Extensions of the Application of MSE to Gulf Menhaden

Doug S. Butterworth and Rebecca A. Rademeyer

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Summary

This document provides extends the MSE simulation-testing process suggested for Gulf Menhaden in Rademeyer and Butterworth (2019) to make specific suggestions for a Management Procedure (MP) which would provide a basis to impose catch limitations on the fishery, though only when survey indices suggest that resource abundance has dropped further than is desirable. In particular, a reasonably large number of robustness tests has been developed to check if the MP (harvest control rule, which would set a catch limit based on recent values of abundance survey indices) provides robust performance (particularly as regards safeguarding the resource from undue depletion) in the face of assessment and other uncertainties. It transpires that for the current range of annual catch sizes, such a rule is really necessary only in the future circumstances of increasing natural mortality or a period of poor recruitment. A tuning criterion is put forward as a basis to compare the performances of different MPs (essentially different choices for the parameters of the harvest control rule). Finally, a suggestion is made for the value of one of these parameters (that of a composite survey abundance index) below which a catch limit would be imposed; higher values for this choice would lead to a greater frequency of (unnecessarily) imposing a catch limit, whereas lower values result in smaller values for lowest level of egg production expected and higher values of the average annual variability in landings. The composite survey index has been above the threshold value suggested for the last ten years.

Introduction

This document provides extensions to the simulation-testing process of Management Strategy Evaluation (MSE) suggested in Rademeyer and Butterworth (2019) for Gulf menhaden. The objective is to develop a "Management Procedure" (MP) that provides a basis to impose catch limitations on the fishery, though only when survey indices suggest that abundance has dropped further than is desirable. The reasons for the desirability of such an approach are set out in Rademeyer and Butterworth (2019). The document first develops a basis to test the robustness of such an MP to alternative possible dynamics for the Gulf menhaden resource and its associated fishery. It then proceeds to provide the results of such tests for alternative possible MPs (essentially different harvest control rules), and provides suggestions on an appropriate trade-off choice on which to base the final selection of an MP.

Methods

The Base Case Operating Model (OM) taken forward here to reflect the dynamics of the Gulf menhaden population as a basis for MP testing mimics the BAM Base Model developed for the assessment of this resource (SEDAR, 2018).

The projections

Key aspects of the 20-year projections conducted are as follows, with full details (including some exceptions to the broad statements made below) set out in Appendix A. Note that the second, third and

last of the bullets below reflect adjustments from procedures followed in Rademeyer and Butterworth (2019).

- Unless otherwise specified, future dynamics are the same as for the BAM Base Model assessment.
- Future annual landings are drawn at random, with replacement, from the 2000-2017 values. The landings in 2018 are taken to be 525 635 mt. Since already half of 2019 has passed, a catch drawn at random from 2000-2017 is assumed for 2019 and then projected forward on this same basis, except when overridden by the harvest control rule, from 2020 to 2039.
- A maximum full fishing mortality (Fmax, taken as 105% of the estimated historical maximum full fishing mortality) is imposed to avoid unrealistic values, i.e. instances where the low size of the resource makes it unlikely the future intended catch could be taken, so that this is overridden by a value corresponding to Fmax. If future fishing mortality is computed to be above Fmax, then the selectivity for that year for age 1 is changed to 0.8 and the fishing mortality is recomputed. If this recomputed fishing mortality is still above Fmax, the landing is recalculated assuming an apical fishing mortality of Fmax (and the "widened" selectivity). The choice of 0.8 (increased from the 0.6 suggested in Rademeyer and Butterworth (2019)) has been made so as to reduce the chance that the resource is "protected" from undue depletion through inability to make the intended catch, rather than by the management rule (MP), and hence provides a more stringent test of the efficacy of that rule.
- A hockey-stick is assumed for the stock-recruitment curve, with the break taken as SSB=1.8×10^6 (in billions of eggs)[1] – see Figure 1.
- Future recruitment residuals are drawn at random, with replacement, from the 1978-2017 model estimated residuals.
- Future survey results are computed assuming log-normal observation error, with standard deviation computed from past (2005+) model estimated error. The selectivity and catchability values are taken to be as estimated for the BAM Base Model. Auto-correlation has been included in the future for the seine index, with the autocorrelation coefficient as estimated in the conditioning[2] of the OM concerned.

Robustness tests

Robustness tests have been developed over recent months in collaboration with a technical group consisting of David Chagaris, Peter Himchak, Robert Leaf, Genny Nesslage and Amy Schueller. These tests are listed in Table 1, and fall into two categories.

a) OMs considered to reflect alternative plausible realities to the Base Case OM, for which any MP considered for implementation must evidence reasonably robust performance (Type A).
b) Other OMs whose plausibility is low at best, but which have been included more with a view to check how far the MPs considered can be "pushed" before they provide inadequate performance) (Type B).

The Management Procedure considered

[1] For convenience all future reference to numbers of eggs ("SSB") will be in units of million billions, so that the break value indicated here becomes 1.8.

[2] There is no indication of auto-correlation in recruitment. For the gillnet index, auto-correlation varies substantially depending on the relative weighting assigned to the two indices, and could be appreciably negative, suggesting (questionably) enhanced precision of the index, so that it was decided to set it to zero when projecting.

The MP considered is empirical. It overrides and reduces a landing drawn from the historical set only if the value of a combined abundance index (J_y for year *y*) falls below a threshold level ($J_{threshold}$) specified for that index. If the threshold is breached, a TAC is set based of the value of this combined index, which is a weighted average of the gill net and seine indices, i.e.:

If $J_y < J_{threshold}$:

$$TAC_{y+1} = \gamma J_y \quad (1)$$

Figure 2 illustrates the rule for a initial choice of control parameter parameter values ($J_{threshold} = 0.8$ and $\gamma = 500$) for this "harvest control rule", and also plots historical values of the combined index. More details are given in Appendix B.

The performance of the MP is reported in terms of a number of performance statistics, which are listed and defined in Appendix C.

Results

Results for conditioning (i.e. fitting the BAM for) the Base Case and Robustness test OMs are shown in Appendix D. Note that results are required only for those tests which involve historical (and not projection only) changes to the Base Case, so that the OM has to be refitted. Throughout the conditioning appears satisfactory, with no indications of systematic lack of fit to the abundance indices.

Figure 3 provides a summary of certain key performance statistics for the Base Case and all the Robustness test OMs, indicating the differences in performance with and without the baseline MP (harvest control rule).

It is evident from Figure 3 that for the more plausible (Type A) OMs, only in the cases of Robustness tests 1.5 (increasing natural mortality *M* in the future) and 4.1 (a period of decreased recruitment in the future) is there any need for some restriction along the lines of a harvest control rule to counter undesirable depletion of the resource through harvesting. Hence it is only for these OMs that projection plots showing the differences in performance with and without the baseline MP in place are shown in the main text (Figure 4 and Table 2). The corresponding plots, together with a Table of performance statistics, for the rest of the OMs are provided in Appendix E.

MP variants

Appendix F shows results for the Base Case OM, and the 1.5 and 4.1 Robustness tests, for changed values of the three control parameters of the Baseline MP ($J_{threshold}$, γ and *p*). It is evident that as the value of *p* is increased, there is a trade-off between an increase in the lowest landing, but a decrease in the lowest egg production (denoted by SSB) value to be expected (this occurs because with a larger value of *p*, there is a greater delay in an adequate response to recent poor values for the resource indices). For further evaluations, the value of *p* was set to 2 to reflect a reasonable choice for this trade-off.

For readier comparison of results, the choice of the other two control parameter values ($J_{threshold}$ and γ) was made by fixing the value of $J_{threshold}$ and then tuning the corresponding value of γ so that the median lowest egg production (denoted by SSB) for the 4.1 Robustness test was equal to 1.0. One cannot expect to achieve the same minimum abundance in the Robustness tests as for the Base Case OM, as they reflect less net resource productivity; note that Figure 5 indicates that in the absence of landings, the lowest resource SSB on projection is a little over 3, whereas for both the 1.5 and 4.1 Robustness tests this

becomes only a little larger than 2. The choice of the value of median SSB = 1.0 as the criterion for tuning was that it similarly achieves a median lowest SSB on projection under harvest that is about 1.0 less than that under harvest for the Base Case OM (see Figure 5; in addition, projections are shown in Figure 6).

For reasons discussed below the tuned MP with $J_{threshold}$ = 0.9 seems to provide the best trade-offs, and is therefore "advocated". Further results for projections under this MP for the Base Case OM, and for the 1.5 and 4.1 Robustness tests, are shown in Figures 7 and 8, with performance statistics reported in Table 3.

As a sensitivity, the replacement of a linear by a quadratic harvest control rule was explored, i.e.:

If $J_y < J_{threshold}$:

$$TAC_{y+1} = \gamma {J_y}^2 \quad (2)$$

with $J_{threshold}$ fixed at 0.9 and γ tuned to 691 so that the median lowest egg production (denoted by SSB) for the 4.1 Robustness test was equal to 1.0.

This improves the lower 5%-ile for the lowest SSB for the two key Robustness tests, though not for the Base Case OM; but this is at the expense of lower lowest landings and higher average annual landings variability (AAV) (see Figure 9 and Table 3). As the benefits of this change appear outweighed by the disadvantages, the choice of a linear rule would seem to be preferred.

Discussion

Figure 5 provides information on the trade-offs involved in making an appropriate choice for the value of the $J_{threshold}$ control parameter. Once $J_{threshold}$ exceeds 0.9, the values of performance statistics shown stabilise, so there seems no advantage in setting this value higher in circumstances where that would have the adverse consequence of the catch limit needing to be imposed more frequently. On the other hand, when $J_{threshold}$ is set lower than 0.9, the lowest landing anticipated drops and AAV increases. This suggests that the choice of an MP with $J_{threshold}$ = 0.9, $\gamma = 500$ thousand mt and p = 2 could be appropriate. Note that the composite index has not fallen below this 0.9 value in the last ten years (see Figure 2).

These values do, however, follow given the tuning choice of a median lowest SSB of 1.0 for the 4.1 Robustness test. While a basis for choosing this value is offered above, a more or less conservative MP could be obtained by increasing or decreasing this choice for the tuning value.

References

Rademeyer, R.A. and Butterworth, D.S. 2019. An initial illustrative example of the application of MSE to Gulf Menhaden to address Issues related to MSC certification and Ecosystem-related Reference Points. Document circulated for internal discussions, January 2019. (17pp)

SEDAR. 2018. SEDAR 63 – Gulf Menhaden Stock Assessment Report. SEDAR, North Charleston SC. 352 pp. available online at: http://sedarweb.org/sedar-63

Table 1: List of the robustness tests used in MP testing. Note that "No refitting" means that the test involves changes in the future only. Type A OMs are considered to reflect alternative plausible realities to the Base Case OM, while the plausibility of Type B OMs is low at best, but these OMs have been included more with a view to check how far the MPs considered can be "pushed" before they provide inadequate performance.

	Base Case	Robustness	No refitting	Type
1. Alternative choices for *M*				
1.1		M'(a)=1.2		A
1.2		M'(a)=M(a)*exp(-0.1(a-2))		A
1.3	Lorenzen mortality vector	M(4+)=1.67		A
1.4		M increases linearly by 40% over next 20 years	x	B
1.5		M increases linearly by 20% over next 20 years	x	A
2. Alternative catch selectivity function				
2.1	S(3) = S(4+) = 0.87	S(3) = S(4+) = 1.0		A
2.2		S(3) = S(4+) = 0.74		A
2.3	S(1) in future as estimated in past	S(1) in future, double that estimated in the past	x	B
3. Indices				
3.1	Linear relationship to abundance: I = q*B	sqrt relationship to abundance I =q*sqrt(B)		A
3.2	Weighting: 4:1 gillnet to seine	Weighting: 1:1 gillnet to seine		A
3.3		Observation error = 0.2	x	A
3.4	Observation error = 0.11	Observation error = 0.3	x	B
3.5		Observation error = 0.5	x	B
3.6	Flat 2+ gillnet selectivity in the future	Increasing 2+ sel. slope over the next 20 years (to 0.4 age 4 in 20yrs)	x	B
4. Period of future poor recruitment				
4.1	Future rec. drawn at random from past values	Five (2020-2024) years of bad recruitments (50%)	x	A
5. Alternative stock-recruitment function				
5.1	Hockey-stick, hinge-point=1.8 billion eggs	Hockey-stick, hinge-point=2.2 billion eggs	x	A
6. Under-reporting of future catches (which is not noticed)				
6.1	Future catches=TAC	Future catches = 1.1TAC (presence of these IUU catches is not realised)	x	A
7. Maximal possible fishing mortality				
7.1	Fmax for projections = 1.05*Fmax historical	Fmax for projections = 1.20*Fmax historical	x	A

Table 2: Performance statistics for the Base Case OM and Robustness tests 1.5 and 4.1 with and without the management rule (Baseline MP).

Performance statistics	Base Case			Robustness 1.5			Robustness 4.1		
NO RULE	Median	10	90	Median	10	90	Median	10	90
Related to catch									
Average landing 2020-2039	494.7	479.2	517.5	484.2	387.8	509.3	371.9	169.9	500.7
Av landing no rule	494.7	479.2	517.5	484.2	387.8	509.3	371.9	169.9	500.7
Av landing with rule	-			-			-		
Lowest landing (2020-2039)	379.9	379.9	425.6	379.9	72.2	400.7	181.9	41.0	379.9
2020 landing	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8
Related to abundance									
Egg(2020)	3.32	2.73	4.10	3.32	2.73	4.10	3.32	2.73	4.10
Egg(2040)	3.17	2.21	4.04	0.78	0.08	1.97	0.59	0.10	3.80
Egg lowest (2020-2039)	2.00	1.44	2.38	0.76	0.08	1.50	0.30	0.05	1.06
Prob Egg(2040) lowest	6			63			9		
Related to catch variability									
AAV 2020-2039	0.15	0.12	0.19	0.16	0.12	0.21	0.20	0.14	0.27
AAV with rule	-			-			-		
Other									
Fraction years rule applied	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
True negative	0.0			0.0			0.0		
Fals negative	0.0			0.0			0.0		
False positive	0.0			0.0			0.0		
True positive	100.0			100.0			100.0		
Prob rule in 2020	0			0			0		
Fraction years Hit Fmax	0	0	0.15	0.35	0.1	0.65	0.85	0.25	0.9
Hit Fmax, landings not taken	0	0	0	0.05	0	0.35	0.65	0	0.85
WITH BASELINE MP	Median	10	90	Median	10	90	Median	10	90
Related to catch									
Average landing 2020-2039	483.8	448.6	511.0	423.9	368.9	466.1	382.4	204.5	459.3
Av landing no rule	494.8	477.8	519.1	497.8	477.0	519.6	498.1	467.3	529.6
Av landing with rule	344.4	0.0	389.5	321.0	234.5	360.0	277.2	145.9	389.0
Lowest landing (2020-2039)	364.2	272.8	400.7	246.9	138.4	336.1	176.5	43.3	300.1
2020 landing	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8
Related to abundance									
Egg(2020)	3.32	2.73	4.10	3.32	2.73	4.10	3.32	2.73	4.10
Egg(2040)	3.19	2.37	4.04	1.59	0.87	2.33	3.16	2.18	4.01
Egg lowest (2020-2039)	2.01	1.48	2.38	1.23	0.67	1.66	0.51	0.14	1.31
Prob Egg(2040) lowest	5			25			0		
Related to catch variability									
AAV 2020-2039	0.16	0.13	0.20	0.17	0.12	0.23	0.18	0.14	0.24
AAV with rule	0.15	0.00	0.26	0.17	0.10	0.24	0.16	0.10	0.27
Other									
Fraction years rule applied	0.10	0.00	0.25	0.40	0.20	0.60	0.53	0.35	0.80
True negative	10.1			43.7			55.5		
Fals negative	0.8			1.4			0.4		
False positive	6.8			12.5			5.8		
True positive	82.4			42.5			38.3		
Prob rule in 2020	0			0			0		
Fraction years Hit Fmax	0	0	0.1	0.1	0	0.2	0.3	0.1	0.45
Hit Fmax, landings not taken	0	0	0	0	0	0	0.05	0	0.15

Table 3: Performance statistics for the Base Case OM and Robustness tests 1.5 and 4.1 without the management rule ("No rule"), with the advocated MP ("MP_2_0.9") and with the quadratic MP ("MP_2_0.9_quad").

	Base Case									Robustness test 1.5									Robustness test 4.1								
	No rule			MP_2_0.9			MP_2_0.9_quad			No rule			MP_2_0.9			MP_2_0.9_quad			No rule			MP_2_0.9			MP_2_0.9_quad		
	Median	10	90	Median	10	90	Median	10	90	Median	10	90	Median	10	90	Median	10	90	Median	10	90	Median	10	90	Median	10	90
Related to catch																											
Average landing 2020-2039	494.7	479.2	517.5	472.3	440.8	502.4	479.8	445.4	509.6	363.3	288.9	432.8	414.0	364.5	455.0	417.4	356.3	452.6	371.9	169.9	500.7	395.9	323.8	439.5	393.9	344.6	438.0
Av landing no rule	494.7	479.2	517.5	496.3	476.4	517.4	495.0	476.4	519.4	363.3	288.9	432.8	501.1	465.7	530.0	500.5	462.5	527.8	371.9	169.9	500.7	495.4	470.3	526.7	494.4	470.0	521.3
Av landing with rule	-			390.0	330.1	426.7	415.6	325.4	496.6	-			347.0	271.5	388.5	344.8	255.1	406.6	-			290.9	221.3	352.8	277.2	202.6	363.5
Lowest landing (2020-2039)	379.9	379.9	425.6	347.5	261.6	397.2	322.2	190.0	400.7	14.6	2.8	69.3	236.1	140.2	318.3	167.9	73.2	265.3	181.9	41.0	379.9	174.7	84.0	254.2	97.3	31.9	191.3
2020 landing	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8
Related to abundance																											
Egg(2020)	3.32	2.73	4.10	3.32	2.73	4.10	3.32	2.73	4.10	3.32	2.73	4.10	3.32	2.73	4.10	3.32	2.73	4.10	3.32	2.73	4.10	3.32	2.73	4.10	3.32	2.73	4.10
Egg(2040)	3.17	2.21	4.04	3.20	2.37	4.07	3.20	2.37	4.05	0.01	0.00	0.07	1.63	0.89	2.39	1.76	1.01	2.40	0.59	0.10	3.80	3.19	2.37	4.07	3.20	2.37	4.05
Egg lowest (2020-2039)	2.00	1.44	2.38	2.02	1.60	2.40	2.01	1.52	2.39	0.01	0.00	0.07	1.32	0.77	1.71	1.31	0.88	1.67	0.30	0.05	1.06	1.00	0.48	1.50	1.00	0.60	1.51
Prob Egg(2040) lowest	6			5			5			100	100	100	24			19			9	9	9	0			0		
Related to catch variability																											
AAV 2020-2039	0.15	0.12	0.19	0.17	0.12	0.21	0.18	0.12	0.25	0.22	0.17	0.28	0.17	0.12	0.25	0.25	0.17	0.35	0.20	0.14	0.27	0.21	0.16	0.27	0.30	0.21	0.42
AAV with rule	-			0.16	0.05	0.24	0.20	0.05	0.43	-			0.17	0.12	0.24	0.29	0.19	0.46	-			0.23	0.15	0.35	0.41	0.25	0.68
Other																			0								
Fraction years rule applied	0.00	0.00	0.00	0.20	0.05	0.40	0.20	0.05	0.40	0.00	0.00	0.00	0.60	0.35	0.70	0.60	0.35	0.70	0.00	0.00	0.00	0.50	0.35	0.65	0.50	0.30	0.65
True negative	0.0			19.4			20.8			0.0			58.0			58.4			0.0			48.7			47.1		
Fals negative	0.0			2.6			2.3			0.0			1.5			1.4			0.0			1.9			2.1		
False positive	0.0			11.4			11.6			0.0			11.6			11.9			0.0			10.0			10.3		
True positive	100.0			66.8			65.4			100.0			29.0			28.4			100.0			39.5			40.6		
Prob rule in 2020	0			0			0			0			0	0	0	0	0	0	0			0	0	0	0	0	0
Fraction years Hit Fmax	0	0	0.15	0	0	0.05	0	0	0.05	0.6	0.4	0.75	0.05	0	0.1	0.05	0	0.15	0.85	0.25	0.9	0.05	0	0.15	0.05	0	0.1
Hit Fmax, landings not taken	0	0	0	0	0	0	0	0	0	0.4	0.25	0.55	0	0	0	0	0	0	0.65	0	0.85	0	0	0	0	0	0

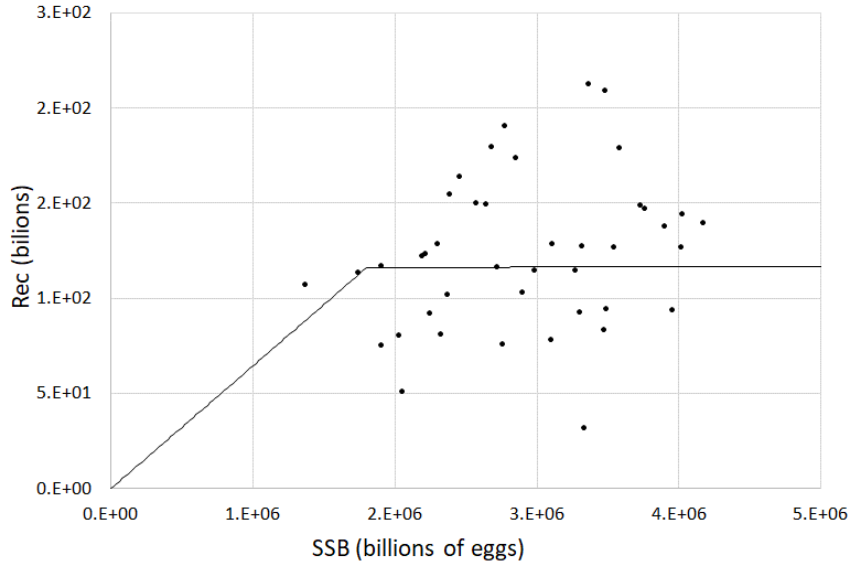

Figure 1: Hockey-stick stock recruitment curve for Gulf Menhaden which is used to compute projected recruitment. The data points are those estimated in the BAM Base Model.

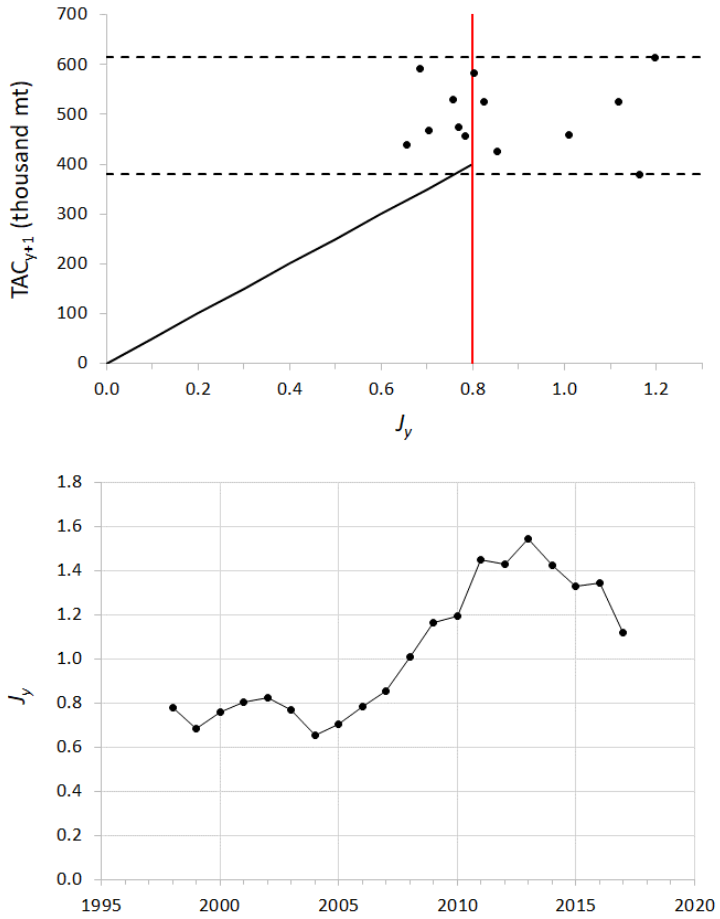

Figure 2: Top plot: Illustration of the management rule (MP) for set control parameter values considered in the example for which results are reported. The horizontal dash lines show the 2000-2017 minimum and maximum landing values. The historical (1999-2017) J_y vs TAC_{y+1} are shown as black dots. Bottom plot: Historical combined index J_y values.

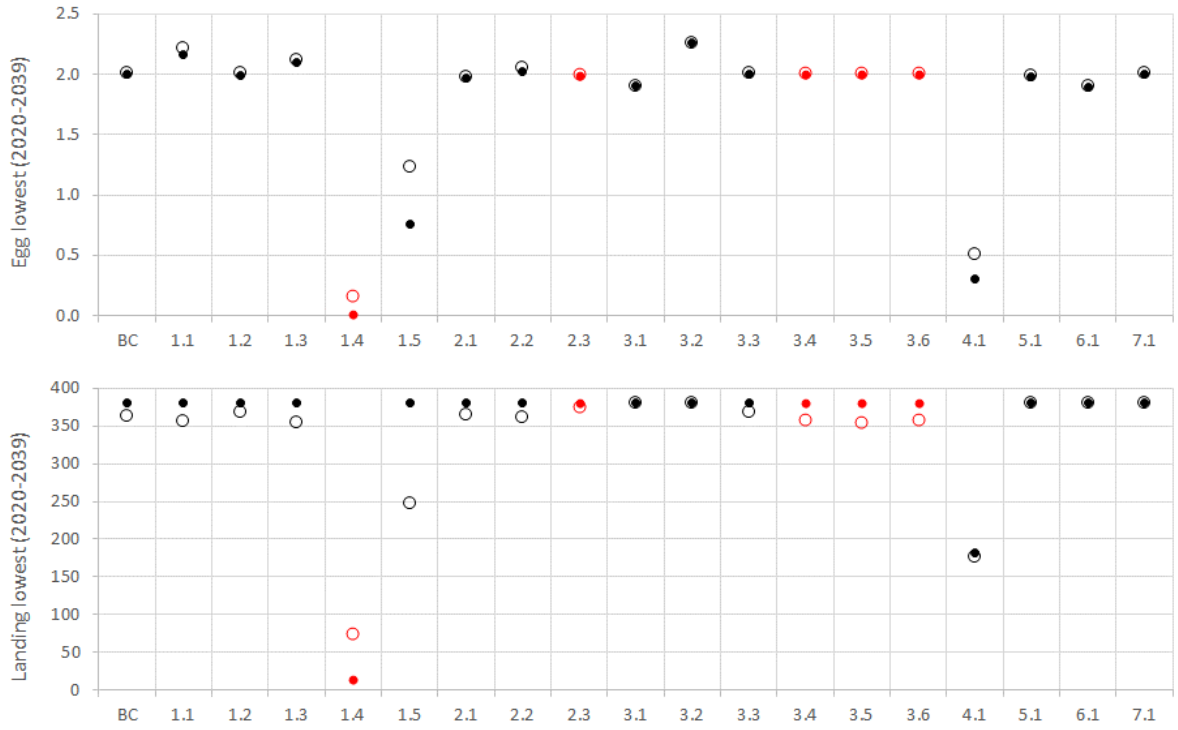

Figure 3: Median lowest egg production and landing values over the 2020-2039 projection period for each of the Base Case and Robustness test OMs without (full circles) and with (open circles) the Baseline MP. Type B OMs are shown in red.

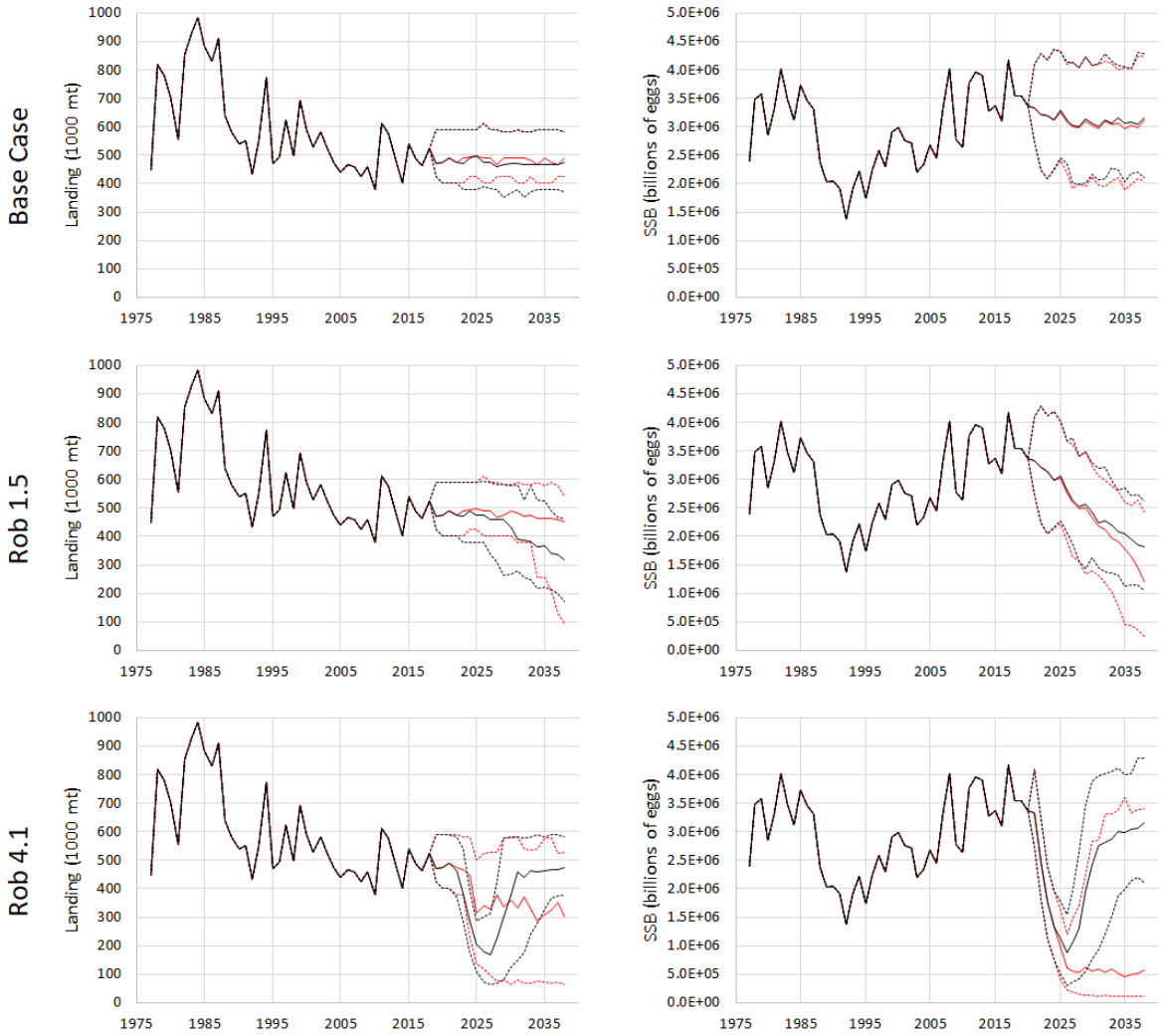

Figure 4: Historical estimates and projected 20-year median with 10%- and 90%-iles for a series of quantities for the **Base Case** OM and **Robustness tests 1.5 and 4.1**, without (red lines) and with the management rule (Baseline MP, black lines)

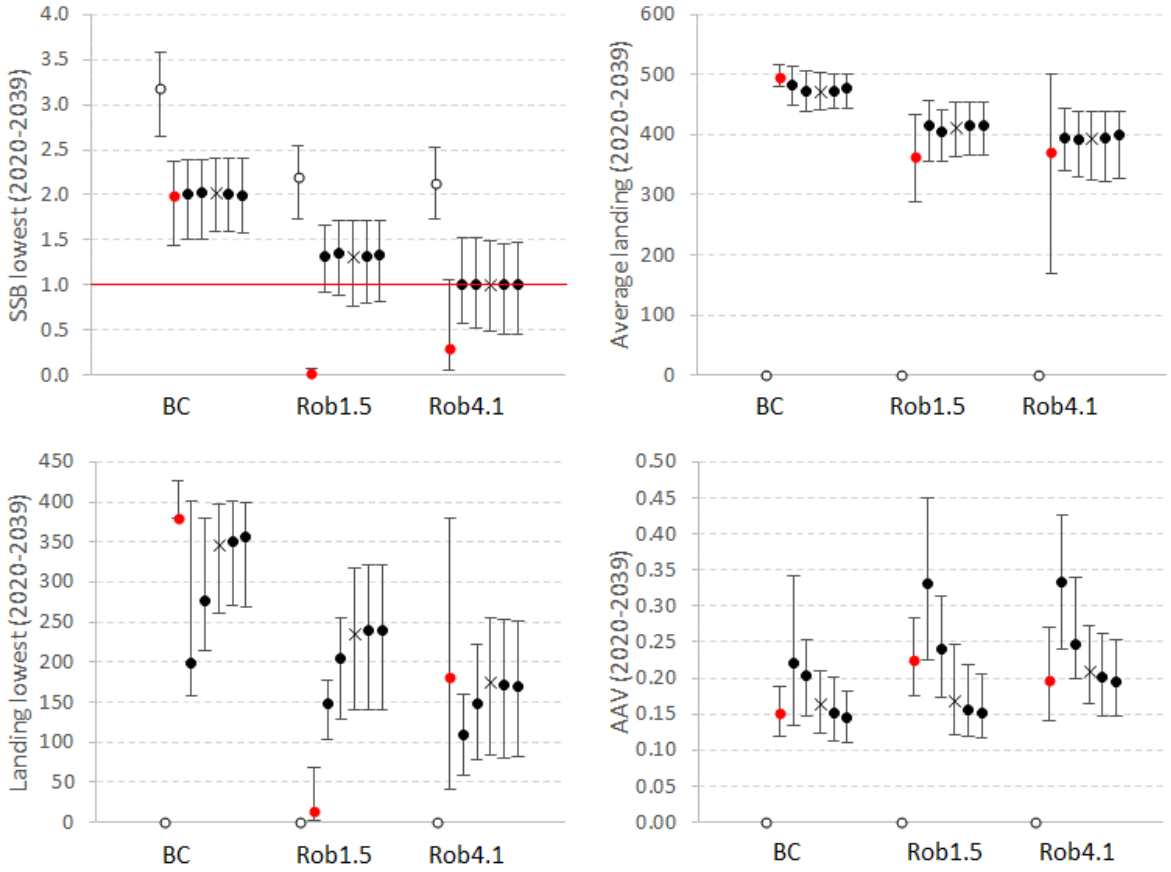

Figure 5: Performance statistics for no landings (for SSB lowest only) (open dot), no harvest control rule (red dot) and MP variants with p = 2 for varying the value of the $J_{threshold}$ control parameter. The γ control parameter value is tuned so that the median SSB for Robustness test 4.1 (poor future recruitment trial) is equal to 1 (shown by the horizontal red line). Results (median with 10%- and 90%-iles) are shown for the Base Case OM and the Robustness tests 1.5 and 4.1. The ($J_{threshold}$; γ) combinations shown are (0.7 ; 293); (0.8 ; 400); (0.9 ; 500) – advocated and shown by crosses; (1.0 ; 505) and (1.1 ; 500).

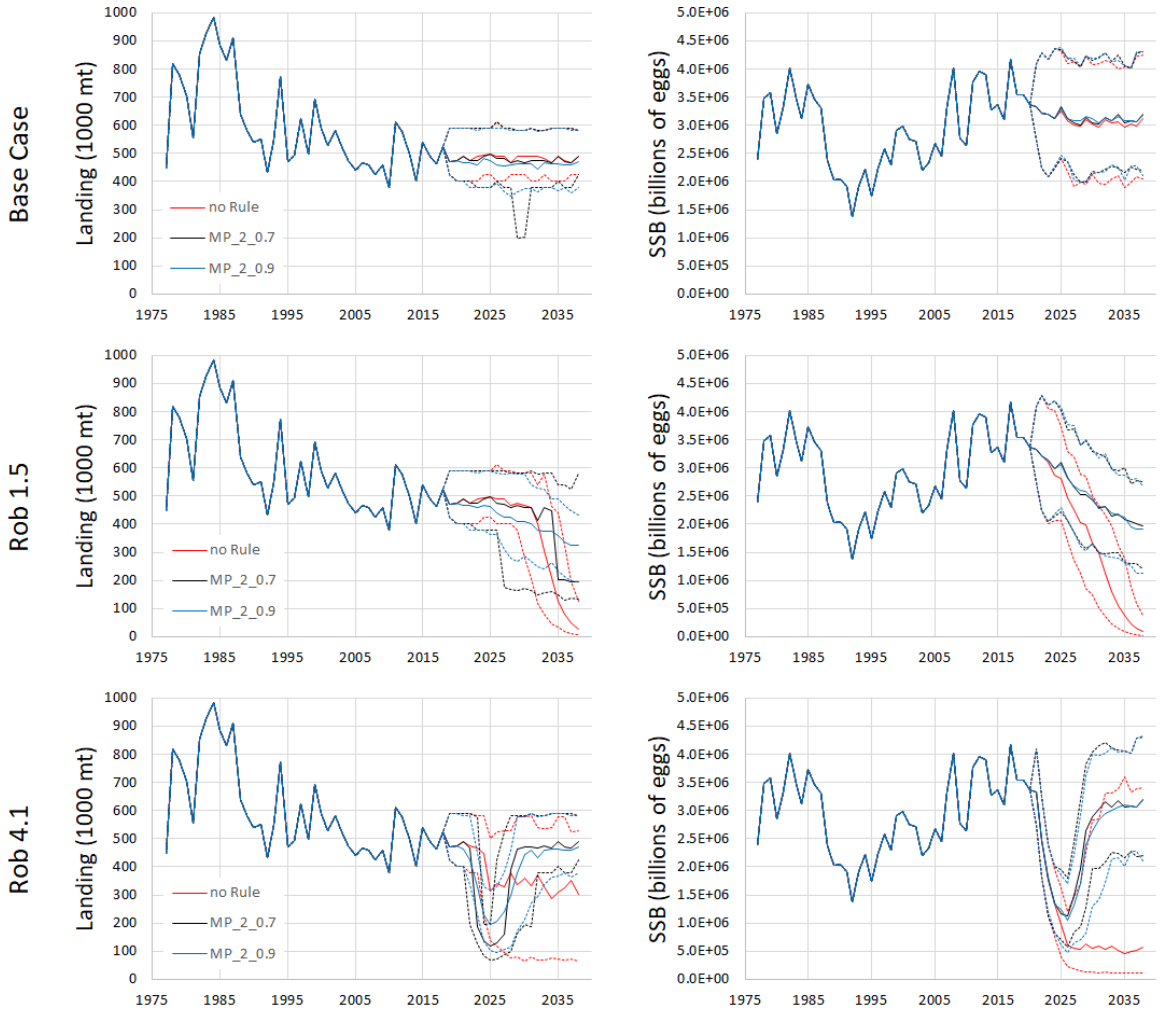

Figure 6: Median (full line) with 10%- and 90%-iles for projected landings and SSB for no harvest control rule and MP variants with p = 2 for $J_{threshold}$ = 0.7 and = 0.9, for the Base Case OM and Robustness tests 1.5 and 4.1.

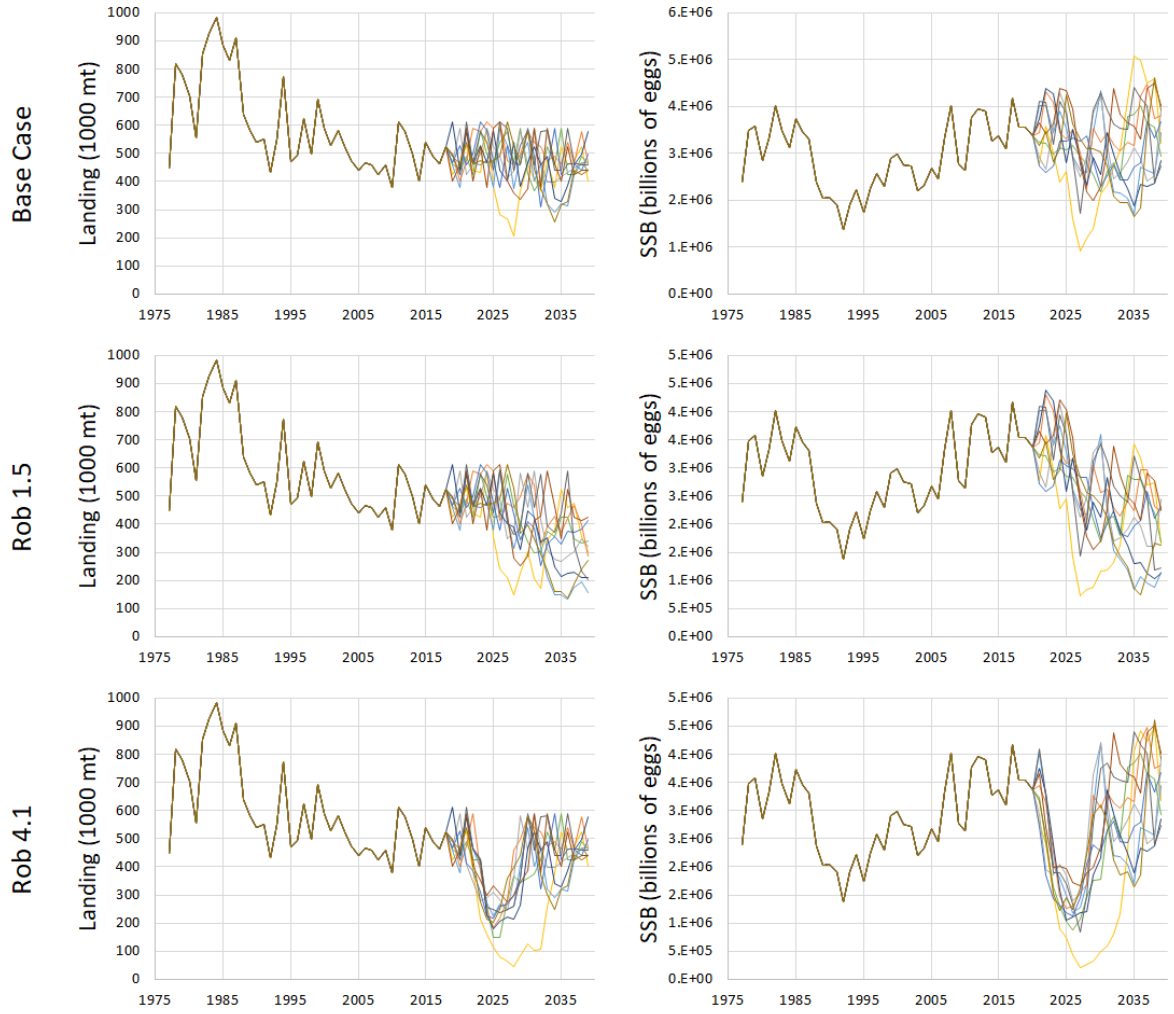

Figure 7: Worm plots for projected landings and SSB for the advocated MP variant with p = 2 for $J_{threshold} = 0.9$, for the Base Case and Robustness tests 1.5 and 4.1.

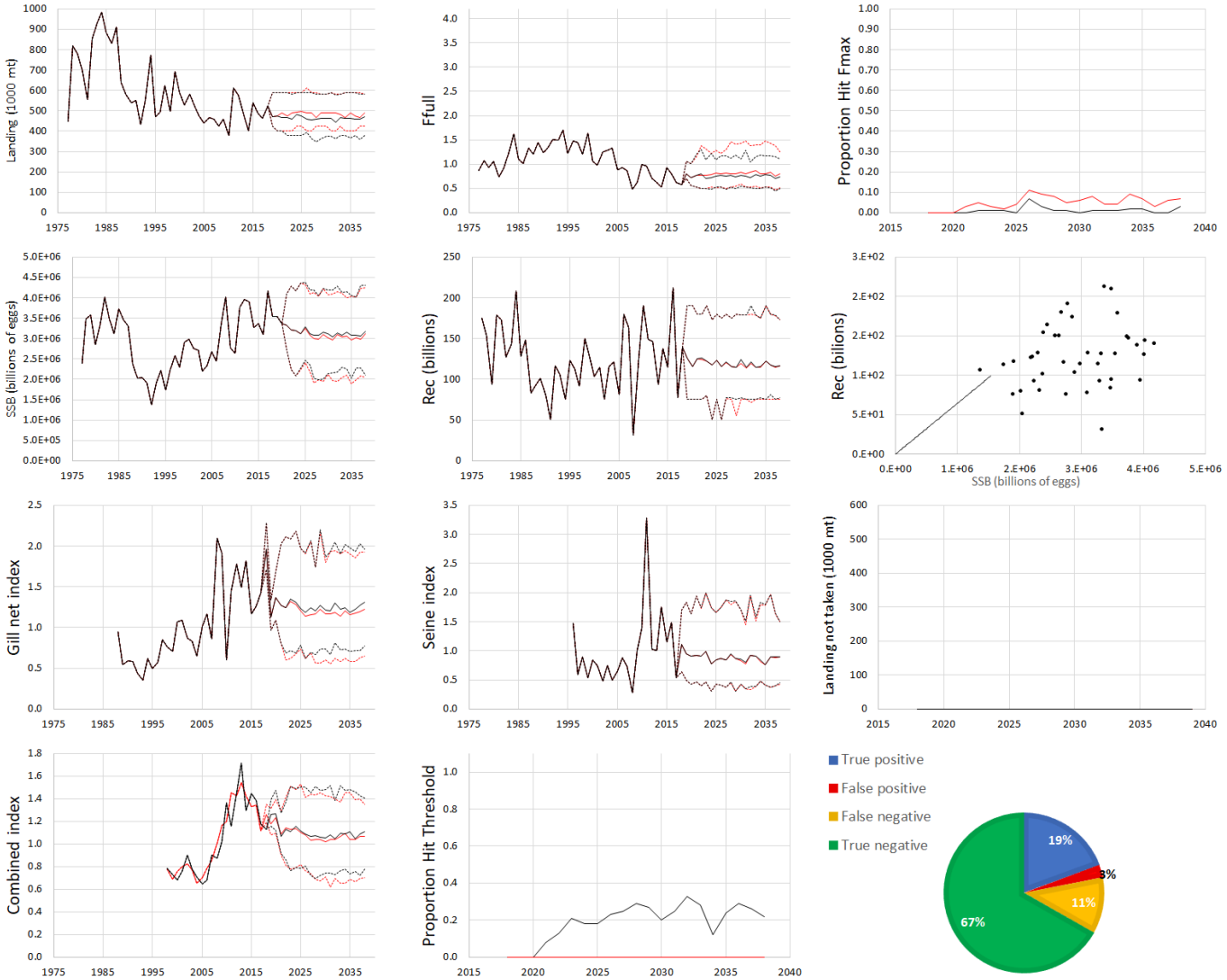

Figure 8a: Historical estimates and projected 20-year median with 10%- and 90%-iles for a series of quantities for the Base Case OM, without (red lines) and with (black lines) the advocated management rule.

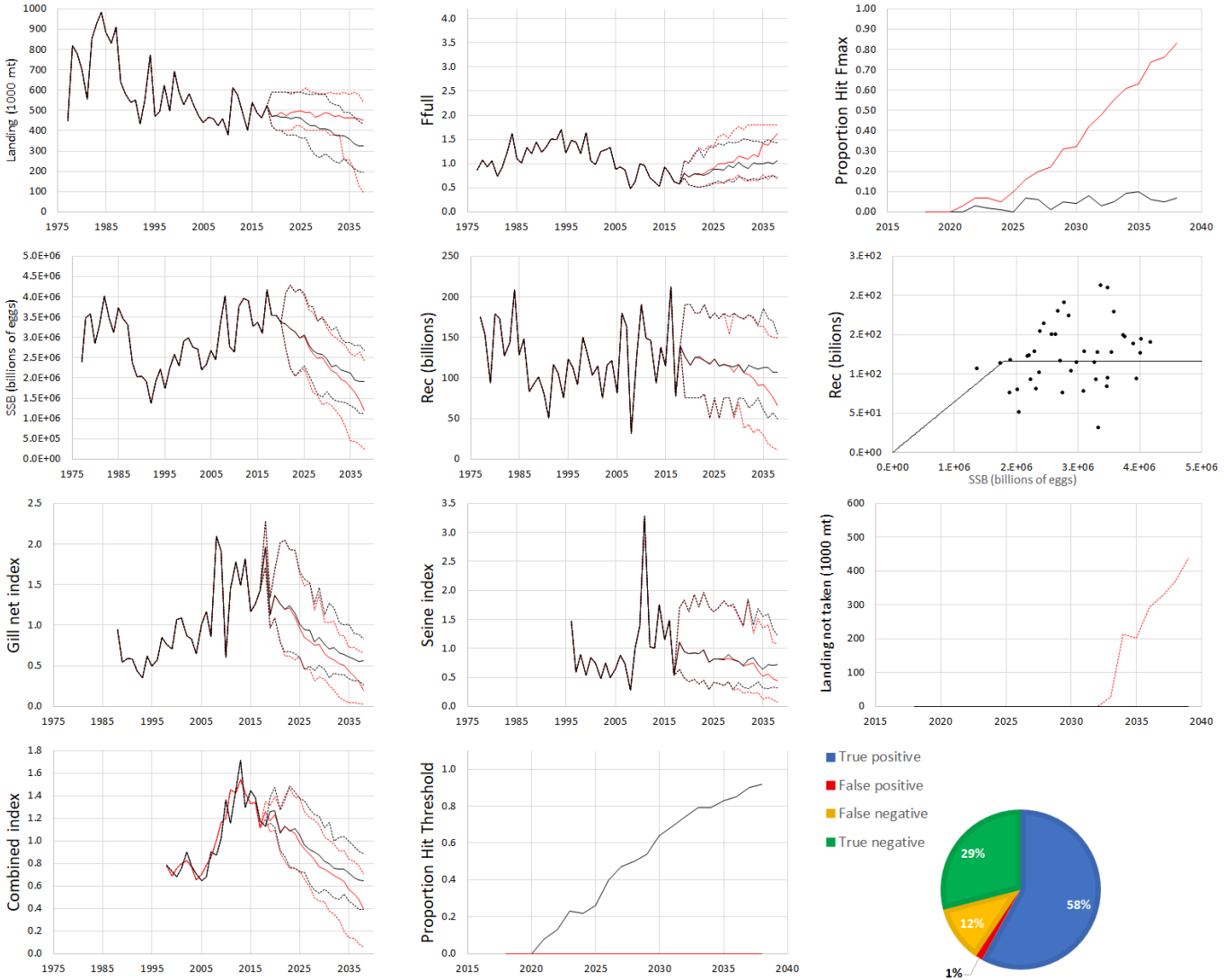

Figure 8b: Historical estimates and projected 20-year median with 10%- and 90%-iles for a series of quantities for Robustness test 1.5, without (red lines) and with (black lines) the advocated management rule.

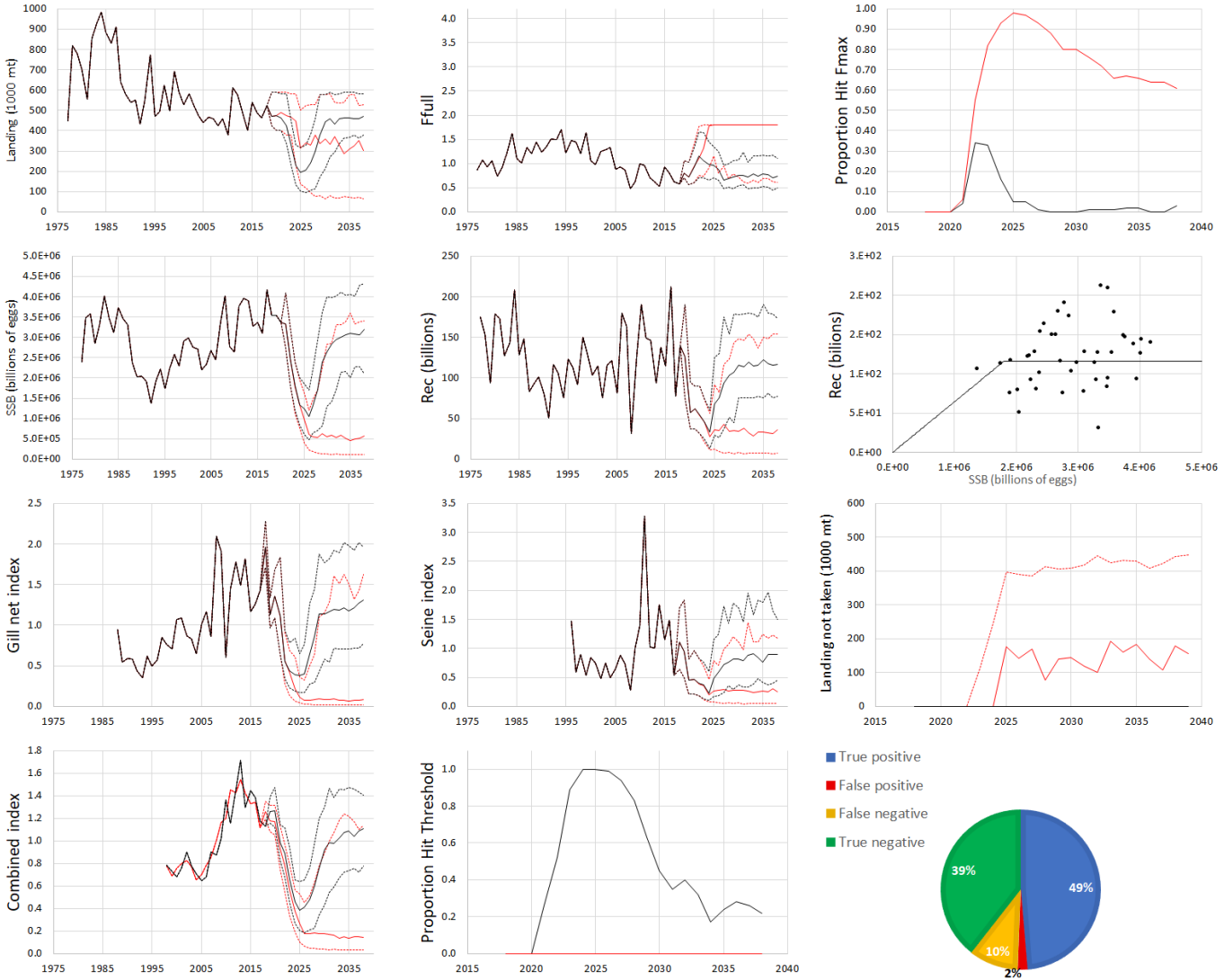

Figure 8c: Historical estimates and projected 20-year median with 10%- and 90%-iles for a series of quantities for Robustness test 4.1, without (red lines) and with (black lines) the advocated management rule.

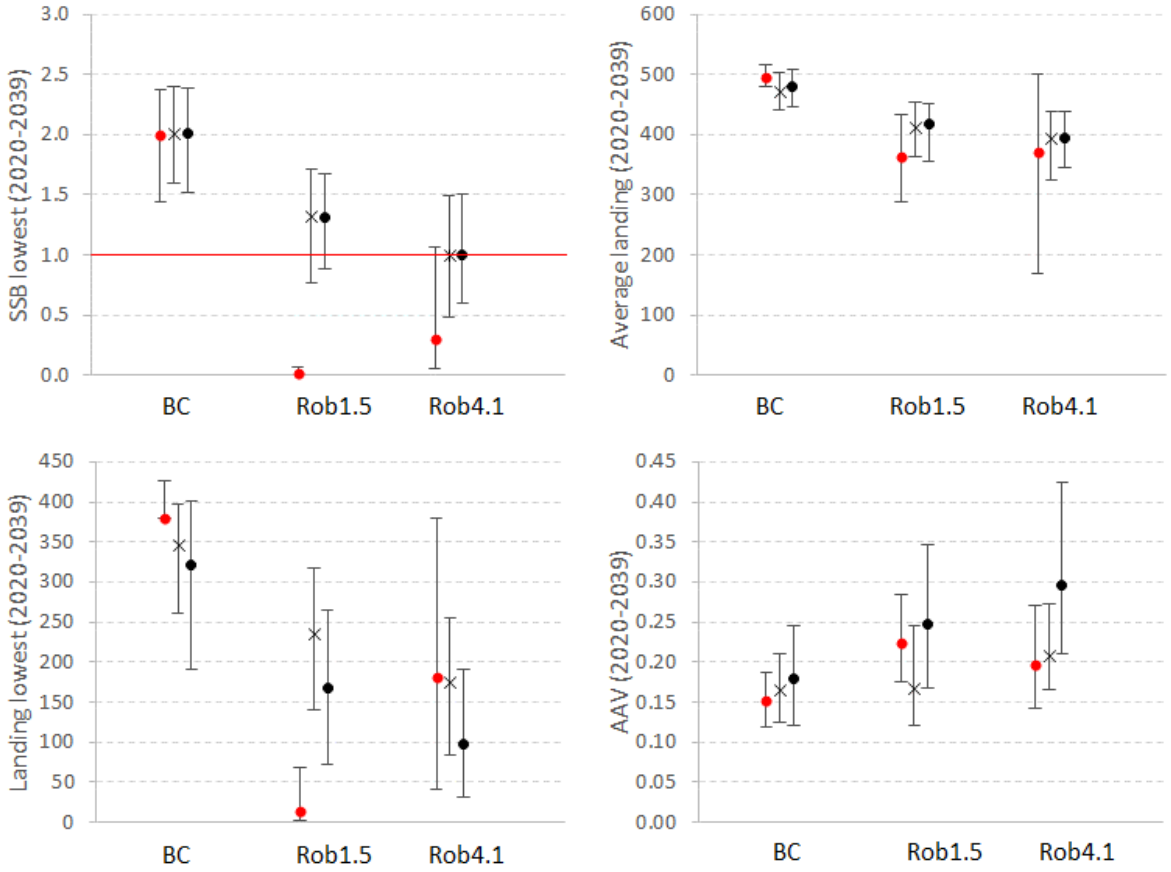

Figure 9: Performance statistics for a) no harvest control rule (red dot), b) the advocated MP variant with p = 2 and $J_{threshold}$ = 0.9 (cross) and c) and MP variant with a quadratic instead of linear function (i.e. $TAC_{y+1} = \gamma {J_y}^2$), with p = 2 and $J_{threshold}$ = 0.9. As for the linear MP, the γ control parameter value is tuned so that the median SSB for the 4.1 Robustness test (poor future recruitment trial) is equal to 1 (shown by the horizontal red line). Results (median with 10%- and 90%-iles) are shown for the Base Case OM and the 1.5 and 4.1 Robustness tests.

Appendix A – Projection methodology details

Projections into the future under a specific management rule (MP) are performed using the following steps.

Step 1: Begin-year numbers at age

The components of the numbers-at-age vector at the start of 2018 ($N_{2018,a}$: *a* =1,…, *m* – where *m* is a plus-group) are obtained from the MLEs for an assessment of the resource. The assessment used here is the BAM Base model.

Step 2: Annual landings

For 2018, $L_{2018} = 525\,635$ mt. (A.1)

From 2019 onwards:

L_y is drawn at random, with replacement, from the observed 2000-2017 landings.

From 2020, if the combined abundance index (see equation B2 In Appendix B) for year *y*-1 is below the threshold value, then a TAC applies to year *y* is computed using the MP (harvest control rule) (see equation (1) of the main text and Appendix B).

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

The $L_{y,a}$ values are obtained under the assumption that the commercial selectivity function (S_a) estimated for the most recent period in the BAM Base Model (1996+) continues in the future. The full fishing mortality F_y is solved iteratively to achieve the annual landing by mass:

$$L_y = \sum_{a=1}^{m} w_a^{mid} N_{y,a} S_a F_y \left(1 - e^{-Z_{y,a}}\right)/Z_{y,a} \quad \text{(A.2)}$$

where

w_a^{mid} is the time invariant weight-at-age in the middle of the year,

$N_{y,a}$ is the number-at-age vector for age *a* at the start of year *y* (with *m* the plus group),

and

$Z_{y,a} = F_y S_a + M_a$ is the total mortality-at-age vector for age *a* and year *y*.

M_a is the natural mortality-at-age *a* (input).

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

$$N_{y+1,1} = R_{y+1} \quad \text{(A.3)}$$

$$N_{y+1,a+1} = N_{y,a} e^{-Z_{y,a}} \quad \text{for } 1 \le a \le m-2 \quad \text{(A.4)}$$

$$N_{y+1,m} = N_{y,m-1} e^{-Z_{y,m-1}} + N_{y,m} e^{-Z_{y,m}} \quad \text{(A.5)}$$

If the intended landing is such that the apical fishing mortality (that at the age at which selectivity is 1) exceeds Fmax, then the selectivity for that year for age 1 is increased to 0.8 and the fishing mortality recomputed. If this recomputed apical fishing mortality is still above Fmax, the landings are instead limited to those corresponding to Fmax (and this "widened" selectivity). Fmax has been selected as 5% above the maximum that occurred historically. The choice of 0.8 (increased from the 0.6 suggested in Rademeyer and Butterworth (2019)) has been made so as to reduce the chance that the resource

is “protected” from undue depletion through inability to make the intended catch rather than by the management rule (MP), and hence provides a more stringent test of the efficacy of that rule.

Step 4: Recruitment

Expected values (in log space) for future recruitments (R_y) are provided by a hockey-stick stock-recruitment relationship:

$$R_y = \begin{cases} R & if\ SSB_y \geq SSB_{threshold} \\ \frac{R}{SSB_{threshold}} SSB_y & if\ SSB_y < SSB_{threshold} \end{cases} \quad \text{(A.6)}$$

where

R is the geometric average of the model estimated past (1977-2017) values,

$SSB_{threshold}$ is a fixed value (1.8 million billion eggs produced),

and

$$SSB_y = \sum_{a=2}^{m} f_a N_{y,a} \quad \text{(A.7)}$$

with

$f_a = \rho_a mat_a fec_a$ the reproductive output of a female fish of age *a*,

ρ_a is the proportion of female at age *a*,

mat_a is the proportion mature at age *a*, and

fec_a is the fecundity at age *a*.

When projecting, error is added to this expected value, so that for simulation replicate *s*, if

$S = \{\varepsilon_y = lnR_y - lnR : y = 1977, \dots, 2017\}$, then when projecting:

$R_y^s = Re^{\varepsilon^*}$

where ε^* is drawn at random with replacement from the set I of ε_y values

Although the Recruitment vs Eggs produced plot from the BAM Base Model assessment shows no obvious relationship between the two, clearly there must eventually be some reduction in the number of recruits to be expected as egg production falls. We have taken the fairly standard approach here of assuming a hockey stick relationship whether the hinge-point occurs at the lowest historical annual egg production estimated, though for robustness and precaution a slightly higher value of 180 000 billion eggs was chosen so as to avoid undue influence from the lowest two historical values.

Step 5:

The projected values for numbers-at-age are used to generate values of the abundance indices I_{y+1}^i (in terms of numbers), and similarly for following years. 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 with autocorrelation is therefore added to the expected value of the abundance index in question (in log space), i.e.:

$$I_y^i = q^i B_y^i e^{\varepsilon_y^i} \quad \text{(A.8)}$$

with

$$\varepsilon_y^i = \varphi_y^i - \rho^i \varphi_{y-1}^i \quad \text{(A.9)}$$

and φ_y^i from $N\left(0, \left(\sigma^i\right)^2\right)$ (A.10)

where

B_y^i is the abundance available to and indexed by the survey:

$$B_y^i = \sum_{a=1}^{m} S_a^i N_{y,a} e^{-Z_{y,a} T^i/12} \quad \text{(A.11)}$$

T^i is the timing of the survey (in month) ($T^i = 6$ for the gill net index and 3 for the seine index).

The autocorrelation coefficient ρ^i for the gillnet index, computed from the historical estimated residuals for the Base Case OM is -0.517 and varies considerably if the relative weighting of the two indices is changed. Negative values of auto-correlation enhance the effective precision of an index, the realism of which is questionable. It was therefore decided to set $\rho^{gill} = 0$ in projections. For the seine index, ρ^i is set at 0.134, the value computed from the historical estimated residuals for the Base Case OM.

The survey selectivities are assumed to remain unchanged. The catchabilities are taken to be those estimated in the OM (the BAM Base Model assessment).

The residual standard deviations σ^i are estimated from the model fit. Since residuals seem to have increased in recent years, the residuals from 2005 onwards have been used for their computation:

$$\sigma^i = \sqrt{\frac{1}{\sum_{y=2005}^{2017} 1} \sum_{y=2005}^{2017} \left(ln I_y^i - ln \hat{I}_y^i\right)^2} \quad \text{(A.12)}$$

where I_y^i is the observed index value in year *y* for survey *i* and $\hat{I}_y^i$ is the corresponding model estimated value this yields σ^i =0.11 for the gill net index and 0.41 for the seine index.

Step 6:

Steps 1-5 are repeated for each future year in turn for as long a period as desired.

Appendix B – The Management Rule (Management Procedure)

The management rule (MP) is empirical. It only overrides and reduces a landing drawn from the historical set if the value of a combined abundance index (see below) falls below a threshold level specified for that index. The basis for the associated computations is set out below:

If $J_y < J_{threshold}$:

$$TAC_{y+1} = \gamma J_y \quad \text{(B.1)}$$

where

TAC_y is the catch limit that applies for year *y*,

$J_{threshold}$ (no units) and γ (units: thousand mt) are control parameter (tuning) values (the initial choices (baseline MP) are $J_{threshold} = 0.8$ and $\gamma = 500$); Figure 2 illustrates the rule for these choices for these control parameter values, and

J_y is a measure of the immediate past level in the abundance indices that are available to use for calculations for year *y*:

$$J_y = \frac{1}{p}\sum_{y'=y-p+1}^{y}\left[\left(w_{gill}\frac{I_{y'}^{gill}}{I_{2017}^{gill}} + w_{seine}\frac{I_{y'}^{seine}}{I_{2017}^{seine}}\right)\Big/\left(w_{gill} + w_{seine}\right)\right] \quad \text{(B.2)}$$

with

I_y^{gill} and I_y^{seine} being the observed gill net and seine indices, respectively, in year *y*,

w_{gill} and w_{seine} being the weights given to each index ($w_{gill} = 4$ and $w_{seine} = 1$ for the baseline MP, and correspond roughly to inverse variance weighting given the standard deviations of the residuals in the BAM Base Model fit),

and *p* being a control parameter (*p* = 3 for the baseline MP); this parameter is used to smooth away some of the noise in the index by averaging over a few years rather than consider only the most recent year.

Note the assumption has been made that when a TAC is set in year *y* for year *y*+1, values of these abundance indices will be available for the current year *y*.

Appendix C – Performance statistics

Landings-related

1) Average landing 2020-2039
2) Average landing in year where control rule was not applied
3) Average landing in years where control rule was applied
4) Lowest landing over 2020-2039
5) Landing in 2020

Abundance (egg-production, Egg)-related

1) Egg(2020)
2) Egg(2040)
3) Lowest Egg over 2020-2040
4) Probability that Egg(2040) is the lowest in the series from 2020 to 2040 (coarse indication of whether recovery is achieved after a decline)

Catch variability-related

1) Average annual absolute percentage change in landings (AAV) over 2019 to 2039
2) When control rule is applied and landing is decreased, average change in landing

Other

1) Fraction of years from 2020 to 2039 that control rule is applied
2) Fraction of years from 2020 to 2039 that control rule is applied, but actual Egg was above threshold (false positive)
3) Fraction of years from 2020 to 2039 that control rule was not applied, but actual Egg was below threshold (false negative)
4) Fraction of years from 2020 to 2039 that control rule is applied, and actual Egg was below threshold (true positive)
5) Probability that control rule is applied for 2020
6) Fraction of years from 2020 to 2039 that Fmax is hit so that selectivity has to be "spread"
7) Fraction of years from 2020 to 2039 that Fmax is hit and catch cannot be taken despite selectivity being "spread"

Notes:

1) Since for some tests the absolute abundances/egg production will change, so that absolute values might mislead, "rel" statistics are reported which are values relative to the median biomass in the absence of any historical or future catch for that test. For non-stationary situations (e.g. M increasing over time in the future), note that this will change (e.g. the concept of "dynamic B0"), so the "rel" statistic will be relative to this projected value in the year in question.
2) The "threshold" is the lowest historical abundance level, here taken to be in terms of egg production (and denoted SSB in the text).

Appendix D – Base Case and Robustness test OM conditioning results

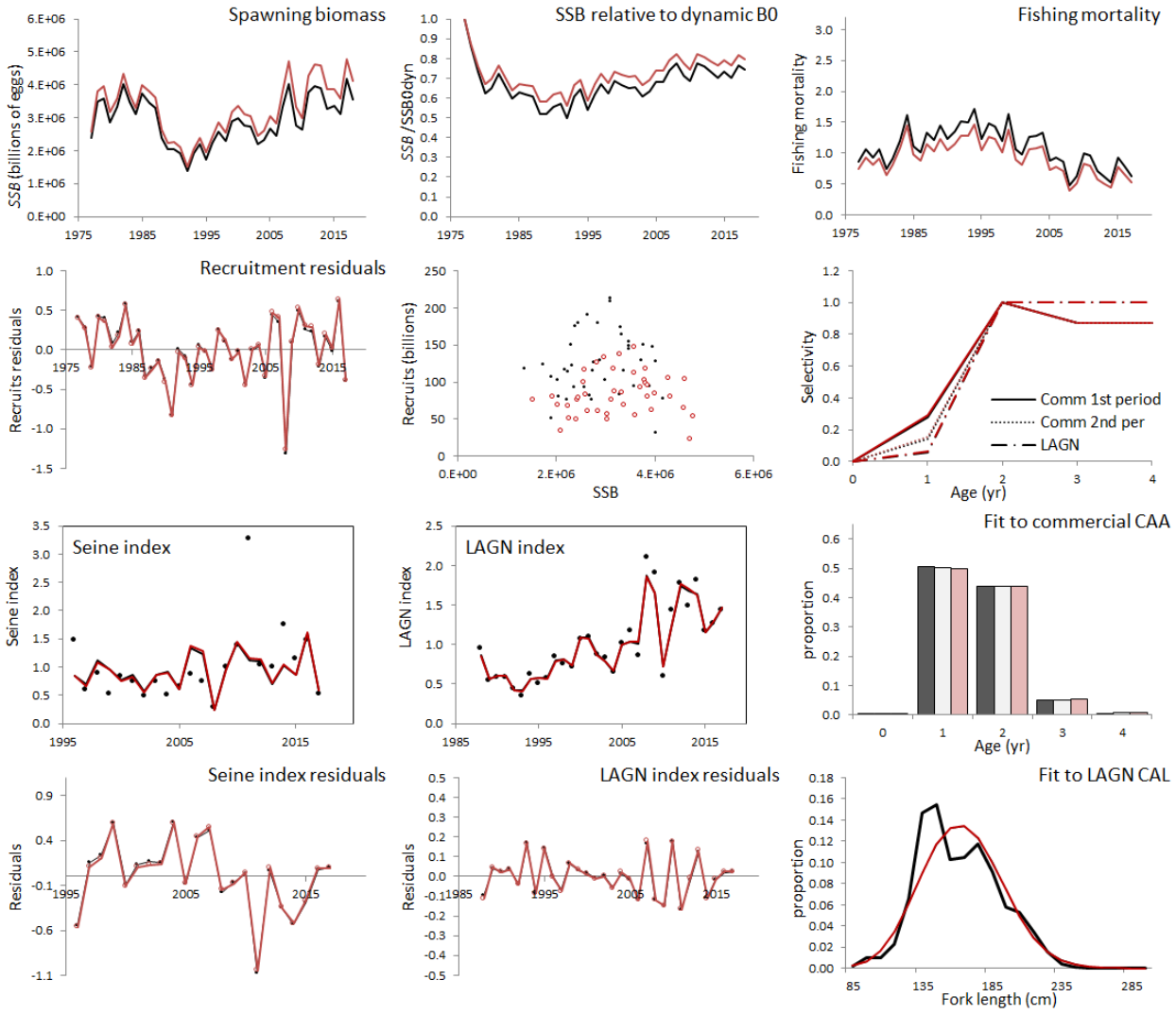

Figure D1a: Assessment results for the Base Case (black lines) and Robustness test 1.1 (*M* = 1.2) OMs.

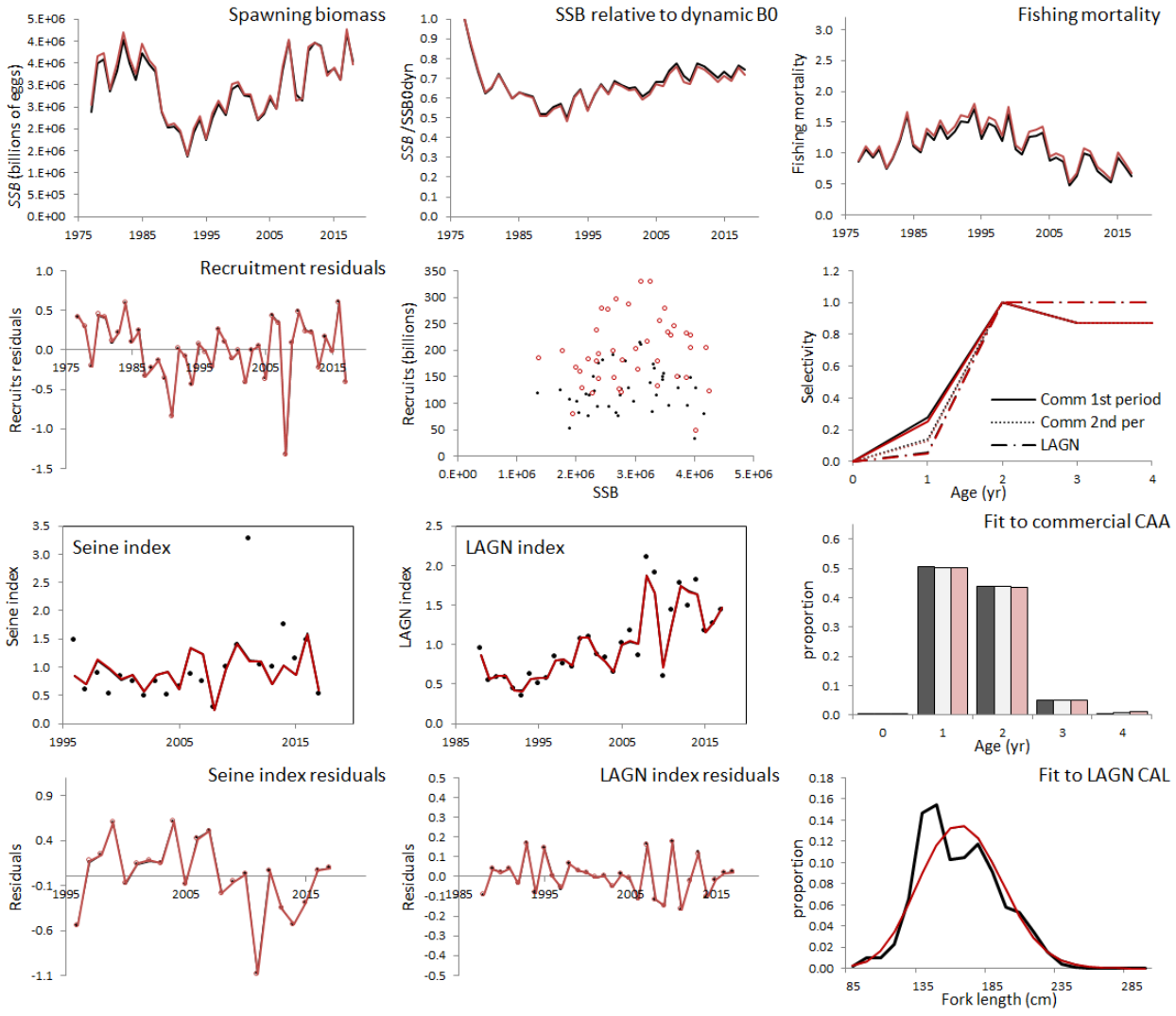

Figure D1b: Assessment results for the Base Case OM (black lines) and Robustness test 1.2 (M'(a)=M(a)*exp(-0.1(a-2))) OMs.

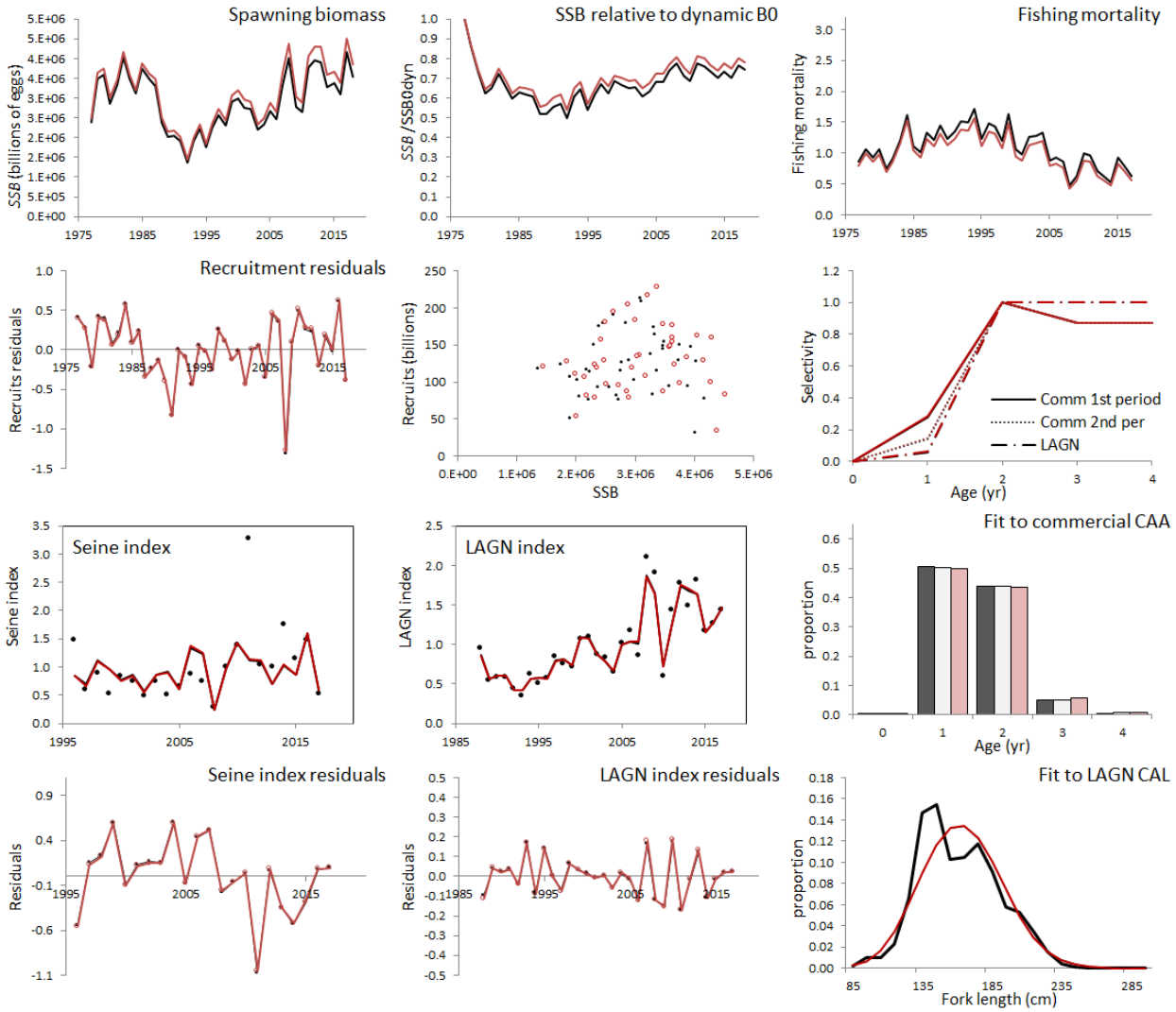

Figure D1c: Assessment results for the Base Case (black lines) and Robustness test 1.3 (M(4+) = 1.67) OMs.

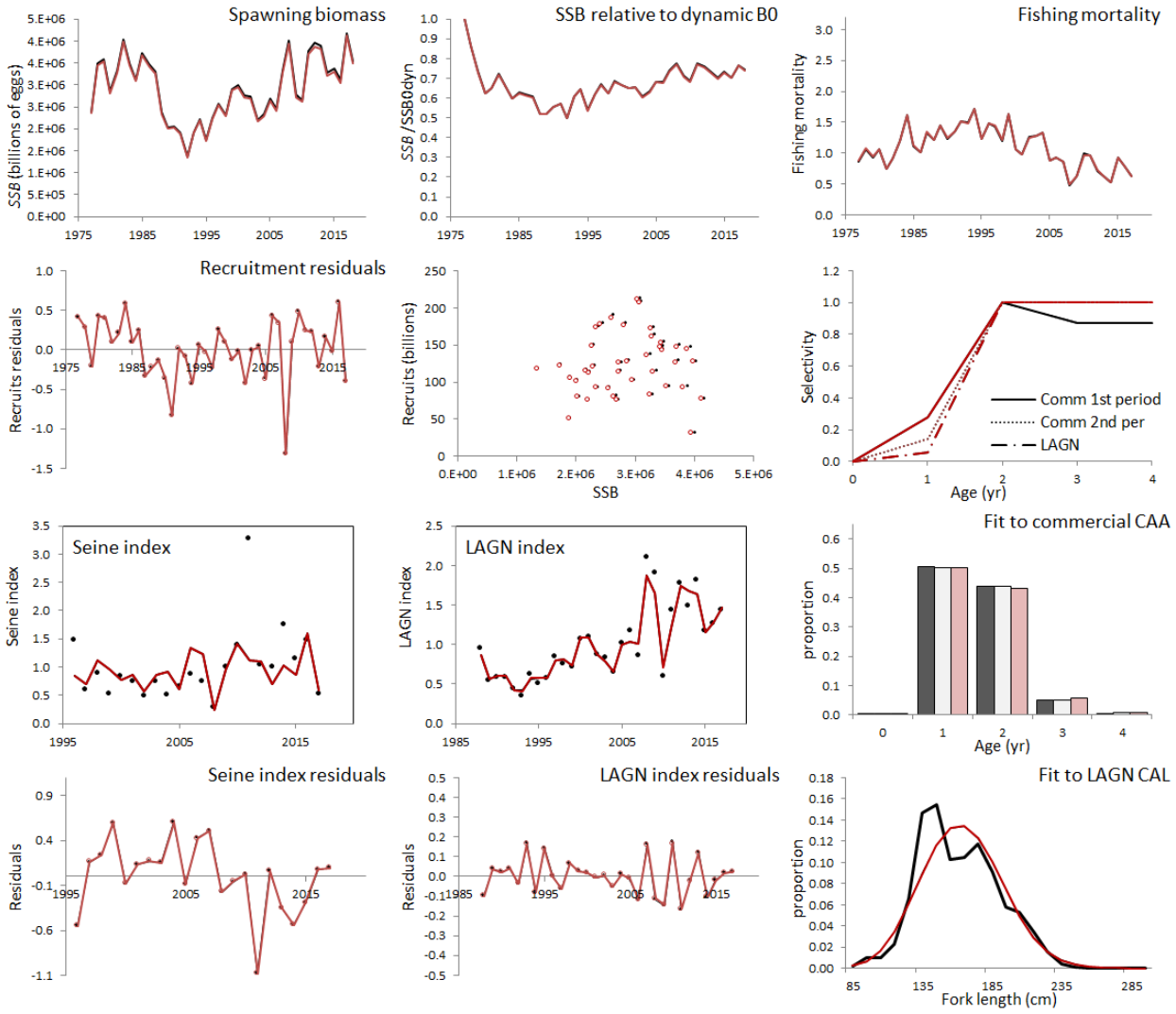

Figure D1d: Assessment results for the Base Case OM (black lines) and Robustness test 2.1 (S(3) = S(4+) = 1.0) OMs.

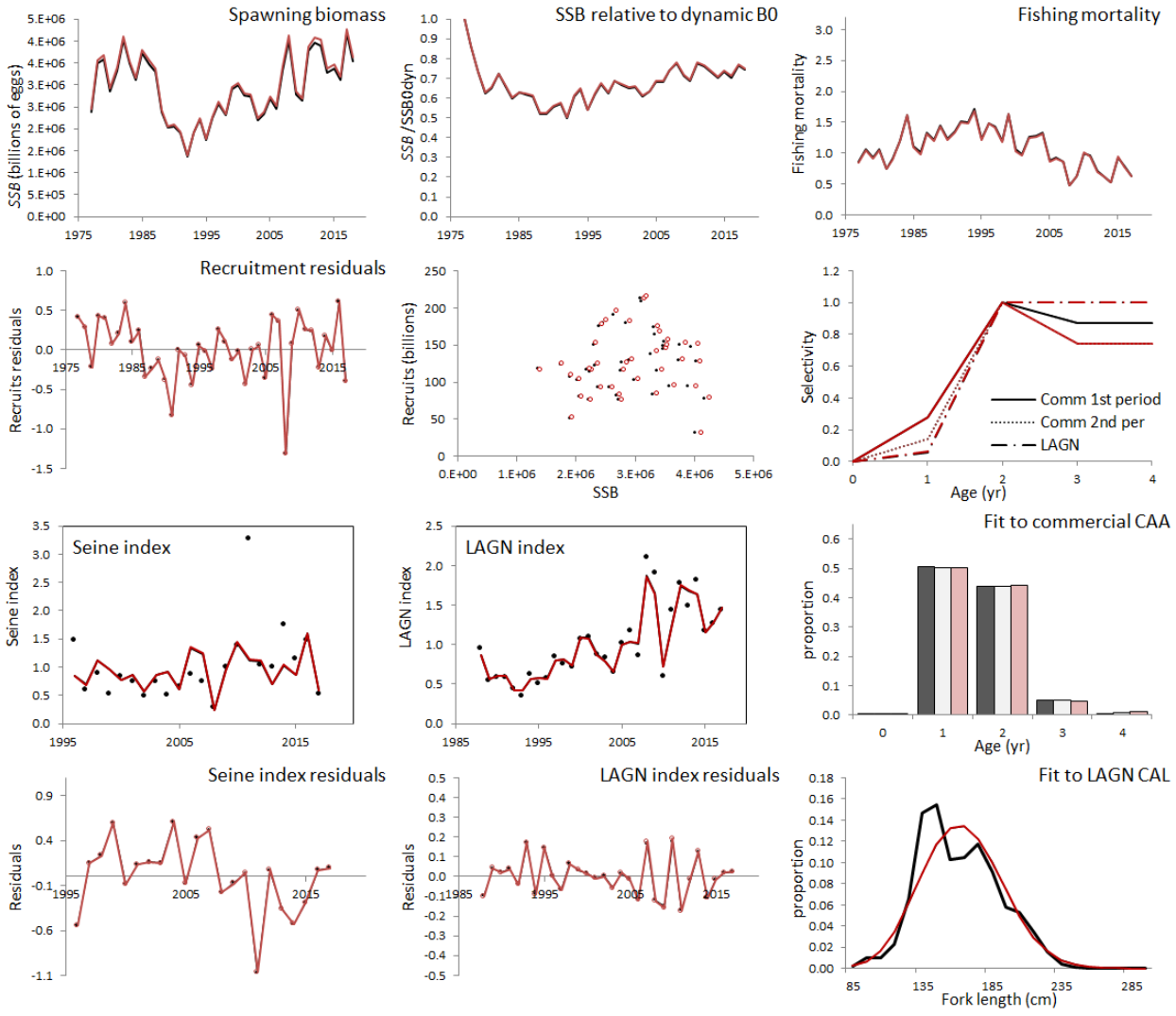

Figure D1e: Assessment results for the Base Case OM (black lines) and Robustness test 2.2 (S(3) = S(4+) = 0.74) OMs.

Base Case (black lines) vs Robustness test 3.1 (I=q*sqrt(B))

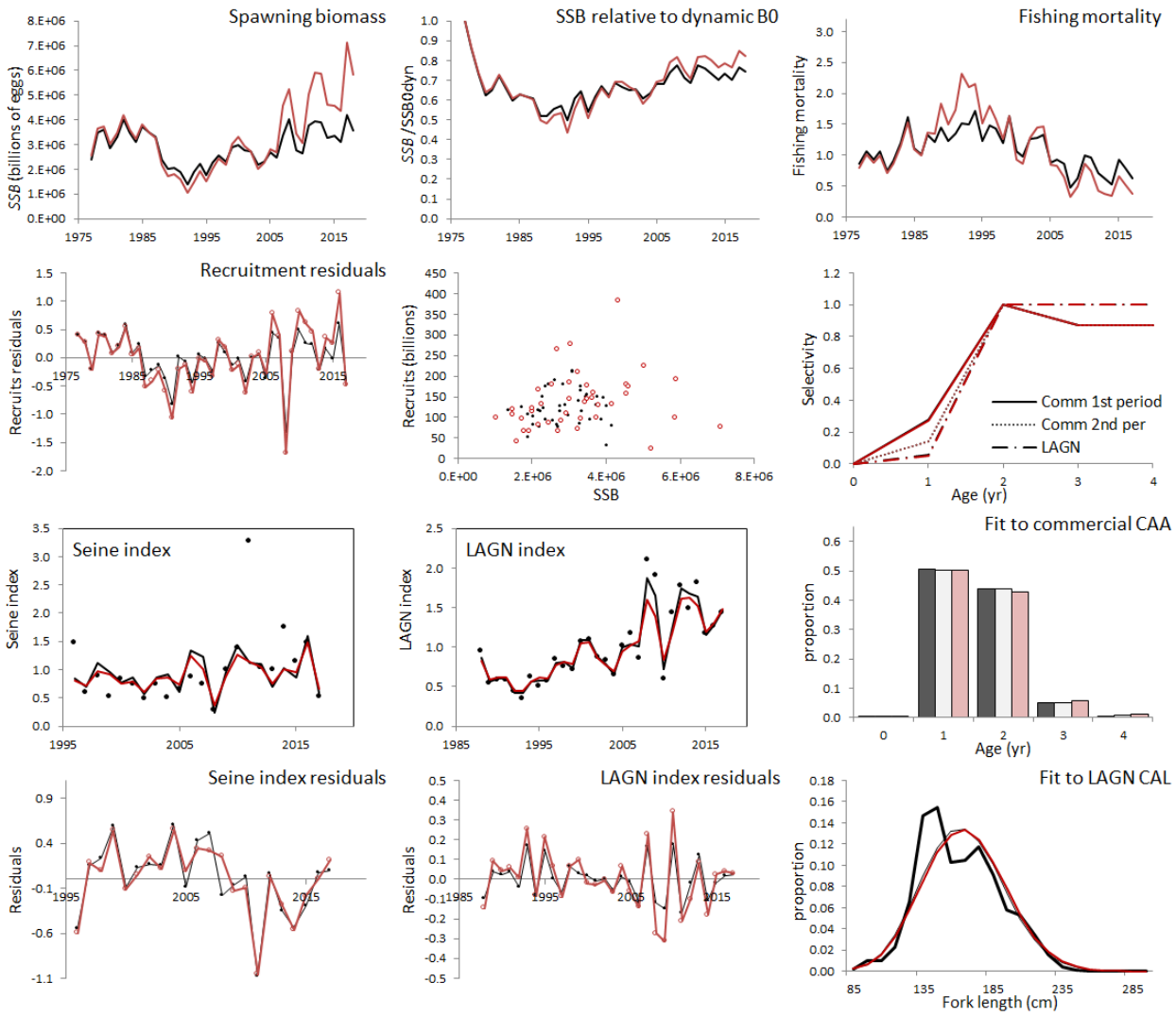

Figure D1f: Assessment results for the Base Case OM (black lines) and Robustness test 3.1 (I=q*sqrt(B)) OMs.

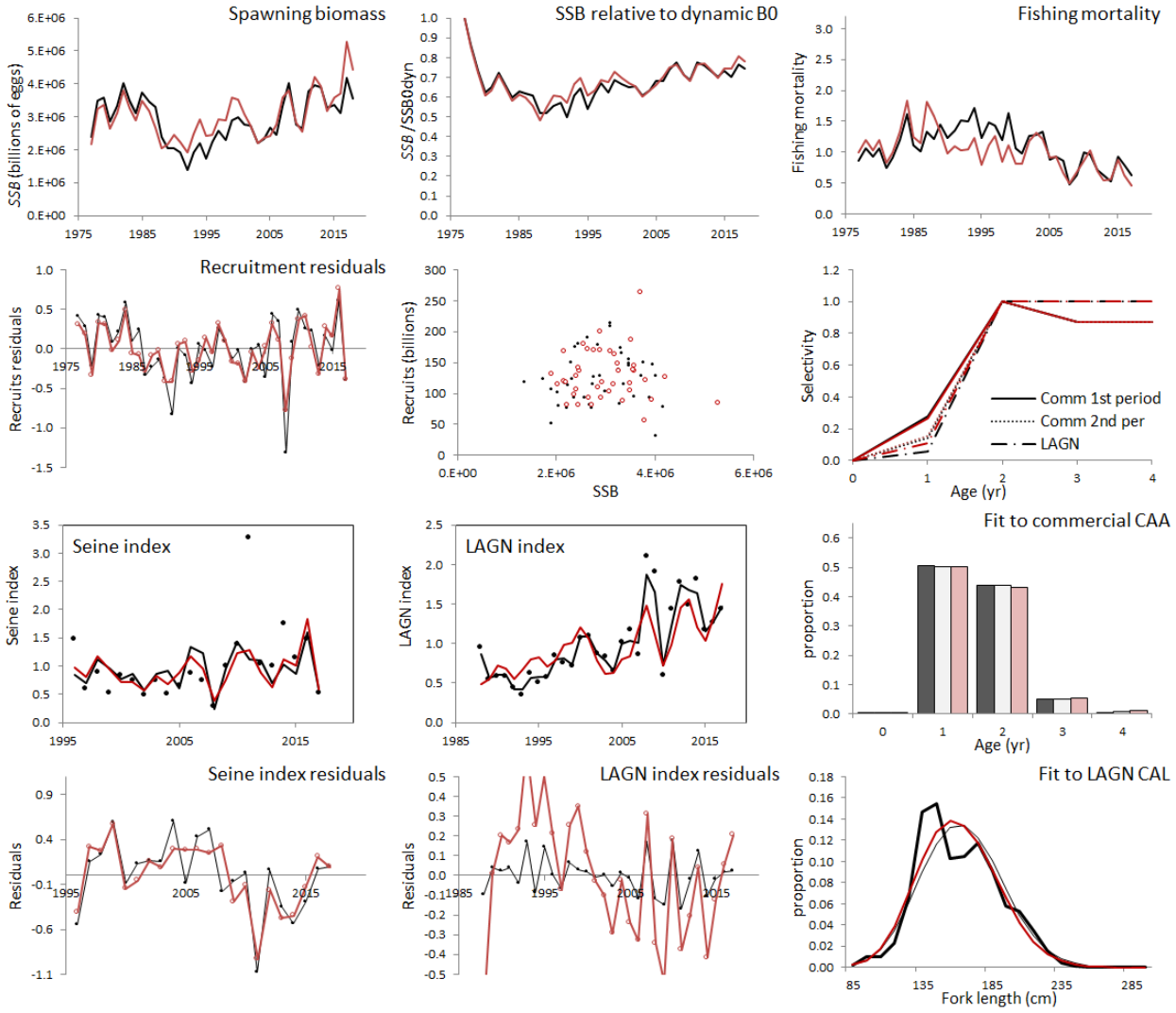

Figure D1g: Assessment results for the Base Case OM (black lines) and Robustness test 3.2 (1:1 weighting) OMs.

Appendix E - Key performance statistics for the Baseline MP under the Base Case OM and all the Robustness tests

Results are shown for the Base Case OM and the different Robustness tests under the baseline MP in Table E1, while Figure E1 plots historical and projected trajectories with and without the baseline MP for all Robustness tests.

Table E1a: Performance statistics for the Base Case OM and Robustness tests 1.1 to 1.5 with and without the management rule (Baseline MP).

Performance_statistics	Base Case			Robustness 1.1			Robustness 1.2			Robustness 1.3			Robustness 1.4			Robustness 1.5		
NO RULE	Median	10	90	Median	10	90	Median	10	90	Median	10	90	Median	10	90	Median	10	90
Related to catch																		
Average landing 2020-2039	494.7	479.2	517.5	494.7	479.2	517.5	494.7	479.2	517.5	494.7	479.2	517.5	363.3	288.9	432.8	484.2	387.8	509.3
Av landing no rule	494.7	479.2	517.5	494.7	479.2	517.5	494.7	479.2	517.5	494.7	479.2	517.5	363.3	288.9	432.8	484.2	387.8	509.3
Av landing with rule	-			-			-			-			-			-		
Lowest landing (2020-2039)	379.9	379.9	425.6	379.9	379.9	425.6	379.9	379.9	425.6	379.9	379.9	425.6	14.6	2.8	69.3	379.9	72.2	400.7
2020 landing	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8
Related to abundance																		
Egg(2020)	3.32	2.73	4.10	3.69	3.05	4.61	3.37	2.72	4.19	3.55	2.91	4.41	3.32	2.73	4.10	3.32	2.73	4.10
Egg(2040)	3.17	2.21	4.04	3.49	2.50	4.53	3.24	2.28	4.17	3.34	2.43	4.25	0.01	0.00	0.07	0.78	0.08	1.97
Egg lowest (2020-2039)	2.00	1.44	2.38	2.17	1.66	2.57	1.99	1.44	2.39	2.10	1.56	2.48	0.01	0.00	0.07	0.76	0.08	1.50
Prob Egg(2040) lowest	6			6			7			5			100			63		
Related to catch variability																		
AAV 2020-2039	0.15	0.12	0.19	0.15	0.12	0.19	0.15	0.12	0.19	0.15	0.12	0.19	0.22	0.17	0.28	0.16	0.12	0.21
AAV with rule	-			-			-			-			-			-		
Other																		
Fraction years rule applied	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
True negative	0.0			0.0			0.0			0.0			0.0			0.0		
Fals negative	0.0			0.0			0.0			0.0			0.0			0.0		
False positive	0.0			0.0			0.0			0.0			0.0			0.0		
True positive	100.0			100.0			100.0			100.0			100.0			100.0		
Prob rule in 2020	0			0			0			0			0			0		
Fraction years Hit Fmax	0	0	0.15	0	0	0.15	0	0	0.15	0	0	0.15	0.6	0.4	0.75	0.35	0.1	0.65
Hit Fmax, landings not taken	0	0	0	0	0	0	0	0	0	0	0	0	0.4	0.25	0.55	0.05	0	0.35
WITH BASELINE MP	Median	10	90	Median	10	90	Median	10	90	Median	10	90	Median	10	90	Median	10	90
Related to catch																		
Average landing 2020-2039	483.8	448.6	511.0	481.5	448.6	510.8	484.2	448.6	511.0	482.8	449.3	511.0	333.7	285.0	401.2	423.9	368.9	466.1
Av landing no rule	494.8	477.8	519.1	493.7	476.0	517.5	494.8	477.2	519.1	494.5	476.3	519.1	501.4	471.7	526.9	497.8	477.0	519.6
Av landing with rule	344.4	0.0	389.5	353.7	0.0	387.1	338.5	0.0	389.7	354.4	0.0	390.4	226.4	136.5	292.6	321.0	234.5	360.0
Lowest landing (2020-2039)	364.2	272.8	400.7	357.3	276.7	395.6	368.5	273.9	400.7	354.1	272.0	396.1	75.4	19.9	185.9	246.9	138.4	336.1
2020 landing	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8
Related to abundance																		
Egg(2020)	3.32	2.73	4.10	3.69	3.05	4.61	3.37	2.72	4.19	3.55	2.91	4.41	3.32	2.73	4.10	3.32	2.73	4.10
Egg(2040)	3.19	2.37	4.04	3.54	2.56	4.53	3.26	2.41	4.17	3.38	2.47	4.25	0.17	0.04	0.51	1.59	0.87	2.33
Egg lowest (2020-2039)	2.01	1.48	2.38	2.21	1.69	2.57	2.02	1.52	2.40	2.12	1.62	2.48	0.17	0.04	0.51	1.23	0.67	1.66
Prob Egg(2040) lowest	5			5			6			4			96			25		
Related to catch variability																		
AAV 2020-2039	0.16	0.13	0.20	0.17	0.13	0.21	0.16	0.13	0.20	0.17	0.13	0.21	0.18	0.13	0.23	0.17	0.12	0.23
AAV with rule	0.15	0.00	0.26	0.16	0.00	0.27	0.15	0.00	0.26	0.16	0.00	0.29	0.18	0.13	0.27	0.17	0.10	0.24
LAgill																		
Fraction years rule applied	0.10	0.00	0.25	0.10	0.00	0.25	0.10	0.00	0.25	0.10	0.00	0.25	0.60	0.45	0.70	0.40	0.20	0.60
True negative	10.1			11.5			9.4			10.9			63.2			43.7		
Fals negative	0.8			1.2			0.9			1.0			0.3			1.4		
False positive	6.8			7.6			6.8			7.6			6.9			12.5		
True positive	82.4			79.8			83.0			80.6			29.7			42.5		
Prob rule in 2020	0			0			0			0			0			0		
Fraction years Hit Fmax	0	0	0.1	0	0	0.05	0	0	0.1	0	0	0.1	0.3	0.15	0.45	0.1	0	0.2
Hit Fmax, landings not taken	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.05	0	0	0

Table E1b: Performance statistics for the Base Case OM and Robustness tests 2.1 to 2.3 with and without the management rule (Baseline MP).

Performance_statistics	Base Case			Robustness 2.1			Robustness 2.2			Robustness 2.3		
NO RULE	Median	10	90	Median	10	90	Median	10	90	Median	10	90
Related to catch												
Average landing 2020-2039	494.7	479.2	517.5	494.7	479.2	517.5	494.7	479.2	517.5	494.7	479.2	517.5
Av landing no rule	494.7	479.2	517.5	494.7	479.2	517.5	494.7	479.2	517.5	494.7	479.2	517.5
Av landing with rule	-			-			-			-		
Lowest landing (2020-2039)	379.9	379.9	425.6	379.9	379.9	425.6	379.9	379.9	425.6	379.9	379.9	425.6
2020 landing	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8
Related to abundance												
Egg(2020)	3.32	2.73	4.10	3.27	2.70	4.02	3.39	2.78	4.22	3.34	2.75	4.12
Egg(2040)	3.17	2.21	4.04	3.13	2.14	4.00	3.24	2.27	4.11	3.18	2.21	4.05
Egg lowest (2020-2039)	2.00	1.44	2.38	1.97	1.37	2.36	2.02	1.48	2.41	1.99	1.40	2.38
Prob Egg(2040) lowest	6			6			5			6		
Related to catch variability												
AAV 2020-2039	0.15	0.12	0.19	0.15	0.12	0.19	0.15	0.12	0.19	0.15	0.12	0.19
AAV with rule	-			-			-			-		
Other												
Fraction years rule applied	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
True negative	0.0			0.0			0.0			0.0		
Fals negative	0.0			0.0			0.0			0.0		
False positive	0.0			0.0			0.0			0.0		
True positive	100.0			100.0			100.0			100.0		
Prob rule in 2020	0			0			0			0		
Fraction years Hit Fmax	0	0	0.15	0	0	0.15	0	0	0.15	0	0	0.05
Hit Fmax, landings not taken	0	0	0	0	0	0	0	0	0	0	0	0
WITH BASELINE MP	Median	10	90	Median	10	90	Median	10	90	Median	10	90
Related to catch												
Average landing 2020-2039	483.8	448.6	511.0	484.0	448.6	511.0	483.8	448.6	511.0	486.4	448.6	512.0
Av landing no rule	494.8	477.8	519.1	494.8	477.8	519.1	494.8	476.3	519.1	493.8	478.1	518.5
Av landing with rule	344.4	0.0	389.5	346.8	0.0	392.5	346.5	0.0	388.2	315.5	0.0	381.2
Lowest landing (2020-2039)	364.2	272.8	400.7	365.2	273.5	400.7	362.2	272.6	400.7	374.7	274.2	400.7
2020 landing	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8
Related to abundance												
Egg(2020)	3.32	2.73	4.10	3.27	2.70	4.02	3.39	2.78	4.22	3.34	2.75	4.12
Egg(2040)	3.19	2.37	4.04	3.13	2.34	4.00	3.26	2.40	4.11	3.18	2.34	4.05
Egg lowest (2020-2039)	2.01	1.48	2.38	1.98	1.46	2.36	2.05	1.50	2.41	2.00	1.45	2.38
Prob Egg(2040) lowest	5			5			4			5		
Related to catch variability												
AAV 2020-2039	0.16	0.13	0.20	0.16	0.13	0.20	0.17	0.13	0.20	0.16	0.13	0.20
AAV with rule	0.15	0.00	0.26	0.15	0.00	0.27	0.15	0.00	0.27	0.12	0.00	0.25
LAgill												
Fraction years rule applied	0.10	0.00	0.25	0.10	0.00	0.25	0.10	0.00	0.25	0.05	0.00	0.25
True negative	10.1			9.9			10.2			8.9		
Fals negative	0.8			0.9			0.8			0.6		
False positive	6.8			6.7			7.0			5.7		
True positive	82.4			82.7			82.1			84.9		
Prob rule in 2020	0			0			0			0		
Fraction years Hit Fmax	0	0	0.1	0	0	0.1	0	0	0.1	0	0	0
Hit Fmax, landings not taken	0	0	0	0	0	0	0	0	0	0	0	0

Table E1c: Performance statistics for the Base Case OM and Robustness tests 3.1 to 3.6 with and without the management rule (Baseline MP).

Performance_statistics	Base Case			Robustness 3.1			Robustness 3.2			Robustness 3.3			Robustness 3.4			Robustness 3.5			Robustness 3.6		
NO RULE	Median	10	90	Median	10	90	Median	10	90	Median	10	90	Median	10	90	Median	10	90	Median	10	90
Related to catch																					
Average landing 2020-2039	494.7	479.2	517.5	494.4	477.2	517.5	494.7	480.0	517.5	494.7	479.2	517.5	494.7	479.2	517.5	494.7	479.2	517.5	494.7	479.2	517.5
Av landing no rule	494.7	479.2	517.5	494.4	477.2	517.5	494.7	480.0	517.5	494.7	479.2	517.5	494.7	479.2	517.5	494.7	479.2	517.5	494.7	479.2	517.5
Av landing with rule	-			-			-			-			-			-			-		
Lowest landing (2020-2039)	379.9	379.9	425.6	379.9	379.9	425.6	379.9	379.9	425.6	379.9	379.9	425.6	379.9	379.9	425.6	379.9	379.9	425.6	379.9	379.9	425.6
2020 landing	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8
Related to abundance																					
Egg(2020)	3.32	2.73	4.10	4.15	3.30	5.82	3.63	3.14	4.31	3.32	2.73	4.10	3.32	2.73	4.10	3.32	2.73	4.10	3.32	2.73	4.10
Egg(2040)	3.17	2.21	4.04	3.40	2.17	4.89	3.29	2.56	4.03	3.17	2.21	4.04	3.17	2.21	4.04	3.17	2.21	4.04	3.17	2.21	4.04
Egg lowest (2020-2039)	2.00	1.44	2.38	1.90	1.12	2.43	2.26	1.88	2.63	2.00	1.44	2.38	2.00	1.44	2.38	2.00	1.44	2.38	2.00	1.44	2.38
Prob Egg(2040) lowest	6			4			5			6			6			6			6		
Related to catch variability																					
AAV 2020-2039	0.15	0.12	0.19	0.15	0.12	0.19	0.15	0.12	0.19	0.15	0.12	0.19	0.15	0.12	0.19	0.15	0.12	0.19	0.15	0.12	0.19
AAV with rule	-			-			-			-			-			-			-		
Other																					
Fraction years rule applied	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
True negative	0.0			0.0			0.0			0.0			0.0			0.0			0.0		
Fals negative	0.0			0.0			0.0			0.0			0.0			0.0			0.0		
False positive	0.0			0.0			0.0			0.0			0.0			0.0			0.0		
True positive	100.0			100.0			100.0			100.0			100.0			100.0			100.0		
Prob rule in 2020	0			0			0			0			0			0			0		
Fraction years Hit Fmax	0	0	0.15	0	0	0.1	0	0	0	0	0	0.15	0	0	0.15	0	0	0.15	0	0	0.15
Hit Fmax, landings not taken	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WITH BASELINE MP	Median	10	90	Median	10	90	Median	10	90	Median	10	90	Median	10	90	Median	10	90	Median	10	90
Related to catch																					
Average landing 2020-2039	483.8	448.6	511.0	494.4	477.2	517.5	494.0	475.0	516.0	483.2	448.4	508.2	482.2	448.1	508.1	481.9	447.1	507.4	483.1	448.6	511.0
Av landing no rule	494.8	477.8	519.1	494.4	477.2	517.5	495.0	479.2	518.0	493.7	476.3	519.1	493.8	477.2	517.6	494.0	478.1	517.8	494.5	478.1	519.1
Av landing with rule	344.4	0.0	389.5	0.0	0.0	0.0	0.0	0.0	383.8	340.0	0.0	388.1	343.1	0.0	389.7	337.7	0.0	385.8	345.4	0.0	389.1
Lowest landing (2020-2039)	364.2	272.8	400.7	379.9	379.9	425.6	379.9	379.9	400.7	367.8	270.9	400.7	357.6	267.3	400.7	353.9	256.7	400.7	359.0	270.4	396.5
2020 landing	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8
Related to abundance																					
Egg(2020)	3.32	2.73	4.10	4.15	3.30	5.82	3.63	3.14	4.31	3.32	2.73	4.10	3.32	2.73	4.10	3.32	2.73	4.10	3.32	2.73	4.10
Egg(2040)	3.19	2.37	4.04	3.40	2.17	4.89	3.29	2.58	4.03	3.19	2.37	4.04	3.20	2.35	4.05	3.20	2.35	4.05	3.19	2.37	4.04
Egg lowest (2020-2039)	2.01	1.48	2.38	1.90	1.12	2.43	2.26	1.88	2.63	2.01	1.48	2.39	2.01	1.48	2.39	2.01	1.48	2.39	2.01	1.51	2.38
Prob Egg(2040) lowest	5			4			3			5			5			5			5		
Related to catch variability																					
AAV 2020-2039	0.16	0.13	0.20	0.15	0.12	0.19	0.15	0.12	0.19	0.16	0.12	0.21	0.17	0.13	0.21	0.17	0.13	0.22	0.17	0.13	0.21
AAV with rule	0.15	0.00	0.26	0.00	0.00	0.00	0.00	0.00	0.21	0.15	0.00	0.31	0.14	0.00	0.29	0.17	0.00	0.30	0.15	0.00	0.28
LAgill																					
Fraction years rule applied	0.10	0.00	0.25	0.00	0.00	0.00	0.00	0.00	0.05	0.10	0.00	0.25	0.10	0.00	0.25	0.10	0.00	0.25	0.10	0.00	0.25
True negative	10.1			0.1			0.9			9.8			9.4			8.4			10.7		
Fals negative	0.8			0.0			0.4			1.3			2.3			3.9			0.9		
False positive	6.8			0.1			3.1			7.0			7.5			8.3			7.3		
True positive	82.4			99.9			95.6			82.0			81.0			79.5			81.2		
Prob rule in 2020	0			0			0			0			0			0			0		
Fraction years Hit Fmax	0	0	0.1	0	0	0.1	0	0	0	0	0	0.1	0	0	0.1	0	0	0.1	0	0	0.1
Hit Fmax, landings not taken	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table E1d: Performance statistics for the Base Case OM and Robustness tests 4.1 to 7.1 with and without the management rule (Baseline MP).

Performance_statistics	Base Case			Robustness 4.1			Robustness 5.1			Robustness 6.1			Robustness 7.1		
NO RULE	Median	10	90	Median	10	90	Median	10	90	Median	10	90	Median	10	90
Related to catch															
Average landing 2020-2039	494.7	479.2	517.5	371.9	169.9	500.7	493.7	464.2	516.0	494.0	477.2	517.4	494.7	479.2	517.5
Av landing no rule	494.7	479.2	517.5	371.9	169.9	500.7	493.7	464.2	516.0	494.0	477.2	517.4	494.7	479.2	517.5
Av landing with rule	-			-			-			-			-		
Lowest landing (2020-2039)	379.9	379.9	425.6	181.9	41.0	379.9	379.9	379.9	400.7	379.9	379.9	425.6	379.9	379.9	425.6
2020 landing	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8
Related to abundance															
Egg(2020)	3.32	2.73	4.10	3.32	2.73	4.10	3.32	2.73	4.10	3.23	2.64	4.01	3.32	2.73	4.10
Egg(2040)	3.17	2.21	4.04	0.59	0.10	3.80	2.87	0.84	3.90	3.05	2.03	3.91	3.17	2.21	4.04
Egg lowest (2020-2039)	2.00	1.44	2.38	0.30	0.05	1.06	1.98	0.80	2.38	1.89	1.16	2.26	2.00	1.44	2.38
Prob Egg(2040) lowest	6			9			12			6			6		
Related to catch variability															
AAV 2020-2039	0.15	0.12	0.19	0.20	0.14	0.27	0.15	0.12	0.20	0.15	0.12	0.19	0.15	0.12	0.19
AAV with rule	-			-			-			-			-		
Other															
Fraction years rule applied	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
True negative	0.0			0.0			0.0			0.0			0.0		
Fals negative	0.0			0.0			0.0			0.0			0.0		
False positive	0.0			0.0			0.0			0.0			0.0		
True positive	100.0			100.0			100.0			100.0			100.0		
Prob rule in 2020	0			0			0			0			0		
Fraction years Hit Fmax	0	0	0.15	0.85	0.25	0.9	0.025	0	0.35	0.1	0	0.3	0	0	0.15
Hit Fmax, landings not taken	0	0	0	0.65	0	0.85	0	0	0.05	0	0	0	0	0	0
WITH BASELINE MP	Median	10	90	Median	10	90	Median	10	90	Median	10	90	Median	10	90
Related to catch															
Average landing 2020-2039	488.7	454.7	512.6	382.4	204.5	459.3	484.9	435.7	513.6	482.4	444.9	513.1	488.7	454.7	513.6
Av landing no rule	494.8	476.3	518.5	498.1	467.3	529.6	495.4	476.0	521.1	495.8	476.0	520.3	494.8	476.3	520.4
Av landing with rule	nan	nan	498.1	277.2	145.9	389.0	404.3	384.0	498.1	402.7	383.0	475.1	nan	nan	498.1
Lowest landing (2020-2039)	379.9	312.1	400.7	176.5	43.3	300.1	379.9	265.1	400.7	379.9	303.4	400.7	379.9	312.1	400.7
2020 landing	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8	473.7	400.7	590.8
Related to abundance															
Egg(2020)	3.32	2.73	4.10	3.32	2.73	4.10	3.32	2.73	4.10	3.23	2.64	4.01	3.32	2.73	4.10
Egg(2040)	3.18	2.36	4.04	3.16	2.18	4.01	3.15	1.96	4.00	3.09	2.26	3.95	3.18	2.36	4.04
Egg lowest (2020-2039)	2.01	1.47	2.38	0.51	0.14	1.31	1.99	1.07	2.38	1.90	1.27	2.28	2.01	1.47	2.38
Prob Egg(2040) lowest	6			0			7			6			6		
Related to catch variability															
AAV 2020-2039	0.15	0.11	0.19	0.18	0.14	0.24	0.15	0.12	0.19	0.15	0.11	0.19	0.15	0.11	0.19
AAV with rule	0.10	0.08	nan	0.16	0.10	0.27	0.10	0.08	nan	0.10	0.07	nan	0.10	nan	0.10
LAgill															
Fraction years rule applied	0.10	0.00	0.30	0.53	0.35	0.80	0.10	0.00	0.40	0.15	0.00	0.35	0.10	0.00	0.30
True negative	10.8			55.5			15.5			16.0			11.0		
Fals negative	0.8			0.4			0.9			1.0			0.8		
False positive	7.4			5.8			6.9			8.2			7.4		
True positive	81.0			38.3			76.8			74.9			80.9		
Prob rule in 2020	0			0			0			0			0		
Fraction years Hit Fmax	0	0	0.1	0.3	0.1	0.45	0	0	0.2	0.05	0	0.2	0	0	0.1
Hit Fmax, landings not taken	0	0	0	0.05	0	0.15	0	0	0	0	0	0	0	0	0

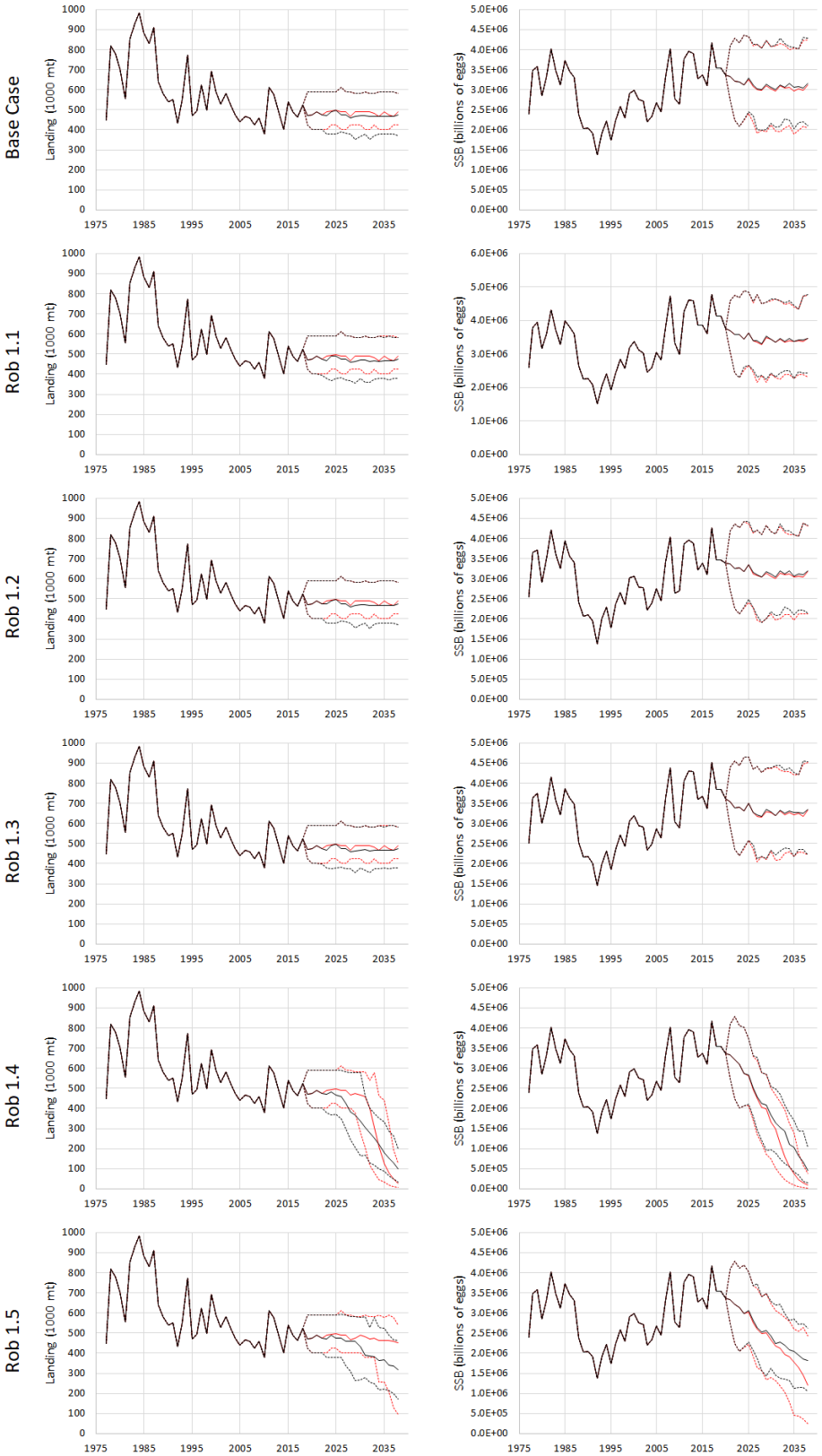

Fig E1a: Historical estimates and projected 20-year median with 10%- and 90%-iles landing and SSB without (red lines) and with the management rule (Baseline MP, black lines) for the Base Case OM and **Robustness test 1.1 to 1.5** OMs.

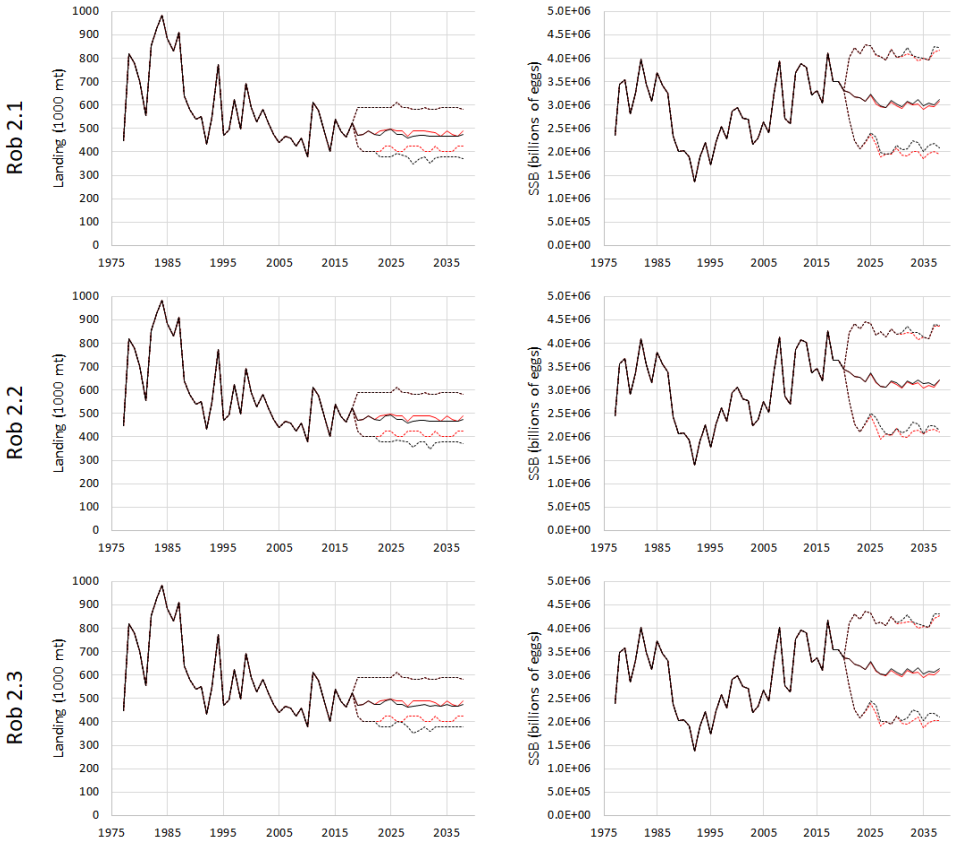

Fig E1b: Historical estimates and projected 20-year median with 10%- and 90%-iles landing and SSB without (red lines) and with the management rule (Baseline MP, black lines) for **Robustness test 2.1 to 2.3** OMs.

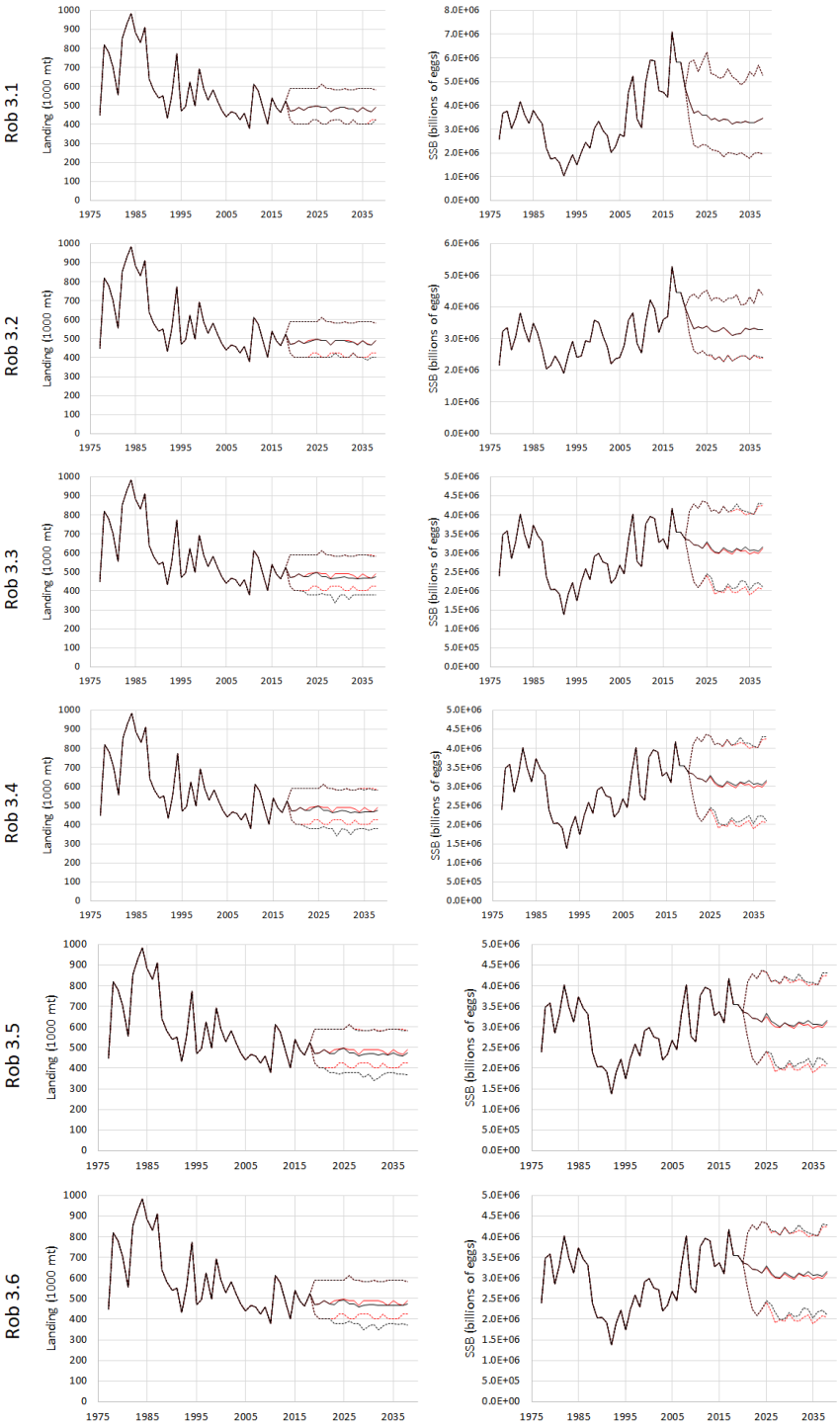

Fig E1c: Historical estimates and projected 20-year median with 10%- and 90%-iles landing and SSB without (red lines) and with the management rule (Baseline MP, black lines) for **robustness test 3.1 to 3.6** OMs.

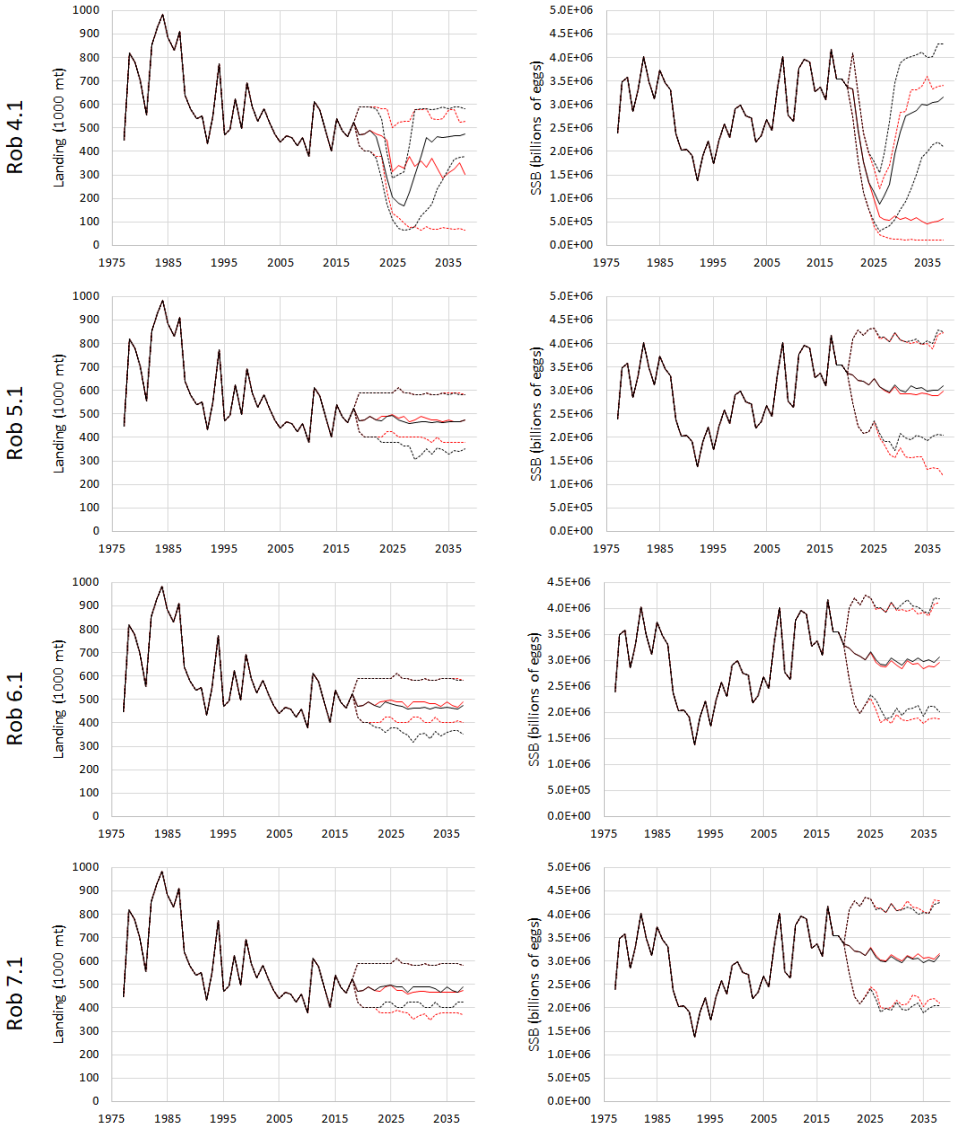

Fig E1d: Historical estimates and projected 20-year median with 10%- and 90%-iles landing and SSB without (red lines) and with the management rule (Baseline MP, black lines) for **Robustness test 4.1 to 7.1** OMs.

Appendix F - Key performance statistics when varying the control parameters of the Baseline MP

Results are shown for varying each of the control parameter values of the baseline MP in turn, and compared to the results in the absence of any control which is shown by the red dot. Medians with 10%- and 90%-iles are shown. Results for the value used in the Baseline MP are indicated by a triangle. The red line shown for the "SSB lowest" plots is the lowest value historically as estimated for the Base Case OM. The plots cover the Base Case OM and the two important Robustness tests: 1.5 (increasing *M* in the future)) and 4.1 (poor recruitment in the future).

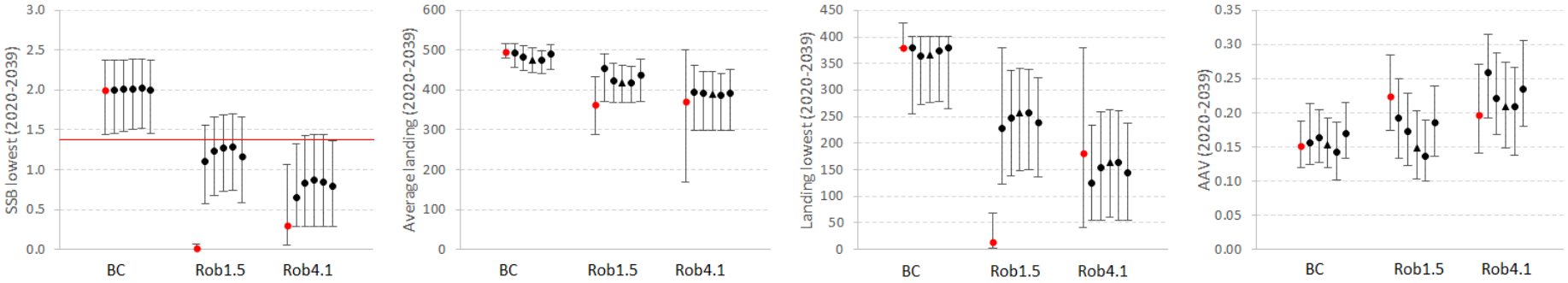

Figure F1a: Performance statistics for no harvest control rule and for **varying values of the $J_{threshold}$** control parameter: 0.60, 0.7, 0.80 (Baseline MP), 0.9 and 1.0. Results are shown for the Base Case OM with the 1.5 and 4.1 Robustness tests.

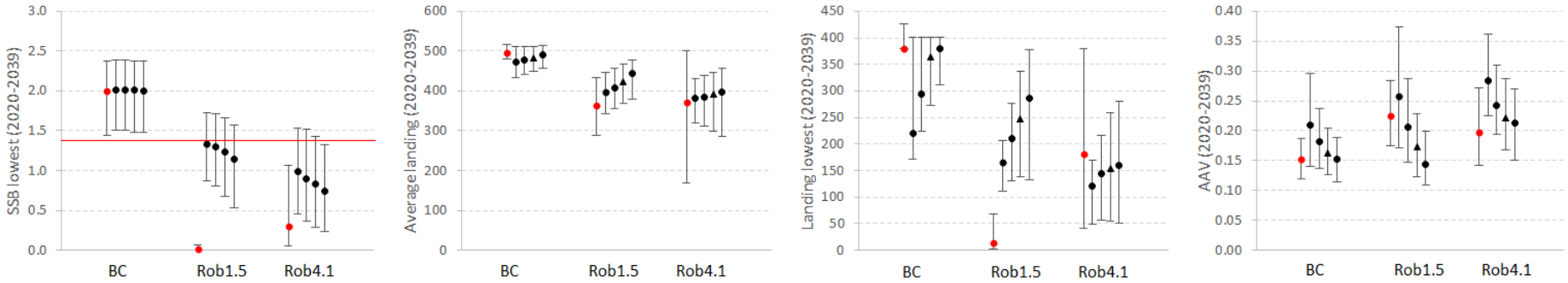

Figure F1b: Performance statistics for no harvest control rule and for **varying values of the** γ control parameter: 300, 400, 500 (Baseline MP), and 600. Results are shown for the Base Case OM with the 1.5 and 4.1 Robustness tests.

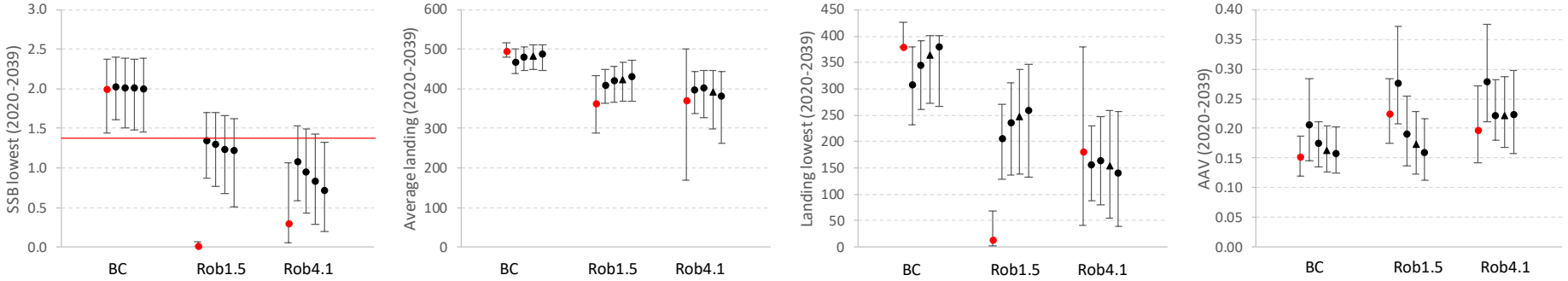

Figure F1c: Performance statistics for no harvest control rule and for **varying values of the *p*** control parameter: 2, 3 (Baseline MP) and 4. Results are shown for the Base Case OM with the 1.5 and 4.1 Robustness tests.