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Results obtained from projecting the squid resource, *Loligo vulgaris reynaudii*, 10 years into the future.

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Introduction

A Bayesian analysis, to take full account of model uncertainty, was recently conducted to assess the status of the squid resource *Loligo vulgaris reynaudii*. The data included in the model comprised:

- Jig catches (1983-2002)
- Trawl catches (1971-2002)
- Jig CPUE (1985-2002)
- Trawl CPUE (1978-1999)
- Autumn survey biomass indices (1988-1997, 1999)
- Spring survey biomass indices (1987, 1990-1995, 2001)

A detailed description of the biomass dynamic model is provided in Appendix A.

Part of the assessment exercise included projecting 10 years into the future under various constant effort scenarios. The results from these projections are presented here.

Projections

Stochastic projections ten years into the future under different constant jig effort scenarios were carried out. The assumptions made for the stochastic projections are as follows:

- The proportion of annual jig effort expended in each period is equivalent to the average observed over the last three years for which data are available.

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

In order to prevent negative biomasses from occurring (as a result of using discrete approximations instead of differential equations for estimating for future constant catch and effort) in the projection period, rules were applied that essentially restricted catches to no more than 95% of the biomass available (see Appendix A).

Results and Discussion

5000 randomly selected samples (generated from the Bayesian analysis) were used to project the biomass 10 years into the future. Table 1 presents average annual jig catches (reflected by the median, 5th and 95th percentiles) for select values of future constant jig effort. A measure of risk is also provided, where risk is defined as the probability of the spawner biomass dropping below 20% of carrying capacity at least once within the 10 year projection period under the fixed level of effort. A similar statistic is provided, but with the 20% being replaced by 10%.

Plots of $\frac{B_y^*}{B_{1971}^*}$ and B_y^* (reflected by the median and associated probability intervals) for four of the fixed effort scenarios are shown in Figures 1 and 2 respectively. Despite the risk statistic being very high at 0.76 for the target (3 million man-hours) and 0.92 for the current (3.7 million man-hours) level of effort, it is evident from Figures 1 and 2 that even these levels of effort (*if maintained*) do not threaten resource extinction. This is because under a constant effort strategy, there is some automatic feedback control since the catches will drop if abundance declines. Thus applying risk criteria similar to those for the main pelagic fisheries (sardine and anchovy, which are managed on a TAC basis) may not be entirely appropriate.

Nevertheless, the high actual current level of effort (3.7 million man-hours) raises concerns. First, as evident from Figures 1 and 2 it would lead to a median resource size (and hence jig CPUE) *lower* than at any time in the past. There is thus good reason to consider reducing this effort level at least to the intended target level of 3 million man-hours. This is illustrated in Table 2 which compares average $\frac{B_y^*}{B_{1971}^*}$ and CPUE respectively over the projection period 2005-2012 for the two levels of effort, with higher averages evident for an effort level of 3 million man-hours. Also shown in Table 2 is that the average values from the projection period are lower than the average for the last 10 years historically (1993-2002), more so for the current than the target level of effort. Figure 3 shows ten CPUE projection realizations for the two levels of effort.

More importantly though, the computations (and the "security" they suggest) depend critically on specified effort levels not being exceeded in any year. The recent trend in Figure 4 of *increasing* actual effort when the intended effort was fixed is thus very worrying, as it could reflect that if resource abundance drops to low levels, vessels will simply increase their hours spent fishing, and hence their effort, to try to maintain total catches, so that the natural "security" provided the resource by a fixed effort approach becomes an illusion.

There would seem two possible approaches to address this problem:

1. vessels each be allocated a maximum number of hours at sea each year, to ensure that they cannot increase effort at times of low catch rate; or
2. further rules be invested whereby, say, if CPUE drops below a certain level, effort is reduced by implementing (what would likely be substantial) increases to the length of the closed season.

At this stage, limitations under 1) would likely permit allowed fishing time to be distributed in any way over the year (except in a closed season of fixed duration), but later refinements might see a need to weight hours spent fishing differently for different months of the year to allow for changing catchabilities of squid from month to month.

Table 1: Average annual jig catches for various future constant effort scenarios and associated risk statistics.

Effort ('000 man-hours)	Average Catch (5th percentile)	Average Catch (Median)	Average Catch (95th percentile)	Risk (biomass drops below 20% of pristine)	Risk (biomass drops below 10% of pristine)
2000	7352.9	5836.5	4628.0	0.27	0.01
3030 (target effort level)	8479.8	6487.7	4798.7	0.76	0.20
3700 (current effort level)	8843.2	6532.3	4409.4	0.92	0.47
4000	8971.2	6471.3	4154.8	0.95	0.58
5000	9115.8	6069.4	3090.1	0.99	0.84
6000	9032.1	5382.2	2083.9	1.00	0.95

Table 2: Average $\frac{B_y^*}{B_{1971}^*}$ **and CPUE for the periods 1993-2002 (historic) and 2005-2012 (projected) for the target and current levels of effort. The values shown in brackets are the 90% probability intervals.**

Effort ('000 man-hours)	Average $\frac{B_y^*}{B_{1971}^*}$ (1993-2002)	Average $\frac{B_y^*}{B_{1971}^*}$ (2005-2012)	Average CPUE (1993-2002).	Average CPUE (2005-2012).
3030 (target effort level)	0.33	0.28	2.31 (0.74;3.63)	2.10 (0.95;3.67)
3700 (current effort level)	0.33	0.22	2.31 (0.74;3.63)	1.68 (0.64;3.07)

Figure 1: Median $\frac{B_y^*}{B_{1971}^*}$ trajectories and associated probability envelopes. A constant level of effort (‘000 man-hours) is assumed in the projection period (2003-2012).

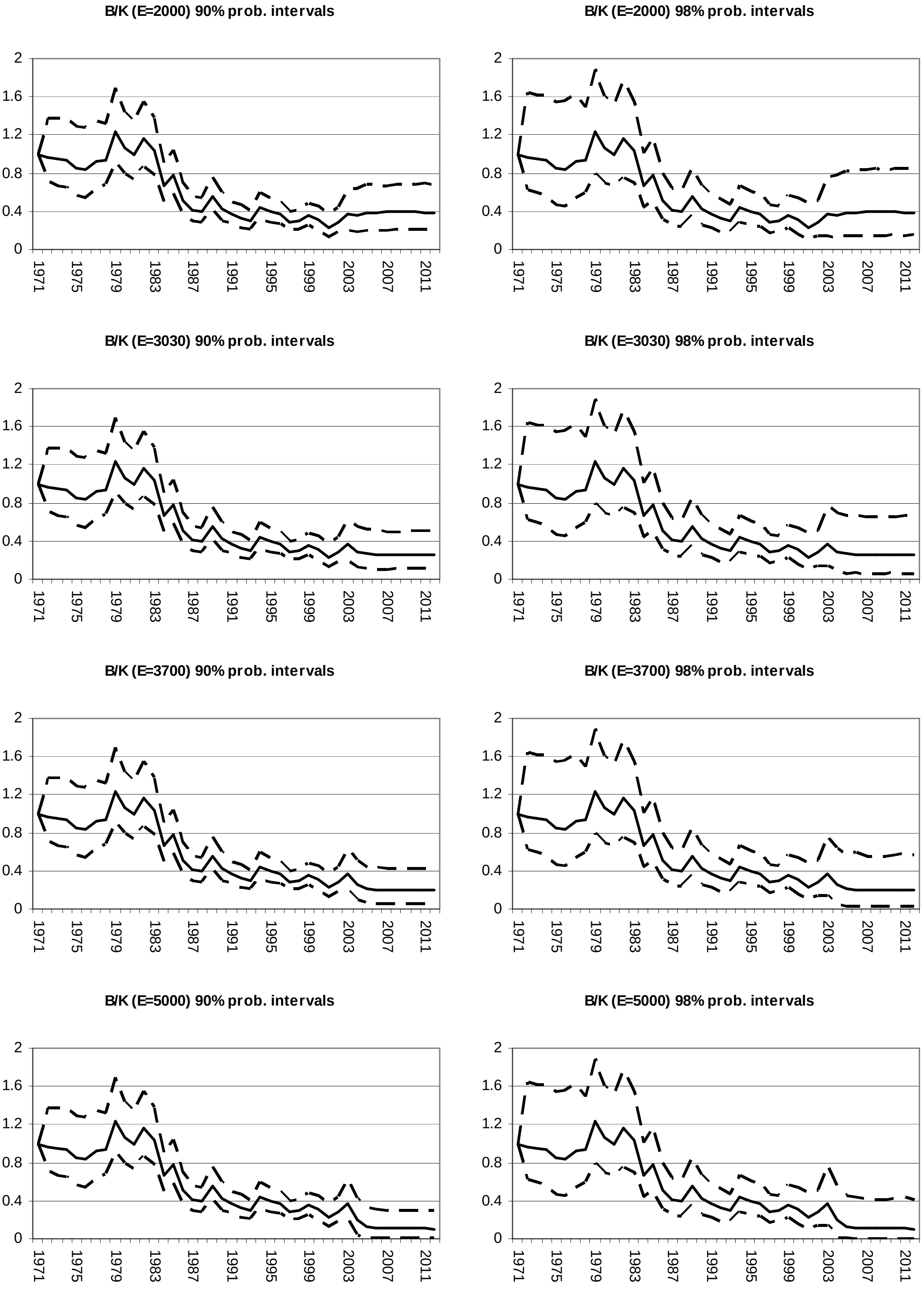


Figure 2: Median B_y^* trajectories and associated probability envelopes. A constant level of effort ('000 man-hours) is assumed in the projection period (2003-2012).

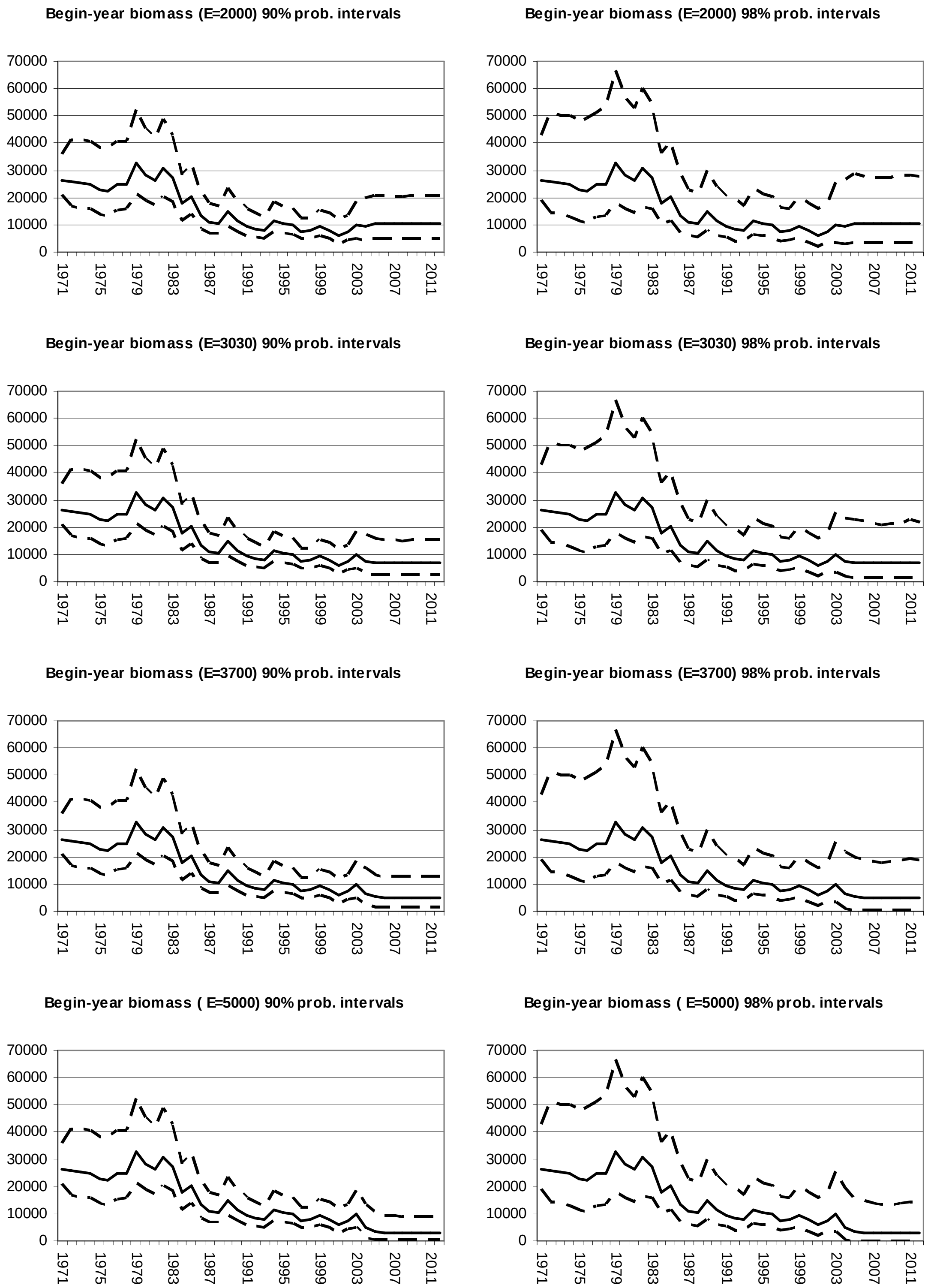


Figure 3a: Historic jig CPUE and ten projected trajectories for E=3030.

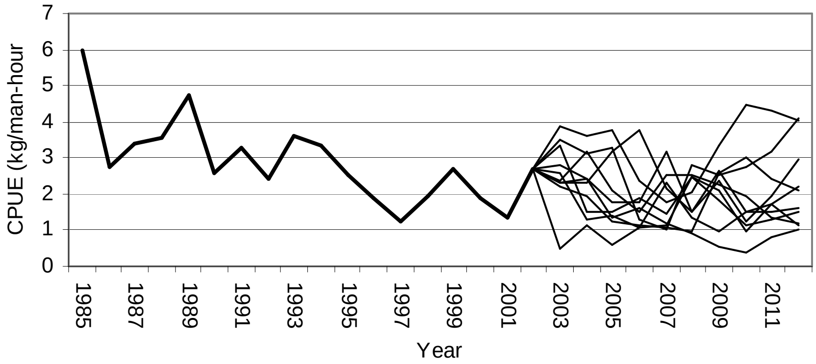


Figure 3b: Historic jig CPUE and ten projected trajectories for E=3700.

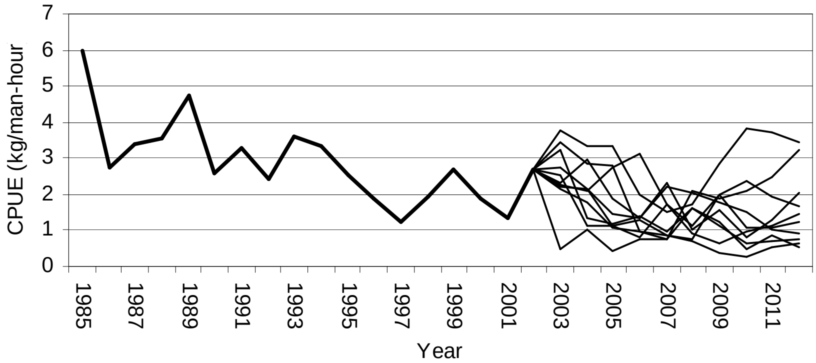
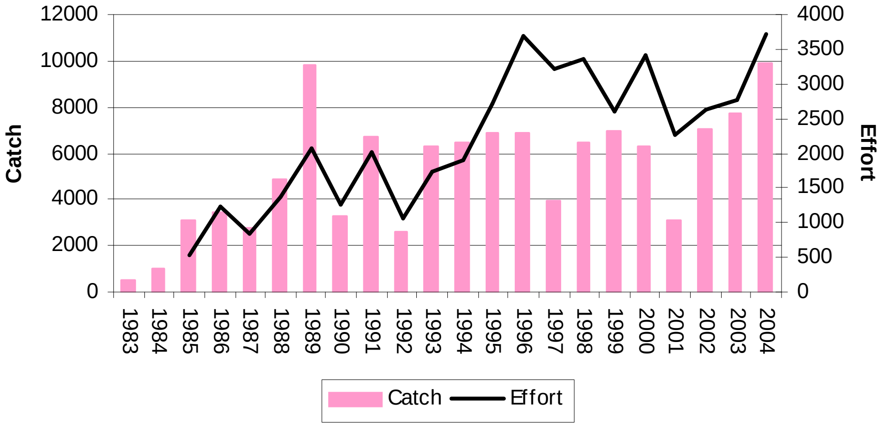


Figure 4: Annual jig catches (t) and effort ('000 man-hours)



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 (Roel and Butterworth, 2000). 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) 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:

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

where:

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

η 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). The estimated residuals may be used to calculate $\hat{\sigma}_R = \sqrt{\frac{1}{n}\sum_y \xi_y^2}$. 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:

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

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:

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

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.

Prior distributions for estimable parameters

The following (uninformative) prior distributions are assumed:

- Pristine recruitment, $R_0 \sim U(0,\infty)$
- Stock-recruitment residuals, $\xi_y \sim N(0, 0.3^2)$
- $g \sim N(1.2, 0.1^2)$

- $\eta \sim (\frac{1-\eta}{0.3+0.97(1-\eta)})/0.9191234596$ (the second denominator being included normalize the prior)
- steepness h is a discrete value ranging from 0.4 – 0.95 in steps of 0.05 (i.e. 12 models in total). Deviance Information Criterion (DIC) was used to weight the models, i.e. assuming that such DICs are equivalent to the marginal posterior probability of each model).

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.