Updated Reference Set for the South African *Merluccius paradoxus* and *M. capensis* Resources and Projections under a series of Candidate OMPs

R.A. Rademeyer and D.S. Butterworth

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

September 2006

Abstract

This paper reports estimates of management quantities for the updated Reference Set for the hake resource, now fitted to two further years of hake abundance indices, as specified at the last meeting of the Demersal Working Group. Estimates for two major variants of the assumptions for this Set are also reported. The empirical OMP introduced earlier is retuned for various *M. paradoxus* recovery levels under differing inter-annual TAC constraints. Performance statistics for the resultant OMP candidates are reported for both the updated Reference Set and the two major robustness tests. Effort projections indicate a reduction of at least one third in the average annual effort applied over the past some five years likely to be needed to secure resource recovery. Suggestions are made for the next steps in the process of finalising a OMP selection.

Introduction

The updated Reference Set (RS) for the joint assessment of the *M. paradoxus* and *M. capensis* resources, as agreed at the last meeting of the Demersal Working Group, includes data up to early 2006 (i.e. it includes the 2006 summer survey results) (see WG/08/06/D:H:29). The Set comprises 24 scenarios which include variations around natural mortality (M1 vs. M4), the historic species split of the catch (C3a vs C3b vs C3c) and steepness (H1 vs H2 vs H3 vs H4). As agreed in Working Group discussions, only the SR2 option for recent recruitment residuals has been retained for the Reference Set. In the SR2 scenarios, the assumed variance σ_R is set to 0.25 from the beginning of the fishery to 2002 and then decreases linearly to 0.1 in 2006, this forces recruitment more towards the deterministic value suggested by the estimated stock-recruitment relationship for the most recent years, for which the cohorts concerned have been less frequently sampled.

This document first reports estimates of management quantities for this updated Reference Set, together with those for two major variants of the assumptions for this Set reflecting more optimistic (SR1 option for recent recruitment) and more pessimistic (20% decrease in *M. capensis* carrying capacity from 1992) appraisals of resource status.

The document then continues by tuning variants of the empirical OMP management procedure of WG/07/06/D:H:21 to various recovery targets for *M. paradoxus* for different options for inter-annual TAC change constraints, and reports performance statistics for the application of these to the updated Reference Set and the two associated major robustness trials.

Results

Updated Reference Set

The overall average and range of estimates of management quantities for the updated Reference Set are shown in Table 1, while Table 2 provides the averages over the individual factors (M, H, C). The full set of results is given in Tables A1 of Appendix A. Fig. A1 in the Appendix plots the corresponding biomass trajectories, focusing on the median, maximum and minimum values for each year, while Fig. A2 shows the survey and commercial fishing selectivities. Note the decreasing trends in abundance indicated for the last decade for both species.

Major robustness tests

Results for two major robustness tests are also presented:

i) "SR1": The assumed variance σ_R is fixed to 0.25 throughout (i.e. the estimates of recruitment strength for more recent cohorts are not shrunk further towards the stock-recruitment function expectation).

ii) "Decr in *K*": In the Reference Set, poorer estimated recruitment for *M. capensis* throughout most of the 1990s and the early 2000s suggest a possible systematic deviation below the stock-recruitment model (see Fig. 4 of WG/06/08/D:H:29). To better reflect this poorer *M. capensis* recruitment (and continue this into the future), the carrying capacity for *M. capensis* has been reduced by 20% from 1992 onwards.

For each of these two robustness tests, only four of the corresponding 24 Reference Set scenarios have been run, using the central of the three assumptions for the timing of the historic change by the offshore trawlers from focussing on *M. capensis* alone to concentrate more on *M. paradoxus* (C3a), the two alternative constraints sets for natural mortality (M1 and M4) and only two of the options for steepness (H1 – steepness is estimated for both species – and H4 – *M. paradoxus* steepness fixed to 0.8 and *M. capensis* steepness fixed to 0.7).

The estimates of management quantities for these two robustness tests are compared to the Reference Set in Table 3. The SR1 scenarios have little impact on the current management quantity estimates, but do impact future projections. The most notable differences in the "Decr in *K*" scenarios compared to the Reference Set are the reductions in the estimates of MSY for *M. capensis*. For both sets of robustness tests, the current *M. capensis : M. paradoxus* ratios are lower than for the corresponding Reference Set scenarios.

One scenario in which a decrease in K^{sp} for *M. capensis* was estimated rather than fixed to 20% has been run. The best estimate for this decrease is of some 17%. Results for this scenario are not presented as the best estimate for the decrease is close to the fixed 20% implemented here. Note that fixing the decrease in carrying capacity in this manner gets an AIC-justified improvement in the model fit compared to the corresponding Reference Set scenario.

The estimated stock-recruitment residuals for one scenario (M4-H1-C3a-SR1) of the Reference Set are compared to the corresponding "SR1" scenario in Fig. 1, and to the corresponding "Decr in *K*" scenario in Fig. 2. The latter are notably less suggestive of model mis-specification for *M. capensis*.

Trajectories for spawning biomass (B^{sp}) for both hake species for one "Decr in *K*" scenario are compared to the corresponding Reference Set scenario in Fig. 3. The fits to CPUE and survey abundance estimates are shown in Figs 4 and 5. Note the lower recent *M. capensis* spawning biomass in absolute terms for the "Decr in *K*" scenario shown compared to that for the corresponding Reference Set scenario.

Replacement yields have been estimated for one scenario (M4-H1-C3a-SR2) for the Reference Set and the corresponding two robustness tests by projecting the biomass forward under the catch which would keep the combined species exploitable biomass more or less constant over the next ten years. The estimated replacement yields for this scenario are:

Reference Set: RY = 137 000 t

SR1: RY = 149 000 t

Decr in *K*: RY =135 500 t.

OMP projections

Reference Set

Recall that the basic algorithm for TAC calculation in the empirical OMP formulation under consideration (see also WG/07/06/D:H:21) is:

$$TAC_y = C_y^{para} + C_y^{cap} \tag{1}$$

with

$$C_y^{spp} = C_{y-1}^{*spp}\left[1+\lambda_y\left(s_y^{spp} - target^{spp}\right)\right] \qquad \text{if } y \le 2006+\text{Y} \quad \text{and}$$

$$C_y^{spp} = C_{y-1}^{*spp}\left[1+\lambda_y\left(s_y^{spp}\right)\right] \qquad \text{if } y > 2006+\text{Y} \tag{2}$$

where

TAC_y is the total TAC recommended for year *y*,

C_y^{spp} is the intended species-disaggregated TAC for year *y*,

C_{y-1}^{*spp} is the achieved catch[1] of species *spp* in year *y*-1,

λ_y is a year-dependent tuning parameter,

Y is a tuning parameter,

$target^{spp}$ is the target rate of increase for species *spp*, and

s_y^{spp} is a measure of the immediate past trend in the abundance indices for species *spp* as available to use for calculations for year *y*.

This trend measure is computed as follows from the species-disaggregated GLM-CPUE ($I_y^{CPUE,spp}$), west coast summer survey ($I_y^{surv1,spp}$) and south coast autumn survey ($I_y^{surv2,spp}$) indices:

- linearly regress $\ln I_y^{CPUE,spp}$ vs. year *y'* for $y' = y-p-1$ to $y' = y-2$, to yield a regression slope value $s_y^{CPUE,spp}$,
- linearly regress $\ln I_y^{surv1,spp}$ and $\ln I_y^{surv2,spp}$ vs. year *y'* for $y' = y-p$ to $y' = y-1$, to yield two regression slope values $s_y^{surv1,spp}$ and $s_y^{surv2,spp}$,

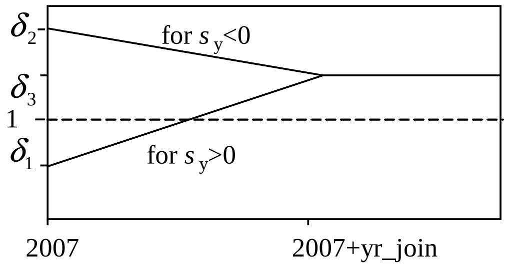
where *p* is the length of the periods considered for these regressions. Note that the reason the trend for surveys is calculated for a period moved one year later than for CPUE is that by the time of year that the TAC recommendation would be computed for the following year, survey results for the current year would be known, but not CPUE as fishing for the year would not yet have been completed.

Then

$$s_y^{spp} = \left(\frac{s_y^{CPUE,spp}}{2} + \frac{s_y^{surv1,spp}}{4} + \frac{s_y^{surv2,spp}}{4}\right) \tag{3}$$

[1] Implemented by applying the species ratio of the catch in year *y*-2 to the TAC for year *y*-1, as the species ratio for year *y*-1 would not yet be known by the time at which a recommendation for the TAC for year *y* would be required.

The function for the year-dependent tuning parameter, λ_y, which is a measure of how responsive the candidate OMP is to change in trend, is shown below:



Results are presented for three candidate empirical OMPs integrated over 10 replicates of each of the 24 Reference Set scenarios. The three candidate OMPs are differentiated by the maximum allowable change in TAC from one year to the next. Initial evaluations indicated that restricting this change to 5% in the absence of further limitations led to extinction of the *M. paradoxus* resource for some scenarios. Thus for OMP1, the maximum increase and decrease are set to 10%. For OMP2 and OMP3, the maximum increase is fixed to 5% and the maximum decrease for the TAC in year *y* ($D_y^{\max}$) depends on the recent average CPUE as at year *y* (I_y) expressed relative to its 2002-2004 average level, the idea being that TAC decrease proportions are kept low unless CPUE falls below some threshold level, following which greater drops are allowed to attempt to reverse adverse resource abundance trends:

$$D_y^{\max} = \begin{cases} D_1 & \text{if } I_y > L_1 \\ D_1 + \dfrac{(D_2 - D_1)}{(L_1 - L_2)^2}(L_1 - I_y)^2 & \text{if } L_1 \geq I_y \geq L_2 \\ D_2 & \text{if } I_y < L_2 \end{cases} \tag{4}$$

where

D_1, D_2, L_1 and L_2 are constants, and

$$I_y = \frac{\sum_{i=y-2}^{y-1} CPUE_i \big/ 2}{\sum_{i=2002}^{2004} CPUE_i \big/ 3}.$$

This maximum decrease is computed for both species and the maximum of the two is applied when computing the TAC.

For OMP2: D_1 = 5%, D_2 = 20%, L_1 = 0.90 and L_2 = 0.70;

For OMP3: D_1 = 5%, D_2 = 35%, L_1 = 0.60 and L_2 = 0.35.

The maximum decrease allowed for each OMP in relation to I_y is shown in Fig. 6.

Three variants with different recovery tunings (median final depletions for *M. paradoxus* of approximately 15, 20 and 25% (of K^{sp}) in 2027) for each candidate OMP are presented in this document. For OMP1, one further recovery tuning (10%) is presented (note that the median current depletion for *M. paradoxus* for the Reference Set is 9% (see Table 1).

The control parameter values (see equation 2 above) for each of these candidate OMP1 tunings are given in Table 4.

A summary of the performance statistics for the Reference Set for each of these candidate OMPs is given in Table 5 and Fig. 7. Note that the OMP2 and OMP3 candidates result in lower average catches compared to OMP1, this being the trade-off for providing greater TAC stability. For higher recovery targets for median *M. paradoxus* spawning biomass, OMP2 and OMP3 are more risk averse, with higher 10%-iles for recovery after 20 years. The 10% recovery option for OMP1 (roughly corresponding to an RY strategy) reflects an unacceptable level of risk of further depletion in terms of this statistic.

Figs. 8, 9 and 10 show trajectories of resource abundance, CPUE and catch for an application of candidates $OMP1_{20\%}$, $OMP2_{20\%}$ and $OMP3_{20\%}$ respectively.

Fig. 11 compares the medians for the four recovery tuning options for OMP1, while Fig. 12 compares the medians for OMP1, OMP2 and OMP3 for a recovery tuning of 20%.

Fig. 13 show trajectories of offshore trawl effort (taken as the total catch over the offshore exploitable biomass, species combined). Note that all the options shown indicate an appreciable reduction (of at least about one third) in the average annual effort applied over the past some five years.

Major robustness tests

Projection results for the SR1 and decrease in *K* robustness tests are compared to those for the corresponding scenarios of the Reference Set. 25 replicates of each of the associated four scenarios have been run. A summary of the performance statistics for OMP1 (recovery tunings of 15, 20 and 25%) is given in Table 6 and Fig. 14.

The Next Steps

The next steps in this process of finalising the choice of an OMP are suggested to be:

a) A narrowing of the range of recovery targets and inter-annual TAC variation constraints by the Demersal Working Group, together with specification of possible further computations required (e.g. for intermediate selections to those reported here).

b) Review of those further results with a view towards presenting outputs for a refined set of options to a meeting of managers and a wider set of stake holders in the hake industry for their feedback.

References

Rademeyer RA and Butterworth DS. 2006. Results of Trials of Candidate OMPs for the South African Hake Resource. Unpublished report, MCM, South Africa. WG/07/06/D:H:21. 15pp.

Rademeyer RA and Butterworth DS. 2006. Updated assessment and projections for the South African hake resources. Unpublished report, MCM, South Africa. WG/08/09/D:H:29. 19pp.

Table 1: Average, with range in parenthesis, of estimates of management quantities for the *M. paradoxus* and *M. capensis* coast-combined resources over 24 cases in the updated Reference Set. *MSY* and associated quantities are given in relation to the selectivity for the offshore fleet.

			Median	Min	Max
	-lnL total		-189.6	-197.3	-174.2
M. paradoxus	K^{sp}		1509	893	2307
	h		0.87	0.80	0.95
	MSY		115	108	119
	B^{sp}_{2006}/K^{sp}		0.09	0.06	0.13
	$B^{sp}_{2006}/MSYL^{sp}$		0.40	0.29	0.56
	$MSYL^{sp}$		0.22	0.18	0.24
	M	0	0.51	0.50	0.80
		1	0.51	0.50	0.80
		2	0.51	0.50	0.80
		3	0.42	0.40	0.64
		4	0.37	0.34	0.54
		5+	0.33	0.30	0.49
M. capensis	K^{sp}		734	544	1063
	h		0.82	0.70	0.95
	MSY		60	54	70
	B^{sp}_{2006}/K^{sp}		0.47	0.36	0.54
	$B^{sp}_{2006}/MSYL^{sp}$		1.68	1.14	2.45
	$MSYL^{sp}$		0.28	0.22	0.33
	M	0	0.75	0.50	1.00
		1	0.75	0.50	1.00
		2	0.75	0.50	1.00
		3	0.55	0.40	0.74
		4	0.43	0.34	0.59
		5	0.34	0.30	0.49
		6	0.34	0.30	0.49
		7+	0.34	0.30	0.49
	SC survey q		0.84	0.64	1.09
2006 species ratio	B^{sp}		2.94	1.24	4.14
	B^{2+}		1.56	0.93	2.32

Table 2: Averages over individual factors of estimates of management quantities for the *M. paradoxus* and *M. capensis* coast-combined resources for the Reference Set. *MSY* and associated quantities are given in relation to the selectivity for the offshore fleet.

			M1	M4	H1	H2	H3	H4	C3a	C3b	C3c
	-lnL total		-182.0	-193.4	-187.7	-188.1	-187.4	-193.0	-185.6	-189.9	-182.3
M. paradoxus	K^{sp}		2006	1095	1566	1578	1507	1492	1620	1484	1606
	h		0.87	0.87	0.87	0.87	0.87	0.95	0.80	0.95	0.80
	MSY		115	113	115	115	112	116	112	116	111
	B^{sp}_{2006}/K^{sp}		0.08	0.10	0.09	0.09	0.10	0.07	0.11	0.07	0.11
	$B^{sp}_{2006}/MSYL^{sp}$		0.37	0.44	0.39	0.38	0.44	0.34	0.47	0.34	0.46
	$MSYL^{sp}$		0.21	0.22	0.22	0.22	0.21	0.19	0.24	0.19	0.24
	M	0	0.50	0.64	0.58	0.57	0.56	0.51	0.61	0.53	0.64
		1	0.50	0.64	0.58	0.57	0.56	0.51	0.61	0.53	0.64
		2	0.50	0.64	0.58	0.57	0.56	0.51	0.61	0.53	0.64
		3	0.40	0.53	0.47	0.46	0.47	0.42	0.50	0.43	0.51
		4	0.34	0.47	0.40	0.40	0.41	0.37	0.43	0.37	0.44
		5+	0.30	0.42	0.36	0.36	0.37	0.33	0.39	0.33	0.39
M. capensis	K^{sp}		901	621	726	728	829	729	725	806	784
	h		0.82	0.82	0.82	0.82	0.82	0.95	0.95	0.70	0.70
	MSY		59	63	59	59	65	64	63	59	58
	B^{sp}_{2006}/K^{sp}		0.40	0.52	0.44	0.45	0.49	0.46	0.45	0.47	0.45
	$B^{sp}_{2006}/MSYL^{sp}$		1.39	2.02	1.64	1.67	1.80	1.96	1.94	1.48	1.44
	$MSYL^{sp}$		0.29	0.26	0.28	0.28	0.28	0.24	0.24	0.32	0.32
	M	0	0.50	1.00	0.75	0.75	0.75	0.75	0.75	0.75	0.75
		1	0.50	1.00	0.75	0.75	0.75	0.75	0.75	0.75	0.75
		2	0.50	1.00	0.75	0.75	0.75	0.75	0.75	0.75	0.75
		3	0.40	0.71	0.56	0.56	0.55	0.55	0.55	0.56	0.57
		4	0.34	0.54	0.44	0.44	0.44	0.43	0.43	0.45	0.46
		5	0.30	0.43	0.37	0.37	0.36	0.35	0.35	0.38	0.39
		6	0.30	0.43	0.37	0.37	0.36	0.35	0.35	0.38	0.39
		7+	0.27	0.43	0.33	0.37	0.36	0.30	0.35	0.38	0.39
	SC survey q		0.97	0.74	0.90	0.89	0.78	0.90	0.90	0.79	0.83
2006 species ratio	B^{sp}		2.50	3.20	2.68	2.74	3.14	3.40	2.02	3.84	2.15
	B^{2+}		1.48	1.78	1.54	1.57	1.80	1.83	1.26	2.08	1.36

Table 3: Estimates of management quantities for the *M. paradoxus* and *M. capensis* coast-combined resources for 4 scenarios of i) the updated Reference Set, ii) with the SR1 option and iii) with a 20% decrease in carrying capacity for *M. capensis* from 1992 onwards (the estimates of K^{sp} and associated ratios are for the present, i.e. including the 20% decrease). *MSY* and associated quantities are given in relation to the selectivity for the offshore fleet.

		Reference Set				**SR1**				**Decrease in *K* for *M. capensis***			
		1	4	5	8	1'	4'	5'	8'	1*	4*	5*	8*
		M1	M1	M4	M4	M1	M1	M4	M4	M1	M1	M4	M4
		C3a	C3a	C3a	C3a	C3a	C3a	C3a	C3a	C3a	C3a	C3a	C3a
		H1	H4	H1	H4	H1	H4	H1	H4	H1	H4	H1	H4
		SR2	SR2	SR2	SR2	SR1	SR1	SR1	SR1	SR2	SR2	SR2	SR2
	-lnL total	-189.3	-174.2	-196.9	-189.7	-199.8	-184.9	-207.3	-199.8	-193.0	-175.8	-198.4	-191.0
M. paradoxus	K^{sp}	1747	2279	1271	961	1743	2273	1288	985	1750	2279	1282	960
	h	0.95	0.80	0.95	0.80	0.95	0.80	0.95	0.80	0.95	0.80	0.95	0.80
	MSY	118	115	117	109	118	115	116	108	118	115	117	109
	B^{sp}_{2006}/K^{sp}	0.06	0.10	0.07	0.12	0.06	0.10	0.07	0.12	0.06	0.10	0.07	0.12
	$B^{sp}_{2006}/MSYL^{sp}$	0.31	0.40	0.35	0.51	0.32	0.39	0.36	0.52	0.30	0.40	0.35	0.51
	$MSYL^{sp}$	0.19	0.24	0.20	0.24	0.19	0.24	0.20	0.24	0.20	0.25	0.21	0.24
	M 0	0.50	0.50	0.53	0.80	0.50	0.50	0.55	0.83	0.50	0.50	0.52	0.81
	1	0.50	0.50	0.53	0.80	0.50	0.50	0.55	0.83	0.50	0.50	0.52	0.81
	2	0.50	0.50	0.53	0.80	0.50	0.50	0.55	0.83	0.50	0.50	0.52	0.81
	3	0.40	0.40	0.45	0.64	0.40	0.40	0.46	0.64	0.40	0.40	0.44	0.64
	4	0.34	0.34	0.40	0.53	0.34	0.34	0.40	0.53	0.34	0.34	0.39	0.54
	5+	0.30	0.30	0.36	0.47	0.30	0.30	0.36	0.46	0.30	0.30	0.36	0.47
M. capensis	K^{sp}	780	929	620	544	779	928	617	541	604	741	521	451
	h	0.95	0.70	0.95	0.70	0.95	0.70	0.95	0.70	0.95	0.70	0.95	0.70
	MSY	57	54	65	57	57	54	65	57	45	43	47	44
	B^{sp}_{2006}/K^{sp}	0.36	0.38	0.51	0.49	0.36	0.38	0.52	0.49	0.35	0.42	0.46	0.48
	$B^{sp}_{2006}/MSYL^{sp}$	1.41	1.14	2.33	1.61	1.41	1.15	2.36	1.62	1.37	1.27	1.99	1.57
	$MSYL^{sp}$	0.25	0.33	0.22	0.30	0.25	0.33	0.22	0.30	0.22	0.27	0.22	0.27
	M 0	0.50	0.50	1.00	1.00	0.50	0.50	1.00	1.00	0.50	0.50	1.00	1.00
	1	0.50	0.50	1.00	1.00	0.50	0.50	1.00	1.00	0.50	0.50	1.00	1.00
	2	0.50	0.50	1.00	1.00	0.50	0.50	1.00	1.00	0.50	0.50	1.00	1.00
	3	0.40	0.40	0.70	0.74	0.40	0.40	0.70	0.74	0.40	0.40	0.68	0.73
	4	0.34	0.34	0.52	0.59	0.34	0.34	0.52	0.59	0.34	0.34	0.48	0.56
	5	0.30	0.30	0.40	0.49	0.30	0.30	0.40	0.49	0.30	0.30	0.35	0.46
	6	0.30	0.30	0.40	0.49	0.30	0.30	0.40	0.49	0.30	0.30	0.35	0.46
	7+	0.30	0.30	0.40	0.49	0.30	0.30	0.40	0.49	0.30	0.30	0.35	0.46
	SC survey q	1.11	0.98	0.78	0.78	1.11	0.98	0.78	0.78	0.96	0.79	0.76	0.68
2006 species ratio	B^{sp}	2.75	1.60	3.60	2.27	2.65	1.62	3.42	2.18	2.07	1.42	2.71	1.85
	B^{2+}	1.45	1.16	1.97	1.32	1.27	1.09	1.72	1.14	1.10	1.03	1.46	1.04

Table 4: Tuning parameters for each candidate OMPs presented in this paper. δ_1, δ_2 and δ_3 are the rate parameters of the year-dependent tuning parameter, λ_y .

Case	p	δ_1	δ_2	δ_3	Yr_join	Target incr para	Target incr cap	Y
OMP1$_{10\%}$	6	0.45	2	1.1	10	0.0000	0	10
OMP1$_{15\%}$	6	0.40	2	1.1	10	0.0183	0	10
OMP1$_{20\%}$	6	0.40	2	1.1	10	0.0240	0	15
OMP1$_{25\%}$	6	0.40	2	1.1	10	0.0303	0	20
OMP2$_{15\%}$	6	0.50	2	1.1	10	0.0073	0	10
OMP2$_{20\%}$	6	0.50	3	1.1	10	0.0157	0	10
OMP2$_{25\%}$	6	0.50	3	1.1	10	0.0355	0	10
OMP3$_{15\%}$	5	0.50	3	1.1	10	0.0510	0	10
OMP3$_{20\%}$	5	0.50	3	1.1	10	0.0523	0	14
OMP3$_{25\%}$	5	0.50	3	1.1	10	0.0572	0	20

Table 5: Summary of performance statistics for three candidate OMPs, tuned to different recovery levels for *M. paradoxus*, for the RS. For each parameter, the median and 90% PIs are shown.

		OMP1				OMP2			OMP3		
		10%	15%	20%	25%	15%	20%	25%	15%	20%	25%
Species combined	avTAC	124.47	123.35	119.23	115.03	121.40	118.40	114.39	118.04	112.97	109.51
	AAV	9.56	9.62	9.56	9.45	8.70	9.02	9.12	8.35	8.42	8.34
	C_{2007}	135.00	135.00	135.00	135.00	135.86	135.86	135.86	142.50	142.50	142.50
		-	-	-	-	-	-	-	-	-	-
		-	-	-	-	-	-	-	-	-	-
	C_{2008}	123.91	121.50	121.50	121.50	126.85	125.67	125.23	135.37	135.37	135.37
		121.50	121.50	121.50	121.50	115.45	112.08	111.32	135.37	135.37	135.37
		133.81	130.86	129.99	128.88	133.73	130.02	129.05	135.38	135.38	135.38
	C_{2009}	116.03	112.31	111.02	109.88	117.23	114.20	112.55	128.61	128.61	128.61
		109.35	109.35	109.35	109.35	102.97	95.70	94.01	128.60	128.60	128.60
		133.64	128.66	127.86	126.98	131.87	128.22	124.34	138.36	138.27	137.91
M. paradoxus	B_{2027}/K	0.100	0.150	0.200	0.250	0.150	0.200	0.250	0.150	0.200	0.250
		0.021	0.069	0.121	0.167	0.063	0.085	0.125	0.061	0.106	0.134
		0.201	0.259	0.313	0.372	0.315	0.406	0.465	0.334	0.355	0.401
	B_{2027}/B_{2007}	1.45	2.13	2.88	3.79	2.19	2.85	3.78	2.59	3.41	4.36
		0.37	1.21	1.96	2.54	1.00	1.53	1.96	0.90	1.38	1.75
		2.88	3.82	4.86	5.98	5.60	7.65	8.87	6.09	6.87	7.89
	$CPUE_{2010}/CPUE_{2003\text{-}2005}$	0.96	0.99	1.00	1.01	0.95	0.99	1.00	0.83	0.83	0.83
		0.54	0.57	0.58	0.59	0.55	0.58	0.59	0.44	0.44	0.44
		1.30	1.33	1.34	1.35	1.34	1.41	1.43	1.17	1.17	1.18
	$CPUE_{2015}/CPUE_{2003\text{-}2005}$	1.06	1.23	1.28	1.33	1.10	1.31	1.45	0.91	0.91	0.94
		0.61	0.77	0.82	0.88	0.65	0.77	0.89	0.45	0.45	0.47
		1.64	1.85	1.92	1.99	1.80	2.12	2.33	1.64	1.64	1.65
M. capensis	B_{2027}/K	0.64	0.67	0.70	0.72	0.68	0.71	0.73	0.67	0.71	0.72
		0.53	0.56	0.59	0.61	0.56	0.57	0.60	0.54	0.58	0.60
		0.80	0.82	0.85	0.87	0.83	0.87	0.89	0.84	0.86	0.87
	B_{2027}/B_{2007}	1.38	1.42	1.49	1.54	1.45	1.50	1.55	1.52	1.60	1.64
		1.13	1.17	1.22	1.26	1.18	1.23	1.27	1.25	1.31	1.33
		1.63	1.70	1.78	1.84	1.74	1.79	1.86	1.87	1.97	2.01
	$CPUE_{2010}/CPUE_{2003\text{-}2005}$	1.31	1.32	1.32	1.32	1.32	1.33	1.33	1.30	1.30	1.30
		1.13	1.14	1.14	1.14	1.14	1.14	1.15	1.12	1.12	1.12
		1.50	1.51	1.51	1.51	1.50	1.50	1.51	1.48	1.48	1.48
	$CPUE_{2015}/CPUE_{2003\text{-}2005}$	1.49	1.53	1.54	1.56	1.51	1.55	1.59	1.47	1.47	1.48
		1.25	1.30	1.31	1.32	1.26	1.29	1.32	1.19	1.19	1.20
		1.73	1.77	1.77	1.79	1.76	1.81	1.86	1.75	1.76	1.76

Table 6: Summary of performance statistics for candidate $OMP1_{20\%}$, for four scenarios of the Reference Set and the corresponding SR1 and decrease in *K* robustness tests. For each performance statistic, the median and 90% PIs are shown.

		$OMP1_{20\%}$ RS	SR1	K2
	avTAC	118.66	130.38	116.83
	AAV	9.43	9.55	9.48
	C_{2007}	135.00 - -	135.00 - -	135.00 - -
	C_{2008}	121.50 121.50 128.77	127.50 121.50 135.10	121.50 121.50 128.02
	C_{2009}	111.64 109.35 124.68	126.74 111.56 139.86	110.54 109.35 123.75
M. paradoxus	B_{2027}/K	0.197 0.109 0.319	0.217 0.125 0.306	0.207 0.117 0.336
M. paradoxus	B_{2027}/B_{2007}	3.04 2.10 4.89	2.87 2.09 4.52	3.16 2.19 5.01
M. paradoxus	$CPUE_{2010}/CPUE_{2003\text{-}2005}$	0.98 0.63 1.34	1.55 1.15 2.26	0.98 0.63 1.34
M. paradoxus	$CPUE_{2015}/CPUE_{2003\text{-}2005}$	1.29 0.85 1.89	1.39 0.93 1.99	1.31 0.86 1.96
M. capensis	B_{2027}/K	0.67 0.56 0.84	0.67 0.56 0.82	0.48 0.40 0.60
M. capensis	B_{2027}/B_{2007}	1.52 1.24 1.77	1.49 1.24 1.78	1.38 1.17 1.64
M. capensis	$CPUE_{2010}/CPUE_{2003\text{-}2005}$	1.36 1.17 1.58	1.48 1.26 1.71	1.15 0.98 1.33
M. capensis	$CPUE_{2015}/CPUE_{2003\text{-}2005}$	1.60 1.33 1.86	1.59 1.35 1.82	1.30 1.10 1.50

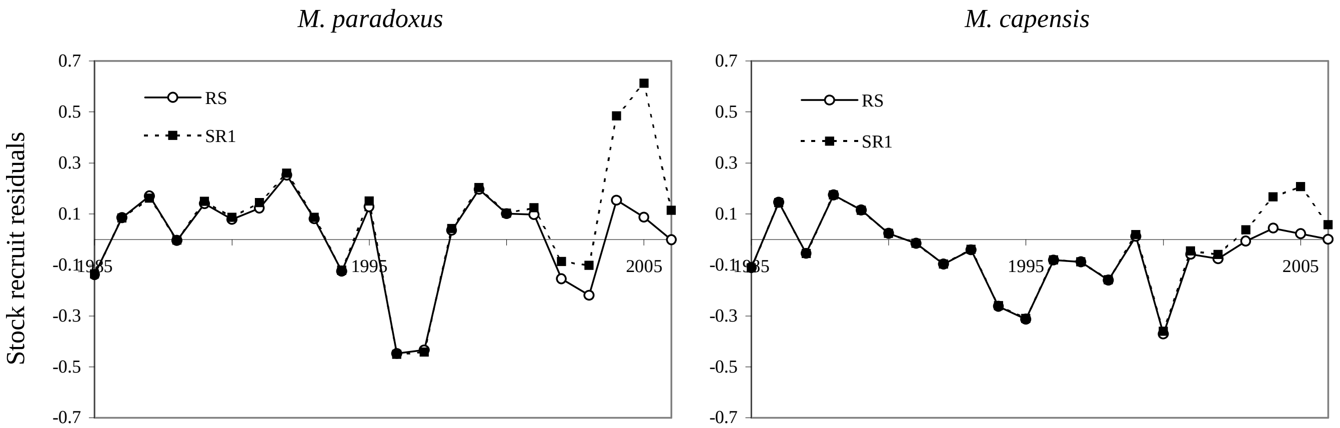


Fig. 1: Time series of recruitment residuals for one scenario (M4-H1-C3a-SR2) of the updated RS ("RS") and the corresponding SR1 scenario (M4-H1-C3a-SR1) ("SR1").

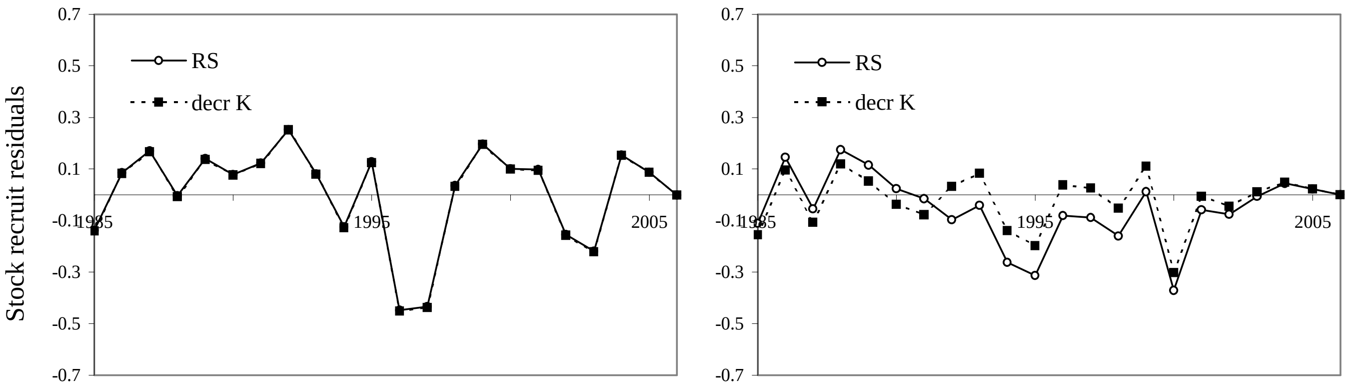


Fig. 2: Time series of recruitment residuals for one scenario (M4-H1-C3a-SR2) of the updated RS ("RS") and the corresponding scenario with a 20% decrease in the *M. capensis K* from 1992 onwards ("decr K").

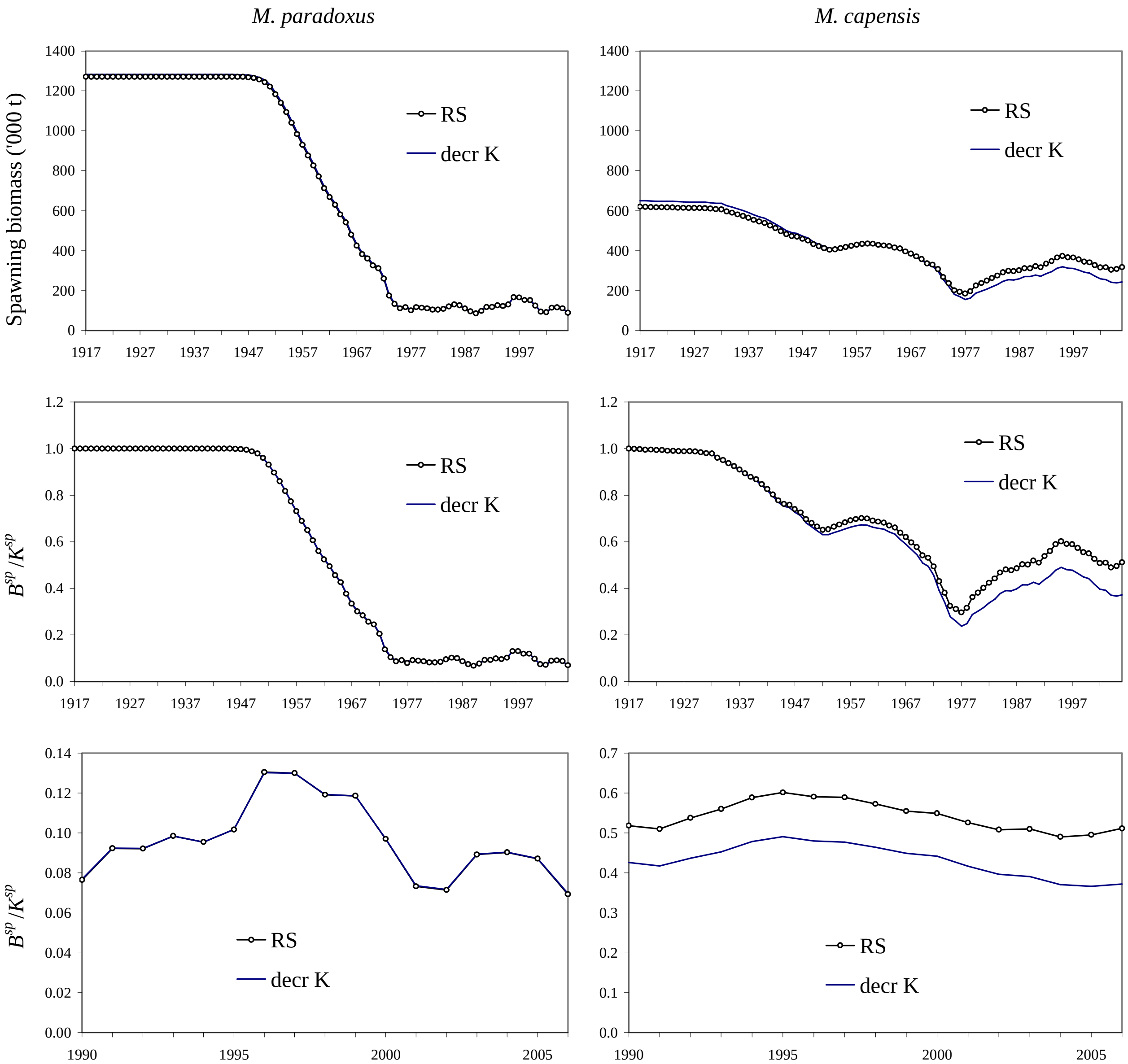


Fig. 3: Trajectories of resource abundance for one scenario (M4-H1-C3a-SR2) of the updated RS ("RS") and the same scenario with a 20% decrease in the *M. capensis K* from 1992 onwards ("decr K"). Resource abundance is expressed in terms of spawning biomass, and of spawning biomass as a proportion of its pre-exploitation level (i.e. *K* at the beginning of the 20th century).

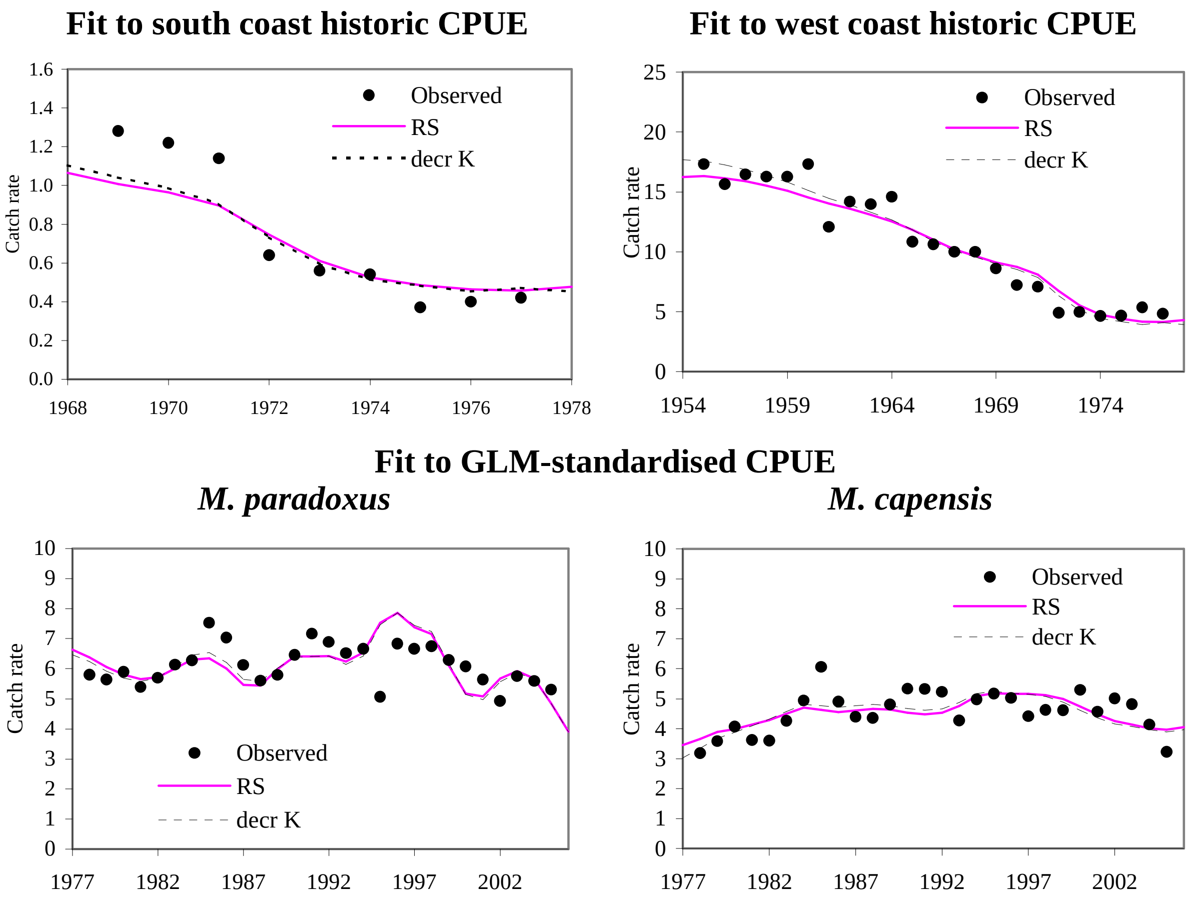


Fig. 4: Fits to the CPUE series of one scenario (M4-H1-C3a-SR2) of the updated RS ("RS") and the comparable scenario with a 20% decrease in the *M. capensis K* from 1992 onwards ("decr K").

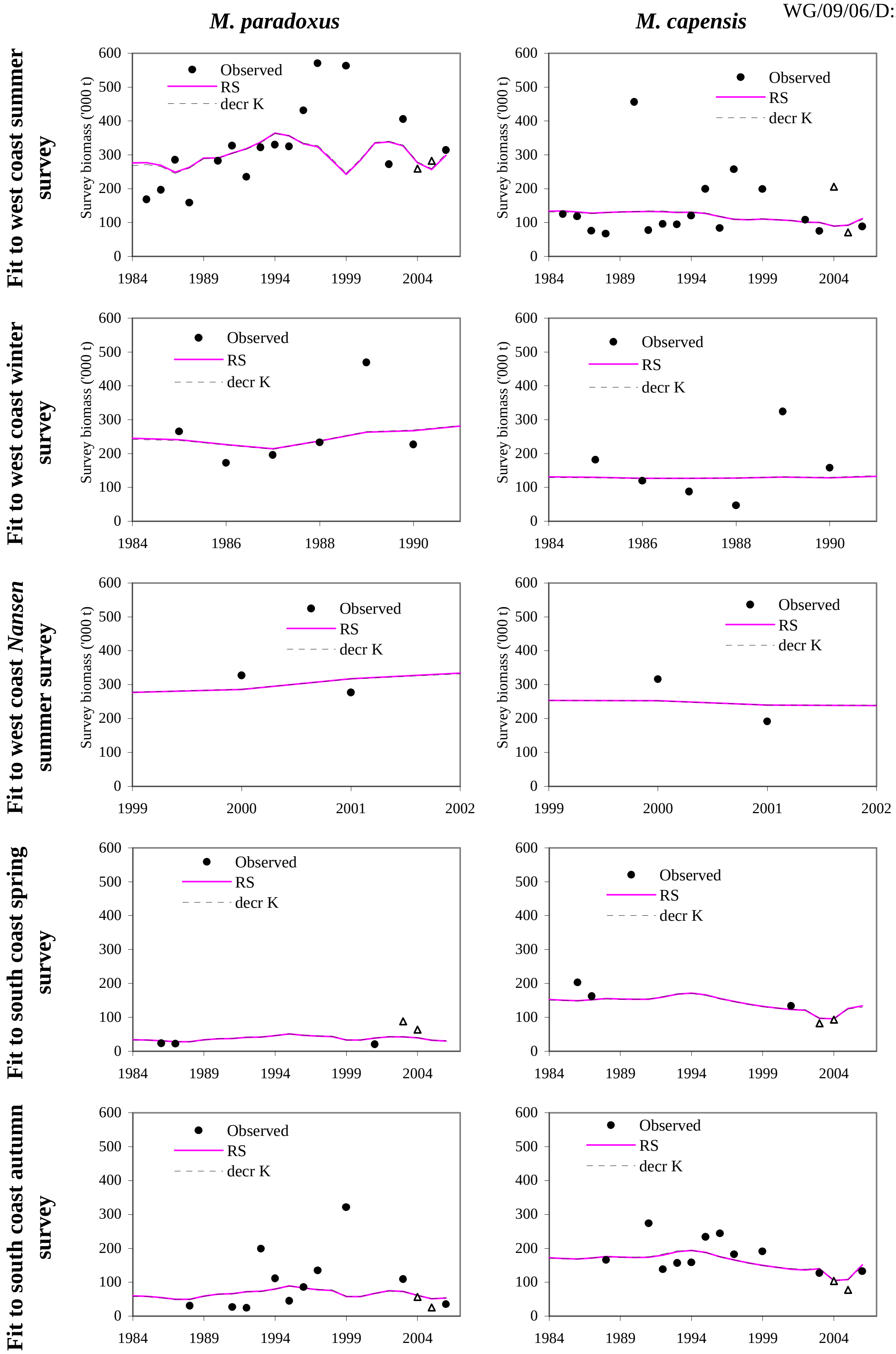


Fig. 5: Fits to the survey series of one scenario (M4-H1-C3a-SR2) of the updated RS ("RS") and the comparable scenario with a 20% decrease in the *M. capensis K* from 1992 onwards ("decr K"). Biomass estimates from surveys conducted with the new *Africana* gear have been rescaled by the ratio of the *q*'s estimated and are marked by Δ..

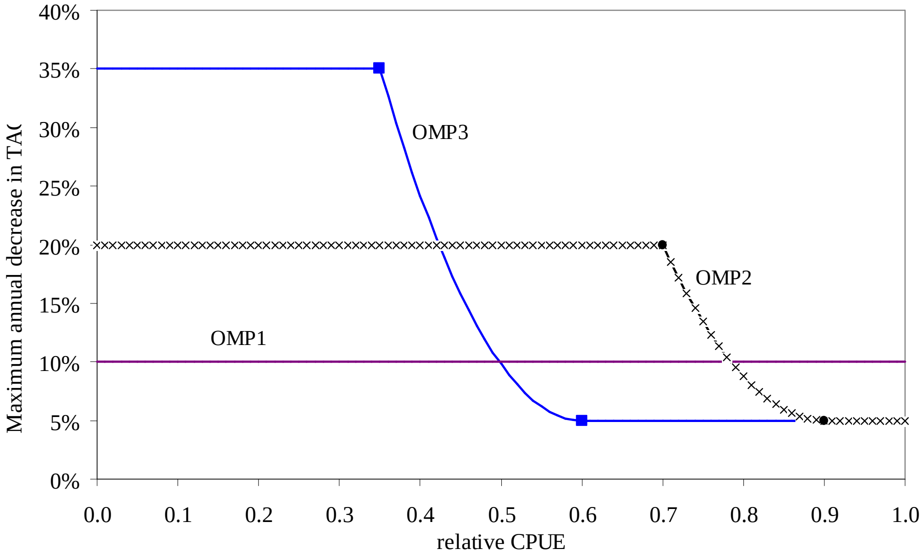


Fig. 6: Maximum allowable decrease in TAC from one year to the next as a function of the "current" CPUE relative to the average of the 2002-2004 values (see text for the precise definition of this ratio I_y) for OMP1, OMP2 and OMP3.

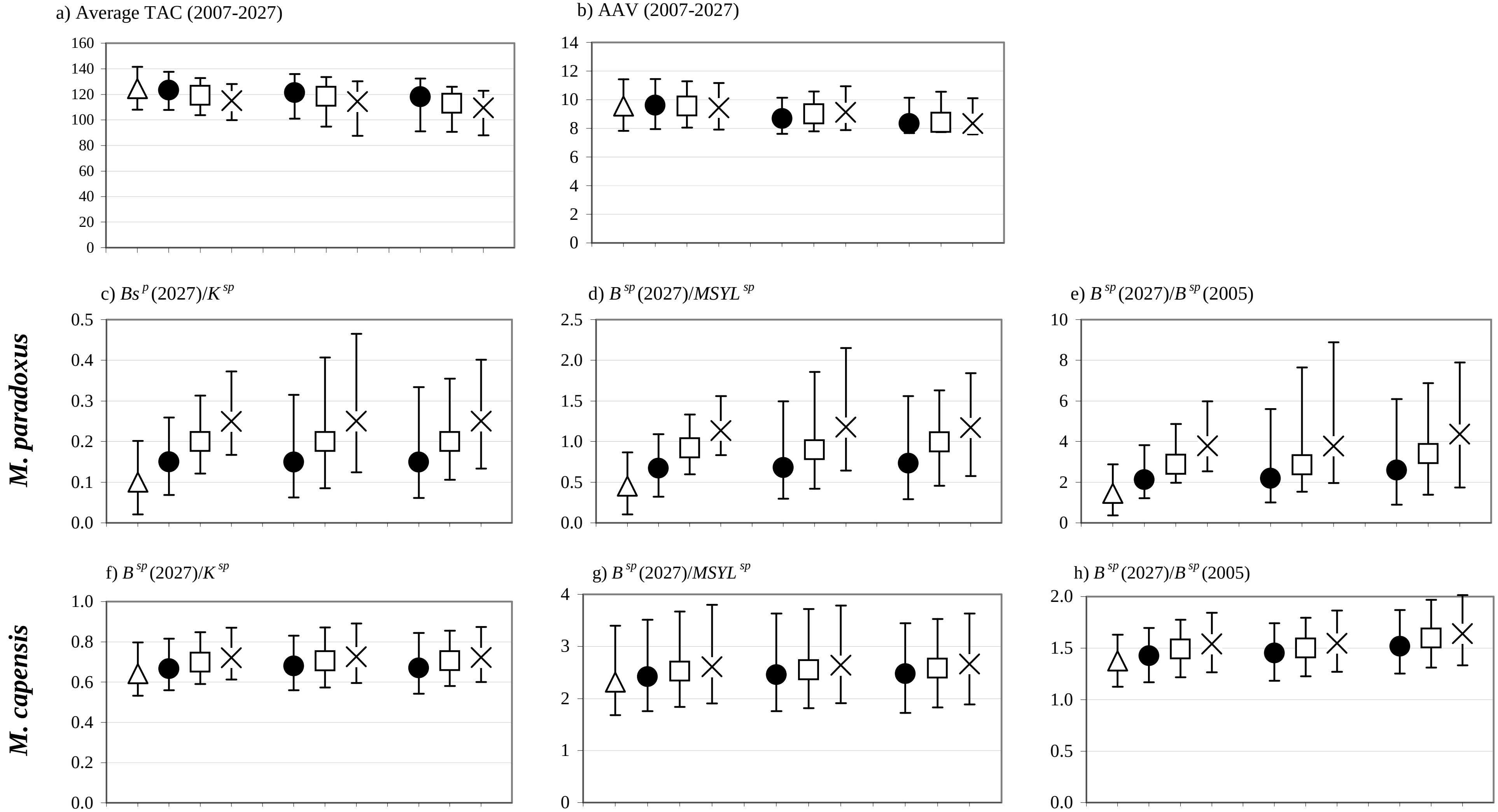


Fig. 7: Graphical summary of performance statistics for three candidate OMPs, tuned to different recovery levels for *M. paradoxus* (10% open triangles, 15% black circles,20% open squares and 25% crosses) for the RS. Each panel shows medians together with 90% PIs.

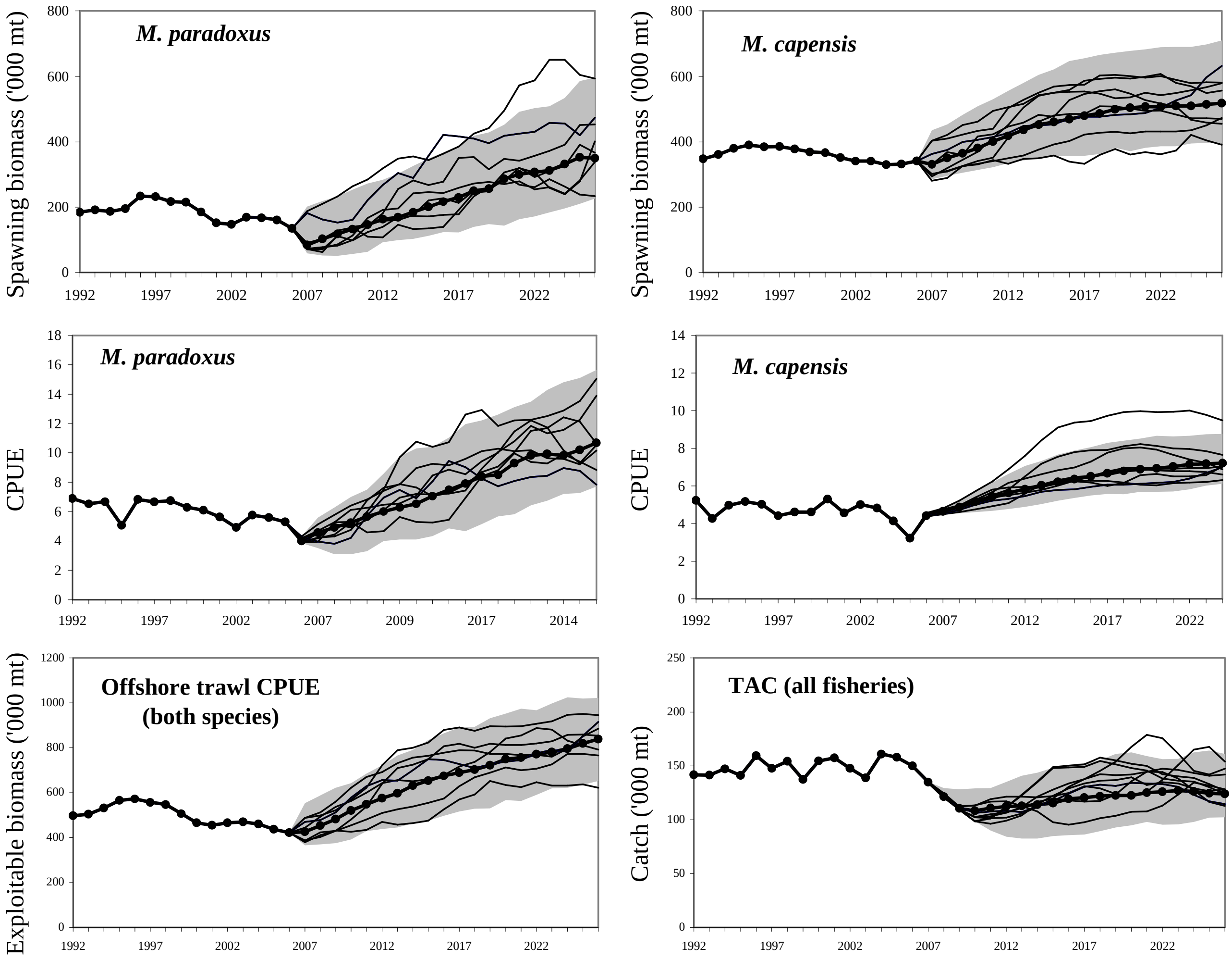


Fig. 8: Trajectories of resource abundance and catch for an application of **$\mathbf{OMP1_{20\%}}$** to the updated Reference Set. Ten individual trajectories are shown, with the median a dark dotted line; the shaded areas show 90% PIs. Note units for species-combined CPUE are those of the exploitable biomass to which it corresponds. Pre-2007, the average spawning biomass and species combined CPUE trajectories of the Reference Set and the actual species disaggregated CPUE and total catch are also shown.

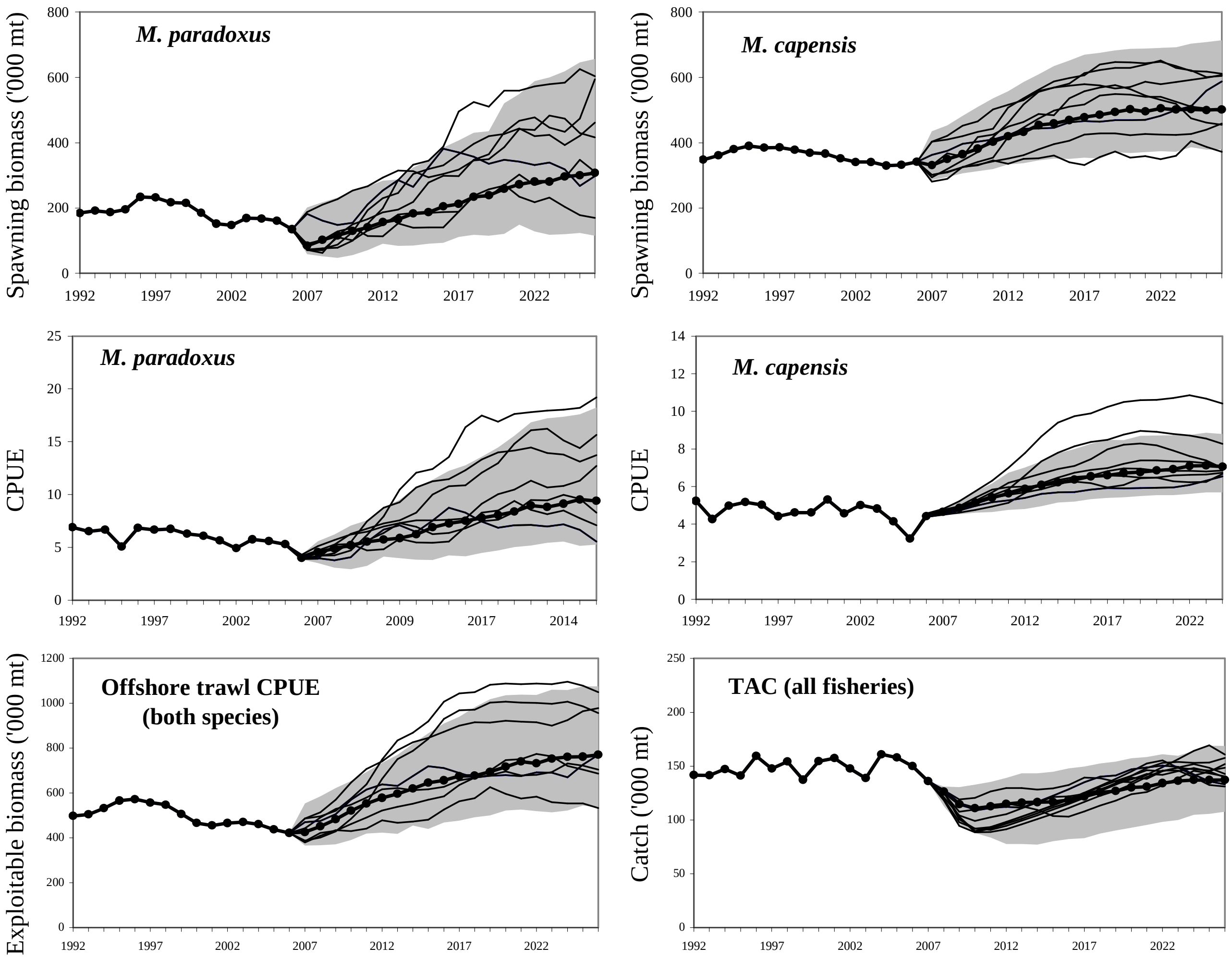


Fig. 9: Trajectories of resource abundance and catch for an application of **OMP2$_{20\%}$** to the updated Reference Set. Ten individual trajectories are shown, with the median a dark dotted line; the shaded areas show 90% PIs. Note units for species combined CPUE are those of the exploitable biomass to which it corresponds. Pre-2007, the average spawning biomass and species combined CPUE trajectories of the Reference Set and the actual species disaggregated CPUE and total catch are also shown.

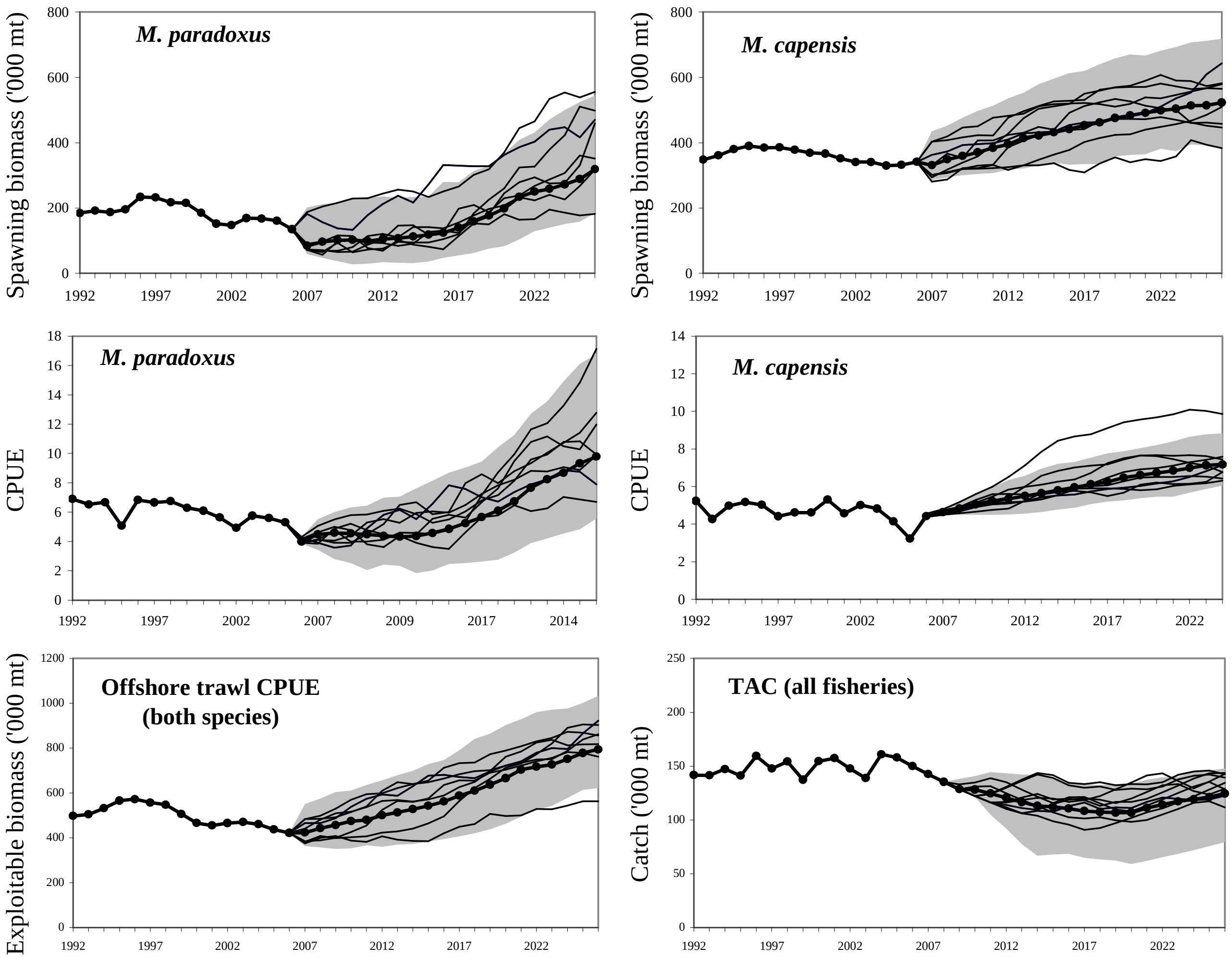


Fig. 10: Trajectories of resource abundance and catch for an application of **OMP3$_{\mathbf{20\%}}$** to the updated Reference Set. Ten individual trajectories are shown, with the median a dark dotted line; the shaded areas show 90% PIs. Note units for species combined CPUE are those of the exploitable biomass to which it corresponds. Pre-2007, the average spawning biomass and species combined CPUE trajectories of the Reference Set and the actual species disaggregated CPUE and total catch are also shown.

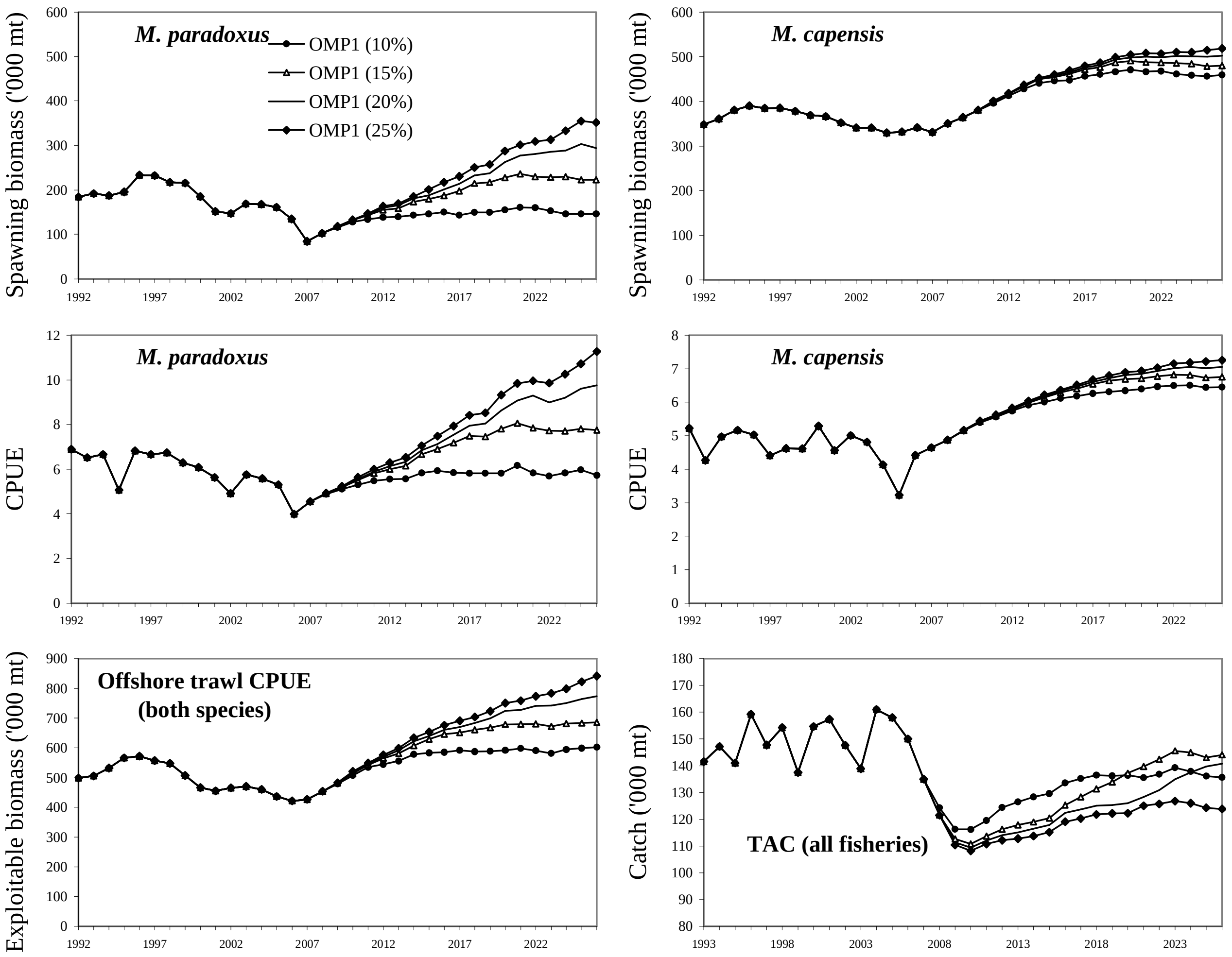


Fig. 11: Median trajectories of resource abundance and catch for an application of OMP1 for four recovery tunings. Note units for species combined CPUE are those of the exploitable biomass to which it corresponds. Pre-2007, the average spawning biomass and species combined CPUE trajectories of the Reference Set and the actual species disaggregated CPUE and total catch are also shown.

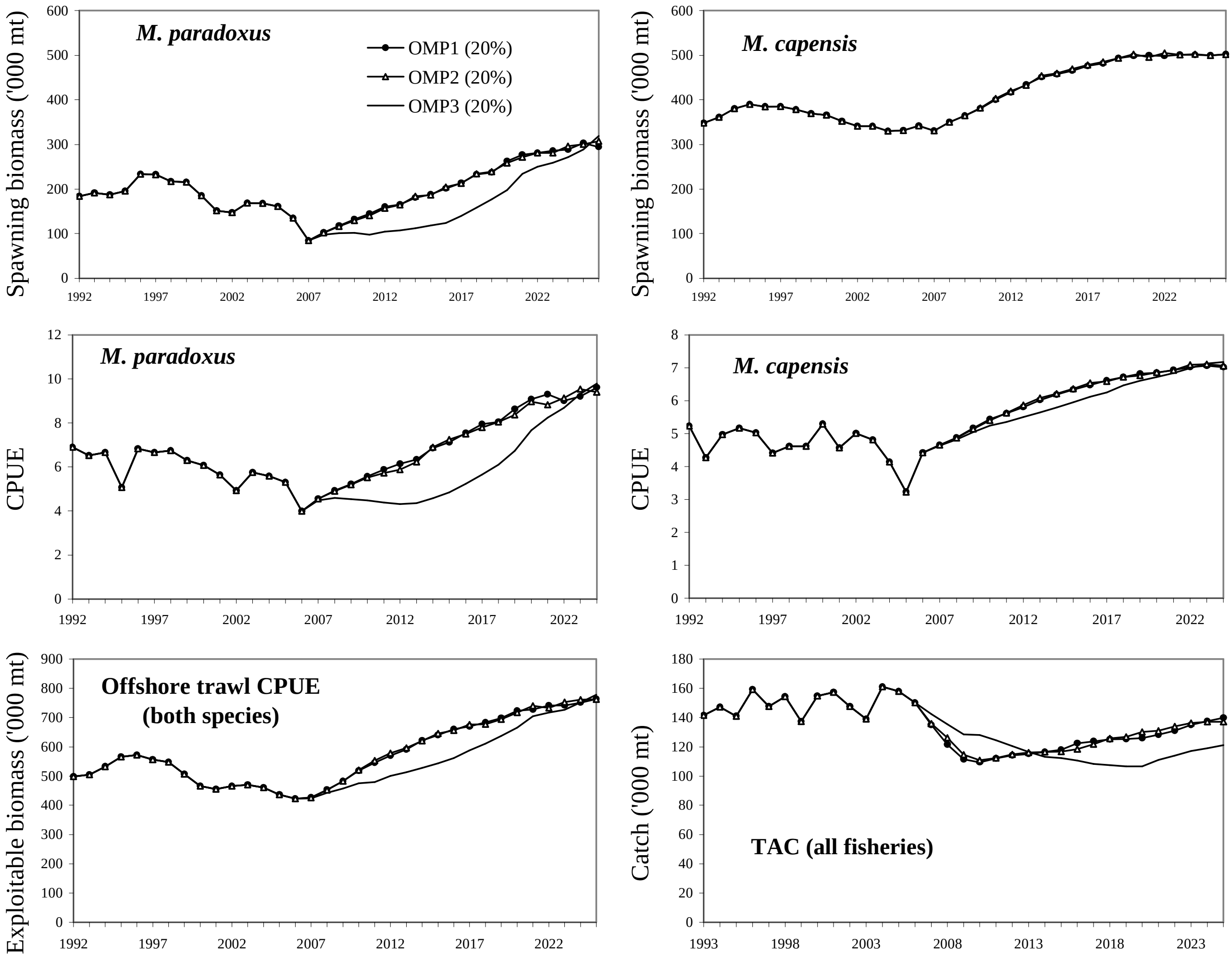


Fig. 12: Median trajectories of resource abundance and catch for an application of OMP1, OMP2 and OMP3 for a 20% recovery tuning. Note units for species combined CPUE are those of the exploitable biomass to which it corresponds. Pre-2007, the average spawning biomass and species combined CPUE trajectories of the Reference Set and the actual species disaggregated CPUE and total catch are also shown.

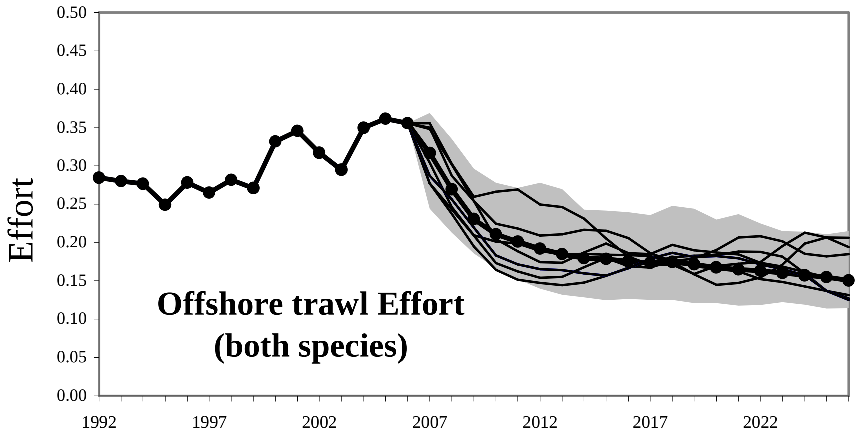


Fig. 13a: Trajectories of offshore trawl effort (total catch over offshore exploitable biomass) for an application of **OMP1$_{20\%}$** to the updated Reference Set. Ten individual trajectories are shown, with the median a dark dotted line; the shaded area shows 90% PIs.

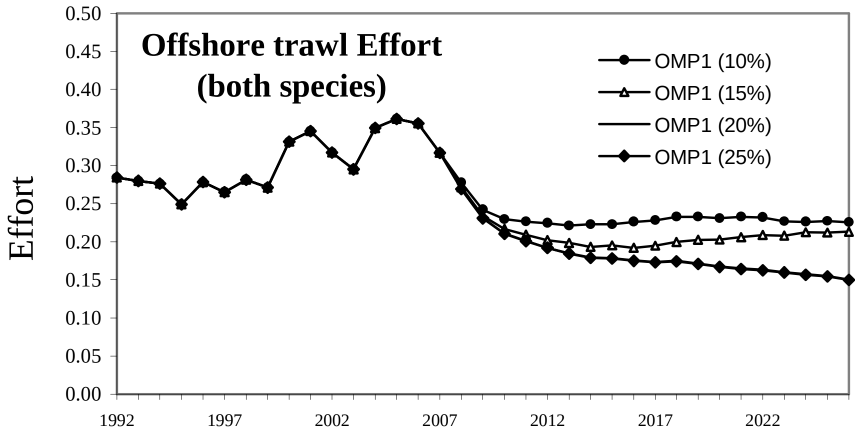


Fig. 13b: Median trajectories of offshore trawl effort (total catch over offshore exploitable biomass) for an application of OMP1 for four recovery tunings. Note: Median effort projections for OMP1$_{20\%}$ and OMP1$_{25\%}$ are the same.

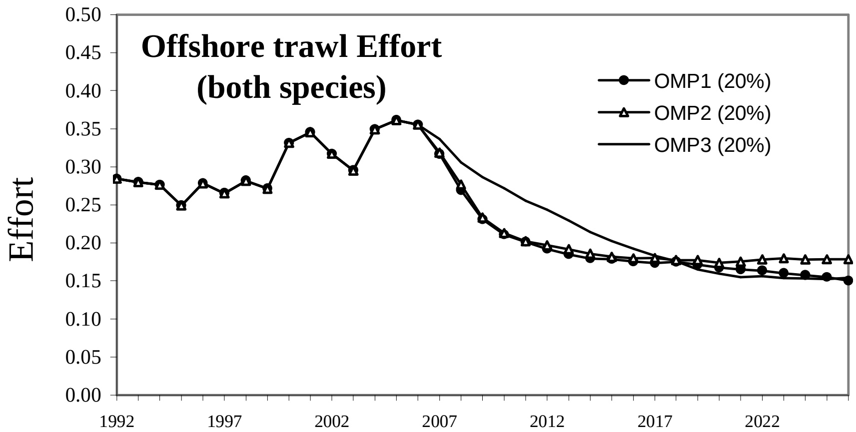


Fig. 13c: Median trajectories of offshore trawl effort (total catch over offshore exploitable biomass) for an application of OMP1$_{20\%}$, OMP2$_{20\%}$ and OMP3$_{20\%}$.

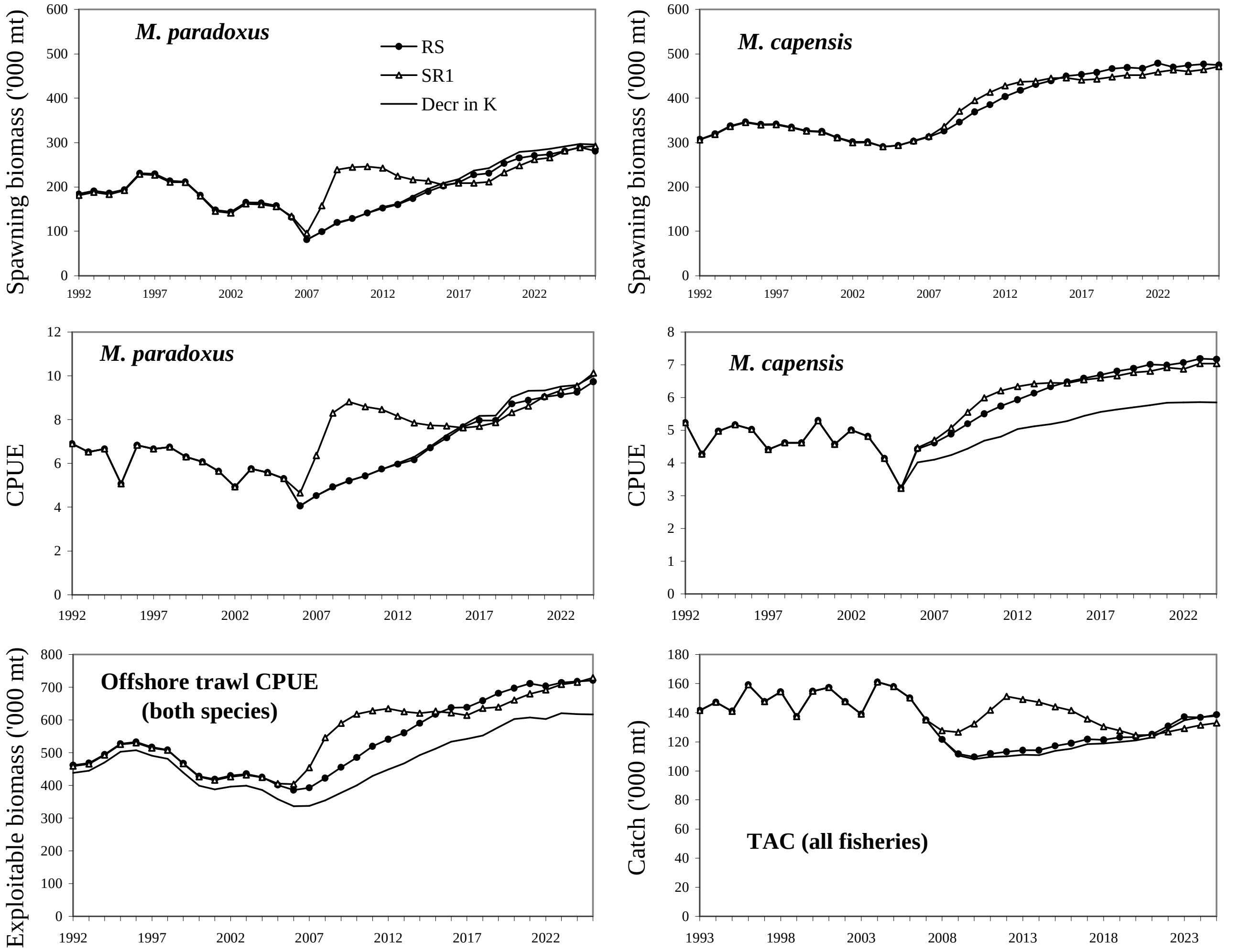


Fig. 14: Median trajectories of resource abundance and catch for an application of $\mathbf{OMP1_{20\%}}$, for four scenarios from the Reference Set and from the corresponding SR1 and decrease in *K* robustness tests. Note units for species combined CPUE are those of the exploitable biomass to which it corresponds. Pre-2007, the average spawning biomass and species combined CPUE trajectories of the four scenarios for the RS/robustness test and the actual species disaggregated CPUE and total catch are also shown.

Appendix A – Further Results for the updated Reference Set

Table A1: Estimates of management quantities of the *M. paradoxus* and *M. capensis* coast-combined resources for the updated Reference Set. *MSY* and associated quantities are given in relation to the selectivity for the offshore fleet.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
		M1	M1	M1	M1	M4	M4	M4	M4	M1	M1	M1	M1	M4	M4	M4	M4	M1	M1	M1	M1	M4	M4	M4	M4
		C3a	C3a	C3a	C3a	C3a	C3a	C3a	C3a	C3b	C3b	C3b	C3b	C3b	C3b	C3b	C3b	C3c	C3c	C3c	C3c	C3c	C3c	C3c	C3c
		H1	H2	H3	H4	H1	H2	H3	H4	H1	H2	H3	H4	H1	H2	H3	H4	H1	H2	H3	H4	H1	H2	H3	H4
		SR2	SR2	SR2	SR2	SR2	SR2	SR2	SR2	SR2	SR2	SR2	SR2	SR2	SR2	SR2	SR2	SR2	SR2	SR2	SR2	SR2	SR2	SR2	SR2
-lnL total		-189.3	-180.7	-184.1	-174.2	-196.9	-191.8	-194.8	-189.7	-189.5	-181.8	-183.9	-175.8	-196.8	-192.1	-194.6	-190.0	-188.3	-176.6	-186.0	-174.2	-197.3	-190.6	-196.3	-189.7
M. paradoxus K^{sp}		1747	2298	1732	2279	1271	979	1265	961	1746	2307	1728	2290	1291	996	1284	980	1744	2241	1735	2230	1157	899	1158	893
h		0.95	0.80	0.95	0.80	0.95	0.80	0.95	0.80	0.95	0.80	0.95	0.80	0.95	0.80	0.95	0.80	0.95	0.80	0.95	0.80	0.95	0.80	0.95	0.80
MSY		118	115	117	115	117	111	115	109	119	116	118	116	117	112	116	110	114	111	114	111	114	109	114	108
B^{sp}_{2006}/K^{sp}		0.06	0.10	0.06	0.10	0.07	0.12	0.07	0.12	0.06	0.10	0.06	0.10	0.07	0.12	0.07	0.12	0.07	0.11	0.07	0.11	0.08	0.13	0.08	0.13
$B^{sp}_{2006}/MSYL^{sp}$		0.31	0.40	0.31	0.40	0.35	0.51	0.34	0.51	0.30	0.40	0.29	0.39	0.34	0.49	0.33	0.50	0.37	0.45	0.36	0.44	0.41	0.56	0.40	0.55
$MSYL^{sp}$		0.19	0.24	0.19	0.24	0.20	0.24	0.20	0.24	0.19	0.24	0.20	0.24	0.20	0.24	0.20	0.24	0.18	0.24	0.18	0.24	0.19	0.24	0.19	0.24
M	0	0.50	0.50	0.50	0.50	0.53	0.72	0.56	0.80	0.50	0.50	0.50	0.50	0.53	0.71	0.56	0.79	0.50	0.50	0.50	0.50	0.52	0.71	0.54	0.74
	1	0.50	0.50	0.50	0.50	0.53	0.72	0.56	0.80	0.50	0.50	0.50	0.50	0.53	0.71	0.56	0.79	0.50	0.50	0.50	0.50	0.52	0.71	0.54	0.74
	2	0.50	0.50	0.50	0.50	0.53	0.72	0.56	0.80	0.50	0.50	0.50	0.50	0.53	0.71	0.56	0.79	0.50	0.50	0.50	0.50	0.52	0.71	0.54	0.74
	3	0.40	0.40	0.40	0.40	0.45	0.60	0.46	0.64	0.40	0.40	0.40	0.40	0.44	0.59	0.46	0.63	0.40	0.40	0.40	0.40	0.45	0.60	0.46	0.62
	4	0.34	0.34	0.34	0.34	0.40	0.52	0.40	0.53	0.34	0.34	0.34	0.34	0.39	0.52	0.40	0.53	0.34	0.34	0.34	0.34	0.41	0.54	0.41	0.54
	5+	0.30	0.30	0.30	0.30	0.36	0.47	0.36	0.47	0.30	0.30	0.30	0.30	0.36	0.47	0.36	0.47	0.30	0.30	0.30	0.30	0.38	0.49	0.38	0.49
M. capensis K^{sp}		780	782	956	929	620	588	614	544	781	793	932	940	617	599	607	554	905	912	1041	1063	675	675	688	676
h		0.95	0.95	0.70	0.70	0.95	0.95	0.70	0.70	0.95	0.95	0.70	0.70	0.95	0.95	0.70	0.70	0.95	0.95	0.70	0.70	0.95	0.95	0.70	0.70
MSY		57	58	55	54	65	63	60	57	57	58	54	54	65	64	60	58	66	67	60	62	70	70	64	64
B^{sp}_{2006}/K^{sp}		0.36	0.36	0.41	0.38	0.51	0.49	0.53	0.49	0.37	0.38	0.40	0.40	0.51	0.49	0.53	0.50	0.45	0.46	0.40	0.43	0.54	0.54	0.53	0.53
$B^{sp}_{2006}/MSYL^{sp}$		1.41	1.41	1.24	1.14	2.33	2.24	1.72	1.61	1.45	1.49	1.21	1.22	2.33	2.25	1.74	1.64	1.79	1.80	1.23	1.29	2.42	2.45	1.73	1.73
$MSYL^{sp}$		0.25	0.25	0.33	0.33	0.22	0.22	0.31	0.30	0.25	0.25	0.33	0.33	0.22	0.22	0.31	0.30	0.25	0.25	0.33	0.33	0.22	0.22	0.31	0.31
M	0	0.50	0.50	0.50	0.50	1.00	1.00	1.00	1.00	0.50	0.50	0.50	0.50	1.00	1.00	1.00	1.00	0.50	0.50	0.50	0.50	1.00	1.00	1.00	1.00
	1	0.50	0.50	0.50	0.50	1.00	1.00	1.00	1.00	0.50	0.50	0.50	0.50	1.00	1.00	1.00	1.00	0.50	0.50	0.50	0.50	1.00	1.00	1.00	1.00
	2	0.50	0.50	0.50	0.50	1.00	1.00	1.00	1.00	0.50	0.50	0.50	0.50	1.00	1.00	1.00	1.00	0.50	0.50	0.50	0.50	1.00	1.00	1.00	1.00
	3	0.40	0.40	0.40	0.40	0.70	0.70	0.73	0.74	0.40	0.40	0.40	0.40	0.70	0.70	0.73	0.74	0.40	0.40	0.40	0.40	0.69	0.70	0.72	0.72
	4	0.34	0.34	0.34	0.34	0.52	0.52	0.57	0.59	0.34	0.34	0.34	0.34	0.52	0.52	0.57	0.59	0.34	0.34	0.34	0.34	0.51	0.51	0.55	0.56
	5	0.30	0.30	0.30	0.30	0.40	0.40	0.46	0.49	0.30	0.30	0.30	0.30	0.40	0.40	0.46	0.48	0.30	0.30	0.30	0.30	0.39	0.39	0.44	0.45
	6	0.30	0.30	0.30	0.30	0.40	0.40	0.46	0.49	0.30	0.30	0.30	0.30	0.40	0.40	0.46	0.48	0.30	0.30	0.30	0.30	0.39	0.39	0.44	0.45
	7+	0.00	0.30	0.30	0.30	0.40	0.40	0.46	0.49	0.30	0.30	0.30	0.30	0.40	0.40	0.46	0.48	0.30	0.30	0.30	0.30	0.39	0.39	0.44	0.45
SC survey q		1.11	1.11	0.92	0.98	0.78	0.84	0.69	0.78	1.09	1.07	0.95	0.94	0.78	0.82	0.68	0.76	0.90	0.89	0.88	0.84	0.72	0.71	0.64	0.64
2006 species ratio	B^{sp}	2.75	1.24	3.82	1.60	3.60	2.38	3.80	2.27	2.87	1.35	3.74	1.74	3.59	2.45	3.80	2.35	3.58	1.72	3.73	1.91	4.00	3.01	4.14	3.04
	B^{2+}	1.45	0.93	1.96	1.16	1.97	1.33	2.14	1.32	1.50	1.00	1.90	1.25	1.98	1.38	2.15	1.37	1.94	1.28	2.01	1.40	2.16	1.61	2.32	1.68

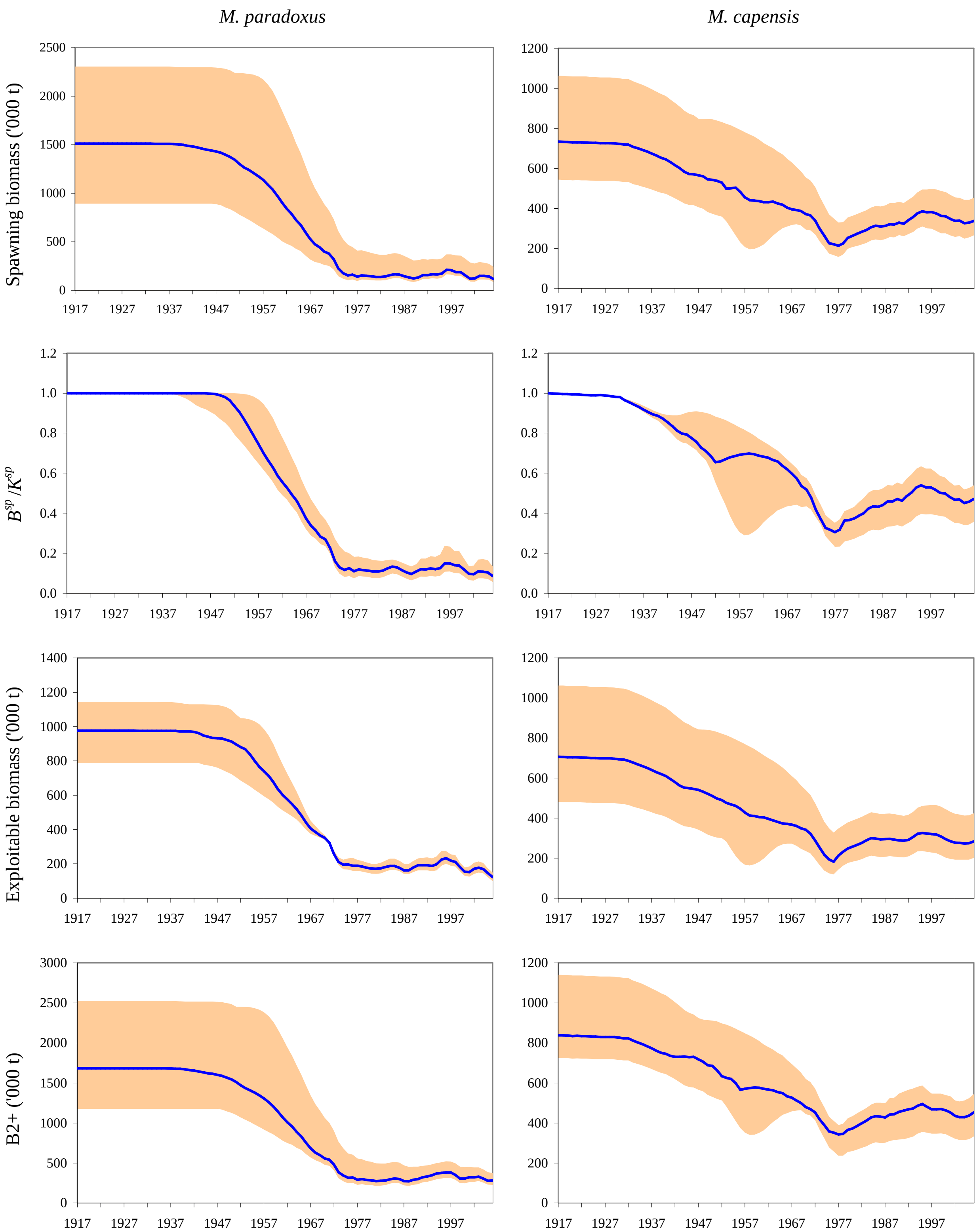


Fig. A1: Trajectories of resource abundance for the updated Reference Set. Resource abundance is expressed in terms of a) spawning biomass, b) spawning biomass as a proportion of its pre-exploitation level, c) exploitable biomass and d) biomass of fish of age 2 and above. The median is indicated by a thick line while the shaded area represents the full uncertainty of the updated Reference Set (minimum and maximum for each year).

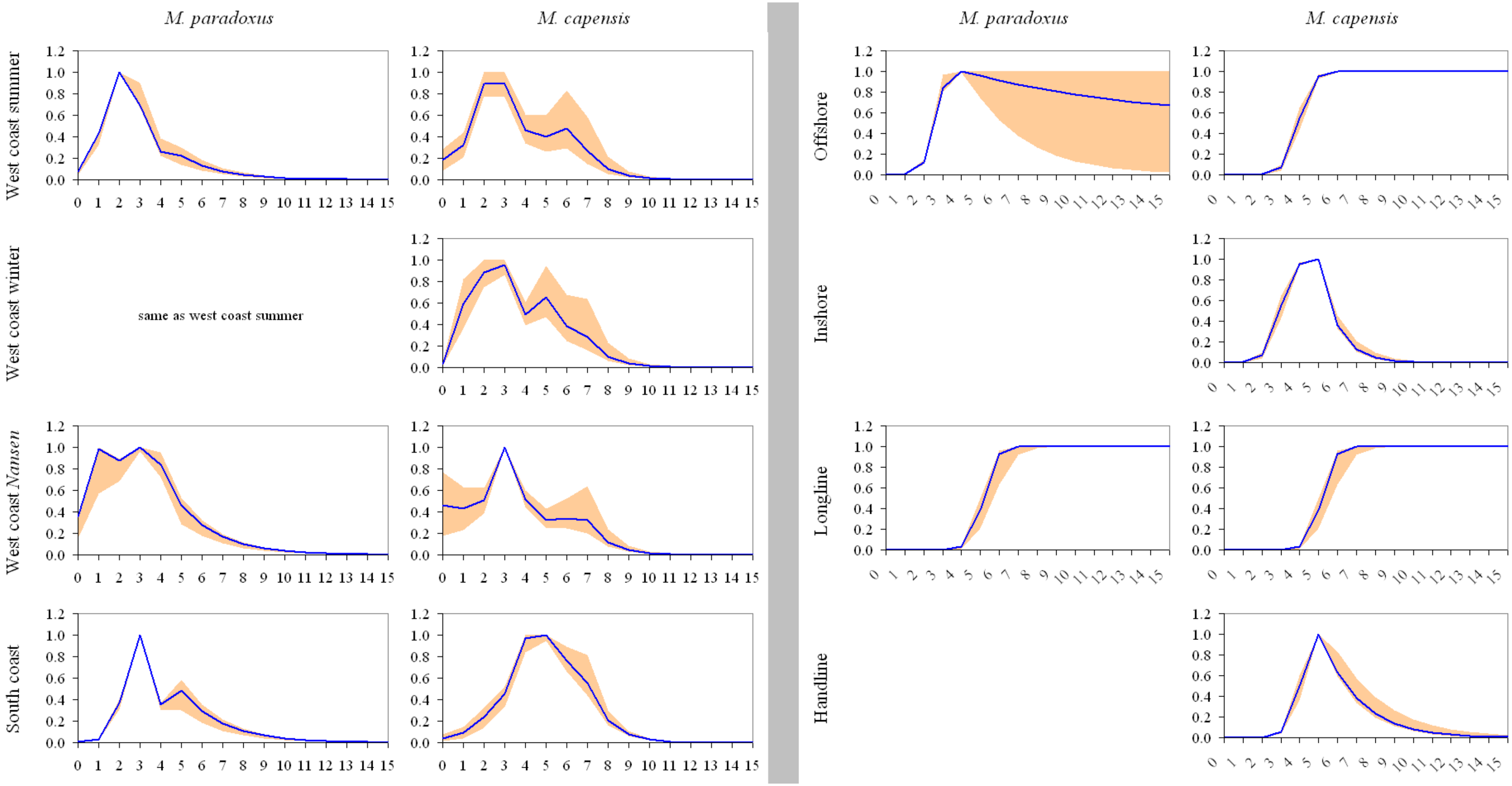


Fig. A2: Estimated survey and commercial fishing selectivities for the updated Reference Set. The median is indicated by a thick line while the shaded area represents the full uncertainty of the updated Reference Set (minimum and maximum for each age).