Further robustness tests for the development of a Management Procedure for Gulf Menhaden

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Summary

This document explores further robustness tests for the proposed Gulf menhaden Management Procedure (MP) which were suggested during the stakeholder meeting held over 17-19 July in New Orleans. Results for a future lowered carrying capacity or larger catches, or for some tests involving combinations of tests conducted previously, reflect either little difference in performance or changes broadly as to be expected. The exception is stochastic episodic events, which have a greater negative impact on conservation performance than equivalent tests with steady increases in natural mortality because reduced recruitment plays a larger role. However, rather than attempt to refine the MP to show more robust performance under such scenarios, the suggestion is made to instead react to them on a case-by-case basis under Exceptional Circumstances provisions.

Introduction

The July 2019 stakeholder workshop on management reference points for Gulf menhaden fisheries held in New Orleans reviewed the results from an initiative to develop a Management Procedure (MP) for this fishery that are detailed in Rademeyer and Butterworth (2019) and Butterworth and Rademeyer (2019). Suggestions were made there for some further tests to be carried out (Report, 2019). This document describes the development of these further tests, and reports performance statistics when the Baseline MP is subjected to these new tests.

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Methods

Full details of the 20-year projections conducted for these tests are set out in Appendix A, while details of the form of MP suggested (together with the specifications for the Baseline MP) are given in Appendix B.

<u>New Robustness tests</u>

The Report (2019) describes four areas where there are more-or-less specific suggestions for further robustness tests: stochastic episodic events, lowered carrying capacity, higher catches and combinations of different trials. The following robustness tests have been developed to address these suggestions.

Stochastic episodic events:

Robustness 1.6:

Natural mortality is doubled with a probability of 10% each year, i.e.:

For *y*>2019, $P\left(M_{y,a}=2M_a\right)=0.1$

Robustness 1.7:

Natural mortality is doubled with a probability of 20% each year, i.e.:

For *y*>2019, $P(M_{y,a} = 2M_a) = 0.2$

Lower carrying capacity:

Robustness 4.2

After five years of management, the expected recruitment from the stock-recruit curve (equation A.6, Appendix A) is reduced by 50% (equivalent to an equivalent drop in carrying capacity), i.e.:

For *y*>2024, $R_y \rightarrow 0.5R_y$

Higher catches:

Robustness 6.2

From 2019, whatever catch is generated each year (drawn at random, with replacement, from the observed 2000-2017 landings, see Step 2 of Appendix A), this catch is increased by 100 thousand mt. As for the Base Case, the control rule will still override this catch if the combined abundance index for the years falls below the specified threshold.

Robustness 6.3

Similar to robustness 6.2, but the catch is increased by 150 thousand mt.

Robustness 6.4

Similar to robustness 6.2, but the catch is increased by 200 thousand mt.

Combinations:

Robustness 8.1

A combination of robustness 3.1 (the indices are assumed to have a square root relationship to abundance) and robustness 1.4 (linear increase in *M* by 40% over the next 20 years).

Robustness 8.2

A combination of robustness 3.1 and robustness 4.1 (five years of bad recruitments).

Robustness 8.3

A combination of robustness 1.5 (linear increase in *M* by 20% over the next 20 years). and robustness 4.1 (five years of bad recruitments).

The list of all the robustness tests considered, both previously and the new ones added here, is given in Table 1.

Results and Discussion

Table 2 provides a full set of performance statistics with and without the Baseline MP for the Base Case OM and for all the new robustness tests. Key results in the form of medians for the lowest egg production over the 2020 to 2039 period, and for the lowest landing over this period, are then shown for both the previous and new tests in Figure 1.

Many of the new tests either show no consequential differences compared to previous results, or give results that are much as might have been expected. Thus, higher catches (6.2, 6.3 and 6.4) have little impact, while a lower carrying capacity (4.2) simply leads to worse performance than for a period of only five years of bad recruitment (4.1). However, for 4.2, the MP does again ameliorate the impact on egg production to a limited extent, as for 4.1. For the more plausible combination test (8.2), the MP is unable to secure much improvement in the lowest egg production, but is able to do so for the combination of an increase in natural mortality M and five years of bad recruitment.

There is, however, some deterioration in performance for the stochastic episodic events tests (1.6 and 1.7) when these are compared to their counterparts (1.5 and 1.4 respectively) which achieve the same net increase in losses to natural mortality on average over time. The reason is that if random large increases in M are compared to the equivalent steady increase in M every year, egg production can drop lower and this is not as well ameliorated by application of the MP. This is because compared to a small increase each year, the occasional large increase in M drops spawning biomass much lower, so that recruitment is reduced more and this continues for a longer period under the hockey-stick stock-recruitment function, than for the steady M increase scenario.

Time could be invested in trying to develop a variant of the MP which is robust to such episodic events. However, since such events would be infrequent anyway, it might be more profitable to use these simulations to assist determine the "signatures" of such events, and to deal with them under "Exceptional Circumstances" provisions. They would then be addressed on a case-by-case basis in practice, and as appropriate to the intensity indicated when they are identified, rather than by means of some generic rule.

References

Butterworth, D.S. and Rademeyer, R.A. 2019. Extensions of the Application of MSE to Gulf Menhaden. Presented during the Stakeholder Workshop on Management Reference Points for Gulf Menhaden Fisheries. 17-19 July 2019, New Orleans.

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.

Report. 2019. Report of the Stakeholder Workshop on Management Reference Points for Gulf Menhaden Fisheries. 17-19 July 2019, New Orleans.

Table 1: List of the robustness tests used in MP testing. The yellow highlighted ones are the "new" tests. 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		M(4+)=1.67		A
1.4	Lorenzen mortality vector	M increases linearly by 40% over next 20 years	x	B
1.5		M increases linearly by 20% over next 20 years	x	B
1.6		Doubling M with a probability of 10%/year	x	A
1.7		Doubling M with a probability of 20%/year	x	B
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)		B
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+ selectivity 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	B
4.2		From 2025, expected recruitment is halved	x	B
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. Future catches				
6.1		Under-reporting: Future catches = 1.1TAC (presence of these IUU catches is not realised)	x	B
6.2	Future catches drawn from past catches*	Higher catches: Future catches = draw from past catches + 100 000 mt (*)	x	A
6.3		Higher catches: Future catches = draw from past catches + 150 000 mt (*)	x	B
6.4		Higher catches: Future catches = draw from past catches + 200 000 mt (*)	x	B
	* control rule will override			
7. Maximal possible fishing mortality				
7.1	Fmax for projections = 1.05*Fmax historical	Fmax for projections = 1.20*Fmax historical	x	B
8. Combination of different trials				
8.1		Test 3.1 + test 1.4	x	B
8.2		Test 3.1 + test 4.1	x	A
8.2		Test 3.1 + test 4.1	x	A

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

Performance_statistics	Base Case			Robustness 1.6			Robustness 1.7			Robustness 4.2			Robustness 6.2			Robustness 6.3			Robustness 6.4			Robustness 8.1			Robustness 8.2			Robustness 8.3		
NO RULE	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	Median	10	90
Related to catch																														
Average landing 2020-2039	494.7	479.2	517.5	372.2	149.1	487.9	193.7	98.1	430.7	290.7	246.3	334.0	593.8	577.2	616.0	643.2	626.9	665.9	690.6	669.4	714.2	414.4	298.9	484.2	483.6	207.9	512.1	224.9	146.6	482.8
Av landing no rule	494.7	479.2	517.5	372.2	149.1	487.9	193.7	98.1	430.7	290.7	246.3	334.0	593.8	577.2	616.0	643.2	626.9	665.9	690.6	669.4	714.2	414.4	298.9	484.2	483.6	207.9	512.1	224.9	146.6	482.8
Av landing with rule	-			-			-			-			-			-			-			-			-			0.00	0.00	0.00
Lowest landing (2020-2039)	379.9	379.9	425.6	81.4	2.1	379.9	7.5	0.1	183.2	2.7	0.6	10.9	479.9	479.9	525.6	529.9	529.9	575.6	579.9	516.7	625.6	41.8	2.2	379.9	379.9	26.2	400.7	21.3	4.3	379.9
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	573.7	500.7	690.8	623.7	550.7	740.8	673.7	600.7	790.8	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	3.24	2.69	3.99	3.24	2.69	3.99	3.24	2.69	3.99	3.12	2.56	3.87	3.06	2.50	3.81	3.00	2.45	3.75	3.98	3.25	4.91	3.98	3.25	4.91	3.24	2.69	3.99
Egg(2040)	3.17	2.21	4.04	0.14	0.00	2.75	0.01	0.00	0.49	0.00	0.00	0.01	2.78	1.63	3.76	2.65	1.38	3.65	2.55	1.19	3.54	0.03	0.00	0.28	2.69	0.06	4.68	0.03	0.00	0.71
Egg lowest (2020-2039)	2.00	1.44	2.38	0.11	0.00	0.88	0.01	0.00	0.32	0.00	0.00	0.01	1.90	1.13	2.45	1.81	0.98	2.36	1.72	0.84	2.24	0.03	0.00	0.28	0.75	0.04	1.73	0.03	0.00	0.57
Prob Egg(2040) lowest	6			36			55			100			13			12			12			91			10			74		
Related to catch variability																														
AAV 2020-2039	0.15	0.12	0.19	0.23	0.15	0.33	0.30	0.18	0.40	0.27	0.22	0.32	0.13	0.10	0.16	0.12	0.09	0.15	0.11	0.08	0.14	0.21	0.15	0.28	0.18	0.13	0.30	0.22	0.15	0.27
AAV with rule	-			-			-			-			-			-			-			0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
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	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			0.0			0.0			0.0		
Fals negative	0.0			0.0			0.0			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			0.0			0.0			0.0		
True positive	100.0			100.0			100.0			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			0			0			0		
Fraction years Hit Fmax	0	0	0.15	0.65	0.15	0.9	0.85	0.5	0.95	0.65	0.55	0.7	0.1	0	0.35	0.2	0.05	0.55	0.4	0.15	0.7	0.45	0.25	0.65	0.3	0	0.9	0.9	0.8	0.95
Hit Fmax, landings not taken	0	0	0	0.5	0	0.9	0.75	0.3	0.95	0.5	0.4	0.6	0	0	0.05	0	0	0.05	0	0	0.1	0.3	0.1	0.5	0.05	0	0.8	0.8	0.1	0.85
WITH BASELINE MP	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	Median	10	90
Related to catch																														
Average landing 2020-2039	483.8	448.6	511.0	340.3	170.3	461.7	203.7	101.6	375.6	285.9	243.3	330.0	570.6	514.5	601.4	600.6	540.7	640.4	631.2	559.7	684.2	414.4	298.9	484.2	483.6	213.4	512.1	318.6	182.5	394.2
Av landing no rule	494.8	477.8	519.1	482.8	443.9	516.8	470.5	409.4	511.2	500.5	467.2	523.2	595.3	575.0	617.0	646.1	622.7	668.3	694.7	669.6	717.5	461.2	434.6	486.0	483.7	399.8	512.1	497.9	451.2	543.4
Av landing with rule	344.4	0.0	389.5	183.0	36.2	287.4	101.9	26.2	233.0	142.0	78.4	219.4	351.5	0.0	388.2	364.5	271.7	388.5	354.8	278.8	382.7	34.9	0.0	84.4	0.0	0.0	212.8	262.4	128.7	310.2
Lowest landing (2020-2039)	364.2	272.8	400.7	75.6	6.9	254.4	18.3	0.2	101.4	51.6	6.8	130.5	365.2	259.3	479.9	351.4	251.4	398.6	339.6	231.9	389.7	41.8	2.2	379.9	379.9	26.2	400.7	134.2	34.8	217.8
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	573.7	500.7	690.8	623.7	550.7	740.8	673.7	600.7	790.8	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	3.24	2.69	3.99	3.24	2.69	3.99	3.24	2.69	3.99	3.12	2.56	3.87	3.06	2.50	3.81	3.00	2.45	3.75	3.98	3.25	4.91	3.98	3.25	4.91	3.24	2.69	3.99
Egg(2040)	3.19	2.37	4.04	1.31	0.10	3.57	0.17	0.00	2.48	0.23	0.03	0.70	2.80	1.99	3.97	2.75	1.90	3.75	2.72	1.81	3.73	0.03	0.00	0.28	2.71	0.06	4.94	1.54	0.47	2.34
Egg lowest (2020-2039)	2.01	1.48	2.38	0.32	0.03	0.94	0.07	0.00	0.48	0.22	0.03	0.59	1.94	1.37	2.45	1.87	1.28	2.37	1.79	1.20	2.26	0.03	0.00	0.28	0.75	0.04	1.73	0.66	0.20	1.18
Prob Egg(2040) lowest	5			15			24			74			9			8			8			91			7			7		
Related to catch variability																														
AAV 2020-2039	0.16	0.13	0.20	0.25	0.16	0.35	0.30	0.24	0.41	0.18	0.13	0.24	0.17	0.12	0.23	0.19	0.12	0.25	0.20	0.14	0.29	0.21	0.15	0.28	0.18	0.13	0.29	0.20	0.15	0.26
AAV with rule	0.15	0.00	0.26	0.33	0.22	0.45	0.35	0.26	0.45	0.19	0.12	0.28	0.23	0.00	0.38	0.29	0.17	0.41	0.29	0.18	0.46	0.37	0.00	0.59	0.00	0.00	0.33	0.21	0.15	0.28
LAgill																														
Fraction years rule applied	0.10	0.00	0.25	0.50	0.10	0.80	0.73	0.40	0.90	0.60	0.55	0.70	0.10	0.00	0.30	0.15	0.05	0.35	0.20	0.05	0.35	0.10	0.00	0.40	0.00	0.00	0.65	0.75	0.50	0.85
True negative	10.1			51.3			72.1			64.7			12.5			16.3			18.7			18.0			20.2			75.5		
Fals negative	0.8			0.7			0.5			0.4			1.5			1.9			2.2			0.1			0.1			0.8		
False positive	6.8			4.3			3.0			3.0			9.8			12.2			14.0			2.6			4.0			7.3		
True positive	82.4			43.9			24.5			32.0			76.2			69.7			65.2			79.4			75.8			16.5		
Prob rule in 2020	0			0			0			0			0			0			0			0			0			0		
Fraction years Hit Fmax	0	0	0.1	0.25	0.1	0.5	0.4	0.2	0.7	0.15	0.05	0.35	0.05	0	0.2	0.15	0.05	0.25	0.2	0.1	0.35	0.45	0.25	0.65	0.3	0	0.85	0.2	0.05	0.3
Hit Fmax, landings not taken	0	0	0	0.1	0	0.2	0.15	0.05	0.35	0	0	0.05	0	0	0	0	0	0	0	0	0	0.3	0.1	0.5	0.05	0	0.7	0	0	0.05

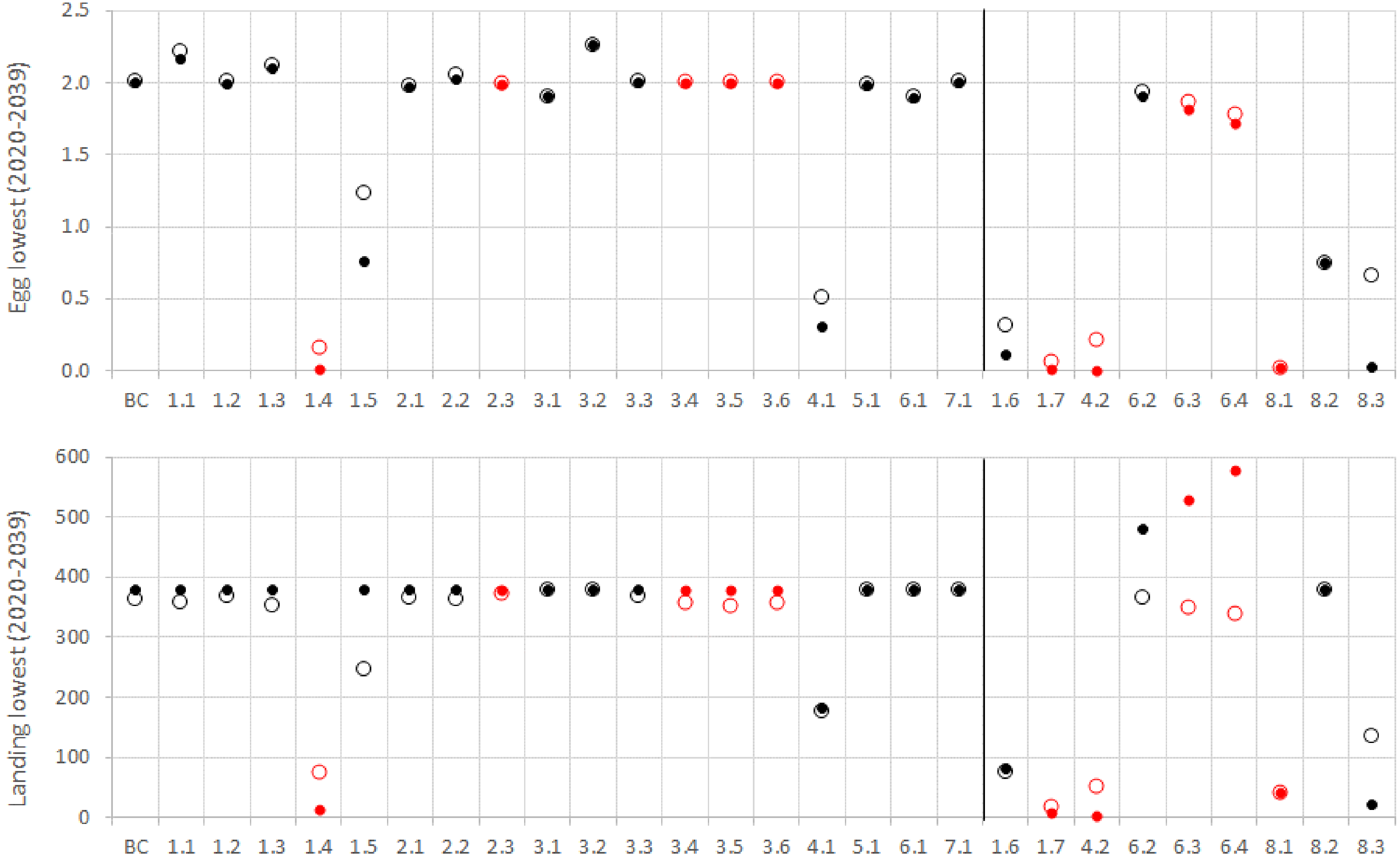

Figure 1: Median lowest egg production and landing values over the 2020-2039 projection period for each of the Base Case and Robustness test OMs without (full circles) and with (open circles) the Baseline MP. The new robustness tests are on the right side of the black vertical line. Type B OMs are shown in red.

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:

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

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):

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

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

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

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:

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

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

$$SSB_y = \sum_{a=2}^{m} f_a\, N_{y,a} \tag{A.7}$$

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

$S = \{\varepsilon_y = lnR_y - lnR : y = 1977, \ldots, 2017\}$, 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.:

$$I_y^i = q^i B_y^i e^{\varepsilon_y^i} \tag{A.8}$$

with

$$\varepsilon_y^i = \varphi_y^i - \rho^i \varphi_{y-1}^i \tag{A.9}$$

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:

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

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:

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

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 $\gamma = 500$); 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*.