Joint Survey and Stock Assessment

Shortfin squid

Illex argentinus
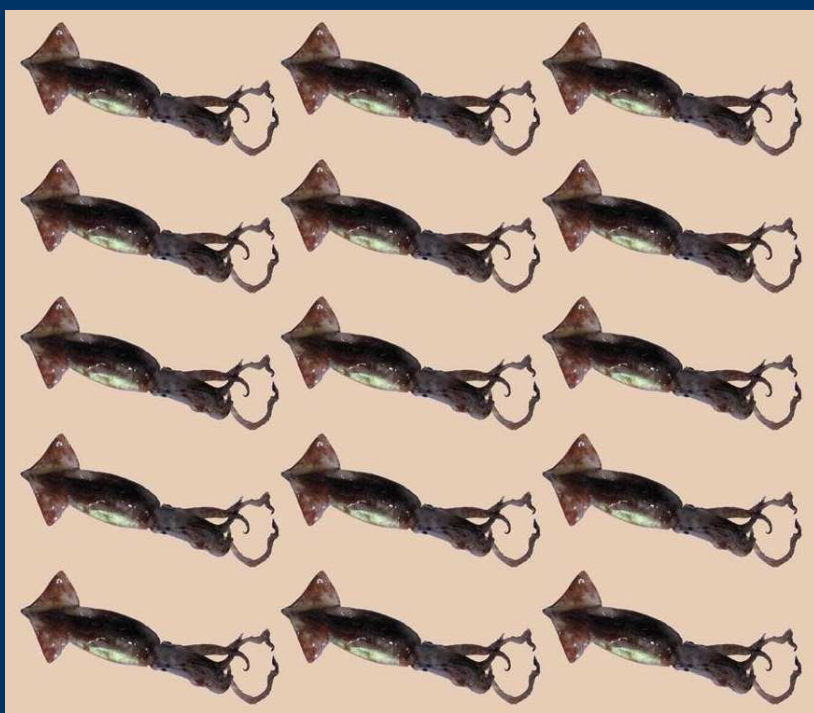
SA - 2019 - ILL

Andreas Winter

Natural Resources - Fisheries
Falkland Islands Government
Stanley, Falkland Islands

October 2019

DESIRE THE RIGHT

Introduction

Shortfin squid *Illex argentinus* is the most abundant squid species in the Southwest Atlantic, and an important commercial fishery stock for Argentina and the Falkland Islands (Barton 2002, Agnew et al. 2005, Sacau et al. 2005, Arkhipkin et al. 2015). With the renewal of fishery data collaboration between Argentina and the Falkland Islands (Mercopress 2018), a stock assessment for *I. argentinus* in 2019 has been calculated.

I. *argentinus* is characterized by an annual life cycle (Rodhouse and Hatfield 1990, Arkhipkin and Roa-Ureta 2005), resulting in an absence of stock carry-over from one year to the next. The suitable methodology used for assessing this short-lived species has been the depletion time-series model (Rosenberg et al. 1990, Basson et al. 1996), which evaluates what levels of abundance and catchability must be extant to sustain the observed rates of catch. *I. argentinus* catches in the Southwest Atlantic exhibit high inter-annual variability (Waluda et al. 1999), and stock assessment can therefore be improved by tuning the depletion model to a fishery-independent estimate of biomass. For the present stock assessment, commercial catch and effort data from Argentine and Falkland Islands licensed jig and trawl fisheries are included, and combined with a recruitment survey biomass estimate taken in February 2019 (Randhawa and Hall in prep.). Accordingly, this stock assessment refers to the area covered by the survey, which is occupied predominantly by the winter-spawning stock of *I. argentinus* (Arkhipkin 2000).

Methods

Survey

A trawl survey for *I. argentinus* was carried out from February 1st to March 6th 2019, on the Argentine research vessel *Victor Angelescu*. *I. argentinus* biomass was estimated from the catches of the 86 trawls taken in the survey (Randhawa and Hall in prep.). Catch (kg) was divided by trawl-swept area to calculate areal density (kg km^{-2}), thus assuming a capturability coefficient = 1 (the commonly used assumption in fishery surveys, Somerton et al. 1999). Trawl-swept area was measured as trawl distance multiplied by average horizontal net opening, and was provided in the data spreadsheets obtained from INIDEP at the end of the survey.

Areal density per trawl was extrapolated to the total survey area using an inverse distance weighting algorithm (Shepard 1968). The total survey area was estimated from its depictions in the Argentine research survey plan (for example, reproduced as Figure 1 in Appendix 4 of SSC (2018)). This survey area is bounded to the north by 45° S latitude, to the south by 51° S and 50 °S latitudes, to the west by the 100 m isobath and to the east by the 200 m and 400 m isobaths. The bathymetry depicted on Figure 1 of the SSC report showed a spatial resolution not available from public resources, e.g., GEBCO[1] (A. Blake, FIFD, pers. comm.). Instead, the Figure 1 image was auto-digitized to produce a boundary coordinate file, which was then converted to WGS 84 projection in UTM sector 20 (A. Blake, FIFD, pers. comm.). This boundary projection was calculated to have a polygon area[2] of 194,370.5 km^2, 1.9% higher than the 55,610.61 nm^2 stated in Table 1 of Appendix 4 of the SSC report. For density extrapolation, this area was divided into 7787 grids of 5 km^2, comparable to the gridding used for calamari and finfish surveys (Goyot et al. 2019, Ramos and Winter 2019).

---

[1] www.gebco.net/data_and_products/gridded_bathymetry_data/
[2] Function areapl, R library splancs.

Inverse distance weighting is a deterministic method of spatial prediction that can be more reliable than kriging for small data sets (Kravchenko 2003, Mueller et al. 2004). The basic inverse distance weighting algorithm assigns a value u to any grid location x that is the weighted average of a known scattered set of points x_i according to the inverse of the i points' distances from the grid location x:

$$u(x) = \begin{cases} \frac{\sum_{i=1}^{N} w_i(x) u_i}{\sum_{i=1}^{N} w_i(x)}, & \text{if } d(x, x_i) \neq 0 \\ u_i, & \text{if } d(x, x_i) = 0 \end{cases} \qquad (1)$$

where

$$w_i(x) = \frac{1}{d(x, x_i)^p}$$

Ideally, the scattered set of points x_i would be spaced equidistant. But because some points may be more clustered than others, an isolation parameter was assigned attributing to points x_i more weight in proportion to being further away from any other point x_i. Isolation parameters (s) were calculated as the standardized mean of distances between each point x_i and all other points x_j:

$$s(x_i) = \overline{d(x_i, x_j)} \qquad \text{, giving a revised inverse distance weighting factor as:}$$

$$w_i(x) = \left(\frac{s(x_i)}{d(x, x_i)} \right)^p \qquad (2)$$

The power parameter p (a positive real number) adjusts the weight of points x_i as a function of distance; higher values of p put higher influence on the points x_i closest to a given interpolated point x. There is no exact recommendation about the choice of power parameter p (Babak and Deutsch 2009), but $p < 2$ has been found to make surfaces relatively flat (Shepard 1968). For this survey analysis, an empirical approach was used of running the inverse distance weighting algorithm with p values from 1 to 25 by 0.25, and for each p calculating the aggregate of log proportional differences between the empirical values of density at every trawl and the interpolation at every trawl from all other trawls (Ramos and Winter 2019). The lowest aggregate of log proportional differences corresponded to the best p value. For the *I. argentinus* data of this survey this criterion was met at $p = 3.25$ (see Appendix Figure A1).

Uncertainty of the *I. argentinus* biomass was estimated by a hierarchical bootstrap algorithm. For 30,000 iterations, survey trawls and their catches were first randomly re-sampled with replacement. Second, each re-sampled trawl was given a random uniform re-assignment of its coordinate position between start latitude and longitude and end latitude and longitude. Then, the isolation parameters were re-calculated for the randomized set of trawl data, and the inverse distance weighted algorithm re-applied. One iteration might thus re-sample any trawl twice or more, but each would have a slightly different position.

Two estimates of *I. argentinus* biomass were calculated: total biomass, and winter spawning biomass only. Winter and summer spawning individuals are distinguishable by the consistency of the mantle tissue and gonadal maturity (H. Randhawa, FIFD, pers. comm.). Winter spawning squid represent the target of the commercial fishery at this time, as they yield a higher quality product. The proportion of total *I. argentinus* biomass that was winter-spawning was calculated from biological samples taken in those trawls which had any *I.*

argentinus catch. Individual squid were measured, weighed, sexed, and classified by maturity and summer or winter-spawning (Randhawa and Hall in prep.). For each trawl the proportion by weight of the winter-spawning vs. total sample was retained. For one trawl that had *I. argentinus* catch but no biological sample, the winter-spawning proportion was interpolated, also by inverse distance weighting, from all other trawls that had a winter-spawning proportion calculated.

For winter-spawning biomass, an additional level was added to the bootstrap algorithm to account for variability in the length/weight/maturity samples used for winter-spawning proportions. Per iteration, the data of each length/weight/maturity sample were randomly re-sampled with replacement, and proportions re-calculated before applying the biomass estimation.

Commercial catch and effort

Stock assessment comprises the period from January 1st 2019 to May 31st 2019, at which time all fisheries target-licensed for *I. argentinus* by Argentina or the Falkland Islands had ended. The data included catch, effort, grid location, and average individual squid weights exchanged according to the SSC (2018) protocol: bi-weekly during jig fishing seasons, monthly outside of jig fishing seasons, and summarized weekly for all vessels.

The general depletion model is based on the equivalence:

$$C_t \quad = \quad q \times E_t \times N_t \times e^{-M/2} \tag{3}$$

where q is the catchability coefficient, M is the natural mortality rate, and C_t, E_t, N_t are catch, fishing effort, and abundance per time interval (weekly). M was derived from the average maximum longevity reported by Arkhipkin and Roa-Ureta (2005) for *I. argentinus* males (372 days) and females (346 days); giving an average of 359 days. The average longevity was converted to mortality using Hoenig's (1983) empirical relationship:

$$\log(M_{days}) \quad = \quad 1.44 - 0.982 \times \log(\max Age_{days}) \tag{4}$$

thus

$$M_{days} \quad = \quad \exp\big(1.44 - 0.982 \times \log(359)\big) \quad = \quad 0.01307$$

and

$$M_{weeks} \quad = \quad M_{days} \times 7 \quad = \quad 0.09149$$

Catch (C_t) and abundance (N_t) are expressed as numbers of squid (Rosenberg et al. 1990). Fishing effort was calculated as fishing vessel-days per week. Jig-line hours and trawl hours per week were also available, but industrial vessels more typically strategize their fishing by choice of area per day, rather than by the exact number of operating hours, making vessel-days a more consistent denominator[3].

I. argentinus in this area are caught by jig and trawl vessels licensed by either Argentina or the Falkland Islands. Each fishery has unique characteristics and accordingly, equation (3) becomes:

---

[3] As long as vessels have essentially the same operational capacity. The vessel specification exchange data confirmed that practically all jiggers had a double-jig configuration. In any case, coefficients of correlation between jig fishing days and jig-line hours were 0.9988 for Argentina and 0.9975 for the Falkland Islands.

$$
\begin{aligned}
C_{t\text{-}AG\text{-}J} \ + \quad &= \quad q_{AG\text{-}J} \times E_{t\text{-}AG\text{-}J} \times N_t \times e^{-M/2} \quad + \\
C_{t\text{-}FK\text{-}J} \ + \quad & \quad\quad q_{FK\text{-}J} \times E_{t\text{-}FK\text{-}J} \times N_t \times e^{-M/2} \quad + \\
C_{t\text{-}AG\text{-}T} \ + \quad & \quad\quad q_{AG\text{-}T} \times E_{t\text{-}AG\text{-}T} \times N_t \times e^{-M/2} \quad + \\
C_{t\text{-}FK\text{-}T} \quad & \quad\quad q_{FK\text{-}T} \times E_{t\text{-}FK\text{-}T} \times N_t \times e^{-M/2}
\end{aligned}
\tag{5}
$$

Equation 5 was solved by optimizing $N_{t=1}$ (the starting abundance), $q_{AG\text{-}J}$, $q_{FK\text{-}J}$, $q_{AG\text{-}T}$, and $q_{FK\text{-}T}$ to minimize the difference between time series of predicted total catch and observed total catch, where total catch is the sum per week of the four fisheries:

$$
\sum_t \left(\log\left(\text{predicted } C_{t\text{-}Total}\right) - \log\left(\text{observed } C_{t\text{-}Total}\right)\right)^2 \Big|_{\text{minimize}}
\tag{6}
$$

$$
C_{t\text{-}Total} \quad = \quad C_{t\text{-}AG\text{-}J} + C_{t\text{-}FK\text{-}J} + C_{t\text{-}AG\text{-}T} + C_{t\text{-}FK\text{-}T}
$$

The assessment was carried out in a Bayesian framework (Punt and Hilborn 1997) whereby the in-season depletion model was conditioned by prior information on the stock; in this case the estimate of the recruitment survey. The mid-point of the recruitment survey was around weeks 7 to 8 (Randhawa and Hall in prep.), thus the prior was expressed as the difference between the survey winter-spawning biomass estimate and the mean of depletion model biomass estimates in weeks 7 and 8:

$$
\sum_t \left(\log(\text{survey biomass}) - \log\left(\text{depl. model biomass}\big|_{t=7}^{t=8}\right)\right)^2 \Big|_{\text{minimize}}
\tag{7}
$$

Bayesian optimization of the depletion was calculated by jointly minimizing equations 6 and 7, using the Nelder-Mead algorithm in R programming package 'optimx' (Nash and Varadhan 2011). Relative weights in the joint optimization were assigned to equations 6 and 7 as the converse of their error estimates; i.e. the error estimate of the survey prior became the weight of the depletion model and the error estimate of the depletion model became the weight of the survey prior. Therefore, the depletion model was first calculated alone, then in Bayesian optimization with the survey prior. Initialization values of $N_{t=1}$, $q_{AG\text{-}J}$, $q_{FK\text{-}J}$, $q_{AG\text{-}T}$, and $q_{FK\text{-}T}$ were assigned, by default, as the survey abundance estimate[4] and catchability coefficients of the fisheries operating in the survey area in weeks 7 and 8. Because a complex model may converge on a local minimum rather than global minimum, the optimization was stabilized by running a feed-back loop that set the N and q parameter outputs of the Bayesian joint optimization (equations 6 + 7) back into the depletion-only minimization (equation 6), re-calculated this minimization and the error estimate resulting from it, then re-calculated the Bayesian joint optimization, and continued this process until both the depletion minimization and the joint optimization remained unchanged.

Bayesian optimization of the depletion model produced the maximum likelihood estimate of starting abundance; $N_{t=1}$. N_t on the final day or any other day of the time series was then calculated as the numbers $N_{t=1}$ of the depletion start day discounted for natural mortality during the intervening period, and subtracting cumulative catch also discounted for natural mortality (CNMD):

$$
N_{t=\text{final day}} \quad = \quad N_{t=1} - CNMD_{t=\text{final day}}
\tag{8}
$$

---

[4] Thus ignoring the fact that the survey abundance estimate is $N_{t=7,8}$ rather than $N_{t=1}$. But for initialization this approximation is adequate.

where

$$CNMD_{t=1} \quad = \quad 0$$
$$CNMD_{t=x} \quad = \quad CNMD_{t=x\text{-}1} \times e^{-M} + C_{t=x\text{-}1} \times e^{-M/2}$$

I. argentinus catch (C_t) and abundance (N_t) numbers used in the model were derived from dividing commercial and survey catch weight reports by the average individual weights of the squid, per 1-week time interval. Average individual weights were obtained from the exchange data, consisting of observer weight measurements. The data included the weekly mean weights and numbers of individual squid measured, per grid of 1° latitude × 1° longitude. For this assessment, weekly averages were calculated as the means among all grids weighted by the numbers of measurements per grid, with an adjustment for the relative distances among grids (more isolated grids got proportionally more weight). By agreement at the SSC, observer weight measurements were taken only in the jig fisheries. This presents a potential bias, as trawl and jig typically catch different size distributions (Koronkiewicz 1995). However, for consistency no other data sources were added. Weeks with no observer data were linear-interpolated or set to the most recent average weights. To mitigate fluctuations by random sampling variation, the time series of weekly average weights was LOESS smoothed. Finally, the time series of weekly estimated biomass (B_t) was calculated in reverse: weekly abundance (N_t) multiplied by the weekly average individual weight.

The error distribution of the *I. argentinus* biomass time series was estimated using a bootstrap algorithm. For each of 30,000 iterations, residuals of the average weight LOESS were permuted and re-smoothed, and a value was chosen randomly from the error distribution of the survey biomass estimate. The Bayesian optimization of the depletion model was then re-calculated with these re-smoothed and randomized values.

Results

Survey

Total *I. argentinus* catches per survey trawl ranged from zero to 561.1 kg, corresponding to areal densities of zero to 14,488.8 kg km^{-2} (Figure 1). Thirteen of the 86 survey trawls reported zero *I. argentinus* catch. No significant relationship was found between catch density and trawl depth, or between catch density and time of day (generalized additive models, $p > 0.10$).

Winter-spawning proportion was 100% in 35 of the 72 trawls that were sampled, and 0% in 2 of the trawls. The aggregate winter-spawning proportion, by weight, of samples was 84.1%.

The inverse distance weighting algorithm was implemented by assuming that each trawl's catch was taken at the midpoint of the trawl track; halfway between start and end coordinates. The resulting total average density was 819.9 kg km^{-2}. Multiplied by the survey area, this gave a total estimated *I. argentinus* biomass of 819.9 × 194370.5 = 159,361.9 tonnes. The two largest local concentrations of *I. argentinus* (in blue on Figure 2 - left) had respectively 19.1% of total biomass (2.1% of the area) and 13.5% of total biomass (1.6% of the area).

Figure 1 [next page]. Distribution of total *I. argentinus* catch densities per survey trawl. Maximum = 14,488.8 kg km^{-2}.

Illex - 2019 Survey
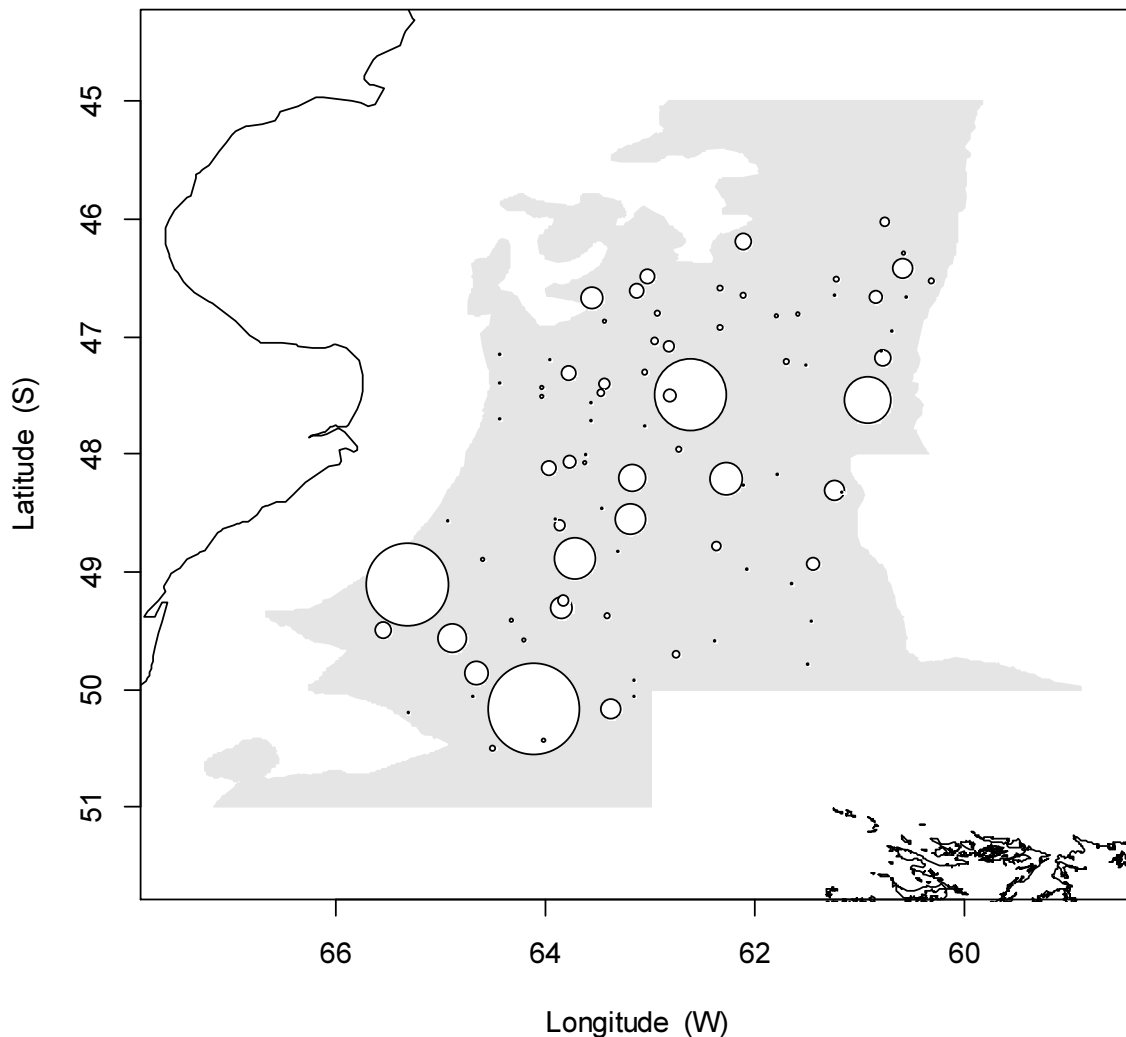
Winter-spawning average density was 747.9 kg km^{-2}, for an estimated biomass of 747.9 × 194370.5 = 145,369.0 tonnes. The same two largest local concentrations of *I. argentinus* had respectively 21.0% of winter-spawning biomass and 14.8% of winter-spawning biomass; relative increases compared to total biomass as the winter-spawning cohort was concentrated more towards the south (Figure 2 - right).

The 95% confidence intervals from the bootstrap algorithm were: 62,309.2 tonnes to 279,733.4 tonnes for total *I. argentinus* biomass, and 62,621.0 tonnes to 278,535.9 tonnes for winter-spawning biomass. The wide spread of the confidence intervals is consistent with the lack of spatial definition of the *I. argentinus* catches (Figure 1). The total biomass estimate of 159,361.9 tonnes was not significantly different (Wilcoxon test, p > 0.3) from the biomass estimate presented by INIDEP: 132,876 tonnes (SSC 2019).

Figure 2 [next page]. Total (left) and winter-spawning (right) *I. argentinus* predicted density estimates per 5 km^2 grids. The colour scale is in kg km^{-2}.

6

Total Illex   Winter - spawning Illex
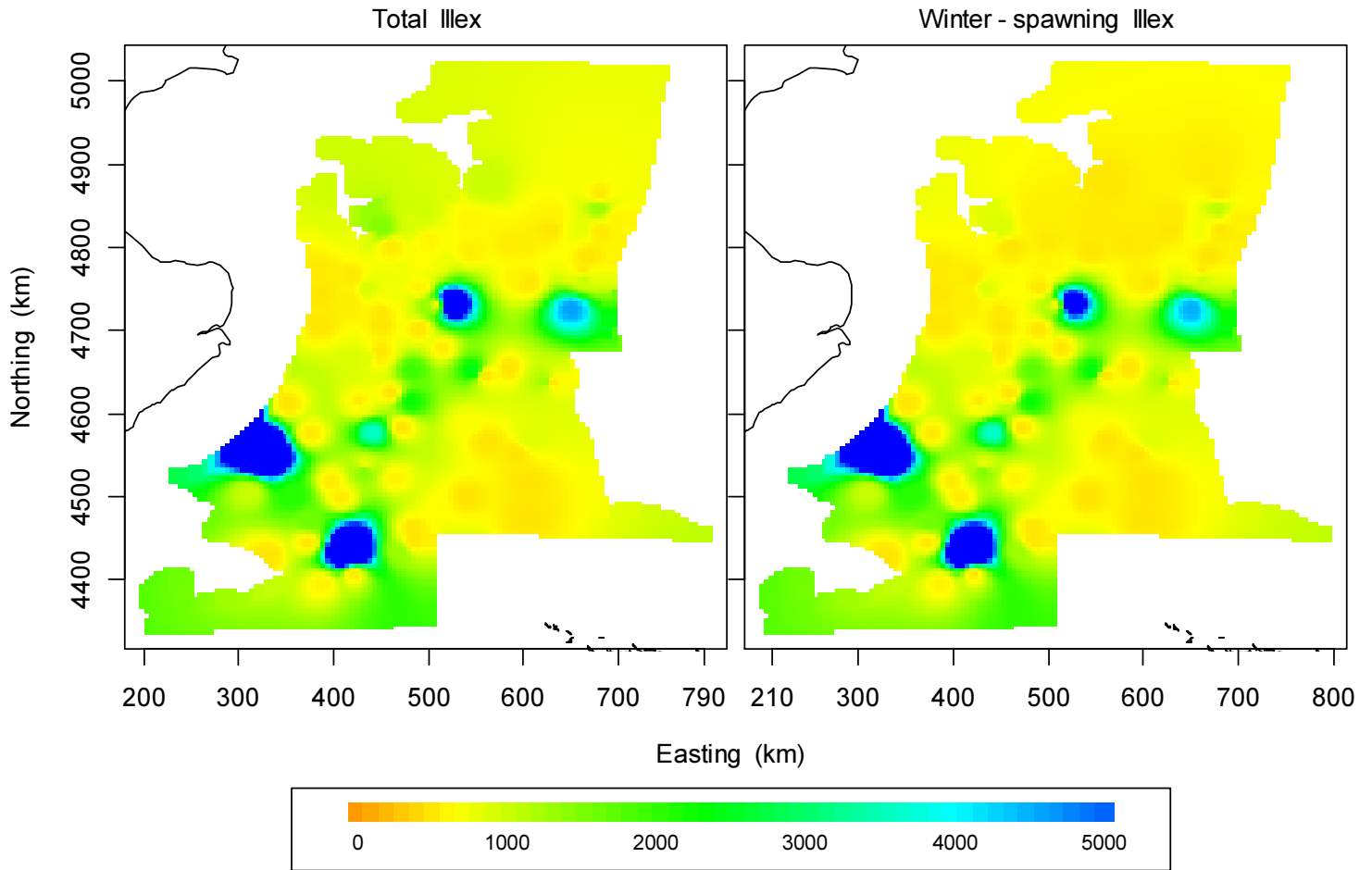
Stock assessment

The assessment period of commercial fishing corresponds to weeks 1 to 22, in 2019. Total reported catches of *I. argentinus* during this period were 82,490 tonnes by Argentine jiggers, 8587 tonnes by Argentine trawlers, 41,533 tonnes by Falklands jiggers, and 1859 tonnes by Falklands trawlers (Table A1). CPUE by Argentine jiggers started high at the beginning of the year, averaging 34.4 tonnes / vessel-day through the first 6 weeks, then decreasing rapidly. Falklands jig fishing started in week 7, averaged 10.2 tonnes / vessel-day through weeks 8 to 11, then decreased but continued at low levels to about week 19. Trawl CPUEs were more variable and generally lower, except for week 6 in the Argentine fishery which achieved 76.7 tonnes / vessel-day (Figure 3). Proportions of total reported *I. argentinus* catches taken inside the survey area[5] were: 89.0% for Argentine jig, 99.2% for Argentine trawl, 11.8% for Falklands jig, and 1.5% for Falklands trawl (Table A1). In particular, during the aggregate of weeks 7 and 8 used for the Bayesian prior, 97.4% of Argentine jig, 97.6% of Argentine trawl, 14.0% of Falklands jig, and 2.8% of Falklands trawl were taken in the survey area (Figure A2).

Figure 3 [next page]. *I. argentinus* total catches per day by week in the jig fisheries (left) and trawl fisheries (right). Light blue: Argentina, dark blue: Falkland Islands.

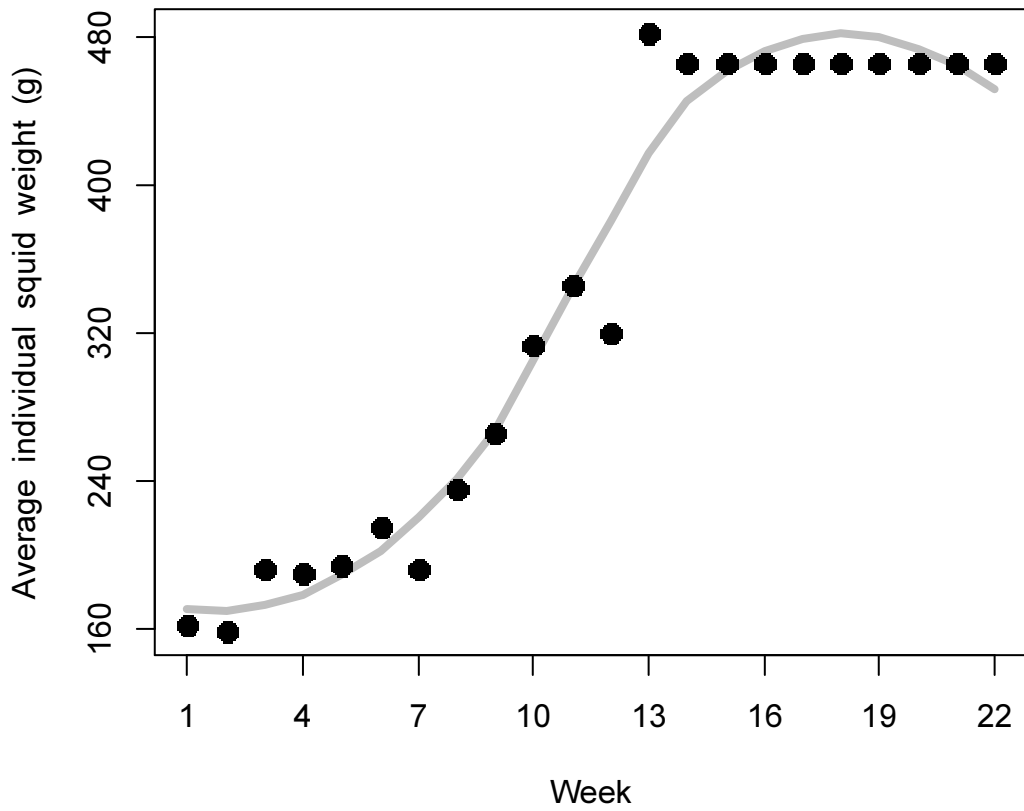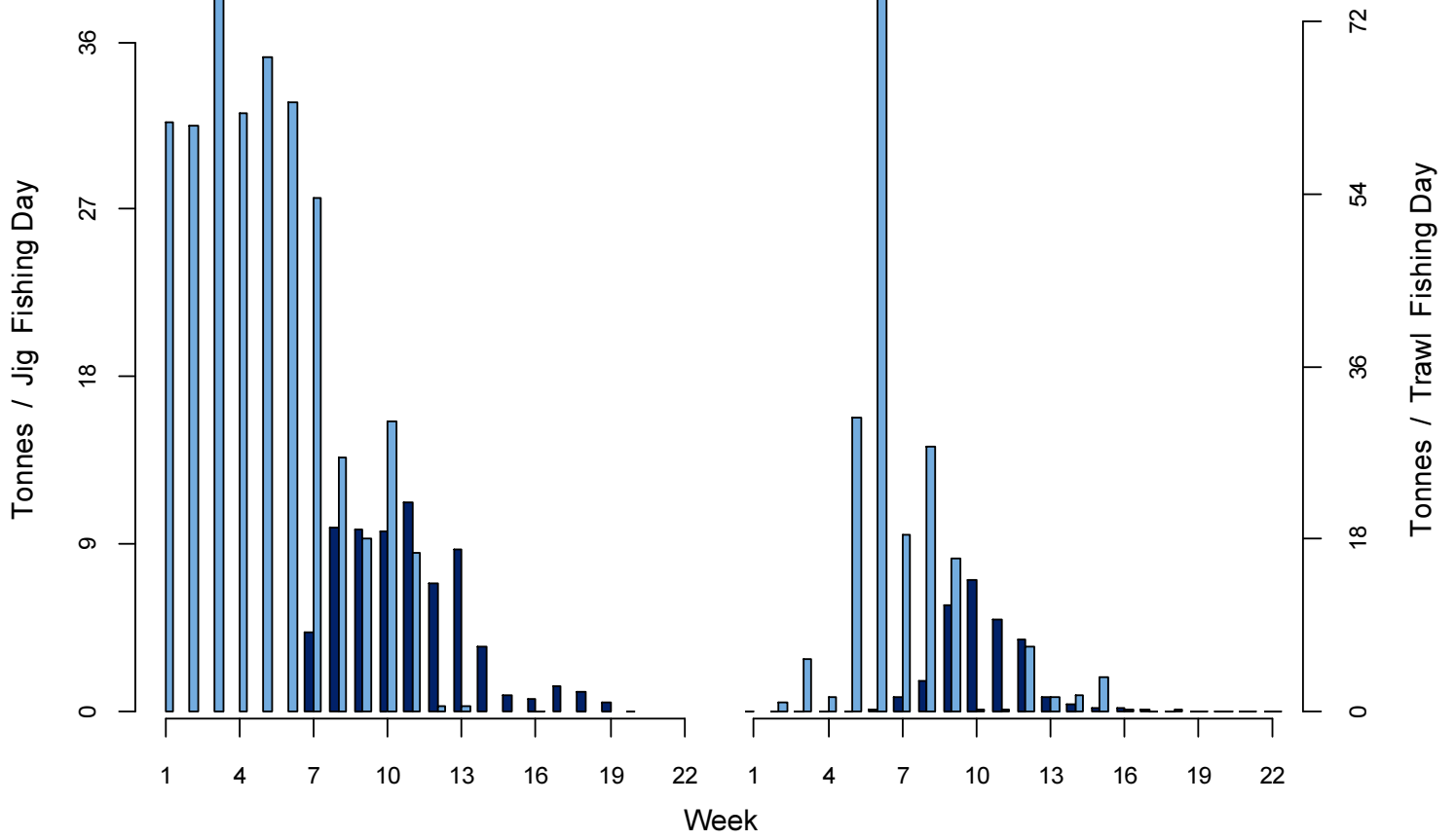[5] Calculated according to the centre of their grid designation.

Figure 4 [previous page]. Weekly average individual *I. argentinus* weights from observer sample data in the jig fisheries, with LOESS smooth (grey line).

Weekly individual weight averages and sample counts are summarized in Appendix Table A2. The LOESS smooth of the time series ($R^2 = 0.908$) resulted in a range of 170 g to 482 g average weight of *I. argentinus* (Figure 4). For the aggregate of weeks 7 and 8, the average individual *I. argentinus* weight was 239 g.

Initialization values for the depletion model optimization, based on the survey and weeks 7/8 data, were: $N_{t=1} = 0.608 \times 10^9$, $q_{AG-J} = 1.774 \times 10^{-4}$ vessel-day^{-1}, $q_{FK-J} = 0.325 \times 10^{-4}$ vessel-day^{-1}, $q_{AG-T} = 2.223 \times 10^{-4}$ vessel-day^{-1}, and $q_{FK-T} = 0.047 \times 10^{-4}$ vessel-day^{-1}. Together with these initialization values, the depletion model assessment was calculated in two versions: using all weekly catch and effort exchange data, and using only the exchange data located inside the survey area. Both versions gave very similar outcomes of the *I. argentinus* biomass time series. The calculation with only data located inside the survey area was retained, having a lower coefficient of variation in the final week (week 22), and being more consistent on theoretical grounds between the survey prior data and the in-season data. The optimization obtained the model fit shown in Figure 5, with parameters summarized in Table 1.
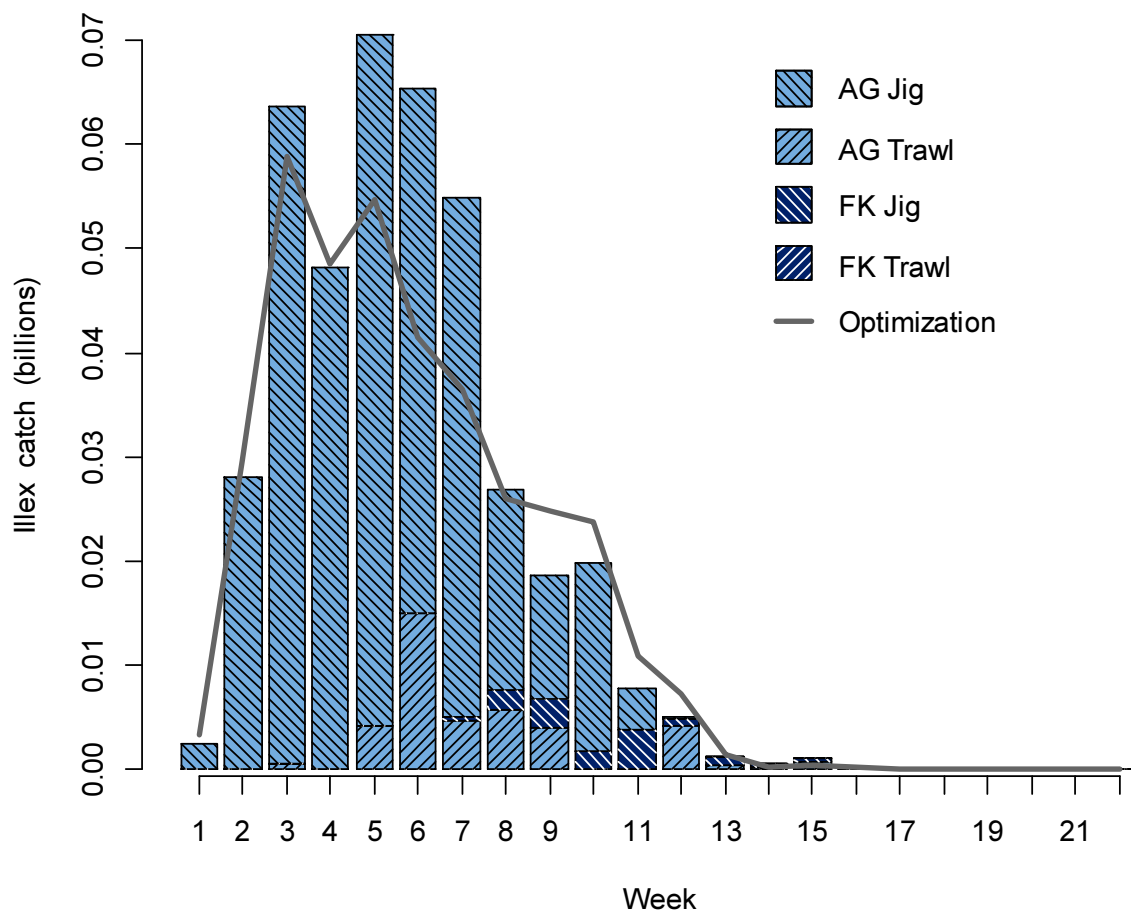

Figure 5. Optimization fit of the Bayesian depletion model. Catch numbers are restricted to within the survey area, thus not exactly comparable to Figure 3.

Table 1. Optimized depletion model parameters (cf. equation 5).

Parameter	Estimation
$N_{t=1}$	1.545×10^{9} N
$q_{AG\text{-}J}$	1.584×10^{-4} vessel-day^{-1}
$q_{FK\text{-}J}$	1.178×10^{-5} vessel-day^{-1}
$q_{AG\text{-}T}$	4.310×10^{-10} vessel-day^{-1}
$q_{FK\text{-}T}$	5.067×10^{-6} vessel-day^{-1}

The resulting maximum likelihood estimate of *I. argentinus* biomass in the survey area decreased from 263,440 tonnes in week 1 (95% confidence interval 152,310 to 451,860 tonnes), to 57,022 tonnes in week 22 (95% confidence interval 15,426 to 123,956 tonnes) (Figure 6).
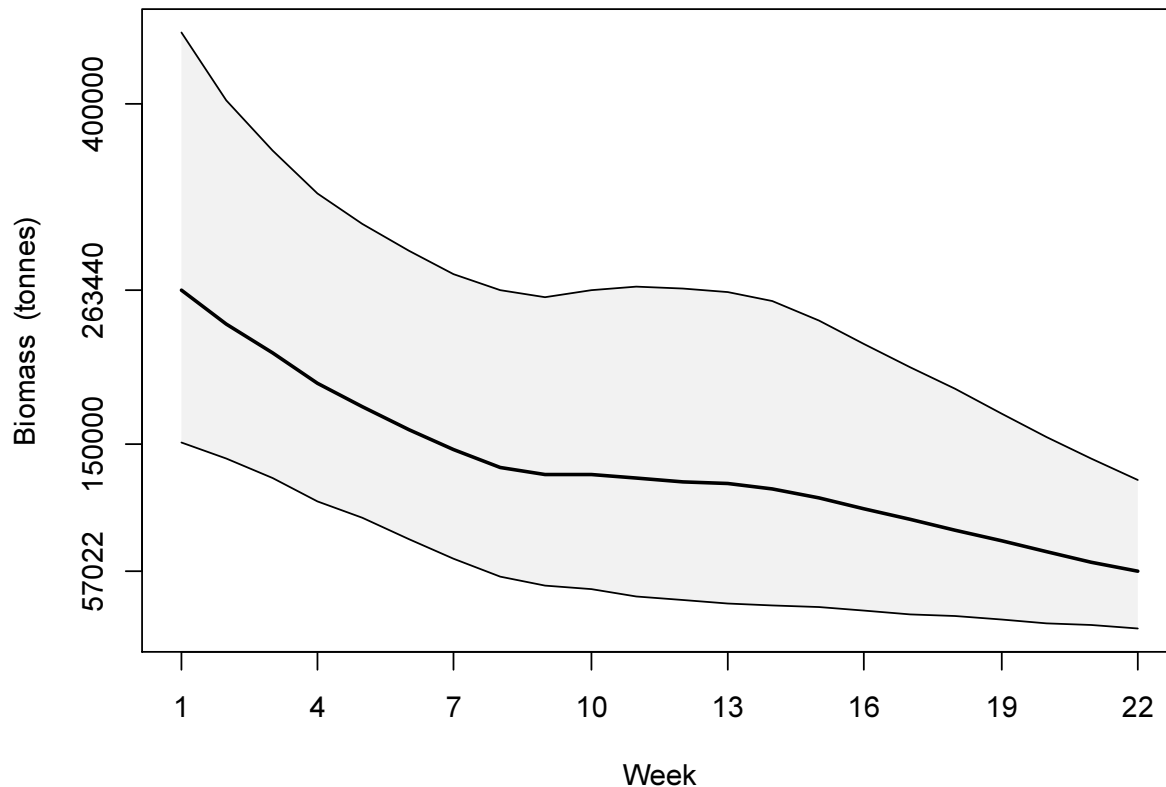

Figure 6. Estimated *I. argentinus* time series in the survey area, week 1 to 22 in 2019.

Conclusion

Beddington et al. (1990) proposed a management target of 40% proportional escapement for the Falkland Islands *I. argentinus* fishery, following convention in other squid fisheries. The management target was subsequently set to an escapement threshold of 40,000 tonnes (Barton et al. 2004). If the estimated starting biomass calculated in this assessment (263,440 tonnes) is considered representative of the entire available *I. argentinus* stock, then the 2019 catch of Argentine fisheries (91,077 t) + Falklands fisheries (43,392 t) = 134,468 t

corresponds to escapement of 49.0% (128,972 tonnes). It is noted, however, that these calculations do not account for high-seas catches or biomass.

Rodhouse et al. (1995) reported that *I. argentinus* recruit to the fishery at about 200 mm mantle length and grow to 300 mm mantle length by the end of the season. Converted according to the length-weight relationship in FIG (2018), this recruitment size is in good agreement with the weight measurements summarized in Figure 4, indicative that since 1995 the squid have continued to be targeted at the same stage in their growth. However, the migratory life history of *I. argentinus* (Hatanaka 1988, Sacau et al. 2005) adds some complication to this species' stock assessment, as movement out of the fishing area may confound depletion. Rosenberg et al. (1990) recommend restricting depletion analysis from the period starting with peak CPUE to when CPUE declines abruptly. To implement such restriction is somewhat subjective, as well as circular, but appropriately cautions the uncertainty of depletion modelling in an open marine system. For comparison, the depletion model optimization was repeated with data restricted to $\leq$ week 16, when *Illex* fishing had practically ended in the survey area (Figure 5). The 16-week optimization inferred no difference in the biomass time series (calculations not shown), only difference in the catchability (q) parameters, suggesting that the stock estimate of *I. argentinus* is robust.

Acknowledgement

References

Agnew, D.J., Hill, S.L., Beddington, J.R., Purchase, L.V., Wakeford, R.C. 2005. Sustainability and management of Southwest Atlantic squid fisheries. Bulletin of Marine Science 76: 579-593.

Arkhipkin, A.I. 2000. Intrapopulation structure of winter-spawned Argentine shortfin squid, *Illex argentinus* (Cephalopoda, Ommastrephidae), during its feeding period over the Patagonian Shelf. Fishery Bulletin 98: 1-13.

Arkhipkin, A.I., Roa-Ureta, R. 2005. Identification of ontogenetic growth models for squid. Marine and Freshwater Research 56: 371-386.

Arkhipkin, A.I., Rodhouse, P.G.K., Pierce, G.J., Sauer, W., Sakai, M., Allcock, L., Arguelles, J., Bower, J.R., Castillo, G., Ceriola, L., Chen, C.-S., Chen, X., Diaz-Santana, M., Downey, N., González, A.F., Granados Amores, J., Green, C.P., Guerra, A., Hendrickson, L.C., Ibáñez, C., Ito, K., Jereb, P., Kato, Y., Katugin, O.N., Kawano, M., Kidokoro, H., Kulik, V.V., Laptikhovsky, V.V., Lipinski, M.R., Liu, B., Mariátegui, L., Marin, W., Medina, A., Miki, K., Miyahara, K., Moltschaniwskyj, N., Moustahfid, H., Nabhitabhata, J., Nanjo, N., Nigmatullin, C.M., Ohtani, T., Pecl, G., Perez, J.A.A., Piatkowski, U., Saikliang, P., Salinas-Zavala, C.A., Steer, M., Tian, Y., Ueta, Y., Vijai, D., Wakabayashi, T., Yamaguchi, T., Yamashiro, C., Yamashita, N., Zeidberg, L.D. 2015. World Squid Fisheries. Reviews in Fisheries Science and Aquaculture 23: 92-252.

Babak, O., Deutsch, C.V. 2009. Statistical approach to inverse distance interpolation. Stochastic Environmental Research and Risk Assessment 23: 543-553.

Barton, J. 2002. Fisheries and fisheries management in Falkland Islands Conservation Zones. Aquatic Conservation: Marine and Freshwater Ecosystems 12: 127–135.

Barton, A.J., Agnew, D.J., Purchase, L.V. 2004. The Southwest Atlantic; achievements of bilateral management and the case for a multilateral arrangement. In: Payne, A.I.L., O'Brien, C.M., Rogers, S.I. (eds.) Management of shared fish stocks. Blackwell Publishing, Oxford, p. 202−222.

Basson, M., Beddington, J.R., Crombie, J.A., Holden, S.J., Purchase, L.V., Tingley, G.A. 1996. Assessment and management techniques for migratory annual squid stocks: the *Illex argentinus* fishery in the Southwest Atlantic as an example. Fisheries Research 28: 3-27.

Beddington, J.R., Rosenberg, A.A., Crombie, J.A., Kirkwood, G.P. 1990. Stock assessment and the provision of management advice for the short fin squid fishery in Falkland Islands waters. Fisheries Research 8: 351-365.

Hatanaka, H. 1988. Feeding migration of short-finned squid *Illex argentinus* in the waters off Argentina. Nippon Suisan Gakkaishi 54: 1343-1349.

Hoenig, J.M. 1983. Empirical use of longevity data to estimate mortality rates. Fishery Bulletin 82: 898-903.

Goyot, L., Derbyshire, C., Jones, J., Tutjavi, V., Winter, A. 2019. *Doryteuthis gahi* stock assessment survey, 2nd season 2019. Stanley, FIG Fisheries Department, 20 p.

Kravchenko, A.N. 2003. Influence of spatial structure on accuracy of interpolation methods. Soil Science Society of America Journal 67: 1564–1571.

Koronkiewicz, A. 1995. Size and maturity differences between trawl and jigger caught short-finned squid *Illex argentinus (Cephalopoda: Ommastrephidae)*. Acta Ichthyologica et Piscatoria 25: 97-112.

Mercopress. 2018. Argentina/UK/Falklands' South Atlantic fisheries joint scientific cruises closer. en.mercopress.com/2018/11/19/argentina-uk-falklands-south-atlantic-fisheries-joint-scientific-cruises-closer.

Mueller, T.G., Pusuluri, N.B., Mathias, K.K., Cornelius, P.L., Barnhisel, R.I., Shearer, S.A. 2004. Map Quality for Ordinary Kriging and Inverse Distance Weighted Interpolation. Soil Science Society of America Journal 68: 2042-2047.

Nash, J.C., Varadhan, R. 2011. optimx: A replacement and extension of the optim() function. R package version 2011-2.27. http://CRAN.R-project.org/package=optimx.

Punt, A.E., Hilborn, R. 1997. Fisheries stock assessment and decision analysis: the Bayesian approach. Reviews in Fish Biology and Fisheries 7:35-63.

Ramos, J.E., Winter, A. 2019. February trawl survey biomasses of fishery species in Falkland Islands waters, 2010-2019. Stanley, FIG Fisheries Department, 46 p.

Randhawa, H.S., Hall, J. In prep. Cruise report VA/0219: Joint *Illex* pre-recruitment survey. Stanley, FIG Fisheries Department, xx p.

Rodhouse, P.G., Hatfield, E.M.C. 1990. Dynamics of growth and maturation in the cephalopod *Illex argentinus* de Castellanos 1960 (Teuthoidea: Ommastrephidae). Philosophical Transactions of the Royal Society of London Series B 329: 229-241.

Rodhouse, P.G., Barton, J., Hatfield, E.M.C., Symon, C. 1995. *Illex argentinus*: life cycle, population structure, and fishery. ICES Marine Science Symposium 199: 425-432.

Rosenberg, A.A., Kirkwood, G.P., Crombie, J.A., Beddington, J.R. 1990. The assessment of stocks of annual squid species. Fisheries Research 8: 335-350.

Sacau, M., Pierce, G.J., Wang, J., Arkhipkin, A.I., Portela, J., Brickle, P., Santos, M.B., Zuur, A.F., Cardoso, X. 2005. The spatio-temporal pattern of Argentine shortfin squid *Illex argentinus* abundance in the southwest Atlantic. Aquatic Living Resources 18: 361-372.

Shepard, D. 1968. A two-dimensional interpolation function for irregularly-spaced data. Proceedings of the 23rd ACM National Conference: 517-524.

Somerton, D., Ianelli, J., Walsh, S., Smith, S., Godø, O.R., Ramm, D. 1999. Incorporating experimentally derived estimates of survey trawl efficiency into the stock assessment process: a discussion. ICES Journal of Marine Science 56: 299-302.

SSC. 2018. 25th Meeting of the Scientific Sub-Committee of the South Atlantic Fisheries Commission, 14-15 November 2018, Foreign and Commonwealth Office, London, UK. Report of the SSC, 34 p.

SSC. 2019. 26th Meeting of the Scientific Sub-Committee of the South Atlantic Fisheries Commission, 17-18 July 2019, ISEN, Buenos Aires, Argentina. Report of the SSC, 14 p.

Waluda, C.M., Trathan, P.N., Rodhouse, P.G. 1999. Influence of oceanographic variability on recruitment in the *Illex argentinus* (Cephalopoda: Ommastrephidae) fishery in the South Atlantic. Marine Ecology Progress Series 183: 159-167.

Appendix

Choice of power parameter *p* for the inverse distance weighting algorithm:

By turn, *I. argentinus* density at each of the 86 trawls was predicted from the other 85 trawls in a 'leave-one-out' format using the inverse distance weighting algorithm. The set of 86 predictions was repeated with *p* values ranging from 1 to 25 by 0.25. The best *p* value is the one that results in the lowest aggregate 'error'; that is the lowest aggregate difference between the empirically calculated densities (from measured catch and trawl dimensions) and the 'leave-one-out' predicted densities of the trawls. To mitigate the outcome being excessively biased towards trawls with high catch results, differences between empirical and predicted densities were computed as the density ratios, and log-transformed so that proportional under-predictions count as much as over-predictions. The absolute values of the logarithms were summed, and to avoid the indetermination of zeros, 1 was added to all density values prior to calculation:

$$\text{Aggregate Difference} = \sum_{n=1}^{86 \text{ trawls}} \text{abs}\left(\log\left(\frac{\left(1 + \textit{Illex } \text{Density}_{\text{empirical}}\right)_n}{\left(1 + \textit{Illex } \text{Density}_{\text{IDW predicted}}\right)_n} \right) \right)$$
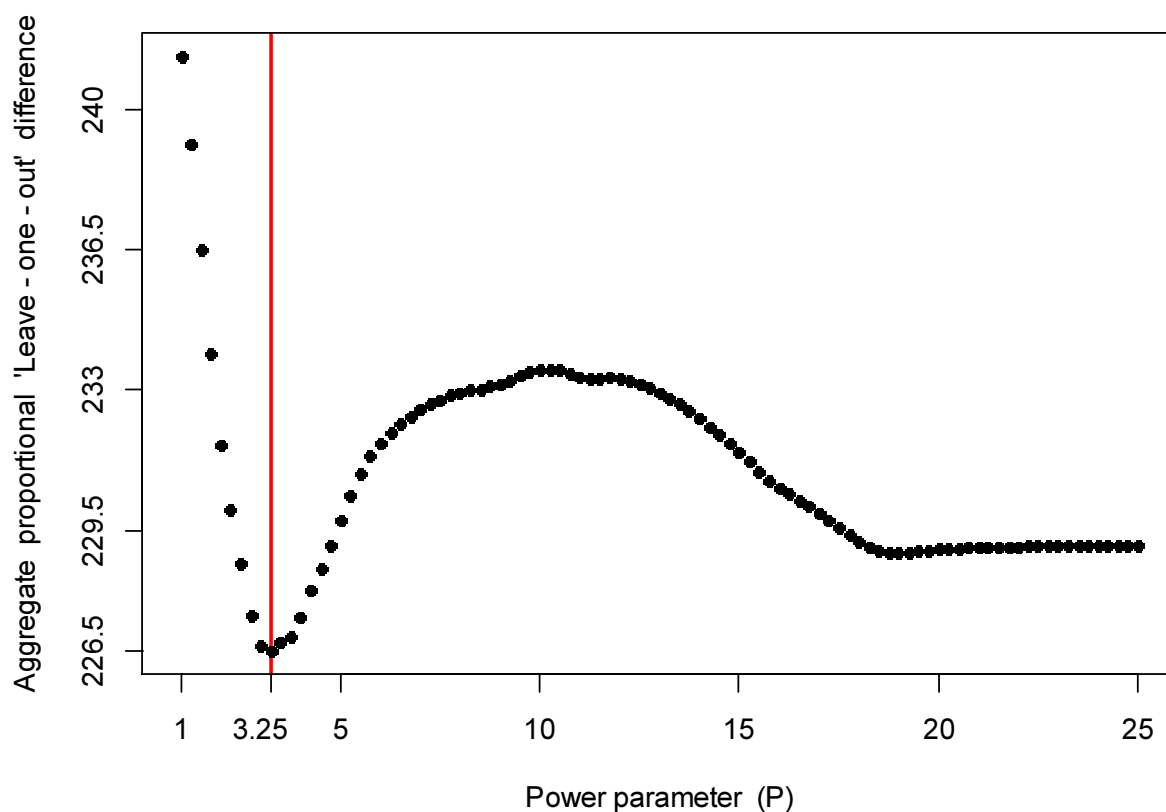

Figure A1. For the *I. argentinus* survey data, the minimum of the aggregate difference was attained at p = 3.25.

14

Table A1. Weekly catches (tonnes) of *I. argentinus* in 2019.

| Week	Argentina				Falkland Islands			
	Jig		Trawl		Jig		Trawl	
	Total	Survey Area	Total	Survey Area	Total	Survey Area	Total	Survey Area
1	824.6	402.4					0.0	
2	9180.9	4506.8	5.5	5.5			0.0	
3	13554.0	12132.0	97.9	97.9			0.0	
4	9201.1	9145.1	18.3	18.3			0.0	
5	13081.8	12931.5	825.7	825.7			0.0	
6	10874.4	10846.9	3220.6	3220.6			2.0	
7	9666.8	9543.3	887.9	887.9	500.0	157.9	34.8	2.6
8	4285.9	4049.9	1271.1	1218.4	4991.2	611.2	103.0	1.3
9	3036.5	3002.8	1037.5	1037.5	6974.3	983.8	424.7	3.8
10	6008.0	5582.1	6.5	6.5	6933.9	574.8	437.8	5.6
11	2696.1	1282.4	2.5	2.4	8018.2	1461.6	364.7	0.5
12	68.0	28.2	886.2	881.0	4266.3	314.1	340.6	4.6
13	11.7	0.2	101.1	98.5	6382.6	374.2	69.8	2.2
14	0.0	0.0	61.1	61.0	2062.9	171.2	38.5	3.3
15	0.0	0.0	153.8	150.2	563.0	171.9	12.6	0.4
16	0.0	0.0	2.4	2.4	245.2	45.2	13.5	1.6
17			2.1	1.5	352.5	28.6	8.0	0.7
18			3.6	0.9	157.8	0	3.9	0.3
19			0.7	0.2	84.7	9.9	2.7	0.2
20			2.0	1.1	0.0	0.0	2.0	0.0
21			0.1	0.1			0.0	0.0
22			0.3	0.3			0.0	0.0
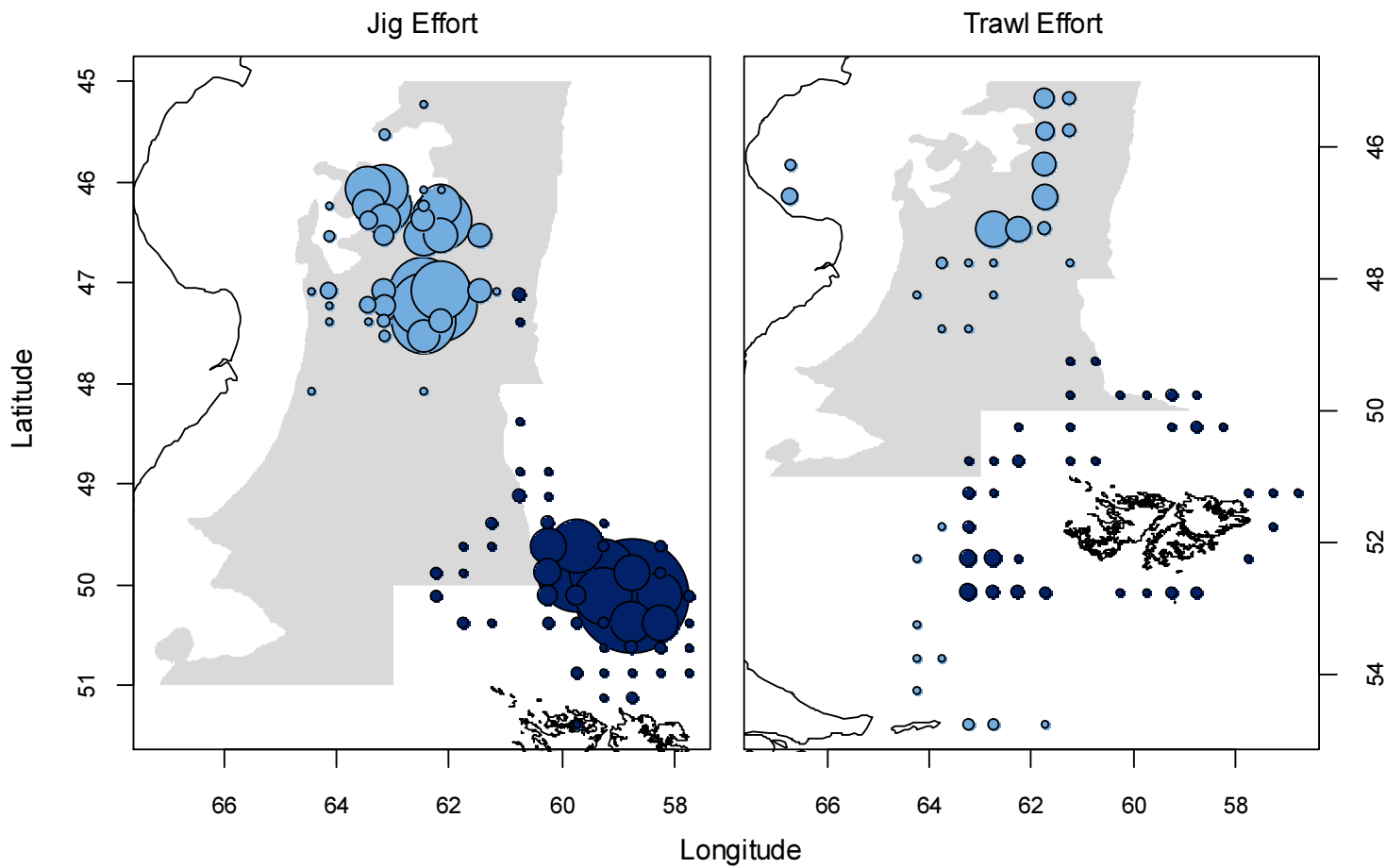
Figure A2. Distributions of jig and trawl fishing effort in weeks 7 and 8, which correspond to the survey period used as a Bayesian prior. Plot symbols are proportional to the numbers of vessel-days per location. Light blue: Argentina, dark blue: Falkland Islands, grey: survey area.

Table A2. Weekly average individual *I. argentinus* weights, and numbers sampled. The combined average weight corresponds to Figure 4.

Week	Argentina		Falkland Islands		Combined
	Avg. wt.	N	Avg. wt.	N	Avg. wt.
1	162.0	150			162.0
2	160.4	3298			158.9
3	192.2	4041			192.4
4	190.0	3893			190.7
5	195.0	4200			195.0
6	215.0	2400			215.0
7	191.9	4049			192.9
8	210.6	3301	344.0	299	236.0
9	253.9	4200	362.6	500	265.9
10	308.4	4650	342.0	500	313.2
11	331.9	1386	380.1	553	345.6
12	208.0	450	454.0	505	319.7
13			482.5	549	482.1
14			466.0	100	466.0
15					466.0
16					466.0
17					466.0
18					466.0
19					466.0
20					466.0
21					466.0
22					466.0