Revised 2010 Assessment of the Tropical Rock Lobster (*Panulirus ornatus*) Fishery in the Torres Straits

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SUMMARY

The new integrated model has been updated with all available information and revisions and improvements to the assessment methodology have been made. The data updates include the latest (June 2010) midyear survey results as well as complete revisions to the commercial CPUE and catch at age data series. The major model revision pertains to 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. The revised model fits all available data well, and is an improvement on the preliminary model version.

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 the setting of the TAC because it integrates all available information in a single self-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 in 2009 has been used to compute a provisional forecast 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 provisional forecast TAC estimate for 2011 is 567t (based on a model estimate of 709t) whereas the provisional forecast TAC for 2012 is 450t.

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 planned to be 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.

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 2010 model assessment update based on recent data updates (Plagányi *et al.* 2010).

Linked research that is planned to be 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. The updated model uses data updates and revisions as presented in Plagányi *et al.* (2010). A summary of the input catch data is shown in Fig. 1. In addition the latest (June 2010) midyear survey results (Table 2) are included in the model. As there is no planned Pre-season (November) survey for 2010, the results presented here provide the current best recommendations for a TAC for 2011.

The following major changes have been made to the 2010 revised assessment model:

- 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 has been completely revised such that a continuous input series is now available for all years 1989-2009 (Plagányi *et al.* 2010) (Table 3).
- The TVH CPUE data input series have been revised, with two alternative series available for the period 1989-2009 (Plagányi *et al.* 2010).
- The model is fitted to additional historic information as described below.
- 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.

Using historic information for the TS TRL resource

Recruitment variability is a fundamental driver of the Torres Straits rock lobster fishery. Estimation of the annual extent of variability about an underlying stock recruitment relationship is achieved by estimating annual recruitment residuals based on fitting to commercial and survey data on catch at age proportions. Data are available for years from 1989 onwards, with the observed proportions in the commercial catch shown in Table 3.

In the absence of data to estimate annual recruitment residuals, recruitment is set at the deterministic value from the stock recruit curve i.e. an “average” recruitment would be estimated for the year 1988. This is usually an adequate historic assumption, but is erroneous in this case because there is both anecdotal and research information indicating that 1988 was an unusually good recruitment year. For example, Pitcher et al. 2001 note as follows: “However, the catch-rate of 1+ lobsters in the 1988 catch was more than two-fold greater than in any subsequent year and the resulting 2+ year-class in 1989 was unusually large...”. If this recruitment is not accounted for in the model, the model tries to reconcile the subsequent dynamics by over-estimating the pristine stock size. There is further information suggesting, for example, that 1986 was similarly a very good year for the fishery. There are historic size composition data available for the years 1985, 1986 and 1989.

As a preliminary method to account for the large 1988 recruitment, catch data from Badu/Mabuiag Islands available between 1988 and 2001 were used indicating the observed relative proportions of the proportion of 1+ lobsters, relative to 2+ lobsters in the catch (Table 3). There is fairly good agreement between this data series and the commercial catch data for the first few years, and the data suggest that the proportion of 1+ lobsters in 1988 was unusually high. Based on the length frequency data for the years 1985-1986, an ad hoc adjustment (Skewes, pers commn., Dennis pers commn) was thus made to add these earlier proportions to the 1988-2001 catch at age proportions data series. By fitting to this “historic” data series (Table 3), the model is thus able to estimate a relatively large recruitment event for 1988, and hence a large 2+ year-class in 1989, as is on record. Sensitivity tests will be conducted to more fully explore the consequences of this ad hoc adjustment to the model.

Table 1. Lobster catches (tonnes whole weight) landed in different jurisdictions from 1973 to 2009. 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 divers	TIB	TVH	AUS trawl	PNG divers	Yule divers	PNG trawl	Total TS
1973	0			0	54	19	562	635
1974	0			0	75	83	107	265
1975	0			0	62	13	214	289
1976	0			0	48	0	262	310
1977	0			0	72	35	131	238
1978	296			0	43	3	187	529
1979	309			0	56	13	0	378
1980	328			21	94	3	589	1035
1981	495			131	96	3	262	987
1982	669			201	102	3	399	1374
1983	433			139	86	0	112	770
1984	331			8	86	0	29	454
1985	537			24	187	16	0	764
1986	891			21	198	62	0	1172
1987	622			0	128	54	0	804
1988	537			0	150	5	0	692
1989	651			0	211	24	0	886
1990	490			0	158	0	0	648
1991	444			0	168	0	0	612
1992	423			0	134	0	0	557
1993	506			0	166	0	0	672
1994	578		134	0	247	0	0	825
1995	557		101	0	257	0	0	814
1996	584		227	0	228	0	0	812
1997	653		285	0	241	0	0	894
1998	661		356	0	201	0	0	862
1999	410		126	0	163	0	0	573
2000	418		130	0	235	0	0	653
2001	122	52	70	0	173	0	5	300
2002	216	68	148	0	327	0	43	586
2003	485	123	362	0	211	0	5	701
2004	723	242	481	0	182	0	0	905
2005	920	375	545	0	228	0	0	1148
2006	289	154	135	0	142	0	0	431
2007	550	279	271	0	228	0	0	778
2008	332	221	111	0	221	0	0	553
2009	228	129	99	0	114	0	0	342

Table 2. Mid-year survey data summary for the period 1989-2010.

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

Table 3. Comparison between commercial catch at age information and historic catch proportions as described in the text.

	1+ historic prop	1+ prop	2+ historic prop	2+ prop
1985	0.41		0.59	
1986	0.42		0.58	
1987				
1988	0.62		0.38	
1989	0.05	0.06	0.95	0.94
1990	0.09	0.12	0.91	0.88
1991	0.12	0.25	0.88	0.75
1992	0.21	0.24	0.79	0.76
1993	0.44	0.21	0.56	0.79
1994	0.43	0.30	0.57	0.70
1995	0.14	0.21	0.86	0.79
1996	0.05	0.25	0.95	0.75
1997	0.08	0.30	0.92	0.70
1998	0.11	0.17	0.89	0.83
1999	0.39	0.31	0.61	0.69
2000	0.02	0.11	0.98	0.89
2001		0.00		1.00
2002		0.03		0.97
2003		0.03		0.97
2004		0.02		0.98
2005		0.01		0.99
2006		0.07		0.93
2007		0.01		0.99
2008		0.05		0.95
2009		0.00		1.00

1.1. RESULTS

1.1.1. Model fits

The fits of the new Integrated Model to all available data sources is shown in Figures 4 – 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 excellent (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 and corresponding model-predicted estimates are shown in Figure 6. The plots are respectively a) model free estimates and b) simple Linear Model estimates of the TVH catch per unit of effort in kg per tender-day from 1994 to 2009. The model fits shown are the best fit case when using each of the two series.

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 incorrect scale of the fit for 1985-1986 is possibly a result of a different fishing selectivity that should be applied to the early period, and this is investigated further in the model sensitivity runs.

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.

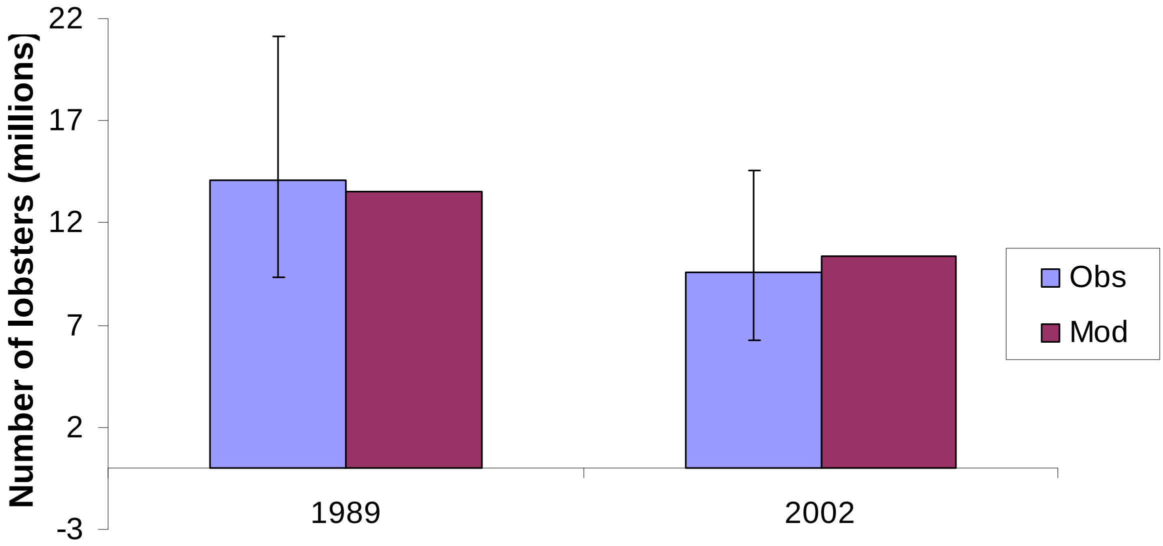


Figure 1. Comparison of benchmark survey observed lobster total abundance (with standard errors) and corresponding model-estimates of abundance.

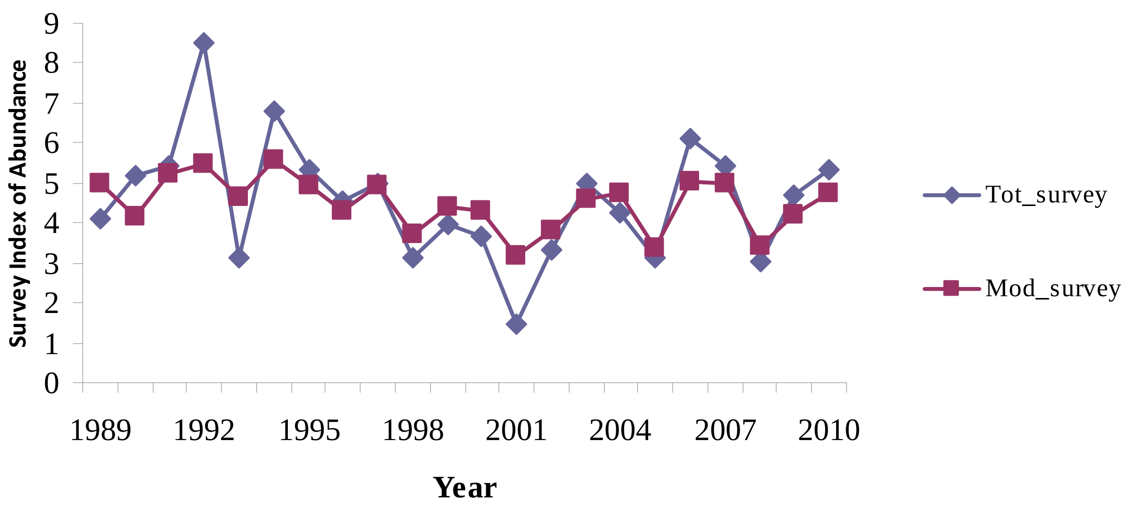
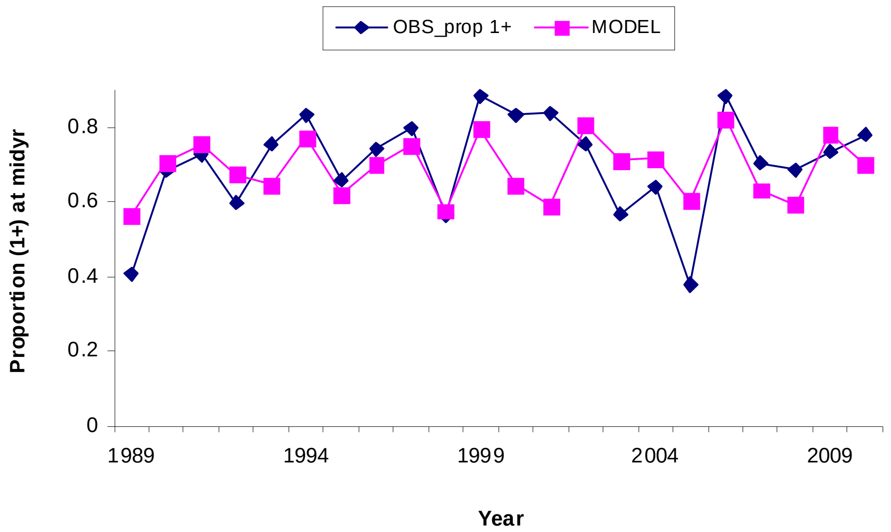


Figure 2. Comparison between survey midyear index of abundance (in terms of total numbers of 1+ and 2+ lobsters) compared with the corresponding model-estimated values.



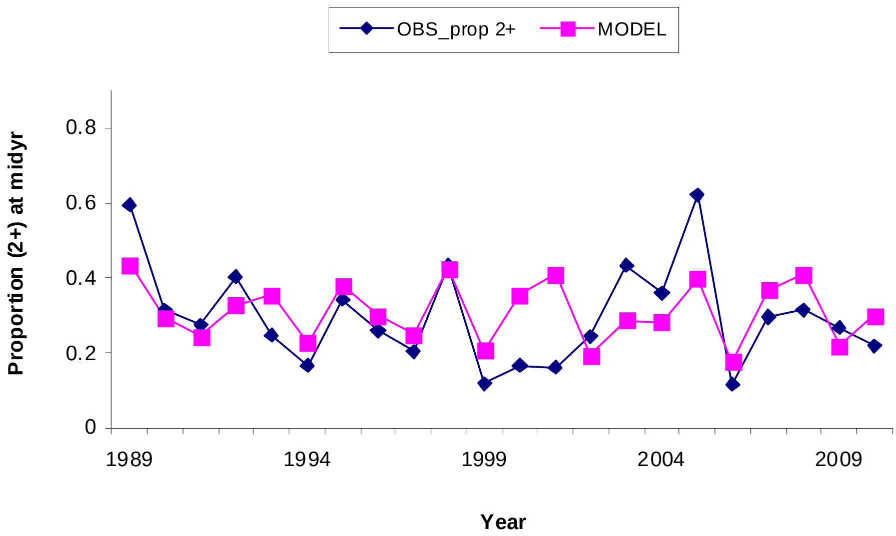
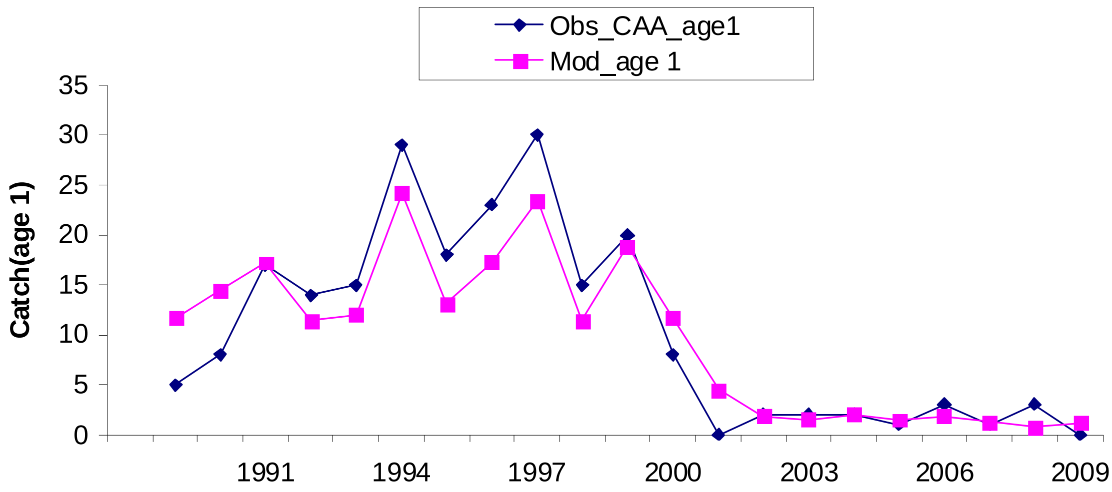


Figure 3. Comparison between observed and model-predicted proportions of 1+ and 2+ lobsters in the midyear survey.



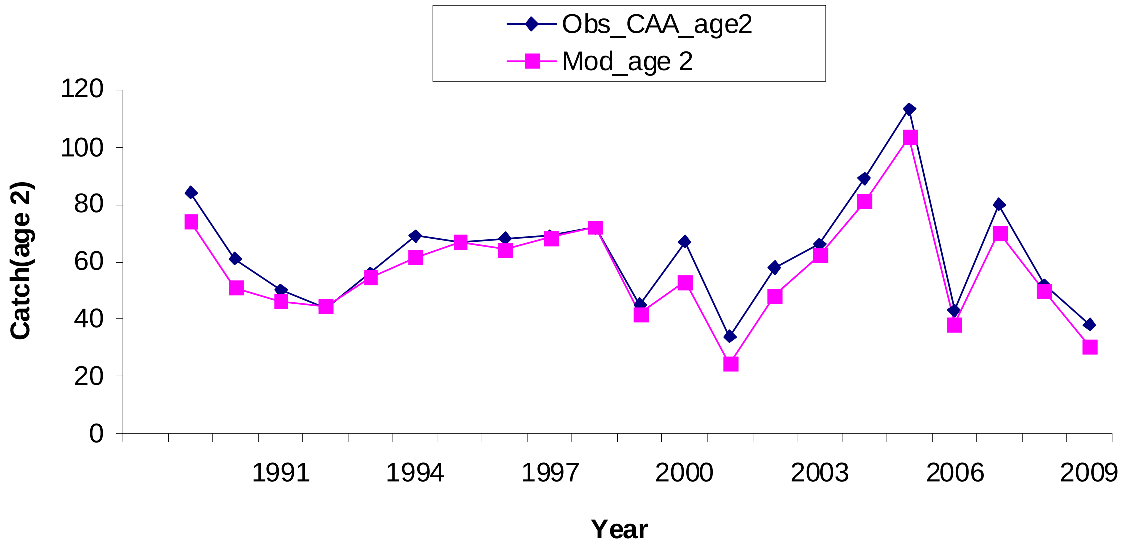


Figure 4. Comparison between available catch-at-age data and corresponding model-predicted estimates.

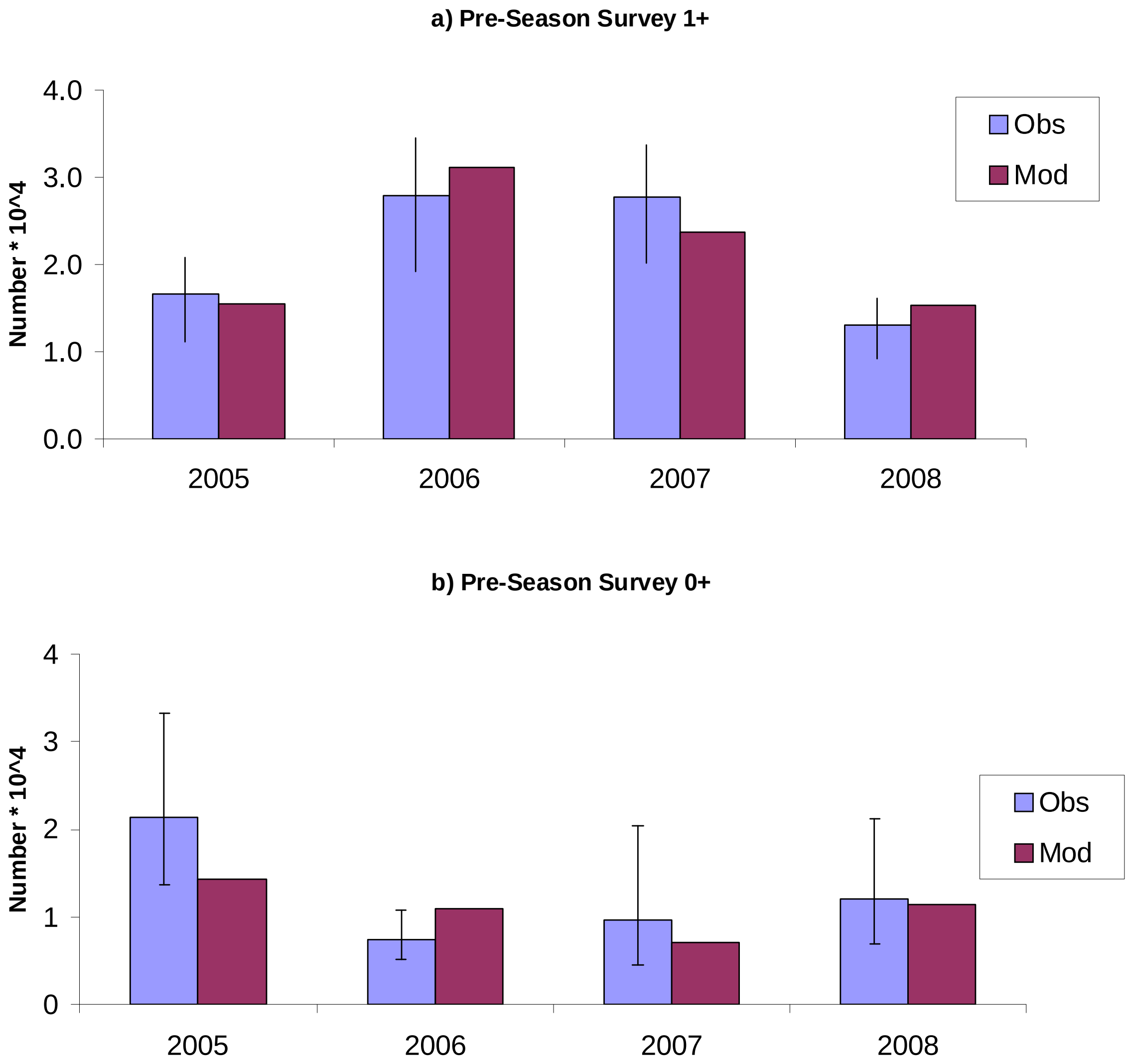
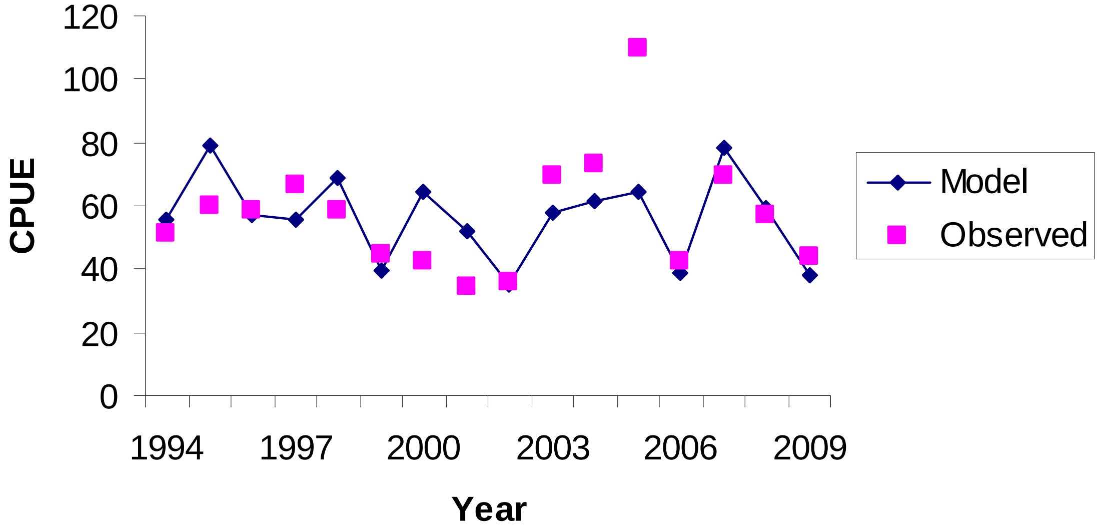


Figure 5. Comparison between observed Pre-season survey data (expressed in terms of number * 10^4) and corresponding model-predicted estimates.

a) REFERENCE CASE



b) ALTERNATIVE CPUE

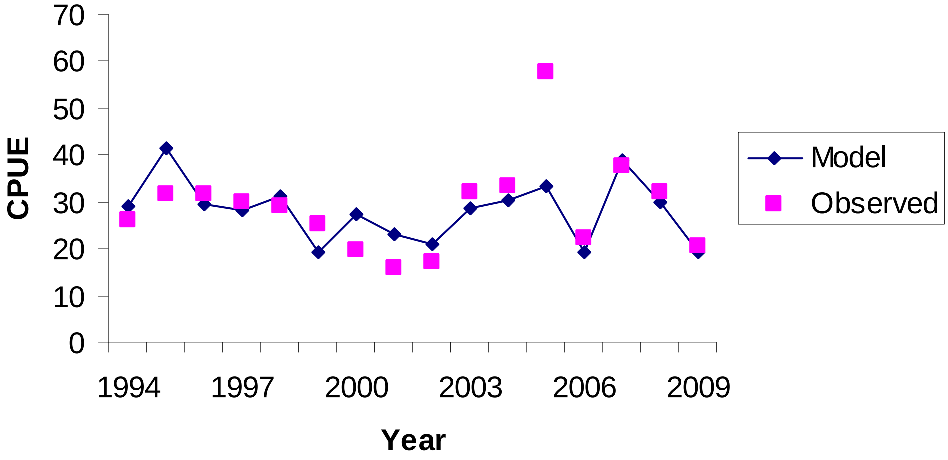
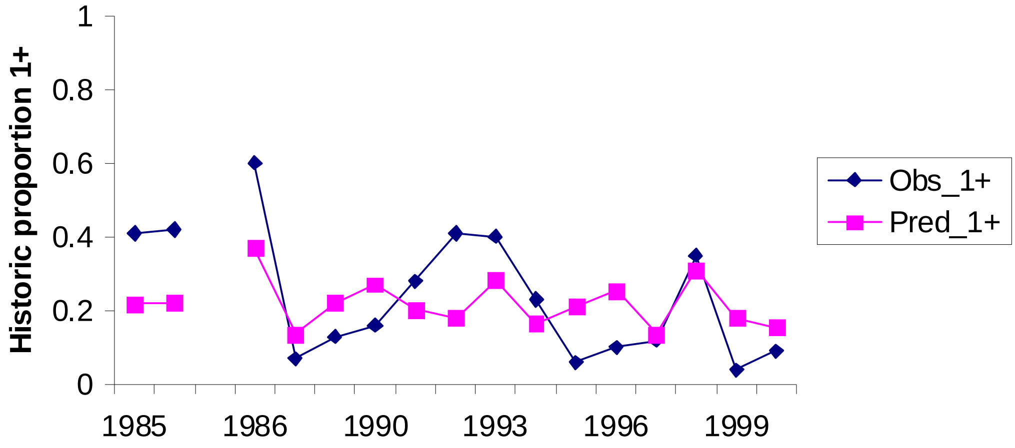


Figure 6. Comparison between CPUE data from the TVH sector and corresponding model-predicted estimates. The plots are respectively a) model free estimates and b) simple Linear Model estimates of the TVH catch per unit of effort in kg per tender-day from 1994 to 2009.



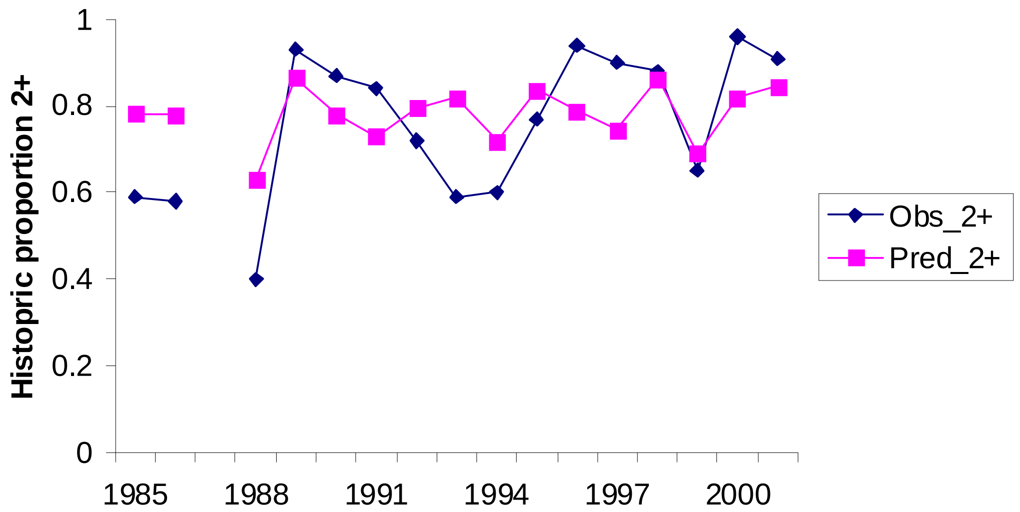


Figure 7. Comparison between historic data and model estimates of the proportions of 1+ and 2+ lobsters in the catch.

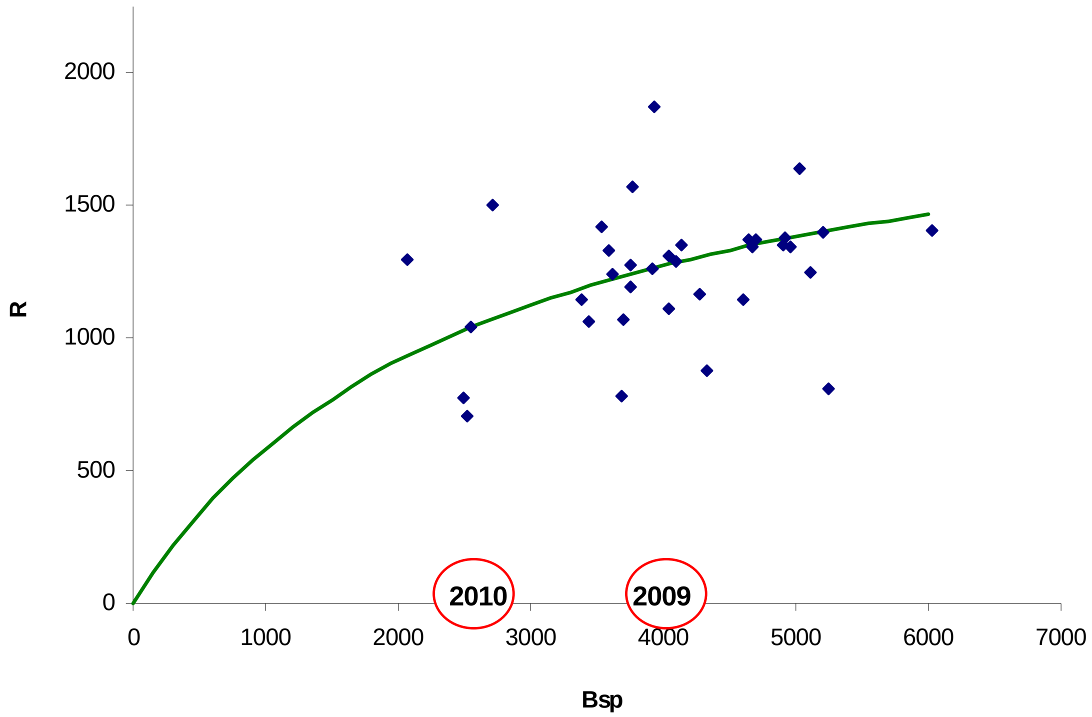


Figure 8. Integrated model stock recruitment relationship of the Torres Strait rock lobster fishery. Diamond symbols are output from the age-structured stock assessment model, solid line is a fitted curve, and circled years highlight spawning stock levels in those years.

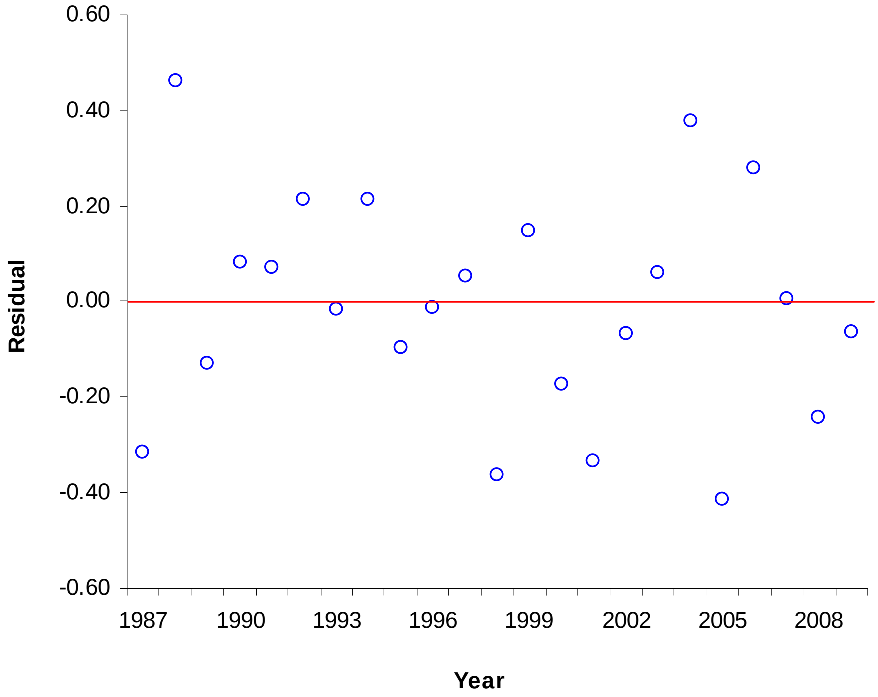


Figure 9. Plot of stock-recruit residuals.

1.1.2. Estimates of model parameters

A summary of model parameter estimates is given in Table 4. A full set of model parameter estimates, depletion statistics and likelihood contributions for the Base-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 28 parameters, namely the starting biomass $B(1973)^{sp}$, natural mortality M, steepness parameter h, 1+ selectivity for the early and post-2002 periods, and 23 stock-recruit residuals. The use of the historic information changed estimates of both natural mortality 0.68 [90% C.I. 0.53 – 0.82] year^{-1}, and steepness 0.43 [90% C.I. 0.20 – 0.62] with large confidence intervals associated with both these estimates.

Table 4. Summary of model parameter estimates from the 2010 Integrated model.

Parameter	Value	90% Confidence Interval	
B(1973) ^{sp} *(tons)*	5199	3784	6614
M	0.68	0.53	0.82
h	0.43	0.20	0.62
Sel (age 1+) early	0.16	0.13	0.19
Sel (age 1+) post2002	0.01	0.00	0.03
Recruitment residuals (1987-2009)		23 parameters	
Model estimates and depletion statistics			
B(2010) ^{sp} *(tons)*	2553	1507	3600
TAC(2011) median	709	506	912
TAC(2012) median	588	391	785
TAC(2011) (tons) Rule 1	567		
Current Depletion			
B(2010) ^{sp} */ B(1973)sp*	0.49	0.36	0.62
Bexp(2010) (tons)	5044	3386	6702
N1+ (mid 2010) million	9.02	6.30	11.74
N2+ (mid 2010) million	3.94	2.82	5.07
Likelihood			
No. parameters estimated	28		
'-lnL:overall	**-97.097**		
AIC	**-138.194**		
Likelihood contributions		**Sigma**	
'-lnL:CAA	-46.38	0.06	
'-lnL:CAAsurv	-12.05	input	
-lnL:CAA historic	-14.97	0.20	
-lnL:Survey Index	-18.38	0.18	
-lnL:Survey benchmark	-3.06	input	
'-lnL:PRESEASON	-6.05	input	
-lnL:PRESEASON 0+	-1.39	input	
-lnL:CPUE	-15.16	0.24	
'-lnL:RecRes	6.68	0.23	

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 0.16 [90% C.I. 0.13 – 0.19] for the period of 1989-2002 and 0.01 [90% C.I. 0.00 – 0.03] for the remaining years. As expected, the decrease in selectivity during the second 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 0.07 year^{-1} to 0.25 year^{-1} (Table 10), with a historic average of 0.15 year^{-1}. The target fishing mortality rate is 0.15 year^{-1}.

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.

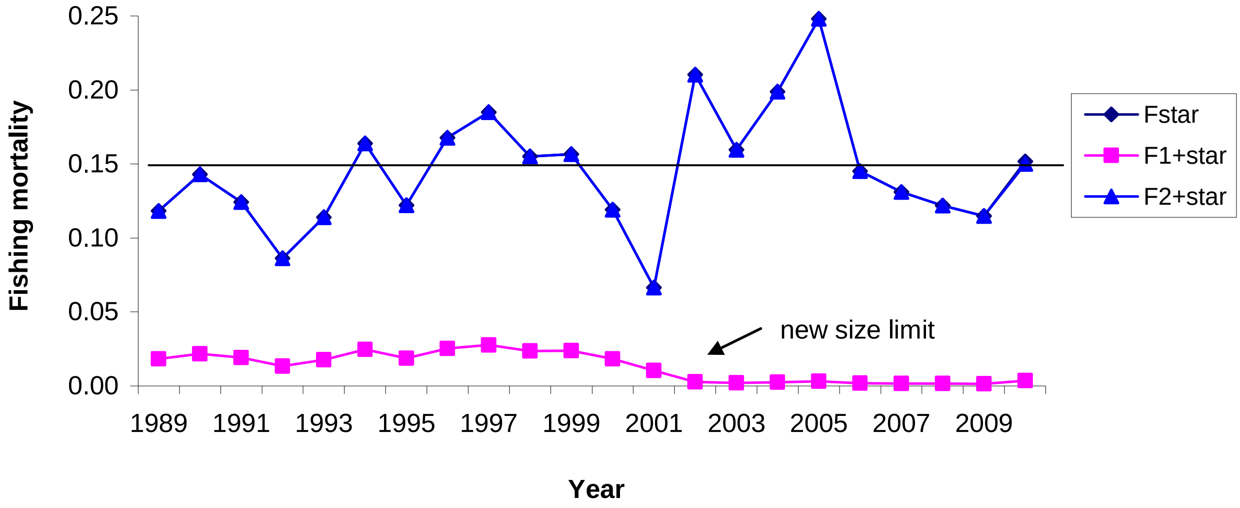


Figure 10. Model-estimated fishing mortality trends for 1+ (F 1+star) and 2+ (F 2+ star) lobsters. The 2002 change in size limit is highlighted and the 2010 fishing mortality set equal to the target value of 0.15.

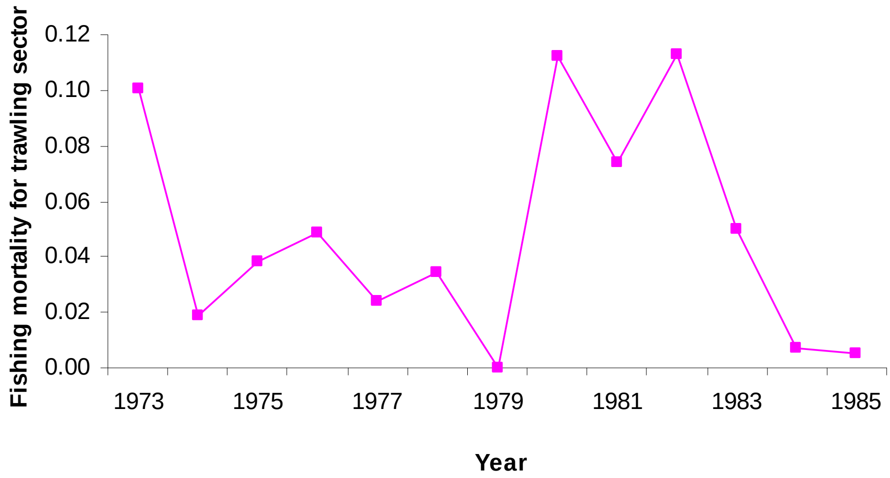


Figure 11. Model-estimated trawling sector fishing mortality trends for the early period of the fishery from 1973 - 1985.

Table 5. Summary of model parameter estimates for the Reference Case and a number of sensitivity tests as shown. Note that the CPUE contribution to the likelihood is downweighted by a factor of 0.1 unless specified otherwise.

	a) Reference Case			b) Alternative CLUE series			c) No weighting on CPUE			d) No CPUE in likelihood		
Parameter	**Value**	**90% Confidence Interval**		**Value**	**90% Confidence Interval**		**Value**	**90% Confidence Interval**		**Value**	**90% Confidence Interval**	
B(1973)sp(tons)	5199	3784	6614	5206	3127	7286	3866	(Model not converged)		5289	3143	7435
M	0.68	0.53	0.82	0.67	0.51	0.84	0.74			0.67	0.51	0.84
h	0.43	0.20	0.62	0.43	0.20	0.76	0.60			0.42	0.20	0.73
Sel (age 1+) early	0.16	0.13	0.19	0.16	0.13	0.19	0.16			0.16	0.13	0.19
Sel (age 1+) post2002	0.01	0.00	0.03	0.01	0.00	0.03	0.02			0.01	0.00	0.03
Recruitment residuals (1987-2009)		23 parameters			23 parameters			23 parameters			23 parameters	
Model estimates and depletion statistics												
B(2010)sp(tons)	2553	1507	3600	2561	1489	3632	2389			2544	1464	3624
TAC(2011) median	709	506	912	712	504	920	580			713	503	923
TAC(2012) median	588	391	785	590	368	812	554			583	357	810
TAC(2011) (tons) Rule 1	567			567						566		
Current Depletion												
B(2010)sp/ B(1973)sp	0.49	0.36	0.62	0.49	0.28	0.70	0.62			0.48	0.27	0.69
Bexp(2010) (tons)	5044	3386	6702	5061	3081	7041	4207			5079	3084	7074
N1+ (mid 2010) million	9.02	6.30	11.74	9.05	6.29	11.82	7.80			9.07	6.28	11.85
N2+ (mid 2010) million	3.94	2.82	5.07	3.96	2.80	5.12	3.23			3.97	2.80	5.13
Likelihood												
No. parameters estimated	28			28			28			28		
'-lnL:overall	**-97.097**			**-96.9743**			**-552.185**	(Model not converged)		**-95.6214**		
AIC	**-138.194**			**-137.949**			**-1048.370**			**-135.243**		
Likelihood contributions		**Sigma**			**Sigma**			**Sigma**			**Sigma**	
'-lnL:CAA	-46.38	0.06		-46.40	0.06		-39.67	0.09		-46.55	0.06	
'-lnL:CAAsurv	-12.05	input		-12.01	input		-10.15	input		-11.90	input	
-lnL:CAA historic	-14.97	0.20		-14.98	0.20		-14.61	0.21		-14.92	0.21	
-lnL:Survey Index	-18.38	0.18		-18.41	0.18		-14.96	0.20		-18.34	0.18	
-lnL:Survey benchmark	-3.06	input		-3.07	input		-2.52	input		-3.07	input	
'-lnL:PRESEASON	-6.05	input		-6.08	input		-4.25	input		-6.07	input	
-lnL:PRESEASON 0+	-1.39	input		-1.37	input		-1.09	input		-1.38	input	
-lnL:CPUE	-15.16	0.24		-13.89	0.25		-476.43	0.00			0.25	
'-lnL:RecRes	6.68	0.23		6.71	0.23		11.49	0.30		6.60	0.23	

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

	a) Reference Case			e) Setting lower bound to sigma CAA			f) No fitting to historic data			g) Estimating different historical selectivity		
Parameter	**Value**	**90% Confidence Interval**		**Value**	**90% Confidence Interval**		**Value**	**90% Confidence Interval**		**Value**	**90% Confidence Interval**	
B(1973)sp(tons)	5199	3784	6614	5351	2960	7741	7493	5006	9979	6502	3792	9211
M	0.68	0.53	0.82	0.67	0.52	0.83	0.65	0.48	0.82	0.67	0.51	0.84
h	0.43	0.20	0.62	0.40	0.20	0.71	0.29	0.20	0.40	0.28	0.20	0.38
Sel (age 1+) early	0.16	0.13	0.19	0.21	0.14	0.28	0.16	0.12	0.19	0.15	0.13	0.18
Sel (age 1+) post2002	0.01	0.00	0.03	0.00	0.00	0.00	0.01	-0.01	0.03	0.01	0.00	0.03
Recruitment residuals (1987-2009)		23 parameters			23 parameters			23 parameters		**0.45**	**0.30**	**0.60**
Model estimates and depletion statistics										(new selectivity parameter)		
B(2010)sp(tons)	2553	1507	3600	2519	1474	3565	2671	1508	3834	2700	1461	3938
TAC(2011) median	709	506	912	704	496	911	763	500	1027	699	464	934
TAC(2012) median	588	391	785	561	333	790	542	298	787	523	280	767
TAC(2011) (tons) Rule 1	567			559			579			534		
Current Depletion												
B(2010)sp/ B(1973)sp	0.49	0.36	0.62	0.47	0.24	0.70	0.36	0.19	0.52	0.42	0.17	0.66
Bexp(2010) (tons)	5044	3386	6702	4976	2997	6956	5514	3316	7713	5872	3946	7798
N1+ (mid 2010) million	9.02	6.30	11.74	8.98	6.20	11.77	9.48	6.15	12.81	8.86	5.79	11.93
N2+ (mid 2010) million	3.94	2.82	5.07	3.95	2.78	5.11	4.25	2.78	5.72	3.89	2.58	5.20
Likelihood												
No. parameters estimated	28			28			26			29		
'-lnL:overall	**-97.097**			**-81.668**			**-82.395**			**-103.038**		
AIC	**-138.194**			**-107.336**			**-112.790**			**-148.076**		
Likelihood contributions		**Sigma**			**Sigma**			**Sigma**			**Sigma**	
'-lnL:CAA	-46.38	0.06		-27.78	0.15		-44.85	0.07		-45.85	0.06	
'-lnL:CAAsurv	-12.05	input		-13.29	input		-11.07	input		-12.00	input	
-lnL:CAA historic	-14.97	0.20		-15.23	0.20		-11.92	0.25		-21.43	0.14	
-lnL:Survey Index	-18.38	0.18		-19.32	0.17		-19.67	0.19		-18.52	0.18	
-lnL:Survey benchmark	-3.06	input		-2.93	input		-3.02	input		-3.08	input	
'-lnL:PRESEASON	-6.05	input		-6.17	input		-6.30	input		-5.46	input	
-lnL:PRESEASON 0+	-1.39	input		-1.27	input		-1.25	input		-1.10	input	
-lnL:CPUE	-15.16	0.24		-17.19	0.21		-14.31	0.25		-14.04	0.25	
'-lnL:RecRes	6.68	0.23		6.02	0.22		5.19	0.21		5.80	0.21	

The fitted Beverton-Holt stock-recruit relationship had a comparatively low estimate of the steepness parameter *h* of 0.43, which although not as low as the 2009 estimate (0.27), was not particularly 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. This suggests that there was a gradual decrease in the numbers of lobsters during the first ten years of the fishery. The model replicates the very large recruitment of 1+ lobsters that occurred in 1989. 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 at approximately half the pristine (1973) spawning biomass level but is expected to fluctuate widely about the average target spawning biomass level of approximately 3400 t, which is 65% of the pristine level. 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 2010 in the Kilcaldie rubble stratum, an important fishing ground, in contrast to average abundance elsewhere (Plagányi *et al.* 2010). This provides a part explanation for the low 2010 spawning biomass estimate.

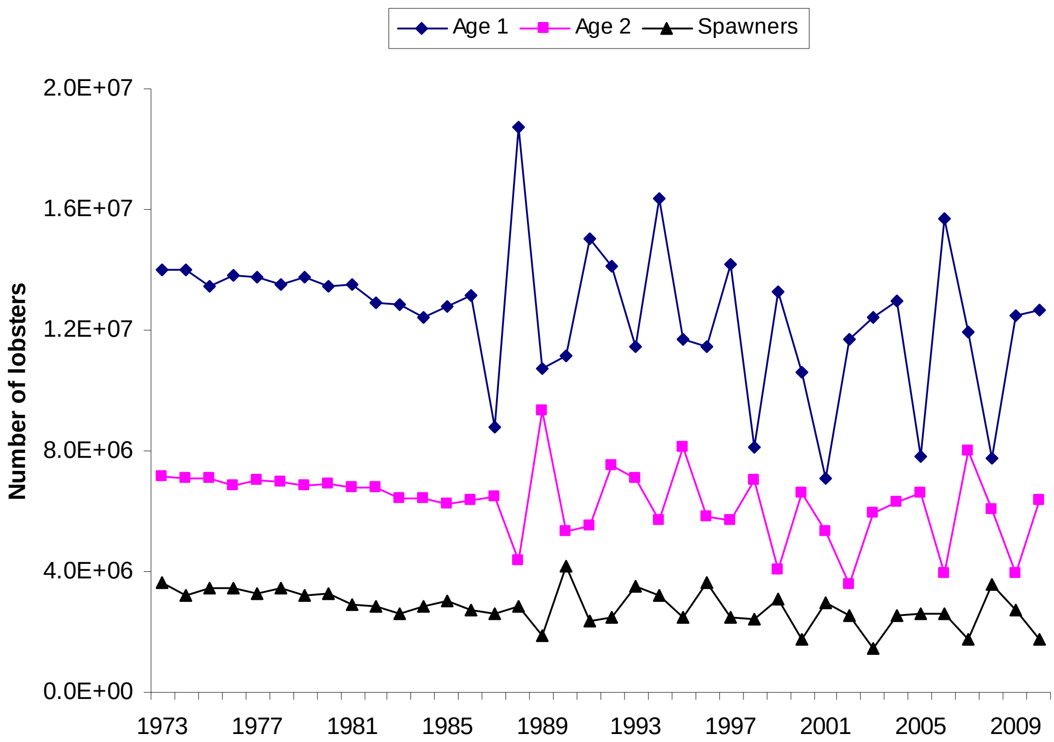


Fig. 12. Model trajectories of the annual numbers of lobsters in each age class for years 1973 to 2010. The increased variability from 1988 onwards is because the model estimates stock recruit residuals for years from 1987 to 2009.

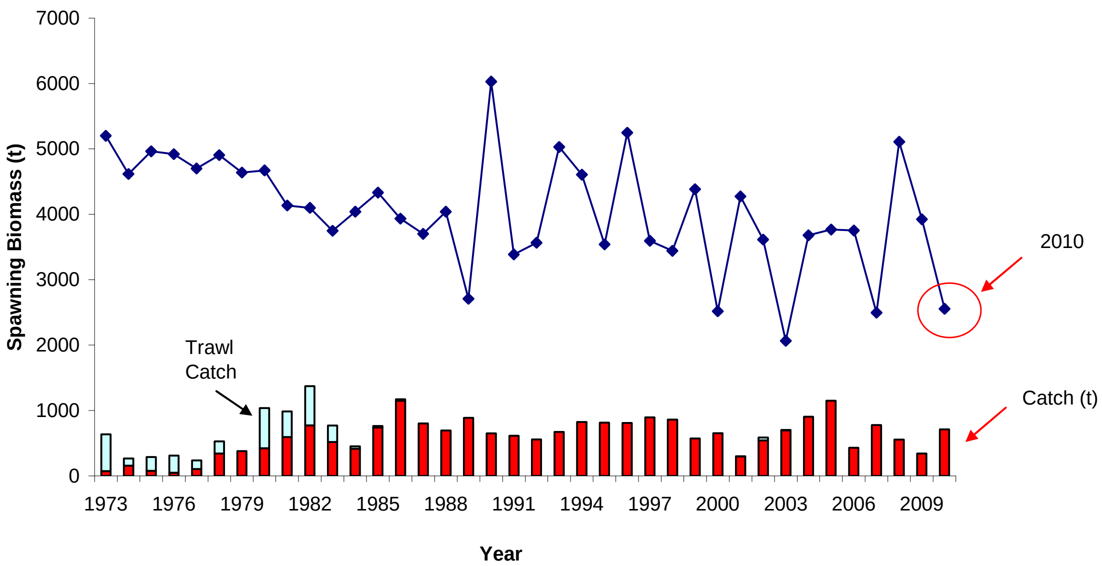


Fig. 13. Model trajectories of the lobster spawning biomass (t) over the model period shown together with annual catches by the trawling and other sectors combined.

The model-predicted spawning biomass trajectory is shown in Figure 14. The current spawning biomass is estimated to be 2550 t [1500; 3600] (Table 4). Note that this is a preliminary estimate only as is assumes that the 2010 catch taken was equal to the TAC value (Table 7), which was a high catch. If the actual catch is lower than this, it will result in a higher estimate of the 2010 spawning biomass and this aspect will be considered further in future model updates. 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 2010 estimate is 5050 t [3390 ; 6700].

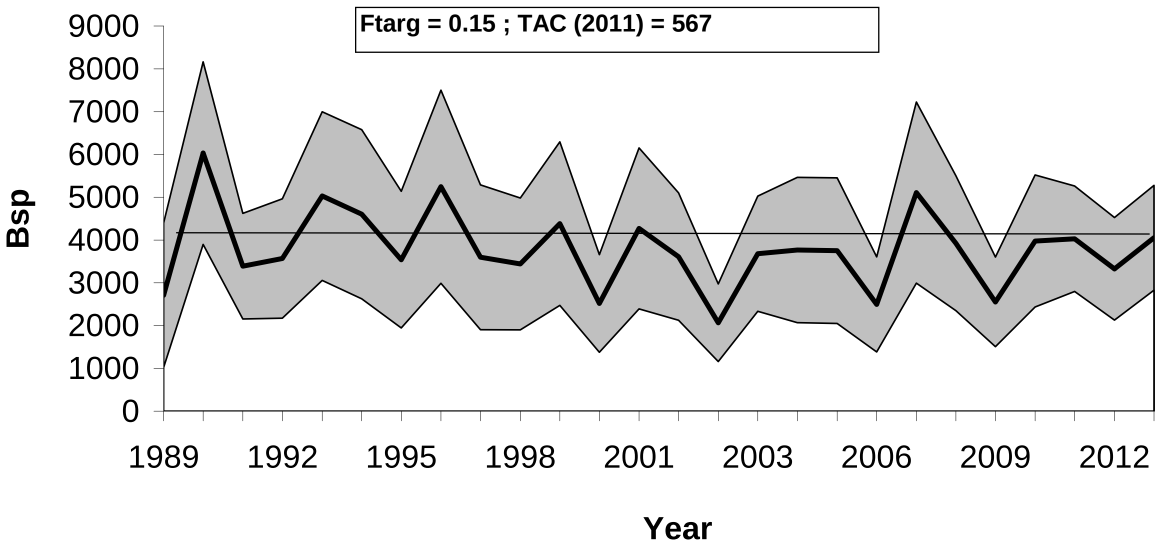


Figure 14. Model-predicted lobster spawning biomass trajectory shown together with Hessian-based 90% confidence intervals. The vertical line indicates the separation between historic and predicted estimates.

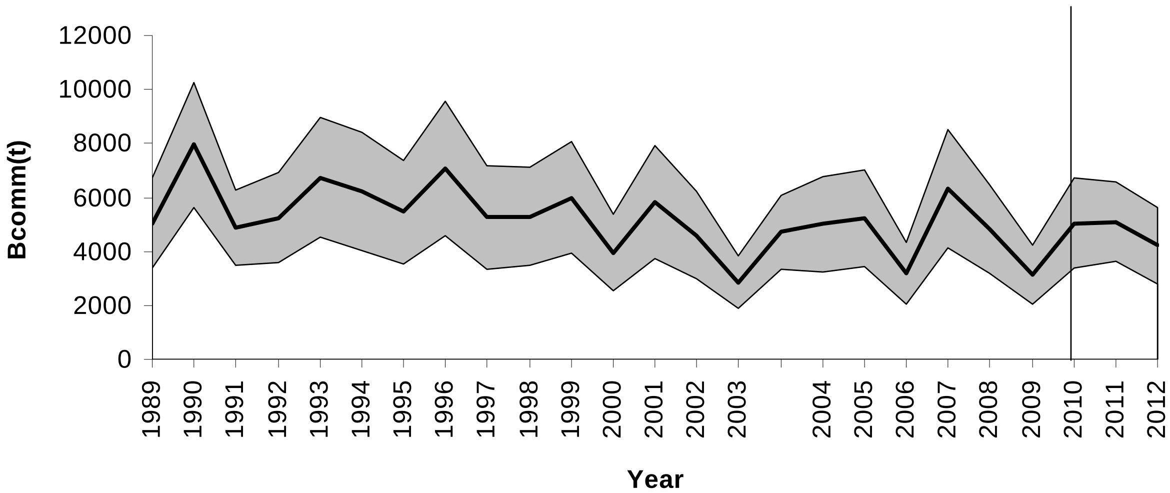


Figure 15. Model-predicted commercially available (also termed exploitable) lobster biomass (Bcomm), which is the sum of all 1+ and 2+ lobsters which are “available” to be caught each year. The shaded area shows the Hessian-based 90% confidence intervals. The vertical line indicates the separation between 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 2010 midyear survey (Fig. 16) suggests the 2011 stock should be at a reasonable 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.

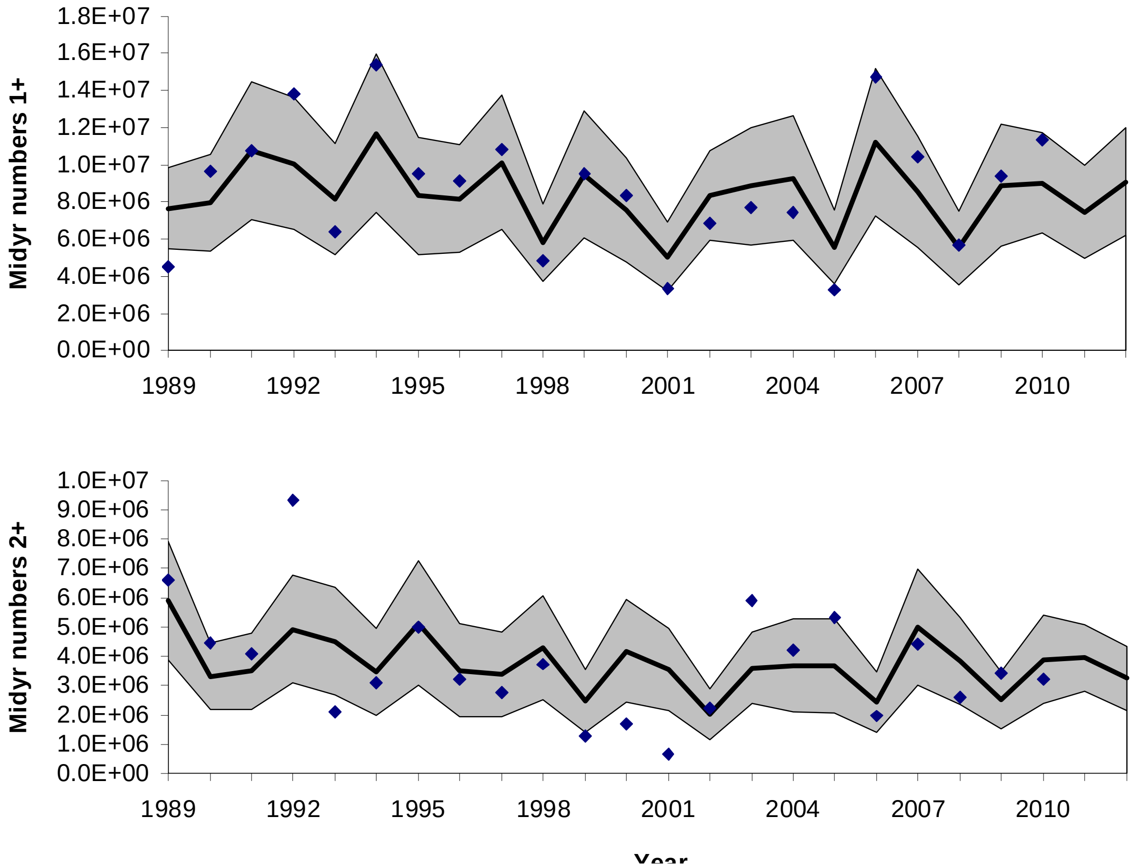


Figure 16. Model-predicted midyear numbers of 1+ and 2+ lobsters shown together with Hessian-based 90% confidence intervals. The solid points are the observed survey numbers.

Sensitivity Tests

The robustness of model results were tested across a number of important sensitivity tests (Table 5). The first set of sensitivity tests shown pertain to the use of the TVH CPUE data. 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 b). In both cases an ad hoc weighting factor of 0.1 was used to downweight the contribution of the CPUE data to the total likelihood because of the otherwise disproportionately large contribution of the CPUE data, and the inability of the model to converge under this scenario (Table 5 – sensitivity c). Changing the weighting factor from 0.1 to 0.5 did not make much difference to model results and this aspect will be explored further in future work. The TAC estimates were relatively insensitive to the inclusion of the CPUE data (Table 5 – sensitivity d) presumably because of the close agreement between the CPUE and survey indices of abundance.

In the Reference Case model, the estimated standard deviation associated with the fit to the catch at age data was perhaps too low, and hence a sensitivity test (Table 5 – sensitivity e) was done to set the lower bound to 0.15. This resulted in slightly improved fits to the other data and slight changes in model results. This aspect will be explored further in future model fits. Model runs were also conducted to estimate an additional variance parameter for the survey data, but the model estimated a negligibly small value.

Sensitivity test (f) investigated the effect on model predictions of not using the historic information on proportions of 1+ and 2+ lobsters in the catch. As explained in the Methods section, the effect of not estimating the large 1989 recruitment event is to estimate a larger pristine spawning biomass population with greater depletion estimated over the early years of the fishery (Table 5 – sensitivity f) (Fig. 17).

One potentially important consideration that has not been taken into account in previous model versions pertains to the fact that a 100mm size limit was only introduced in 1988 (and changed to 115 mm in 2002). This means that the fishing selectivity may have been different during the early years of the fishery with fishers taking relatively more smaller lobsters. The model already incorporates a different fishing selectivity for the trawling sector as well as two different selectivity parameters for the pre-2002 and post-2002 periods to reflect the smaller take of 1+ lobsters post-2002. However, it may be important to include a different fishing selectivity for the pre-1988 period as well. The model estimate of the "historic" 1+ selectivity parameter significantly improves the model fit (Table 5 – sensitivity g) and suggests that relatively more smaller lobsters were taken in the early years (parameter estimate is 0.45 with 90% CI [0.3;0.6] compared to 0.16 for 1989-2001). Note that the historic 1+ selectivity parameter is not one because there are other factors (e.g. growth rate, size and availability) that would limit full selectivity on this age class compared to the 2+ age class. Better estimation of the early fishing selectivity also improves the fit to the historic data (Fig. 18). However there are some other reasonably substantial changes to the model that result under this scenario, and hence this aspect and possible refinement first needs to be discussed at the RAG meeting before deciding to change the Reference Case choice.

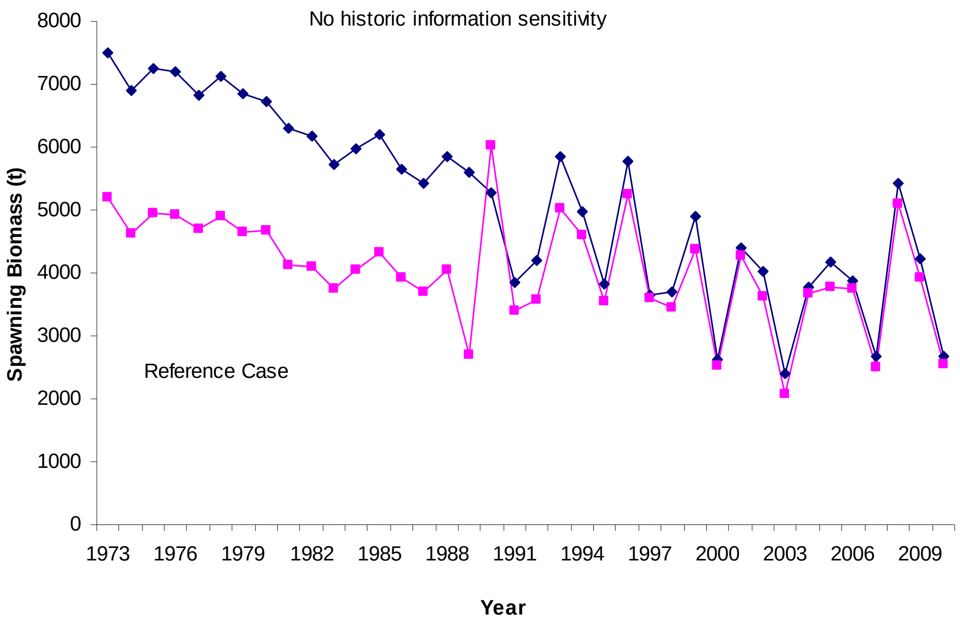


Figure 17. Comparison between the spawning biomass trajectory from the Reference Case model with that estimated by a model version that doesn't include the historic information that is used to inform on the large 1989 recruitment event.

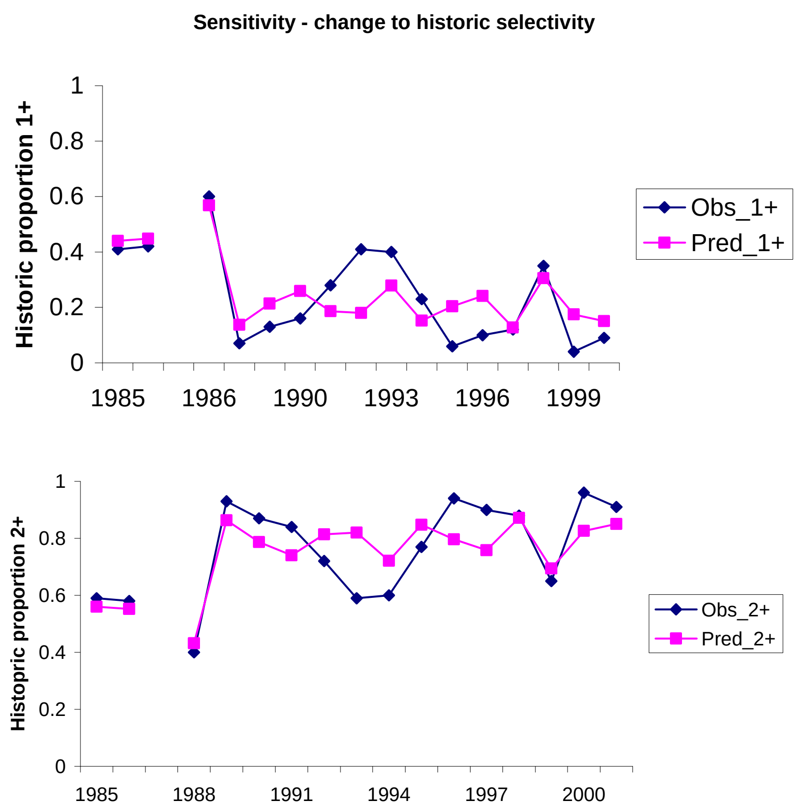


Fig. 18. Model fit to historic data when estimating a different historical fishing selectivity as per sensitivity test g in Table 5.

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).

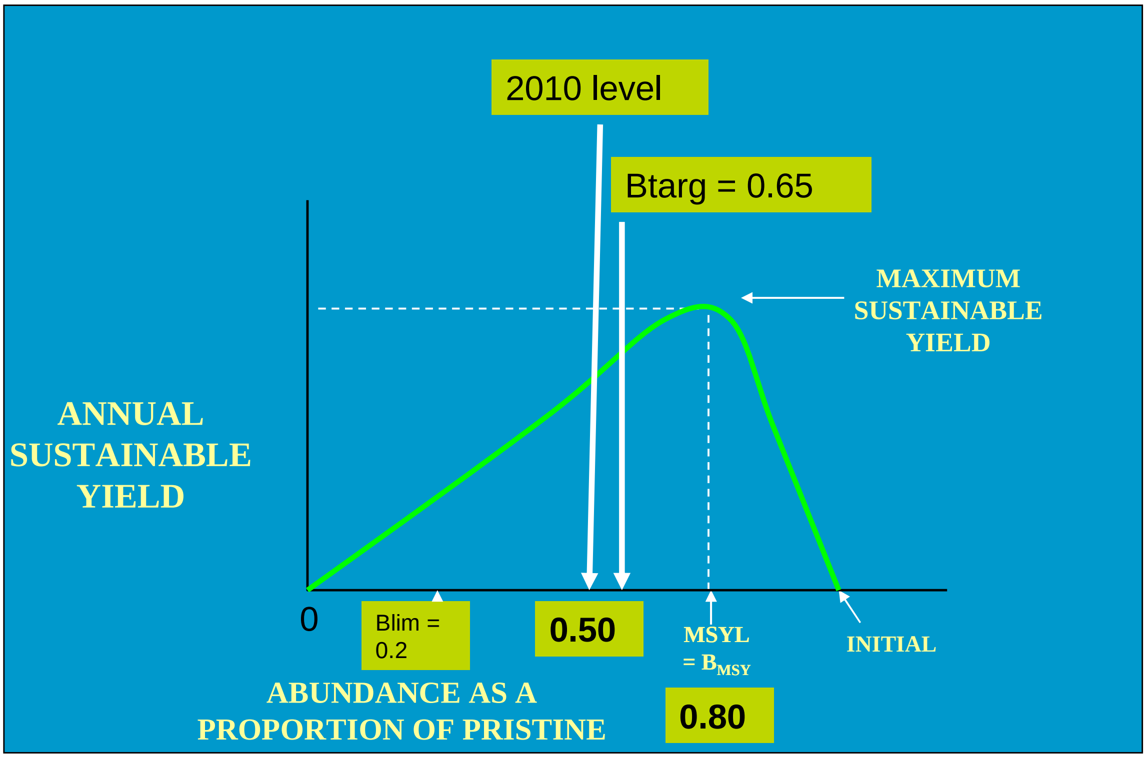


Figure 19. Schematic summary of Reference Points and management quantities (see text for details). Note that the 2010 level indicated is preliminary only for reasons mentioned in the text.

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 61% 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 0.2 (Table 6).

Table 6. Summary of model estimates of Reference levels and Management Quantities.

Model Estimate	Value	Management Quantities	
$B(1973)^{sp}$	5199		
$B(2010)^{sp}$	2553	$BMSY^{sp}$ *(tons)*	4159
Current Depletion $B(2010)^{sp}$ / $B(1973)^{sp}$	0.49	$BMSY^{sp} / B_0^{sp}$	0.8
$B(2008)^{sp} / B(1973)^{sp}$; $B(2009)^{sp} / B(1973)^{sp}$	0.98; 0.75	$Bcurrent/B_{targ}$	0.76
$F(2008),F(2009)$	0.12; 0.11	F_{targ}	0.15
$F(2009)/F_{targ}$	0.73	$FMSY$	0.14
B_{targ} *(tons)*	3380		
$Bcurrent/BMSY^{sp}$	0.61		
$Bcurrent/B_{lim}$	2.5	B_{lim}	0.2
		MSY (tons)	650

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 revised estimate of FMSY.

TAC ESTIMATION FOR 2011

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 total catch for 2009 in the Torres Strait was 342 tonnes, 76% of the Final TAC (450 tonnes) set for 2009 (Table 7). The Torres Strait TRL fishery catches have thus far been below the TAC. This has been attributed to a combination of underreporting of catch, economic and/or weather conditions.

The furnishment of accurate catch statistics is critical under the new TAC setting process. It could be useful to explain to stakeholders that the perception that underreporting of catch leads to increases in the TAC for the following year is not necessarily true - often a higher catch means that the resource is more productive and this information is included into the model for TAC setting the following year and may lead to a higher TAC being set than without this information.

The provisional forecast TAC for 2011 is 567t, determined as the lower bound of the 75% confidence interval associated with a model estimate of 709t. The provisional forecast TAC for 2012 is 450t (Table 8). The results presented in this document assume the 2010 catch is equal to the TAC level and hence it is important to note that if catches are less than this, the current (2010) estimate of spawning biomass will be higher.

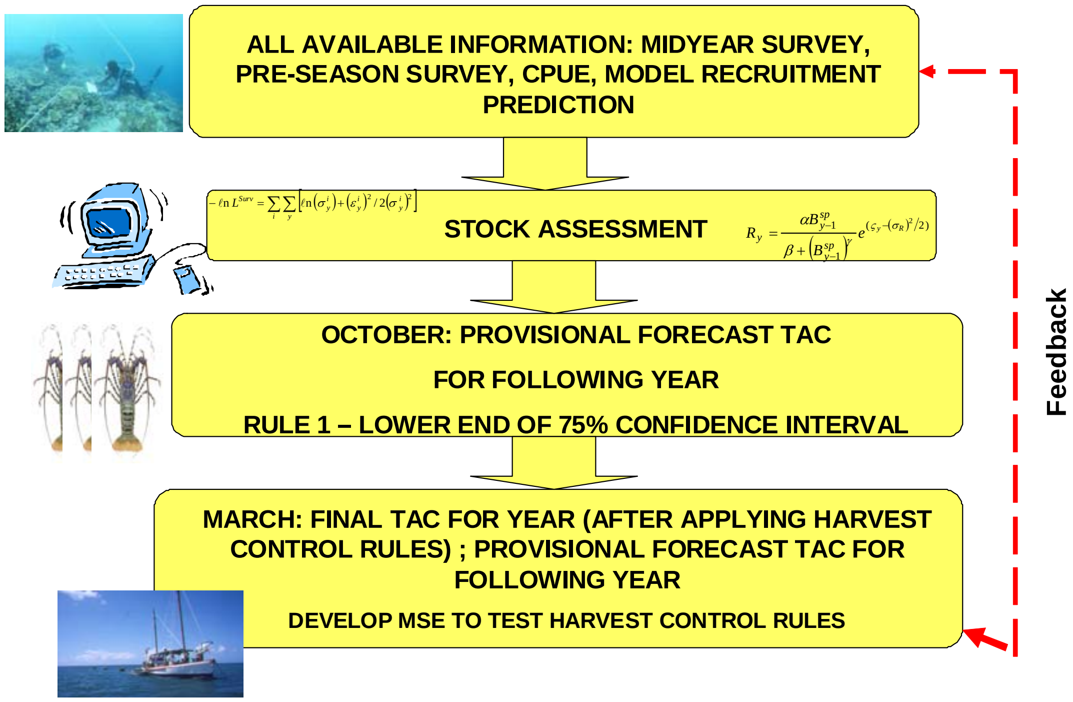


Figure 21. TAC setting process using the new Integrated model.

Table 7. Performance of Torres Strait TRL fishery against TAC for 2006-2009

	Model TAC (t)	Model preliminary TAC	Catch (t)
2006	471		431
2007	842		778
2008	751		553
2009	450		342
2010	853	678	
2011	(709)	567	
2012	(587)	450	

Table 8. Provisional forecast TAC estimates for the Torres Strait TRL fishery for 2011-2012

Year	Provisional forecast TAC (t)	Estimate (t)	75% Confidence Interval	
2011	567	**709**	567	851
2012	450	**588**	450	726
		Estimate (t)	90% Confidence Interval	
		709	506	912
		588	391	785

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.

Overall the resource is estimated to be in good condition, although there are suggestions that the 2010 spawning biomass is relatively low. The provisional TAC estimate for 2011 is reasonably high, and follows the high prediction that was made for 2010. The provisional forecast estimate for 2012 is lower.

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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.

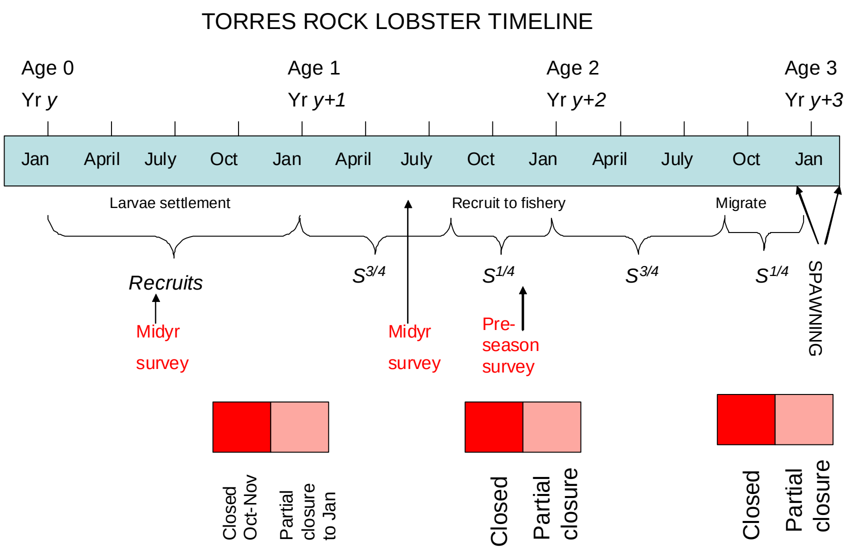

Figure A-1. Summary timeline for Torres Strait Rock Lobster model.

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:

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

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

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

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:

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

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

$$B_y^{sp} = w_3^{st} \cdot N_{y,3} \qquad 5$$

where

w_3^{st} 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

$$SPR_{virg} = w_3^{st} N_3^{virg} \qquad 8$$

with

$$N_1^{virg} = 1 \qquad 9$$

$$N_a^{virg} = N_{a-1}^{virg} e^{-M_{a-1}} \qquad \text{for } 2 < a \le m \qquad 10$$

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:

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

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

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:

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

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

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

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

where $\left(\sigma_y^s\right)^2 = \ln\left(1 + \left(CV_y\right)^2\right)$ 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:

$$\ell n\, \hat{q}_s = 1/n_i \sum_y \left(\ln I_y^i - \ln \hat{B}_y^{ex}\right) \qquad 33$$

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:

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

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

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

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

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:

$p_{y,a} = C_{y,a}^{surv} / \sum_{a'} C_{y,a'}^{surv}$ 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 T_{89} = 9.0 (±1.9) million lobsters, and for 1989, T_{89} = 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 $\varepsilon_{89} = \ell n\left(T_{89}\right) - \ell n\left(\hat{N}_{1989,1}^{mid} + \hat{N}_{1989,2}^{mid}\right)$;

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

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

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 $N\left(0,(\sigma_R)^2\right)$,

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.