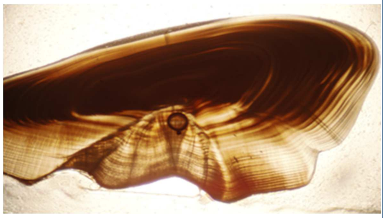
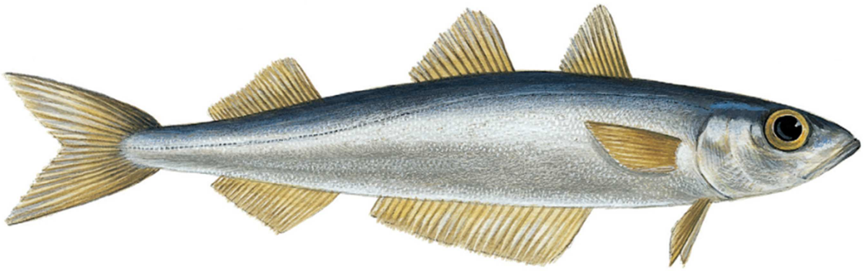
Stock assessment of Southern blue whiting (*Micromesistius australis*) in the Falkland Islands





SA–2019–BLU

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Jorge E. Ramos (R scripts, data analyses, elaboration of report)
Andreas Winter (R Scripts, elaboration of report)

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Stock assessment of Southern blue whiting (*Micromesistius australis*) in the Falkland Islands

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Summary

The Southwest Atlantic blue whiting stock (BWS) was assessed with the optimized catch-only method (OCOM). Using OCOM, the most conservative estimate of the median MSY was 80,171 t, and the stock biomass in 2018 was estimated in 201,974 t, which was 15.23% of the stock biomass in 1987. The length-based Bayesian biomass estimation method (LBB) estimated the biomass in 2018 at about 39% of the biomass that would provide MSY. LBB also estimated that length at 50% catch (42.8 cm) was approximately 3 cm below the optimum length at catch (46 cm). Modal total lengths of females and males had statistically significant decreases from 2002 to 2018. Females and males had non-statistically significant declining trends in age at 50% maturity and in length at 50% maturity. Based on B_{2018}/B_{MSY} = 0.305, we recommend that the present catch limit of the BWS should be 30.5% of MSY: 80,171 × 0.305 = 24,452 t. In Falkland Islands waters, the BWS is caught mainly during August and September under A, W and X licences, and from March to April under G licence. Under S licence, most catches occurred during October and November. The recommended catch limit of the BWS in Falklands waters ranged between 2,905 t and 8,150 t based on different criteria.

Introduction

Southern blue whiting *Micromesistius australis* (Norman, 1937; Gadidae) is a bentho-pelagic fish that occurs in temperate shelf waters of the Southeast Pacific between 42°S and 57°S (southern Chile) and in the Southwest Atlantic between 37°S and 55°S (Argentina and Falkland Islands) at 20–800 m depth (Aguayo et al. 2010; Froese & Pauly 2019). Spawning grounds of this species are located to the south of the Falkland Islands at 200–300 m depths during September and October (Shubnikov et al. 1969; Pájaro & Macchi 2001; Macchi et al. 2005), which vary in size and location depending on the intensity of the Falkland Current (Arkhipkin et al. 2009, 2012). Other spawning grounds occur at 200–300 m depths off the southern coast of Chile, between Golfo de Penal and Peninsula de Tres Mortes (Arkhipkin et al. 2009).

Part of the population migrates from the Atlantic in June-July to spawn in Chilean waters in August, and by the middle of November moves back to its Atlantic feeding grounds (Lillo et al. 1999). Individuals that spawn in Falkland Islands waters move to the Patagonian Shelf and remain in that area until December–January before moving further south to feeding grounds in the Scotia Sea (Barabanov 1982), where mixing likely occurs at the immature stage during the Antarctic summer (Perrotta 1982; Barabanov et al. 1984). In the Patagonian shelf, Southern blue whiting preys mainly upon euphausiids and amphipods (*Themisto gaudichaudii*), and upon other species when available (Brickle et al. 2009).

Connectivity between the Southwest Atlantic and Southeast Pacific was confirmed by otolith chemistry (Arkhipkin et al. 2009) and mitochondrial DNA analyses (Shaw 2003, 2005), whereas microsatellite analysis revealed sub-population structure in Falkland and Chilean waters (Shaw 2003, 2005). Therefore, for the purpose of this report Southern blue whiting from the Falkland Islands, Argentina and Chile will be referred to as Southwest Atlantic blue whiting stock (BWS).

Southern blue whiting is a commercially important species in Chile, where it was first caught in 1978 as bycatch in the Southern hake (*Merluccius australis*) fishery in the austral zone (43–57°S; Aguayo et al. 2010). In the Chilean fishery, this species is caught at sizes between 29 and 118 cm of total length (TL), and at ages up to 18 years although most individuals occur at maximum 13 years; fishing mortality is estimated at 0.2668 for males and 0.2314 for females (Aguayo et al. 2010). In Argentina, the fishery for Southern blue whiting takes place from 45°S to 56°S, where individuals are caught at 17–60 cm TL and at maximum 21 years old (Cassia 2000); size at maturity of females was estimated at 37.8 cm TL (Pájaro & Macchi 2001). In Falkland waters, *M. australis* is caught by trawlers throughout the year, with lower catches during late autumn and early winter. Currently, there is a no-fishing area for S-licensed vessels targeting hoki and Southern blue whiting to the South and Southwest of the Falkland Islands from 1 July to 15 October (Falkland Islands Government 2018). However, there has been only sporadic S-licence fishing since its implementation in 2007. Low catch limits and high operative costs have prevented fishers from targeting the BWS during 2017 and 2018 under S licence. The average contribution of this species to the trawl fishery production in Falklands waters is 10% since 1987 and about 2% over the last decade (Falkland Islands Government 2018).

Given that the BWS is targeted by different inter-boundary fisheries, these must be accounted for stock assessment. Restricted access to catch and effort data from fisheries outside Falklands waters prevent the use of CPUE as indices of relative abundance, and require the alternative of data-poor stock assessment methods (Froese et al. 2017, 2018; Zhou et al. 2018). The aim of this report is to provide metrics for the management of the BWS, including biological information necessary to implement the required stock assessment approaches.

Methods

Commercial catch

Commercial fishing around the Falkland Islands was not distinguished from other parts of the Southwest Atlantic prior to 1982 and catch data by species were recorded systematically from 1987 only (Falkland Islands Government 1989). Therefore, total commercial fishery catches of the BWS were examined from 1987 to 2018. Commercial catch data from the Falkland Islands is available at http://www.fig.gov.fk/fisheries/publications/fishery-statistics (Falkland Islands Government 2018). Catch data from Argentina is available at https://www.agroindustria.gob.ar/sitio/areas/pesca_maritima/desembarques/ (Sánchez et al. 2012; Navarro et al. 2014). Catch data from Chile was accessed from http://www.sernapesca.cl/informes/estadisticas (SERNAPESCA 1990, 2000, 2011). Total catch of the BWS in Chilean waters during 2018 was provided by Instituto del Fomento

Pesquero (IFOP) on request given that the data was not available online at the time of producing this report, and therefore should be considered as preliminary (R. Céspedes, IFOP, *pers. comm.*). Spearman correlation was implemented to examine the association between annual catch of the Falkland Islands and Argentina, and to examine the association between the annual catch of the Falkland Islands and Chile.

Temporal and spatial patterns of the BWS commercial catch in Falkland Islands waters during 2018 and for the period 2008–2018 were examined by licence type. In addition, mean, maximum and minimum monthly catch, effort and CPUE from 2008 to 2018 were examined. CPUE per month was estimated as the sum of catches of the month from 2008 to 2018 divided by the sum of effort of the month from 2008 to 2018. The spatial examination of mean CPUE per month and grid square from 2008 to 2018 was estimated as the sum of catches of the month per grid square from 2008 to 2018 divided by the sum of effort of the month per grid square from 2008 to 2018.

Biomass estimation

Optimized Catch-Only Method (OCOM)

The Optimized Catch-Only Method (OCOM) developed for data-poor fish stocks uses time series of catches and priors for the intrinsic population growth rate (r) derived from basic life history parameters, and for stock saturation (S) based on catch trends (Zhou et al. 2018). Stock saturation refers to the biomass of the stock at the end of the catch time series relative to the unfished biomass (Zhou et al. 2017). This method applies an optimization of the Graham-Schaefer surplus production model to search the potential parameter space (Schaefer 1954):

$$B_{y+1} = B_y + r \cdot B_y \left(1 - \frac{B_y}{K}\right) - C_y$$

where B_y = biomass at the start of time step y; r = intrinsic growth rate; K = carrying capacity (equal to the initial biomass B_0 for a surplus production model); C_y = known catch during time-step y. Catches per year (C_y) were the total annual catches of the BWS.

Population intrinsic growth rate (r) was calculated from the generalized empirical relationship (Zhou et al. 2018):

$$r = 2 \cdot F_{MSY}$$

Fishing at maximum sustainable yield (F_{MSY}) was estimated as $F_{MSY} = 0.87 \cdot M$ for teleosts (Zhou et al. 2012), where M is instantaneous natural mortality rate.

To avoid potentially negative values being sampled, a lognormal distribution was implemented as follows:

$$r \sim \text{lognormal}(\mu_r, \sigma^2_r)$$

where mean r (μ_r) = log(2F_{MSY}), and uncertainty of r (σ_r^2) = $\sigma_M^2 + \sigma_e^2$. Measurement error in M (σ_M^2) = 0.23 and the process error in the relationship between M and F_{MSY} (σ_e^2) = 0.0012; hence, uncertainty of r (σ_r^2) = 0.2312 (Zhou et al. 2018).

Natural mortality M was calculated from two different empirical life-history equations (Kenchington 2014; Zhou et al. 2018):

$$M1 = 4.899 \cdot t_{max}^{-0.916}$$

$$M2 = \frac{4.3}{t_{max}}$$

where t_{max} = maximum age.

Maximum age was taken from the Falkland Islands Fisheries Department (FIFD) age-length database. Natural mortality estimated using the equation M2 can be overestimated in species with pronounced senescence (Kenchington 2014). This may be the case of Southern blue whiting based on its age-length relationship examined using the von Bertalanffy equation. The von Bertalanffy equation was implemented using the package 'fishmethods' (Nelson 2017) in R Studio (RStudio Team 2016):

$$L = L_\infty \cdot \left(1 - e^{-k(t - t_0)}\right)$$

where t_0 = theoretical age at zero length.

Time series of annual biomass were calculated by randomly drawing values of growth rate (r) and biomass ratio $B_{current}/B_0$ from their distributions, iterated and optimized 10,000× following Zhou et al. (2018). Medians and 95% confidence intervals (CI) were computed for parameters r, K, $B_0 = B_{1987}$, and $B_{current} = B_{2018}$. MSY was also reported and was defined from the Graham-Schaefer production model as indicated in Hilborn & Walters (1992):

$$MSY = \frac{r \cdot K}{4}$$

where r = intrinsic growth rate, and K = carrying capacity.

Length frequencies, and age and length at maturity

Total length and age data were collected on board commercial vessels that carried out bottom trawls (A, G, and W licences) and pelagic trawls (S licence) during spring (November and December), summer (January, February, March), and autumn (April and May) in Falkland Islands waters. Total length and age data were also collected on board research cruises (E licence) carried out during February. Total length was measured to the nearest centimetre from random samples to avoid any bias in length frequencies of caught individuals. Age data were taken from random and non-random samples to complete the whole range of age-size pairs for calculating the Von Bertalanffy age-length relationship. Data from June to October were excluded given that part of the BWS emigrates from Falkland waters during those months (Lillo et al. 1999), which may bias length and age frequencies. The deposition of growth rings in otoliths was examined to determine the age of 7,927 individuals (3,836 females and 4,091 males) for the analysis of age at 50% maturity. Length and age data of 8,144 individuals (3,836 females; 4,091 males; 217 juveniles) collected throughout the year from 2000 to 2018 were used for the Von Bertalanffy calculation. All otoliths were processed at the Sea Fisheries Institute in Gdynia (Poland), except for the otolith of one male that was processed at the FIFD.

Sex was identified and maturity stage was determined following Brickle et al. (2005; modified from Nikolsky 1963): I) immature; II) resting; III) early developing; IV) late developing; V) ripe; VI) running; VII) spent; VIII) recovering spent. An additional category (0) referred to juveniles which sex could not be determined. Gonadal maturity of fish is cyclical, for instance fish pass from post-spawning phase VIII to the pre-spawning phase II. In this sense, maturity stages ≤ I are always juveniles, stage II consists of both individuals that have never spawned before (juveniles) and individuals who are resting following spawning (adults), and stages ≥ III are always adults (H. Randhawa, FIFD, *pers. comm.*). Therefore, maturity assignment was simplified to a dichotomous classification of: 0) juvenile (stages ≤ I), or 1) adult (stages ≥ III), omitting stage II. The dichotomous maturity classification was modelled vs. length and vs. age on a binomial distribution, and length and age at 50% maturity was extracted from the logistic function of the binomial model for each year and for females and males separately, as well as for females and males pooled. The resulting data allowed for examining length-frequency distributions, and age and length at 50%

maturity from 2002 to 2018. Length-frequency modes were calculated for each year by implementing LOESS (degree = 2, span = 0.75).

Length-Based Bayesian biomass estimation method (LBB)

The Length-Based Bayesian biomass estimation method (LBB) for evaluating data-poor stocks is based on the principle of calculating relative rates of natural mortality (M) over somatic growth (k), i.e. M/k, and fishing mortality (F) over somatic growth (k), i.e. F/k. This approach cancels out absolute values of time and biomass, reducing the data requirements to lengths only. M/k and F/k are used to derive indices of yield per recruit with and without fishing. The ratio of these indices estimates the "current" exploited biomass relative to "unfished" biomass ($B_{current}/B_0$). LBB also provides estimates for length at catch (Lc), optimum length at catch (Lc_{opt}), the ratio of length at catch relative to optimum length at catch (Lc/Lc_{opt}), asymptotic length (L_∞), alpha (steepness of the ogive), relative fishing mortality (F/M), and the ratio of observed biomass relative to the biomass that would provide maximum sustainable yield (B/B_{MSY}), among others. LBB was run with the Gibbs sampler JAGS (https://sourceforge.net/projects/mcmc-jags/files/JAGS/4.x/) through the package 'R2jags' (Su & Yajima 2015) in R Studio (RStudio Team 2016) following Froese et al. (2018).

LBB was performed on length data that had been sampled randomly in Falkland Islands commercial fishing trawlers under A, G and W licences (i.e. bottom trawls), and S licence (pelagic trawls) from November to May. LBB produces plots of the raw data per year that help identify and exclude years that are unfit for analysis (Froese et al. 2018); data fit for analysis have a symmetrical two-tailed distribution and no outliers. Southern blue whiting length data from commercial vessels collected from 2002 to 2018 were suitable for the LBB analysis (length frequencies from 2006, and 2012–2016 did not show the distribution required for LBB and were excluded); therefore, $B_{current} = B_{2018}$ and $B_0 = B_{2002}$. Length data from research cruises (i.e. E licence) conducted every February since the year 2000 were also examined, however none of these data showed the distribution required for LBB and were therefore not analysed.

CMSY

The CMSY (Catch – MSY) method was implemented to estimate population parameters from catch data and resilience of the species (Froese et al. 2017). Resilience is defined by the spawning stock biomass per recruit that corresponds to replacement fishing mortality; resilience to fishing mortality is affected by productivity indexes such as intrinsic rate of population growth (r), carrying capacity (K), fecundity, age at maturity, and longevity (Musick 1999). For instance, stocks with greater intrinsic rate of population growth, greater carrying capacity, greater fecundity, younger age at maturity, and shorter longevity may have greater resilience. Monte Carlo simulations were used to detect viable maximum intrinsic rate of population increase (r) and unexploited population size or carrying capacity (K) pairs from probable ranges of these parameters. Pairs of r-K were visualized in a scatterplot where CMSY searched for the most probable r-K pair. This method relies on the principle that defines r as the maximum rate of increase for the examined population, which should be found among the highest viable r-values. Median biomass levels and 95% CI were derived from the validated r and K pairs. The prior range of r was taken from the OCOM output of r, which is within the prior range of r reported for this species in Fishbase (0.54; 0.36 – 0.82, 95% CI) and that corresponds to the resilience level 'Medium' (Froese & Pauly 2019; https://www.fishbase.se/summary/Micromesistius-australis.html). Hence, for the CMSY analysis Southern blue whiting was assigned the resilience level 'Medium' (Froese et al. 2017, 2019).

The lower and upper bounds of the prior range for carrying capacity (K) were estimated as follows (Froese et al. 2017):

$$\mathrm{K_{low}} = \frac{\max(\mathrm{C})}{\mathrm{r_{high}}}\ ,\ \mathrm{K_{high}} = \frac{4\max(\mathrm{C})}{\mathrm{r_{low}}}$$

where K_{low} = lower bound of the prior range of K; max(C) = maximum catch in the time series; r_{high} = upper bound of the range of r-values that the CMSY method will explore; K_{high} = upper bound of the prior range of K; r_{low} = lower bound of the range of r-values that the CMSY method will explore.

Depletion is the reduction, through overfishing, in the level of abundance of the exploitable segment of a stock that prevents the realization of the maximum productive capacity (Van Oosten 1949). To provide prior estimates of relative biomass at the beginning and end of the time series, one of the possible four broad depletion ranges (Very strong:

0.01–0.2: Strong: 0.01–0.4; Medium: 0.2–0.6; Low: 0.4–0.8; Froese et al. 2019) was chosen based on $B_{current}/B_0$ estimated with OCOM and LBB.

The area distribution of commercial and research BWS data from the Falkland Islands used for this stock assessment is indicated in Fig. 1.

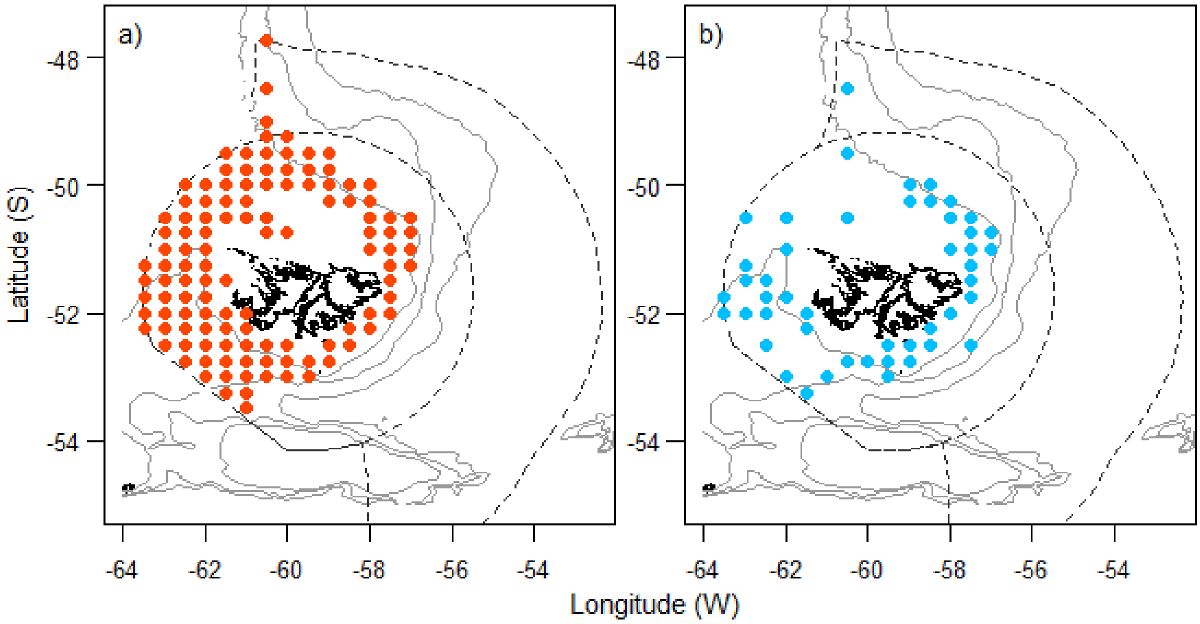

Fig. 1. Distribution of Southern blue whiting sampling data by a) commercial trawlers under A, G, S and W licences in red, and b) February research surveys under E licence in blue within the Falkland Islands Conservation Zones (FICZ and FOCZ). Dots indicate the mid-point of each grid square and represent catches taken within the FICZ and FOCZ.

Catch limits

Total Allowable Catch of BWS must be partitioned between the Falkland Islands, Argentine and Chilean fisheries. Historical catch is often used to estimate quota allocation on international and regional scales (Lynham 2013). For BWS in Falklands waters, various catch limits were proposed based on average catch and relative average contribution (%) by the Falkland Islands, Argentina and Chile over different periods of time (i.e. 10-, 5-, and 3-year average), and alternatively on equal share of the total catch of the BWS, i.e. 33.33% each.

Results

Commercial catch

Catches of BWS in the Falkland Islands have averaged 23,345 t per year since 1987; the maximum catch was observed in 1990 (72,351 t), followed by a constant decrease to reach the lowest catch in 2018 (992 t). Average annual catch was 4,022 t from 2009 to 2018, whereas it was relatively low from 2014 to 2018 (3,024 t), and from 2016 to 2018 (2,905 t). The Falkland Islands have the smallest 10-year average contribution (12.6 ± 5.1%) to the total production of the BWS; Argentina and Chile contribute 40.9 ± 16.1% and 46.5 ± 15.4% of the catch, respectively. The mean annual catch of the BWS in Argentina over the period 1987–2018 was 40,873 t. Catches in Argentina increased from 1987 to reach a maximum in 1993 (128,525 t), followed by a steep decrease to reach the lowest catch in 2011 (3,518 t); catches from 2012 to 2018 have remained below 16,000 t per year. The mean annual catch of the BWS in Chile over the period 1987–2018 was 19,111 t. Catches in Chile increased from 1987 to reach a maximum in 1998 (40,857 t), and have decreased gradually to 5,199 t in 2018 (Fig. 2; Appendix I). Annual catches of the BWS from Falkland Islands and Argentina had a significant correlation ($r = 0.50$, $n = 32$, $p = 0.03$). There was no correlation between annual catches from the Falkland Islands and Chile ($r = -0.11$, $n = 32$, $p = 0.56$; Appendix II).

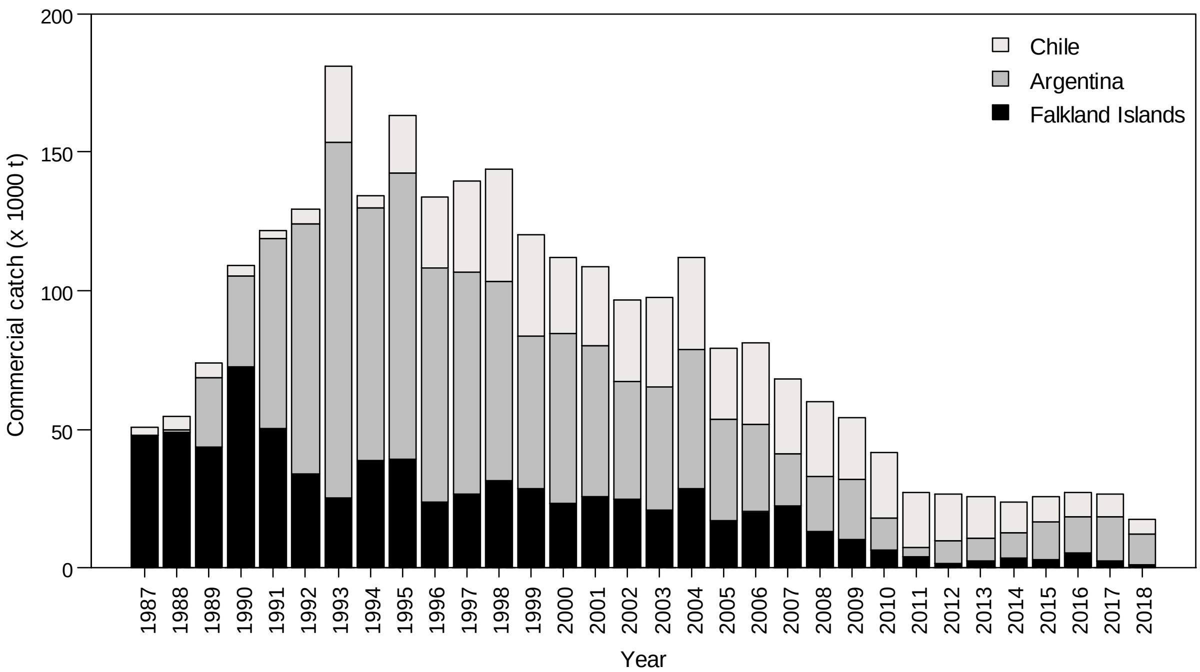

Fig. 2. Commercial total catch of the Southwest Atlantic blue whiting stock from 1987 to 2018. Catch data from Chile for the year 2018 are preliminary (R. Céspedes, IFOP, *pers. comm.*).

In 2018, approximately 85% of the BWS catch in Falkland Islands waters was under W licence. Minor contributions to the commercial catch occurred also from G– (5%), X– (4%) and A–licensed vessels (3%; Table I). The average over the period 2008 – 2018 showed that the main catch contributions were from S– (45%) and W–licensed vessels (31%). X–, G–, and A–licensed vessels contributed 9%, 6%, and 6%, respectively. Minor contributions were also observed from C–, E–, and F–licensed vessels (Table I). CPUE is similar from October to January under S licence. Southern blue whiting is caught mainly during August and September under A, W and X licences, and from March to April under G licence (Appendixes III–VII). Under S licence, most catches per grid square occurred during October and November along the south, southeast and east of the FICZ. Under W and A licences, most catches per grid square during August and Sept occurred to the southwest of the FICZ. Most catches under G-licensed vessels occurred along the west of the FICZ, whereas most catches by X-licensed vessels occurred to the southeast (Appendixes VIII–XII).

Table I. Catch of Southern blue whiting per licence type in Falkland Islands waters during 2018 and over the period 2008 – 2018.

Licence	Catch (2018; t)	Relative catch (2018; %)	Mean catch (2008 – 2018; t)	Relative mean catch (2008 –2018; %)
A	28	2.82	312	6.46
B	0	0.00	0	0.00
C	0	0.00	10	0.21
E	30	3.02	61	1.27
F	0	0.00	13	0.27
G	53	5.34	293	6.07
L	0	0.00	0	0.00
O	0	0.00	0	0.00
R	0	0.00	0	0.00
S	0	0.00	2,168	44.84
W	846	85.28	1,517	31.38
X	35	3.53	459	9.49
Y	0	0.00	0	0.00
Z	0	0.00	0	0.00
Total	992	100.00	4,834	100.00

Age-length relationship

The age-length relationship of females and males pooled gave the following values: L_∞ = 58.4 cm, k = 0.252, and t_0 = -0.503 years (Fig. 3a). Length and age of females ranged from 12 to 70 cm, and from 1 to 29 years, respectively. The age-length relationship of females gave the following values: L_∞ = 60.6 cm, k = 0.225, and t_0 = -0.838 years (Fig. 3b). Length and age of males ranged from 12 to 65 cm and from 1 to 31 years, respectively. The age-length relationship of males gave the following values: L_∞ = 56.52 cm, k = 0.251, and t_0 = -0.721 years for males (Fig. 3c).

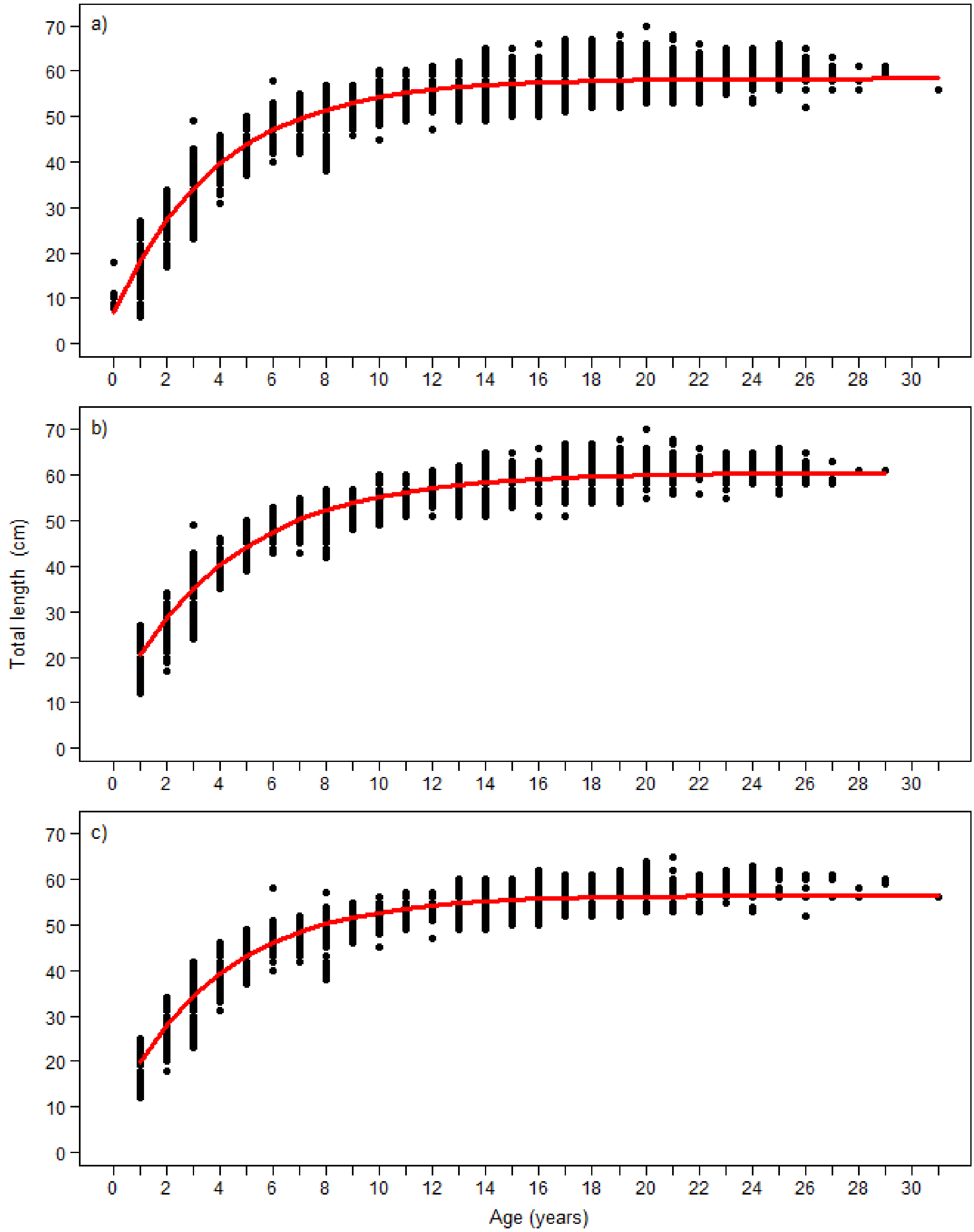

Fig. 3. von Bertalanffy age-length relationship of Southern blue whiting from the Falkland Islands. a) Females and males pooled; b) females; c) males.

The range of female modal lengths was 25–61 cm during the period 2002–2018. Modal lengths significantly decreased at a rate of 1.5 mm per year (p = 0.030) from 2002 to 2018; some cyclicality was observed when length increased over a few consecutive years (e.g. 2014–2017) as a cohort grew, and subsequently decreased as the next cohort began to predominate in abundance (Fig. 4a; see length frequencies per year in Appendix XIII). The range of male modal lengths was 24–56 cm during the period 2002–2018. Modal lengths significantly decreased at a rate of 1.4 mm per year (p = 0.001) from 2002 to 2018. Modal length again had an overall decreasing trend despite cohort cyclicality (e.g. 2006–2009, 2011–2013, and 2014–2017) (Fig. 4b; see length frequencies per year in Appendix XIV).

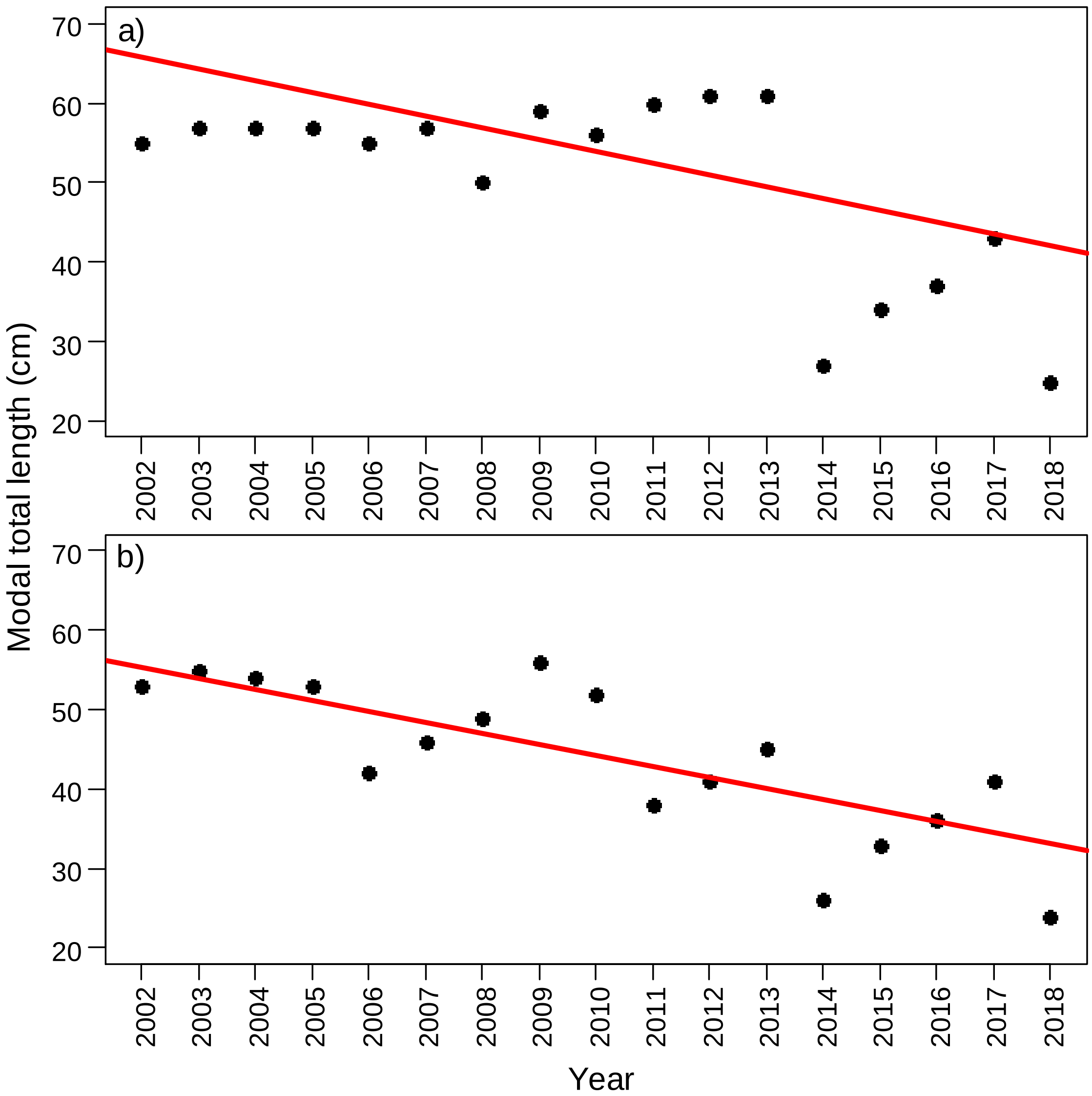

Fig. 4. Annual modes of Southern blue whiting a) female and b) male total length in the Falkland Islands. Linear regression of modes vs. year (red line; regression weighted by the inverse RMSD of each year's LOESS function).

Age and length at maturity

Mean age at 50% maturity of females and males pooled was estimated at 2.6 years from 2002 to 2018. In females, a non-statistically significant negative trend (p = 0.462) in annual average age at 50% maturity occurred at a rate of 0.03 years per year from 2002 to 2018 (Fig. 5a), with mean age at 50% maturity estimated at 3.5 years. In males, a non-statistically significant negative trend (p = 0.415) in annual average age at 50% maturity occurred at a rate of 0.03 years per year from 2002 to 2018 (Fig. 5b), with mean age at 50% maturity estimated at 2.6 years. Annual age at 50% maturity curves per year can be consulted in Appendixes XV–XVI.

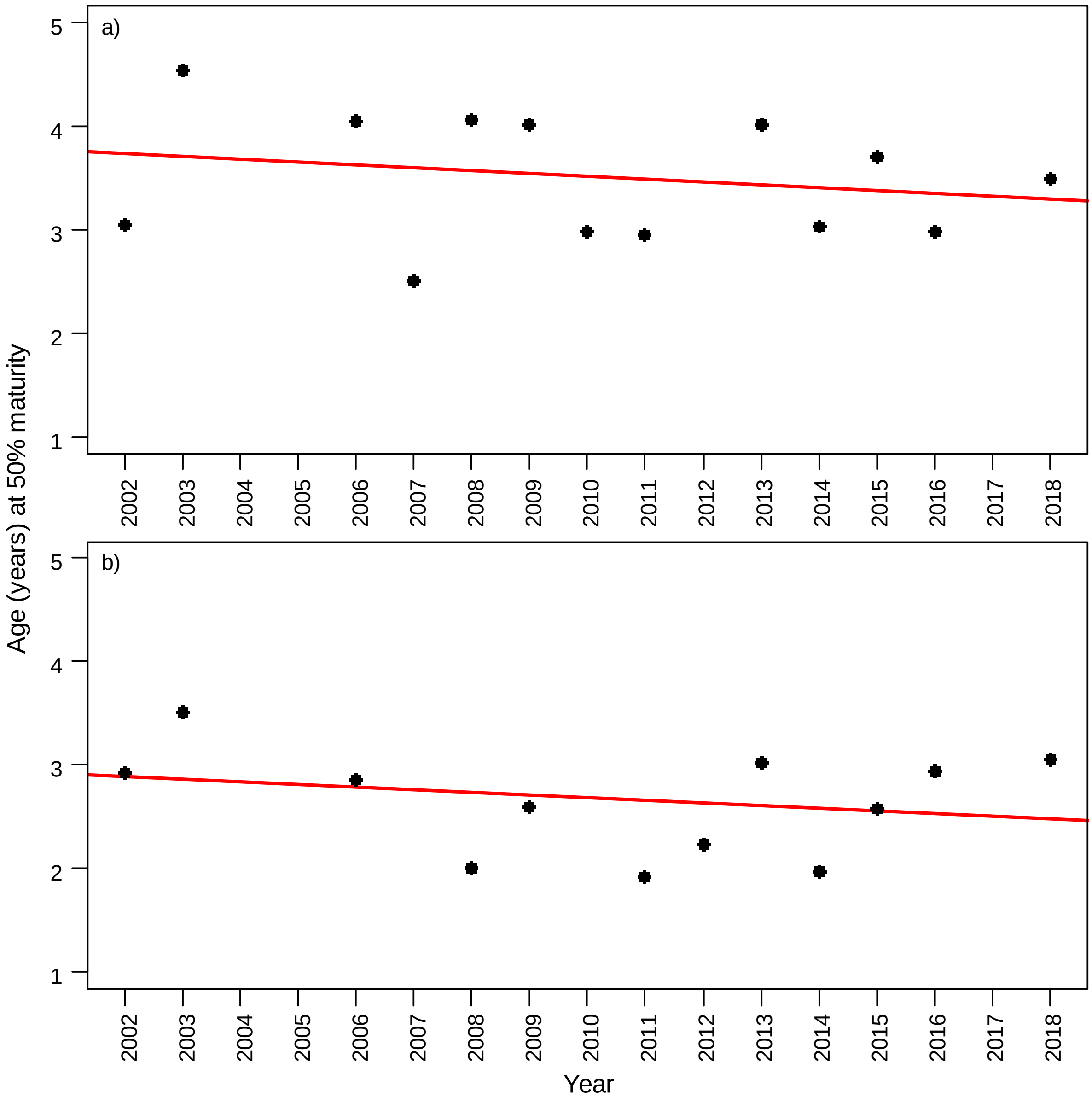

Fig. 5. Linear regression of age at 50% maturity of a) female and b) male Southern blue whiting vs. year (regression weighted by the R^2 of each year's logistic function).

Mean TL at 50% maturity of females and males pooled was estimated at 31.97 cm from 2002 to 2018. In females, a non-significant negative trend ($p = 0.541$) in annual average length at 50% maturity was observed (Fig. 6a), with mean TL at 50% maturity estimated at 34.97 cm. In males, a non-significant negative trend ($p = 0.433$) in annual average length at 50% maturity was observed (Fig. 6b), with mean TL at 50% maturity estimated at 31.49 cm. Annual length at 50% maturity curves per year can be consulted in Appendixes XVII–XVIII.

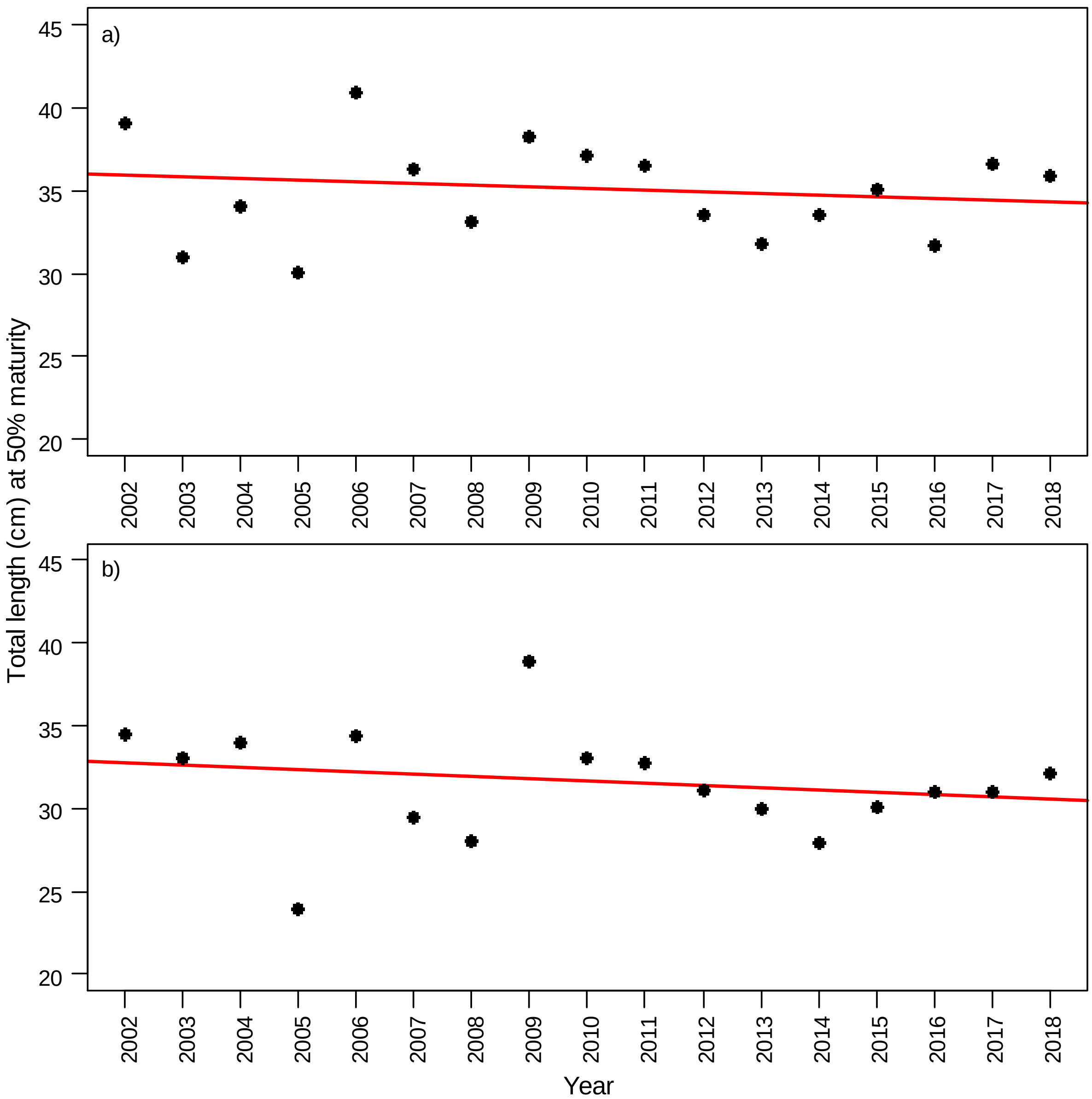

Fig. 6. Linear regression of length at 50% maturity of a) female and b) male Southern blue whiting vs. year (regression weighted by the R^2 of each year's logistic function).

Biomass estimation

The different calculations for empirical life-history mortality provided the following results:

$$M1 = 4.899 \cdot t_{max}^{-0.916} = 0.2109$$

$$M2 = \frac{4.3}{t_{max}} = 0.1387$$

where t_{max} = 31 years.

Total lengths of 43,594 individuals caught in commercial vessels were used for the LBB calculations. From 2002 to 2009, and from 2017 to 2018, the biomass of Southern blue whiting was below the biomass that can produce MSY. The biomass estimated for 2018 relative to the biomass estimated for 2002 (B_{2018}/B_{2002}) was 0.16 (0.12 – 0.19; 95% CI), and the ratio of observed biomass to the biomass that would provide maximum sustainable yield (B/B_{MSY}) was estimated in 0.39 (0.29 – 0.48; 95% CI) (Table II; Appendix XIX).

Table II. Summary of LBB parameters for Southern blue whiting caught in Falkland waters from commercial length data, 2002 to 2018 except 2006 and 2012–2016. Lc50 = length at 50% catch; Lc = length at first catch; L_∞ = asymptotic length; Lc95 = length at 95% catch; alpha = steepness of the ogive; Lmean = Mean length; Lopt = Optimum length; Lc_{opt} = optimum length at catch; L95th = Length at 95% of the length range; F/M = relative fishing mortality; F/K = fishing mortality relative to somatic growth rate; B/B_0 = "Current" biomass (2016) relative to "unfished" biomass (2002); B/B_{MSY} = ratio of observed biomass to the biomass that would provide maximum sustainable yield. Medians with 95% confidence intervals in parentheses.

Estimates for 2018			
Parameter	Output	Parameter	Output
Lc50	42.8 (34.8 – 50.6)	L95th	59
Lc/L_∞	0.66 (0.54 – 0.78)	$L95th/L_\infty$	0.91
Lc95	75.2	F/M	4.4 (3.7 – 5.2)
alpha	0.022 (0.021 – 0.023)	F/K	6.7 (5.7 – 7.5)
Lmean/Lopt	1	B/B_0	0.16 (0.12 – 0.19)
Lc/Lc_{opt}	0.93	B/B_{MSY}	0.39 (0.29 – 0.48)

Prior distributions for growth rates r were calculated in R Studio (RStudio Team 2016) using different mortality estimates:

$$r_1 \sim \exp(\text{norm}(\log(\mu_r), \sigma_r)) = \exp(\text{norm}(\log(2 \cdot 0.87 \cdot 0.2109), \text{sqrt}(0.2312)))$$

$$r_5 \sim \exp(\text{norm}(\log(\mu_r), \sigma_r)) = \exp(\text{norm}(\log(2 \cdot 0.87 \cdot 0.1387), \text{sqrt}(0.2312)))$$

The prior distribution for stock saturation S was calculated in R Studio (RStudio Team 2016) based on B_{2018}/B_{2002} estimated with LBB:

$$S \sim \text{norm}\ (\mu_{B/B0}, \sigma_{B/B0}) = \text{norm}\ (0.1553, 0.0274)$$

Parameters estimated from the OCOM Graham-Schaefer production model based on the different mortality rates are summarized in Table III. OCOM outputs estimated from the lowest natural mortality (M = 0.1387) produced the lowest estimate of median MSY and were selected over the other OCOM estimate as a precautionary approach. Median intrinsic growth rate was estimated at 0.2418, equivalent to a potential 27% increase of the population per year by implementing $e^{0.2418} - 1$. Carrying capacity was 1,326,281 t (725,809 – 2,010,723 t; 95% CI). The biomass of BWS in 2018 was estimated at 201,974 t (99,383 – 353,791 t; 95% CI) and the MSY was estimated at 80,171 t (47,018 – 112,931; 95% CI). Accordingly, a continuous decrease in biomass was estimated from 1987 (1,326,291 t) to 2018 (201,974 t; Fig. 7), with the biomass of 2018 comprising 15.23% of the biomass in 1987 (B_{2018}/B_{1987} = 0.1523).

Table III. OCOM Graham-Schaefer production model parameters and estimates of biomass and MSY for Southwest Atlantic blue whiting stock, using commercial catch data from 1987 to 2018. M = mortality rate; r = intrinsic growth rate; K = carrying capacity; B_{1987} = biomass in 1987; B_{2018} = biomass in 2018; MSY = maximum sustainable yield. Medians with 95% confidence intervals in parentheses; selected outputs are indicated in bold font.

M	r	K	B_{1987}	B_{2018}	B_{2018}/B_{1987}	MSY
0.2109	0. 3670 (0. 1410 – 0.9442)	1041023 (526145 – 1713672)	1041034 (526101 – 1713694)	159777 (75819 – 300002)	0.1535	95529 (60467 – 124180)
0.1387	**0.2418** **(0.0939 – 0.6224)**	**1326281** **(725809 – 2010723)**	**1326291** **(726240 – 2010765)**	**201974** **(99383 – 353791)**	**0.1523**	**80171** **(47018 – 112931)**

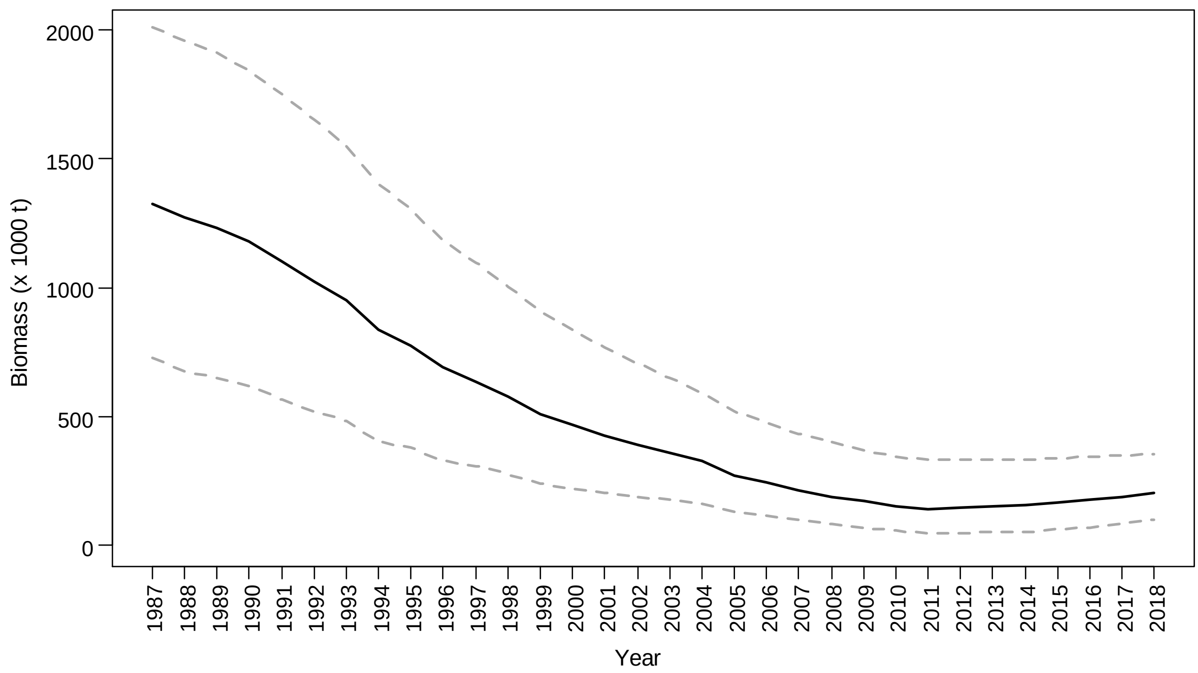

Fig. 7. Median and 95% confidence intervals of annual Southwest Atlantic blue whiting stock biomass from 1987 to 2018 estimated from the OCOM Graham-Schaefer production model. The parameters were M = 0.1387; F_{MSY} = 0.87; r (σ_r^2) = 0.2312; $\mu_{B/B0}$ = 0.1553; and $\sigma_{B/B0}$ = 0.0274.

The OCOM estimate of r (0.2418; 0.0939 – 0.6224, 95% CI) overlaps 'medium' resilience for Southern blue whiting (Froese et al. 2017) and was used as prior range of r (0.0939 – 0.6224) for CMSY. The depletion levels estimated by OCOM: B_{2018}/B_{1987} = 0.1523, and LBB: B_{2018}/B_{2002} = 0.16 overlap both 'strong' (0.01 – 0.40) and 'very strong' (0.01 – 0.20) depletion prior ranges (Froese et al. 2019). Therefore, 95% CI of prior range of r (0.0939 – 0.6224) estimated using OCOM were set for CMSY to examine scenarios of 'strong' and 'very strong' depletion (Table IV). CMSY analysis under 'strong' depletion scenario produced outputs that are more comparable to OCOM estimates. The CMSY analysis under 'strong' depletion scenario suggests that the BWS was caught below MSY from 1987 to 2018 (Fig. 8a). However, biomass declined gradually from the early 1990s to 2018 (Fig. 8b). Exploitation levels (F/F_{MSY}) had a variable but overall increasing trend (Fig. 8c). CMSY suggests that the BWS is overfished ($B < B_{MSY}$), and overfishing is currently occurring ($F > F_{MSY}$) while the stock is too small to produce MSY (Fig. 8d).

Table IV. CMSY parameters, and estimated biomass and MSY for the Southwest Atlantic blue whiting stock commercial catches from 1987 to 2018, calculated with prior range of r = 0.0939 – 0.6224, and 'strong' and 'very strong' depletion priors. r = intrinsic growth rate; K = carrying capacity; F_{MSY} = fishing mortality corresponding to maximum sustainable yield; B_{MSY} = stock size that can produce maximum sustainable yield; B_{2018} = biomass in 2018; MSY = maximum sustainable yield; B/B_{MSY} (2018) = ratio of the stock biomass in 2018 to the stock biomass that can produce maximum sustainable yield; F_{2018} = fishing mortality in 2018; F/F_{MSY} = ratio of fishing mortality to the fishing mortality rate at maximum sustainable yield. Medians with 95% confidence intervals in parentheses.

	CMSY	
	Strong depletion	Very strong depletion
r	0.361	0.355
	(0.221 - 0.587)	(0.215 – 0.586)
K	1,970,000	3,581,000
	(747,000 – 5,195,000)	(1,604,000 – 7,996,000)
F_{MSY}	0.0650	0.0499
	(0.0399 – 0.1060)	(0.0303 – 0.0823)
B_{MSY}	985,000	1,791,000
	(374,000 – 2,598,000)	(802,000 – 3,998,000)
B_{2018}	177,000	252,000
	(25,800 – 384,000)	(42,800 – 683,000)
MSY	178,000	318,000
	(61,400 – 514,000)	(151,000 – 670,000)
B/B_{MSY} (2018)	0.1800	0.140
	(0.0262 – 0.3890)	(0.024 – 0.382)
F_{2018}	0.0985	0.0695
	(0.0456 – 0.6770)	(0.0256 – 0.4090)
F/F_{MSY}	1.520	1.390
	(0.701 – 10.400)	(0.519 – 8.190)

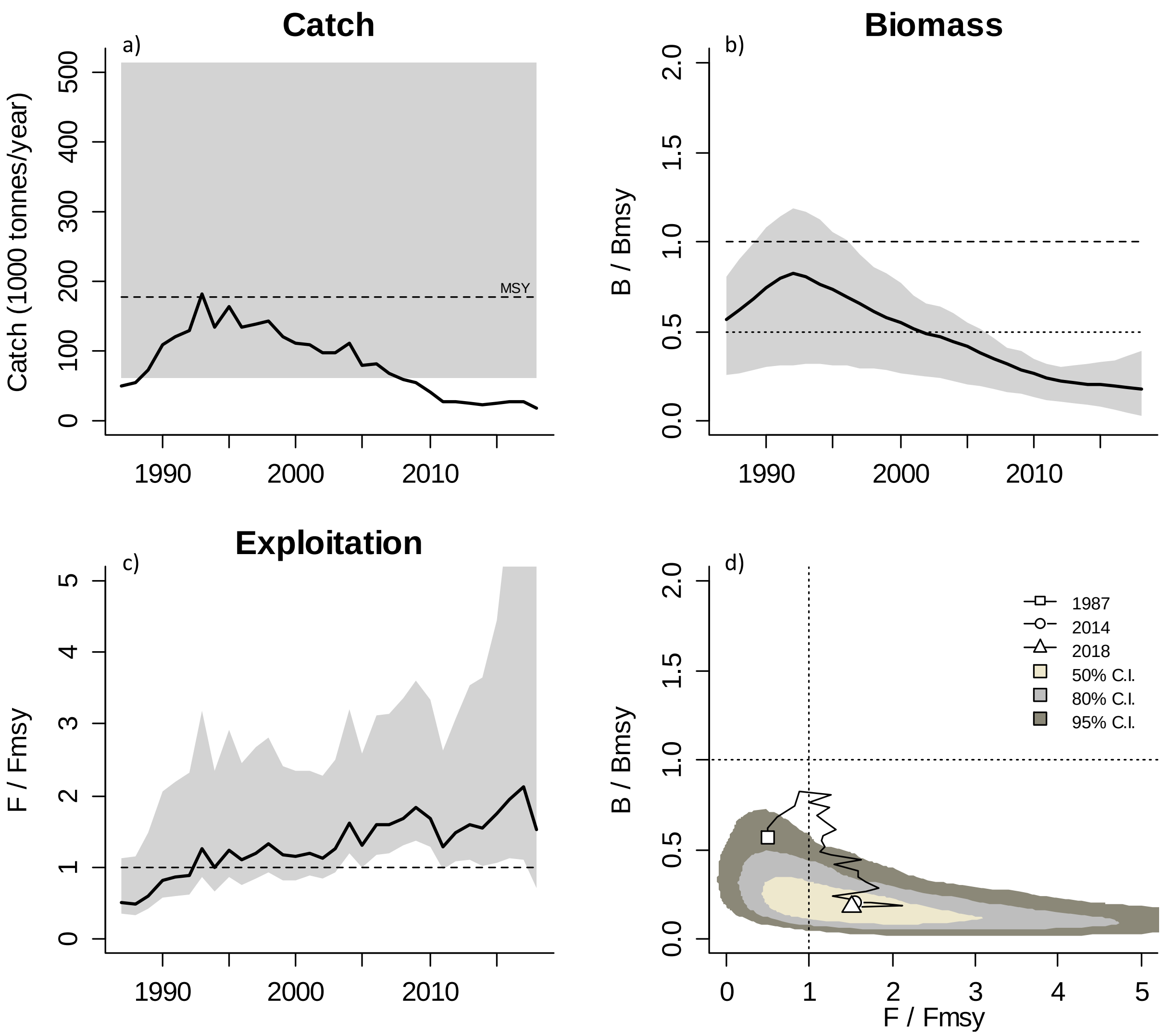

Fig. 8. Outputs of CMSY analysis under 'strong' depletion scenario for the Southwest Atlantic blue whiting stock. a) Southern blue whiting catches relative to the CMSY estimate of MSY, with indication of 95% confidence limits in grey; b) Relative total biomass (B/B_{MSY}), with the grey area indicating uncertainty; c) relative exploitation (F/F_{MSY}); d) Trajectory of relative stock size (B/B_{MSY}) over relative exploitation (F/F_{MSY}).

Conclusions

Since 1987, the Falkland Islands have contributed on average 27% of the total annual catch of the BWS; this proportion has decreased to 12.6% in the last decade. Most BWS catches in Falkland Islands waters from 2008 to 2018 were from S, W, A and G licences, with most catches from S-licensed vessels.

The no-fishing area for S-licensed vessels (targeting hoki and Southern blue whiting) to the South and Southwest of the Falkland Islands from 1 July to 15 October protects Southern blue whiting during its spawning season in September and October in Falklands waters but does not overlap with the maximum catches of this species that occur to the Southeast of East Falkland from October to January. Catch restrictions under S licence could be shifted from 1 July–15 October to posterior dates between September and January and towards the southeast to protect this species during the spawning season. However, more detailed examination would be required before implementing changes to S licence.

OCOM suggests that the 2018 stock size was 15.23% of the 1987 stock size. This finding is in agreement with the estimation made using the LBB analysis, which suggests that the 2018 stock size was 16% of the 2002 stock size ($B_{2018}/B_{2002} = 0.16$). LBB also estimated that the BWS biomass in 2018 was approximately 39% of the biomass that would provide maximum sustainable yield ($B/B_{MSY} = 0.39$). Based on the lowest estimate of mortality ($M = 0.1387$), OCOM provided the most precautionary estimate of MSY (80,171 t). In addition, OCOM detected a declining trend in the BWS biomass over time; a similar biomass trend was estimated during the 1990's in other studies (Wöhler et al. 2002). A relative stabilization in biomass was also detected by OCOM in the most recent years. Accordingly, the ratio of Lc/Lcopt was estimated in 0.93 using LBB, which suggests that length at catch is nearly the optimum length at catch. However, Southern blue whiting has 'low' to 'medium' resilience (Froese & Pauly 2019) and the potential to increase the size of the population in about only 27% per year. CMSY estimated higher biomass and MSY compared to OCOM, however both analyses estimated similar biomass declining trends. The trajectory of relative stock size (B/B_{MSY}) as a function of fishing pressure (F/F_{MSY}) generated using CMSY suggests that the stock of Southern blue whiting is overfished ($B < B_{MSY}$) and there is ongoing overfishing while the stock is too small to produce maximum sustainable yield ($F > F_{MSY}$).

Although studies suggest that stocks can yield sustainable harvests at levels considered overfished (Hilborn 2010) and despite the BWS not being the primary target in any Falkland Islands fishery, the various metrics of the BWS indicate a need for precautionary management. According to the Schaefer model $B_{MSY} = 0.5$ K (Froese et al. 2017), $B_{MSY} = 663{,}141$ t from the OCOM estimate of K (1,326,281 t). Froese et al. (2011) proposed 0.5 B_{MSY} as a limit reference point for closing target fisheries. Therefore, we recommend that by proportion with $B_{2018}/B_{MSY} = 201{,}974 / 663{,}141 = 0.305$, the present catch limit of the BWS should be 30.5% of the OCOM's MSY estimate: $80{,}171 \times 0.305 = 24{,}452$ t.

Corresponding catch limit alternatives for the Falkland Islands based on different average-catch criteria are presented in Table V.

Table V. Catch limit alternatives for Southern blue whiting in Falkland Islands waters.

Criteria	Threshold	Catch limit (t)
Average catch		
10-year	4,022	4,022
5-year	3,024	3,024
3-year	2,905	2,905
Relative average contribution		
10-year (12.64%)	24,452 x 0.1264	3,091
5-year (12.13%)	24,452 x 0.1213	2,966
3-year (11.51%)	24,452 x 0.1151	2,814
Equal share		
33.3%	24,452 x 0.3333	8,150

The alternatives of catch limits for the Falkland Islands ranged from 2,905 t to 8,150 t. These alternatives represent hypothetical options, as other factors may be relevant to the catch limits. For example, the Falkland Islands Government has restricted S licence allocations to 2,000 t annually, which contributes to lower BWS catches and therefore lower relative average contributions than would otherwise have been realized. The catch limit for the Falkland Islands should take as reference the MSY suggested for the BWS (24,452 t), and not only the average catch. For instance, equal partition of the MSY between the three fisheries (33.33% each) that target the BWS resulted in 8,150 t. In contrast, catch limits estimated from the relative average contribution of the Falkland Islands to the total catch of the BWS ranged between 2,814 t and 3,091 t. Catch limit alternatives estimated in this study are lower than the BWS catch limit (30,000 t) established in Argentina for 2019 (https://www.pescare.com.ar/establecen-la-captura-maxima-de-merluza-2019/). Important considerations must be taken into account to determine catch limits. For instance, in this assessment a method based on length frequencies (LBB) was implemented to estimate B/B_0. However, this analysis was performed using biological data from only a portion (i.e. the

Falkland Islands) of the distribution of the BWS, which may not be representative of the entire stock and thus may bias biomass estimates. In addition, the likelihood of overfished status detected in this study should be addressed and the sources of overfishing to determine catch limits with greater accuracy should be identified. The reason is that catch limits for the Falkland Islands may not achieve the recovery of this shared stock if catch limits outside Falklands waters are not estimated under similar criteria and if further regulations are not implemented.

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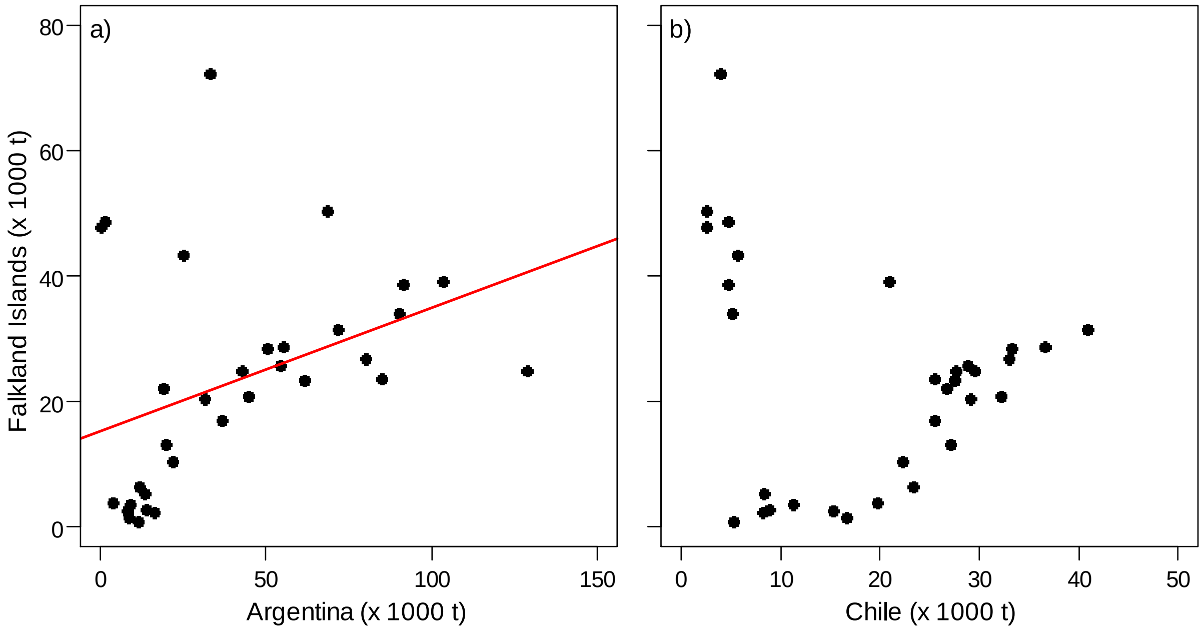
Appendix

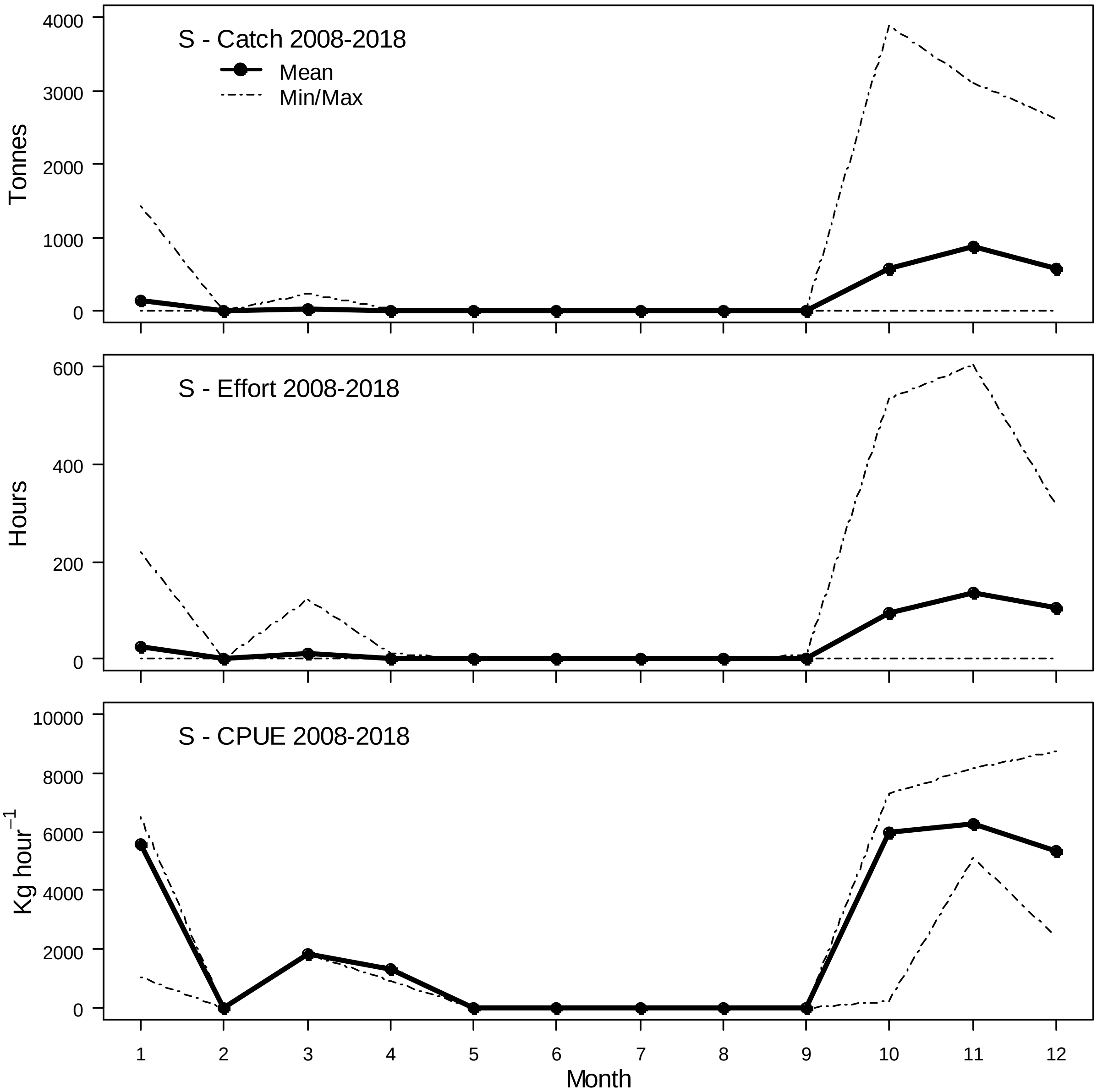
Appendix I. Commercial catches by year (t) of Southern blue whiting in Chilean, Argentine and Falkland Islands waters. Catch data from Chile for the year 2018 is preliminary (R. Cespedes, IFOP, *pers. comm.*).

Year	Chile	Argentina	Falkland Islands	Total
1987	2,573	189	47,861	50,623
1988	4,710	1,307	48,678	54,695
1989	5,578	24,936	43,475	73,989
1990	3,931	32,845	72,351	109,127
1991	2,609	68,445	50,491	121,545
1992	5,149	90,095	34,078	129,323
1993	27,607	128,525	24,945	181,077
1994	4,664	91,048	38,697	134,410
1995	20,917	103,224	39,206	163,347
1996	25,445	84,625	23,742	133,811
1997	32,875	79,937	26,791	139,603
1998	40,857	71,626	31,483	143,966
1999	36,508	55,098	28,655	120,261
2000	27,459	61,313	23,371	112,143
2001	28,755	54,311	25,735	108,801
2002	29,409	42,453	24,908	96,770
2003	32,168	44,584	20,798	97,550
2004	33,169	50,216	28,554	111,939
2005	25,425	36,663	17,047	79,135
2006	29,115	31,292	20,532	80,939
2007	26,701	18,979	22,204	67,885
2008	27,086	19,841	13,209	60,136
2009	22,221	21,677	10,395	54,293
2010	23,301	11,628	6,471	41,400
2011	19,629	3,518	3,940	27,088
2012	16,675	8,379	1,596	26,650
2013	15,304	7,887	2,698	25,889
2014	11,191	9,050	3,612	23,853
2015	8,809	13,831	2,790	25,430
2016	8,269	13,236	5,415	26,920
2017	8,233	15,897	2,309	26,439
2018	5,199	11,289	992	17,480

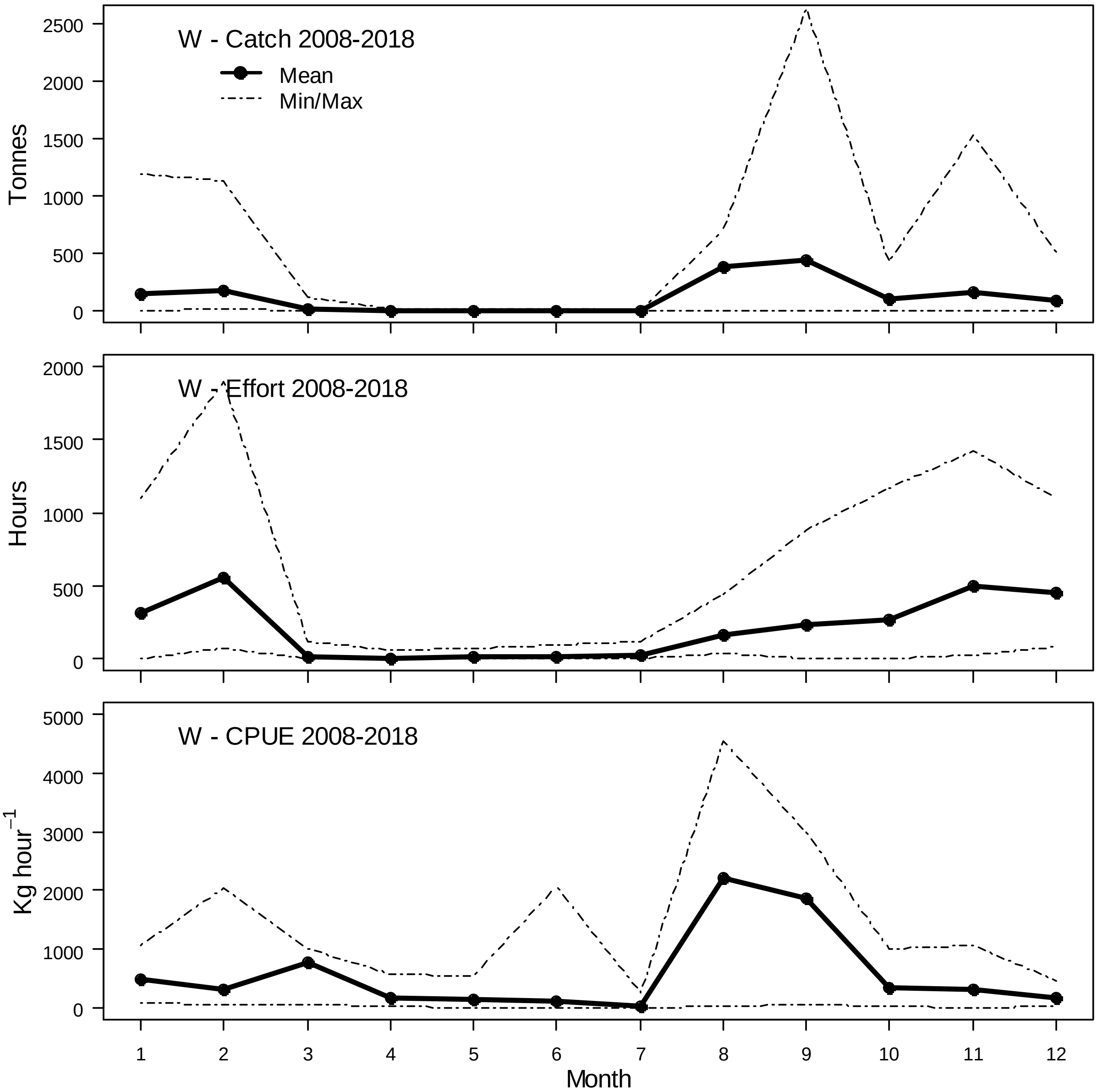
Appendix II. Correlation of Southern blue whiting annual catches between fisheries. a) Correlation between Falkland Islands and Argentine Southern blue whiting annual catches from 1987 to 2018 (r = 0.50, n = 32, p = 0.03). b) Correlation between Falkland Islands and Chilean Southern blue whiting annual catches from 1987 to 2018 (r = -0.11, n = 32, p = 0.56).



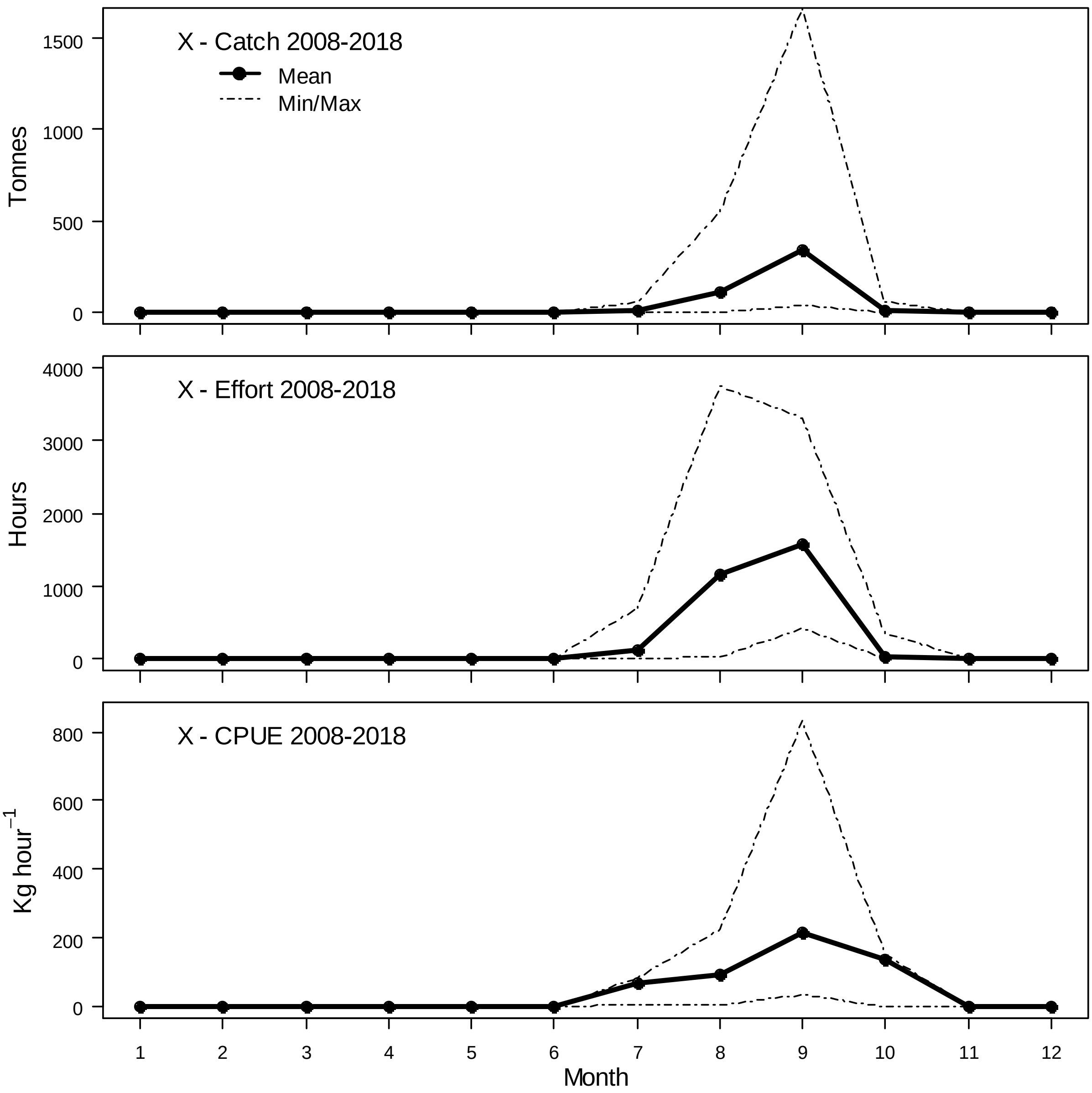
Appendix III. Mean monthly catch, effort and CPUE of Southern blue whiting by S-licensed vessels in Falklands waters from 2008 to 2018.



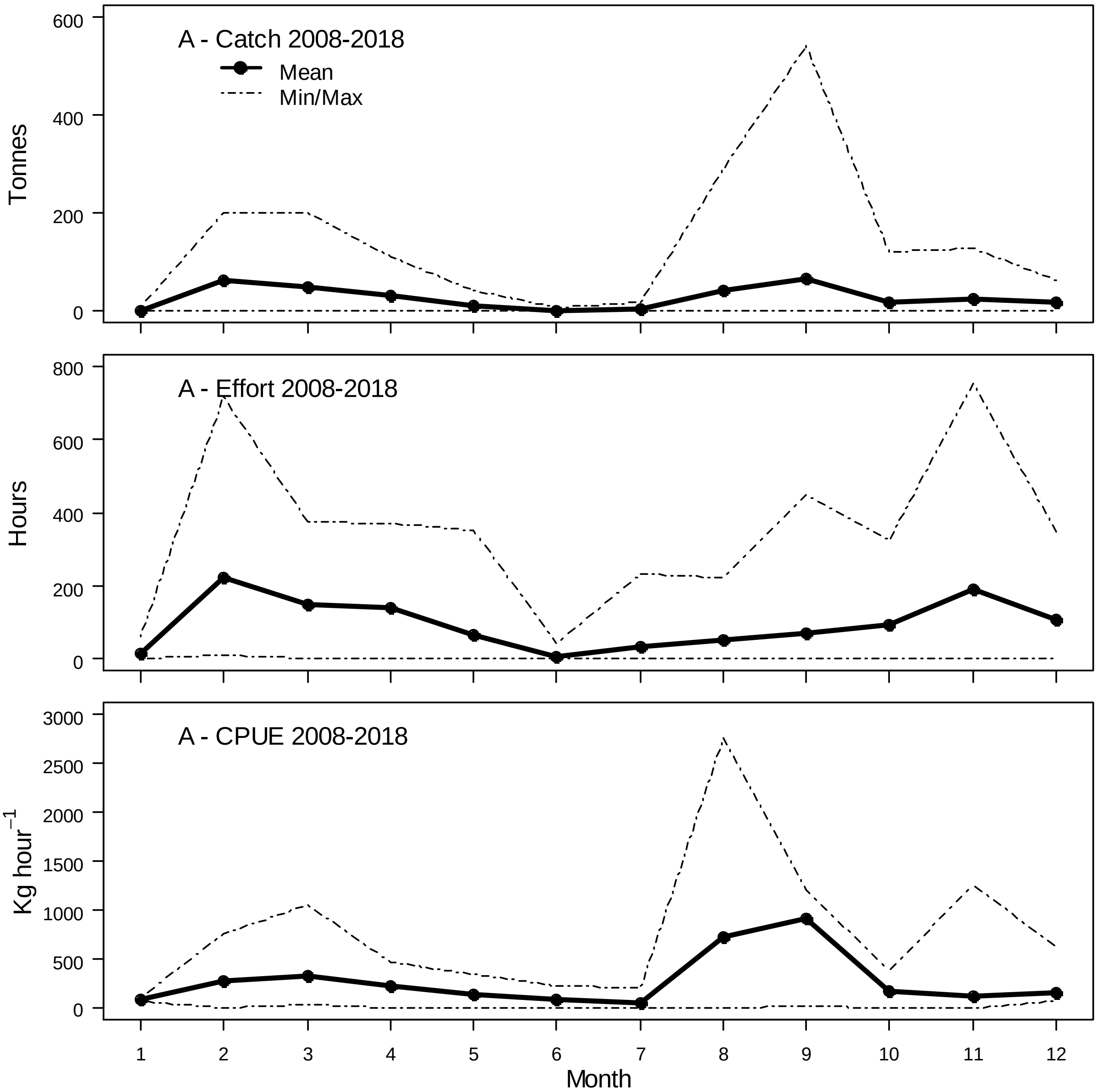
Appendix IV. Mean monthly catch, effort and CPUE of Southern blue whiting by W-licensed vessels in Falklands waters from 2008 to 2018.



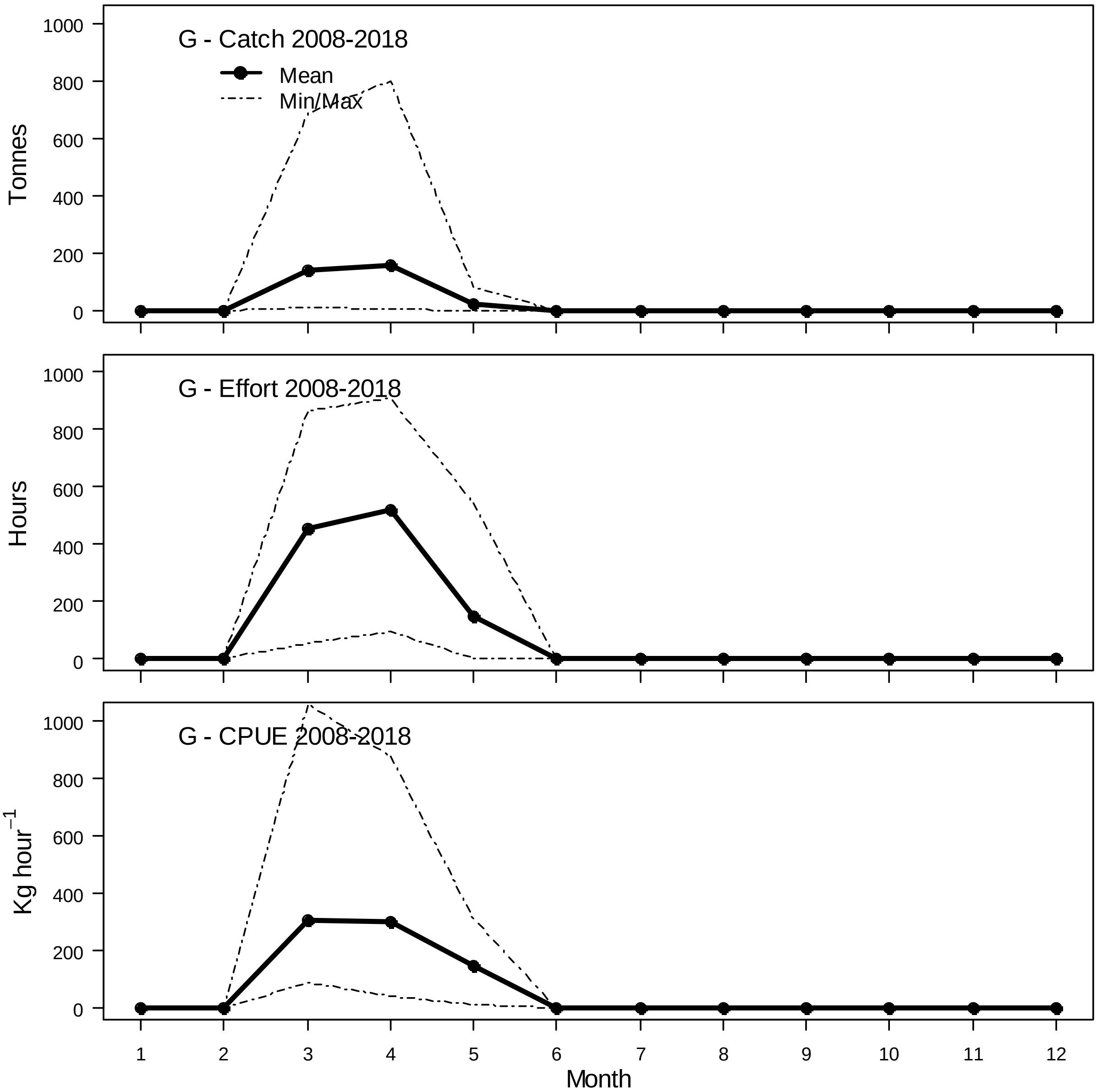
Appendix V. Mean monthly catch, effort and CPUE of Southern blue whiting by X-licensed vessels in Falklands waters from 2008 to 2018.



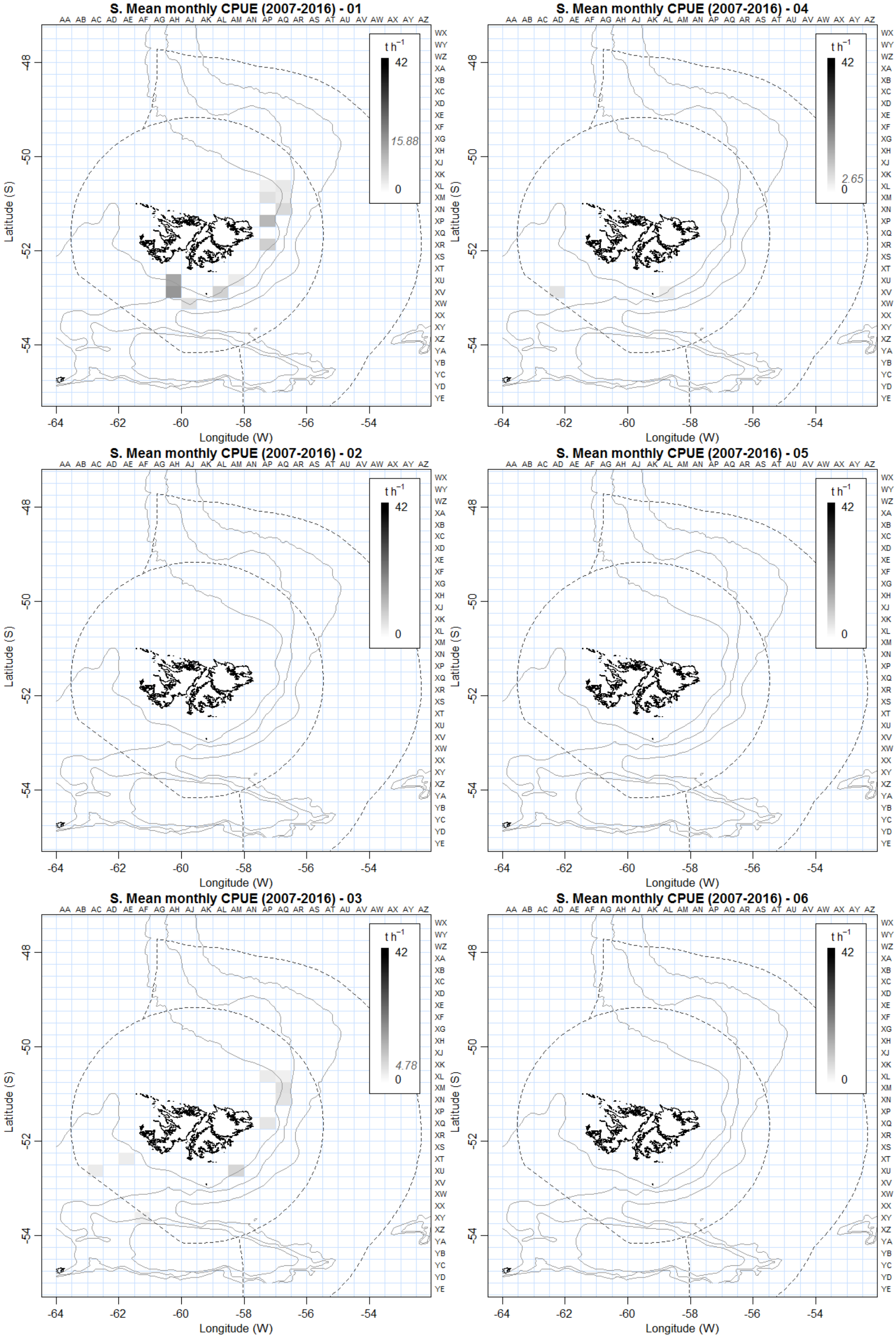
Appendix VI. Mean monthly catch, effort and CPUE of Southern blue whiting by A-licensed vessels in Falklands waters from 2008 to 2018.

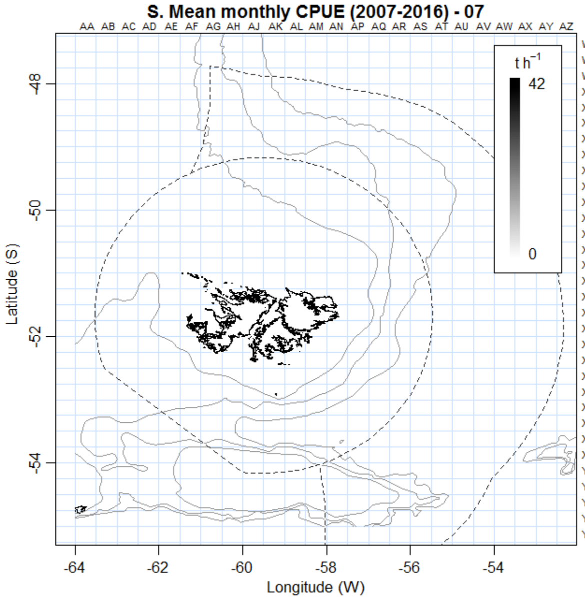


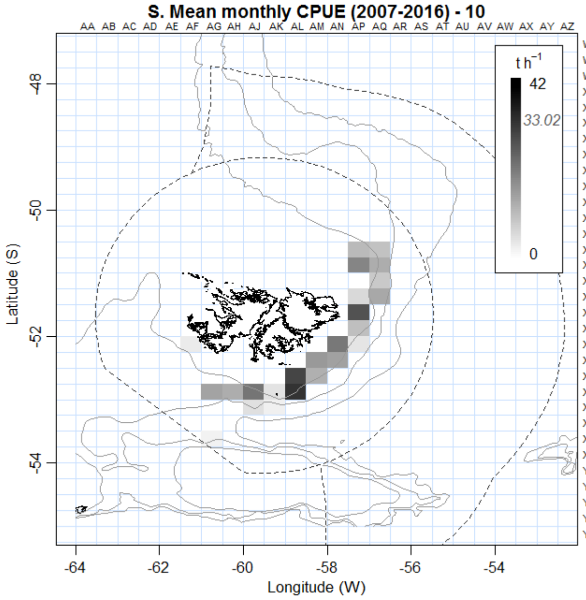
Appendix VII. Mean monthly catch, effort and CPUE of Southern blue whiting by G-licensed vessels in Falklands waters from 2008 to 2018.

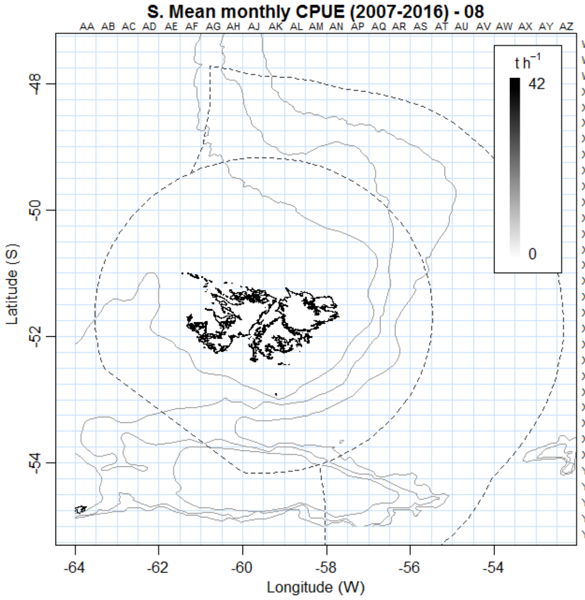


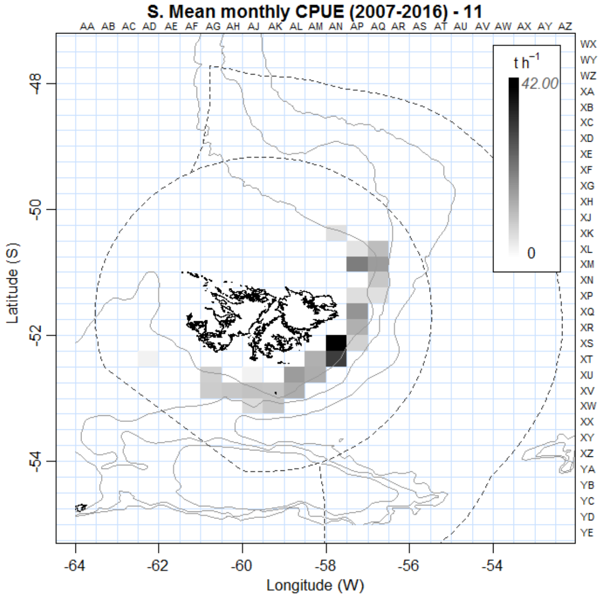
Appendix VIII. Monthly spatial distribution of CPUE (t · h^{-1}) of Southern blue whiting by S-licensed vessels in Falklands waters from 2007 to 2016.

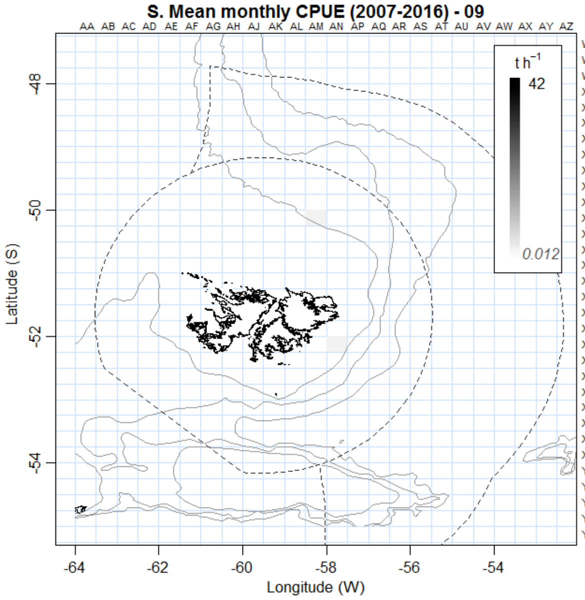


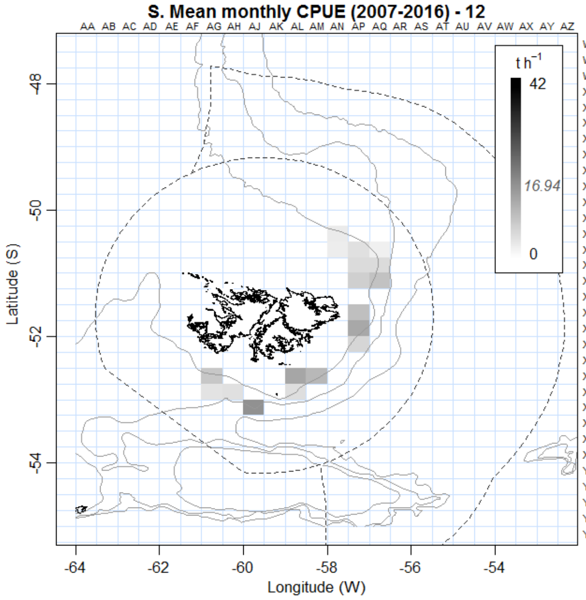

S. Mean monthly CPUE (2007-2016) - 07
t h-1
42
0
Latitude (S)
Longitude (W)


S. Mean monthly CPUE (2007-2016) - 10
t h-1
42
33.02
0
Latitude (S)
Longitude (W)

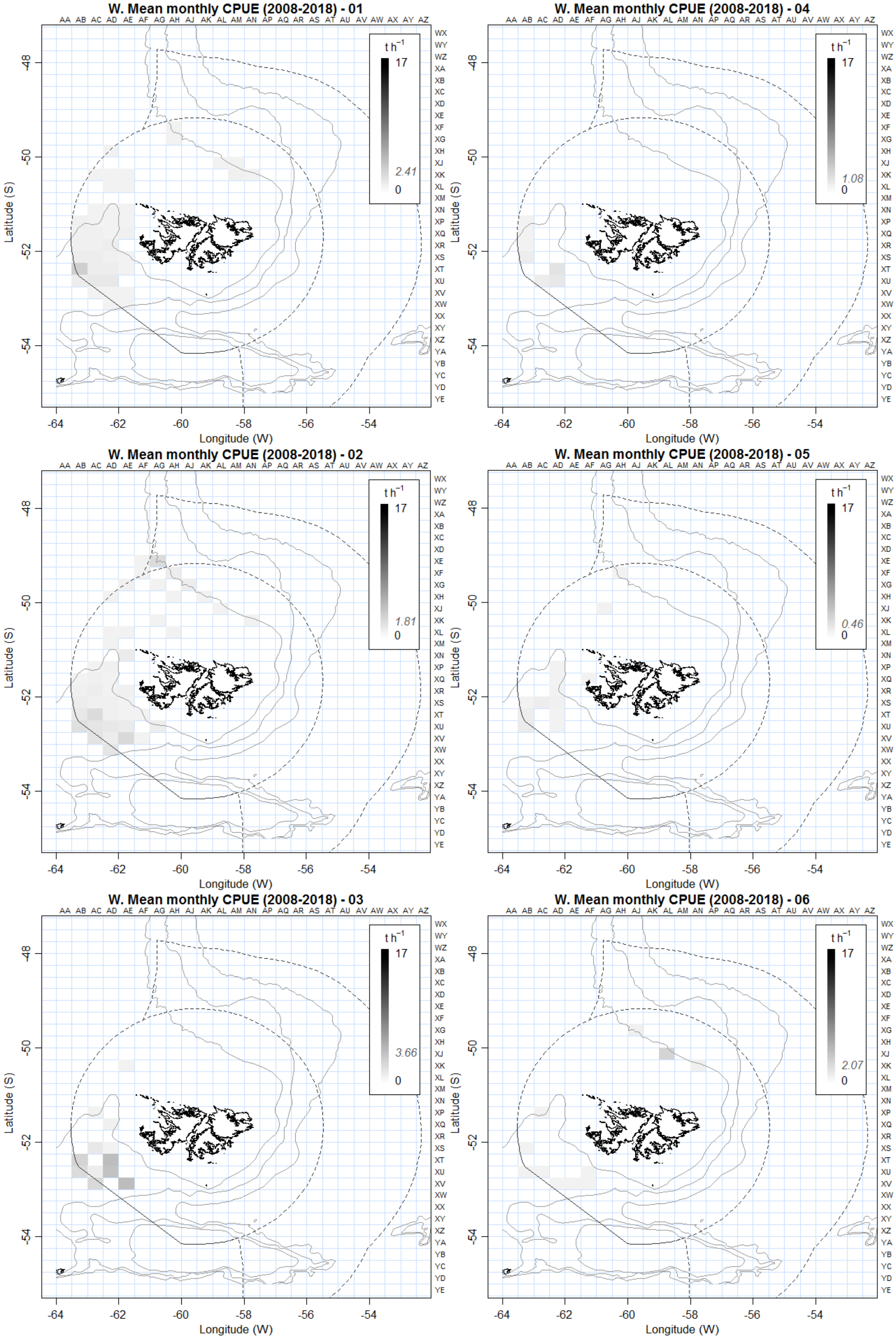

S. Mean monthly CPUE (2007-2016) - 08
t h-1
42
0
Latitude (S)
Longitude (W)

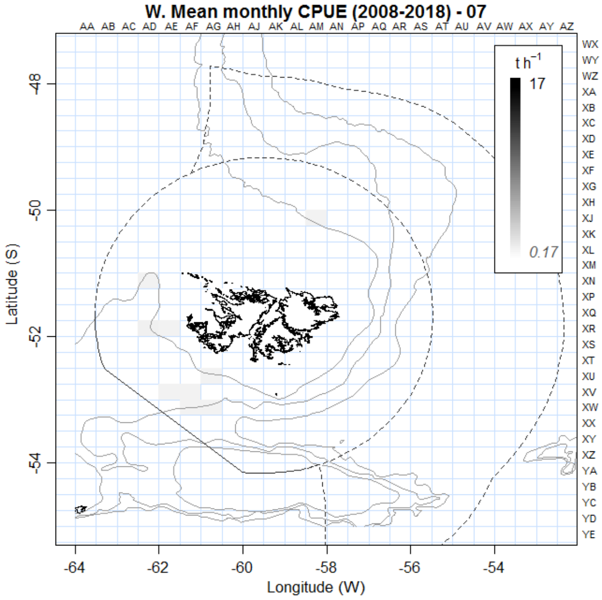

S. Mean monthly CPUE (2007-2016) - 11
t h-1
42.00
0
Latitude (S)
Longitude (W)

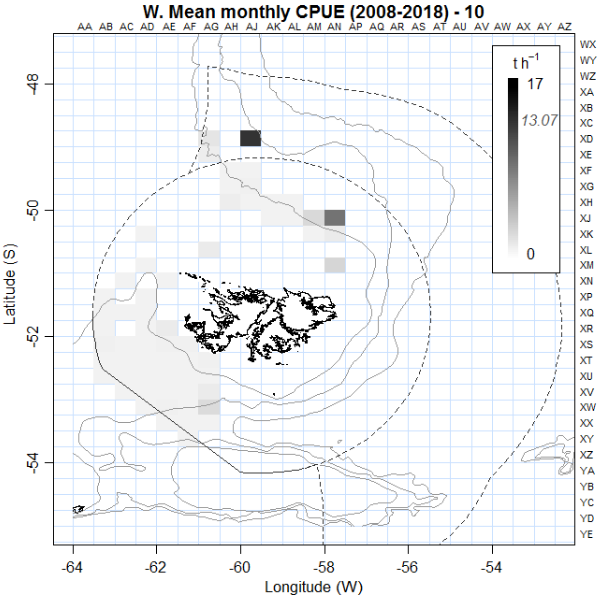

S. Mean monthly CPUE (2007-2016) - 09
t h-1
42
0.012
Latitude (S)
Longitude (W)

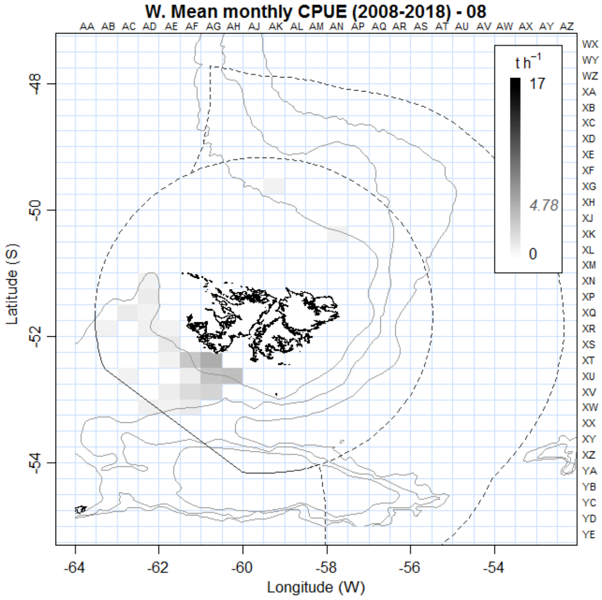

S. Mean monthly CPUE (2007-2016) - 12
t h-1
42
16.94
0
Latitude (S)
Longitude (W)

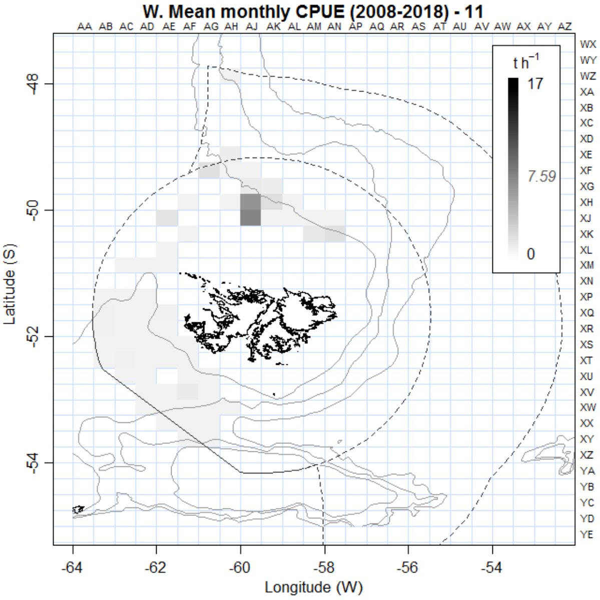
Appendix IX. Monthly spatial distribution of CPUE ($t \cdot h^{-1}$) of Southern blue whiting by W-licensed vessels in Falklands waters from 2008 to 2018.

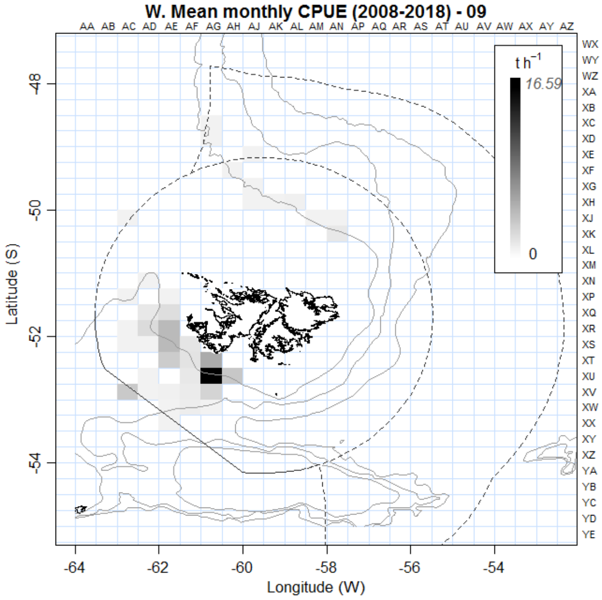


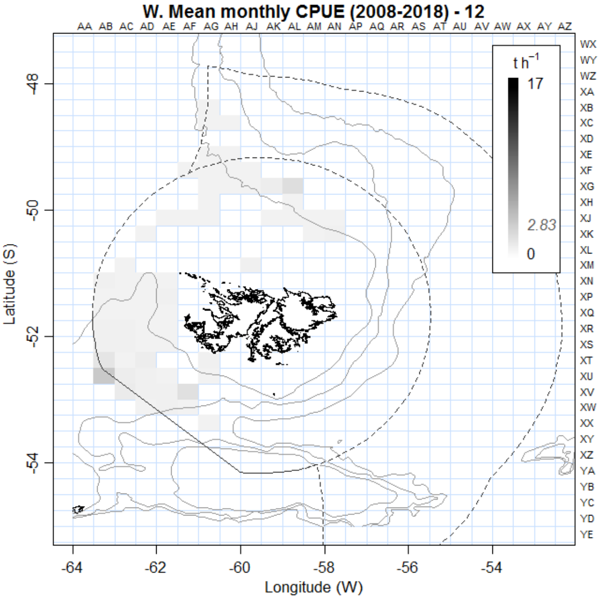

W. Mean monthly CPUE (2008-2018) - 07
t h^{-1}
17
0.17
Latitude (S)
Longitude (W)


W. Mean monthly CPUE (2008-2018) - 10
t h^{-1}
17
13.07
0
Latitude (S)
Longitude (W)

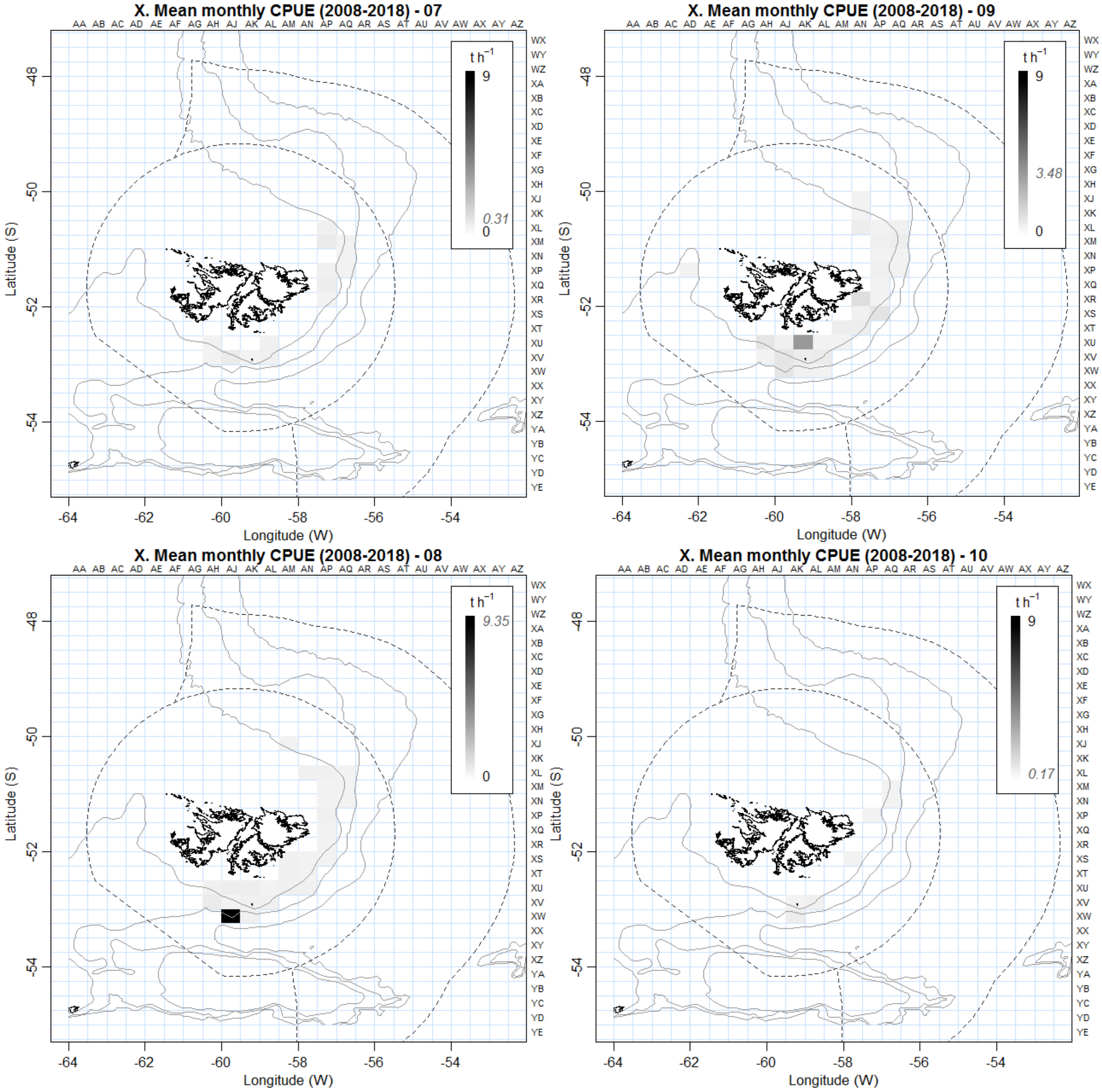

W. Mean monthly CPUE (2008-2018) - 08
t h^{-1}
17
4.78
0
Latitude (S)
Longitude (W)


W. Mean monthly CPUE (2008-2018) - 11
t h^{-1}
17
7.59
0
Latitude (S)
Longitude (W)

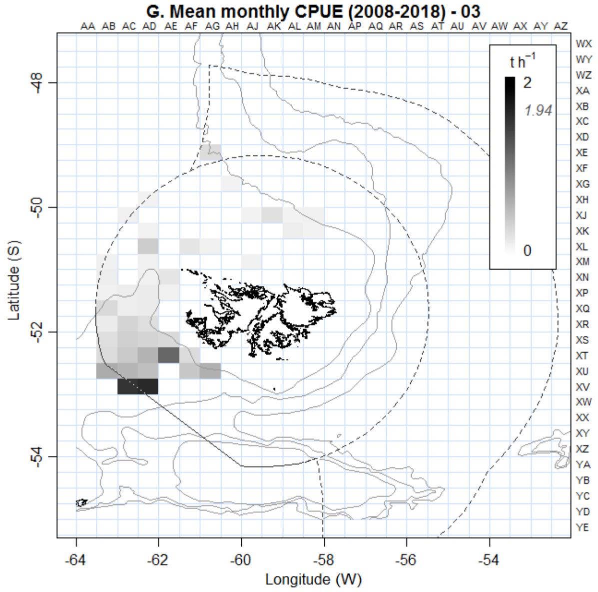

W. Mean monthly CPUE (2008-2018) - 09
t h^{-1}
16.59
0
Latitude (S)
Longitude (W)

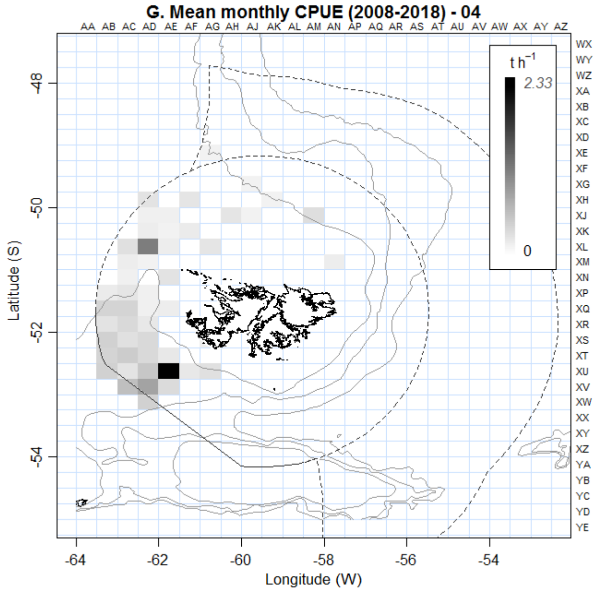

W. Mean monthly CPUE (2008-2018) - 12
t h^{-1}
17
2.83
0
Latitude (S)
Longitude (W)

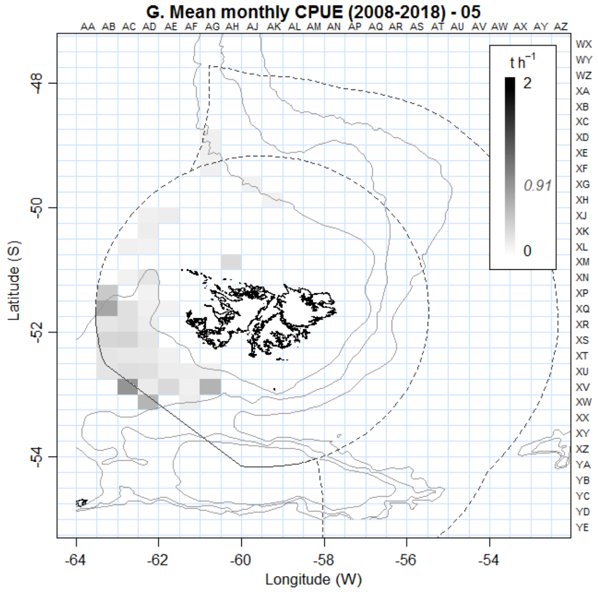
Appendix X. Monthly spatial distribution of CPUE ($t \cdot h^{-1}$) of Southern blue whiting by X-licensed vessels in Falklands waters from 2008 to 2018.



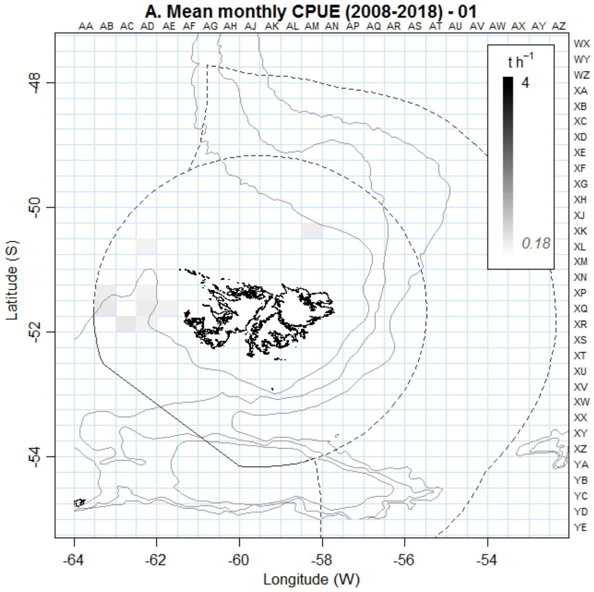
Appendix XI. Monthly spatial distribution of CPUE ($t \cdot h^{-1}$) of Southern blue whiting by G-licensed vessels in Falklands waters from 2008 to 2018.

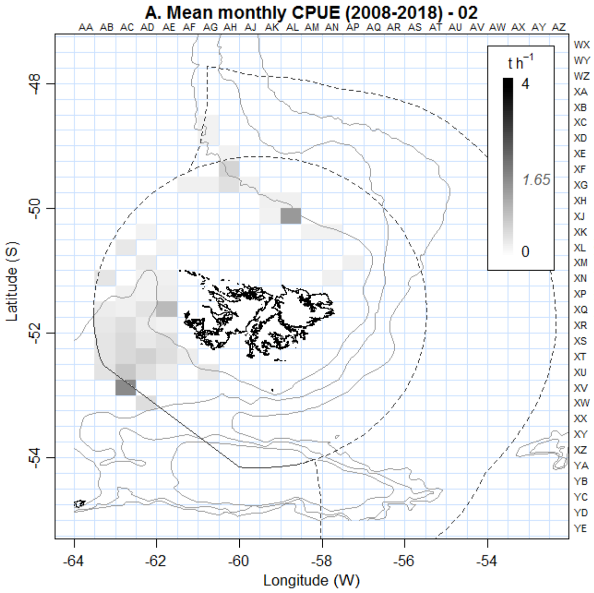


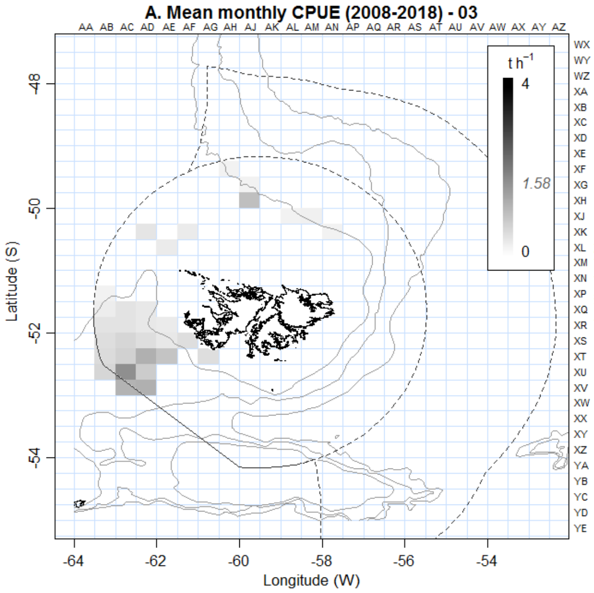


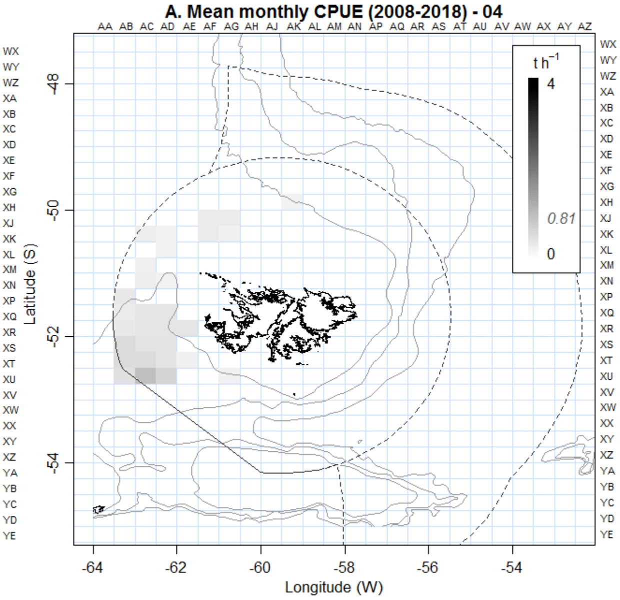


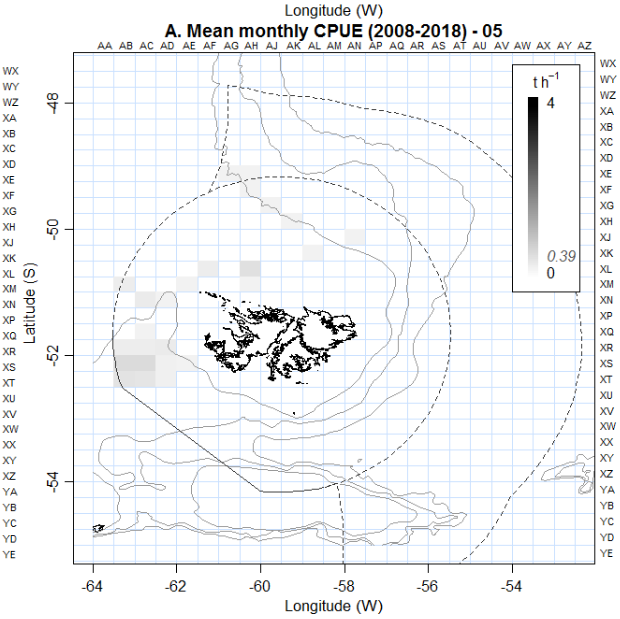
Appendix XII. Monthly spatial distribution of CPUE (t · h^{-1}) of Southern blue whiting by A-licensed vessels in Falklands waters from 2008 to 2018.

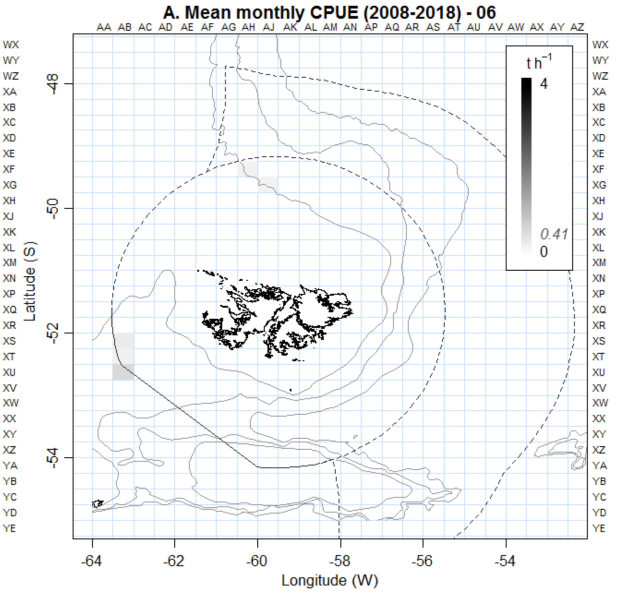


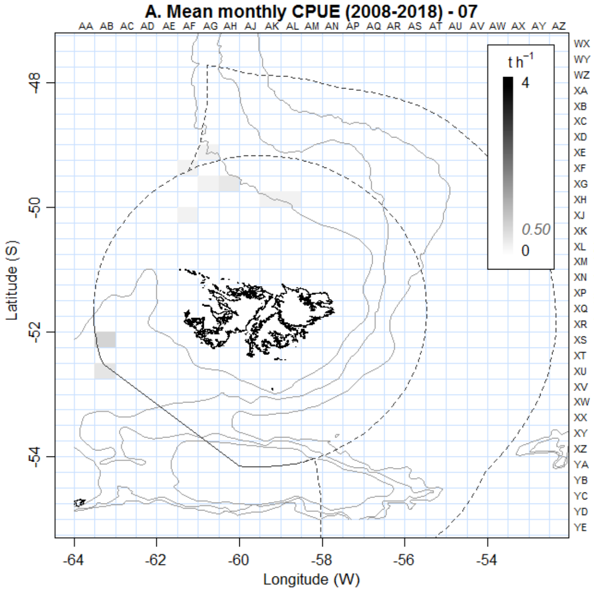


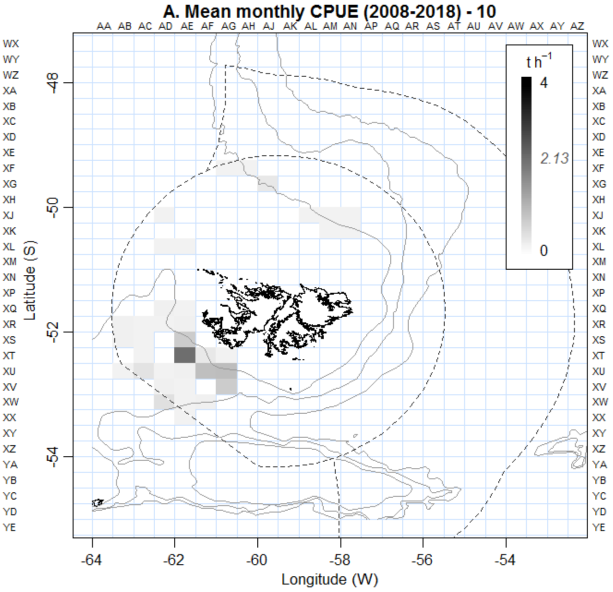


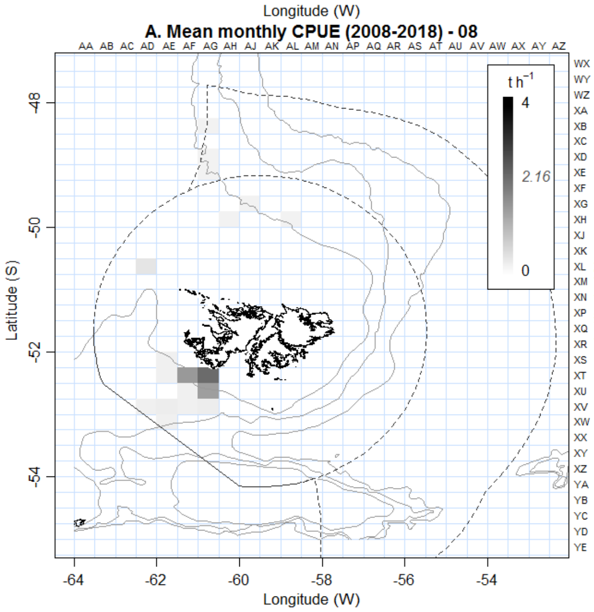


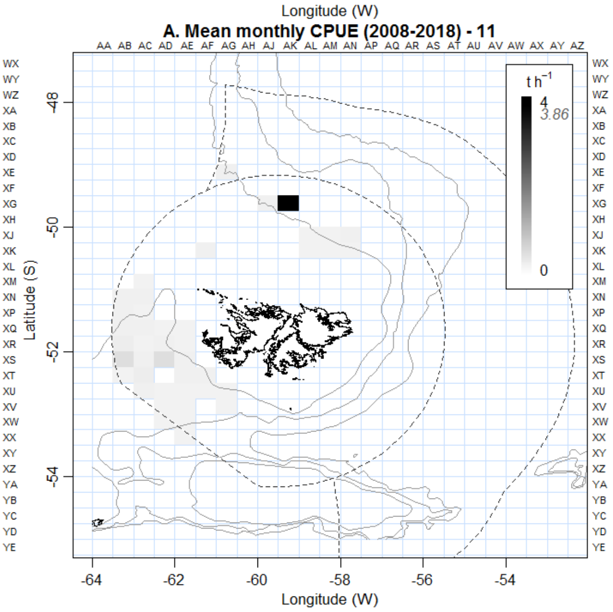


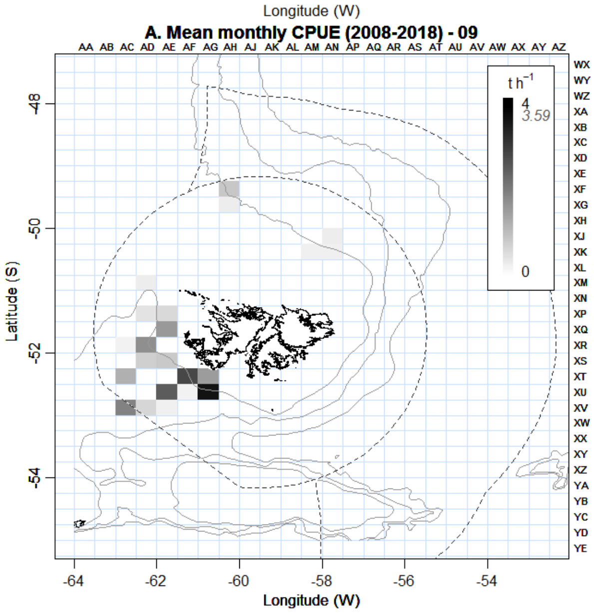


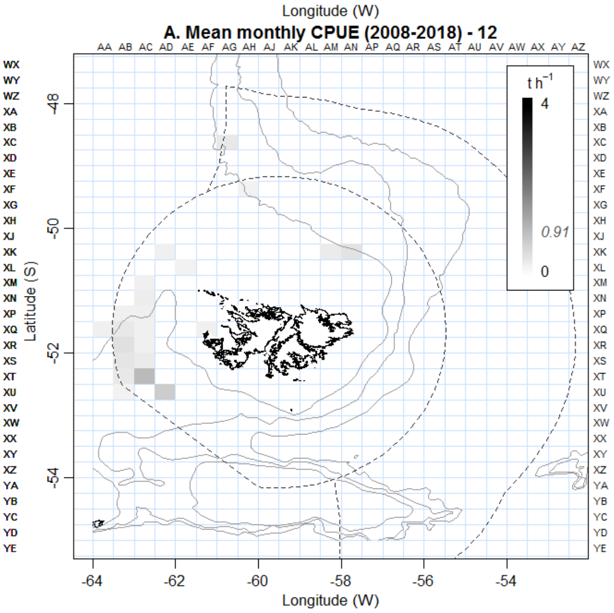

A. Mean monthly CPUE (2008-2018) - 07
t h^{-1}
4
0.50
0
Latitude (S)
Longitude (W)


A. Mean monthly CPUE (2008-2018) - 10
t h^{-1}
4
2.13
0
Latitude (S)
Longitude (W)

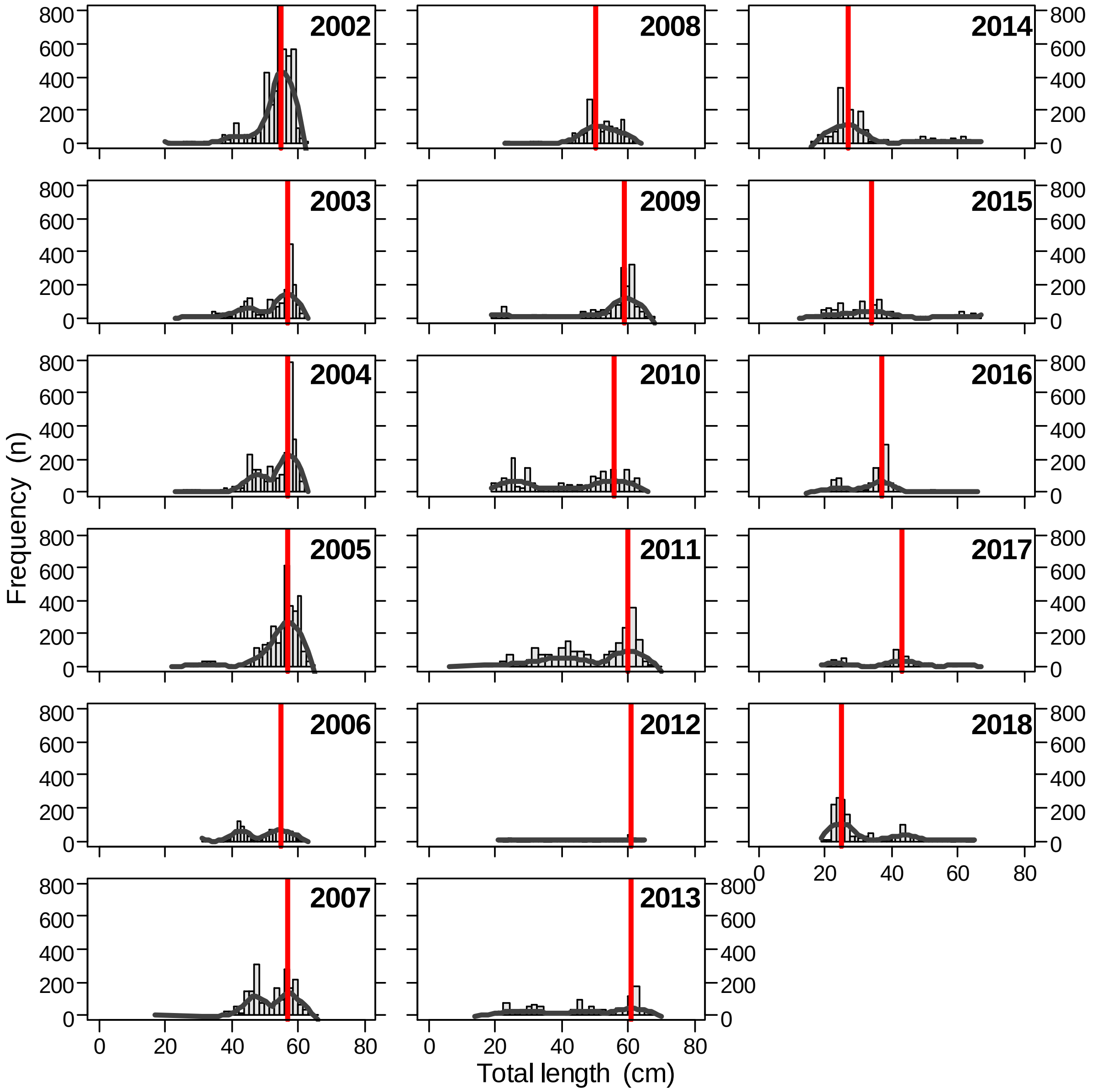

A. Mean monthly CPUE (2008-2018) - 08
t h^{-1}
4
2.16
0
Latitude (S)
Longitude (W)


A. Mean monthly CPUE (2008-2018) - 11
t h^{-1}
4
3.86
0
Latitude (S)
Longitude (W)

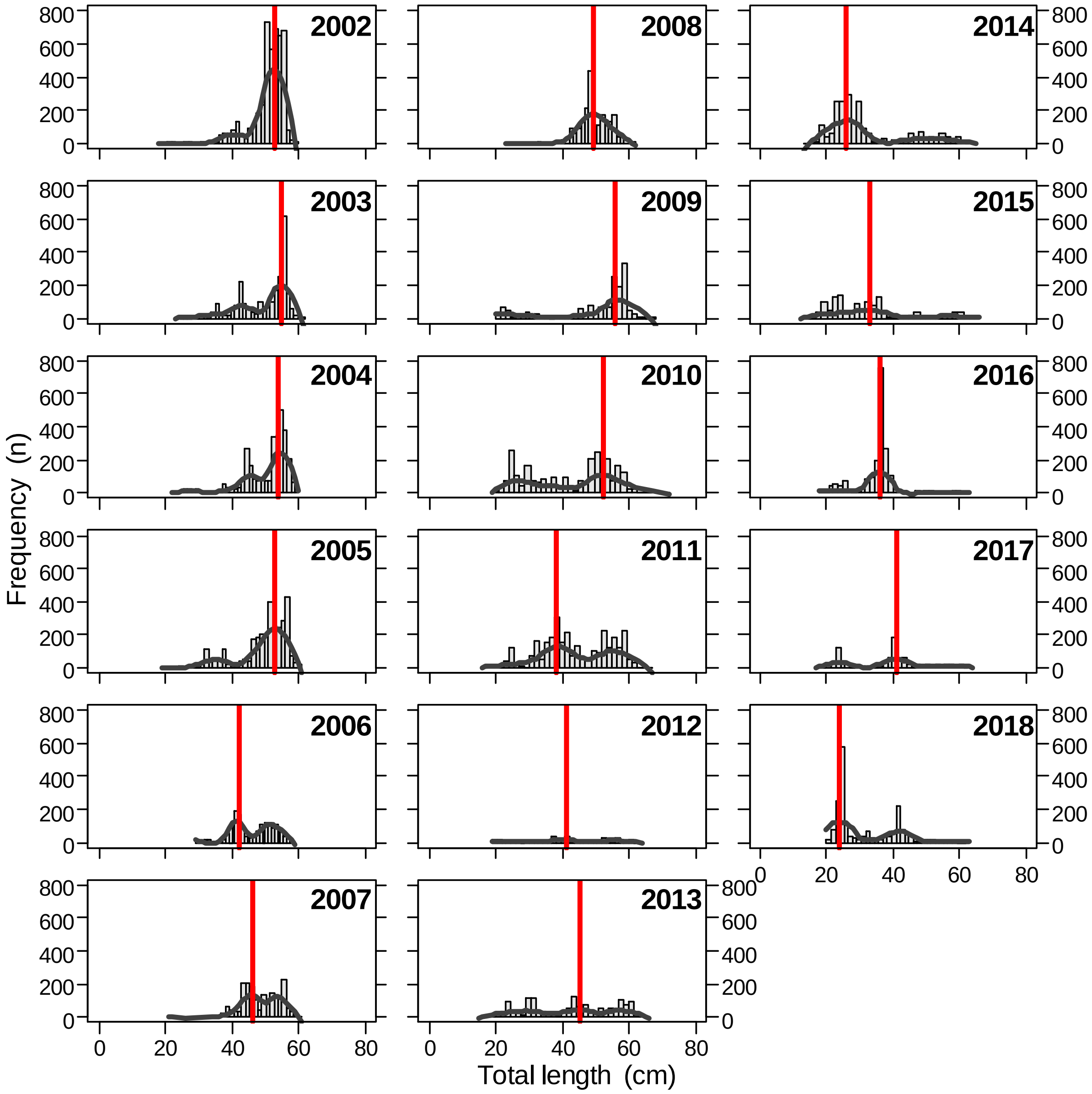

A. Mean monthly CPUE (2008-2018) - 09
t h^{-1}
4
3.59
0
Latitude (S)
Longitude (W)


A. Mean monthly CPUE (2008-2018) - 12
t h^{-1}
4
0.91
0
Latitude (S)
Longitude (W)

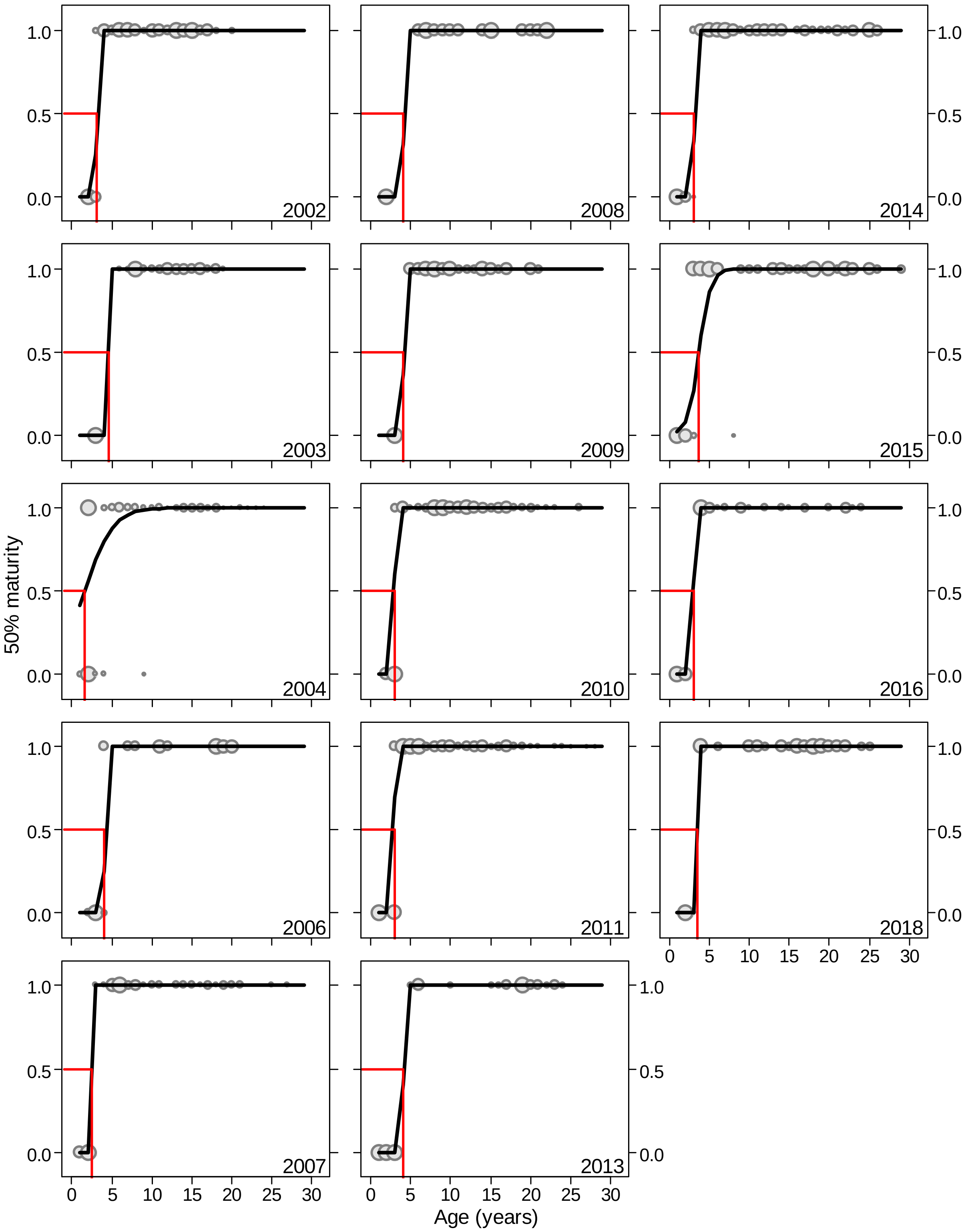
Appendix XIII. Annual modes of female Southern blue whiting total lengths in the Falkland Islands from 2002 to 2018. The modes (vertical red lines) are calculated from LOESS smooths over the length distributions to mitigate sampling fluctuations. n_{2002} = 4,247; n_{2003} = 1,848; n_{2004} = 2,880; n_{2005} = 3,199; n_{2006} = 1,054; n_{2007} = 1,951; n_{2008} = 1,479; n_{2009} = 1,475; n_{2010} = 1,988; n_{2011} = 2,163; n_{2012} = 168; n_{2013} = 1,157; n_{2014} = 1,570; n_{2015} = 883; n_{2016} = 1,045; n_{2017} = 593; n_{2018} = 1,407.



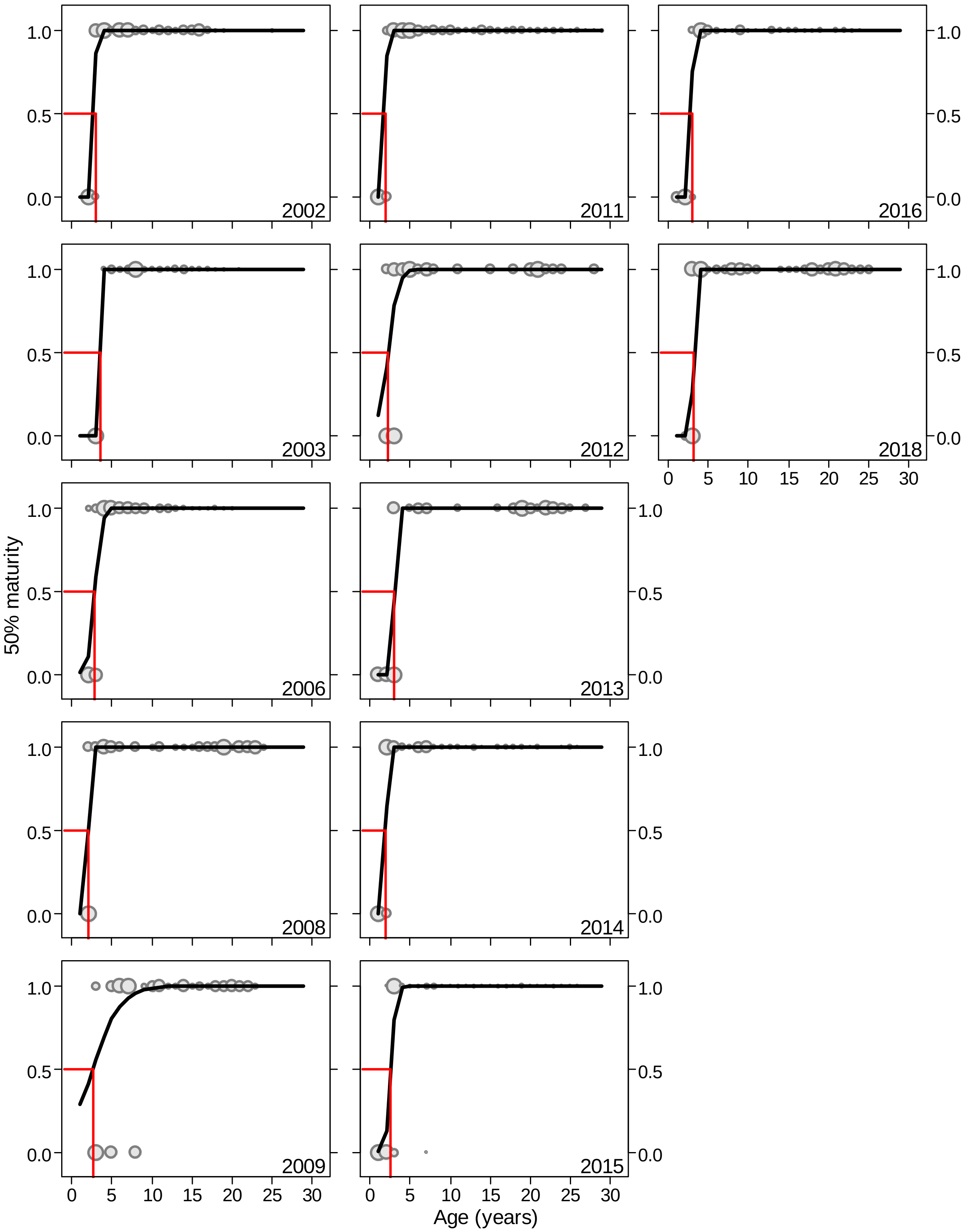
Appendix XIV. Annual modes of male Southern blue whiting total lengths in the Falkland Islands from 2002 to 2018. The modes (vertical red lines) are calculated from LOESS smooths over the length distributions to mitigate sampling fluctuations. n_{2002} = 4,576; n_{2003} = 2,372; n_{2004} = 3,018; n_{2005} = 3,062; n_{2006} = 1,697; n_{2007} = 1,932; n_{2008} = 2,076; n_{2009} = 1,572; n_{2010} = 2,564; n_{2011} = 2,993; n_{2012} = 357; n_{2013} = 1,466; n_{2014} = 2,078; n_{2015} = 1,251; n_{2016} = 1,948; n_{2017} = 880; n_{2018} = 1,912.



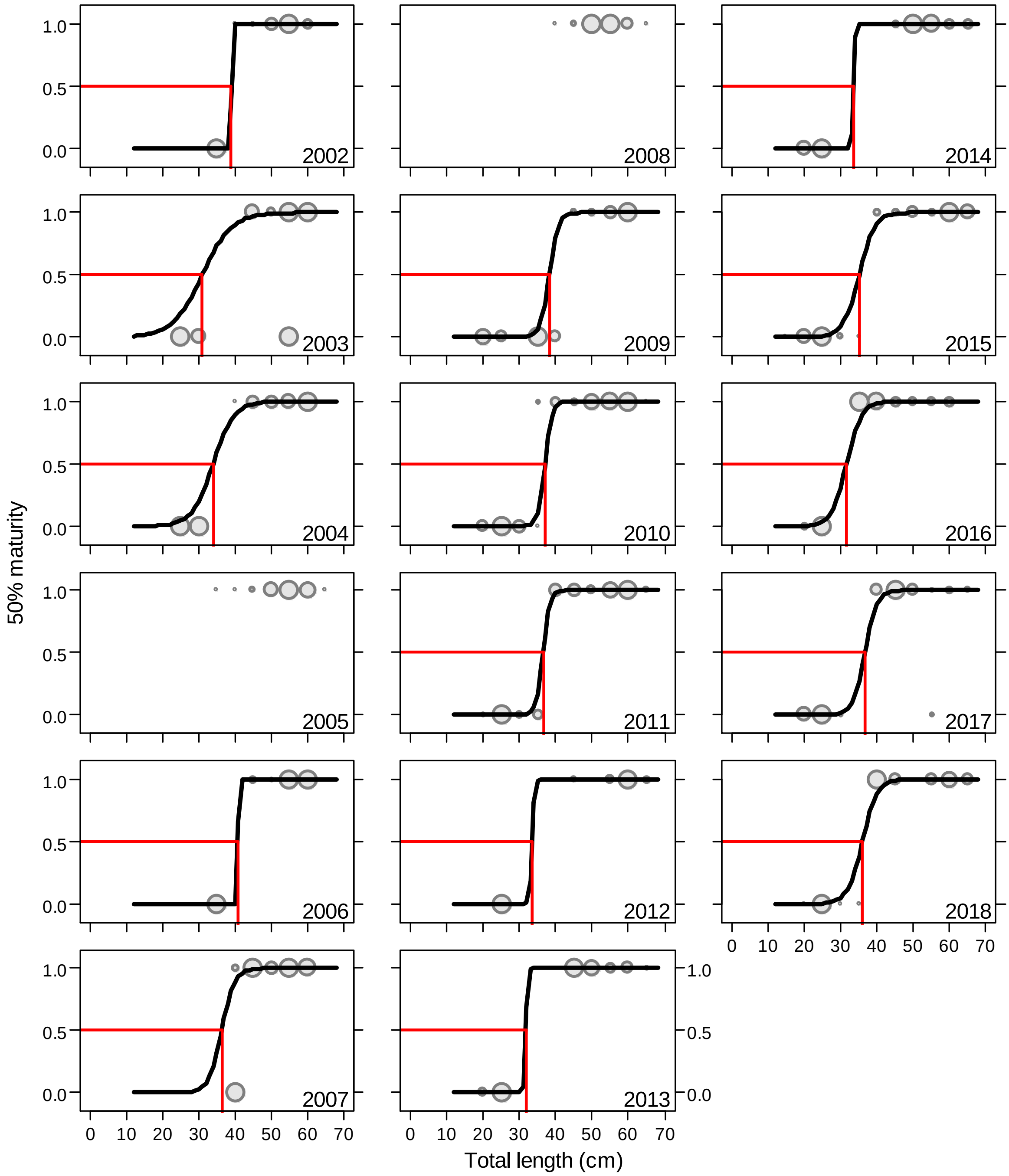
Appendix XV. Age at 50% maturity of female Southern blue whiting in the Falkland Islands from 2002 to 2018. Logistic regressions were made for age vs. juvenile (0: maturity stages 0 and I) and adult (1: maturity stages III+).



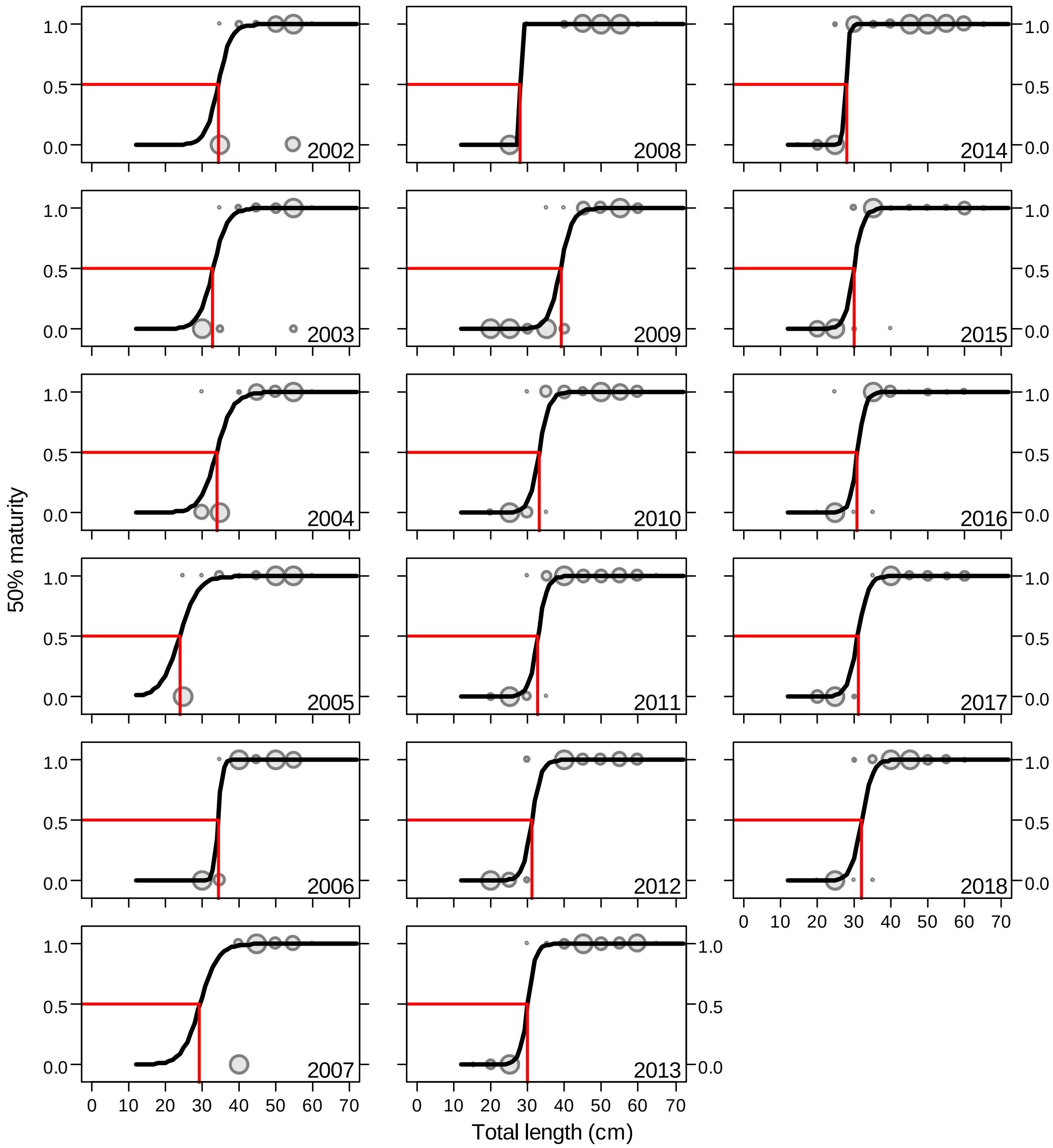
Appendix XVI. Age at 50% maturity of male Southern blue whiting in the Falkland Islands from 2002 to 2018. Logistic regressions were made for age vs. juvenile (0: maturity stages 0 and I) and adult (1: maturity stages III+).



Appendix XVII. Total length at 50% maturity of female Southern blue whiting in the Falkland Islands from 2002 to 2018. Logistic regressions were made for total length vs. juvenile (0: maturity stages 0 and I) and adult (1: maturity stages III+). Juvenile stages (0: maturity stages 0 and I) were not found during 2005 and 2008.



Appendix XVIII. Total length at 50% maturity of male Southern blue whiting in the Falkland Islands from 2002 to 2018. Logistic regressions were made for total length vs. juvenile (0: maturity stages 0 and I) and adult (1: maturity stages III+).



Appendix XIX. LBB implemented on Southern blue whiting from Falkland Islands waters. a) accumulated total length frequency data used to estimate priors Lc, L_∞, and Z/K; b) total length frequency data for the first year in the time series (2002), and c) total length frequency data for the last year in the time series (2018), with fit (red curve) of the LBB master equation that provides estimates of Z/k and L_∞. d) Lmean (bold black line) relative to Lopt, and Lc (dashed black line) relative to Lc_{opt}; e) relative fishing pressure F/M (black line) and 95% confidence limits (dotted lines), with indication of the reference level where F = M (green horizontal line); f) relative biomass B/B_0 (black line) with 95% confidence limits (dotted black lines), a proxy for B_{MSY} (green dashed line), for 0.5 B_{MSY} (red dotted line), and confidence limits of 2018 (blue vertical line) are indicated.