Falkland Island Fisheries Department

Loligo gahi Stock Assessment, Second Season 2010

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Index

Summary

1) The second season *Loligo* fishery of 2010 was open for 78 days, from July 15 to September 30. 36,993 tonnes of *Loligo* catch were reported; the highest total for a second season since 1995. 71.7% of this catch was taken north of 52º S.
2) Due to frequent movement of the fishing fleet, catch depletion could not be adequately modelled in the north and south sub-areas separately. Instead, the model was applied to the entire Loligo Box fishing zone.
3) Depletion was first identified to have started on July 25, ten days after season opening. Subsequent *Loligo* arrival and depletion events were inferred to have started on August 17, September 2, and September 24, based on changes in CPUE, *Loligo* sizes, and sex ratios. These inferences of arrival and depletion were not highly distinct in the data, but a four-depletion scenario ultimately fit the catch distributions best over the later (end) part of the season, which determines escapement.
4) In-season immigration was estimated at 16,170 ± 24,446 tonnes. Combined with the pre-season estimate of 62,391 ± 22,960 tonnes, a total of 78,561 ± 33,538 tonnes of *Loligo* were present in the Falkland Islands fishing zone during the second season of 2010.
5) Final estimates for *Loligo* remaining in the Loligo Box at the end of the season were:

   $0.256 \pm 0.097 \times 10^9$ squid (19,458 tonnes);

   with the risk of escapement biomass at the end of the season being less than 10,000 tonnes estimated at 13.7%.

Introduction

The second season of the *Loligo gahi* squid fishery in 2010 started on July 15, and ended by directed closure on September 30. Total reported *Loligo* catch by X-licensed vessels was 36,993 tonnes, which is the highest total for second season since 1995 (Payá, 2010). The preseason survey (Winter et al., 2010) had estimated a minimum available biomass of 51,754 tonnes. This preseason biomass was fairly evenly distributed throughout the 'Loligo Box' (Figure 1), with an average density of 3.53 mt km^{-2} north of 52 ºS, and an average density of 3.06 mt km^{-2} south of 52 ºS (Winter et al., 2010). The 52 ºS latitude had been used as a nominal boundary between assessment sub-areas in the first season (Winter, 2010), and for the second season survey and in-season management. Generally, *Loligo* stock assessment is subdivided in two or three areas (Roa-Ureta and Arkhipkin, 2007; Payá, 2009b; 2010) to reflect movements of different units of the stock (Arkhipkin and Middleton, 2002; Arkhipkin et al., 2004a; 2004b). The most appropriate subdivision is periodically re-evaluated.

Loligo gahi has an annual life cycle (Patterson, 1988), and since there is no carry-over of biomass from year to year, stock assessments are made with a depletion model (Agnew et al., 1998; Roa-Ureta and Arkhipkin, 2007; Arkhipkin et al., 2008). A depletion model back-calculates an estimate of initial stock 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, 2007a; b; 2009b; 2010).

Successive arrivals are revealed by discontinuities in the data. Fishing on a single, closed cohort would be expected to yield gradually decreasing CPUE, but gradually increasing average squid sizes. When instead these measures change suddenly, or in contrast to expectation, then the arrival of a new group may be inferred. In this event, the new group arrival/depletion is parameterized and modelled separately. Squid from preceding groups that are still alive at the next arrival are included in the next model, as there is no practical way to distinguish them in the fishery. Ultimately, the most important depletion model is that of the last group, since this will determine whether the escapement biomass limit of 10,000 tonnes (FIG, 2010) has been fulfilled.

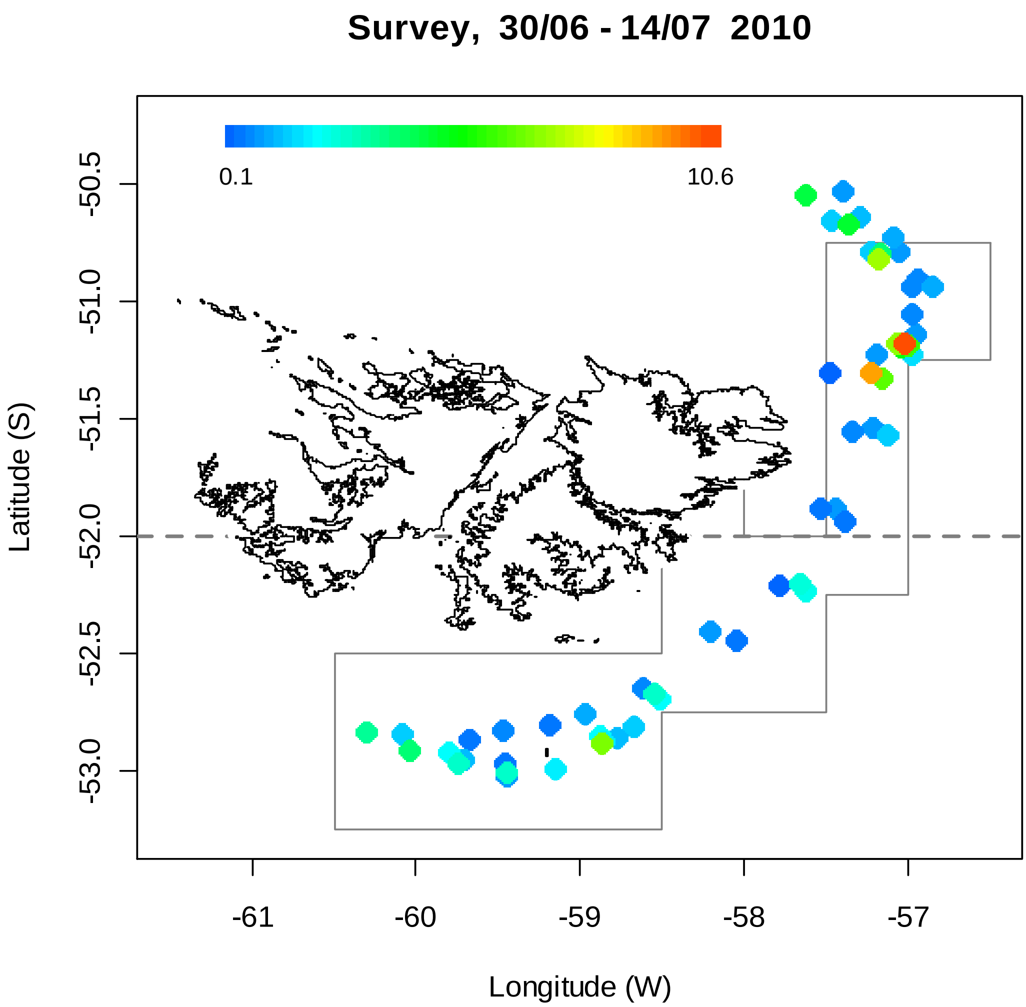


Figure 1. Spatial distribution of *Loligo* 2nd-season pre-season survey catches, scaled to catch weight (maximum = 10.6 tonnes). 57 catches were taken during the survey. The ‘Loligo Box’ fishing zone, as well as the 52 ºS parallel delineating the nominal boundary between north and south assessment areas, are shown in gray.

As in previous seasons (e.g., Payá, 2009b; 2010, Winter, 2010), stock assessment for the second season 2010 was calculated in a Bayesian framework (Punt and Hilborn, 1997), whereby results of the depletion model are conditioned by prior information on the stock. Distributions of the stock estimates (i.e., measures of their statistical uncertainty) were then computed using a Markov Chain Monte Carlo

(MCMC) with Metropolis-Hastings algorithm (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 probability distribution of the model outcome. This approximation is useful for models such as depletion, which have probability distributions that are difficult to sample directly.

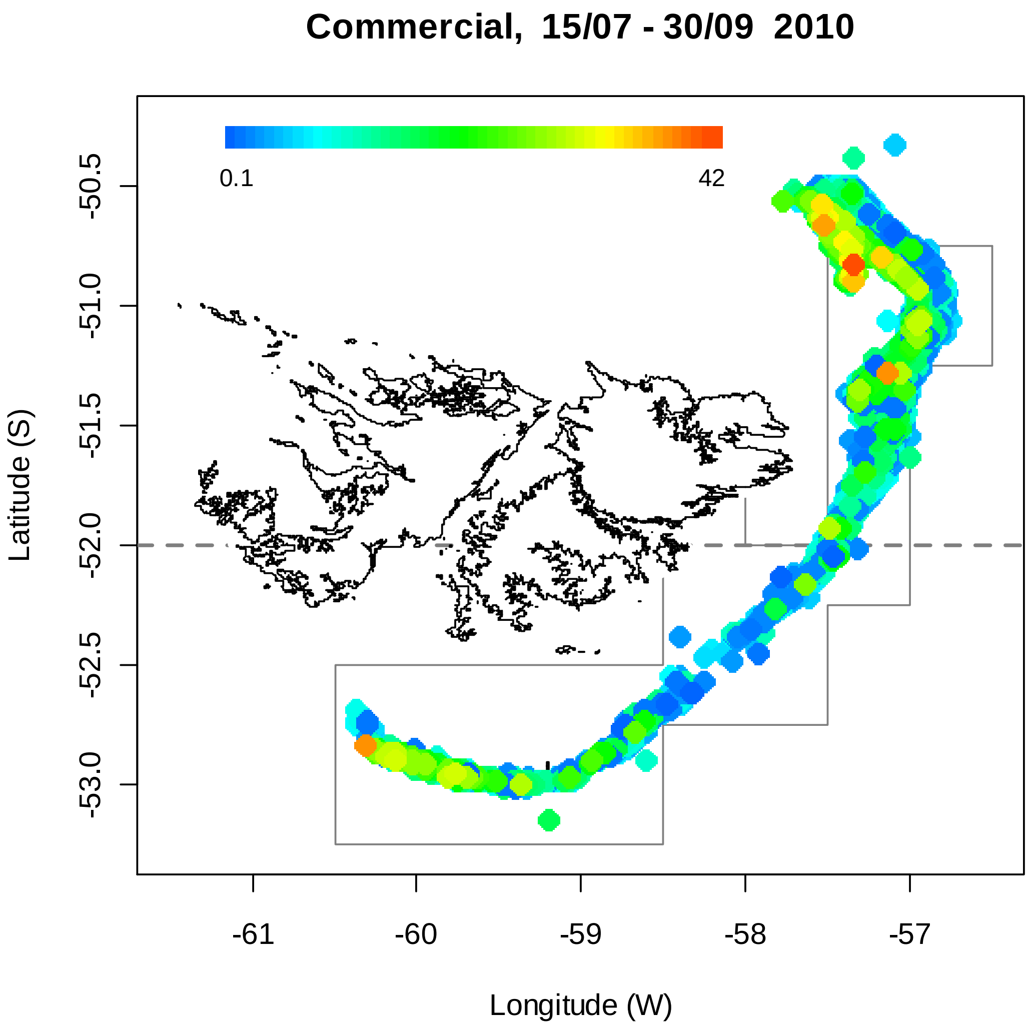


Figure 2. Spatial distribution of *Loligo* 2nd-season commercial catches, scaled to catch weight (maximum = 42 tonnes). 4122 catches were taken during the season. The 'Loligo Box' fishing zone, as well as the 52 ºS parallel delineating the nominal boundary between north and south assessment areas, are shown in gray.

Stock assessment
Data

In the second season *Loligo* fishery, 71.7% of *Loligo* catch (Figure 2) and 69.4% of effort (vessel-days) were taken north of 52 ºS, vs. 28.3% of catch and 30.6% of effort south of 52 ºS. This represents a significant change from the first season, when 99.5% of catch was taken south of 52 ºS (Winter, 2010). *Loligo* comprised 86% of the catch north of 52 ºS, and 94% of the catch south of 52 ºS. In both sub-areas most of the bycatch (>70%) was rock cod (*Patagonotothen ramsayi*). Between 10 and 16 vessels were fishing in the second *Loligo* season on any day, for a total of 1168 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. Five FIFD observers were deployed in the second season *Loligo* fishery for a total of 130 observer-days. Throughout the 78 days of the season, 28 days had 1 observer covering, 39 days had two observers, and 8 days had three observers. Three days had no observer coverage because of weather or port calls. Each observer sampled an average of 384 *Loligo* daily, and reported their maturity stages, sex, and lengths to 0.5 cm.

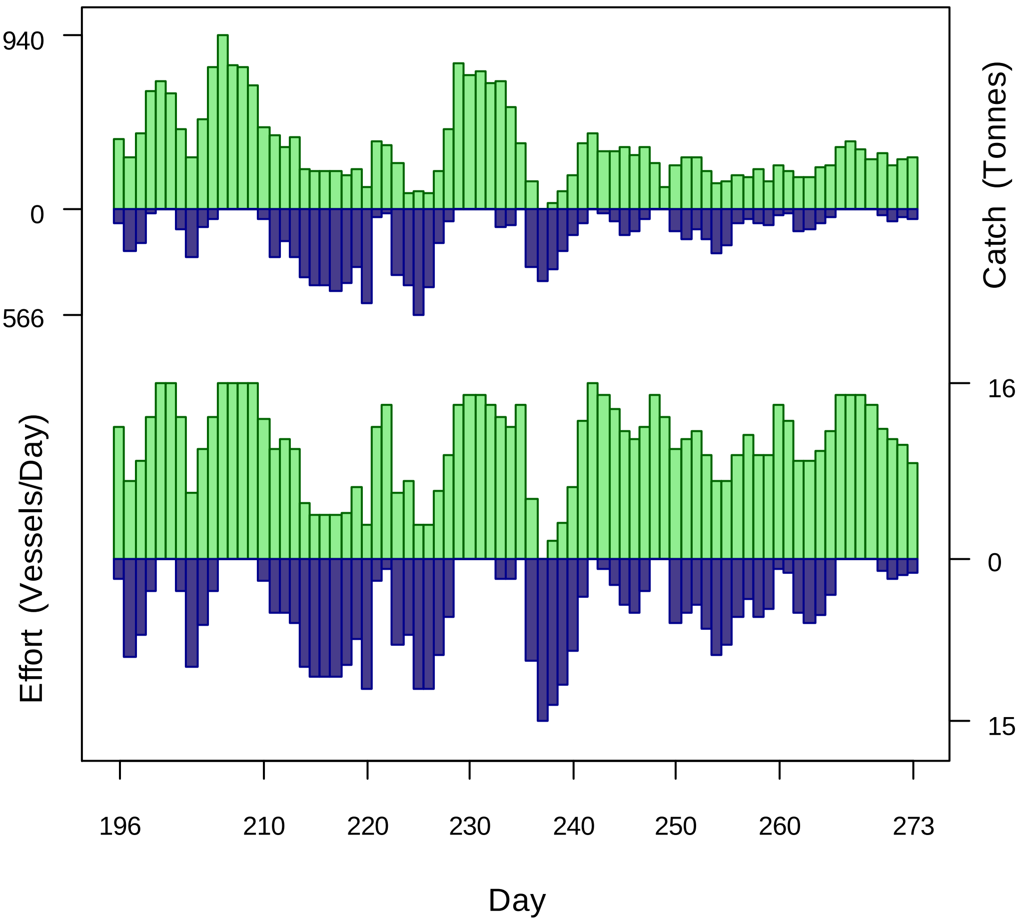


Figure 3. Daily total catch and effort distribution by assessment sub-area north (green) and south (purple) of the 52º S parallel in the *Loligo* 2nd season 2010. The season was opened from July 15 (chronological day 196) to September 30 (chronological day 273). As much as 940 tonnes *Loligo* were caught per day north of 52º S; as much as 566 tonnes *Loligo* were caught per day south of 52º S. As many as 16 vessels fished per day north of 52º S; as many as 15 vessels fished per day south of 52º S.

Group arrivals / depletion curves

The second season was characterized by much movement of the fleet between north and south sub-areas. The preponderance of effort switched back and forth 12 times throughout the season (Figure 3). As a result, depletion curves by separate north and south sub-areas converged poorly, and in-season management as well as post-season analysis were based instead on combined assessment of the entire fishery. 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, to more consistently represent vessels' overall fishing power, which is a factor of processing capacity as well as trawling capacity. Average individual *Loligo* sizes were expressed as weight (kg), converted from mantle lengths using Roa-Ureta and Arkhipkin's (2007) formula with combined data from 2006 and 2007:

$$weight(kg) = 0.32411926 \times length(cm)^{1.97547877} \times 1000^{-1}$$

Mantle lengths were obtained from in-season observer data, and also 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 1-3 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 examined. Males were consistently larger than females from observer samples in both north and south sub-areas (Figure 4). The pre-season survey had also shown geographic differences in *Loligo* size distributions, with larger and more mature *Loligo* occurring south of 52 ºS (Winter et al., 2010). In-season, this was somewhat evident from observer samples (Figure 5, top), and more consistently evident from commercial size categories (Figure 5, middle), until around day 223 (August 11).

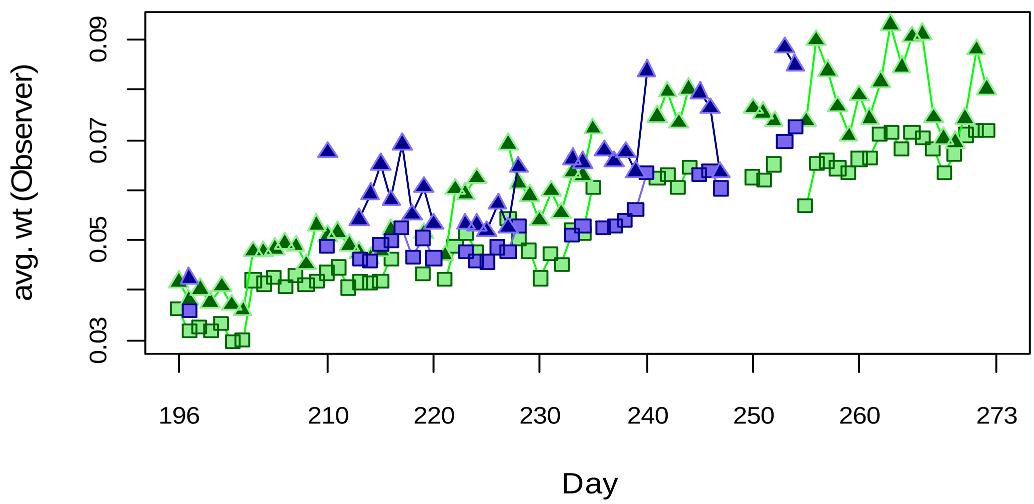


Figure 4. Per day, average individual *Loligo* weights (kg) by sex from observer sampling. Male: Δ female: □. Data from the assessment sub-areas north and south of the 52º S parallel are in green and purple, respectively; data from consecutive days are joined by line segments.

Depletion model and prior

The formulation of the Bayesian assessment model has been described previously (e.g., Payá, 2007b). For the second season 2010 assessment, probability density function of the prior, and log-likelihood of the depletion curve, were assumed to follow a Gaussian distribution. Likelihood calculations of the depletion curves were also standardized for differences in catchability among vessels, because the fishing fleet fluctuates from day to day. Three chains of the MCMC were computed for each model. One chain was started at the estimated optimum *Loligo* number (i.e., the chain was started about where it was expected to end), one chain was started at a low underestimate, and one chain was started at a high overestimate, to check that the algorithm did converge. Chains were run for 30,000 iterations; the first 3,000 iterations were discarded as burn-in sections (initial phases over which the algorithm stabilizes), then thinned by a factor of three to reduce serial correlation (only every third iteration was retained). Convergence of the three chains was accepted if the variance among chains was less than 10% higher than the variance within chains (Payá, 2009). When convergence was satisfied the three chains were combined as one set of 27,000 samples.

The Bayesian prior for depletion at the start of the season was based on the pre-season survey estimate for total biomass. This estimate had been calculated at a minimum of 51,754 ± 5248 tonnes from all survey data, and a maximum of 73,088 ± 8638 tonnes excluding survey data after sunset (Winter et al., 2010). These minimum and maximum estimates were combined by iterating 100,000 random normal variables with a mean equal to a random uniform value in the range of [51754, 73088], and a standard error equal to that random uniform value multiplied by the average coefficient of variation (CV; standard error divided by the mean) of the two estimates:

$$i_{n=1:100000} = r.norm\left(mean = r.unif\,[51754,73088], sd = mean \times \left(\overline{\frac{5248}{51754}, \frac{8638}{73088}} \right) \right).$$

The resulting distribution of 100,000 iterations was 62,391 ± 9260 tonnes. Payá (2010) and Winter (2010) estimated a net escapement of 22%, which was added to the standard error:

$$62{,}391 \pm \left(\frac{9260}{62{,}391} + .220 \right) \;=\; 62{,}391 \pm 36.8\% \;=\; 62{,}391 \pm 22{,}960 \text{ tonnes.}$$

The 22% was added as a linear increase in the variability, not in the absolute 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., 2010). *Loligo* were sampled at 57 survey stations, giving a geospatially-averaged (both sexes) mantle length of 12.62 cm, equivalent to 0.0485 kg. Accordingly, estimated *Loligo* numbers at the end of the survey / start of the season (day 196) were:

$$N_{\text{day }196} = \frac{62{,}391 \times 1000}{0.0485} \pm \sqrt{36.8\%^2 + 12.7\%^2 + 0.4\%^2}$$

$$= 1.286 \times 10^9 \pm 38.9\% = 1.286 \times 10^9 \pm 0.501 \times 10^9$$

where 36.8% is the CV in biomass estimate (above), 12.7% is the CV of the geostatistical model used to calculate average length, and 0.4% is the CV due to length-frequency sampling, estimated from bootstrapping (Efron, 1981).

With depletion starting on day *x* after the start of the season (day 196), *Loligo* numbers at the start of depletion are discounted for both catch and estimated natural mortality occurring during the intervening days:

$${}_{\text{prior}}N_{\text{day }x} = N_{\text{day }196} \times e^{-M \times (\text{day }x - \text{day }196)} - CNMD_{\text{day }x}$$

where CNMD is the cumulative catch in numbers discounted for the proportion that would have died naturally anyway over the period of time:

$$CNMD_{\text{start day}} = 0$$
$$CNMD_{\text{day }x} = CNMD_{\text{day }x\text{-}1} \times e^{-M} + C_{n\text{ day }x\text{-}1} \times e^{-M/2}$$

C_n is the daily catch total in numbers. This is calculated as the daily reported *Loligo* catch tonnage divided by the day's average individual weight. Days' average individual weights were calculated separately for sub-areas north and south of 52 ºS. Observer data were used primarily for the average individual weights. When (or where) observer data were not available, commercial size categories were used secondarily. North and south were then averaged in proportion to their reported catch tonnage for the day. Natural mortality M was considered constant at 0.0133 day^{-1} (Roa-Ureta and Arkhipkin, 2007).

For subsequent arrival / depletions during the season, the Bayesian prior could not be based on the pre-season survey, since it was assumed that the subsequent depletions involve different groups of *Loligo*. Instead, it is inferred that the ratio of *Loligo* numbers on a subsequent depletion start day (day *y*), over the *Loligo* numbers on the initial depletion start day (day *x*), should be proportional to the ratio of CPUE on those two days. CPUE were calculated as the aggregate CPUE (in numbers of *Loligo*) of all vessels fishing on either day. To moderate the influence of exceptional variations on this ratio (since depletion start days were to a large extent identified by having exceptional CPUE), the time series of CPUE was modelled by a generalized additive model (GAM; Hastie and Tibshirani, 1990) of daily aggregate CPUE vs. day count:

$$CPUE_{\text{day }y} = GAM(agg.CPUE_{\text{day}} \sim s(Day)) \,|_{\text{day }y}$$

This GAM was highly significant at $p < 0.001$. and the expected CPUE of the GAM were used to calculate the ratio:

$${}_{\text{prior}}N_{\text{day }y} = {}_{\text{prior}}N_{\text{day }x} \times CPUE_{\text{day }y} / CPUE_{\text{day }x}$$

The posterior distribution maximum likelihood of *Loligo* numbers on any depletion starting day *x* (or *y*) is defined as the maximum of the prior likelihood distribution multiplied by the depletion model likelihood distribution:

$$\text{max.likelihood}\,(N_{\text{day }x}) \;=\; \text{max.likelihood}\,({}_{\text{prior}}N_{\text{day }x} \times {}_{\text{depletion}}N_{\text{day }x})$$

By calculating vessel catchability coefficients (q) from the maximum likelihood posterior, expected catch numbers on any day *i* can be projected back from the model. Catchability coefficients (q) represent the operational efficiency of the vessels in a given environment (Arreguin-Sanchez 1996).

$${}_{\text{expected}}C_{n\ \text{day }i} \;=\; q_{avg} \times \text{effort}_{\text{day }i} \times {}_{\text{predicted}}N_{\text{day }i} \times e^{-M/2}, \qquad \text{where}$$

$${}_{\text{predicted}}N_{\text{day }i} \;=\; N_{\text{day }x} \times e^{-M \times (\text{day }i - \text{day }x)} - \text{CNMD}_{\text{day }i}, \qquad \text{and}$$

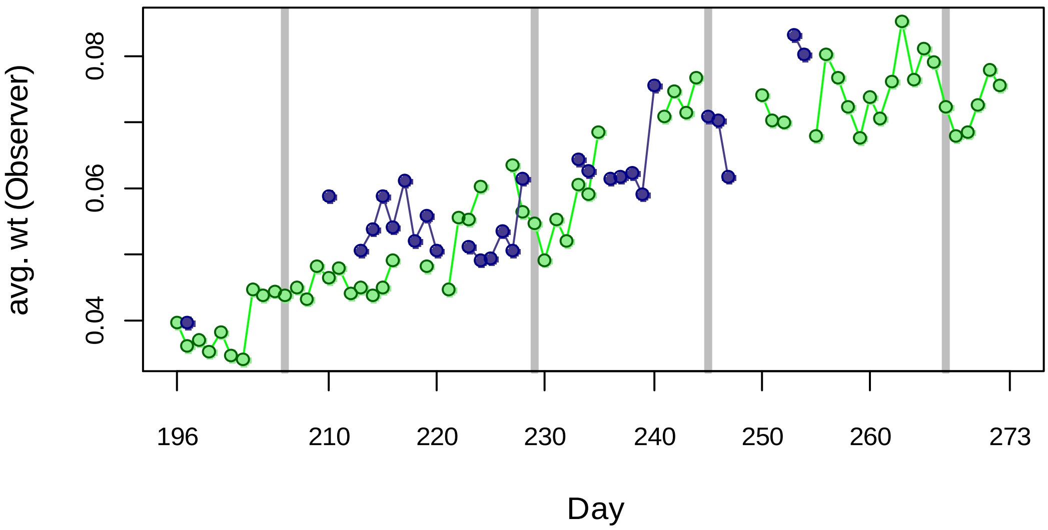
$$q_{avg} \;=\; \sum \left(\overline{e^{\log\left(\frac{\text{CPUE}_{\text{vessel}j\ \text{day}\,i}}{{}_{\text{predicted}}N_{\text{day x}} \times e^{-M/2}}\right)}}_{\text{vessel }j} \times \text{effort}_{\text{vessel }j} \right) / \sum \text{effort}_{\text{vessel }j}$$

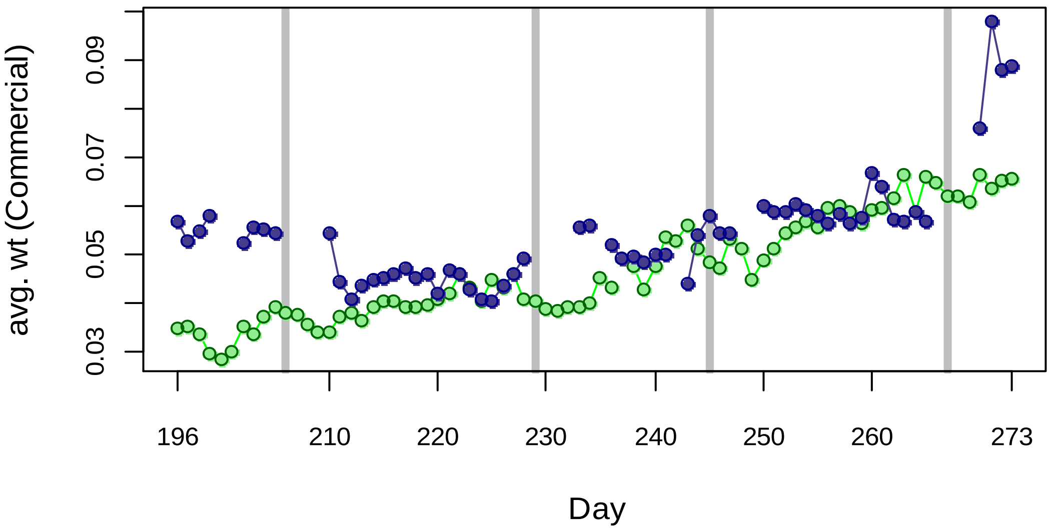
Depletion scenario selection

The *Loligo* data and CPUE time series showed four days that could plausibly represent the onset of separate depletions (Figures 5 and 6).

- The first, day 206 (July 25), followed what was likely the 'fishing-up' phase of the season, during which vessels harvested the densest aggregations of the stock. *Loligo* seasons have often shown an initial lag phase before depletion (Payá, 2009a; 2010, Winter, 2010). CPUE overall and CPUE in the north reached a peak while CPUE in the south reached a low point (Figure 6). Female proportion (in the north) was also at a local peak (Figure 5, bottom).
- On day 229 (August 17), CPUE overall and CPUE in the north again reached a peak (Figure 6), while CPUE in the south was at the tail of a steep declining trend over the 5 previous days (in fact, all fishing vessels had left the south by day 229; Figure 3). Day 229 was just before the start of an increasing trend in average size from observer data (Figure 5, top), and just after the start of a decreasing trend in the proportion of females (Figure 5, bottom).
- On day 245 (September 2) CPUE peaked in both the north and south sub-areas, and average sizes from commercial data were at endpoints of opposing trends: decreasing in the north and increasing in the south.
- On day 267 (24 September), average size and female proportion from observer data were both at minima, and CPUE (in the north) reached a small peak.

Evidence of changes in the *Loligo* stock was also shown by the time series of catch numbers (Figures 7-10); in some instances more strongly because catch numbers represent a ratio of two measures: catch biomass over average weight. However, these trends overall were not highly distinct from the general variability of the data, and inferences of new group arrivals are subjective and uncertain. Therefore, four scenarios were examined, assuming respectively a single depletion starting on day 206; two depletions starting on day 206 and day 229; three depletions starting on days 206, 229, and 245, and four depletions starting on days 206, 229, 245, and 267.


avg. wt (Observer)
0.04
0.06
0.08
196
210
220
230
240
250
260
273
Day


avg. wt (Commercial)
0.03
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260
273
Day

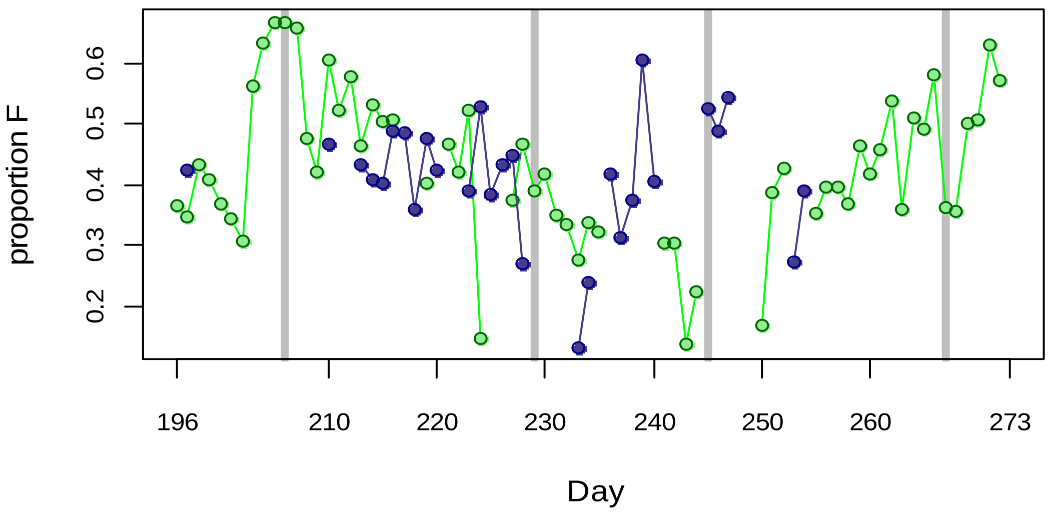
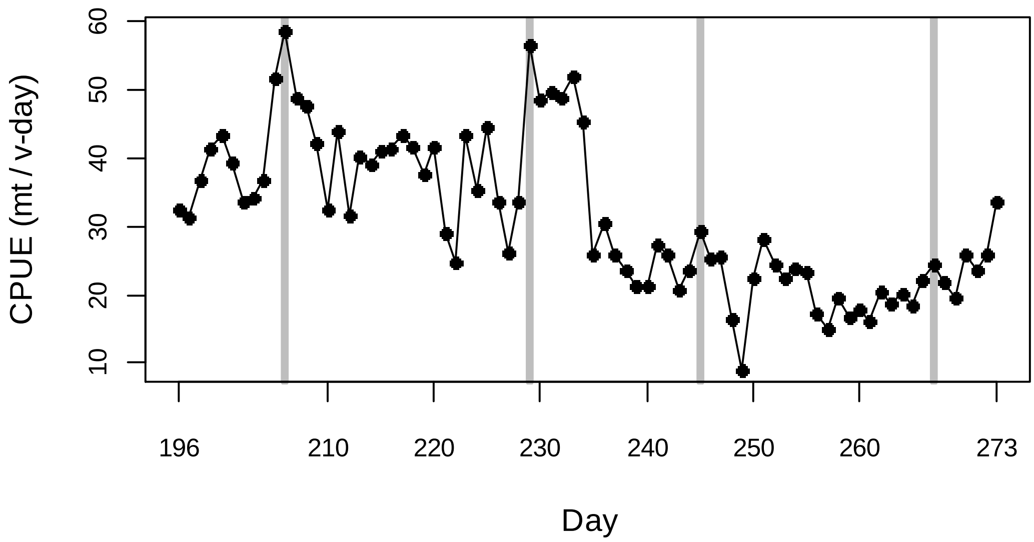

proportion F
0.2
0.3
0.4
0.5
0.6
196
210
220
230
240
250
260
273
Day

Figure 5 [previous page]. Per day, average (both sexes) individual *Loligo* weights (kg) from observer sampling (top), average individual *Loligo* weights from commercial size categories (middle), and proportions of females from observer sampling (bottom). Data from the assessment sub-areas north and south of the 52º S parallel are in green and purple, respectively; data from consecutive days are joined by line segments. Gray vertical bars indicate days that were identified as the onset of depletions: days 206, 229, 245 and 267.



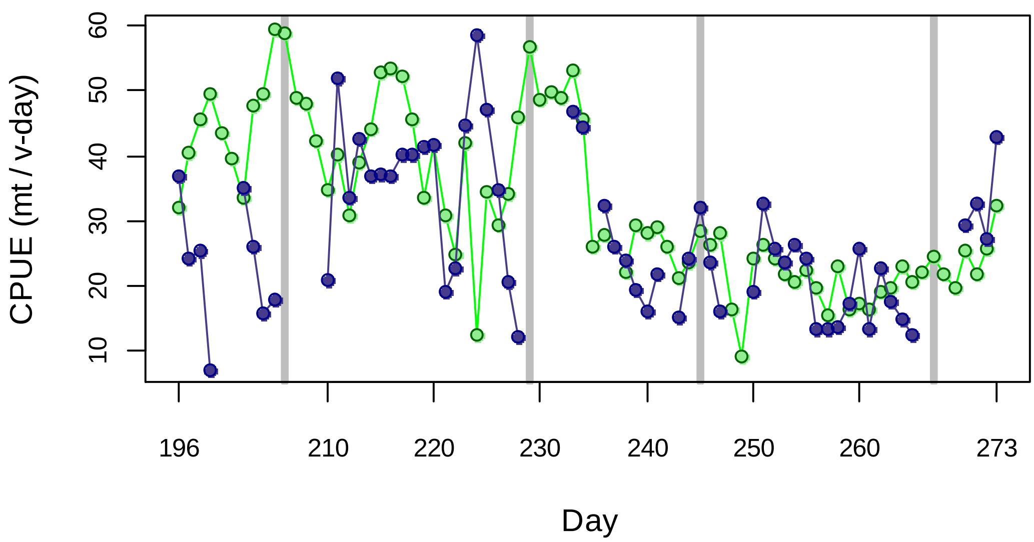


Figure 6. CPUE in metric tonnes per vessel per day, for the entire *Loligo* fishery (top), and separately by north of 52º S (green) and south of 52º S (purple) (bottom). Gray vertical bars indicate days that were identified as the onset of depletions: days 206, 229, 245 and 267. A particularly bad weather event caused the low CPUE on days 248-249.

The most appropriate scenario of modelling 1, 2, 3, or 4 arrival / depletion events was selected by comparing expected catch numbers projected from the models to the estimated actual catch numbers (reported catch weight divided by individual weight). Root mean-squared errors between expected and estimated actual catch numbers were calculated as:

$$\text{RMSE} = \sqrt{\left({}_{\text{expected}}C_n - {}_{\text{actual}}C_n\right)_i^2}$$

Trends of the residuals (differences between expected and actual catch numbers) were examined for bias (i.e., how many consecutive catches were either under- or overestimated by the model).

The 1-depletion scenario is shown in Figure 7. Notably, the model overestimated the first 15 days' catches and underestimated the last 12 days' catches. RMSE for the 1-depletion scenario is:

$$\text{RMSE}_{\text{day 206-273}} = 0.00306 \times 10^9$$

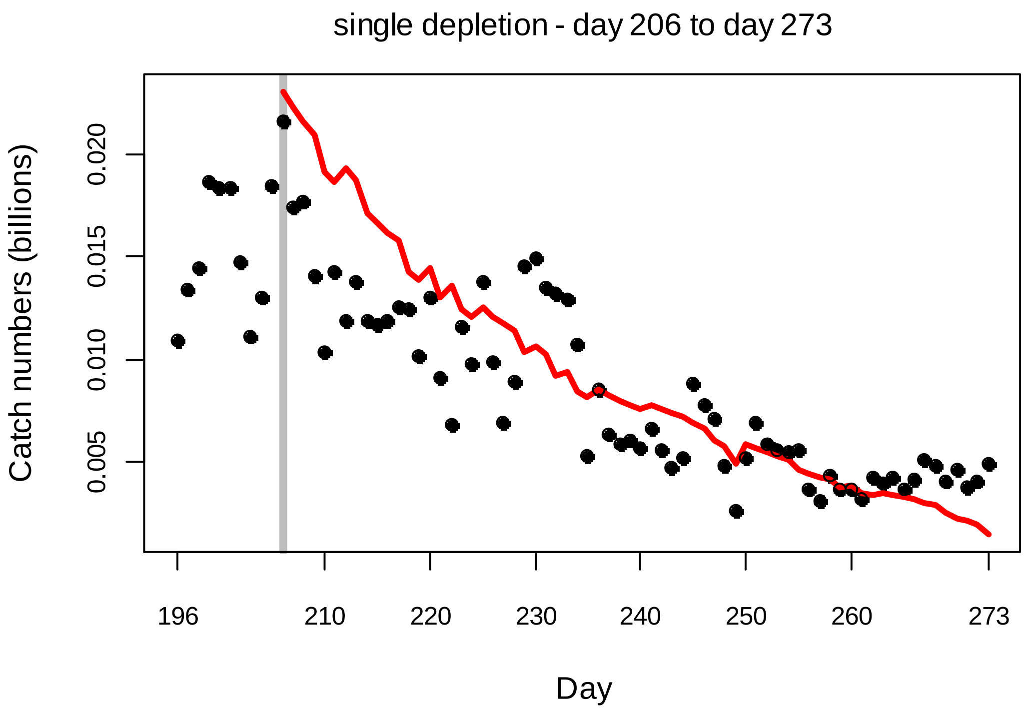


Figure 7. Daily estimated catch numbers (black points) and expected catch numbers (red lines) projected from the model scenario assuming one single depletion started on day 206.

The 2-depletion scenario is shown in Figure 8. The depletion from day 206 to day 228 is much better fit by being modelled separately. The start of the second depletion on day 229 is fit poorly, with the first six days' catch being strongly underestimated by the model. In fact, the catch model estimate on day 229 is no higher than the catch model estimate on day 228, even though the main reason for identifying day 229 as the start of a depletion was the increase in CPUE. The period from approx. day 229 to 245 is generally difficult to fit, because the high catches at the start of this period constrain the model to assume that N is quite high, but the rapid decline in catches thereafter imposes a low average catchability on the model (q_{avg}). As a result, the realized catches don't decrease the assumed N very much, and the curve of expected catches remains relatively flat. The last 8 days' catches were underestimated by the model. RMSE for the 2-depletion scenario are:

RMSE $_{\text{day 206-228}}$	=	0.00210×10^9
RMSE $_{\text{day 229-273}}$	=	$\underline{0.00226 \times 10^9}$
weighted avg.	=	0.00221×10^9

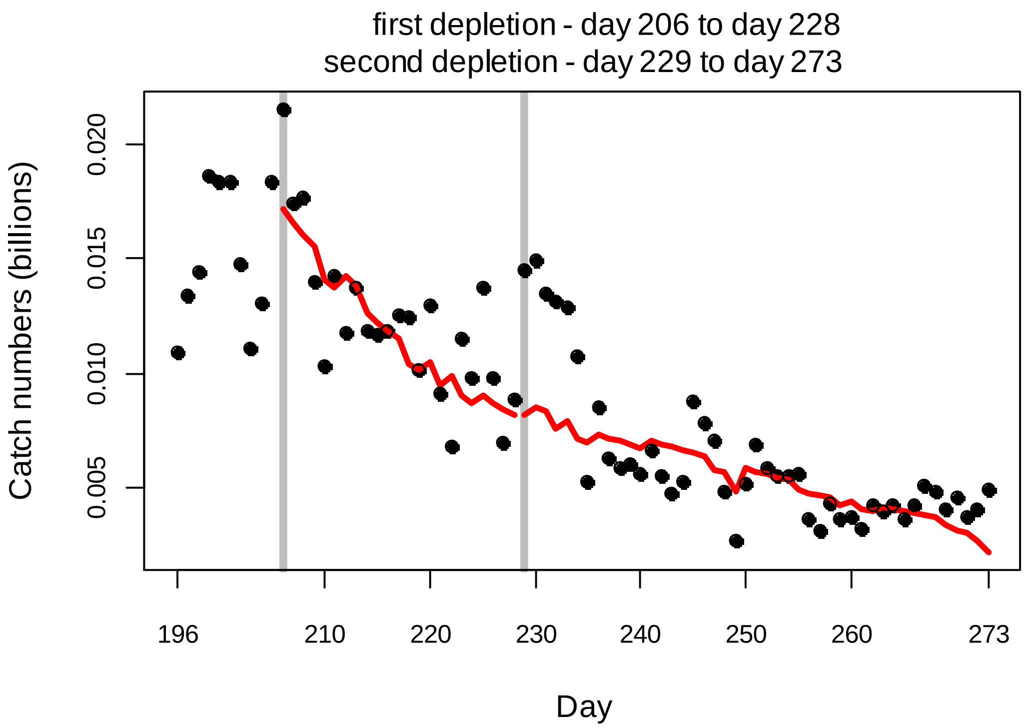


Figure 8. Daily estimated catch numbers (black points) and expected catch numbers (red lines) projected from the model scenario assuming two depletions, starting on days 206 and 229.

The 3-depletion scenario is shown in Figure 9. The peak starting on day 245 is well fit by the 3rd depletion model, but the last 8 days' catches remain underestimated. The model cannot represent the slowly increasing catch trend that starts around day 261. RMSE for the 3-depletion scenario are:

RMSE $_{\text{day 206-228}}$	=	0.00210×10^9
RMSE $_{\text{day 229-244}}$	=	0.00321×10^9
RMSE $_{\text{day 245-273}}$	=	$\underline{0.00123 \times 10^9}$
weighted avg.	=	0.00199×10^9

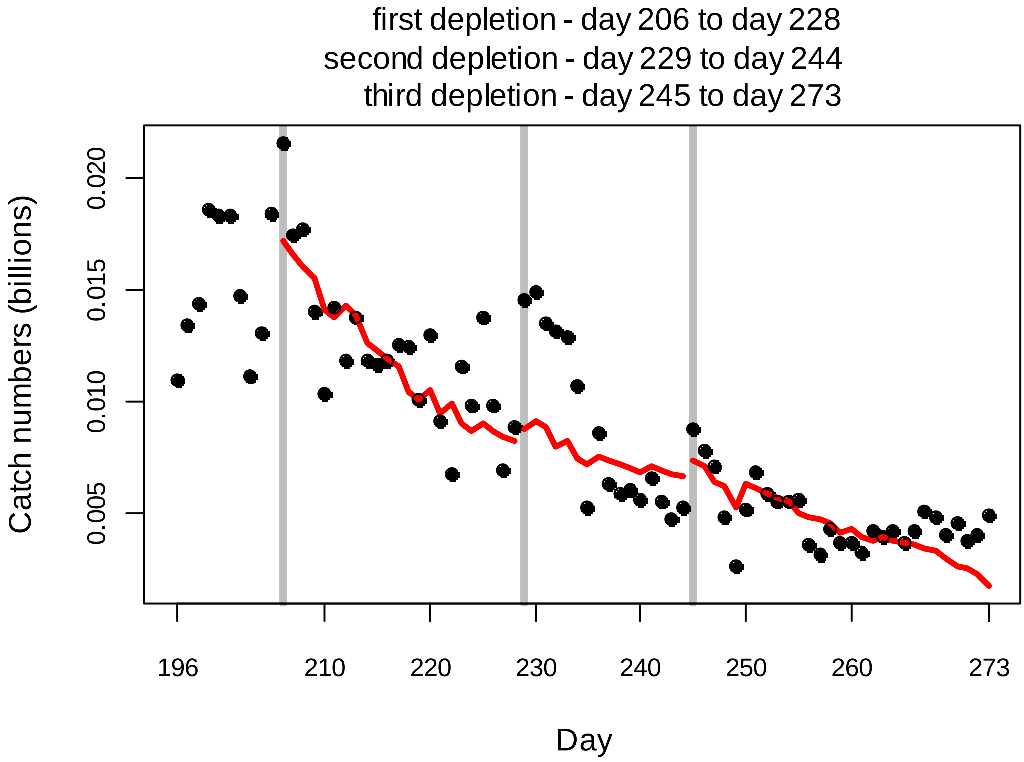


Figure 9. Daily estimated catch numbers (black points) and expected catch numbers (red lines) projected from the model scenario assuming three depletions, starting on days 206, 229 and 245.

The 4-depletion scenario is shown in Figure 10. The 4th depletion is, realistically, too short to model a time series of catches accurately, but provides estimation over the final 7 days which do not have a true catch depletion trend. Truncating the third depletion at day 266 also results in a lower expected catch trend over the period starting at day 245, because q_{avg} is no longer influenced by the increasing catch trend at the very end of the season. RMSE for the 4-depletion scenario are:

$$\text{RMSE}_{\text{day } 206\text{-}228} = 0.00210 \times 10^9$$
$$\text{RMSE}_{\text{day } 229\text{-}244} = 0.00321 \times 10^9$$
$$\text{RMSE}_{\text{day } 245\text{-}266} = 0.00103 \times 10^9$$
$$\text{RMSE}_{\text{day } 267\text{-}273} = \underline{0.00082 \times 10^9}$$
$$\text{weighted avg.} = 0.00188 \times 10^9$$

The average RMSE naturally decrease as more separate models are included in the scenario and each model fits the data more precisely. It does not mean that the models become statistically more significant. However, since the purpose of the analysis is to estimate biomass at the end of the season, not predict future catches, fitting the data is the relevant criterion. In particular, it was decided that consecutive model underestimates of the catches on the 8 or more final days represented too much bias (Figures 7-9). Therefore, the 4-depletion scenario was selected (Figure 10). Four depletions are consistent with the numbers of group arrival / depletions that have been observed in other seasons (Payá, 2010; references therein; Winter, 2010).

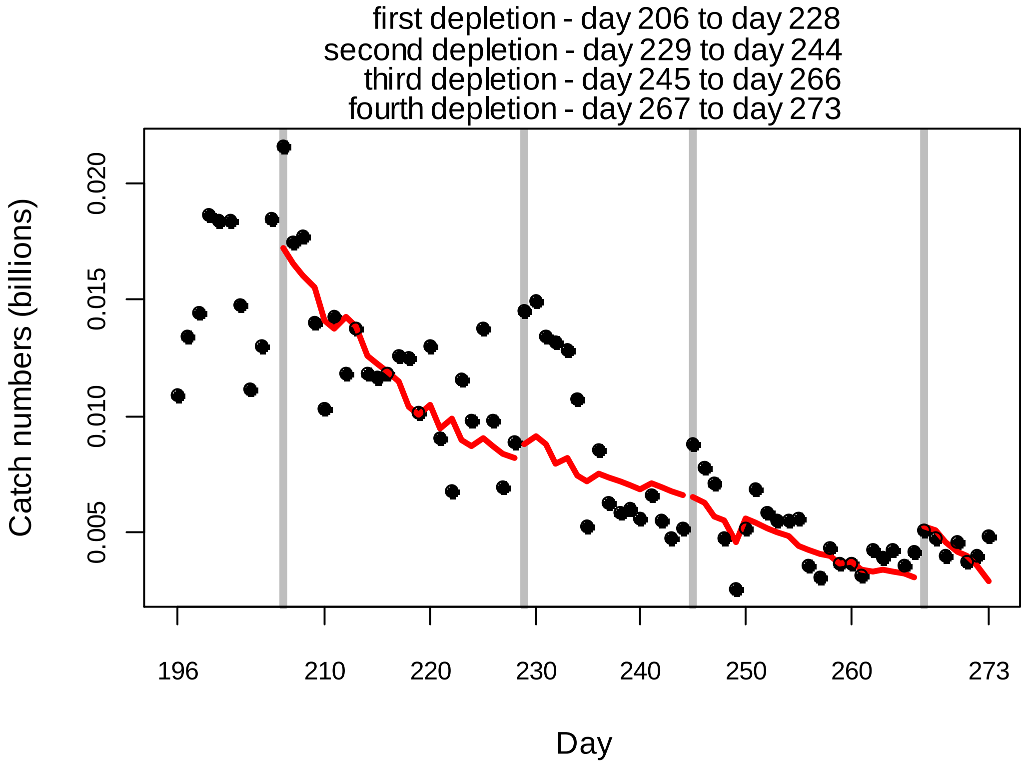


Figure 10. Daily estimated catch numbers (black points) and expected catch numbers (red lines) projected from the model scenario assuming four depletions, starting on days 206, 229, 245 and 267.

Analysis of 4-depletion scenario

First depletion

For the first depletion assumed to start on day 206, the estimated prior for initial numbers was:

$$_{\text{prior}}N_{\text{day 206}} = 1.286 \times 10^9 \times e^{-0.0133 \times 10} - 0.142 \times 10^9 = 0.984 \pm 0.383 \times 10^9$$

where the standard error of 0.383×10^9 is based on the same CV (38.9%) as described above for $N_{\text{day 196}}$. This estimate is equivalent to the maximum of the prior likelihood distribution (Figure 11, red line). The maximum likelihood of the depletion model was found at $_{\text{depletion}}N_{\text{day 206}} = 0.965 \times 10^9$, but with little differentiation among values ranging from 0.8 to 1.2×10^9 (Fig. 11, blue line). This is not unexpected, considering the relatively short duration (23 days) over which the depletion was optimized. The resulting posterior distribution was therefore mostly driven by the prior, and had maximum likelihood at $_{\text{post}}N_{\text{day 206}} = 0.983 \times 10^9$ (Fig. 11, gray bars). Mean and standard error of the MCMC were $1.028 \pm 0.344 \times 10^9$. Note that the depletion model had zero likelihood below $_{\text{depletion}}N_{\text{day 206}} = 0.311 \times 10^9$. Any less would have resulted in negative numbers beyond the end of that time period (day 228):

$$\frac{CNMD_{\text{day 228}}}{e^{(-M \times (\text{day 228 - day 206}))}} = \frac{0.232 \times 10^9}{e^{(-0.0133 \times 22)}} = 0.311 \times 10^9$$

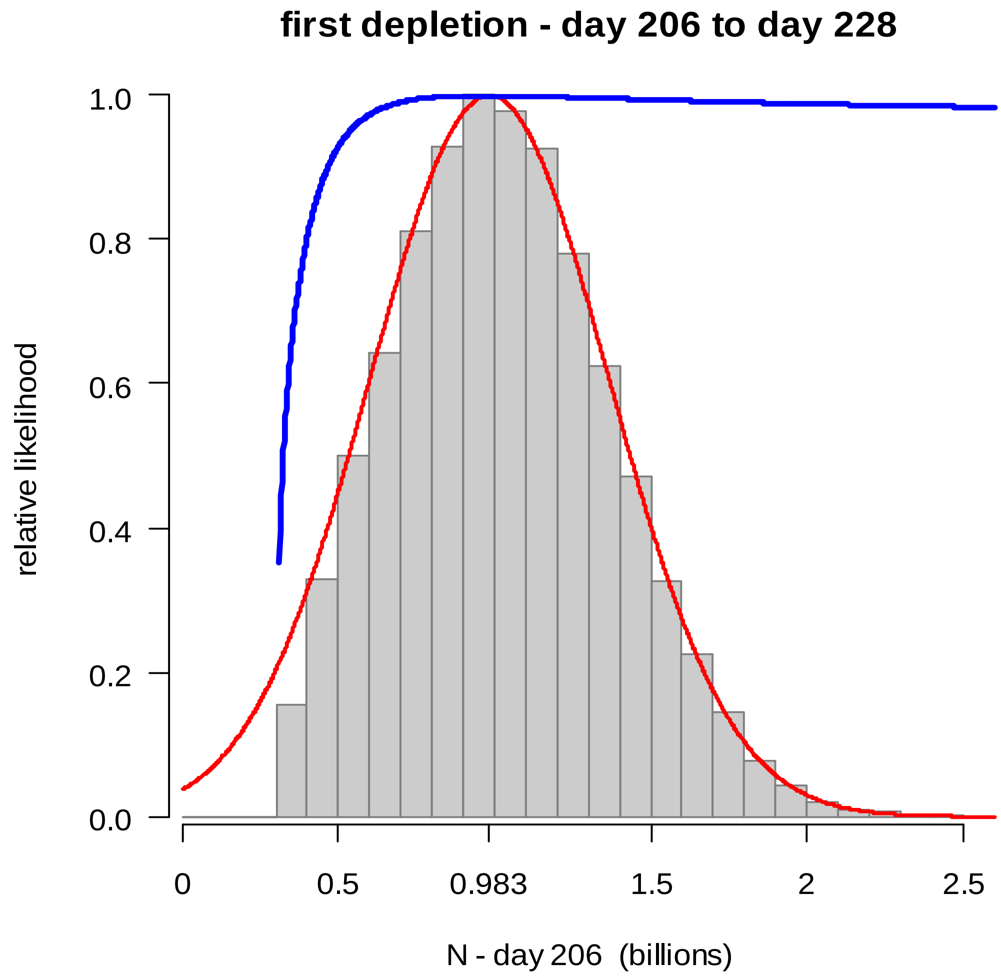


Figure 11. Model likelihood distributions for N billion *Loligo* present in the fishery on day 206 (July 25). Red line: prior model (derived from pre-season survey data), blue line: depletion model from day 206 to day 228, gray bars: posterior.

Second depletion

For the second arrival / depletion assumed to start on day 229, the estimated prior for initial numbers was:

$$
\begin{aligned}
{}_{\text{prior}}\,N_{\text{day 229}} &= {}_{\text{prior}}\,N_{\text{day 206}} \times CPUE_{\text{day 229}} / CPUE_{\text{day 206}} \\
&= 0.984 \times 10^{9} \times (0.785 \times 10^{6}\ \text{vessel}^{-1} / 1.011 \times 10^{6}\ \text{vessel}^{-1}) \\
&= 0.764 \times 10^{9}
\end{aligned}
$$

Note that this CPUE ratio (0.785/1.011 = 0.776) is lower than the CPUE ratio implied by Figure 6 (top), which is expressed in tonnes, not numbers. Variability of this prior included the standard error of ${}_{\text{prior}}\,N_{\text{day 206}}$ plus standard error of the CPUE ratio, which itself is the sum of standard errors of the GAM predictions on days 206 and 229:

$$CV_{prior}\, N_{day\ 229} = \sqrt{\left(\frac{0.383\times10^9}{0.984\times10^9}\right)^2 + \left(\frac{0.043\times10^6}{0.785\times10^6}\right)^2 + \left(\frac{0.044\times10^6}{1.011\times10^6}\right)^2}$$

$$= 0.396$$

Thus:

$$_{prior}\, N_{day\ 229} = 0.764 \times 10^9 \pm 39.6\% = 0.764 \pm 0.302 \times 10^9$$

Likelihood distributions of the second depletion are in Figure 12. The distribution of $_{prior}\, N_{day\ 229}$ is shown as a red line with maximum at 0.764 billion. The depletion model maximum likelihood was found at $_{depletion}\, N_{day\ 229} = 0.217 \times 10^9$ (blue line). The difficulty in depletion-modelling this period of the time series (noted previously) resulted in a maximum likelihood that is considerably lower than the prior distribution maximum likelihood. The posterior distribution maximum likelihood was then obtained at $_{post}\, N_{day\ 229} = 0.752 \times 10^9$ (gray bars).

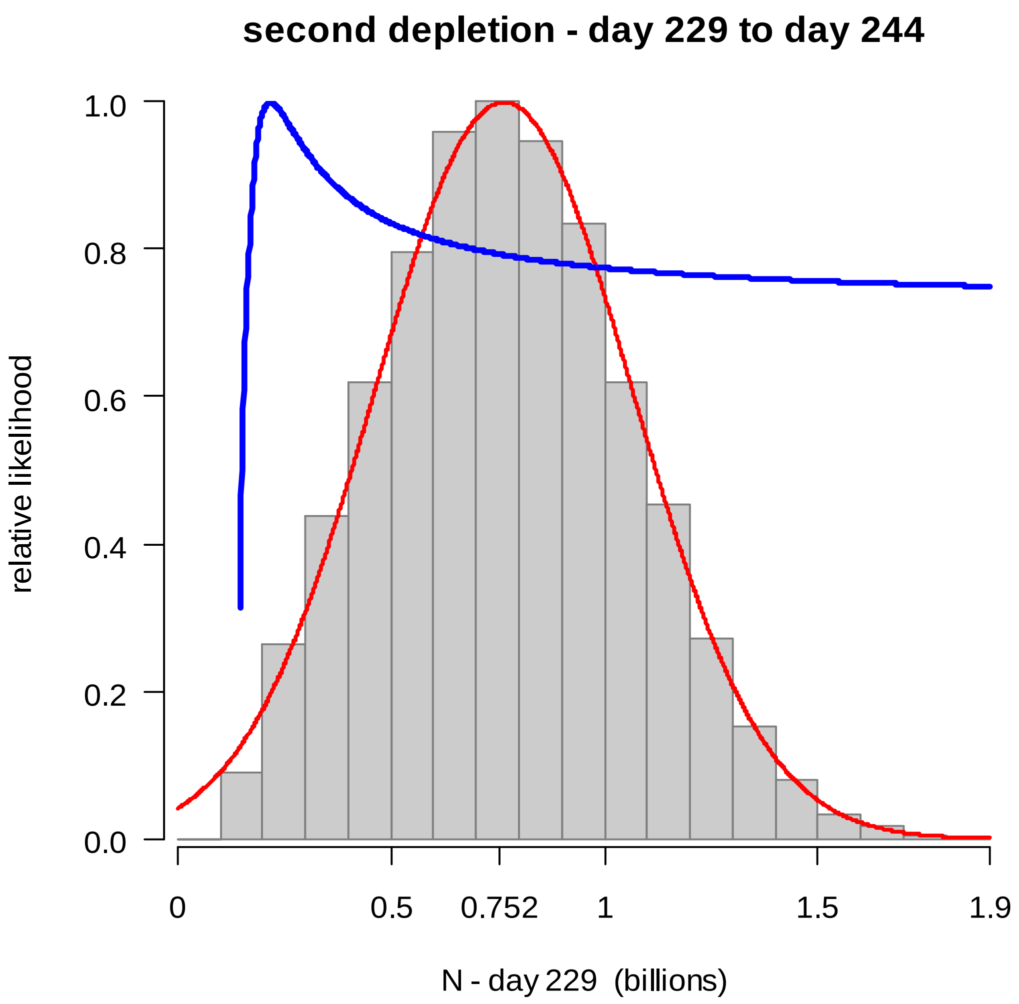


Figure 12. Model likelihood distributions for N billion *Loligo* present in the fishery on day 229 (August 17). Red line: prior model (from CPUE ratio and pre-season survey data), blue line: depletion model from day 229 to day 244, gray bars: posterior.

Third depletion

For the third arrival / depletion assumed to start on day 245, the estimated prior for initial numbers was:

$$
\begin{aligned}
{}_{prior}\,N_{day\ 245} &= {}_{prior}\,N_{day\ 206} \times CPUE_{day\ 245} / CPUE_{day\ 206} \\
&= 0.984 \times 10^{9} \times (0.362 \times 10^{6}\ vessel^{-1} / 1.011 \times 10^{6}\ vessel^{-1}) \\
&= 0.356 \times 10^{9}
\end{aligned}
$$

With variability calculated as before:

$$
{}_{prior}\,N_{day\ 245} = 0.356 \pm 0.146 \times 10^{9}
$$

Likelihood distributions of the third depletion are in Figure 13. Maximum likelihood of the depletion model (blue line) was in this case higher than maximum likelihood of the prior (red line): 0.487 vs. 0.356 × 10^{9}. The posterior distribution maximum likelihood was obtained at ${}_{post}\,N_{day\ 245} = 0.358 \times 10^{9}$ (gray bars).

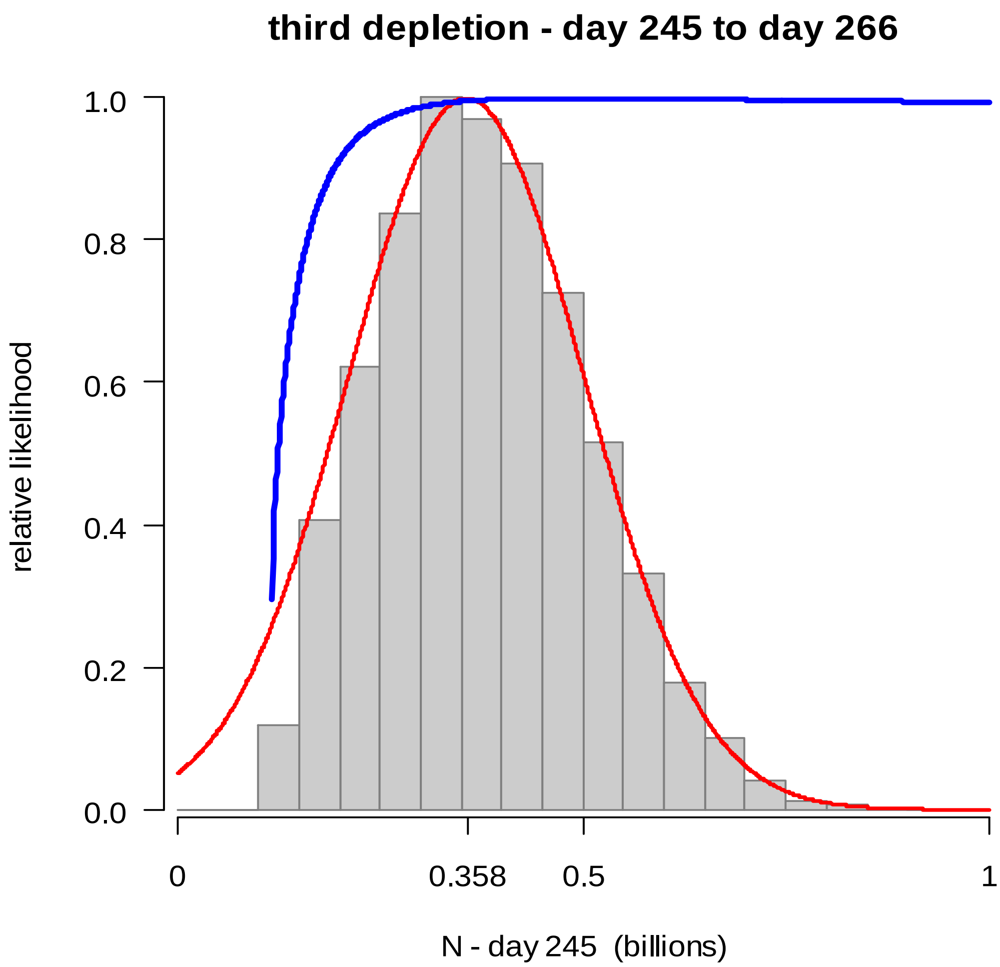


Figure 13. Model likelihood distributions for N billion *Loligo* present in the fishery on day 245 (September 2). Red line: prior model (from CPUE ratio and pre-season survey data), blue line: depletion model from day 245 to day 266, gray bars: posterior.

Fourth depletion

For the fourth arrival / depletion assumed to start on day 267, the estimated prior for initial numbers was:

$_{prior}\,N_{day\ 267} = {}_{prior}\,N_{day\ 206} \times CPUE_{day\ 267} / CPUE_{day\ 206}$
$= 0.984 \times 10^9 \times (0.298 \times 10^6\ vessel^{-1} / 1.011 \times 10^6\ vessel^{-1})$
$= 0.290 \times 10^9$
$_{prior}\,N_{day\ 245} = 0.290 \pm 0.121 \times 10^9$

Likelihood distributions of the fourth depletion are in Figure 14. The depletion model (blue line) did not converge to a maximum likelihood but became asymptotic at N values greater than approximately 0.700×10^9, at which level the likelihood of the prior (red line) became nearly zero. Lack of convergence in the depletion model is not surprising, given the very short time series and the poorly defined decreases in catch over that time series. The posterior distribution maximum likelihood was obtained at $_{post}\,N_{day\ 267} = 0.305 \times 10^9$ (gray bars).

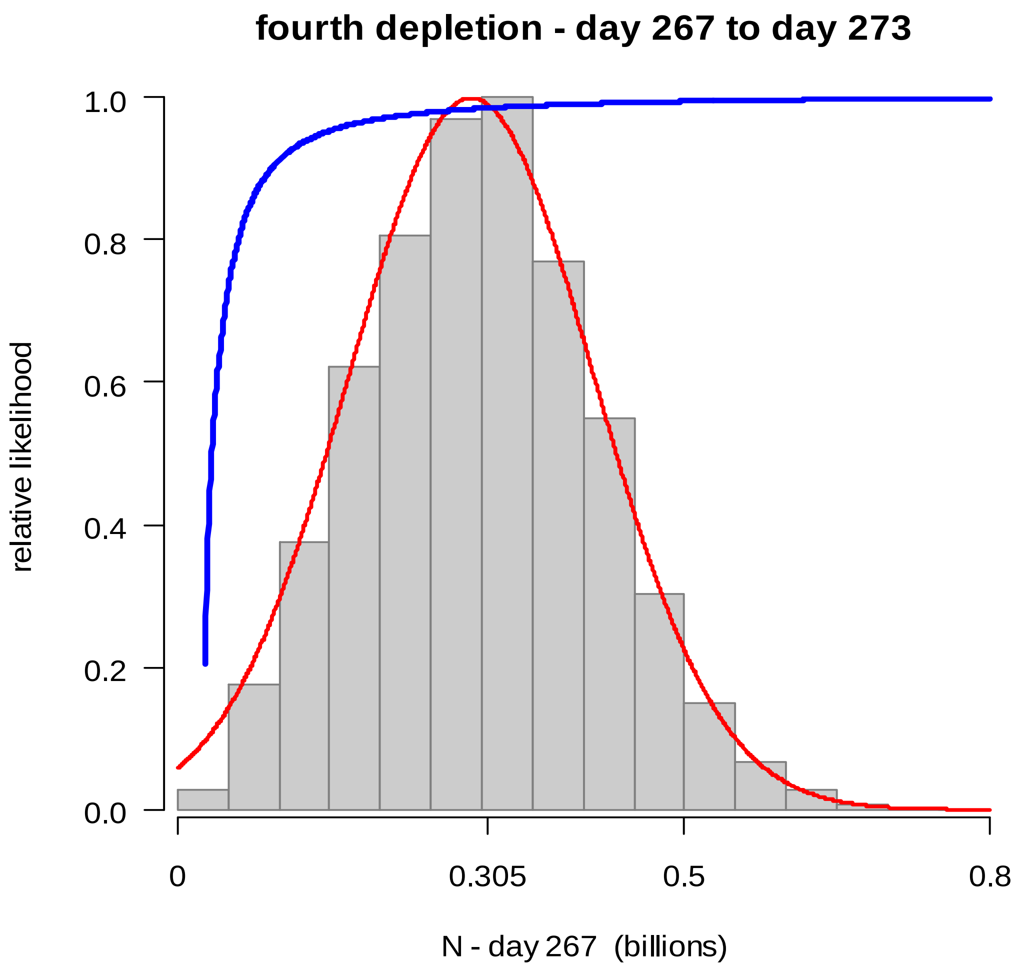


Figure 14. Model likelihood distributions for N billion *Loligo* present in the fishery on day 267 (September 24). Red line: prior model (from CPUE ratio and pre-season survey data), blue line: depletion model from day 267 to day 273, gray bars: posterior.

Escapement biomass

The estimated number of *Loligo* in the fishing area at the end of the season (day 273; September 30) was multiplied by the expected individual weight of *Loligo* on day 273, to obtain the escapement biomass.

Estimated number of *Loligo* on day 273 was derived from the fourth depletion posterior carried forward from day 267 to day 273:

$$
\begin{aligned}
N_{\text{day }273} &= {}_{\text{post}}N_{\text{day }267} \times e^{-M \times (\text{day }273 - \text{day }267)} - CNMD_{\text{day }267} \\
&= 0.305 \times 10^{9} \times e^{-0.0133 \times 6} - 0.025 \times 10^{9} \\
&= 0.256 \times 10^{9}
\end{aligned}
$$

Expected individual weight was derived from a generalized additive model ($p < 0.001$) of daily average individual weight (observer estimate or commercial estimate; see above) vs. day count:

$$
\begin{aligned}
\text{avg.Wt}_{\text{day }273} &= \text{GAM}(\text{avg.Wt}_{\text{day}} \sim s(\text{Day}))\;|_{\text{ day }273} \\
&= 0.0759 \text{ kg}
\end{aligned}
$$

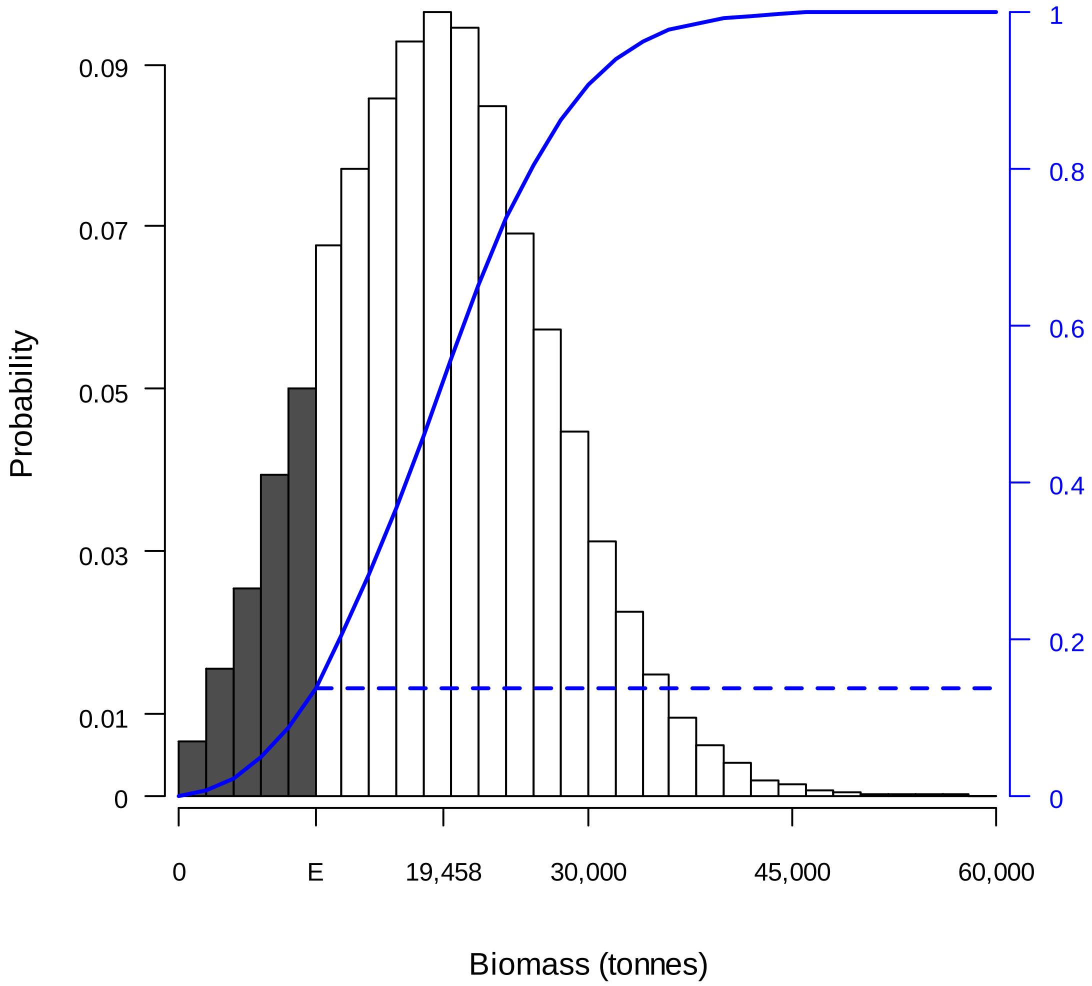


Figure 15 [previous page]. Probability distribution of *Loligo* biomass at the end of the season, September 30. Distribution samples less than the minimum biomass escapement limit of 10,000 tonnes (“E”) are shaded dark gray. Cumulative probability is shown as a solid blue curve. The broken blue line indicates that the probability of less than 10,000 tonnes escapement biomass is 13.7%.

Error distribution of the escapement biomass was estimated by randomly re-sampling, with replacement, the MCMC for ${}_{post}\,N_{day\ 267}$, calculating the corresponding value of $N_{day\ 273}$, and multiplying this value by a randomized bootstrap sample of the GAM for $avg.Wt_{day\ 273}$. This randomization was iterated 135,000× (5× the length of the MCMC). The resulting distribution is shown in Figure 15. Maximum probability of the escapement biomass was 19,458 tonnes. The risk analysis (Francis, 1991) of the fishery was defined as the proportion of the randomizations that failed to reach the escapement biomass limit of 10,000 tonnes. This risk was equal to 13.7% (Figure 15).

Immigration and catch rate

Total *Loligo* immigration was inferred as the difference between the posterior estimate on each depletion start day (when the immigrations putatively occurred) and the number on that day that would be accounted for by depletion of the preceding estimated biomass alone. Day 206 was the start of a depletion, but was not considered an immigration day. For day 229:

$$ {}_{post}\,N_{day\ 229} \quad = \quad 0.752 \times 10^9 \pm 37.5\% \quad = \quad 0.752 \pm 0.282 \times 10^9 $$

$$ \begin{aligned} N_{day\ 229} &= {}_{post}\,N_{day\ 206} \times e^{-M \times (day\ 229 - day\ 206)} - CNMD_{day\ 229} \\ &= 0.983 \times 10^9 \times e^{-0.0133 \times (229-206)} - 0.238 \times 10^9 \\ &= 0.486 \times 10^9 \pm 33.5\% \quad = \quad 0.486 \pm 0.163 \times 10^9 \end{aligned} $$

$$ \begin{aligned} {}_{immigration}\,N_{day\ 229} &= (0.752 - 0.486) \pm \sqrt{0.282^2 + 0.163^2} \times 10^9 \\ &= 0.266 \pm 0.325 \times 10^9. \end{aligned} $$

Coefficients of variation were obtained from the MCMC.
Expected individual weight on day 229 was:

$$ \begin{aligned} avg.Wt_{day\ 229} &= GAM(avg.Wt_{day} \sim s(Day)) \mid_{day\ 229} \\ &= 0.0550 \pm 0.0006\ kg \end{aligned} $$

The immigration biomass was therefore:

$$ \begin{aligned} {}_{immigration}\,B_{day\ 229} &= 0.266 \times 10^9 \times 0.0550/1000 \pm \sqrt{\left(\frac{0.325}{0.266}\right)^2 + \left(\frac{0.0006}{0.0550}\right)^2} \\ &= 14{,}630 \pm 17{,}876\ tonnes \end{aligned} $$

For day 245:

$$ {}_{post}\,N_{day\ 245} \quad = \quad 0.358 \times 10^9 \pm 33.7\% \quad = \quad 0.358 \pm 0.121 \times 10^9 $$

$$N_{\text{day 245}} = {}_{\text{post}}N_{\text{day 229}} \times e^{-M \times (\text{day 245} - \text{day 229})} - CNMD_{\text{day 245}}$$
$$= 0.752 \times 10^9 \times e^{-0.0133 \times (245-229)} - 0.123 \times 10^9$$
$$= 0.485 \times 10^9 \pm 37.5\% \qquad = 0.485 \pm 0.182 \times 10^9$$

$${}_{\text{immigration}}N_{\text{day 245}} = (0.358 - 0.485) \pm \sqrt{0.121^2 + 0.182^2} \times 10^9$$
$$= -0.127 \pm 0.219 \times 10^9.$$

$$\text{avg.Wt}_{\text{day 245}} = \text{GAM}(\text{avg.Wt}_{\text{day}} \sim s(\text{Day}))\,|_{\text{day 245}}$$
$$= 0.0626 \pm 0.0007 \text{ kg}$$

$${}_{\text{immigration}}B_{\text{day 245}} = -0.127 \times 10^9 \times 0.0626/1000 \pm \sqrt{\left(\frac{0.219}{0.127}\right)^2 + \left(\frac{0.0007}{0.0626}\right)^2}$$
$$= -7950 \pm 13{,}710 \text{ tonnes}$$

For day 267:

$${}_{\text{post}}N_{\text{day 267}} = 0.305 \times 10^9 \pm 38.1\% \qquad = 0.305 \pm 0.116 \times 10^9$$

$$N_{\text{day 267}} = {}_{\text{post}}N_{\text{day 245}} \times e^{-M \times (\text{day 267} - \text{day 245})} - CNMD_{\text{day 267}}$$
$$= 0.358 \times 10^9 \times e^{-0.0133 \times (267-245)} - 0.092 \times 10^9$$
$$= 0.175 \times 10^9 \pm 33.7\% \qquad = 0.175 \pm 0.059 \times 10^9$$

$${}_{\text{immigration}}N_{\text{day 267}} = (0.305 - 0.175) \pm \sqrt{0.116^2 + 0.059^2} \times 10^9$$
$$= 0.130 \pm 0.130 \times 10^9.$$

$$\text{avg.Wt}_{\text{day 267}} = \text{GAM}(\text{avg.Wt}_{\text{day}} \sim s(\text{Day}))\,|_{\text{day 267}}$$
$$= 0.0730 \pm 0.0011 \text{ kg}$$

$${}_{\text{immigration}}B_{\text{day 245}} = 0.130 \times 10^9 \times 0.0730/1000 \pm \sqrt{\left(\frac{0.130}{0.130}\right)^2 + \left(\frac{0.0011}{0.0730}\right)^2}$$
$$= 9490 \pm 9491 \text{ tonnes}$$

Note that the estimated immigration on day 245 comes out negative. This is consistent with the absence of increase in model-projected catch on day 245 (Figure 10), and suggests that the appearance of an arrival / depletion event on that day may have been specious. The total estimated immigration biomass is:

$$14{,}630 - 7950 + 9490 \pm \sqrt{17{,}876^2 + 13{,}710^2 + 9491^2} \qquad = 16{,}170 \pm 24{,}446 \text{ tonnes}$$

And the estimated total biomass (initial + immigration) to have been present in the Falkland Islands Loligo Box fishery zone in the second season of 2010 is:

$$62{,}391 \pm 22{,}960 + 16{,}170 \pm 24{,}446 \qquad = 78{,}561 \pm 33{,}538 \text{ tonnes}$$

Giving a total catch rate of:

$$36{,}993 / 78{,}561 \pm 33{,}538 \text{ tonnes} \qquad = 47.1\% \pm 42.7\%$$

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