An assessment of the horse mackerel resource including projections and an evaluation of the reliability of a potential index of juvenile abundance

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Abstract

The horse mackerel population is assessed using an age-structured production model (ASPM) with a stochastic component associated with the annual recruitment. The model is fitted to abundance estimates from two swept area demersal research surveys, a GLM-standardised CPUE series for the mid-water trawl fishery, and length distribution data for the pelagic, demersal and mid-water components of the fishery. Because these data have limited information content, four assessment variants are considered corresponding to two choices for the bias of the swept area abundance estimates and for the stock-recruitment steepness h. The results are insensitive to alternative series for the historic catch or how to split catches between the demersal and mid-water trawl fisheries, but do indicate some support for negative bias in the swept area estimates of abundance. The estimates of annual recruitment from these assessments show only a relatively weak correlation with an index of juvenile abundance provided by the November pelagic surveys. Including this index when fitting the ASPM makes little difference to the results.

1 Introduction

The South African horse mackerel (*Trachurus trachurus capensis*) fishery consists of a demersal/midwater fishery concentrated on the South coast and a pelagic purse-seine fishery concentrated on the West coast. Adult horse mackerel are taken as by-catch by the demersal trawl fleet and as a targeted catch by the midwater trawl fleet. Juvenile horse mackerel are taken as by-catch by the pelagic purse-seine fleet. Since 2000, a Precautionary Upper Catch Limit (PUCL) for juvenile horse mackerel of 5000t has been in place for the pelagic purse-seine fishery.

The November 2010 pelagic acoustic survey biomass estimate indicated a substantial increase in horse mackerel on the West coast. Subsequently, in the current 2011 fishing season, large by-catches of juvenile horse mackerel have become problematic for industry. Therefore, in March 2011, the Demersal Scientific Working Group (DSWG) agreed to an *ad hoc* increase of 5000t to the PUCL for the current season. This was considered a once-off adjustment to sustain industry pending further analyses of horse mackerel data, but there are concerns that catches by the mid-water trawl fishery may be compromised if this continues.

This paper seeks particularly an evaluation of the November pelagic survey biomass index as a predictor of juvenile abundance and hence its potential usefulness for a more adaptive process of annually adjusting the PUCL. Additionally, the assessment model developed is used to make projections under future constant catch scenarios.

2 Data

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 two possible time series for the combined demersal and mid-water historical catches for the period 1950-2009, which differ slightly only for the period 1978-1999. Sensitivity of the results to the choice between these two is examined later.

As the model requires separate catch series for the demersal and mid-water fisheries, it is necessary to split historical catches. The catch allocated to each fishery is chosen to match the proportion of the combined mid-water and demersal catch that was reported for that fishery according to the catch series used in the 2007 assessment (Johnston & Butterworth, 2007). This series is now known to be somewhat inaccurate (Singh, 2011), but it is also assumed that the catch split has little appreciable effect on the model. This assumption is later validated by sensitivity tests.

The historical catch series for the pelagic and combined demersal and mid-water fisheries are reported in Table 1, and shown graphically in Figure 1.

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. The GLM is described in detail in Appendix B. These biomass indices are reported in Table 2.

2.3 Recruitment indices

Biomass estimates derived from the November pelagic acoustic surveys for the years 1997-2009 are available for both the West Coast only and the entire assessment area (Coetzee, 2011). These biomass estimates are considered to reflect recruitment and, in some cases, used as such when fitting the assessment model. They are reported in Table 3.

2.4 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*. These datasets each cover the same years as their corresponding biomass index (Table 2). The catch-at-length proportions for each dataset averaged over years are shown in Figure 2.

3 Method

An age-structured production model (ASPM) is used to model the South African horse mackerel fishery. Once fitted to data, the model's recruitment estimates are compared to November pelagic acoustic surveys to assess the reliability of these surveys. Additionally, the model provides projections under future catch scenarios and is intended to be used in the future for the simulation testing of horse mackerel management procedures. See Appendix A for the full details of the ASPM and its associated likelihood components.

The fit of the model to the data estimates the following thirty-two parameters:

K^{sp}	the pre-exploitation spawning biomass;
q_{spr}	the catchability coefficient corresponding to the Spring demersal survey;
a^d_{kink}	the position (age) of the kink in the demersal selectivity function;
μ^d	the rate of decrease of the demersal selectivity function after age 5;
a^m_{kink}	the position (age) of the kink in the midwater selectivity function;
μ^m	the rate of decrease of the midwater selectivity functions after age 5; and
ς_y	fluctuations about expected recruitment for the period 1983-2008 such that $\bar{\varsigma} = 0$.

3.1 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 the value satisfactorily. The variants are:

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

3.3 Sensitivity tests

There are a few decisions which must be made in developing an assessment for which there is little defensible basis, thus the sensitivity of the model to these choices is assessed. However, as there are four model variants (section 3.1), it is impractical to test sensitivities for all of these variants. Instead, model variant 1 (q_{aut} = 0.5; *h* = 0.6) is selected as the base case, and its sensitivity is assessed and assumed to be indicative of the sensitivities of the other model variants. The sensitivity of a model to a factor is assessed by visually comparing the estimated spawning biomass trajectory and recruitment trajectory given differing assumptions.

Test A: Demersal and mid-water catch series

There are two equally plausible combined demersal and mid-water historical catch series, thus sensitivity tests are performed by fitting the base case model when separately using each series and comparing the results.

Test B: Demersal and mid-water catch split

The model requires separate catch series for the demersal and mid-water fisheries; however, only combined demersal and mid-water historical catch series are available. Therefore, annual historical catches must be split between fisheries, but it is unclear how best to do so. To test the sensitivity to this split, models are fitted and compared when separately assuming that these catch series reflect either only demersal or only mid-water catches.

Test C: Using pelagic surveys when fitting the model

It is important that the ASPM's recruitment estimates are robust and reliable if they are to be used either to validate the pelagic acoustic surveys' ability to index recruitment or to determine the extent to which pelagic fishery allocations can be varied safely. However, as mentioned above, it is evident that the model has little power to estimate fluctuations about the expected recruitment. Therefore, it may be beneficial to include pelagic acoustic survey biomass estimates when fitting the ASPM. Note that pelagic survey data are available for both the West Coast only and the full survey area; accordingly, the base case model is fitted when separately using each series. The associated likelihood component is described in full in Appendix A.2.1. For this sensitivity test, the correlation coefficient for the regression between recruitment estimates and pelagic survey biomass estimates are reported in Table 4.

Test D: Period for which recruitment fluctuations, ς_y, are estimated

Recruitment fluctuations are estimated for the period 1983-2008, because length-frequency data are available for these years. However, according to the AIC, estimating these fluctuations for this period does not improve the model. Thus, the base case model is tested for sensitivity to the period for which recruitment fluctuations are estimated. The following options are considered:

- estimate ς_y for the period 1997-2008, as these are the years for which pelagic acoustic surveys are available; and
- set all $\varsigma_y = 0$.

3.4 Correlations

To assess the reliability of the pelagic acoustic survey biomass estimates as a predictor of juvenile horse mackerel abundance, the correlation of these biomass estimates for both the West Coast only and the full survey area with the ASPM's recruitment estimates for the following year is calculated. The West Coast is considered separately as it contains a high proportion of juvenile horse mackerel. The correlation is measured by calculating the Pearson correlation coefficient.

3.5 Projections

The model is used to project the resource biomass ahead for the period 2010-2030. It is assumed that demersal catch remains constant at the catch level reported for 2009, which is 4185 MT. All permutations of the following scenarios are considered.

Future pelagic catch scenarios

- 5000 MT annually
- 10000 MT annually
- 15000 MT annually

Future midwater catch scenarios

- 29815 MT annually
- 39815 MT annually
- 55815 MT annually

4 Results

The sensitivity of the base case model to the choice of demersal and mid-water catch series (sensitivity test A) and demersal and mid-water historic catch split (sensitivity test B) is illustrated by Figure 3 and Figure 4 through comparisons of estimated spawning biomass and of the estimated recruitment trajectories, respectively. Figure 5 shows the estimated spawning biomass trajectory and recruitment trajectory when the base case model is fitted using pelagic survey biomass estimates (sensitivity test C). The quality of these fits is illustrated by Figure 6. Figure 7 shows the effect on the base case model of changing the period for which recruitment fluctuations are estimated (sensitivity test D).

Table 4 reports the following for each of the four model variants and sensitivity test C: parameter estimates and their associated CVs; the estimated current spawning biomass level; the values of the various log-likelihood components and correlation coefficients for regressions between predicted recruitment and biomass estimates based on pelagic surveys. The fit of each model variant to the both demersal surveys and the mid-water CPUE series is illustrated in Figure 8. Estimated selectivity-at-age functions for the demersal and mid-water fleets are shown in Figure 9. Estimated spawning biomass trajectories and recruitment trajectories for all model variants are illustrated in Figure 10 and Figure 11, respectively. Comparisons between pelagic survey biomass estimates for the West Coast, pelagic survey biomass estimates for the full survey area and estimated recruitment for the year following the survey are shown by Figure 12. Note that this comparison is shown only for model 1 as similar figures for the other model variants are practically indistinguishable. Figure 13 provides a graphical representation of the correlation between pelagic survey biomass estimates and recruitment as estimated by model 1. Figures 14-16 show the projection results of model variants for all future catch scenarios considered.

5 Discussion

The model is not sensitive to the choice demersal and mid-water catch series or the demersal and mid-water historic catch split (Fig. 3, 4), but it is somewhat sensitive to changes in the period for which recruitment fluctuations are estimated (Fig. 7). Given the importance of reliable recruitment estimates to this work and the imprecision of recruitment estimates (Fig. 12), it may be beneficial to include the pelagic surveys when fitting the model. However, Figures 5 and 6 indicates that when these surveys are included they have little effect on results and the model fits these data poorly. Figure 17 illustrates the effect of increasing the weighting of the pelagic survey likelihood component by a factor of five.

Table 4 indicates that Model 1 and Model 2, both of which assume $q_{aut} = 0.5$, fit the data appreciably better (by about 5 log-likelihood points) than the other model variants. This provides further support to the notion that the demersal swept area surveys are negatively biased (Fig. B1).

An encouraging feature of the model results is the indication of improvements in spawning biomass over the last five years (Fig. 10), probably as a result of strong recruitment in the last decade (Fig. 11). However, in terms of medium to long term projections (Fig. 14, 15, 16) there appears to be little to support an increase in pelagic PUCL or the mid-water fishing catch.

Table 4 indicates that there is a weak correlation between the estimates of recruitment and pelagic acoustic survey results, for both the West Coast and the full survey area. As is evident from Figure 12, the pelagic survey results show much greater variability than do the assessment results for recruitment. At this stage it is unclear if either the pelagic survey estimates are weak predictors of incoming horse mackerel recruitment strength, or that there are problems with modelling which require further attention.

References

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Johnston, S.J. and Butterworth, D.S. 2007. The South African horse mackerel assessment for 2007 using an age-structured production model, with future biomass projections. MCM document, 2007:WG-Dem:HM:10

Singh, L. 2011. Horse mackerel demersal and midwater commercial catches from 1950-2009. DAFF Fisheries Branch document, FISHERIES/2011/SWG-DEM&PEL/HMTT/09

Table 1: Historical annual landing (‘000 MT) for the pelagic fisheries and two series for the demersal and mid-water fisheries

Year	Pelagic	Demersal & Mid-water	Demersal & Mid-water (alternative)
1949	3.36	-	-
1950	49.90	0.45	0.45
1951	98.90	1.11	1.11
1952	102.60	1.23	1.23
1953	85.20	1.46	1.46
1954	118.10	2.55	2.55
1955	78.80	1.93	1.93
1956	45.80	1.33	1.33
1957	84.60	0.96	0.96
1958	56.40	2.07	2.07
1959	17.70	2.08	2.08
1960	62.90	3.71	3.71
1961	38.90	3.63	3.63
1962	66.70	3.08	3.08
1963	23.30	1.40	1.40
1964	24.40	9.52	9.52
1965	55.00	7.02	7.02
1966	26.30	7.60	7.60
1967	8.80	6.19	6.19
1968	1.40	9.12	9.12
1969	26.80	12.25	12.25
1970	7.90	17.87	17.87
1971	2.20	33.33	33.33
1972	1.30	20.56	20.56
1973	1.60	33.90	33.90
1974	2.50	38.39	38.39
1975	1.60	55.46	55.46
1976	0.40	50.98	50.98
1977	1.90	116.40	116.40
1978	3.60	37.29	37.29
1979	4.30	53.59	53.58
1980	0.40	39.24	39.14
1981	6.10	41.21	41.22
1982	1.10	32.18	32.18
1983	2.10	38.33	38.33
1984	2.80	37.97	37.97
1985	0.70	27.28	27.28
1986	0.50	31.67	31.09
1987	2.83	38.67	38.48
1988	6.40	41.48	41.48
1989	25.87	59.52	56.89
1990	7.65	56.72	56.72
1991	0.58	37.86	41.66
1992	2.06	34.52	39.89
1993	11.65	36.00	36.00
1994	8.21	20.03	20.03
1995	1.99	10.79	10.79
1996	18.92	32.00	31.70
1997	12.65	31.21	38.14
1998	26.68	46.42	57.68
1999	2.06	17.96	29.52
2000	4.50	24.64	24.64
2001	0.92	28.04	28.04
2002	8.15	15.96	15.96
2003	1.01	28.87	28.87
2004	2.05	32.09	32.09
2005	5.63	34.29	34.29
2006	4.82	22.19	22.19
2007	1.90	29.84	29.84
2008	2.28	28.22	28.22
2009	3.36	33.12	33.12

Table 2: Biomass indices and the associated CVs (where available) used when fitting the model. Shaded data indicate surveys that were not performed by the *Africana* or that did not extend beyond 200m and, therefore, are excluded when fitting the model.

Year	Autumn survey Abundance (MT '000)	Autumn survey CV	Spring survey Abundance (MT '000)	Spring survey CV	CPUE
1986			97.36	0.13	
1987			332.97	0.14	
1988	159.07	0.29			
1989	138.20	0.54			
1990	122.75	0.28	551.22	0.22	
1991	352.19	0.23	575.01	0.17	
1992	422.21	0.23	477.29	0.27	
1993	435.28	0.20	307.17	0.16	
1994	340.72	0.26	337.59	0.16	
1995	195.13	0.24	276.37	0.23	
1996	261.77	0.23			
1997	241.02	0.23			
1998					
1999	330.63	0.24			
2000	322.42	0.33			
2001			316.72	0.18	
2002					
2003	146.72	0.24	231.36	0.20	0.752
2004	195.73	0.32	366.50	0.19	0.628
2005	175.04	0.21			0.874
2006	386.57	0.20	350.28	0.19	0.973
2007	243.58	0.40	473.22	0.19	1.374
2008	279.86	0.27	300.00	0.17	0.987
2009	337.16	0.24			1.121
2010	271.80	0.37			1.291

Table 3: Biomass estimates ('000 MT) based on the November pelagic acoustic surveys.

Year	West Coast only	Full survey area
1997	22.98	23.27
1998	1.83	20.39
1999	1.04	5.12
2000	0.85	196.06
2001	5.96	52.91
2002	4.26	15.29
2003	10.32	21.47
2004	0.94	43.14
2005	8.14	12.45
2006	11.96	49.80
2007	0.68	0.98
2008	1.66	11.66
2009	6.29	12.82

Table 4: Summary of 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 metric tonnes. Hessian-based CVs for estimated parameters are given in brackets.

			Model 1	Model 2	Model 3	Model 4	Sensitivity test C (West Coast)	Sensitivity test C (Full survey area)
Input parameters		q_2	0.5	1.0	0.5	1.0	0.5	0.5
		h	0.6	0.6	0.9	0.9	0.6	0.6
Estimated parameters		K^{sp}	1364 (0.08)	975 (0.06)	1239 (0.09)	800 (0.10)	1363 (0.08)	1354 (0.08)
		q_{spr}	0.50 (0.10)	1.01 (0.10)	0.50 (0.09)	0.90 (0.11)	0.50 (0.10)	0.50 (0.10)
		a^d_{kink}	1.44 (0.22)	1.84 (0.22)	1.43 (0.23)	1.68 (0.23)	1.47 (0.22)	1.43 (0.23)
		μ^d	0.55 (0.44)	0.46 (0.55)	0.54 (0.46)	0.42 (0.47)	0.56 (0.45)	0.55 (0.45)
		a^m_{kink}	5.00 (0.01)	5.00 (0.00)	5.00 (0.01)	5.00 (0.01)	5.00 (0.00)	5.00 (0.00)
		μ^m	1.17 (0.61)	0.78 (0.59)	1.16 (0.61)	0.96 (0.61)	1.27 (0.66)	1.15 (0.60)
Current spawning biomass		B^{sp}_{curr}	972	436	974	462	978	964
		B^{sp}_{curr}/K^{sp}	0.71	0.45	0.79	0.58	0.72	0.71
Negative log-likelihoods		-ln$L$ (S-R)	7.28	10.39	7.15	7.82	7.92	7.63
		-ln$L$ (abund)	-2.65	-3.56	-2.44	-0.44	-3.09	-2.87
		-ln$L$ (CAL)	22.85	25.84	22.67	25.27	23.03	23.02
		-ln$L$ (total)	27.49	32.68	27.38	32.66	34.46	36.19
Regressions	West coast only	r	0.13	0.16	0.14	0.21	0.38	0.19
		r (log)	0.43 (log)	0.50	0.42	0.53	0.68	0.49
		s (log)	3.10 (log)	4.01	3.02	4.50	4.16	3.22
	Full survey area	r	-0.12	-0.18	-0.11	-0.17	-0.14	0.07
		r (log)	0.11	0.10	0.11	0.10	0.20	0.42
		s (log)	0.83 (log)	0.86	0.88	0.88	1.32	2.98

Figure 1: Historical annual landing for the pelagic fisheries and the two series for the demersal and mid-water fisheries

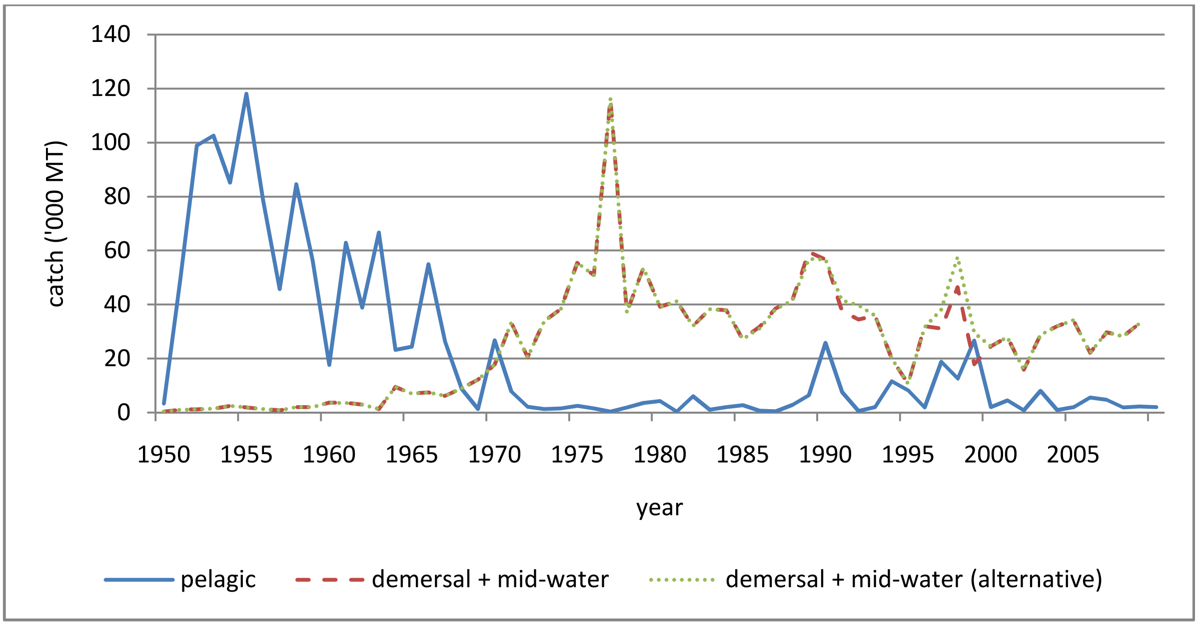


Figure 2: Mean catch-at-length proportions for the *Desert Diamond*, Spring demersal survey and Autumn demersal survey.

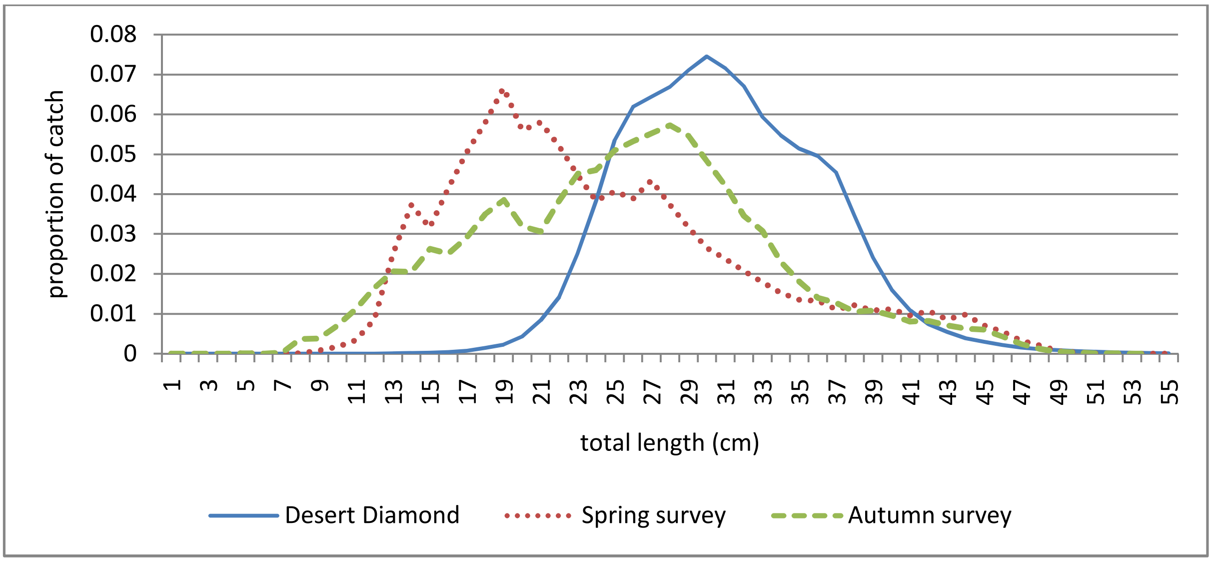


Figure 3: Sensitivity tests A and B. Comparison between spawning biomass trajectories as estimated by models fitted when using: a) the base case demersal and mid-water catch series and the alternative catch series with catches split between fisheries according to historic data; b) the base case catch series split according to historic data and under the assumption that this series reflects either only mid-water or only demersal catches; and c) the alternative catch series split according to historic data and under the assumption that this series reflects either only mid-water or only demersal catches.

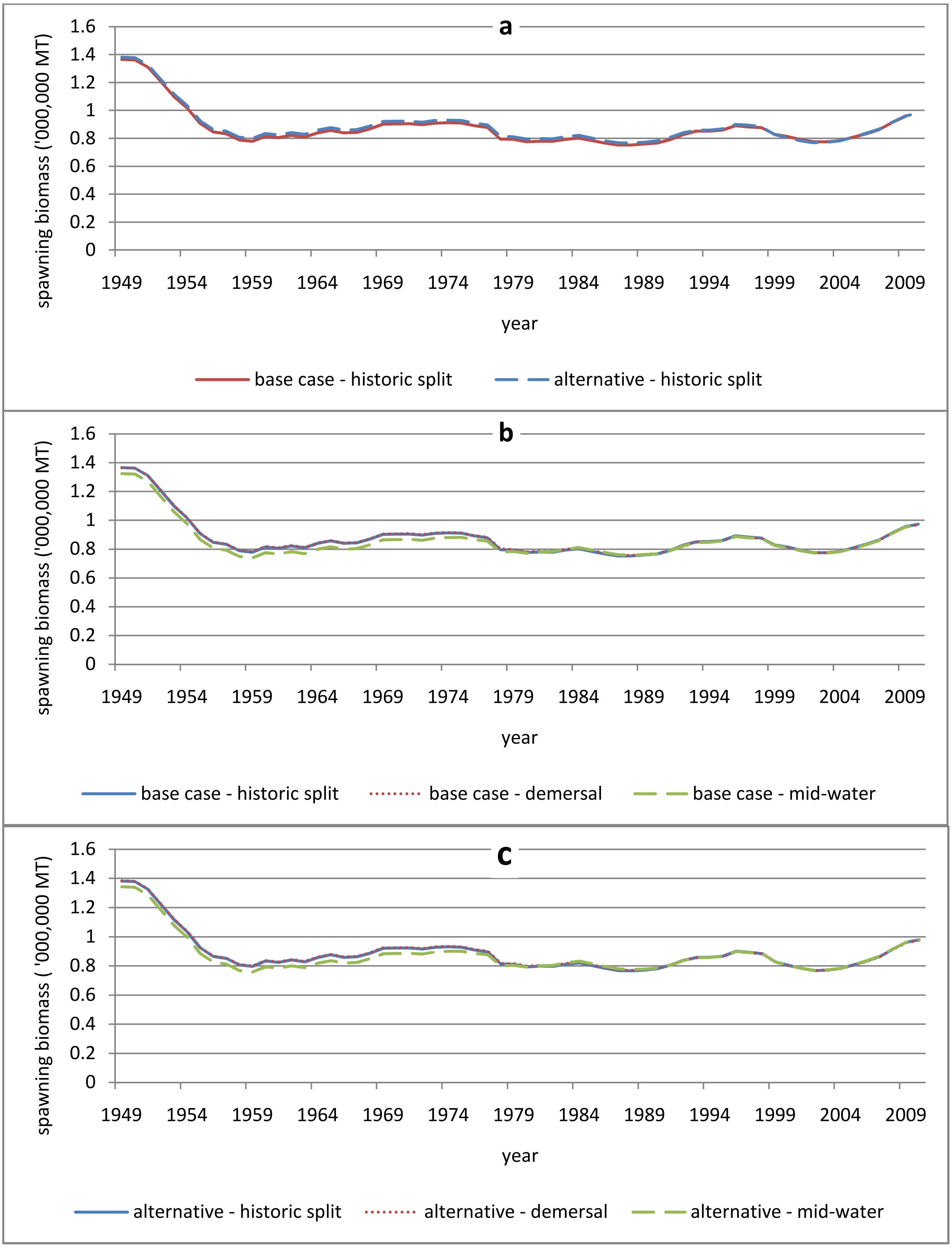


Figure 4: Sensitivity test A and B. Comparison between recruitment as estimated by the base case model fitted when using: a) the base case demersal and mid-water catch series and the alternative catch series with catches split between fisheries according to historic data; b) the base case catch series split according to historic data and under the assumption that this series reflects either only mid-water or only demersal catches; and c) the alternative catch series split according to historic data and under the assumption that this series reflects either only mid-water or only demersal catches.

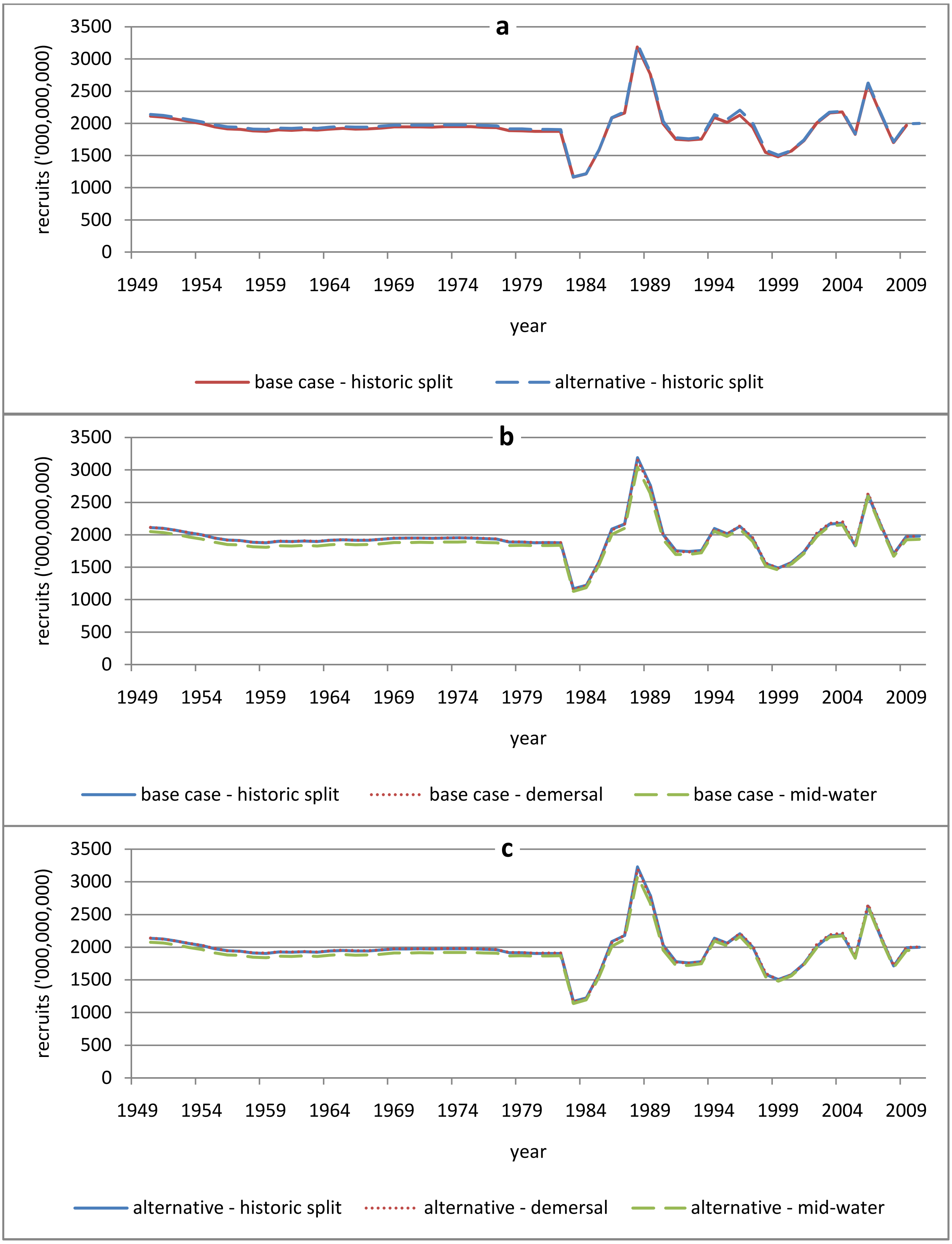


Figure 5a: Sensitivity test C. Comparison between spawning biomass trajectories as estimated by the base case model, the model fitted using pelagic acoustic survey biomass estimates for the West Coast, and the model fitted using pelagic acoustic biomass estimates for the full survey area.

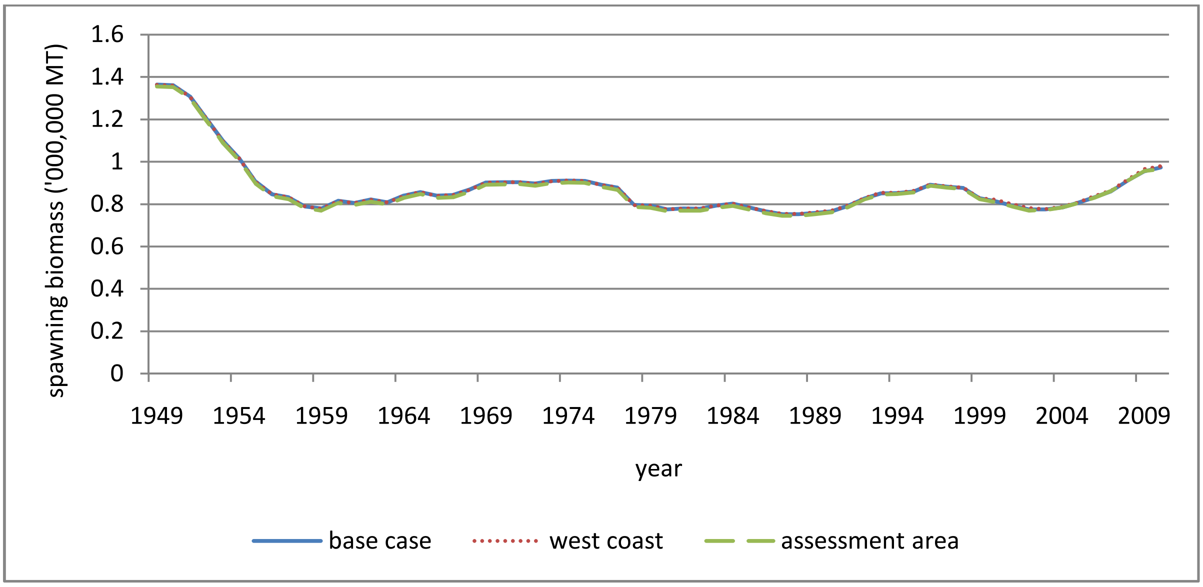


Figure 5b: Sensitivity test C. Comparison between recruitment trajectories as predicted by the base case model, the model fitted using pelagic acoustic survey biomass estimates for the West Coasts, and the model fitted using pelagic acoustic biomass estimates for the full survey area.

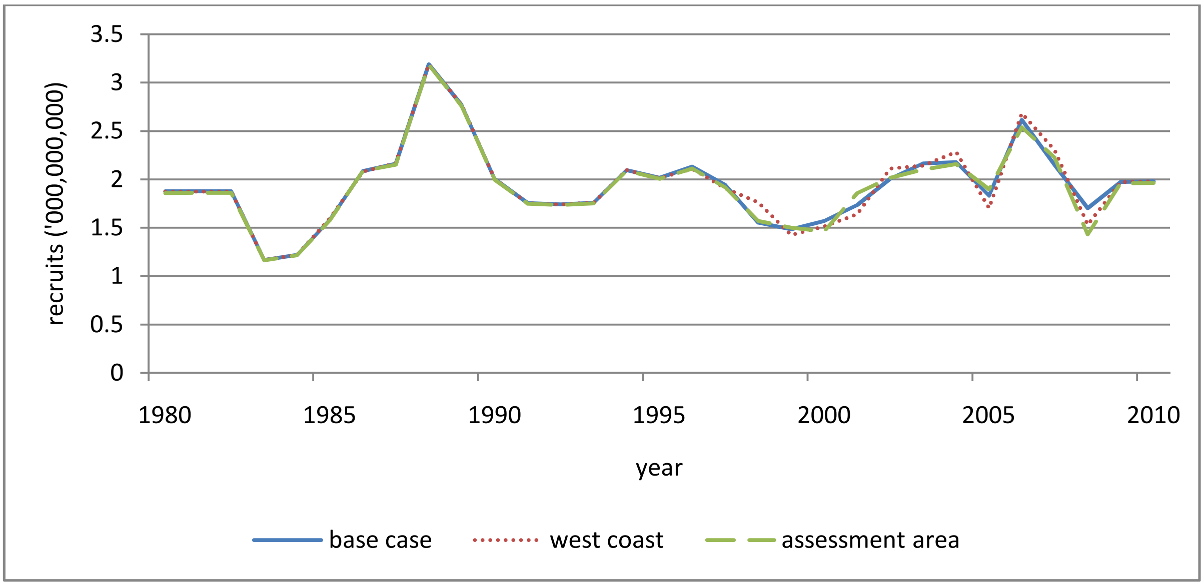


Figure 6: Sensitivity test C. Comparison between predicted and observed recruitment index for the base case model fitted using either pelagic acoustic survey biomass estimates for the West Coast, or pelagic acoustic survey biomass estimates for the full survey area.

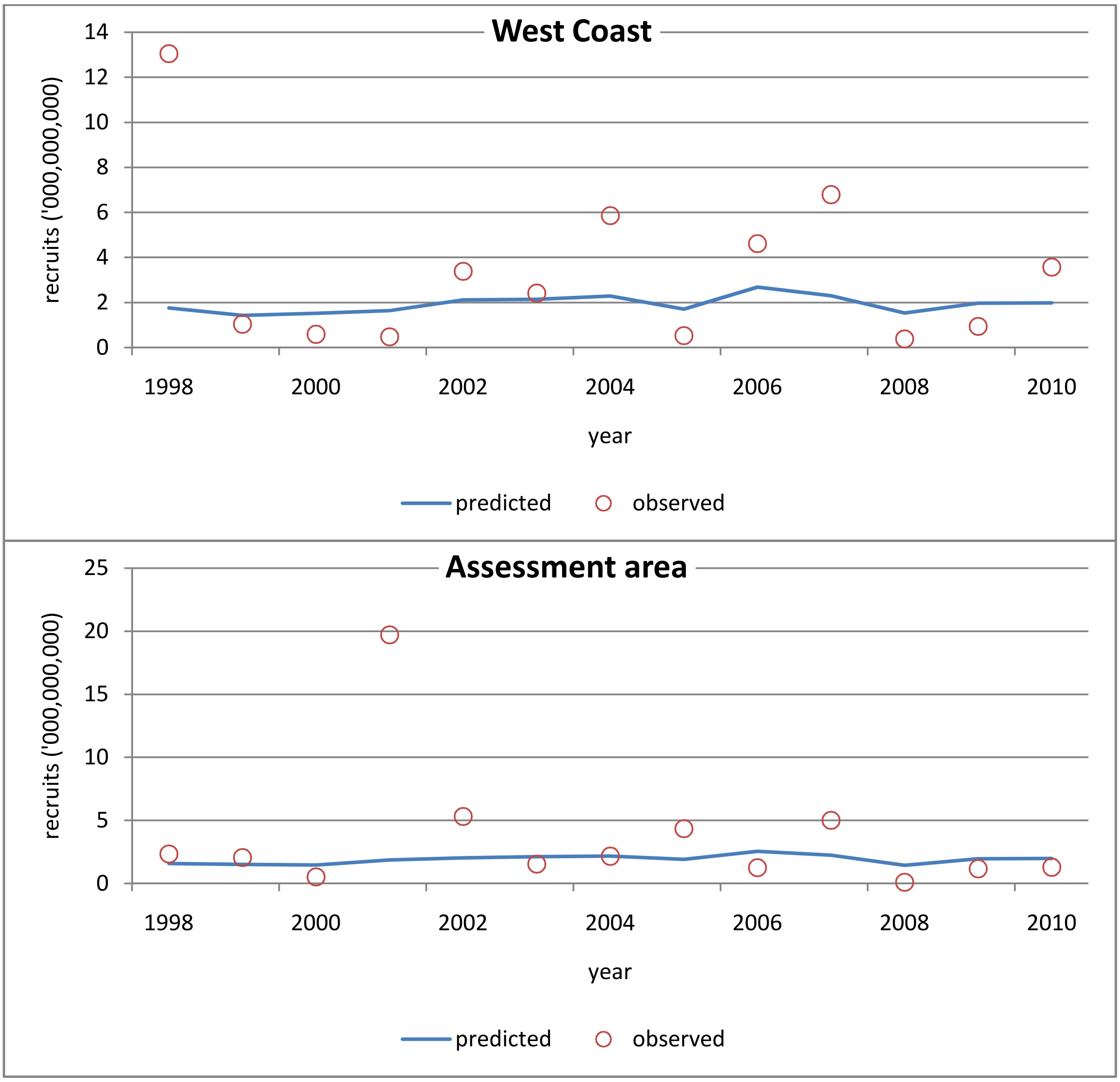


Figure 7a: Sensitivity test D. Comparison between spawning biomass trajectories as estimated by the base case model, which estimates recruitment fluctuations for the period 1983-2008; a model which estimates these fluctuations for the period 1997-2008; and a model which does not include these fluctuations.

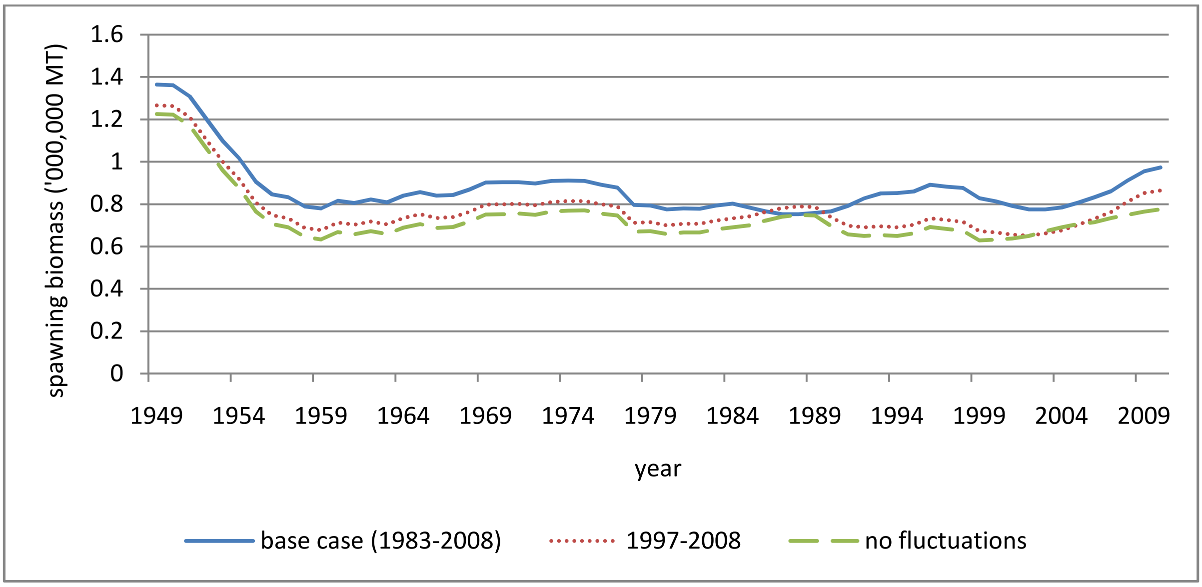


Figure 7b: Sensitivity test D. Comparison between recruitment trajectories as estimated by the base case model, which estimates recruitment fluctuations for the period 1983-2008; a model which estimates these fluctuations for the period 1997-2008; and a model which does not include these fluctuations.

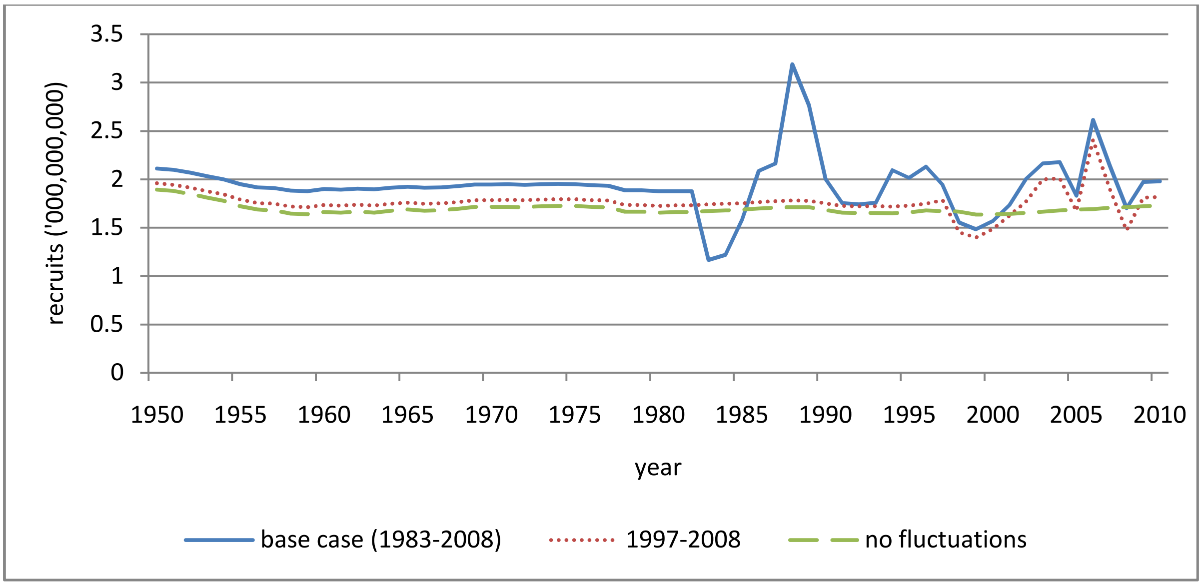


Figure 8: Model fits to Spring demersal survey biomass estimates, Autumn demersal survey biomass estimates, and the mid-water CPUE series.

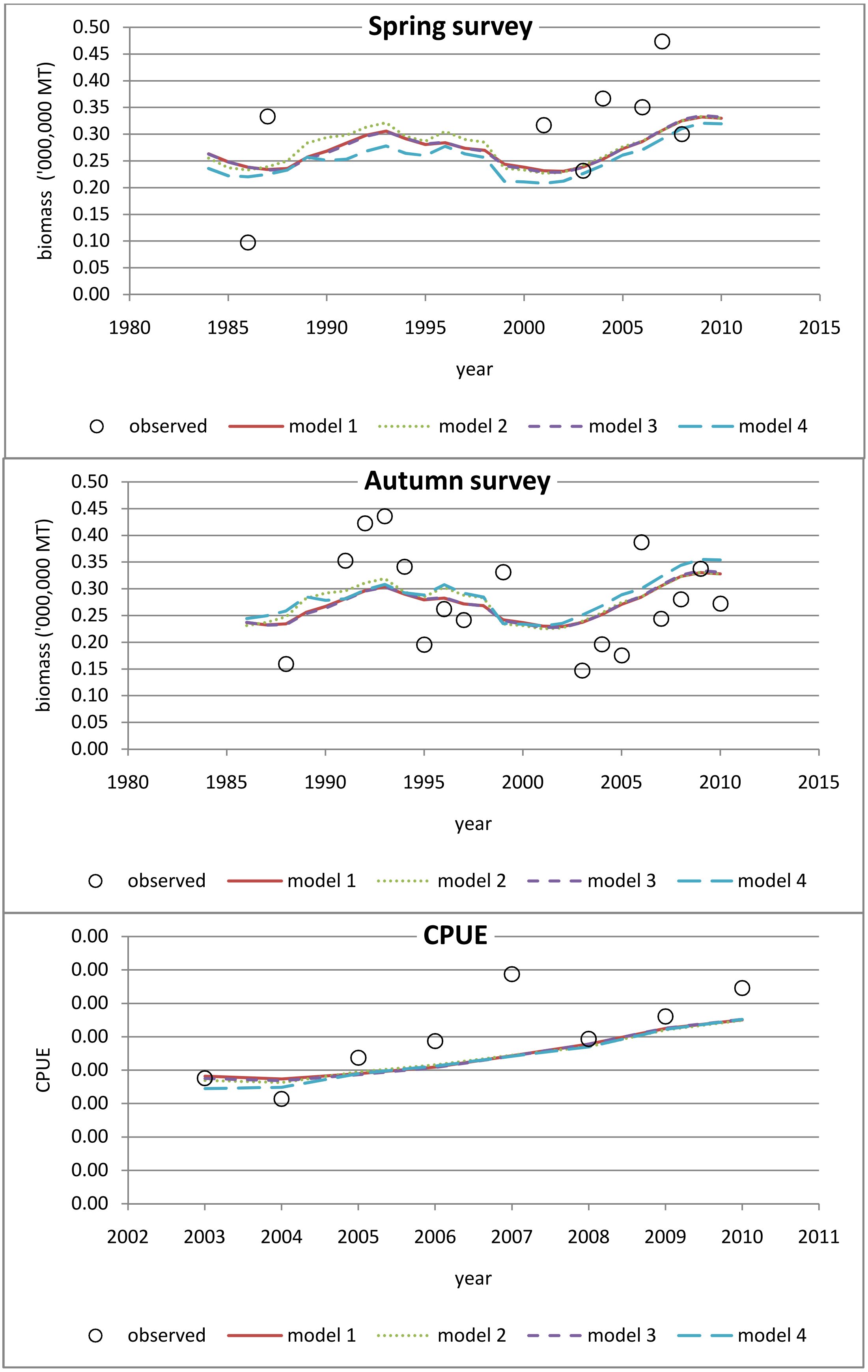


Figure 9: Estimated selectivity-at-age functions for all model variants for the demersal fishery and for the mid-water fishery.

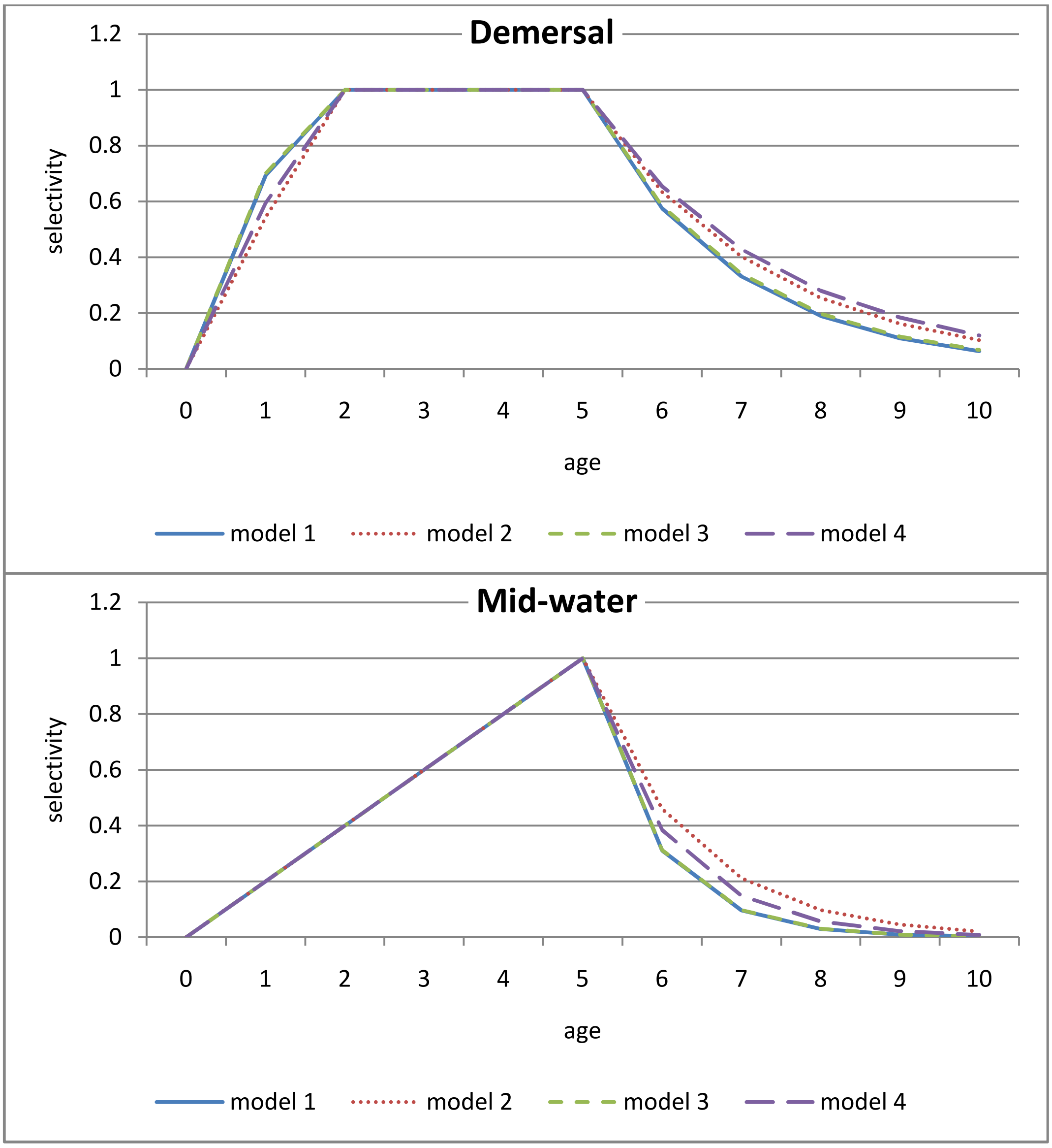


Figure 10: Estimated spawning biomass trajectories for all model variants.

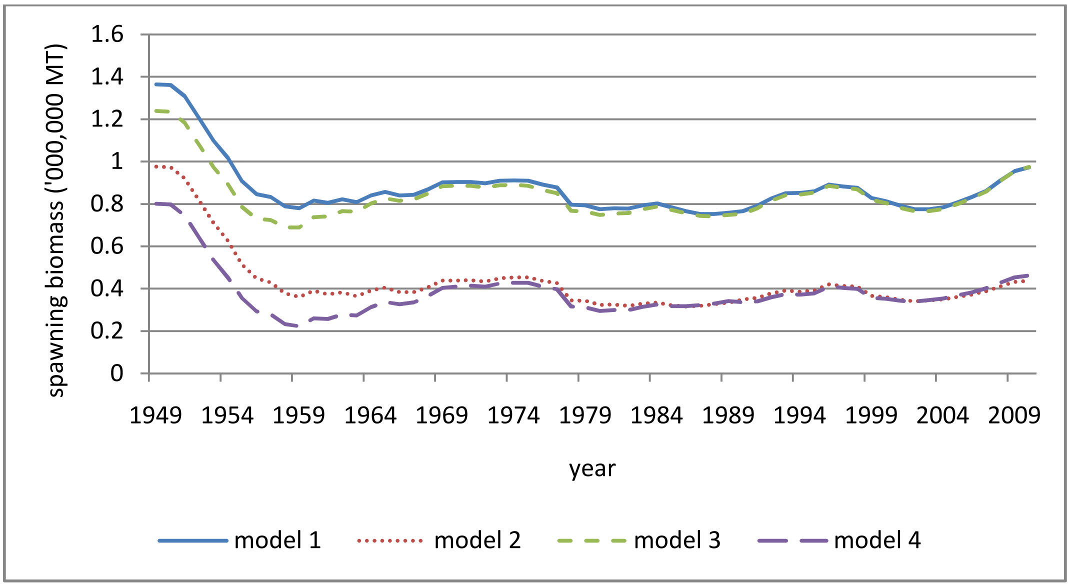


Figure 11: Estimated recruitment trajectories for all model variants.

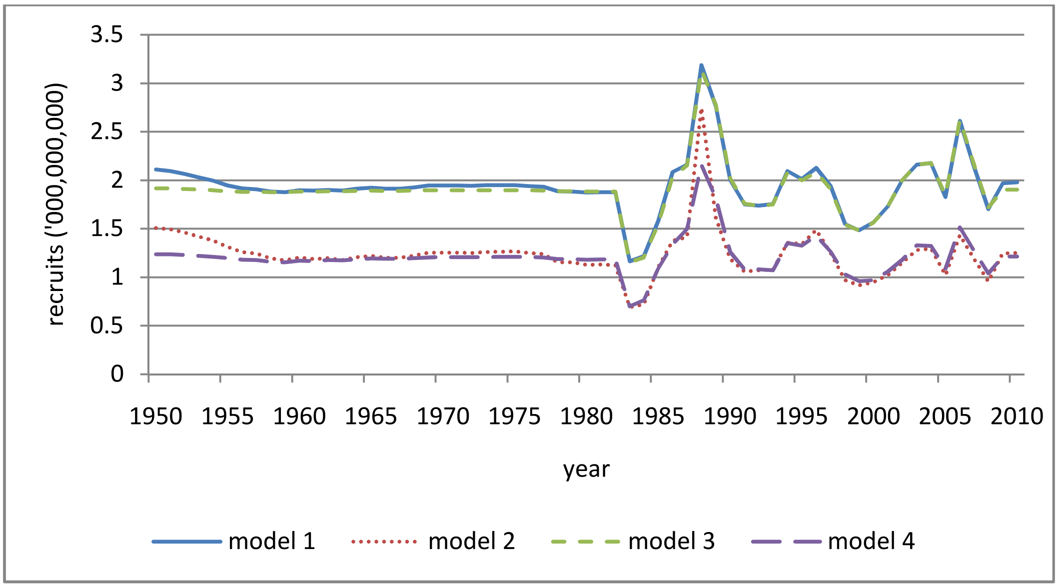


Figure 12: Normalised time series of pelagic survey biomass estimates for the West Coast, pelagic survey biomass estimates for the full survey area, and recruitment as estimated by model 1. Error bars on recruitment indicate the 95% confidence intervals.

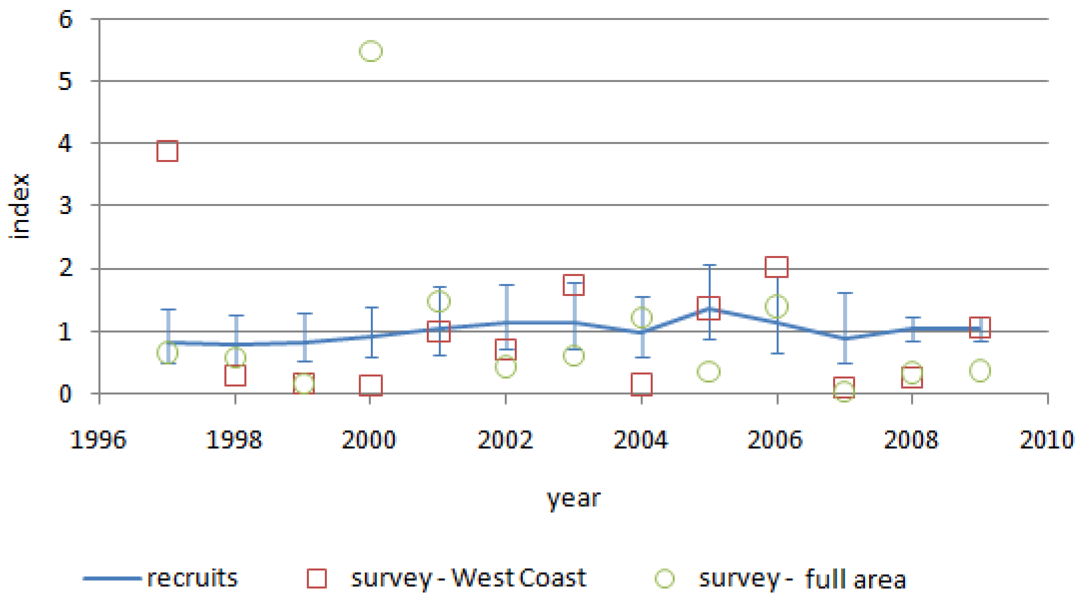
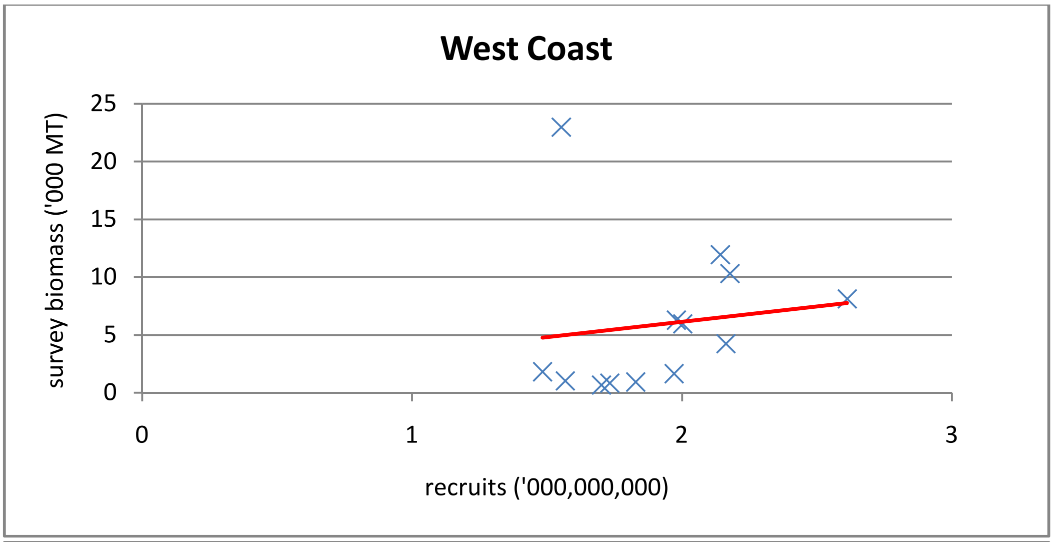


Figure 13: Regressions between pelagic survey biomass estimates for the West Coast and estimated recruitment; and pelagic survey biomass estimates for the full survey area and estimated recruitment. Recruitment estimates shown below are as estimated by model 1.



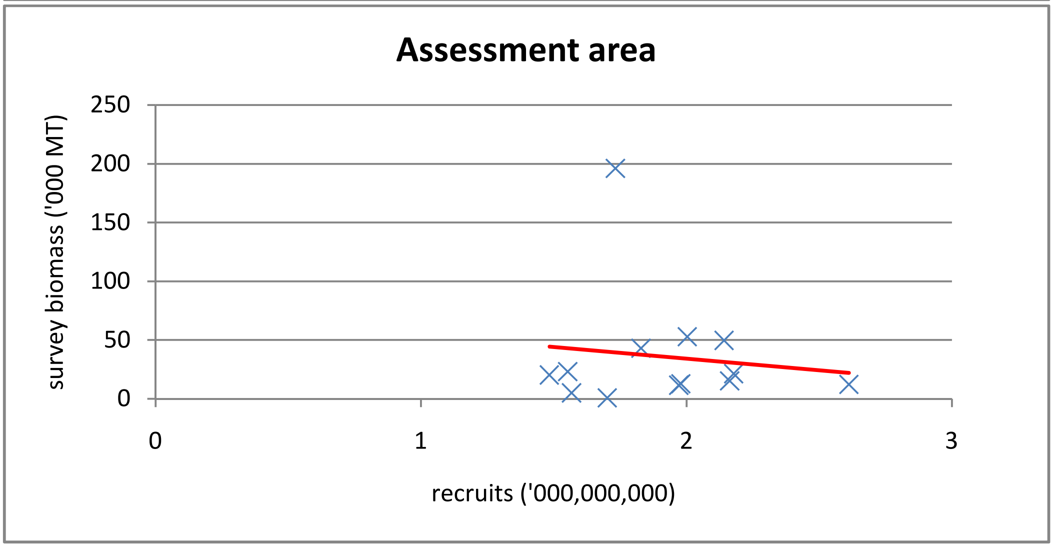


Figure 14: Trajectories of spawning biomass relative to K^{sp} for the 34000 MT demersal plus midwater constant catch scenario and all three future pelagic catch scenarios. Trajectories are shown for the four model variants.

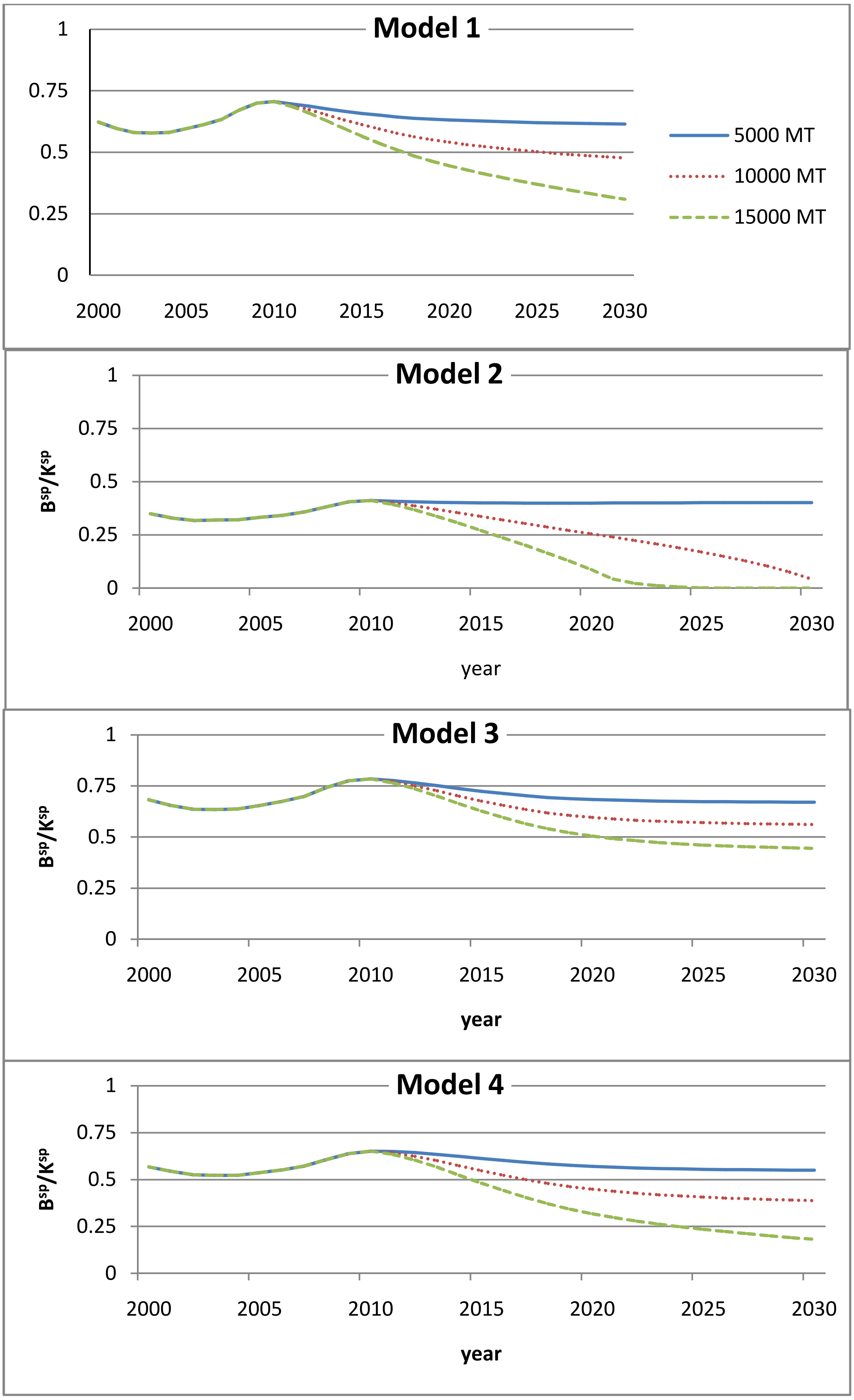


Figure 15: Trajectories of spawning biomass relative to K^{sp} for the 44000 MT demersal plus midwater constant catch scenario and all three future pelagic catch scenarios. Trajectories are shown for the four model variants.

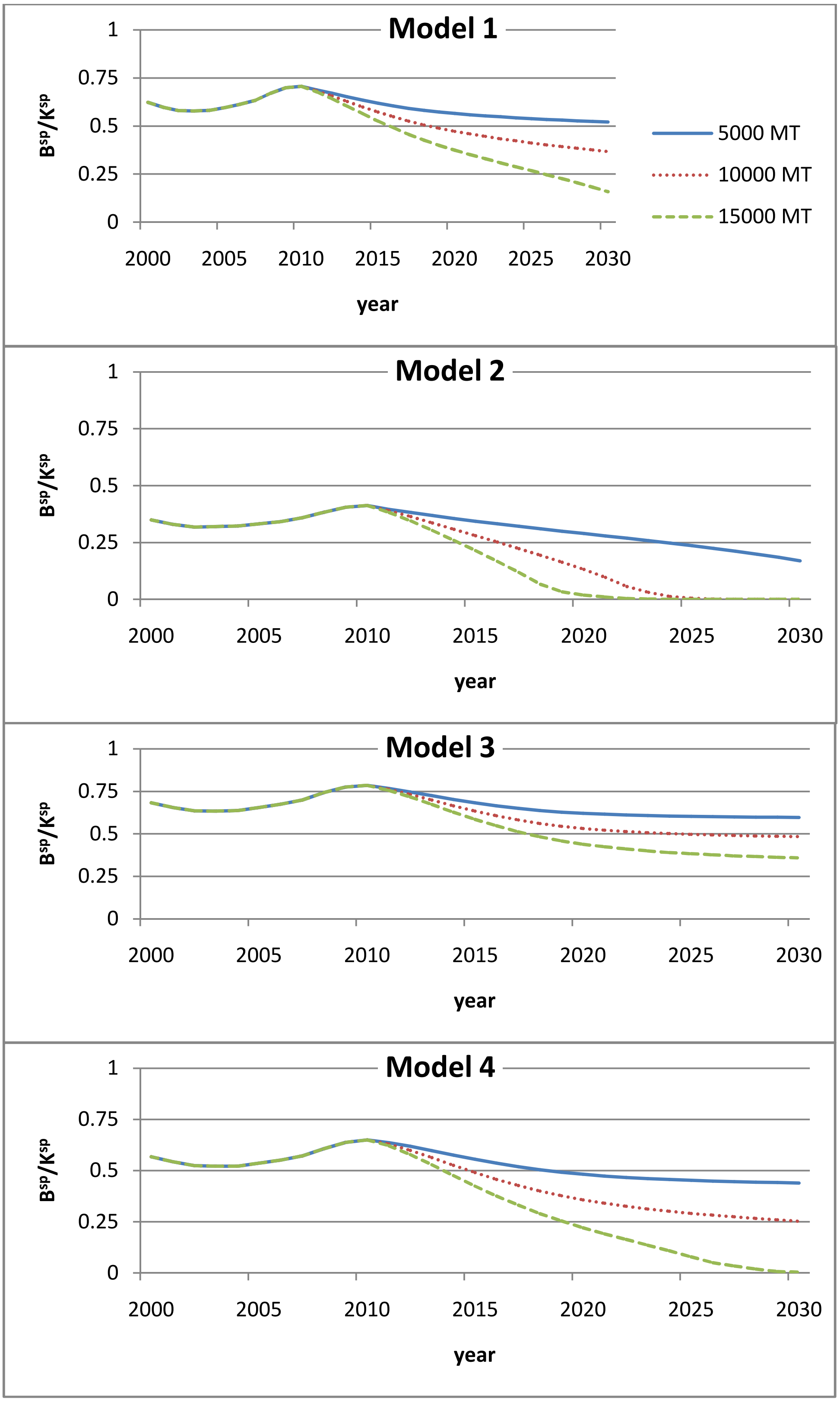


Figure 16: Trajectories of spawning biomass relative to K^{sp} for the 60000 MT demersal plus midwater constant catch scenario and all three future pelagic catch scenarios. Trajectories are shown for the four model variants.

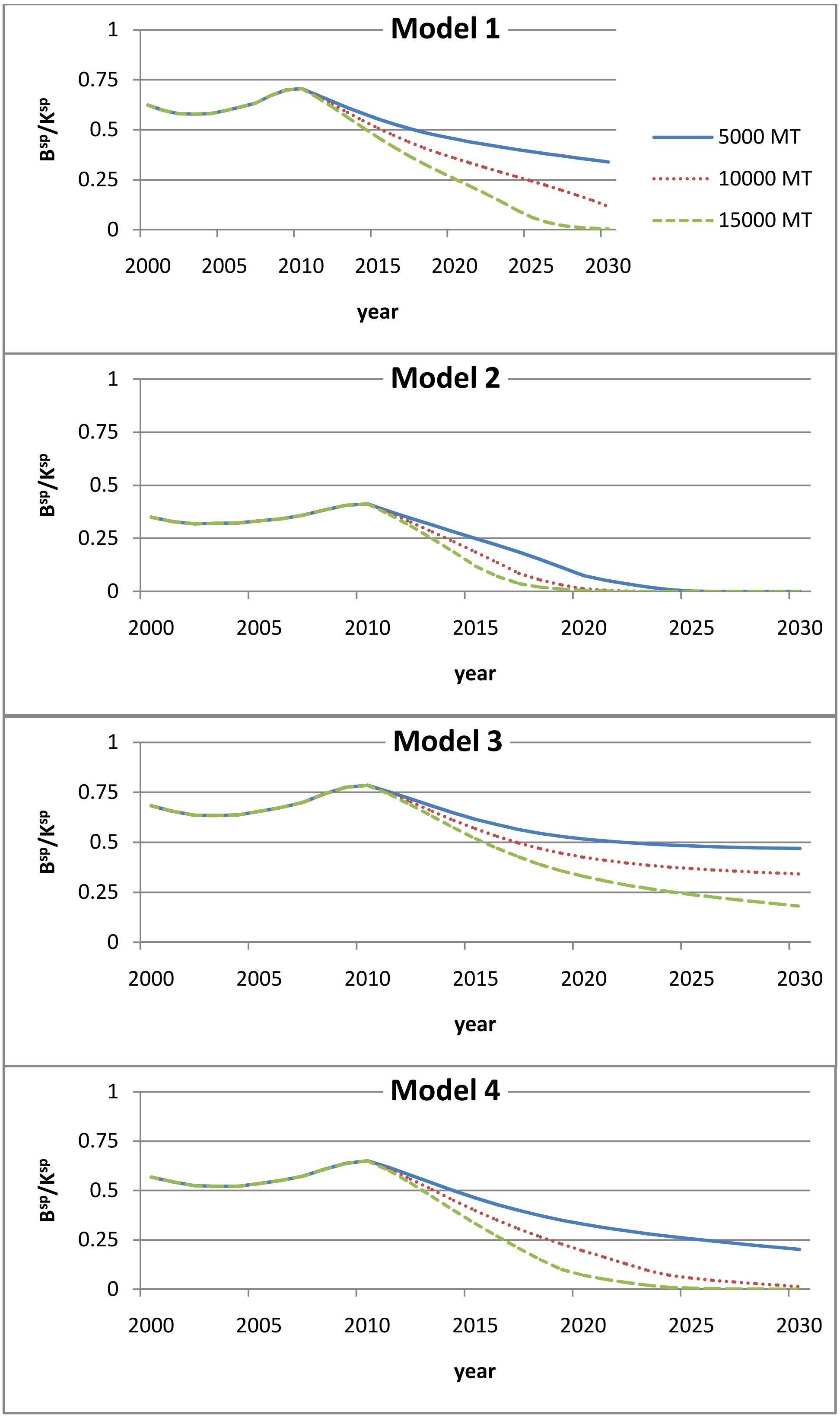
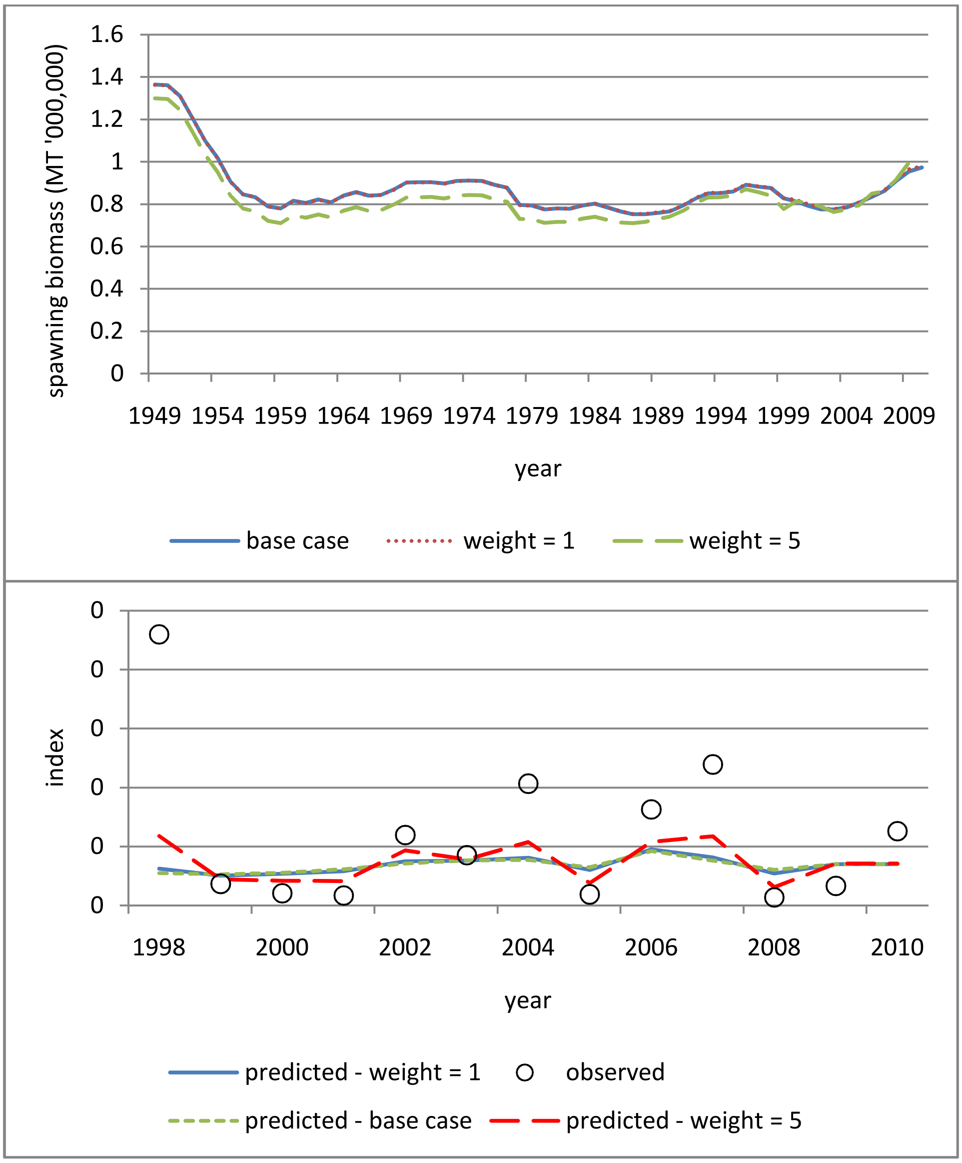


Figure 17: Comparison of estimated spawning biomass and predicted recruitment index between base case models fitted to pelagic survey biomass estimates for the West Coast with the weight for the associated likelihood component set to 0, 1 and 5.



Appendix A

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

A.1 Dynamics

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

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

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

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

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:

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

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:

$$C^f_y = \sum_{a=0}^{m} w_{a+\frac{1}{2}} C^f_{y,a}$$

$$= \sum_{a=0}^{m} w_{a+\frac{1}{2}} S^f_a F^f_y N_{y,a} e^{-M_a/2} \tag{A.5}$$

where S^f_a is the fishing selectivity-at-age for fleet *f*. [Note that the pelagic selectivity is assumed to change over time (Table A.1)]. F^f_y 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:

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

or numbers:

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

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

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

and

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

A.1.1 Demersal and mid-water selectivity

It is possible to estimate the selectivity-at-age for both the mid-water and demersal fleets, because the model is fitted using catch-at-length data from these two fleets separately. Experimentation showed that a function of the form used in the earlier assessment of Johnston and Butterworth (2007) (increasing linearly to $S_a = 1$) provided a good fit to the data. Furthermore, a parameter is added to allow the selectivity to decrease for older horse mackerel, which is supported by improvement of the Akaike information criterion (AIC) measure. Therefore, selectivity functions of the following form are used:

$$S_a^f = \begin{cases} a / a_{kink}^f & a < a_{kink}^f \\ 1 & a_{kink}^f < a \le 5 \\ e^{-\mu^f (a-5)} & a > 5 \end{cases}$$

where

- f indicates the fishery/fleet concerned and in this case, is either d (demersal) or m (midwater);
- S_a^f is the selectivity for horse mackerel of age a for fleet f;
- a_{kink}^f is the age at which selectivity reaches 1 for fleet f; and
- μ^f reflects the rate at which selectivity decreases for horse mackerel older than 5 years for fleet f.

A.1.2 Stock-recruitment relationship

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

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

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:

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

where

α and β are spawner biomass-recruitment parameters, and

ς_y are stock-recruitment residuals reflecting fluctuations about the expected 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:

$$hR_0 = R\left(0.2K^{sp}\right) \qquad \text{(A.12)}$$

from which it follows that:

$$h = 0.2\left[\beta + K^{sp}\right] / \left[\beta + 0.2K^{sp}\right] \qquad \text{(A.13)}$$

and hence:

$$\alpha = \frac{4hR_0}{5h-1} \qquad \text{(A.14)}$$

and:

$$\beta = \frac{K^{sp}(1-h)}{5h-1} \qquad \text{(A.15)}$$

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:

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

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

A.2 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.

A.2.1 Abundances indices

The model is ordinarily fitted to three abundance indices: Spring and Autumn demersal survey biomass estimates, and a commercial mid-water CPUE series (Table 2). Further, as a sensitivity test, the model is additionally fitted to pelagic acoustic survey biomass estimates. The associated likelihood contributions are calculated by assuming that the observed abundance index is log-normally distributed about its expected value:

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

where

- s indicates the abundance index concerned and is either aut (autumn), spr (spring), $cpue$ or pel (pelagic);
- I_y^s is the observed value of index s in year y;
- $\hat{I}_y^s$ is the corresponding model estimated value; 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:

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

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

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

Reliable coefficients of variation are available for these series (Table 2); therefore, the standard deviations are calculated by the following formula:

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

The CPUE index is assumed to reflect midwater exploitable biomass:

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

and the biomass pelagic acoustic survey biomass estimate in year y is assumed to reflect recruitment in year $y+1$:

$$\hat{I}_y^{pel} = q_{pel} R_{y+1}.$$

Reliable estimates of coefficients of variation and catchability are unavailable for the CPUE and pelagic survey series; therefore, these are set to their maximum likelihood estimates

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

and

$$\ln\ q_s = 1/n \sum_y \varepsilon_y^s.$$

A.2.2 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:

$$C_{y,l}^f = \sum_a A_{l,a} C_{y,a}^f \qquad \text{(A.20)}$$

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:

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

where

- $p_{y,l}^s$ 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:

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

Note that allowance is made for a minus group (fish 19cm and smaller) and a plus group (fish 40cm and larger), and length classes are specified with intervals of 2cm.

A.2.3 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:

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

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

A.3 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, which are listed in Table A.1;
w_a	start-of-year mass of a horse mackerel of age a, which is listed in Table A.1;
$w_{a+\frac{1}{2}}$	mid-year mass of a horse mackerel of age a, which is listed in Table A.1;
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 for the Autumn demersal survey, which is considered to be either 1 or 0.5.

a	S_a^p 1948-1962	S_a^p 1963-1967	S_a^p 1968+	w_a (g)	$w_{a+\frac{1}{2}}$ (g)
0	0.00	0.14	0.28	1.82	8.74
1	0.00	0.50	1.00	22.57	43.80
2	0.30	0.40	0.50	72.14	106.83
3	1.00	0.50	0.00	146.88	191.20
4	0.50	0.25	0.00	238.71	288.41
5	0.50	0.25	0.00	339.40	390.88
6	0.25	0.13	0.00	442.17	492.73
7	0	0.00	0.00	542.11	589.96
8	0	0.00	0.00	636.01	680.06
9	0	0.00	0.00	722.00	761.75
10+	0	0.00	0.00	799.27	834.57

Table A.1: Pelagic fishery selectivity-at-age (Johnston and Butterworth, 2007) and weight-at-age vectors. Note that, as was the case for the 2007 assessment, there are three pelagic selectivity vectors for three different periods.

Appendix B

GLM standardised CPUE series

Observer data, provided by Jan van der Westhuizen (pers. commn), cover a variety of vessels and fisheries. However, the *Desert Diamond* has accounted for the vast majority (81%, by mass) of the horse mackerel caught since 2003. Therefore, this GLM uses only data recorded by the *Desert Diamond*, a midwater trawl vessel, which covers the years 2003-2010. The aim is to produce a reliable CPUE series that can be used to when fitting the horse mackerel assessment model.

Method

To provide insight into the relationship between CPUE and each effect considered, the mean marginal CPUE was calculated at different levels of each effect and plotted. The marginals suggest that there are linear relationships between CPUE and depth, wind speed and the percentage of the moon visible; therefore, these effects are treated as continuous explanatory variables. The other effects are not related to CPUE in a simple manner, so their ranges are split into intervals where necessary to reflect changes, and they are treated as categorical variables.

The trawl data indicates that the *Desert Diamond* heavily targets two separate regions, one offshore of Mossel Bay and the other offshore off Port Elizabeth (Fig. B.1). Therefore, possible interactions between the region fished, can be specified by longitude, and other effects were considered. Depth was the only effect which was found to differ significantly between regions (Fig. B.2), thus an interaction between depth and longitude is included in the GLM.

Therefore, the GLM assumes that:

$$\log(\mathrm{CPUE}+\delta) = (b_1 + \mathrm{dep.long}) \times \mathrm{depth} + b_2 \times \mathrm{wind\_speed} + b_3 \times \mathrm{lunar\_phase} + \mathrm{year} + \mathrm{month} + \mathrm{time} + \mathrm{longitude} + \mathrm{wind\_dir} + \mathrm{constant}$$

where:

CPUE is the catch per unit effort for the trawl:

$$\mathrm{CPUE} = \mathrm{catch}/(\mathrm{trawl\_time} \times \mathrm{trawl\_speed} \times \mathrm{vertical\_opening}),$$

where catch is the mass of the horse mackerel caught, trawl_time is the duration of the trawl, trawl_speed is the speed of the vessel during the trawl and vertical_opening refers to the size of the opening of the trawl net;

δ is equal to $\alpha \times \overline{\mathrm{CPUE}}$, where α=0.05, and is added to avoid the problem of taking the logarithm of zero when no horse mackerel catch was reported for the trawl;

b_1 is the regression coefficient associated with depth;

$\mathrm{dep.long}$	is the interaction of longitude and the depth effect;
b_2	is the regression coefficient associated with $\mathrm{wind\_speed}$ in Beaufort scale;
b_3	is the regression coefficient associated with $\mathrm{lunar\_phase}$;
depth	is the depth of the trawl in metres;
$\mathrm{wind\_speed}$	is the wind speed in Beaufort scale, as estimated by an onboard observer;
$\mathrm{lunar\_phase}$	is the percentage of the moon that is lighted;
year	is the effect due to the year;
month	is the effect due to the month;
time	is the effect due to the time of day, taken as the time midway through the trawl;
$\mathrm{longitude}$	is the effect due to the longitude, taken as the average of the starting longitude and ending longitude of the trawl;
$\mathrm{wind\_dir}$	is the effect due to the wind direction during the trawl; and
$\mathrm{constant}$	is the regression constant.

The choice of a small $\alpha = 0.05$ is somewhat arbitrary; therefore, to check that this choice is not of great importance, the resulting GLM standardised CPUE series are compared for $\alpha = 0.01$ and $\alpha = 0.075$ (Fig. B.3). An attempt was made to avoid this issue altogether by modelling CPUE with a Poisson distribution, however this model did not converge successfully.

Table B.1 summarises the effects and the estimates obtained for their values.

Results

The model used in the GLM was able to account for 21.6 percent of the variation of CPUE about its mean. Table B.1 gives the estimated slope parameters for the continuous variables and the estimated effect size for the categorical variables, as well the associated standard errors. Figures B.2 and B.3 show comparisons between mean marginal CPUE and GLM standardised CPUE for depth and year, respectively. A standardised CPUE series is produced by setting all effects in the GLM, apart from effect of interest, to a constant reference level. Thus, as the effect of interest is varied, all changes to the CPUE are attributable to that effect. Note that marginal and standardised results can differ because of the impacts of other effects. Figure B.4 shows diagnostic plots of the standardised residuals.

Discussion

Upward trends in both the marginal CPUE and GLM standardised CPUE (Fig. B.3) are encouraging and consistent with abundance estimates from demersal surveys (Figure 4), which indicate a recent increase in exploitable biomass. It is also apparent from Figure B.3 that the choice of α within a reasonable range has negligible effect on the standardisation results. Furthermore, the absence of a systematic pattern in the residuals and the close match to a normal distribution provides support for the model used (Fig. B.4).

Demersal surveys do not reflect the pattern in trawling locations that is clear from the trawling data (Fig. B.1). Conversations with trawler captains suggest that the regions offshore of Mossel Bay and Port Elizabeth are targeted as they are believed to have high horse mackerel densities. Therefore, it is concerning that demersal surveys do not indicate higher horse mackerel CPUEs in these heavily targeted regions or lower CPUEs off Tsitsikamma. The disparity between commercial and survey data may, in part, be due to the fact that the surveys are demersal, while the commercial data are taken from a midwater vessel. The absence of surveys in the heavily targeted region at about 200m offshore of Mossel Bay (as this area is not amenable to demersal trawls) calls into question the assumption that q_{aut}, the catchability coefficient of the Autum demersal survey, falls somewhere between 0.5 and 1.

Type	Effect	Level	Estimate	Standard error	Significant
continuous	depth	west of 23.4°E	0.00037	0.00064	
		east of 23.4°E	-0.0057	0.0013	
	wind speed	-	0.025	0.012	*
	% moon visible		-0.15	0.049	*
categorical	year	2003	0	-	-
		2004	-0.16	0.093	
		2005	0.14	0.094	
		2006	0.24	0.096	*
		2007	0.56	0.095	*
		2008	0.25	0.097	*
		2009	0.37	0.097	*
		2010	0.50	0.098	*
	month	Jan	0	-	-
		Feb	0.19	0.088	*
		Mar	0.093	0.084	
		Apr	-0.0028	0.085	
		May-Sep	-0.28	0.069	*
		Oct	-0.058	0.087	
		Nov	0.13	0.084	
		Dec	0.23	0.083	*
	time of day	00:00-01:00	0	-	-
		01:00-02:00	-0.19	0.10	
		02:00-03:00	-0.38	0.095	*
		03:00-12:00	-0.69	0.076	*
		12:00-13:00	-0.55	0.19	*
		13:00-14:00	-0.60	0.20	*
		14:00-15:00	-0.38	0.19	*
		15:00-16:00	-0.27	0.22	
		16:00-17:00	-0.14	0.20	
		17:00-18:00	-0.018	0.22	
		18:00-19:00	0.78	0.16	*
		19:00-20:00	0.53	0.094	*
		20:00-21:00	0.32	0.085	*
		21:00-22:00	0.021	0.088	
		22:00-23:00	-0.12	0.098	
		23:00-24:00	0.027	0.10	
	longitude	west of 23.4°E	0	-	-
		east of 23.4°E	0.073	0.16	
	wind direction	45°-225°	0	-	-
		225°-45°	-0.087	0.036	*

Table B.1:Summary of effects included in the model and the associated estimated values. Effects significant at the 5% level are shown by *.

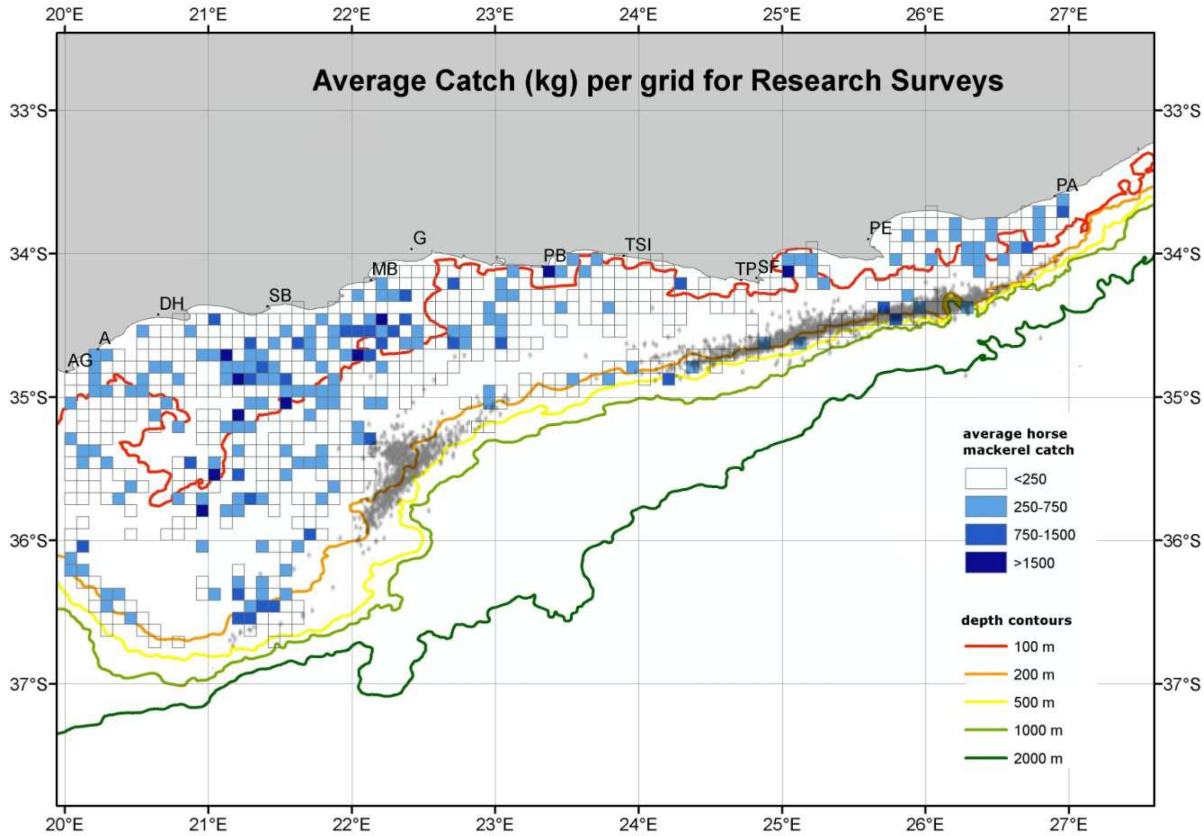


Figure B.1: Correspondence between *Desert Diamond* trawl locations and demersal survey average horse mackerel catches (with standardised effort) over the last decade. *Desert Diamond* trawl locations are marked by semi-transparent grey dots.

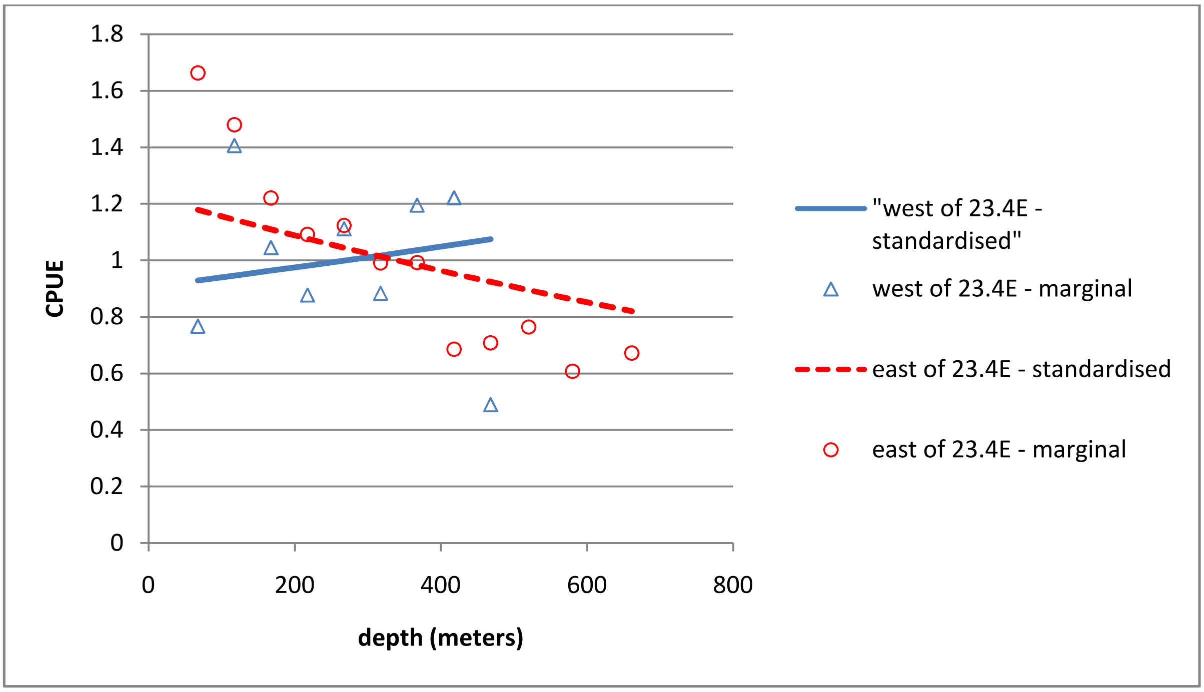


Figure B.2: Comparison between mean marginal CPUE and standardised CPUE at various depths for the two fishing regions.

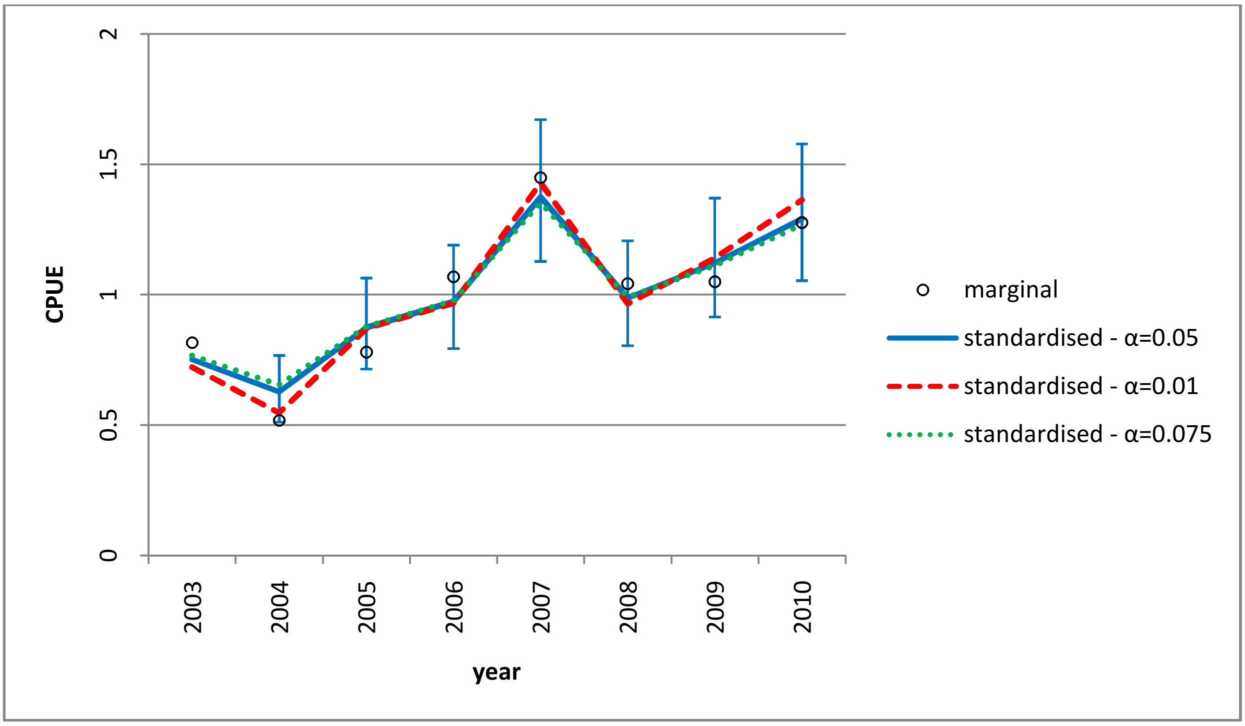


Figure B.3: Comparison between mean marginal CPUE and standardised CPUE for each year. The standardised CPUE series is shown for different values of α. Error bars indicate the 95% confidence interval of the standardised CPUE series (relative to the 2003 value) for $\alpha = 0.05$, as this is the series which is used in the assessment.

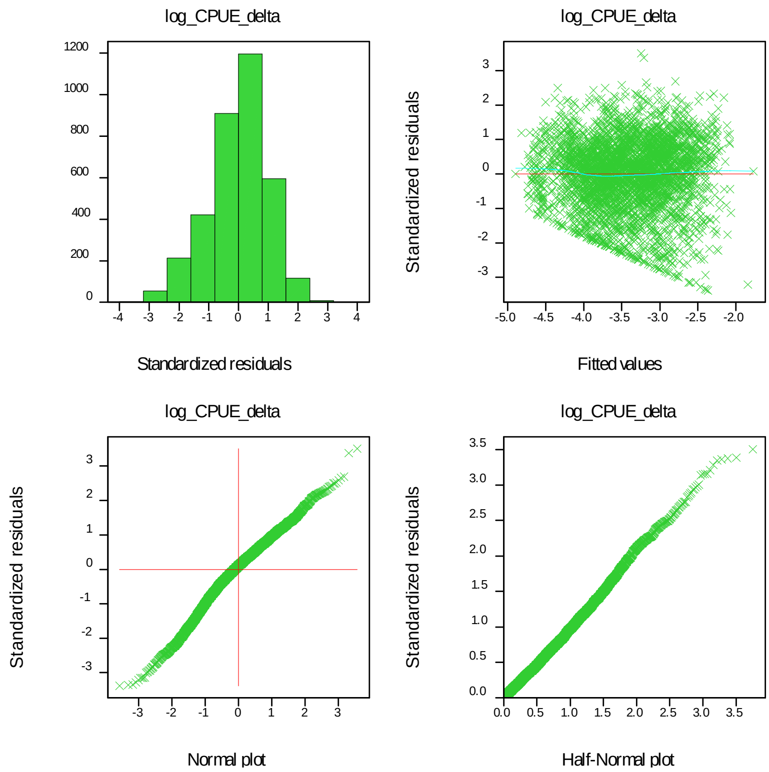


Figure B.4: Diagnostic plots of standardized residuals.