Results towards the selection of OMP-18rev

C.L. de Moor*

Correspondence email: *carryn.demoor@uct.ac.za*

Following the declaration of Exceptional Circumstances for anchovy in 2020, an anchovy-only revised Operational Management Procedure (OMP-18rev) is to be agreed and used to set the anchovy Total Allowable Catches until a new joint sardine-anchovy OMP can be developed. This document presents performance statistics for Candidate Management Procedures with alternative Critical Biomass thresholds under a range of model scenarios to inform the selection of OMP-18rev.

Keywords: anchovy, Operating Models, Operational Management Procedure, OMP-18rev

Introduction

Following the declaration of Exceptional Circumstances first for sardine and subsequently for anchovy, recommendations for Total Allowable Catches (TACs) and Total Allowable Bycatches (TABs) for South African sardine and anchovy are no longer set according to OMP-18 (de Moor 2018a). Under Exceptional Circumstances, the Small Pelagic Scientific Working Group (SWG-PEL) has provided recommendations for sardine and anchovy TACs and TABs based on ad-hoc advice frequently linked to short-term projections from the most recent assessment of the resource.

An OMP-18rev for South African sardine and anchovy, using Operating Models (OMs) tuned to data available up to the end of 2019, was initially being developed during the latter part of 2020 (de Moor 2020a). The SWG-PEL subsequently decided that an anchovy-only OMP-18rev should instead be selected and the sardine resource continue to be managed using ad-hoc advice based on short-term projections until a new joint Operational Management Procedure (OMP) is ready, expected towards the end of 2022. This document presents the results towards the selection of an anchovy-only OMP-18rev, following the same methodology of de Moor (2020a), but without any dependence on a model of the sardine resource (de Moor 2021).

Methods

de Moor (2020b) reported on the conditioning of the anchovy Operating Models (OMs) to the available historical data and the selection of a baseline OM, A_{BH}, from the suite of robustness tests:

A_{2BH} - Two Beverton Holt stock-recruitment curves, with uniform priors on steepness and carrying capacity, one estimated using data from 1984 to 1999 and the other from 2000 to 2019. The latter stock-recruitment relationship is assumed for future years.

A_{2BHrtn} - Two Beverton Holt stock-recruitment curves, with uniform priors on steepness and carrying capacity, one estimated using data from 1984 to 1999 and 2013 to 2019, and the other from 2000 to 2012. The latter stock-recruitment relationship is assumed for future years.

A_{R} - Ricker stock-recruitment curve, with uniform priors on steepness and carrying capacity.

A_{HS} - Hockey stick stock-recruitment curve, with uniform priors on the log of the maximum recruitment and on the

* MARAM (Marine Resource Assessment and Management Group), Department of Mathematics and Applied Mathematics, University of Cape Town, Rondebosch, 7701, South Africa.

ratio of the spawning biomass at the inflection point to carrying capacity.

A_{M1} - $\bar{M}_j^A = \bar{M}_{ad}^A = 0.9$ (for comparison with the baseline assessment of 2007).

A_{M2} - $\bar{M}_j^A = 1.5$ and $\bar{M}_{ad}^A = 1.2$ (alternative $\bar{M}_j^A$, similar to A_{BH} in terms of value of the negative log joint posterior mode).

A_{Mad} - Annually varying adult natural mortality, i.e. random effects model with $\sigma_{ad} = 0.2$ and $\rho \sim U(0,1)$.

A_{Mj} - Annually varying juvenile natural mortality, i.e. random effects model with σ_j =0.2 and $\rho \sim U(0,1)$.

A_{M2000+} - Natural mortality assumed to have increased in 2000; i.e. $\bar{M}_j^A = \bar{M}_{ad}^A = 1.2$year^{-1} prior to 2000 and $\bar{M}_j^A = \bar{M}_{ad}^A = 1.5$ year^{-1} from 2000 onwards. The Beverton-Holt stock recruitment relationship was estimated to correspond to the years 2000 onwards, with no stock-recruitment relationship assumed prior to 2000.

A_4 - No plus group, all remaining fish assumed to die as they reach age 5.

A_{DD} - Density dependent natural mortality: $\bar{M}_{j,y}^A = \bar{M}_{ad,y}^A = \bar{M} + e^{-\chi B_{y-1}^A}$.

A_{com2} - Commercial selectivity was modelled using a double-logistic curve.

A_{kegg} - Egg survey bias estimated with uninformative prior, i.e. $ln(k_g^A) \sim U(-100,0.7)$.

A_{lamR} - Additional variance (over and above the survey sampling CV) associated with the recruit survey fixed $(\lambda_r^A)^2$=0.

A_{lamN2} - Additional variance (over and above the survey sampling CV) associated with the November survey fixed $(\lambda_N^A)^2 = 0.02$.

A_{low}[1] - Five consecutive years of future poor recruitment, i.e. $\varepsilon_{1,y}^A$=-1.5[2] for $y = 2025 - 2029$.

A_{high}[1] - Five consecutive years of future good recruitment, i.e. $\varepsilon_{1,y}^A$=1.5[2] for $y = 2025 - 2029$.

The methodology and Operating Models (OMs, including implementation error and observation error) to be used to simulation test the anchovy-only OMP-18rev have been fully specified in de Moor (2021). The key differences in this OM from that which was being used to develop a joint sardine-anchovy OMP-18rev (de Moor 2020c) relate to the implementation error of closure of the anchovy fishery due to sardine bycatch constraints and observation error excluding correlation between sardine and anchovy in the November and recruit acoustic survey estimates of abundance.

Management Strategy Evaluation involves the selection of a Management Strategy (OMP in the South African context) that is robust to a range of uncertainties (e.g. Punt *et al*. 2016). The same method used by de Moor (2020a) is initially followed to obtain the key anchovy tuning parameter, α, for Candidate MPs for a range of B_{crit}^A values by initially only considering the baseline OM, A_{BH}. The ability of these CMPs to handle the inherent uncertainty surrounding this anchovy resource is then checked against the robustness tests to see if any or all of these CMPs suffice.

Results

No Future Catch

Figures 1 and 2 show that the November biomass and recruitment is projected to be within the same range as that observed and estimated historically.

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[1] These two OMs are new, but do not require reconditioning on historical data as differences from A_{BH} only occur in future years.

[2] While Figure 3 of de Moor (2020a) indicates standardised residuals can often extend to ±2, even reaching -4 in some cases, standardised residuals of ±1.5 for five consecutive years were considered to reflect relatively good/poor future recruitment scenarios.

The future 'observations' generated for the recruit surveys (assumed to take place mid-May each year) are compared against those historically observed in Figure 3. The June 2020 and 2021 survey estimates are shown together with that predicted from the OM which is conditioned on data up to November 2019. Importantly, the estimates observed are within the range of that predicted. Given the updated methodology used in de Moor (2021) compared to de Moor (2018b) to generate recruitment in the initial year (November 2019 in this case), de Moor (2020a) additionally tuned a CMP assuming an 'upper recruitment extreme' and found little change to the selected α parameter. Figure 4 similarly shows the future November survey 'observations' with the November 2020 estimate within the range predicted.

Tuning alpha according to the method of de Moor (2020a)

Key performance statistics for the baseline OM, A_{BH}, are shown in Table 1. Under a no future catch scenario, the risk to the anchovy resource is simulated to be higher given 4 more years data than that simulated using the OM based on data up to 2015. Risk to the anchovy resource is defined as the probability of anchovy spawner biomass being below that of 1996 (the lowest historical level) over the 20 year projection period (de Moor 2018a). The additive increase in risk under a no catch scenario is 1.2% (from 0.018 to 0.030). The risk under OMP-18, however, increases by 13.9% from the old OM to A_{BH}.

Applying OMP-14 to A_{BH} results in $Risk_A = 0.193$ (Table 1) and following the method of de Moor (2020a), "CMPd"[3] is tuned with $\alpha = 0.907$ to also have $Risk_A = 0.193$. As a means to reduce the risk of the anchovy resource dropping to the risk threshold without impacting catches when the anchovy resource is healthy, "CMPe" and "CMPf" use the same α values, but higher B^A_{crit} values of 700 and 800 thousand tons, respectively, compared to $B^A_{crit} = 600$ for CMPd.

Performance statistics

The annual anchovy catch under CMPd is simulated to range from 8 to 350 000t, with a median of 350 000t and an average of 275 000t. The risk to the resource is 0.193, an additive increase of 16.3% from a no catch scenario. OMP-18 was selected with an additive increase of 7.1% in risk from a no catch scenario. Risk decreases to 0.178 for CMPe and 0.164 for CMPf. A risk of 0.164 is an additive increase of 13.4% from the no catch scenario. The decreased risk associated with CMPe and CMPf correspond with a small decrease in average catch (from 275 to 274 and 273 000t, respectively) and no change to the median catch of 350 000t (Figure 5). Table 1 and Figure 6 additionally show the annual risk[4] under the alternative CMPs, which increases with decreasing B^A_{crit}.

The simulated distribution of initial anchovy TAC in 2022 and 2023 is more spread out compared to the distribution of realised catch, primarily due to the maximum (final) TAC of 350 000t being taken in the majority of simulations (Figure 7).

Robustness Tests

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[3] "CMPa" is tuned with $\alpha = 0.933$ excluding the initial 2020 anchovy TAC of 299 700t.

[4] The probability of the anchovy spawner biomass is below the 1996 level in a particular year.

Tables 2 and 3 shows the key performance statistics for CMPd ($B^A_{crit} = 600$) and CMPf ($B^A_{crit} = 800$) under plausible alternative OMs. While the risk under the baseline OM is 0.193 for CMPd and 0.164 for CMPf, risk can be considerably higher or lower under alternative OMs. In all model scenarios, the risk to the resource is lower for CMPf ($B^A_{crit} = 800$) than for CMPd ($B^A_{crit} = 600$), with the benefit in terms of lower risk under CMPf increasing for OMs that have a greater risk (Figure 5a). Risk to the resource is lowest and average annual catch is highest under the most recruitment-optimistic scenarios of A_{HS}, A_{high} and A_{2BH}. Risk to the resource is greatest under A_{low}, A_R and A_{3BH} (Tables 2,3 and Figures 5,6). These results suggest that even CMPf with a higher $B^A_{crit} = 800$ would not be sufficiently precautionary if consecutive years of poor recruitment are encountered.

Summary

As OMP-18rev is to be a revision OMP, rather than a new OMP, limited changes to the HCR formulae and parameter values are being tested. This document has shown the performance statistics under three alternative CMPs with the same key control parameter of $\alpha = 0.907$, but with different values for the Critical Biomass threshold, B^A_{crit}. While the α value was selected tuning the CMP to the baseline hypothesis, the selected CMP should ideally be robust to plausible uncertainties in the underlying population dynamics. Simulation testing CMPs while taking a range of plausible uncertainties into account is one of the key reasons for undertaking Management Strategy Evaluation. Results herein suggest that an anchovy-only OMP-18rev may not be robust to future consecutively poor anchovy recruitment scenarios, but in all cases the risk to the resource is lower for higher B^A_{crit} values.

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Table 1. Key summary performance statistics assuming the baseline anchovy-only OM of A_{BH} for a no catch scenario, OMP-18 and OMP-14 as well as CMPs with $B_{crit}^{A}=600$, tuned to the same risk level as OMP-14: "CMPa" (excluding initial 2021 anchovy TAC) and "CMPe" (with anchovy initial TAC in 2021 = 299 700t). Performance statistics for CMPs with $B_{crit}^{A}=700$ and $B_{crit}^{A}=800$ are also given. The first columns additionally show the performance statistics under a no catch scenario and OMP-18 using the OM available in 2018. Where appropriate, medians and 90% probability intervals are provided, and for some statistics the means are provided additionally and shown in **bold**. All biomasses are given in thousands of tons.

	OM using data up to 2015		A_{BH}								
	No Catch	OMP-18	No Catch	OMP-18	OMP-14	CMPa	CMPb	CMPc	CMPd	CMPe	CMPf
α	-	1.16	-	1.16	0.889	0.933	0.933	0.933	0.907	0.907	0.907
B_{crit}^{A}						600	700	800	600	700	800
$Risk_A$	0.018	0.089	0.030	0.228	**0.193**	**0.193**	0.176	0.161	**0.193**	0.178	0.164
$p(B_{2020}^{sp,A}<B_{1996}^{sp,A})$			0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
$p(B_{2021}^{sp,A}<B_{1996}^{sp,A})$			0.08	0.16 (+8)	0.15 (+7)	0.15 (+7)	0.14 (+6)	0.14 (+6)	0.18 (+10)	0.18 (+10)	0.18 (+10)
$p(B_{2022}^{sp,A}<B_{1996}^{sp,A})$			0.05	0.18 (+13)	0.16 (+11)	0.16 (+11)	0.15 (+10)	0.14 (+9)	0.17 (+12)	0.17 (+12)	0.16 (+11)
$p(B_{2023}^{sp,A}<B_{1996}^{sp,A})$			0.04	0.20 (+16)	0.16 (+12)	0.16 (+12)	0.15 (+11)	0.13 (+9)	0.18 (+14)	0.17 (+13)	0.15 (+11)
$p(B_{2024}^{sp,A}<B_{1996}^{sp,A})$			0.04	0.21 (+17)	0.17 (+13)	0.17 (+13)	0.16 (+12)	0.15 (+11)	0.18 (+14)	0.16 (+12)	0.15 (+11)
$B_{2036}^{sp,A}$ or $B_{2040}^{sp,A}$	**3384** 2341	**2669** 1613	**2920** 2344 [654,7178]	**1778** 1143 [132,5706]	**1754** 1130 [171,5561]	**1862** 1222 [163,5856]	**1895** 1240 [189,5866]	**1927** 1269 [214,5866]	**1872** 1236 [170,5859]	**1904** 1253 [197,5866]	**1935** 1279 [218,5866]
$B_{2036}^{sp,A}/B_{2019}^{sp,A}$ or $B_{2040}^{sp,A}/B_{2019}^{sp,A}$	1.6	1.1	1.9 [0.4,8.7]	0.8 [0.1,6.4]	0.9 [0.1,6.2]	1.0 [0.1,6.4]	1.0 [0.1,6.5]	1.0 [0.1,6.7]	0.9 [0.1,6.4]	1.0 [0.1,6.5]	1.0 [0.1,6.7]
$B_{2036}^{sp,A}/B_{1996}^{sp,A}$ or $B_{2040}^{sp,A}/B_{1996}^{sp,A}$	4.9	3.4	5.0 [1.4,15.7]	2.3 [0.3,12.5]	2.3 [0.3,12.1]	2.5 [0.3,12.5]	2.6 [0.4,12.6]	2.6 [0.5,12.6]	2.5 [0.3,12.5]	2.6 [0.4,12.6]	2.6 [0.5,12.6]
$B_{2036}^{sp,A}/K^{A}$ or $B_{2040}^{sp,A}/K^{A}$	1.2	0.9	0.7 [0.2,2.0]	0.4 [0.0,1.6]	0.3 [0.0,1.6]	0.4 [0.0,1.6]	0.4 [0.0,1.6]	0.4 [0.1,1.6]	0.4 [0.0.,1.6]	0.4 [0.0,1.6]	0.4 [0.1,1.7]
$B_{min}^{sp,A}$	920	543	816 [263,1742]	280 [62,1069]	326 [79,1015]	327 [73,1094]	355 [83,1094]	376 [96,1094]	328 [69,1102]	348 [82,1102]	361 [90,1102]
$B_{min}^{sp,A}/B_{1996}^{sp,A}$	2.0	1.2	1.65 [0.55,4.06]	0.58 [0.13,2.35]	0.66 [0.17,2.20]	0.68 [0.15,2.46]	0.73 [0.18,2.46]	0.78 [0.21,2.46]	0.67 [0.15,2.47]	0.70 [0.17,2.47]	0.74 [0.19,2.47]
$B_{min}^{sp,A}/K^{A}$	0.5	0.3	0.25 [0.07,0.50]	0.09 [0.01,0.30]	0.10 [0.02,0.30]	0.10 [0.02,0.33]	0.11 [0.02,0.33]	0.12 [0.02,0.33]	0.10 [0.02,0.32]	0.11 [0.02,0.33]	0.12 [0.02,0.33]
C^{A}	**11** 0 [0,0]	**311** 350	**0** 0 [0,0]	**283** 350 [4,350]	**312** 346 [8,450]	**276** 350 [9,350]	**275** 350 [8,350]	**274** 350 [7,350]	**275** 350 [8,350]	**274** 350 [6,350]	**273** 350 [5,350]
Med C^{A} [5]	0 [0,0]	350	0 [0,0]	350 [48,350]	355 [72,450]	349 [71,350]	349 [65,350]	350 [62,350]	350 [63,350]	350 [62,350]	350 [57,350]
C_{now}^{A} [6]	0 [0,0]	350	0 [0,0]	350 [19,350]	357 [23,450]	350 [26,350]	350 [20,350]	350 [14,350]	350 [10,350]	350 [6,350]	350 [3,350]
MAV^{A} [7]	-	0.00	-	0.00 [0.00,0.87]	0.24 [0.00,0.83]	0.09 [0.00,0.79]	0.09 [0.00,0.79]	0.09 [0.00,0.81]	0.10 [0.00,0.78]	0.10 [0.00,0.79]	0.11 [0.00,0.82]
$p(B_{y}^{Aobs}<B_{crit}^{A},B_{y}<B_{crit}^{A}/k_{N}^{A})$	-	0.07	-	0.23	0.20	0.20	0.22	0.24	0.20	0.22	0.25
$p(B_{y}^{Aobs}<B_{crit}^{A},B_{y}\geq B_{crit}^{A}/k_{N}^{A})$	-	0.01	-	0.03	0.03	0.03	0.03	0.04	0.03	0.03	0.04
$p(B_{y}^{Aobs}\geq B_{crit}^{A},B_{y}<B_{crit}^{A}/k_{N}^{A})$	-	0.01	-	0.03	0.03	0.02	0.03	0.03	0.03	0.03	0.03
$p(B_{y}^{Aobs}\geq B_{crit}^{A},B_{y}\geq B_{crit}^{A}/k_{N}^{A})$	-	0.91	-	0.72	0.74	0.75	0.72	0.68	0.75	0.72	0.68
Avg # years $B_{y}^{Aobs}<B_{crit}^{A}$ consec	-	2.3	-	2.8	2.4	2.5	2.5	2.5	2.7	2.7	2.7

[5] This gives the median and 90%ile of the 1000 median (over 20 years for each simulation) catches.

[6] Catch statistics calculated over 2021 to 2023 only.

[7] Median and 90%ile of $AAV_{y}^{b}=\left|C_{tot,y}^{S,b}-C_{tot,y-1}^{S,b}\right|/C_{tot,y-1}^{S,b}$

Table 2. Key summary performance statistics for CMPd with $B_{crit}^{A} = 600$ (and $\alpha = 0.907$) under alternative anchovy OMs. The first column additionally shows the performance statistics under a no catch scenario using A_{BH}. Where appropriate, medians and 90% probability intervals are provided, and for some statistics the means are provided additionally and shown in **bold**. All biomasses are given in thousands of tons.

	No Catch	A_{BH}	A_{2BH}	A_{3BH}	A_{2BHrtn}	A_{R}	A_{HS}	A_{M1}	A_{M2}	A_{Mad}	A_{Mj}
$Risk_A$ under no catch		0.030	0.028	0.082	0.037	0.052	<0.001	0.037	0.052	0.047	0.034
$Risk_A$	0.030	0.193	0.084	0.267	0.209	0.299	0.040	0.243	0.237	0.228	0.182
$p\left(B_{2020}^{sp,A} < B_{1996}^{sp,A}\right)$	0.08	0.08	0.04	0.08	0.08	0.08	0.01	0.08	0.07	0.10	0.06
$p\left(B_{2021}^{sp,A} < B_{1996}^{sp,A}\right)$	0.08	0.18 (+10)	0.10	0.20	0.20	0.20	0.01	0.21	0.17	0.20	0.15
$p\left(B_{2022}^{sp,A} < B_{1996}^{sp,A}\right)$	0.05	0.17 (+12)	0.08	0.21	0.19	0.22	0.01	0.22	0.19	0.21	0.16
$p\left(B_{2023}^{sp,A} < B_{1996}^{sp,A}\right)$	0.04	0.18 (+14)	0.08	0.23	0.18	0.23	0.02	0.22	0.19	0.21	0.15
$p\left(B_{2024}^{sp,A} < B_{1996}^{sp,A}\right)$	0.04	0.18 (+14)	0.08	0.23	0.19	0.26	0.02	0.22	0.20	0.21	0.16
$B_{2040}^{sp,A}$	**2920** 2344 [654,7178]	**1872** 1236 [170,5859]	**4253** 3303 [229,10475]	**1798** 1176 [39,6179]	**1429** 1051 [219,3953]	**1720** 1002 [79,5537]	**2246** 2157 [388,3943]	**1971** 1261 [166,6357]	**1775** 1184 [100,5685]	**1936** 1243 [127,6418]	**1986** 1347 [125,6002]
$B_{2040}^{sp,A}/B_{2019}^{sp,A}$	1.9 [0.4,8.7]	0.9 [0.1,6.4]	1.6 [0.2,5.9]	0.9 [0.0,5.5]	0.9 [0.1,4.3]	0.7 [0.1,6.1]	1.3 [0.4,2.7]	0.9 [0.1,6.2]	0.9 [0.1,6.5]	1.0 [0.1,7.5]	1.0 [0.1,6.2]
$B_{2040}^{sp,A}/B_{1996}^{sp,A}$	5.0 [1.4,15.7]	2.5 [0.3,12.5]	7.1 [0.6,24.2]	2.3 [0.1,13.8]	2.0 [0.4,8.9]	2.1 [0.2,12.9]	4.5 [0.8,9.7]	2.1 [0.3,10.7]	2.4 [0.2,12.1]	2.4 [0.3,13.7]	3.0 [0.3,13.9]
$B_{2040}^{sp,A}/K^{A}$	0.7 [0.2,2.0]	0.4 [0.0.,1.6]	0.8 [0.1,2.1]	0.4 [0.0,1.6]	0.5 [0.1,1.6]	0.2 [0.0,1.3]	0.8 [0.1,1.1]	0.4 [0.1,1.6]	0.3 [0.0,1.5]	0.4 [0.0,1.6]	0.4 [0.0,1.7]
$B_{min}^{sp,A}$	816 [263,1742]	328 [69,1102]	1089 [97,6294]	334 [21,1261]	311 [91,760]	222 [41,1319]	1415 [240,2325]	366 [88,1196]	307 [44,1114]	292 [57,1224]	371 [64,1248]
$B_{min}^{sp,A}/B_{1996}^{sp,A}$	1.65 [0.55,4.06]	0.67 [0.15,2.47]	2.22 [0.21,13.36]	0.65 [0.04,2.99]	0.63 [0.18,1.66]	0.48 [0.09,2.89]	2.98 [0.57,5.68]	0.59 [0.14,2.20]	0.64 [0.10,2.61]	0.59 [0.11,2.58]	0.78 [0.14,2.80]
$B_{min}^{sp,A}/K^{A}$	0.25 [0.07,0.50]	0.10 [0.02,0.32]	0.26 [0.03,1.01]	0.12 [0.01,0.34]	0.14 [0.03,0.34]	0.06 [0.01,0.30]	0.52 [0.08,0.67]	0.11 [0.02,0.33]	0.09 [0.01,0.32]	0.09 [0.01,0.31]	0.11 [0.02,0.34]
C^{A}	**0** 0 [0,0]	**275** 350 [8,350]	**316** 350 [56,350]	**252** 330 [0,350]	**267** 304 [20,350]	**243** 310 [0,350]	**329** 350 [225,350]	**267** 330 [9,350]	**262** 350 [0,350]	**269** 350 [4,350]	**276** 350 [7,350]
Med C^{A}	0 [0,0]	350 [63,350]	350 [147,350]	338 [0,350]	312 [119,350]	323 [9,350]	350 [206,350]	333 [79,350]	350 [11,350]	350 [43,350]	350 [44,350]
C_{now}^{A}	0 [0,0]	350 [10,350]	350 [68,350]	336 [9,350]	315 [23,350]	323 [3,350]	350 [245,350]	335 [21,350]	350 [5,350]	350 [8,350]	350 [16,350]
MAV^{A}	-	0.10 [0.00,0.78]	0.00 [0.00,0.41]	0.13 [0.00,0.91]	0.18 [0.00,0.74]	0.13 [0.00,0.98]	0.00 [0.00,0.36]	0.14 [0.00,0.80]	0.11 [0.00,0.91]	0.10 [0.00,0.80]	0.08 [0.00,0.83]
$p\left(B_y^{Aobs} < B_{crit}^{A}, B_y < B_{crit}^{A}/k_N^{A}\right)$	-	0.20	0.08	0.26	0.21	0.30	0.04	0.19	0.23	0.21	0.19
$p\left(B_y^{Aobs} < B_{crit}^{A}, B_y \geq B_{crit}^{A}/k_N^{A}\right)$	-	0.03	0.01	0.03	0.04	0.02	0.00	0.03	0.03	0.03	0.03
$p\left(B_y^{Aobs} \geq B_{crit}^{A}, B_y < B_{crit}^{A}/k_N^{A}\right)$	-	0.03	0.01	0.03	0.04	0.03	0.01	0.03	0.03	0.03	0.02
$p\left(B_y^{Aobs} \geq B_{crit}^{A}, B_y \geq B_{crit}^{A}/k_N^{A}\right)$	-	0.75	0.90	0.68	0.72	0.65	0.95	0.75	0.71	0.73	0.76
Avg # years $B_y^{Aobs} < B_{crit}^{A}$ consecutively	-	2.7	3.2	3.7	2.2	3.9	4.3	2.8	3.3	2.9	2.8

Table 2 (continued).

	No Catch	A_{BH}	A_{M2000+}	A_4	A_{DD}	A_{com2}	A_{kegg}	A_{lamR}	A_{lamN2}	A_{low}	A_{high}
$Risk_A$ under no catch		0.030	0.033	0.033	0.050	0.033	0.034	0.019	0.030	0.209	0.016
$Risk_A$	0.030	0.193	0.222	0.191	0.248	0.215	0.181	0.156	0.195	0.480	0.081
$p\left(B_{2020}^{sp,A} < B_{1996}^{sp,A}\right)$	0.08	0.08	0.02	0.07	0.07	0.07	0.06	0.01	0.06	0.08	0.08
$p\left(B_{2021}^{sp,A} < B_{1996}^{sp,A}\right)$	0.08	0.18 (+10)	0.08	0.18	0.18	0.19	0.15	0.08	0.16	0.18	0.18
$p\left(B_{2022}^{sp,A} < B_{1996}^{sp,A}\right)$	0.05	0.17 (+12)	0.11	0.17	0.18	0.19	0.15	0.09	0.16	0.17	0.17
$p\left(B_{2023}^{sp,A} < B_{1996}^{sp,A}\right)$	0.04	0.18 (+14)	0.13	0.17	0.19	0.19	0.16	0.10	0.18	0.18	0.18
$p\left(B_{2024}^{sp,A} < B_{1996}^{sp,A}\right)$	0.04	0.18 (+14)	0.16	0.18	0.21	0.18	0.16	0.12	0.17	0.18	0.18
$B_{2040}^{sp,A}$	**2920** 2344 [654,7178]	**1872** 1236 [170,5859]	**1379** 1191 [73,3627]	**1932** 1258 [132,6115]	**1409** 999 [117,3933]	**1876** 1277 [163,5718]	**2168** 1493 [159,6618]	**2020** 1460 [210,6088]	**1929** 1291 [169,6058]	**1579** 993 [81,5497]	**2122** 1490 [259,6291]
$B_{2040}^{sp,A}/B_{2019}^{sp,A}$	1.9 [0.4,8.7]	0.9 [0.1,6.4]	0.8 [0.1,3.3]	1.0 [0.1,6.2]	0.8 [0.1,4.4]	0.9 [0.1,5.8]	1.0 [0.1,6.3]	0.8 [0.1,4.2]	1.0 [0.1,5.9]	0.7 [0.1,5.8]	1.2 [0.2,7.4]
$B_{2040}^{sp,A}/B_{1996}^{sp,A}$	5.0 [1.4,15.7]	2.5 [0.3,12.5]	2.4 [0.1,8.5]	2.7 [0.3,13.7]	2.1 [0.3,8.7]	2.6 [0.3,11.8]	2.8 [0.3,13.1]	2.8 [0.4,12.7]	2.6 [0.3,12.1]	2.0 [0.2,11.8]	3.1 [0.6,13.5]
$B_{2040}^{sp,A}/K^A$	0.7 [0.2,2.0]	0.4 [0.0.,1.6]	0.5 [0.0,1.3]	0.4 [0.0,1.6]	0.1 [0.0,0.5]	0.4 [0.1,1.6]	0.4 [0.0,1.6]	0.4 [0.1,1.5]	0.4 [0.1,1.6]	0.3 [0.0,1.6]	0.5 [0.1,1.7]
$B_{min}^{sp,A}$	816 [263,1742]	328 [69,1102]	575 [49,1377]	334 [64,1158]	272 [57,993]	326 [77,1179]	391 [85,1273]	458 [107,1365]	338 [84,1173]	117 [13,306]	472 [100,1439]
$B_{min}^{sp,A}/B_{1996}^{sp,A}$	1.65 [0.55,4.06]	0.67 [0.15,2.47]	1.20 [0.11,3.47]	0.70 [0.14,2.73]	0.57 [0.12,2.25]	0.65 [0.14,2.34]	0.71 [0.16,2.74]	0.91 [0.21,2.87]	0.68 [0.16,2.46]	0.24 [0.03,0.69]	0.97 [0.23,3.23]
$B_{min}^{sp,A}/K^A$	0.25 [0.07,0.50]	0.10 [0.02,0.32]	0.21 [0.01,0.49]	0.09 [0.01,0.31]	0.03 [0.01,0.12]	0.10 [0.02,0.33]	0.11 [0.02,0.33]	0.12 [0.03,0.35]	0.10 [0.02,0.32]	0.03 [0.00,0.11]	0.14 [0.03,0.42]
C^A	**0** 0 [0,0]	**275** 350 [8,350]	**270** 350 [0,350]	**274** 350 [6,350]	**259** 324 [2,350]	**272** 350 [7,350]	**279** 350 [13,350]	**283** 350 [24,350]	**275** 350 [11,350]	**188** 217 [0,350]	**317** 350 [150,350]
Med C^A	0 [0,0]	350 [63,350]	350 [5,350]	350 [39,350]	332 [39,350]	350 [44,350]	350 [93,350]	350 [110,350]	350 [72,350]	227 [0,350]	350 [307,350]
C_{now}^A	0 [0,0]	350 [10,350]	350 [39,350]	350 [17,350]	341 [12,350]	350 [19,350]	350 [24,350]	350 [71,350]	350 [20,350]	350 [10,350]	350 [10,350]
MAV^A	-	0.10 [0.00,0.78]	0.00 [0.00,0.94]	0.10 [0.00,0.79]	0.13 [0.00,0.87]	0.10 [0.00,0.86]	0.08 [0.00,0.70]	0.06 [0.00,0.69]	0.11 [0.00,0.83]	0.26 [0.00,0.92]	0.00 [0.00,0.19]
$p\left(B_y^{Aobs} < B_{crit}^A, B_y < B_{crit}^A/k_N^A\right)$	-	0.20	0.21	0.20	0.23	0.20	0.18	0.15	0.19	0.48	0.08
$p\left(B_y^{Aobs} < B_{crit}^A, B_y \geq B_{crit}^A/k_N^A\right)$	-	0.03	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02
$p\left(B_y^{Aobs} \geq B_{crit}^A, B_y < B_{crit}^A/k_N^A\right)$	-	0.03	0.02	0.02	0.03	0.03	0.02	0.02	0.03	0.03	0.01
$p\left(B_y^{Aobs} \geq B_{crit}^A, B_y \geq B_{crit}^A/k_N^A\right)$	-	0.75	0.75	0.75	0.71	0.74	0.77	0.80	0.75	0.46	0.89
Avg # years $B_y^{Aobs} < B_{crit}^A$ consecutively	-	2.7	4.5	2.8	3.0	2.8	2.6	2.5	2.6	5.4	1.9

Table 3. Key summary performance statistics for CMPf with $B_{crit}^{A} = 800$ (and $\alpha = 0.907$) under alternative anchovy OMs. The first column additionally shows the performance statistics under a no catch scenario using A_{BH}. Where appropriate, medians and 90% probability intervals are provided, and for some statistics the means are provided additionally and shown in **bold**. All biomasses are given in thousands of tons.

	No Catch	A_{BH}	A_{2BH}	A_{3BH}	A_{2BHrtn}	A_{R}	A_{HS}	A_{M1}	A_{M2}	A_{Mad}	A_{Mj}
$Risk_A$ under no catch		0.030	0.028	0.082	0.037	0.052	<0.001	0.037	0.052	0.047	0.034
$Risk_A$	0.030	0.164	0.076	0.241	0.182	0.258	0.027	0.215	0.208	0.198	0.157
$p(B_{2020}^{sp,A} < B_{1996}^{sp,A})$	0.08	0.08	0.04	0.08	0.08	0.08	0.01	0.08	0.07	0.10	0.06
$p(B_{2021}^{sp,A} < B_{1996}^{sp,A})$	0.08	0.18 (+10)	0.10	0.20	0.20	0.20	0.01	0.21	0.17	0.20	0.15
$p(B_{2022}^{sp,A} < B_{1996}^{sp,A})$	0.05	0.16 (+11)	0.08	0.20	0.17	0.21	0.01	0.21	0.18	0.20	0.15
$p(B_{2023}^{sp,A} < B_{1996}^{sp,A})$	0.04	0.15 (+11)	0.08	0.21	0.16	0.22	0.02	0.20	0.17	0.19	0.14
$p(B_{2024}^{sp,A} < B_{1996}^{sp,A})$	0.04	0.15 (+11)	0.07	0.21	0.17	0.24	0.02	0.19	0.18	0.19	0.15
$B_{2040}^{sp,A}$	**2920** 2344 [654,7178]	**1935** 1279 [218,5866]	**4268** 3309 [301,10475]	**1853** 1222 [55,6383]	**1469** 1075 [276,3955]	**1837** 1124 [124,5876]	**2268** 2162 [619,3989]	**2044** 1334 [226,6441]	**1841** 1264 [136,5739]	**2008** 1304 [170,6722]	**2042** 1407 [173,6002]
$B_{2040}^{sp,A}/B_{2019}^{sp,A}$	1.9 [0.4,8.7]	1.0 [0.1,6.7]	1.6 [0.2,6.1]	0.9 [0.0,5.8]	0.9 [0.2,4.5]	0.8 [0.1,6.3]	1.3 [0.5,2.7]	1.0 [0.2,6.4]	0.9 [0.1,6.6]	1.1 [0.1,7.7]	1.1 [0.1,6.3]
$B_{2040}^{sp,A}/B_{1996}^{sp,A}$	5.0 [1.4,15.7]	2.6 [0.5,12.6]	7.1 [0.7,24.2]	2.4 [0.1,13.9]	2.1 [0.5,9.0]	2.3 [0.2,14.0]	4.5 [1.2,9.7]	2.2 [0.4,10.8]	2.5 [0.3,12.3]	2.6 [0.3,14.2]	3.1 [0.4,14.1]
$B_{2040}^{sp,A}/K^{A}$	0.7 [0.2,2.0]	0.4 [0.1,1.7]	0.8 [0.1,2.1]	0.4 [0.0,1.6]	0.5 [0.1,1.6]	0.3 [0.0,1.3]	0.8 [0.2,1.1]	0.4 [0.1,1.7]	0.4 [0.0,1.5]	0.4 [0.0,1.6]	0.4 [0.0,1.7]
$B_{min}^{sp,A}$	816 [263,1742]	361 [90,1102]	1089 [119,6294]	359 [27,1261]	343 [111,770]	281 [57,1319]	1415 [368,2325]	400 [117,1196]	353 [62,1114]	335 [70,1224]	401 [83,1248]
$B_{min}^{sp,A}/B_{1996}^{sp,A}$	1.65 [0.55,4.06]	0.74 [0.19,2.47]	2.22 [0.27,13.36]	0.71 [0.06,2.99]	0.69 [0.22,1.70]	0.59 [0.11,2.88]	2.98 [0.81,5.68]	0.67 [0.19,2.20]	0.72 [0.13,2.64]	0.67 [0.13,2.58]	0.86 [0.19,2.78]
$B_{min}^{sp,A}/K^{A}$	0.25 [0.07,0.50]	0.12 [0.02,0.33]	0.26 [0.03,1.01]	0.13 [0.01,0.34]	0.16 [0.04,0.35]	0.07 [0.01,0.30]	0.52 [0.13,0.67]	0.12 [0.03,0.33]	0.10 [0.01,0.32]	0.10 [0.02,0.31]	0.12 [0.02,0.34]
C^{A}	**0** 0 [0,0]	**273** 350 [5,350]	**315** 350 [40,350]	**250** 336 [0,350]	**262** 308 [12,350]	**245** 327 [0,350]	**329** 350 [235,350]	**266** 338 [7,350]	**261** 350 [0,350]	**268** 350 [3,350]	**275** 350 [5,350]
Med C^{A}	0 [0,0]	350 [57,350]	350 [132,350]	341 [0,350]	314 [96,350]	332 [7,350]	350 [246,350]	342 [68,350]	350 [11,350]	350 [44,350]	350 [42,350]
C_{now}^{A}	0 [0,0]	350 [3,350]	350 [31,350]	337 [1,350]	315 [10,350]	324 [0,350]	350 [245,350]	343 [10,350]	350 [1,350]	350 [3,350]	350 [6,350]
MAV^{A}	-	0.11 [0.00,0.82]	0.00 [0.00,0.59]	0.12 [0.00,0.94]	0.21 [0.00,0.84]	0.15 [0.00,0.97]	0.00 [0.00,0.34]	0.14 [0.00,0.85]	0.11 [0.00,0.91]	0.10 [0.00,0.84]	0.09 [0.00,0.86]
$p(B_{y}^{Aobs} < B_{crit}^{A}, B_{y} < B_{crit}^{A}/k_{N}^{A})$	-	0.25	0.10	0.31	0.29	0.34	0.04	0.25	0.28	0.27	0.24
$p(B_{y}^{Aobs} < B_{crit}^{A}, B_{y} \geq B_{crit}^{A}/k_{N}^{A})$	-	0.04	0.02	0.04	0.05	0.03	0.01	0.04	0.04	0.03	0.04
$p(B_{y}^{Aobs} \geq B_{crit}^{A}, B_{y} < B_{crit}^{A}/k_{N}^{A})$	-	0.03	0.01	0.03	0.05	0.03	0.01	0.03	0.03	0.03	0.03
$p(B_{y}^{Aobs} \geq B_{crit}^{A}, B_{y} \geq B_{crit}^{A}/k_{N}^{A})$	-	0.68	0.87	0.62	0.61	0.60	0.94	0.68	0.65	0.67	0.69
Avg # years $B_{y}^{Aobs} < B_{crit}^{A}$ consecutively	-	2.7	2.9	3.4	2.4	3.8	3.3	2.8	3.2	2.9	2.7

Table 3 (continued).

	No Catch	A_{BH}	A_{M2000+}	A_4	A_{DD}	A_{com2}	A_{kegg}	A_{lamR}	A_{lamN2}	A_{low}	A_{high}
$Risk_A$ under no catch		0.030	0.033	0.033	0.050	0.033	0.034	0.019	0.030	0.209	0.016
$Risk_A$	0.030	0.164	0.195	0.165	0.215	0.186	0.155	0.125	0.168	0.437	0.072
$p\left(B_{2020}^{sp,A} < B_{1996}^{sp,A}\right)$	0.08	0.08	0.02	0.07	0.07	0.07	0.06	0.01	0.06	0.08	0.08
$p\left(B_{2021}^{sp,A} < B_{1996}^{sp,A}\right)$	0.08	0.18 (+10)	0.08	0.18	0.18	0.19	0.15	0.08	0.16	0.18	0.18
$p\left(B_{2022}^{sp,A} < B_{1996}^{sp,A}\right)$	0.05	0.16 (+11)	0.10	0.16	0.18	0.18	0.14	0.08	0.15	0.16	0.16
$p\left(B_{2023}^{sp,A} < B_{1996}^{sp,A}\right)$	0.04	0.15 (+11)	0.12	0.15	0.18	0.17	0.15	0.09	0.16	0.15	0.15
$p\left(B_{2024}^{sp,A} < B_{1996}^{sp,A}\right)$	0.04	0.15 (+11)	0.15	0.16	0.18	0.16	0.13	0.10	0.15	0.15	0.15
$B_{2040}^{sp,A}$	**2920** 2344 [654,7178]	**1935** 1279 [218,5866]	**1417** 1203 [106,3650]	**1993** 1317 [176,6115]	**1472** 1077 [167,3934]	**1943** 1342 [220,5875]	**2226** 1542 [216,6627]	**2080** 1496 [285,6096]	**1990** 1330 [223,6132]	**1673** 1071 [109,5532]	**2146** 1496 [300,6296]
$B_{2040}^{sp,A}/B_{2019}^{sp,A}$	1.9 [0.4,8.7]	1.0 [0.1,6.7]	0.8 [0.1,3.4]	1.1 [0.1,6.2]	0.9 [0.1,4.5]	1.1 [0.1,5.9]	1.1 [0.1,6.3]	0.8 [0.1,4.3]	1.1 [0.1,6.0]	0.8 [0.1,5.9]	1.2 [0.2,7.4]
$B_{2040}^{sp,A}/B_{1996}^{sp,A}$	5.0 [1.4,15.7]	2.6 [0.5,12.6]	2.5 [0.2,8.6]	2.8 [0.4,14.0]	2.2 [0.4,8.8]	2.5 [0.4,12.0]	2.9 [0.4,13.3]	2.9 [0.5,12.7]	2.8 [0.4,12.1]	2.2 [0.2,11.8]	3.2 [0.7,13.5]
$B_{2040}^{sp,A}/K^A$	0.7 [0.2,2.0]	0.4 [0.1,1.7]	0.5 [0.0,1.3]	0.4 [0.0,1.6]	0.1 [0.0,0.5]	0.4 [0.1,1.6]	0.4 [0.0,1.6]	0.4 [0.1,1.5]	0.4 [0.1,1.6]	0.3 [0.0,1.6]	0.5 [0.1,1.7]
$B_{min}^{sp,A}$	816 [263,1742]	361 [90,1102]	577 [69,1377]	366 [79,1157]	318 [71,993]	362 [96,1179]	425 [113,1273]	495 [145,1365]	369 [106,1173]	147 [18,363]	495 [115,1439]
$B_{min}^{sp,A}/B_{1996}^{sp,A}$	1.65 [0.55,4.06]	0.74 [0.19,2.47]	1.25 [0.16,3.47]	0.77 [0.17,2.73]	0.67 [0.15,2.25]	0.73 [0.18,2.34]	0.79 [0.20,2.74]	0.99 [0.27,2.87]	0.77 [0.20,2.47]	0.30 [0.04,0.82]	1.02 [0.27,3.23]
$B_{min}^{sp,A}/K^A$	0.25 [0.07,0.50]	0.12 [0.02,0.33]	0.22 [0.02,0.49]	0.11 [0.02,0.31]	0.04 [0.01,0.12]	0.11 [0.02,0.33]	0.12 [0.02,0.33]	0.13 [0.04,0.35]	0.11 [0.03,0.32]	0.04 [0.00,0.13]	0.15 [0.03,0.42]
C^A	**0** 0 [0,0]	**273** 350 [5,350]	**270** 350 [0,350]	**272** 350 [4,350]	**257** 336 [2,350]	**271** 350 [5,350]	**277** 350 [9,350]	**281** 350 [17,350]	**273** 350 [7,350]	**185** 224 [0,350]	**314** 350 [87,350]
Med C^A	0 [0,0]	350 [57,350]	350 [5,350]	350 [43,350]	338 [32,350]	350 [52,350]	350 [73,350]	350 [107,350]	350 [67,350]	234 [0,350]	350 [315,350]
C_{now}^A	0 [0,0]	350 [3,350]	350 [17,350]	350 [7,350]	343 [4,350]	350 [8,350]	350 [10,350]	350 [36,350]	350 [8,350]	350 [3,350]	350 [3,350]
MAV^A	-	0.11 [0.00,0.82]	0.00 [0.00,0.97]	0.10 [0.00,0.85]	0.15 [0.00,0.87]	0.11 [0.00,0.89]	0.08 [0.00,0.79]	0.06 [0.00,0.74]	0.11 [0.00,0.85]	0.29 [0.00,0.93]	0.00 [0.00,0.22]
$p\left(B_y^{Aobs} < B_{crit}^A, B_y < B_{crit}^A/k_N^A\right)$	-	0.25	0.24	0.25	0.28	0.26	0.23	0.20	0.24	0.52	0.12
$p\left(B_y^{Aobs} < B_{crit}^A, B_y \geq B_{crit}^A/k_N^A\right)$	-	0.04	0.03	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03
$p\left(B_y^{Aobs} \geq B_{crit}^A, B_y < B_{crit}^A/k_N^A\right)$	-	0.03	0.02	0.03	0.03	0.03	0.03	0.03	0.04	0.03	0.02
$p\left(B_y^{Aobs} \geq B_{crit}^A, B_y \geq B_{crit}^A/k_N^A\right)$	-	0.68	0.70	0.68	0.65	0.67	0.70	0.73	0.68	0.41	0.84
Avg # years $B_y^{Aobs} < B_{crit}^A$ consecutively	-	2.7	3.9	2.7	3.0	2.6	2.6	2.5	2.6	5.4	1.9

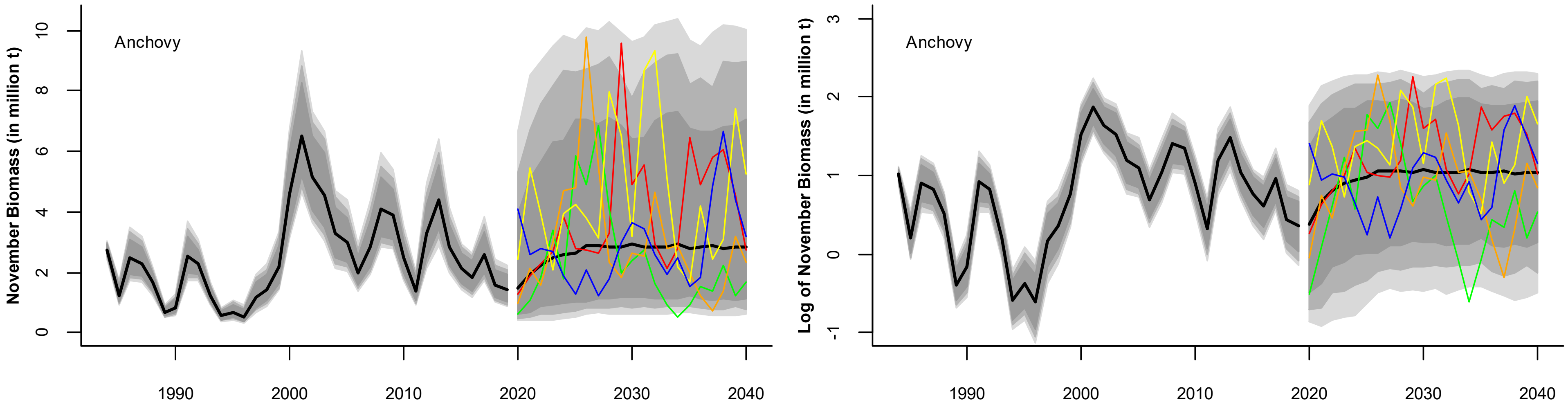

Figure 1. The historical anchovy November biomass and corresponding projected biomass under a no future catch scenario under the anchovy-only OM. Posterior medians are shown by the solid black line and the 80%ile, 90%ile and 95%ile by progressively lighter grey shading. The first five replicates are shown as example coloured 'worm plots'.

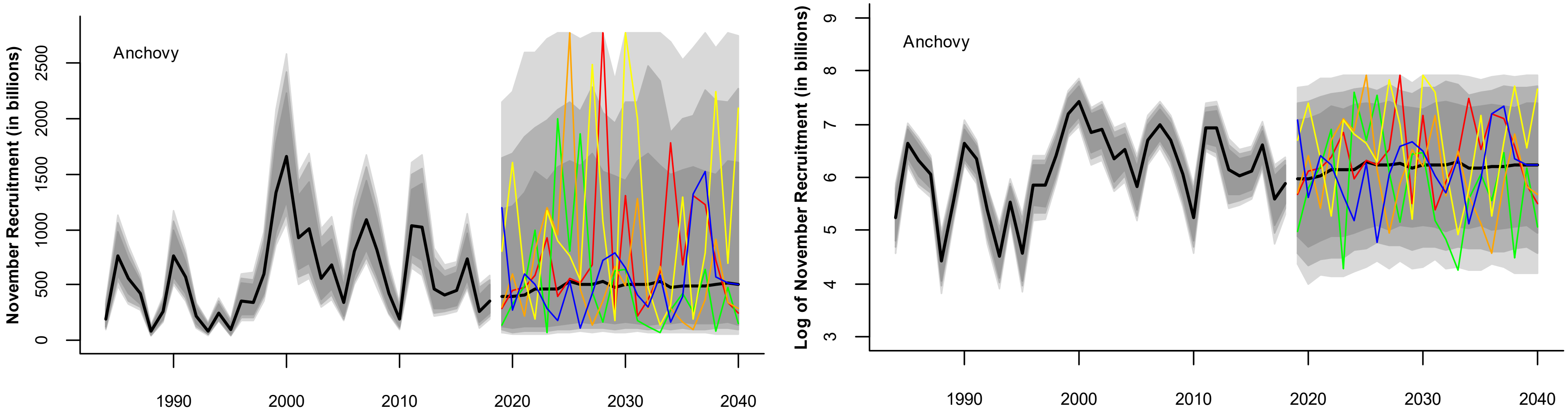

Figure 2. The historical anchovy November recruitment and corresponding projected recruitment under a no future catch scenario under the anchovy-only OM. Posterior medians are shown by the solid black line and the 80%ile, 90%ile and 95%ile by progressively lighter grey shading. The first five replicates are shown as example coloured 'worm plots'.

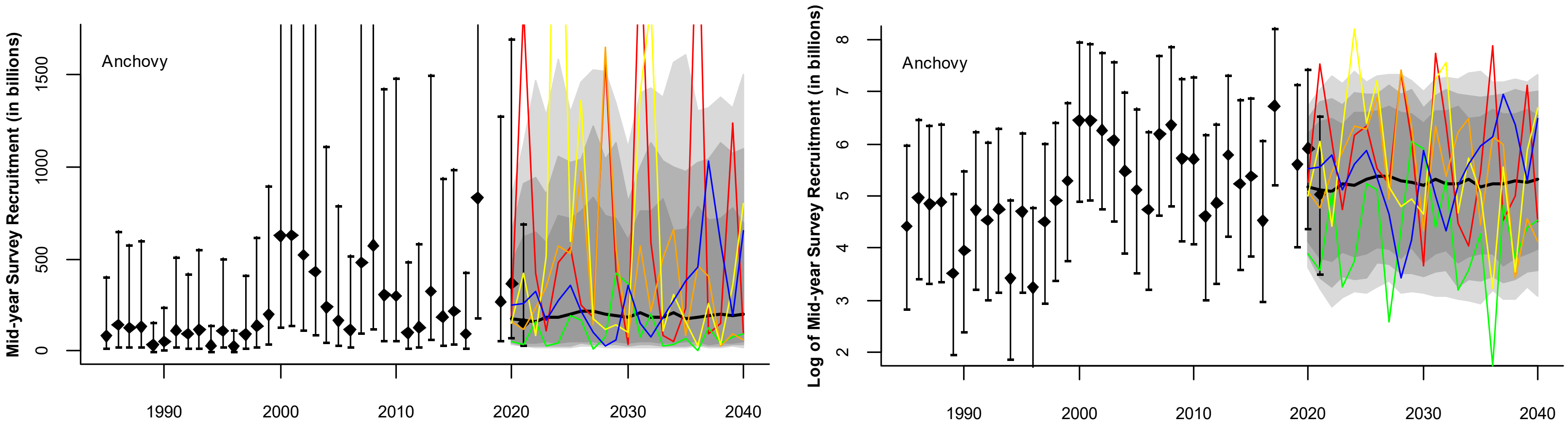

Figure 3. The historical anchovy survey estimates of recruitment (in May – July each year) and simulated future mid-May recruitment survey 'observations' under a no future catch scenario. Historical estimates are shown together with the 95% confidence interval taking survey CV and additional variance into account. For anchovy, additional variance differs by replicate; the median is used for this illustration. Posterior medians are shown by the solid black line and the 80%ile, 90%ile and 95%ile (taking survey CV and additional variance into account) by progressively lighter grey shading. The first five replicates are shown as example coloured 'worm plots'.

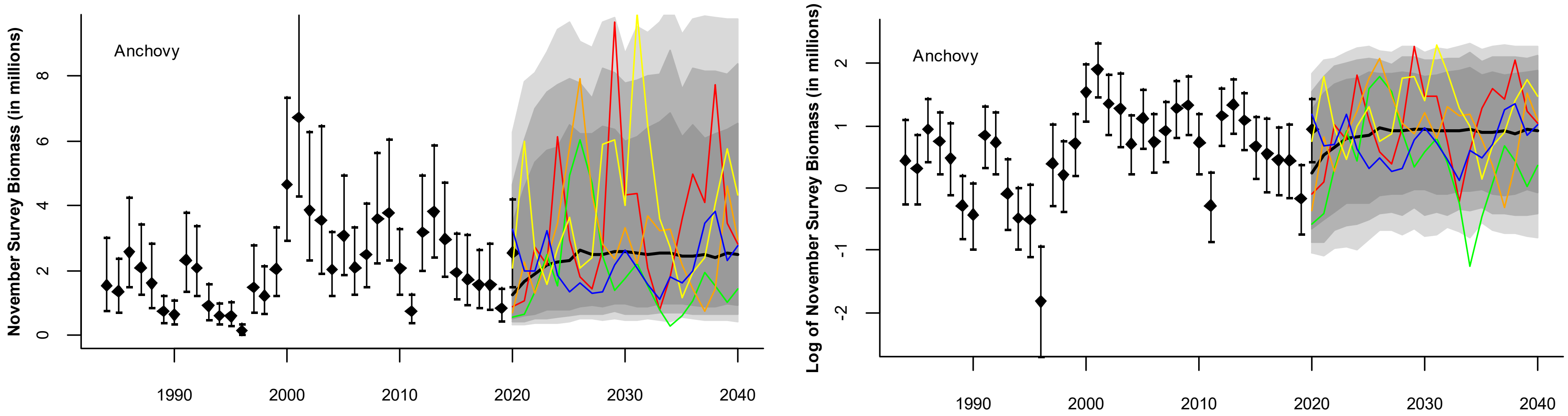

Figure 4. The historical anchovy survey estimates of biomass (in Oct – Dec each year) and simulated future November survey 'observations' under a no future catch scenario. Historical estimates are shown together with the 95% confidence interval taking survey CV and additional variance into account. For anchovy, additional variance differs by replicate; the median is used for this illustration. Posterior medians are shown by the solid black line and the 80%ile, 90%ile and 95%ile (taking survey CV and additional variance into account) by progressively lighter grey shading. The first five replicates are shown as example coloured 'worm plots'.

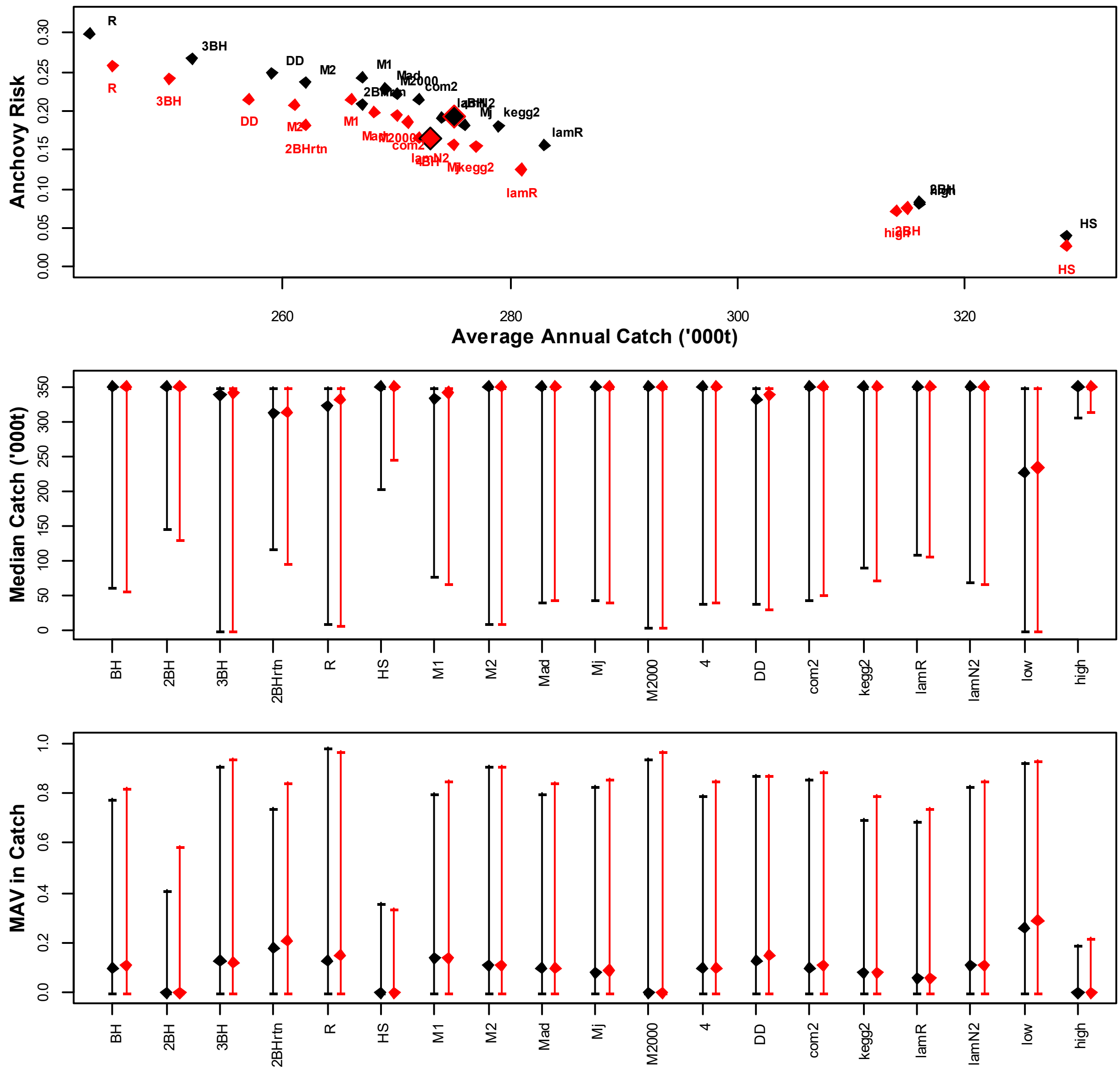

Figure 5. The (top) trade-off between anchovy risk and average anchovy catch[8], (middle) median and 95% probability interval for median catch (Med C^A), and (lower) median and 95% probability intervals for MAV. Results are shown for the baseline OM and all robustness tests under CMPd (black) and CMPf (red).

[8] A_{low} has a risk higher than (0.524 for CMPd, 0.490 for CMPf) and average catch lower than (171 for CMPd, 169 for CMPf) that shown in this scale.

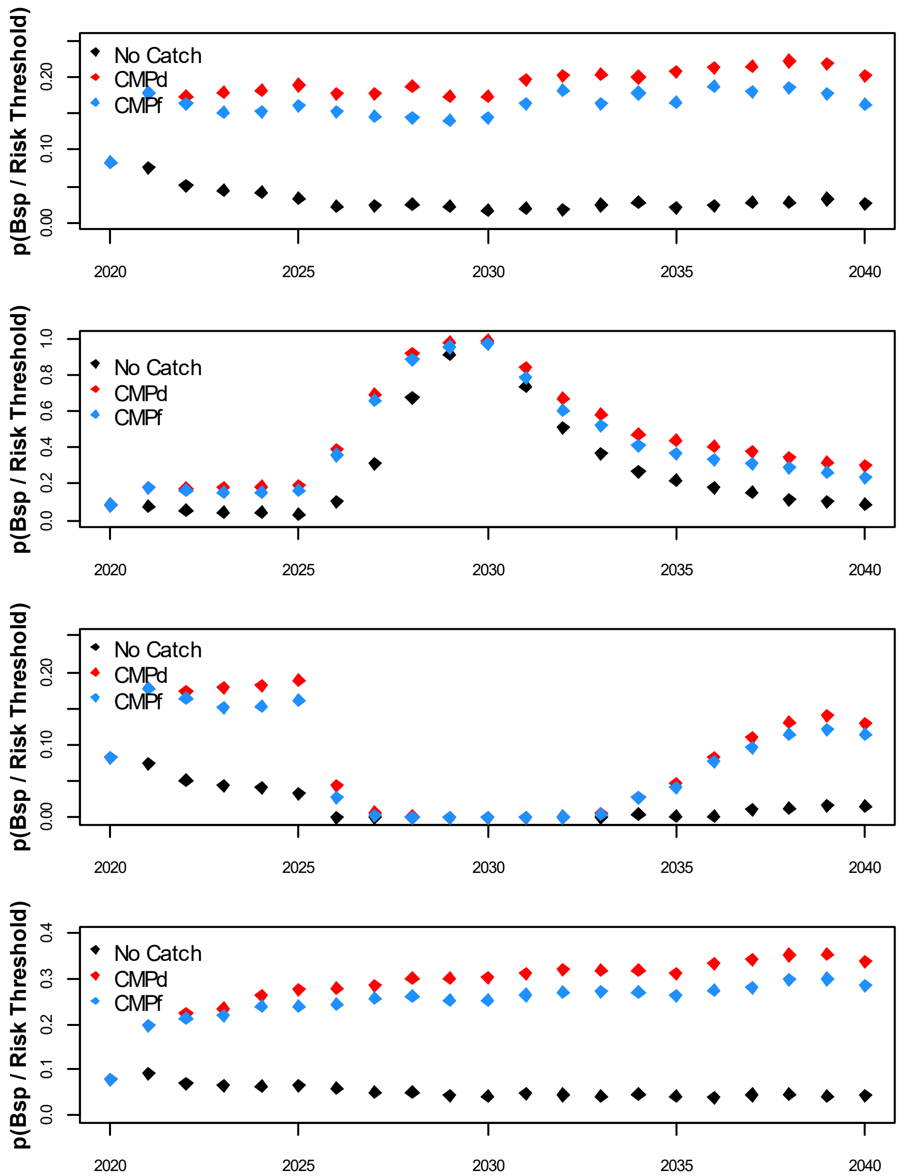

Figure 6. The annual 'risk' (probability that the anchovy spawner biomass is below the risk threshold) to the anchovy resource under CMPd and CMPf compared to a no future catch scenario for A_{BH} (top), A_{low} (middle), A_{high} (middle) and A_{Ricker} (lower).

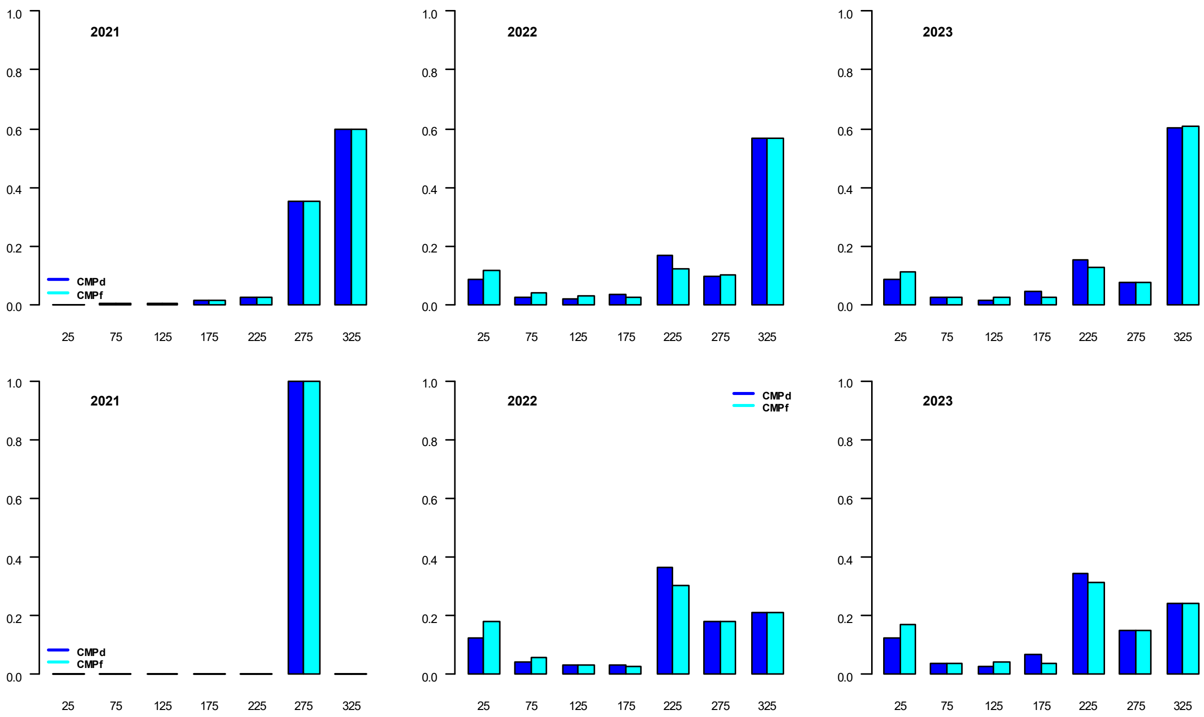

Figure 7. Histograms of realised anchovy catch (top row) and annual *initial* anchovy TAC (lower row) for CMPd and CMPf under A_{BH}.