OMP-18 development: alternative constraints relating to the sardine Critical Biomass metarule

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Introduction

A reference case Harvest Control Rule (HCR) for sardine was selected as having the following constraints (de Moor 2018a,b; Appendix A):

- A stable directed sardine TAC of 50 000t.
- A minimum directed sardine TAC of 10 000t.
- A maximum directed sardine TAC of 200 000t.
- The maximum proportion by which the directed sardine TAC can be decreased from one year to the next (in the absence of the Critical Biomass metarule and linear smoothing) of 0.2
- Critical Biomass threshold of 350 000t on total survey estimated sardine biomass.
- Linear smoothing of the HCR applying for 350 000t above the Critical Biomass threshold, i.e. from 350 000t to 700 000t[1].

Following de Moor (2018d), this document considers alternative constraints to the Critical Biomass metarule of the sardine HCR.

Method

The 'baseline' HCRs used for comparison in this document are a modification from the Reference Case such that:

i) If $B_{y-1}^{obs,S} < B_{crit}^{S}$, a constraint of a maximum decrease or increase[2] of $p_{crit}^{S} = x\%$ from the previous year's TAC applies.

ii) If $B_{y-1}^{obs,S} < B_{crit}^{S}$, a constraint of a maximum decrease or increase[2] of $p_{crit}^{S} = x\%$ from the previous year's TAC applies, but the maximum decrease constraint applies to the minimum of TAC_{y-1}^{S} or $c_{stbl}^{S}/(1-p_{crit}^{S})$.

The alternatives tested in this document include $p_{crit}^{S} = 0.3$, $p_{crit}^{S} = 0.4$ and $p_{crit}^{S} = 0.5$ against a stable TAC of 50 000t, 65 000t and 75 000t.

Given a constraint of $p_{crit}^{S} = 0.5$ and a stable TAC of 65 000t, alternative Critical Biomass thresholds of 300 and 400 000t are tested together with a status quo range (350 000t) for linear smoothing compared to a smaller (100 000t) range.

The sardine Operating Model (OM) used to simulation test these alternative rules is the same as that used by de Moor (2018d), which assumes 8% of the south coast spawner biomass contributes to the west coast 'effective' spawner biomass and a baseline movement hypothesis MoveR (de Moor 2017). However, the initial directed sardine and anchovy TACs

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[1] This is to avoid any discontinuities in the rule at the Critical Biomass threshold given the metarule below 350 000t does not allow for any 20% constraint in the decrease in directed sardine TAC from one year to the next.

[2] The maximum of 10 000t or $c_{crit}^{S} TAC_{y-1}^{S}$ is used as the constraint.

already awarded for 2018 are now used as a minimum for the 2018 TACs in all projections. Projections assuming a stable TAC of 50 000t given in this document, will therefore not necessarily match those given by de Moor (2018d).

All projections are undertaken assuming the interim OMP-18 anchovy HCR which has a maximum anchovy TAC of 350 000t and a scale-down factor applied to the initial anchovy TAC of 0.85 (de Moor 2018c, Appendix A).

Results and discussion

Taking account of the directed sardine TAC of 59 214t already awarded for 2018 increases the risk to the sardine resource. The β control parameters for the cases with a stable TAC of 50 000t (Table 1) are thus lower than those in de Moor (2018d) to ensure the HCR continues to satisfy a risk of < 0.15.

The reference case can be retuned with a stable TAC of 75 000t. While the median total catch differs little from that with a stable TAC of 50 000t, the 95%ile is 9% lower due to a lower β control parameter (Figure 1, Table 1). However, the annual variation in directed sardine catches is also lower (Figure 2). The alternative HCR options i) and ii) with a stable TAC of 75 000t cannot satisfy the risk criteria, even when $\beta = 0$.

The HCRs can be tuned to a stable TAC of 65 000t for the reference case and for options i) and ii) with 40% and 50% constraints, but not with a 30% constraint (Table 1). As the stable TAC increases, the β control parameter decreases to maintain the risk criteria of <0.15 (Table 1). Increasing the stable TAC from 50 to 65 000t results in a lower median total directed sardine catch for the reference case. For the alternative HCR options i) and ii) the median total catch increases slightly, while the upper 95%ile decreases (Figure 1). Increasing the stable TAC from 50 to 65 000t reduces the median MAV (though in most cases not the 95%ile) (Figure 2), even though frequency with which the Critical Biomass metarules are employed (i.e. proportion of times $B_{y-1}^{obs,S} < B_{crit}^{S}$) are at most 2% more.

While options i) and ii) have lower β control parameters compared to the reference case (Table 1), with lower total catches (Figures 1 and 6), options i) and ii) have a smaller total MAV (Figures 2 and 6) with a corresponding lower probability that the directed sardine TAC will drop below 20 000t (Figure 3). The impact of both the lower β, and the constraint on inter-annual changes in TAC for low biomass values is demonstrated in a few simulated trajectories in Figure 4. The actual sardine biomass, and simulated survey estimated biomass, corresponding to these TAC trajectories are shown in Figure 5.

The difference between options i) and ii) decreases as the constraint percentage applied when $B_{y-1}^{obs,S} < B_{crit}^{S}$ increases and as the stable TAC increases. As a result, there is little difference in the performance statistics for options i) and ii) at the upper end of the range tested, i.e. for $p_{crit}^{S} = 50\%$ and $c_{stbl}^{S} = 65$ (Figure 6).

The Harvest Control Rules tested in this document result in the Critical Biomass metarule been unnecessarily applied in about 15% of future simulations, while the metarule is not used when it should have been in about 10% of the time (Figure 3). These 'errors' in applying the Critical Biomass metarule reflect the typical survey error. The former corresponds to simulations where the survey estimate of biomass is below 350 000t, while the true biomass is above the corresponding threshold. The latter corresponds to simulations where the survey estimate of biomass is above 350 000t, but the true biomass is below the corresponding threshold. Some examples of survey error are demonstrated in Figure 5. The Critical Biomass metarule is appropriately applied in about 21% of simulations.

If one selects $p^S_{crit} = 0.5$ and a stable TAC of 65 000t, alternative Critical Biomass thresholds have little impact on the median total directed sardine catch (Figure 7a). This is because the stable TAC of 65 000t is frequently awarded. However, the lower β control parameters for a Critical Biomass threshold of 300 000t results in a substantial decrease to the 95%ile of the total directed sardine catch, while the higher β control parameters for a Critical Biomass threshold of 400 000 results in a higher 95%ile of total directed sardine catch compared to that simulated with a Critical Biomass threshold of 350 000t. On the other hand, the median and 5%ile of MAV decreases as the Critical Biomass threshold decreases (Figure 7b). The 5%ile of 0.0 for a Critical Biomass threshold of 300 000t results from the high frequency with which the stable TAC of 65 000t is awarded, while for higher Critical Biomass thresholds, the TACs increase to higher values (Figure 7a) and thus the catch variability between years increases (Figure 7b).

Acknowledgements

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References

de Moor CL. 2017. A summary of the operating models being used to simulation test OMP-18 for South African sardine and anchovy. MARAM International Stock Assessment Workshop, 27 November – 1 December 2017, Cape Town. Document MARAM/IWS/2017/Sardine/P6

de Moor CL. 2018a. Some comparisons against a reference sardine Harvest Control Rule for OMP-18. DAFF: Branch Fisheries Document FISHERIES/2018/MAR/SWG-PEL/03.

de Moor CL. 2018b. Considering the variability in directed sardine catches for the current OMP-18 reference case HCR. DAFF: Branch Fisheries Document FISHERIES/2018/MAR/SWG-PEL/04.

de Moor CL. 2018c. Considering alternative constraints to the anchovy Harvest Control Rule. DAFF: Branch Fisheries Document FISHERIES/2018/APR/SWG-PEL/06.

de Moor CL. 2018d. OMP-18 development: alternative constraints on the sardine Harvest Control Rule. DAFF: Branch Fisheries Document FISHERIES/2018/MAY/SWG-PEL/07rev.

de Moor CL, Coetzee J, Durholtz D, Merkle D, van der Westhuizen JJ and Butterworth DS. 2012. A record of the generation of data used in the 2012 sardine and anchovy assessments. DAFF Branch Fisheries document: FISHERIES/2012/AUG/SWG-PEL/41.

Table 1. The sardine control parameter β that results from tuning the HCR to a risk<0.15 given alternative constraints of stable TACs, c^S_{stbl}, and restrictions in the inter-annual increase/decrease in TACs if $B^{obs,S}_{y-1} < B^S_{crit}$. A number in brackets indicates the risk>0.15 that results with $\beta = 0$, i.e. for these combinations the risk criteria could not be satisfied.

	Reference Case	Option i)			Option ii)		
		$p^S_{crit} = 0.3$	$p^S_{crit} = 0.4$	$p^S_{crit} = 0.5$	$p^S_{crit} = 0.3$	$p^S_{crit} = 0.4$	$p^S_{crit} = 0.5$
$c^S_{stbl} = 50$	0.170	0.074	0.091	0.106	0.088	0.103	0.112
$c^S_{stbl} = 65$	0.145	(0.15095)	0.060	0.083	(0.15095)	0.065	0.084
$c^S_{stbl} = 75$	0.108	(0.1589)	(0.15475)	(0.15155)	(0.1589)	(0.15475)	(0.15155)

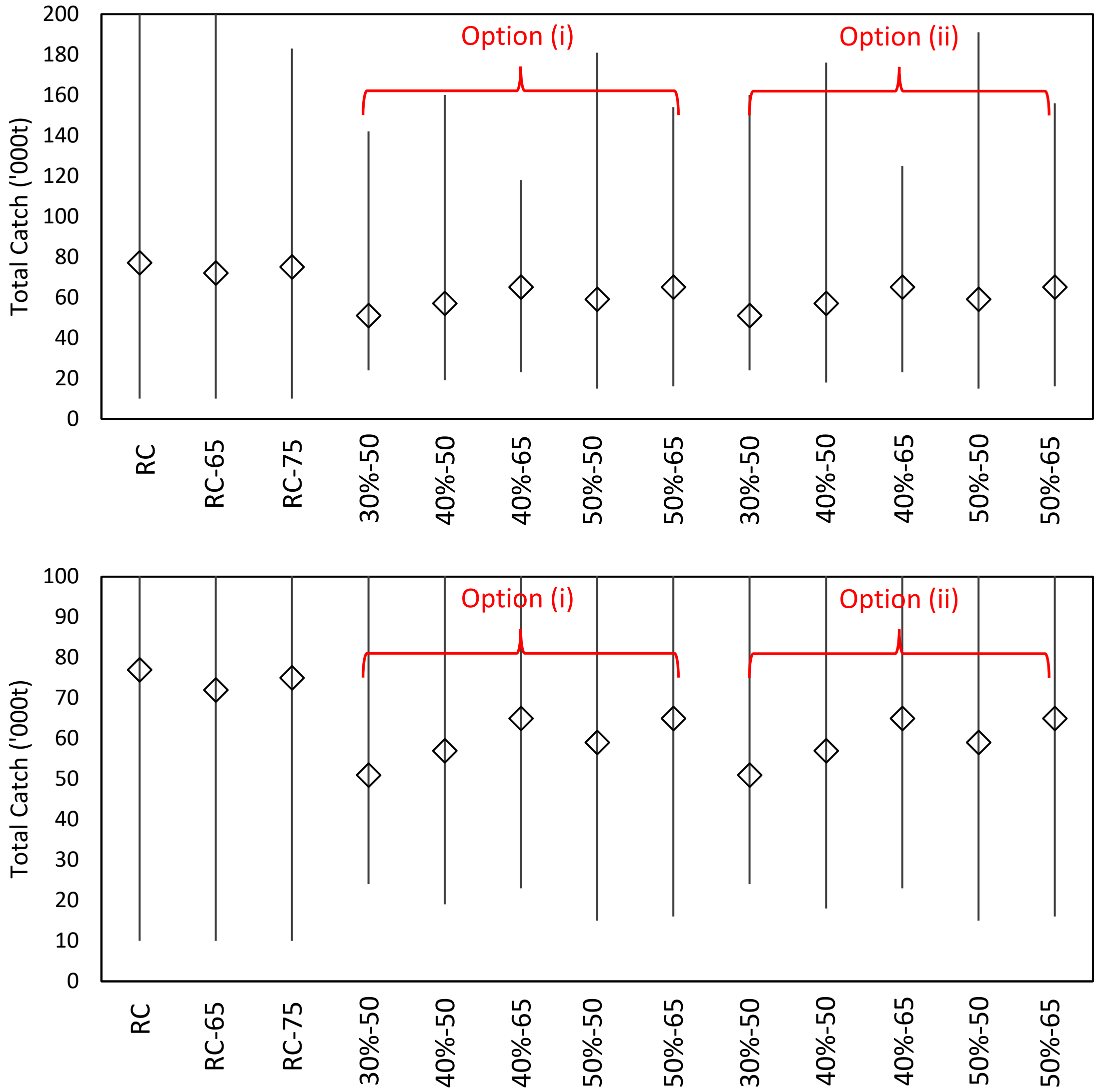
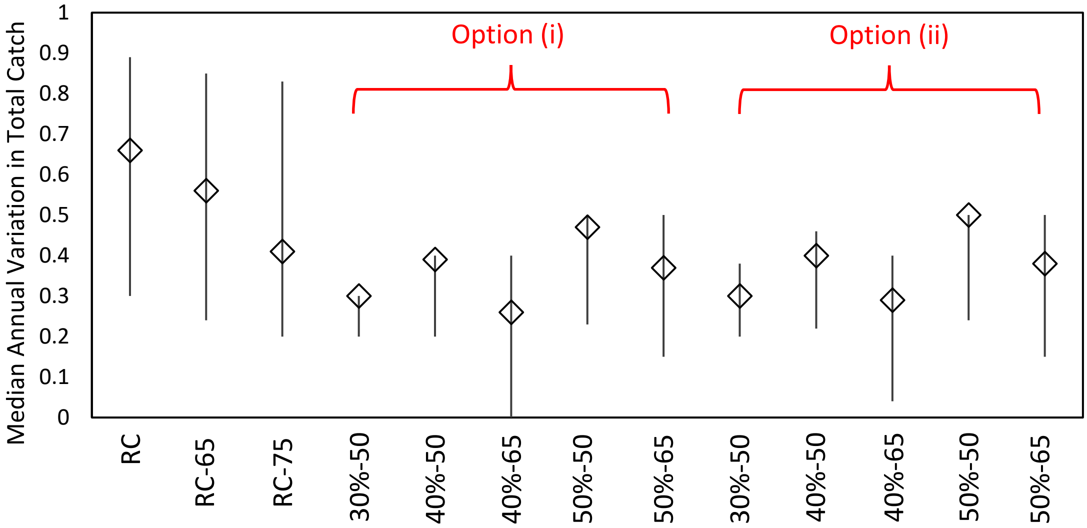


Figure 1. The median and 90% probability intervals for total directed sardine catch, tuned to risk of <0.15 for all HCRs tested in this document. The HCR labels denote either the reference case ("RC"), or the constraint % for the alternative options i) and ii), followed by the stable TAC in 1000t. The lower panel compares has a smaller vertical axis range.



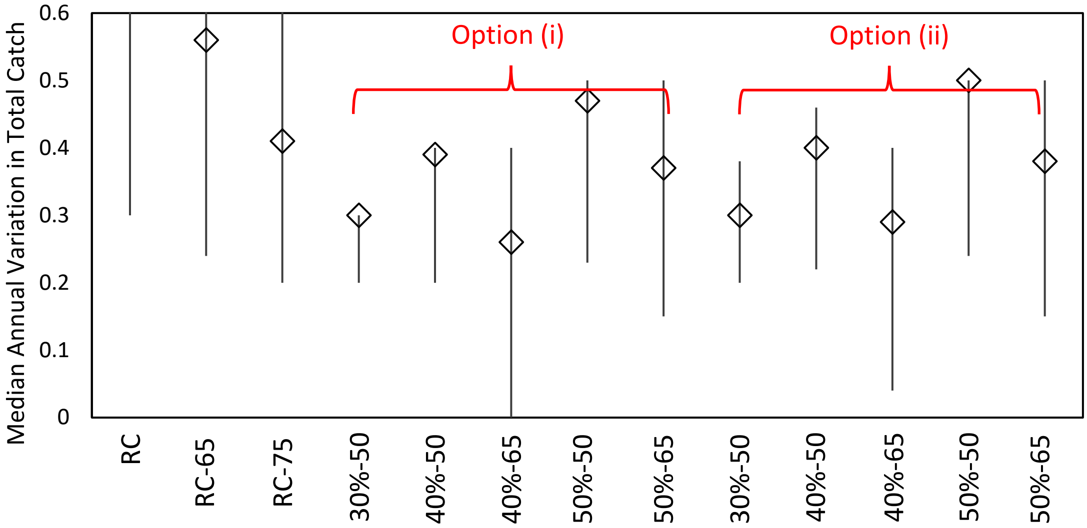


Figure 2. The median and 90% probability intervals for median annual variation in total directed sardine catch, tuned to risk of <0.15 for all HCRs tested in this document. The HCR labels denote either the reference case ("RC"), or the constraint % for the alternative options i) and ii), followed by the stable TAC in 1000t. The lower panel compares has a smaller vertical axis range.

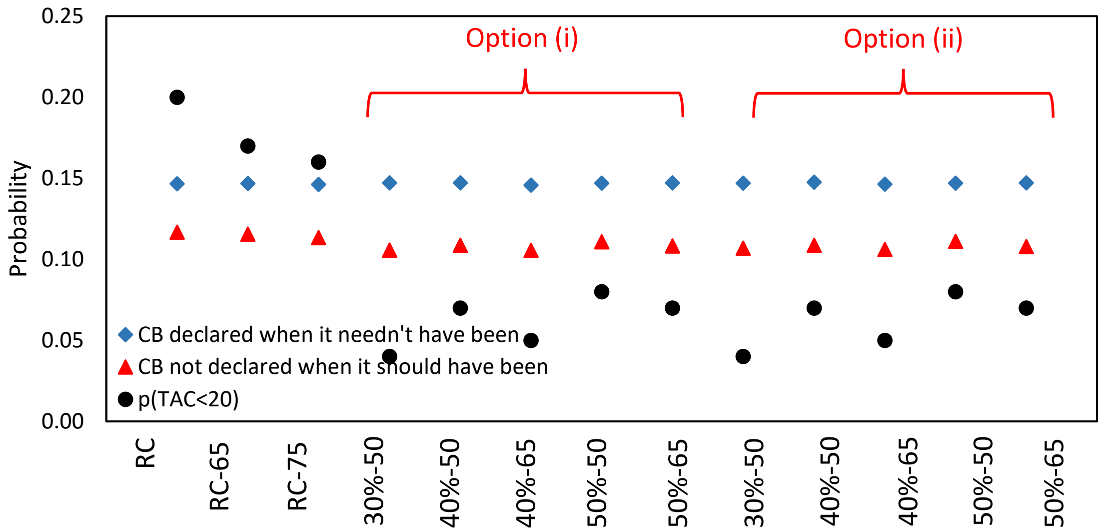


Figure 3. The probability that the directed sardine TAC is less than 20 000t, and the probability that the Critical Biomass metarules are either employed unnecessarily or not employed when necessary, for all HCRs tested in this document tuned to risk of <0.15. The HCR labels denote either the reference case ("RC"), or the constraint % for the alternative options i) and ii), followed by the stable TAC in 1000t.

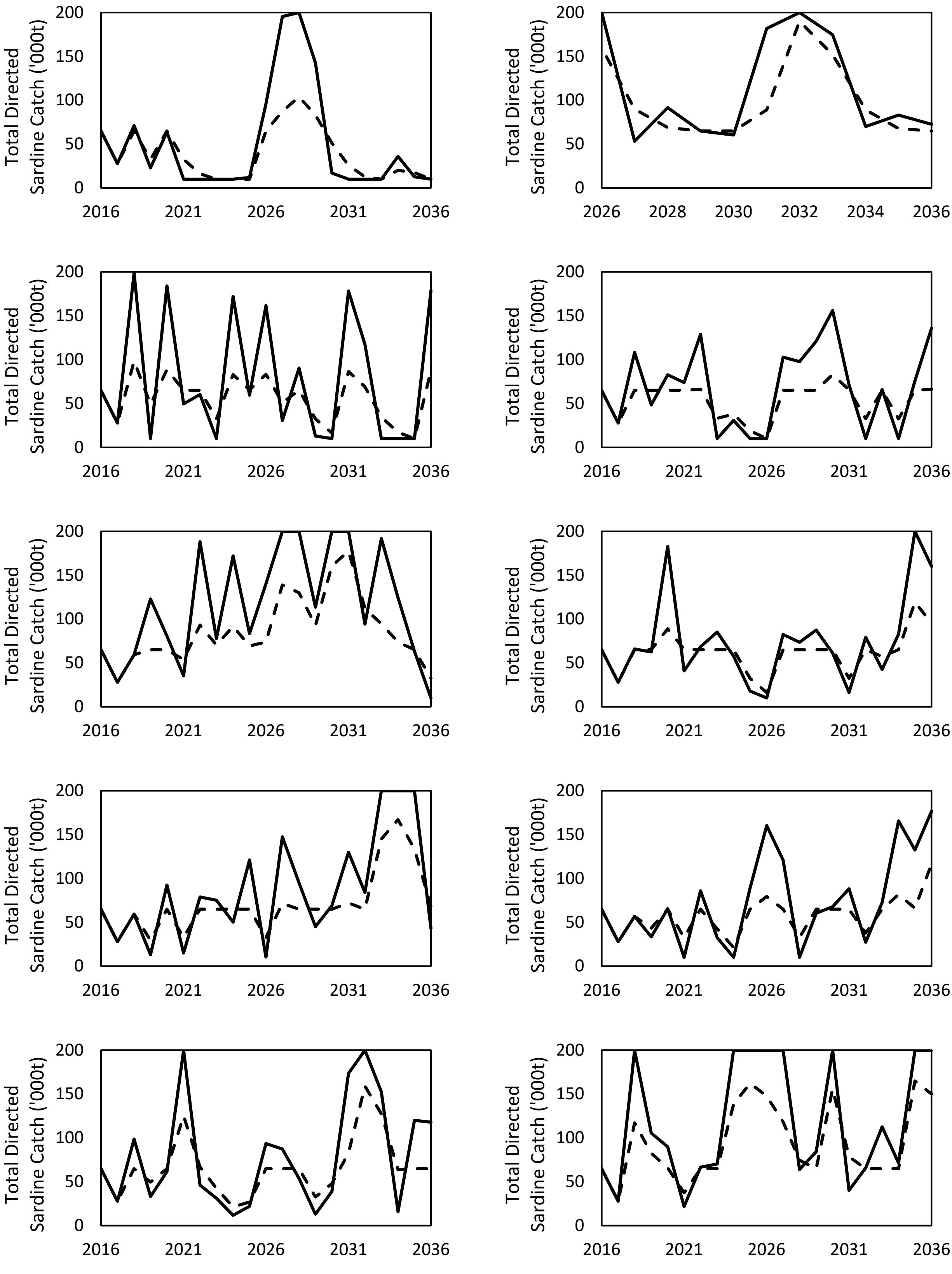


Figure 4. Trajectories of total directed sardine catch from 10 simulations. Trajectories are shown for the Reference Case sardine HCR with a stable TAC of 50 000t (solid), with $\beta = 0.170$, and the HCR with a 50% constraint on changes in the TAC if $B_{y-1}^{obs,S} < B_{crit}^{S}$, but the maximum decrease constraint applies to the minimum of TAC_{y-1}^{S} or $c_{stbl}^{S}/(1 - p_{crit}^{S})$ and a stable TAC of 65 000t (dashed line), with $\beta = 0.084$.

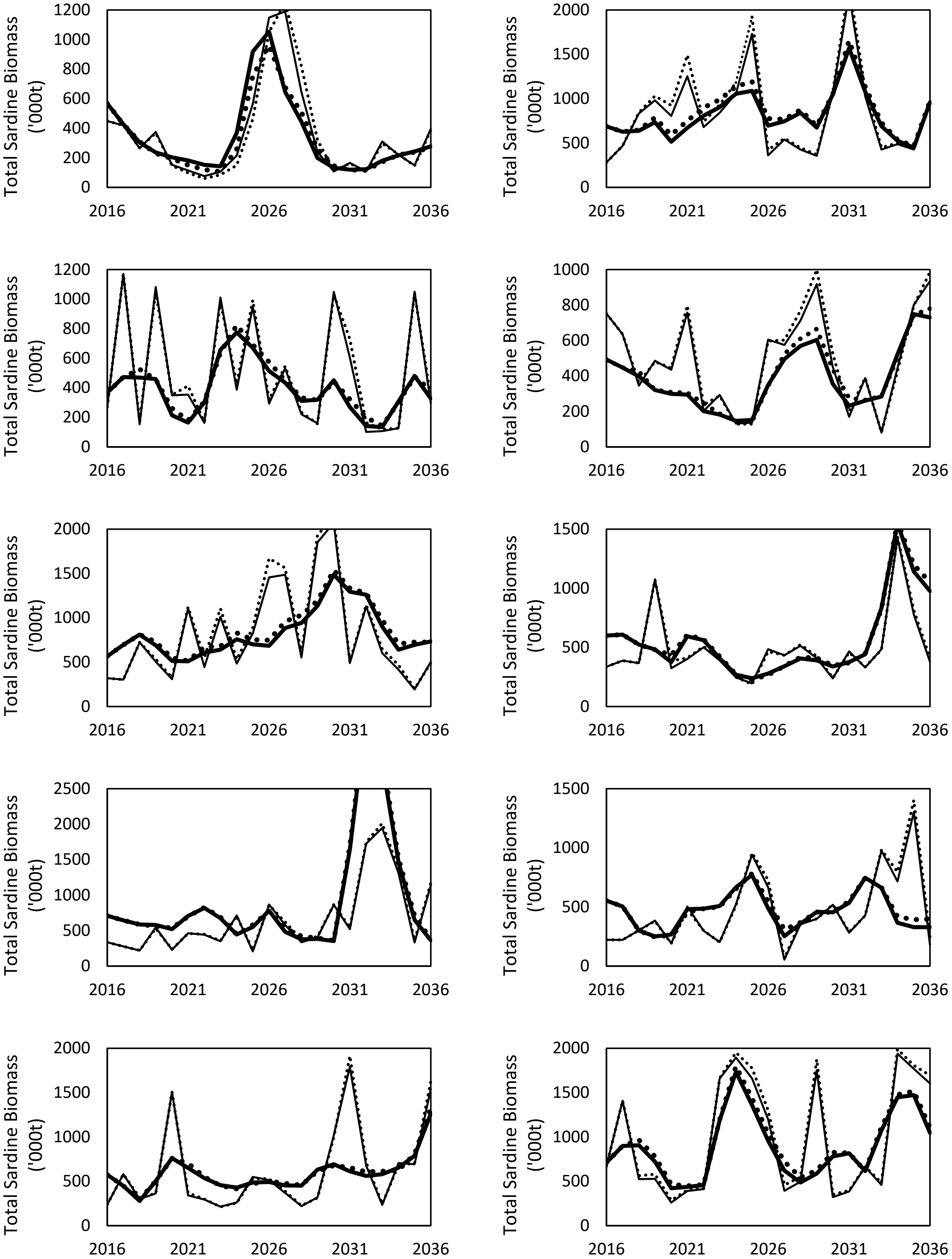
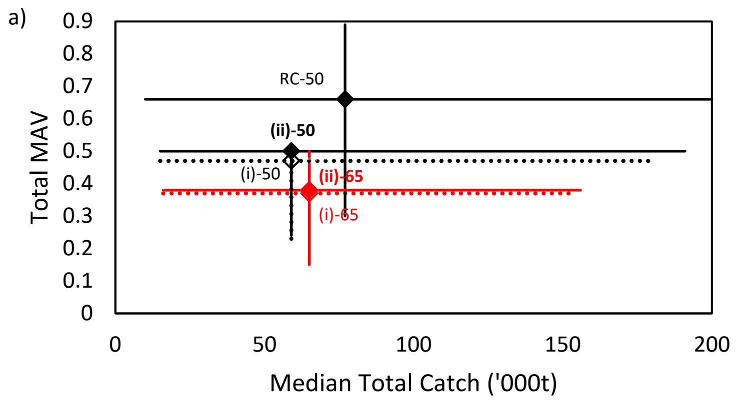


Figure 5. Trajectories of simulated total "true" (**bold lines**) against survey estimated (thin lines) sardine biomass from 10 simulations. Trajectories are shown for the Reference Case sardine HCR with a stable TAC of 50 000t (solid lines), with $\beta = 0.170$, and the HCR with a 50% constraint on changes in the TAC if $B_{y-1}^{obs,S} < B_{crit}^{S}$, but the maximum decrease constraint applies to the minimum of TAC_{y-1}^{S} or $c_{stbl}^{S}/(1 - p_{crit}^{S})$ and a stable TAC of 65 000t (dotted lines), with $\beta = 0.084$. The y-axis differs between plots.



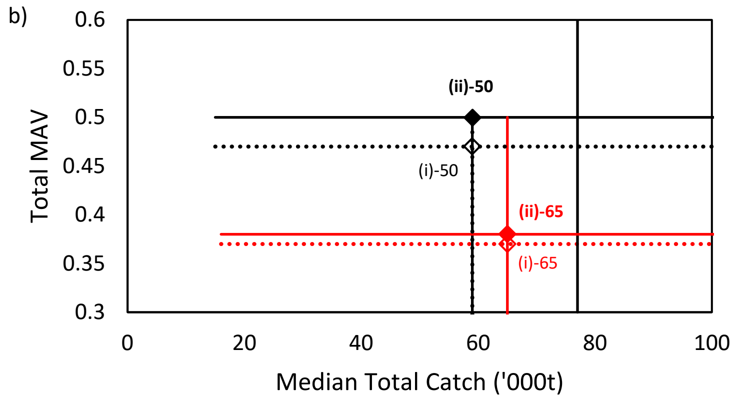


Figure 6. The median and 90% probability intervals of MAV in the total directed sardine catch and median total directed sardine catch, tuned to a risk of <0.15. The data labels indicate first the Reference Case, or option i) or ii) with $p^S_{crit} = 0.5$, and secondly the stable TAC of 50 or 65 000t. The lower figure is a repeat of the upper figure, but over a smaller range for both axes.

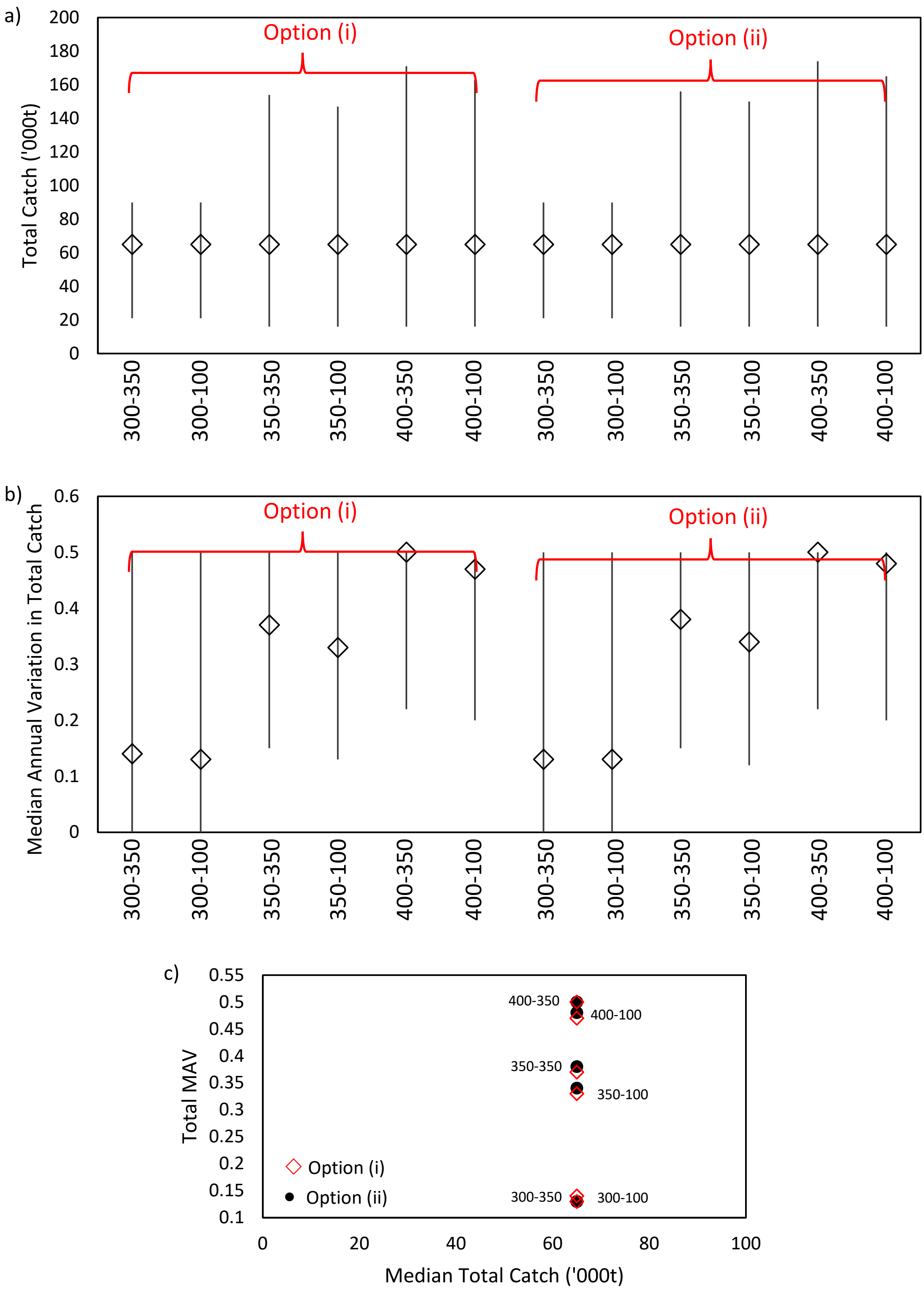


Figure 7. The median and 90% probability intervals for a) total directed sardine catch and b) median annual variation in total directed sardine catch, tuned to risk of <0.15. The HCRs compared have different Critical Biomass thresholds (first number in the labels) and different ranges for linear smoothing (second number in the labels), but all have $p_{crit}^{S} = 0.5$, and a stable TAC of 65 000t. Figure c) plots the medians of a) and b) against one another.

Appendix A: Reference Case Harvest Control Rules

In this Appendix, catches-at-age are given in numbers of fish (in billions), whereas the TACs and TABs are given in thousands of tons. Sardine and anchovy total allowable catches (TACs) and sardine total allowable bycatches (TABs) are set at the start of the year and the latter two are revised during the year. All parameters are defined in Table A.1.

Initial TACs / TAB (January)

The directed >14cm sardine TAC and initial directed anchovy TAC and TAB for ≤14cm sardine bycatch with anchovy directed fishing are based on the results of the November biomass survey. These limits are announced prior to the start of the pelagic fishery at the beginning of each year.

The directed sardine TAC is set at a proportion of the previous year's November survey estimate of biomass, but subject to the constraints of a minimum, stable and a maximum value. The TAC is subject to a maximum percentage decrease from the previous year's TAC. Different constraints on inter-annual decreases above and below a 'two-tier' threshold will be investigated before the final OMP-18 is agreed, but are omitted from this interim OMP-18.

The directed anchovy initial TAC is based on how the most recent November survey estimate of biomass survey relates to the historical average between 1984 and 1999. In the absence of further information, which will become available after the May recruitment survey, this initial TAC assumes the forthcoming recruitment (which will form the bulk of the catch) will be the *historical* average. A 'scale-down' factor, δ, is therefore introduced to provide a buffer against possible poor recruitment. The anchovy TAC is subject to similar constraints as apply for sardine, but include a two-tier threshold.

OMP-18 includes a fixed anchovy TAB, TAB^A, for sardine-only right holders, and a fixed >14cm sardine TAB, TAB^S_{big}, consisting mainly of adult sardine bycatch with round herring and to a lesser extent with anchovy (see Table A.1). OMP-18 also includes a fixed allocation for $\leq$ 14cm sardine bycatch with round herring, $TAB^S_{y,smallrh}$ (Table A.1), and an allocation for $\leq$ 14cm sardine bycatch in the >14cm directed sardine landings, set proportional to the directed sardine TAC. Finally, a ≤14cm sardine TAB with anchovy is set proportional to the anchovy TAC.

Directed >14cm sardine TAC: $$TAC^S_y = \beta B^{obs,S}_{y-1} \quad \text{(OMP.1)}$$

subject to: $$max\{(1 - c^S_{mxdn})TAC^S_{y-1}; c^S_{stbl}\} \leq TAC^S_y \leq c^S_{mxtac} \quad \text{(OMP.2)}$$

Initial directed anchovy TAC: $$TAC^A_{y,init} = \alpha\delta q\left(p + (1-p)\frac{B^{obs,A}_{y-1}}{\bar{B}^A_{Nov}}\right) \quad \text{(OMP.3)}$$

subject to: $$\begin{array}{ll} max\{(1 - c^A_{mxdn})TAC^A_{y-1}; c^A_{mntac}\} \leq TAC^A_{y,init} \leq c^A_{mxtac} & if\ TAC^A_{y-1} \leq c^A_{tier} \\ max\{(1 - c^A_{mxdn})c^A_{tier}; c^A_{mntac}\} \leq TAC^A_{y,init} \leq c^A_{mxtac} & if\ TAC^A_{y-1} > c^A_{tier} \end{array} \quad \text{(OMP.4)}$$

≤14cm sardine TAB with directed >14cm sardine catch: $$TAB^S_{y,small} = \omega TAC^S_y \quad \text{(OMP.5)}$$

Initial ≤14cm sardine TAB with anchovy: $$TAB^S_{y,anch,init} = \gamma_y TAC^A_{y,init} \quad \text{(OMP.6)}$$

where: $$\gamma_y = 0.1 + \frac{\gamma_{max}}{1+exp\left(-ln(19)\frac{B_{y-1}^{obs,S}-B_{50}}{B_{95}-B_{50}}\right)}. \quad \text{(OMP.7)}$$

Here γ_y increases according to a logistic curve from 10% in years in which the survey estimated sardine biomass, $B_{y-1}^{obs,S}$, is poor to average, towards a maximum when sardine biomass is higher.

To maintain continuity in the directed sardine and initial anchovy TACs as the Critical Biomass thresholds (see below), B_{crit}^S and B_{crit}^A, are approached from above and below, the following linear smoothing is applied.

If $B_{crit}^S \le B_{y-1}^{obs,S} \le B_{crit}^S + \Delta^S$:

$$TAC_y^S = \left(1 - \frac{B_{y-1}^{obs,S} - B_{crit}^S}{\Delta^S}\right) c_{stbl}^S + \left(\frac{B_{y-1}^{obs,S} - B_{crit}^S}{\Delta^S}\right) TAC_y^{S\prime} \quad \text{(OMP.8)}$$

where c_{stbl}^S is the TAC output from equation (OMP.15) when $B_{y-1}^{obs,S} = B_{crit}^S$, while $TAC_y^{S\prime}$ is the value output from equation (OMP.2) when $B_{y-1}^{obs,S} = B_{crit}^S + \Delta^S$.

If $B_{crit}^A \le B_{y-1}^{obs,A} \le B_{crit}^A + \Delta^A$:

$$TAC_{y,init}^A = \left(1 - \frac{B_{y-1}^{obs,A} - B_{crit}^A}{\Delta^A}\right) c_{stbl}^A + \left(\frac{B_{y-1}^{obs,A} - B_{crit}^A}{\Delta^A}\right) TAC_y^{A\prime} \quad \text{(OMP.9)}$$

where c_{stbl}^A is the TAC output from equation (OMP.16) when $B_{y-1}^{obs,A} = B_{crit}^A$, while $TAC_y^{A\prime}$ is the value output from equation (OMP.4) when $B_{y-1}^{obs,A} = B_{crit}^A + \Delta^A$.

Revised TACs / TAB (June)

The anchovy TAC and sardine TAB midyear revisions are based on the most recent November and now also recruit survey estimates of abundance. As the estimate of recruitment is now available, the 'scale-down' factor, δ, is no longer required to set the anchovy TAC. The additional constraints include ensuring that the revised anchovy TAC is not less than the initial anchovy TAC.

The revised ≤14cm sardine TAB with anchovy is calculated using an estimate of the ratio, r_y, of juvenile sardine to anchovy, provided this ratio is larger than γ_y, which was used to set the initial TAB.

Revised anchovy TAC: $$TAC_y^A = \alpha q \left(p \frac{N_{y-1,0}^A}{\bar{N}_0^A} + (1-p)\frac{B_{y-1}^{obs,A}}{\bar{B}_{Nov}^A}\right) \quad \text{(OMP.10)}$$

subject to:
$$\begin{aligned} &max\{TAC_{y,init}^A; (1-c_{mxdn}^A)TAC_{y-1}^A; c_{mntac}^A\} \le TAC_y^A \le c_{mxtac}^A \quad if\ TAC_{y-1}^A \le c_{tier}^A \\ &max\{TAC_{y,init}^A; (1-c_{mxdn}^A)c_{tier}^A; c_{mntac}^A\} \le TAC_y^A \le c_{mxtac}^A \quad if\ TAC_{y-1}^A > c_{tier}^A \end{aligned} \quad \text{(OMP.11)}$$

The anchovy TAC equations require that $N_y^{obs,A}$, the recruitment numbers estimated in the survey, be back-calculated to November of the previous year, assuming a fixed value of 1.2 *year*$^{-1}$ for M_j^A. The back-calculated recruitment numbers are calculated as follows:

$$N_{y-1,0}^A = \left(N_y^{obs,A} e^{t_y \times 1.2/12} + C_{y,0bs}^A\right) e^{6\times1.2/12} \quad \text{(OMP.12)}$$

Revised <14cm sardine TAB with anchovy:

$$TAB_{y,anch}^S = \lambda_y TAC_{y,init}^A + r_y\left(TAC_y^A - TAC_{y,iniy}^A\right) \quad \text{(OMP.13)}$$

where: $\lambda_y = max\{\gamma_y, r_y\}$

As for the initial TAC, continuity in the revised anchovy TAC as the Critical Biomass threshold is approached from above and below, is maintained by applying the following linear smoothing.

If $B^A_{crit} \leq B^A_{y,proj} \leq B^A_{crit} + \Delta^A$:

$$TAC^A_y = \left(1 - \frac{B^A_{y,proj} - B^A_{crit}}{\Delta^A}\right) c^A_{stbl} + \left(\frac{B^A_{y,proj} - B^A_{crit}}{\Delta^A}\right) TAC^{A\prime}_y \qquad \text{(OMP.14)}$$

where c^A_{stbl} is the TAC output from equation (OMP.21) when $B^{obs,A}_{y-1} = B^A_{crit}$, while $TAC^{A\prime}_y$ is the value output from equation (OMP.11) when $B^{obs,A}_{y-1} = B^A_{crit} + \Delta^A$, and $B^A_{y,proj}$ is defined by equation (OMP.18).

Note that by construction $TAB^S_{y,anch} \geq TAB^S_{y,anch,init}$ and $TAC^A_y \geq TAC^A_{y,init}$.

Critical Biomass Metarule

Sardine directed TAC

If $B^{obs,S}_{y-1} < B^S_{crit}$, then Critical Biomass metarules apply for the directed sardine TAC:

$$TAC^S_y = \begin{cases} c^S_{mntac} & if\ \frac{B^{obs,S}_{y-1}}{B^S_{crit}} < x^S \\ max\left\{c^S_{mntac}; c^S_{stbl}\left(\frac{\frac{B^{obs,S}_{y-1}}{B^S_{crit}} - x^S}{1 - x^S}\right)^2\right\} & if\ x^S < \frac{B^{obs,S}_{y-1}}{B^S_{crit}} < 1 \end{cases} \qquad \text{(OMP.15)}$$

The metarule is quadratic, tending to zero at a proportion, x^S of the threshold B^S_{crit}, but there is an additional absolute minimum TAC, c^S_{mntax}, that overrides this rule.

Initial Anchovy TAC

If $B^{obs,A}_{y-1} < B^A_{crit}$, then Critical Biomass metarules apply for the initial anchovy TAC:

Initial TAC:
$$TAC^A_{y,init} = \begin{cases} 0 & if\ \frac{B^{obs,A}_{y-1}}{B^A_{crit}} < x^A \\ c^A_{stbl}\left(\frac{\frac{B^{obs,A}_{y-1}}{B^A_{crit}} - x^A}{1 - x^A}\right)^2 & if\ x^A < \frac{B^{obs,A}_{y-1}}{B^A_{crit}} < 1 \end{cases} \qquad \text{(OMP.16)}$$

The metarule allows for the TAC to be set to zero if the survey estimated anchovy biomass falls below x^A of the threshold B^A_{crit}.

Revised Anchovy TAC

The results of the most recent November and recruit surveys are projected forward, taking natural and anticipated fishing mortality into account, in order to provide a proxy ($B^A_{y,proj}$) for the forthcoming November survey, and hence have a basis for invoking the Critical Biomass metarule, if necessary. Defining $TAC^{A\prime\prime}_y$ as the value output from equation (OMP.11) for $B^{obs,A}_{y-1}$ and $N^A_{y-1,0}$:

A projected survey estimate of anchovy biomass consisting of recruits from year y, $B^A_{y,proj0}$, is calculated as follows:

$$B^A_{y,proj0} = k^A_N \times max\left\{0; \left(\frac{N^{obs,A}_y}{k^A_r} - \left[\frac{TAC^{A''}_y + TAB^A - \overline{w}^A_{1c}C^A_{y,1}}{\overline{w}^A_{0c}} - C^A_{y,0bs}\right]\right) e^{-(6-t_y)\times 1.2/12}\overline{w}^A_1\right\}. \quad \text{(OMP.17)}$$

The total projected survey estimate of anchovy biomass, $B^A_{y,proj}$, is thus:

$$B^A_{y,proj} = k^A_N \left(\frac{B^{obs,A}_{y-1}}{k^A_N \overline{w}^A_1} e^{-5\times 1.2/12} - C^A_{y,1}\right) e^{-7\times 1.2/12}\overline{w}^A_2 + B^A_{y,proj0} \quad \text{(OMP.18)}$$

The recruit survey result in year y (in numbers) that would be sufficient to yield a $B^A_{y,proj}$ value of exactly B^A_{crit} is calculated as follows:

$$\theta = \frac{\left[B^A_{crit} - \left(B^A_{y,proj} - B^A_{y,proj0}\right)\right]}{k^A_N \overline{w}^A_1} e^{(6-t_y)\times 1.2/12} + \frac{TAC^{A''}_y + TAB^A - \overline{w}^A_{1c}C^A_{y,1}}{\overline{w}^A_{0c}} - C^A_{y,0bs} \quad \text{(OMP.19)}$$

This is back-calculated to November of the previous year in the same way as equation (OMP.12) during OMP implementation:

$$N^{A*}_{y-1,0} = \left(k^A_r \theta e^{t_y \times 1.2/12} + C^A_{y,0bs}\right) e^{6\times 1.2/12} \quad \text{(OMP.20)}$$

If $B^A_{y,proj} < B^A_{crit}$, then Critical Biomass metarules apply for the anchovy TAC. The anchovy TAC is calculated by reducing c^A_{stbl} by the ratio (squared) of the 'baseline' TAC (i.e. that from OMP.10) evaluated with the annual recruitment for year y to that calculated using θ. The rule allows for the TAC to be set to zero (or to the initial anchovy TAC, if greater than zero) if the survey estimated anchovy recruitment or biomass falls below a quarter of the corresponding threshold. Defining $= \frac{p\frac{N^A_{y-1,0}}{\bar{N}^A_0} + (1-p)\frac{B^{obs,A}_{y-1}}{\bar{B}^A_{Nov}}}{p\frac{N^{A*}_{y-1,0}}{\bar{N}^A_0} + (1-p)\frac{B^{obs,A}_{y-1}}{\bar{B}^A_{Nov}}}$:

$$TAC^S_y = \begin{cases} max\{0; TAC^A_{y,init}\} & if\ R < x^A \\ max\left\{TAC^A_{y,init}; c^A_{stbl}\left(\frac{R - x^A}{1 - x^A}\right)^2\right\} & if\ x^A < R < 1 \end{cases} \quad \text{(OMP.21)}$$

Table A1. Definitions of the Reference Case control parameters and constraints, together with their values, as well as other data input required in the Harvest Control Rule formulae. All mass-related quantities are given in thousands of tons.

		Definition	Value
Key Control Parameters tuned to meet target risk levels	β	Directed sardine catch control parameter	0.17
	α	Directed anchovy catch control parameter for normal season	0.889
Fixed TABs	TAB^S_{big}	Fixed >14cm sardine bycatch	7
	TAB^A	Fixed anchovy bycatch for sardine only right holders	0.5
	$TAB^S_{y,small,rh}$	Fixed ≤14cm sardine bycatch with round herring	1.0
Fixed Control Parameters and Constraints Constraints	δ	Scale-down factor applied to initial anchovy TAC to provide a buffer against possible poor recruitment	0.85
	p	Weighting given to recruitment survey compared to November survey in setting anchovy TAC	0.7
	q	Constant reflecting average annual TAC under OMP-99 if $\alpha = 1$	300
	$\bar{B}^A_{Nov}$	Historical average 1984 to 1999 November survey estimate of anchovy total biomass	1380
	$\bar{N}^A_0$	Average of 1985 to 1999 May survey estimated anchovy recruitment, back-calculated to 1 November of the previous year	222 billion
	ω	Estimate of the maximum proportion of ≤14cm sardine bycatch in the >14cm sardine catch	0.07
	γ_y	Initial (conservative) estimate of anticipated juvenile sardine : anchovy ratio	OMP.7
	γ_{max}	Maximum of the logistic curve for γ_y	0.1
	B_{50}	Survey estimate of sardine total biomass where the logistic curve for γ_y reaches 50%	2000
	B_{95}	Survey estimate of sardine total biomass where the logistic curve for γ_y reaches 95%	3178
	c^S_{mntac}	Absolute minimum directed sardine TAC	10
	c^S_{stbl}	Stable directed sardine TAC	50
	c^A_{stbl}	Stable anchovy TAC	120
	c^S_{mxtac}	Maximum directed sardine TAC	200
	c^A_{mxtac}	Maximum total anchovy TAC	350
	c^S_{tier}	Two-tier threshold for directed sardine TAC	255
	c^A_{tier}	Two-tier threshold for anchovy TAC	330
	c^S_{mxdn}	Maximum proportion by which directed sardine TAC can be reduced annually	0.20
	c^A_{mxdn}	Maximum proportion by which anchovy TAC can be reduced annually	0.25
	B^S_{crit}	November survey estimated biomass threshold below which Critical Biomass metarules are invoked for sardine	350
	B^A_{crit}	November survey estimated biomass threshold below which Critical Biomass metarules are invoked for anchovy	600
	Δ^S	Linear smoothing is introduced below $B^S_{crit} + \Delta^S$ before sardine Critical Biomass metarules are applied (to ensure continuity)	350
	Δ^A	Linear smoothing is introduced below $B^A_{crit} + \Delta^A$ before sardine Critical Biomass metarules are applied (to ensure continuity)	100
	x^S	The proportion of B^S_{crit} below which the metarule sets the directed sardine TAC to zero	0.25
	x^A	The proportion of B^A_{crit} below which the metarule sets the anchovy TAC to zero	0.25

Table A1 (continued).

		Definition	Value
Working parameters	$N_{y-1,0}^{A}$	The survey estimate of anchovy recruitment, $N_{y}^{obs,A}$, back-calculated to 1 November $y-1$ by taking natural and fishing mortality into account	OMP.12
	r_y	The ratio of juvenile sardine to anchovy "in the sea" during May of year y, calculated as the average of $r_{y,sur}$ and $r_{y,com}$	
	$B_{y,proj}^{A}$	Total projected survey estimate of anchovy biomass in November of year y	OMP.18
	k_N^A	Multiplicative bias associated with the November survey of anchovy total biomass (median of posterior distribution used)	0.633
	k_r^A	Multiplicative bias associated with the recruit survey of anchovy recruitment (median of posterior distribution used)	0.525
Data Used in December $y-1$ HCR Formulae	$B_{y-1}^{obs,S}$	November survey estimate of sardine total biomass in year $y-1$ (in thousands of tons)	
	$B_{y-1}^{obs,A}$	November survey estimate of anchovy total biomass in year $y-1$ (in thousands of tons)	
Data Used in June y HCR Formulae	$N_{y}^{obs,A}$	May survey estimate of anchovy recruitment in year y (in billions)	
	t_y	Day of commencement of recruitment survey in year y (time in months after 1 May)	
	$C_{y,1}^{A}$	Anchovy catch at age 1[3] from 1 November of year $y-1$ to the day before the commencement of the recruitment survey (in billions)	
	$C_{y,0bs}^{A}$	Anchovy catch at age 0[6] from 1 November of year $y-1$ to the day before the commencement of the recruitment survey (in billions)	
	$r_{y,sur}$	Ratio of juvenile sardine to anchovy (by mass) indicated by the recruitment survey	
	$r_{y,com}$	Ratio of juvenile sardine to anchovy (by mass) in the commercial catches[4] during May, based on the commercial catches comprising at least 50% anchovy only	
	$\overline{w}_1^A$	Average historical anchovy weight-at-age 1 in November (in gm) (median of posterior distribution used)	10.833
	$\overline{w}_2^A$	Average historical anchovy weight-at-age 2 in November (in gm) (median of posterior distribution used)	14.503
	$\overline{w}_{0c}^A$	Average historical catch weight-at-age 0 (in gm)	5.484
	$\overline{w}_{1c}^A$	Average historical catch weight-at-age 1 (in gm)	12.702

[3] Monthly cut-off lengths are used to split the anchovy catch into age 0 and age 1. The monthly cut-off lengths for November to March are given in de Moor *et al.* (2012), while the monthly cut-off lengths for April, May and June (if needed) are dependent on the recruit cut-off length used for the recruit survey in year y.

[4] Only commercial catches comprising at least 50% anchovy with sardine bycatch are considered.