Falkland Islands Fisheries Department

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# *Loligo* Stock Assessment, First Season 2013

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## Summary

1) The first season *Loligo* fishery of 2013 was open for the scheduled 50 days from February 24th to April 14th, plus an extension of 3 days until April 17th for vessels that had optionally started up to 3 days later. 19,908 tonnes of *Doryteuthis gahi* catch were reported; an intermediate amount compared to previous first seasons. 34.9% of *D. gahi* catch and 31.7% of effort were taken south of 52.5º S, 64.8% of *D. gahi* catch and 67.5% of effort were taken north of 51.5º S, and less than 1% in the central region of the Loligo Box.
2) Sub-areas north and south of 52º S were depletion-modelled separately. In the north sub-area, 3 in-season depletion periods were inferred to have started on March 3rd, March 15th, and April 1st. In the south sub-area, 3 in-season depletion periods were inferred to have started on March 17th, March 27th, and April 7th.
3) Approximately 28,500 tonnes of *D. gahi* (95% confidence interval: [19,868 to 69,845] tonnes) were estimated to have immigrated into the Loligo Box during first season 2013, representing 85% of the *D. gahi* biomass in the fishing zone.
4) The final total estimate for *D. gahi* remaining in the Loligo Box at the end of first season 2013 was:
   Maximum likelihood of 13,500 tonnes, with a 95% confidence interval of [5341 to 55,116] tonnes.
   The risk of *D. gahi* escapement biomass at the end of the season being less than 10,000 tonnes was estimated at 10.15%.

## Introduction

The first season of the 2013 *Loligo* fishery (*Doryteuthis gahi* – Patagonian squid) started on February 24th with 11 vessels participating. Five vessels took the option of starting (and ending) the season later under the new flex rule: two vessels started on February 25th, one on February 26th, and two on February 27th. The vessel conducting the pre-season survey was still surveying on February 24th (Winter et al., 2013). However, that vessel on that day was surveying outside the Loligo Box and therefore its catch for the 24th was not included in the season depletion model. The season was ended by directed closure on April 14th, and 1, 2, or 3 days later for those vessels that had started later. Total reported catch by C-licensed vessels was 19,908 tonnes *D. gahi*, an intermediate amount compared to previous first seasons (Table 1).

As in previous seasons, the *D. gahi* stock assessment was conducted with depletion time-series models (Agnew et al., 1998; Roa-Ureta and Arkhipkin, 2007; Arkhipkin et al., 2008). Because *D. gahi* 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 *D. gahi* groups arrive in successive waves after the start of the season (Roa-Ureta, 2012). 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 squid grow. When instead these data change suddenly, or in contrast to expectation, the immigration of a new group to the population is indicated.

Table 1. *Loligo* season catch comparisons since 2004. Days: total number of calendar days open to licensed *Loligo* fishing including (since 1st season 2013) extension days; V-Days: aggregate number of licensed *Loligo* fishing days reported by all vessels for the season.

| | Season 1 | | | Season 2 | | |
|---|---|---|---|---|---|---|
| | Catch (t) | Days | V-Days | Catch (t) | Days | V-Days |
| 2004 | | | | 17,559 | 78 | 1271 |
| 2005 | 24,605 | 45 | 576 | 29,659 | 78 | 1210 |
| 2006 | 19,056 | 50 | 704 | 23,238 | 53 | 883 |
| 2007 | 17,229 | 50 | 680 | 24,171 | 63 | 1063 |
| 2008 | 24,752 | 51 | 780 | 26,996 | 78 | 1189 |
| 2009 | 12,764 | 50 | 773 | 17,836 | 59 | 923 |
| 2010 | 28,754 | 50 | 765 | 36,993 | 78 | 1169 |
| 2011 | 15,271 | 50 | 771 | 18,725 | 70 | 1099 |
| 2012 | 34,767 | 51 | 770 | 35,026 | 78 | 1095 |
| 2013 | 19,908 | 53 | 782 | | | |

In the event of a new group arrival, the depletion calculation is modified to account for this influx. This can be done two ways: (1) by a sequential algorithm that re-starts the depletion time-series on the date of a new group arrival (Roa-Ureta and Arkhipkin, 2007), allowing for different catchability coefficients in the different periods of the depletion time-series, or (2) by a simultaneous algorithm (Roa-Ureta, 2012) that adds new arrivals on top of the stock previously present, and assumes a common catchability coefficient for the entire depletion time-series. The main purpose of *D. gahi* assessment is to estimate the season-end biomass, in relation to the escapement threshold of 10,000 tonnes (Agnew et al., 2002; Barton, 2002). Therefore in practice only the most recent sequence of the depletion time-series is of concern when using modelling approach (1) (sequential algorithm). The basic form of the DeLury depletion model corresponding to this approach can be written as:

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

where q is the catchability coefficient, M is natural mortality, considered constant at 0.0133 $day^{-1}$ (Roa-Ureta and Arkhipkin, 2007), and $C_{day}$, $E_{day}$, $N_{day}$ are catch (numbers of *D. gahi*), fishing effort, and abundance (numbers of *D. gahi*) per day. The sequence 'per day' starts with the day that depletion is considered to have started, or that the most recent *D. gahi* group arrived. If two depletions are included in the same model, corresponding to approach (2) (simultaneous algorithm), then:

$$C_{day} = q \times E_{day} \times (N1_{day} + (N2_{day} \times i2\big|_0^1)) \times e^{-M/2} \quad \textbf{(2)}$$

where i2 is a dummy variable taking the values 0 or 1 if 'day' is before or after the start day of the second depletion. For more than two depletions, $N3_{day}$, i3, $N4_{day}$, i4, etc., would be included following the same pattern.

The original form of the DeLury depletion model proposed a linear relationship of catch vs. fishing effort and abundance, which means that if effort or abundance is doubled then – all else being equal – catch will double. But in reality, the relationships may depart from linearity. Increases in effort can elicit diminishing returns. Increases and decreases in abundance can increase or decrease relative catchability, depending on habitat conditions or the behaviour of the squid. To relate this nonlinearity in the model, the catch equation can be expanded (taking equation (2) for example) as:

$$\mathrm{C}_{\mathrm{day}} \qquad = \mathrm{q} \times \mathrm{E}_{\mathrm{day}}{}^{\alpha} \times (\mathrm{N1}_{\mathrm{day}}{}^{\beta} + (\mathrm{N2}_{\mathrm{day}}{}^{\beta} \times \mathrm{i2}\big|_0^1)) \times \mathrm{e}^{-\mathrm{M}/2} \qquad \textbf{(3)}$$

where α and β are respectively the effort and abundance hyper-parameters: α < 1 reflects effort saturability in the fishery, α > 1 effort synergy, β < 1 reflects hyperstability of the target stock and β > 1 hyperdepletion (Roa-Ureta, 2012). All approaches to the model (simultaneous or sequential; with or without hyper-parameters) have advantages and disadvantages. The simultaneous algorithm uses more of the available data (Roa-Ureta, 2012), but if depletion does not develop until the later part of the season then the model will be poorly specified by fitting early data that contribute little information to the final outcome. Hyper-parameters relax the assumption of linearity, but increase the required degrees of freedom and may distort the effects of the primary parameters. All approaches were tested and the most suitable ones selected for the *Loligo* stock assessment.

## Methods

Previous *Loligo* stock assessments (e.g., Winter, 2012a, b) were calculated in a Bayesian framework whereby results of the depletion model are conditioned by prior information on the stock from the pre-season survey. In the current season, the survey ending February 24th estimated a low biomass of only 5333 tonnes *D. gahi* (Winter et al., 2013) which is unrepresentative for what turned out to be an average commercial season (Table 1). For the second season in a row (cf. Winter, 2012c), survey biomass was therefore not used as a Bayesian prior, and likelihood of the depletion models was instead calculated directly by optimizing the log difference between actual catch numbers and predicted catch numbers per day, in log scale. Because of the added variability in fishing effort resulting from the flexibility in season start and end days – implemented for the first time this season – differences per day were weighted by the number of vessels fishing, and the output likelihood profile was statistically corrected by a factor relating to the number of days of the depletion period (Roa-Ureta, 2011):

$$\left((n\mathrm{Days} - 2)/2\right) \times \log\left(\sum_{days}\left(\log\left(\mathrm{predicted\ C}_{\mathrm{day}}\right) - \log\left(\mathrm{actual\ C}_{\mathrm{day}}\right)\right)^2 \times n\mathrm{V}_{\mathrm{day}}\right) \qquad \textbf{(4)}$$

The optimization gives values for the parameters q, $\mathrm{N}_{\text{start day}}$ (of however many depletions in the model) and if used α and β.

Distributions of the likelihood estimates of these parameters (i.e., measures of their statistical uncertainty) were computed using Markov Chain Monte Carlo (MCMC) (Gamerman and Lopes, 2006), a recommended method for fisheries assessments (Magnusson et al., 2012). MCMC is an iterative method which generates random stepwise changes to the proposed outcome of a model (in this case, the number of *D. gahi*) 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. The MCMC of the depletion models were run for 1,000,000 iterations; the first 1000 iterations were discarded as burn-in sections (initial phases over which the algorithm stabilizes); and the chains were thinned by a factor of 10 to reduce serial correlation (only every tenth iteration was retained). For each model three chains were run; one chain initiated with the parameter values obtained from optimizing equation (4) in the given model version, one chain initiated with these parameters ×2, and one chain initiated with these parameters ×¼.

The estimate of *D. gahi* numbers on the final day of a time series is calculated as the numbers N of the depletion start days discounted for natural mortality during the intervening period, and subtracting cumulative catch also discounted for natural mortality (CNMD). Taking for example a two-depletion period:

$$N_{\text{final day}} = N1_{\text{start day 1}} \times e^{-M\,(\text{final day} - \text{start day 1})} + N2_{\text{start day 2}} \times e^{-M\,(\text{final day} - \text{start day 2})} - CNMD_{\text{final day}} \quad \textbf{(5)}$$

where

$$CNMD_{\text{day 1}} = 0$$

$$CNMD_{\text{day x}} = CNMD_{\text{day x-1}} \times e^{-M} + C_{\text{day x-1}} \times e^{-M/2} \quad \textbf{(6)}$$

$N_{\text{final day}}$ is then multiplied by the expected individual weight of *D. gahi* on the final day to give biomass. Expected individual weight is calculated using generalized additive models (GAM) applied to the time series of daily average individual sizes. Daily average individual sizes are obtained from mantle lengths measured in-season by observers, and also derived from in-season commercial data as the proportion of product weight that vessels reported per market size category. Observer mantle lengths are scientifically precise, but restricted to 1-2 vessels at any one time that may or may not be representative of the entire fleet. Commercially proportioned mantle lengths are relatively imprecise, but cover the entire fishing fleet. Therefore, both sources of data were used. Daily average individual weights were calculated by averaging observer size samples and commercial size categories where observer data were available, otherwise only commercial size categories.

The likelihood distribution of final day biomass was computed by drawing random normal values with mean and standard deviation from the GAM calculation for individual biomass on the final day, multiplying these values by random draws of $N_{\text{final day}}$ from equation (5) applied to the $N_{\text{start}}$ outputs of the MCMC, and iterating the process for 6× the number of MCMC outputs. Maximum likelihood of the final day biomass was defined as the peak of the likelihood histogram with 1000-tonne intervals.

## Stock assessment

### Data

The pre-season survey caught its highest concentrations of *D. gahi* on the last day; inshore of the Loligo Box around 51.3° S 57.8° W. A few light concentrations of *D. gahi* were also caught in the Beauchêne sub-area, but the overall distribution suggested that most *D. gahi* had not yet out-migrated (Figure 1 and Winter et al., 2013). This was corroborated by water temperatures being colder than usual for the time of year (A. Arkhipkin, FIFD, personal communication). In-season catches were strongly polarized towards either the Beauchêne sub-area (south of 52.5° S and west of 58.5° W): 34.9% of *D. gahi* catch and 31.7% of effort, or north of 51.5° S: 64.8% of *D. gahi* catch and 67.5% of effort. Less than 1% of catch or effort occurred throughout the central part of the Loligo Box (Figure 2). Given this strong partition, sub-areas north and south of 52° S were depletion-modelled separately.

Between 2 and 16 vessels fished in the commercial season on any day (median = 16; Figure 3), for a total of 782 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.

Three FIFD observers were deployed on three vessels in the fishery for a total of 65 observer-days. Throughout the 53 days of the season, 5 days had no observer covering, 31 days had 1 observer covering, and 17 days had two observers covering. Each observer sampled an average of 426 *D. gahi* daily, and reported their maturity stages, sex, and lengths to 0.5 cm.

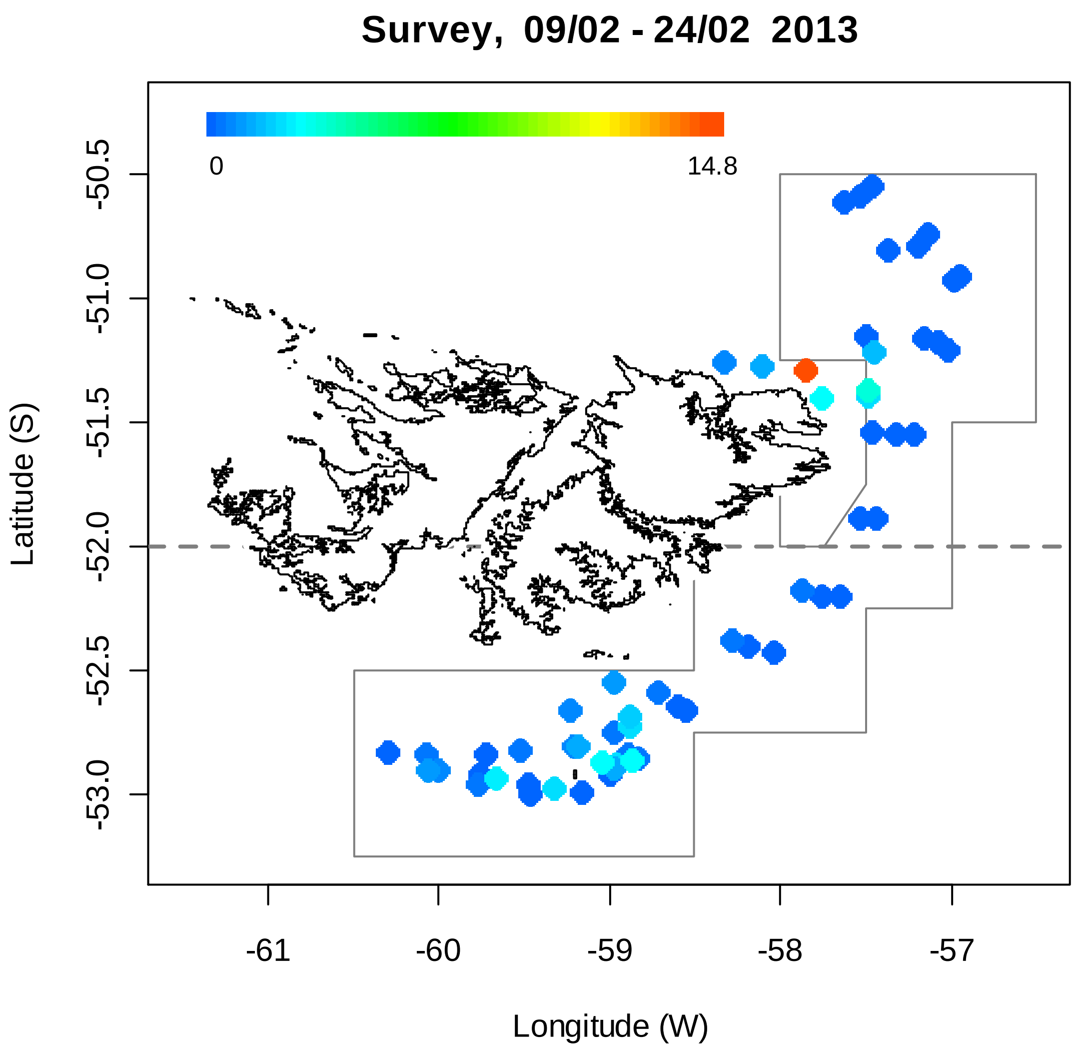
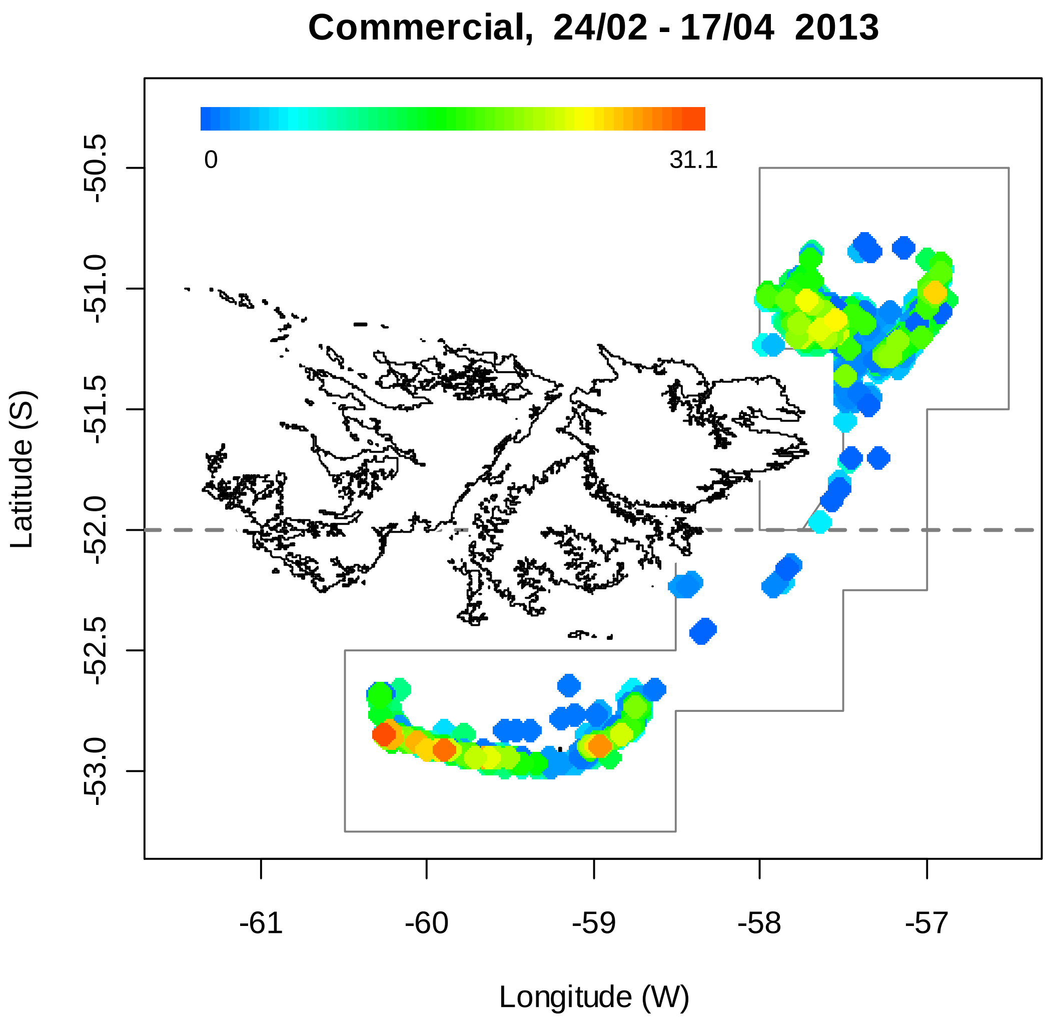



Figure 1. Spatial distribution of *D. gahi* 1st-season pre-season survey catches, colour-scaled to catch weight (maximum = 14.8 tonnes). Sixty catches are represented. The ‘Loligo Box’ fishing zone, as well as the 52 ºS parallel delineating the boundary between north and south assessment sub-areas, are shown in gray.

Figure 2 [below]. Spatial distribution of *D. gahi* 1st-season commercial catches, colour-scaled to catch weight (maximum = 31.1 tonnes). 2552 catches were taken during the season. The 'Loligo Box' fishing zone, as well as the 52 ºS parallel delineating the boundary between north and south assessment sub-areas, are shown in gray.




## Group arrivals / depletion criteria

Start and end days of depletions - following arrivals of new *D. gahi* groups - were judged primarily with reference to daily changes in CPUE, with additional information from sex proportions, maturity, and average individual *D. gahi* sizes. CPUE was calculated as metric tonnes of *D. gahi* 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 *D. gahi* sizes were expressed as weight (kg), converted from mantle lengths using the length-weight relationship $W = \alpha \cdot L^{\beta}$ (Froese, 2006). Length-weight measurements were not taken during this season's pre-season survey, so the relationship was inferred from data of the two preceding 1st seasons. A Monte Carlo test determined that the length-weight relationship was significantly different between

1st season 2011 and 1st season 2012; therefore their data were averaged. The resulting optimized relationship used for 1st season 2013 was:

$$\text{weight (kg)} = 0.2115716 \times length\ (cm)^{2.1627141} / 1000 \quad \textbf{(7)}$$

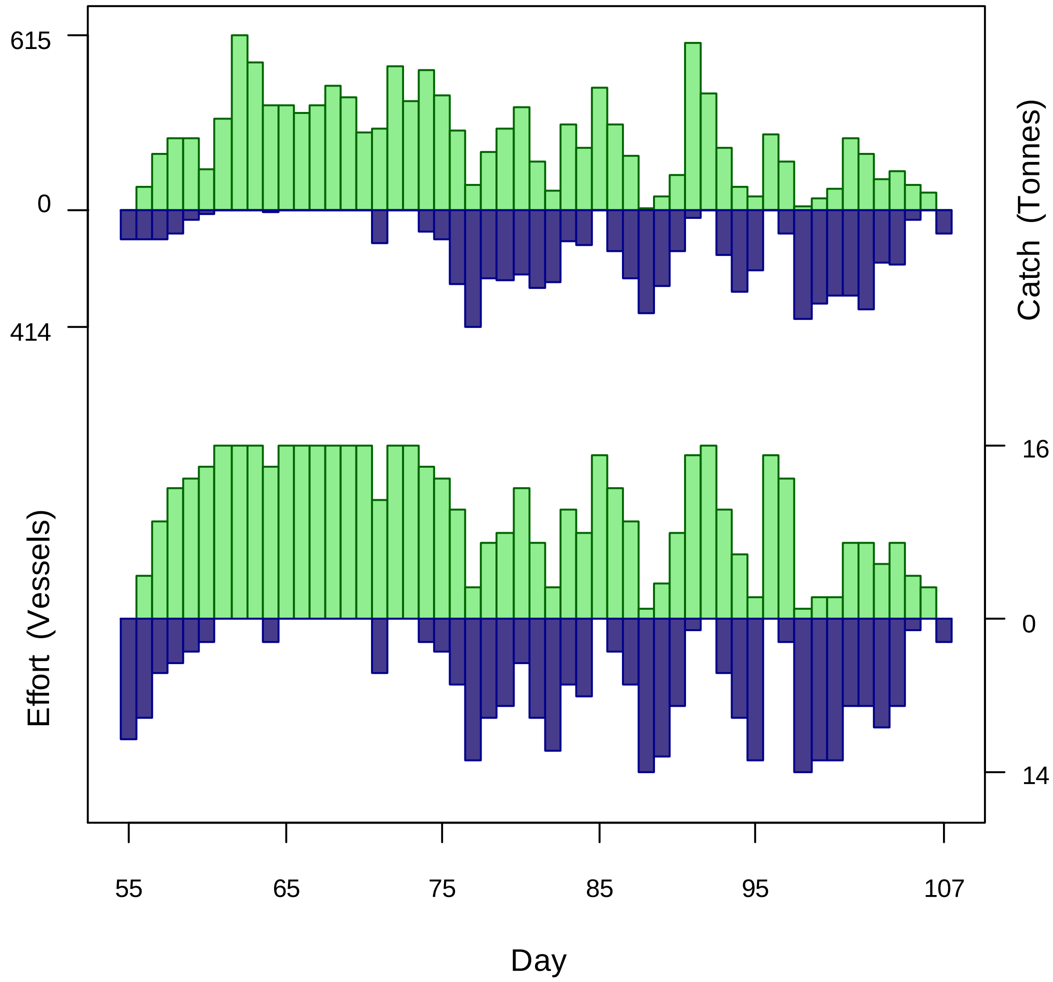



Figure 3. Daily total *D. gahi* catch and effort distribution by assessment sub-area north (green) and south (purple) of the 52º S parallel in the *Loligo* 1st season 2013. The season was open from February 24th (chronological day 55) to April 17th (chronological day 107). As many as 16 vessels fished per day north of 52º S; as many as 14 vessels fished per day south of 52º S. As much as 615 tonnes *D. gahi* was caught per day north of 52º S; as much as 414 tonnes *D. gahi* was caught per day south of 52º S.

The *D. gahi* data and CPUE time series showed considerable variability throughout the season. Three days in the north and three days in the south were identified that most plausibly represented the onset of separate depletions (Figures 4 and 5).

- The first in-season depletion north was identified on day 62 (3rd March), with a strong increase in CPUE over 2 days (Figure 4), a strong increase in the proportion of females from the day before (Figure 5), and a slight peak in average commercial weights from continuous-increasing 2 days before to continuous-decreasing 5 days after (Figure 5).

- The second in-season depletion north was identified on day 74 (15th March) as the culmination of an uneven increase in CPUE over 5 days (Figure 4), an increase in the proportion of females from the day before (Figure 5), and a small but continuous increase in average commercial weights over 8 days.
- The third in-season depletion north was identified on day 91 (1st April), with a strong increase in CPUE from the day before (the highest north CPUE of the season, Fig. 4), a strong increase in the proportion of females from the day before (Fig. 5), and an increase over 4 days in average commercial weights (Fig. 5).
- The first in-season depletion south was identified on day 76 (17th March), which was the first day that CPUE exceeded 25 tonnes vessel-day$^{-1}$ by more than 3 vessels fishing (Figure 4).
- The second in-season depletion south was identified on day 86 (27th March), which was the first day of higher CPUE after 4 days of decrease and 1 day of no fishing (Figure 4).
- The third in-season depletion south was identified on day 97 (7th April), which had the highest CPUE since day 86; and in particular following 3 days of decrease bracketed by 2 days of no fishing (Figure 4).

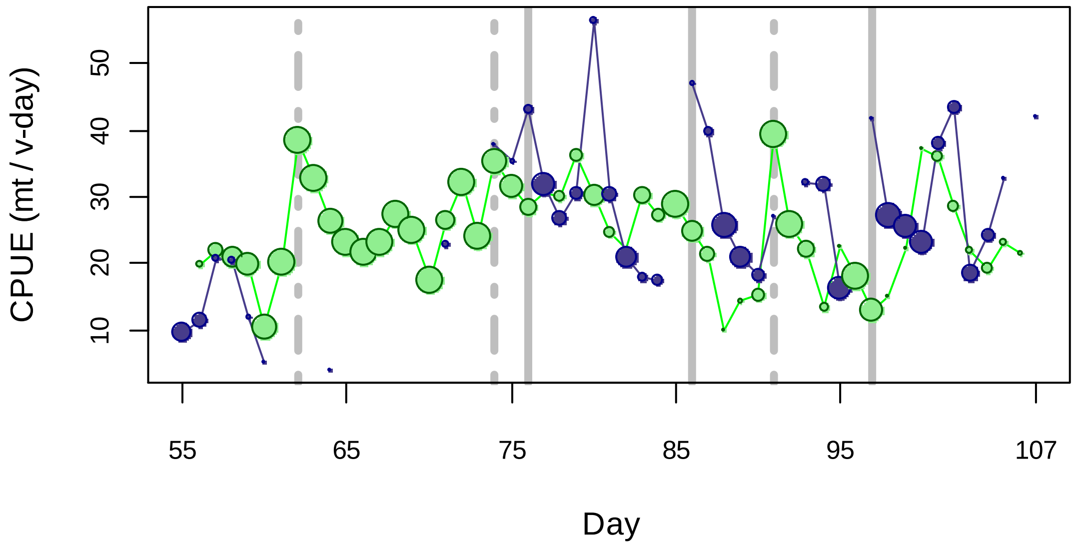
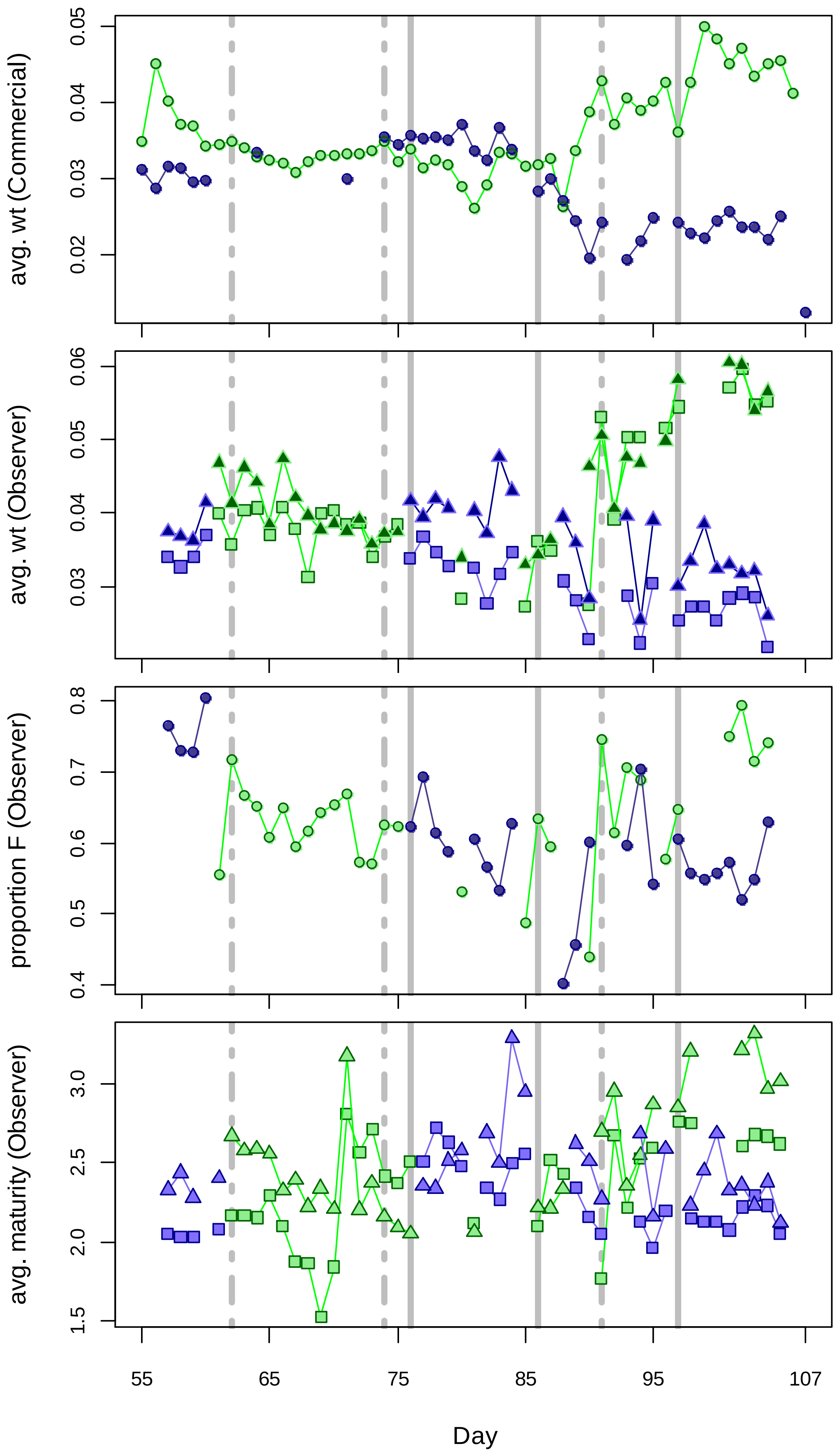



Figure 4. CPUE in metric tonnes per vessel per day, by assessment sub-area north (green) and south (purple) of the 52º S parallel. Circle sizes are proportioned to the numbers of vessels fishing. Data from consecutive days are joined by line segments. Broken gray bars indicate days 62, 74, and 91, identified as the start of in-season depletion or immigration north. Solid gray bars indicate days 76, 86, and 97, identified as the start of in-season depletion south.

Figure 5 [Next page]. Top graph: Average individual *D. gahi* weights (kg) per day from commercial size categories. 2nd graph: Average individual *D. gahi* weights (kg) by sex per day from observer sampling. 3rd graph: Proportions of female *D. gahi* per day from observer sampling. Bottom graph: avg. maturity value by sex per day from observer sampling. Males: triangles, females: squares, unsexed: circles. North sub-area: green, south sub-area: purple. Data from consecutive days are joined by line segments. Broken gray bars indicate days 62, 74, and 91, identified as the start of in-season depletion north. Solid gray bars indicate days 76, 86, and 97, identified as the start of in-season depletion south.


avg. wt (Commercial)
avg. wt (Observer)
proportion F (Observer)
avg. maturity (Observer)
55
65
75
85
95
107
Day

## Depletion models

The different versions of the depletion model (simultaneous or sequential; with or without hyper-parameters) were optimized in R code for the north and south sub-areas. Outcomes and optimization details are shown in Appendix 1.

In the north sub-area, MCMC of all versions revealed that the depletion model stabilized in two alternate states: low catchability coefficient q with corresponding high N values, and high q with low N (Figure A2.1). The low q state corresponded to N values in excess of 5 billion *D. gahi*, which was unrealistic and therefore considered a spurious optimization. Parameters corresponding to $q \leq 0.0005$ (see horizontal line through the top graph of Figure A2.1) were excluded from calculating the likelihood distribution of the stock. With this constraint, all model versions gave plausible outputs of the in-season biomass depletion (Table A1.1), showing season-end maximum likelihood estimates ranging from 4500 tonnes (model version C and D) to 15,500 tonnes (model version B) (see Figure A1.1). Model version D (final peak only, no hyper-parameters) was selected for having the narrowest 1 standard deviation range of the season-end likelihood distribution: 18,767 – 2834 = 15,933 (Fig. A1.1).

Expected individual weight on the final day (day 107) was 46.2 ± 2.3 g (Figure A3.1). The resulting likelihood distribution of *D. gahi* biomass in the north sub-area on day 107 is shown in Figure 6 (equivalent to Fig. A1.1-D), with maximum likelihood and 95% confidence interval centred on the maximum likelihood of:

$B_{N\ day\ 107}$ = 4500 tonnes ~ 95% CI [1721 – 35,161] tonnes **(8)**

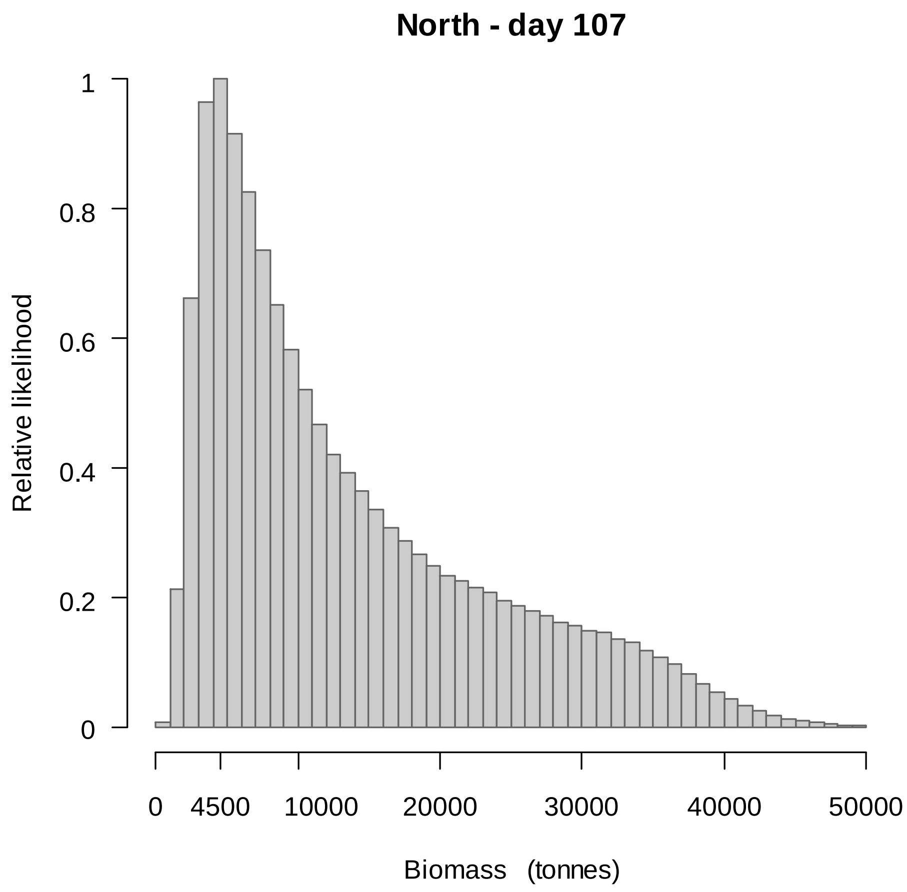


Figure 6 [Previous page]. Likelihood distribution of *D. gahi* biomass in the north sub-area on day 107 (April 17th). The maximum likelihood is centred on 4500 tonnes.

In the south sub-area, no model versions that fitted data to the end of the season (day 107, or alternatively, day 104; excluding the extra days) gave plausible outputs. The CPUE time series from day 97 onwards showed considerable variability but no effective depletion towards the end (Figure 4), and could therefore not be fit realistically by any model parameters (Figure A1.2). Instead, the south sub-area was depletion-modelled to the end of the 2nd depletion period, ending on day 95 (Figure 4). Among model versions to day 95, period-end maximum likelihood estimates ranged from 2500 tonnes (model version D4) to 4500 tonnes (model version A4) (see Figure A1.2). Model version D4 (final peak only, no hyper-parameters) was selected for having the narrowest 1 standard deviation range of the period-end likelihood distribution: 10,599 – 1373 = 9226 (Figure A1.2). Expected individual weight on day 95 was 25.7 ± 1.1 g (Figure A3.1).

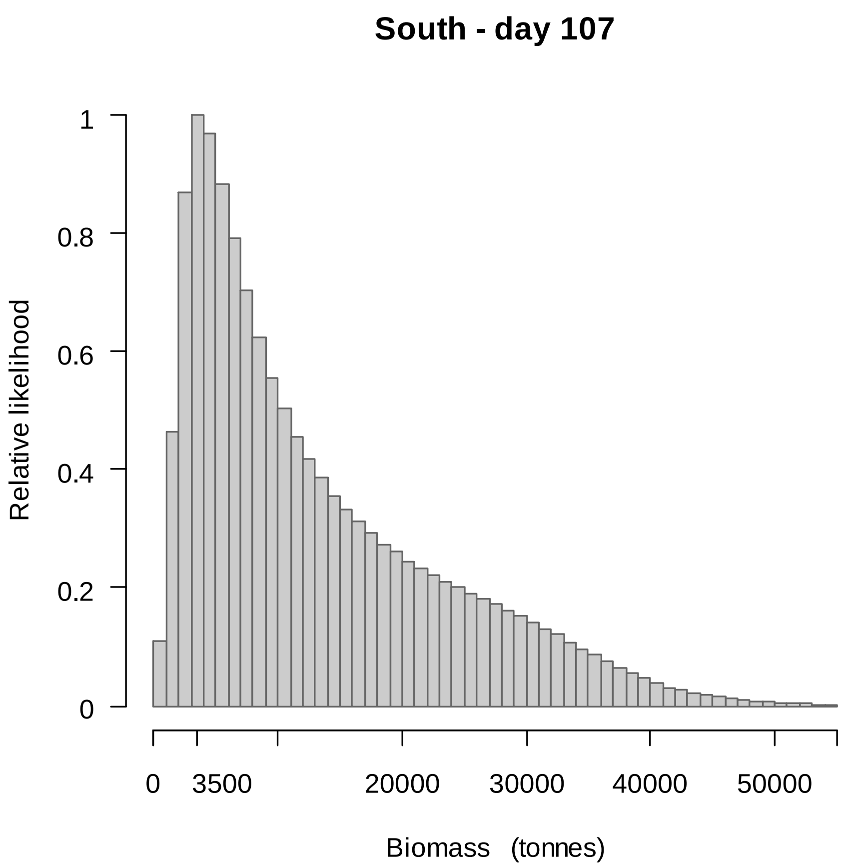



Figure 7. Likelihood distribution of *D. gahi* biomass in the south sub-area on day 107 (April 17th). The maximum likelihood is centred on 3500 tonnes.

Biomass at the end of the second depletion period south was extrapolated to the end of the season by the CPUE ratio of the end of the season over the end of the second depletion period. End of the season was defined from day 102 onwards, i.e., the last 3 days of the regular season plus the extra days. Variability of this ratio was estimated by randomly sampling with replacement the vessels that took catches over the season end days, then calculating the ratio of these vessels' CPUE vs. the day-95 CPUE, and multiplying by 1 day-95 biomass value drawn randomly from the day-95 biomass distribution (Figure A1.2-D4). The randomization was iterated for the number of units in the day-95 biomass distribution; > 1,000,000×. The resulting likelihood distribution of *D. gahi* biomass in the south sub-area on day 107 is shown in Figure 7, with maximum likelihood and 95% confidence interval centred on the maximum likelihood of:

$$B_{\text{S day 107}} = B_{\text{S day 95}} \times \text{CPUE}_{\text{day [102 – 107]}} / \text{CPUE}_{\text{day 95}}$$
$$= 3500 \text{ tonnes} \sim 95\% \text{ CI } [941 – 34{,}506] \text{ tonnes} \qquad \textbf{(9)}$$

## Escapement biomass

Escapement biomass was defined as the aggregate biomass of *D. gahi* at the end of the season (day 107; April 17$^{th}$) for the north and south sub-areas combined (equations 8 + 9). The north and south sub-area biomasses are assumed to be independent and therefore the aggregate was calculated by adding the respective north and south likelihood distributions in random order. The likelihood distribution of the aggregate escapement biomass is shown in Figure 8. Because both north and south likelihood distributions were strongly right-skewed (Figures 6 and 7), the maximum likelihood of the escapement biomass is substantially higher than the sum of the north and south maximum likelihoods.

$$B_{\text{Total day 107}} = B_{\text{N day 107}} + B_{\text{S day 107}}$$
$$= 13{,}500 \text{ tonnes} \sim 95\% \text{ CI } [5341 – 55{,}116] \text{ tonnes} \qquad \textbf{(10)}$$

The risk of the fishery, defined as the proportion of the escapement biomass distribution below the conservation limit of 10,000 tonnes (Agnew et al., 2002; Barton, 2002), was equal to 10.15%.

## Immigration

*D. gahi* immigration during the season was inferred as the difference between *D. gahi* biomass at the end of the pre-season survey (Winter et al., 2013) and *D. gahi* biomass at the end of the commercial season (escapement biomass) plus catch. The likelihood distribution of this difference was calculated by repeated iterations of drawing a random value from the escapement biomass distribution (equation 10), adding the season catch, and subtracting a random draw from the likelihood distribution of the pre-season survey biomass:

$$B_{\text{Season Immigration}} = B_{\text{Total day 107}} + C_{\text{Season}} - B_{\text{Survey end}}$$
$$= 13{,}500 \ [5341 - 55{,}116] + 19{,}908 - 5333 \ [4143 - 6661]$$
$$= 28{,}500 \text{ tonnes} \sim 95\% \text{ CI } [19{,}868 – 69{,}845] \text{ tonnes} \qquad \textbf{(11)}$$

Note that this represents, more specifically, the biomass resulting from immigration rather than the biomass that immigrated; it is not taken into account that the squid would have been smaller on the date they entered the fishing zone and subsequently grew. However, in-season natural mortality is taken into account through the CNMD factor (equations 5 and 6). By this estimate, in-season immigration represents 85% of the *D. gahi* biomass to have been present in the fishing zone in the 1st season of 2013: 28,500/(13,500 + 19,908) = 0.853.

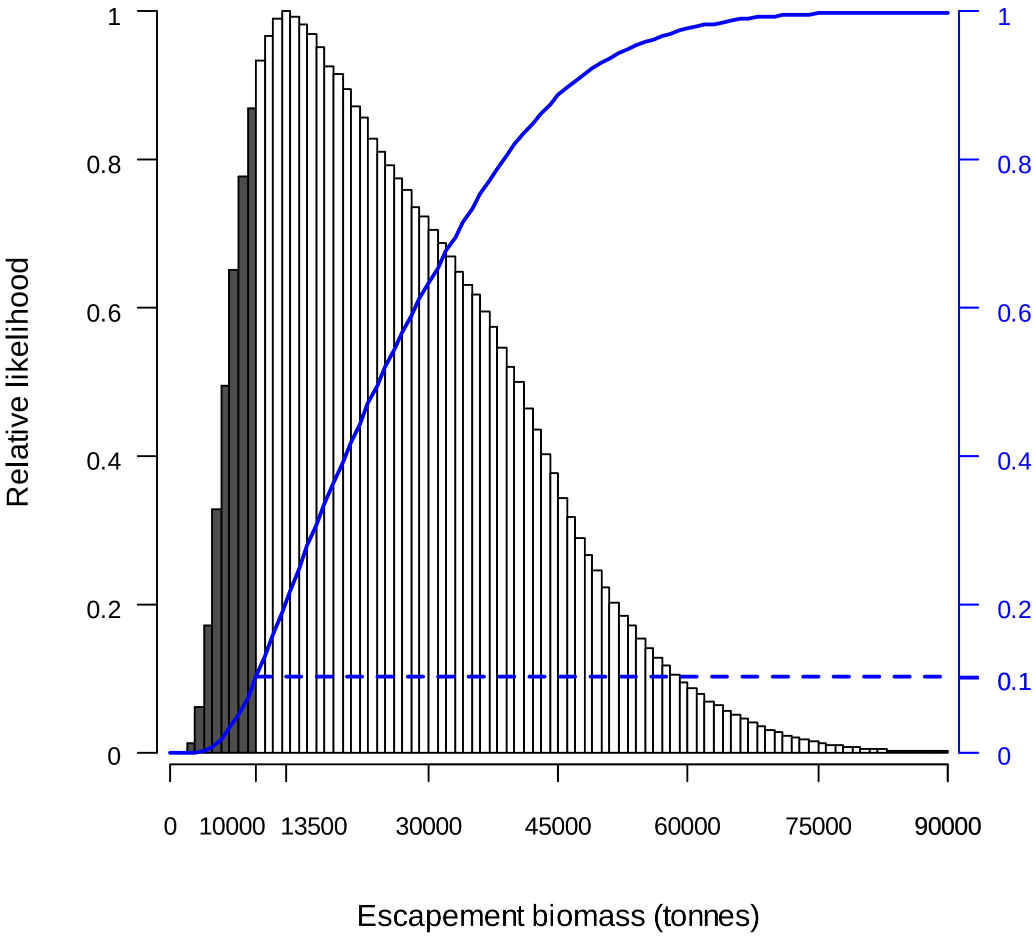



Figure 8. Likelihood distribution of *D. gahi* biomass at the end of the season, April 17th. Distribution outcomes less than the biomass escapement limit of 10,000 tonnes are shaded dark gray. Cumulative likelihood is shown as a solid blue curve. The broken blue line indicates the cumulative likelihood of less than 10,000 tonnes escapement biomass: 10.15%.

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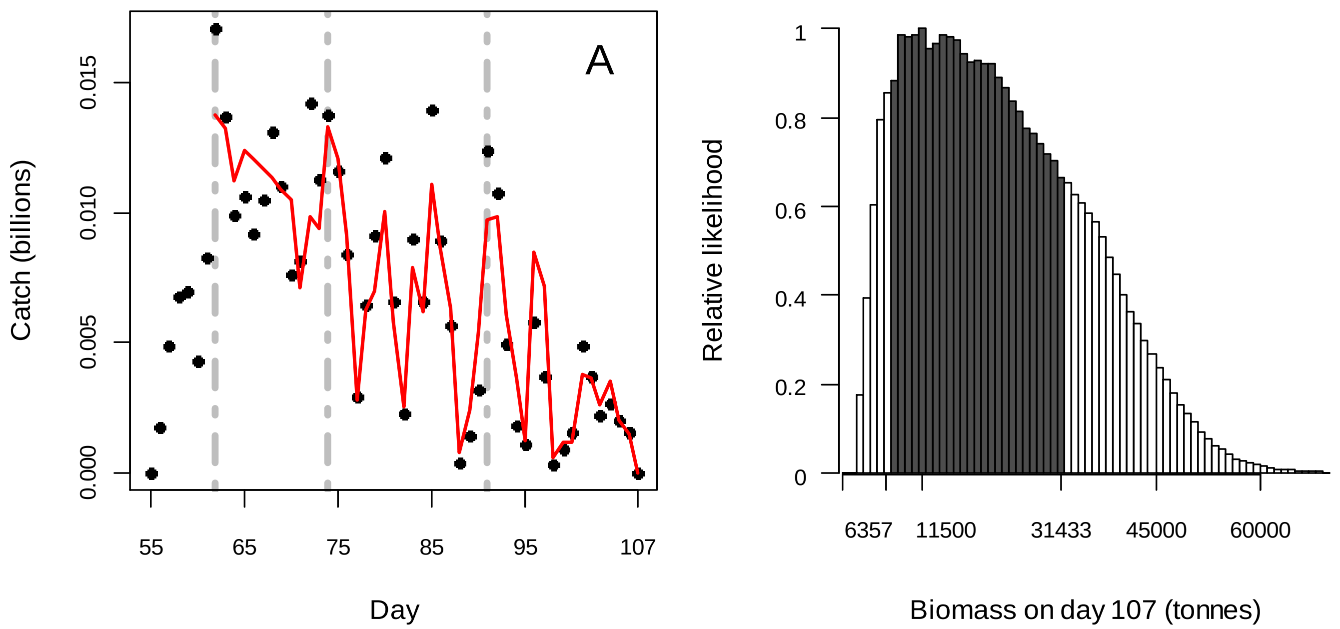
## Appendix

**(A.1)** Evaluation of different versions of the depletion model.

Table A1.1. Optimized numbers of *D. gahi* at depletion end, catchability coefficients, and hyper-parameters of the different versions of the depletion model (versions B and D don't fit hyper-parameters; the hyper-parameters are 1 by default) tested in the north sub-area.

| Sub-area | | Model version | N (billions) Depletion end | Catchability coefficient | Hyper-parameters Effort | Hyper-parameters Abundance |
|---|---|---|---|---|---|---|
| N | A | all 3 peaks, hyper-parameters end-day: 107 | 0.133 | $1.86 \cdot 10^{-3}$ | 0.954 | 0.630 |
| N | B | all 3 peaks, no hyper-parameters end-day: 107 | 0.328 | $1.36 \cdot 10^{-3}$ | 1 | 1 |
| N | C | final peak only, hyper-parameters end-day: 107 | 0.085 | $5.37 \cdot 10^{-3}$ | 0.843 | 0.981 |
| N | D | final peak only, no hyper-parameters end-day: 107 | 0.153 | $2.44 \cdot 10^{-3}$ | 1 | 1 |

Figure A1.1 [below]. Left: Daily estimated catch numbers (black points) and expected catch numbers (red lines) from depletion model versions applied to the north sub-area (see Table A1.1). Broken gray bars: days 62, 74, and 91, identified as the start days of depletion north. Right: Likelihood distribution of *D. gahi* biomass at the end-day of the depletion computed by MCMC with the parameters of the corresponding model. Plot bars = 1000 tonnes each. Bars shaded gray are within ± 1 normal standard deviation of the maximum likelihood (because the distributions tended to be skewed, calculated as [.3174 to 1] of the points < maximum likelihood, and [0 to .6826] of the points > maximum likelihood).



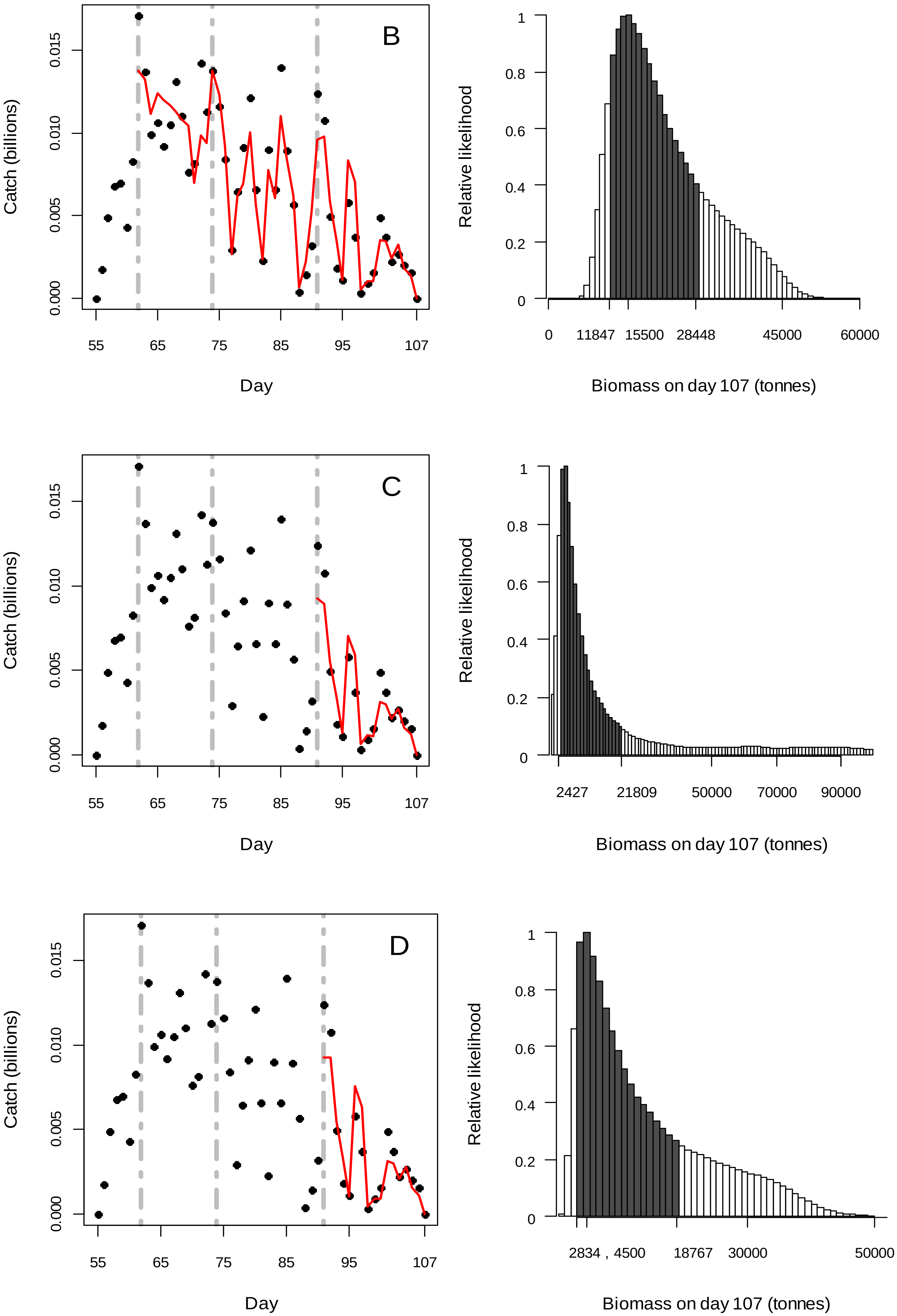
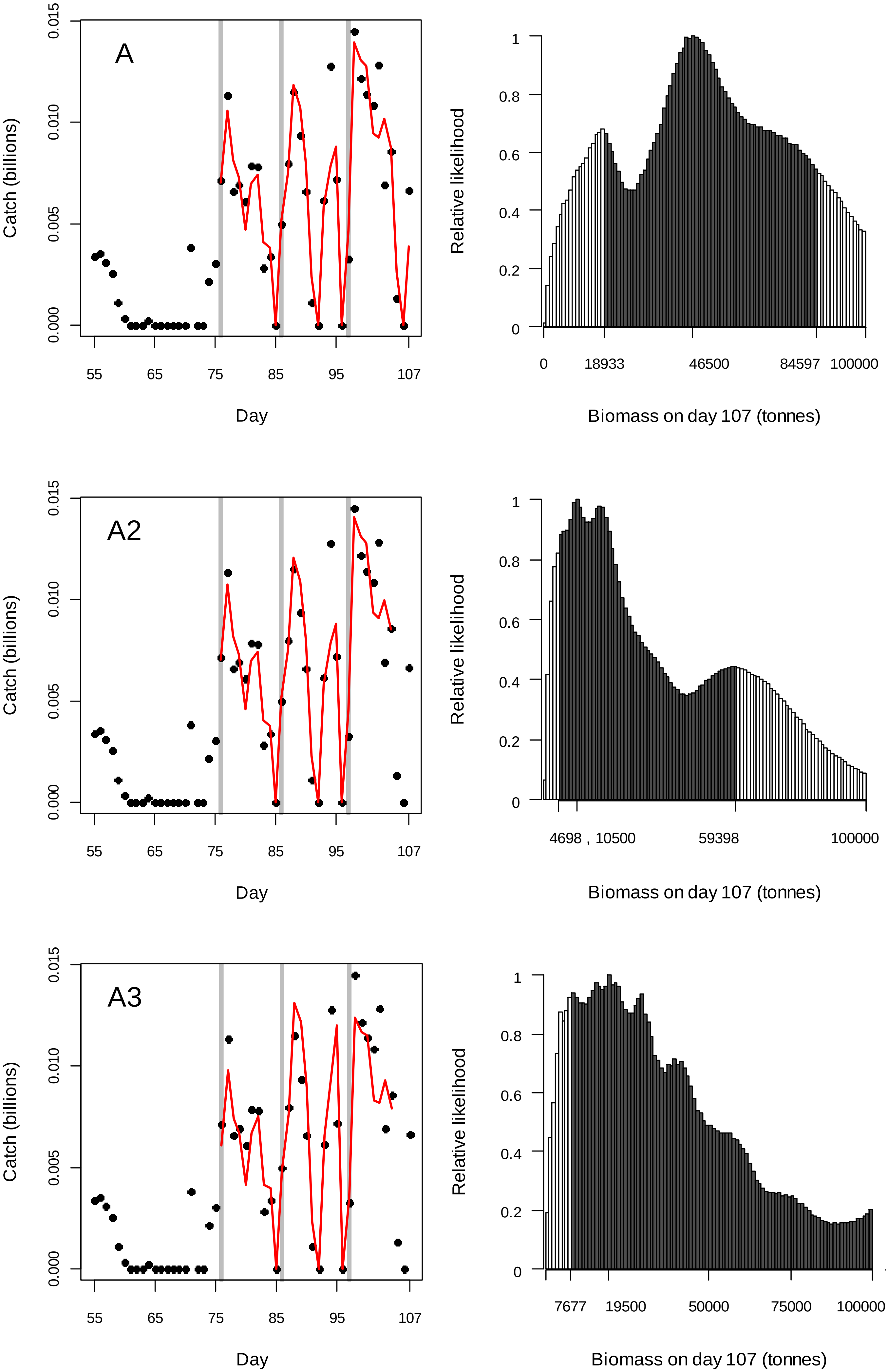

B
Catch (billions)
0.000
0.005
0.010
0.015
55
65
75
85
95
107
Day
Relative likelihood
0
0.2
0.4
0.6
0.8
1
0
11847
15500
28448
45000
60000
Biomass on day 107 (tonnes)
C
Catch (billions)
0.000
0.005
0.010
0.015
55
65
75
85
95
107
Day
Relative likelihood
0
0.2
0.4
0.6
0.8
1
2427
21809
50000
70000
90000
Biomass on day 107 (tonnes)
D
Catch (billions)
0.000
0.005
0.010
0.015
55
65
75
85
95
107
Day
Relative likelihood
0
0.2
0.4
0.6
0.8
1
2834 , 4500
18767
30000
50000
Biomass on day 107 (tonnes)

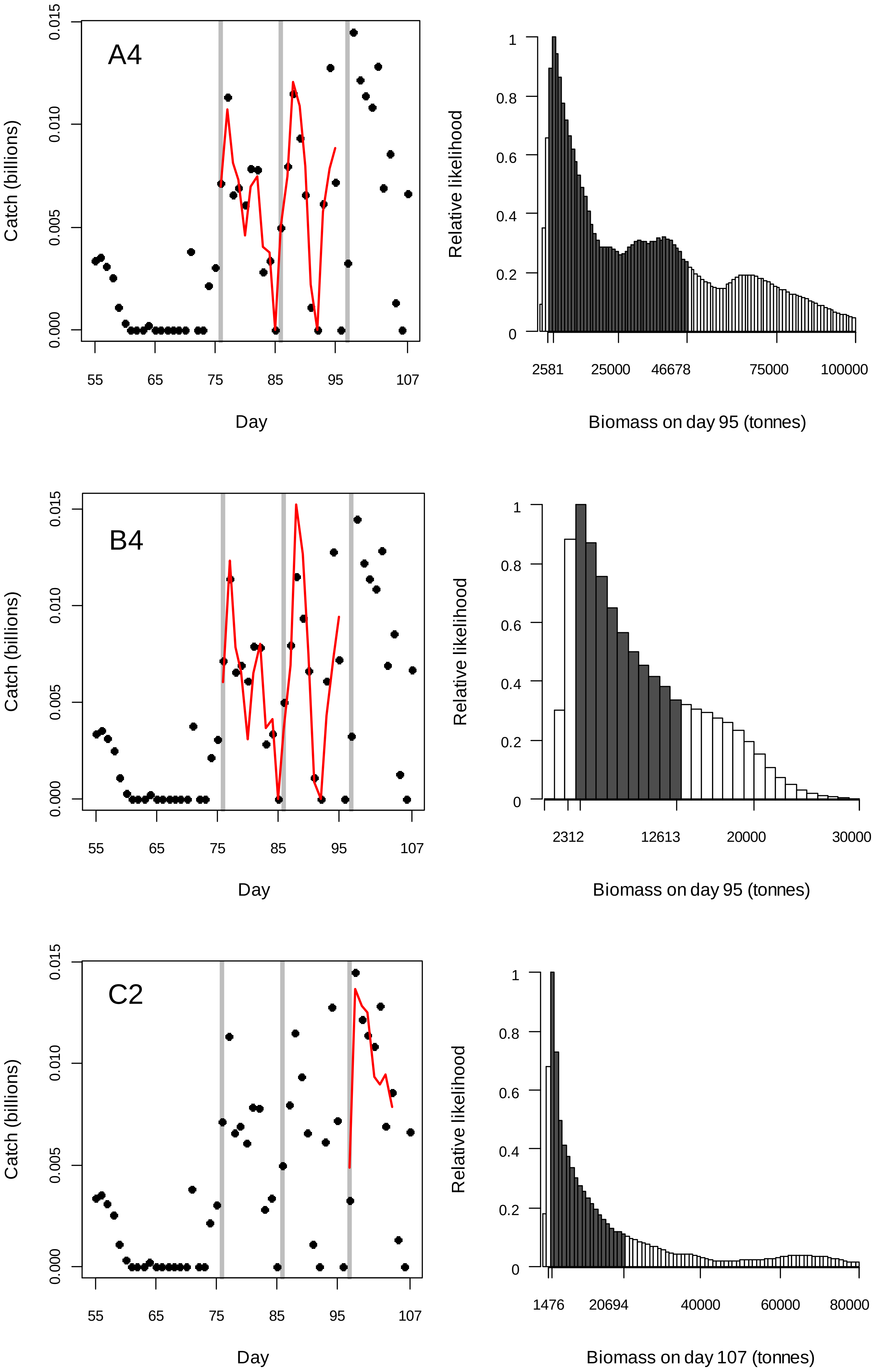
Table A1.2. Estimated numbers of *D. gahi* at depletion end, catchability coefficients, and hyper-parameters of the different versions of the depletion model (versions B and D don't fit hyper-parameters; the hyper-parameters are 1 by default) tested in the south sub-area. Numbered versions of the same letter have the same basic structure (single or multiple peaks; hyper-parameters or not, but differences in some of the data implemented.

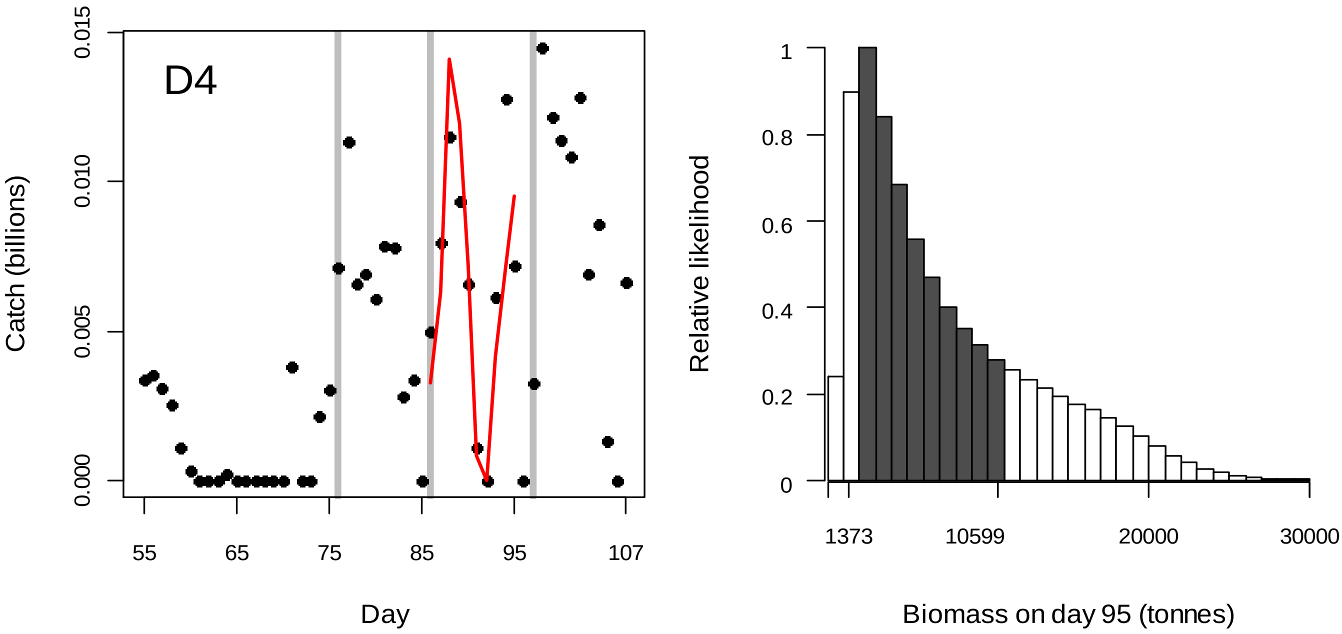
| Sub-area | Model version | | N (billions) Depletion end | Catchability coefficient | Hyper-parameters | |
|---|---|---|---|---|---|---|
| | | | | | Effort | Abundance |
| S | A | all 3 peaks,<br>hyper-parameters<br>end-day: 107 | 0.069 | $4.71\cdot10^{-3}$ | 0.567 | 0.220 |
| S | A2 | all 3 peaks,<br>hyper-parameters<br>end-day: 104 | 0.057 | $4.74\cdot10^{-3}$ | 0.584 | 0.232 |
| S | A3 | 1st & 2nd peak,<br>hyper-parameters<br>end-day: 104 | 0.094 | $2.89\cdot10^{-3}$ | 0.648 | 0.149 |
| S | A4 | 1st & 2nd peak,<br>hyper-parameters<br>end-day: 95 | 0.009 | $4.54\cdot10^{-3}$ | 0.594 | 0.226 |
| S | B | all 3 peaks,<br>no hyper-parameters<br>end-day: 107 | 0.396 | $2.34\cdot10^{-3}$ | 1 | 1 |
| S | B4 | 1st & 2nd peak,<br>no hyper-parameters<br>end-day: 95 | 0.009 | $5.95\cdot10^{-3}$ | 1 | 1 |
| S | C | final peak only,<br>hyper-parameters<br>end-day: 107 | 0.034 | $5.01\cdot10^{-3}$ | 0.531 | 0.189 |
| S | C2 | final peak only,<br>hyper-parameters<br>end-day: 104 | 0.000 | $4.51\cdot10^{-3}$ | 0.535 | 0.118 |
| S | D | final peak only,<br>no hyper-parameters<br>end-day: 107 | > 10 | $3.07\cdot10^{-6}$ | 1 | 1 |
| S | D4 | 2nd peak only,<br>no hyper-parameters<br>end-day: 95 | 0.009 | $4.21\cdot10^{-3}$ | 1 | 1 |

Figure A1.2 [below]. Left: Daily estimated catch numbers (black points) and expected catch numbers (red lines) from depletion model versions applied to the south sub-area (see Table A1.2). Solid gray bars: days 76, 86, and 97, identified as the start days of depletion south. Right: Likelihood distribution of *D. gahi* biomass at the end-day of the depletion computed by MCMC with the parameters of the corresponding model. Plot bars = 1000 tonnes each. Bars shaded gray are within ± 1 normal standard deviation of the maximum likelihood (because the distributions tended to be skewed, calculated as [.3174 to 1] of the points < maximum likelihood, and [0 to .6826] of the points > maximum likelihood). Bar plots are truncated to a maximum of 100,000 tonnes, and correspondingly the upper limit of the gray shaded section may be off the plot. Note that not all model versions in Table A1.2 or included in the figure; only the ones that showed stable and plausible outcomes in the original optimization or the MCMC calculation.



A
Catch (billions)
0.000
0.005
0.010
0.015
55
65
75
85
95
107
Day
Relative likelihood
0
0.2
0.4
0.6
0.8
1
0
18933
46500
84597
100000
Biomass on day 107 (tonnes)
A2
Catch (billions)
Day
Relative likelihood
4698 , 10500
59398
100000
Biomass on day 107 (tonnes)
A3
Catch (billions)
Day
Relative likelihood
7677
19500
50000
75000
100000
Biomass on day 107 (tonnes)


A4
Catch (billions)
0.000
0.005
0.010
0.015
55
65
75
85
95
107
Day
Relative likelihood
0
0.2
0.4
0.6
0.8
1
2581
25000
46678
75000
100000
Biomass on day 95 (tonnes)
B4
Catch (billions)
0.000
0.005
0.010
0.015
55
65
75
85
95
107
Day
Relative likelihood
0
0.2
0.4
0.6
0.8
1
2312
12613
20000
30000
Biomass on day 95 (tonnes)
C2
Catch (billions)
0.000
0.005
0.010
0.015
55
65
75
85
95
107
Day
Relative likelihood
0
0.2
0.4
0.6
0.8
1
1476
20694
40000
60000
80000
Biomass on day 107 (tonnes)




**(A.2)** MCMC restrictions.

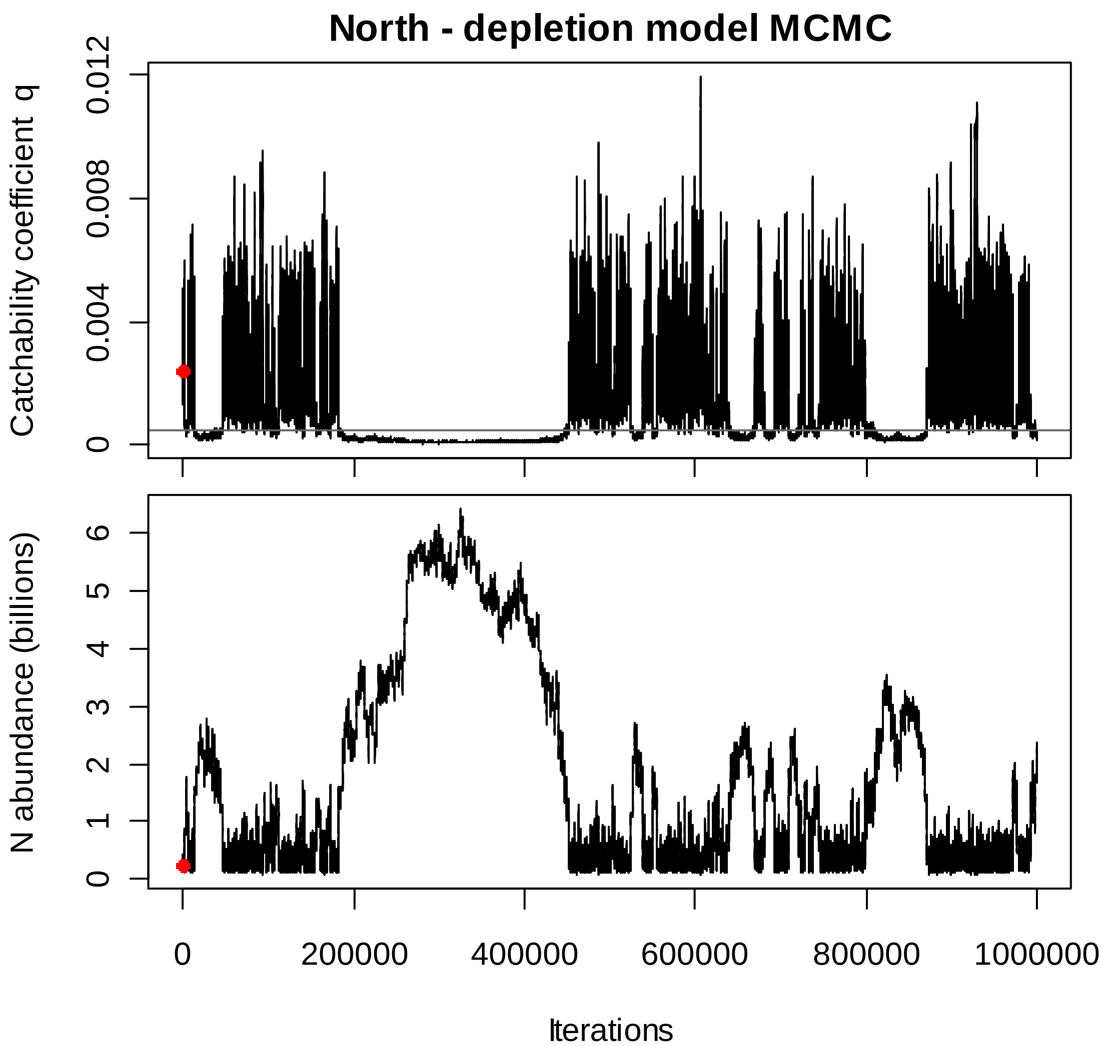


Figure A2.1 [above]. Markov Chain Monte Carlo iteration from the north sub-area depletion model (version D), showing the two alternating 'states' of low or high catchability coefficient q (top graph), with corresponding high or low N abundance (bottom graph). Horizontal gray line on the top graph shows the q = 0.0005 threshold line used to reject the low q state. Red dots on both graphs indicate the respective optimized values.

**(A.3)** Expected individual *D. gahi* weights calculated from generalized additive models (GAM) of the daily observer measurements and average vessel market size categories throughout the season.

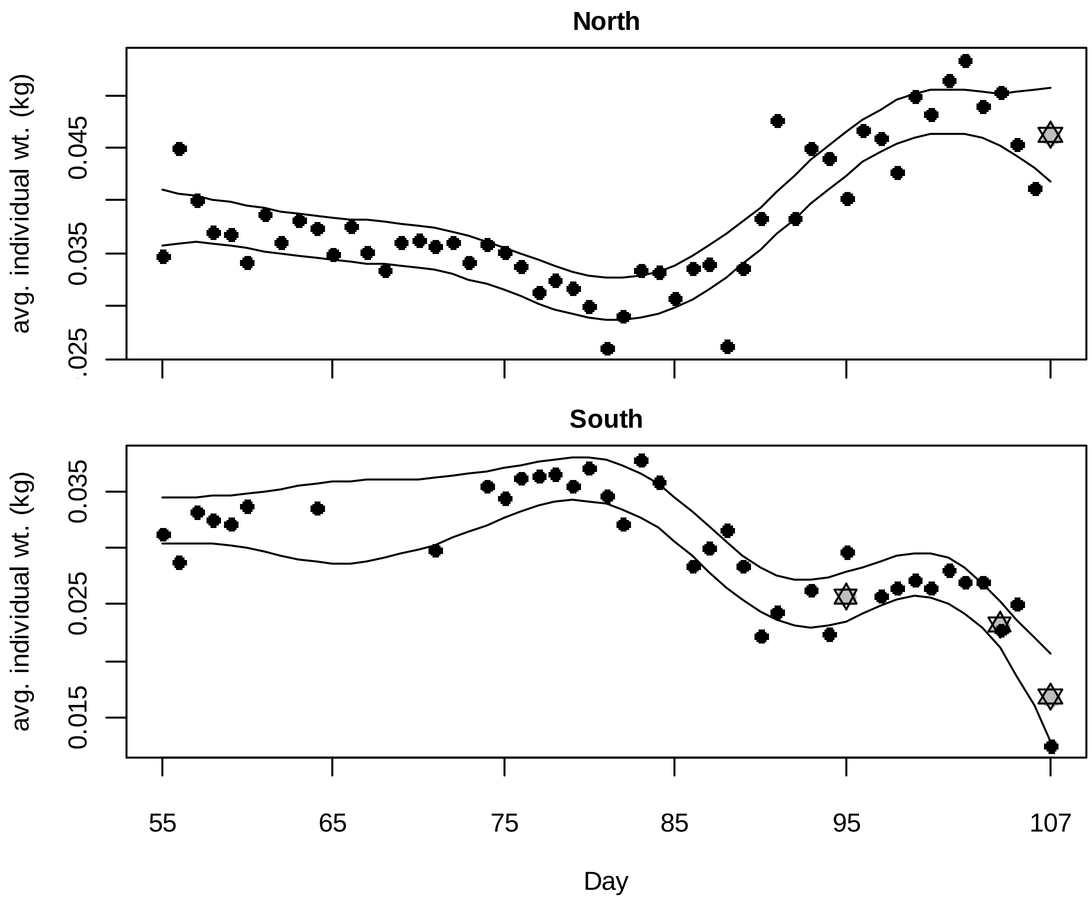



Figure A3.1. Daily average *D. gahi* weights (black points) and 95% confidence intervals of GAMs (black lines) of seasonal trend in average individual weight. Star symbols indicate the expected average weights on the modelled depletion period end days: Wt $_{N\ day\ 107}$ = 46.2 ± 2.3 g (top), Wt $_{S\ day\ 95}$ = 25.7 ± 1.1 g, Wt $_{S\ day\ 104}$ = 23.2 ± 1.0 g, Wt $_{S\ day\ 107}$ = 16.8 ± 2.0 g (bottom).