 (19.90; 20.63)	23.26 (19.72; 29.20)	0.05	0.25	3.29 (2.17; 5.54)
	OM2b	0.96 (0.36; 1.74)	0.59	0.35	0.74 (0.27; 1.08)	0.36	0.25	8	1.17 (0.37; 2.86)	0.78 (0.25; 1.49)	0	0.06	20.32 (19.94; 20.91)	25.51 (20.96; 32.19)	0.03	0.25	4.05 (2.32; 8.92)
	OM5a	1.15 (0.65; 2.09)	0.29	0.08	0.90 (0.57; 1.31)	0.39	0.25	0	0.97 (0.41; 1.83)	0.80 (0.35; 1.45)	0	0.01	20.25 (19.89; 20.79)	23.26 (19.46; 30.84)	0.04	0.25	3.19 (2.24; 5.49)
	OM6a	0.85 (0.33; 2.17)	0.60	0.44	0.60 (0.24; 0.90)	0.37	0.25	10	1.34 (0.57; 3.38)	0.93 (0.30; 2.15)	0	0.12	20.19 (19.91; 20.62)	23.95 (19.39; 33.02)	0.05	0.23	3.68 (2.31; 7.79)
	Rob10a	0.84 (0.23; 1.67)	0.66	0.48	0.69 (0.21; 1.20)	0.40	0.25	10	0.80 (0.36; 1.61)	0.48 (0.12; 1.00)	0	0.09	20.67 (20.23; 21.32)	30.25 (24.10; 39.79)	0.04	0.25	5.01 (3.24; 7.58)
	OM12b	0.69 (0.28; 1.35)	0.80	0.64	0.57 (0.24; 0.76)	0.40	0.25	13	1.21 (0.47; 2.78)	0.89 (0.32; 1.78)	0	0.11	20.25 (19.93; 20.70)	25.16 (20.56; 32.30)	0.05	0.17	4.19 (2.39; 8.77)
	Rob13	0.98 (0.48; 1.73)	0.51	0.18	0.47 (0.25; 0.86)	0.49	0.25	9	0.89 (0.37; 2.10)	0.89 (0.37; 1.55)	0	0.08	20.20 (19.90; 20.63)	21.45 (18.62; 26.45)	0.06	0.25	2.80 (2.26; 4.22)
	Rob14	1.03 (0.59; 1.89)	0.47	0.14	0.81 (0.51; 1.05)	0.40	0.25	3	1.29 (0.54; 2.52)	0.95 (0.45; 1.58)	0	0.01	20.20 (19.90; 20.64)	23.58 (19.89; 29.74)	0.05	0.25	3.45 (2.14; 5.72)
	Rob15	0.78 (0.28; 1.53)	0.75	0.55	0.65 (0.24; 0.96)	0.45	0.25	15	0.76 (0.30; 1.83)	0.71 (0.24; 1.46)	0	0.10	20.18 (19.87; 20.60)	21.60 (18.43; 26.64)	0.06	0.25	2.85 (2.12; 5.70)
	Rob16	0.98 (0.52; 1.88)	0.54	0.22	0.79 (0.43; 1.04)	0.41	0.25	8	1.17 (0.51; 2.33)	0.89 (0.36; 1.59)	0	0.01	20.20 (19.90; 20.64)	23.15 (19.70; 28.73)	0.05	0.25	3.21 (2.20; 5.32)
	Rob17	0.98 (0.43; 1.88)	0.55	0.28	0.75 (0.38; 1.05)	0.41	0.25	10	1.06 (0.48; 2.26)	0.85 (0.30; 1.55)	0	0.03	20.20 (19.89; 20.63)	22.68 (19.34; 28.10)	0.05	0.25	3.07 (2.14; 5.20)
CMP2	OM0	1.12 (0.67; 2.05)	0.31	0.09	0.86 (0.57; 1.10)	0.30	0.25	0	1.56 (0.70; 2.92)	1.02 (0.51; 1.76)	0	0.00	15.20 (14.96; 15.54)	18.95 (15.69; 24.04)	0.02	0.25	2.45 (0.66; 4.91)
	OM2b	1.06 (0.44; 1.87)	0.41	0.19	0.85 (0.39; 1.12)	0.26	0.25	3	1.61 (0.52; 3.71)	0.89 (0.31; 1.70)	0	0.02	15.29 (14.99; 15.75)	21.23 (16.97; 28.57)	0.01	0.25	3.43 (1.26; 6.93)
	OM5a	1.25 (0.77; 2.22)	0.16	0.06	0.97 (0.64; 1.32)	0.33	0.25	0	1.16 (0.50; 2.18)	0.88 (0.43; 1.66)	0	0.00	15.23 (14.95; 15.66)	18.51 (15.18; 24.74)	0.02	0.25	0.02 (0.01; 0.05)
	OM6a	0.97 (0.37; 2.38)	0.53	0.29	0.67 (0.33; 0.94)	0.29	0.25	4	1.75 (0.73; 4.02)	1.04 (0.34; 2.33)	0	0.04	15.19 (14.96; 15.53)	19.61 (15.57; 27.52)	0.04	0.23	0.03 (0.01; 0.06)
	Rob10a	1.01 (0.40; 1.84)	0.46	0.28	0.83 (0.37; 1.28)	0.37	0.25	7	1.07 (0.47; 2.02)	0.59 (0.19; 1.12)	0	0.02	15.56 (15.22; 16.08)	25.02 (19.46; 32.75)	0.02	0.25	0.04 (0.02; 0.07)
	OM12b	0.86 (0.39; 1.57)	0.64	0.39	0.64 (0.30; 0.81)	0.31	0.25	7	1.83 (0.76; 3.66)	1.12 (0.39; 2.01)	0	0.05	15.23 (14.98; 15.59)	22.17 (17.36; 28.58)	0.01	0.17	0.04 (0.02; 0.08)
	Rob13	1.15 (0.69; 1.93)	0.26	0.07	0.54 (0.30; 0.94)	0.40	0.25	3	1.32 (0.55; 2.57)	1.03 (0.58; 1.70)	0	0.04	15.20 (14.96; 15.54)	17.33 (14.75; 21.62)	0.03	0.25	0.02 (0.01; 0.04)
	Rob14	1.14 (0.70; 2.05)	0.25	0.06	0.87 (0.59; 1.10)	0.32	0.25	0	1.64 (0.77; 3.02)	1.05 (0.58; 1.78)	0	0.00	15.20 (14.96; 15.54)	19.17 (15.80; 24.38)	0.02	0.25	0.03 (0.01; 0.05)
	Rob15	**1.00** (0.49; 1.88)	0.52	0.20	0.78 (0.43; 1.02)	0.32	0.25	7	1.21 (0.51; 2.47)	0.94 (0.37; 1.65)	0	0.01	15.18 (14.94; 15.51)	17.80 (14.95; 22.53)	0.02	0.25	0.02 (0.01; 0.04)
	Rob16	1.10 (0.67; 2.01)	0.31	0.11	0.85 (0.56; 1.12)	0.32	0.25	0	1.55 (0.69; 2.89)	1.01 (0.51; 1.72)	0	0.00	15.19 (14.96; 15.54)	18.82 (15.70; 23.69)	0.02	0.25	0.02 (0.01; 0.05)
	Rob17	1.11 (0.59; 2.05)	0.34	0.10	0.84 (0.51; 1.10)	0.31	0.25	0	1.45 (0.63; 2.77)	0.98 (0.42; 1.70)	0	0.00	15.19 (14.95; 15.53)	18.51 (15.44; 23.43)	0.02	0.25	0.02 (0.01; 0.05)
CMP2ic20	OM0	1.15 (0.67; 1.99)	0.26	0.06	0.85 (0.51; 1.13)	0.39	0.25	0	1.45 (0.70; 2.80)	1.03 (0.59; 1.72)	0	0.01	19.91 (19.68; 20.24)	20.14 (17.79; 23.82)	0.04	0.25	0.02 (0.02; 0.04)
	OM2b	1.11 (0.59; 2.02)	0.34	0.10	0.85 (0.51; 1.11)	0.35	0.25	0	1.56 (0.53; 3.56)	0.96 (0.40; 1.63)	0	0.01	20.00 (19.71; 20.44)	21.64 (18.66; 26.99)	0.03	0.25	0.03 (0.02; 0.05)
	OM5a	1.27 (0.77; 2.16)	0.16	0.05	0.96 (0.62; 1.32)	0.38	0.25	0	1.10 (0.51; 2.06)	0.88 (0.49; 1.52)	0	0.01	19.95 (19.68; 20.36)	20.08 (17.58; 24.84)	0.04	0.25	0.03 (0.02; 0.04)
	OM6a	1.02 (0.43; 2.29)	0.49	0.23	0.65 (0.31; 0.96)	0.36	0.25	0	1.70 (0.70; 4.00)	1.05 (0.44; 2.31)	0	0.03	19.90 (19.69; 20.23)	20.62 (17.67; 26.57)	0.05	0.23	0.03 (0.02; 0.05)
	Rob10a	1.08 (0.52; 2.02)	0.37	0.13	0.88 (0.47; 1.31)	0.39	0.25	5	1.08 (0.49; 2.09)	0.65 (0.26; 1.17)	0	0.00	20.26 (19.94; 20.75)	24.64 (20.76; 30.76)	0.03	0.25	0.04 (0.02; 0.05)
	OM12b	0.91 (0.47; 1.57)	0.61	0.32	0.65 (0.39; 0.83)	0.39	0.25	9	1.77 (0.87; 3.50)	1.14 (0.52; 2.02)	0	0.01	19.95 (19.71; 20.29)	21.71 (18.48; 27.02)	0.05	0.17	0.03 (0.02; 0.06)
	Rob13	1.13 (0.65; 1.99)	0.32	0.09	0.52 (0.27; 0.91)	0.48	0.25	5	1.17 (0.55; 2.42)	0.98 (0.57; 1.65)	0	0.06	19.91 (19.68; 20.24)	19.02 (17.06; 22.39)	0.05	0.25	0.03 (0.02; 0.04)
	Rob14	1.16 (0.73; 1.99)	0.23	0.06	0.85 (0.54; 1.13)	0.39	0.25	0	1.53 (0.77; 2.89)	1.05 (0.61; 1.72)	0	0.01	19.92 (19.69; 20.24)	20.37 (17.90; 24.12)	0.04	0.25	0.03 (0.02; 0.04)
	Rob15	**1.00** (0.50; 1.77)	0.51	0.24	0.74 (0.39; 1.02)	0.42	0.25	11	1.03 (0.48; 2.17)	0.90 (0.40; 1.62)	0	0.02	19.90 (19.67; 20.21)	19.16 (17.10; 22.51)	0.06	0.25	0.03 (0.02; 0.04)
	Rob16	1.13 (0.70; 1.99)	0.28	0.08	0.85 (0.50; 1.09)	0.41	0.25	0	1.43 (0.66; 2.66)	1.02 (0.58; 1.71)	0	0.01	19.91 (19.68; 20.24)	20.06 (17.80; 23.55)	0.05	0.25	0.02 (0.02; 0.04)
	Rob17	1.14 (0.61; 2.00)	0.31	0.09	0.83 (0.47; 1.11)	0.41	0.25	0	1.33 (0.62; 2.66)	0.97 (0.53; 1.70)	0	0.01	19.91 (19.68; 20.23)	19.77 (17.55; 23.24)	0.05	0.25	0.02 (0.02; 0.04)

Table 2: Total negative log-likelihood for the fits of each of the Operating Models to the data. For the OMs for which the -lnL is not directly comparable to that of the baseline OM (OM0) because of fitting to different data or different assumptions made, the value is shown in grey. The difference in -lnL compared to OM0 value is shown where there is comparability.

	-lnL	Δ-lnL
OM0	-342.2	
OM1a	*-475.9*	
OM2a	-341.3	0.9
OM2b	-342.7	-0.5
OM3a	-341.7	0.5
OM3b	-340.1	2.1
OM4a	-342.6	-0.4
OM5a	*-205.8*	
OM5b	*-767.1*	
OM6a	*-318.5*	
OM7a	*-306.5*	
OM8a	-330.3	11.8
OM11a	*-345.1*	
OM11b	-341.9	0.3
OM11c	-330.0	12.2
OM12a	-341.7	0.5
OM12b	-329.2	13.0

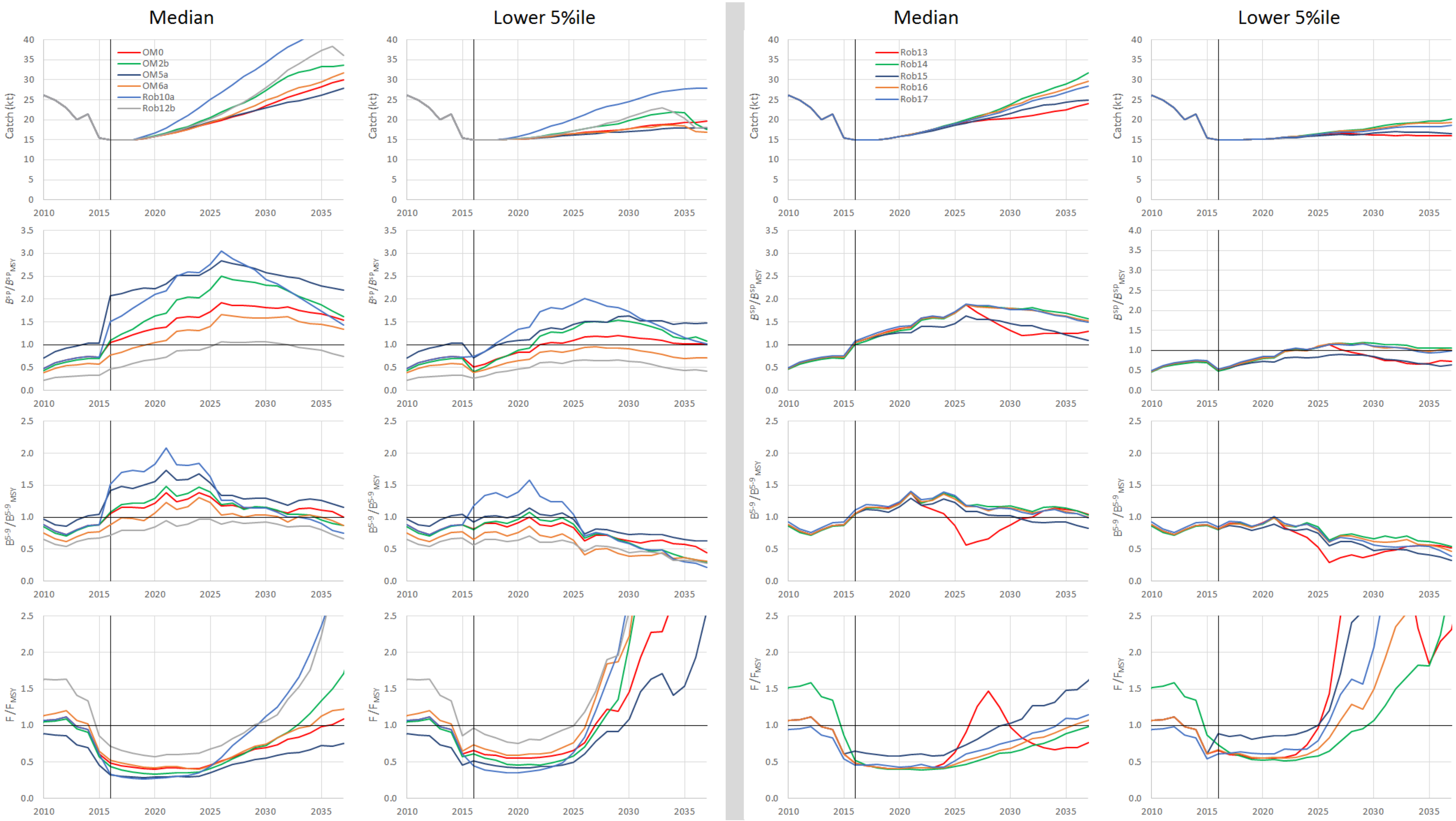

Fig. 1a. Projected median and lower 5%iles for catch, spawning and exploitable biomass (both relative to B_{MSY}) and F/F_{MSY} (the upper 5%iles are plotted instead of lower 5%iles) for each OM in the Reference Set under **CMP1**.

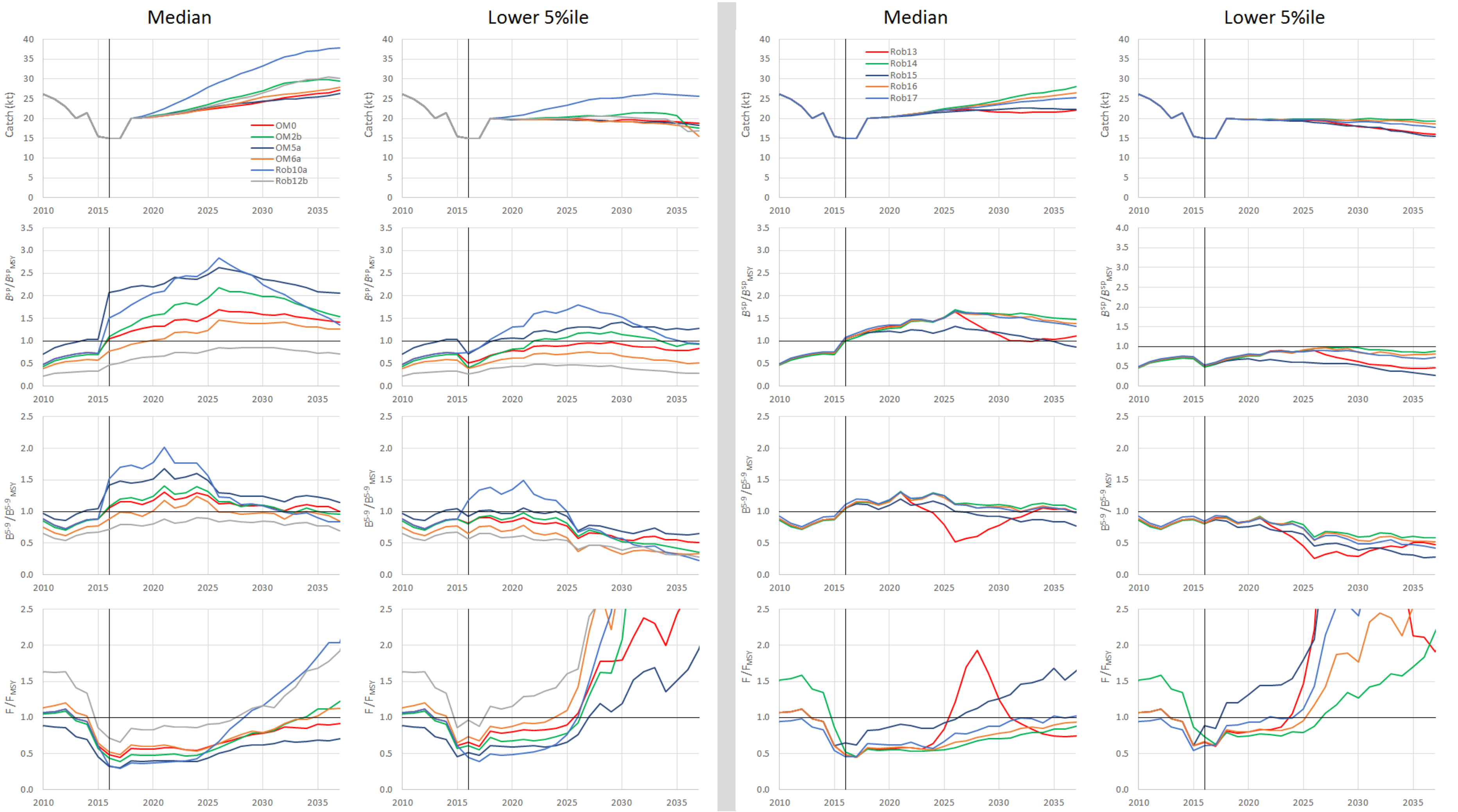

Fig. 1b. Projected median and lower 5%iles for catch, spawning and exploitable biomass (both relative to B_{MSY}) and F/F_{MSY} (the upper 5%iles are plotted instead of lower 5%iles) for each OM in the Reference Set under **CMP1ic20.**

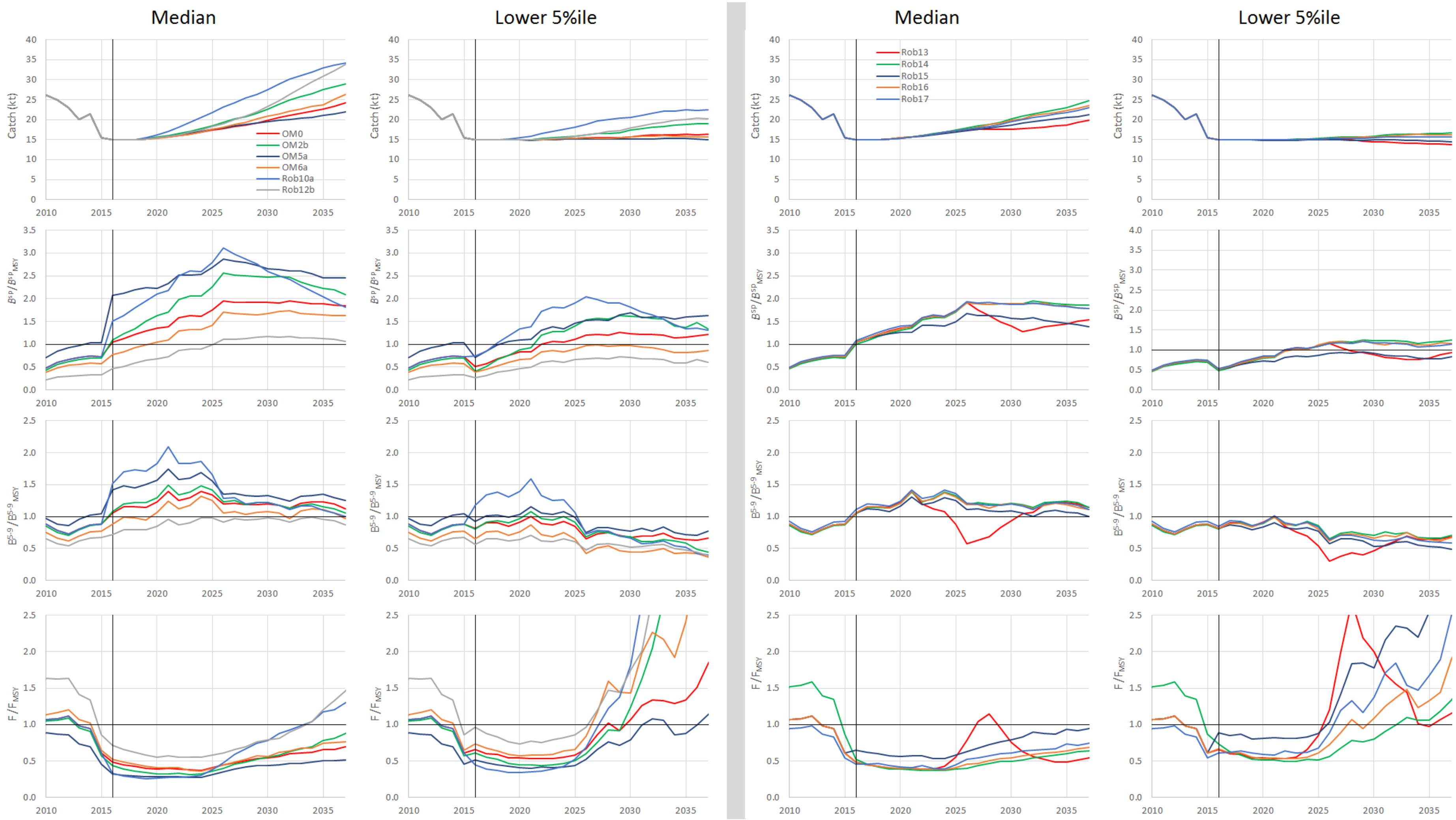

Fig. 1c. Projected median and lower 5%iles for catch, spawning and exploitable biomass (both relative to B_{MSY}) and F/F_{MSY} (the upper 5%iles are plotted instead of lower 5%iles) for each OM in the Reference Set under **CMP2.**

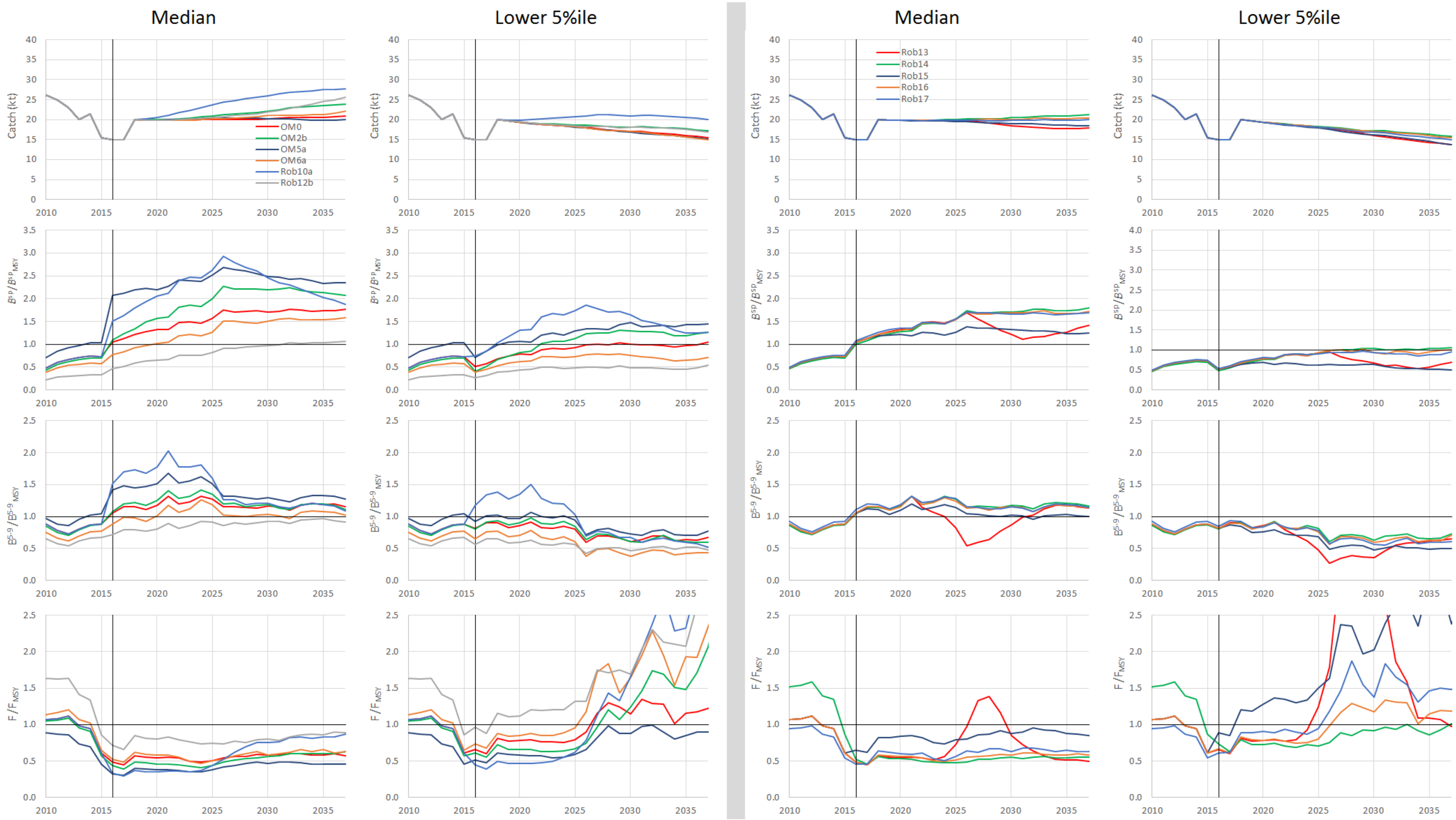

Fig.1d. Projected median and lower 5%iles for catch, spawning and exploitable biomass (both relative to B_{MSY}) and F/F_{MSY} (the upper 5%iles are plotted instead of lower 5%iles) for each OM in the Reference Set under **CMP2ic20.**

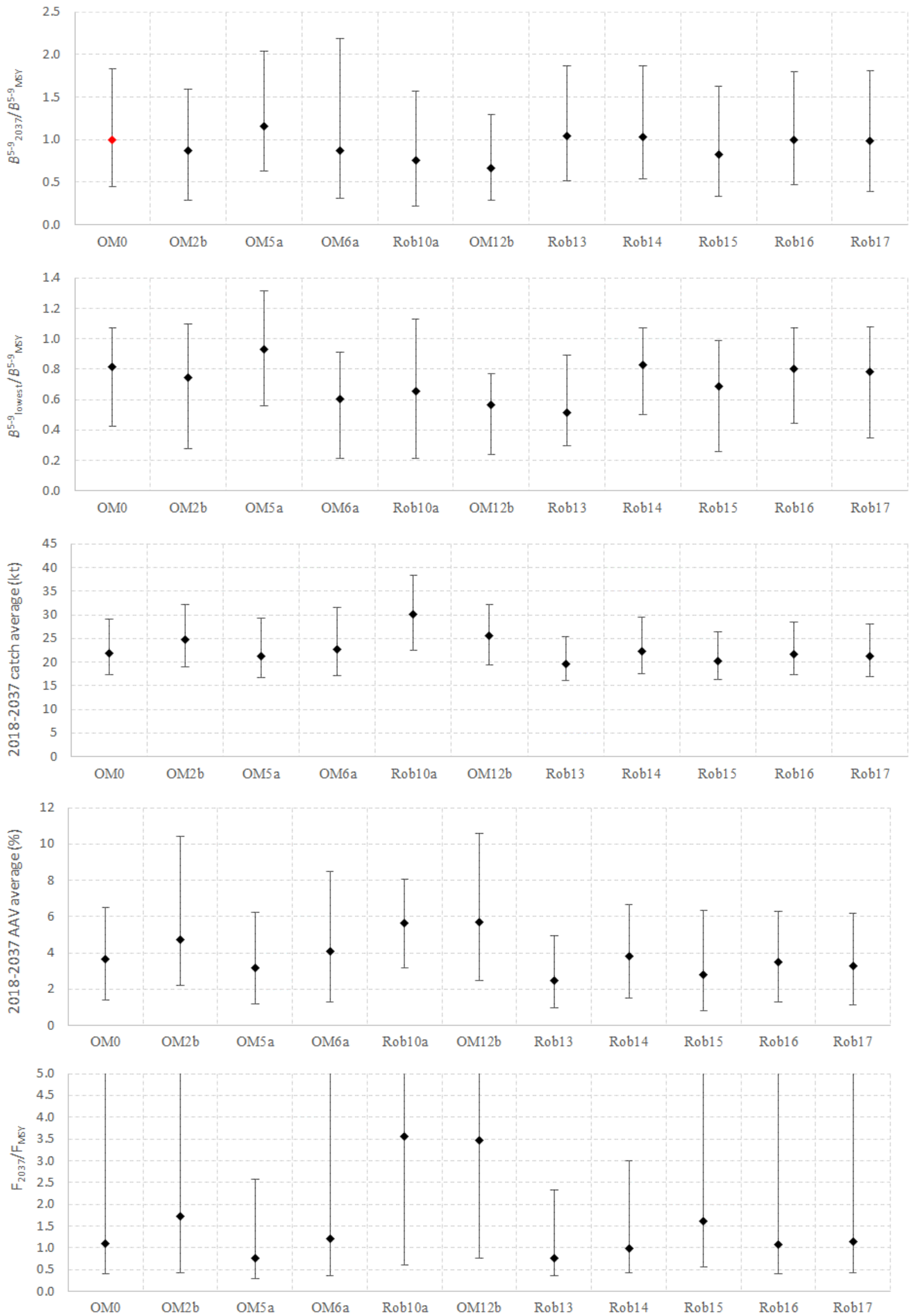

Fig. 2a. Projected median and 90% PIs for a series of performance statistics for each OM in the Reference Set under **CMP1** (tuned to median $B^{5\text{-}9}_{2037}/B_{MSY}=1$ for OM0, shown in red).

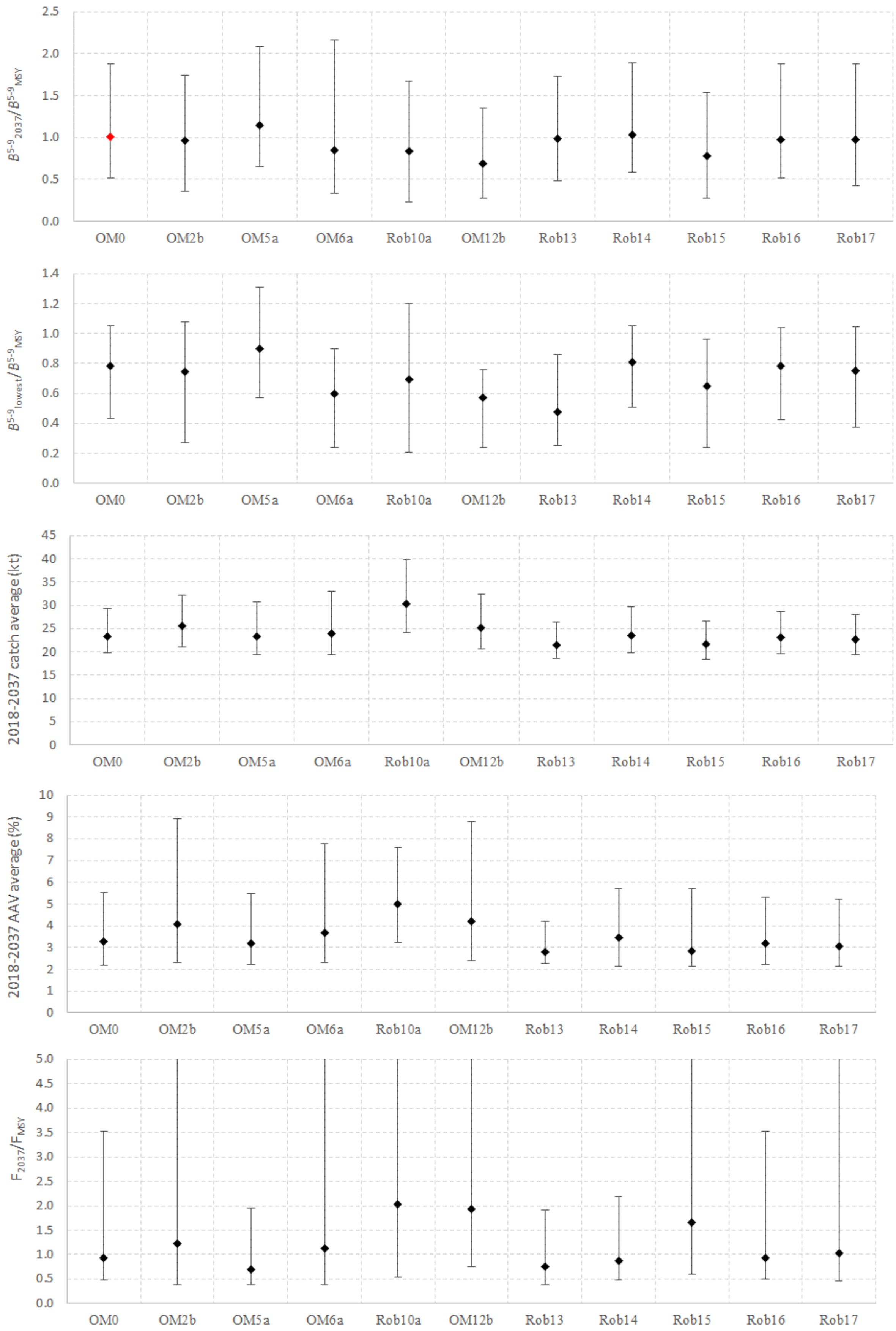

Fig. 2b. Projected median and 90% PIs for a series of performance statistics for each OM in the Reference Set under **CMP1ic20** (tuned to median $B^{5\text{-}9}{}_{2037}/B_{MSY}$=1 for OM0, shown in red).

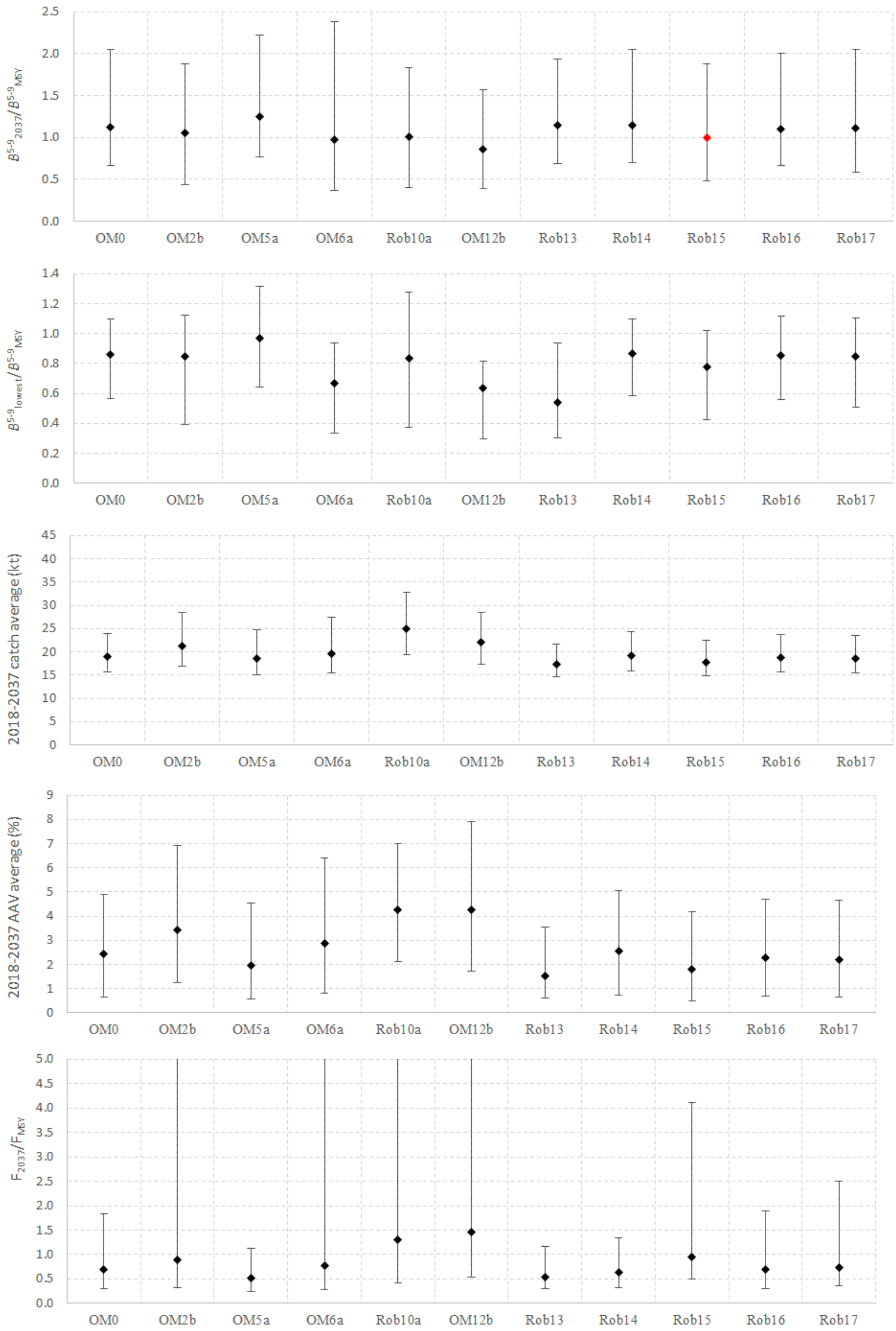

Fig. 2c. Projected median and 90% PIs for a series of performance statistics for each OM in the Reference Set under **CMP2** (tuned to median B^{5-9}_{2037}/B_{MSY}=1 for Rob15, shown in red).

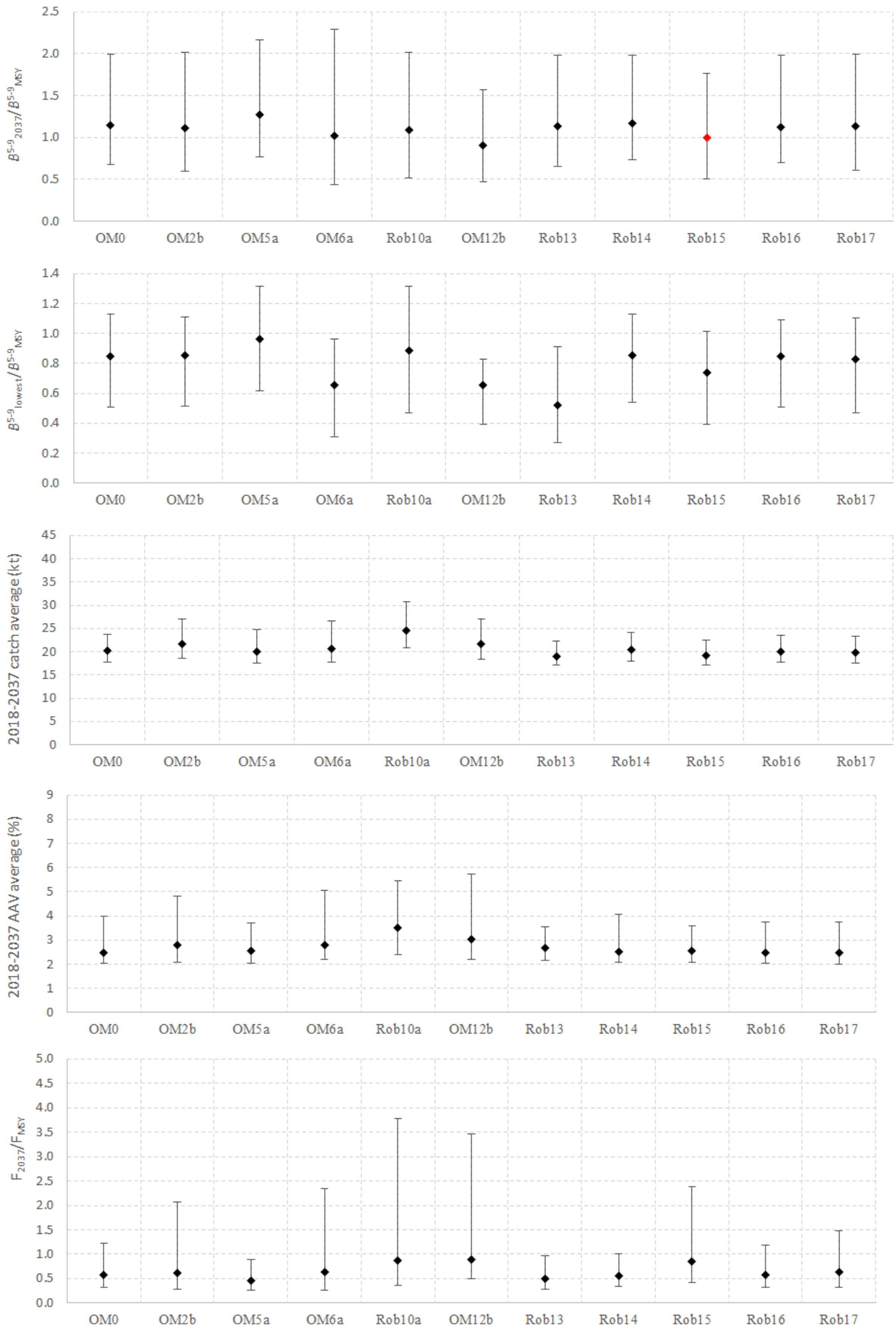

Fig. 2d. Projected median and 90% PIs for a series of performance statistics for each OM in the Reference Set under **CMP2ic20** (tuned to median $B^{5\text{-}9}_{2037}/B_{MSY}=1$ for Rob15, shown in red).

Appendix A

Algebraic details of the Statistical Catch-at-Age Model

The text following sets out the equations and other general specifications of the Statistical Catch-at-Age (SCAA) assessment model applied to Greenland halibut, followed by details of the contributions to the (penalised) log-likelihood function from the different sources of data available and assumptions concerning the stock-recruitment relationship. Quasi-Newton minimization is applied to minimize the total negative log-likelihood function to estimate parameter values (the package AD Model Builder™, Otter Research, Ltd is used for this purpose).

Where options are provided under a particular section, the section concludes with a statement in **bold** as to which option was selected for the baseline Operating Model (OM0) selected.

A.1. Population dynamics

A.1.1 Numbers-at-age

The resource dynamics are modelled by the following set of population dynamics equations:

$$N_{y+1,0} = R_{y+1} \quad \text{(A.1)}$$

$$N_{y+1,a+1} = N_{y,a}e^{-Z_{y,a}} \quad \text{for } 0 \le a \le m-2 \quad \text{(A.2)}$$

$$N_{y+1,m} = N_{y,m-1}e^{-Z_{y,m-1}} + N_{y,m}e^{-Z_{y,m}} \quad \text{(A.3)}$$

where

$N_{y,a}$ is the number of fish of age *a* at the start of year *y*,

R_y is the recruitment (number of 0-year-old fish) at the start of year *y*,

m is the maximum age considered (taken to be a plus-group).

$Z_{y,a} = F_yS_{y,a} + M_a$ is the total mortality in year *y* on fish of age *a*, where

M_a denotes the natural mortality rate for fish of age *a*,

F_y is the fishing mortality of a fully selected age class in year *y*, and

$S_{y,a}$ is the commercial selectivity at age *a* for year *y*.

A.1.2. Recruitment

The number of recruits (i.e. new 0-year olds) at the start of year *y* is assumed to be related to the spawning stock size (i.e. the biomass of mature fish) by Beverton-Holt stock-recruitment relationship, allowing for annual fluctuation about the deterministic relationship.

$$R_y = \frac{\alpha B_y^{sp}}{\beta + B_y^{sp}} e^{\left(\varphi_y - (\sigma_R)^2/2\right)} \quad \text{(A.4)}$$

where

α and β are spawning biomass-recruitment relationship parameters,

φ_y reflects fluctuation about the expected recruitment for year *y*, which is assumed to be normally distributed with standard deviation σ_R (which is input in the applications considered here); these residuals are treated as estimable parameters in the model fitting process.

B_y^{sp} is the spawning biomass at the start of year *y*, computed as:

$$B_y^{sp} = \sum_{a=1}^{m} f_a\, w_{y,a}^{strt} N_{y,a} \quad \text{(A.5)}$$

where

$w_{y,a}^{strt}$ is the mass of fish of age *a* during spawning, and

f_a is the proportion of fish of age *a* that are mature.

In order to work with estimable parameters that are more biologically meaningful, the stock-recruitment relationship is re-parameterised in terms of the pre-exploitation (virgin) equilibrium spawning biomass B_0 and the steepness, *h*, of the stock-recruitment relationship, which is the proportion of the virgin recruitment R_0 that is realised at a spawning biomass level of 20% of the virgin spawning biomass:

$$\alpha = \frac{4hR_0}{5h-1} \tag{A.6}$$

and

$$\beta = \frac{B_0(1-h)}{5h-1} \tag{A.7}$$

where

$$R_0 = B_0 \Big/ \left[\sum_{a=1}^{m-1} f_a w_{y_0,a}^{strt} exp\left(-\sum_{a'=0}^{a-1} M_{a'}\right) + f_m w_{y_0,m}^{strt} \frac{exp\left(-\sum_{a'=0}^{m-1} M_{a'}\right)}{1-exp(-M_m)}\right] \tag{A.8}$$

For baseline run, *h* is fixed to 0.8 and σ_R=0.4.

A.1.3. Total catch and catches-at-age

The total catch by mass in year *y* is given by:

$$C_y = \sum_{a=0}^{m} w_{y,a}^{mid} C_{y,a} = \sum_{a=0}^{m} w_{y,a}^{mid} N_{y,a} S_{y,a} F_y \left(1 - e^{-Z_{y,a}}\right) \big/ Z_{y,a} \tag{A.9}$$

where

$w_{y,a}^{mid}$ denotes the mass of fish of age *a* landed in year *y*,

$C_{y,a}$ is the catch-at-age, i.e. the number of fish of age *a*, caught in year *y*.

A.1.4. Initial conditions

As the first year for which catch data are available for the Greenland halibut stock considered does not correspond to the first year of (appreciable) exploitation, one cannot necessarily make the conventional assumption in the application of SCAA's that this initial year reflects a population (and its age-structure) at pre-exploitation equilibrium. For the first year (y_0=1960) considered in the model therefore, the starting numbers-at-age 0 are estimated directly and an average fishing mortality is applied for ages 1 to *m*:

$$N_{y_0,a} = \begin{cases} N_{y_0,0} & \text{for } a = 0 \\ N_{y_0,a-1} e^{-(M_{a-1}+\vartheta)} & \text{for } 1 < a < m \\ N_{y_0,m-1} e^{-(M_{m-1}+\vartheta)} \big/ \left(1 - e^{-(M_m+\vartheta)}\right) & \text{for } a = m \end{cases} \tag{A.10}$$

where ϑ characterises the average fishing proportion over the years immediately preceding y_0.

The following penalties are added to the total negative log-likelihood:

$$pen^{N_0} = \frac{\left(lnN_{y_0,0} - lnR_o\right)^2}{2\sigma_R^2} \tag{A.11}$$

where R_o is the recruitment expected at carrying capacity

and

$$pen^{\vartheta} = \frac{\vartheta^2}{2\sigma_\vartheta^2} \tag{A.12}$$

with $\sigma_\vartheta = 0.1$

A.2. The (penalised) likelihood function

The model can be fit to (a subset of) survey biomass indices, and commercial and survey catch-at-age and catch-at-age data to estimate model parameters (which may include residuals about the stock-recruitment function, facilitated through the incorporation of a penalty function described below). Contributions by each of these to the negative of the (penalised) log-likelihood (- λnL) are as follows.

A.2.1. Survey biomass data

The likelihood is calculated assuming that a survey biomass index is lognormally distributed about its expected value:

$$I_y^i = \hat{I}_y^i e^{\varepsilon_y^i} \quad \text{or} \quad \varepsilon_y^i = ln\left(I_y^i\right) - ln\left(\hat{I}_y^i\right) \tag{A.13}$$

where

I_y^i is the survey index for survey *i* in year *y*,

$\hat{I}_y^i = \hat{q}^i \hat{B}_y^i$ is the corresponding model estimate, where

$\hat{q}^i$ is the constant of proportionality (catchability) for the survey biomass series *i*, and

ε_y^i from $N\left(0, \left(\sigma_y^i\right)^2\right)$.

The model estimate of survey biomass index is computed as:

$$B_y^i = \sum_{a=0}^{m} w_{y,a}^i S_a^i N_{y,a} e^{-Z_{y,a} T^i/12} \tag{A.14}$$

where

S_a^i is the survey selectivity for age *a*, which is taken to be year-independent.

T^i is the month in which the survey is taking place (see Table App.A1), and

$w_{y,a}^i$ denotes the mass of fish of age *a* from survey *i* in year *y*.

The contribution of the survey biomass data to the negative of the log-likelihood function (after removal of constants) is then given by:

$$-lnL^{\text{survey}} = \sum_i \sum_y \left\{ ln\left(\sqrt{\left(\sigma_y^i\right)^2 + \left(\sigma_{Add}^i\right)^2}\right) + \frac{\left(\varepsilon_y^i\right)^2}{2\left(\left(\sigma_y^i\right)^2 + \left(\sigma_{Add}^i\right)^2\right)} \right\} \tag{A.15}$$

where

σ_y^i is the standard deviation of the residuals for the logarithm of index *i* in year *y*, and

σ_{Add}^i is the square root of the additional variance for survey biomass series *i*, which is estimated in the model fitting procedure, with an upper bound of 0.5.

In this case, however, external estimates of σ_y^i (from survey sampling variance) are not available. So homoscedasticity of residuals is assumed, so that estimation of additional variance falls away and $\sigma_y^i = \sigma^i$ is estimated in the fitting procedure by its maximum likelihood value (with a minimum estimate of 0.15 imposed to prevent overweighting through overfitting):

$$\sigma^i = \sqrt{\frac{1}{n^i} \sum_y \left(lnI_y^i - ln\left(q^i B_y^i\right)\right)^2} \tag{A.16}$$

The constant of proportionality q^i for survey biomass index *i* is estimated by its maximum likelihood value:

$$lnq^i = \frac{1}{n^i} \sum_y \left(lnI_y^i - lnB_y^i\right) \tag{A.17}$$

A.2.3. Commercial catches-at-age

The "sqrt(p)" method is used to compute the contribution of the catch-at-age data to the negative of the log-likelihood function. The formulation mimics a multinomial form for the error distribution by forcing near-equivalent variance-mean relationship for the error distributions:

$$-lnL^{CAA} = w^{CAA} \sum_y \sum_a \left[ln(\sigma^{com}) + \left(\sqrt{lnp_{y,a}} - \sqrt{ln\hat{p}_{y,a}}\right)^2 / 2(\sigma_a^{com})^2 \right] \tag{A.18}$$

where

$p_{y,a} = C_{y,a} / \sum_{a'} C_{y,a'}$ is the observed proportion of fish caught in year *y* that are of age *a*,

$\hat{p}_{y,a} = \hat{C}_{y,a} / \sum_{a'} \hat{C}_{y,a'}$ is the model-predicted proportion of fish caught in year *y* that are of age *a*, with

$\hat{C}_{y,a} = N_{y,a} S_{y,a} F_y \left(1 - e^{-Z_{y,a}}\right) / Z_{y,a}$ (A.19)

and

σ_a^{com} is the standard deviation associated with the catch-at-age data, which is estimated in the fitting procedure by:

$\hat{\sigma}_a^{com} = \sqrt{\sum_y \left(\sqrt{lnp_{y,a}} - \sqrt{ln\hat{p}_{y,a}}\right)^2 / \sum_y 1}$ (A.20)

The w^{CAA} weighting factor in equation A.18 may be set to a value less than 1 to downweight the contribution of the catch-at-age data (which tend to be positively correlated between adjacent age groups) to the overall negative log-likelihood compared to that of the survey biomass data.

Commercial catches-at-age are incorporated in the likelihood function using equation (A.18), for which the summation over age a is taken from age a_{minus} (considered as a minus group) to a_{plus} (a plus group).

For the baseline run, $\boldsymbol{w^{CAA} = 0.2}$.

A.2.4. Survey catches-at-age

The survey catches-at-age are incorporated into the negative of the log-likelihood in an analogous manner to the commercial catches-at-age, assuming an "adjusted" lognormal error distribution (equation (A.18)) where:

$p_{y,a}^i = C_{y,a}^i / \sum_{a'} C_{y,a'}^i$ is the observed proportion of fish of age a in year y for survey i,

$\hat{p}_{y,a}^i$ is the expected proportion of fish of age a in year y in the survey i, given by:

$\hat{p}_{y,a}^i = S_a^i N_{y,a} e^{-Z_{y,a} T^i / 12} / \sum_{a'} S_{a'}^i N_{y,a'} e^{-Z_{y,a'} T^i / 12}$ (A.21)

A.2.5. Stock-recruitment function residuals

The stock-recruitment residuals are assumed to be lognormally distributed. Thus, the contribution of the recruitment residuals to the negative of the (now penalised) log-likelihood function is given by:

$-lnL^{pen} = \sum_{y=y_1}^{y_2} \left(\varphi_y^2 / 2\sigma_R^2\right)$ (A.22)

where

φ_y from $N(0, \sigma_R^2)$,

σ_R is the standard deviation of the log-residuals, which is input. σ_R=0.4

B.2.7. Catches

$-lnL^{Catch} = \sum_y \frac{lnC_y - ln\hat{C}_y}{2\sigma_C^2}$ (A.23)

where

C_y is the observed catch in year y,

$\hat{C}_y$ is the predicted catch in year y (equation A.9), and

$\sigma_C = 0.1$ is the input CV input.

A.3. Estimation of precision

Where quoted, CV's or 90% probability interval estimates are based on the Hessian.

A.4. Model parameters

B.4.1. Fishing selectivity-at-age:

For the surveys, the fishing selectivities are either estimated separately for ages a_1 to a_2 or are modelled by a double normal shape:

$$S_a = \begin{cases} exp\left(-\frac{(a-a_{max})^2}{2\sigma_{left}^2}\right) & \text{for } a \le a_{max} \\ exp\left(-\frac{(a-a_{max})^2}{2\sigma_{right}^2}\right) & \text{for } a > a_{max} \end{cases} \qquad (A.24)$$

where σ_{left}, σ_{right} and a_{max} are estimable parameters.

When the fishing selectivity is estimated separately for ages a_1 to a_2, the selectivity is taken to increase exponentially from age 0 to a_1-1 and to remain flat above a_2:

$$S_a = \begin{cases} S_{a+1}\frac{S_{a_1}}{S_{a_1+1}} & a < a_1 \\ \text{estimated freely} & a_1 \le a \le a_2 \\ S_{a_2} & a > a_2 \end{cases} \qquad (A.25)$$

The selectivity for the EU surveys is taken to be flat for the 10+ group.

The commercial fishing selectivities are modelled by a double-normal shape. For the baseline run, the selectivity is estimated for each of four periods: 1960-1989, 1990-1995, 1996-2003 and 2004+.

A.4.2. Other parameters

Stock-recruit standard dev.			
σ_R	0.4		
Model plus group			
m	14		
CAA minus and plus groups	a_{minus}	a_{plus}	T^i
Can. Fall 2J3K	1	8	9
EU 3M 0-700m	1	9	7
EU 3M 0-1400m	4	10	7
EU 3M70 0-1400m	4	10	7
Can. Spring 3LNO	1	8	5
EU 3L	1	10	8
EU 3NO	1	10	6
Can. Fall 3LNO	0	8	11
Commercial	5	10	
Natural mortality:			
M	0.12, age-independent		
Proportion mature-at-age:			
f_a	100% mature at age 10		
Weight-at-age:			
$w_{y,a}^{strt}$	input, ages 0-10+		
$w_{y,a}^{mid}$	input, ages 0-10+		
$w_{y,a}^{i}$	input, ages 0-10+		

Appendix B: Candidate Management Procedures Testing Methodology

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 2016 ($N_{2016,a}$: $a = 0,\ldots, m$) 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.:

$$N_{2016,a} \rightarrow N_{2016,a}e^{\varepsilon_a}$$

where ε_a is generated from the variance-covariance matrix (B.1)

Step 2: Catch

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

For 2016 and 2017 the 2016 TAC is assumed:

$$C_y = 14997 \text{ t} \tag{B.2}$$

For 2018, the TAC is fixed (to 15 000t unless otherwise specified).

From 2019 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 2015) continues in the future. F_y[3] is solved iteratively to achieve that the annual catch by mass:

$$C_y = \sum_{a=0}^{m} w_{y,a}^{mid} N_{y,a} S_{y,a} F_y \left(1 - e^{-Z_{y,a}}\right) / Z_{y,a} \tag{B.3}$$

where $w_{y,a}^{mid}$ is taken as the average of the last 10 years (2006-2015) weight-at-age vectors, and hence that:

$$C_{y,a} = N_{y,a} S_{y,a} F_y \left(1 - e^{-Z_{y,a}}\right) / Z_{y,a} \tag{B.4}$$

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

$$N_{y+1,0} = R_{y+1} \tag{B.5}$$

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

$$N_{y+1,a+1} = N_{y,a}e^{-Z_{y,a}} \quad \text{for } 0 \le a \le m-2 \tag{B.6}$$

$$N_{y+1,m} = N_{y,m-1}e^{-Z_{y,m-1}} + N_{y,m}e^{-Z_{y,m}} \tag{B.7}$$

The plus-group *m* is 14.

Step 4: Recruitment

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

$$R_y = \frac{4hR_0B_y^{sp}}{b_0(1-h)+(5h-1)B_y^{sp}}e^{(\varphi_y-(\sigma_R)^2/2)} \tag{B.8}$$

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 σ_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).

$$B_y^{sp} = \sum_{a=1}^{m} f_a\, w_{y,a}^{strt}N_{y,a} \tag{B.9}$$

where $w_{y,a}^{strt}$ is taken to be the average of the last 10 years (2006-2015) weight-at-age vectors.

Step5:

The information obtained in Step 1 is used to generate values of the abundance indices I_{2016}^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.:

$$I_y^i = q^iB_y^ie^{\varepsilon_y^i} \tag{B.10}$$

with

ε_y^i from $N(0,(\sigma^i)^2)$

where

B_y^i is the biomass available to the survey:

$$B_y^i = \sum_{a=0}^{m} w_{y,a}^iS_a^iN_{y,a}e^{-Z_{y,a}T^i/12} \tag{B.11}$$

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.

Step 6:

Given the new survey indices I_y^i compute TAC_{y+1} using the CMP (aside from the fixed values assumed for 2016 to 2018).

<u>Step 7</u>:

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.

Performance Targets and Statistics

NAFO (2017c) 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) were agreed (NAFO 2017b) to capture these objectives:

1. Restore to within a prescribed period of time or maintain at B_{MSY}:

- $B_{2037}^{5-9}/B_{MSY}^{5-9}$: median and 90%PI;
- Proportion $B_{2037}^{5-9} < B_{MSY}^{5-9}$;
- Proportion $B_{2037}^{5-9} < 0.8B_{MSY}^{5-9}$;

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:

- $B_{lowest}^{5-9}/B_{MSY}^{5-9}$: median and 90%PI;
- Proportion $B_{2022}^{5-9} < B_{2018}^{5-9}$;

3. Low risk of exceeding F_{MSY} :

- Count $\left[P\left(F_y > F_{MSY}\right) > 0.3\right]$ for y=2018 to 2037;

4. Very low risk of going below an established threshold:

- $B_{2037}^{sp}/B_{MSY}^{sp}$: median and 90%PI;
- $B_{2037}^{5-9}/B_{2018}^{5-9}$: median and 90%PI;
- Count $\left[P\left(B_y^{5-9} < 0.3B_{MSY}^{5-9}\right) > 0.1\right]$ for y=2018 to 2037;
- Proportion $B_{lowest}^{5-9}/B_{MSY}^{5-9} < 0.3$

5. Maximize yield in the short, medium and long term :

- $\sum_{y=2018}^{2020} C_y/3$: median and 90%PI;
- $\sum_{y=2018}^{2037} C_y/20$: median and 90%PI;

6. The risk of steep decline of stock biomass should be kept moderately low:

- Proportion $B_{2037}^{5-9} < 0.75B_{2018}^{5-9}$

7. Keep inter-annual TAC variation below “an established threshold”:

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

A total of 100 forward projections are run for each trial.

Plots of annual catch and B^{5-9} may be produced for each trial, with one showing the median and 90% probability envelopes, and another showing the first 10 realisations (“worm plots”).

Appendix C
Variants on the tuning parameters

In selecting CMP1, the authors have made selections for some of the tuning parameters and the form (target- vs. slope-based) of the CMP. Results are presented for variants of these choices under the baseline OM (OM0). All the CMPs presented are tuned to achieve median $B^{5-9}_{2037}/B^{5-9}_{MSY} = 1$ for the baseline (except for b) below), by varying the tuning parameter α.

a) Equal vs inverse variance weighting for the surveys indices:
Equation (2) in the main text is replaced by:

$$J_y = \frac{1}{3}\sum_{i=1}^{3}\frac{J^i_{curr}}{J^i_{target}} \tag{C.1}$$

b) Slope-based vs target-based:
Equations (1-4) in the main text are replaced by:

$$TAC_{y+1} = TAC_y\left(1 + \lambda_{up/down}s_y\right) \tag{C.2}$$

where

$\lambda_{up/down}$ are tuning parameters: $\lambda_{up} = 1$ and $\lambda_{down} = 2$, as for the previous MP adopted for Greenland halibut

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

$$s_y = \sum_{i=1}^{3}\frac{1}{(\sigma^i)^2}s_y \Big/ \sum_{i=1}^{3}\frac{1}{(\sigma^i)^2} \tag{C.3}$$

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.

Using to the slope-based approach, it turned out to be impossible to tune the $\lambda_{up/down}$ to get median $B^{5-9}_{2037}/B^{5-9}_{MSY} = 1$. Instead therefore, to get a direct comparison with the target-based approach, CMP1 has been tuned to the same $B^{5-9}_{2037}/B^{5-9}_{MSY}$ as obtained under the slope-based approach.

c) Interannual TAC change constraints:
CMP1 has interannual TAC change constraints of $\Delta_{up/down}$= 10%. Other options presented here are $\Delta_{up/down}$=5%, 15% and 20%.

d) Value of γ:
CMP1 uses γ=0.05. Other options presented here use γ=0.03 and γ=0.1

e) Number of years over which to average the surveys:
For CMP1, J^i_{curr} is computed over the last 3 years of available data (*q*=3). Other options presented here use *q*=5 and *q*=7.

Performance statistics results (medians and 90% PIs) are given in Table App.C.1 for the baseline OM under the series of CMPs considered. Some of the performance statistics (medians and 90% PIs) are compared in Figure App.C.1.

Table App.C.1: Performance measures under a series of CMP for the baseline OM (OM0); the pink highlights show instances where desired performance criterion specified by the Falmouth RBMS meeting (NAFO 2017a) has not been met.

	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	$B^{5\text{-}9}_{2037}/B^{5\text{-}9}_{msy}$	$B^{5\text{-}9}_{2037} < B^{5\text{-}9}_{msy}$	$B^{5\text{-}9}_{2037} < 0.8B^{5\text{-}9}_{msy}$	$B^{5\text{-}9}_{lowest}/B^{5\text{-}9}_{msy}$	$B^{5\text{-}9}_{2022} < B^{5\text{-}9}_{2018}$		$(F_{2018\text{-}2037} > F_{msy}) > 0.3$	$B^{sp}_{2037}/B^{sp}_{2018}$	$B^{5\text{-}9}_{2037}/B^{5\text{-}9}_{2018}$	$(B^{5\text{-}9}_{2018\text{-}2037} < 0.3B^{5\text{-}9}_{msy}) > 0.1$	$B^{5\text{-}9}_{lowest}/B^{5\text{-}9}_{msy} < 0.3$	avC: 2018-2020	avC: 2018-2037	$B^{5\text{-}9}_{2037} < 0.75B^{5\text{-}9}_{2018}$		AAV: 2018-2037
		median (90%PI)	Proportion	Proportion	median (90%PI)	Proportion		Count	median (90%PI)	median (90%PI)	Count	Proportion	median (90%PI)	median (90%PI)	Proportion		median (90%PI)
	Criteria		<=0.5	<=0.25		<Ω	Ω					<=0.1			<β	β	
Survey weighting	inv. variance (CMP1)	**1.00** (0.45; 1.83)	0.49	0.22	0.81 (0.42; 1.07)	0.31	0.25	5	1.35 (0.56; 2.53)	0.89 (0.35; 1.59)	0	0.00	15.39 (15.10; 15.81)	21.85 (17.36; 29.02)	0.02	0.25	3.64 (1.38; 6.50)
	equal weight	**1.00** (0.45; 1.81)	0.49	0.21	0.80 (0.40; 1.06)	0.31	0.25	5	1.31 (0.57; 2.48)	0.89 (0.37; 1.56)	0	0.00	15.40 (15.07; 16.08)	22.20 (17.12; 29.63)	0.02	0.25	3.63 (1.33; 6.74)
Slope vs. target	target (CMP1)	**1.00** (0.45; 1.83)	0.49	0.22	0.81 (0.42; 1.07)	0.31	0.25	5	1.35 (0.56; 2.53)	0.89 (0.35; 1.59)	0	0.00	15.39 (15.10; 15.81)	21.85 (17.36; 29.02)	0.02	0.25	3.64 (1.38; 6.50)
	slope	1.23 (0.82; 2.18)	0.12	0.04	0.89 (0.59; 1.19)	0.33	0.25	0	1.67 (1.04; 2.95)	1.08 (0.67; 1.89)	0	0.00	16.10 (14.07; 16.55)	17.09 (13.61; 21.81)	0.02	0.25	5.61 (3.90; 7.02)
	CMP1 tuned to slope	**1.23** (0.75; 2.13)	0.18	0.06	0.90 (0.59; 1.14)	0.30	0.25	0	1.74 (0.85; 3.25)	1.09 (0.64; 1.83)	0	0.00	15.01 (14.82; 15.28)	16.50 (14.22; 19.95)	0.01	0.25	1.25 (0.46; 3.31)
Interannual change constraint	5%	**1.00** (0.54; 1.93)	0.50	0.17	0.81 (0.41; 1.08)	0.31	0.25	5	1.27 (0.62; 2.55)	0.90 (0.43; 1.63)	0	0.00	15.50 (15.18; 15.76)	22.76 (18.32; 24.66)	0.02	0.25	4.02 (1.83; 4.71)
	10% (CMP1)	**1.00** (0.45; 1.83)	0.49	0.22	0.81 (0.42; 1.07)	0.31	0.25	5	1.35 (0.56; 2.53)	0.89 (0.35; 1.59)	0	0.00	15.39 (15.10; 15.81)	21.85 (17.36; 29.02)	0.02	0.25	3.64 (1.38; 6.50)
	15%	**1.00** (0.44; 1.82)	0.50	0.24	0.81 (0.42; 1.06)	0.31	0.25	5	1.34 (0.56; 2.52)	0.88 (0.35; 1.58)	0	0.00	15.40 (15.11; 15.82)	21.96 (17.42; 29.53)	0.02	0.25	3.68 (1.40; 6.64)
	20%	**1.00** (0.45; 1.83)	0.49	0.23	0.81 (0.42; 1.06)	0.31	0.25	5	1.35 (0.56; 2.53)	0.88 (0.35; 1.59)	0	0.00	15.39 (15.10; 15.81)	21.85 (17.36; 29.34)	0.02	0.25	3.64 (1.38; 6.59)
γ value	γ=0.03	**1.00** (0.50; 1.91)	0.50	0.20	0.82 (0.43; 1.07)	0.31	0.25	5	1.31 (0.57; 2.56)	0.91 (0.35; 1.58)	0	0.00	15.44 (15.21; 15.76)	21.86 (18.27; 27.46)	0.02	0.25	3.64 (1.84; 5.96)
	γ=0.05 (CMP1)	**1.00** (0.45; 1.83)	0.49	0.22	0.81 (0.42; 1.07)	0.31	0.25	5	1.35 (0.56; 2.53)	0.89 (0.35; 1.59)	0	0.00	15.39 (15.10; 15.81)	21.85 (17.36; 29.02)	0.02	0.25	3.64 (1.38; 6.50)
	γ=0.1	**1.00** (0.37; 1.68)	0.50	0.26	0.80 (0.32; 1.06)	0.31	0.25	6	1.31 (0.47; 2.50)	0.87 (0.23; 1.65)	0	0.04	15.34 (14.87; 16.01)	22.89 (15.88; 31.93)	0.02	0.25	4.02 (1.15; 8.58)
Average over q years	q=3 (CMP1)	**1.00** (0.45; 1.83)	0.49	0.22	0.81 (0.42; 1.07)	0.31	0.25	5	1.35 (0.56; 2.53)	0.89 (0.35; 1.59)	0	0.00	15.39 (15.10; 15.81)	21.85 (17.36; 29.02)	0.02	0.25	3.64 (1.38; 6.50)
	q=5	1.00 (0.43; 1.84)	0.51	0.25	0.81 (0.41; 1.07)	0.31	0.25	5	1.33 (0.55; 2.58)	0.89 (0.33; 1.58)	0	0.01	15.30 (15.12; 15.56)	21.87 (17.58; 28.73)	0.02	0.25	3.72 (1.49; 6.94)
	q=7	1.00 (0.44; 1.86)	0.50	0.26	0.81 (0.41; 1.07)	0.30	0.25	5	1.34 (0.56; 2.62)	0.90 (0.33; 1.60)	0	0.01	15.24 (15.11; 15.43)	21.70 (17.68; 27.82)	0.02	0.25	3.77 (1.61; 7.13)

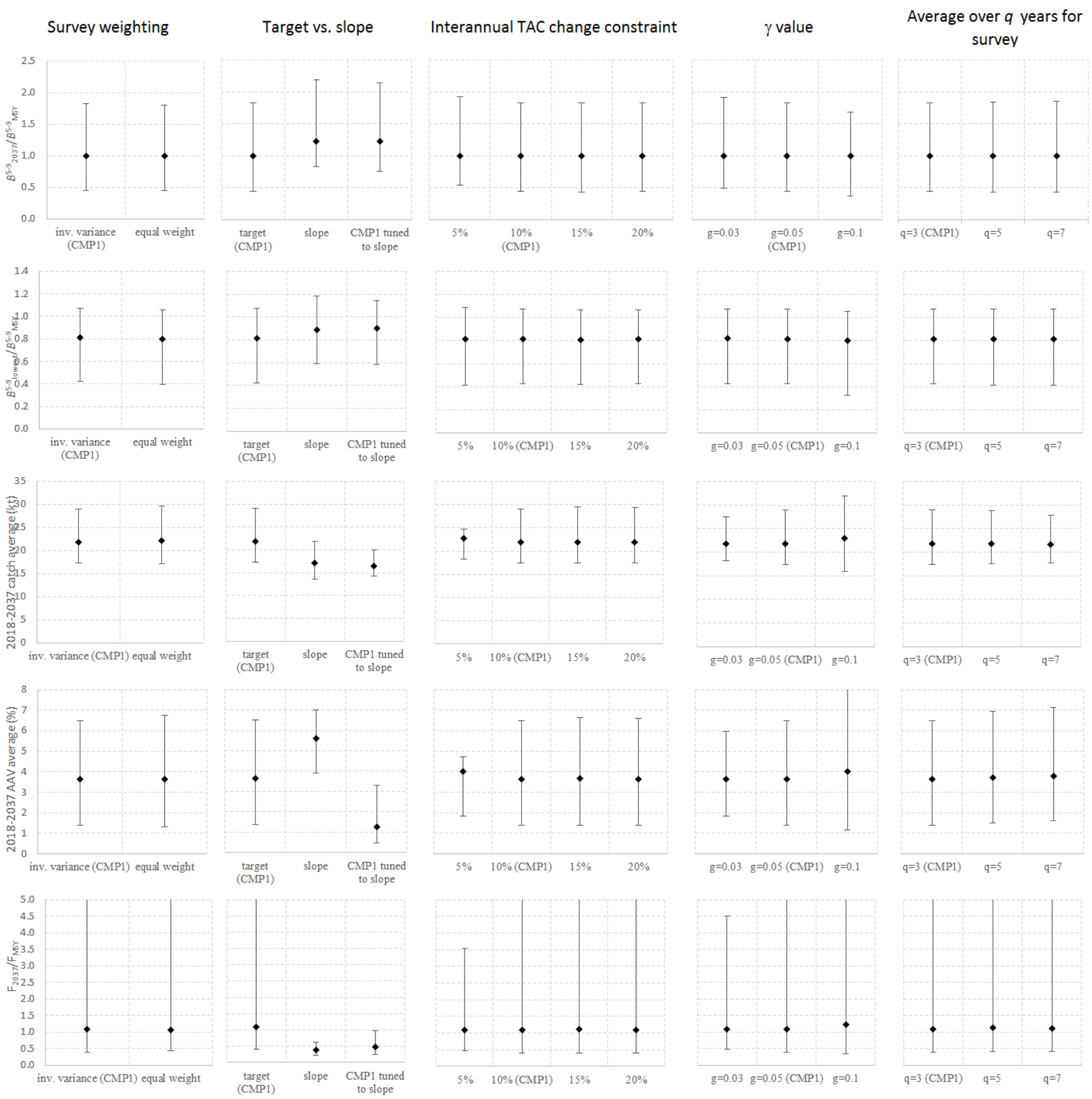

Fig. App.C.1. Projected median and 90% PIs for a series of performance statistics for the baseline OM (OM0) under a series of CMPs. The symbol "g" used in the legends corresponds to γ.

Appendix D

All OMs and robustness tests under CMP1

Results are presented for all the OMs and robustness tests under CMP1. The full set of trials is listed below:

Trials affecting the past (and hence requiring assessment re-runs), based on the SCAA model:

1) Alternative to past input survey data set:
    a. O3
2) Alternative steepness parameter (baseline: h=0.8):
    a. h=0.7
    b. h=0.9
3) Alternative natural mortality (baseline: M=0.12):
    a. M=0.2
    b. M increasing linearly from 0.12 at age 10 to 0.5 at age 14+
4) Alternative maturity-at-age (baseline: 100% mature at 10+):
    a. 100% mature at 14+
5) Alternative CAA -lnL weighting (baseline: Wcaa=0.2):
    a. Wcaa=0.1
    b. Wcaa=0.5
6) Alternative σ_R value (baseline: σ_R =0.4):
    a. σ_R =0.6
7) Alternative σ_C value (baseline: σ_C =0.1):
    a. σ_C =0.2
8) Starting (1960) biomass:
    a. Force to XSA/SAM-style level (total biomass of 200 000t in 1975)
9) Sensitivity for methods for estimating 1960 starting numbers-at-age vector
    a. This was to be decided, but was not pursued given insensitivity of results to other aspects of the starting situation
10) Current (2016) numbers:
    a. 1.2 baseline estimates
    b. 0.8 baseline estimates[4]
11) Commercial selectivities:
    a. 6 instead of 4 survey blocks
    b. Descending limb: normal to negative exponential
    c. Force less doming
12) EU survey selectivity shape:
    a. Exponential decrease from plus group (instead of flat)
    b. Force less doming

Trials affecting the future only:

13) Poor future recruitment (5 years of half the recruitment predicted under the stock-recruit curve)
14) Commercial selectivity for projections which differs most from that for the most recent block

[4] Note that these have been referenced as Rob10a/b rather than OM10a/b in the Tables and Figures as they do not require refitting the model to the data.

15) Future catches 30% greater than TAC
16) Process error in future dynamics (random error on My,a with variance as indicated by SAM models
17) Zero selectivity on 10+ in the future (forecast yield does not rely on the plus group biomass)

Performance statistics results (medians and 90% PIs) are given in Table App.D.1 and some of the performance statistics (medians and 90%PI) are compared in Figure App.D.1.

Table App.D.1: Performance measures under CMP1 for each OM and robustness tests; the pink highlights show instances where desired performance criterion specified by the Falmouth RBMS meeting (NAFO 2017a) has not been met. The trials highlighted in grey are members of the Reference Set considered in the main text.

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	$B^{5\text{-}9}_{2037}/B^{5\text{-}9}_{msy}$	$B^{5\text{-}9}_{2037} < B^{5\text{-}9}_{msy}$	$B^{5\text{-}9}_{2037} < 0.8B^{5\text{-}9}_{msy}$	$B^{5\text{-}9}_{lowest}/B^{5\text{-}9}_{msy}$	$B^{5\text{-}9}_{2022} < B^{5\text{-}9}_{2018}$		$(F_{2018\text{-}2037} > F_{msy}) > 0.3$	$B^{sp}_{2037}/B^{sp}_{2018}$	$B^{5\text{-}9}_{2037}/B^{5\text{-}9}_{2018}$	$(B^{5\text{-}9}_{2018\text{-}2037} < 0.3B^{5\text{-}9}_{msy}) > 0.1$	$B^{5\text{-}9}_{lowest}/B^{5\text{-}9}_{msy} < 0.3$	avC: 2018-2020	avC: 2018-2037	$B^{5\text{-}9}_{2037} < 0.75B^{5\text{-}9}_{201}$		AAV: 2018-2037
	median (90%PI)	Proportion	Proportion	median (90%PI)	Proportion		Count	median (90%PI)	median (90%PI)	Count	Proportion	median (90%PI)	median (90%PI)	Proportion		median (90%PI)
Criteria		<=0.5	<=0.25		<Ω	Ω					<=0.1			<β	β	
OM0	**1.00** (0.45; 1.83)	0.49	0.22	0.81 (0.42; 1.07)	0.31	0.25	5	1.35 (0.56; 2.53)	0.89 (0.35; 1.59)	0	0.00	15.39 (15.10; 15.81)	21.85 (17.36; 29.02)	0.02	0.25	3.64 (1.38; 6.50)
OM1a	1.03 (0.57; 1.84)	0.45	0.15	0.77 (0.47; 0.94)	0.09	0.25	4	1.50 (0.73; 2.80)	1.17 (0.51; 1.97)	0	0.00	15.24 (15.03; 15.47)	20.08 (16.35; 26.27)	0.00	0.22	3.16 (1.06; 5.90)
OM2a	1.02 (0.55; 1.85)	0.48	0.17	0.79 (0.49; 1.02)	0.37	0.25	5	1.26 (0.61; 2.22)	0.96 (0.42; 1.67)	0	0.01	15.35 (15.08; 15.75)	20.32 (16.43; 26.75)	0.03	0.25	3.04 (0.91; 5.82)
OM2b	0.87 (0.29; 1.60)	0.65	0.41	0.75 (0.28; 1.09)	0.27	0.25	7	1.24 (0.38; 3.18)	0.74 (0.22; 1.62)	0	0.06	15.50 (15.14; 16.07)	24.71 (19.05; 32.10)	0.01	0.25	4.73 (2.18; 10.41)
OM3a	1.03 (0.53; 1.88)	0.42	0.15	0.84 (0.46; 1.05)	0.26	0.25	4	1.31 (0.44; 2.82)	0.95 (0.42; 1.75)	0	0.00	15.36 (15.09; 15.74)	22.18 (17.82; 29.14)	0.02	0.25	3.79 (1.64; 6.64)
OM3b	1.07 (0.52; 1.94)	0.37	0.13	0.88 (0.47; 1.15)	0.25	0.25	4	1.18 (0.29; 2.91)	0.91 (0.38; 1.61)	0	0.00	15.39 (15.11; 15.78)	22.53 (18.23; 29.81)	0.01	0.25	3.86 (1.73; 6.58)
OM4a	0.98 (0.43; 1.74)	0.56	0.29	0.75 (0.37; 1.02)	0.37	0.25	7	1.38 (0.68; 2.48)	0.88 (0.32; 1.61)	0	0.02	15.38 (15.08; 15.86)	21.23 (16.53; 28.86)	0.03	0.25	3.34 (0.92; 6.74)
OM5a	1.15 (0.63; 2.04)	0.29	0.11	0.93 (0.56; 1.32)	0.33	0.25	0	1.03 (0.43; 1.97)	0.82 (0.36; 1.58)	0	0.00	15.44 (15.09; 15.96)	21.33 (16.71; 29.23)	0.02	0.25	3.17 (1.16; 6.25)
OM5b	0.94 (0.50; 1.79)	0.55	0.26	0.75 (0.42; 0.94)	0.34	0.25	6	1.64 (0.82; 3.12)	1.04 (0.43; 1.77)	0	0.00	15.30 (15.10; 15.54)	20.69 (17.41; 26.65)	0.01	0.24	3.35 (1.30; 5.86)
OM6a	0.87 (0.31; 2.19)	0.59	0.41	0.61 (0.21; 0.91)	0.30	0.25	8	1.46 (0.61; 3.55)	0.93 (0.26; 2.15)	0	0.08	15.38 (15.11; 15.80)	22.72 (17.17; 31.49)	0.04	0.23	4.07 (1.30; 8.49)
OM7a	0.97 (0.44; 1.78)	0.55	0.28	0.78 (0.41; 0.99)	0.28	0.25	5	1.48 (0.64; 2.81)	0.96 (0.37; 1.69)	0	0.00	15.34 (15.09; 15.69)	21.75 (17.38; 28.46)	0.01	0.25	3.69 (1.43; 6.54)
OM8a	0.96 (0.41; 1.76)	0.54	0.29	0.74 (0.38; 0.92)	0.21	0.25	5	1.78 (0.73; 3.37)	1.07 (0.41; 1.93)	0	0.02	15.43 (15.13; 15.87)	25.52 (19.15; 34.08)	0.01	0.22	5.33 (2.50; 8.27)
Rob10a	0.75 (0.21; 1.57)	0.71	0.56	0.66 (0.21; 1.13)	0.37	0.25	10	0.82 (0.42; 1.65)	0.43 (0.12; 1.05)	1	0.12	15.84 (15.42; 16.38)	30.13 (22.46; 38.32)	0.02	0.25	5.65 (3.19; 8.05)
Rob10b	1.06 (0.54; 1.87)	0.44	0.11	0.61 (0.42; 0.84)	0.26	0.25	0	1.94 (0.86; 3.64)	1.55 (0.90; 2.76)	0	0.01	15.03 (14.84; 15.29)	16.25 (13.72; 20.57)	0.01	0.13	1.57 (0.63; 3.93)
OM11a	0.97 (0.43; 1.81)	0.54	0.28	0.78 (0.39; 0.98)	0.26	0.25	5	1.41 (0.65; 2.76)	0.98 (0.36; 1.76)	0	0.00	15.31 (15.07; 15.62)	20.93 (16.97; 27.31)	0.01	0.24	3.35 (1.17; 6.09)
OM11b	1.00 (0.45; 1.83)	0.49	0.22	0.81 (0.42; 1.07)	0.31	0.25	5	1.35 (0.56; 2.53)	0.89 (0.35; 1.59)	0	0.00	15.39 (15.10; 15.81)	21.85 (17.36; 29.02)	0.02	0.25	3.64 (1.38; 6.50)
OM11c	0.94 (0.48; 1.74)	0.56	0.25	0.72 (0.42; 0.88)	0.20	0.25	4	1.87 (0.86; 3.52)	1.14 (0.49; 1.95)	0	0.00	15.33 (15.10; 15.64)	22.82 (18.06; 29.92)	0.01	0.21	4.42 (1.94; 7.23)
OM12a	1.01 (0.43; 1.82)	0.48	0.23	0.81 (0.42; 1.09)	0.32	0.25	5	1.30 (0.55; 2.43)	0.87 (0.34; 1.57)	0	0.00	15.41 (15.10; 15.84)	21.96 (17.40; 29.51)	0.02	0.25	3.65 (1.36; 6.59)
OM12b	0.66 (0.28; 1.30)	0.82	0.64	0.56 (0.24; 0.77)	0.31	0.25	10	1.31 (0.56; 3.03)	0.82 (0.32; 1.76)	0	0.10	15.44 (15.14; 15.87)	25.54 (19.47; 32.17)	0.01	0.17	5.71 (2.49; 10.56)
Rob13	1.04 (0.52; 1.86)	0.43	0.14	0.52 (0.29; 0.89)	0.42	0.25	6	1.11 (0.41; 2.29)	0.93 (0.40; 1.61)	0	0.05	15.39 (15.10; 15.81)	19.53 (16.07; 25.30)	0.03	0.25	2.45 (0.98; 4.92)
Rob14	1.03 (0.54; 1.87)	0.42	0.15	0.83 (0.50; 1.07)	0.33	0.25	3	1.44 (0.64; 2.63)	0.91 (0.42; 1.61)	0	0.00	15.39 (15.10; 15.81)	22.24 (17.53; 29.48)	0.02	0.25	3.82 (1.48; 6.65)
Rob15	0.82 (0.33; 1.63)	0.68	0.46	0.69 (0.26; 0.99)	0.33	0.25	11	0.97 (0.42; 2.05)	0.78 (0.26; 1.48)	0	0.06	15.37 (15.08; 15.78)	20.14 (16.32; 26.34)	0.02	0.25	2.81 (0.81; 6.36)
Rob16	1.00 (0.47; 1.80)	0.50	0.25	0.80 (0.44; 1.07)	0.33	0.25	5	1.32 (0.56; 2.54)	0.88 (0.35; 1.60)	0	0.00	15.39 (15.10; 15.81)	21.70 (17.35; 28.45)	0.02	0.25	3.48 (1.31; 6.28)
Rob17	0.99 (0.39; 1.81)	0.52	0.30	0.78 (0.35; 1.08)	0.32	0.25	7	1.23 (0.52; 2.40)	0.84 (0.28; 1.56)	0	0.02	15.39 (15.10; 15.80)	21.25 (17.00; 27.98)	0.02	0.25	3.27 (1.14; 6.19)

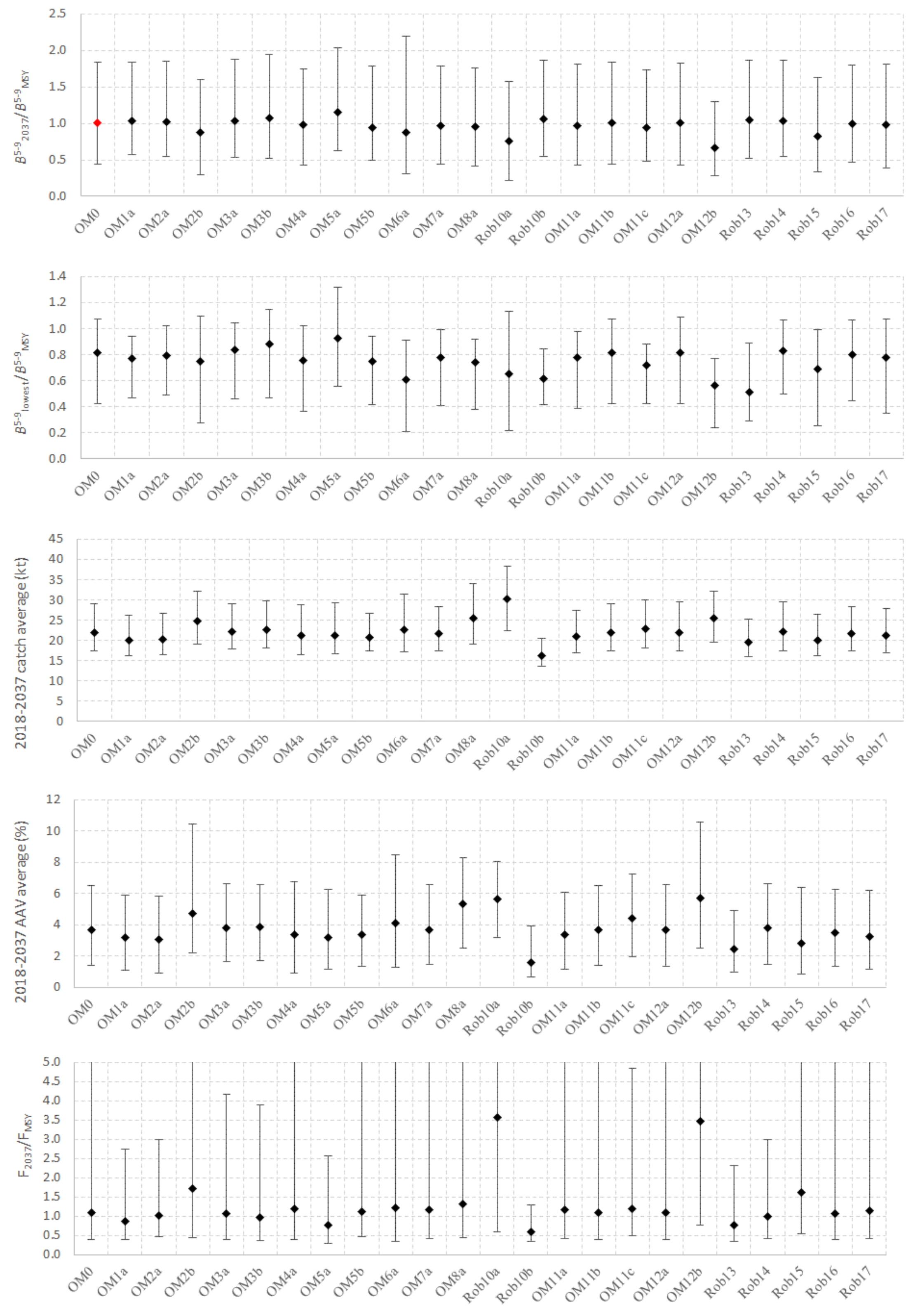

Fig. App.D.1. Projected median and 90% PIs for a series of performance statistics for each OM and robustness tests under CMP1.

Appendix E

Worm plots for the baseline OM (OM0) under CMP1

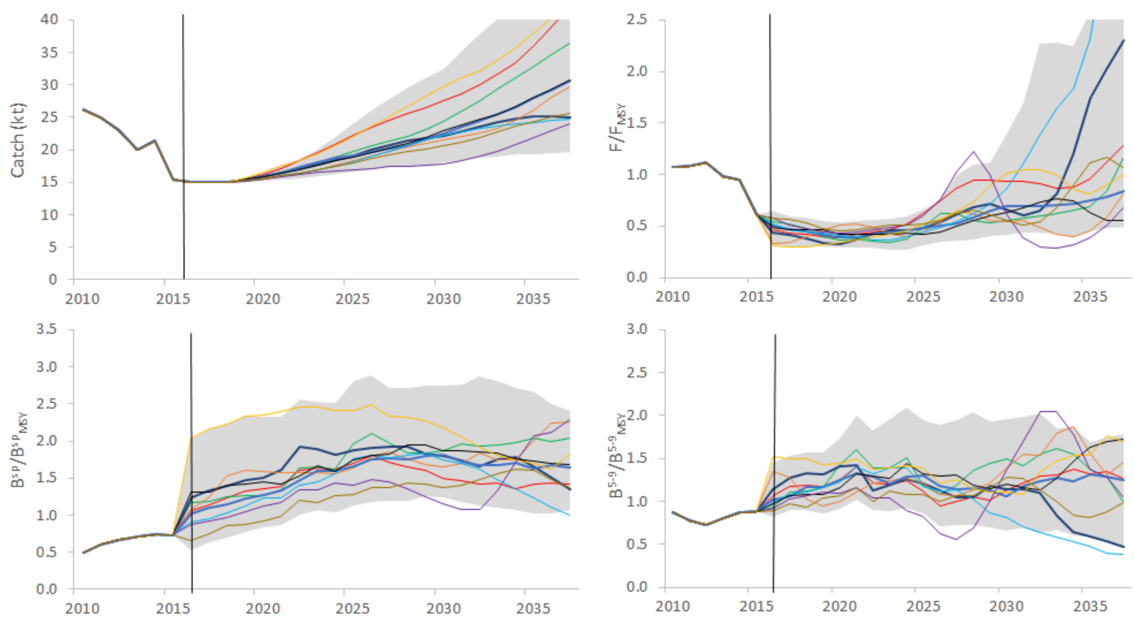

Fig. App.E.1. "Worm" plots showing individual trajectories as well as the 90% probability envelopes (grey shading) for catch, fishing mortality relative to F_{MSY}, and spawning and exploitable biomass (both relative to B_{MSY}), for the baseline OM (OM0) under CMP1.

Appendix F
Comparison of different CMPs under the baseline OM (OM0)

Results are presented for the baseline OM (OM0) under various CMPs:

No future catch and CMPs with a range of initial (2018) TAC (all – except C=0 – tuned to $B^{5-9}_{2037}/B^{5-9}_{MSY} = 1$):

- C=0,
- TAC_{2018}=12 500t,
- TAC_{2018}=15 000t (=CMP1 of the main text),
- TAC_{2018}=17 500t ,
- TAC_{2018}=20 000t (=CMP1ic20 of the main text), and
- TAC_{2018}=25 000t

Various α values:

- CMP1 (a=0.91),
- CMP1.5 (a=1.0, the average a between CMP1 and CMP2),
- CMP2 (a=1.09), and
- CMP3 (a=1.7, tuned so that the probability that $B^{5-9}_{2022} < B^{5-9}_{2018}$ is equal 0.25).

Table App.F.1: Performance measures under a series of CMPs for the baseline OM (OM0); the pink highlights show instances where desired performance criterion specified by the Falmouth RBMS meeting (NAFO 2017a) has not been met. Bold values indicate the tuning target for that CMP.

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	$B^{5\text{-}9}_{2037}/B^{5\text{-}9}_{msy}$	$B^{5\text{-}9}_{2037} < B^{5\text{-}9}_{msy}$	$B^{5\text{-}9}_{2037} < 0.8B^{5\text{-}9}_{msy}$	$B^{5\text{-}9}_{lowest}/B^{5\text{-}9}_{msy}$	$B^{5\text{-}9}_{2022} < B^{5\text{-}9}_{2018}$		$(F_{2018\text{-}2037} > F_{msy}) > 0.3$	$B^{sp}_{2037}/B^{sp}_{2018}$	$B^{5\text{-}9}_{2037}/B^{5\text{-}9}_{2018}$	$(B^{5\text{-}9}_{2018\text{-}2037} < 0.3B^{5\text{-}9}_{msy}) > 0.1$	$B^{5\text{-}9}_{lowest}/B^{5\text{-}9}_{msy} < 0.3$	avC: 2018-2020	avC: 2018-2037	$B^{5\text{-}9}_{2037} < 0.75B^{5\text{-}9}_{201}$		AAV: 2018-2037
	median (90%PI)	Proportion	Proportion	median (90%PI)	Proportion		Count	median (90%PI)	median (90%PI)	Count	Proportion	median (90%PI)	median (90%PI)	Proportion		median (90%PI)
Criteria		<=0.5	<=0.25		<Ω	Ω					<=0.1			<β	β	
C=0	1.56 (1.04; 2.55)	0.04	0.02	1.03 (0.75; 1.36)	0.09	0.25	0	2.95 (1.53; 5.12)	1.36 (0.80; 2.27)	0	0.00	0.00 (0.00; 0.00)	0.00 (0.00; 0.00)	0.00	0.25	0.00 (0.00; 0.00)
TAC_{2018}=12.5kt	**1.00** (0.43; 1.81)	0.50	0.26	0.82 (0.40; 1.09)	0.26	0.25	5	1.39 (0.58; 2.81)	0.87 (0.33; 1.61)	0	0.01	12.97 (12.69; 13.37)	21.41 (16.26; 28.80)	0.01	0.25	5.89 (3.33; 8.76)
TAC_{2018}=15kt	**1.00** (0.45; 1.83)	0.49	0.22	0.81 (0.42; 1.07)	0.31	0.25	5	1.35 (0.56; 2.53)	0.89 (0.35; 1.59)	0	0.00	15.39 (15.10; 15.81)	21.85 (17.36; 29.02)	0.02	0.25	3.64 (1.38; 6.50)
TAC_{2018}=17.5kt	**1.00** (0.47; 1.88)	0.51	0.20	0.80 (0.43; 1.06)	0.35	0.25	5	1.26 (0.52; 2.46)	0.89 (0.35; 1.58)	0	0.01	17.82 (17.51; 18.25)	22.66 (18.63; 29.24)	0.03	0.25	3.39 (1.53; 6.02)
TAC_{2018}=20kt	**1.00** (0.51; 1.88)	0.49	0.18	0.78 (0.43; 1.05)	0.39	0.25	7	1.19 (0.51; 2.43)	0.91 (0.35; 1.58)	0	0.01	20.20 (19.90; 20.63)	23.26 (19.72; 29.20)	0.05	0.25	3.29 (2.17; 5.54)
TAC_{2018}=25kt	**1.00** (0.53; 1.77)	0.50	0.18	0.76 (0.43; 1.03)	0.51	0.25	11	1.05 (0.49; 2.27)	0.89 (0.39; 1.56)	0	0.01	24.93 (24.63; 25.35)	24.68 (21.87; 29.10)	0.06	0.25	4.15 (3.67; 5.32)
CMP1	**1.00** (0.45; 1.83)	0.49	0.22	0.81 (0.42; 1.07)	0.31	0.25	5	1.35 (0.56; 2.53)	0.89 (0.35; 1.59)	0	0.00	15.39 (15.10; 15.81)	21.85 (17.36; 29.02)	0.02	0.25	3.64 (1.38; 6.50)
CMP1.5	1.07 (0.59; 1.96)	0.36	0.13	0.84 (0.53; 1.08)	0.31	0.25	2	1.47 (0.64; 2.76)	0.97 (0.42; 1.69)	0	0.00	15.28 (15.02; 15.65)	20.17 (16.41; 26.08)	0.02	0.25	2.98 (0.93; 5.66)
CMP2	1.12 (0.67; 2.05)	0.31	0.09	0.86 (0.57; 1.10)	0.30	0.25	0	1.56 (0.70; 2.92)	1.02 (0.51; 1.76)	0	0.00	15.20 (14.96; 15.54)	18.95 (15.69; 24.04)	0.02	0.25	2.45 (0.66; 4.91)
CMP3	1.28 (0.80; 2.23)	0.14	0.04	0.93 (0.63; 1.17)	**0.25**	0.25	0	1.99 (0.98; 3.70)	1.13 (0.66; 1.92)	0	0.00	10.13 (9.97; 10.36)	13.27 (10.90; 17.00)	0.01	0.25	4.69 (2.69; 7.25)

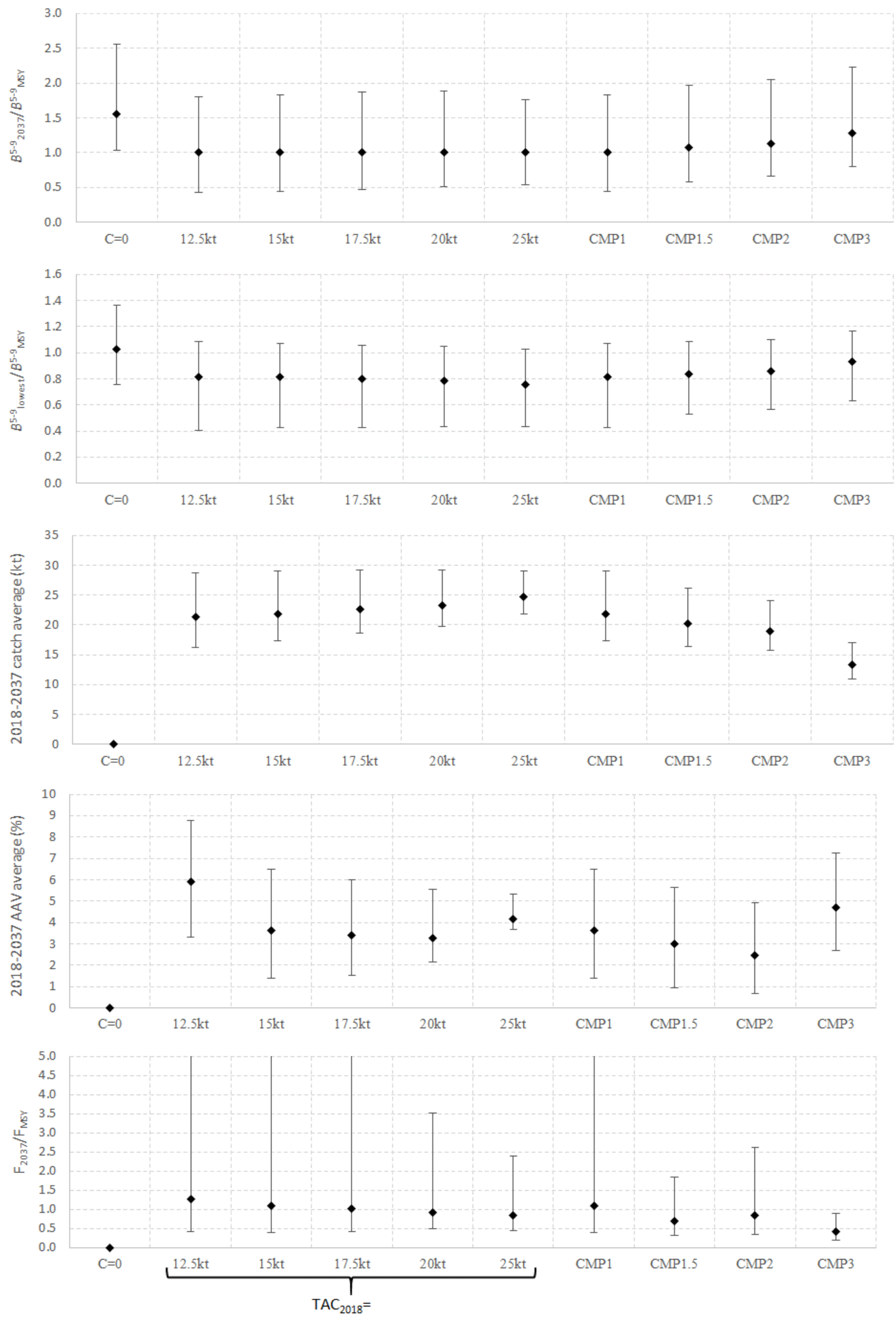

Fig. App.F.1. Projected median and 90% PIs for a series of performance statistics for the baseline OM under a series of CMP1.

Appendix G
Tuning parameters

Table App.G.1: Tuning parameters for each of the CMPs presented in this paper; changes from selections for CMP1 are shown in bold; the parameter whose value is tuned to achieve a median exploitable biomass in 2037 equal to B_{MSY} is α

	in Table	TAC_{2018}	q	γ_{up}	γ_{down}	Δ_{up}	Δ_{down}	α
CMP1	1	15 000t	3	0.05	0.05	0.10	0.10	0.91
CMP1ic20	1	**20 000t**	3	0.05	0.05	0.10	0.10	1.14
CMP2	1	15 000t	3	0.05	0.05	0.10	0.10	1.09
CMP2ic20	1	**20 000t**	3	0.05	0.05	0.10	0.10	1.09
equal weight	App.C.1	15 000t	3	0.05	0.05	0.10	0.10	1.00
slope	App.C.1	15 000t	**5**	-	-	0.10	0.10	-
CMP1 tuned to slope	App.C.1	15 000t	3	0.05	0.05	0.10	0.10	1.36
Δ=5%	App.C.1	15 000t	3	0.05	0.05	**0.05**	**0.05**	0.83
Δ=15%	App.C.1	15 000t	3	0.05	0.05	**0.15**	**0.15**	0.90
Δ=20%	App.C.1	15 000t	3	0.05	0.05	**0.20**	**0.20**	0.91
γ=0.03	App.C.1	15 000t	3	**0.03**	**0.03**	0.10	0.10	0.70
γ=0.1	App.C.1	15 000t	3	**0.10**	**0.10**	0.10	0.10	1.12
q=5	App.C.1	15 000t	**5**	0.05	0.05	0.10	0.10	0.88
q=7	App.C.1	15 000t	**7**	0.05	0.05	0.10	0.10	0.86
TAC_{2018}=12.5kt	App.F.1	**12 500t**	3	0.05	0.05	0.10	0.10	0.79
TAC_{2018}=17.5kt	App.F.1	**17 500t**	3	0.05	0.05	0.10	0.10	1.01
TAC_{2018}=25kt	App.F.1	**25 000t**	3	0.05	0.05	0.10	0.10	1.45
CMP1.5	App.F.1	15 000t	3	0.05	0.05	0.10	0.10	1.00
CMP3	App.F.1	15 000t	3	0.05	0.05	0.10	0.10	1.70

Appendix H (see footnote 2)
Computation glitch

Table App.H.1: Performance measures for the two CMPs and two OMs (OM0, the baseline OM and Rob13, poor future recruitment) for the results presented in the main text and corrected for the glitch in the projections discovered subsequent to the presentation of this document; the pink highlights show instances where desired performance criterion specified by the Falmouth RBMS meeting (NAFO 2017b) has not been met. Values shown in **bold** indicate that the tuning parameter α was adjusted to achieve that result for that OM/CMP.

		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] term
		Perf. stats	$B^{5\text{-}9}_{2037}/B^{5\text{-}9}_{msy}$	$B^{5\text{-}9}_{2037} < B^{5\text{-}9}_{msy}$	$B^{5\text{-}9}_{2037} < 0.8B^{5\text{-}9}_{msy}$	$B^{5\text{-}9}_{lowest}/B^{5\text{-}9}_{msy}$	$B^{5\text{-}9}_{2022} < B^{5\text{-}9}_{2018}$		$(F_{2018\text{-}2037} > F_{msy}) > 0.3$	$B^{sp}_{2037}/B^{sp}_{2018}$	$B^{5\text{-}9}_{2037}/B^{5\text{-}9}_{2018}$	$(B^{5\text{-}9}_{2018\text{-}2037} < 0.3B^{5\text{-}9}_{msy}) > 0.1$	$B^{5\text{-}9}_{lowest}/B^{5\text{-}9}_{msy} < 0.3$	avC: 2018-2020
			median (90%PI)	Proportion	Proportion	median (90%PI)	Proportion		Count	median (90%PI)	median (90%PI)	Count	Proportion	median (90%PI)
		Criteria		<=0.5	<=0.25		<Ω	Ω					<=0.1	
CMP1	OM0	Original	**1.00** (0.45; 1.83)	0.49	0.22	0.81 (0.42; 1.07)	0.31	0.25	5	1.35 (0.56; 2.53)	0.89 (0.35; 1.59)	0	0.00	15.39 (15.10; 15
		Corrected	1.05 (0.62; 1.88)	0.44	0.14	0.73 (0.47; 0.95)	0.39	0.25	0	1.84 (0.84; 3.48)	1.19 (0.65; 2.03)	0	0.01	15.20 (14.96; 15
	Rob13	Original	1.04 (0.52; 1.86)	0.43	0.14	0.52 (0.29; 0.89)	0.42	0.25	6	1.11 (0.41; 2.29)	0.93 (0.40; 1.61)	0	0.05	15.39 (15.10; 15
		Corrected	1.06 (0.62; 1.83)	0.44	0.15	0.47 (0.25; 0.80)	0.39	0.25	6	1.45 (0.63; 3.00)	1.11 (0.66; 1.98)	0	0.11	15.20 (14.96; 15
CMP1ic20	OM0	Original	1.00 (0.51; 1.88)	0.49	0.18	0.78 (0.43; 1.05)	0.39	0.25	7	1.19 (0.51; 2.43)	0.91 (0.35; 1.58)	0	0.01	20.20 (19.90; 20
		Corrected	1.02 (0.57; 1.84)	0.47	0.18	0.69 (0.40; 0.94)	0.56	0.25	0	1.51 (0.69; 3.07)	1.09 (0.63; 1.94)	0	0.02	20.00 (19.75; 20
	Rob13	Original	0.98 (0.48; 1.73)	0.51	0.18	0.47 (0.25; 0.86)	0.49	0.25	9	0.89 (0.37; 2.10)	0.89 (0.37; 1.55)	0	0.08	20.20 (19.90; 20
		Corrected	0.93 (0.45; 1.72)	0.56	0.28	0.41 (0.17; 0.75)	0.56	0.25	8	1.03 (0.36; 2.61)	1.04 (0.49; 1.79)	3	0.18	20.00 (19.75; 20