Falkland Islands Fisheries Department

Loligo gahi Stock Assessment, First Season 2012

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Index

Summary

1) The first season *Loligo* fishery of 2012 was open for 51 days, from February 24 to April 14. 34,767 tonnes of *Loligo* catch were reported; the highest total for a first season since 2004. 34.1% of *Loligo* catch and 37.5% of effort were taken north of 52º S.
2) Sub-areas north and south of 52º S were depletion-modelled separately. In the north sub-area, two depletion periods were inferred to have started on March 7 and March 16. In the south sub-area, two depletion periods were inferred to have started on March 1 and March 31.
3) An estimated combined total (initial stock + in-season immigration) of 70,381 ± 36,857 tonnes *Loligo* passed through the fishing zone during first season 2012.
4) The final total estimate for *Loligo* remaining in the Loligo Box at the end of first season 2012 was:
   Maximum likelihood of 19,912 tonnes, with a 95% confidence interval of [11,231 to 26,459] tonnes.
   The risk of *Loligo* escapement biomass at the end of the season being less than 10,000 tonnes was estimated at 0.98%.

Introduction

The first season of the 2012 *Loligo gahi* squid fishery started on February 24, and ended by directed closure on April 14. Total reported *Loligo* catch by C-licensed vessels was 34,767 tonnes, the highest total for a first season since 2004, and in fact higher than the combined total catch of both seasons in 2011 (Table 1).

Table 1. *Loligo* season catch comparisons since 2004.

	Season 1		Season 2	
	Catch (t)	Days	Catch (t)	Days
2004			17,559	78
2005	24,605	45	29,659	78
2006	19,056	50	23,238	53
2007	17,229	50	24,171	63
2008	24,752	51	26,996	78
2009	12,764	50	17,836	59
2010	28,754	50	36,993	78
2011	15,271	50	18,725	70
2012	34,767	51		

As in previous seasons, the *Loligo* stock assessment was conducted with a depletion time-series model (Agnew et al., 1998; Roa-Ureta and Arkhipkin, 2007; Arkhipkin et al., 2008). Because *Loligo* has an annual life cycle (Patterson, 1988; Arkhipkin, 1993), stock cannot be derived from a standing biomass carried over from prior years (Rosenberg et al., 1990). The depletion model instead back-calculates an estimate of initial abundance from data on catch, effort, and natural mortality (Roa-Ureta and Arkhipkin, 2007). In its basic form (DeLury, 1947) the depletion model assumes a closed population in a fixed area for the duration of the assessment. This assumption is imperfectly met in the Falkland Islands fishery, where stock analyses have often shown that *Loligo* groups arrive in successive waves after the start of the season (Payá, 2010; Winter, 2011). Arrivals of successive groups are inferred from discontinuities in the catch data. Fishing on a single, closed cohort would be expected to yield gradually decreasing CPUE, but gradually increasing average individual sizes, as the *Loligo* grow. When instead these data change suddenly, or in contrast to expectation, the recruitment of a new group to the population is indicated.

In the event of a new group arrival, the depletion calculation is modified to account for this influx. Since last season, the modification has been modelled two ways (Winter, 2012): 1) by a simultaneous algorithm ('CatDyn'; Roa-Ureta, 2011) that adds new arrivals on top of the stock previously present, and assumes a common catchability coefficient (Arreguin-Sanchez, 1996) for the entire depletion time-series, and 2) a sequential algorithm that re-starts the depletion time-series on the date of a new group arrival (Roa-Ureta and Arkhipkin, 2007), allowing for different catchability coefficients in the different periods of the depletion time-series. The simultaneous and sequential algorithms are shown schematically in Figure A1.1 (Appendix 1). Either modelling approach may be augmented with hyper-parameters of effort and abundance. The basic form of the DeLury depletion model proposes a linear relationship of catch vs. fishing effort and abundance:

$$C_{n\ day} = q \times E_{day} \times N_{day} \times e^{-M/2} \tag{1}$$

where $C_{n\ day}$, E_{day}, N_{day} are catch (numbers of *Loligo*), fishing effort and abundance (numbers of *Loligo*) per day, q is the catchability coefficient and M is natural mortality, considered constant at 0.0133 day^{-1} (Roa-Ureta and Arkhipkin, 2007). A linear relationship means that if effort or abundance is doubled then – all else being equal – catch will double. But in reality, the relationships may depart significantly from linearity. Increases in effort are likely to elicit diminishing returns. Increases and decreases in abundance may increase or decrease relative catchability, depending on habitat conditions or the behaviour of the *Loligo*. To relate this nonlinearity in the model, the catch equation is re-defined as:

$$C_{n\ day} = q \times E_{day}{}^{\alpha} \times N_{day}{}^{\beta} \times e^{-M/2} \tag{2}$$

where α and β are respectively the effort and abundance hyper-parameters (Roa-Ureta, 2010). Advantages and disadvantages of using either the simultaneous algorithm or sequential algorithm, with or without hyper-parameters, are discussed in Winter (2012).

The *Loligo* stock assessment was calculated in a Bayesian framework (Punt and Hilborn, 1997), whereby results of the depletion model are conditioned by prior information on the stock; in this case the information from the pre-season survey. The depletion likelihood function was calculated as the difference between actual catch numbers and predicted catch numbers from the model:

$$\sum_{days} \left(\log\left(\text{predicted } C_{n\ day}\right) - \log\left(\text{actual } C_{n\ day}\right) \right)^2 \tag{3}$$

The prior likelihood function was calculated as the difference between the survey-derived N estimates and the model-derived N estimates:

$$\frac{1}{2 \cdot SD_{N\,survey}^{\;2}} \sum_{depletions} \left(\log\left(N_{survey}\right) - \log\left(N_{model}\right)\right)^2 \qquad \textbf{(4)}$$

Bayesian optimization of the model was calculated by jointly minimizing equations **(3)** and **(4)**. Distributions of the stock likelihood estimates (i.e., measures of their statistical uncertainty) were computed using a Markov Chain Monte Carlo (MCMC) (Gamerman and Lopes, 2006), a method that is commonly employed for fisheries assessments (Magnusson et al., 2012). MCMC is an iterative method which generates random stepwise changes to the proposed outcome of a model (in this case, the number of *Loligo*) and at each step, accepts or nullifies the change with a probability equivalent to how well the change fits the model parameters compared to the previous step. The resulting sequence of accepted or nullified changes (i.e., the 'chain') approximates the likelihood distribution of the model outcome.

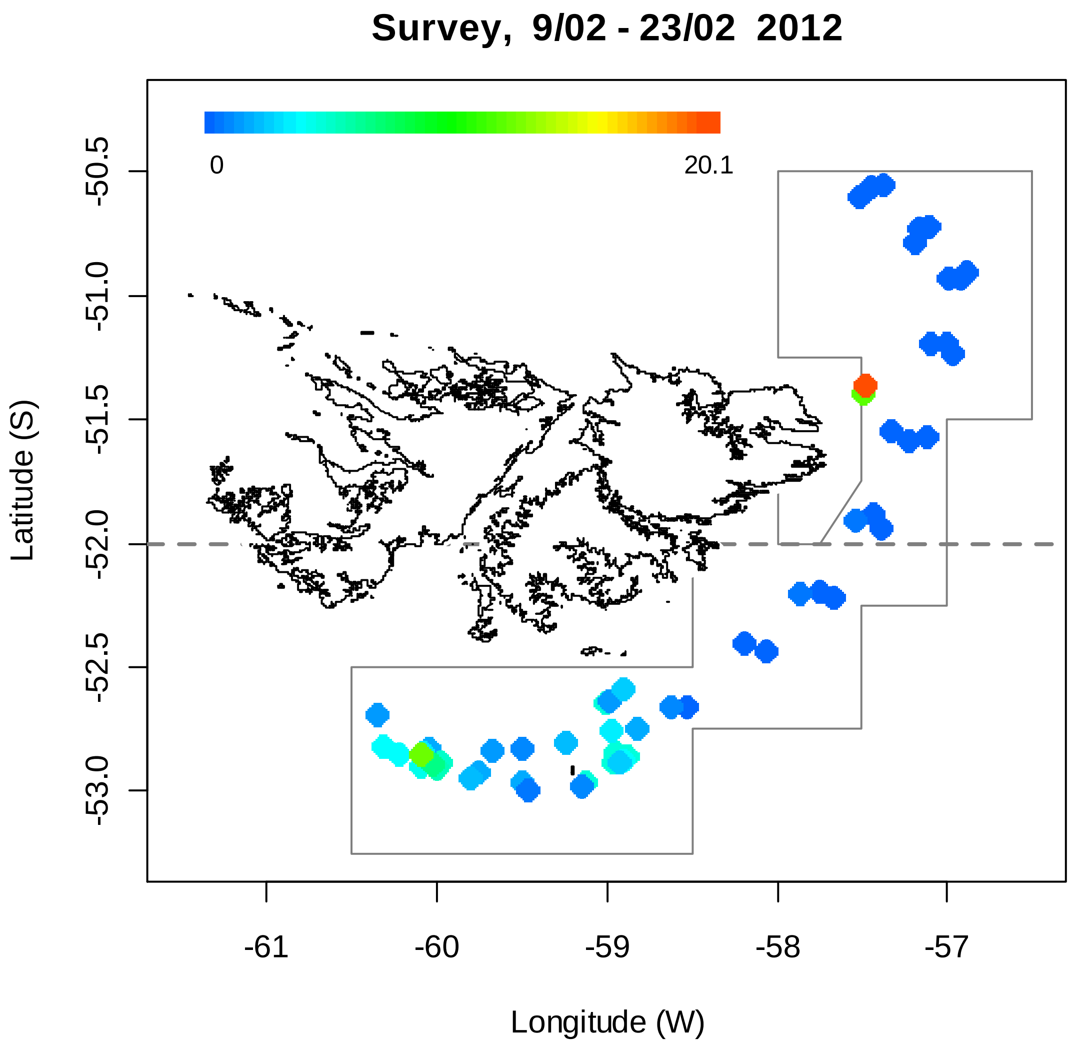

Figure 1. Spatial distribution of *Loligo* 1st-season 2012 pre-season survey catches, scaled to catch weight (maximum = 20.1 tonnes). Fifty-six survey catches were taken. The 'Loligo Box' fishing zone, as well as the 52 °S parallel delineating the nominal boundary between north and south assessment sub-areas, are shown in gray.

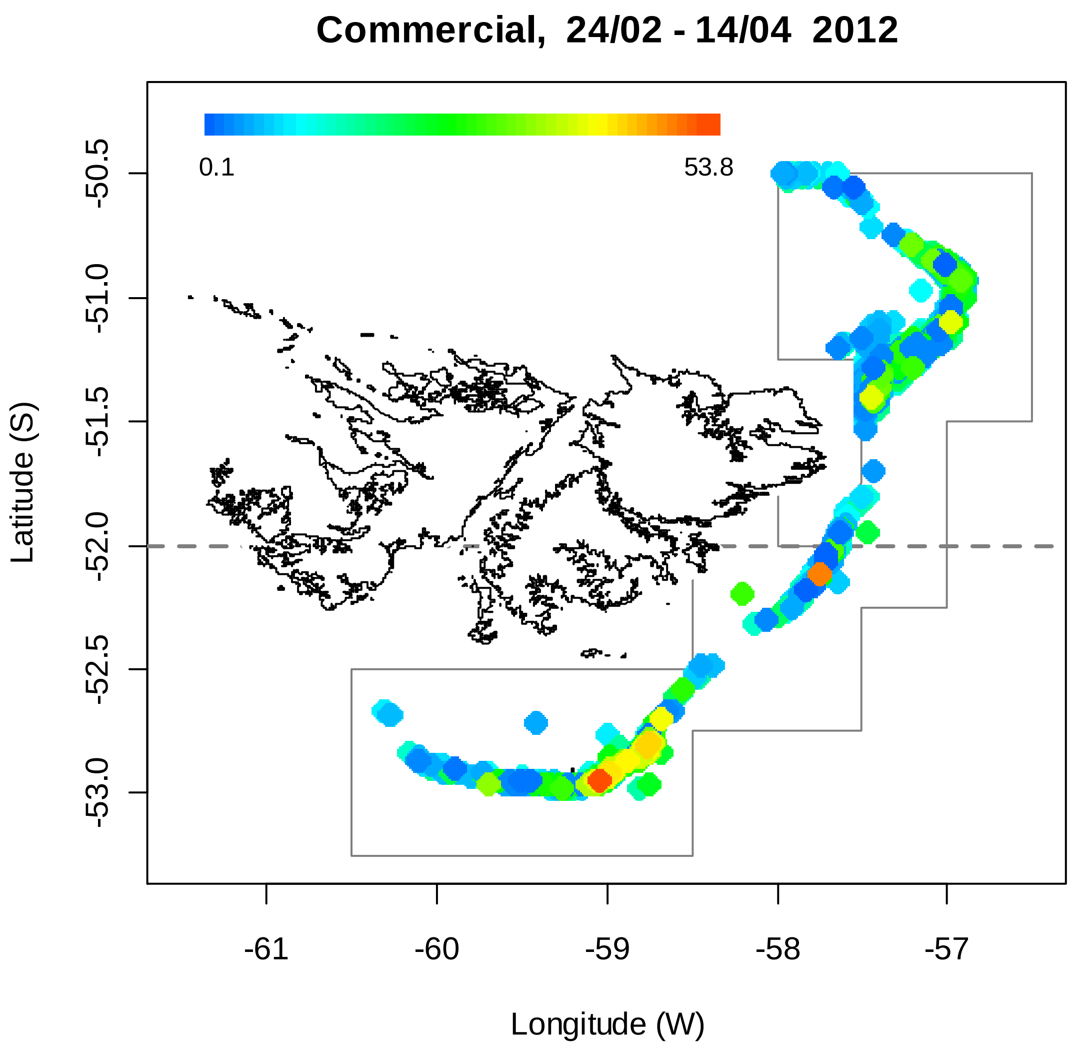

Figure 2. Spatial distribution of *Loligo* 1st-season 2012 commercial catches, scaled to catch weight (maximum = 53.8 tonnes). 2219 catches were taken during the season. The 'Loligo Box' fishing zone, as well as the 52 ºS parallel delineating the nominal boundary between north and south assessment sub-areas, are shown in gray.

Stock assessment

Data

The 2012 first pre-season survey caught 127.6 tonnes *Loligo* in the fishing area, with highest catches concentrated south and in grid unit XPAP (Winter et al., 2012; Figure 1). Commercial catches in-season showed a broader distribution of medium to good *Loligo* catch concentrations (Figure 2). Latitude 52 ºS was again used as a nominal boundary between north (North-Central) and south (Beauchêne) assessment sub-areas. Over the season, 34.1% of *Loligo* catch and 37.5% of effort (vessel-days) were taken north of 52 ºS, vs. 65.9% of catch and 62.5% of effort south of 52 ºS. More than 96% of northern *Loligo* catch was taken during one period of 24 consecutive days (Figure 3), and the high catches in this season resulted in fewer search movements by vessels than in other seasons.

Between 11 and 16 vessels fished in the commercial season on any day (Figure 3), for a total of 769 vessel-days. These vessels reported daily catch totals to the FIFD and electronic logbook data that included trawl times, positions, and product weight by market size categories.

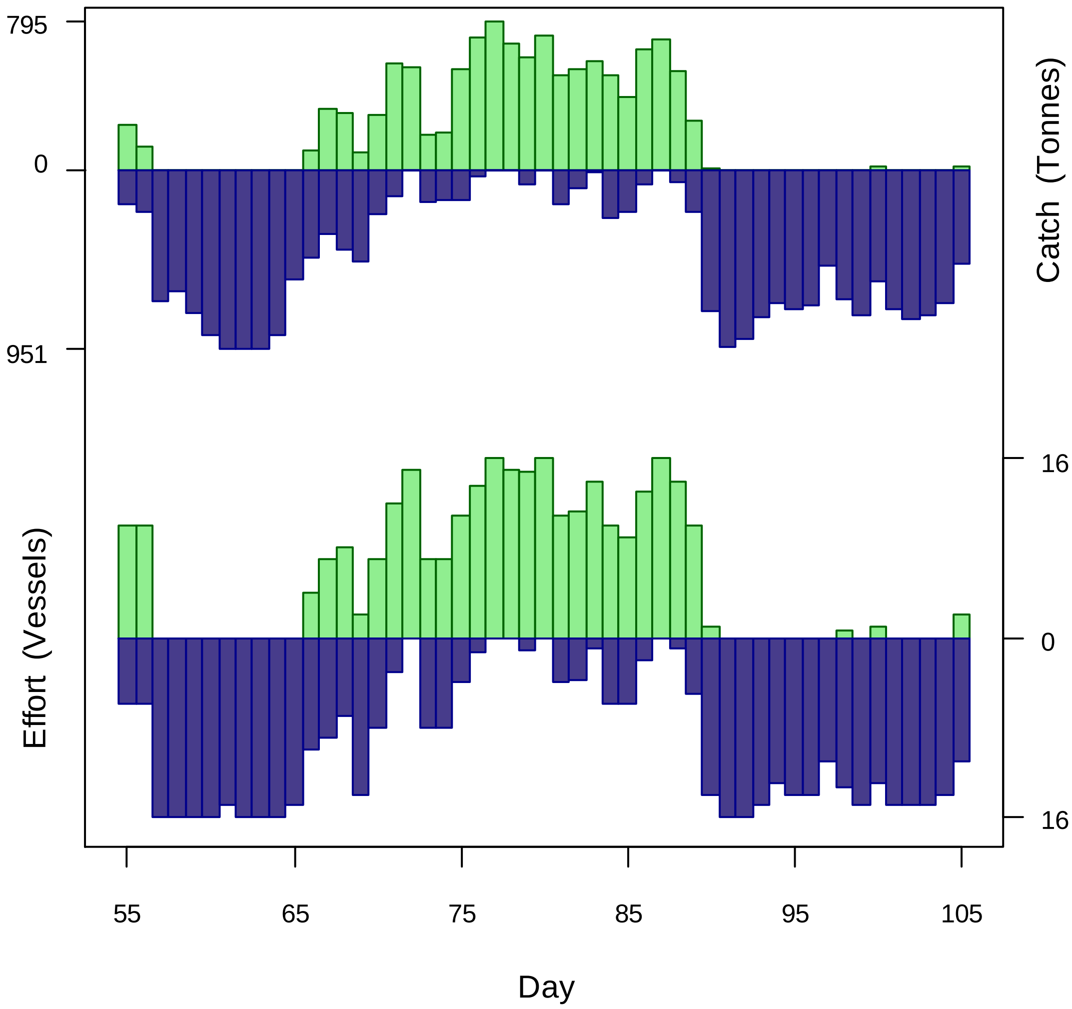

Figure 3. Daily total *Loligo* catch and effort distribution by assessment sub-area north (green) and south (purple) of the 52º S parallel in the *Loligo* 1st season 2012. The season was opened from February 24 (chronological day 55) to April 14 (chronological day 105). As many as 16 vessels fished per day north of 52º S; as many as 16 vessels fished per day south of 52º S. As much as 795 tonnes *Loligo* were caught per day north of 52º S; as much as 951 tonnes *Loligo* were caught per day south of 52º S.

Two FIFD observers were deployed on three vessels in the fishery for a total of 65 observer-days. Throughout the 51 days of the season, 2 days had no observer covering, 33 days had 1 observer covering, and 16 days had two observers covering. Each observer sampled an average of 407 *Loligo* daily, and reported their maturity stages, sex, and lengths to 0.5 cm.

Group arrivals / depletion criteria

Start and end days of depletions - following arrivals of new *Loligo* groups - were judged from daily changes in CPUE, *Loligo* sex proportions, and average individual *Loligo* sizes. CPUE was calculated as metric tonnes of *Loligo* caught per vessel per day. Days were used rather than trawl hours as the basic unit of effort. Commercial vessels do not trawl standardized duration hours, but rather durations that best suit their daily processing requirements. An effort index of days is therefore more consistent. Daily average individual *Loligo* sizes were expressed as weight (kg), converted from mantle lengths using Roa-Ureta and Arkhipkin's (2007) formula optimized on length-weight data from the pre-season survey (Winter et al., 2012):

$$\text{weight (kg)} = 0.20308 \times \textit{length}\ (cm)^{2.16559} / 1000 \qquad \textbf{(5)}$$

For the daily average individual sizes, mantle lengths were obtained from in-season observer data, and also inferred from in-season commercial data as the proportion of product weight that vessels reported per market size category. Observer mantle lengths are scientifically precise, but restricted to 1-2 vessels at any one time that may or may not be representative of the entire fleet. Commercially proportioned mantle lengths are relatively imprecise, but cover the entire fishing fleet. Therefore, both sources of data were used. Daily average individual weights were calculated by averaging observer size samples and commercial size categories where observer data were available, otherwise only commercial size categories.

Depletion period selection

Sub-areas north and south of 52ºS were depletion-modelled separately, as in most seasons. *Loligo* data and CPUE time series showed two days north and two days south that plausibly represent the onset of separate depletions (Figures 4 and 5).

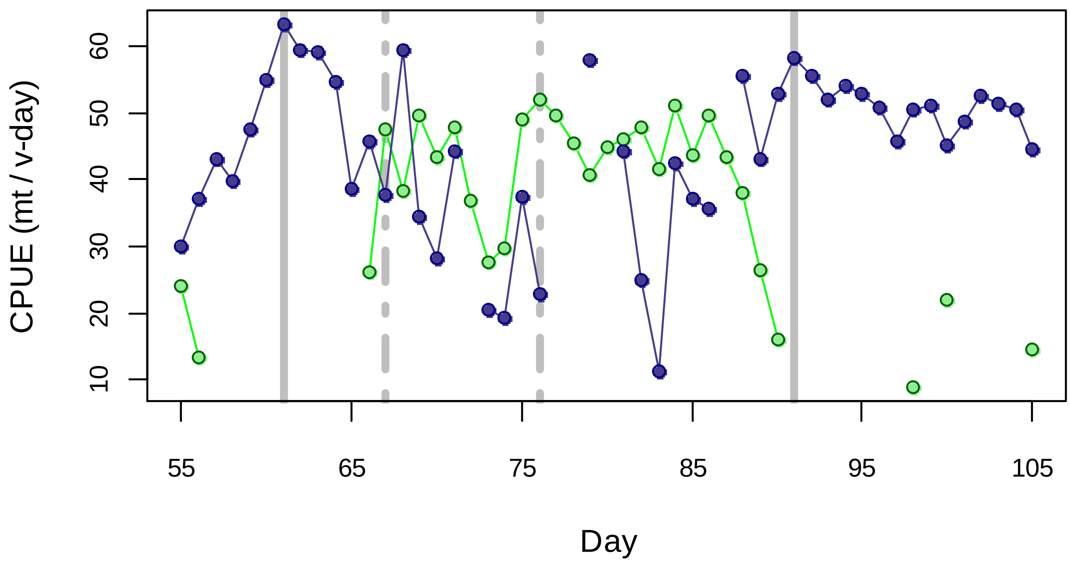

Figure 4. CPUE in metric tonnes per vessel per day, by assessment sub-area north (green) and south (purple) of the 52º S parallel.

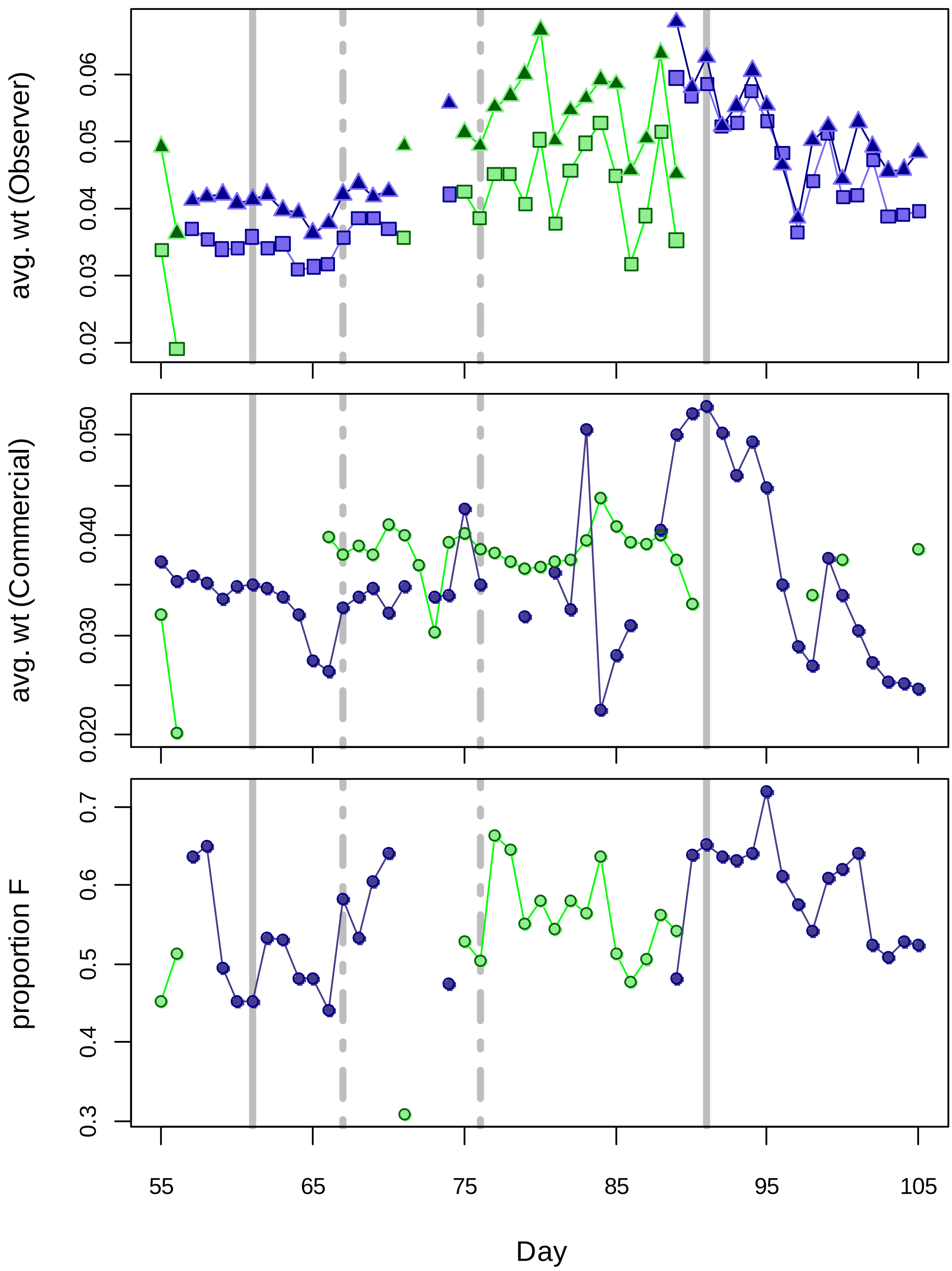

Figure 5. Top: Average individual *Loligo* weights (kg) by sex per day from observer sampling. Males: triangles, females: squares. Middle: Average individual *Loligo* weights (kg) per day from commercial size categories (unsexed). Bottom: Proportions of female *Loligo* per day from observer sampling. North sub-area: green, south sub-area: purple. Data from consecutive days are joined by line segments. Broken gray vertical bars indicate days that were identified as the start of depletion periods north: days 67 and 76. Solid gray vertical bars indicate days that were identified as the start of depletion periods south: days 61 and 91.

- Start of the first depletion period north was identified on day 67 (7 March); the second day of continuous fishing in the north with a strong increase in CPUE (Figure 4).
- Start of the second depletion period north was identified on day 76 (16 March), as the peak of three days' increasing CPUE (Figure 4). The proportion of female *Loligo* increased sharply the next day, but continued to be variable (Figure 5).
- Start of the first depletion period south was identified on day 61 (1 March); at the first major peak in CPUE (Figure 4).
- Start of the second depletion period south was identified on day 91 (31 March). Average commercial weights reached their highest peak of the season and proportion of females showed a sharp increase (Figure 5). CPUE in the south was at its highest peak since day 68 (Figure 4).

Depletion models

Four versions of the depletion model were tested by optimizing equation **(3)**: the simultaneous model with hyper-parameters (A), the simultaneous model without hyper-parameters (B), and the sequential model with (C) and without (D) hyper-parameters. Comparative results are given in Table A1.1 and Figures A1.2 and A1.3.

For the north sub-area, model versions A, B and C all projected implausibly low ending *Loligo* numbers, given the high catch rates. Model version D (sequential model without hyper-parameters) projected moderate ending *Loligo* numbers, and reasonably similar catchability coefficients between the first and second depletion period. Model version D was therefore used.

For the south sub-area, no model version gave a particularly good fit to the catch time series over the last two weeks. The level of catch-rate depletion was low in the south over this two-week period, and the performance of depletion modelling depends on a strong slope (McAllister et al., 2004; Robert et al., 2010). Model version C was the only model version that did not give impossibly high ending *Loligo* numbers (Table A1.1). However, this model version produced an extremely low abundance hyper-parameter of $6.50 \cdot 10^{-9}$, which meant that the model was effectively non-selective to *Loligo* numbers. The first depletion period did have a reasonable outcome with model version D, and therefore an alternative was tested (D*) for the second depletion period by constraining its catchability coefficient to the 95% confidence interval of the first depletion period. This constraint gave realistic parameters as well as *Loligo* numbers, and model version D* was therefore used.

The MCMC of the models were run for 50,000 iterations; the first 1000 iterations were discarded as burn-in sections (initial phases over which the algorithm stabilizes); and the chains were thinned by a factor of 3 to reduce serial correlation (only every third iteration was retained). To check for convergence each chain was initiated 4× with different combinations of high and low *Loligo* numbers (N) and catchability coefficients (q): ¼× N and ¼× q, 2× N and 2× q, ¼× N and 2× q, and 2× N and ¼× q; where the starting point values of N and q were the results of jointly optimizing equations **(3)** and **(4)**. For the second depletion period south, iterations of q were subject to the constraint of falling within the 95% confidence interval of q of the first depletion period south, as noted above. Convergence of the four chains was accepted if the variance among chains was less than 10% higher than the variance within chains (Brooks and Gelman, 1998). When convergence was satisfied the four chains were combined as one set of 65,336 samples ((50,000 – 1000) ÷ 3) × 4).

Priors

Prior information for the stock assessment was the pre-season survey. This survey had estimated a total *Loligo* biomass of 30,706 tonnes with a 95% confidence interval of [20,543 to 44,626 t] (Winter et al., 2012), corresponding to a standard deviation of ±6259 tonnes. From acoustic data analyses, Payá (2010) estimated a net escapement of up to 22%, which was added to the standard deviation:

$$30{,}706 \pm \left(\frac{6{,}259}{30{,}706} + .220 \right) \;=\; 30{,}706 \pm 42.4\% \;=\; 30{,}706 \pm 13{,}014 \text{ tonnes.} \qquad \textbf{(6)}$$

The 22% was added as a linear increase in the variability, but was not used to reduce the total estimate, because *Loligo* that escape one trawl are likely to be part of the biomass concentration that is available to the next trawl. This estimate in biomass was converted to an estimate in numbers using the size-frequency distributions sampled during the pre-season survey (Winter et al., 2012).

Loligo were sampled at 48 pre-season survey stations, giving a weighted-average[1] mantle length (both sexes) of 11.24 cm. This corresponds to 0.038 kg average individual weight. Error distribution of the average individual weight was estimated by randomly re-sampling the length-frequency data 10000×, which gave a coefficient of variation of 1.1%. The average coefficient of variation of the length-weight relationship (equation **(5)**) was 8.7%. Combining all sources of variation with the pre-season survey biomass estimate and average individual weight gave estimated *Loligo* numbers, at the survey end / season start (February 24; day 55) of:

$$N_{\text{day 55}} = \frac{30{,}706 \times 1000}{0.038} \pm \sqrt{42.4\%^2 + 1.1\%^2 + 8.7\%^2}$$

$$= 0.801 \times 10^9 \pm 43.3\% = 0.801 \times 10^9 \pm 0.347 \times 10^9 \qquad \textbf{(7)}$$

which was split between north and south of 52 ºS as:

$$N_{\text{N day 55}} = 0.269 \times 10^9 \pm 0.223 \times 10^9 \qquad \textbf{(7N)}$$
$$N_{\text{S day 55}} = 0.532 \times 10^9 \pm 0.185 \times 10^9 \qquad \textbf{(7S)}$$

For the first depletion periods north and south (starting on days 67 and 61, respectively), priors were calculated as $N_{\text{N day 55}}$ and $N_{\text{S day 55}}$ discounted for catch and estimated natural mortality occurring during the intervening days (CNMD):

$$CNMD_{\text{day 0}} = 0$$
$$CNMD_{\text{day } x} = CNMD_{\text{day x-1}} \times e^{-M} + C_{\text{n day x-1}} \times e^{-M/2} \qquad \textbf{(8)}$$

resulting in:

$$N_{\text{N prior day 67}} = N_{\text{N day 55}} \times e^{-M\,(67-55)} - CNMD_{\text{N1 day 67}} \qquad \textbf{(9)}$$
$$= 0.217 \times 10^9 \pm 0.180 \times 10^9$$

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[1] Weighted for spatial distribution of *Loligo* densities.

$$N_{S\ prior\ day\ 61} = N_{S\ day\ 55} \times e^{-M\ (61-55)} - CNMD_{S1\ day\ 61} = 0.403 \times 10^9 \pm 0.140 \times 10^9 \quad \textbf{(10)}$$

Standard deviations in **(9)** and **(10)** were calculated as the coefficients of variation equivalent to those in **(7N)** and **(7S)**.

For the second depletion periods north and south (starting on days 76 and 91, respectively), the N_N and N_S priors could not be extrapolated directly from the pre-season survey, since it was assumed that the subsequent depletions involved different groups of *Loligo*. Instead, it was inferred that the ratio of *Loligo* numbers starting the second depletion period, over the *Loligo* numbers at the end of the previous depletion period, should be proportional to the ratio of CPUE at the respective start and end days. For stability the CPUE ratios were averaged over three days before and after the start of the new depletion. *Loligo* numbers at the end of the previous depletion were calculated from the equivalent of equations **(9)** or **(10)**. Based on this algorithm, for the second depletion north starting on day 76:

$$N_{N\ prior\ day\ 76} = 0.164 \times 10^9 \quad \text{(details in \textbf{(A2.1)})}$$

However, the minimum N of *Loligo* that needed to be present on day 76 to leave no less than two individuals on the last day of the season (day 105) (and thus not have the stock go extinct), given catch and natural mortality, was:

$$N^{min}_{N\ prior\ day\ 76} = 2 + CNMD_{N2\ day\ 105} / e^{-M(105-76)} = 0.201 \times 10^9 \quad \textbf{(11)}$$

The N^{min} prior was therefore retained instead. For the second depletion south starting on day 91:

$$N_{S\ prior\ day\ 91} = 0.096 \times 10^9 \quad \text{(details in \textbf{(A2.2)})}$$

Likewise, the minimum N of *Loligo* that needed to be present on day 91 to leave no less than two individuals on the last day of the season was:

$$N^{min}_{S\ prior\ day\ 91} = 2 + CNMD_{S2\ day\ 105} / e^{-M(105-91)} = 0.263 \times 10^9 \quad \textbf{(12)}$$

Standard deviations of these second depletion N_N and N_S priors were calculated as the geometric sums of three components: coefficient of variation of the first depletion period N prior (equation **(9)** or **(10)**), variability of the CPUE ratio, calculated by randomly re-sampling the catches and efforts of vessels fishing on the three days before and after, and coefficient of variation of the second N from the depletion model. Because the algorithm had failed to obtain N prior values sufficient for minimal stock size on the last day of the season, standard deviations were additionally multiplied by the ratios of N^{min}_{prior} over $N_{prior;}$ thus for the north sub-area a factor of 0.201/0.164 = 1.226, and for the south sub-area a factor of 0.263/0.096 = 2.740. The complete second depletion prior estimates were then (details in equations **A2.3**, **A2.4**):

$$N^{min}_{N\ prior\ day\ 76} = 0.201 \times 10^9 \pm 0.211 \times 10^9 \quad \textbf{(13)}$$

$$N^{min}_{S\ prior\ day\ 91} = 0.263 \times 10^9 \pm 0.316 \times 10^9 \quad \textbf{(14)}$$

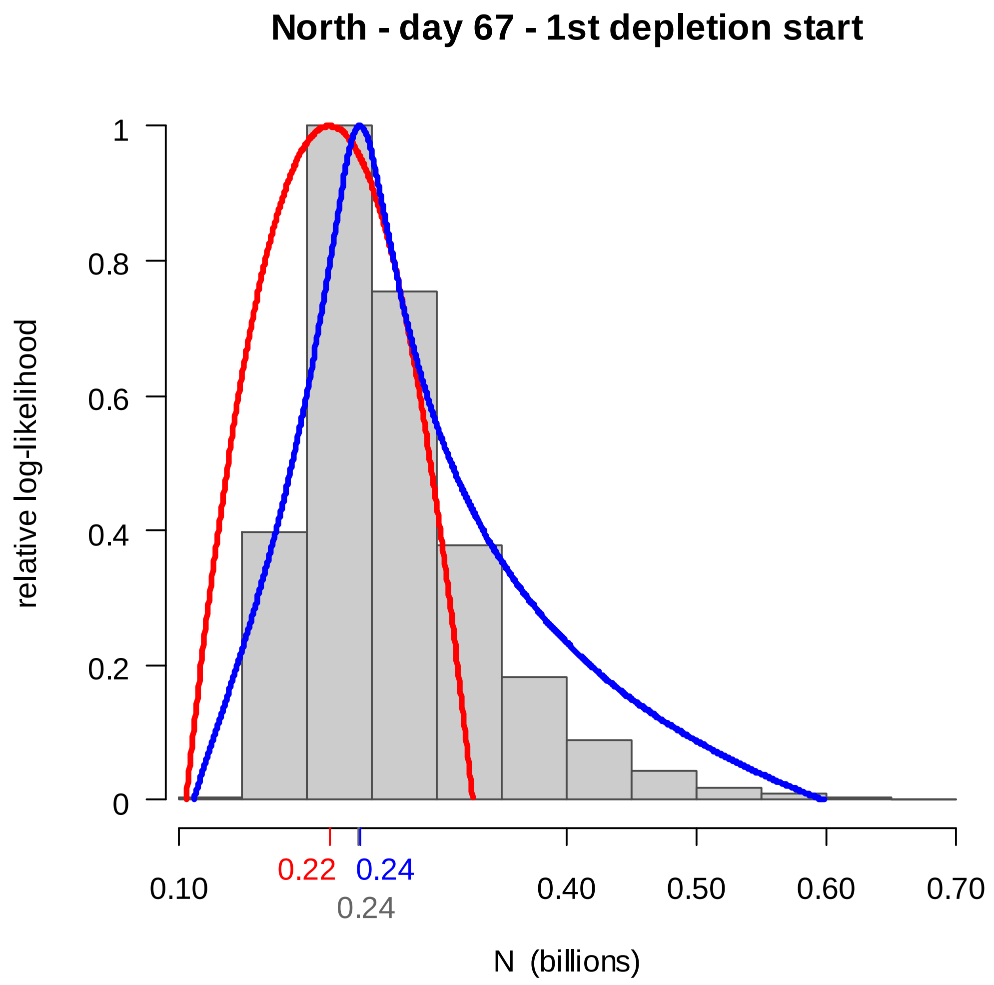


Figure 6. Likelihood distributions for N billion *Loligo* present in the north sub-area on day 67 (March 7). Red line: prior model (derived from pre-season survey data), blue line: depletion model, gray bars: combined Bayesian model.

Depletion analyses

North

The N likelihood distribution at the start of the first depletion period north (day 67) is shown in Figure 6. Maximum likelihood of the prior (red line) corresponds to equation **(9)** ($N_{N\ prior\ day\ 67} = 0.217 \times 10^9$), while maximum likelihood of the depletion model (blue line) occurred only slightly higher at $N_{N\ depletion\ day\ 67} = 0.240 \times 10^9$. The combined Bayesian model max. likelihood was $N_{N\ day\ 67} = 0.239 \times 10^9$ (gray bars).

The N likelihood distribution at the start of the second depletion period north (day 76) is shown in Figure 7. The prior distribution (with maximum corresponding to $N^{min}{}_{N\ prior\ day\ 76} = 0.201 \times 10^9$ (equation **13**)) was not even in range of the histogram of the combined Bayesian model (gray bars) with maximum at $N_{N\ day\ 76} = 0.426 \times 10^9$, indicative that three weeks after the start of the season, the pre-season survey provided minimal information on the stock biomass in the north. The combined Bayesian model was explained primarily by the depletion (blue line), with maximum likelihood at $N_{N\ depletion\ day\ 76} = 0.460 \times 10^9$.

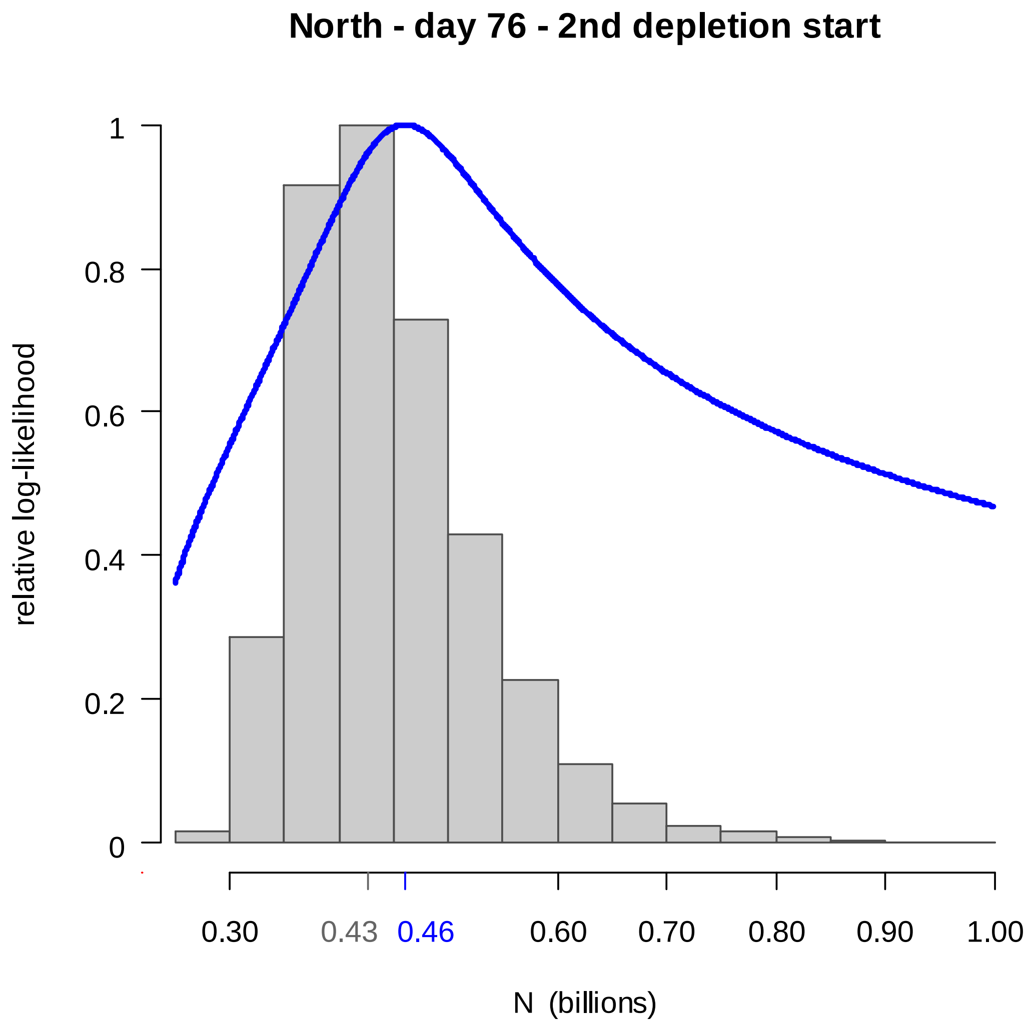


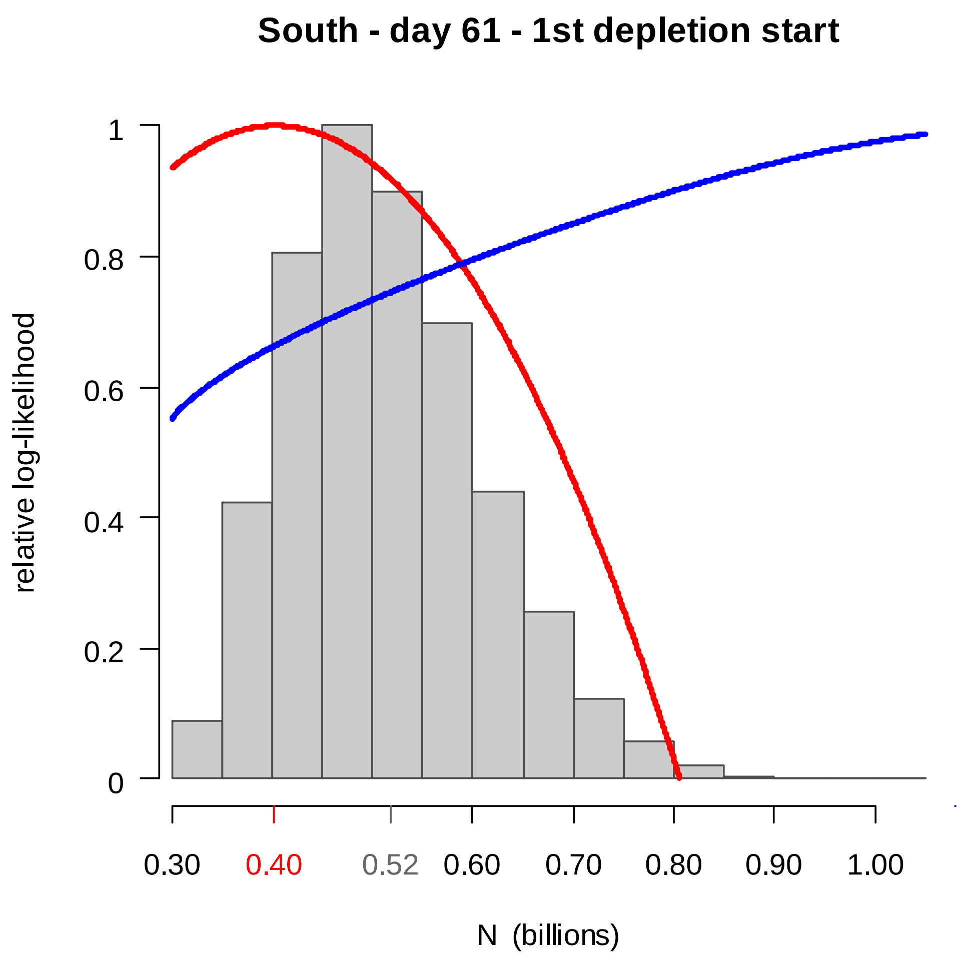
Figure 7. Likelihood distributions for N billion *Loligo* present in the north sub-area on day 76 (March 16). Blue line: depletion model, gray bars: combined Bayesian model.

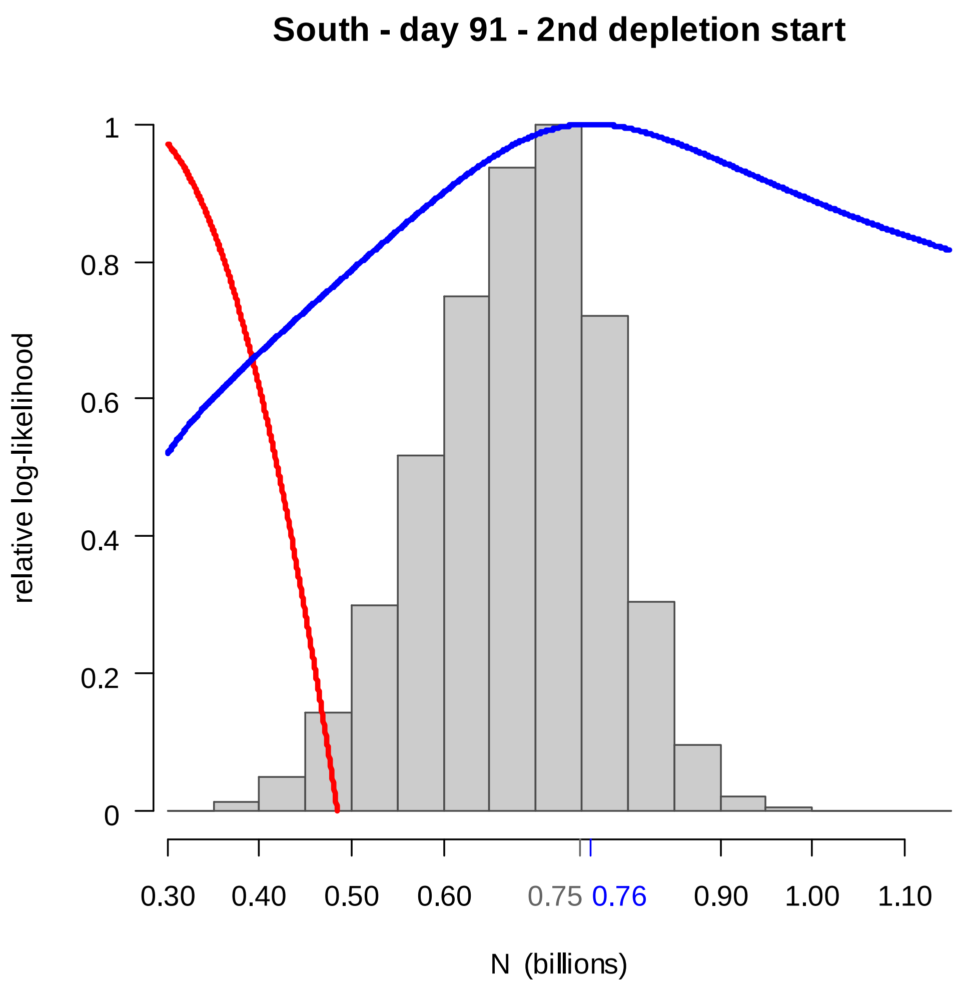
South

The N likelihood distribution at the start of the first depletion period south (day 61) is shown in Figure 8. Maximum likelihood of the prior (red line) corresponds to equation **(10)** ($N_{S\ prior\ day\ 61} = 0.403 \times 10^9$), while maximum likelihood of the depletion model (blue line) was above the histogram range at $N_{S\ depletion\ day\ 61} = 1.191 \times 10^9$. The shallow curve of the blue line shows that the high catch rates and in-season depletion gave relatively little information on actual *Loligo* abundance. Accordingly, the combined Bayesian model (gray bars) was driven primarily by the prior, with maximum likelihood at $N_{S\ day\ 61} = 0.518 \times 10^9$.

Figure 8 [next page]. Likelihood distributions for N billion *Loligo* present in the south sub-area on day 61 (March 1). Red line: prior model (derived from pre-season survey data), blue line: depletion model, gray bars: combined Bayesian model.

Figure 9 [next page]. Likelihood distributions for N billion *Loligo* present in the south sub-area on day 91 (March 31). Red line: prior model (derived from pre-season survey data), blue line: depletion model, gray bars: combined Bayesian model.


South - day 61 - 1st depletion start
relative log-likelihood
1
0.8
0.6
0.4
0.2
0
0.30
0.40
0.52
0.60
0.70
0.80
0.90
1.00
N (billions)


South - day 91 - 2nd depletion start
relative log-likelihood
1
0.8
0.6
0.4
0.2
0
0.30
0.40
0.50
0.60
0.75
0.76
0.90
1.00
1.10
N (billions)

The N likelihood distribution at the start of the second depletion period south (day 91) is shown in Figure 9. Similar to the second depletion period north, the second depletion period south received little information from the pre-season survey, with the prior (red line) at a maximum likelihood ($N_{S\ prior\ day\ 91} = 0.263 \times 10^9$; equation **14**) that was below the histogram range of the combined Bayesian model (gray bars). Maximum likelihood of the combined Bayesian model was $N_{S\ day\ 91} = 0.747 \times 10^9$, just slightly lower than the maximum likelihood of the depletion model alone (blue line) at $N_{S\ depletion\ day\ 91} = 0.760 \times 10^9$.

Immigration and aggregate biomass

Loligo immigration N (after the start of the season) was inferred as the difference between the N maximum likelihood estimate on each second depletion start day (when the immigrations putatively occurred) and the predicted number on that day that would be accounted for by depletion of the previous population alone. This immigration number was multiplied by the average individual weight to give biomass. Expected individual weights were calculated from generalized additive models (GAM) of the daily observer measurements and average vessel market size categories throughout the season. GAM plots are shown in Figure 10.

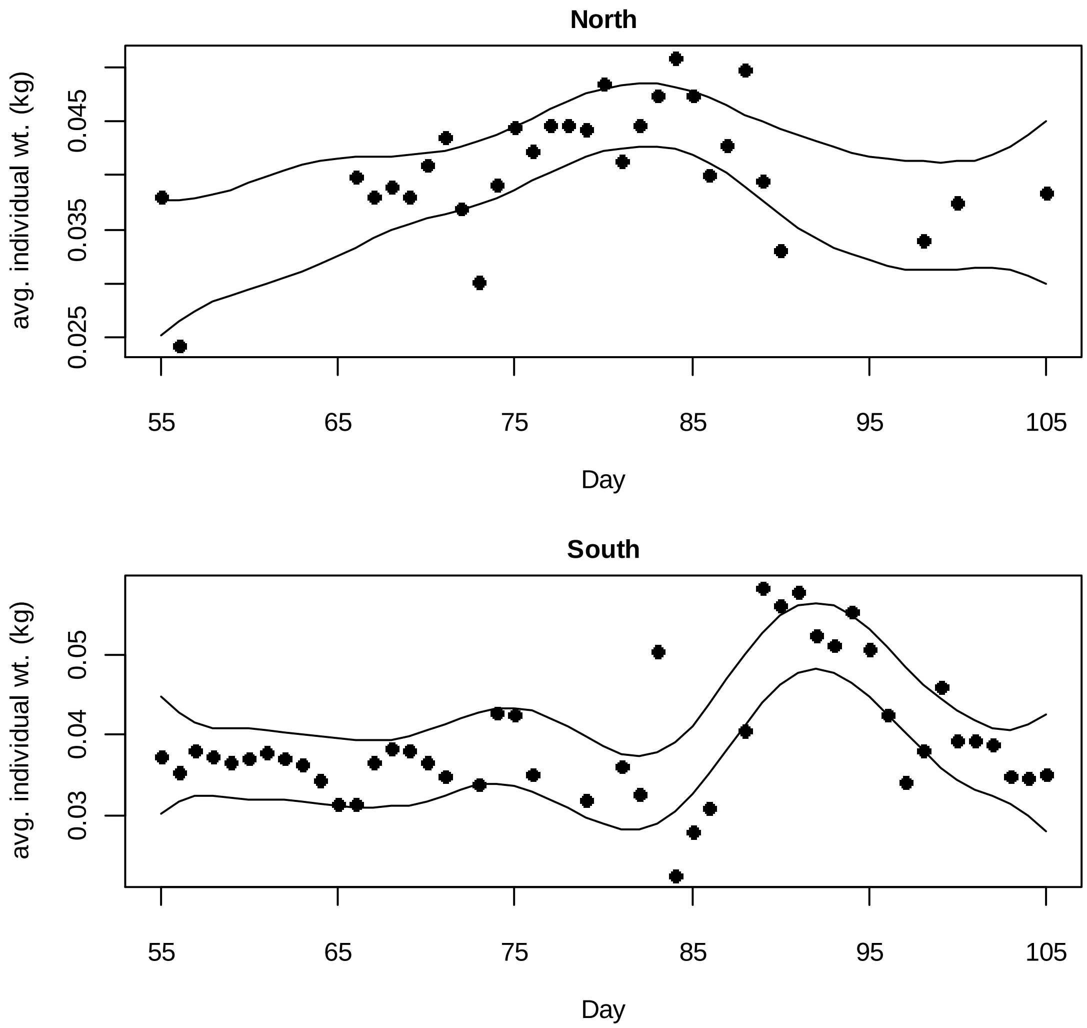


Figure 10 [previous page]. Daily average individual *Loligo* weights (black points) and 95% confidence intervals of GAMs (black lines) of seasonal variation in average individual weight.

For the second depletion north (day 76), immigration was:

$$N_{N2\ day\ 76} = N_{N\ day\ 76} - N_{N1\ day\ 76} = 0.288 \pm 0.095 \times 10^9$$

$$B_{N\ immigration\ day\ 76} = N_{N2\ day\ 76} \times Wt_{N\ day\ 76} = 12{,}210 \pm 4037 \text{ tonnes} \quad \textbf{(15)}$$

Details of calculations are given in equations **A2.5**. For the second depletion south (day 91), immigration was:

$$N_{S2\ day\ 91} = N_{S\ day\ 91} - N_{S1\ day\ 91} = 0.583 \pm 0.101 \times 10^9$$

$$B_{S\ immigration\ day\ 91} = N_{S2\ day\ 91} \times Wt_{S\ day\ 91} = 30{,}319 \pm 5415 \text{ tonnes} \quad \textbf{(16)}$$

Details of calculations are given in equations **A2.6**. The total estimated immigration biomass was:

$$_{immigration}B_{total} = 12{,}210 + 30{,}319 \pm \sqrt{4037^2 + 5415^2}$$

$$= 42{,}529 \pm 6755 \text{ tonnes} \quad \textbf{(17)}$$

The estimated aggregate biomass (initial + immigration) to have passed through the Falkland Islands Loligo Box fishery zone in the first season of 2012 was (details of calculations in equations **(A2.5)**):

$$B_{N\ day\ 67} + B_{S\ day\ 61} + B_{N\ immigration\ day\ 76} + B_{S\ immigration\ day\ 91}$$

$$= 70{,}381 \pm 36{,}857 \text{ tonnes} \quad \textbf{(18)}$$

Escapement biomass

Escapement biomass was estimated from the number of *Loligo* in the fishing area at the scheduled end of the season (day 105; April 14) multiplied by the expected individual weight of *Loligo* on day 105. Calculations were made separately by north and south sub-areas, then summed.

Numbers of *Loligo* on day 105 were calculated by catch and mortality discounting the N maximum likelihoods of the second depletion start days:

$$N_{N\ day\ 105} = N_{N\ day\ 76} \times e^{-M\ (105-76)} - CNMD_{N2\ day\ 105}$$

$$= 0.426 \times 10^9 \times e^{-M\ 105-219)} - CNMD_{N2\ day\ 105}$$

$$= 0.153 \times 10^9 \quad \textbf{(19N)}$$

$$N_{S\ day\ 105} = N_{S\ day\ 91} \times e^{-M\ (105-91)} - CNMD_{S2\ day\ 105}$$

$$= 0.747 \times 10^9 \times e^{-M\ 105-91)} - CNMD_{S2\ day\ 105}$$

$$= 0.402 \times 10^9 \quad \textbf{(19S)}$$

These numbers were multiplied by the expected individual weights of *Loligo* on day 105, calculated from the GAMs (Figure 10). Expected individual weights were 37.5 ± 3.8 g in the north sub-area, and 35.3 ± 3.8 g in the south sub-area.

The maximum likelihood biomasses were thus:

$B_{N\ day\ 105}$ $= 0.153 \times 10^9 \times 37.5$ g $=$ 5,724 tonnes **(20N)**

$B_{S\ day\ 105}$ $= 0.399 \times 10^9 \times 35.3$ g $=$ 14,188 tonnes **(20S)**

$B_{total\ day\ 105}$ $=$ 19,912 tonnes **(20)**

Likelihood distributions of the escapement biomasses were calculated by substituting the values of $N_{N\ day\ 76}$ and $N_{S\ day\ 91}$ in equations **(19)** with random draws from their respective MCMCs, and substituting individual weights with random draws from the normal distribution with respectively mean = 37.5 and standard deviation = 3.8 (north), and mean = 35.3 and standard deviation = 3.8 (south), then multiplying N and weights together as in equations **(20)**. Random draws were iterated 5× the number of retained MCMC values (5 × 65,336 = 326,680), then added together for north and south sub-areas. This represents the total escapement biomass distribution, shown in Figure 11. The 95% confidence of escapement biomass estimates is [11,231 to 26,459] tonnes. The risk of the fishery, defined as the proportion of the escapement biomass distribution below the conservation limit of 10,000 tonnes (Barton, 2002; Arkhipkin et al., 2008), was found equal to 0.98% (Figure 11).

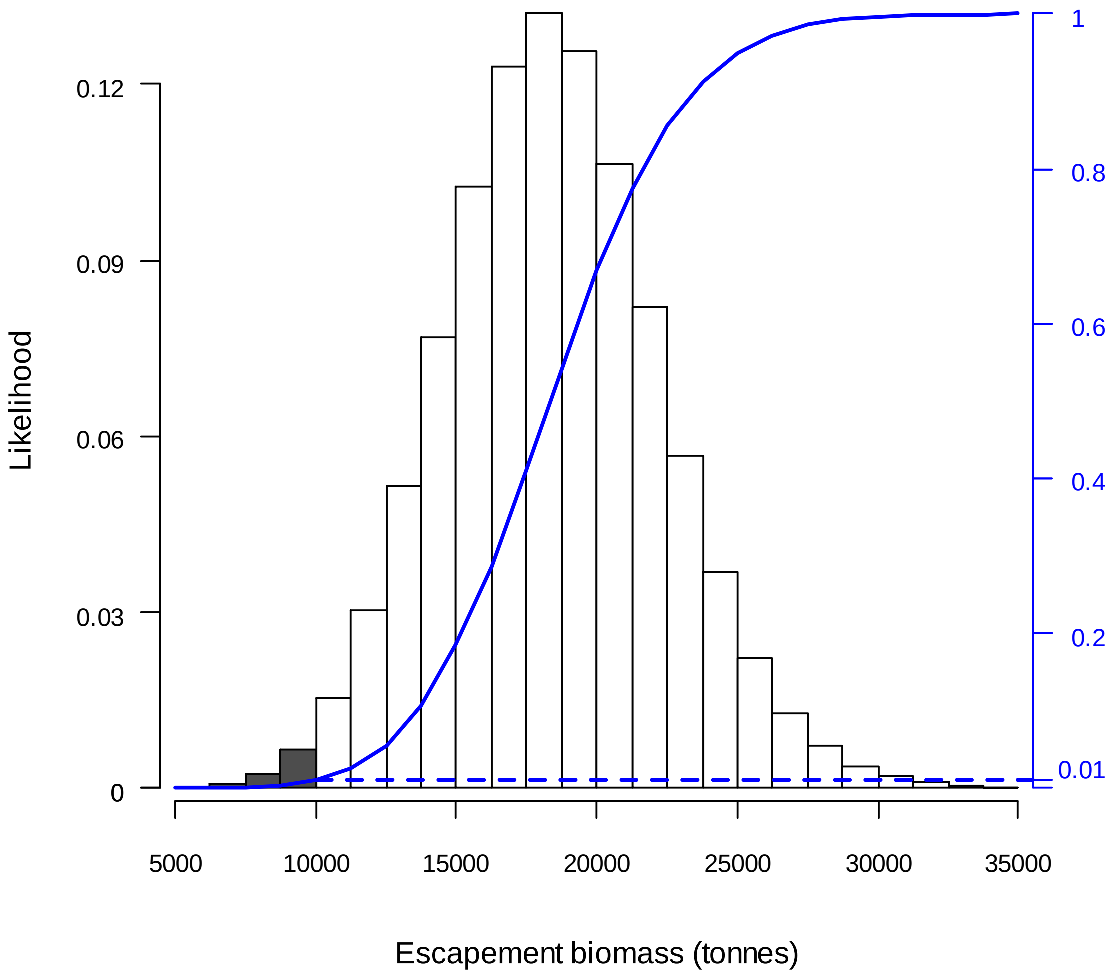


Figure 11. Probability distribution of *Loligo* biomass at the end of the season, April 14. Distribution outcomes less than the biomass escapement limit of 10,000 tonnes are shaded dark gray. Cumulative probability is shown as a solid blue curve. The broken blue line indicates that the probability of less than 10,000 tonnes escapement biomass was 0.98%.

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Appendix 1. Evaluation of different versions of the depletion model.

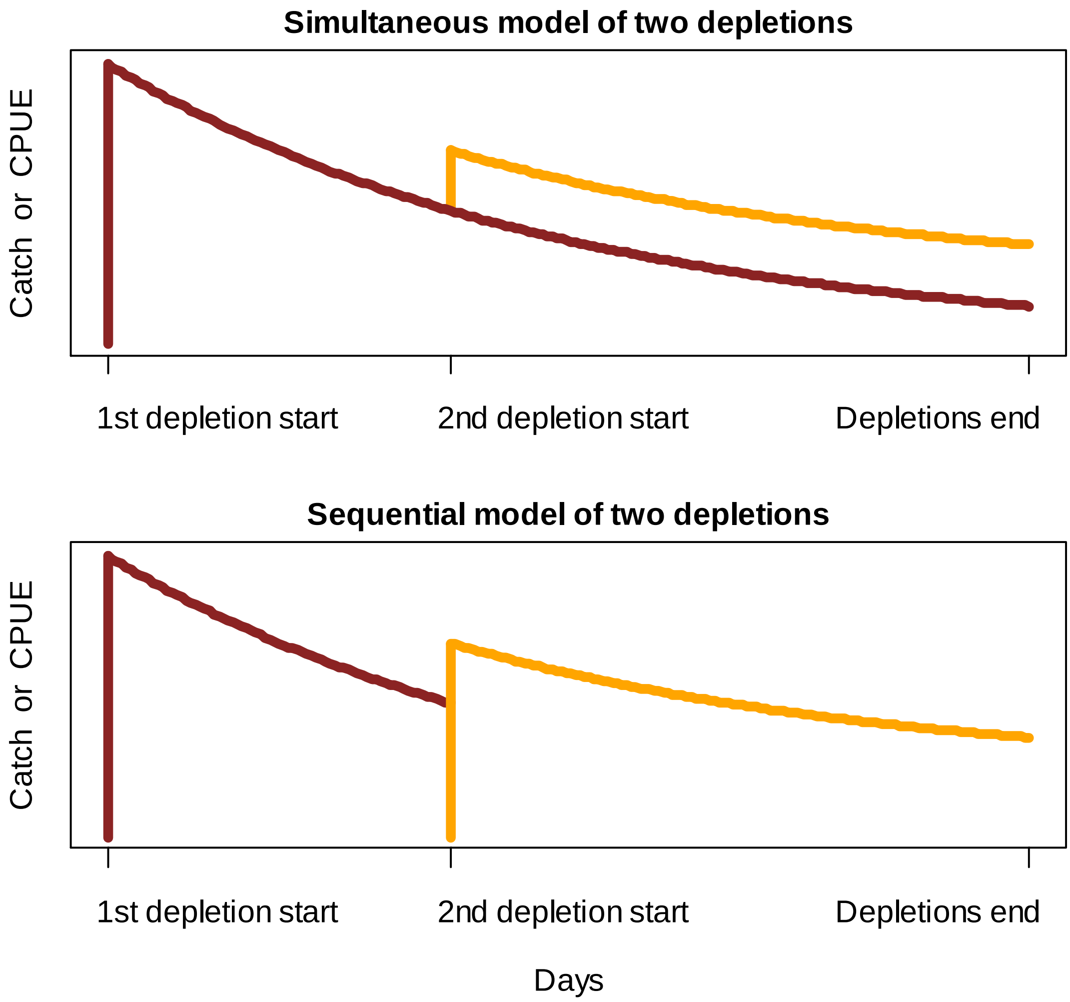

Figure A1.1. Schematic of the difference between simultaneous depletion modelling (as implemented by CatDyn) and sequential depletion modelling. In the simultaneous model numbers of *Loligo* from the two depletion curves must be added together on any day; in the sequential model the second depletion curve includes the numbers from the first one.

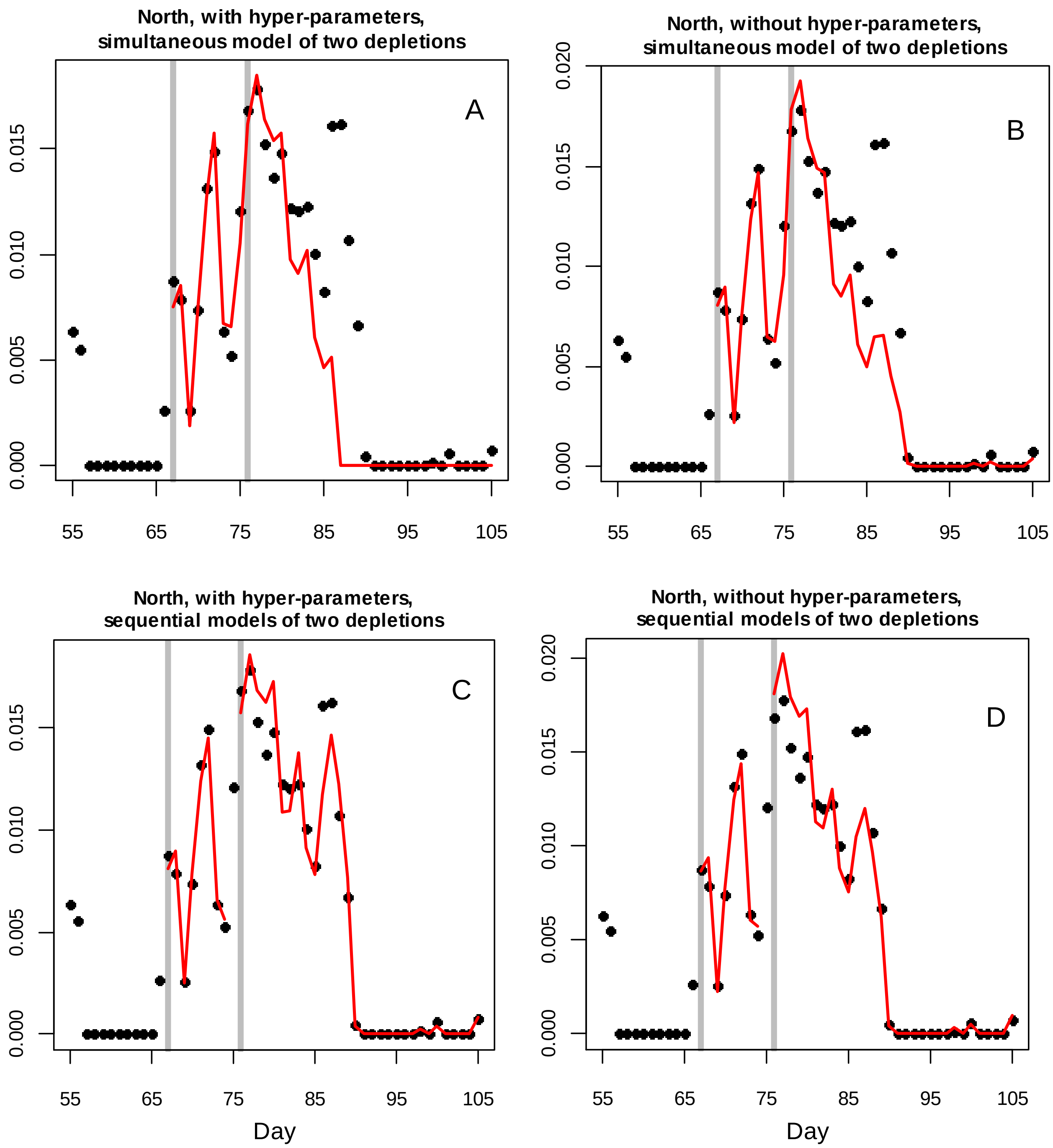

Figure A1.2. Daily estimated catch numbers (black points) and expected catch numbers (red lines) projected from the north sub-area depletion periods starting on days 67 and 76, under four versions of the depletion model.

Figure A1.3 [next page]. Daily estimated catch numbers (black points) and expected catch numbers (red lines) projected from the south sub-area depletion periods starting on days 61 and 91, under four versions of the depletion model, plus a modified version with restricted catchability coefficient q.

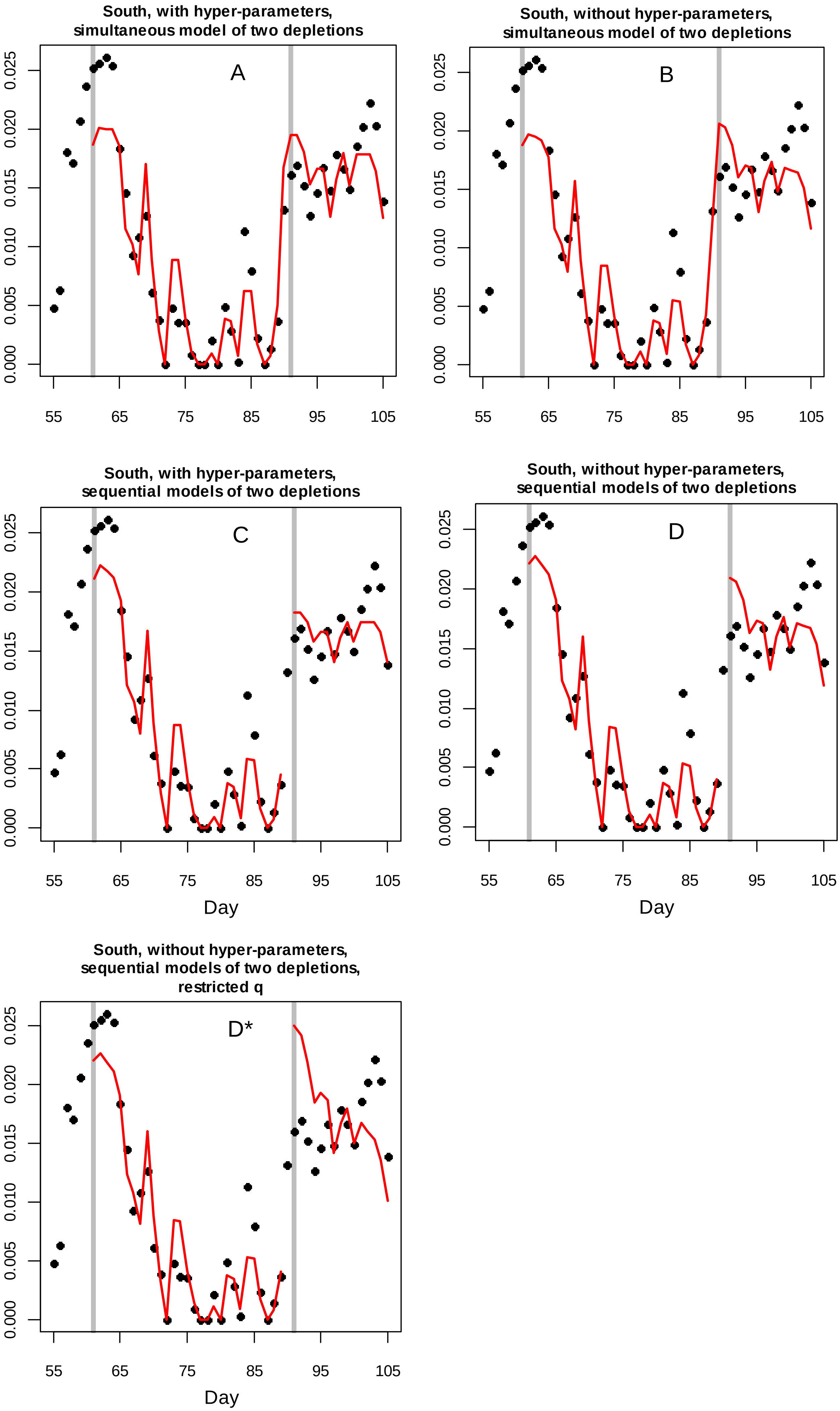
South, with hyper-parameters,
simultaneous model of two depletions
A
South, without hyper-parameters,
simultaneous model of two depletions
B
South, with hyper-parameters,
sequential models of two depletions
C
South, without hyper-parameters,
sequential models of two depletions
D
South, without hyper-parameters,
sequential models of two depletions,
restricted q
D*
0.000
0.005
0.010
0.015
0.020
0.025
55
65
75
85
95
105
Day

Table A1.1. Estimated numbers of *Loligo*, root mean square errors (RMSE) of actual catch vs. predicted catch numbers, and catchability coefficients and hyper-parameters of the different versions of the depletion model (versions B and D don't fit hyper-parameters; they are 1 by default). For versions C and D, separate values are given for the first and second depletion periods. Refer to Figures A1.2 and A1.3 for description of the model versions.

Sub-area	Model version	N (billions)		RMSE	catchability coefficient	Hyper-parameters	
		Start	End			Effort	Abundance
N	A	0.21	0.00	$1.89 \cdot 10^{-3}$	$1.42 \cdot 10^{-3}$	1.072	0.267
N	B	0.44	0.08	$1.51 \cdot 10^{-3}$	$2.62 \cdot 10^{-3}$	1	1
N	C	0.07	0.00	$0.66 \cdot 10^{-3}$	$1.85 \cdot 10^{-3}$	0.903	0.101
		0.23	0.02		$0.96 \cdot 10^{-3}$	1.148	0.157
N	D	0.24	0.16	$0.86 \cdot 10^{-3}$	$5.19 \cdot 10^{-3}$	1	1
		0.46	0.18		$2.91 \cdot 10^{-3}$	1	1
S	A	31.48	17.15	$2.16 \cdot 10^{-3}$	$0.63 \cdot 10^{-3}$	1.162	0.073
S	B	127.27	108.31	$2.31 \cdot 10^{-3}$	$0.01 \cdot 10^{-3}$	1	1
S	C	0.57	0.22	$1.85 \cdot 10^{-3}$	$1.36 \cdot 10^{-3}$	1.090	0.361
		0.55	0.24		$2.69 \cdot 10^{-3}$	0.693	$6.50 \cdot 10^{-9}$
S	D	1.19	0.65	$2.09 \cdot 10^{-3}$	$1.24 \cdot 10^{-3}$	1	1
		5846.65	4851.40		$0.02 \cdot 10^{-5}$	1	1
S	D*	1.19	0.65	$2.57 \cdot 10^{-3}$	$1.24 \cdot 10^{-3}$	1	1
		0.91	0.53		$1.74 \cdot 10^{-3}$	1	1

Appendix 2. Details of calculations.

(A2.1) Prior estimate for *Loligo* numbers at the start of the second depletion period north (day 76):

$$N_{N1\ prior\ day\ 76} = N_{N\ day\ 55} \times e^{-M\ (76-55)} - CNMD_{N2\ day\ 76}$$
$$= 0.269 \times 10^9 \times e^{-M\ (76-55)} - CNMD_{N2\ day\ 76}$$
$$= 0.118 \times 10^9$$
$$N_{N\ prior\ day\ 76} = N_{N1\ prior\ day\ 76} \times CPUE_{N\ day[76,\ 77,\ 78]} / CPUE_{N\ day[73,\ 74,\ 75]}$$
$$= N_{N1\ prior\ day\ 76} \times 49.06 / 35.39$$
$$= 0.164 \times 10^9$$

(A2.2) Prior estimate for *Loligo* numbers at the start of the second depletion period south (day 91):

$$N_{S1\ prior\ day\ 91} = N_{S\ day\ 55} \times e^{-M\ (91-55)} - CNMD_{S2\ day\ 91}$$
$$= 0.532 \times 10^9 \times e^{-M\ (91-55)} - CNMD_{S2\ day\ 91}$$
$$= 0.087 \times 10^9$$
$$N_{S\ prior\ day\ 91} = N_{S1\ prior\ day\ 91} \times CPUE_{S\ day[91,\ 92,\ 93]} / CPUE_{S\ day[88,\ 89,\ 90]}$$
$$= N_{S1\ prior\ day\ 91} \times 55.27 / 50.49$$
$$= 0.096 \times 10^9$$

(A2.3) Standard deviation of second depletion prior north:

$$CV_{N\ prior\ day\ 67} = 0.180 / 0.217 = 82.9\% \qquad \text{(equation } \mathbf{(9)}\text{)}$$
$$CV_{N\ CPUE\ ratio} = 16.3\%$$

$$N_{N\ depletion\ day\ 76\ to\ 105} = N_{N\ depletion\ day\ 76} \times e^{-M\ ((76\ to\ 105)-105)} - CNMD_{N2\ day\ 76\ to\ 105}$$
$$pred\ C_{n\ N\ day\ 76\ to\ 105} = q_{N\ deplet.\ day\ 76} \times effort_{N\ day\ 76\ to\ 105} \times N_{N\ depletion\ day\ 76\ to\ 105} \times e^{-M/2}$$

$$CV_{N\ depletion\ day\ 76\ to\ 105} = mean\left(\frac{\sqrt{\left(pred\ C_{n\ N\ day\ 76\ to\ 105} - observ\ C_{n\ N\ day\ 76\ to\ 105}\right)^2}}{observ\ C_{n\ N\ day\ 76\ to\ 105}}\right)$$
$$= 12.1\%$$
$$CV_{N\ prior\ day\ 76} = \sqrt{0.829^2 + 0.163^2 + 0.121^2} = 85.4\%$$
$$CV_{N\ min\ prior\ day\ 76} = 85.4\% \times N^{min}_{N\ prior\ day\ 76} / N_{N\ prior\ day\ 76} = 104.9\%$$
$$sd\ N^{min}_{N\ prior\ day\ 76} = N^{min}_{N\ prior\ day\ 76} \times 104.9\% = 0.211 \times 10^9$$

(A2.4) Standard deviation of second depletion prior south:

$$CV_{S\ prior\ day\ 61} = 0.140 / 0.403 = 34.8\% \qquad \text{(equation } \mathbf{(10)}\text{)}$$
$$CV_{S\ CPUE\ ratio} = 8.9\%$$

$$N_{S\ depletion\ day\ 91\ to\ 105} = N_{S\ depletion\ day\ 91} \times e^{-M\ ((91\ to\ 105)-105)} - CNMD_{S2\ day\ 91\ to\ 105}$$
$$pred\ C_{n\ S\ day\ 91\ to\ 105} = q_{S\ deplet.\ day\ 91} \times effort_{S\ day\ 91\ to\ 105} \times N_{S\ depletion\ day\ 91\ to\ 105} \times e^{-M/2}$$

$$CV_{S\ depletion\ day\ 91\ to\ 105} = \text{mean}\left(\frac{\sqrt{\left(\text{pred } C_{n\,S\,day\,91\,to\,105} - \text{observ } C_{n\,S\,day\,91\,to\,105}\right)^2}}{\text{observ } C_{n\,S\,day\,91\,to\,105}} \right)$$

$= 25.0\%$

$CV_{S\ prior\ day\ 91} = \sqrt{0.348^2 + 0.089^2 + 0.250^2} = 43.8\%$

$CV_{S\ min\ prior\ day\ 91} = 43.8\% \times N^{min}_{S\ prior\ day\ 91} / N_{S\ prior\ day\ 91} = 120.3\%$

$sd\ N^{min}_{S\ prior\ day\ 91} = N^{min}_{S\ prior\ day\ 91} \times 120.3\% = 0.316 \times 10^9$

(A2.5) Estimated immigration at the start of the second depletion period north, day 76.

$N_{N1\ day\ 76} = N_{N\ day\ 67} \times e^{-M\,(76-67)} - CNMD_{N1\ day\ 76}$
$= 0.138 \pm 0.072 \times 10^9$

Where 0.072×10^9 is equivalent to the coefficient of variation of the MCMC (gray bars, Fig. 6).

$N_{N2\ day\ 76} = 0.426 \pm 0.085 \times 10^9 - 0.138 \pm 0.072 \times 10^9$
$= 0.288 \pm \sqrt{.085^2 + .072^2} \times 10^9 = 0.288 \pm 0.095 \times 10^9$
$= 0.288 \pm 32.9\%$

$Wt_{N\ day\ 76} = 42.4 \pm 1.5\ g = 42.4\ g \pm 3.5\%$ (Figure 10, top)

$B_{N\ immigration\ day\ 76} = 0.288 \times 10^9 \pm 32.9\% \times 42.4 \pm 3.5\%$
$= 12{,}210$ tonnes $\pm \sqrt{0.329^2 + .035^2} = 12{,}210 \pm 33.1\%$
$= 12{,}210 \pm 4037$ tonnes

(A2.6) Estimated immigration at the start of the second depletion period south, day 91.

$N_{S1\ day\ 91} = N_{S\ day\ 61} \times e^{-M\,(91-61)} - CNMD_{S1\ day\ 91}$
$= 0.164 \pm 0.031 \times 10^9$

Where 0.097×10^9 is equivalent to the coefficient of variation of the MCMC (gray bars, Fig. 8).

$N_{S2\ day\ 91} = 0.747 \pm 0.097 \times 10^9 - 0.164 \pm 0.031 \times 10^9$
$= 0.583 \pm \sqrt{.097^2 + .031^2} \times 10^9 = 0.583 \pm 0.101 \times 10^9$
$= 0.583 \pm 17.4\%$

$Wt_{S\ day\ 91} = 52.0 \pm 2.1\ g = 52.0\ g \pm 4.1\%$ (Figure 10, bottom)

$B_{S\ immigration\ day\ 91} = 0.583 \times 10^9 \pm 17.4\% \times 52.0 \pm 4.1\%$
$= 30{,}319$ tonnes $\pm \sqrt{0.174^2 + .041^2} = 30{,}319 \pm 17.9\%$
$= 30{,}319 \pm 5415$ tonnes

(A2.7) Estimated total biomass (initial + immigration) that passed through the Loligo Box fishery zone in the first season of 2012:

$Wt_{N\ day\ 67} = 38.0 \pm 1.9\ g = 38.0\ g \pm 5.0\%$

$Wt_{S\ day\ 61}$ = 36.3 ± 2.2 g = 36.3 g $\pm 6.1\%$

$N_{N\ day\ 67}$ = $0.239 \pm 0.072 \times 10^9 = 0.239 \pm 30.3\%$

$N_{S\ day\ 61}$ = $0.518 \pm 0.097 \times 10^9 = 0.518 \pm 18.7\%$

$B_{N\ day\ 67}$ = $Wt_{N\ day\ 67} \times N_{N\ day\ 67}$

$= 38.0\text{ g} \pm 5.0\% \times 0.239 \pm 30.3\% = 9057 \pm \sqrt{0.303^2 + .050^2}$

$= 9057 \pm 30.7\%$

$B_{S\ day\ 61}$ = $Wt_{S\ day\ 61} \times N_{N\ day\ 61}$

$= 36.3\text{ g} \pm 6.1\% \times .518 \pm 18.7\% = 18795 \pm \sqrt{0.187^2 + .061^2}$

$= 18{,}795 \pm 19.7\%$

$B_{N\ day\ 67} + B_{S\ day\ 61} + B_{N\ immigration\ day\ 76} + B_{S\ immigration\ day\ 91}$

$= 9057 + 18{,}795 + 12{,}210 + 30{,}319$

$\pm \sqrt{0.307^2 + 0.197^2 + 0.331^2 + 0.179^2}$

$= 70{,}381 \pm 52.4\% = 70{,}381 \pm 36{,}857$ tonnes