Falkland Island Fisheries Department

Loligo gahi Stock Assessment, First Season 2010

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Index

Summary

1) The first season *Loligo* fishery of 2010 was open for 50 days, from February 24 to April 14. 28,754 tonnes of *Loligo* catch were reported; the highest total for a first season since 2000. 99.5% of this catch was taken south of 52º S.
2) Four waves of *Loligo* arrival / depletion (including the stock present at the start of the season) were identified south of 52º S, on Feb. 27, Mar. 13, Mar. 22, and Apr. 6. No separate waves of *Loligo* arrival / depletion were identified in the small amount of catch north of 52º S
3) High uncertainty in the in-season depletion models resulted in *Loligo* count and biomass estimates being determined mostly by CPUE proportions of the pre-season survey biomass.
4) Final estimates for *Loligo* remaining in the Falkland Islands fishing zone at the end of the season were:
   - South of 52º S: $0.754 \pm 0.255 \times 10^9$ squid; 38,587 ± 13,098 tonnes
   - North of 52º S: $0.022 \pm 0.007 \times 10^9$ squid; 788 ± 280 tonnes
   - Total: $0.776 \pm 0.255 \times 10^9$ squid; 39,375 ± 13,104 tonnes
5) The risk of the escapement biomass actually being less than 10,000 tonnes was estimated at 1.1%.
6) In-season immigration was estimated at 29,425 ± 11,509 tonnes. Combined with the pre-season estimate of 60,500 ± 17,545 tonnes, a total of 89,925 ± 20,983 tonnes of *Loligo* were present in the Falkland Islands fishing zone during first season of 2010.

Introduction

The first season of the *Loligo gahi* squid fishery in 2010 started on February 24, and was ended by directed closure on April 14. Total reported *Loligo* catch was 28,754 tonnes, which is the highest total for first season since 2000 (Payá, 2010). The pre-season survey (Arkhipkin et al., 2010) had estimated an available biomass of 60,500 tonnes. This pre-season biomass was heavily concentrated in the southern part of the 'Loligo Box' fishing zone (Figure 1), and the subsequent distribution of commercial catches showed the same southward concentration (Figure 2). *Loligo* stock assessment is usually subdivided in two or three areas (Roa-Ureta and Arkhipkin, 2007; Payá, 2009; 2010) to reflect movements of different units of the stock (Arkhipkin and Middleton, 2002; Arkhipkin et al. 2004a; 2004b). Based on the observed distributions, the 2010 first season fishery was assessed in a 'north' and 'south' area delineated by the 52º S parallel.

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). 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; 2009; 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 lengths.

When instead these measures change suddenly, or in contrast to expectation, then the arrival of a new group may be inferred. Each new group arrival/depletion must be parameterized and modelled as a separate event. 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.

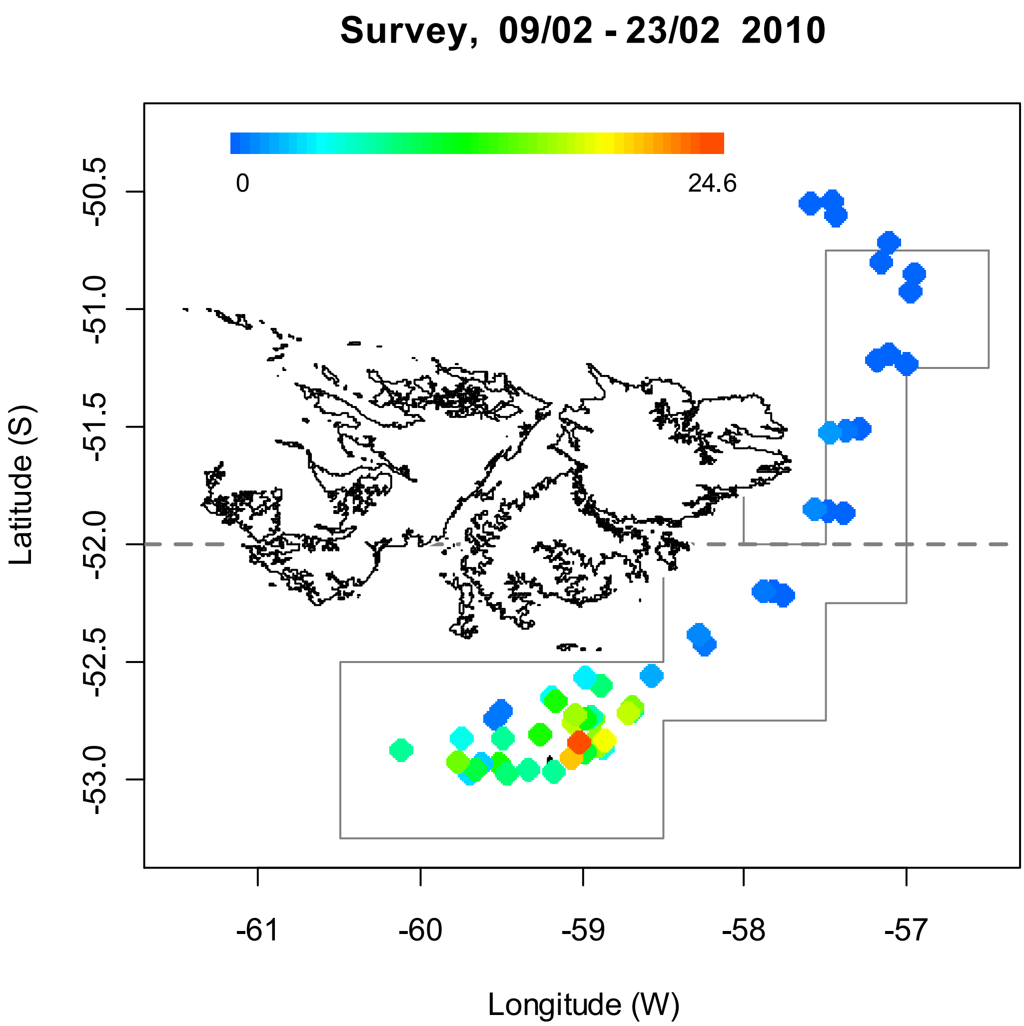

Figure 1. Spatial distribution of *Loligo* pre-season survey catches, scaled to catch weight (maximum = 24.6 tonnes). 55 catches are represented. The ‘Loligo Box’ fishing zone, as well as the 52 ºS parallel delineating the boundary between north and south assessment areas, are shown in gray.

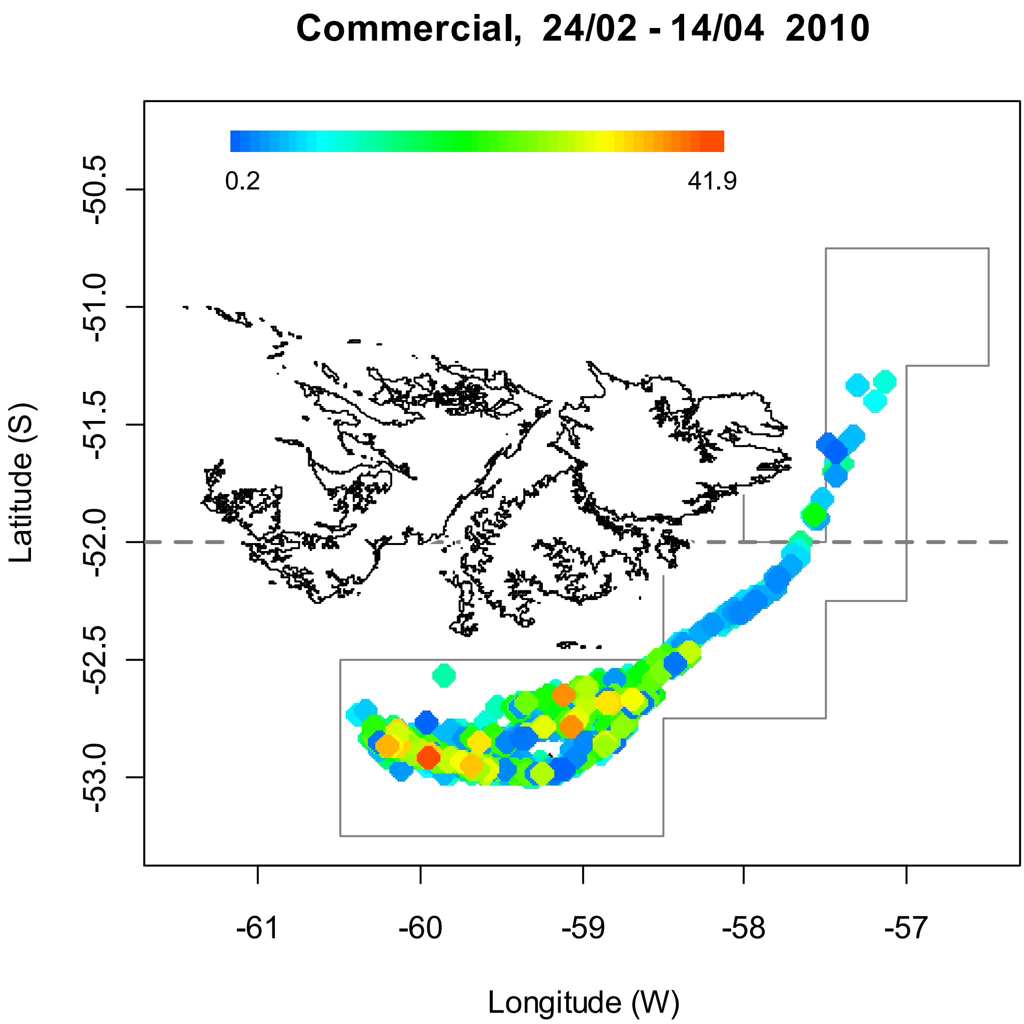

Figure 2. Spatial distribution of *Loligo* first-season commercial catches, scaled to catch weight (maximum = 41.9 tonnes). 2224 catches are represented. The 'Loligo Box' fishing zone, as well as the 52 ºS parallel delineating the boundary between north and south assessment areas, are shown in gray.

As in previous seasons (e.g., Payá, 2009; 2010), stock assessment for the first 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* squid) 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 set 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.

Stock assessment
Data

Between 13 and 16 vessels were operational in the *Loligo* fishery on any day, for a season total of 765 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. Two FIFD observers were deployed in the *Loligo* fishery for a total of 56 observer-days. Additionally, an observer assigned to the *Ilex* fishery reported *Loligo* data for one day. Through the total season of 50 days, 37 days had 1 observer covering, and 10 days had two observers. Three days had no observer coverage because of seasickness or port calls. Observers sampled several hundred *Loligo* daily, and reported their maturity stages, sex, and lengths to 0.5 cm.

Depletion events

Start and end days of depletion events, following arrivals of new *Loligo* groups, were judged from daily changes in CPUE and in average individual mantle lengths (ML). CPUE was calculated as total tonnes caught per total hours fishing effort. Because the fishing fleet fluctuated, hours of effort were standardized according to vessels' rated fishing power (Payá et al., 2009). Average MLs were obtained from commercial and observer data. Commercial average MLs are relatively imprecise, but cover the entire fishing fleet. Observer average MLs are scientifically precise, but restricted to one or two vessels that may or may not be representative of the entire fleet. Therefore, both sources of data were examined. Commercial average MLs were back-calculated from the proportion of product weight that vessels reported per market size category. Observer average MLs were calculated from the means of daily sampled lengths.

In the southern area (south of 52 ºS), four depletion events were identified according to these criteria. The time series of CPUE, commercial average ML, and observer average ML are shown in Figure 3. Consecutive days in Figure 3 are joined by line segments, and for illustration, overlaid on the 95% confidence interval of the GAM trend of each parameter vs. the day count (in gray; GAM = generalized additive model; Hastie and Tibshirani, 1990). The depletion events are highlighted by coloured fields.

- The first depletion event was considered to have started on day 58 (Feb. 27; three days after season opening) and ended on day 69. On day 58 commercial average ML decreased while observer average ML increased (indicating that length variability was increasing), and CPUE started to decrease the next day. On day 69 CPUE, commercial average ML, and observer average ML all started to increase for at least 4 consecutive days.
- The second depletion event started on day 72 and ended on day 77. On day 72, commercial average ML showed a slight decrease after 3 days' increase, and CPUE started to decrease the next day. On day 77, CPUE started to increase after 4 consecutive days of decrease.
- The third depletion event started on day 81 and ended on day 94. On day 81 CPUE and commercial average ML decreased after periods of increase. On day 94 CPUE started to increase, and both commercial and observer average ML were noticeably higher than on the previous days.
- The fourth depletion event started on day 96 and was considered to continue through the end of the season (day 104). On day 96 CPUE, commercial average ML, and observer average ML all started decreases.

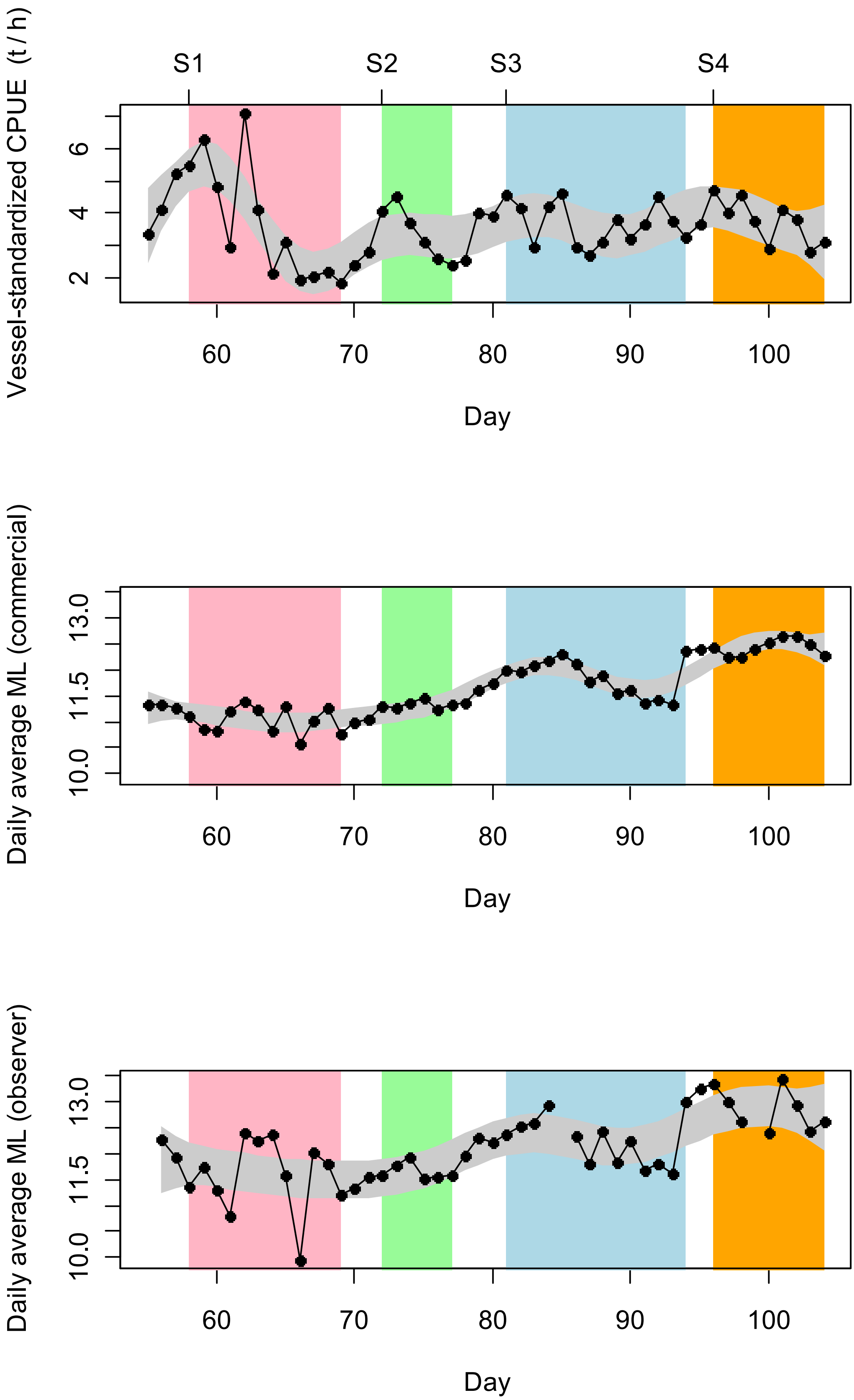

Figure 3. Season daily time series south of 52 ºS. Description of plots on page 6.

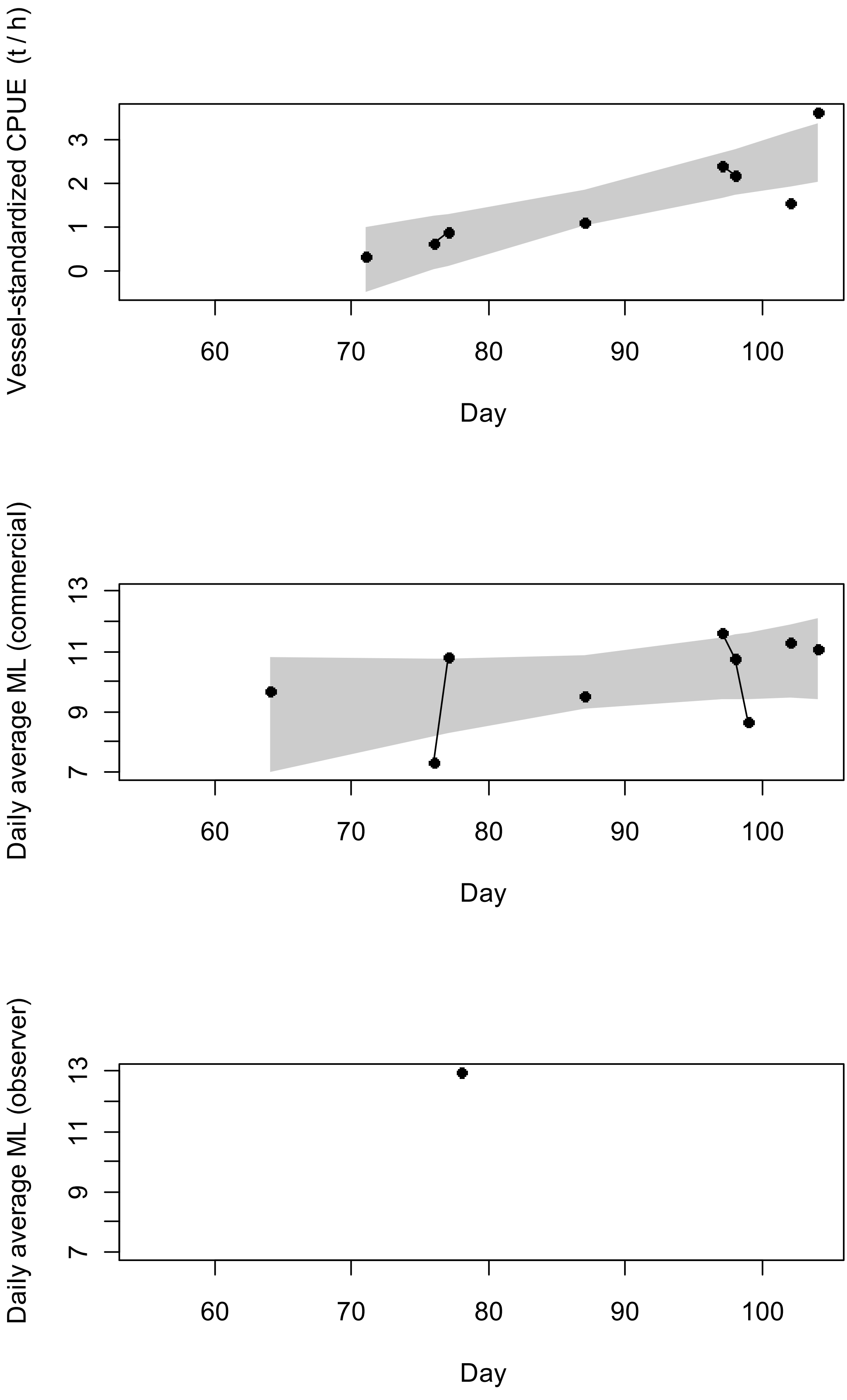

Figure 4. Season daily time series north of 52 ºS. Description of plots on page 9.

In the northern area (north of 52 ºS), fishing effort was too sparse to validate attempts at distinguishing different arrival and depletion events. Therefore, only a single *Loligo* group since the start of the season was assumed. The time series of CPUE, commercial average ML, and observer average ML are shown in Figure 4. Consecutive days in Figure 4 are joined by line segments and for illustration, overlaid on the 95% confidence interval of the GLM trend of each parameter vs. the day count (in gray; GLM = generalized linear model; McCullagh and Nelder, 1989; data were too sparse for GAM).

Depletion model

The formulation of the depletion model has been described previously (e.g., Payá, 2007b). In some previous seasons' *Loligo* assessments, all depletion events were included as components of a single model, with the assumption of equal catchability coefficients during the different depletion events (Payá, 2007a). In the present stock assessment, depletion events were modelled separately to reduce the complexity of the models and thereby reduce the risk of converging models on local optima rather than on global optima. The equivalence of catchability coefficients (indices of vessel catch efficiency; Hilborn and Walters, 1992) was evaluated a posteriori. Three chains of 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.

1st south depletion

For the first depletion event south of 52º S, the Bayesian prior was based on the pre-season survey. The kriging model used by Arkhipkin et al. (2010) predicted a total biomass of 60,500 tonnes with a standard error of ±3,835 tonnes. However, analyses of acoustic backscatter during previous surveys have suggested that 20 to 45% of *Loligo* biomass may escape from bottom trawls by swimming higher in the water column. Payá (2010) assumed a survey catchability of 78% (i.e., 22% escapement). Based on these precedents, we defined the total season-starting biomass (B_0) as the survey estimate of 60,500 tonnes with a coefficient of variation of 7% (kriging model) + 22% (escapement variability). Thus:

B_0: 60,500 ± (7% + 22%) = 60,500 ± 17,545 tonnes.

This starting biomass was split between the northern and southern areas according to the proportions of areal distribution modelled in the pre-season survey (Arkhipkin et al., 2010). In the pre-season survey, 3% of *Loligo* biomass occurred north of 52º S and 97% of *Loligo* biomass occurred south of 52º S. Thus:

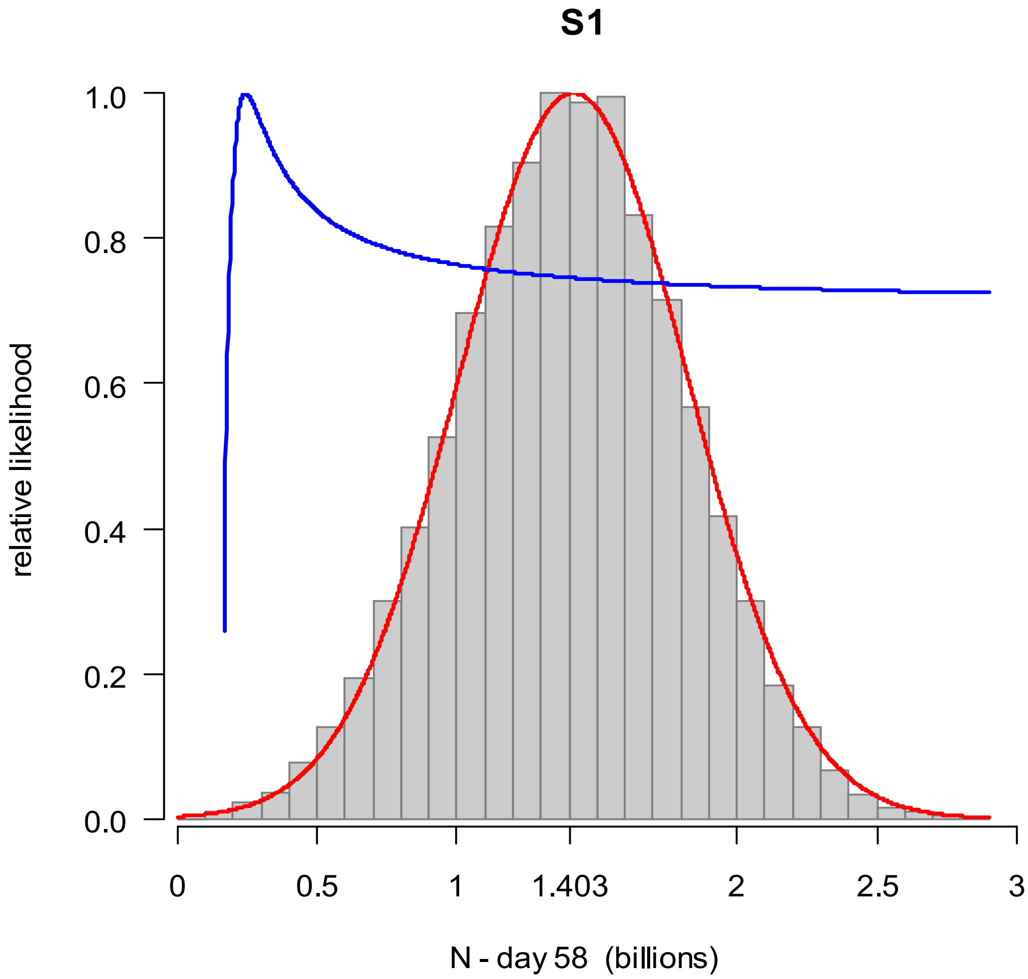

Figure 5. Likelihood distributions for numbers of *Loligo* south of 52º S on day 58 (Feb. 27), for the depletion event from day 58 to day 69. Red line: prior, blue line: depletion model, gray bars: posterior estimate.

N B_0:	60,500 ± 17,545 tonnes × 3%	= 1,815 ± 526 tonnes.
S B_0:	60,500 ± 17,545 tonnes × 97%	= 58,685 ± 17,019 tonnes.

Starting numbers of *Loligo* were converted from biomass using the average individual weights calculated during the survey: 0.0380 ± 0.0003 kg in the north and 0.0393 ± 0.0001 kg in the south. Thus:

N N_0:	1,815 ± 526 t × 0.0380 ± 0.0003 kg^{-1}	= 0.048 ± 0.014 × 10^9.
S N_0:	58,685 ± 17,019 t × 0.0393 ± 0.0001 kg^{-1}	= 1.493 ± 0.433 × 10^9.

The first depletion event was considered to have started on day 58, four days after the end of the survey. Accordingly, the prior for *Loligo* numbers on this day was depreciated by four days' mortality, using the mortality parameter of 0.0133 day^{-1} (Roa-Ureta and Arkhipkin, 2007):

S1 N_{prior}: $1.493 \pm 0.433 \times 10^9 \times e^{(-0.0133 \times 4 \text{ days})} = 1.416 \pm 0.411 \times 10^9$.

The prior was assumed normally distributed, and therefore distributed symmetrically around the value of 1.416 billion *Loligo* on day 58 (Figure 5). In contrast, the likelihood of the depletion model itself reached maximum at the much lower count of 0.243 billion *Loligo*, but decreased only slowly with increasing counts and was still, for example, about 72% of maximum at a count of 3 billion *Loligo*. Because of this lack of selectivity in the depletion model, the posterior distribution, calculated with the MCMC, was almost entirely driven by the prior (Figure 5). The maximum likelihood posterior estimate for *Loligo* numbers on day 58 was $1.403 \pm 0.408 \times 10^9$.

2nd south depletion

For the second depletion event south of 52º S, starting on day 72, the prior could not be based on the pre-season survey, since it is assumed that this depletion involved a different group of squid. Instead, it was inferred that with essentially the same fleet fishing in the same area, the ratio of CPUE (day 72) / CPUE (day 58) should be proportional to the ratio biomass (day 72) / biomass (day 58). CPUE were taken from the GAM trend shown in the top panel of Figure 3: 5.352 ± 0.329 t hr^{-1} on day 58, and 3.219 ± 0.339 t hr^{-1} on day 72. To convert biomass to numbers, a GAM trend of daily average individual weights, derived from the mantle lengths, was also calculated (not shown): 0.0414 ± 0.0011 kg on day 58 and 0.0432 ± 0.0007 kg on day 72. Numbers of *Loligo* on day 58 were given by the maximum likelihood posterior of the 1st depletion event: $1.403 \pm 0.408 \times 10^9$. Thus, the prior estimate for *Loligo* numbers on day 72 (intermediate standard errors omitted for clarity) was:

S2 N_{prior}: $1.403 \times 10^9 \times (3.219/5.352) \times (0.0414/0.0432) = 0.809 \pm 0.256 \times 10^9$.

The prior, depletion model likelihood, and posterior distribution are shown on Figure 6. The likelihood of the depletion model reached maximum at 0.172 billion *Loligo*, and became asymptotic with high *Loligo* counts at about 83% of maximum. As a result, the posterior distribution, calculated with the MCMC, was again almost entirely driven by the prior and equated a final estimate for *Loligo* numbers on day 72 of $0.805 \pm 0.255 \times 10^9$. Note that this final estimate represents the number of all *Loligo* in the southern area on day 72, not just the number having arrived in the second wave.

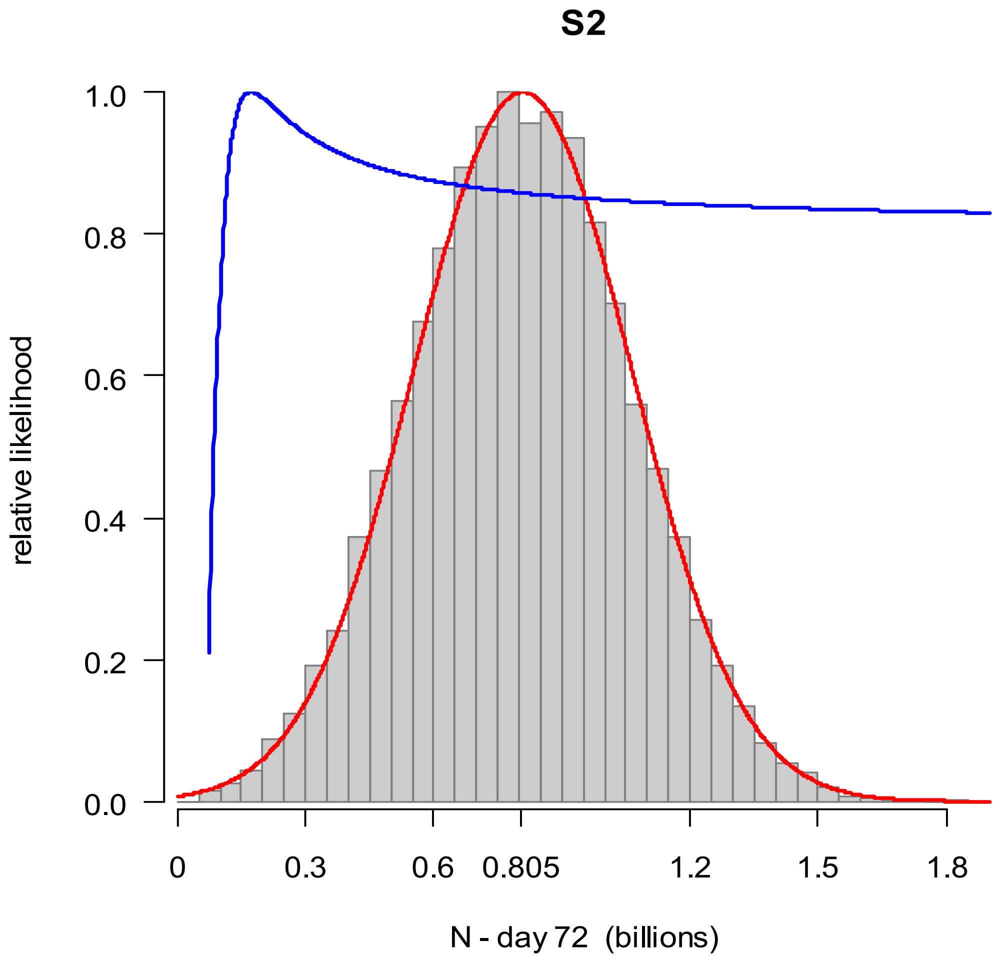

Figure 6. Likelihood distributions for numbers of *Loligo* south of 52º S on day 72 (Mar. 13), for the depletion event from day 72 to day 77. Red line: prior, blue line: depletion model, gray bars: posterior estimate.

3rd south depletion

For the third depletion event south of 52º S, starting on day 81, the prior was again inferred from the ratios of CPUE and average individual weights vs. day 58. CPUE on day 81 was 3.745 ± 0.335 t hr^{-1}, and average individual weight was 0.0452 ± 0.0007 kg. Thus, the prior estimate for *Loligo* numbers on day 81 was:

S3 N_{prior}: $1.403 \times 10^9 \times (3.745/5.352) \times (0.0414/0.0452) = 0.899 \pm 0.281 \times 10^9$.

The prior, depletion model likelihood, and posterior distribution are shown on Figure 7. In this case the depletion model failed to converge, as evident by its continuing increase of likelihood over the entire range of *Loligo* numbers tested. This is not surprising, as the top panel of Figure 3 shows practically no net decrease in CPUE over the range from day 81 to day 94. Calculation of a posterior distribution is therefore spurious and only the S3 prior itself can be considered a meaningful estimate of *Loligo* numbers.

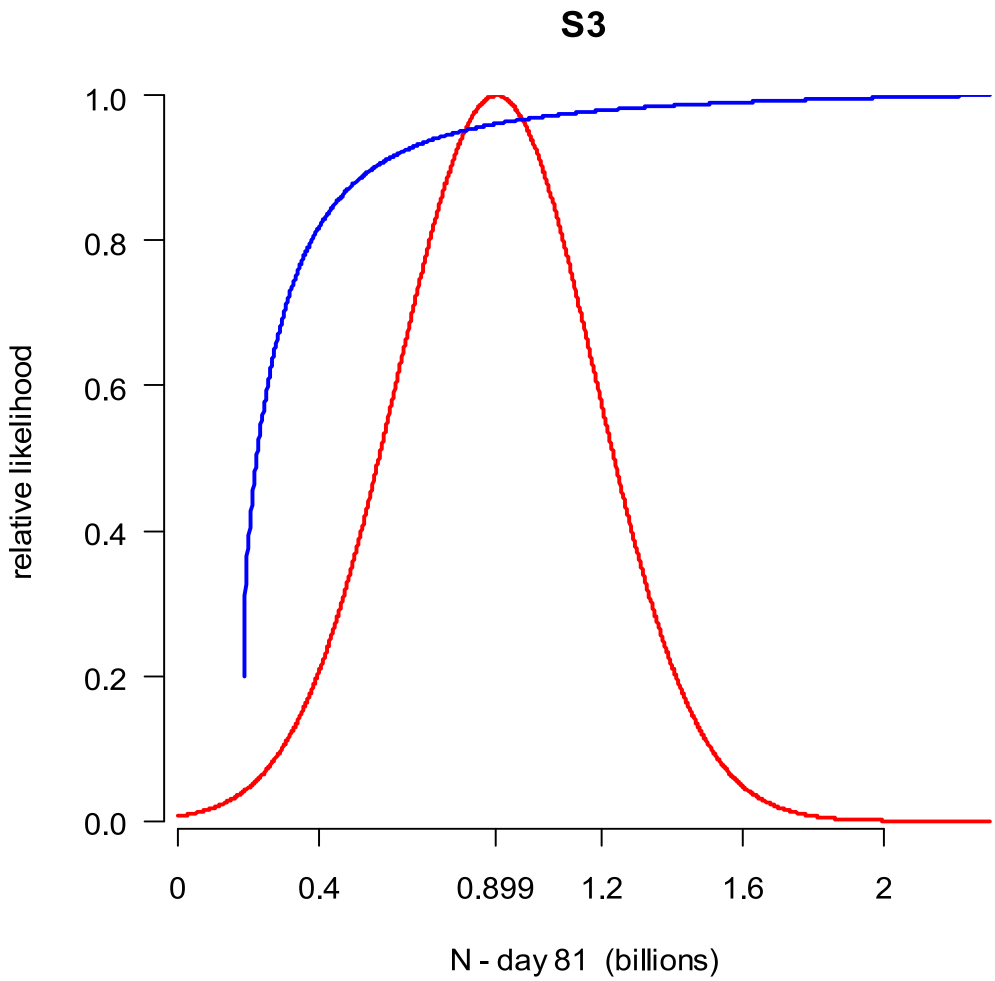

Figure 7. Likelihood distributions for numbers of *Loligo* south of 52º S on day 81 (Mar. 22), for the depletion event from day 81 to day 94. Red line: prior, blue line: depletion model. A posterior estimate is not shown due to the failure of the depletion model to converge.

4th south depletion

For the fourth depletion event south of 52º S, starting on day 96, CPUE and average individual weight on the starting day were: 4.179 ± 0.319 t hr^{-1} and 0.0491 ± 0.0008 kg. Thus, the prior estimate for *Loligo* numbers on day 96 was:

S4 N_{prior}: $1.403 \times 10^9 \times (4.179/5.352) \times (0.0414/0.0491) = 0.924 \pm 0.285 \times 10^9$.

The prior, depletion model likelihood, and posterior distribution are shown on Figure 8. The likelihood of the depletion model reached maximum at 0.378 billion *Loligo*, but decreased from the maximum by less than 3% as *Loligo* counts increased. Therefore the maximum likelihood posterior estimate for *Loligo* numbers on day 96 was essentially equivalent to the prior, at $0.925 \pm 0.284 \times 10^9$.

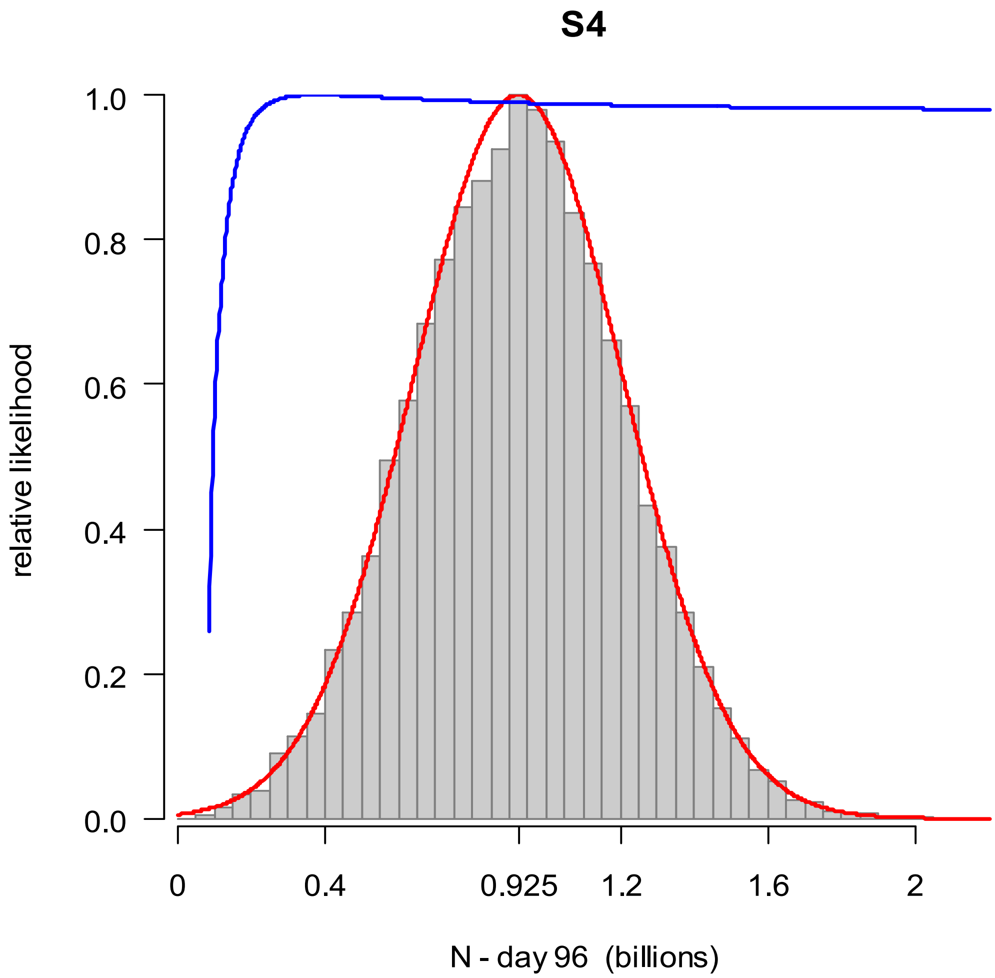

Figure 8. Likelihood distributions for numbers of *Loligo* south of 52º S on day 96 (Apr. 6), for the depletion event from day 96 to day 104. Red line: prior, blue line: depletion model, gray bars: posterior estimate.

South depletion summary

The starting day *Loligo* count estimates for each depletion event were projected forward with catch deductions to the starting day of the next depletion, through every day of the season (Figure 9). The first three days of the season, before the start of the 1st depletion event, were projected forward from the end of the survey. The model outcomes, as shown on Figure 9, suggest that the 2nd depletion event, starting on day 72, may have been illusive: the *Loligo* count estimate on this day is actually lower than on the previous day projected from the previous depletion. This possibility has support in the progression of average individual MLs: neither the commercial MLs nor the observer MLs show any real discontinuity on that day (lower two panels on Figure 3). The other two depletion event transitions estimate that $0.290 \pm 0.368 \times 10^9$ *Loligo* immigrated to the southern fishing area on or around day 81, and $0.368 \pm 0.370 \times 10^9$ *Loligo* immigrated to the southern fishing area on or around day 96, for a total of $0.658 \pm 0.522 \times 10^9$. Alternatively, to circumvent the 'deficit' of the 2nd depletion event, it may be inferred that total immigration is the difference between catch plus remaining squid, and the numbers of initial squid reduced by natural mortality alone. Thus:

S C_{total}: (in-season assessment; assuming 1.6% c.v.) $= 0.635 \pm 0.010 \times 10^9$.
S N_{final} (S4): (projection of 4th depletion to day 104) $= 0.754 \pm 0.255 \times 10^9$.

S N_{final} (M): $1.493 \pm 0.433 \times 10^9 \times e^{(-0.0133 \times 50 \text{ days})}$ $= 0.768 \pm 0.223 \times 10^9$.

Immigration: $0.635 + 0.754 - 0.768$ $= 0.621 \pm 0.339 \times 10^9$.

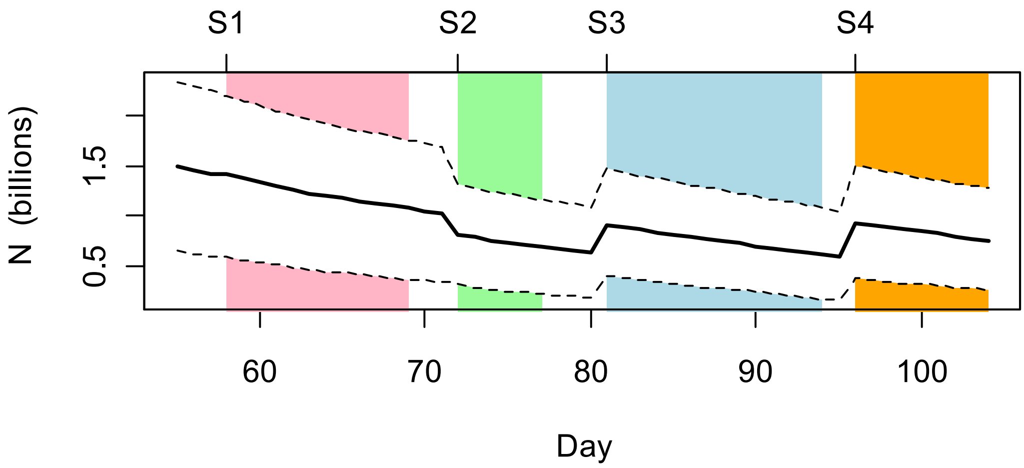

Figure 9. Depletion-modelled estimates of *Loligo* numbers by day south of 52º S; ± 95% confidence intervals. The depletion events are shown as coloured fields.

Catchability coefficients derived from the MCMC were: $0.72 \pm 1.27 \times 10^{-4}$, $1.35 \pm 8.17 \times 10^{-4}$, $1.71 \pm 4.11 \times 10^{-4}$, and $0.98 \pm 4.44 \times 10^{-4}$ respectively for depletion events S1, S2, S3, and S4. Differences among catchability coefficients were statistically significant and suggest that vessels fished progressively more efficiently until about the last 9 days of the season.

North depletion summary

As noted above, the low amount of data from the fishing area north of 52º S could not justify inferences of different arrival / depletion events throughout the season. Therefore, estimation of *Loligo* numbers present at the end of the season was based on the starting numbers (from the survey):

N N_0: $1{,}815 \pm 526$ t $\times 0.0380 \pm 0.0003$ kg^{-1} $= 0.048 \pm 0.014 \times 10^9$.

N N_0 was projected forward with catch deductions through every day of the season (Figure 10). The estimate of *Loligo* numbers in the north on the final day of the season was $0.022 \pm 0.007 \times 10^9$.

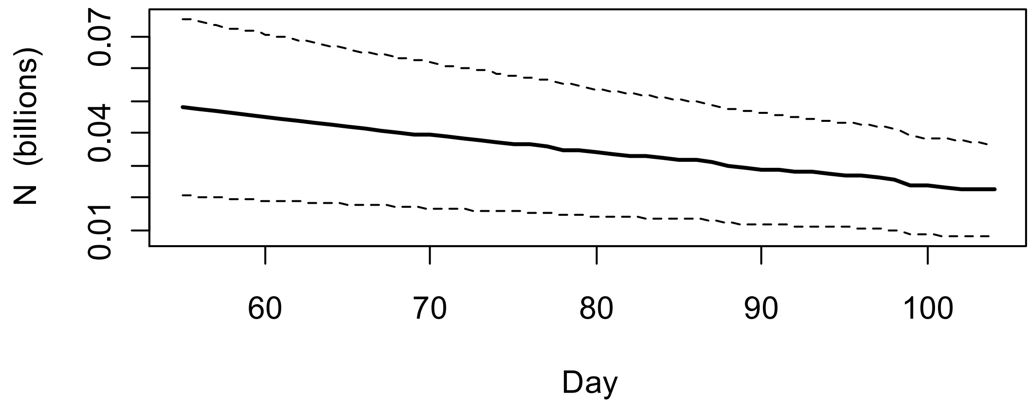

Figure 10. Depletion-modelled estimates of *Loligo* numbers by day north of 52º S; ± 95% confidence intervals.

Escapement biomass and total catch rate

The estimated numbers of *Loligo* in the southern and northern fishing areas at the end of the season (day 104; April 14) were converted to biomass using the respective GAM trends of daily average individual weights. The GAM trends predicted average individual weights on day 104 of 0.0358 ± 0.0045 kg in the north and 0.0512 ± 0.0013 kg in the south. These average individual weights were multiplied by the *Loligo* numbers, randomly permuted, then south and north added together. The resulting probability distribution of total season-end biomass is shown on Figure 11. The central expectation of this distribution is a biomass of 39,375 tonnes, with a 1.1% risk of the actual biomass being less than the 10,000 tonne escapement limit.

Using the more conservative estimate of $0.621 \pm 0.339 \times 10^9$ in-season squid immigrants (see 'South depletion summary', above), and assuming that 44% of these immigrated on day 81 and 56% on day 96, the immigration biomass is:

$44\% \times 0.621 \pm 0.339 \times 10^9 \times 0.0452 \pm 0.0007$ kg squid^{-1} +
$56\% \times 0.621 \pm 0.339 \times 10^9 \times 0.0491 \pm 0.0008$ kg squid^{-1} = 29,425 ± 11,509 tonnes.

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

60,500 ± 17,545 tonnes + 29,425 ± 11,509 tonnes = 89,925 ± 20,983 tonnes.

Giving a total catch rate: 28,754 t / 89,925 ± 20,983 t = 32 ± 7.5%

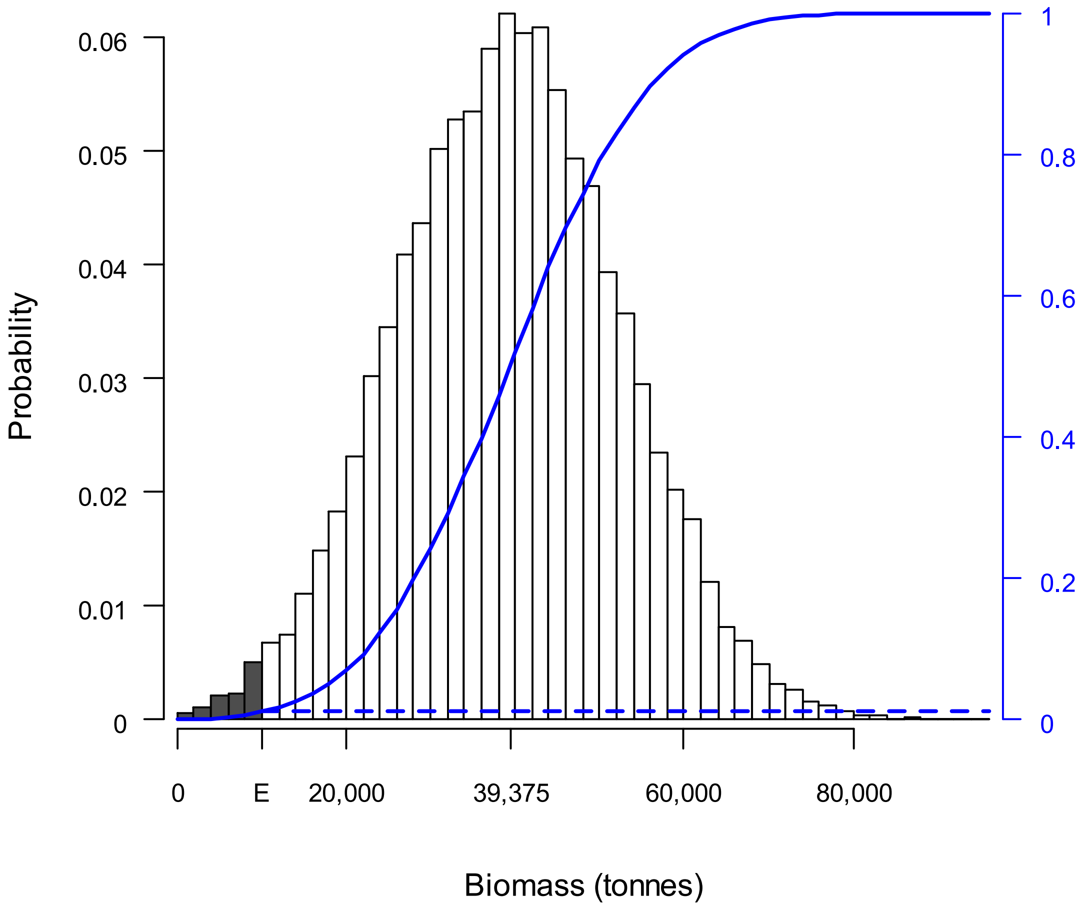

Figure 11. Probability distribution of *Loligo* biomass at the end of the season, April 14. Distribution samples less than the minimum biomass escapement limit of 10,000 tonnes (“E”) are shaded dark gray. Cumulative probability is shown as a solid blue curve. The broken blue line indicates that the probability of less than 10,000 tonnes biomass is 0.011.

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