Proposed Catch Control Rules for Horse Mackerel Bycatch in the Small Pelagics fishery and Directed Catch in the Midwater Trawl Fishery

L B Furman and D S Butterworth
Marine Resource Assessment and Management Group (MARAM)
Department of Mathematics and Applied Mathematics
University of Cape Town

This document summarises the results of recent work on the development of rules for setting limits on horse mackerel catches.

Section 1 describes the development of a revised Precautionary Upper Catch Level (PUCL) Rule for the horse mackerel bycatch in the small pelagics fishery. A specific proposal for implementation is put forward.

Section 2 considers the directed catch allocation in the midwater trawl fishery, and investigates a number of simple experimental Management Procedure (MP) control rules , based on future CPUE and survey results, that would allow cautious increase of the current constant TAC for this sector of the fishery, with the aim of benefitting from the current likely underutilization of the resource. Results are provided for a number of candidates MPs amongst which a choice needs to be made.

Appendix A provides results from an updated assessment and projection model, while Appendix B sets out the mathematical details of these models.

Section 1 - PUCL rule

1.1 Introduction

Since 2000, the annual juvenile horse mackerel bycatch in the small pelagics fishery has been limited by a Precautionary Upper Catch Limit (PUCL) of 5000 tonnes. However, this is problematic as occasionally juvenile horse mackerel are highly catchable and, as a result, the anchovy fishery is disrupted through having to avoid areas with high horse mackerel bycatch. This can lead to a substantial loss of anchovy catch. Therefore, the goal is to develop a dynamic PUCL rule that is able to take advantage of years with increased juvenile horse mackerel abundance, without unduly decreasing the directed midwater horse mackerel catch or increasing the risk of depletion of the resource.

PUCL rules based on horse mackerel recruit abundance estimates calculated from hydroacoustic surveys of pelagic fish on the West Coast (west of Cape Agulhas) were tested using the Management Procedure (MP) approach; however, they offered little benefit. These results are not unexpected, as earlier work suggests that these hydroacoustic surveys may be poor predictors of horse mackerel recruit abundance.

Therefore the material below describes and test the efficacy of a PUCL approach that does not rely on indices of horse mackerel recruit abundance, which is hereafter referred to as the PUCL_3 rule.

1.2 PUCL_3 Rule

The PUCL_3 rule limits the bycatch over a three year period to a fixed amount, in other words:

$$\mathrm{allocation}_y = \mathrm{PUCL}_3 - \mathrm{bycatch}_{y-1} - \mathrm{bycatch}_{y-2}\ ,$$

where PUCL_3 is the fixed, total amount that may be caught over a three year period; $\mathrm{allocation}_y$ refers to the pelagic bycatch allocation in year *y*; and $\mathrm{bycatch}_y$ refers to the actual bycatch that was taken in year *y*. This PUCL rule should allow for flexibility in years of high recruit abundance.

However, there is a potential, although unlikely, drawback. If an unusually high bycatch follows two years of low bycatch, then the bycatch allocation for the subsequent two years would also be low. In order to resolve this, the allocation in any single year can additionally be limited to a fixed amount. For the purposes of this work, the effect of additionally limiting the allocation to one half of PUCL_3 is also tested.

In this paper, the PUCL_3 rule with the additional limit is referred to as *$PUCL_3$ – reserve*, while rule without is called *$PUCL_3$ – no reserve*.

1.3 Distribution Scaling Factor *k*

In previous work, it has been shown that while it is important to model the extent of the PUCL annual undercatch for simulations, pelagic horse mackerel bycatch shows effectively no correlation with either the assessed horse mackerel recruitment or the biomass available to the pelagic fishery. Therefore, undercatch is modelled by assuming that in the absence of a PUCL, future bycatches would follow the same distribution as bycatches in the 1968-2000 period.

It was also shown that if this assumption is accurate, then there is no need for a PUCL, as future bycatches would, on average, be sufficiently small that they pose little risk to the resource. However, it is difficult to determine how confident one can be that this assumption will continue to hold into the future.

Therefore, for simulation purposes, all future pelagic bycatches drawn from this distribution are multiplied by a distribution scaling factor *k*:

$$\mathrm{bycatch}_y = k\ \mathrm{bycatch}_y^*$$

where $\mathrm{bycatch}_y^*$ is the bycatch drawn from the past distribution, and $\mathrm{bycatch}_y$ is the bycatch for year y that is actually used in the simulation. *k* provides a means of specifying the extent to which the future bycatches might have a larger average than the past bycatches.

1.4 Method

In order to determine an appropriate value for PUCL_3, candidate PUCL rules are tested by simulating the dynamics of the resource into the future. The general details of the assessment and projections are described in Appendix A. For these projections specifically, it is additionally assumed that demersal bycatch and directed midwater catch are 6750 tonnes (the average over the last 5 years) and 31500 tonnes, respectively.

PUCL_3 is tuned to give the same risk level that was deemed acceptable when setting the current fixed PUCL of 5000 tonnes in the 2007 assessment. Here, risk is defined as the lowest value over the projection period of the lower 5%-ile of spawning biomass relative to pristine level for the most pessimistic assessment model (no bias in swept area abundance estimates and *h*=0.6), because the most pessimistic model suggests the greatest limitation on PUCL_3.

However, as it is unclear what value for *k* should be used, PUCL_3 is tuned for a variety of *k* values that are considered tocover the plausible range.

1.5 Results

Figure 1.1 shows how PUCL_3 must change with *k* in order to maintain acceptable risk to the horse mackerel resource. Table 1.1 summarises these results and compares various performance statistics for different valuesof *k*.

Figure 1.2 and Table 1.2 are in response to an enquiry from J. Coetzee regarding the sensitivity of the main results to basing future bycatches on the historic bycatches from 1980-1999, instead of 1968-1999.

1.6 Discussions

It is recommended that $PUCL_3$ should be set at 18000 tonnes, which corresponds to a *k* value between 2 and 2.5. For *k* values greater than this, $PUCL_3$ does not reduce appreciably, so if *k* has been underestimated it is unlikely that there will be a sudden negative response of the resource. The $PUCL_3$ rule should be implemented for the 2013 fishing season and, due to the unusually high bycatch in 2011, the allocated bycatch for 2013 should be calculated as

$$\text{allocation}_{2013} = 18000 - \text{bycatch}_{2012} - \overline{\text{bycatch}}_{2000-2010}$$

where $\overline{\text{bycatch}}_{2000-2010} = 3400$ t is the average bycatch over the period 2000-2010.

There is little appreciable difference between the recommended $PUCL_3$ for the *PUCL3 – reserve* and *PUCL3 – no reserve* rules. Therefore, deciding between them should primarily be an issue of industry preference.

The main results are sensitive to the assumption that future bycatches will instead be similar to those from the period 1980-1999. However, this is not a large effect and the recommended $PUCL_3$ would only differ by between 1000-2000 tonnes.

Table 1.1: Summary of results. Under the *PUCL rule* heading, *no reserve* refers to the PUCL rule with no limit on the allocation to any single year, other than the three year total, while *reserve* refers to the PUCL rule where the allocation to any single year is additionally limited to one half of $PUCL_3$. The headings *Lower 5%-ile* B/B_0 and *Median* B/B_0 refer to the lower 5%-ile and median of spawning biomass relative to prisitine level after 30 years. The heading *% time anchovy disrupted* represents the average probability that an anchovy fishing season will be disrupted by reaching the allocation under $PUCL_3$. This is determined by counting the number of times in the simulation when the bycatch would have been larger, were it not for the $PUCL_3$ rule. Note that *Lower 5%-ile* B/B_0 is the same for all cases except k=1, because $PUCL_3$ was tuned in all cases to give the same level of risk; however, for $k=1$, the lowest achievable value (with an infinite $PUCL_3$) was 34%. Also, with k=1 and an infinite $PUCL_3$ there is no distinction between *no reserve* and *reserve* PUCL rules as the reserve would be infinite.

Distribution scaling factor *k*	PUCL rule	$PUCL_3$ (tonnes)	Lower 5%-ile B/B_0	Median B/B_0	% time anchovy disrupted	Mean annual bycatch (tonnes)
1	**-**	∞	34%	58.7%	0%	3803
1.25	**no reserve**	35600	31%	56.3%	1%	4718
	reserve	36550	31%	56.4%	2%	4684
1.5	**no reserve**	22800	31%	55.6%	15%	4967
	reserve	23970	31%	55.4%	15%	4957
2	**no reserve**	18790	31%	55.1%	37%	5090
	reserve	19360	31%	54.9%	37%	5102
2.5	**no reserve**	17330	31%	54.8%	52%	5098
	reserve	17590	31%	55%	52%	5093
3	**no reserve**	16470	31%	54.8%	62%	5060
	reserve	16875	31%	55%	62%	5117
∞	**no reserve**	15695	31%	54.7%	100%	5231
	reserve	15610	31%	55%	100%	5203

Table 1.2: Summary or results for *no reserve* PUCL rule and with future bycatches drawn from historic distribution of bycatches from 1980-2000. This is to be compared with Table 1.1 which shows the same results, except with future bycatches drawn from historic distribution of bycatches from 1968-2000.

Distribution scaling factor *k*	$PUCL_3$ (tonnes)	Lower 5%-ile B/B_0	Median B/B_0	% time anchovy disrupted	Mean annual bycatch (tonnes)
1	∞	31	57	0	4451
1.25	24000	31	56	12	4980
1.5	20000	31	55	28	5021
2	17000	31	55	49	4922
2.5	16000	31	55	62	4892
3	15750	31	55	69	4950

∞	15000	31	55	100	5000

Figure 1.1: Shows how $PUCL_3$ must vary as k varies in order to maintain acceptable risk. Here, *no reserve* refers to the PUCL rule with no limit on the allocation to any single year, other than the three year total, while *reserve* refers to the PUCL rule where the allocation to any single year is additionally limited to one half of $PUCL_3$.

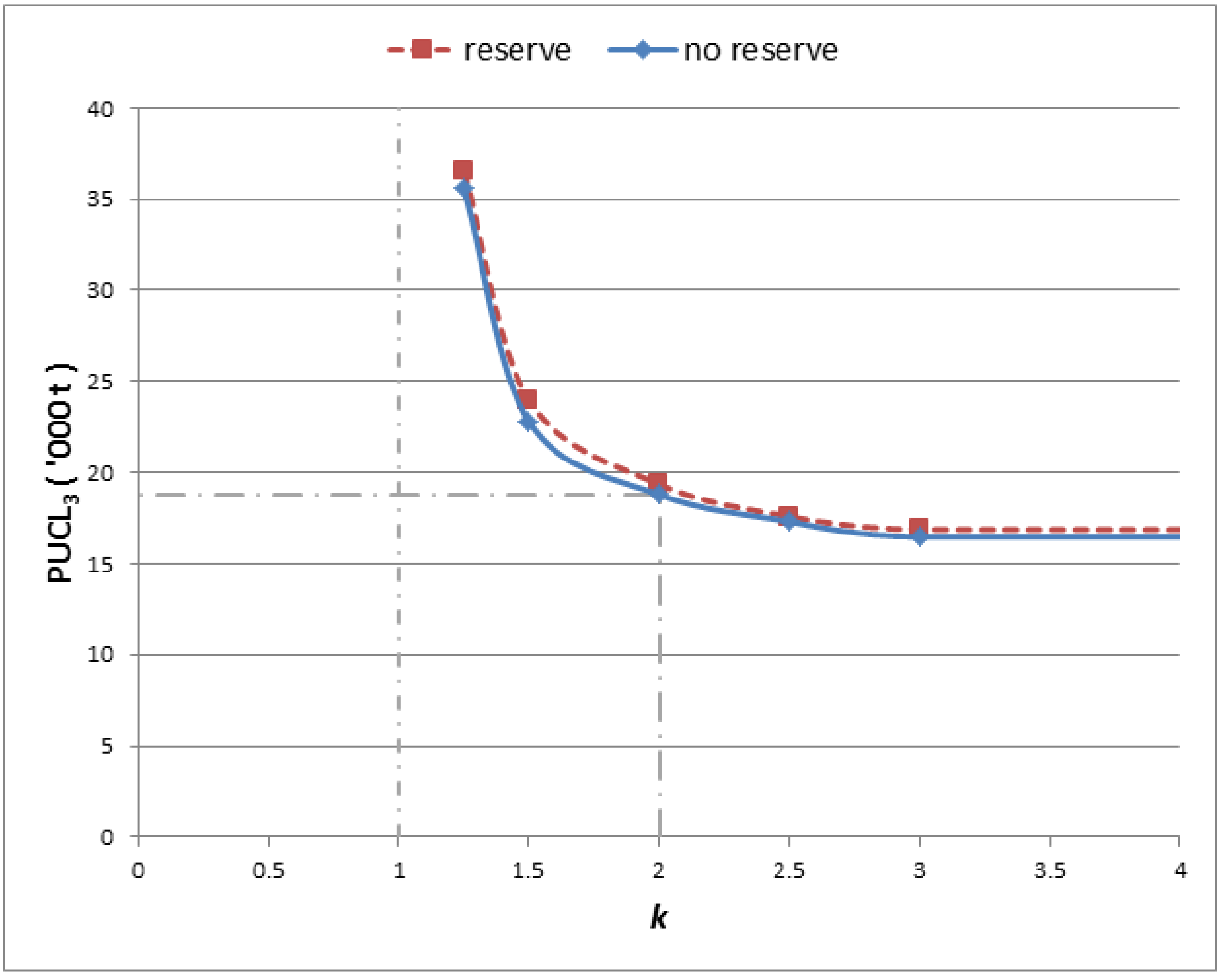
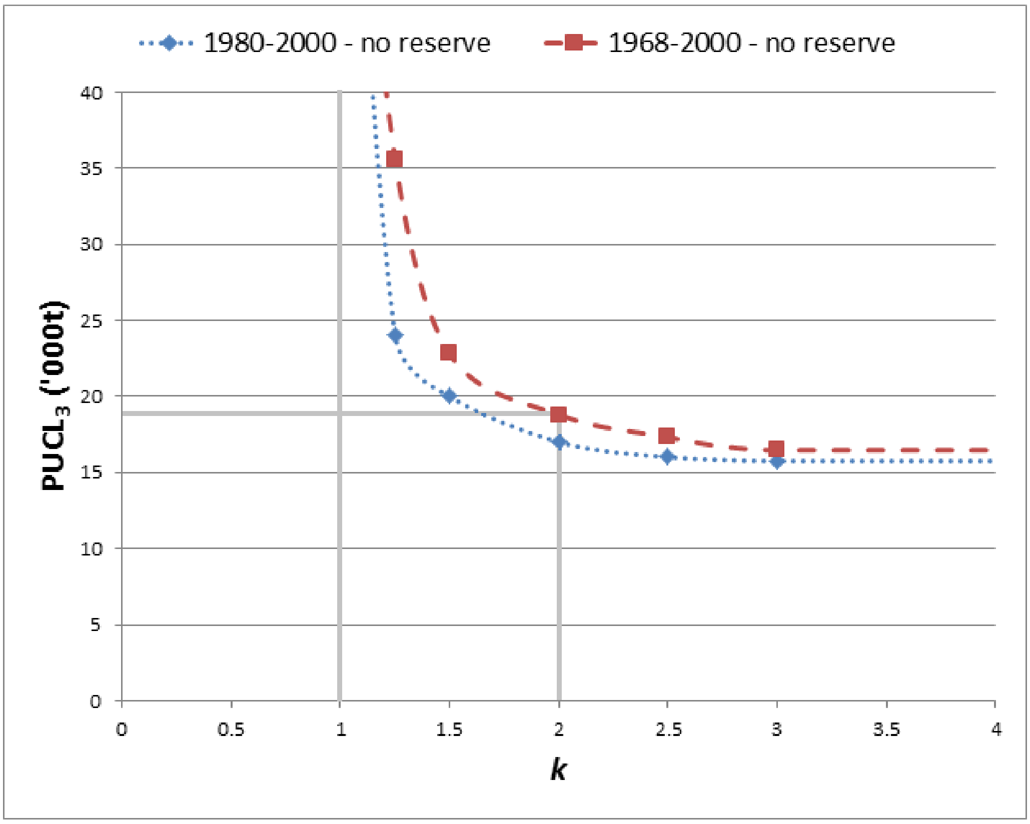


Figure 1.2: This figure shows how $PUCL_3$ must vary as k varies in order to maintain acceptable risk. Here, *1968-2000 - no reserve* refers to the PUCL rule with no limit on the allocation to any single year and with future bycatches drawn from the historic distribution of bycatches from 1968-2000, while *1980-2000 – no reserve* refers to the same PUCL rule, but with future catches drawn from historic distribution of bycatches from 1980-2000.



Section 2 - Directed TAC rule

2.1 Introduction

The directed midwater horse mackerel fishery is currently managed with a fixed TAC of 31500 tonnes. However, it is strongly suspected that absolute biomass estimates from demersal swept area surveys are negatively biased, and that therefore the resource is underutilized. This paper shows the results of a preliminary test of an adaptive rule to experimentally increase the midwater TAC, so as to secure improved utilization without undue increase in the risk of unintended reduction of resource abundance.

The tests are conducted on two Operating Models (OMs) for the horse mackerel resource:

a) Pessimistic model: Model 1: $q_{\text{aut}} = 0.5$; $h = 0.6$
b) Optimistic model: Model 4: $q_{\text{aut}} = 1.0$; $h = 0.9$

2.2 Adapative Midwater Rule

Figure 2.1 illustrates the form of the adaptive rule. Effectively, if recent abundance indices are high compared to averages over a fixed past period, the TAC is increased; conversely, if recent abundance indices are correspondingly low, the TAC is decreased. A single index of abundance is required; therefore, the directed midwater CPUE series and the Autumn demersal survey biomass estimates are combined to form a single index. Recent relative levels of the CPUE and demersal survey indices are given by:

$$CPUE_y^{rel} = \frac{\frac{1}{3}\sum_{y-3}^{y-1} CPUE_i}{\frac{1}{7}\sum_{2003}^{2009} CPUE_i} \quad \text{and} \quad Survey_y^{rel} = \frac{\frac{1}{3}\sum_{y-3}^{y-1} Survey_i}{\frac{1}{7}\sum_{2003}^{2009} Survey_i}$$

The combined index is a weighted average of the relative levels of the two indices:

$$I_y = w\ CPUE_y^{rel} + (1-w)Survey_y^{rel}.$$

This midwater TAC rule has four parameters (see Figure 2.1):

X_{incr} is the largest possible percentage *increase* in $TAC_{mw}$from one year to the next;

X_{decr} is the largest possible percentage *decrease* in TAC_{mw} from one year to the next;

I_{incr} is the of$I_y$above which there is a X_{incr} increase toTAC_{mw}; and

I_{decr} is the value of $I_y$below which there is a X_{decr} decrease to TAC_{mw}

where TAC_{mw} is the midwater component of the horse mackerel TAC, the other components being considered as fixed.

Each year, TAC_{mw} is determined according to the rule

$$TAC_{mw}(y+1) = \Delta(y) TAC_{mw}(y)$$

where

$$\Delta(y) = \begin{cases} 1 - X_{decr} & \text{for} \quad I(y) < I_{decr} \\ 1 - X_{decr} + \dfrac{X_{incr} + X_{decr}}{I_{incr} - I_{decr}}(I(y) - I_{decr}) & \text{for} \quad I_{decr} \le I(y) < I_{incr} \\ 1 + X_{incr} & \text{for} \quad I(y) \ge I_{incr} \end{cases}$$

Additionally, the directed midwater TAC is not allowed to drop below 25000 tonnes.

2.3 Method

Candidate midwater TAC rules are tested by simulating the dynamics of the resource into the future. The general details of the assessment and projections are described in Appendix A. The additional specific assumptions for these projections are that: future pelagic PUCLs are determined by the $PUCL_3$ rule, with $PUCL_3$ = 18000 tonnes(see Section 1); the bycatch distribution scaling factor *k* is fixed at 2; and, unless stated otherwise, demersal bycatch is fixed at 12500 tonnes.

Parameters for the midwater rule were tuned to give the same risk as the current midwater TAC of 31500 tonnes (risk is defined as the lowest value over the projection period of the lower 5%-ile of spawning biomass relative to pristine level for the pessimistic model), while improving utilisation as much as possible. Acceptable values for X_{decr} and X_{incr} were indentified in discussions with stakeholders. In contrast, I_{decr} and I_{incr} were chosen using a simplex optimisation routine, *MATLAB*'s *fminsearch*. The objective function is equal to the square of the difference between the actual risk and the desired risk, plus the average mean annual catch of both the pessimistic and optimistic models over the period 2012-2013.

A variety of adaptive TAC rules variants were tested: the *base* case, with X_{decr}= 15% and X_{incr}= 10%; the *smaller* X_{incr} case, with X_{incr}= 5%; the *larger* X_{decr} case, with X_{decr}= 20%; and the *demersal shortfall* case. The *demersal shortfall* case is in the same spirit as the $PUCL_3$ rule: if the demersal bycatch is less than the 12500 allowance, the midwater TAC will be adjusted upwards by the shortfall a few years later. Specifically, this would come into operation for the first time in 2016, with the average annual shortfall in the demersal bycatch take compared to 12500 tonnes over the years 2012, 2013 and 2014 added to the TAC, and similarly for the years following.

2.4 Results

Figure 2.2 compares the projected spawning biomass trajectories of the *base* case to those with a fixed TAC of 31500 tonnes when noise is not added to future "observed" abundance indices in the projection model. Table 2.1 summarises these results.

Figure 2.3 compares the projected spawning biomass trajectories of the *base* case to those with a fixed TAC of 31500 tonnes when noise is added to future “observed” abundance indices in the projection model.

Figure 2.4 compares the projected spawning biomass trajectories for all cases when noise is added to future “observed” abundance indices in the projection model. Table 2.2 summarises these results.

2.5 Discussion

Under the idealised situation where there are no future erors in dices or fluctuations about the stock recruitment relationship, the adaptive procedure (control rule) secures increases in average annual catches of about 2500 and 15000 tons for the pessimistic and optimistic scenarios respectively, for the same risk in comparison to the constant allocation case.

However, once account of realistic error/fluctuation levels is taken, performance deteriorates somewhat, with these improvements dropping to about 4000 tons, and a lesser ability shown by the procedure to differentiate between the optimistic and pessimistic scenarios. Nevertheless catch increases are effectively guaranteed to 2014. By that time more research results that will enable the optimistic and pessimistic scenarios to be distinguished should be available and allow these computations to be updated.

It is evident that decreasing the maximum annual increase from 10% to 5% leads to improved levels of utilisation in the longer term. However this is at the expense of shorter term catch performance for the industry, so that it is anticipated that this would not be preferred by them.

The *Demersal Shortfall* case also leads to improved utilization, but this is at the expense of a slightly increased mean interannual TAC variability. This trade-off would have to be considered by stakeholders. It would be worthwhile to investigate the effect of this rule on other combinations of X_{decr} and X_{incr} in the future.

Table 2.2: Results of projections over the period 2012-2040 **without** observation erors or recruitment fluctuations in the projection model for the *Base Case* and *Constant Catch* midwater TAC rules. The heading *Mean Annual Catch* refers to the mean annual midwater catch; *Optimistic – Pessimistic* refers to the difference between the mean annual midwater catch for the optimistic and pessimistic models; *Lower 5%-ile B/B_0* refers to the lowest lower 5%-ile of spawing biomass relative to pristine level during the projection period; *Median B/B_0* refers to the median spawning biomass relative to pristine level at the end of the projection period (2040); and *Mean Interannual TAC Variability* refers to the mean absolute value of the percentage change in the TAC from one year to the next during the projection period.

Variant	Assessment Model	X_{decr}	X_{incr}	I_{decr}	I_{incr}	Mean Annual Catch	Optimistic - Pessimistic	Lower 5%-ile B/B_0	Median B/B_0	Mean Interannual TAC Variability
Constant Catch	**Pessimistic**	-	-	-	-	31500	0	39%	41%	0.3%
	Optimistic					31500		73%	73%	
Base Case	**Pessimistic**	15%	10%	0.67	0.91	33920	12454	39%	43%	5.0%
	Optimistic					46374		66%	70%	3.8%

Table 2.2: Results of projections over the period 2012-2040 **with** future errors in the projection model (recruitment fluctuations and errors in CPUE and demersal surveys) for a variety of midwater TAC rules. Refer to the caption for Table 2.1 for an explanation of the headings.

Variant	Assessment Model	X_{decr}	X_{incr}	I_{decr}	I_{incr}	Mean Annual Catch	Optimistic - Pessimistic Catch	Lower 5%-ile B/B_0	Median B/B_0	Mean Interannual TAC Variability
Constant Catch	**Pessimistic**	-	-	-	-	31500	0	15%	46%	0.3%
	Optimistic					31500		55%	77%	
Base Case	**Pessimistic**	15%	10%	0.55	1.26	35107	1014	15%	45%	4.6%
	Optimistic					36121		54%	77%	4.6%
Smaller X_{incr}	**Pessimistic**	15%	5%	0.57	0.92	37158	4463	15%	42%	4.7%
	Optimistic					41621		52%	73%	4.8%
Larger X_{decr}	**Pessimistic**	20%	10%	0.71	1.09	35718	2197	15%	45%	6.0%
	Optimistic					37915		53%	76%	6.5%
Demersal Shortfall	**Pessimistic**	15%	10%	0.56	1.22	43743	824	15%	46%	7.0%

Optimistic			44567	55%	77%	6.6%

Figure 2.1: Shows the form and parameters of the adaptive midwater allocation rule.

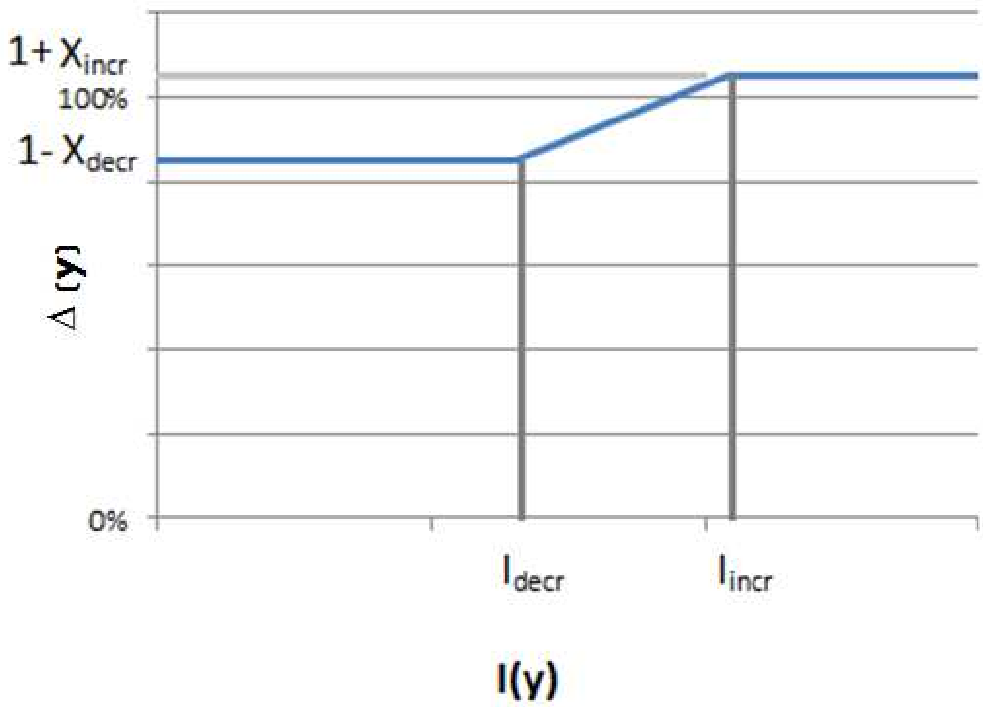
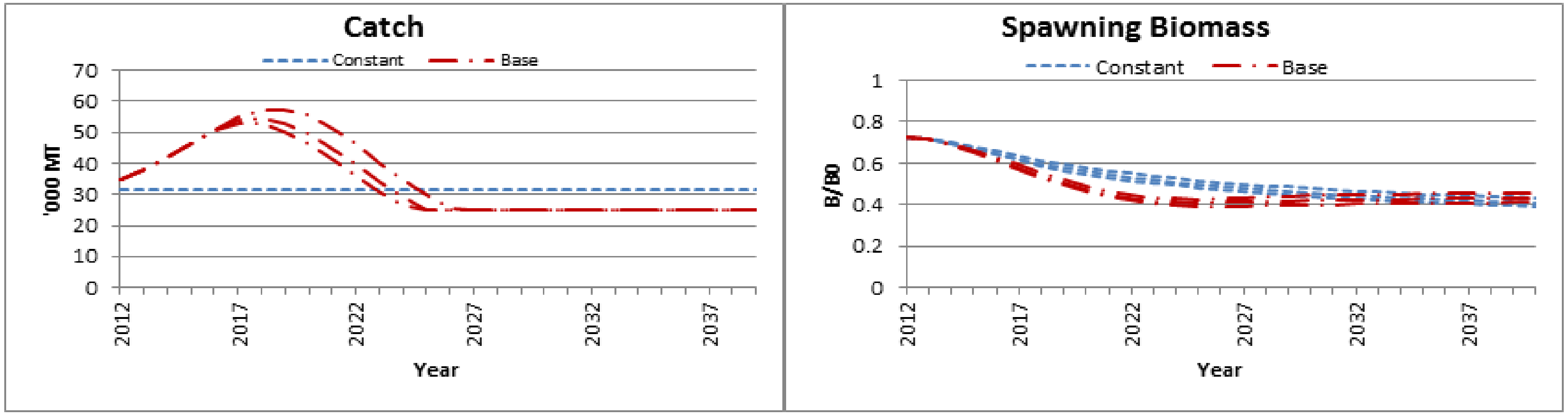
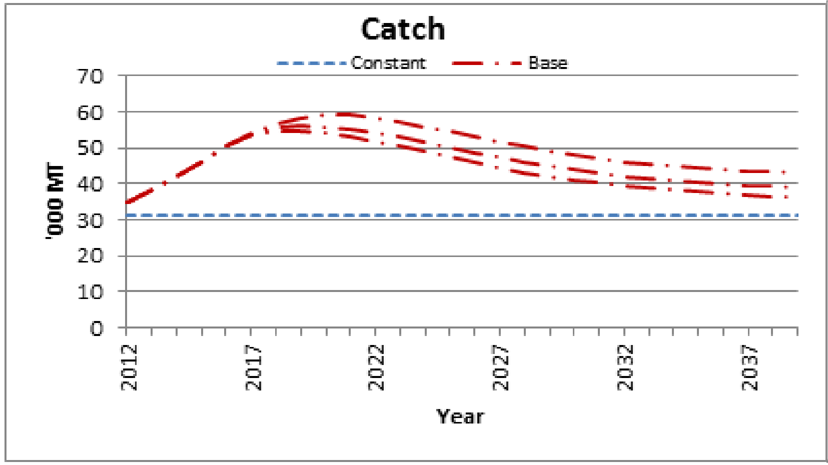


Figure 2.2: Medians and 90% probability envelopes of annual midwater catch and spawning biomass relative to pristine level from projections over the period 2012-2040. These results assume that there **is no** errors during the projection period (i.e. no fluctuations about expected recruitment or errors in observed CPUE or demersal survey indices). Results are shown for the *Constant Catch* and *Base Case* midwater TAC rules, and for the *Pessimistic* and *Optimistic* assessment models.

PESSIMISTIC



OPTIMISTIC


Catch
Constant
Base
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50
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10
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'000 MT
2012
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2022
2027
2032
2037
Year

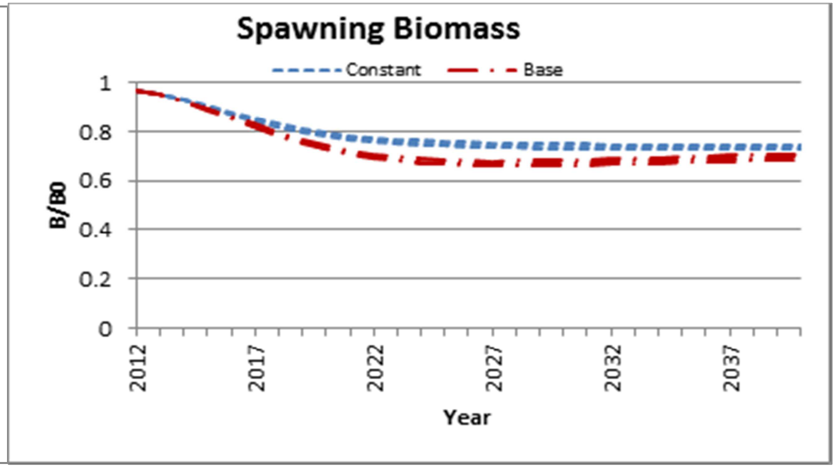
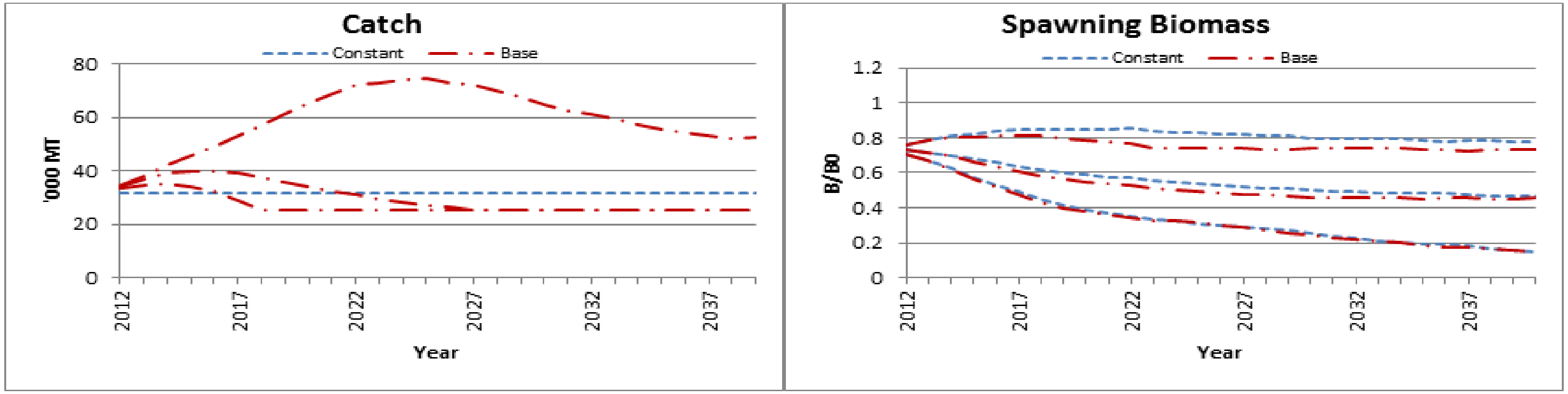
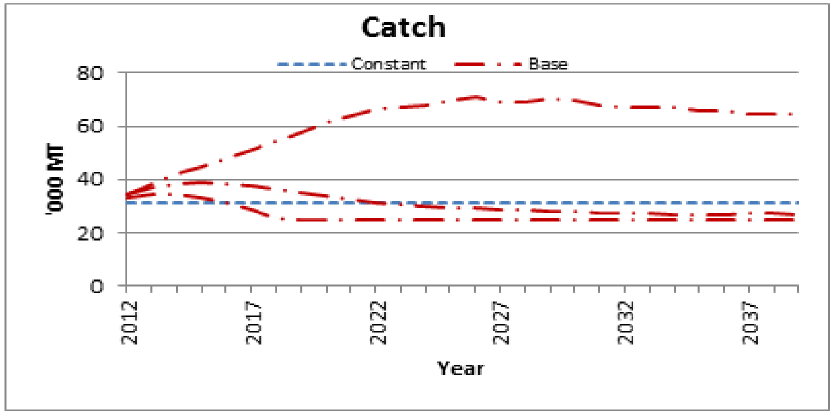

Spawning Biomass
Constant
Base
1
0.8
0.6
0.4
0.2
0
B/B0
2012
2017
2022
2027
2032
2037
Year

Figure 2.**3**: Medians and 90% probability envelopes of annual midwater catch and spawning biomass relative to pristine level from projections over the period 2012-2040. These results assume that there error during the projection periods (i.e. there are fluctionations about expected recruitment and errors in observed CPUE and demersal survey indices). Results are shown for the *Constant Catch* and *Base Case* midwater TAC rules, and for the *Pessimistic* and *Optimistic* assessment models.

PESSIMISTIC



OPTIMISTIC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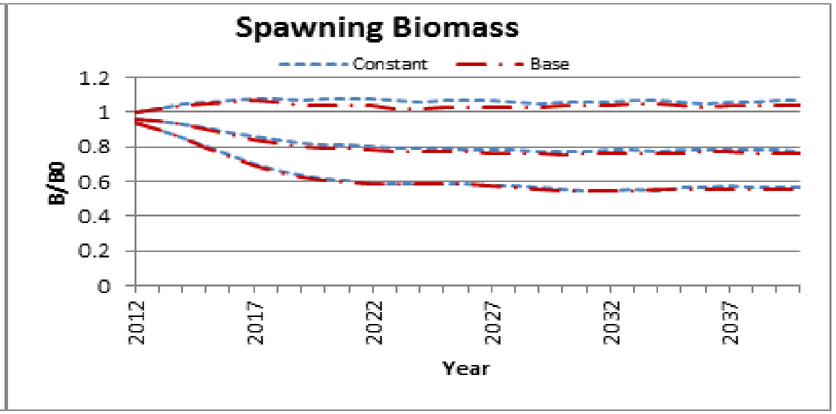
Spawning Biomass
Constant
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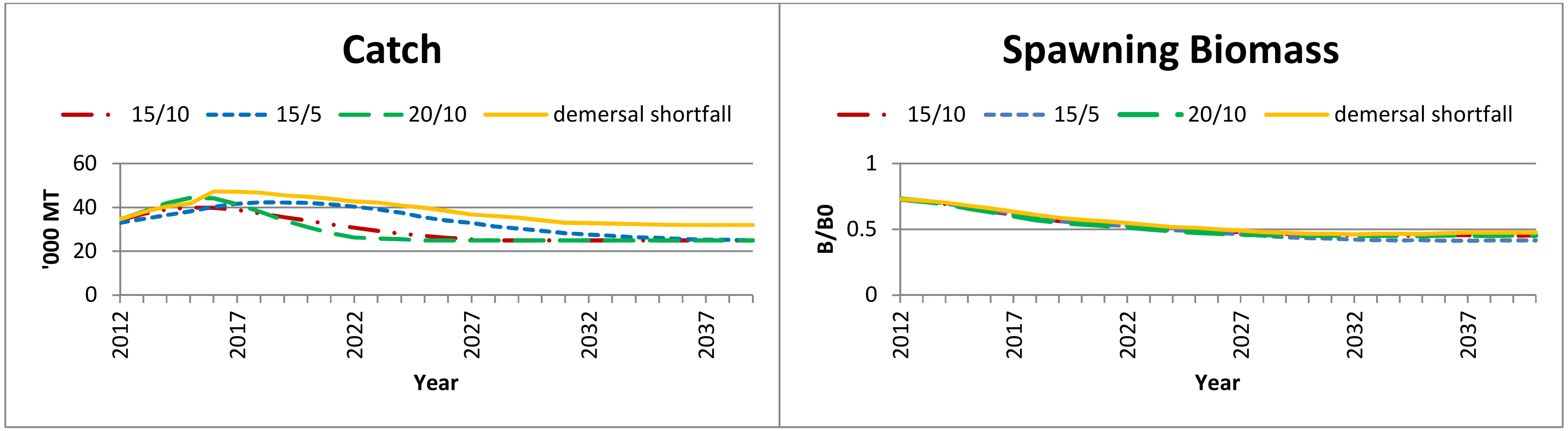
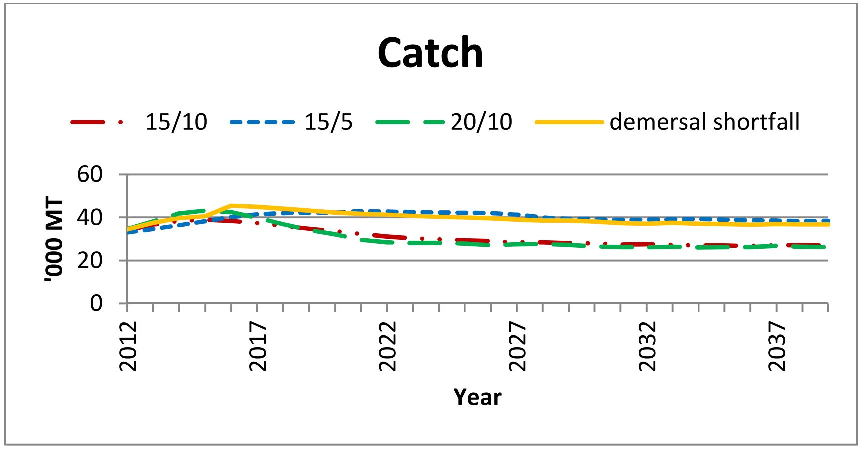
Figure 2.4: Medians of annual midwater catch and spawning biomass relative to pristine level from projections over the period 2012-2040. These results assume that there **is** error during the projection periods (i.e. there are fluctionations about expected recruitment and errors in observed CPUE and demersal survey indices). Results are shown for all adaptive midwater TAC rules, and for the *Pessimistic* and *Optimistic* assessment models.

PESSIMISTIC



OPTIMISTIC


Catch
15/10
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demersal shortfall
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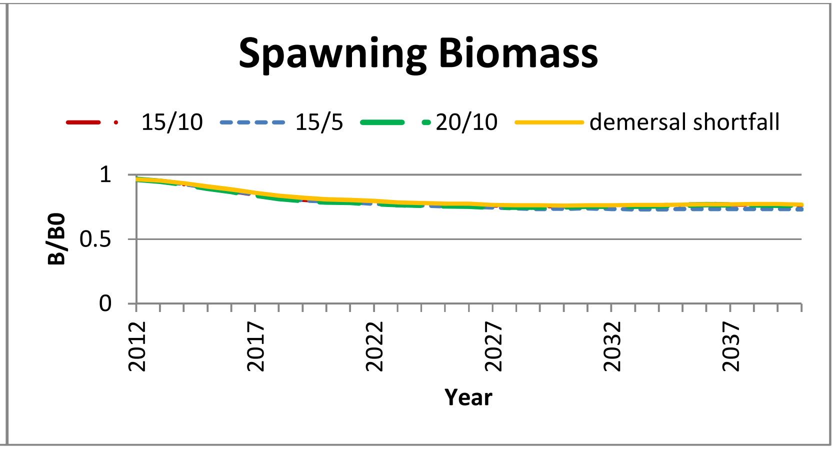
Year


Spawning Biomass
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15/5
20/10
demersal shortfall
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2037
Year

Appendix A

Updated assessment an projection model results

This Appendix describes an update and extension to the age-structured production model assessment of Johnston and Butterworth (2007), which is used to produce the results described in the main text.

A.1 Introduction

The age-structured production model assessment of Johnston and Butterworth (2007) is extended and updated below, with results provided for four alternative assessments reflecting combinations of two possible choices for survey catchability (relative bias) q and stock-recruitment steepness h as in the past.

A.2 Data

A.2.1 Historical catches

Coetzee (pers. commn) has provided a historical catch series for the pelagic fisheries for the years 1949-2009. Singh (2011) has provided a time series for the combined demersal and mid-water historical catches for the period 1950-2009.

A.2.2 Biomass Indices

Three biomass indices are used when fitting the model. Fairweather (pers. commn) provided two sets of biomass estimates and their associated CVs that are derived from demersal swept area surveys conducted on the South coast during both Spring and Autumn. Observer data, provided by van der Westhuizen (pers. commn), were used to produce a GLM standardised CPUE series for a midwater trawl vessel, *Desert Diamond*, which operates on the South coast.

A.2.3 Length-frequency Data

Three length-frequency datasets are used when fitting the model. Fairweather (pers. commn) provided catch-at-length data from the Spring and Autumn demersal swept area surveys. Van der Westhuizen (pers. commn) provided catch-at-length data from the *Desert Diamond*.

A.3 Method

An age-structured production model (ASPM) is used to assess the South African horse mackerel fishery. The model provides projections under future catch scenarios and is used for the simulation testing of horse mackerel management procedures. Appendix B provides the full details of the ASPM and its associated likelihood components.

A.3.1 Model Parameters

The fit of the model to the data estimates the following forty-one parameters:

K^{sp} the pre-exploitation spawning biomass;

q_{spr} the catchability coefficient corresponding to the Spring demersal survey;

σ_{spr} the additional standard deviation associated with the Spring demersal survey, over and above the annual reported CVs;

σ_{aut} the additional standard deviation associated with the Autumn demersal survey;

$a_{sel}^{f,i}$ the age at the center of the Gaussian for the selectivity curve for fleet *f* over period *i*;

$\sigma_{sel}^{f,i}$ the standard deviation of the Guassian selectivity curve for fleet *f* over period *i*;

ς_y fluctuations about expected recruitment for the period 1983-2009 such that $\bar{\varsigma}$ = 0.

A.3.2 Model Variants

As was the case for the 2007 assessment of Johnston and Butterworth (2007), four model variants are considered corresponding to four combinations of values for the catchability coefficient of the Autumn demersal survey, q_{aut}, and the "steepness" of the stock-recruitment curve, h. q_{aut} is set externally as the demersal swept area surveys are known to be biased, but to an unknown extent, and for the limited data available, the model is unable to estimate its value satisfactorily. The variants are:

- Model 1: $q_{\text{aut}} = 0.5$; $h = 0.6$
- Model 2: $q_{\text{aut}} = 1.0$; $h = 0.6$
- Model 3: q_{aut} = 0.5; h = 0.9
- Model 4: q_{aut} = 1.0; h = 0.9

A.3.3 Projection Model

Projections are run for the period 2010-2039. As catch data are available for the 2010 and 2011, the actual observed values are used for those years. Beyond 2011, projected future annual catches depend on the projection in question and are detailed in the relevant sections.

During projections, it is assumed that recruitment residuals are serially correlated, with a Pearson correlation coefficient of 0.47. This *r* value is taken from the serial correlation of the estimated recruitment residuals from the assessment model. Future recruitment residuals are generated for 2010 onwards, using the estimated residual for 2009 to initiate the process. The residuals are drawn from a normal distribution with a standard deviation of 0.3, because this is the value assumed for the assessment model.

Multiplicative observation errors for future "observed" CPUE values from 2011 onwards are drawn from a log-normall distribution where the logarithm has a mean of zero and a standard deviation as estimated in the corresponding assessment model fit. For 2010, the actual observed CPUE is used.

Multiplicative observation errors for future "observed" demersal Autumn surveys are drawn from log-normall distributions where the logarithm has a mean of zero. The variance for these distributions are a combination of σ_{aut} and a CV. Future CVs are drawn randomly with replacement from historic autumn survey CVs.

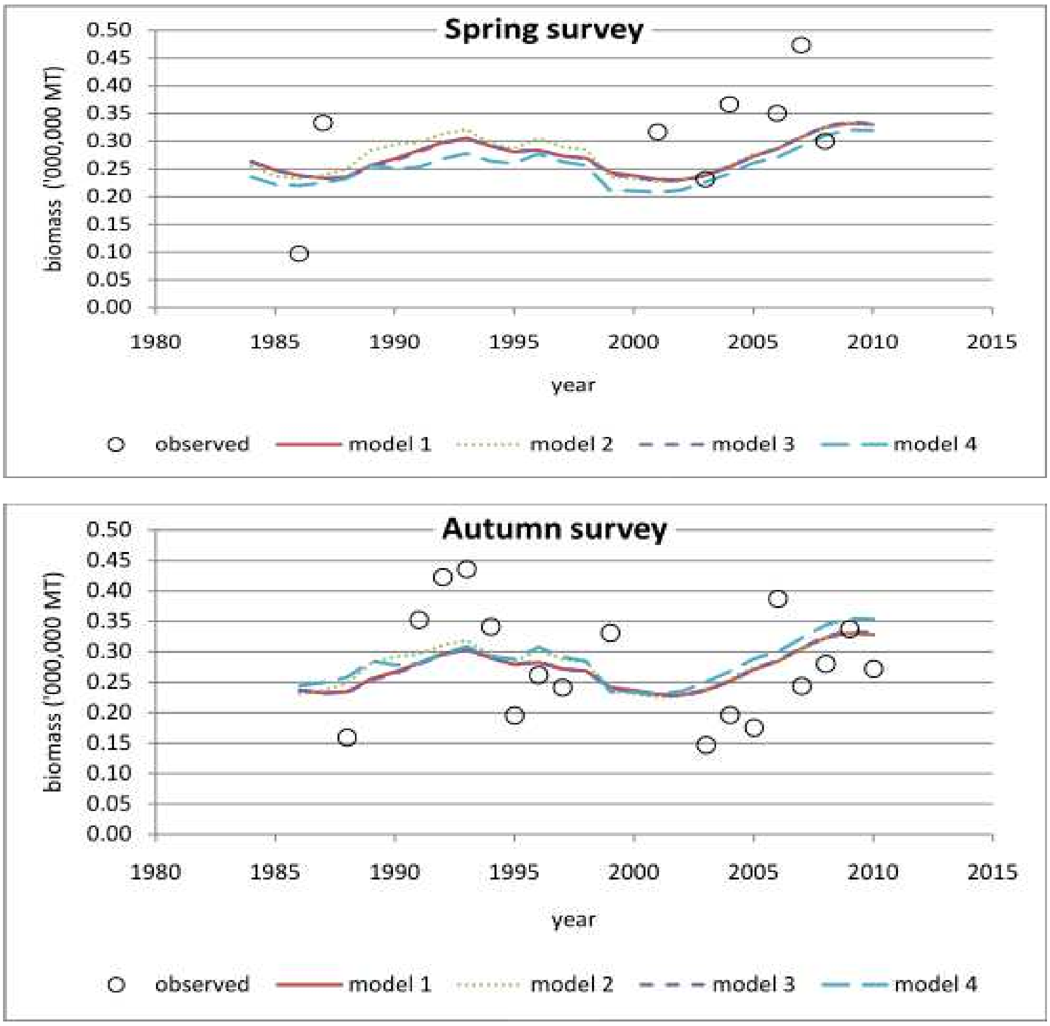
Results

Figure A1 shows the model fits to Spring and Autumn demersal survey biomass estimates, and the directed midwater CPUE series. Figure A2 and Figure A3 show estimated spawning biomass and recruitment trajectories, respectively. Table A1 the values of various log-likelihood components.

Table A1: Summary of assessment results. Under the 'Negative log-likelihoods' heading, 'S-R' refers to the contribution from stock-recruitment residuals, 'abund' refers to the contribution from biomass indices and 'CAL' refers to the contribution from length-frequency data. Biomass units are thousands of tons.

		Model 1	**Model 2**	**Model 3**	**Model 4**
Input parameters	q_2	0.5	1.0	0.5	1.0
	h	0.6	0.6	0.9	0.9
Negative log-likelihoods	**-ln$L$ (S-R)**	5.60	6.18	5.42	5.71
	-ln$L$ (abund)	-0.23	-5.99	0.46	0.31
	-ln$L$ (CAL)	20.67	25.54	20.60	25.45
	-ln$L$ (total)	26.04	25.73	26.48	31.47

Figure A1: Model fits to Spring demersal survey biomass estimates, Autumn demersal survey biomass estimates, and the mid-water CPUE series.



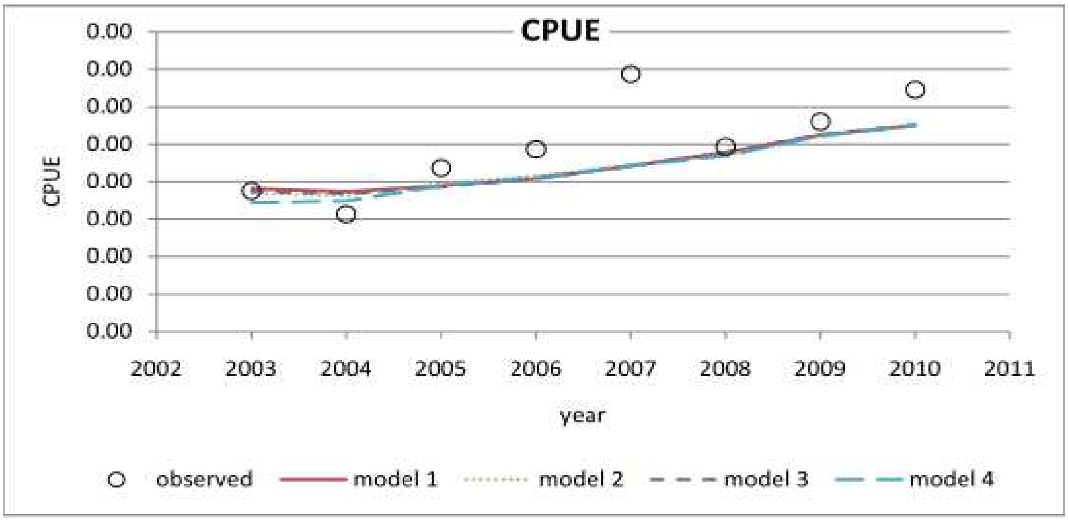


Figure A2: Estimated spawning biomass trajectories for all model variants.

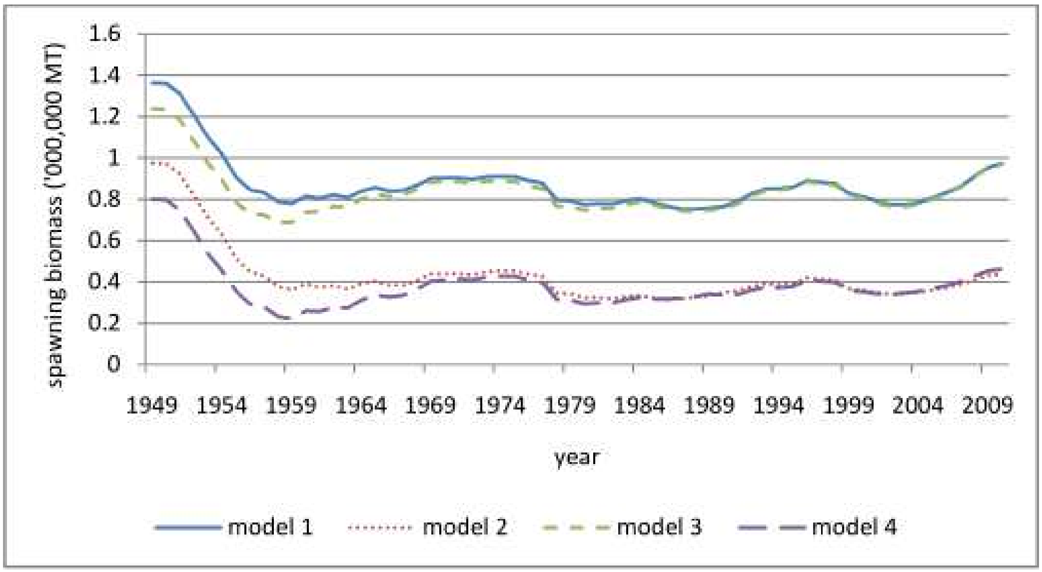
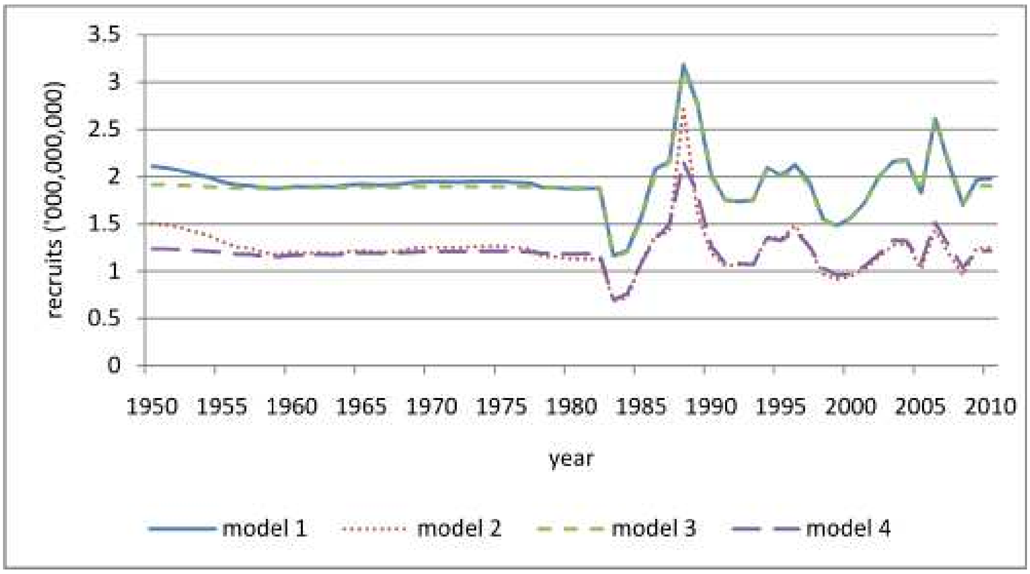


Figure A3: Estimated recruitment trajectories for all model variants.


3.5
3
2.5
2
1.5
1
0.5
0
recruits ('000,000,000)
1950 1955 1960 1965 1970 1975 1980 1985 1990 1995 2000 2005 2010
year
model 1
model 2
model 3
model 4

Appendix B

Mathematical details of the age-structured production model (ASPM)

B.1 Dynamics

The dynamics of the population are described using the following deterministic equations:

$$N_{y+1,0} = R_{y+1} \tag{B.1}$$

$$N_{y+1,a+1} = (N_{y,a}e^{-\frac{M_a}{2}} - C_{y,a})e^{-\frac{M_a}{2}} \qquad 0 \le a \le m\text{-}2 \tag{B.2}$$

$$N_{y+1,m} = (N_{y,m}e^{-\frac{M_m}{2}} - C_{y,m})e^{-\frac{M_m}{2}} + (N_{y,m-1}e^{-\frac{M_{m-1}}{2}} - C_{y,m-1})e^{-\frac{M_{m-1}}{2}} \tag{B.3}$$

where

$N_{y,a}$	is the number of horse mackerel of age *a* at the start of year *y*;
$C_{y,a}$	is the total number of horse mackerel of age *a* taken by the pelagic, demersal and midwater fleets combined, in year *y*;
R_y	is the number of recruits at the start of year *y*(see Section A.2);
M_a	is the natural mortality rate for fish of age *a*; and
m	is the minimum age of the plus-group (*m* = 10 for this paper).

The approximation of the fishery as a pulse catch in the middle of the season is considered of sufficient accuracy for present purposes.

The total number of horse mackerel of age *a* caught each year ($C_{y,a}$) is given by:

$$C_{y,a} = \sum_f C^f_{y,a} \tag{B.4}$$

where *f* indicates the fishery/fleet concerned and in this case, is either *p* (pelagic), *d* (demersal) or m (midwater).

The annual catch by mass (C^f_y) for fleet *f* is given by:

$$\begin{aligned} C^f_y &= \sum_{a=0}^{m} w_{a+\frac{1}{2}} C^f_{y,a} \\ &= \sum_{a=0}^{m} w_{a+\frac{1}{2}} S^f_a F^f_y N_{y,a} e^{-M_a/2} \end{aligned} \tag{B.5}$$

where S_a^f is the fishing selectivity-at-age for fleet *f*. [Note that the pelagic selectivity is assumed to change over time]. F_y^f is the fleet-specific fishing mortality for a fully selected age class in year *y*, and $w_{a+\frac{1}{2}}$ denotes the mid-year mass of a horse mackerel of age *a*.

The fleet-specific exploitable component of abundance is computed in terms of exploitable biomass at mid-year:

$$B_y^f = \sum_{a=0}^{m} w_{a+\frac{1}{2}} S_a^f N_{y,a} e^{-M_a/2} \qquad \text{(B.6)}$$

or numbers:

$$N_y^f = \sum_{a=0}^{m} S_a^f N_{y,a} e^{-M_a/2} \qquad \text{(B.7)}$$

The proportion of the resource harvested each year (F_y^f) by fleet *f* is therefore given by:

$$F_y^f = C_y^f / B_y^f \qquad \text{(B.8)}$$

and

$$C_{y,a}^f = S_a^f F_y^f N_{y,a} e^{-M_a/2} \qquad \text{(B.9)}$$

B.2 Stock-recruitment relationship

The spawning biomass in year *y* is given by:

$$B_y^{sp} = \sum_{a=a_m}^{m} w_a N_{y,a} \qquad \text{(B.10)}$$

where a_m is the age corresponding to 100% sexual maturity, which is assumed here to be described by a knife-edge function of age, and w_a is the mass of horse mackerel of age a at the start of the year.

The number of recruits at the start of fishing year *y* is related to the spawner stock size by a Beverton-Holt stock-recruitment relationship:

$$R\left(B_y^{sp}\right) = \frac{\alpha\, B_y^{sp}}{\beta + B_y^{sp}} e^{\varsigma_y} \qquad \text{(B.11)}$$

where

α and β are stock-recruitment parameters, and

ς_y are stock-recruitment residuals reflecting fluctuations about the median recruitment in year y.

In order to work with estimable parameters that are more biologically meaningful, the stock-recruit relationship is re-parameterised in terms of the pre-exploitation equilibrium spawning biomass, K^{sp}, and the "steepness" of the stock-recruit relationship, where "steepness" is the fraction of pristine recruitment (R_0) that results when spawning biomass drops to 20% of its pristine level:

$$hR_0 = R\left(0.2K^{sp}\right) \tag{B.12}$$

from which it follows that:

$$h = 0.2\left[\beta + K^{sp}\right] / \left[\beta + 0.2K^{sp}\right] \tag{B.13}$$

and hence:

$$\alpha = \frac{4hR_0}{5h-1} \tag{B.14}$$

and:

$$\beta = \frac{K^{sp}(1-h)}{5h-1} \tag{B.15}$$

Given a value for the pre-exploitation spawning biomass K^{sp} of horse mackerel, together with the assumption of an initial equilibrium age structure, pristine recruitment can be determined from:

$$R_0 = K^{sp} / [\sum_{a=a_m}^{m-1} w_a e^{-\sum_{a'=0}^{a-1} M_{a'}} + w_m e^{-\sum_{a'=0}^{m-1} M_{a'}} / (1 - e^{-M_m})] \tag{B.16}$$

Numbers-at-age for subsequent years are then computed by means of equations (B.1)-(B.11).

B.3 Demersal survey and Midwater Selectivity

Demersal survey and midwater selectivities are assumed to have Gaussian forms. Two parameters for each Gaussian are estimated, its center and its width:

$$S_a^{f,i} = e^{\left(a - a_{sel}^{f,i}\right)^2 / \left(\sqrt{2}\sigma_{sel}^{f,i}\right)^2}.$$

where *f* is the fleet, *i* is the period in question, and *a* is the age of the fish, $S_a^{f,i}$ is the selectivity-at-age, $a_{sel}^{f,i}$ is the center of the Gaussian, and $\sigma_{sel}^{f,i}$ is a parameter controling the width of the Gaussian.

Only one selectivity curve is used for the midwater fleet, and it covers the period 1949-2009. However, in order to better fit catch-at-length data, demersal survey selectivity was separated into five periods. For the periods 1949-1993, 1994-1997, 2004-2006 and 2007-2009 different demersal selectivity curves were estimated. Demersal selectivity for the period 1998-2003 was taken to be an average of the 1994-1997 and 2004-2006 selectivities

B.4 Likelihood functions

The model is fitted to three biomass indices and three sets of length-frequency data. Stock-recruitment residuals also contribute to the (penalised) negative log-likelihood.

B.4.1 Biomass indices

The model is fitted to three biomass indices: Spring and Autumn demersal survey biomass estimates, and commercial midwater CPUE data. The associated likelihood contributions are calculated by assuming that the observed abundance index is log-normally distributed about its expected value:

$$I_y^s = \hat{I}_y^s e^{\varepsilon_y^S} \qquad \text{or} \qquad \varepsilon_y^s = \ell n(I_y^s) - \ell n(\hat{I}_y^s) \tag{B.17}$$

where

- s indicates the biomass index concerned and is either aut (autumn), spr (spring) or $cpue$;
- I_y^s is the observed value of index s in year y;
- $\hat{I}_y^s$ $= q_s\, B_y^f$ is the corresponding model estimated value, where B_y^f is the model value for exploitable resource biomassat mid-year for the appropriate fleet, in year y, given by equation (A.6); and
- q_s is the catchability coefficient corresponding to index s.

The negative of the log-likelihood function (after removal of constants) is then given by:

$$-\ell \mathrm{n}L = \sum_s \sum_y \left[\ell \mathrm{n}\sigma_y^s + \left(\varepsilon_y^s\right)^2 / 2\left(\sigma_y^s\right)^2 \right] \tag{B.18}$$

The Spring and Autumn demersal survey biomass indices are assumed to reflect demersal exploitable biomass:

$$\hat{I}_y^s = q_s\, B_y^d \; .$$

Reliable sampling coefficients of variation are available for these series; therefore, the standard deviations are calculated by the following formula:

$$\sigma_y^s = \sqrt{\sigma_s^2 + \ln(1 + CV_{s,y}^2)} \quad . \tag{B.19}$$

where σ_s is an estimated parameter reflecting variance in survey s in addition to that described by its sampling CV.

The CPUE index is assumed to reflect midwater exploitable biomass:

$$\hat{I}_y^{cpue} = q_{cpue}\, B_y^m \; .$$

Reliable estimates of coefficients of variation and catchability are not available for this series; therefore, these are set to their maximum likelihood estimates

$$\sigma^{cpue} = \sqrt{1/n \sum_y \left(\varepsilon_y^{cpue}\right)^2}$$

and

$$\ln q_{cpue} = 1/n \sum_y \varepsilon_y^{cpue}.$$

B.4.2 Length-frequency

Model estimated catch-at-length proportions are fitted to Spring and Autumn demersal survey length-frequency data, and commercial midwater length-frequency data.

Model catch-at-age estimates (equation A.9) are converted to catch-at-length estimates using an age-length relationship:

$$C_{y,l}^f = \sum_a A_{l,a} C_{y,a}^f \tag{B.20}$$

where $A_{l,a}$ is the proportion of fish of age a that are of length l, which is calculated by assuming that lengths at a given age a are normally distributed according to $N\left(l(a), \left(\beta l(a)\right)^2\right)$, where $l(a)$ is the mean length of a mackerel of age a and β is a constant taken to be equal to 0.075 (for which reasonable fits to the data were obtained).

The contribution of catch-at-length data to the negative of the log-likelihood function when assuming a log-normal error distribution and when making an adjustment to effectively weight in proportion to sample size is given by:

$$-\ln L = w_{cal} \sum_s \sum_y \sum_l \left[\ln\left(\sigma_{cal}^s / \sqrt{p_{y,l}^s}\right) + p_{y,l}^s \left(\ln p_{y,l}^s - \ln \hat{p}_{y,l}^s\right)^2 / 2(\sigma_{cal}^s)^2\right] \tag{B.21}$$

where

w_{cal} is a weighting for this likelihood contribution, which is fixed at 0.35;

$p_{y,l}^s$ is the observed proportion of fish caught in year y that are of length l for dataset s;

$\hat{p}_{y,l}^s$ $= C_{y,l}^f / \sum_l C_{y,l}^f$ is the model predicted proportion of fish caught in year y of length l in dataset s, where f is the appropriate fleet;and

σ_{cal}^s is the standard deviation associated with dataset s, estimated in the fitting procedure by:

$$\sigma_{cal}^s = \sqrt{\sum_y \sum_l p_{y,l}^s \left(\ln p_{y,l}^s - \ln \hat{p}_{y,l}^s\right)^2 / \sum_y \sum_l 1} \tag{B.22}$$

Note that allowance is made for a minus group (fish 10 cm and smaller) and a plus group (fish 50 cm and larger), and length classes are specified with intervals of 5 cm.

B.4.3 Stock-recruitment residuals

It is assumed that these residuals are log-normally distributed and are not serially correlated. Therefore, the contribution to the (penalised) negative log-likelihood function is given by:

$$-\ln L = \sum_y \frac{\varsigma_y^2}{2\sigma_R^2} \tag{B.23}$$

where σ_R is the standard deviation of the log residuals, which is assumed to be equal to 0.3.

B.5 Input parameters

The input parameters are set to take the following values:

M	natural mortality, equal to 0.3 yr^{-1};
S_a^p	selectivity-at-age values used for the pelagic fleet;
w_a	start-of-year mass of a horse mackerel of age a;
$w_{a+\frac{1}{2}}$	mid-year mass of a horse mackerel of age a;
a_m	age of sexual maturity, equal to 2 years;
h	the steepness of the stock-recruit relationship, is taken to be either 0.6 or 0.9; and
q_{aut}	catchability coefficient of the Autumn demersal survey, is considered to be either 1 or 0.5.

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