Australian Government Queensland Government Torres Strait Regional Authority

TORRES STRAIT PZJA PROTECTED ZONE JOINT AUTHORITY

TROPICAL ROCK LOBSTER RESOURCE ASSESSMENT GROUP (TRL RAG)	**MEETING No. 10** 23-24 August 2011
2011 updated stock assessment (CSIRO)	**Agenda Item 3.2:**

PURPOSE

This document summarises the latest update of the integrated model. The data updates include the latest (June 2011) midyear survey results as well as revisions to the commercial CPUE and catch-at-age data series.

BACKGROUND

See attached assessment document.

DISCUSSION

The revised model fits all available data well, and is an improvement on previous model versions.

FINANCIAL IMPLICATIONS

Nil

2011 Assessment of the Tropical Rock Lobster (*Panulirus ornatus*) Fishery in the Torres Straits

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Report for presentation at TRL Resource Assessment Group, August 2011

SUMMARY

This document summarises the latest update of the integrated model. The data updates include the latest (June 2011) midyear survey results as well as revisions to the commercial CPUE and catch-at-age data series. The revised model fits all available data well, and is an improvement on previous model versions.

The new integrated model is the preferred method for setting TACs under the future quota management system. It deviates from the previous three stage approach to setting the TAC, because it integrates all available information in a single consistent framework. This facilitates an understanding of the way in which data inputs ultimately translate into an assessment of resource status and productivity, sustainable catch levels and hence TAC estimates. The model TAC estimate is used to recommend a TAC for the forthcoming year, subject to pre-specified harvest control rules that pertain to the status of the stock relative to the target level. The same method as previously has been used to compute a preliminary TAC for the following year: this is set more conservatively by selecting the lower end of the 75% confidence interval so that there is a low probability that it will be higher than the Final TAC. The preliminary TAC for 2012 is 964t whereas the forecast TAC for 2013 is 769t.

The TAC setting process should be adaptively revised and modified each year, taking new data into account. The effectiveness of the harvest control rules in achieving management objectives should be examined using a Management Strategy Evaluation (MSE) approach. Linked research that is being undertaken as part of the Torres Strait lobster MSE project will serve to better evaluate and test the robustness of a range of plausible harvest strategies for use in combination with the model TAC estimate.

The revised Reference Case includes the following specifications (see Plaganyi et al. 2010):

- fitting to the CPUE data assuming a hyperstable relationship, and setting a lower bound of 0.25 to the variance associated with the CPUE data because it is less reliable than the survey data;
- increasing the stock recruit variance parameter from 0.3 to 0.5 to capture larger fluctuations in recruitment;
- estimating a different selectivity for the 1973-1988 period;
- using as the new Reference spawning biomass level the annual biomass of mature lobsters on 1 November each year i.e. at the start of the annual migration period;
- setting the forecasted 2011 catch equal to the TAC i.e. 803t;

estimating the 2011 recruitment residual;

the use of historic information to permit estimation of a large recruitment event that is known to have occurred in 1988, the year before the long-term surveys commenced. This is an important development as if this good recruitment is not accounted for in the model, the model tries to reconcile the subsequent dynamics by over-estimating the pristine stock size. Appropriate weightings are applied to the contribution of the historic catch proportion information to the likelihood (0.5 weighting applied), and setting a lower bound to the variance associated with the commercial catch-at-age data (0.1).

Background information on the above specifications is given in Plaganyi et al. (2010) and this document.

INTRODUCTION

A new stock assessment model (termed the "Integrated Model") (Plagányi *et al.* 2009) was developed in 2009 for the following reasons:

- The new model facilitates the move to a quota management system, in that it integrates all available information into a single framework to output a TAC estimate;
- The new model addresses all of the concerns highlighted in a review of the previous stock assessment approach (Bentley 2006, Ye et al. 2006, 2007);
- The new model incorporates the Pre-Season survey data as well as CPUE data available from the TVH sector;
- The growth relationships used in the model were revised;
- The new model is of a form that can be used as an Operating Model in a Management Strategy Evaluation (MSE) framework, given that the need for a MSE to support the management of the TRL fishery has been identified by the TRL RAG.

The new model outputs a single TAC estimate (with Confidence Interval) for each year, which is an integrated estimate that takes into account all available sources of information. The Integrated Model is a widely used approach for providing TAC advice with associated uncertainties. More formally, it is a Statistical Catch-at-Age Analysis (SCAA) (e.g. Fournier and Archibald 1982). This paper summarises the 2011 model assessment update based on recent data updates.

Linked research being undertaken as part of the MSE project will serve to better evaluate and test the robustness of a range of plausible harvest strategies for use in combination with the model TAC estimate.

METHODS

The model details are given in Appendix 1 of this document. A summary of the input catch data is shown in Table 1. In addition the latest (June 2011) midyear survey results (Table 2) are included in the model. As there is no planned Pre-season (November) survey for 2011, the results presented here provide the current best recommendations for a TAC for 2012, but these estimates should be considered less reliable in the absence of a Pre-season survey.

The model incorporates the following recent changes made in 2010:

- The trawl catch has been separated from the other catches because of differences in the selectivity / targeting of the trawling sector which was focused predominantly on migrating 2+ lobsters. This is important because in the early years the trawling catch comprised 35 – 90% of the total TRL catch (Table 1).
- The commercial catch-at-age data series was revised such that a continuous input series is now available for all years 1989-2010 (Plagányi *et al.* 2010) (Table 3).
- The TVH CPUE data input series have been revised and updated, with two alternative series available for the period 1989-2010 (Plagányi *et al.* 2010).
- The model is fitted to additional historic information as described in Plagányi et al. (2010).
- An adjustment has been made to the model to allow use of a separate selectivity function to be applied to the period 1973 to 1988, prior to the introduction of a MLS of 100mm TL in July 1988. The model already accounts for the subsequent size limit change to 115mm in 2002.

Previous model simulations had suggested some conflict between the CPUE and survey indices of abundance, and the model failed to converge if the CPUE information was accorded the same weight as the survey information. This was partly because the CPUE data are derived from the TVH sector only, whereas the survey data is an index of the entire population. Furthermore, the spatial distribution of fishing effort is different for the TVH and TIB sectors. Commercial catches and survey data are heavily influenced by spatial and temporal changes in lobster distribution. For example, zero 2+ lobsters were recorded in June 2009 in the Kircaldie rubble stratum, an important fishing ground, in contrast to average abundance of 2+ elsewhere (Plagányi *et al.* 2010).

The relationship between stock abundance and CPUE was explored, and found to be better represented by a hyperstable relationship, than the assumption that CPUE is proportional to stock abundance (see e.g. Harley *et al.* 2001). We used a power curve with a hyperstability shape parameter of 0.75, and tested sensitivity to other values. This suggests that CPUE remains high while stock abundance declines. This is consistent also with results from considering an ecometric production function approach (Pascoe et al. in prep).

Table 1. Lobster catches (tonnes whole weight) landed in different jurisdictions from 1973 to 2010. Catches comprised of both whole animals and tails have been converted into units of whole mass using the conversion ratio of 1kg tail=2.677 kg live.

YEAR	AUS_DIVE	TIB	TVH	AUS_TRAWL	PNG_DIVER	YULE_DIVERS	PNG_TRAWL	QLD_EAST_COAST	TOTAL TS
-------	----------	--------	--------	---------	----------	-----------	---------	--------------	------------
1973	0			0	54	19	562.2	0	73
1974	0			0	75	83	107.1	0	158
1975	0			0	62	13	214.2	0	75
1976	0			0	48	0	262.3	0	48
1977	0			0	72	35	131.2	0	107
1978	296.1			0	43	3	187.4	0	342.1
1979	308.5			0	56	13	0	0	377.5
1980	328.4			21	94	3	588.9	0	425.4
1981	495.1			131	96	3	262.3	0	594.1
1982	669.2			201	102	3	398.9	0	774.2
1983	432.9			139	86	0	112.4	0	518.9
1984	330.9			8	86	0	29.4	0	416.9
1985	537.4			24	187	16	0	0	740.4
1986	890.6			21	198	62	0	0	1150.6
1987	622			0	128	54	0	0	804
1988	537.4			0	150	5	0	8	692.4
1989	651			0	211	24	0	13	886
1990	490.1			0	158	0	0	5	648.1
1991	444.1			0	168	0	0	8	612.1
1992	423.2			0	134	0	0	15	557.2
1993	505.7			0	166	0	0	5	671.7
1994	577.8		133.5	0	247	0	0	10	824.8
1995	556.9		101	0	257	0	0	38	813.9
1996	584.1		226.9	0	228	0	0	66	812.1
1997	653.1		285	0	241	0	0	58	894.1
1998	661.4		356.2	0	201	0	0	78	862.4
1999	409.6		126.3	0	163	0	0	129	572.6
2000	418		130.1	0	235	0	0	152	653
2001	122.4	52	70.4	0	173	0	5.4	206	295.4
2002	215.7	68	147.7	0	327	0	42.8	117	542.7
2003	484.6	123	361.6	0	211	0	5.4	104	695.6
2004	723.4	242.4	481	0	182	0	0	187	905.4
2005	919.5	374.6	545	0	228	0	0	142	1147.5
2006	289.2	153.7	135.4	0	142	0	0	200	431.2
2007	550.5	279	271.4	0	228	0	0	237	778.5
2008	332.5	221.5	111	0	221	0	0	243	553.5
2009	236	136.9	99	0	161.4	0	0	198	397.4
2010	470	190.7	279.3	0	292.8	0	0	119	762.8

Table 2. Mid-year survey data summary for the period 1989-2011. Indices reflect abundance.

Year	Nb of transect	Age-group 1	SE Age-group 1	Age-group 2	SE Age-group 2
1989	40	1.66	0.24	2.43	0.3
1990	40	3.54	0.79	1.64	0.28
1991	40	3.95	0.54	1.5	0.34
1992	40	5.08	0.77	3.43	0.67
1993	40	2.34	0.49	0.77	0.33
1994	40	5.64	1.62	1.14	0.3
1995	40	3.5	0.59	1.83	0.94
1996	40	3.35	0.56	1.18	0.39
1997	40	3.97	0.67	1.02	0.25
1998	40	1.78	0.43	1.37	0.36
1999	40	3.49	0.89	0.47	0.24
2000	40	3.06	1.19	0.62	0.22
2001	40	1.23	0.25	0.24	0.09
2002	73	2.51	0.35	0.82	0.31
2003	43	2.83	0.52	2.17	0.64
2004	72	2.72	0.41	1.54	0.43
2005	71	1.19	0.18	1.96	0.69
2006	73	5.41	0.93	0.72	0.34
2007	70	3.83	1.1	1.62	0.54
2008	72	2.09	0.28	0.96	0.35
2009	68	3.44	0.52	1.26	0.37
2010	67	4.16	0.61	1.18	0.3
2011	65	5.12	0.81	2.24	0.47

Table 3. Summary of commercial catch at age information.

Year	Age 1	Age 2
1989	5	84
1990	8	61
1991	17	50
1992	14	44
1993	15	56
1994	29	69
1995	18	67
1996	23	68
1997	30	69
1998	15	72
1999	20	45
2000	8	67
2001	0.001	34
2002	2	58
2003	2	66
2004	2	89
2005	1	113
2006	3	43
2007	1	80
2008	3	52
2009	0.001	44
2010	3	53

1.1. RESULTS

1.1.1. Model fits

The fits of the new Integrated Model to all available data sources is shown in Figures 1 – 9. The starting number of lobsters is estimated and Figure 1 compares the benchmark survey (Ye et al. 2004) observed total lobster abundances in 1989 and 2002 with the corresponding model estimates. The Integrated model is fitted to the survey midyear index of abundance (in terms of total numbers of 1+ and 2+ lobsters) (Figure 2) and the observed and model-predicted proportions in each age class are compared in Figure 3.

The model fits to the recently revised catch at age data are adequate (Figure 4). The variability in the lobster age groups is well captured and the model reflects the post-2001 (increased size limit) decrease in the relative proportion of 1+ lobsters that are caught.

There are only four data points available from the Pre-season survey, and the model was fitted to data on both 0+ and 1+ abundance, with a close fit evident (Figure 5). The fit is better for the 1+ age group than the 0+ age group, but incorporation of the latter assists in strengthening prediction of future lobster abundance, even given the fairly large uncertainty associated with these estimates.

Comparisons between CPUE data from the TVH sector (in kg per tender-day from 1994 to 2010) and corresponding model-predicted estimates (model free version) are shown in Figure 6a. The Reference Case assumes a hyperstable relationship between biomass and CPUE as follows (Fig. 6b):

$$\left(\frac{C}{E}\right)_y = q\left(B_y^{ex}\right)^{0.75}$$

Comparison between historic data and model estimates of the proportions of 1+ and 2+ lobsters in the catch is shown in Figure 7. The fit in the early years is reasonably good, with the later deviations in the fit partly a result of a slight conflict between these data and the catch at age data see Table 3).

The fitted stock-recruit relationship from the Base-case model version is shown in Figure 8, which also highlights the spawning stock biomass estimates in recent years. The stock-recruit residuals are shown in Figure 9, with no clear patterns evident. Figure 9 represents a substantial improvement on previous stock-recruit residual plots derived for this resource. There is considerable variation about the stock-recruit curve (as is expected), but nonetheless there is some support for an underlying stock-recruit relationship.

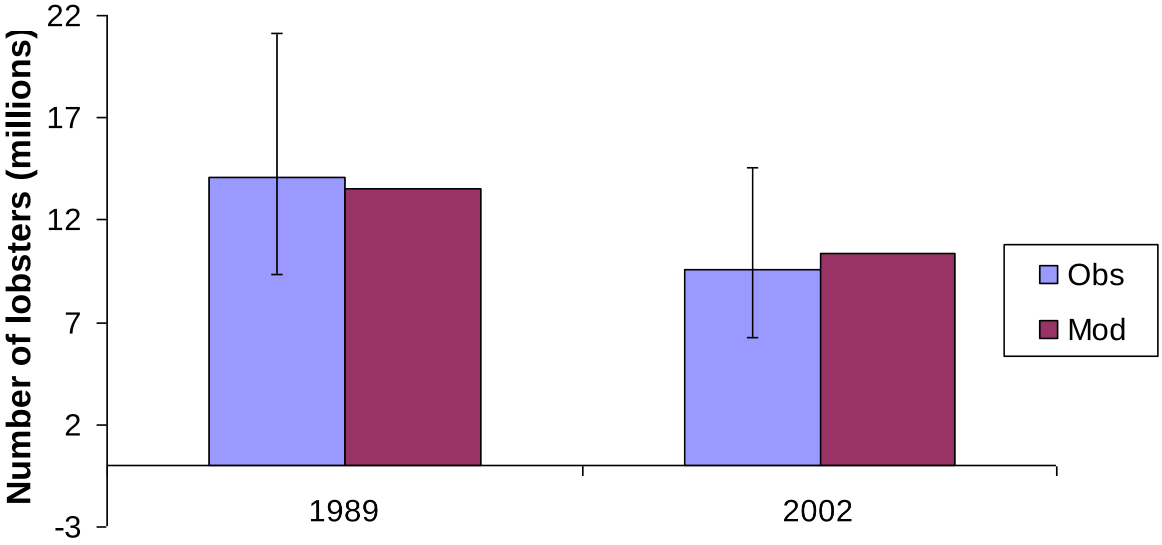


Figure 1. Comparison of benchmark survey observed lobster total abundance (with standard errors) and corresponding Reference Case model-estimates of abundance.

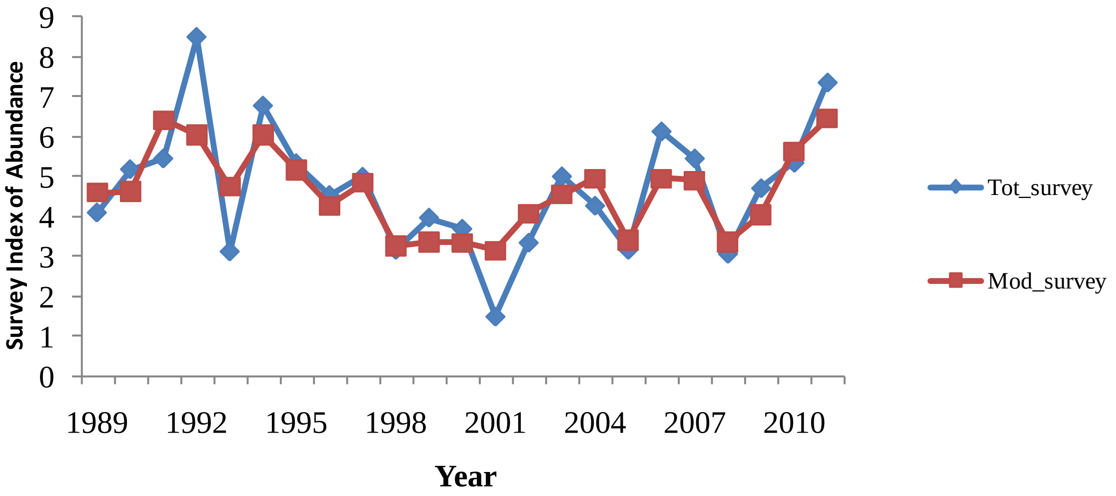


Figure 2. Comparison between survey midyear index of abundance (in terms of total numbers of 1+ and 2+ lobsters) compared with the corresponding model-estimated values.

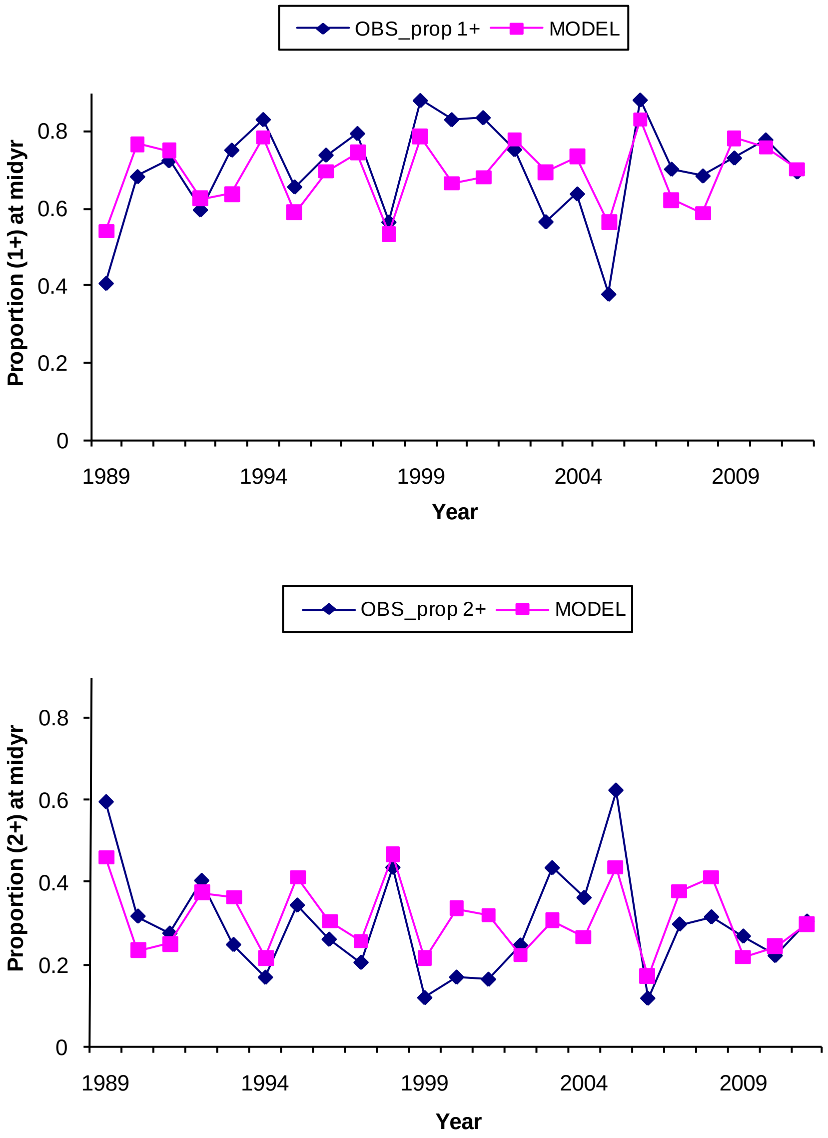
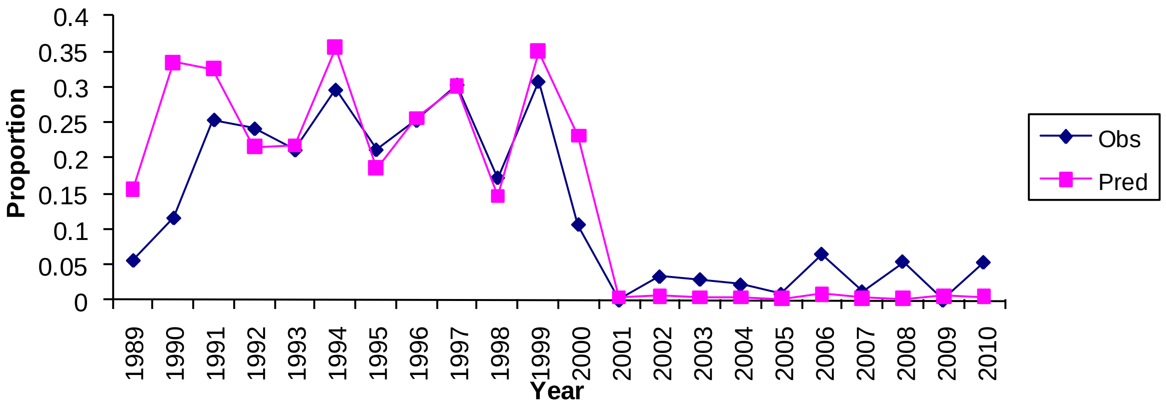


Figure 3. Comparison between observed and model-predicted proportions of 1+ and 2+ lobsters in the midyear survey.


a) Age 1+

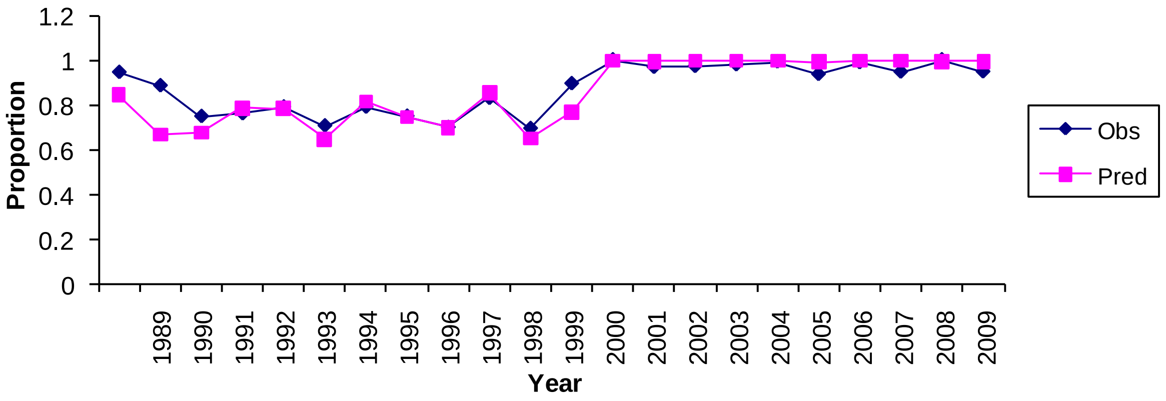
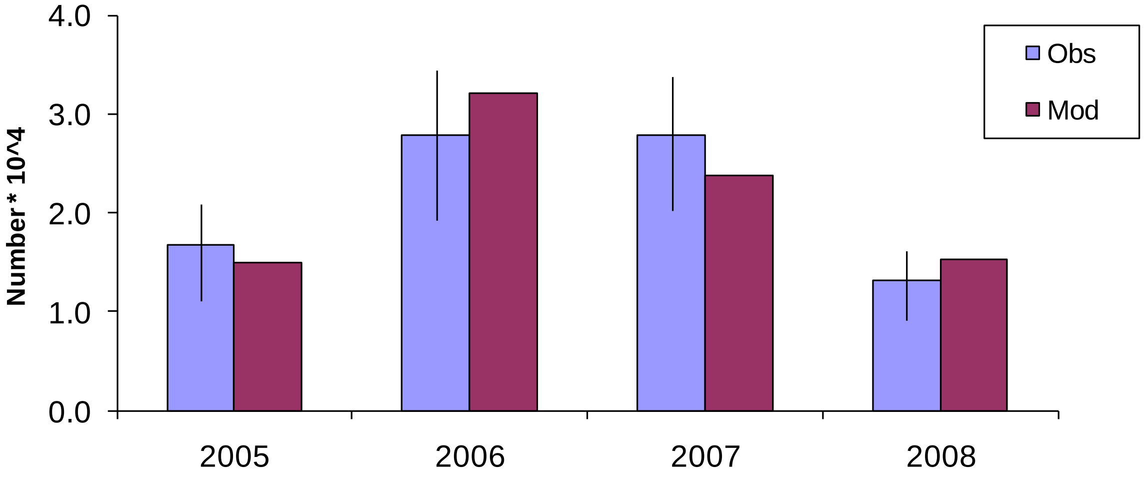

b) Age 2+

Figure 4. Comparison between available catch-at-age data and corresponding model-predicted estimates.

a) Pre-Season Survey 1+



b) Pre-Season Survey 0+

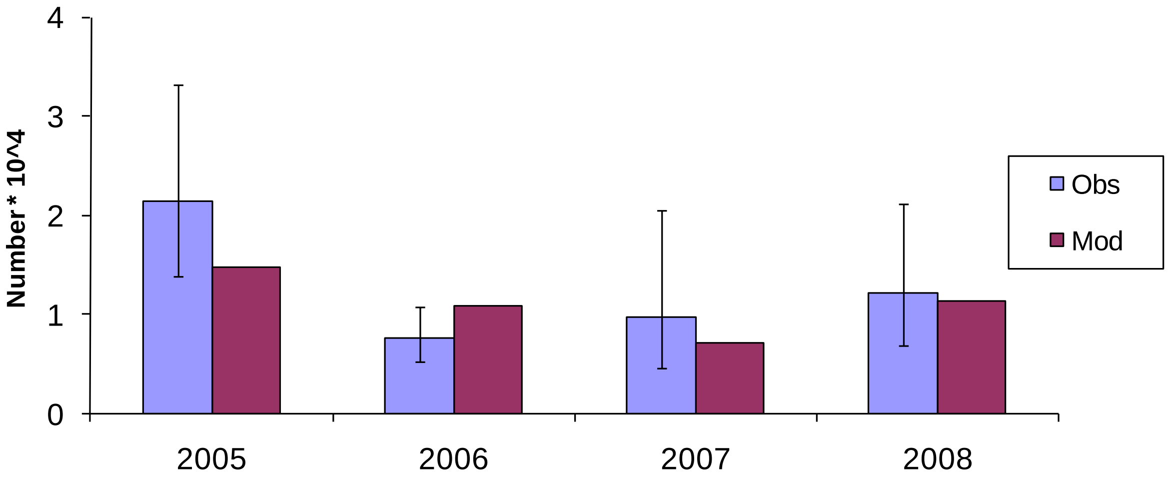
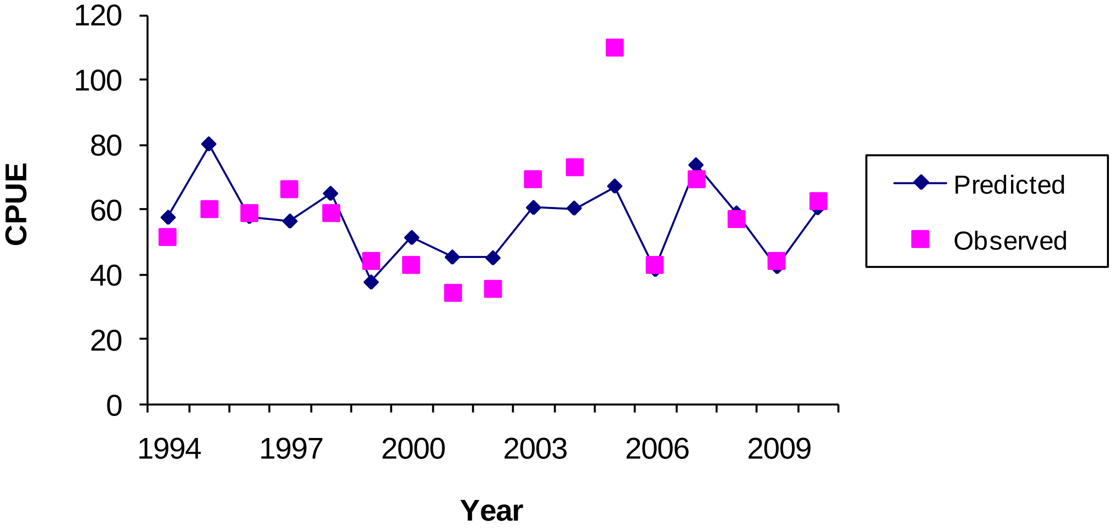


Figure 5. Comparison between observed Pre-season survey data (expressed in terms of number * 10^4) and corresponding model-predicted estimates.

a) REFERENCE CASE FIT



b) HYPERSTABLE RELATIONSHIP

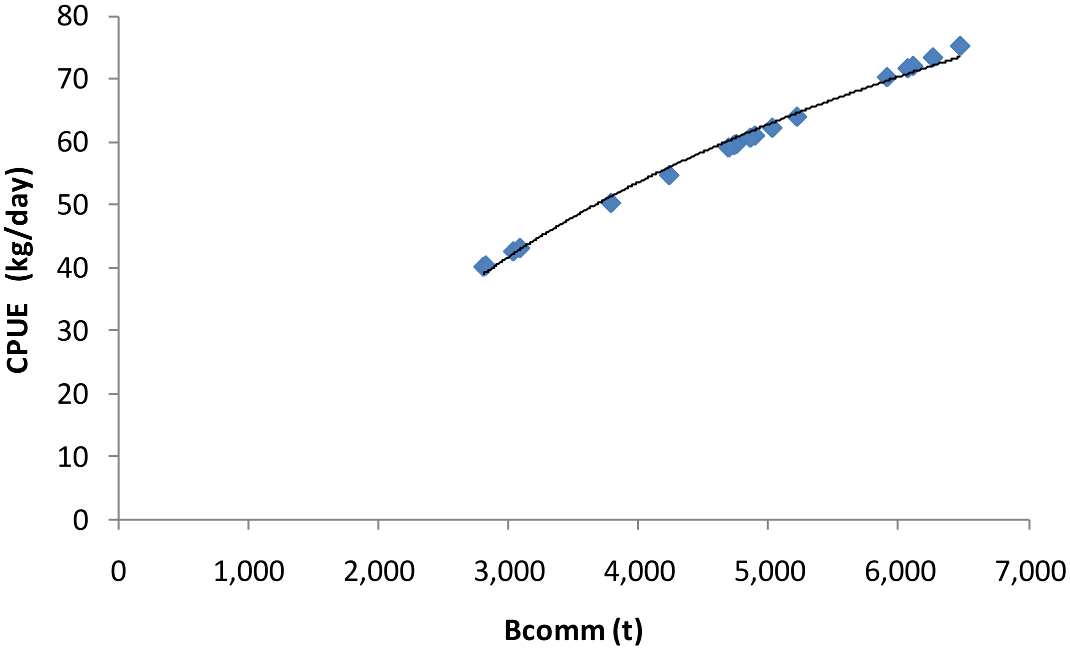


Figure 6. Comparison between CPUE data from the TVH sector and corresponding model-predicted estimates. The plots are respectively a) fit of the model to CPUE model free estimates and b) plot of the hyperstable relationship (with power shape parameter 0.75) between CPUE and exploitable biomass. TVH catch per unit of effort are in units of kg per tender-day from 1994 to 2010.

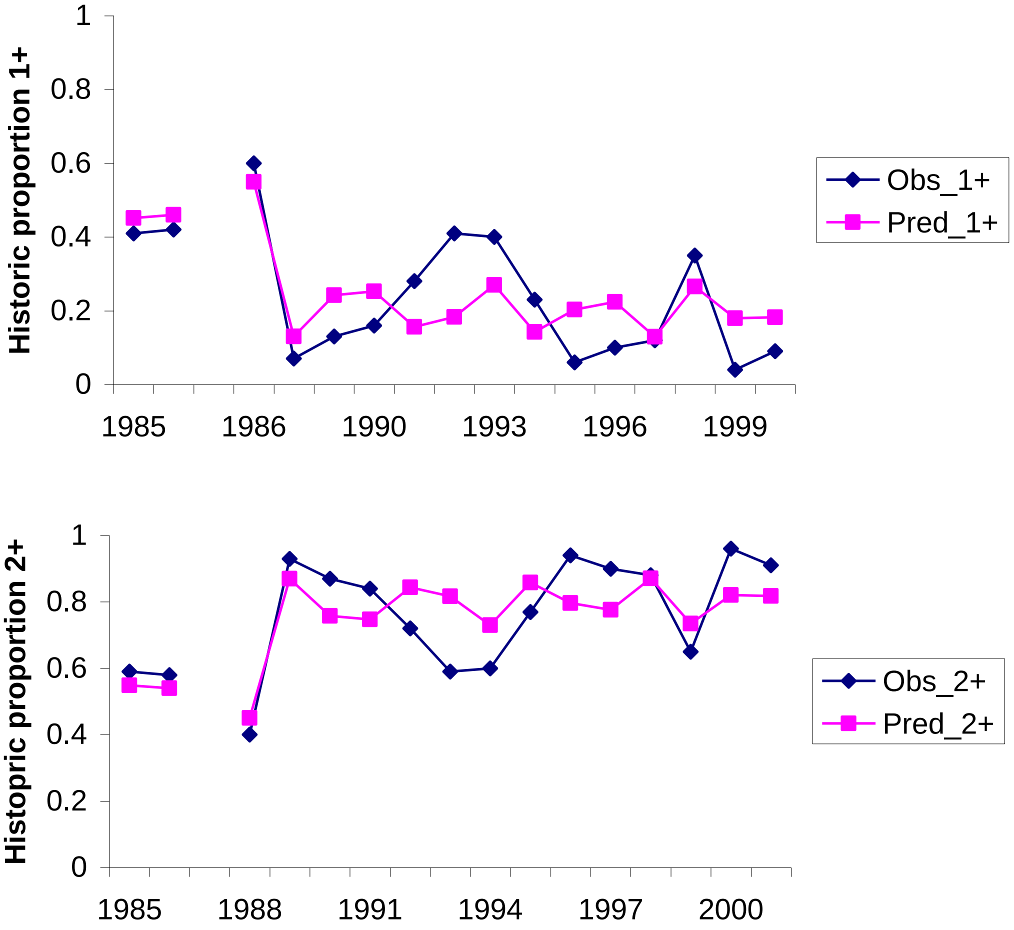


Figure 7. Comparison between historic data and model estimates of the proportions of 1+ and 2+ lobsters in the catch.

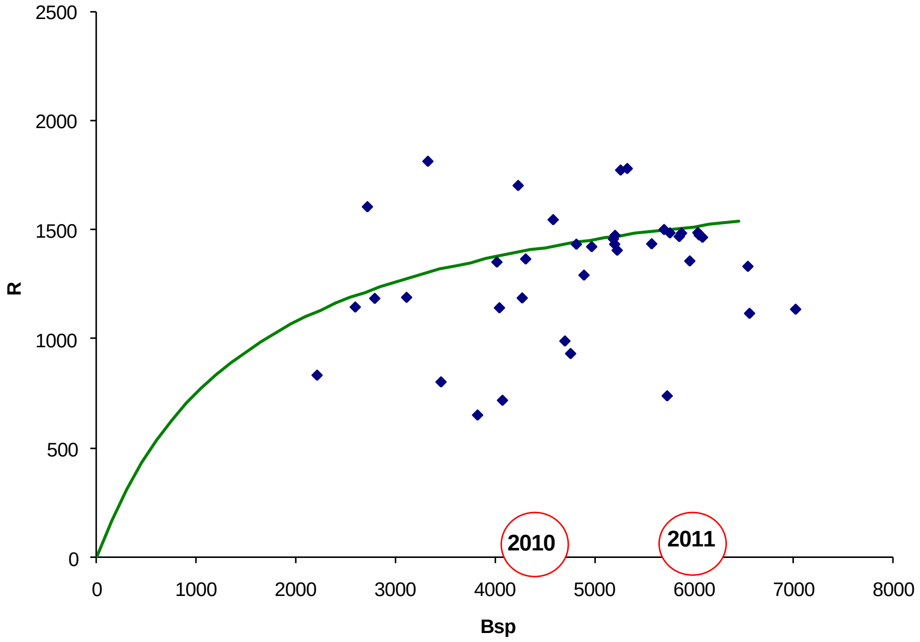


Figure 8. Integrated model stock recruitment relationship of the Torres Strait rock lobster fishery. Diamond symbols are output from the age-structured stock assessment model, solid line is a fitted curve, and circled years highlight spawning stock levels in those years.

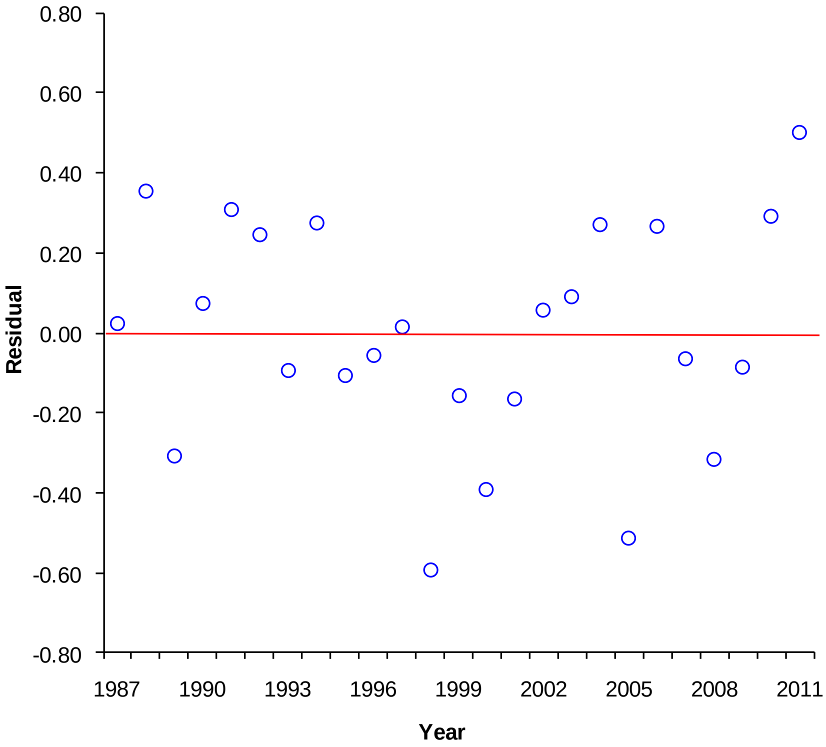


Figure 9. Plot of stock-recruit residuals.

1.1.2. Estimates of model parameters

A summary of model parameter estimates is given in Table 4 for the pre-RAG Reference Case model. A full set of model parameter estimates, depletion statistics and likelihood contributions for the Reference Case and a number of key sensitivities is given in Table 5 a and b. In all cases the 90% Hessian-based Confidence Intervals (CI) are given alongside. The new Integrated model estimates a total of 31 parameters, namely the starting biomass $B(1973)^{sp}$, natural mortality M, steepness parameter h, 1+ selectivity for the 1973-1988, 1989-2001 and post-2002 periods, and 25 stock-recruit residuals. The natural mortality estimate of 0.66 [90% C.I. 0.52 – 0.81] year^{-1} is reasonably estimated but the steepness parameter 0.54 [90% C.I. 0.20 – 0.95] could not be reliably estimated. However, model results were robust across a range of steepness values.

Table 4. Summary of model parameter estimates from the revised 2011 Integrated model.

Parameter	**Value**	**90% Confidence Interval**	
$B(1973)^{sp}$ *(tons)*	5691	3029	8352
M	0.66	0.52	0.81
h	0.54	0.20	0.95
Sel (age 1+) 1973-1988	0.14	0.02	0.27
Sel (age 1+) 1989-2001	0.21	0.03	0.39
Sel (age 1+) post2002	0.00	0.00	0.10
Recruitment residuals (1987-2011)		25 parameters	
Model estimates and depletion statistics			
$B(2011)^{sp}$ *(tons)*	5961	3058	8864
Current Depletion (Nov) $B(2011)^{sp} / B(1973)sp$	1.05	0.50	1.59
Bexp(2011) (tons)	6533	3664	9402
N1+ (mid 2011) million	12.20	6.40	17.99
No. parameters estimated	31		
'-lnL:overall	**-103.846**		
AIC	**-145.692**		
Likelihood contributions		**Sigma**	**q**
'-lnL:CAA	-103.85	0.10	
'-lnL:CAAsurv	-15.85	input (Table 2)	
-lnL:CAA historic	-38.06	0.25	
-lnL:Survey Index	-22.24	0.16	
-lnL:Survey benchmark	-2.75	input (Fig. 1)	
'-lnL:PRESEASON	-5.73	input (Fig. 5)	
-lnL:PRESEASON 0+	-1.58	input (Fig. 5)	
-lnL:CPUE	-15.57	0.25	0.10
'-lnL:RecRes	3.80	0.28	

Full selectivity of the 2+ age class is assumed given they are the target of the fishery and are assumed caught before the end of September, before they migrate out the Torres Straits. Selectivity of 1+ lobsters is substantially less because they are usually only susceptible to fishing after September and not all individuals will have attained the minimum legal size by that time. The selectivity coefficient for age 1+ lobsters was 0.14 for 1973-1988, 0.21 for the period of 1989-2001 and 0.001 for the remaining years. As expected, the decrease in selectivity during the recent time period is a consequence of a change in management measures having been introduced in 2002, which included an increase in the minimum legal size (to 115 mm tail length), a 4-month extension of the hookah ban (October to January) and a 2-month fishing closure (October-November) (Ye et al. 2006).

Following from the above, the level of fishing mortality on age 1+ lobsters is expected to be substantially less than that on age 2+ lobsters (Figure 10), with a decreasing trend evident following the implementation of the new management measures in 2002. The fishing mortality rate for age 2+ lobsters ranged from 0.09 year^{-1} to 0.21 year^{-1} (Figure 10), with a historic average of 0.15 year^{-1}. The target fishing mortality rate is 0.15 year^{-1}. The 2010 catch of 763t exceeded the target fishing mortality rate (0.17) whereas the 2011 TAC recommendation was slightly below the target fishing mortality rate (0.13) (as could only be assessed retrospectively).

The fishing mortality estimates above refer to the combined estimate when lumping all TRL catches in the Torres Straits, except the trawling sector (Australian and PNG combined) catches. The latter are assumed to target 2+ lobsters only and are substantial in the early years only (1973 – 1984) (Figure 11), with small catches taken during the period (2001-2003) and zero values for all other years.

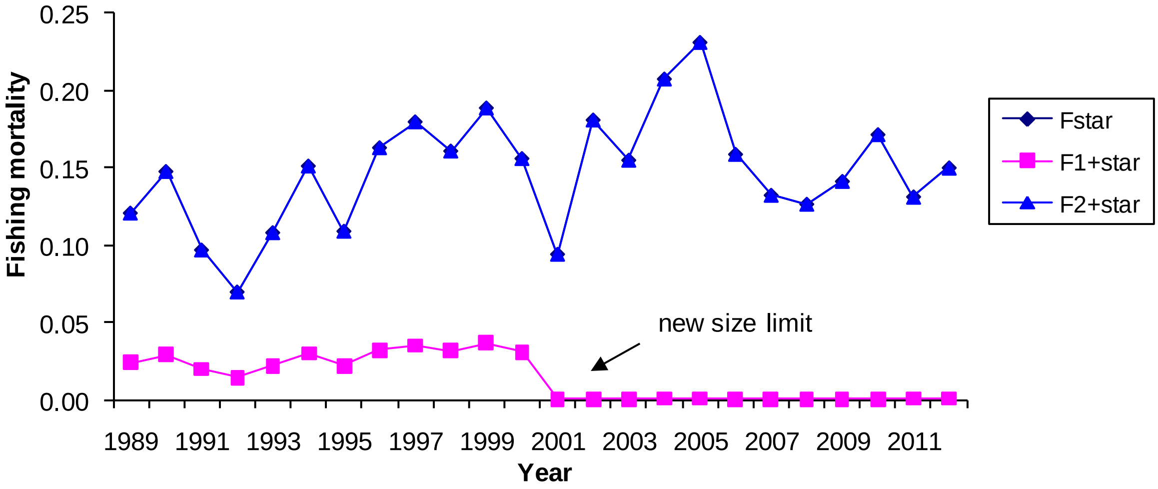


Figure 10. Model-estimated fishing mortality trends for 1+ (F 1+star) and 2+ (F 2+ star) lobsters. The 2002 change in size limit is highlighted and the 2011 fishing mortality set equal to the target value of 0.15.

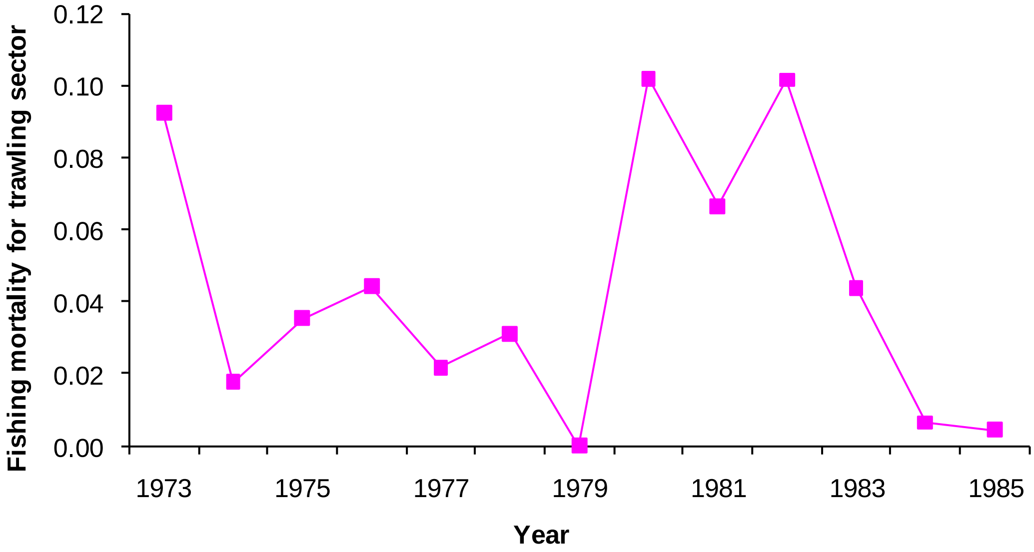


Figure 11. Model-estimated trawling sector fishing mortality trends for the early period of the fishery from 1973 - 1985.

Table 5. Summary of model parameter estimates for the pre-RAG Reference Case and a number of sensitivity tests as shown.

	a) Reference Case			**b) Hyperstability shape par = 0.5**			**c) Alternative CPUE index**			**d) Recruit residual sigma=0.3**		
Parameter	**Value**	**90% Confidence Interval**		Value	90% Confidence Interval		Value	90% Confidence Interva		Value	90% Confidence Interva	
B(1973) ^{sp} *(tons)*	5691	3029	8352	5688	3032	8344	5688	3032	8344	4803	3320	6286
M	0.66	0.52	0.81	0.66	0.52	0.81	0.66	0.52	0.81	0.66	0.52	0.80
h	0.54	0.20	0.95	0.54	0.20	0.95	0.54	0.20	0.95	0.67	0.20	0.95
Sel (age 1+) 1973-1988	0.14	0.02	0.27	0.14	0.02	0.27	0.14	0.02	0.27	0.47	0.27	0.66
Sel (age 1+) 1989-2001	0.21	0.03	0.39	0.21	0.03	0.39	0.21	0.03	0.39	0.16	0.09	0.24
Sel (age 1+) post2002	0.00	0.00	0.10	0.00	0.00	0.10	0.00	0.00	0.10	0.03	0.00	0.20
Recruitment residuals (1987-2011)		25 parameters		25 parameters			25 parameters			25 parameters		
Model estimates and depletion statistics												
B(2011) ^{sp} *(tons)*	5961	3058	8864	5959	3058	8859	5959	3058	8859	5416	2995	7836
TAC(2012) model	964	497	1432	964	497	1431	964	497	1431	864	490	1238
TAC(2013) model	769	485	1053	769	485	1053	769	485	1053	708	488	929
Current Depletion (Nov)												
B(2011) ^{sp} */ B(1973)sp*	1.05	0.50	1.59	1.05	0.50	1.59	1.05	0.50	1.59	1.15	0.72	1.57
Bexp(2011) (tons)	6533	3664	9402	6532	3664	9400	6532	3664	9400	6113	3636	8589
N1+ (mid 2011) million	12.20	6.40	17.99	12.21	6.41	18.00	12.21	6.41	18.00	10.73	6.15	15.31
No. parameters estimated	31			31			31			31		
'-lnL:overall	**-103.846**			-103.846			-103.846			-109.938		
AIC	**-145.692**			-145.692			-145.692			-157.876	(not comparable)	
Likelihood contributions		**Sigma**	**q**		**Sigma**	**q**		**Sigma**	**q**		**Sigma**	
'-lnL:CAA	-103.85	0.10		-103.85	0.10		-103.85	0.10		-109.94	0.10	
'-lnL:CAAsurv	-15.85	input (Table 2)		-15.85			-15.85			-15.05		
-lnL:CAA historic	-38.06	0.25		-38.06	0.25		-38.06	0.25		-38.06	0.14	
-lnL:Survey Index	-22.24	0.16		-22.24	0.16		-22.24	0.16		-20.53	0.16	
-lnL:Survey benchmark	-2.75	input (Fig. 1)		-2.75			-2.75			-2.61		
'-lnL:PRESEASON	-5.73	input (Fig. 5)		-5.73			-5.73			-5.82		
-lnL:PRESEASON 0+	-1.58	input (Fig. 5)		-1.58			-1.58			-1.47		
-lnL:CPUE	-15.57	0.25	0.10	-15.57	0.25	0.85	-15.57	0.25	0.10	-24.25	0.15	
'-lnL:RecRes	3.80	0.28		3.80	0.28		3.80	0.28		8.31	0.24	

Table 5b. (Continued) Summary of model parameter estimates.

	a) Reference Case			**e) CPUE sigma=0.1**			**f) Historic index sigma = 0.1**			**g) CPUE sig=0.15 & hyps par=0.5**		
Parameter	**Value**	**90% Confidence Interval**		Value	90% Confidence Interva		Value	90% Confidence Interva		Value	90% Confidence Interval	
B(1973) ^{sp} *(tons)*	5691	3029	8352	5044	3350	6738	5440	3069	7810	5560	1101	10020
M	0.66	0.52	0.81	0.66	0.51	0.81	0.67	0.52	0.81	0.65	0.50	0.80
h	0.54	0.20	0.95	0.60	0.20	0.83	0.60	0.20	0.95	0.60	0.20	0.95
Sel (age 1+) 1973-1988	0.14	0.02	0.27	0.18	-1.81	2.17	0.44	0.24	0.64	0.13	0.06	0.20
Sel (age 1+) 1989-2001	0.21	0.03	0.39	0.23	-1.47	1.93	0.16	0.09	0.22	0.20	0.02	0.39
Sel (age 1+) post2002	0.00	0.00	0.10	0.00	0.00	0.11	0.04	0.00	0.24	0.06	0.00	0.35
Recruitment residuals (1987-2011)		25 parameters			25 parameters			25 parameters			25 parameters	
<u>Model estimates and depletion statistics</u>												
B(2011) ^{sp} *(tons)*	5961	3058	8864	5346	2767	7924	5886	3035	8737	5875	3015	8736
TAC(2012) model	964	497	1432	850	454	1247	977	507	1447	1018	520	1517
TAC(2013) model	769	485	1053	706	482	930	779	491	1067	809	417	1202
Current Depletion (Nov)												
B(2011) ^{sp} */ B(1973)sp*	1.05	0.50	1.59	1.07	0.61	1.54	1.08	0.55	1.62	1.06	0.14	1.98
Bexp(2011) (tons)	6533	3664	9402	5928	3458	8398	6668	3712	9625	6729	3460	9998
N1+ (mid 2011) million	12.20	6.40	17.99	10.70	5.73	15.68	12.14	6.38	17.89	12.37	6.47	18.26
No. parameters estimated	31			31			31			31		
'-lnL:overall	**-103.846**			-115.822			-108.41			-109.751		
AIC	**-145.692**			-169.644	(not comparable)		-154.820	(not comparable)		-157.502	(not comparable)	
<u>Likelihood contributions</u>		**<u>Sigma</u>**	**<u>q</u>**		**<u>Sigma</u>**			**<u>Sigma</u>**	**<u>q</u>**		**<u>Sigma</u>**	**<u>q</u>**
'-lnL:CAA	-103.85	0.10		-115.82	0.10		-108.41	0.10		-109.75	0.10	
'-lnL:CAAsurv	-15.85	input (Table 2)		-14.44			-15.85			-14.88		
-lnL:CAA historic	-38.06	0.25		-38.06	0.25		-38.06	0.13		-38.06	0.25	
-lnL:Survey Index	-22.24	0.16		-21.09	0.17		-22.00	0.16		-21.95	0.17	
-lnL:Survey benchmark	-2.75	input (Fig. 1)		-2.59			-2.76			-2.67		
'-lnL:PRESEASON	-5.73	input (Fig. 5)		-6.34			-5.73			-5.75		
-lnL:PRESEASON 0+	-1.58	input (Fig. 5)		-1.38			-1.60			-1.70		
-lnL:CPUE	-15.57	0.25	0.10	-31.14	0.10		-15.57	0.25	0.10	-24.25	0.15	0.85
'-lnL:RecRes	3.80	0.28		5.10	0.32		4.05	0.28		5.38	0.33	

The fitted Beverton-Holt stock-recruit relationship had a comparatively low estimate of the steepness parameter *h*, which although not as low as the 2010 estimate (0.54), was not well estimated given the large associated confidence interval. The change in the steepness estimate was a result of adding the historic data to the model, which permitted estimation of a large recruitment event in 1988 (prior to the start of the survey data) and hence a different interpretation of resource history. Across all sensitivities tested, the steepness estimate was consistently much lower than the median *h* value of 0.74 - from a distribution of *h* values for stock-recruit functions fitted to the fisheries stock recruitment database developed by R.A. Myers and colleagues (Myers *et al*. 1995). However, low steepness examples do exist, particularly for shorter-lived species such as prawns (Dichmont et al. 2003). A further meta-analysis by Myers et al. 2002 demonstrated a decreasing relationship between steepness and reproductive longevity. *P. ornatus* differs dramatically from most other rock lobster species which have been subject to stock assessments in that it is much faster growing with a reproductive longevity of around 3-6 years compared to in excess of 8 years for many other species (e.g. McKoy 1985, Johnston and Butterworth 2005, Montgomery and Craig 2005). It's productivity is thus likely to be more similar to other short-lived species such as prawns than to slow growing lobsters. A low steepness has a number of important implications, including that it implies that a larger spawner stock size is more optimal. Whereas a stock characterised by a stock-recruit relationship with high steepness can produce "pretty good yields" even at very low spawning biomass levels, stocks with low steepness are predicted to produce high yields only at much larger spawning biomass levels, and have a low resilience to fishing (Hilborn 2010).

As previously, there is a lot of scatter associated with the plot of spawning stock and subsequent recruitment estimates. This is not uncommon, particularly for shorter-lived species, but highlights the limitations of predicting future recruitment based on current estimates of spawning biomass. In this case model predictions are improved because of the availability of mid-year survey information, although no recent Pre-season survey 0+ and 1+ data are available (see Fig. 5).

1.1.3. Model trajectories

The model-predicted numbers of 1+ and 2+ lobsters for the entire model period are shown in Fig. 12. There is considerable inter-annual variability in stock size, with the extent of the variability consistent with that observed from field studies.

The lobster spawning biomass (t) trajectory is given in Fig. 13. The stock is currently estimated to be only slightly below the pristine (1973) spawning biomass level but is expected to fluctuate widely about the average target spawning biomass level.

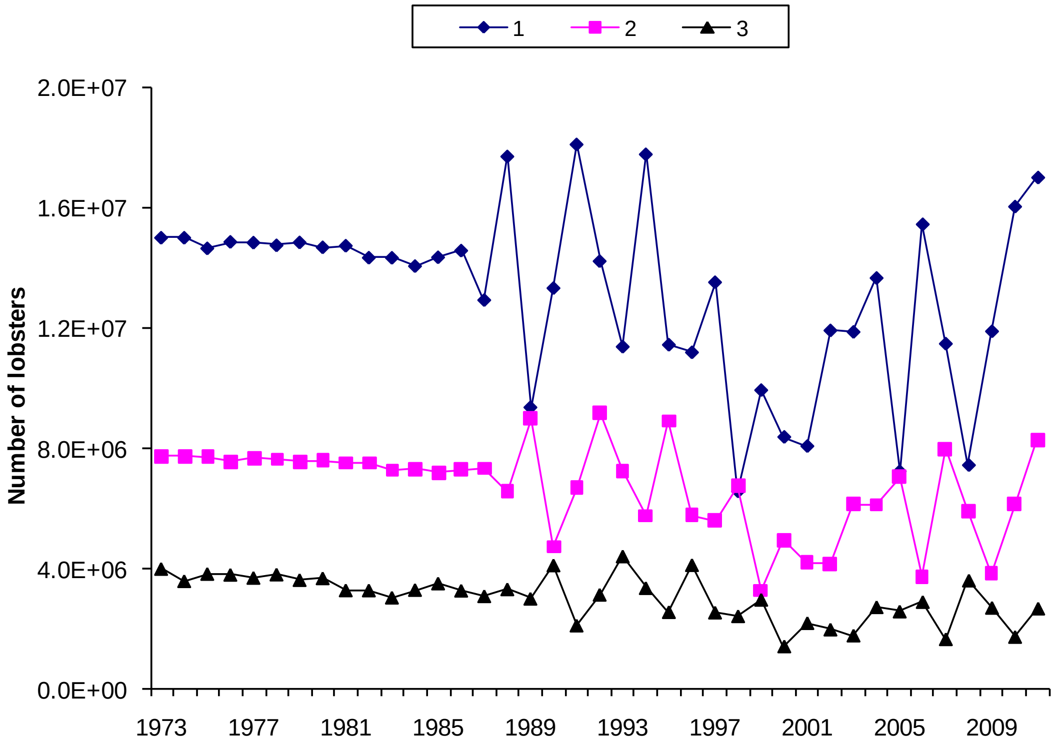


Fig. 12. Model trajectories of the annual numbers of lobsters in each age class at the start of each of years 1973 to 2011. The increased variability from 1988 onwards is because the model estimates stock recruit residuals for years from 1987 to 2011.

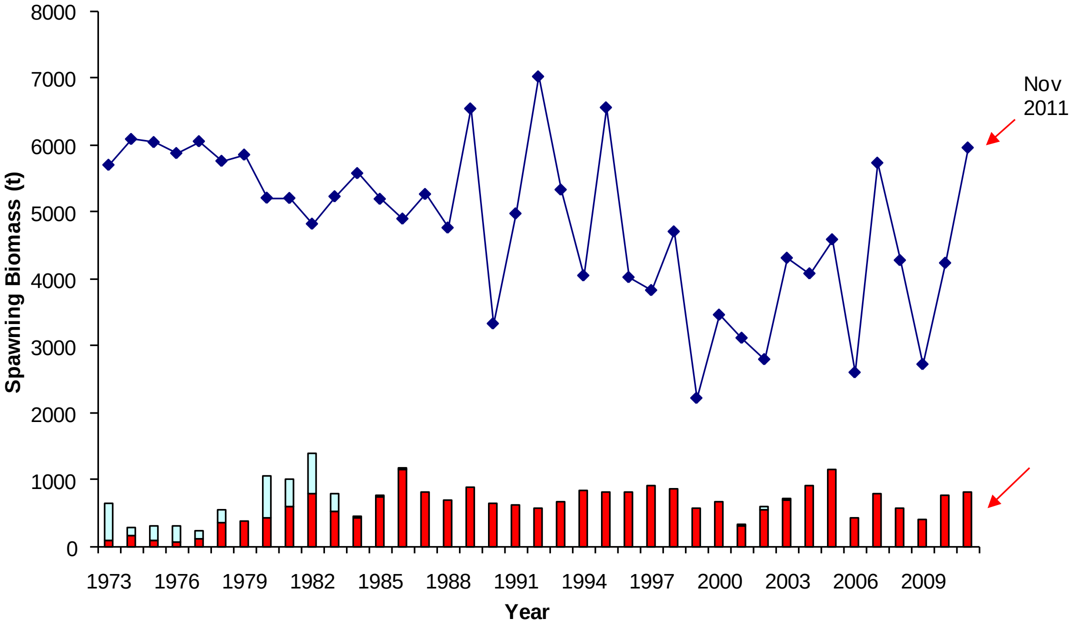


Fig. 13. Model trajectories of the lobster spawning biomass (t) over the model period shown together with annual catches by the trawling and other sectors combined.

The model-predicted spawning biomass trajectory is shown in Figure 14. The November 2011 spawning biomass is estimated to be 5960 t [3058; 8864] (Table 4). Note that this is a preliminary estimate only as is assumes that the 2011 catch taken is equal to the TAC. Figure 15 shows the model-predicted commercially available (also termed exploitable) lobster biomass, computed as the sum of all 1+ and 2+ lobsters which are "available" to be caught each year. The current 2011 estimate is 6533 t [3664; 9402].

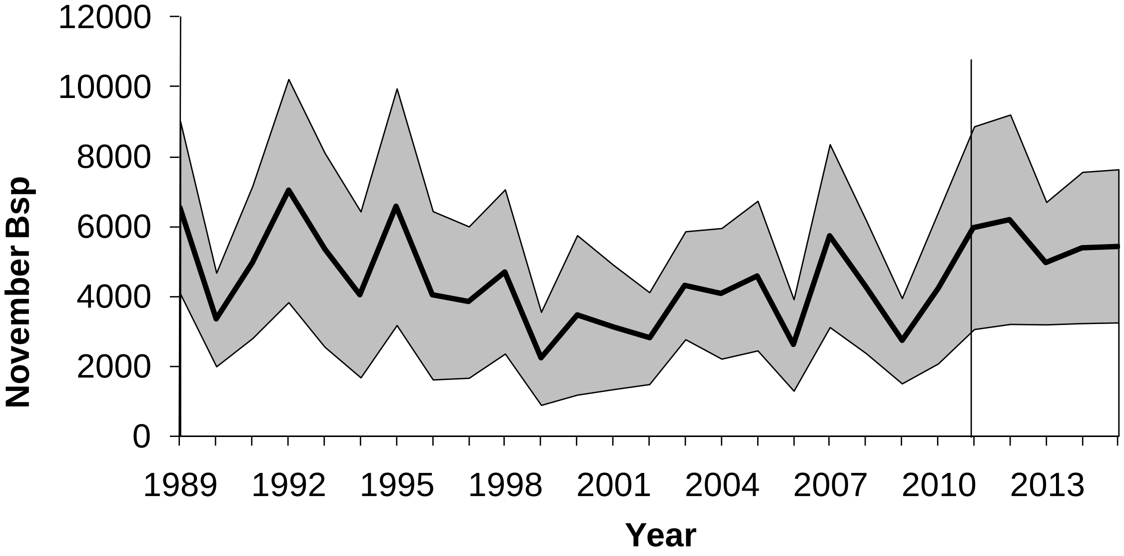


Figure 14. Model-predicted lobster November spawning biomass trajectory shown together with Hessian-based 90% confidence intervals. The vertical line indicates the separation between historic and predicted estimates.

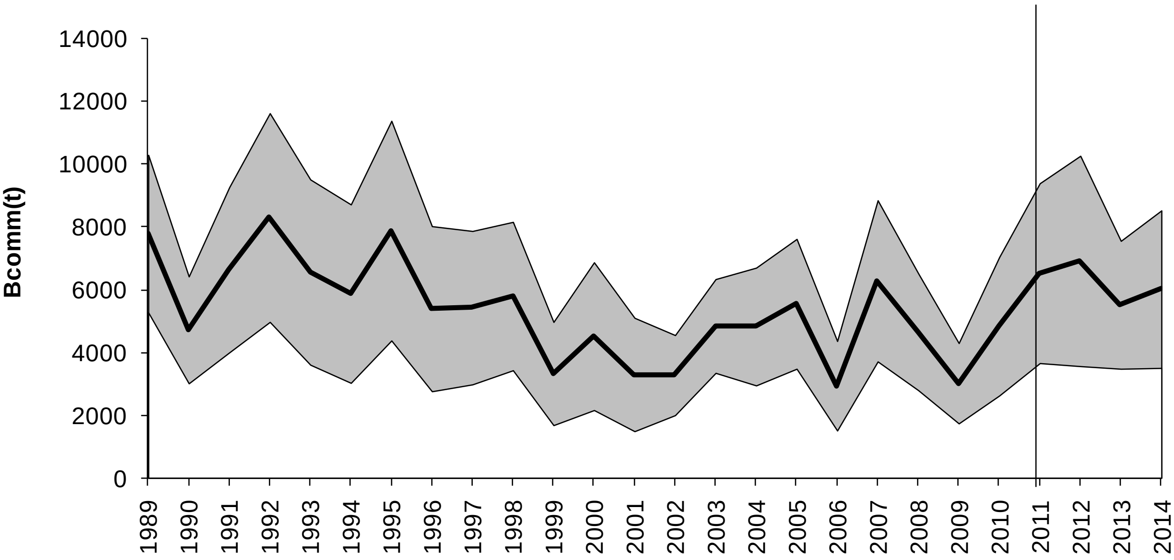


Figure 15. Model-predicted commercially available (also termed exploitable) lobster biomass (Bcomm), which is the sum of all 1+ and 2+ lobsters which are "available" to be caught each year. The shaded area shows the Hessian-based 90% confidence intervals. The vertical line indicates the separation between historic and predicted estimates.

The model-predicted midyear numbers of 1+ and 2+ lobsters (together with Hessian-based 90% confidence intervals) are shown in Figure 16. The high 1+ abundance observed in the 2011 midyear survey (Fig. 16) suggests the 2012 stock should be at a good level. Recruitment levels recorded during the mid-year surveys are not as effective as those from pre-season surveys given the long delay between the survey and the fishery opening. Once the quota management system is in place it will be critical to determine recruitment levels so that TACs are set at appropriate levels.

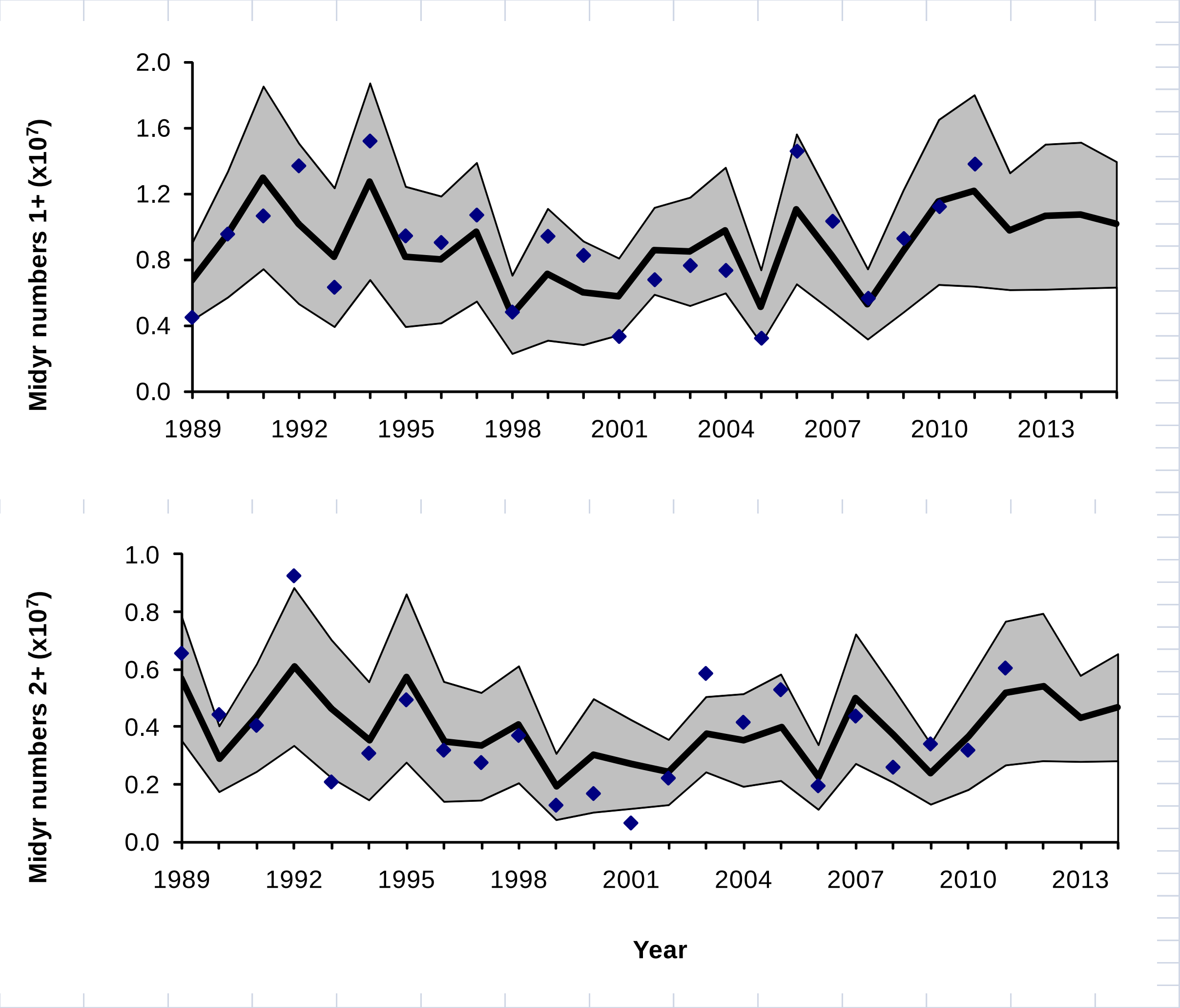


Figure 16. Model-predicted midyear numbers of 1+ and 2+ lobsters shown together with Hessian-based 90% confidence intervals. The solid points are the observed survey numbers.

Sensitivity Tests

The robustness of model results were tested across a number of important sensitivity tests (Table 5). The first sensitivity test shown pertains to using a different hyperstability shape parameter (0.5, compared with 0.75 in the Reference Case model) to control the relationship between CPUE and stock abundance. Sensitivity scenario b) did not differ much compared with the Reference Case because the variance parameter associated with the CPUE information is fairly high (0.25) and hence the CPUE likelihood contribution is effectively downweighted. Larger differences are evident when reducing the lower bound on the variance associated with the CPUE data, as per Sensitivity scenarios e and g. Figure 18 shows the improvement in model fit to CPUE data, together with deterioration in fit to survey data, under sensitivity (e) that accords more weight to the CPUE series likelihood contribution because the lower bound of the sigma parameter is set at 0.1 rather than 0.25 as in the Reference Case

The Reference Case used the model free estimates of the TVH catch per unit of effort and there wasn't much difference when using the alternative linear model estimates instead (Table 5 – sensitivity c).

Initial simulations showed that it was difficult to accurately mimic the high stock abundance observed in 2011 without increasing the variance parameter associated with estimation of the stock-recruitment residuals. The Reference Case thus used a value of 0.5, compared with the previous assessment which used 0.3. As the fishery-independent survey provides the most reliable index of stock abundance, it was considered important to fit the recent upward trend (compare Fig. 17 (Sensitivity d) and Fig. 2 (Reference Case)).

The final sensitivity test (Table 5 – sensitivity f) investigated the effect of changing the lower bound of the variance for the historic CAA information from 0.25 to 0.1.

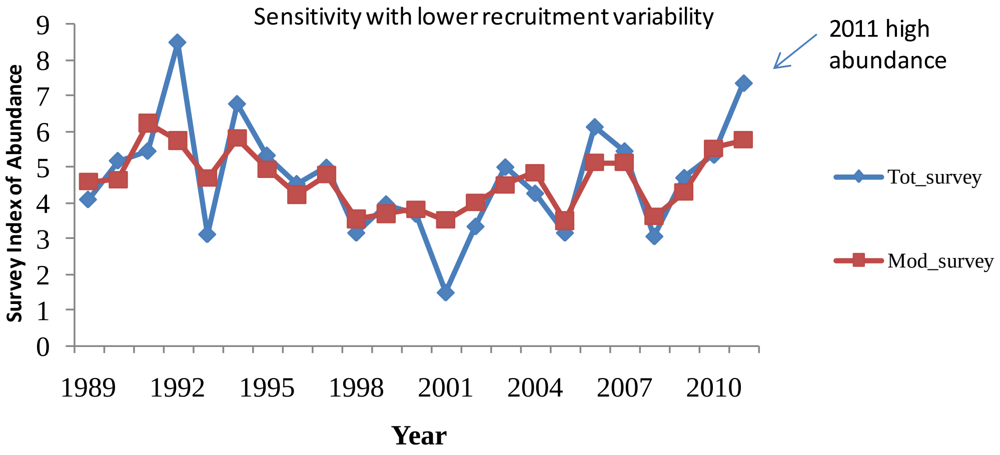
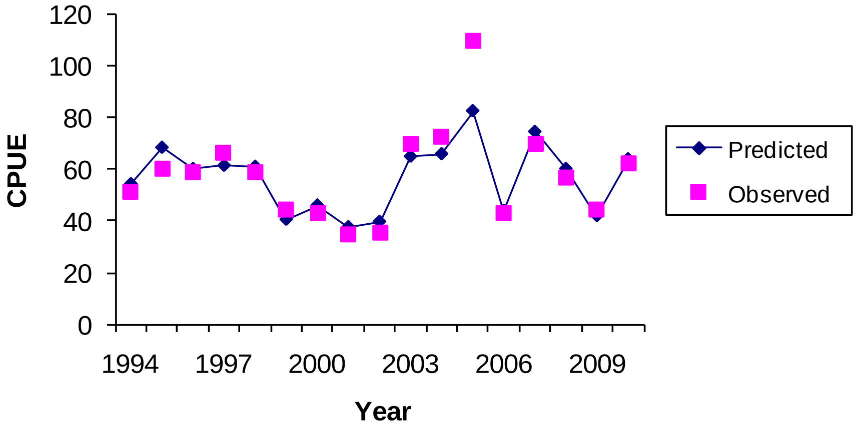


Figure 17. Comparison of model and survey index of abundance when using a model version with a lower value for the variance controlling the extent of recruitment variability.

a)



b)

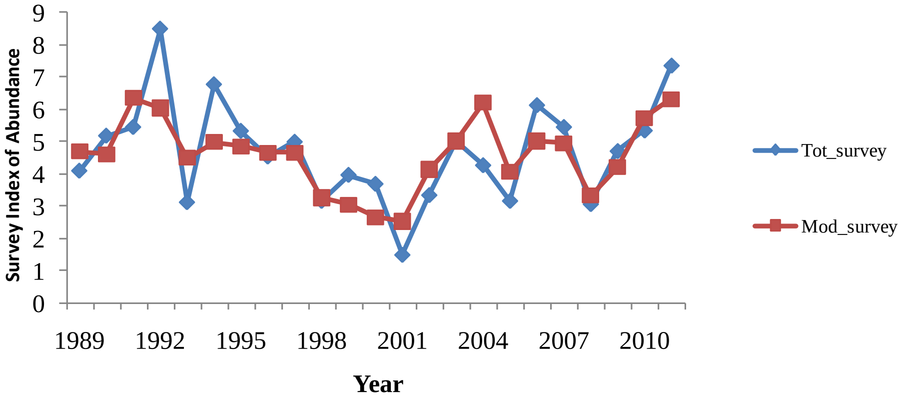


Fig. 18. Improved model fit to a) CPUE data shown together with deterioration in fit to b) survey data when using a model version that accords more weight to the CPUE series likelihood contribution because the lower bound of the sigma parameter is set at 0.1 rather than 0.25 as in the Reference Case.

1.1.4. Productivity of the lobster stock

The Precautionary approach to fisheries management (FAO 1995) emphasizes the need to implement management plans that contain target, limit and threshold reference points, and that include decision rules shown to be robust to uncertainty. Reference points are pre-specified levels that reflect stock status (eg Spawning Biomass *Bsp* or fishing mortality rate *F).* Important reference points are thus *B*MSY, the level of *Bsp* corresponding to deterministic Maximum Sustainable Yield, *MSY* as well as target reference points which specify preferred targets for management to aim at (Figure 19).

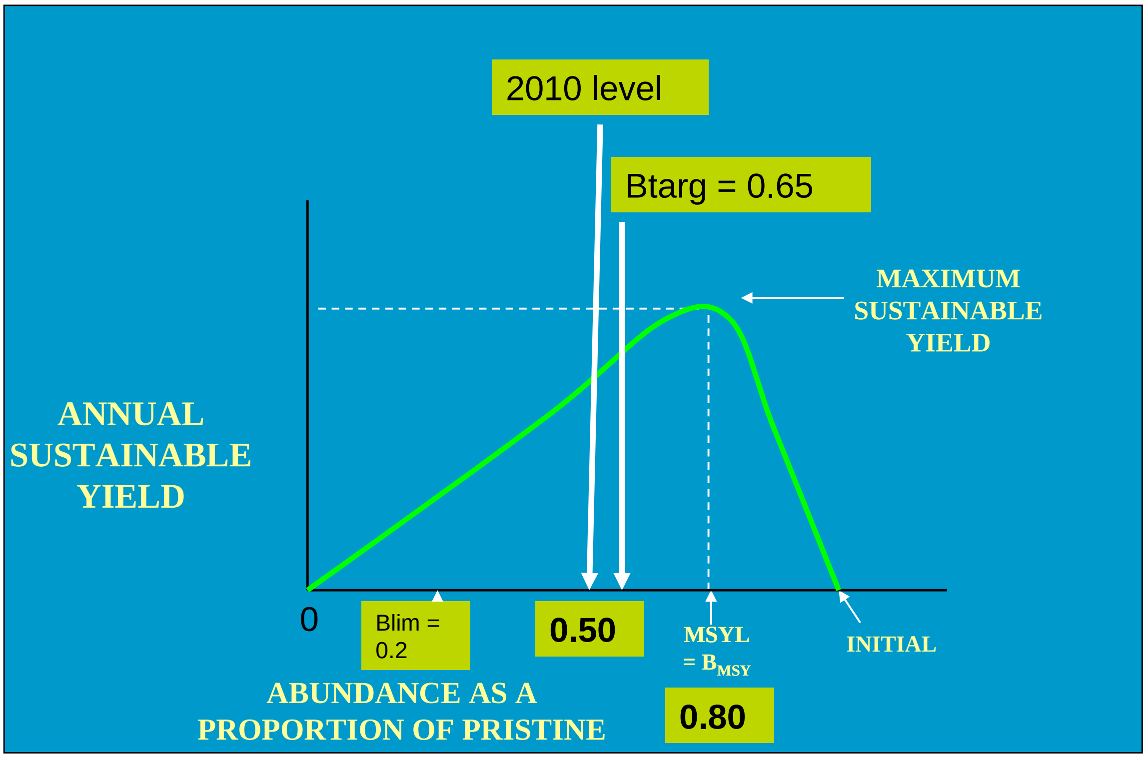


Figure 19. Schematic summary of Reference Points and management quantities (see text for details).

The model estimate of the maximum sustainable yield of the lobster fishery is about 650 tonnes whole weight, which is achieved at a spawning biomass of 4150 tonnes (*B*MSY), which is 80% of the pristine spawning biomass level (i.e. *B*MSYL = 0.80) (Table 6). The stock is currently estimated to be at 130% of *B*MSY. The estimated MSY is close to the average historic catch (1973-2008) of 645 tonnes. The fishing mortality at which MSY is achieved was estimated to be about 0.14 year^{-1}. Note that these are estimated quantities only and hence have associated errors and uncertainties. Moreover, they correspond to deterministic assumptions regarding the stock-recruit relationship, yet for variable recruit-driven fisheries such as this, yield is determined predominantly by the strength of recruitment, and hence annual sustainable yields can be expected to fluctuate widely about the deterministically predicted estimates. Even given annual fluctuations, the stock is estimated to be far from the default limit reference level of 0.5* *B*MSYL (Table 6).

Table 6. Summary of model estimates of Reference levels and Management Quantities. Note that the annual November spawning biomass is cited because it represents the number of mature lobsters undertaking the spawning migration each year.

Model Estimate	Value		Management Quantities	
$B(1973)^{sp}$	5691			
$B(2011)^{sp}$	5961		$BMSY^{sp}$ (tons)	4553
Current Depletion $B(2011)^{sp} / B(1973)^{sp}$	1.05		$BMSY^{sp} / B_0{}^{sp}$	0.8
$B(2009)^{sp} / B(1973)^{sp}$; $B(2010)^{sp} / B(1973)^{sp}$	0.48; 0.74		$Bcurrent/B_{targ}$	1.31
Ave depletion over last 5 yrs	0.8		F_{targ}	0.15
$F(2009)$,$F(2010)$	0.14; 0.17		$FMSY$	0.14
$F(2010)/F_{targ}$	1.13			
B_{targ} (tons)	4553			
$Bcurrent/BMSY^{sp}$	1.31		B_{lim}	0.4
$Bcurrent/B_{lim}$	2.6			

Rather than relying on unreliable estimates of *B*MSY, a sensible target reference point to specify where management should aim was selected, consistent with the approach used previously, to be the average fishing mortality over the past two decades, namely 0.15 year^{-1} , which is similar to the estimate of FMSY.

TAC ESTIMATION FOR 2012

1.2. INTRODUCTION

In July 2005 the PZJA decided to transfer the management of the Torres Strait rock lobster fishery from input controlled to a quota management system. There exist a few challenges for the quota management system. Firstly, there is high variability in lobster recruitment. The Torres Strait rock lobster has a short life span, and most lobsters die before reaching the age of three. Oceanographic conditions have a great influence on recruitment and subsequently the stock abundance. Secondly, the Torres Strait lobster fishery catch is almost exclusively comprised of age 2+ lobsters under current input controls. Therefore, annual lobster catches fluctuate with recruitment to a great extent. This translates into setting a TAC based on the estimate of recruitment, which is much more difficult than setting a TAC for a multiple cohort stock. Besides these technical challenges, there is also a need for changes in governance of the fishery. The Torres Strait lobster fishery has never adopted any harvest strategy rules for its management. Although development of harvest strategies is mandatory for Commonwealth Fisheries, Torres Strait fisheries are exempted due to their unique social and economic situations and to the complexity involved in management. However, harvest control rules are absolutely critical for a quota-managed fishery to avoid the potential subjectivity in the setting of TAC and the conflict between various interest-groups. As part of a linked lobster MSE project, a range of harvest control rules will be tested for the Torres Strait lobster fishery.

The Torres Strait TRL fishery catches have in the past been far below the TAC. This was attributed to a combination of underreporting of catch, economic and/or weather conditions. However, in recent years the gap has narrowed substantially. The total catch for 2009 in the Torres Strait was 397 t which was revised upwards from a previous estimate of 342 tonnes, and hence was 88% of the Final TAC (450 tonnes) set for 2009 (Table 7). The furnishment of accurate catch statistics is critical under the new TAC setting process. The 2010 catch of 763t was 89% of the TAC and the 2011 catch is expected to be very high.

The preliminary TAC for 2012 is 637t, determined as the lower bound of the 75% confidence interval associated with a model estimate of 964t. The forecast TAC for 2013 is 769t (Table 7). The results presented in this document assume the 2011 catch is equal to the TAC value of 803t. Note that the confidence interval associated with this TAC recommendation was 445t-1160t, highlighting the large uncertainties associated with model predictions, and the need for a pre-season survey to narrow the uncertainty.

Table 7. Preliminary and forecast TAC estimates for the Torres Strait TRL fishery for 2012-2013

	Year				
TAC/Catch (t)	**2009**	**2010**	**2011**	**2012**	**2013**
Forecast TAC (90% CI)		837 (541 – 1133)	731 (463-999)	532 (282-782)	769 (485-1053)
Preliminary TAC (90% CI)	450 (314-587)	853 (603-1103)	803 (445-1160)	964 (497-1432)	*Oct 2012*
Preliminary TAC allocation	402	678	552	637	*Oct 2012*
Final TAC	450	853*	803[$]	*Mar 2012*	*Mar 2013*
Catch	397[#]	763	-	-	-

* Note with the revisions made to the model in 2010, the adjusted 2010 catch corresponding to the target fishing mortality rate, is 720t.

[#] Catch adjusted upwards from 342t

$ Retrospectively calculated value = 920t

The provisional final and forecast TACs are outputted from the Integrated model in the same way, but with different degrees of uncertainty surrounding the estimates as additional information from the fishery is included. It should be noted that the final TAC is not just the outcome of the stock assessment process but also the harvest control rules. It is recommended that the effectiveness of the harvest control rules in achieving management objectives be examined using a Management Strategy Evaluation (MSE) approach. A provisional forecast TAC for the following year is set in October using mid-season survey data on the abundance of one year old lobsters. As agreed by the RAG, the provisional forecast TAC needs to be conservative so that when the final TAC is set in March the following year, there is a low probability that it will be less than the provisional forecast TAC. The provisional forecast TAC is thus set in October using the lower end of 75% confidence intervals. The use of the lower end of the 75% confidence interval is referred to in Tables in this document as Rule 1.

1.3. DISCUSSION

The revised and updated model adequately fits the available data and integrates all available information into a single framework to output a TAC estimate as required for a change to a quota management system. The use of a single model facilitates understanding of the way in which data inputs translate into an assessment of the status and productivity of the resource and hence an associated TAC estimate. Moreover, parameter estimates and resource trajectories are presented together with confidence intervals to illustrate the extent of uncertainty associated with model predictions.

An important assumption of the current and previous assessments is that the Torres Straits rock lobster resource is a closed population, but this is clearly not the case given they migrate eastwards out the Torres Straits (Moore and MacFarlane 1984, Skewes et al. 1994). It is not known to what extent mixing occurs with the eastern component of the stock, and hence whether these two stock components should rather be treated as a single stock in computing a spawning stock biomass. This aspect will be investigated during a related MSE project, and it is hoped will shed further light on estimation of the stock-recruitment steepness parameter.

Overall the resource is estimated to be in excellent condition. The preliminary TAC recommendation for 2012 is higher than estimates from the previous 5 years, and is higher than all recent catches, except for year 2005, and hence it would be advisable to confirm this prediction with a preseason survey, or to adopt a precautionary approach in the absence of further information.

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APPENDIX 1 - ABBREVIATIONS & GLOSSARY

AFMA. Australian Fisheries Management Authority.

ASPM. Age-Structured production Model

CPUE. Catch Per Unit Effort

CSIRO. Commonwealth Scientific and Industrial Research Organisation.

MSE. Management Strategy Evaluation

PNG NFA. Papua New Guinea National Fisheries Authority.

PZJA. Protected Zone Joint Authority.

TSRA. Torres Strait Regional Authority.

TAC. Total allowable catch.

QMS. Quota management system.

APPENDIX 2 - STOCK ASSESSMENT EQUATIONS

1.4. INTRODUCTION

Torres Strait rock lobsters emigrate in spring and breed during the subsequent summer (November-February) (Moore and MacFarlane, 1984; MacFarlane and Moore, 1986). Therefore, the number of age 2+ lobsters at the middle of the breeding season (December) should represent the size of the spawning stock (Figure A-1). A schematic summary timeline underlying the new Integrated model is presented in Figure A-1. To simplify computations, the new model assumes catches, migration and spawning occur at discrete times, with quarterly updates to the dynamics of each age class. Catches of 2+ individuals are assumed taken as a pulse at midyear, with individuals migrating out of the Torres Straits at the end of the third quarter, and a spawning biomass being computed at the end of the year. Catches of 1+ lobsters are assumed taken at the end of the third quarter, when a proportion of this age class have grown large enough to be available to fishers.

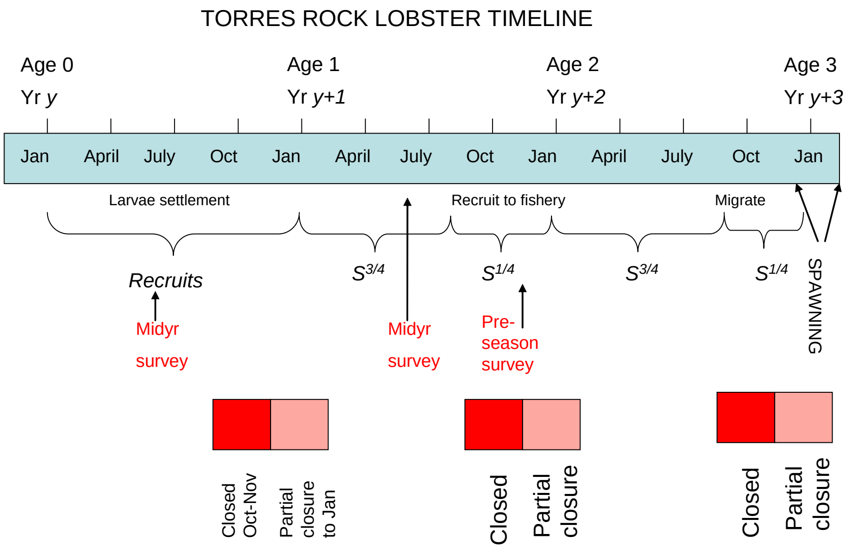

Figure A-1. Summary timeline for Torres Strait Rock Lobster model.

P. ornatus is an unusually fast growing lobster and hence analyses are expected to be sensitive to changes in assumption regarding growth rate (length vs age) and mass-at-length. Previous modelling studies used the Trendall et al. (1988) relationship:

$$CL_m = 177\left(1 - e^{-0.386(m/12-0.411)}\right)$$

where CL is carapace length (mm) and m is age in months for aspects of the computations. However, after converting length to mass using the morphometric relationship:

TOTWT=0.00258*(CL^2.76014)

the Trendall et al (1988) relationship translates into average individual masses that are less than the observed average mass of lobsters caught in the fishery. The Integrated model thus uses the Phillips et al. (1992) male growth relationship:

$$CL = L_\infty \left(1 - e^{-kt}\right)$$

where $L_\infty = 165.957 \quad mm$;
$\kappa = -0.0012$; and
t is age in DAYS.

THE INTEGRATED MODEL

An age-structured model of the Torres Rock Lobster population dynamics is developed and fitted to the available abundance indices by maximising the likelihood function. The model equations and the general specifications of the model are described below, followed by details of the contributions to the log-likelihood function from the different sources of data available. Quasi-Newton minimization is used to minimize the total negative log-likelihood function (the package AD Model Builder^{TM}, Otter Research, Ltd is used for this purpose.

1.4.1. Lobster population dynamics

1.4.1.1. Numbers-at-age

The resource dynamics are modelled by the following set of population dynamics equations:

$$N_{y+1,1} = R_{y+1} \qquad 1$$

$$N_{y+1,a+1} = \left(N_{y,a}\, e^{-3M_a/4} - C_{y,a}\right) e^{-M_a/4} \qquad \text{for } a\text{=1} \qquad 2$$

$$N_{y+1,a+1} = \left(N_{y,a}\, e^{-M_a/2} - C_{y,a}\right) e^{-M_a/2} \qquad \text{for } a\text{=2} \qquad 3$$

where

$N_{y,a}$ is the number of lobsters of age *a* at the start of year *y* (which refers to a calendar year),

R_y is the recruitment (number of 1-year-old lobsters) at the start of year *y*,

M_a denotes the natural mortality rate on lobsters of age *a*,

$C_{y,a}$ is the predicted number of lobsters of age *a* caught in year *y*, and

m is the maximum age considered (taken to be 3).

These equations simply state that for a closed population, with no immigration and emigration, the only sources of loss are natural mortality (predation, disease, etc.) and fishing mortality (catch). They reflect Pope's form of the catch equation (Pope, 1972) (the catches are assumed to be taken as a pulse at midyear for the 2+ class and at the start of the third quarter for the 1+ class) rather than the more customary Baranov form (Baranov, 1918) (for which catches are incorporated under the assumption of steady continuous fishing mortality). Pope's form has been used in order to simplify computations.

1.4.1.2. Recruitment

The number of recruits (i.e. new 1-year old lobsters – it is simpler to work with 1- rather than 0-year old lobsters as recruits) at the start of year *y* is assumed to be related to the spawning stock size (i.e. the biomass of mature lobsters) by a modified Beverton-Holt stock-recruitment relationship (Beverton and Holt, 1957), allowing for annual fluctuation about the deterministic relationship:

$$R_y = \frac{\alpha B^{sp}_{y-1}}{\beta + \left(B^{sp}_{y-1}\right)^{\gamma}} e^{(\varsigma_y - (\sigma_R)^2/2)} \qquad 4$$

where

α, β and γ are spawning biomass-recruitment relationship parameters (note that cases with γ > 1 lead to recruitment which reaches a maximum at a certain spawning biomass, and thereafter declines towards zero, and thus have the capability of mimicking a Ricker-type relationship),

ς_y reflects fluctuation about the expected recruitment for year *y*, which is assumed to be normally distributed with standard deviation σ_R (which is input in the applications considered here); these residuals are treated as estimable parameters in the model fitting process. Estimating the stock-recruitment residuals is made possible by the availability of catch-at-age data, which give some indication of the age-structure of the population.

B^{sp}_y is the spawning biomass at the start of year *y*, computed as:

$$B^{sp}_y = w^{st}_3 \cdot N_{y,3} \qquad 5$$

where

w^{st}_3 is the mass of lobsters of age 3 (i.e. in December during the spawning season).

In order to work with estimable parameters that are more meaningful biologically, the stock-recruitment relationship is re-parameterised in terms of the pre-exploitation equilibrium spawning biomass, K^{sp}, and the "steepness", *h*, of the stock-recruitment relationship, which is the proportion of the virgin recruitment that is realized at a spawning biomass level of 20% of the virgin spawning biomass:

$$\beta = \frac{\left(K^{sp}\right)^{\gamma}\left(1 - 5h0.2^{\gamma}\right)}{5h - 1} \qquad 6$$

and

$$\alpha = \frac{\beta + \left(K^{sp}\right)^{\gamma}}{SPR_{virg}} \qquad 7$$

where

$$SPR_{virg} = w^{st}_3 N^{virg}_3 \qquad 8$$

with

$$N^{virg}_1 = 1 \qquad 9$$

$$N^{virg}_a = N^{virg}_{a-1} e^{-M_{a-1}} \qquad \text{for} \quad 2 < a \le m \qquad 10$$

1.4.1.3. Total catch and catches-at-age

The catch by mass in year y is given by:

$$C_y = w_1^{land} N_{y,1} e^{-3M_a/4} S_{y,1} F_y^{1+} + w_2^{mid} N_{y,2} e^{-M_a/2} S_{y,2} F_y^{2+} \qquad 11$$

Where

w_a^{land} denotes the mass of lobsters of age a that are landed at the end of the third quarter,

w_a^{mid} denotes the mid-year mass of lobsters of age a,

$S_{y,a}$ is the commercial selectivity (i.e. vulnerability to fishing gear) at age a for year y; and

F_y is the fished proportion (of the 1+ and 2+ classes) of a fully selected age class.

The model estimate of the exploitable ("available") component of biomass is calculated by converting the numbers-at-age into mass-at-age (using the individual weights of the 1+ lobsters assumed landed at the end of the third quarter, and the 2+ lobsters assumed landed at midyear):

$$B_y^{ex,1+} = w_1^{land} S_{y,1} N_{y,1} e^{-3M_a/4} \qquad 12$$

$$B_y^{ex,2+} = w_2^{mid} S_{y,2} N_{y,2} e^{-M_a/2} \qquad 13$$

and hence:

$$B_y^{ex} = B_y^{ex,1+} + B_y^{ex,2+} \qquad 14$$

The 2010 model version computes the catch by mass separately for the trawling sector, which is assumed to target 2+ lobsters only. The exploitable component of biomass for this sector is thus based on Equation (13) only and assumes full selectivity of the 2+ age group.

The model estimates of the midyear numbers of lobsters are:

$$N_y^{mid} = N_{y,1} e^{-M_1/2} + \left(N_{y,2}\, e^{-M_2/2} - C_{y,2}\right) \qquad 15$$

i.e.

$$N_{y,1}^{mid} = N_{y,1} e^{-M_1/2} \qquad 16$$

$$N_{y,2}^{mid} = N_{y,2}\, e^{-M_2/2} - C_{y,2} \qquad 17$$

Similarly, the model estimate of numbers for comparison with the Pre-Season November survey are as follows:

$$N_{y,1}^{pre} = \left(N_{y,1} e^{-3M_1/4} - C_{y,1}\right) e^{-M_1/6} \qquad 18$$

$$N_{y,2}^{pre} = N^{mid}{}_{y,2}\, e^{-5M_2/12} \tag{19}$$

The proportion of the 1+ and 2+ age classes harvested each year (F_y^{1+}) are given respectively by:

$$F_y^{1+} = C_y^{1+} \; / B_y^{exp,1+} \tag{20}$$

$$F_y^{2+} = C_y^{2+} \; / B_y^{exp,2+} \tag{21}$$

where C_y^{1+} and C_y^{2+} are the catch by mass in year *y* for age classes 1 and 2, such that:

$$C_y^{1+} = p_{y,1+} C_y \tag{22}$$

and

$$C_y^{2+} = \left(1 - p_{y,1+}\right) C_y \tag{23}$$

with $p_{y,1+}$ representing the 1+ proportion of the total catch.

Given different fishing proportions for the two age classes, the numbers-at-age removed each year from each age class can be computed from:

$$C_{y,1} = S_{y,1} F_y^{1+} N_{y,1} e^{-3M_a/4} \qquad \text{for } a = 1\text{, and} \tag{24}$$

$$C_{y,2} = S_{y,2} F_y^{2+} N_{y,2} e^{-M_a/2} \qquad \text{for } a = 2 \tag{25}$$

The fully selected fishing proportion (*F*) is related to the annual fishing mortality rate (*F**) as follows:

$$1 - F = e^{-F^*} \tag{26}$$

1.4.1.4. Initial conditions

Although some exploitation occurred before the first year for which data are available for the lobster stock, this is considered relatively minor and hence the stock is assumed to be at its pre-exploitation biomass level in the starting year and hence the fraction (θ) is fixed at one in the analysis described here:

$$B_{y_0}^{sp} = \theta \cdot K^{sp} \tag{27}$$

with the starting age structure:

$$N_{y_0,a} = R_{start} N_{start,a} \qquad \text{for } 1 \le a \le m \tag{28}$$

where

$$N_{start,1} = 1 \tag{29}$$

$$N_{start,a} = N_{start,a-1} e^{-M_{a-1}} \qquad \text{for } 2 \le a \le m-1 \tag{30}$$

1.4.2. The (penalised) likelihood function

Model parameters are estimated by fitting to survey abundance indices, commercial and survey catch-at-age data as well as standardised CPUE data in some cases. A penalty function is included to permit estimation of residuals about the stock-recruitment function.

Contributions by each of these to the negative of the log-likelihood ($-\ell nL$) are as follows.

1.4.2.1. Survey abundance data

The same methodology is applied for the midyear and pre-season surveys, except that for the former the index represents the total 1+ and 2+ numbers, whereas for the pre-season the fit is only to the 1+ lobsters as most of the older lobsters will have migrated out of the region by November. The likelihood is calculated assuming that the observed midyear (and pre-season) survey abundance index is log-normally distributed about its expected value:

$$I_y^i = \hat{I}_y^i \exp(\varepsilon_y^i) \quad \text{or} \quad \varepsilon_y^i = \ell n(I_y^i) - \ell n(\hat{I}_y^i) \tag{31}$$

where

I_y^i is the scaled survey abundance index for year *y* and series *i*,

$\hat{I}_y^i = \hat{q}_s \hat{N}_y^{survey}$ is the corresponding model estimate, where $\hat{N}_y^{survey}$ is the model estimate of midyear numbers, given by equation 15 for the midyear survey, and for the pre-season survey it is given by equation 18.

$\hat{q}_s$ is the constant of proportionality (catchability) for the survey, and

ε_y^i from $N\left(0, (\sigma_y^i)^2\right)$.

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

$$-\ell n L^{Surv} = \sum_i \sum_y \left[\ln(\sigma_y^i) + (\varepsilon_y^i)^2 / 2(\sigma_y^i)^2\right] \tag{32}$$

where $(\sigma_y^s)^2 = \ln(1 + (CV_y)^2)$ and the coefficient of variation (CV_y) of the resource abundance estimate for year *y* is input.

The survey catchability coefficient $\hat{q}_s$ is estimated by its maximum likelihood value:

$$\ell n \hat{q}_s = 1/n_i \sum_y (\ln I_y^i - \ln N_y^{ex}) \tag{33}$$

1.4.2.2. Commercial catches-at-age

The contribution of the catch-at-age data to the negative of the log-likelihood function under the assumption of an "adjusted" lognormal error distribution is given by:

$$-\ell n L^{CAA} = \sum_y \sum_a \left[\ell n\left(\sigma_{com} / \sqrt{p_{y,a}}\right) + p_{y,a}(\ell n\, p_{y,a} - \ell n\, \hat{p}_{y,a})^2 / 2(\sigma_{com})^2\right] \tag{34}$$

where

$p_{y,a} = C_{y,a} / \sum_{a'} C_{y,a'}$ is the observed proportion of lobsters caught in year *y* that are of age *a*,

$\hat{p}_{y,a} = \hat{C}_{y,a} / \sum_{a'} \hat{C}_{y,a'}$ is the model-predicted proportion of lobsters caught in year *y* that are of age *a*, where

$$\hat{C}_{y,1} = N_{y,1}\, e^{-3M_a/4}\, S_{y,1}\, F_y^{1+} \tag{35}$$

$$\hat{C}_{y,2} = N_{y,2}\, e^{-M_a/2}\, S_{y,2}\, F_y^{2+} \qquad 36$$

and

σ_{com} is the standard deviation associated with the catch-at-age data, which is estimated in the fitting procedure by:

$$\hat{\sigma}_{com} = \sqrt{\sum_y \sum_a \left(\ell n\, p_{y,a} - \ell n\, \hat{p}_{y,a}\right)^2 / \sum_y \sum_a 1} \qquad 37$$

The same approach is applied when fitting to the historic catch proportion data.

1.4.2.3. Survey catches-at-age

The survey catches-at-age are incorporated into the negative of the log-likelihood in an analogous manner to the commercial catches-at-age, assuming an adjusted log-normal error distribution (equation 25) where:

$p_{y,a} = C^{surv}_{y,a} / \sum_{a'} C^{surv}_{y,a'}$ is the observed proportion of lobsters of age *a* in year *y*,

$\hat{p}_{y,a}$ is the expected proportion of lobsters of age *a* in year *y* in the survey, given by:

$$\hat{p}_{y,a} = N_{y,a} \Big/ \sum_{a'=1}^{2} N_{y,a} \qquad 38$$

Benchmark Survey Estimates of Absolute Abundance

The absolute abundance of lobsters is estimated by fitting to data from two benchmark midyear surveys. The total 2002 population estimate, together with 95% confidence interval, was *T₈₉* = 9.0 (±1.9) million lobsters, and for 1989, *T₈₉* = 14.0 (±2.9) million lobsters (Pitcher et al. 1992). The 2+ year class was estimated at 1.77 (±0.38) million in 2002, and the 1+ year-class was at 5.2 (±1.5) million.

The approach is similar to that described above for the survey relative abundance index. The contribution of the survey data to the negative of the log-likelihood function (after removal of constants) is then given by:

$$-\ell n\, L^{Bench} = \ell n\left(\sigma_{89}\right) + \left(\varepsilon_{89}\right)^2 / 2\left(\sigma_{89}\right)^2 + \ell n\left(\sigma_{02}\right) + \left(\varepsilon_{02}\right)^2 / 2\left(\sigma_{02}\right)^2 \qquad 39$$

where $\varepsilon_{89} = \ell n\left(T_{89}\right) - \ell n\left(\hat{N}^{mid}_{1989,1} + \hat{N}^{mid}_{1989,2}\right)$;

$\varepsilon_{02} = \ell n\left(T_{02}\right) - \ell n\left(\hat{N}^{mid}_{2002,1} + \hat{N}^{mid}_{2002,2}\right)$; and

$\left(\sigma_y\right)^2 = \ln\left(1 + \left(CV_y\right)^2\right)$ and the two coefficients of variation (CV_{89} and CV_{02}) are input.

1.4.2.4. Stock-recruitment function residuals

The stock-recruitment residuals are assumed to be log-normally distributed and serially correlated. Thus, the contribution of the recruitment residuals to the negative of the (now penalised) log-likelihood function is given by:

$$-\ell nL^{pen} = \sum_{y=y1+1}^{y2}\left[\left(\frac{\lambda_y - \rho\lambda_{y-1}}{\sqrt{1-\rho^2}}\right)^2 \Big/ 2\sigma_R^2\right] \qquad 40$$

where

$\lambda_y = \rho\lambda_{y-1} + \sqrt{1-\rho^2}\,\varepsilon_y$ is the recruitment residual for year *y*, which is estimated for year *y*1 to *y*2 (see equation 4),

ε_y from $N(0,\sigma_R^2)$,

σ_R is the standard deviation of the log-residuals, which is input, and

ρ is the serial correlation coefficient, which is input.

In the interest of simplicity, equation 40 omits a term in λ_{y1} for the case when serial correlation is assumed ($\rho \neq 0$), which is generally of little quantitative consequence to values estimated.

The analyses conducted in this paper have however all assumed $\rho = 0$.

1.4.3. Model parameters

Natural mortality:

Natural mortality (M_a) is generally taken to be age independent and is estimated in the model fitting process.

In sensitivity tests where age-dependence is admitted, it is taken to have the form:

$$M_a = \mu_1 + \mu_2/a \qquad 41$$

Fishing selectivity-at-age:

The commercial selectivity is taken to differ over the 1973-2002 and 2002+ periods. Full selectivity of the 2+ class is assumed, with a separate selectivity parameter being estimated for each period for the 1+ class.