Setting priorities for future hake research: how this is informed by the OMP robustness testing process

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Abstract

The results from robustness tests of the OMP adopted last year for the hake resource are used to assign priorities for research, with the outcome compared to that from the Environmental Risk Analysis (ERA) exercise. Broad similarities are evident, with both approaches indicating that improved information on the extent of recruitment variability and on the species (also sex) composition of the commercial catches is a high priority. However the OMP approach suggests low priority for *M. capensis* size structure issues, in contrast to the ERA. Key research needs, roughly in order of priority, are seen to be: ageing, sampling the commercial catches for species and sex, improved precision of abundance indices, improved information on discards, and (primarily in a trans-boundary context) genetic analyses to detect possible stock structure.

Introduction

An Operational Management Procedure (OMP), which provides a basis to make management recommendations such as TACs for a resource, is in essence simply a formula. This formula is selected following a simulation testing process which indicates the expected performances of different formulae in terms of management objectives related to high catches, low risks to the resource, and industrial stability.

Candidate OMPs are tested against "Operating Models" (OMs) which reflect alternative possibilities for the dynamics of the fishery and fish population under harvest. It is important to check (through the simulation testing process) that the performance of the OMP advocated is reasonably robust across a range of operating models, i.e. the formula must, through the mechanism of feedback control, be able to come close to achieving management objectives even if the underlying reality differs from the most-favoured assessment model.

A key consideration in selecting OMPs is to ensure that risk criteria are met over the range of (at least the more plausible) robustness tests, and the scenarios which result in the largest resource depletion can turn out to be important determinants of the OMP selected. If, however, subsequent research can show these scenarios to be inconsistent with new information, less conservative OMPs allowing greater catches for the same perceived risk can be adopted in future.

A primary aim of research focussed on resource management is thus to see whether scenarios reflecting poor resource productivity can be eliminated. Thus an important secondary utility of the results from an OMP testing process is to shed light on priority areas (in this management context) for future research: for the OMP chosen, the core question then becomes which robustness tests reflect poor performance, particularly in terms of excessive depletion of the resource?

This paper seeks to pursue this exercise using results from the robustness testing of the OMP adopted in 2006 (OMP-2007) as a revised basis for setting future TACs for the South African hake resource (Rademeyer and Glazer, 2006). It then continues by comparing the inferences drawn from this process with the priorities suggested by an ecological risk assessment exercise for hake conducted in 2006 (Nel *et al.*, 2007).

Methods and Results

Table 1 lists the full set of robustness tests considered at some stage in the process leading to selection of OMP-2007. A detailed description of the scenario which each test represents is given in Appendix A.

Appendix A commences by detailing the factors which were varied in the scenarios that constituted the Reference Set (RS) of OMs used for the core testing and tuning of OMP-2007. These factors were selected from amongst initial screening tests as those covering the ranges of key assessment uncertainties which had the most important effects on resource projections under alternative harvesting formulae (see also Fig. 1). For convenience, the C4 robustness test (reflecting uncertainty about the species composition of recent commercial catches) is listed here, though it was not part of the RS.

Because of the length of time taken to complete the testing and selection process, and updating of assessments while it progressed (culminating eventually in a final testing process which had to be truncated to meet the OMP adoption deadline), the procedures followed to reduce the initially very large set of robustness tests changed somewhat over time. Thus Fig. 2 (see Appendix B for assistance in interpreting such plots) reflects results for tests that were eliminated at any early stage through simple testing under constant catch scenarios. Note that this elimination was not always on the basis of no substantial difference from performance statistics for the RS, but sometimes because a group of tests had all shown similar deviations in their results compared to those for the RS, so that not all such tests were retained for further analyses to ease the computational burden.

Fig. 3 includes the full set of robustness tests originally intended for inclusion in the final set against which OMP-2007 would be trialled. As for Fig. 2, the results for Fig. 3 are under a constant catch scenario, rather than the final feedback-control OMP-2007. To further ease computation, for tests which required refitting to past data to finalise the OMs, only a restricted number of scenarios from the RS were considered, with results from such tests compared to those for a RS also reduced in this manner.

The final core set of six robustness trials against which OMP-2007 was tested are included in Fig. 4. This set was selected either because the factor concerned had been of interest in the process of choosing the RS, or because earlier tests had suggested appreciable sensitivity of results for performance statistics. For the same reasons as detailed above, a number of these tests were integrated over only a small number of the scenarios comprising the RS.

Interpretation in terms of Research Priority for Management Needs

Table 2 attempts a comparative summary of the results from the Ecological Risk Assessment (ERA) exercise (Nel *et al.*, 2007) with those from the OMP testing process, by linking (where possible) the issues identified in the former with specific tests carried out under the latter.

The "Impact" column of Table 2 attempts on H/M/L ranking of the robustness tests in terms of differences in performance statistics under that test compared to under the RS (or restricted RS) used. An H ranking reflects instances where the lower 5%-ile of a projected resource abundance measure is notably below that for the corresponding RS (only for resources below *MSYL – M. paradoxus* in this case). An M classification is accorded either for a lesser such reduction, or for a large positive result for catches taken and resource status compared to the RS. An L ranking reflects a notable but small effect, whereas blanks indicate no substantial sensitivity. (Note that this does not imply that the scenario considered does not reflect importantly different biology; rather only that it is not important in a management context because the OMP testing predicts essentially unchanged performance whichever scenario applies, so that resolution of the different associated hypotheses is not a management priority even though it might be of biological interest.)

We consider in turn the robustness tests ranked H, M or L in Table 2, and comment on the associated research requirements.

Priority H

1) B7 – σ_R = 0.4 (the level of interannual variability in recruitment is greater than indicated by the assessment).
Research needs: Improved/additional ageing
Commercial catch sampling for disaggregation by species and sex
Improved survey and CPUE precision

2) C1 vs C2 vs C3 (uncertainty regarding pre-1978 time trend in the commercial catch split from primarily *M. capensis* to primarily *M. paradoxus*).
Research needs: More information on spatial patterns of species distribution and past spatial patterns of fishing

3) C4 (uncertainty about post-1977 species split of commercial catches).
Research needs: On board sampling of commercial catches

In terms of the ERA outcome, these relate to:

Issue 5: Uncertainty about variability in recruitment

Issue 7: Uncertainty about the proportion of each hake species in total catch

Priority M

1) A1b – with discards and B3c/d – disc 3 (past discards only from both trawlers and longliners, and trawler discards in the past with an increase in age 3 discards from 1996 continued into the future (B3c), though perhaps reduced by 50% (B3d)).
(Note that the record is unclear as to why B3c and B3d were not taken forward to the final stage of robustness testing – possibly this was because the DWG considered that given observer coverage, such a level of future discarding was implausible.)
Research needs: Improved monitoring of discards

2) M1 vs M4 (uncertainty about the value of natural mortality and its variation with age).

Research needs: Improved/additional ageing
Commercial catch sampling for disaggregation by species and sex
Age-dependence of spatial variation and escapement from trawl nets to inform on selectivity-at-age
Multi-species analyses of age-specific predation on hake

3) SR1 (uncertainty about most recent recruitments)
Research needs: Improved/additional ageing
Improved survey precision

4) B8 (decreases in *K* – past of future)
Research needs: Predictively reliable ecosystem models (long-term)

5) A7b (Ricker stock recruitment function).
Research needs: Long-term monitoring to achieve greater contrast for assessment (Note: Primary utility would be indication that *M. paradoxus* is not as depleted as current assessments suggest.)

In terms of the ERA outcome, these relate to:

Issue 2: Fishing mortality underestimated due to discarding and survival after escapement [1) above]

Issue 3: Uncertainty about the estimation of natural mortality (predation and cannibalism) [2) and possibly 3) above]

<u>Priority L</u>

1) A10d – mat age=7 (this surrogates the size-specific fecundity per unit mass concern by assuming that hake which spawn from ages 4 to 6 make no effective contribution to recruitment).
Research needs: Further modelling studies to ascertain whether there are circumstances where this effect would be larger, and hence justify improved experimental estimation of fecundity vs size relationships.

2) B6 – ll sel (longline selectivity on ages 4 and 5 increases over time).
Research needs: Data on longline catch size structure, and ageing thereof.

In terms of the ERA outcome, these relate to:

Issue 12: *M. capensis*: Size structure may have been affected by fishing – the additional effect of removing more large hake.

<u>Other comments</u>

It is perhaps a surprise that robustness tests concerned with biases in data (e.g. B4a, B4b concerning survey gear calibration factors) are not included above. However, these were "eliminated" on the basis of tests involving constant catches (see Fig. 3a), and their results may manifest greater differences from the RS under the feedback control approach of OMP-2007. There would therefore seem a case to further test OMP-2007 under some of the Fig. 3 robustness tests as originally planned.

Some of the ERA issues listed in Table 2 have no related robustness tests listed, which begs commentary:

a) Issues 8 and 10 related to possible sharing of stocks with Namibia (particularly *M. paradoxus*). A pre-requisite to this is a joint SA-Namibian hake assessment including spatial structure, as has been recommended for some time. However that in turn has the further pre-requisite of a shared and agreed database (BCLME, 2006), whose preparation has yet to commence. The conclusion of this BCLME workshop should also be noted: “there are major uncertainties about whether there are multiple or shared stocks for both Cape hake species, particularly for *M. paradoxus*” (BCLME, 2006, pg 3). Core candidates for research needs here are tagging and further genetics studies.

b) Issue 9: *M. paradoxus*: stock status is below B_{MSY}. This is an assessment outcome, and hence a composite result based on all data rather than a specific consequence of a certain subset with related research needs. Many of the research needs identified above would lead to an improved estimate of this status were they successfully pursued. It should be noted that this result is of particular importance externally, as it is, for example, a key consideration in the MSC appraisal of the satisfactory nature of hake management in reconsideration of ecolabelling certification.

c) Issue 13: *M. capensis*: size structure may have been affected by fishing – continued impact of fishing on small hake. Current (RS) assessments do not indicate this to be a serious concern. To the extent that it might be, this is informed by the research needs identified for Issue 2 (discarding) and Issue 3 (natural mortality estimation).

d) Issues 6, 4 and 1: Basic knowledge of the life-history strategy is not well understood, together with migration and distribution change issues. Existing and planned future modelling studies can address movement issues to the extent that the information content of the data permits, while at a trans-boundary level this would seem to restate the concerns of Issues 8 and 10 addressed in a) above.

e) Issue 11: *M. capensis*: uncertainty and disagreement as to the status of the stock. See note on this appended to Table 2 – this issue as stated appears to reflect a misunderstanding.

f) Issue 14: *M. capensis*: increase in parasites which could affect fecundity and marketing. This was given a low risk weighting in the ERA, and hardly relates to OMP robustness testing.

In summary

There is reasonably good correspondence between the risk levels assigned by the ERA process and the outcomes of the robustness testing (for issues which both address). Issues 5 (recruitment variability) and 7 (species composition of commercial catch) were accorded a risk level of 18 in the ERA process, and a H ranking for robustness test results. Issues 2 (discarding) and 3 (natural mortality), also risk levels of 18, rank M here. Issue 9 (*M. paradoxus* stock status) is an overarching one, and clearly earmarked as important by both approaches.

The differences are that *M. capensis* size structure concerns (Issue 12, risk level 24; and Issue 13, risk level 18) are not seen as ones of major concern in terms of robustness test results.

From a research needs perspective, the following appear the priorities (roughly in order):

I) Ageing

II) Species (and sex) composition of commercial catches

III) Improved precision of abundance indices (developing environmental relationships?)

IV) Improved information on discards

to which genetic analyses to detect possible stock structure might be added primarily in a trans-boundary concerns context.

References

BCLME. 2006. Agreed report of the joint hake research planning workshop, Cape Town 9-12th May 2006. (23pp).

Nel, DC, Cochrane, K, Petersen, SL, Shannon, LJ, van Zyl, B and Honig, MB (Eds). 2007. Ecological risk assessment: a tool for implementing an ecosystem approach for southern African fisheries. WWF South Africa Report Series – 2007/Marine/002. (203 pp.)

Rademeyer RA and Glazer JP. The 2006 Operational Management Procedure for the South African *Merluccius paradoxus* and *M. capensis* Resources. Unpublished report, MCM, South Africa.

Table 1: Complete list of robustness tests considered in the hake OMP testing process. The six tests that were included in the final stage of OMP testing (see text for detail) are shaded. Note that tests that are not circled involve changes to data or assumptions that include the past, and hence require refitting the population model to provide the operating model used for the OMP test concerned. This refitting is not needed for tests that are circled which concern modifications to assumptions for the future only.

i. Different assumptions about discards and catch series		
1	"A1a – disc1"	Include past discards for offshore and inshore trawlers. No discards in the future.
2	"A1b – with discards"	As "A1a - disc1" but with discards from longliners as well. No discards in the future.
3	"A1c – disc3"	As "A1b - with discards" plus discards of age 3 from trawlers from 1996 onwards. No discards in the future.
4	"B3a – disc1"	Future discarding is assumed as in the past in "A1a - disc1".
5	"B3b – disc2"	Future discarding is assumed as in the past in "A1b - with discards".
6	"B3c – disc3"	Future discarding is assumed as in the past in "A1c - disc3".
7	"B3d – disc3"	As "B3c -disc3" but discarding of 3-yr old (only) is reduced by 50% in the future.
8	"A2 – SC unrep catches"	Include small unreported offshore trawl catch on the south coast pre-1967.
9	"A11 – line catches"	Modified longline and handline catch series for 2003 and 2004.
ii. Different assumptions about recruitment and carrying capacity		
10	"SR1"	No dampening of stock recruitment fluctuations in recent years
11	"A7 – Ricker-like"	Ricker-like stock-recruitment curve.
12	"A7b –Ricker forced"	Ricker stock-recruitment curve constrained so max recruitment occurs at 45% of *K* for each species.
13	"A3 – σ_R=0.4"	Increased variability in recruitment in the past only.
14	"B7 – σ_R=0.4"	Increased variability in recruitment in the past and in the projections.
15	"Decr in past *capensis K*"	Carrying capacity for *M. capensis* reduced by 20% from 1992 onwards.
16	"A4 – decr *K* in past"	Carrying capacity for both species decreased linearly by 30% over 1980-2000 period.
⑰	"B8 – decr future K"	Carrying capacity for both species decrease by 30% in the projections.
iii. Different assumptions about biological information		
18	"A5a – M2"	Upper bounds of 1.0 and 0.3 for ages 2 and 5+ for natural mortality.
19	"A5b – M3"	Upper bounds of 0.5 for both ages 2 and 5+ for natural mortality.
20	"A9a – dens dep mat"	Density dependent maturity-at-age (age 3 varies from 0% to 100% mature).
21	"A9b – mat=3"	Age-at-maturity taken to be 3+ throughout.
22	"A10a – size-dep spawning"	Size dependent spawning by using egg production rather than spawning biomass as input to SR relationship.
23	"A10b – size-dep spawning"	As "A10a - size-dep spawning" but take account that bigger fish make bigger eggs with better survival rate.
24	"A10c – size-dep spawning"	As "A10a - size-dep spawning" but take account that bigger fish make bigger eggs with better survival rate.
25	"A10d – mat age = 7"	Age-at-maturity taken to be 7+ throughout.
iv. Different assumptions about current resource status		
26	"A8 - force depletion"	Recent spawning biomass forced to 40% and 30% of pre-exploitation level for *M. paradoxus* and *M. capensis* respectively.
27	"A8b – force para depl 0.3 "	Recent *M. paradoxus* spawning biomass forced to 30% of pre-exploitation level.
28	"A8c – force cap depl 0.3 "	Recent *M. capensis* spawning biomass forced to 30% of pre-exploitation level.
29	"A8d – force cap depl 0.2 "	Recent *M. capensis* spawning biomass forced to 20% of pre-exploitation level.
30	"A8e – force depl 0.3 "	Recent *M. capensis* and *M. paradoxus* spawning biomasses forced to 30% of pre-exploitation level.
31	"A8f – cap depl 0.2, h=0.7 "	As "A8c - force cap depl 0.2" with steepness fixed at 0.7 for *M. capensis* .
v. Others		
32	"A12 – diff off sel"	Shift in offshore trawl fishing selectivity from 1975 to 1978.
33	"B4a – cal factor=0.6"	Calibration factor for *M. capensis* between the old and new gear of the *Africana* decreased from 0.8 to 0.6.
34	"B4b – cal factor=0.9"	Calibration factor for *M. capensis* between the old and new gear of the *Africana* increased to 0.9.
vi. Changes in the future		
㉟	"B1 – no fut surv"	Research surveys are assumed not to become available in the future.
㊱	"B2 – CPUE trend"	Future changes in fishing efficiency (upward trend of 2% per annum) are not detected.
㊲	"B5a – Fratio decr"	30% increase in *M. capensis* catches in the projections.
㊳	"B5b – Fratio incr"	30% decrease in *M. capensis* catches in the projections.
㊴	"B6 – ll sel"	Future longline selectivity assumed to increase on ages 4 and 5 in the projections.

Table 2: List of issues and associated risk as identified by the initial EAF meeting (Nel *et al*., 2007, pg. 32), linked to the robustness tests that addressed these and the impact (H/M/L) on OMP performance statistics relative to the Reference Set (RS).

ID		Risk	Adressed by robustness test	Impact
12	*M. capensis* : Size structure may have been affected by fishing - the additional effect of removing more large hake	24	"A9a – dens dep mat"	
			"A9b – mat=3"	
			"A10a – size-dep spawning"	
			"A10b – size-dep spawning"	
			"A10c – size-dep spawning"	
			"A10d – mat age = 7"	L
			"B6 – ll sel"	L
2	Both hake sp: Fishing mortality is underestimated due to discarding and survival after escapement	18	"A1a – disc1"	
			"A1b – with discards"	M
			"A1c – disc3"	
			"B3a – disc1"	
			"B3b – disc2"	
			"B3c – disc3"	M
			"B3d – disc3"	M
3	Both hake sp: Uncertainty about the estimation of natural mortality (predation & cannibalism)	18	RS (M1 vs M4)	M
			"A5a – M2"	
			"A5b – M3"	
5	Both hake sp: Uncertainty about variability in recruitment	18	"SR1"	M
			"A3 – σ_R=0.4"	
			"B7 – σ_R=0.4"	H
			"A7b - Ricker forced"	M
			"Decr in past capensis K"	M
			"B8 – decr future K"	M
			RS (H1 vs H2 vs H3 vs H4)	N/A
7	Both hake sp: Uncertainty about the proportion of each hake species in total catch	18	RS (C1 vs C2 vs C3)	H
			C4	H
			"B5a – Fratio decr"	
			"B5b – Fratio incr"	
8	*M. paradoxus* : Stocks are shared between Namibia and South Africa	18		
9	*M. paradoxus* : Stock status is below BMSY	18		
13	*M. capensis* : Size structure may have been affected by fishing - Continued impact of fishing on small hake	18		
6	Both hake sp: Basic knowledge of the life-history strategy is not well understood	15		
11	*M. capensis* : Uncertainty & disagreement as to the status of the stock - model projections do not match commercial and research survey findings *	12	"A8 - force depletion"	
			"A8b – force para depl 0.3 "	
			"A8c – force cap depl 0.3 "	
			"A8d – force cap depl 0.2 "	
			"A8e – force depl 0.3 "	
			"A8f – cap depl 0.2, h=0.7 "	
10	*M. capensis* : Stocks are shared with Namibia	9		
1	Both hake sp: changes in distribution	8		
4	Both hake sp: Uncertainty about longshore, offshore and vertical migration in the water column	8		
14	*M. capensis* : Increase in parasites which could affect fecundity & marketing	6		
-	Issues unlisted in Nel *et al* . (2007) Errors in past or future data/related assumptions	-	"A2 – SC unrep catches"	
			"A11 – line catches"	
			"B4a – cal factor=0.6"	
			"B4b – cal factor=0.9"	
			"A12 – diff off sel"	
			"B1 – no fut surv"	
			"B2 – CPUE trend"	

* This commentary may reflect a misunderstanding; the parameter values for the model are estimated by seeking the best match between such findings and model predictions for the past (and not for "projections").

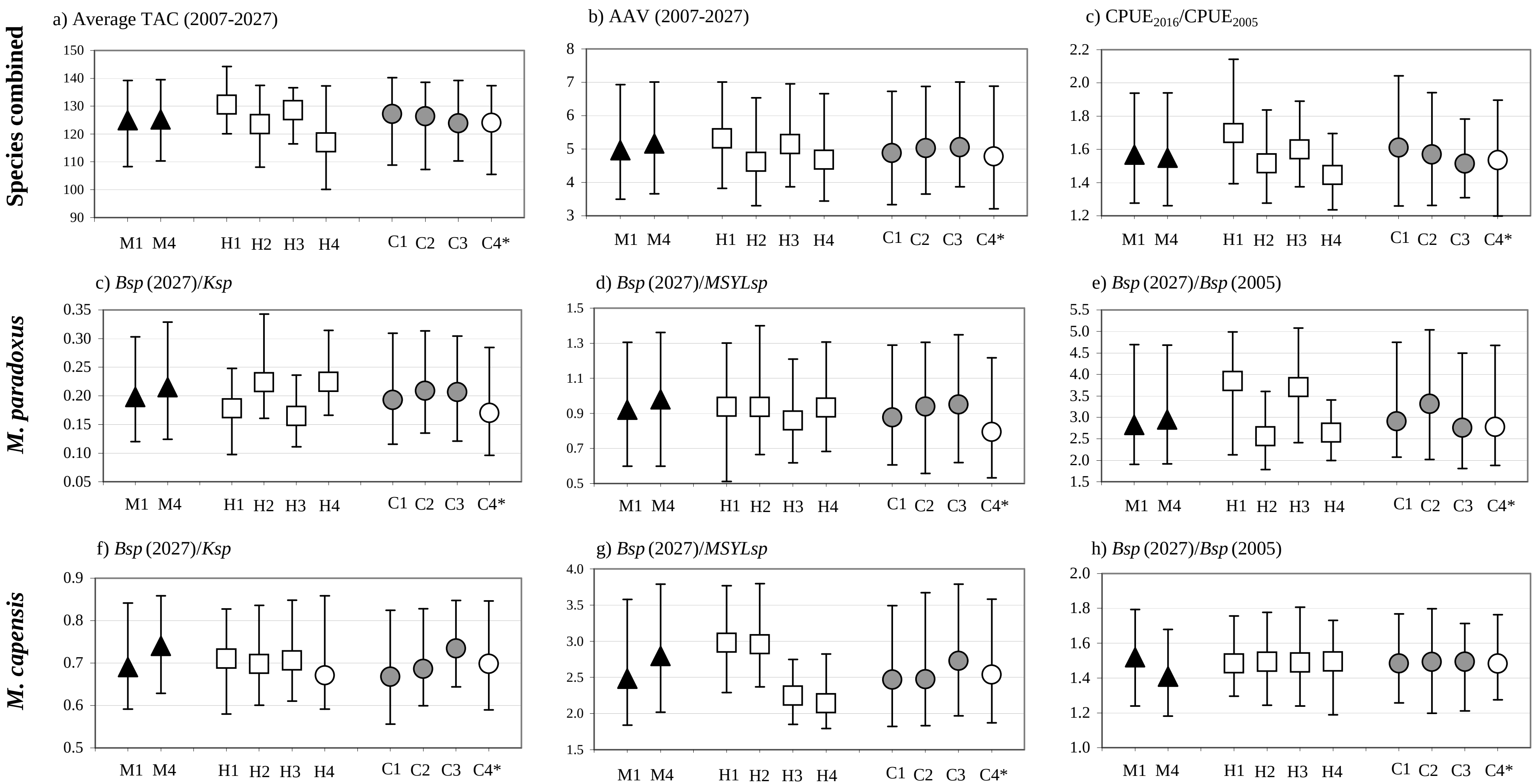


Fig. 1: Graphical summary of performance statistics for the OMP for the different factors (M- natural mortality, H -steepness of the stock recruitment curve and C – species split of the catches) of the RS, where results for each have been integrated over the other factors. Each panel shows medians together with 90% PIs. Note: C4* was not included in the RS but is shown here for comparison purposes (see text for detail).

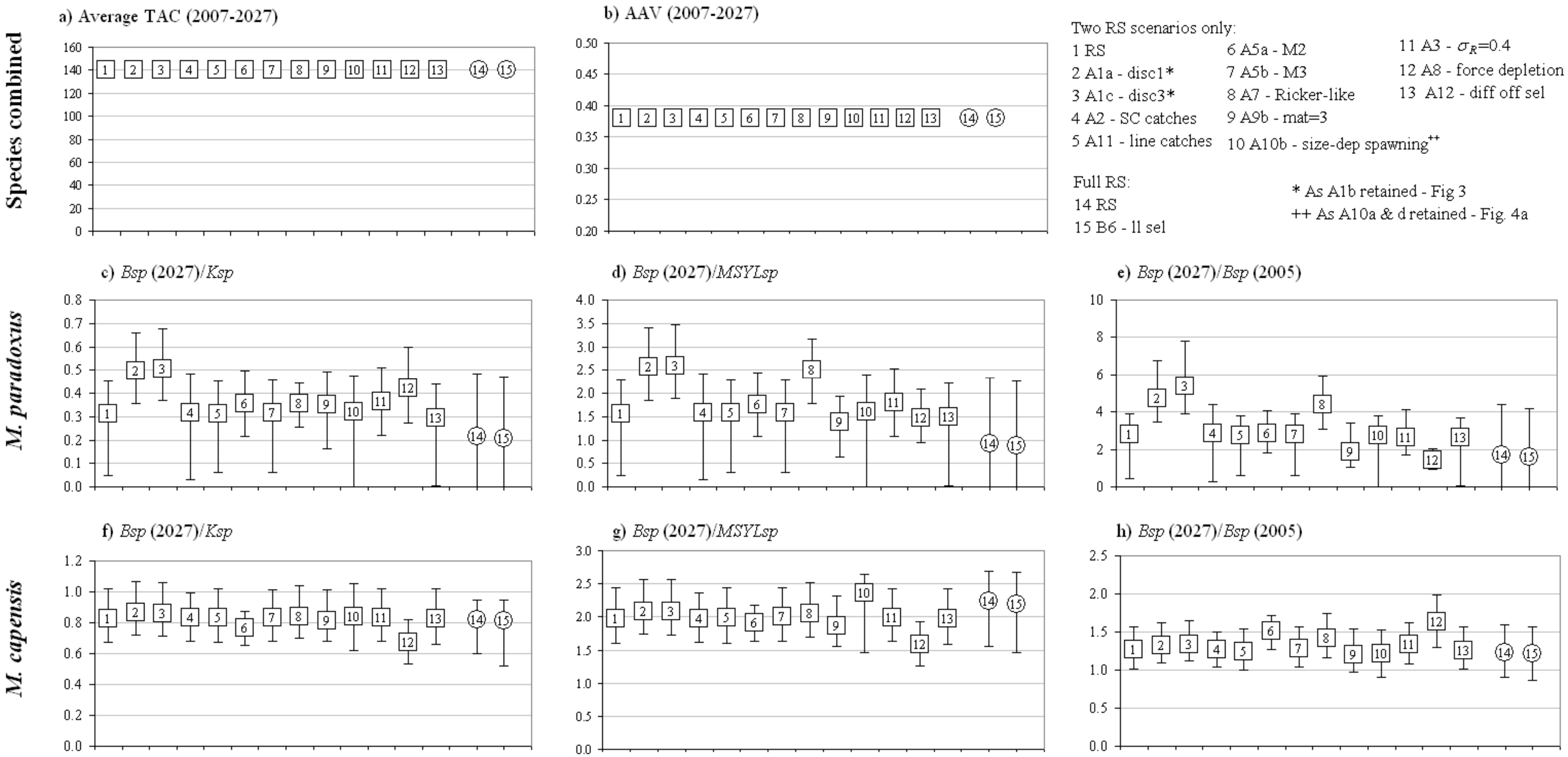


Fig. 2: Graphical summary of performance statistics for a constant catch of 140 000t for an earlier version of the RS and a series of robustness tests. Each panel shows medians together with 90% PIs.

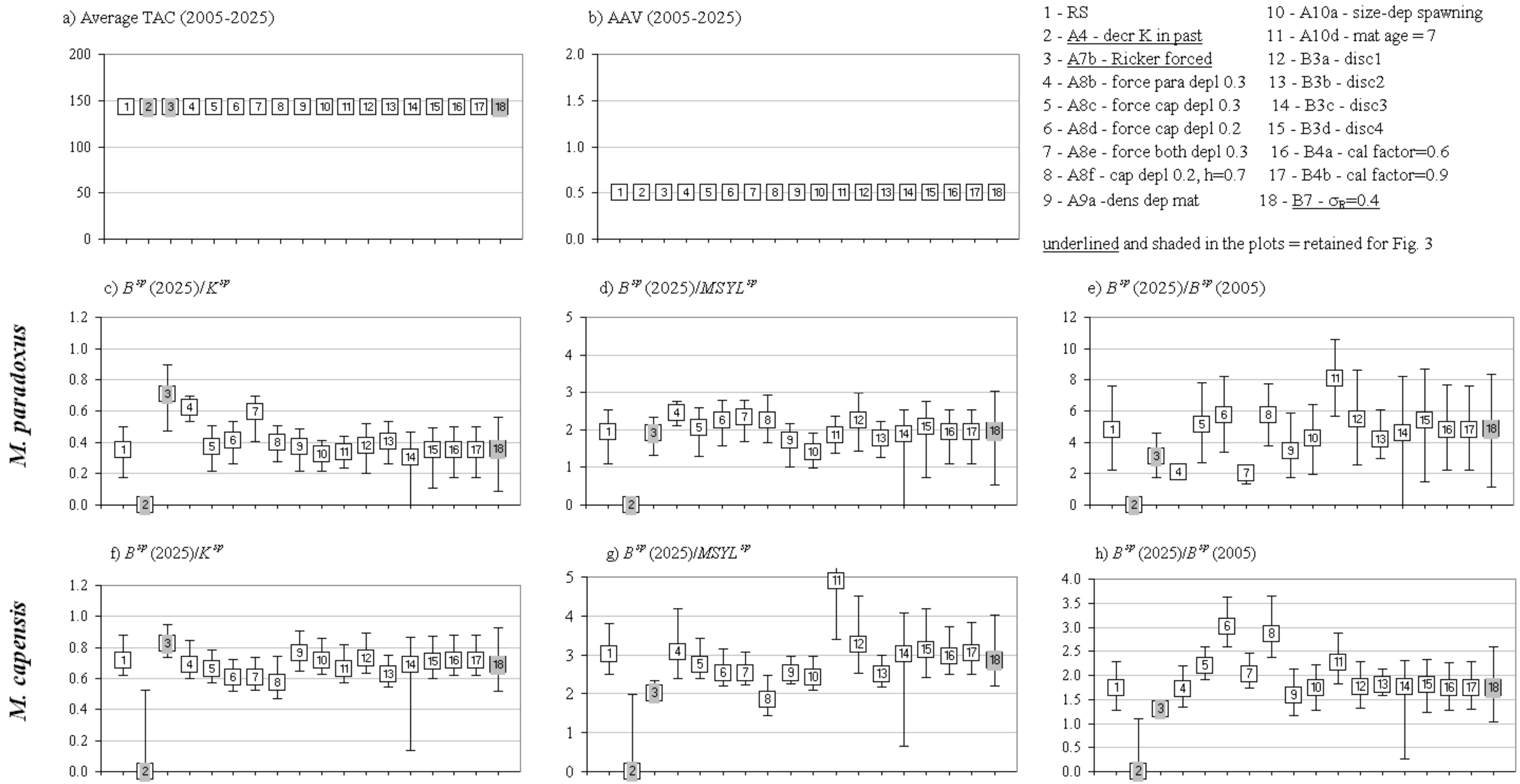


Fig. 3a: Graphical summary of catch performance statistics (median and 95% CI) under a future constant catch of 142 000 t, for a series of robustness tests, averaged over two scenarios (M1/M4-C1-H1-SR2) within the RS (which at the stage these tests were run included both SR1 and SR2). Note: AAV is not zero because of the change in TAC from 2006 to 2007.

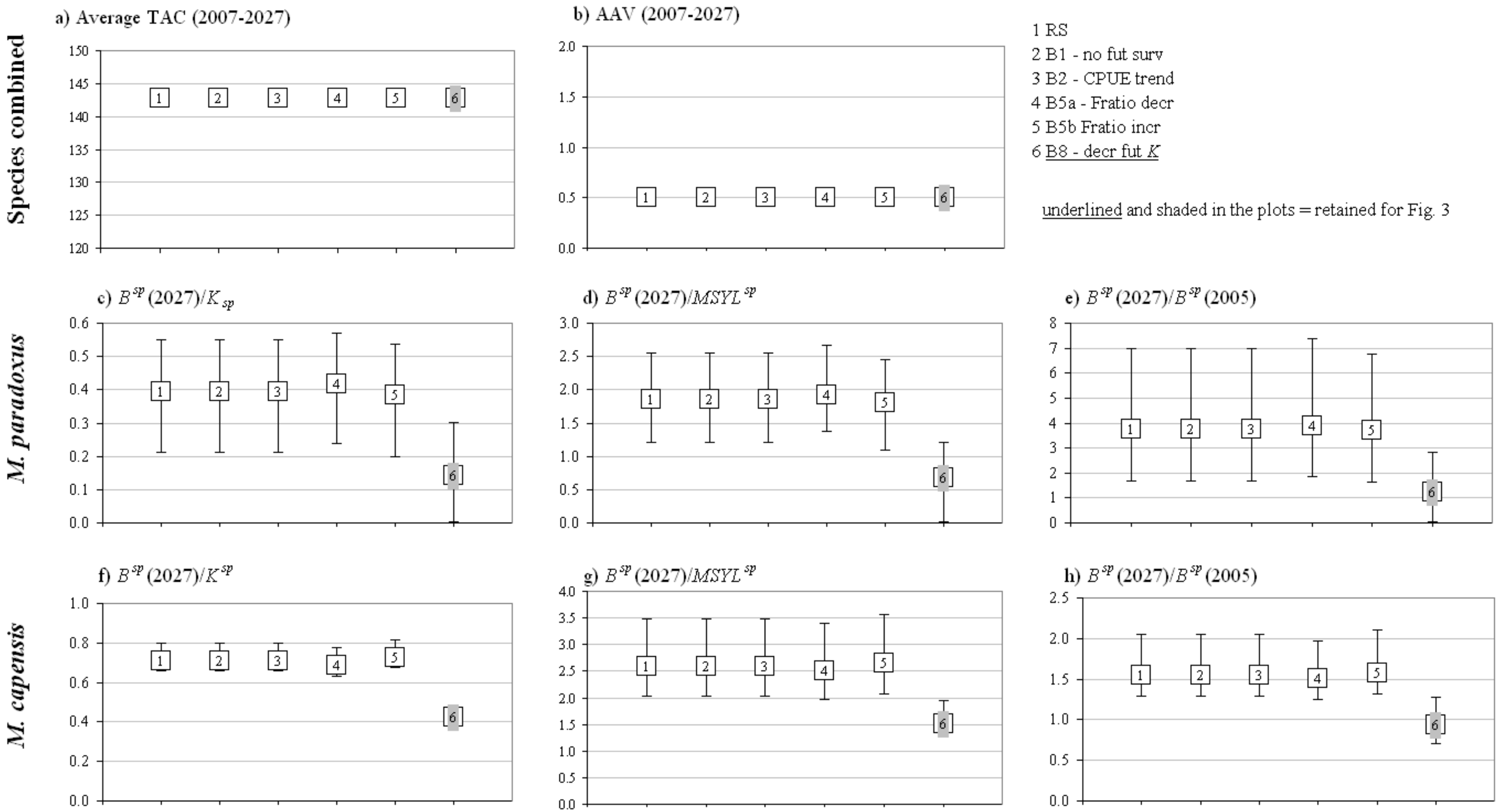
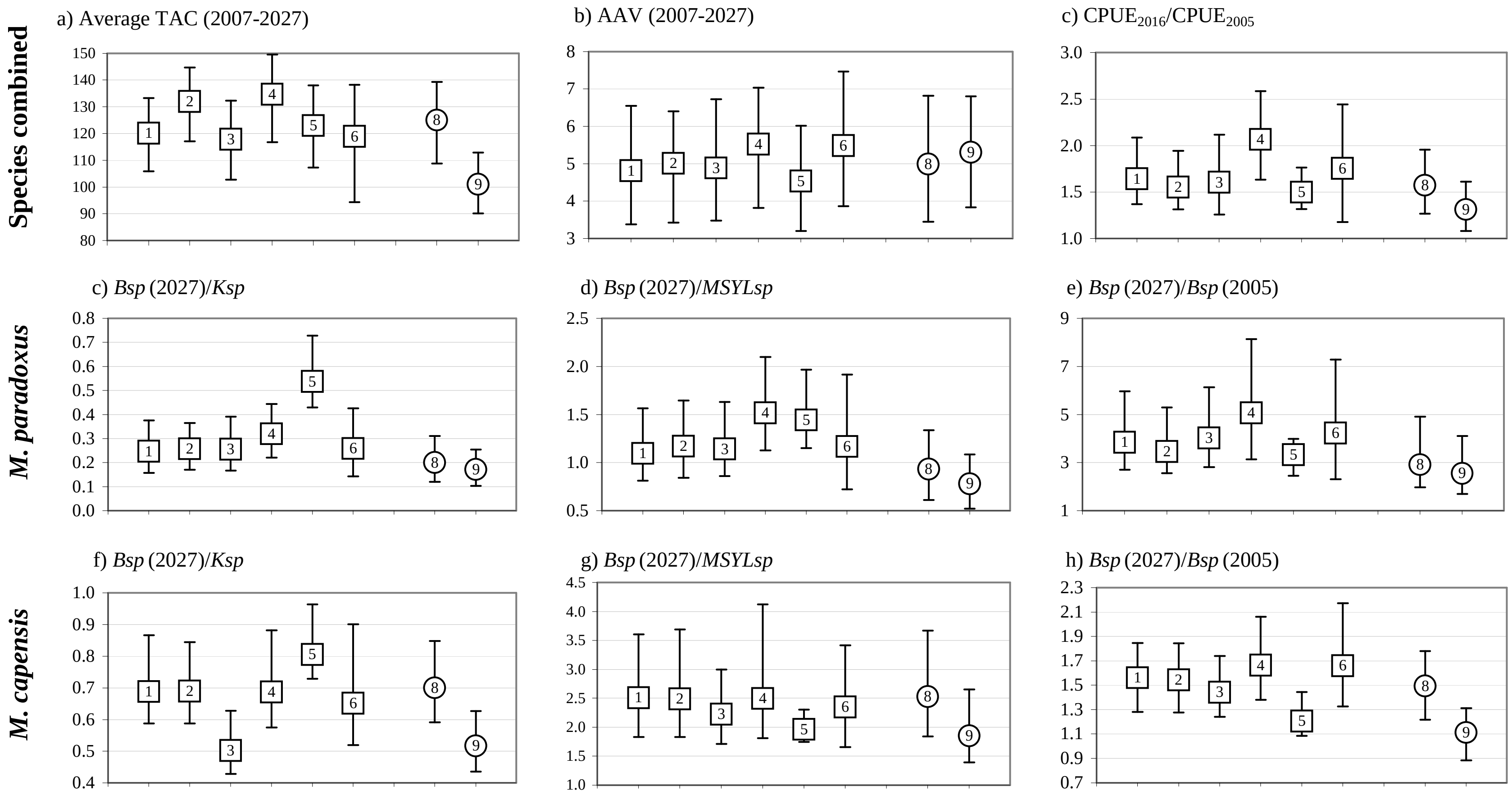


Fig. 3b: Graphical summary of catch performance statistics (median and 95% CI) under a future constant catch of 142 000 t, for a series of robustness tests, averaged over all of the RS scenarios (which at the stage these tests were run included both SR1 and SR2). Note: AAV is not zero because of the change in TAC from 2004 to 2006.



Four scenarios only (open squares):
1 – Reference Set 4 – A1b – with discards
2 – SR1 5 – A7b – Ricker forced
3 – Decr in past *capensis K* 6 – B7 – σ_R=0.4

All 24 scenarios (open circles):
8 – Reference Set
9 – B8 – decr in future *K*

Fig. 4: Graphical summary of performance statistics for the OMP adopted, tuned to one recovery level for *M. paradoxus* for the RS and a series of robustness tests. Each panel shows medians together with 90% PIs. The ratios associated with the estimates of K^{sp} are for the present K^{sp}, i.e. in the case of the “Decr in past *capensis K*” test including the 20% decrease, and in the case of test B8 before the future decrease in carrying capacity.

Appendix A – Detailed List of Reference Set Factors and Robustness Tests

1. Reference Set factors

M. Natural mortality:

M1: upper bounds of 0.5 and 0.3 on ages 2 and 5/5+ respectively are implemented;
M4: upper bounds of 1.0 and 0.5 on ages 2 and 5/5+ respectively are implemented.

H. Steepness parameter:

H1: the steepness parameters (*h*) for both *M. capensis* and *M. paradoxus* are estimated in the minimisation process;
H2: for *M. paradoxus*, *h* is fixed at 0.8 (lower than the 0.95 typically estimated), while this parameter is estimated for *M. capensis*;
H3: for *M. capensis*, *h* is fixed at 0.7 (lower than the 0.8-0.9 typically estimated), while this parameter is estimated for *M. paradoxus*;
H4: for *M. paradoxus*, *h* is fixed at 0.8, and for *M. capensis*, *h* is fixed at 0.7.

C. Species split of the catch:

C1: the logistic function used to split the pre-1978 offshore commercial catches by species has the parameters P_1=1950 and P_2=1.5;
C2: the logistic function used to split the pre-1978 offshore commercial catches by species has the parameters P_1=1940 and P_2=1.5;
C3: the logistic function used to split the pre-1978 offshore commercial catches by species has the parameters P_1=1957 and P_2=1.5.
C4*: as C1 but the post-1977 offshore trawl catches of *M. capensis* in the offshore commercial catches have been decreased by approximately 20% on the west coast and 10% on the south coast by introducing an upward bias in the *M. capensis* proportion by depth.

Note: C4* is not included in the final RS but is shown here to assist comparison.

2. Full set of robustness tests

Note: The six robustness tests that have been used in the final OMP testing are underlined here.

2.i. Different assumptions about discards and catch series

1) "**A1a – disc1**"
Discarding is considered to occur for the offshore and inshore trawlers only. Discarding for both fleets is modelled as an increase in commercial selectivity of 0.2 for ages 1 and 2 for catches of both *M. capensis* and *M. paradoxus*. Thus the amount of catch discarded is not an input, but computed within the assessment from the fishing mortality estimated for the offshore and inshore trawlers to take their recorded landings. This discarding is assumed to occur from the beginning of the fishery to the present. This discarding is assumed to occur from the beginning of the fishery to the present but is **not** carried through to the projections.

2) "**<u>A1b – with discards</u>**"
Discarding is considered to occur for the offshore and inshore trawlers as in "A1a – disc1". The loss of fish from longlines is also included by doubling the fishing mortality from this fleet.

3) "**A1c – disc3**"
As A1a above, but from 1996 onwards, the offshore and inshore trawl fleets are assumed to discard age 3 as well. As in A1a above, this is modelled by increasing the commercial selectivity by 0.2 for age 3 for catches of both *M. capensis* and *M. paradoxus*.

4) "**B3a – disc1**"
Future discarding is assumed to occur in the offshore and inshore fleets only, as in A1a.

5) “**B3b – disc2**”
Future discarding is assumed to occur in the offshore and inshore fleets, as well as the longline fleet, as in A1b.

6) “**B3c – disc3**”
Discarding is assumed to occur in the offshore and inshore fleets as in A1c.

7) “**B3d – disc3**”
As B3c above, but the discarding of 3-yr-olds (only) is reduced by 50% in the future.

8) “**A2 – SC unrep catches**”
This robustness test includes unreported catches from the south coast offshore fleet; indeed, in the RS, offshore catches on the south coast are assumed to have started in 1967 only, but it is known that some vessels operated in the region right from the beginning of the 20th century; these unreported catches are included here and are assumed to have increased linearly from 100t in 1917 to 5000t in 1967 (with the species-split based on the appropriate logistic equation).

9) **“A11 – line catches**”
The catch series for the longline and handline fisheries are modified for recent years. Estimates of handline catches are brought down from 5941t to 2500t in 2003 and from 6888t to 1600t in 2004.

2.ii. Different assumptions about recruitment and carrying capacity

10) “**<u>SR1</u>”**
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) in the assessment scenarios considered for the Reference Set.

11) “**A7 – Ricker-like**”
The stock-recruit relationship for the RS has the form $R = \frac{\alpha B_{sp}}{\beta + (B_{sp})^{\gamma}}$, with γ fixed to 1.0 (Beverton-Holt) for both species. Here instead, γ is fixed to 1.5 for *M. paradoxus*, $\gamma = 1.0$ for *M. capensis*.

12) “**<u>A7b –Ricker forced</u>**”
Instead of the Beverton-Holt stock-recruit relationship used in the RS, the stock-recruit relationship in this robustness test is of the Ricker form: $R = \alpha B_{sp} e^{-\beta B_{sp}}$. Furthermore, the stock-recruit curve for each species is constrained so that maximum recruitment occurs when the spawning biomass is at 45% of pristine level.

13) “**A3 – σ_R=0.4**”
The variability for stock-recruitment fluctuations in the past is increased from σ_R =0.25 in the RS to σ_R=0.4. For the projections, σ_R is kept at 0.25.

14) “**<u>B7 – σ_R=0.4</u>**“
In conjunction with increased variability for the stock-recruitment fluctuations in the past, future variability is also increased (to σ_R=0.4, compared to 0.25 for the Reference Set).

15) “**<u>Decr in past *capensis K*</u>**”
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.

16) “**A4 – decr K in past**”
The carrying capacity of both species is assumed to have decreased linearly by 30% over the 1980 to 2000 period.

17) “**<u>B8 – decr future *K*</u>**”
The carrying capacity *K* for both species is assumed to decrease linearly by 30%, starting in 2007, to reach the reduced level in 2011.

2.iii. Different assumptions about biological information

18) "**A5a – M2**"
The RS incorporates some uncertainty in the natural mortality estimates. In cases "M1", upper bounds on the natural mortality of 0.5 and 0.3 on ages 2 and 5/5+ respectively are implemented, while in cases "M4", upper bounds of 1.0 and 0.5 on ages 2 and 5/5+ respectively are implemented. In this robustness test, the following bounds are implemented: 1.0 and 0.3 for ages 2 and 5/5+ respectively.

19) "**A5b – M3**"

In this robustness test, the following bounds on the natural mortality estimates are implemented: 0.5 for both ages 2 and 5/5+.

20) "**A9a – dens dep mat**"
In the RS, the maturity-at-age is assumed to be independent of stock density for all ages. In this robustness test, the assumption is made that 0% of fish of age 3 are mature at B^{4+} = pristine, and 100% are mature at $B^{4+}=0$, with a linear relationship in between these two extremes.

21) "**A9b – mat=3**"
The age-at-maturity is taken to be 3+ throughout, instead of 4+ in the RS.

22) "**A10a – size-dep spawning**"
An egg production index is used for input to the stock-recruitment relationship instead of spawning biomass; this is obtained by multiplying numbers-at-age by an age-dependent fecundity index obtained from Osborne (2004):

M. paradoxus : $Y_a = 8.02L_a^{2.67}$ *M. capensis* : $Y_a = 0.15L_a^{3.49}$

23) "**A10b – size-dep spawning**"
As A10a, but to take into account that bigger fish make bigger eggs with a better survival rate, the fecundity index Y_a has been arbitrarily halved for fish of age 4 for *M. paradoxus* and for fish of age 4 and 5 for *M. capensis*.

24) "**A10c – size-dep spawning**"
As A10a, but Y_a is set to zero for age 4 for *M. paradoxus* and for ages 4 and 5 for *M. capensis*.

25) "**A10d – mat age = 7**"
The age-at-maturity is taken to be 7+ throughout, instead of 4+ in the RS.

2.iv. Different assumptions about current resource status

26) "**A8 – force depletion**"
The spawning biomass of M. paradoxus in 2004 is forced upwards to 40% of its pre-exploitation level, while the spawning biomass for M. capensis is forced downwards to 30% of its pre-exploitation level, both through the use of penalty functions.

27) "**A8b – force para depl 0.3** "
The spawning biomass of *M. paradoxus* in 2004 is forced to 30% of its pre-exploitation level through the use of penalty functions.

28) "**A8c – force cap depl 0.3** "
The spawning biomass of *M. capensis* in 2004 is forced to 30% of its pre-exploitation level through the use of penalty functions.

29) "**A8d – force cap depl 0.2** "
The spawning biomass of *M. capensis* in 2004 is forced to 20% of its pre-exploitation level through the use of penalty functions.

30) "**A8e – force depl 0.3** "
The spawning biomasses of *M. paradoxus* and *M. capensis* in 2004 are forced to 30% of their pre-exploitation level (i.e. for both species) through the use of penalty functions.

31) "**A8f – cap depl 0.2, h=0.7** "
The spawning biomass of *M. capensis* in 2004 is forced to 20% of its pre-exploitation level through the use of penalty functions and the steepness parameter for this species is fixed at 0.7.

2.v. Others

32) "**A12 – diff off sel**"
The offshore trawlers selectivity for *M. paradoxus* is modified by estimating a third set of logistic selectivity parameters and applying the resulting curve from 1917 to 1975. The selectivity curve estimated for 1984 is assumed to apply from 1978 to 1984, with a linear interpolation from 1975 to 1978. This 1975 to 1978 shift affects mainly 1 and 2 year old fish and selectivity for *M. capensis* at these ages is very low so that no adjustments are made for this species.

33) "**B4a – cal factor=0.6**"
The calibration factor between the *Africana* with the old gear and the *Africana* with the new gear for *M. capensis* is decreased from 0.8 to 0.6.

34) "**B4b – cal factor=0.9**"
The calibration factor between the *Africana* with the old gear and the *Africana* with the new gear for *M. capensis* is increased from 0.8 to 0.9.

2.vi. Changes in the future

35) "**B1 – no fut surv**"
Biomass and catch-at-age information from research surveys are assumed not to become available in the future.

36) "**B2 – CPUE trend**"
Future changes in fishing efficiency are not detected. This is modelled by assuming an undetected upward trend in catching efficiency of 2% per year, so that for future data generated:

$$CPUE(y) \rightarrow CPUE(y)\exp[0.02(y-2004)]$$

37) "**B5a – Fratio decr**"
In the RS, future catches are disaggregated by species using a constant F_{ratio} ($F_{ratio} = F_{para} / F_{cap}$), which has been calculated as the average of the 2002-2004 estimates. In this robustness test, the F_{ratio} for the offshore fleet is decreased by 30% to model an increase in *M. capensis* catches.

38) "**B5b – Fratio incr**"
Here the F_{ratio} for the offshore fleet is increased by 30% to model a decrease in *M. capensis* catches.

39) "**B6 – ll sel**"
The selectivity for the longline fleet on ages 4 and 5 is assumed to increase linearly over a five year period commencing in 2005, to reach that on age 6+.

Appendix B – Basic explanation of the plots

In the development of an Operational Management Procedure (OMP) the consequences (for both the resource and the associated fishery) of a proposed formula for setting TACs based on resource monitoring data available at the time in question is assessed by simulation. For a particular model or sets of model (Reference Set, robustness tests), each simulation involves projecting the biomass trajectory forward for a fixed period with the future catches determined by the OMP. The historic catch data used in the models remain unchanged from one simulation to the next (unless potential errors in such catches is under consideration); however, future catches can vary due to stochastic effects – both recruitment variability and noise in future CPUE and survey abundance indices, as well as imprecision associated with the estimates of parameters describing the stock's dynamics (this variation is on top of trends in such catches that result from the OMP aiming to achieve a certain target abundance over a specified time period). In the figures in the main paper, a set of performance statistics are plotted. Once the stochastic effects are taken into account, the result for each of these quantities is a distribution arising from alternative realisations of these stochastic effects. The results are reported in the form of medians and 90%-iles of these distributions.

Performance statistics fall under three headings, each pertaining to one of three mutually contradictory underlying objectives:

a) Catch related (objective: as high as possible)
Average annual TAC (2007-2027)

b) Interannual catch variability related (objective: as low as possible)
Average Annual Variation in TAC (AAV) expressed as a percentage of the average annual catch

c) Resource risk related (objective: risk as low as possible so resource abundance kept/aimed high, e.g. about MSYL – applies to both hake species)
Spawning biomass at the end of a 20-year projection period relative to K^{sp}, $MSYL^{sp}$ and $B^{sp}(2005)$ (i.e. change in abundance over projection period)

Plots for each of these performance statistics are shown for the application of the hake OMP adopted (or sometimes first a constant catch) to each of a series of alternative models for hake/fishery dynamics in what is know as robustness testing.

The main point of the exercise in the context of this paper is to check for which of these tests performance differs appreciably from that for the Reference Set (RS – "best assessment" of the resource).