Falkland Island Fisheries Department

Loligo gahi Stock Assessment, Second Season 2011

Andreas Winter

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Index

Summary

1) The second season *Loligo* fishery of 2011 was open for 70 days, from July 15 to September 22. 18,725 tonnes of *Loligo* catch were reported; only about half as much as the second season 2010 but higher than second season 2009. 26.5% of *Loligo* catch and 33.7% 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 July 20 and August 7. In the south sub-area, two depletion periods were inferred to have started on July 15 and July 24.
3) An estimated combined total (initial stock + in-season immigration) of 62,565 ± 21,238 tonnes *Loligo* passed through the fishing zone during second season 2011, giving a catch rate of 29.9% ± [22.3%, 45.3%].
4) The final total estimate for *Loligo* remaining in the Loligo Box at the end of the season was:
   Maximum likelihood of 15,209 tonnes, with 95% confidence interval of [4,970 to 43,673] tonnes.
   The risk of *Loligo* escapement biomass at the end of the season being less than 10,000 tonnes was estimated at 26.2%.
5) The season was characterized by a high difference between the pre-season survey estimate and in-season catch rates. As a result, model estimates for *Loligo* biomass reflect a relatively high uncertainty.

Introduction

The second season of the 2011 *Loligo gahi* squid fishery started on July 15, and ended by emergency closure on September 22. Total reported *Loligo* catch by X-licensed vessels was 18,725 tonnes, the third-lowest for a second season since 2004 (Table 1). By contrast, the pre-season survey had taken the highest *Loligo* catch and recorded the second-highest biomass estimate since 2006 (Winter et al., 2011b).

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

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), 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, 2010; 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 model is modified to account for this increment of abundance. For previous *Loligo* assessments (e.g., Winter, 2011) the modification was done by re-setting the depletion period to the starting date of the latest group arrival. For the current season, an updated model was implemented that combines multiple waves of arrival / depletion into a single algorithm ('CatDyn'; Roa-Ureta, 2011). A single algorithm has the advantage that it combines data from the entire season time series, and may therefore give a more accurate representation overall. A disadvantage is that individual depletion periods are fit less precisely, and better-resolved depletion periods within the time series may be penalized by having to 'share' the optimization of the model with more poorly resolved depletion periods. Shorter depletion periods within the time series may also be penalized by having less weight in the overall optimization of the model. The most important depletion period is always the final one, as this determines the escapement biomass at the end of the season. If the final depletion were relatively penalized, this would have to be taken into consideration in interpreting the model.

A further addition to the updated CatDyn model is the inclusion of 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:

$$C_{n\ day} = q \times E_{day} \times N_{day} \times e^{-M/2} \qquad \textbf{(1)}$$

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 (Arreguin-Sanchez, 1996) and M is the natural mortality. 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 CatDyn form of the catch equation is expressed as:

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

where α and β are respectively the effort and abundance hyper-parameters (Roa-Ureta, 2010). While adding nonlinear flexibility to the relationship, inclusion of these hyper-parameters may also have some disadvantage by increasing the data requirements for the model to optimize properly. For evaluation, the CatDyn model was therefore tested against the previously used approach of re-setting sequential depletions, and with or without hyper-parameters. The best approaches were applied to the catch-effort time series. Comparisons are further described in Appendix 1.

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:

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

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

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

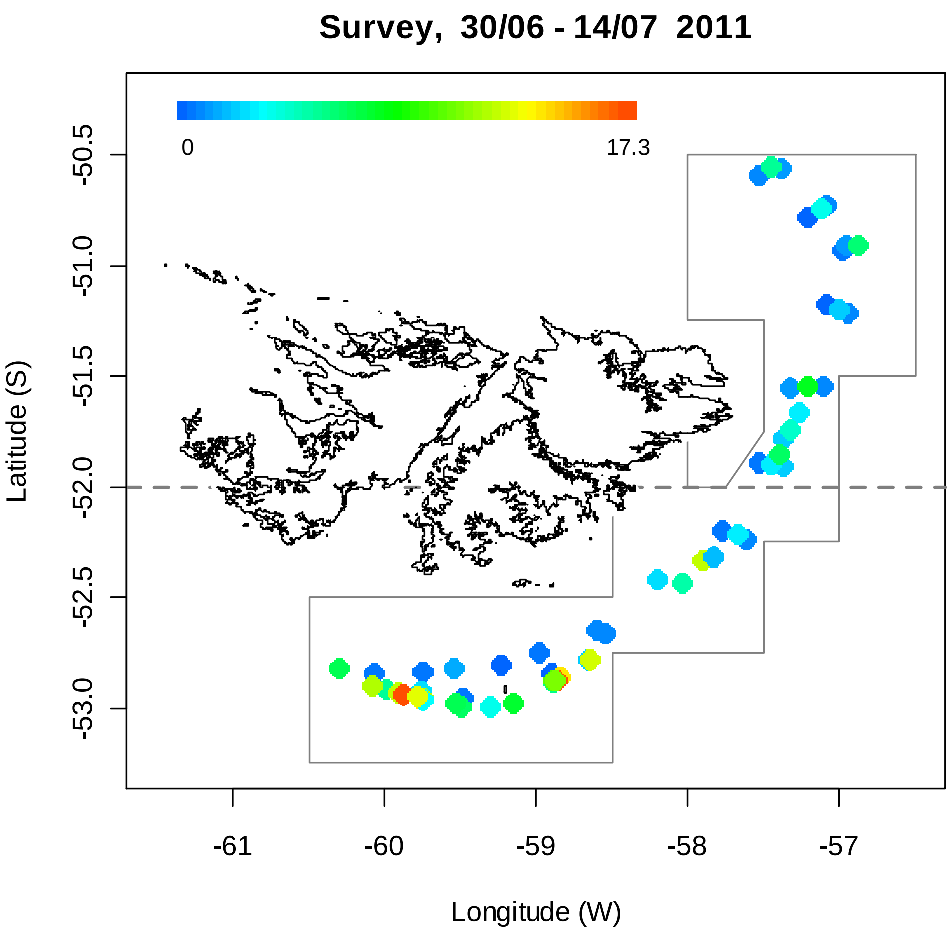
Bayesian optimization of the model was calculated by jointly minimizing equations **(3)** and **(4)**. Distributions of the stock likelihood estimates (i.e., measures of their statistical uncertainty) were computed using a Markov Chain Monte Carlo (MCMC) (Gamerman and Lopes, 2006). MCMC is an iterative 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.

Stock assessment
Data

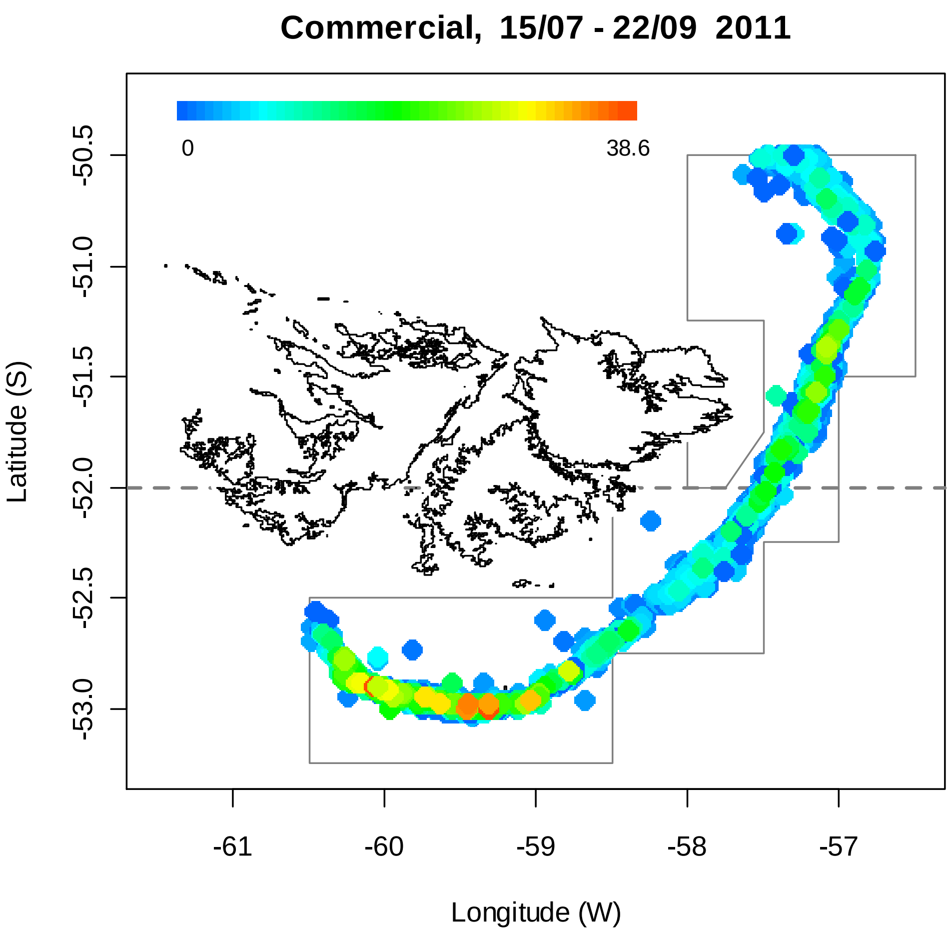
The 2011 second pre-season survey had caught 276 tonnes *Loligo* in the fishing area, with highest catches concentrated south in the Loligo Box (Winter et al., 2011; Figure 1). Commercial catches in-season showed a similar distribution of catch concentrations (Figure 2). Latitude 52 ºS was again used as a nominal boundary between north (North-Central) and south (Beauchêne) assessment sub-areas. Over the season, 26.5% of *Loligo* catch and 33.7% of effort (vessel-days) were taken north of 52 ºS, vs. 73.5% of catch and 66.3% of effort south of 52 ºS. This represents a significant reversal from last year, when 71.7% of catch and 69.4% of effort were taken north of 52 ºS during 2nd season (Winter, 2010). Effort preponderance switched 20× between north and south over the course of the season (Figure 3). Six days had ≥75% of the fleet fishing north, while 30 days had ≥75% of the fleet fishing south.

Figure 1 [next page]. Spatial distribution of *Loligo* 2nd-season pre-season survey catches, scaled to catch weight (maximum = 17.3 tonnes). Fifty-nine catches are represented. The 'Loligo Box' fishing zone, as well as the 52 ºS parallel delineating the nominal boundary between north and south assessment areas, are shown in gray.

Figure 2 [next page]. Spatial distribution of *Loligo* 2nd-season commercial catches, scaled to catch weight (maximum = 38.6 tonnes). 3502 catches were taken during the season. Map layout as in Figure 1.

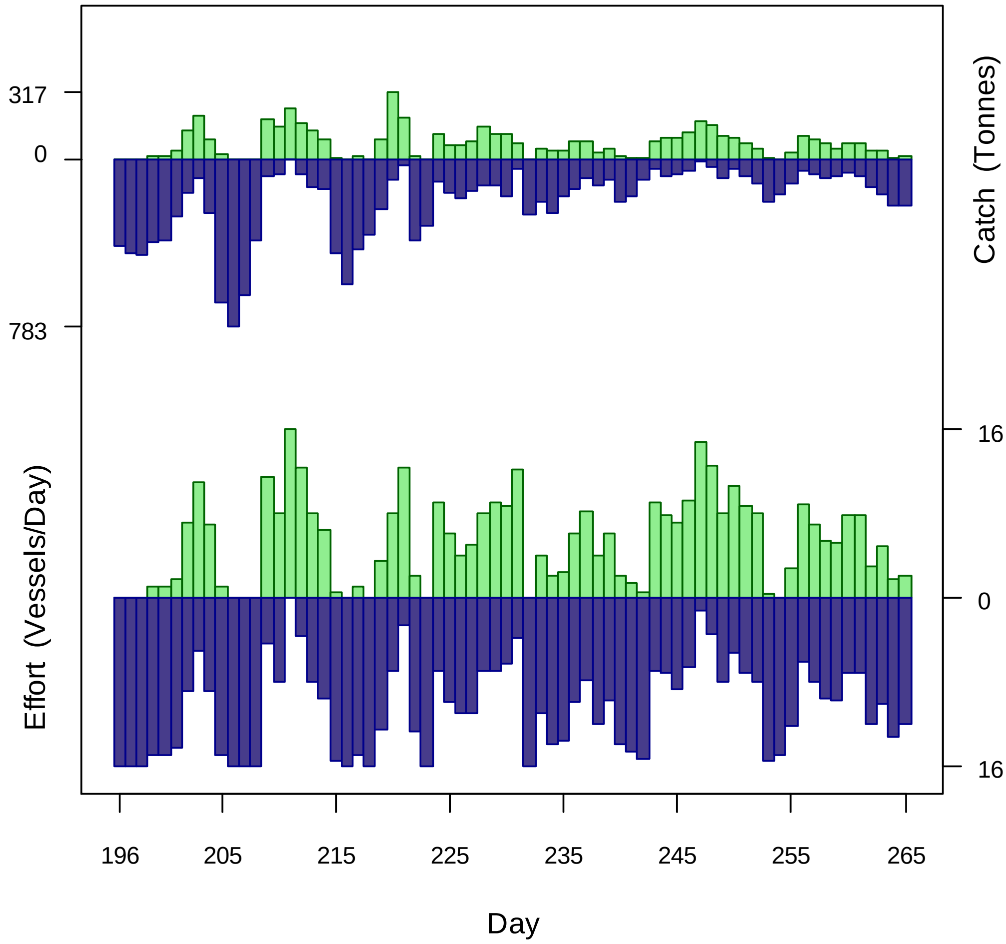


Survey, 30/06 - 14/07 2011
0
17.3
Latitude (S)
-50.5
-51.0
-51.5
-52.0
-52.5
-53.0
-61
-60
-59
-58
-57
Longitude (W)



Commercial, 15/07 - 22/09 2011
0
38.6
Latitude (S)
-50.5
-51.0
-51.5
-52.0
-52.5
-53.0
-61
-60
-59
-58
-57
Longitude (W)

Figure 3 [below]. Daily total *Loligo* catch and effort distribution by assessment sub-area north (green) and south (purple) of the 52º S parallel in the *Loligo* 2nd season 2011. The season was opened from July 15 (chronological day 196) to September 22 (chronological day 265). 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 317 tonnes *Loligo* were caught per day north of 52º S; as much as 783 tonnes *Loligo* were caught per day south of 52º S.



Between 14 and 16 vessels fished in the commercial season on any day (Figure 3), for a total of 1099 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.

Four FIFD observers were deployed on four vessels in the fishery for a total of 90 observer-days. Throughout the 70 days of the season, 50 days had one observer covering, and 20 days had two observers covering (not counting a short period during which two observers were deployed together on the same vessel, to train the new observer). 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., 2011b):

$$\text{weight (kg)} = 0.19990 \times length\ (cm)^{2.15469} / 1000 \qquad \textbf{(5)}$$

For the daily average individual sizes, mantle lengths were obtained from in-season observer data, and also derived from in-season commercial data as the proportion of product weight that vessels reported per market size category (Payá, 2006). 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

With the movement of the fishing fleet throughout the season, both sub-areas north and south of 52ºS had sufficiently regular effort to be depletion-modelled separately, as in most seasons. The *Loligo* data and CPUE time series showed two days in the north and two days in the south that plausibly represent the onset of separate depletions (Figures 4 and 5).

- The first depletion period north was identified on day 201 (20 July), after a strong increase in CPUE (Figure 5) and coincident with a peak in average commercial weight (Figure 4, middle). (Observer weight samples were not available in the north at that time).
- The second depletion period north was identified on day 219 (7 August), with a sharp increase in CPUE following a declining trend over 10-11 previous days (Figure 5). On the same day average commercial weights and average male observer weights increased following several days of declining trends, and the proportion of females in observer samples decreased strongly (Figure 4).
- The first depletion period south was identified on day 196 (15 July); the first day of the season, with a 'build-up' over 3 days followed by 5 days of decreasing CPUE (Figure 5).
- The second depletion period south was identified on day 205 (24 July), the second of two days with sharply increasing CPUE (Figure 5), and the day that average commercial weights and average male observer weights stabilized from 3 days of consecutive decrease (Figure 4).

Discontinuities in average weights, proportion of females, and CPUE suggest a further depletion period may have started on day 212 (31 July) in the south (Figures 4 and 5). However, around this date fishing effort in the south was too low to make the interpretation reliable (Figure 3).

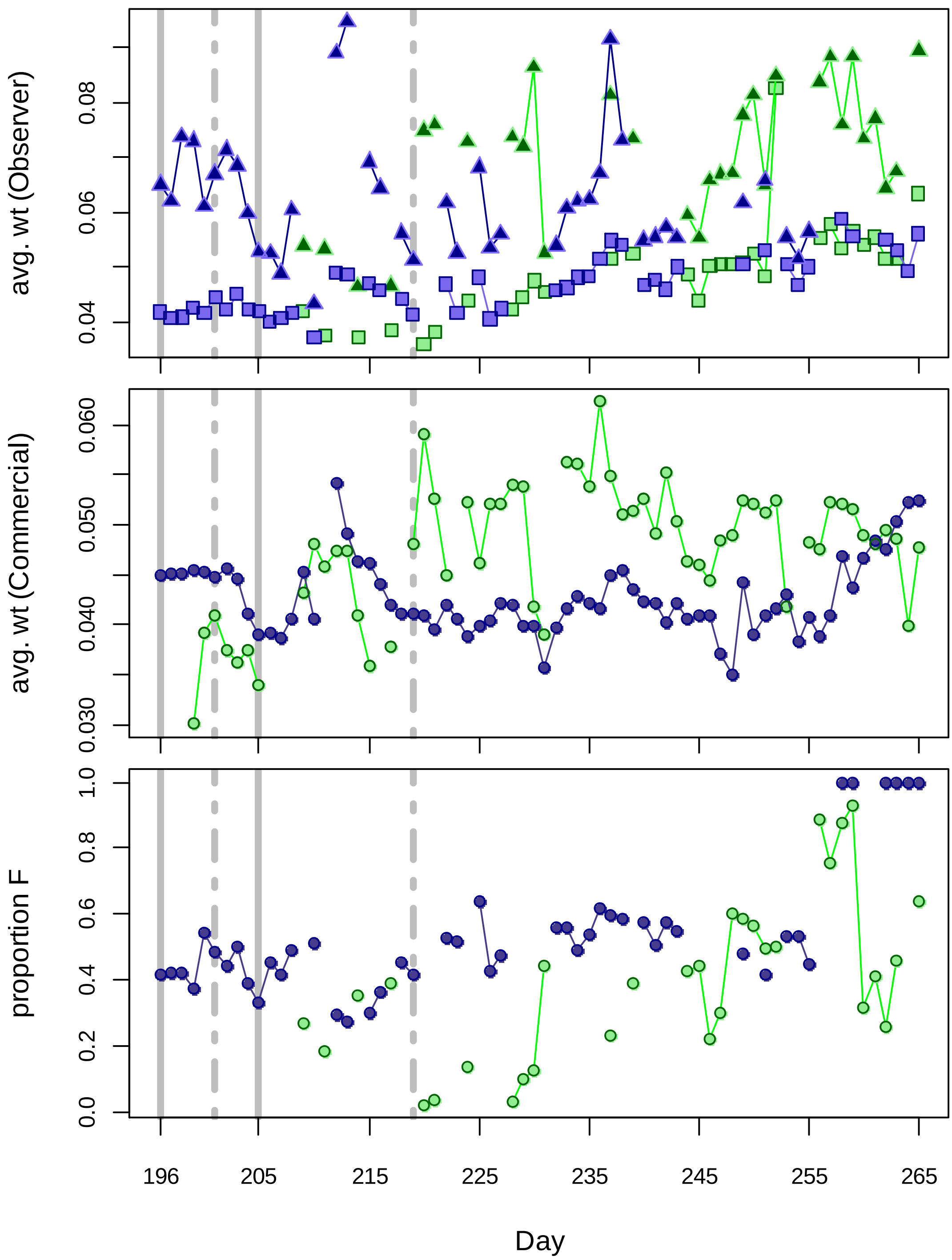
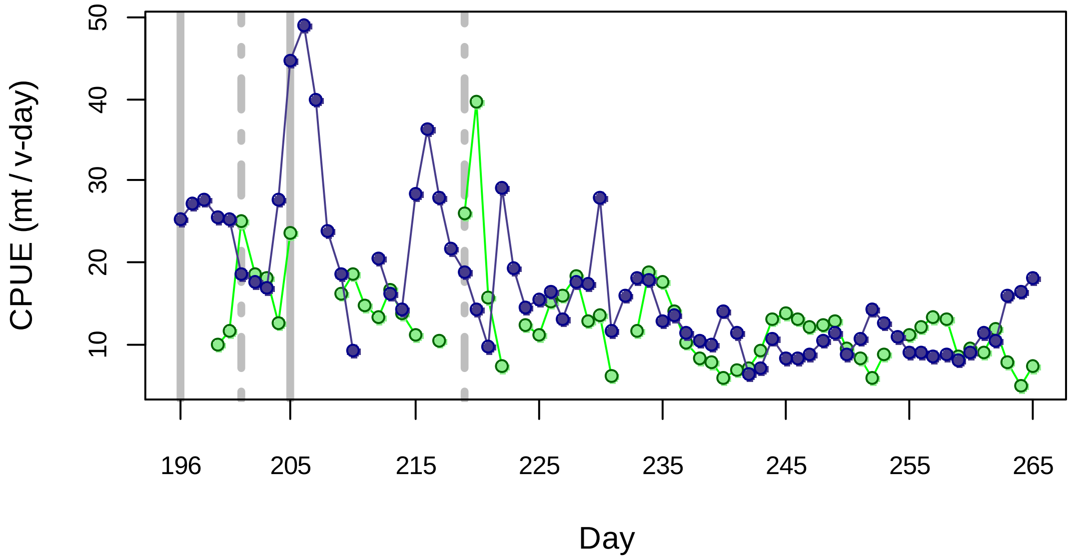


Figure 4. Top: Average individual *Loligo* weights (kg) by sex per day from observer sampling. Males: triangles, females: squares. Middle: Average individual *Loligo* weights (kg) per day from commercial size categories. Bottom: Proportions of female *Loligo* per day from observer sampling. North sub-area: 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 onset of depletions north: days 201 and 219. Solid gray vertical bars indicate days that were identified as the onset of depletions south: days 196 and 205.

Figure 5 [next page]. CPUE in metric tonnes per vessel per day, by assessment sub-area north (green) and south (purple) of the 52º S parallel. Plot symbols and colours as in Figure 4.



Depletion model and priors

The formulation of the Bayesian assessment model has been described previously (e.g., Payá, 2010). For the second season 2011 assessment, probability density function of the prior, and log-likelihood of the depletions, were assumed to follow a Gaussian distribution. Because of the larger number of parameters estimated in the CatDyn depletion model (two depletion starts north and south, the catchability coefficient, and the two hyper-parameters; see equation **(2)**), the MCMC rejected nearly all iterations once a chain stabilized, and therefore multiple chains were initiated to generate likelihood distributions of the stock estimates. Chains were initiated with 1200 random uniform variations of the starting abundance and catchability coefficient estimates between >0× and 2× of their optimal values. Each of the 1200 chains were run for 30,000 iterations; the first 5,000 iterations were discarded as burn-in sections (initial phases over which the algorithm stabilizes), then every 500th iteration was retained, giving a total of 61,200 values for the likelihood distribution of each parameter.

The CatDyn depletion model was based on equation **(2)**, with the abundance N_{day} expanded to distinguish the arrival of the two groups of abundance N_1 and N_2:

$$N_{day} = N_{1day} \times e^{-M(day - start\ 1)} + D_2|_0^1 \times N_{2\ day} \times e^{-M(day - start\ 2)} - CNMD_{day} \quad \textbf{(7)}$$

where $D_2|_0^1$ is a dummy variable = 0 if ‘day’ is before the start of the second depletion, and = 1 if ‘day’ is on or after the start of the second depletion. CNMD is the cumulative catch in numbers discounted for the proportion that would have died naturally anyway by that day:

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

Natural mortality M is considered constant at 0.0133 day^{-1} (Roa-Ureta and Arkhipkin, 2007). C_n (catch total in numbers) is calculated as the daily reported *Loligo* catch tonnage divided by the day's average individual weight.

The pre-season survey estimate for total *Loligo* biomass had been calculated at 51,562 tonnes with a 95% confidence interval of [30,092 to 82075] (Winter et al., 2011b), corresponding to a standard deviation of ±15,334 tonnes. From acoustic data analyses, Payá (2010) and Winter (2010) estimated a net escapement of up to 22%, which was added to the standard deviation:

$$51{,}562 \pm \left(\frac{15{,}334}{51{,}562} + .220 \right) \; = \; 51{,}562 \; \pm \; 51.7\% \; = \; 51{,}562 \; \pm \; 26{,}678 \text{ tonnes.} \qquad \textbf{(9)}$$

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., 2011b).

Loligo were sampled at 58 pre-season survey stations, giving a weighted-average[1] mantle length (both sexes) of 12.45 cm. This corresponds to 0.046 kg average individual weight (equation 1). 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 39.0%, and taking the average standard deviation of the length-weight relationship (equations **(A2.1)** in Appendix 2), which gave a coefficient of variation of 29.8%. The cubic interpolation used for estimating spatial distribution in this survey (Winter et al., 2011b) has no intrinsic error (unlike the geostatistical model used in other surveys, e.g., Winter et al., 2011a), but likely contributed to the relatively high variation of the length-frequency re-sampling. Combining all sources of variation with the pre-season survey biomass estimate and average individual weight thus gave estimated *Loligo* numbers, at the survey end / season start (July 15; day 196) of:

$$N_{\text{day }196} = \frac{51{,}562 \times 1000}{0.046} \pm \sqrt{51.7\%^2 + 39.0\%^2 + 29.8\%^2}$$

$$= 1.126 \times 10^9 \pm 71.3\% = 1.126 \times 10^9 \pm 0.803 \times 10^9 \qquad \textbf{(10)}$$

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

$$N_{N \text{ day } 196} = 0.193 \times 10^9 \pm 0.128 \times 10^9 \qquad \textbf{(10N)}$$

$$N_{S \text{ day } 196} = 0.933 \times 10^9 \pm 0.790 \times 10^9 \qquad \textbf{(10S)}$$

For the first depletion period south starting on day 196, $N_{S \text{ day } 196}$ could be used directly as the prior. For the first depletion north that did not start until five days later, the prior was discounted for catch and estimated natural mortality occurring during the intervening days:

$$N_{N1 \text{ prior day } 201} = N_{N \text{ day } 196} \times e^{-M\,(201-196)} - CNMD_{N \text{ day } 201} \qquad \textbf{(11)}$$

$$= 0.180 \times 10^9 \pm 0.119 \times 10^9$$

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

For the second depletion periods north and south, 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, 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 equation **(11)**. For the second depletion north starting on day 219 (details in equations **(A2.2)**, Appendix 2):

$$N_{N\ prior\ day\ 219} = N_{N2\ prior\ day\ 219} - N_{N1\ prior\ day\ 219} = 0.178 \times 10^9 \qquad \textbf{(12)}$$

For the second depletion south starting on day 205 (details in equations **(A2.3)**, Appendix 2):

$$N_{S\ prior\ day\ 205} = 1.657 \times 10^9 \qquad \textbf{(13)}$$

Error distributions of these N_N and N_S priors were calculated as the geometric sums of three components: the coefficient of variation of the first depletion period N prior (e.g., equation **(8)**), the 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 the coefficient of variation of the second N from the depletion model (e.g., equations **(2)** and **(7)**).

Depletion analyses

North

For the north sub-area, the complete CatDyn model (with hyper-parameters; simultaneous modelling of both depletion periods) was used. This model had the lowest root mean square error (Table A1.1) and showed a good fit between actual catch numbers and predicted catch numbers, with a slight trend of underestimating high catches near the end of the season (Figure A1.2-A).

The N likelihood distribution at the start of the first depletion period north (day 201) is shown in Figure 6. Maximum likelihood of the prior (red line) corresponds to equation **(11)** ($N_{N1\ prior\ day\ 201} = 0.180 \times 10^9$), while maximum likelihood of the depletion model occurred much higher at $N_{N\ depletion\ day\ 201} = 1.321 \times 10^9$ (blue line, but maximum out of range on Figure 6). The combined model maximum likelihood occurred at $N_{N\ day\ 201} = 0.208 \times 10^9$. The likelihood distribution surrounding this maximum was bimodal (gray bars on Figure 6), indicative that optimization of this depletion was very sensitive to the MCMC input values.

The N likelihood distribution at the start of the second depletion period north (day 219) is shown in Figure 7. This figure shows only the N *Loligo* estimated to have immigrated on day 219. The total N *Loligo* present on day 219 would be the sum of Figure 7 plus the N from the first immigration still alive by day 219. However, the total N likelihood distribution would require independently recombining the first and second depletion period likelihood distributions, which cannot be represented as a two-dimensional graph. Maximum likelihood of the prior for day 219 immigration corresponds to $N_{N\ prior\ day\ 219} = 0.178 \times 10^9$ (equations **(12)**; red line, but maximum out of range on Figure 7), while maximum likelihood of the depletion model occurred at $N_{N\ depletion\ day\ 219}$ = approx. zero (blue line, but maximum out of range on Figure 7).

The combined model maximum likelihood occurred at $N_{N\ day\ 219} = 0.046 \times 10^9$ (gray bars).

Figure 6 and especially Figure 7 include notably flat likelihood curves of the priors and depletion model (red and blue lines). Likelihood curves are calculated by ranging N_1 or N_2 and fixing all other parameters (N_2 or N_1, q, α, β) at their optimized values. With five parameters, changing the value of one parameter effects relatively little difference on the likelihood, and hence the curves are flat. This is more pronounced for the second depletion period because the second depletion period, being shorter, has less weight in the overall model. By comparison, the combined model likelihood distributions (gray bars) simultaneously vary all parameters and thus show much more selectivity with respect to N.

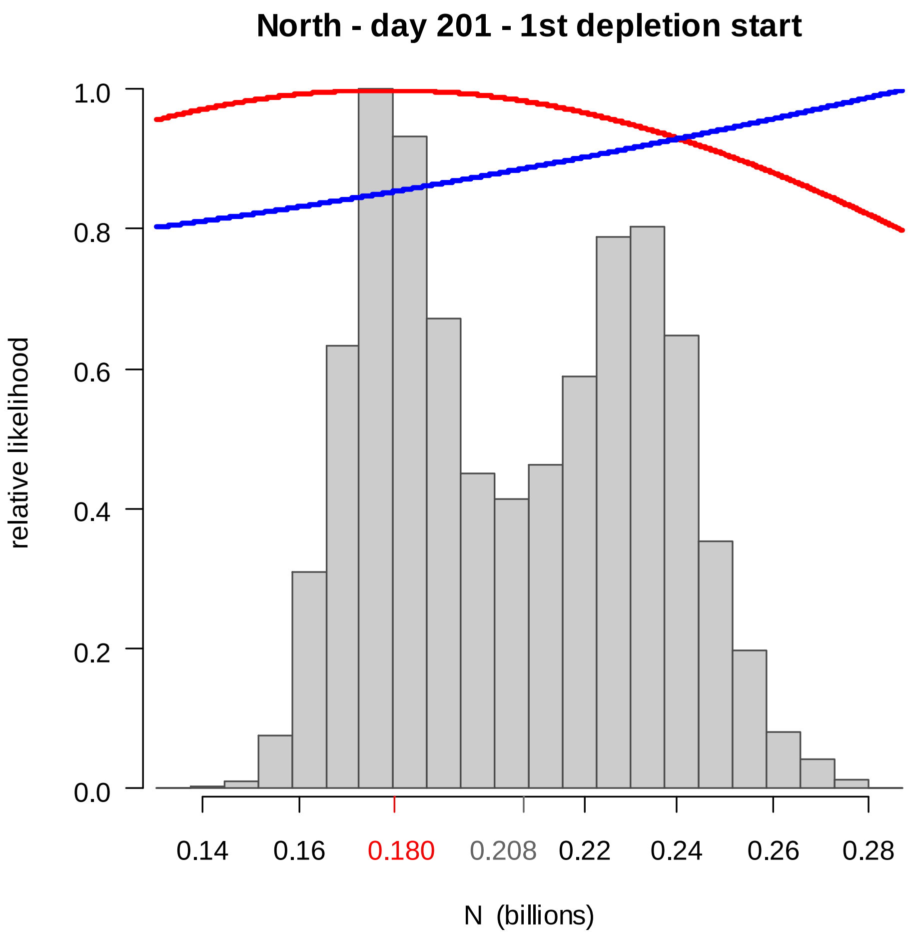
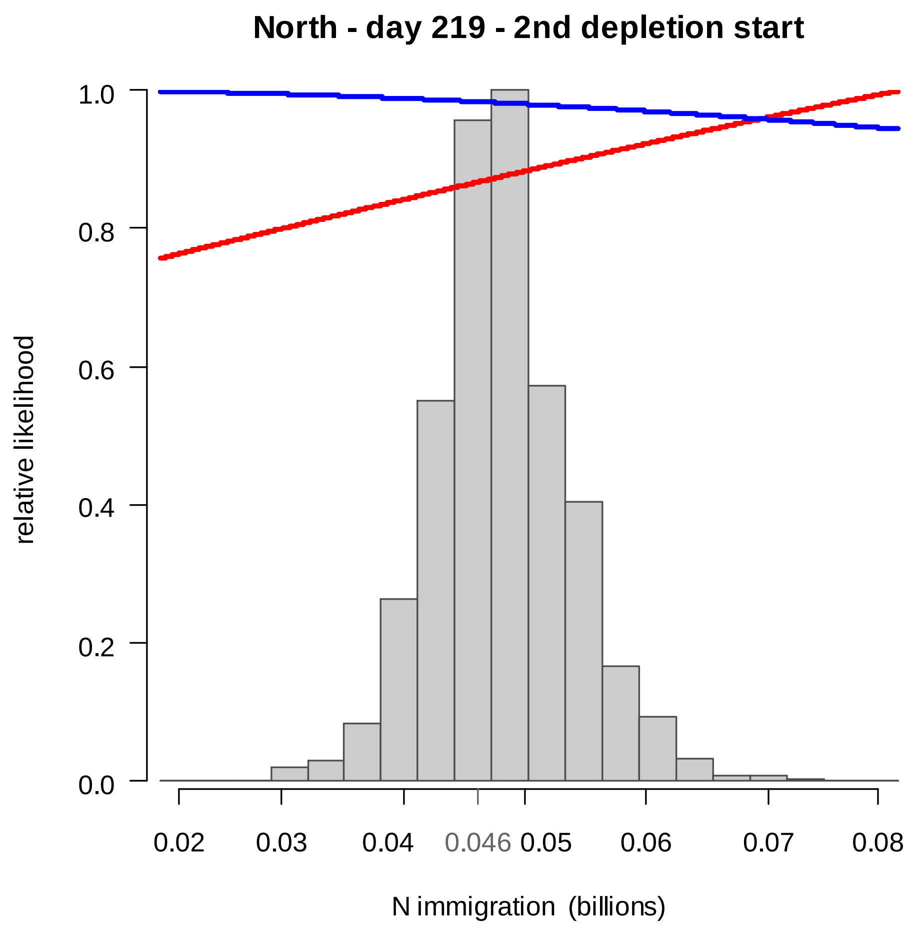


Figure 6. Likelihood distributions for N billion *Loligo* present in the north sub-area on day 201 (July 20). Red line: prior model (derived from pre-season survey data), blue line: depletion model, gray bars: combined model.

Figure 7 [next page]. Likelihood distributions for N billion *Loligo* having immigrated into the north sub-area on day 219 (August 7). Red line: prior model (derived from pre-season survey data), blue line: depletion model, gray bars: combined model.



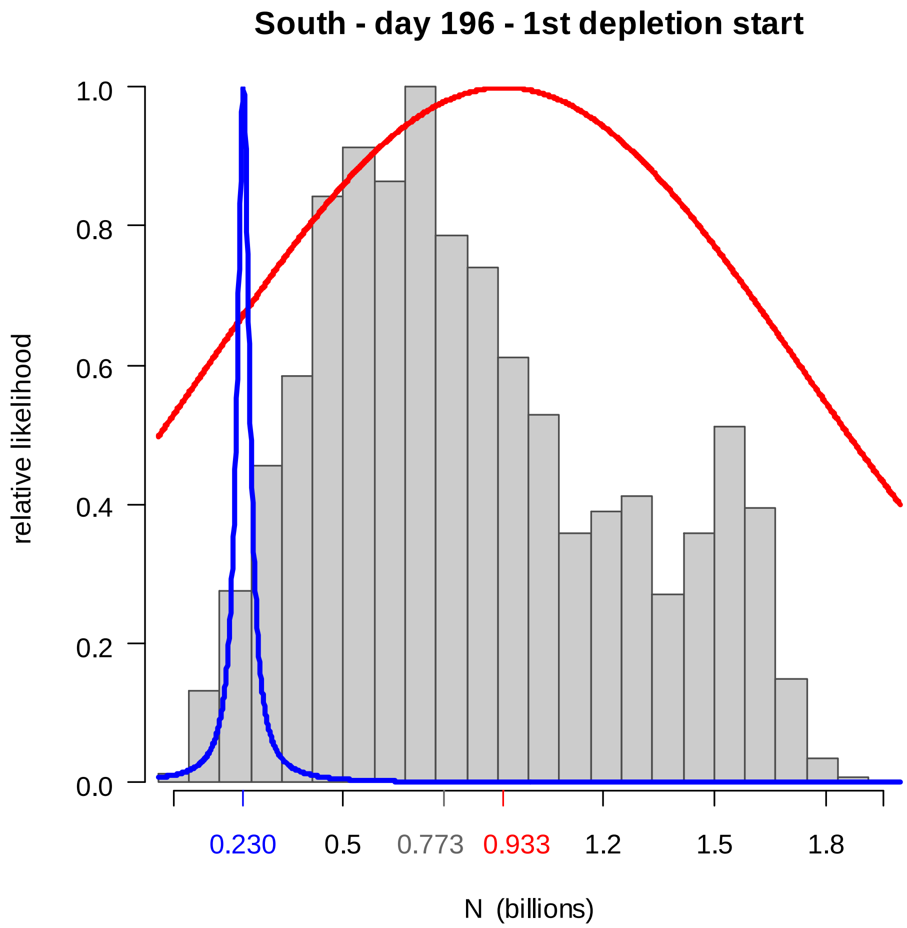
South

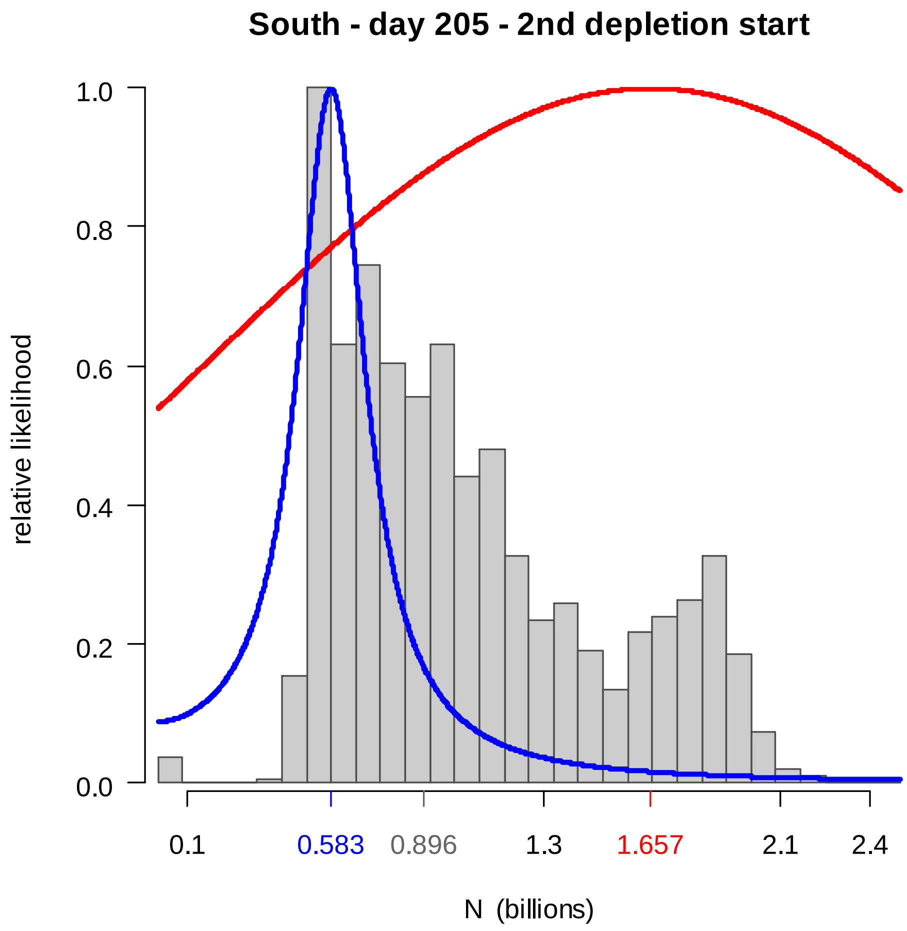
For the south sub-area, the CatDyn model showed consistent underestimation of catch from day 244 onwards (Figure A1.3-A). Sequential modelling of the two depletion periods without hyper-parameters better captured the variability over the end of the season (Figure A1.3-D), and was therefore used instead. Catchability (q) was realistically similar between the two depletion periods (Table A1.1: q = 2.48 and 1.45 $\times 10^{-3}$; less than 2× difference). However, even this model version did not fully reflect the catch increases over the final three days (Figure A1.2-D).

The N likelihood distribution at the start of the first depletion period south (day 196) is shown in Figure 8. Maximum likelihood of the prior (red line) corresponds to equation **(10S)** ($N_{S\ day\ 196} = 0.933 \times 10^9$), while maximum likelihood of the depletion model (blue line) occurred at $N_{S\ depletion\ day\ 196} = 0.230 \times 10^9$. The combined model maximum likelihood occurred at $N_{S\ day\ 196} = 0.773 \times 10^9$ (gray bars), and was thus more strongly determined by the prior than by the depletion model.

Figure 8 [next page]. Likelihood distributions for N billion *Loligo* present in the south sub-area on day 196 (July 15). Red line: prior model (derived from pre-season survey data), blue line: depletion model, gray bars: combined model.

Figure 9. Likelihood distributions for N billion *Loligo* present in the south sub-area on day 205 (July 24). Red line: prior model (derived from pre-season survey data), blue line: depletion model, gray bars: combined model.


South - day 196 - 1st depletion start
relative likelihood
1.0
0.8
0.6
0.4
0.2
0.0
0.230
0.5
0.773
0.933
1.2
1.5
1.8
N (billions)


South - day 205 - 2nd depletion start
relative likelihood
1.0
0.8
0.6
0.4
0.2
0.0
0.1
0.583
0.896
1.3
1.657
2.1
2.4
N (billions)

The N likelihood distribution at the start of the second depletion period south (day 205) is shown in Figure 9. Maximum likelihood of the prior (red line) corresponds to equation **(13)** ($N_{S\ prior\ day\ 205} = 1.657 \times 10^9$), while maximum likelihood of the depletion model (blue line) occurred at $N_{S\ depletion\ day\ 205} = 0.583 \times 10^9$. The combined model maximum likelihood occurred at $N_{S\ day\ 205} = 0.896 \times 10^9$ (gray bars). The distribution of MCMC outcomes again suggests a bimodal likelihood.

Escapement biomass

Escapement biomass was estimated from the number of *Loligo* in the fishing area at the scheduled end of the season (day 273; September 30) multiplied by the expected individual weight of *Loligo* on day 273. Calculations were made separately by north and south sub-areas, then summed.

Numbers of *Loligo* on day 273 were calculated according to the equivalent of equation **(11)**, starting with the maximum likelihoods of N:

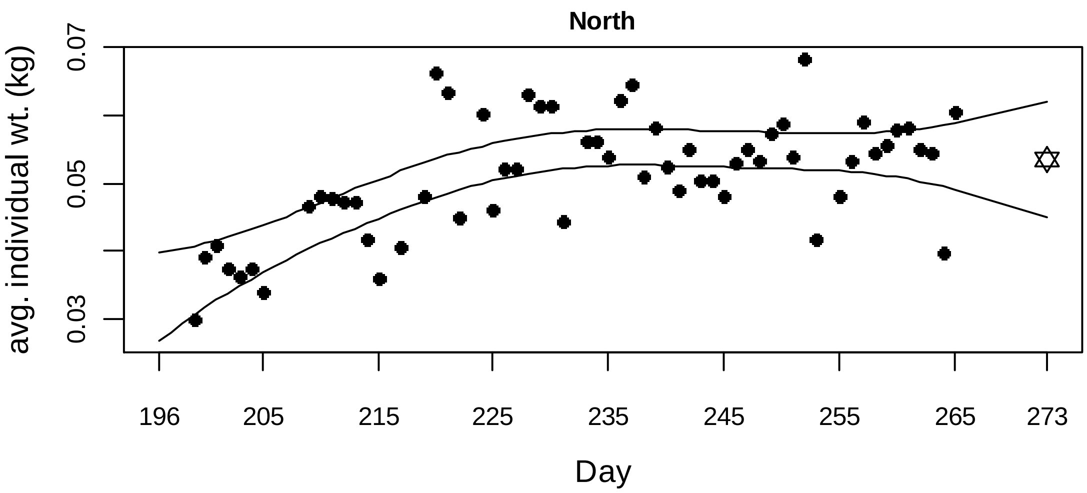
$$\begin{aligned} N_{N1\ day\ 273} &= N_{N\ day\ 201} \times e^{-M\ (273-201)} - CNMD_{N1\ day\ 273} \\ &= 0.208 \times 10^9 \times e^{-M\ (273-201)} - CNMD_{N1\ day\ 273} \\ &= 0.025 \times 10^9 \end{aligned} \quad \textbf{(14A)}$$

$$\begin{aligned} N_{N2\ day\ 273} &= N_{N\ day\ 219} \times e^{-M\ (273-219)} - CNMD_{N2\ day\ 273} \\ &= 0.046 \times 10^9 \times e^{-M\ (273-219)} - CNMD_{N2\ day\ 273} \\ &= 0.000 \times 10^9 \end{aligned} \quad \textbf{(14B)}$$

$$\begin{aligned} N_{S2\ day\ 273} &= N_{S\ day\ 205} \times e^{-M\ (273-205)} - CNMD_{S2\ day\ 273} \\ &= 0.896 \times 10^9 \times e^{-M\ (273-205)} - CNMD_{S2\ day\ 273} \\ &= 0.229 \times 10^9 \end{aligned} \quad \textbf{(14C)}$$

Both $N_{N1\ day\ 273}$ and $N_{N2\ day\ 273}$ are calculated because the simultaneous CatDyn model was used in the north, but only $N_{S2\ day\ 273}$ because the sequential model was used in the south (cf. Figure A1.1). Note that the maximum likelihood estimate of $N_{N2\ day\ 273}$ actually contributed zero to the end season total N (equation **(14B)**).

Expected individual weights of *Loligo* on day 273 were extrapolated from generalized additive models (GAM) of the daily average individual weights calculated throughout the season (day 196 to day 265). GAM plots are shown in Figure 10. The extrapolated weight was 53.5 ± 4.4 g in the north sub-area, and 60.7 ± 7.7 g in the south sub-area.



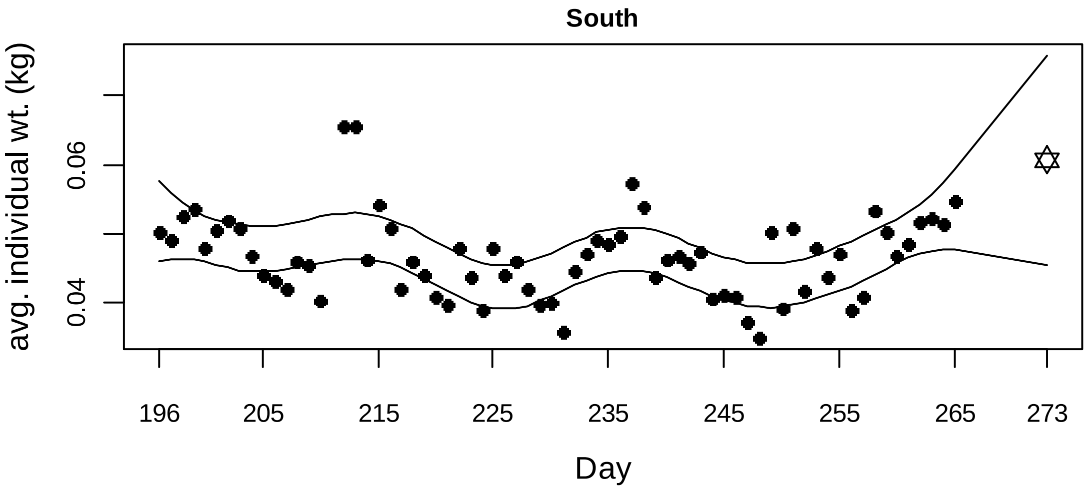


Figure 10. Daily average individual *Loligo* weights (black points) and 95% confidence intervals of GAMs (black lines) of seasonal variation in average individual weight. Extrapolations to the scheduled last day of the season (day 273) are shown as stars: 0.0535 kg in the north sub-area and 0.0607 kg in the south sub-area.

Likelihood distributions of the escapement biomass were calculated by substituting values from the MCMC likelihood distributions of N (gray bars in Figures 6, 7, and 9) – instead of the maximum likelihood values of $N_{N\ day\ 201}$, $N_{N\ day\ 219}$, $N_{S\ day\ 205}$ in equations **(14A, B, C)**; then substituting day 273 individual weight values drawn from a normal distribution with mean and standard deviation of the GAM extrapolations – instead of the GAM extrapolations, and multiplying them together. The substitutions and their multiplication were randomly iterated 306000× (5× the number of values retained from the MCMC), and these 306000 iterations, added together for the north and south sub-areas, represent the total escapement biomass distribution. This is shown in Figure 11. The 95% confidence interval of the total escapement biomass distribution was [4970, 43673] tonnes. Maximum likelihood of the total escapement biomass was:

$$(N_{N1\ day\ 273} + N_{N2\ day\ 273}) \times 53.5\ \text{g (north)} + N_{S2\ day\ 273} \times 60.7\ \text{g (south)} = 15209.3\ \text{t} \qquad \textbf{(15)}$$

The risk of the fishery, defined as the proportion of the escapement biomass distribution below the conservation limit of 10,000 tonnes (Barton, 2002), was found equal to 26.2% (Figure 11).

Immigration and catch rate

Loligo immigration (after the start of the season) was inferred as the difference between the 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. The immigration number was multiplied by the average individual weight from the GAM (above) to give biomass.

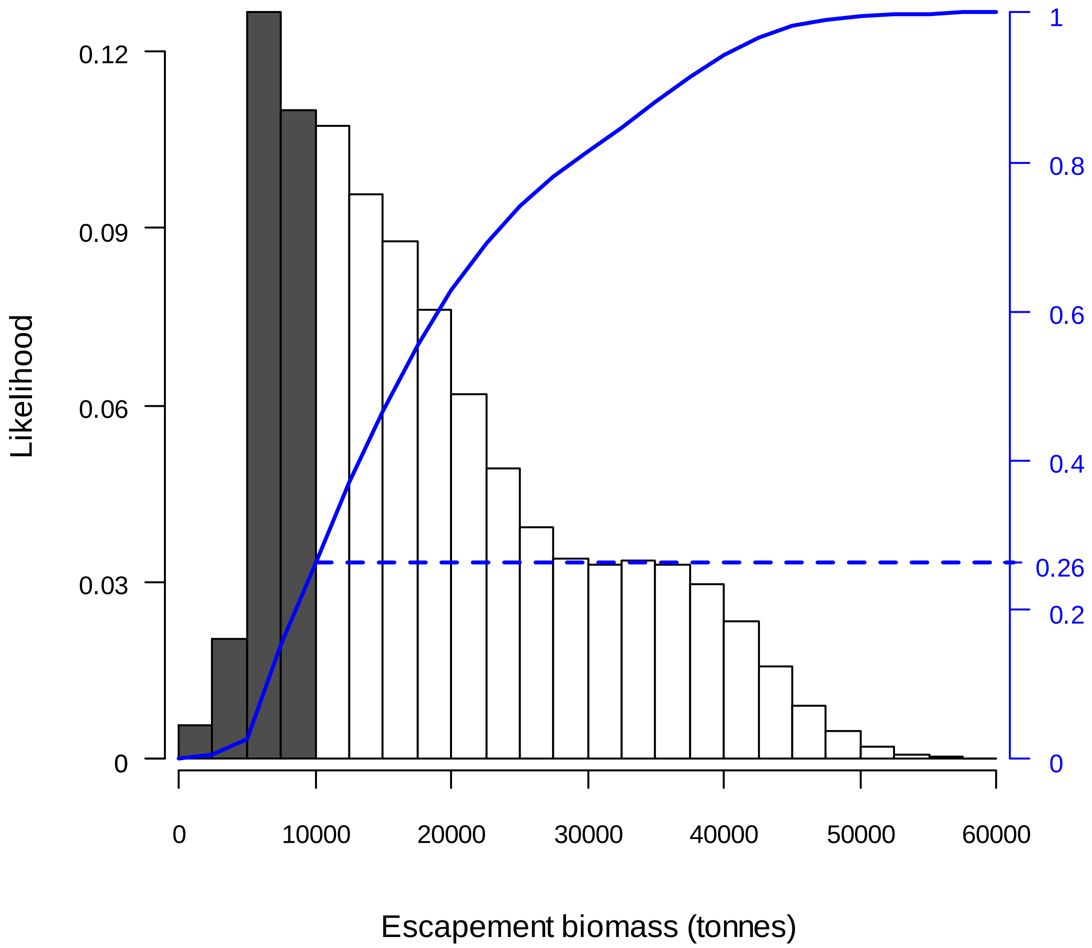


Figure 11. Probability distribution of *Loligo* biomass at the scheduled end of the season, September 30. Distribution samples less than the biomass escapement limit of 10,000 tonnes are shaded dark gray. Cumulative probability is shown as a solid blue curve. The broken blue line indicates that the probability of less than 10,000 tonnes escapement biomass was 26.2%.

For the second depletion north, on day 219, $N_{N\ day\ 219} = 0.046 \pm 0.006 \times 10^9$, where 0.006×10^9 (12.3%) is the standard deviation of the MCMC outcomes (gray bars on Figure 7). Avg. weight on day 219 was $Wt_{N\ day\ 219} = 50.2 \pm 1.5$ g (Figure 10, top). Multiplied together:

$$
\begin{aligned}
B_{N\ immigration\ day\ 219} &= N_{N\ day\ 219} \times Wt_{N\ day\ 219} \\
&= 0.046 \times 10^9 \pm 12.3\% \times 50.2 \pm 2.9\% \\
&= 2314 \pm \sqrt{.123^2 + .029^2} \quad = 2{,}314 \pm 293 \text{ tonnes} \qquad \textbf{(16)}
\end{aligned}
$$

For the second depletion south, on day 205, $N_{S\ day\ 205} = 0.896 \pm 0.445 \times 10^9$, where 0.445×10^9 is the standard deviation of the MCMC outcomes (gray bars on Figure 9). Because the depletion south was modelled sequentially, $N_{S\ day\ 205}$ includes the number of *Loligo* remaining from the first depletion, which must be subtracted (details of calculations in equations **(A2.4)**):

$$N_{S2\ day\ 205} = N_{S\ day\ 205} - N_{S1\ day\ 205} = 0.263 \pm 0.557 \times 10^9$$

$$B_{S\ immigration\ day\ 205} = N_{S2\ day\ 205} \times Wt_{S\ day\ 205} = 12{,}561 \pm 26{,}627 \text{ tonnes} \qquad \textbf{(17)}$$

The standard deviation is high because it includes both the uncertainty of how many *Loligo* were present, and the uncertainty of how many of the *Loligo* present were immigrants of the second depletion period.

The total estimated immigration biomass was:

$$_{immigration}B_{total} = 2{,}314 + 12{,}561 \pm \sqrt{293^2 + 26{,}627^2}$$

$$= 14{,}874 \pm 26{,}629 \text{ tonnes} \qquad \textbf{(18)}$$

The estimated total biomass (initial + immigration) to have passed through the Falkland Islands Loligo Box fishery zone in the second season of 2011 was (details of calculations in equations **(A2.5)**, Appendix 2):

$$B_{N\ day\ 201} + B_{S\ day\ 196} + B_{N\ immigration\ day\ 219} + B_{S\ immigration\ day\ 205}$$

$$= 62{,}565 \pm 21{,}238 \text{ tonnes} \qquad \textbf{(19)}$$

Giving a total catch rate of:

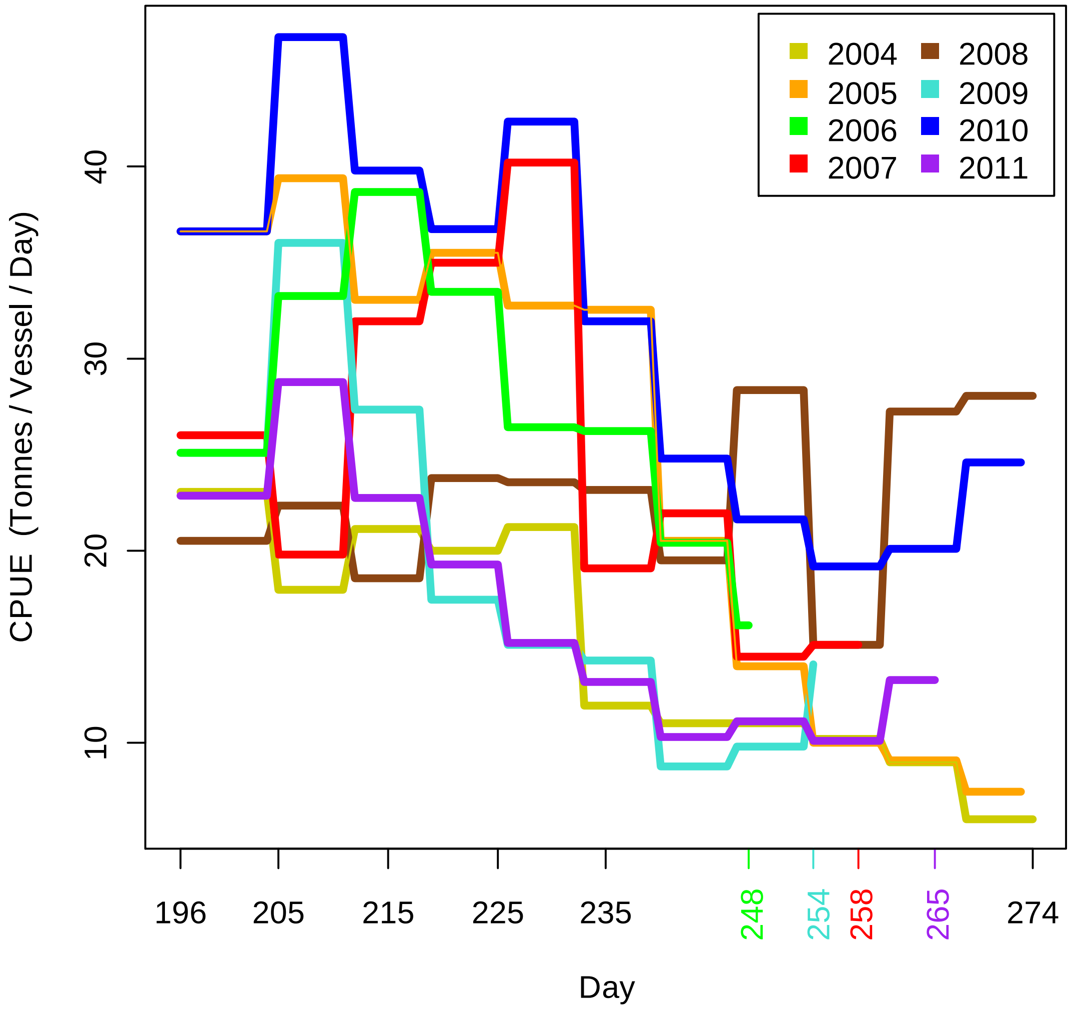
$$18{,}725 / (62{,}565 \pm 21{,}238) = 29.9\% \pm [22.3\%, 45.3\%] \qquad \textbf{(20)}$$

Fishery closure

The second *Loligo* season of 2011 was closed by emergency order at 23:59 on September 22, eight days ahead of scheduled season end. The closure decision was made during the week prior to September 22, and at this time CPUEs were among the lowest on record in the fishery.

For comparison, time series of total *Loligo* CPUE are plotted for all 2nd seasons since 2004, when the current seasonal schedule and stock assessment format were initiated (Anon. 2005). Of these eight 2nd seasons (Figure 12), four were open for scheduled duration (until September 30th; day 273 (day 274 in leap years)), and four were closed before schedule because of depletion risk in excess of conservation target: 2006 - closed Sept. 5 (day 248) (Payá, 2006), 2007 - closed Sept. 15 (day 258) (Payá, 2007), 2009 - closed Sept. 11 (day 254) (Payá, 2010), and 2011 - closed Sept. 22 (day 265). In the week prior to the 2011 closure (day 254 to day 260), the 2011 2nd season CPUE averaged 10.04 t / vessel / day, slightly more than the 2005 2nd season CPUE (10.00 t / vessel / day) and slightly less than the 2004 2nd season CPUE (10.24 t / vessel / day) (Figure 12). Both the 2004 and 2005 2nd seasons continued for scheduled duration. The low but consistent catch rates towards the end of the 2011 2nd season suggest that a dispersed low level of immigration, rather than an aggregated pulse, may have continued to enter the fishing zone. However, this is not conclusive from the available information.

Figure 12 [next page]. 2nd season time series of *Loligo* CPUE, 2004 to 2011, by 7-day block-averages. End dates are indicated for those seasons that were closed before schedule.



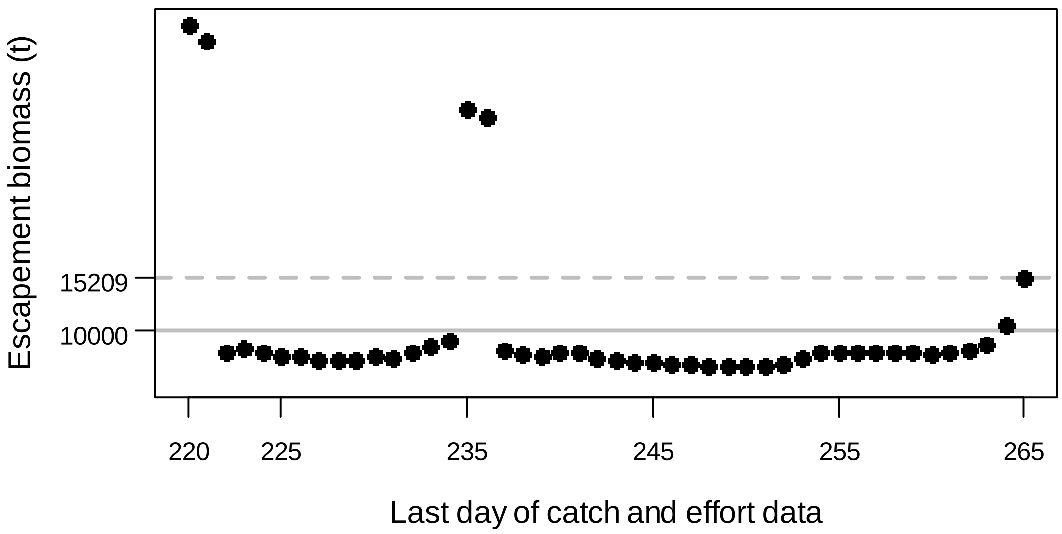


Figure 13. Retrospective analysis of the maximum likelihood estimate for *Loligo* escapement biomass with data up to days prior to the season end (day 265); starting with the day after the latest immigration on day 219. The two indications of very high estimates are spurious; up to days 220 and 221 there were (understandably) not yet enough data for a realistic estimate, up to days 235 and 236 the model destabilized.

Further, a retrospective analysis of depletion projection indicates that the maximum likelihood escapement biomass of 15,209 t (equation **(15)**) was attained only with inclusion of the very last day of catch and effort data (day 265) (Figure 13). Catch rates increased over the final four days of the season (Figures 4 and 12), and this increase constrained the model to assume a higher initial biomass. For data cut-offs between day 254 and day 263, the model projected near-constant escapement biomasses of just under 9,000 tonnes (Figure 13). This is lower than was estimated in-season, because the CatDyn model was not yet implemented in-season and the sequential model used instead had projected a higher biomass in the north sub-area. The low catch rates and lack of increase in escapement biomass projection motivated the decision to close the fishery.

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

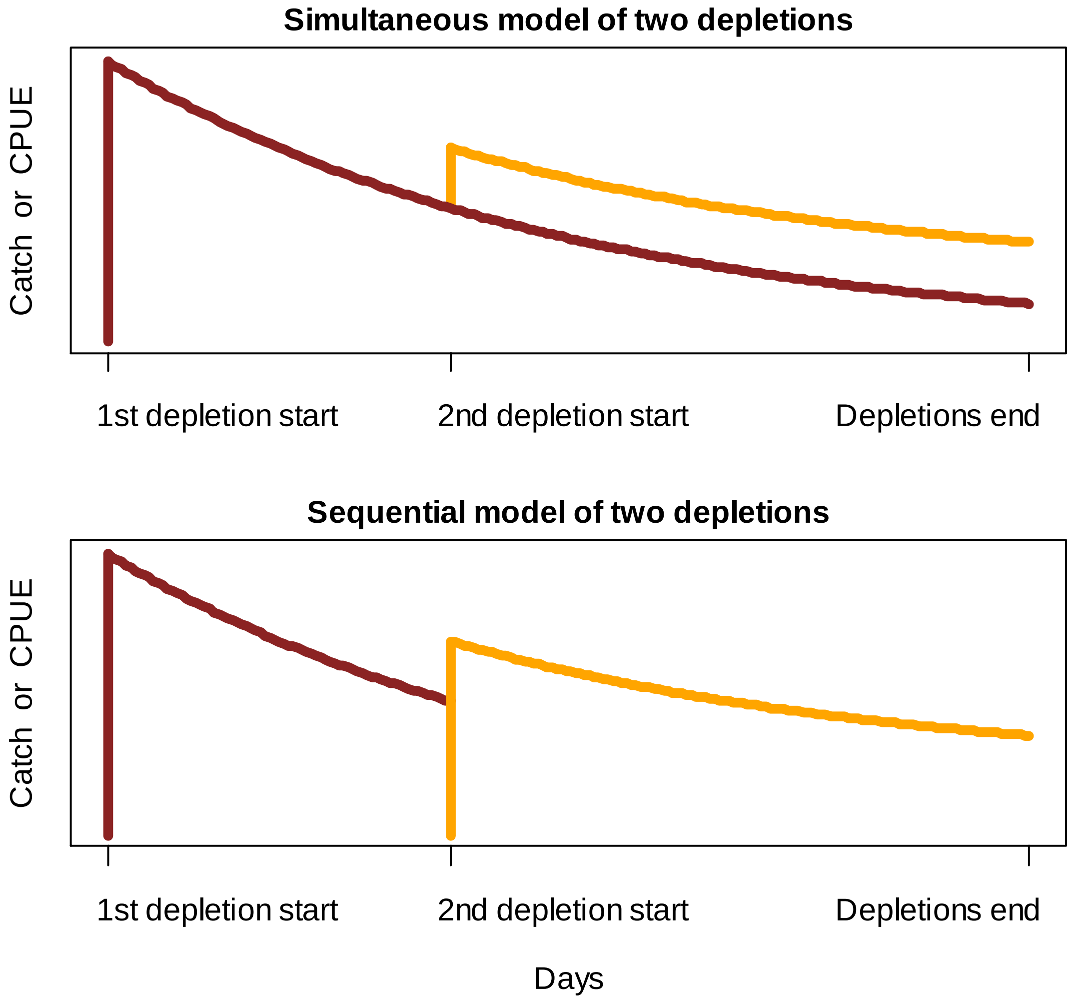

Figure A1.1. Schematic of the difference between simultaneous depletion modelling (as implemented by CatDyn) and sequential depletion modelling. In the simultaneous model numbers of *Loligo* from the two depletion curves must be added together on any day; in the sequential model the second depletion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

Table A1.1. Root mean square errors of actual catch vs. predicted catch numbers of different versions of the depletion model, and catchability coefficients of the models. For versions C and D, the two consecutive q numbers are the catchability coefficients of the first and second depletion. Refer to Figures A1.2 and A1.3 for description of the model versions.

Model version	North			South		
	RMSE	q		RMSE	q	
A	$0.45 \cdot 10^{-3}$	$0.46 \cdot 10^{-3}$		$1.30 \cdot 10^{-3}$	$0.09 \cdot 10^{-3}$	
B	$0.46 \cdot 10^{-3}$	$0.51 \cdot 10^{-3}$		$1.68 \cdot 10^{-3}$	$1.29 \cdot 10^{-3}$	
C	$0.43 \cdot 10^{-3}$	$5.28 \cdot 10^{-3}$	$0.95 \cdot 10^{-3}$	$1.28 \cdot 10^{-3}$	$0.59 \cdot 10^{-3}$	$0.12 \cdot 10^{-3}$
D	$0.45 \cdot 10^{-3}$	$5.11 \cdot 10^{-3}$	$0.22 \cdot 10^{-3}$	$1.43 \cdot 10^{-3}$	$2.48 \cdot 10^{-3}$	$1.45 \cdot 10^{-3}$

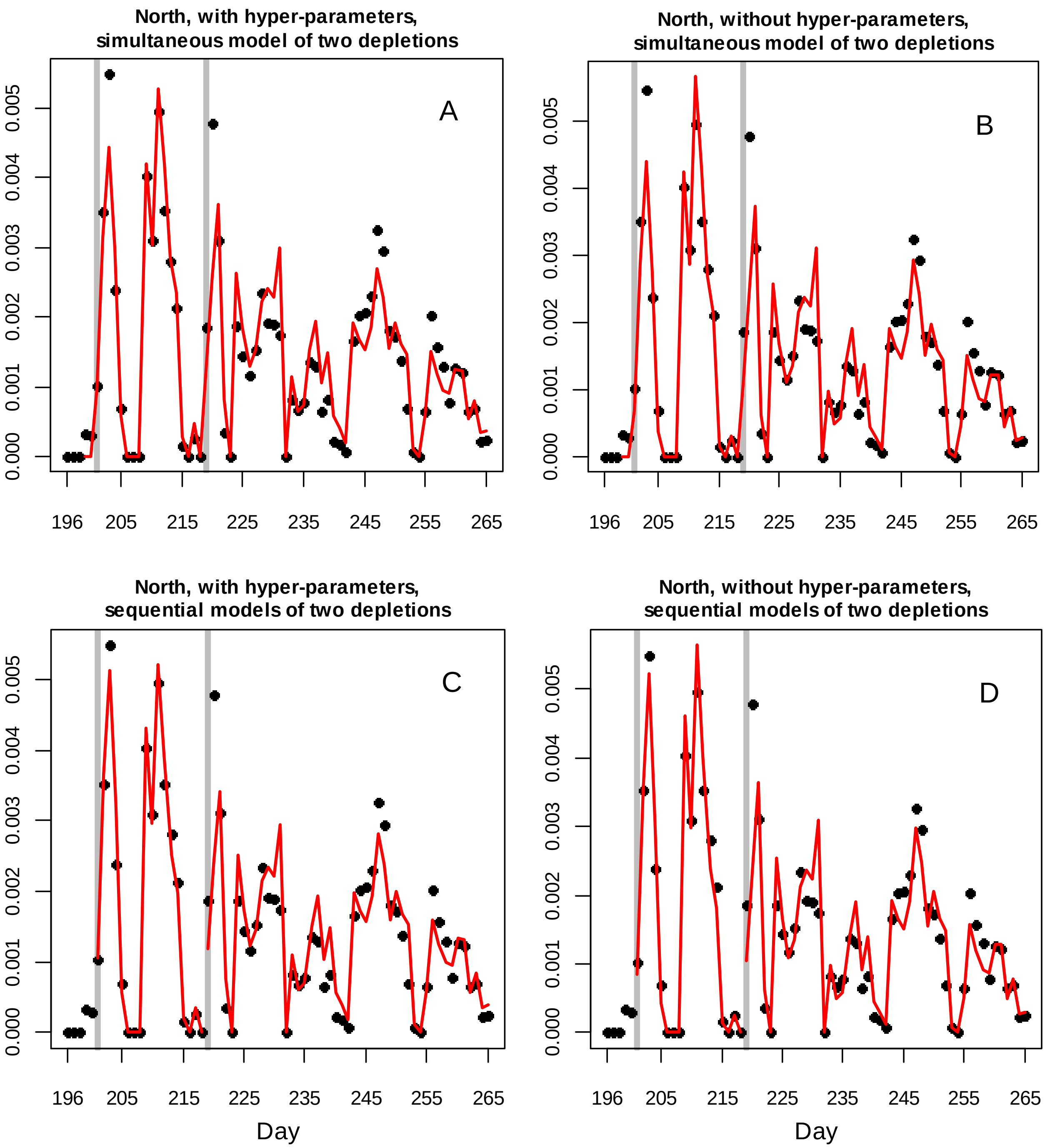

Figure A1.2. Daily estimated catch numbers (black points) and expected catch numbers (red lines) projected from the north sub-area depletion periods starting on days 201 and 219, under four versions of the depletion model.

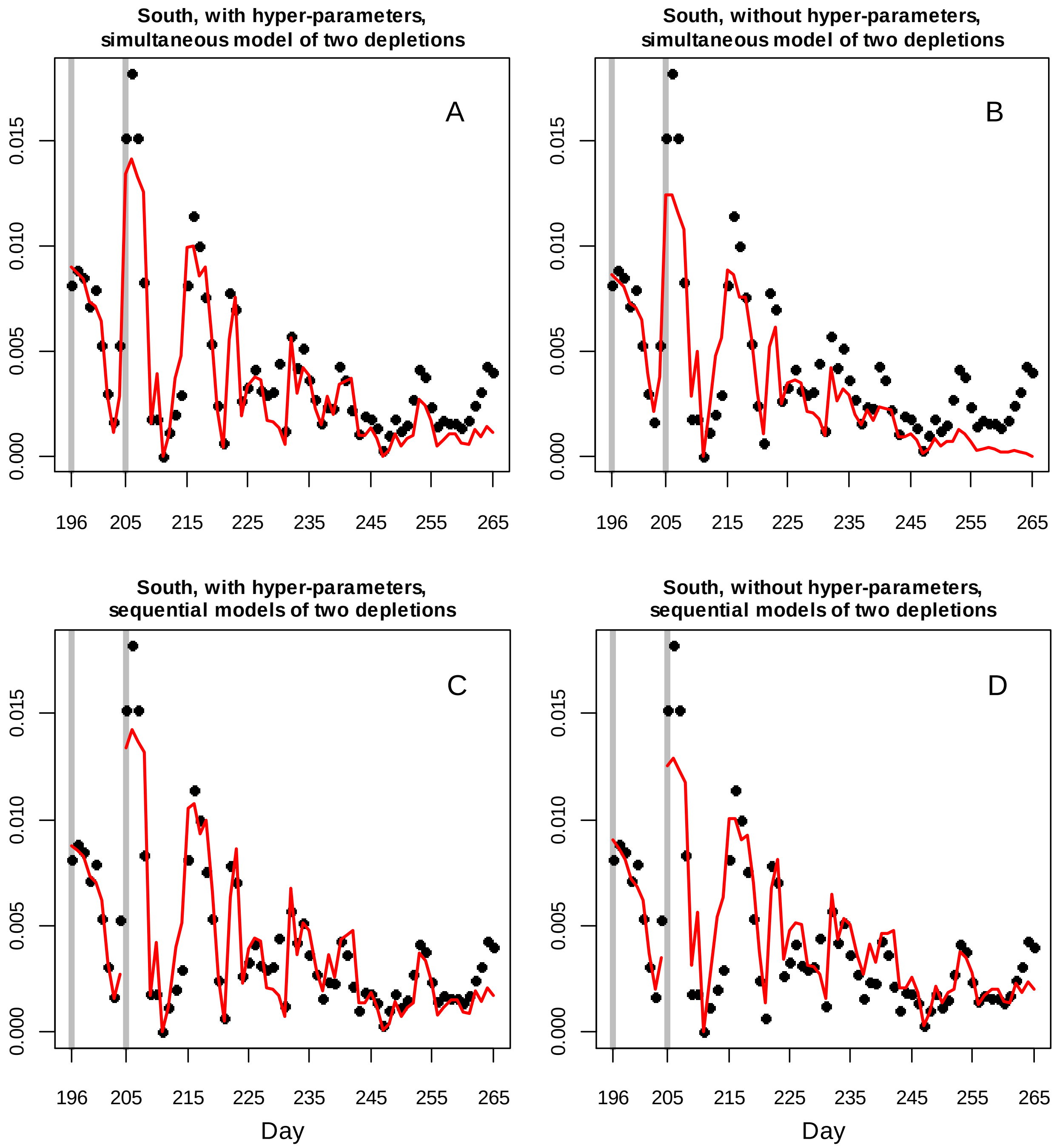

Figure A1.3. Daily estimated catch numbers (black points) and expected catch numbers (red lines) projected from the south sub-area depletion periods starting on days 196 and 205, under four versions of the depletion model.

Appendix 2. Details of calculations.

(A2.1) Standard deviations (SD) of the *Loligo* length-weight conversion estimated by Taylor series approximation derived from function MBWpDaypSam.Fk in Roa-Ureta (2011):

$$SD_{\text{weight / day}} = \left(\left(\frac{1}{\sum N_{i/day}} \right)^2 \times (x_1 + x_2 + x_3) \right)^{0.5} / 1000$$

$$x_1 = 2a \times \text{cov}_{a,b} \times \sum_{days} \left(\frac{a \times lengths_i^{\,b} \times N_{i/day}}{a} \right) \times \sum_{days} \left(\frac{\log(lengths_i) \times \left(a \times lengths_i^{\,b} \times N_{i/day}\right)}{a} \right)$$

$$x_2 = SD_a \times \left(\sum_{days} \left(\frac{a \times lengths_i^{\,b} \times N_{i/day}}{a} \right) \right)^2$$

$$x_3 = SD_b \times a \times \left(\sum_{days} \left(\frac{\log(lengths_i) \times \left(a \times lengths_i^{\,b} \times N_{i/day}\right)}{a} \right) \right)^2$$

where a is the linear parameter of the length-weight relationship (here; = 0.19990), b is the power parameter of the length-weight relationship (here; = 2.15469), $lengths_i$ are the *Loligo* mantle length measurement intervals (i = 4 to 30 cm by 0.5 cm) and $N_{i/day}$ are the number of *Loligo* measured per length interval per day. Standard deviations of a and b, as well as the covariance between a and b, were estimated by bootstrap re-sampling with replacement 10000× the length-weight measurements, optimizing a and b at each resample, and calculating the standard deviations of the 10000 values.

(A2.2) Prior estimate for *Loligo* numbers at the start of the second depletion period north (day 219):

$$\begin{aligned}
N_{N1\ \text{prior day 218}} &= N_{N1\ \text{prior day 201}} \times e^{-M\,(218-201)} - CNMD_{N\ \text{day 218}} \\
&= 0.180 \times 10^9 \times e^{-M\,(218-201)} - CNMD_{N\ \text{day 218}} \\
&= 0.114 \times 10^9 \\
N_{N1\ \text{prior day 219}} &= N_{N1\ \text{prior day 201}} \times e^{-M\,(219-201)} - CNMD_{N\ \text{day 219}} \\
&= 0.180 \times 10^9 \times e^{-M\,(219-201)} - CNMD_{N\ \text{day 219}} \\
&= 0.112 \times 10^9 \\
N_{N2\ \text{prior day 219}} &= N_{N1\ \text{prior day 218}} \times CPUE_{N\ \text{day}[219,\,220,\,221]} / CPUE_{N\ \text{day}[216,\,217,\,218]} \\
&= N_{N1\ \text{prior day 218}} \times 27.2 / 10.6 \\
&= 0.290 \times 10^9 \\
N_{N\ \text{prior day 219}} &= N_{N2\ \text{prior day 219}} - N_{N1\ \text{prior day 219}} = 0.178 \times 10^9
\end{aligned}$$

(A2.3) Prior estimate for *Loligo* numbers at the start of the second depletion period south (day 205):

$$\begin{aligned}
N_{S1\ \text{prior day 205}} &= N_{S1\ \text{prior day 196}} \times e^{-M\,(205-196)} - CNMD_{S\ \text{day 205}} \\
&= 0.933 \times 10^9 \times e^{-M\,(205-196)} - CNMD_{S\ \text{day 205}}
\end{aligned}$$

$$= 0.775 \times 10^9$$

$$N_{S\ prior\ day\ 205} = N_{S1\ prior\ day\ 205} \times CPUE_{S\ day[205,\ 206,\ 207]} / CPUE_{S\ day[202,\ 203,\ 204]}$$
$$= N_{S1\ prior\ day\ 205} \times 44.4 / 20.8$$
$$= 1.657 \times 10^9$$

(A2.4) Estimated immigration at the start of the second depletion period south (day 205).

$$N_{S1\ day\ 205} = N_{S\ day\ 196} \times e^{-M\ (205-196)} - CNMD_{S1\ day\ 205}$$
$$= 0.633 \times 10^9 \pm 52.7\%$$

where 52.7% is the std. dev. of the MCMC (gray bars, Fig. 8)

$$N_{S2\ day\ 205} = 0.896 \pm 0.445 \times 10^9 - 0.633 \pm 0.334 \times 10^9$$
$$= 0.263 \pm \sqrt{.445^2 + .334^2} \times 10^9 = 0.263 \pm 0.557 \times 10^9$$

$$B_{S\ immigration\ day\ 205} = 0.263 \pm 0.557 \times 10^9 \times 47.8 \pm 1.7\ \text{g} \quad \text{(Figure 10, bottom)}$$
$$= 0.263 \times 10^9 \pm 212.0\% \times 47.8 \pm 3.5\%$$
$$= 12{,}561 \pm \sqrt{2.120^2 + .035^2} = 12{,}561 \pm 26{,}627\ \text{tonnes}$$

(A2.5) Estimated total biomass (initial + immigration) that passed through the Loligo Box fishery zone in the second season of 2011:

$$B_{N\ day\ 201} + B_{S\ day\ 196} + B_{N\ immigration\ day\ 219} + B_{S\ immigration\ day\ 205}$$

$$\begin{aligned}
= &\ N_{N\ day\ 201} \times Wt_{N\ day\ 219} \\
&+ N_{S\ day\ 196} \times Wt_{S\ day\ 196} \\
&+ 2{,}314 \pm 293\ \text{tonnes} \\
&+ 12{,}561 \pm \sqrt{\left(\frac{.445}{.896}\right)^2 + .035^2}\ \text{tonnes}
\end{aligned}$$

$$\begin{aligned}
= &\ (0.208 \pm 0.028) \times 10^9 \times (37.2 \pm 2.2)\ \text{g} \\
&+ (0.773 \pm 0.408) \times 10^9 \times (51.7 \pm 3.0)\ \text{g} \\
&+ 2{,}314 \pm 293\ \text{tonnes} \\
&+ 12{,}561 \pm \sqrt{\left(\frac{.445}{.896}\right)^2 + .035^2}\ \text{tonnes}
\end{aligned}$$

$$\begin{aligned}
= &\ (0.208 \pm 0.028) \times 10^9 \times (37.2 \pm 2.2)\ \text{g} \\
&+ (0.773 \pm 0.408) \times 10^9 \times (51.7 \pm 3.0)\ \text{g} \\
&+ 2{,}314 \pm 293\ \text{tonnes} \\
&+ 12{,}561 \pm 6261\ \text{tonnes}
\end{aligned}$$

Note that here, the standard deviation for $B_{S\ immigration\ day\ 205}$ is lower (compared to **A2.4**), because the goal is just to estimate total biomass, and not evaluate the distinction of what were previous *Loligo* and what were new immigrants on day 205.

$$\begin{aligned}
= &\ (0.208 \times 10^9 \pm 13.5\%) \times (37.2 \pm 6.0\%)\ \text{g} \\
&+ (0.773 \times 10^9 \pm 52.7\%) \times (51.7 \pm 5.7\%)\ \text{g} \\
&+ 2{,}314 \pm 293\ \text{tonnes}
\end{aligned}$$

+ 12,561 ± 6,261 tonnes

= 7,723 ± $\sqrt{.135^2 + .060^2}$ = 7,723 ± 1,140 tonnes

+ 39,968 ± $\sqrt{.527^2 + .057^2}$ = 39,968 ± 21,206 tonnes

+ 2,314 ± 293 tonnes

+ 12,561 ± 6,261 tonnes

= 7,723 + 39,968 + 2,314 + 12,561

± $\sqrt{1,140^2 + 21,206^2 + 293^2 + 6,261^2}$

= 62,565 ± 21,238 tonnes