Near final specifications for the sex- and area-specific Operating Models for testing OMPs for the South Coast rock lobster resource

S.J. Johnston and D.S. Butterworth

MARAM
Department of Mathematics and Applied Mathematics
University of Cape Town
Rondebosch, 7701

Introduction

This document reports results of nine different models for the assessment of the South Coast rock lobster resource and associated fishery at an area-specific level. It is proposed that from these nine models, a smaller set will be selected to form a "Reference Set" to be used as operating models for the testing of alternate management procedures, with the remainder serving as operating models for robustness tests.. One of the main new aspects of these results is the use of the "new" historic catch series which allocates overcatch on the basis of the areal distribution of catches by Hout Bay Fishing; more the details about this are to be found in Glazer and Butterworth (2008a).

Data

The following input data are used in all models presented here:

1. Commercial catch data for each Area. The "old" series is reported in Glazer (2008a) and the updated "new" series in Glazer and Butterworth (2008a).
2. CPUE series for each Area from GLM analyses reported in Glazer and Butterworth (2008b).
3. Catch-at-length data for each Area and both sexes as reported in Glazer and Butterworth (2008c).

Methods

A number of model features have been explored. These included:

- TVS = time varying selectivity – two forms are presented (MARAM and OLRAC methods)
- ES = effort saturation
- Catch series = old versus new catch series (see Glazer and Butterworth 2008a for details)
- CDW = down-weighting of the log likelihood contribution from the catch-at-length data by a multiplicative factor of 0.1

Results are presented in detail for the following 9 models:

Model #	Catch series	TVS Method/ES	CDW	Program name
0	NEW	No TVS or ES	NO	xnoes
1	OLD	MARAM	NO	susana3
2	OLD	OLRAC	NO	olrac3e
3	NEW	MARAM	NO	m2nc
4	NEW	OLRAC	NO	olnc
5	NEW	ES	NO	es4
6	NEW	MARAM	YES	cdw01nc
7	NEW	OLRAC	YES	cdwol
8	NEW	ES	YES	es401

The MARAM and OLRAC methods of time-varying selectivity are described in full in Johnston and Butterworth (2008b). The effort saturation approach is described in full in Johnston and Butterworth (2008c). Note that to prevent overweighting of the CPUE data, model fits impose the constraint that $\sigma_{CPUE} \geq 0.10$.

CC Projections under best fits

To provide some indication of the current sustainable yields associated with each of the operating model candidates, each model is projected ahead under the current catch allocation, i.e.173 MT for Area 1, 134 MT for Area 2 and 74 MT for Area 3. These projections make the following assumptions:

Stock-recruit residuals

For all models it is assumed that for 1998+ the stock-recruit residuals are zero.

Total recruitment proportional split per Area

It is assumed that for 2001+, the average of the estimated proportions (for the 1973-2000 period) apply.

Selectivity

Models 1, 3 and 6 (time varying selectivity MARAM method) – it is assumed that for 2006+ $\delta_y^{m/f,A}$ =0.

Models 2, 4 and 7 (time-varying selectivity OLRAC method) - it is assumed that for 2006+ the average of the 1973-2005 $x_y^{m/f,A}$ values applies.

More pertinent measures of sustainable yield are provided by replacement yield (RY) estimates. These are calculated for each model such that $B_{2015}^{sp} = B_{2006}^{sp}$. The RY is defined here to be a constant catch which is applied each year (2007+) to each Area with the same current relative areal proportional breakdown (Area 1 = 45.4%, Area 2 = 35.2% and Area 3 = 19.4%).

Proposed Reference Set (RS) and Robustness tests

It is proposed that the Reference Set (RS) of underlying operating models, under which alternate candidate OMPs for the resource will be tested will consist of the following:

RC A: Model 3 – MARAM time-varying selectivity, new catch
RC B: Model 4 – OLRAC time-varying selectivity, new catch
RC C: Model 5 – Effort saturation, new catch

This selection is suggested because the new catch series areal split used allows the effort saturation hypothesis to provide an improved fit to the CPUE data, and these three models effectively span the complete range of current spawning biomass depletion of the resource that is covered by the remaining models (B_{06}^{sp}/K^{sp} from 0.32 to 0.47). The remaining six operating models would be used for robustness tests.

Robustness tests will also be required which reflect uncertainty in the values of productivity (reflected by *h* and *M*) and current abundance. It is proposed that these robustness tests be defined as follows (note that the existing operating models all fix $M = 0.1$ yr^{-1}):

R1: RC A with $h = \hat{h} + 0.1$
R2: RC A with $h = \hat{h} - 0.1$ (or possibly $h = \hat{h} - 0.2$)

R3: RC A with $M = 0.07$
R4: RC A with $M = 0.15$.

R5: RC A with $B_{2006}^{sp} = \hat{B}_{2006}^{sp} *1.1$ (or possibly $B_{2006}^{sp} = \hat{B}_{2006}^{sp} *1.2$)
R6: RC A with $B_{2006}^{sp} = \hat{B}_{2006}^{sp} *0.95$

Similar variants of RC B and RC C could be considered, but considerations of time will likely preclude this.

Results and Discussion

Tables 1-9: report detailed results for the nine specified models.
Tables 10a and b: provide comparisons of the CPUE and catch-at-length σ values respectively, for each of the nine models.
Table 11: provides comparisons between models of quantities of key interest.

Figures 1a-c compare the fit to observed CPUE trends for Models 0-2 (Figure 1a), Models 3-5 (Figure 1b) and Models 6-8 (Figure 1c). Figure 2a compares Models 3, 4 and 5 fits to observed catch-at-length data for 1995. Figures 2b and 2c provide similar plots but for the years 2002 and 2005 respectively.

Figure 3 shows plots of the stock recruit residuals for Models 1-8. Figure 4 shows the areal proportional recruitment λ values for Models 3-5. The mean value for each case is also indicated on each plot. Figure 5 shows the time-varying selectivity parameter $\delta_y^{m/f}$ values estimated for Model 3. The average value in each case is also indicated. Figure 6 shows the time-varying $x_y^{m/f}$ parameter values estimated for Model 4, with the average value shown in each case.

Assumptions required for future projections for OMP testing

When projecting the population forwards for simulation testing of various OMP candidates, a number of assumptions need to be made for the operating models to be used. Here the authors provide a suggested framework.

1. Stock-Recruit residuals

For 1998+ $$R_y = \frac{\alpha B_y^{sp}}{\beta + (B_y^{sp})} e^{\varepsilon_y} \qquad \varepsilon_y \sim N(0, \sigma_R^2) \tag{1}$$

where σ_R =0.4

[see Johnston and Butterworth (2008a) – Equations 7 and 37].

However, given indications of some serial correlation in the plots in Figure 3, should an AR(1) process rather be considered?

2. Proportional split of recruitment R_y by Area

For each Area A we have estimated λ_y^A for 1973 to 2000 (see Johnston and Butterworth (2008a) Equations 28 and 29 reproduced below as Equations 2 and 3).

$$R_y^A = \lambda_y^{*,A} R_y \tag{2}$$

where

$$\lambda_y^{*,A} = \frac{\lambda^A e^{\varepsilon_{A,y}}}{\sum_A \lambda^A e^{\varepsilon_{A,y}}} \tag{3}$$

and

$$\varepsilon_{A,y} \sim N(0, \sigma_\varepsilon^2); \qquad \sigma_\varepsilon = 0.05.$$

The $\varepsilon_{A,y}$ are thus further estimable parameters. From these estimated values we can thus calculate $\bar{\lambda}^A$ and σ_λ^A (the mean and standard deviation).

Then for future years, 2001+

$$\lambda_y^{A,S} = \bar{\lambda}^A e^{\varepsilon_y^{A,S}} \quad \text{where } \varepsilon_y^{A,S} \sim N(0, \sigma_\lambda^{A^2}) \tag{4}$$

and for each year, $$\lambda_y^{A,S} \rightarrow \frac{\lambda_y^{A,S}}{\sum_{A=1}^{3} \lambda_y^{A,S}} \tag{5}$$

where S is the simulation index. (Note that the assessments provide values for numbers at age at the start of 2007 which are to be projected forward. The provisions of Equation (4) will be effected by the relevant scaling of these numbers for ages 1-5 which have hardly been affected by catches.)

3 Selectivity

MARAM selectivity models (Models 1, 3 and 6)

Model 2 estimates $\delta_y^{m/f,A}$ for 1994 to 2004 (see Johnston and Butterworth (2008a) Equation 24 reproduced below as Equation 6).

$$S_{y,l}^{m/f,A} = \frac{1}{1+e^{-\ln 19(l-(l_{50}^{m/f,A}+\delta_y^{m/f,A})/\Delta^{m/f,A}}} \tag{6}$$

If these δ values change fairly randomly from year to year, we would suggest:

for 2005+ $\quad \delta_y^{m/f,A,S} = \bar{\delta}^{m/f,A} + \eta_y^{m/f,A,S}$ (7)

where $\quad \eta_{y\leq}^{m/f,A,S} \sim N(0, \sigma_\delta^{m/f,A^2})$ (8)

where $\bar{\delta}^{f/m,A}$ and $\sigma_\delta^{m/f,A}$ are calculated as the mean and standard deviation of the 1994 to 2004 estimates.

Note that for Area 3 where there are two selectivity functions (see Johnston and Butterworth (2008b),

$$S_{y,l}^{m/f,3} = (1-\mu)S1_{y,l}^{m/f,3} + \lambda\mu S2_l^{m/f,3} \tag{9}$$

where

$S1_{y,l}^{m/f,3}$ is the original selectivity function (as used for other Areas) and simulated for the future by Equation 7,

$S2_l^{m/f,3} = e^{-\left(l-l_{m/f}^*\right)^2/\omega^2}$ (the second normal-shaped selectivity function which remains fixed over time), and

the μ remains constant in the future at the estimated value.

Inspection of the parameter estimates in Figure 5 suggests that the first four years are poorly informed by the data and should be omitted when computing $\bar{\delta}_y^{m/f}$. Furthermore, these are indications of serial correlation in the residuals, so that a completely random process might be replaced by an AR(1) series approach.

<u>OLRAC selectivity models (Models 2, 4 and 7)</u>
See Johnston and Butterworth (2008b) Equations 8-13 reproduced below as Equations 10-15:

$$\bar{S}_l^{m/f,A} = \frac{1}{1+e^{-\ln 19(l-l_{50}^{m/f,A})/\Delta^{m/f,A}}} \qquad (10)$$

$$S_{y,l}^{m/f,A} = \bar{S}_l^{m/f,A}\alpha_{y,l}^{m/f,A} \qquad (11)$$

where

$$\alpha_{y,l}^{m/f,A} = \frac{x_y^{m/f,A}}{X_y^{m/f,A}} \qquad l \le 50 \qquad (12)$$

$$\alpha_{y,l}^{m/f,A} = \frac{x_y^{m/f,A} + (l-50)(1-x_y^{m/f,A})(l_{kink}-50)}{X_y^{m/f,A}} \qquad 50 \le l \le l_{kink} \qquad (13)$$

$$\alpha_{y,l}^{m/f,A} = \frac{1}{X_y^{m/f,A}} \qquad l > l_{kink} \qquad (14)$$

and where

$$X_y^{m/f,A} = \left\{ \sum_{l=l1}^{50} x_y^{m/f,A} + \sum_{l=51}^{l_{kink}} \left[x_y^{m/f,A} + \frac{(l-50)(1-x_y^{m/f,A})}{l_{kink}-51} \right] + \sum_{l=l_{kink}}^{l2} l \right\} / (l2-l1+1) \qquad (15)$$

The $x_y^{m/f,A}$ are the key time dependent parameters. The estimates of past values shown in Figure 6 show strong serial correlation, though that in part arises from the penalty on changes between years in the estimation procedure (Johnston and Butterworth 2008b). We advocate an approach to generating future values similar to the AR(1) process suggested for the MARAM models in the previous section, except with the autocorrelation parameters likely set somewhat less than indicated by the series shown in Figure 6.

<u>Effort Saturation (Models 5 and 8)</u>
Here as there is no time dependency in selectivity for this model, no further specifications for future selectivity are required.

4. Future data generation
We will need to generate future CPUE values. Whichever model is fit, there is a model estimate for $CPUE_y^A$ for past years. Projected into the future, the model provides expected $CP\hat{U}E_y^A$ values for each year and Area. Future CPUE values will be generated for each area A from:

$$CPUE_y^{A,S} = CP\hat{U}E_y^{A,S}\exp(\varepsilon_y^{A,S}) \qquad \varepsilon_y^{A,S} \sim N(0, \sigma_{CPUE}^{A^2}) \qquad (16)$$

At a later stage, future catch-at-length data may also be generated to allow for testing of the possible use of such data inputs to the OMP as well.

Suggested TAC rule for initial OMP testing

Plans are to start off with a simple rule based on recent CPUE trends, *viz.*

$$TAC_{y+1} = TAC_y(1+\lambda s_y^A) \qquad (17)$$

where

s_y^A is the slope parameter from a regression of $\ln CPUE_y^A$ versus y over the last five years for each area A, and

$$s_y = \sum_{A=1}^{3} w^A s_y^A \qquad (18)$$

where $w^A = \dfrac{\frac{1}{\sigma_S^{A^2}}}{\sum_{A'=1}^{3}(\frac{1}{\sigma_S^{A'^2}})}$

and σ_S^A is the standard error of the regression estimate of s_y^A.

A rule to control the inter-annual TAC variation would also be applied e.g. no more that 10% up or down from year to year.

How should the future catch be divided by Area? We suggest for a start to take the average areal split over the last five years and use that for each year in the future.

References

Glazer, J.P. 2008. South Coast rock lobster catches per area. MCM document, WG/04/08/SCRL8.

Glazer, J.P. and D.S. Butterworth. 2008a. Alternative calculation of catches per Area in the South Coast rock lobster fishery. MCM document, WG/05/08/SCRL?.

Glazer, J.P. and D.S. Butterworth. 2008b. A generalized linear model applied to the South Coast rock lobster CPUE data to obtain area-specific indices of abundance. MCM document, WG/04/08/SCRL?

Glazer, J.P. and D.S. Butterworth. 2008b. Size composition of male and female South Coast rock lobsters per season and area. MCM document, WG/04/08/SCRL?

Johnston, S.J. and D.S. Butterworth. 2008a. The Age-Structured Production model for the South Coast rock lobster population extended to be sex- and area-specific, to fit to catch-at-length data, and to use Pope's approximation.. MCM document, WG/02/08/SCRL1.

Johnston, S.J. and D.S. Butterworth. 2008b. Further results for the sex- and area-specific Age-Structured Production model for the South Coast rock lobster resource. MCM document, WG/03/08/SCRL3.

Johnston, S.J. and D.S. Butterworth. 2008c. Further specifications for the sex- and area-specific Operating Models for testing OMPs for the South Coast rock lobster resource MCM document, WG/04/08/SCRL12.

Table 1: Model 0 (no time varying selectivity or effort saturation effects, but **two** selectivity functional forms for Area 3) estimated parameters and quantities of management interest. The **new** catch series is used. Biomass quantities are in MT. The number of parameters estimated is 140.

Parameter/quantity		**Global**	**Area 1**	**Area 2**	**Area 3**
Total number of estimable parameters		140			
K^{sp}	total female spawning biomass	772			
h	S/R steepness parameter	0.733			
λ^A	proportion R to Area A		0.38	0.44	0.18
μ^A	rel. female scaling parameter for Area A		1.25	1.24	1.19
$l_{50}^{m,A}$	length at 50% selectivity for male lobsters in Area A (mm)		66.9	61.8	59.0
$l_{95}^{m,A}$	length at 95% selectivity for male lobsters in Area A (mm)		76.6	67.9	59.1
$l_{50}^{f,A}$	length at 50% selectivity for female lobsters in Area A (mm)		64.7	61.2	73.3
$l_{95}^{f,A}$	length at 95% selectivity for male lobsters in Area A (mm)		71.5	68.7	80.4
β^*	growth function parameter	0.104			
$L_\infty^{m,A}$	L_∞ for male lobsters in Area A (mm)		104.77	107.21	112.71
$L_\infty^{f,A}$	L_∞ for female lobsters in Area A (mm)		101.06	100.74	110.27
κ	growth curve parameter (yr^{-1})	0.09			
t_0	growth curve parameter (yr^{-1})	-1.93			
l_m^*		63.23			
l_f^*		63.20			
ϖ		7.24			
λ		0.76			
-ln L (CPUE)		-83.22	-28.95	-20.69	-72.77
CPUE σ			0.191	0.224	0.297
-ln L (CAL)		-170.74	-72.77	-20.04	-77.93
CAL σ			0.062	0.096	0.061
SR residual penalty		7.53			
Time varying selectivity penalty		-			
Growth parameters penalty		2.23			
Time varying recruitment penalty		17.47			
Total –ln$L$ value		-225.60			
B_{06}^{sp} / K^{sp}		0.34			
$B_{06}^{\exp,A} / K_{1973}^{\exp,A}$		0.30	0.33	0.29	0.26
$B_{06}^{\exp,A}$		504	178	213	113
$B_{2015}^{sp} / B_{2006}^{sp}$ *		0.89			
RY		330			

* The basis for this projection under a total future annual catch of 381 tons is detailed in the text.

Table 2: Model 1 (time varying selectivity MARAM method – a combination of **two** selectivity functional forms for Area 3) estimated parameters and quantities of management interest. The **old** catch series is used. Biomass quantities are in MT. The number of parameters estimated is 206.

Parameter/quantity		Global	Area 1	Area 2	Area 3
Total number of estimable parameters		206			
K^{sp}	total female spawning biomass	796			
h	S/R steepness parameter	0.705			
λ^A	proportion R to Area A		0.38	0.40	0.22
μ^A	rel. female scaling parameter for Area A		1.25	1.25	1.20
$l_{50}^{m,A}$	length at 50% selectivity for male lobsters in Area A (mm)		67.90	62.00	60.00
$l_{95}^{m,A}$	length at 95% selectivity for male lobsters in Area A (mm)		77.32	62.00	60.00
$l_{50}^{f,A}$	length at 50% selectivity for female lobsters in Area A (mm)		65.82	62.29	74.29
$l_{95}^{f,A}$	length at 95% selectivity for male lobsters in Area A (mm)		72.45	69.24	81.06
β^*	growth function parameter	0.104			
$L_\infty^{m,A}$	L_∞ for male lobsters in Area A (mm)		104.94	107.04	112.58
$L_\infty^{f,A}$	L_∞ for female lobsters in Area A (mm)		101.05	100.39	110.22
κ	growth curve parameter (yr^{-1})	0.089			
t_0	growth curve parameter (yr^{-1})	-1.94			
l_m^*		63.22			
l_f^*		63.22			
ϖ		7.25			
λ		0.77			
-ln L (CPUE)		-80.07	-36.40	-22.30	-21.36
CPUE σ			0.173	0.281	0.290
-ln L (CAL)		-183.67	-77.01	-29.23	-77.45
CAL σ			0.061	0.092	0.061
SR residual penalty		7.53			
Time varying selectivity penalty		3.26			
Growth parameters penalty		2.34			
Time varying recruitment penalty		17.50			
Total –ln$L$ value		-231.66			
B_{06}^{sp} / K^{sp}		0.35			
$B_{06}^{\exp,A} / K_{1973}^{\exp,A}$		0.30	0.33	0.28	0.32
$B_{06}^{\exp,A}$		529	176	191	162
$B_{2015}^{sp} / B_{2006}^{sp}$ *		0.89			
RY		328			

* The basis for this projection under a total future annual catch of 381 tons is detailed in the text.

Table 3: Model 2 (time varying selectivity OLRAC method – variant 3e) estimated parameters and quantities of management interest. The **old** catch series is used. Biomass quantities are in MT. The number of parameters estimated is 332.

Parameter/quantity		**Global**	**Area 1**	**Area 2**	**Area 3**
Total number of estimable parameters		332			
K^{sp}	total female spawning biomass	1084			
h	S/R steepness parameter	0.753			
λ^A	proportion R to Area A		0.35	0.32	0.33
μ^A	rel. female scaling parameter for Area A		1.28	1.67	1.47
$l_{50}^{m,A}$	length at 50% selectivity for male lobsters in Area A (mm)		64.58	61.26	50.45
$l_{95}^{m,A}$	length at 95% selectivity for male lobsters in Area A (mm)		74.48	64.05	50.64
$l_{50}^{f,A}$	length at 50% selectivity for female lobsters in Area A (mm)		63.97	60.70	66.65
$l_{95}^{f,A}$	length at 95% selectivity for male lobsters in Area A (mm)		70.04	68.07	77.45
β^*	growth function parameter	0.130			
$L_\infty^{m,A}$	L_∞ for male lobsters in Area A (mm)		104.83	107.34	111.36
$L_\infty^{f,A}$	L_∞ for female lobsters in Area A (mm)		98.32	101.33	108.07
κ	growth curve parameter (yr^{-1})	0.079			
t_0	growth curve parameter (yr^{-1})	-1.77			
l_m^*		63.82			
l_f^*		61.80			
ϖ		6.63			
λ		0.871			
-ln L (CPUE)		-93.73	-43.80	-32.37	-17.56
CPUE σ			0.134	0.199	0.331
-ln L (CAL)		-269.08	-61.52	-54.81	-152.75
CAL σ			0.066	0.081	0.045
SR residual penalty		4.38			
Time varying selectivity penalty		8.14			
Growth parameters penalty		6.54			
Time varying recruitment penalty		12.94			
Total –ln$L$ value		-298.09			
B_{06}^{sp} / K^{sp}		0.47			
$B_{06}^{\exp,A} / K_{1973}^{\exp,A}$		0.34	0.38	0.29	0.38
$B_{06}^{\exp,A}$		569	221	210	138
$B_{2015}^{sp} / B_{2006}^{sp}$ *		0.97			
355					

* The basis for this projection under a total future annual catch of 381 tons is detailed in the text.

Table 4: Model 3 (time varying selectivity MARAM method – a combination of **two** selectivity functional forms for Area 3) estimated parameters and quantities of management interest. The **new** catch series is used. Biomass quantities are in MT. The number of parameters estimated is 206.

Parameter/quantity	**Global**	**Area 1**	**Area 2**	**Area 3**
Total number of estimable parameters	206			
K^{sp} total female spawning biomass	781			
h S/R steepness parameter	0.713			
λ^A proportion R to Area A		0.37	0.44	0.19
μ^A rel. female scaling parameter for Area A		1.25	1.23	1.19
$l_{50}^{m,A}$ length at 50% selectivity for male lobsters in Area A (mm)		67.84	61.98	60.03
$l_{95}^{m,A}$ length at 95% selectivity for male lobsters in Area A (mm)		77.19	61.98	60.03
$l_{50}^{f,A}$ length at 50% selectivity for female lobsters in Area A (mm)		65.81	62.31	74.42
$l_{95}^{f,A}$ length at 95% selectivity for male lobsters in Area A (mm)		72.38	62.31	81.12
β^* growth function parameter	0.104			
$L_\infty^{m,A}$ L_∞ for male lobsters in Area A (mm)		104.94	107.05	112.59
$L_\infty^{f,A}$ L_∞ for female lobsters in Area A (mm)		101.05	100.40	110.22
κ growth curve parameter (yr^{-1})	0.090			
t_0 growth curve parameter (yr^{-1})	-1.93			
l_m^*	63.21			
l_f^*	63.28			
ϖ	7.25			
λ	0.76			
-ln L (CPUE)	-83.55	-33.91	-28.60	-21.02
CPUE σ		0.188	0.226	0.294
-ln L (CAL)	-180.20	-77.49	-24.92	-77.78
CAL σ		0.061	0.094	0.061
SR residual penalty	7.20			
Time varying selectivity penalty	3.25			
Growth parameters penalty	2.31			
Time varying recruitment penalty	17.54			
Total –ln$L$ value	-231.23			
B_{06}^{sp} / K^{sp}	0.34			
$B_{06}^{\exp,A} / K_{1973}^{\exp,A}$	0.29	0.33	0.29	0.26
$B_{06}^{\exp,A}$	503	177	211	115
$B_{2015}^{sp} / B_{2006}^{sp}$ *	0.89			
RY	330			

* The basis for this projection under a total future annual catch of 381 tons is detailed in the text.

Table 5: Model 4 (time varying selectivity OLRAC method – variant 3e) estimated parameters and quantities of management interest. The **new** catch series is used. Biomass quantities are in MT. The number of parameters estimated is 332.

Parameter/quantity		**Global**	**Area 1**	**Area 2**	**Area 3**
Total number of estimable parameters		332			
K^{sp}	total female spawning biomass	1110			
h	S/R steepness parameter	0.724			
λ^A	proportion R to Area A		0.30	0.32	0.38
μ^A	rel. female scaling parameter for Area A		1.26	1.55	1.33
$l_{50}^{m,A}$	length at 50% selectivity for male lobsters in Area A (mm)		66.03	62.70	52.97
$l_{95}^{m,A}$	length at 95% selectivity for male lobsters in Area A (mm)		74.87	68.82	74.64
$l_{50}^{f,A}$	length at 50% selectivity for female lobsters in Area A (mm)		65.41	62.34	55.90
$l_{95}^{f,A}$	length at 95% selectivity for male lobsters in Area A (mm)		71.79	70.01	74.05
β^*	growth function parameter	0.119			
$L_\infty^{m,A}$	L_∞ for male lobsters in Area A (mm)		104.73	106.21	110.04
$L_\infty^{f,A}$	L_∞ for female lobsters in Area A (mm)		99.16	100.63	107.58
κ	growth curve parameter (yr^{-1})	0.084			
t_0	growth curve parameter (yr^{-1})	-1.98			
l_m^*		64.11			
l_f^*		62.27			
ϖ		6.24			
λ		0.87			
-ln L (CPUE)		-89.40	-39.24	-36.40	-13.76
CPUE σ			0.157	0.173	0.377
-ln L (CAL)		-269.06	-61.51	-45.97	-153.57
CAL σ			0.063	0.084	0.045
SR residual penalty		4.23			
Time varying selectivity penalty		7.38			
Growth parameters penalty		4.29			
Time varying recruitment penalty		14.78			
Total –ln$L$ value		-296.70			
B_{06}^{sp} / K^{sp}		0.47			
$B_{06}^{\exp,A} / K_{1973}^{\exp,A}$		0.37	0.36	0.34	0.43
$B_{06}^{\exp,A}$		584	201	222	161
$B_{2015}^{sp} / B_{2006}^{sp}$ *		0.98			
RY		360			

* The basis for this projection under a total future annual catch of 381 tons is detailed in the text.

Table 6: Model 5 (effort saturation in Areas 1, 2 and 3, no time-varying selectivity) estimated parameters and quantities of management interest. The **new** catch series is used. Biomass quantities are in MT. The number of parameters estimated is 146.

Parameter/quantity	**Global**	**Area 1**	**Area 2**	**Area 3**
Total number of estimable parameters	146			
K^{sp} total female spawning biomass	793			
h S/R steepness parameter	0.714			
λ^A proportion R to Area A		0.37	0.45	0.18
μ^A rel. female scaling parameter for Area A		1.24	1.21	1.19
$l_{50}^{m,A}$ length at 50% selectivity for male lobsters in Area A (mm)		67.96	63.00	59.09
$l_{95}^{m,A}$ length at 95% selectivity for male lobsters in Area A (mm)		77.63	63.00	59.11
$l_{50}^{f,A}$ length at 50% selectivity for female lobsters in Area A (mm)		65.80	61.99	74.46
$l_{95}^{f,A}$ length at 95% selectivity for male lobsters in Area A (mm)		72.59	69.33	81.36
β^* growth function parameter	0.104			
$L_\infty^{m,A}$ L_∞ for male lobsters in Area A (mm)		104.94	107.04	112.59
$L_\infty^{f,A}$ L_∞ for female lobsters in Area A (mm)		101.06	100.40	110.22
κ growth curve parameter (yr^{-1})	0.090			
t_0 growth curve parameter (yr^{-1})	-1.94			
l_m^*	63.28			
l_f^*	63.25			
ϖ	7.30			
λ	0.76			
E'		209	205	161
-ln L (CPUE)	-84.31	-34.19	-29.03	-21.09
CPUE σ		0.186	0.223	0.293
-ln L (CAL)	-169.76	-73.29	-18.86	-77.61
CAL σ		0.062	0.097	0.061
SR residual penalty	7.53			
Growth parameters penalty	2.34			
Time varying recruitment penalty	17.71			
Total –ln$L$ value	-224.27			
B_{06}^{sp}/K^{sp}	0.35			
$B_{06}^{\exp,A}/K_{1973}^{\exp,A}$	0.30	0.33	0.31	0.26
$B_{06}^{\exp,A}$	526	180	230	116
$B_{2015}^{sp}/B_{2006}^{sp}$ *	0.89			
RY	325			

* The basis for this projection under a total future annual catch of 381 tons is detailed in the text.

Table 7: Model 6 (time varying selectivity MARAM method – a combination of **two** selectivity functional forms for Area 3) estimated parameters and quantities of management interest. The **new** catch series is used and the catch-at-length data are **down-weighted** by a factor of 0.1 in the likelihood. Biomass quantities are in MT. The number of parameters estimated is 206.

Parameter/quantity		**Global**	**Area 1**	**Area 2**	**Area 3**
Total number of estimable parameters		206			
K^{sp}	total female spawning biomass	731			
h	S/R steepness parameter	0.938			
λ^A	proportion R to Area A		0.38	0.41	0.21
μ^A	rel. female scaling parameter for Area A		2.08	3.00	1.44
$l_{50}^{m,A}$	length at 50% selectivity for male lobsters in Area A (mm)		67.61	62.00	60.01
$l_{95}^{m,A}$	length at 95% selectivity for male lobsters in Area A (mm)		76.82	62.00	60.01
$l_{50}^{f,A}$	length at 50% selectivity for female lobsters in Area A (mm)		67.96	66.60	75.77
$l_{95}^{f,A}$	length at 95% selectivity for male lobsters in Area A (mm)		75.81	76.83	79.69
β^*	growth function parameter	0.110			
$L_\infty^{m,A}$	L_∞ for male lobsters in Area A (mm)		104.45	107.10	112.39
$L_\infty^{f,A}$	L_∞ for female lobsters in Area A (mm)		100.18	100.83	110.09
κ	growth curve parameter (yr^{-1})	0.089			
t_0	growth curve parameter (yr^{-1})	-1.98			
l_m^*		63.74			
l_f^*		63.95			
ϖ		7.75			
λ		0.74			
-ln L (CPUE)		-119.73	-44.18	-48.95	-26.60
CPUE σ			0.132	0.112	0.243
-ln L (CAL)*		-27.21	-19.55	31.79	-39.46
CAL σ			0.079	0.124	0.071
SR residual penalty		4.28			
Time varying selectivity penalty		0.200			
Growth parameters penalty		2.19			
Time varying recruitment penalty		5.67			
Total –ln$L$ value		-110.80			
B_{06}^{sp} / K^{sp}		0.32			
$B_{06}^{\exp,A} / K_{1973}^{\exp,A}$		0.34	0.32	0.35	0.34
$B_{06}^{\exp,A}$		779	233	368	176
$B_{2015}^{sp} / B_{2006}^{sp}$ *		0.97			
		365			

* These values are downweighted by a factor of 0.10 in the total -*ln*L

Table 8: Model 7 (time varying selectivity OLRAC method – variant 3e) estimated parameters and quantities of management interest. The **new** catch series is used and the catch-at-length data are **down-weighted** by a factor of 0.1 in the likelihood. Biomass quantities are in MT. The number of parameters estimated is 322.

Parameter/quantity		**Global**	**Area 1**	**Area 2**	**Area 3**
Total number of estimable parameters		332			
K^{sp}	total female spawning biomass	1170			
h	S/R steepness parameter	0.912			
λ^A	proportion R to Area A		0.33	0.28	0.43
μ^A	rel. female scaling parameter for Area A		2.34	2.94	3.00
$l_{50}^{m,A}$	length at 50% selectivity for male lobsters in Area A (mm)		65.05	12.71	39.46
$l_{95}^{m,A}$	length at 95% selectivity for male lobsters in Area A (mm)		73.13	34.82	45.37
$l_{50}^{f,A}$	length at 50% selectivity for female lobsters in Area A (mm)		66.79	1.76	17.45
$l_{95}^{f,A}$	length at 95% selectivity for male lobsters in Area A (mm)		73.85	17.89	26.93
β^*	growth function parameter	0.124			
$L_\infty^{m,A}$	L_∞ for male lobsters in Area A (mm)		104.48	109.49	118.04
$L_\infty^{f,A}$	L_∞ for female lobsters in Area A (mm)		94.88	99.84	108.29
κ	growth curve parameter (yr^{-1})	0.087			
t_0	growth curve parameter (yr^{-1})	-1.96			
l_m^*		57.03			
l_f^*		50.00			
ϖ		11.77			
λ		0.98			
-ln L (CPUE)		-169.31	-46.05	-62.57	-60.69
CPUE σ			0.123	0.100	0.100
-ln L (CAL)*		175.4	-3.73	61.53	117.6
CAL σ			0.085	0.144	0.132
SR residual penalty		3.18			
Time varying selectivity penalty		2.31			
Growth parameters penalty		1.31			
Time varying recruitment penalty		6.09			
Total –ln$L$ value		-130.28			
B_{06}^{sp} / K^{sp}		0.47			
$B_{06}^{\exp,A} / K_{1973}^{\exp,A}$		0.30	0.39	0.26	0.21
$B_{06}^{\exp,A}$		674	340	234	99
$B_{2015}^{sp} / B_{2006}^{sp}$ *		1.01			
RY		385			

* These values are downweighted by a factor of 0.10 in the total -*ln*L

Table 9: Model 8 (effort saturation in Areas 1, 2 and 3, no time-varying selectivity) estimated parameters and quantities of management interest. The **new** catch series is used and the catch-at-length data are **down-weighted** by a factor of 0.1 in the likelihood. Biomass quantities are in MT. The number of parameters estimated is 146.

Parameter/quantity		**Global**	**Area 1**	**Area 2**	**Area 3**
Total number of estimable parameters		146			
K^{sp}	total female spawning biomass	976			
h	S/R steepness parameter	0.828			
λ^{A}	proportion R to Area A		0.34	0.33	0.33
μ^{A}	rel. female scaling parameter for Area A		2.76	2.98	1.23
$l_{50}^{m,A}$	length at 50% selectivity for male lobsters in Area A (mm)		67.52	61.89	59.98
$l_{95}^{m,A}$	length at 95% selectivity for male lobsters in Area A (mm)		76.77	68.10	60.00
$l_{50}^{f,A}$	length at 50% selectivity for female lobsters in Area A (mm)		69.23	67.34	72.95
$l_{95}^{f,A}$	length at 95% selectivity for male lobsters in Area A (mm)		77.89	79.22	74.61
β^{*}	growth function parameter	0.115			
$L_{\infty}^{m,A}$	L_{∞} for male lobsters in Area A (mm)		102.88	106.62	108.78
$L_{\infty}^{f,A}$	L_{∞} for female lobsters in Area A (mm)		97.77	101.82	105.92
κ	growth curve parameter (yr^{-1})	0.091			
t_0	growth curve parameter (yr^{-1})	-1.99			
l_m^{*}		63.65			
l_f^{*}		63.12			
ϖ		7.41			
λ		0.86			
E'			352	420	121
-ln *L* (CPUE)		-121.30	-45.78	-47.92	-28.03
CPUE σ			0.125	0.116	0.231
-ln *L* (CAL)*		-9.93	0.280	26.18	-36.40
CAL σ			0.087	0.121	0.072
SR residual penalty		2.60			
Growth parameters penalty		2.12			
Time varying recruitment penalty		5.03			
Total –ln*L* value		-113.47			
B_{06}^{sp} / K^{sp}		0.37			
$B_{06}^{\exp,A} / K_{1973}^{\exp,A}$		0.37	0.32	0.33	0.46
$B_{06}^{\exp,A}$		1042	286	340	416
$B_{2015}^{sp} / B_{2006}^{sp}$ *		1.03			
RY		390			

* These values are downweighted by a factor of 0.10 in the total -*ln*L

.

Table 10a: Comparisons of the CPUE σ values for each of the nine models.

Model	Area 1	Area 2	Area 3
0	0.191	0.224	0.297
1	0.173	0.281	0.290
2	0.145	0.235	0.369
3	0.188	0.226	0.293
4	0.157	0.173	0.377
5	0.187	0.223	0.293
6	0.132	0.112	0.242
7	0.123	0.100*	0.100*
8	0.125	0.116	0.231

* Constraint boundary

Table 10b: Comparisons of the catch-at-length σ values for each of the nine models.

Model	Area 1	Area 2	Area 3
0	0.062	0.096	0.061
1	0.061	0.092	0.061
2	0.063	0.084	0.045
3	0.061	0.094	0.061
4	0.063	0.084	0.045
5	0.062	0.097	0.061
6	0.079	0.124	0.071
7	0.085	0.144	0.133
8	0.087	0.121	0.072

Table 11: Comparisons between Models 0-8 of key parameters and management quantities.

Parameter/quantity	**Model 0**	**Model 1**	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**	**Model 8**
	xnoes	susana3	olrac3e	m2nc	olnc	es4	cdw01nc	cdwol	es401
	No TVS or ES + new catch	MARAM TVS + old catch	OLRAC TVS + old catch	MARAM TVS + new catch	OLRAC TVS + new catch	ES + new catch	MARAM TVS + CDW + new catch	OLRAC TVS +CDW + new catch	ES + CDW + new catch
K^{sp} (female)	772	796	1044	781	1110	793	731	1170	976
h	0.733	0.705	0.739	0.713	0.723	0.714	0.938	0.912	0.828
-ln L (CPUE)	-83.22	-80.07	-83.43	-83.55	-89.40	-84.31	-119.73	-169.31	-121.73
-ln L (CAL)	-170.74	-183.67	-272.95	-180.20	-269.06	-169.76	-27.21*	175.4*	-9.93*
Total –ln$L$ values	-224.60	-231.66	-293.20	-231.23	-296.70	-224.27	-110.80	-130.28	-113.47
# estimable parameters	140	206	332	206	332	146	206	332	146
AIC	-169.20	-51.32	77.6	-50.46	70.6	-156.5	190.4	403.4	65.0
B_{06}^{sp} / K^{sp}	0.34	0.35	0.46	0.34	0.47	0.35	0.32	0.47	0.37
$B_{06}^{\exp} / K^{\exp}$	0.30	0.30	0.36	0.29	0.37	0.30	0.34	0.30	0.37
$B_{06}^{\exp}$	504	529	551	503	584	526	779	674	1042
$B_{2015}^{sp} / B_{2006}^{sp}$ **	0.89	0.89	0.97	0.89	0.98	0.89	0.97	1.01	1.03
RY	330	328	355	330	360	325	365	385	390

* These values are down-weighted by a factor of 0.10 when added to the total –*ln*L
** Under a future annual catch of 381 MT,=

Figure 1a: Comparison of model fits to observed CPUE trends for Models 0, 1 and 2.

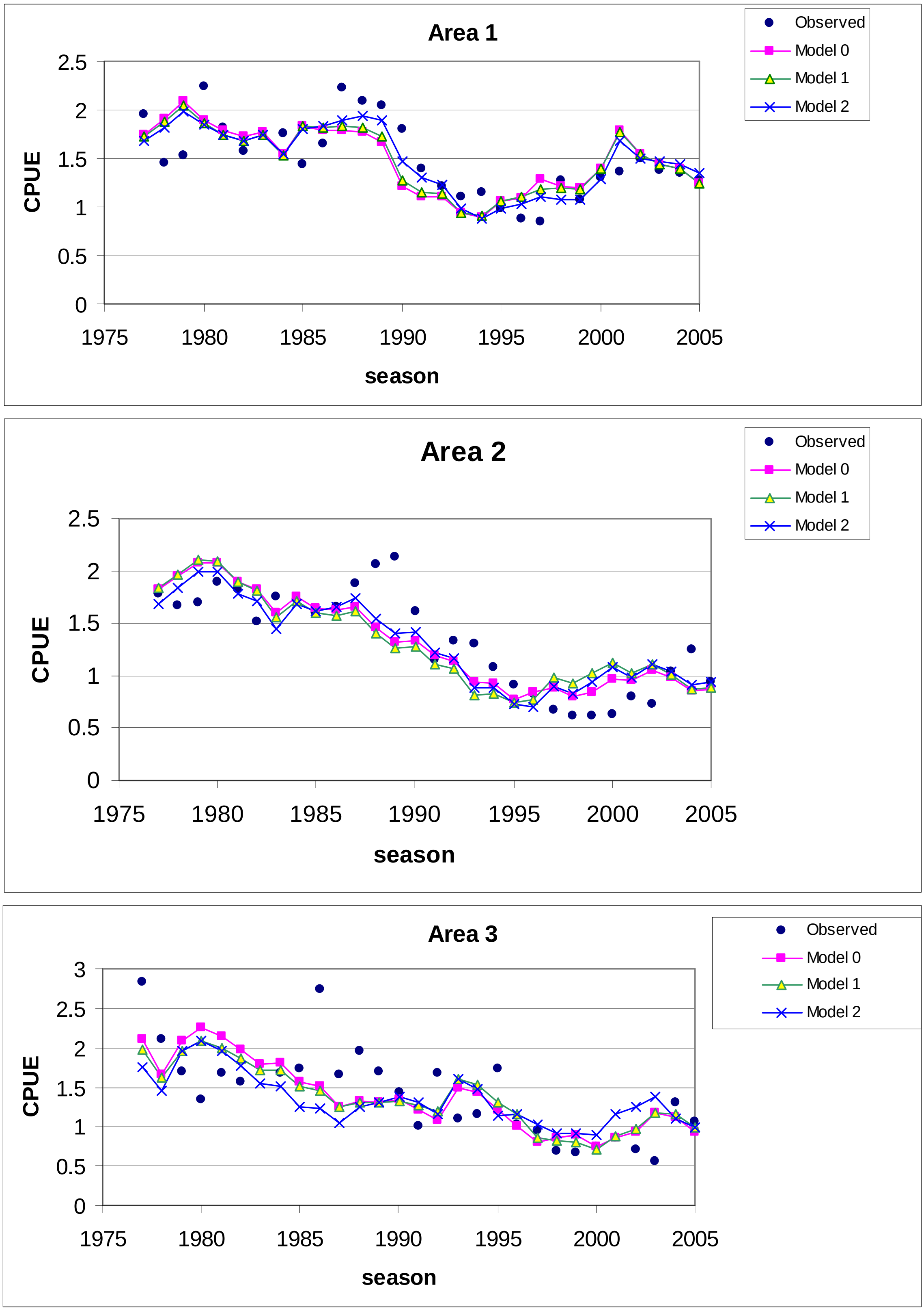


Figure 1b: Comparison of model fits to observed CPUE trends for Models 3, 4 and 5.

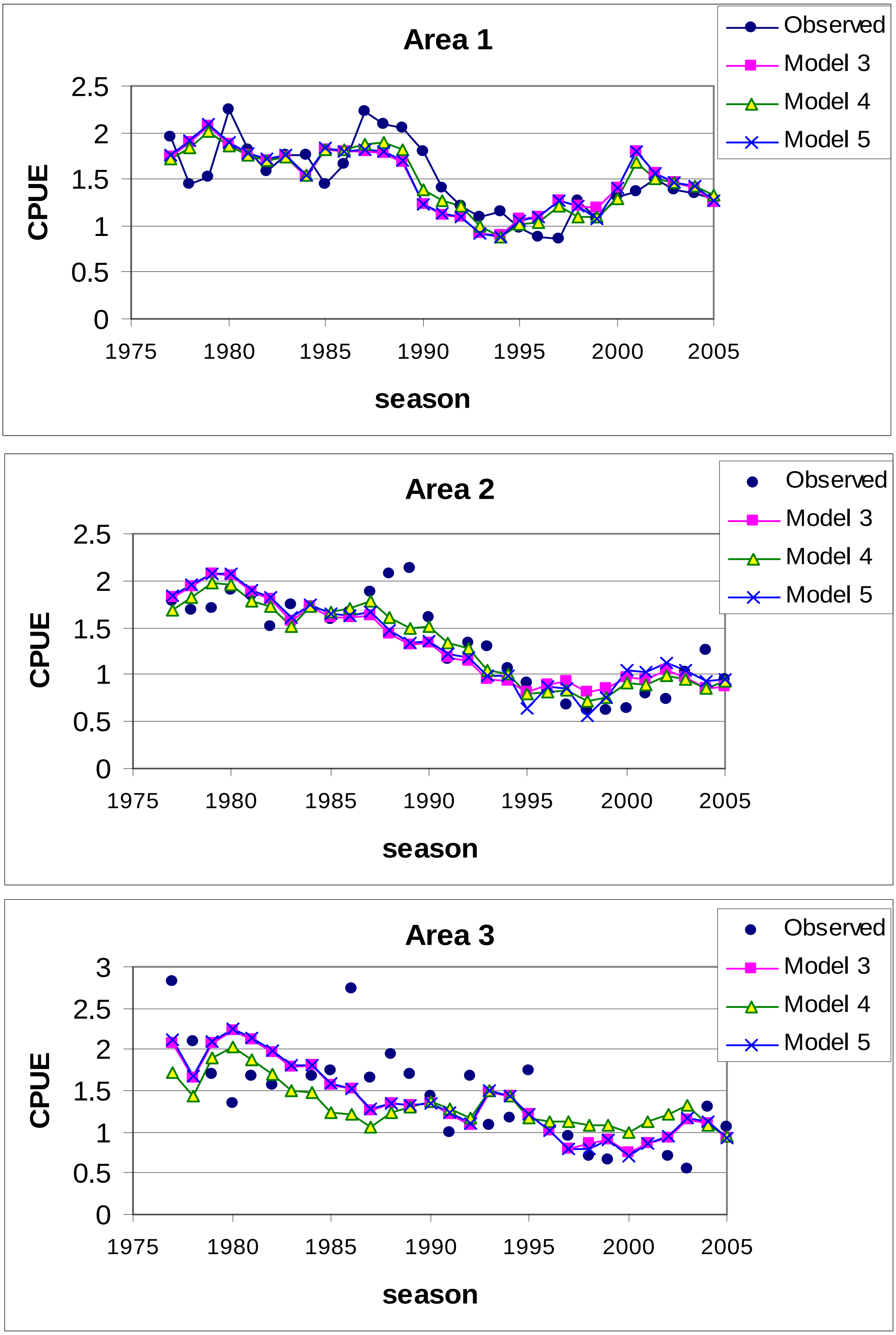
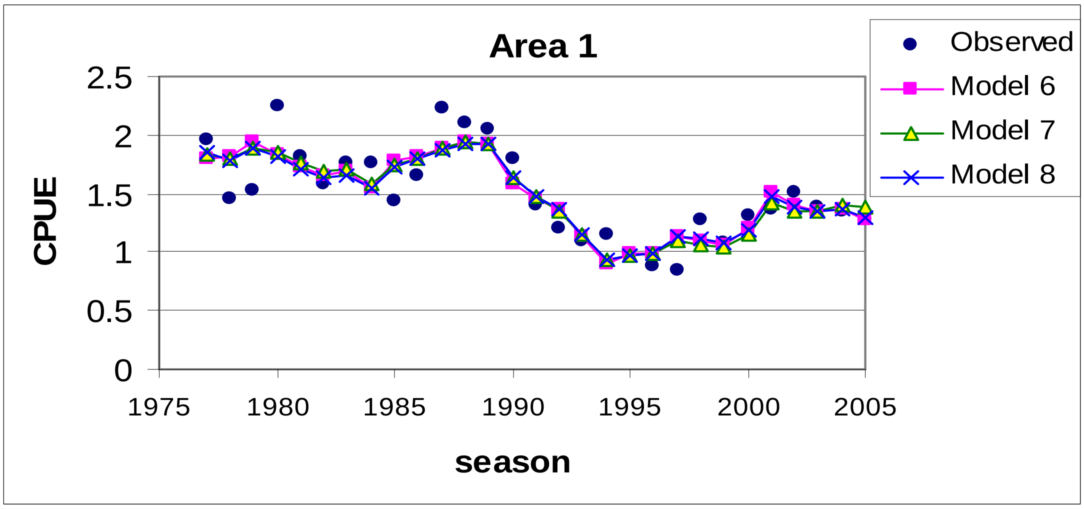
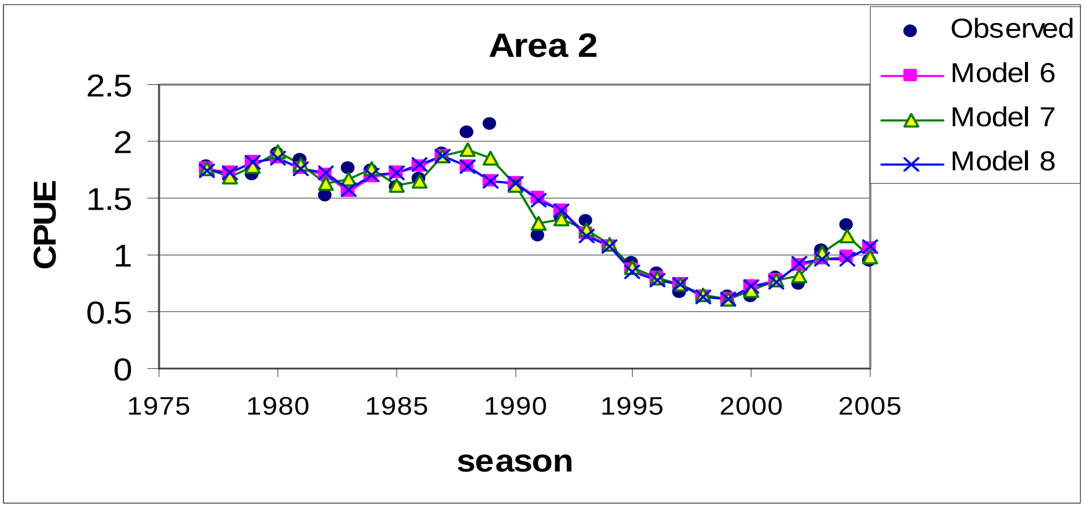


Figure 1c: Comparison of model fits to observed CPUE trends for Models 6, 7 and 8.





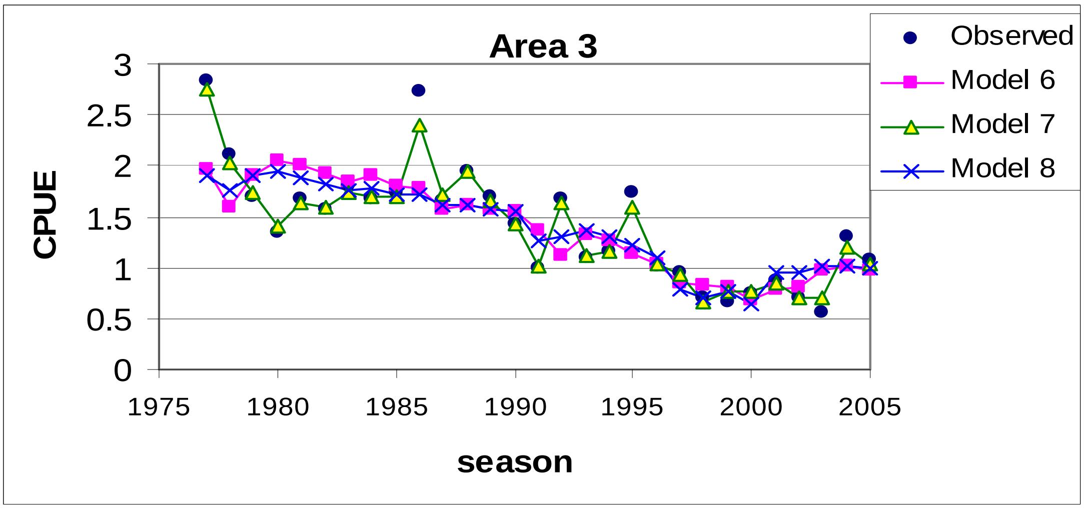


Figure 2a: Comparison of model fits to observed catch-at-length (CAL) trends for Models 3, 4 and 5 for 1995 (an early year in the data period). Note that proportions sum to 1 for males and females combined.

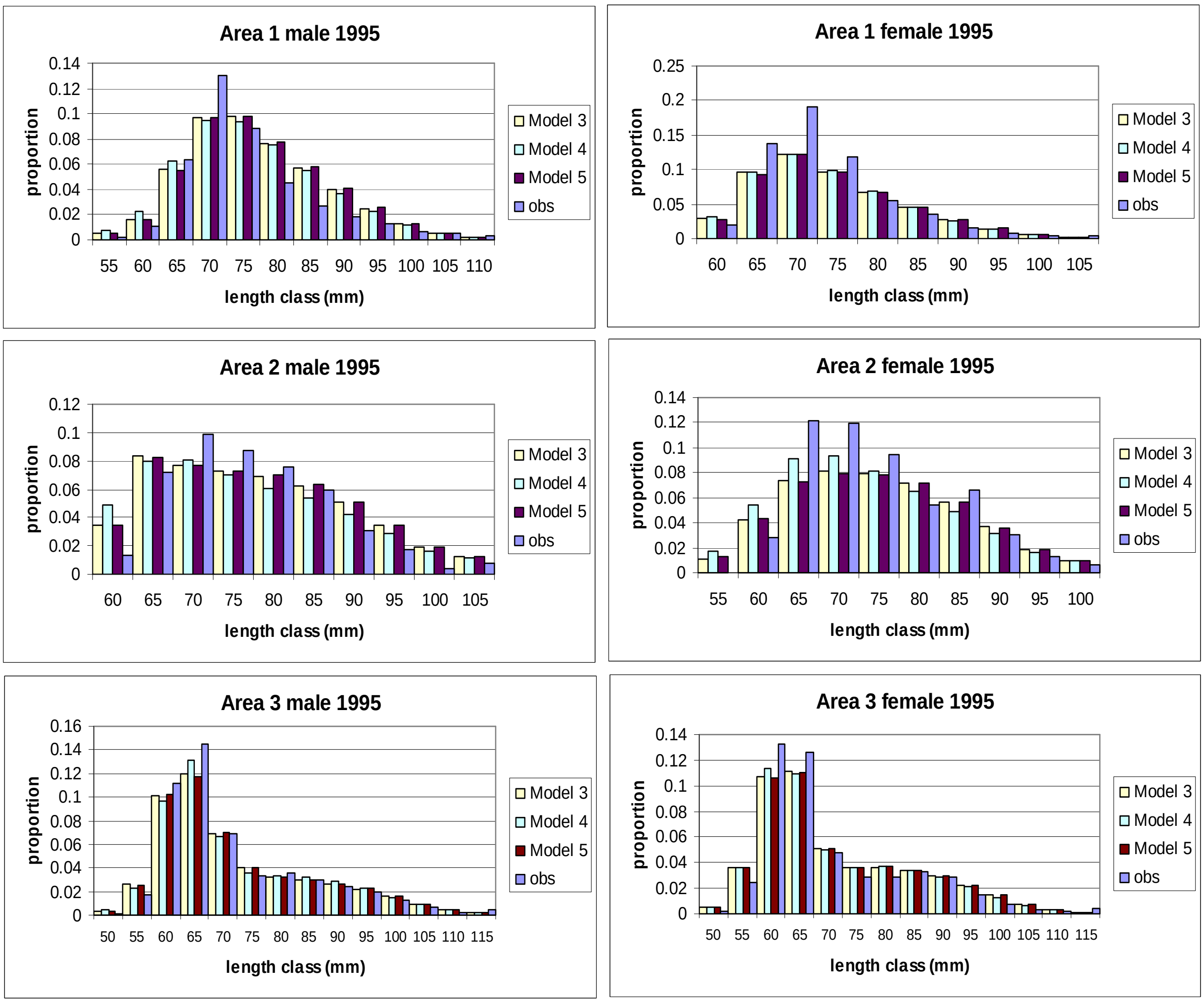


Figure 2b: Comparison of model fits to observed catch-at-length (CAL) trends for Models 3, 4 and 5 for 2002 (a middle year in the data period). Note that proportions sum to 1 for males and females combined.

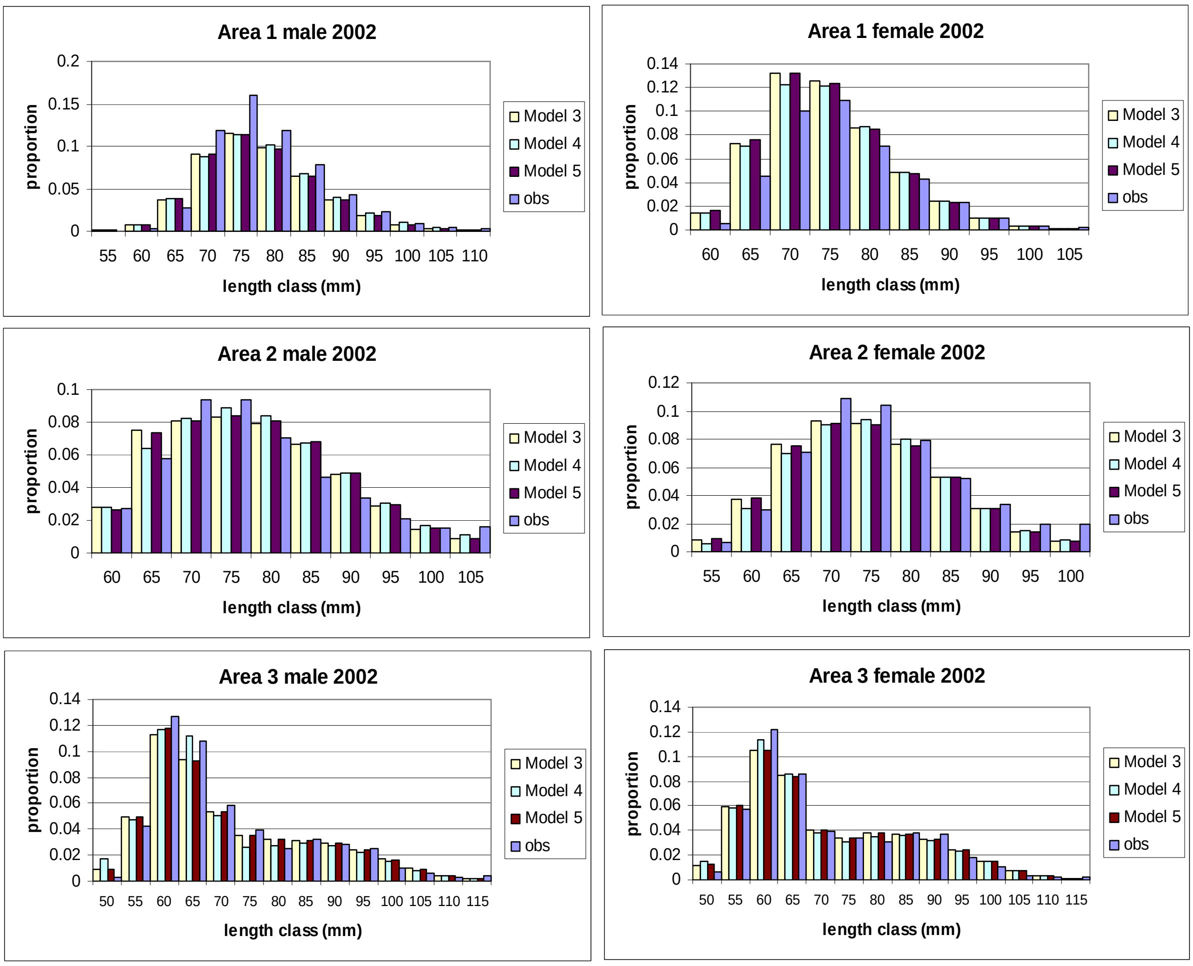


Figure 2c: Comparison of model fits to observed catch-at-length (CAL) trends for Models 3, 4 and 5 for 2005 (the last year in the data period). Note that proportions sum to 1 for males and females combined.

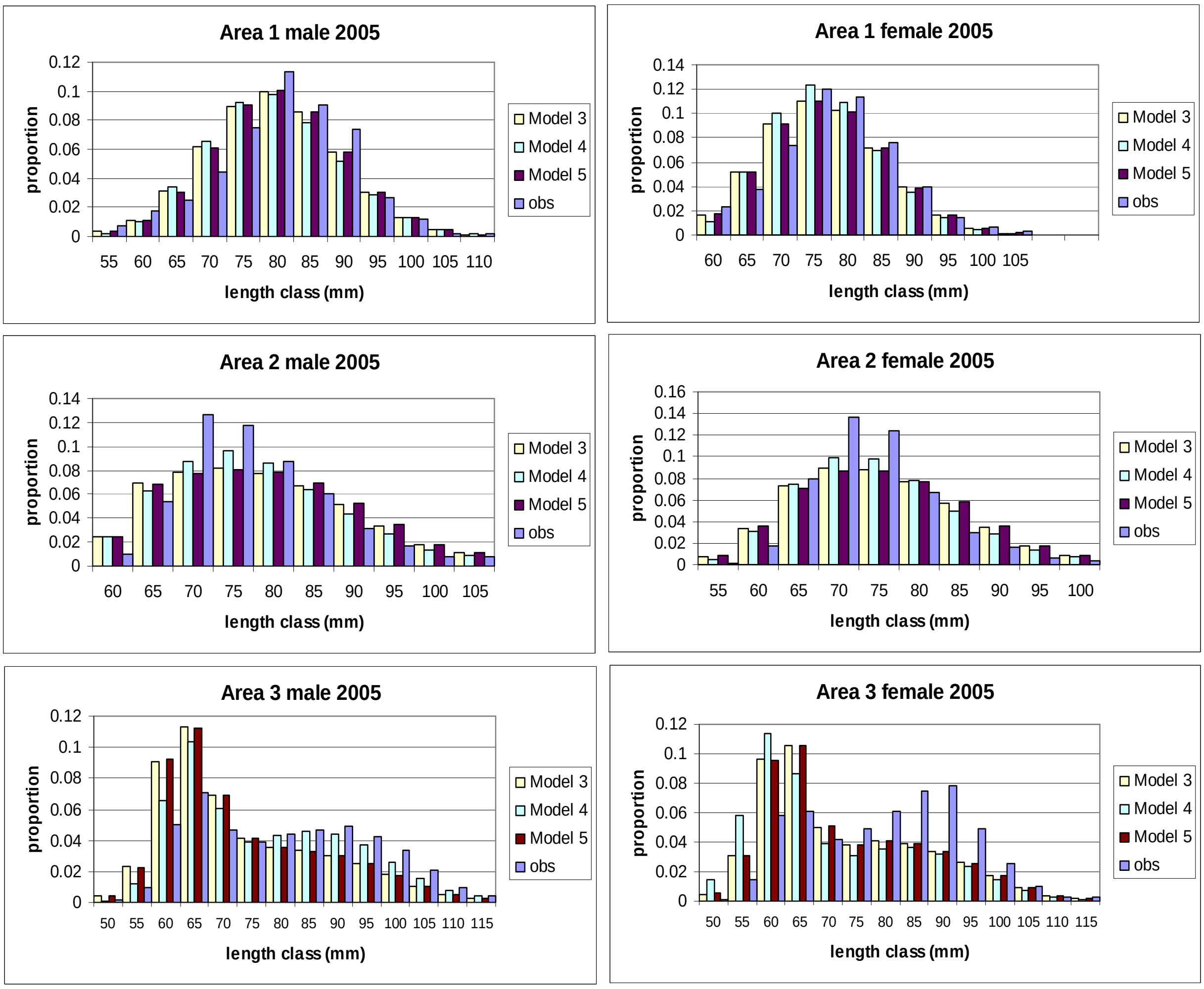


Figure 3: Plots of the stock recruit residuals for Models 1-8.

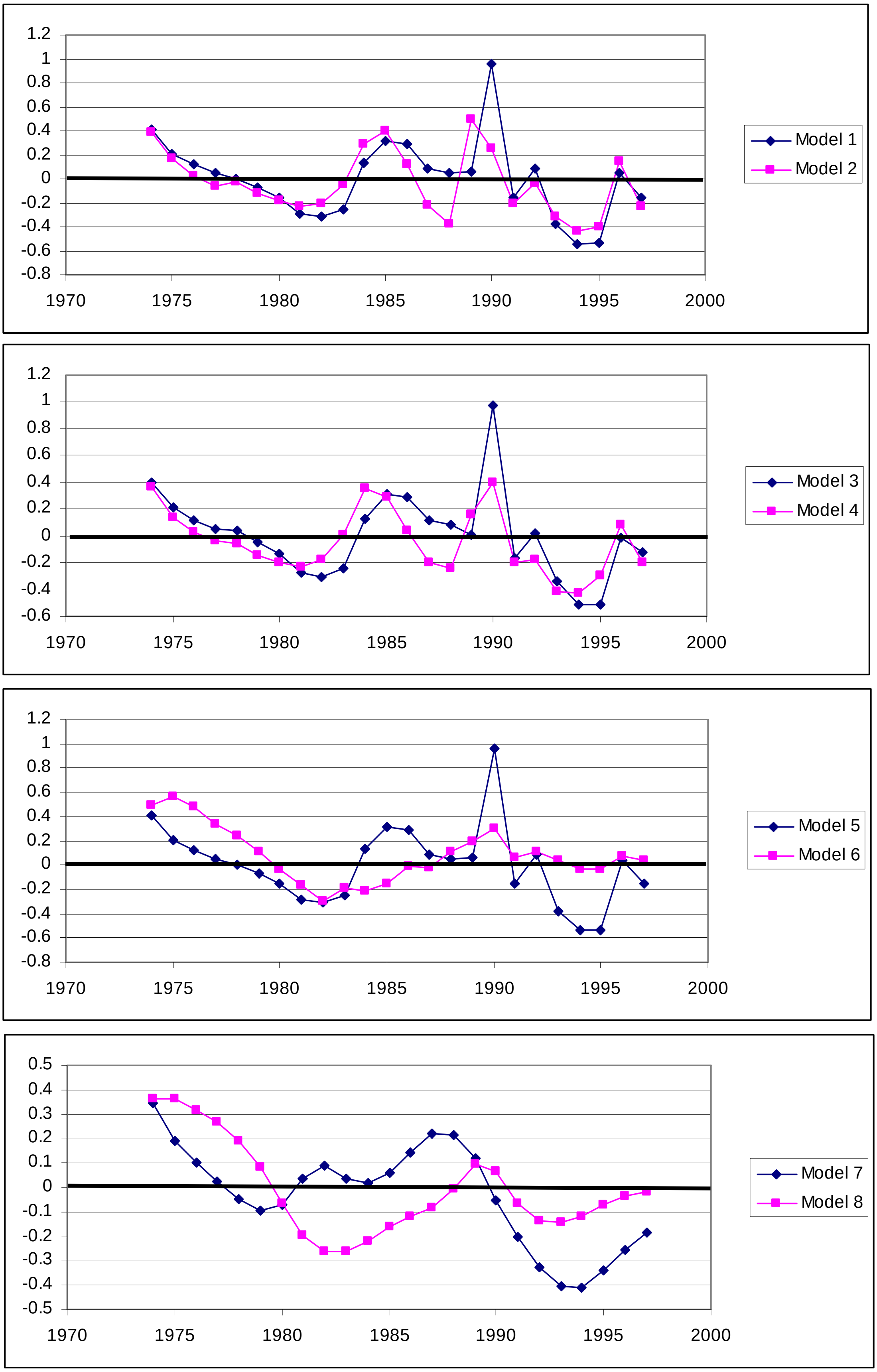


Figure 4: The areal proportional recruitment λ values for Models 3, 4 and 5. The horizontal line shows the mean in each case.

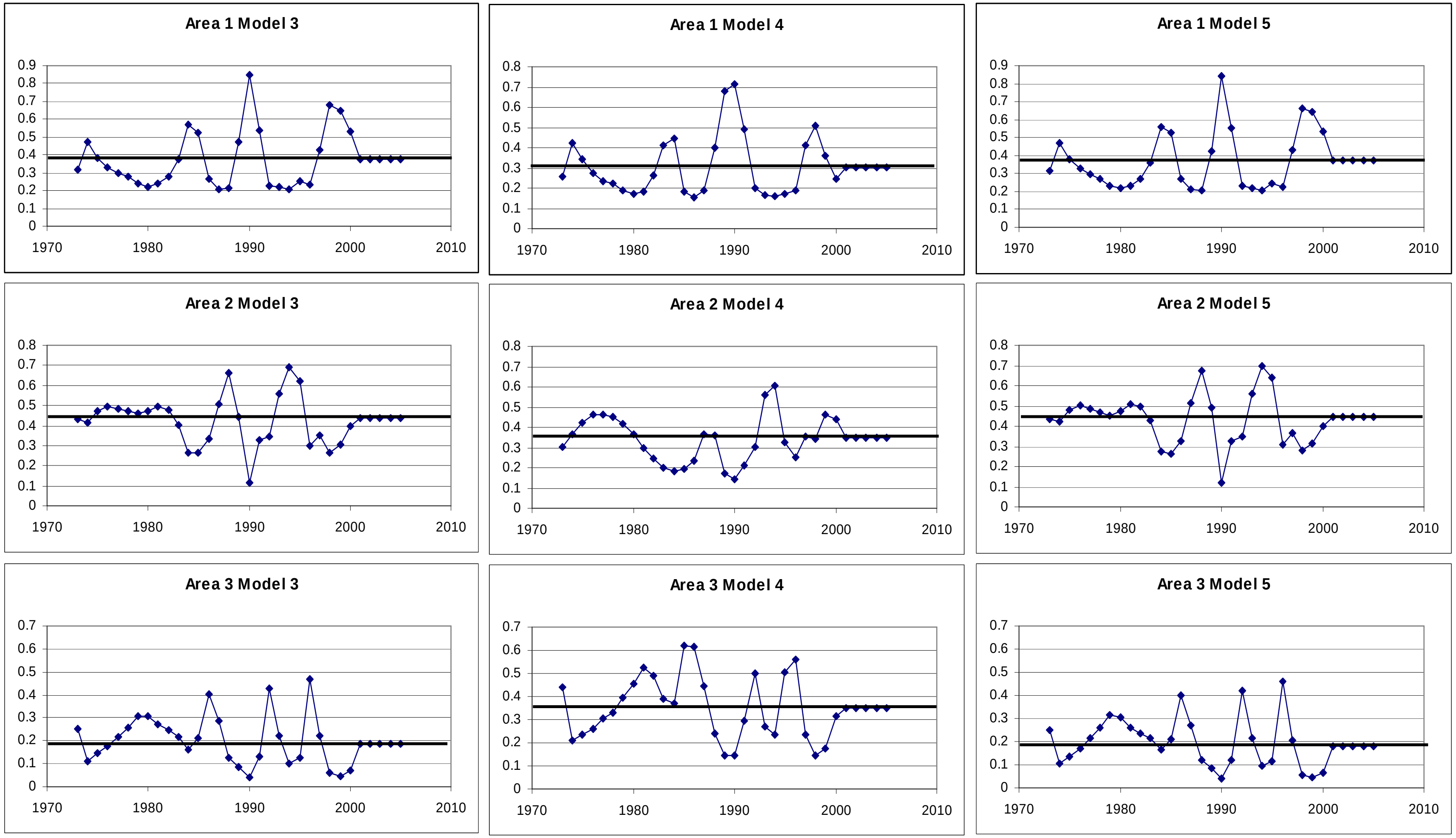


Figure 5: The MARAM method time-varying selectivity parameter $\delta_y^{m/f}$ values for each Area (and male and female) for Model 3. The horizontal line shows the average value in each case.

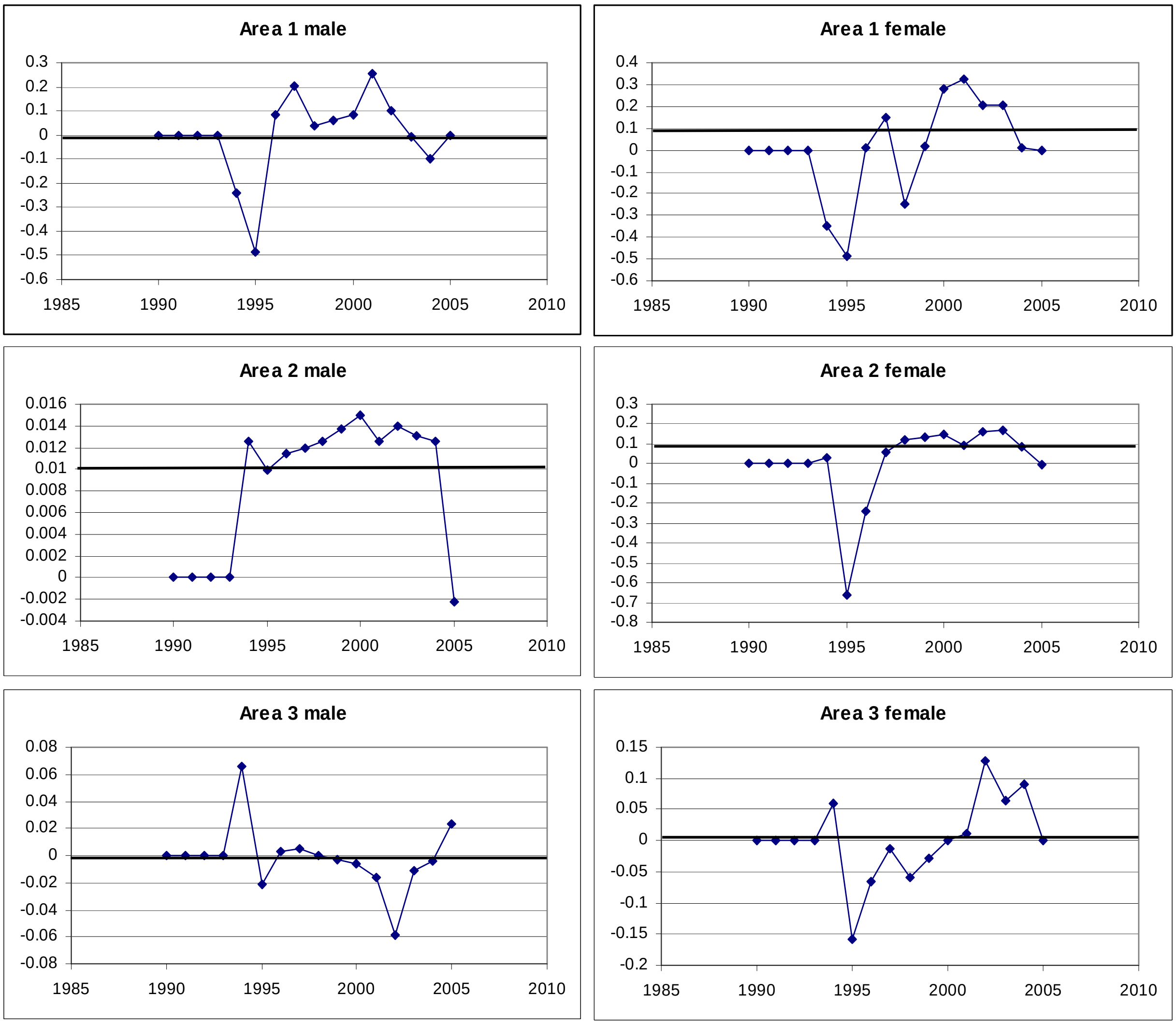


Figure 6: The OLRAC method time-varying selectivity parameter $x_y^{m/f}$ values for each Area (and male and female) for Model 4. The horizontal line shows the average value in each case.