A Bayesian Analysis of the Squid Resource *Loligo reynaudii*

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Introduction

A Bayesian assessment of the squid resource was last performed in 2010. This paper presents results from an updated Bayesian assessment given that additional years' data are now available.

The data

The following data are included in the analyses:

- jig catch data: 1985 – 2011: Table 1
- trawl catch data: 1971 – 2011: Table 2
- jig CPUE data: 1995 – 2011: Table 3
- trawl CPUE data: 1978-1999: Table 4
- spring survey biomass index: Table 5
- autumn survey biomass index: Table 5

The model

The model specifications are provided in Appendix A. The following prior distributions have been selected for the estimable parameters:

$\ell n X \sim U(0 ; 12.0)$, where initial recruitment, $R_0 = \exp(\ell n X)$
$h \sim U(0.5 ; 1.0)$ but multiplied by the function $(h-0.499)/(0.001+h-0.499)$
$\eta \sim U(0.01 ; 0.99)$
$g \sim N(1.2 ; 0.1^2)$
Stock-recruitment residuals $\xi_y \sim N(0 ; \sigma^2_R)$; σ_R is assumed to be 0.3 on input.

The basis for selecting the parameters of the prior for *g* is that Roel (1998) indicated that values of *g* less than 1 were not considered plausible given the short life-span of this species, and that values above 2 led to unrealistically high values of estimated biomass. The other priors are intended to be uninformative, but have been slightly modified for particular reasons. The upper bound of about 160 thousand tons placed on R_0 is to avoid bad behaviour sometimes shown by the MCMC slipping into a domain where R_0 is enormous which hinders convergence; values that large are clearly unrealistic, so the MCMC is precluded from going into a region of parameter space that sees R_0 some 6800 times bigger than its posterior mode value.

Previously, model convergence proved problematic for values of *h* below 0.5, even though these were marginally preferred by the data. However, since values of *h* below 0.5 are rarely found in fish populations, it was decided to place an effective lower bound of 0.5 on *h.* The multiplying function used to adjust the uniform prior on *h* values above 0.5 is to preclude a maximum likelihood estimate exactly on the boundary which leads to problems in calculating a Hessian and hence initiating MCMC in ADMB.

Results

For the Bayesian posterior computations a MCMC chain of 300 million samples was run. A burn-in of 3 million was discarded and the remaining chain was thinned by selecting one in every 3000 samples to reduce autocorrelation. 5000 samples were then selected randomly, with replacement from the chain and were used to perform stochastic projections 10 years into the future under various constant effort scenarios. The assumptions made relating to effort in the projections are as follows:

- The proportion of annual jig effort expended in each period is equivalent to the average observed over the last 3 years for which data are available, and is 0.30:0.70 for Jan-Mar:Apr-Dec.

- Future trawl effort is constant and is equivalent to the average standardized effort in the trawl fishery over the last 5 years for which data are available.

- The proportion of annual trawl effort expended in each period is equivalent to the average observed over the last 5 years for which data are available, and is 0.19:0.81 for Jan-Mar:Apr-Dec.

The parameter estimates at the joint posterior mode are shown in Table 6, and fits to the indices of abundance at the joint posterior mode are shown in Figures 1a-e. The begin-year biomass time series (B_y^*) is shown in Figure 2 and the stock-recruitment residuals are shown in Figure 3, with both 2010 and 2011 showing below-average recruitment. The fit to the stock-recruitment relationship is shown in Figure 4. Also shown in Figure 4 is the replacement line; this reflects an exact balance between additions from recruitment and losses to mortality, and intersects the stock-recruitment curve at *K* in the absence of fishing mortality.

The diagnostics from the tests of Geweke (1992), Raftery and Lewis (1992) and Heidelberger and Welch (1983) were monitored for instances of non-convergence in the MCMC (these tests are used to show when convergence has not occurred rather than to prove that convergence to the posterior mode has occurred (Gamerman, 1997)). Two of the 41 recruitment residuals failed the Geweke convergence diagnostic, indicating that a longer chain is ideally required, while six of the 41 stock-recruitment residuals failed the Heidelberger and Welch (1983) half-width test, indicating that a longer chain is ideally required. According to the Raferty and Lewis convergence diagnostic thinning, burn-in and chain length was sufficient for all estimable parameters.

The median average annual catch as a function of different constant future levels of effort, together with 90% probability intervals obtained from the projections is shown in Figure 5, and is compared with that obtained from the Bayesian assessment performed in 2010. Also included in this Figure is the median average annual catch derived in 2008, where 12 assessments were conducted, each for a discrete value of *h* ranging from 0.4 to 0.5 in steps of 0.05. These were then integrated over using Deviance Information Criterion weighting. The curve derived from the 2012 assessment is similar to that from the 2010 assessment and suggests that the fishery could potentially accommodate greater effort than is currently the case.

Figure 6 indicates the median average annual catch as a function of different constant future levels of effort, together with 90% probability intervals obtained from projecting forward from the joint posterior mode for the 2012 assessment. 5000 simulations were undertaken with both observation and process error taken into account. This curve suggests a more pessimistic appraisal when compared with the 2012 curves presented in Figure 5, suggesting very limited scope for an increase in effort in this fishery.

Figure 7 presents median begin-year biomass (B_y^*) trajectories, together with 90% probability intervals for the 5000 randomly selected samples under various constant future effort scenarios, while Figure 8 presents median B_y^* / K (begin-year biomass relative to pristine biomass, K, where $K=B^*_{1971}$) trajectories and associated probability intervals. Of note in both Figures is the fact that the lower 5^{th} percentile shows a downward trend for the projection period (2012-2021) for effort levels in excess of 300 000 man-days.

References

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Table 1: Jig catches (tons) per period per annum (source: SABS/NCRS).

Year	Jan-Mar	Apr-Dec	Total
1985	117	2487	2604
1986	248	3151	3399
1987	170	2627	2797
1988	213	4614	4827
1889	2044	7534	9578
1990	459	1728	2187
1991	149	4330	4479
1992	218	1752	1970
1993	309	6402	6711
1994	2493	4356	6849
1995	1735	5578	7313
1996	1828	4996	6824
1997	945	2829	3774
1998	1644	4919	6563
1999	1662	4973	6635
2000	1217	4844	6061
2001	719	2228	2947
2002	1819	7795	9614
2003	2166	9654	11820
2004	5028	8233	13261
2005	2758	6389	9147
2006	3583	5708	9291
2007	2044	7394	9438
2008	3034	5987	9021
2009	3242	7099	10341
2010	3665	7112	10777
2011	3154	4642	7796

Table 2: Trawl catches (tons) per period per annum (source: DAFF Demersal database).

Year	Jan-Mar	Apr-Dec	Total
1971	26.64	46.36	73
1972	186.88	325.12	512
1973	342	595	937
1974	1322	2300	3622
1975	1331.86	2317.14	3649
1976	769.77	339.23	1109
1977	1205.21	2096.79	3302
1978	1021.2	3967.8	4989
1979	2080.57	3035.43	5116
1980	1006.84	2047.16	3054
1981	1719.16	2036.84	3756
1982	1536.75	2067.25	3604
1983	2304.69	1810.31	4115
1984	586.7	1528.3	2115
1985	1633.12	2053.88	3687
1986	222.88	715.12	938
1987	238.3	413.7	652
1988	169.36	651.64	821
1989	413.2	749.8	1163
1990	290.36	454.64	745
1991	141.72	351.28	493
1992	90.22	196.78	287
1993	50.62	227.38	278
1994	220.1	266.9	487
1995	125.43	213.57	339
1996	155.23	205.77	361
1997	75.6	161.4	237
1998	128.37	187.62	316
1999	90.94	183.72	274.7
2000	81.66	272.3	354
2001	119.41	124.85	244.3
2002	62.73	142.43	205.2
2003	76.14	261.67	337.8
2004	123.38	267.91	391.3
2005	94.6	279.25	373.9
2006	134.22	223.97	358.2
2007	126.77	369.32	496.1
2008	169.43	353.76	523.2
2009	395.8	363.63	759.4
2010	221.55	339.02	560.6
2011	256.86	202.7	459.6

Table 3: Nominal jig CPUE (kg/man-day) per period per annum (source: DAFF jig catch and effort database), restricted to data from the core 19 vessels and to 3≤crew≤20.

Year	Jan-Mar	Apr-Dec
1995	30.4775	31.2428
1996	29.4909	25.3617
1997	15.8811	16.2417
1998	18.2149	26.1064
1999	29.6601	25.8285
2000	19.6776	28.1567
2001	21.3603	19.419
2002	22.3957	30.575
2003	28.4355	37.0259
2004	45.0045	26.742
2005	22.8518	21.9654
2006	30.4779	22.4927
2007	23.3741	28.2382
2008	28.3779	35.8869
2009	37.1909	31.5025
2010	30.4395	25.8589
2011	26.3356	17.7881

Table 4: Trawl CPUE (kg/min) per period per annum (source: DAFF Demersal database).

Year	Jan-Mar	Apr-Dec
1978	13.772	7.460
1979	19.974	7.923
1980	14.522	4.309
1981	17.778	8.120
1982	16.505	4.942
1983	24.098	3.224
1984	8.895	4.016
1985	12.689	3.165
1986	6.197	2.805
1987	5.785	2.106
1988	5.596	3.145
1989	8.811	3.427
1990	6.246	2.069
1991	5.282	2.343
1992	3.842	1.717
1993	3.531	2.086
1994	6.585	2.137
1995	5.205	2.077
1996	5.252	2.104
1997	4.336	1.787
1998	4.831	2.214
1999	5.175	1.840

Table 5: Spring and autumn survey biomass indices (tons) - RS Africana old gear only.

Spring survey index		
Year	**Index**	**CV**
1986	8638	1880
1987	12111	1733
1988	No survey	
1989		
1990	13434	1849
1991	23595	4021
1992	10034	1448
1993	14409	2437
1994	15255	2383
1995	13616	1549
1996	No survey	
1997		
1998		
1999		
2000		
2001	10558	1532
2002	No survey	
2003	New Gear Survey	
2004		
2005	No survey	
2006	12763	1295
2007	New Gear Survey	
2008		
2009	No survey	
2010		
2011		

Autumn survey index		
Year	**Index**	**CV**
1988	9075	1336
1989	19025	4191
1990	9222	1832
1991	14695	3503
1992	13145	1476
1993	22361	3938
1994	22377	5331
1995	23511	3021
1996	27968	2673
1997	10026	1049
1998	No survey	
1999	19495	2230
2000	Nansen survey	
2001	No survey	
2002		
2003	22448	2937
2004	New Gear survey	
2005		
2006	20118	2187
2007	New Gear survey	
2008		
2009		
2010	16938	2363
2011	New Gear survey	

Table 6: Parameter estimates at the joint posterior mode. Units for R_0, B*1971 and B*2012 are tons.

Model parameters	Estimate
R_0 (initial recruitment)	24039
h	0.512
eta	0.328
g	1.257
B*1971	33592
B*2012	7903
B*2012/B*1971	0.235
stock-recruit residuals	
σ_R (input)	0.30
σ_R (estimated)	0.23
CPUE jig Jan-Mar	
q	0.002989
sigma	0.294
CPUE jig Apr-Dec	
q	0.001604
sigma	0.222
CPUE trawl Jan-Mar	
q	0.000576
sigma	0.242
CPUE trawl Apr-Dec	
q	0.000140
sigma	0.253
Survey Autumn	
q	1.210620
sigma	0.420
Survey spring	
q	0.659763
sigma	0.332
-lnL values	
jig A-D	-8.431
trawl J-M	-7.452
Trawl A-D	-5.909
autumn	6.121
spring	1.360
S/R residuals	-0.007
penalties	-1.143
total	-15.461

Figure 1a-e: Observed and model estimated indices of abundance at the joint posterior mode.

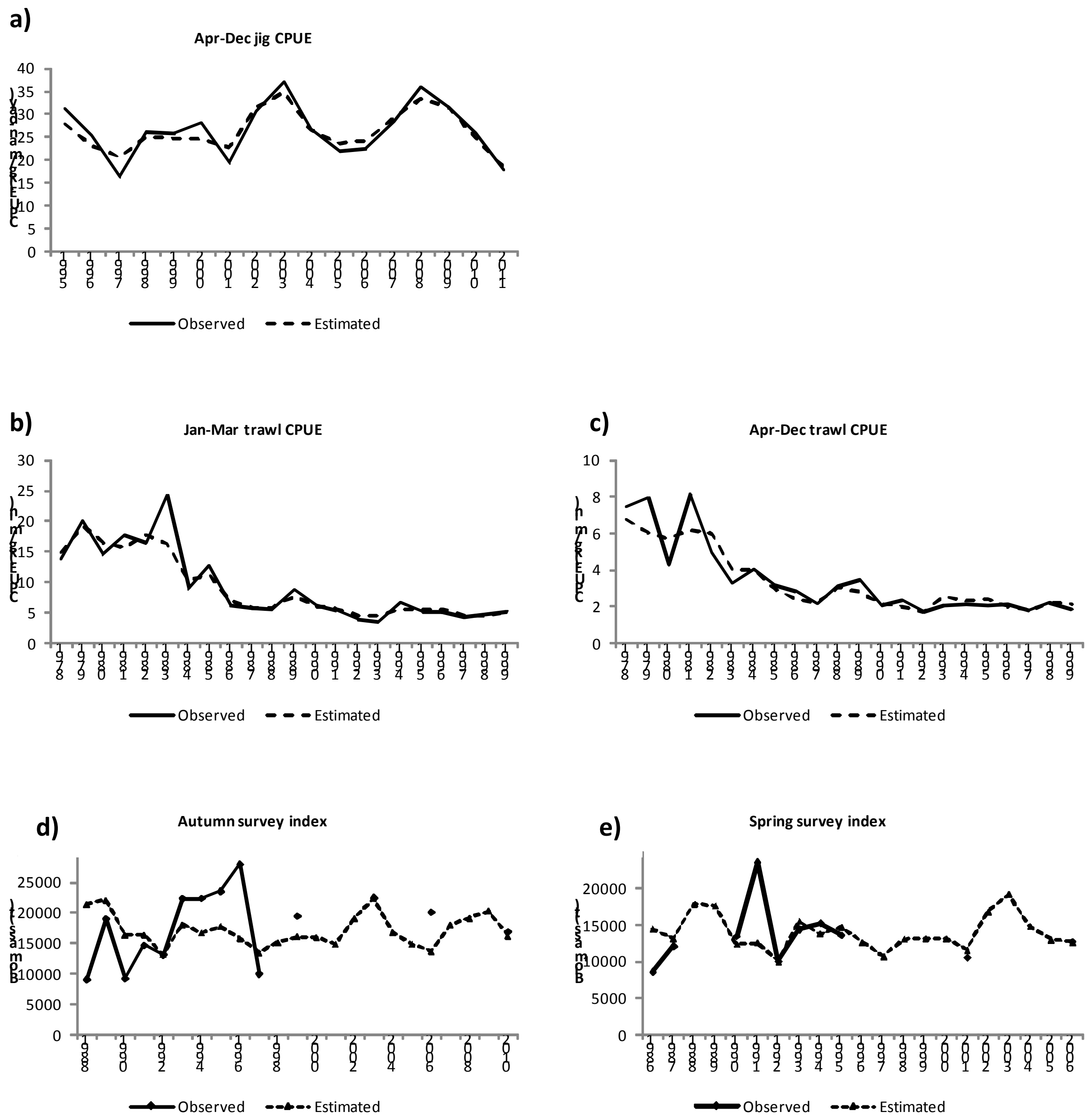


Figure 2: Begin-year biomass (B_y) time series.

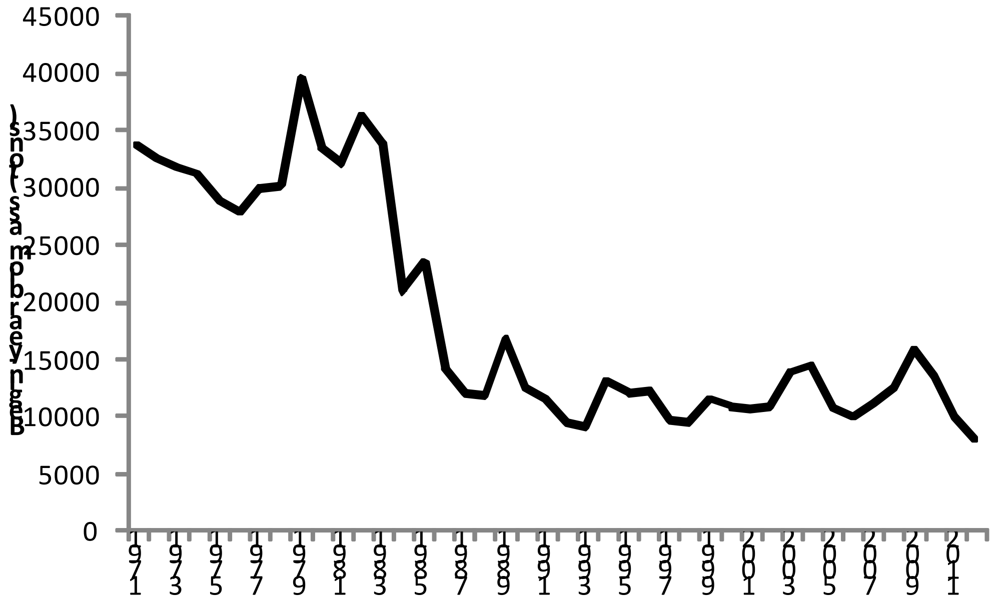


Figure 3: Estimated stock-recruitment residuals.

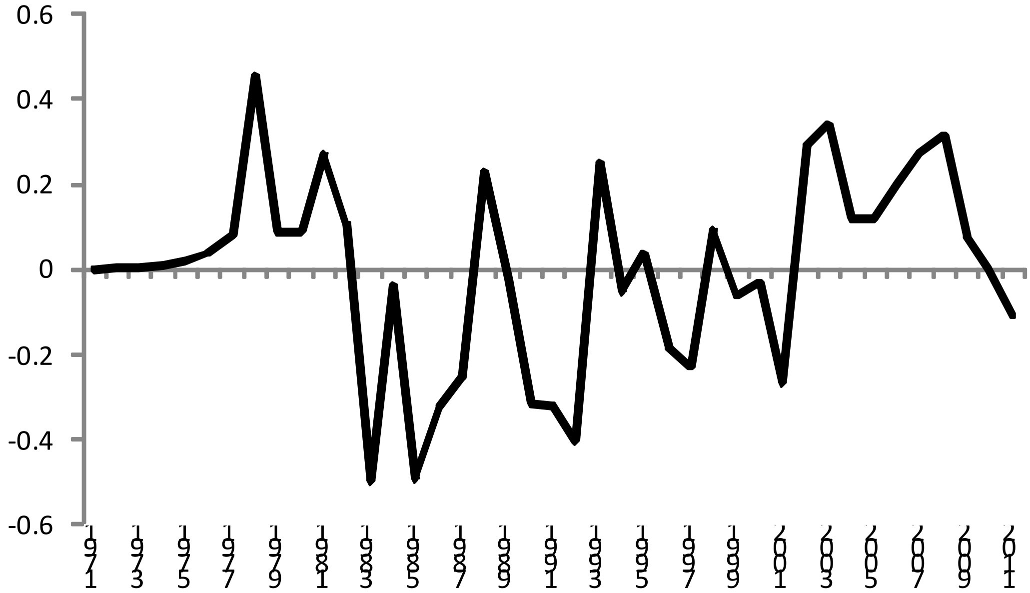


Figure 4: Model predicted stock-recruitment relationship and associated replacement line. The data points shown are the posterior mode estimates from the stock recruitment values each year, and the straight line through the origin is the replacement line.

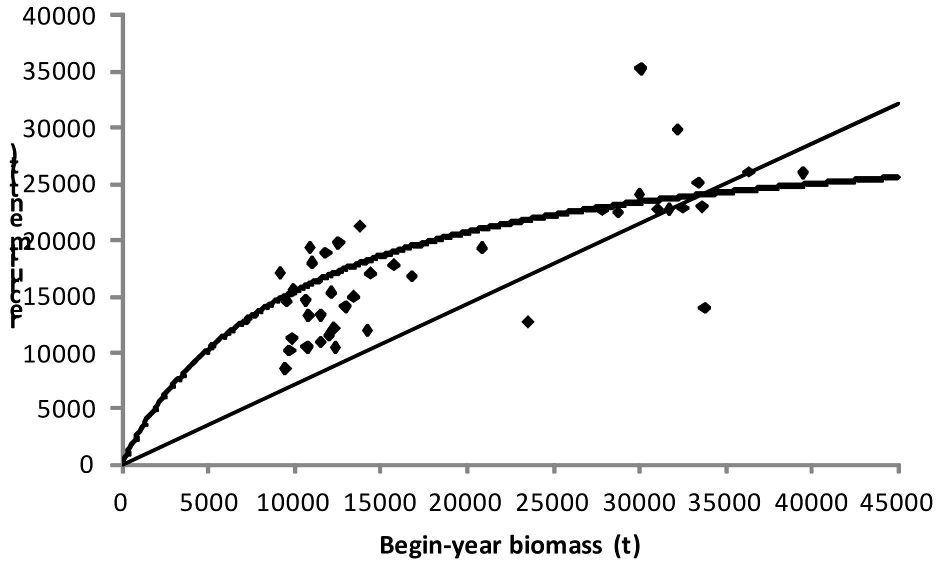


Figure 5: Median average annual catch (tons), with 90% probability intervals, for fixed levels of future effort, expressed in terms of man-days. The curves obtained in the 2012 assessment are compared with those obtained for the 2010 assessment, as well as with the curves derived from an assessment conducted in 2008 where 12 models were run for discrete values of *h* (ranging from 0.4-0.95), and the results were then integrated over *h* using Deviance Information Criterion weighting. The arrow indicates the current level of effort (300 000 man-days).

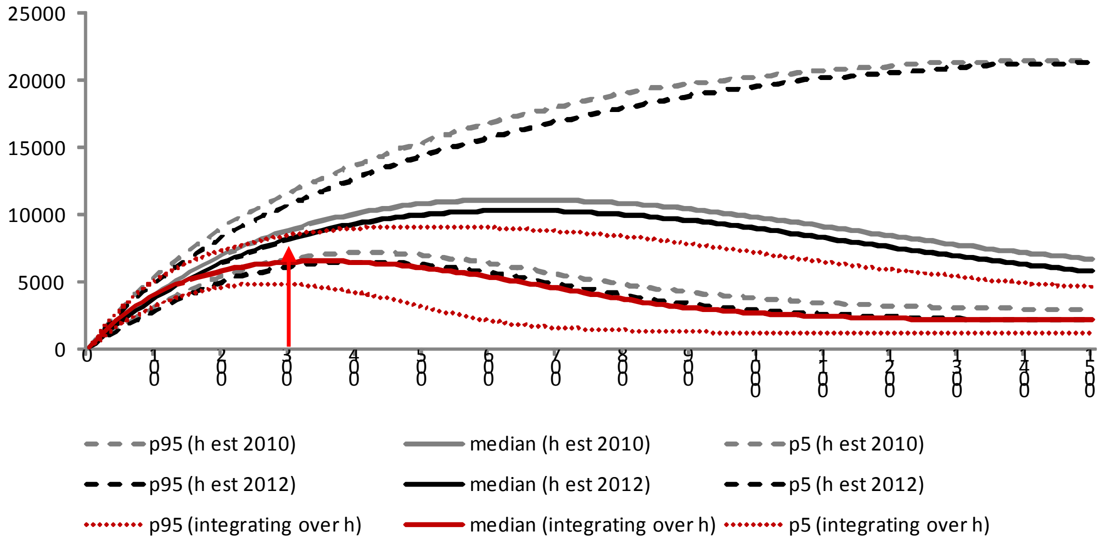


Figure 6: Median average annual catch (tons) and 90% probability intervals derived from running forward projections off the posterior mode results. 5000 simulations were conducted, with both observation and process error taken into account. The arrow indicates the current level of effort (300 000 man-days).

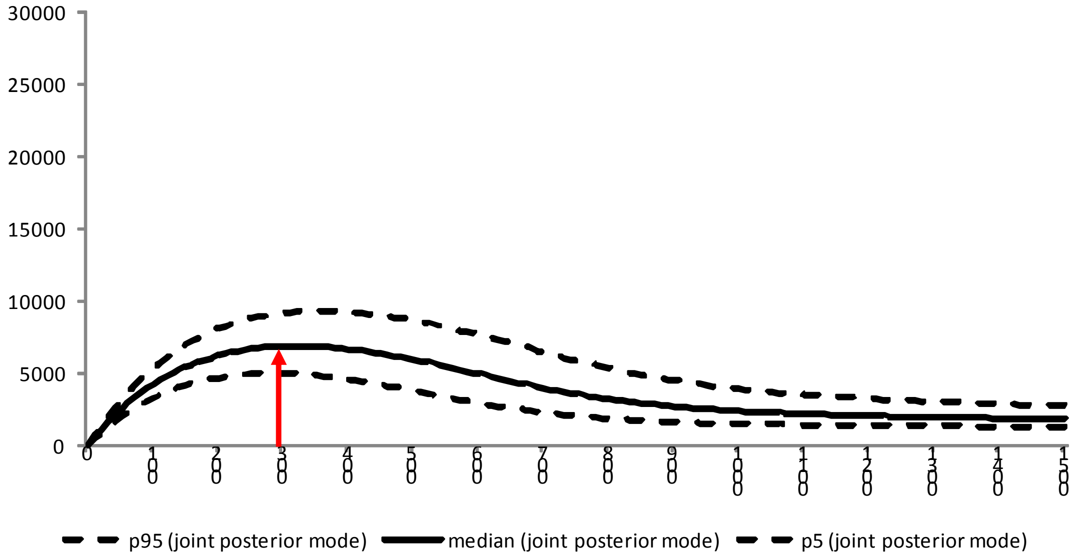


Figure 7: Median begin-year biomass (B_y^*) trajectories (tons) and associated probability envelopes. A constant level of effort is assumed for the projection period (2012-2021).

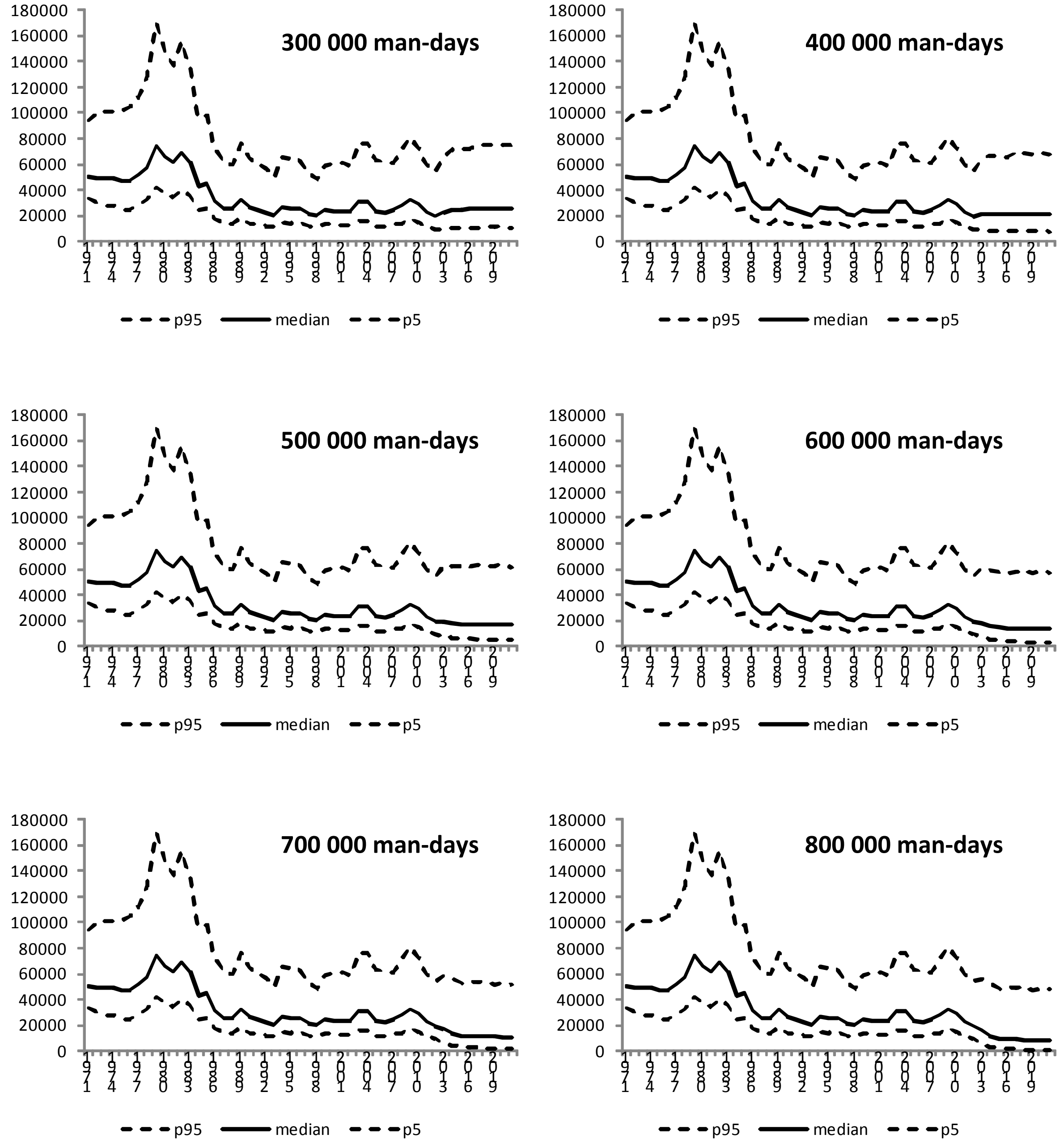
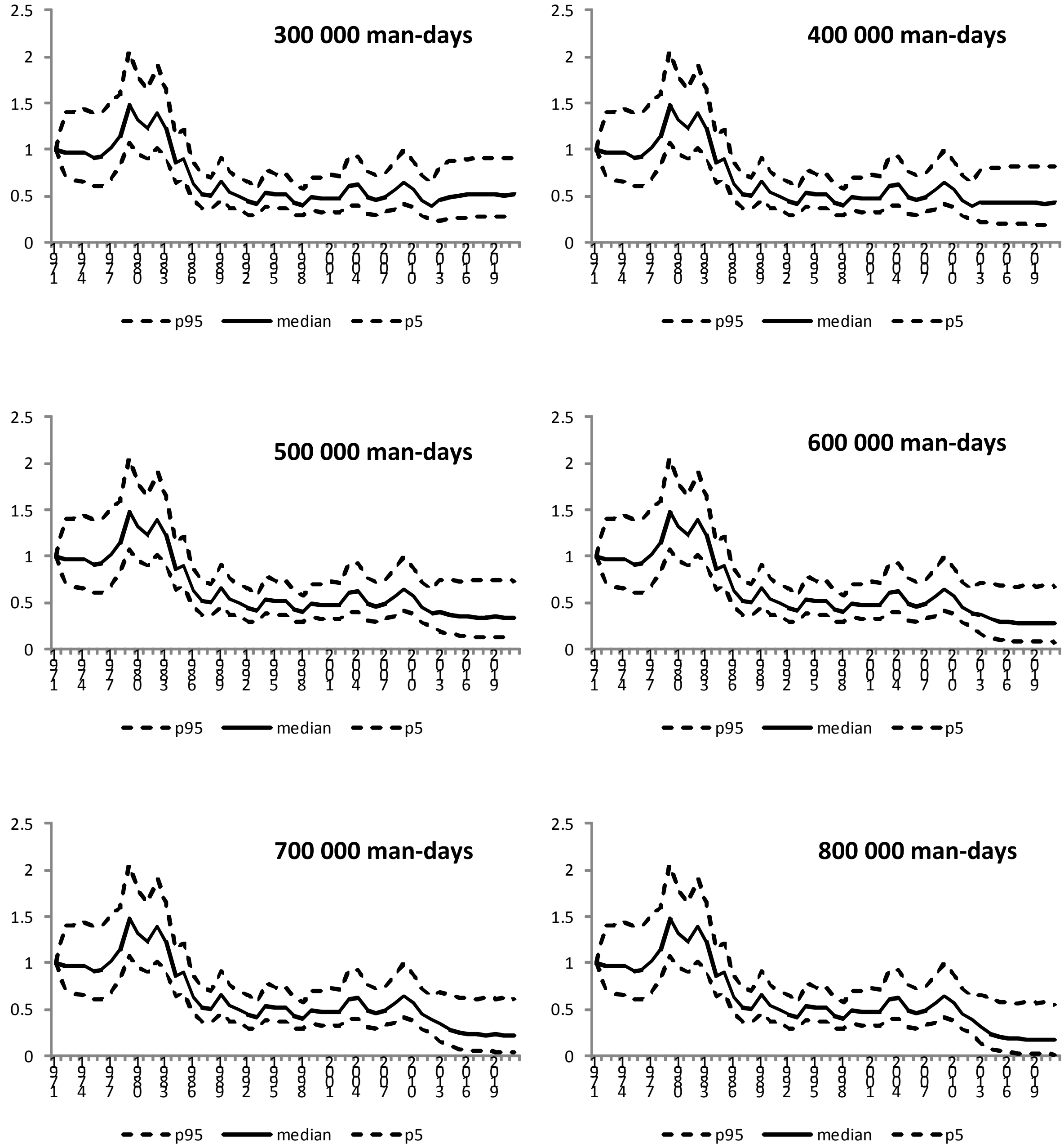


Figure 7: Median B_y^* / K trajectories and associated probability envelopes. A constant level of effort is assumed for the projection period (2012-2021).



APPENDIX A: The biomass dynamics model specifications and projection-related catch equations and rules

The population model splits a year into two time periods, January-March and April-December, to better reflect the dynamics of the stock and the two fisheries (jig and trawl) that exploit it. Hardly any recruitment takes place in the January – March period, and jig and trawl catches are disproportionately divided between this and the April-December period (Roel and Butterworth, 2000). The biomass time series is estimated by projecting the assumed pristine biomass at the start of the period B_0^* (= B_{1971}^* = K) forward given the historic annual catches.

The biomass dynamics for the two periods are given by:

$$B_y = B_y^* e^{-g/4} - C_y^{jig\ J-M} - C_y^{trawl\ J-M} \qquad \text{A.1}$$

$$B_{y+1}^* = B_y e^{-3g/4} + R_y - C_y^{jig\ A-D} - C_y^{trawl\ A-D} \qquad \text{A.2}$$

where B_y^* is the biomass in year *y* at the start of January,

B_y is the biomass in year *y* at the start of April,

$C_y^{jig\ J-M}$ is the jig catch taken in year *y* between January and March,

$C_y^{jig\ A-D}$ is the jig catch taken in year *y* between April and December,

$C_y^{trawl\ J-M}$ is the trawl catch taken in year *y* between January and March,

$C_y^{trawl\ A-D}$ is the trawl catch taken in year *y* between April and December, and

g is a composite parameter that accounts for natural mortality, emigration and growth.

R_y is the recruitment in year *y*:

$$R_y = \frac{\alpha B_y^* \left(1 - \eta F_{y-1}^{jig}\right)}{\beta + B_y^*} e^{\left(\xi_y - \frac{\sigma_R^2}{2}\right)} \qquad \text{A.3}$$

where:

$$F_y^{jig} = \frac{C_y^{jig\ A-D}}{B_y e^{-3g/4} + R_y} \qquad \text{A.4}$$

η is an estimable parameter and controls the extent to which recruitment is affected by jig fishing mortality. ξ_y is the process error reflecting fluctuation about the expected recruitment for year *y*, drawn from $N(0,\sigma_R^2)$. These residuals are treated as estimable parameters in the model fitting process (σ_R is assumed to be 0.3 on input). The estimated residuals may be used to calculate an estimated $\hat{\sigma}_R = \sqrt{\frac{1}{n}\sum_y \xi_y^2}$ on output. The $\frac{\sigma_R^2}{2}$ term is to correct for bias given the skewness of the log-normal distribution.

α and *β* are stock-recruit relationship parameters. In order to work with estimable parameters that are more meaningful biologically, the stock-recruit relationship is re-parameterized in terms of pre-exploitation equilibrium biomass, *K*, and the "steepness", *h*, of the stock-recruitment relationship ("steepness" being the fraction of pristine recruitment that results when biomass drops to 20% of its pristine level):

$$hR_0 = R(0.2K) \qquad \text{A.5}$$

from which it follows that:

$$h = \frac{0.2(\beta + K)}{\beta + 0.2K} \qquad \text{A.6}$$

and hence:

$$\alpha = \frac{4hR_0}{5h-1} \qquad \text{A.7}$$

and

$$\beta = \frac{K(1-h)}{5h-1} \qquad \text{A.8}$$

The likelihood is calculated assuming that the abundance indices are log-normally distributed about their expected values:

$$I_y^i = \hat{I}_y^i e^{\varepsilon_y^i} \quad \text{or} \quad \varepsilon_y^i = \ell n(I_y^i) - \ell n(\hat{I}_y^i) \qquad \text{A.9}$$

where

I_y^i is the abundance index for year *y* and series *i*, $\hat{I}_y^i = \hat{q}^i \overline{B}_y$ is the corresponding model estimate ($\hat{q}^i$ being the catchability coefficient corresponding to series *i* and $\overline{B}_y$ the average biomass during a given period in year *y*), and ε_y^i is the observation error corresponding to series *i* in year *y*.

For the January-March trawl index,

$$\overline{B}_y = \frac{B_y^* + B_y^* e^{-g/4} - C_y^{jig\ J-M} - C_y^{trawl\ J-M}}{2} \qquad \text{A.10}$$

For the April-December jig and trawl indices,

$$\overline{B}_y = \frac{B_y + R_y + B_{y+1}^*}{2} \qquad \text{A.11}$$

For the autumn survey biomass index,

$$\overline{B}_y = B_y + 0.5R_y \qquad \text{A.12}$$

For the spring survey biomass index

$$\overline{B}_y = B_y + R_y \qquad \text{A.13}$$

The contribution of each abundance index to the negative log-likelihood function (after the removal of constants) is given by:

$$-\ell nL_i = n\ \ell n\sigma *^i + \frac{1}{2(\sigma *^i)^2} \sum_{y=1}^{n_i} (\varepsilon_y^i)^2 \qquad \text{A.14}$$

where $\hat{\sigma} *^i = \sqrt{(\hat{\sigma}^i)^2 + C^2}$ A.15

$$\hat{\sigma}^i = \sqrt{\frac{1}{n_i} \sum_y (\varepsilon_y^i)^2} \qquad \text{A.16}$$

and C=0.2. The introduction of the C factor is to ensure that no abundance index receives unrealistically high weight in the fitting process.

The contribution of the stock-recruitment residuals to the negative log-likelihood function is given by:

$$-\ell nL = \sum_y [\ell n\sigma_R + \frac{1}{2\sigma_R^2}\xi_y^2] \qquad \text{A.17}$$

This is a penalty term, being the equivalent in a frequentist framework of what would reflect a normal prior in a Bayesian context.

The derivation of future catches given variability about the catch-effort relationship

The catch-effort relationship $(\frac{C}{E}) = q\overline{B}e^{\varepsilon}$, may be re-arranged to yield $C = qE\overline{B}e^{\varepsilon}$. Substituting equation A.10 for $\overline{B}$ will yield the future catches made in the January-March period for the trawl and jig fisheries respectively. Ignoring the y subscripts, these are thus:

$$C^{trawl,J-M} = \frac{q_{trawl,J-M}E_{trawl,J-M}e^{\xi^{trawl,J-M}}B^*(1+e^{\frac{-g}{4}})}{(2+q_{jig,J-M}E_{jig,J-M}e^{\xi^{jig,J-M}}+q_{trawl,J-M}E_{trawl,J-M}e^{\xi^{trawl,J-M}})} \qquad \text{A.18}$$

$$C^{jig,J-M} = \frac{q_{jig,J-M}E_{jig,J-M}e^{\xi^{jig,J-M}}B^*(1+e^{\frac{-g}{4}})}{(2+q_{jig,J-M}E_{jig,J-M}e^{\xi^{jig,J-M}}+q_{trawl,J-M}E_{trawl,J-M}e^{\xi^{trawl,J-M}})} \qquad \text{A.19}$$

Similarly, for the second period (April-December), substituting equation A.11 for $\overline{B}$ will yield the future catches made in the trawl and jig fisheries respectively:

$$C^{trawl,A-D} = \frac{q_{trawl,A-D}E_{trawl,A-D}e^{\varepsilon_{trawl,A-D}}\{B(1+e^{\frac{-3g}{4}})+2R\}}{(2+q_{jig,A-D}E_{jig,A-D}e^{\varepsilon_{jig,A-Dy}}+q_{trawl,A-D}E_{trawl,A-D}e^{\varepsilon_{trawl,A-D}})} \qquad \text{A.20}$$

$$C^{jig,A-D} = \frac{q_{jig,A-D} E_{jig,A-D} e^{\varepsilon_{jig,A-D}} \{B(1+e^{\frac{-3g}{4}}) + 2R\}}{(2 + q_{jig,A-D} E_{jig,A-D} e^{\varepsilon_{jig,A-Dy}} + q_{trawl,A-D} E_{trawl,A-D} e^{\varepsilon_{trawl,A-D}})} \qquad \text{A.21}$$

$\varepsilon_i \sim N(0,(\hat{\sigma}^{*i})^2)$, *i* denoting each index of abundance.

Rules for projections

If the estimated biomass in the second period was less than $0.05(B^* \times e^{\frac{-g}{4}})$ then the first period catches were set to $0.95p(B^* \times e^{\frac{-g}{4}})$ and the second period biomass to $0.05(B^* \times e^{\frac{-g}{4}})$. Similarly, if the estimated biomass in the first period of the following year was less than $0.05(B \times e^{\frac{-3g}{4}} + R)$ then the second period catches from the previous year were set to $0.95p(B \times e^{\frac{-3g}{4}} + R)$ and the first period biomass to $0.05(B \times e^{\frac{-3g}{4}} + R)$. *p* apportions the catches in the correct ratio for each period and each fishing type.