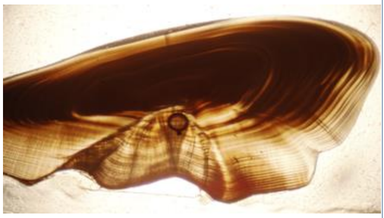
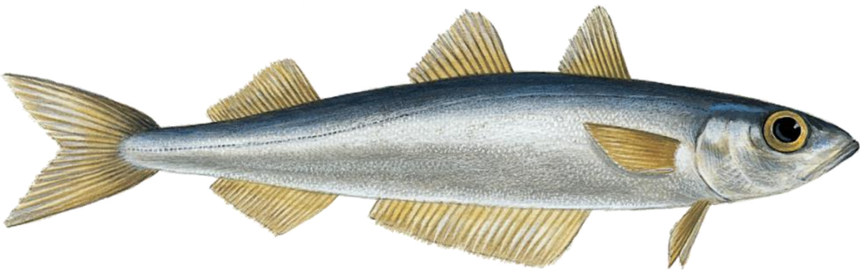
Stock assessment of southern blue whiting (*Micromesistius australis australis*) in the Falkland Islands

SA–2020–BLU



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4 November 2020

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Jorge E. Ramos (R scripts, data analyses, elaboration of report)
Frane Skeljo (R scripts, elaboration of report)
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Stock assessment of southern blue whiting (*Micromesistius australis australis*) in the Falkland Islands

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Summary

The southern blue whiting stock (SBW) including Falkland Islands, Argentina, and Chile commercial data was assessed with the optimized catch-only method (OCOM) and Catch-Maximum Sustainable Yield (CMSY).

OCOM resulted in lower annual total biomass estimates compared with CMSY; therefore, as a precautionary approach OCOM outputs were selected to estimate catch limits. The most conservative OCOM estimate of median MSY was 83,158 t; carrying capacity K was estimated at 1,267,952 t, and total biomass in 2019 was estimated in 192,973 t, which is 15.22% of the total biomass in the first year of the time series (1987).

Based on B_{MSY} = 0.5K and B_{2019}/B_{MSY} = 0.304, the overall catch limit of SBW (including Falkland Islands, Argentina, and Chile) should be 30.4% of MSY: 83,158 × 0.304 = 25,280 t.

For the Falkland Islands only, the recommended catch limit of SBW is between 1,502 t and 2,796 t according to the relative average contribution criterion.

In Falkland Islands waters, SBW was caught mainly from October to January (2007–2016) to the east and southeast under S–licence, although this licence has not been used since 2017. Over the last decade (2010–2019) SBW was caught mainly during August and September to the southwest, south, and east under A–, W– and X– licences, whereas most catches under G–licence were from March to April along the west.

Introduction

Southern blue whiting *Micromesistius australis 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 of the Southwest Atlantic between 37°S and 55°S (Argentina and Falkland Islands). The depth range is 100 to 800 m (Aguayo et al. 2010; Froese & Pauly 2019). Spawning occurs during September and October to the south of the Falkland Islands at 200–300 m depths (Shubnikov et al. 1969; Pájaro & Macchi 2001; Macchi et al. 2005), with spawning grounds varying 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 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).

Connectivity between the Southwest Atlantic and Southeast Pacific was confirmed by otolith chemistry (Arkhipkin et al. 2009) and mitochondrial DNA analyses (Shaw 2003, 2005). Therefore, southern blue whiting from the Falkland Islands, Argentina and Chile are referred to as a single stock SBW.

In Chile, SBW was first caught as bycatch in the austral zone Southern hake (*Merluccius australis*) fishery in 1978 (43–57°S; Aguayo et al. 2010). Over the period 1990–2011, individuals between 16 and 70 cm of total length (TL) and maximum ages over 24 years were caught by the Chilean fleet (Contreras et al. 2013); size at 50% maturity was estimated at 36 cm TL (Córdova et al. 2003). In Argentina, SBW fishery takes place from 45°S to 56°S, individuals are caught at 17–60 cm TL and at maximum 21 years old (Cassia 2000); size at 50% maturity of females was estimated at 37.8 cm TL (Pájaro & Macchi 2001). In Falkland Islands waters, SBW is currently caught as bycatch by trawlers throughout the year, with lower catches during late autumn and early winter (austral seasons). The average contribution of this species to the trawl fishery in Falkland Islands waters is 10% since 1987 and only about 2% during the period 2009–2018 (Falkland Islands Government 2019). Surimi vessels have targeted SBW sporadically in Falkland Islands waters since 2007, and a no-fishing area for the surimi fleet is implemented to the South and Southwest of the Falkland Islands from 1 July to 15 October (Falkland Islands Government 2019). Low catches and high operative costs have prevented surimi vessels from targeting SBW since 2017.

During the period 2009 to 2018, the Falkland Islands contributed on average 12.6%, Argentina 40.9%, and Chile 46.5% per year of the total SBW catch in the Southwest Atlantic and the Southeast Pacific (Ramos & Winter 2019). Given that SBW is targeted by the Falkland Islands, Argentina and Chile, fisheries from the three nations are accounted for stock assessment.

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 SBW catch data were examined from 1987 to 2019 (Falkland Islands [http://www.fig.gov.fk/fisheries/publications/fishery-statistics; Falkland Islands Government 2019], Argentina [https://www.agroindustria.gob.ar/sitio/areas/pesca_maritima/desembarques/; Sánchez et al. 2012; Navarro et al. 2014], and Chile [http://www.sernapesca.cl/informes/estadisticas; SERNAPESCA 1990, 2000, 2011]). Total catch of SBW in Chile for 2019 was provided by Instituto de Fomento Pesquero (IFOP), and should be considered as preliminary (R. Céspedes, IFOP, *pers. comm.*). Spearman rank correlation was implemented to examine the association between annual catch of the Falkland Islands and Argentina, and the Falkland Islands and Chile.

Commercial catch of SBW in Falkland Islands waters were examined by licence type for 2019. Temporal patterns of the 10-year (2010–2019) average, maximum and minimum monthly catch, effort and CPUE were examined. CPUE per month was estimated as the sum of catches of the month from 2010 to 2019 divided by the sum of effort of the month from 2010 to 2019. Spatial examination of the 10-year (2010–2019) average CPUE per month and grid square from 2010 to 2019 was estimated as the sum of catches of the month per grid square from 2010 to 2019 divided by the sum of effort of the month per grid square from

2010 to 2019. Temporal and spatial patterns of the surimi fishery (S-licence) landings were examined for the most recent 10-year period with data (2007–2016).

Length-weight relationship

The length-weight relationship was calculated as $W = aL^b$, based on the total length (cm) and weight (g) measurements of 66,606 random samples collected in Falkland Islands commercial catches from 1993 to 2020.

Length-age relationship

The length-age relationship was described by the von Bertalanffy growth model:

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

where t_0 = theoretical age at zero length. The package 'fishmethods' (Nelson 2017) was used in R Studio (RStudio Team 2016), and the length-at-age relationship was based on age estimates and total length measurements of 9,130 random samples collected in Falkland Islands commercial catches from 2000 to 2018.

Biomass estimation

Biomasses were estimated using the Optimized Catch-Only Method (Zhou et al. 2018) and Catch-Maximum Sustainable Yield (CMSY; Froese et al. 2017). Evaluating different methods in parallel presents the opportunity to comparatively estimate the performance of stock assessments (Cadrin & Dickey-Collas 2015).

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 sum of SBW annual catches in the Falkland Islands, Argentina and Chile. The Graham-Schaefer surplus production model has two unknown parameters, r and K. Given that S = B_y/K, K can be solved if prior information on r and S is available (Zhou et al. 2018).

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 calculated as F_{MSY} = 0.87 · M for teleosts (Zhou et al. 2012), where M is instantaneous natural mortality rate.

To avoid negative values being sampled, a lognormal distribution was implemented in R Studio (RStudio Team 2016):

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

where mean r (μ_r) = log(2F_{MSY}), and variance 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, variance of r (σ_r^2) = 0.2312 (Zhou et al. 2018).

Natural mortality (M) was calculated following Kenchington (2014):

$$M = \frac{4.3}{t_{max}} = 0.14$$

where t_{max} (maximum age) = 31 years. Maximum age was taken from the Falkland Islands Fisheries Department (FIFD) age-length database. For comparison, natural mortality was also taken from studies in Falkland Islands and Argentina (M = 0.15; Giussi et al. 2007; Falkland Islands Government 2013) and Chile (M = 0.18; Contreras et al. 2013).

The prior distribution for stock saturation S was calculated in R Studio (RStudio Team 2016) based on B/B_0 (B_{2018}/B_{2002}) estimated in Ramos & Winter (2019):

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

where $\mu_{B/B0}$ = 0.1553 and $\sigma_{B/B0}$ = 0.0274.

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 $B_{current} = B_{2019}$. 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.

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 and was used to set the resilience levels in CMSY (Froese et al. 2017, 2019). The prior range of r is within the range of r reported for this species in Fishbase (0.54; 0.36 – 0.82, 95% CI) (Froese & Pauly 2019).

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

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

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). Depletion is equal to 1 – S (saturation). 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.

Catch limits

The stock assessments were used to estimate a total allowable catch for SBW, which would be allocated between the Falkland Islands, Argentina, and Chile. Historical catch is often used to estimate quota allocation on international and regional scales (Lynham 2014). For SBW in Falkland Islands fisheries, hypothetical catch limits were proposed based on the following alternate criteria:

1) 10–, 5–, and 3–year average catch in the Falkland Islands.
2) 10–, 5–, and 3–year average contributions (%) of the Falkland Islands relative to the combined catch of SBW in Falkland Islands, Argentina and Chile, apportioned from the total allowable catch for SBW.
3) Equal share of the total catch limit of SBW between the Falkland Islands, Argentina and Chile, i.e. 33.33% each.

Total allowable catch was based on the inference of MSY. The biomass that can sustain MSY (B_{MSY}) was calculated following Schaefer (1954):

$$B_{MSY} = 0.5\ K$$

Carrying capacity (K) was taken from the selected model. The proportion B_{2019}/B_{MSY} was multiplied by the MSY estimate to calculate the catch limit for SBW (including Falkland Islands, Argentina and Chile).

0.5 B_{MSY} can be considered the biomass below which recruitment tends to be impaired and the stock is in danger of collapsing (Froese et al. 2011). This reference point was based on the comparison of lower stock limits used in Europe (B_{pa} = precautionary reference point for spawning stock biomass) relative to B_{MSY} (Froese & Proelß 2010). Froese et al. 2011) proposed 0.5 B_{MSY} as a limit reference point for closing target fisheries, and suggested that this should be the default limit biomass below which additional measures must be activated, e.g. minimizing bycatch in other fisheries. Therefore, biomass estimates in 2019 were compared with 0.5 $B_{MSY.}$

Results

Commercial catch

Catches of SBW in the Falkland Islands have averaged 22,653 t per year since 1987; the maximum catch occurred in 1990 (72,351 t) followed by a constant decrease to reach the lowest catch in 2019 (518 t). The 10-year average (2010–2019) annual catch was 3,034 t; the 5-year average (2015–2019) annual catch was 2,405 t and the 3-year average (2017–2019) annual catch was 1,273 t. The Falkland Islands have the smallest 10-year average proportion (11.1 ± 5.3%) to the total catch of SBW; Argentina and Chile contribute 42.6 ± 16.8% and 46.3 ± 15.4% of the catch, respectively. The mean annual catch of the SBW in Argentina over the period 1987–2019 was 39,897 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 2019 have remained below 16,000 t per year, and the catch in 2019 was 8,639 t. The mean annual catch of the SBW in Chile over the period 1987–2019 was 18,715 t. Catches in Chile increased from 1987 to reach a maximum in 1998 (40,857 t), and have decreased gradually to 6,075 t in 2019 (Fig. 1; Appendix I). Catches in Falkland Islands waters were relatively higher compared with Argentina and Chile early in the time series, although complete information was not available to relate catches with effort. Over the following years, catches were higher in Argentina and Chile compared with the Falkland Islands. The Spearman rank correlation analysis revealed strong and positive significant correlations between annual catches from Falkland Islands and Argentina ($r = 0.89$, $n = 25$, $p < 0.001$), and from Falkland Islands and Chile ($r = 0.85$, $n = 25$, $p < 0.001$), from 1995 to 2019 (Appendix II).

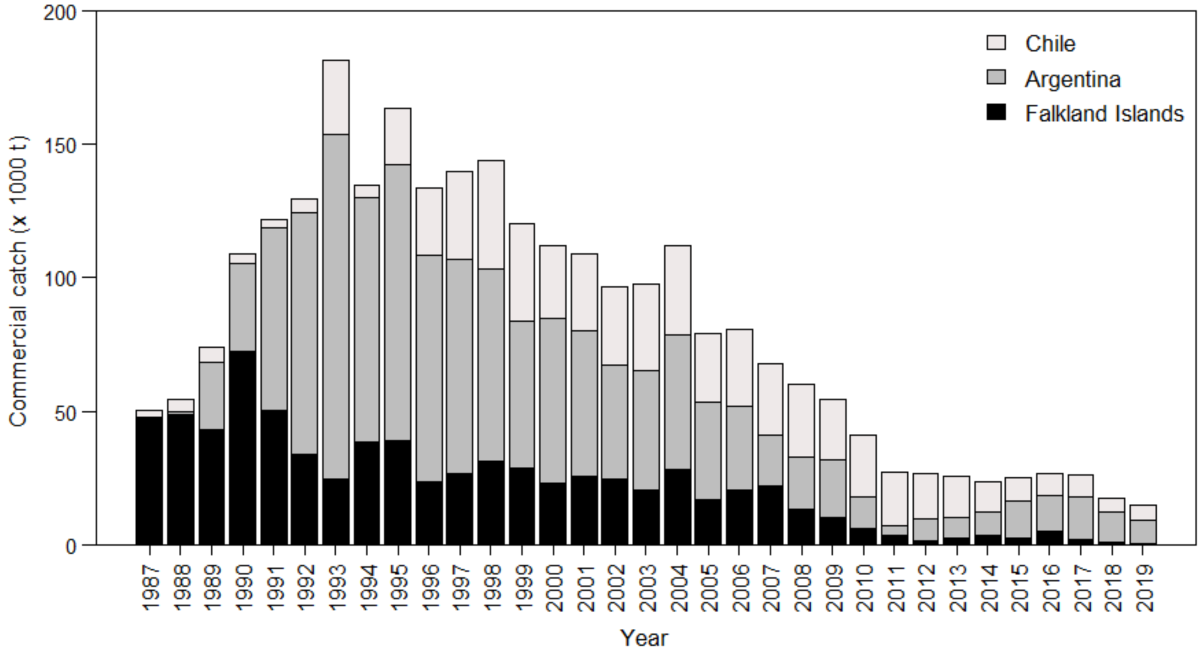

Fig. 1. Commercial total catch of the southern blue whiting stock from 1987 to 2019. Catch data from Chile for the year 2019 are preliminary (R. Céspedes, IFOP, *pers. comm.*).

In 2019, approximately 96% of the SBW catch in Falkland Islands waters was under W–licence. Minor contributions to the commercial catch occurred also from A– (0.9%), G– (0.7%), C– (0.05%), and X– (0.01%) licensed vessels. The experimental E–licence contributed 2.7% of the SBW catch (Table I). The main contributions to the 10-year average (2010–2019) were from W– (39%) and S–licensed vessels (28%). X–, G–, and A–licensed vessels contributed 14%, 10%, and 6%, respectively. C– and F–licensed vessels contributed < 1%, whereas E–licence contributed 1.8% (Table I). Over the period 2010–2019, the main catches under W–licence were in August to the southwest (Appendixes III–IV), and in September to the south and east under X–licence (Appendixes V–VI). Under A–licence, main catches were in September in a few grid squares to the southwest; however, SBW was also caught in August, and from February to April to the west and southwest (Appendixes VII–VIII). March and April were the months of greater CPUE along the west under G–licence (Appendixes IX–X). The S–licence has not been used since 2017 and its mean annual catch over the period 2007–2016 was 3,600 t; with most catches occurring from October to January to the south and east, and with higher CPUE in October (Appendixes XI–XII).

Table I. Catch of the southern blue whiting stock per licence type in Falkland Islands waters during 2019, and 10-year average catch (2010–2019). S-licence was not used during 2017–2019, hence the S-licence 10-year average catch is from 2007 to 2016.

Licence	Catch (2019; t)	Relative catch (2019; %)	Catch (10-year average; t)	Relative catch (10-year average; %)
A	4.69	0.91	173.50	5.72
B	0.00	0.00	0.00	0.00
C	0.26	0.05	9.76	0.32
E	14.07	2.72	53.38	1.76
F	0.00	0.00	14.54	0.48
G	3.71	0.72	314.71	10.37
L	0.00	0.00	0.00	0.00
O	0.00	0.00	0.00	0.00
R	0.00	0.00	0.00	0.00
S	0.00	0.00	856.50	28.23
W	494.87	95.59	1177.85	38.82
X	0.06	0.01	433.91	14.30
Y	0.00	0.00	0.00	0.00
Z	0.00	0.00	0.00	0.00

Length-weight relationship

The length-weight relationship and parameters are summarized in Fig. 2.

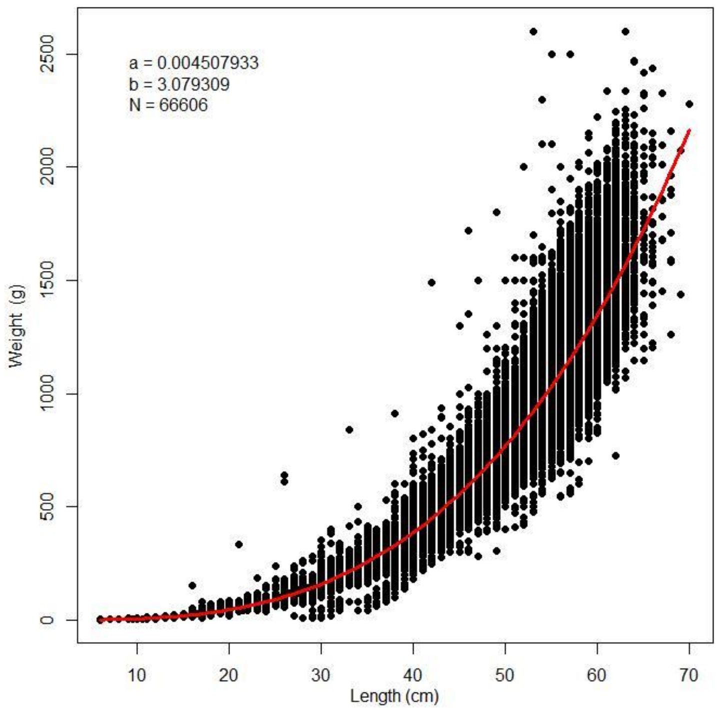

Fig. 2. Length-weight relationship of southern blue whiting in Falkland Islands waters, females and males pooled.

Length-age relationship

The age-length relationship of females and males pooled gave the following values: L_∞ = 59.34 cm, k = 0.203, and t_0 = 1.456 years (Fig. 3). 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_∞ = 60.7 cm, k = 0.229, and t_0 = -0.754 years. 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_∞ = 56.8 cm, k = 0.249, and t_0 = -0.704 years.

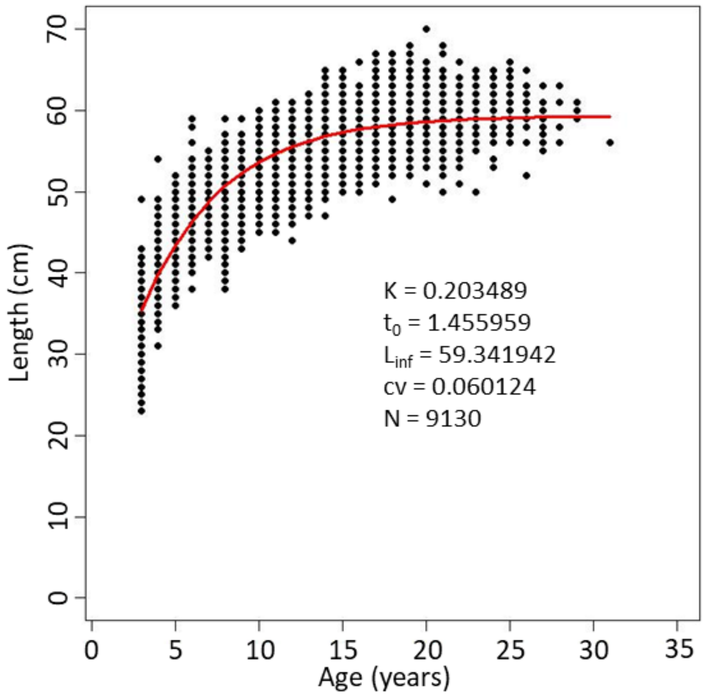

Fig. 3. von Bertalanffy age-length relationship of southern blue whiting from the Falkland Islands, females and males pooled. Note that ages 0, 1 and 2 are omitted.

Biomass estimation

Parameters estimated from the OCOM Graham-Schaefer production model based on the different mortality rates are summarized in Table II. OCOM outputs produced using the natural mortality (M) = 0.15 were comparable with CMSY outputs, and were selected over OCOM estimates using other natural mortalities (M = 0.14; M = 0.18). Median intrinsic growth rate was estimated at 0.2624, equivalent to a potential 30% increase of the population per year by implementing $e^{0.2624} - 1$. Carrying capacity was 1,267,952 t (677,253 – 1,944,162 t; 95% CI). The biomass of SBW in 2019 was estimated at 192,973 t (95,004 – 335,643 t; 95% CI) and the MSY was estimated at 83,158 t (49,699 – 115,640; 95% CI).

Accordingly, a continuous decrease in biomass was estimated from 1987 (1,267,857 t) to 2019 (192,973 t; Fig. 4; Appendix XIII), with the biomass of 2019 comprising 15.22% of the biomass in 1987 (B_{2019}/B_{1987} = 0.1522).

Table II. OCOM Graham-Schaefer production model parameters and estimates of biomass and MSY for southern blue whiting stock, using commercial catch data from 1987 to 2019. M = mortality rate; r = intrinsic growth rate; K = carrying capacity; B_{1987} = biomass in 1987; B_{2019} = biomass in 2019; MSY = maximum sustainable yield. Medians with 95% confidence intervals in parentheses; selected outputs are indicated in bold font.

		OCOM	
M	0.14	**0.15**	0.18
r	0.2418 (0.0953 – 0.6333)	**0.2624** **(0.1025 – 0.6830)**	0.3155 (0.1252–0.8266)
K	1,325,356 (716,546 – 1,996,898)	**1,267,952** **(677,253 – 1,944,162)**	1,141,193 (584,747 – 1,802,631)
B_{1987}	1,325,514 (716,227 – 1,997,129)	**1,267,857** **(677,928 – 1,944,171)**	1,141,165 (584,333 –1,802,487)
B_{2019}	201,598 (97,276 – 351,369)	**192,973** **(95,004 – 335,643)**	174,291 (82,104 – 311,593)
B_{2019}/B_{1987}	0.1521	**0.1522**	0.1527
MSY	80,115 (47,505 – 113,445)	**83,158** **(49,699 – 115,640)**	89,997 (56,308–120,842)

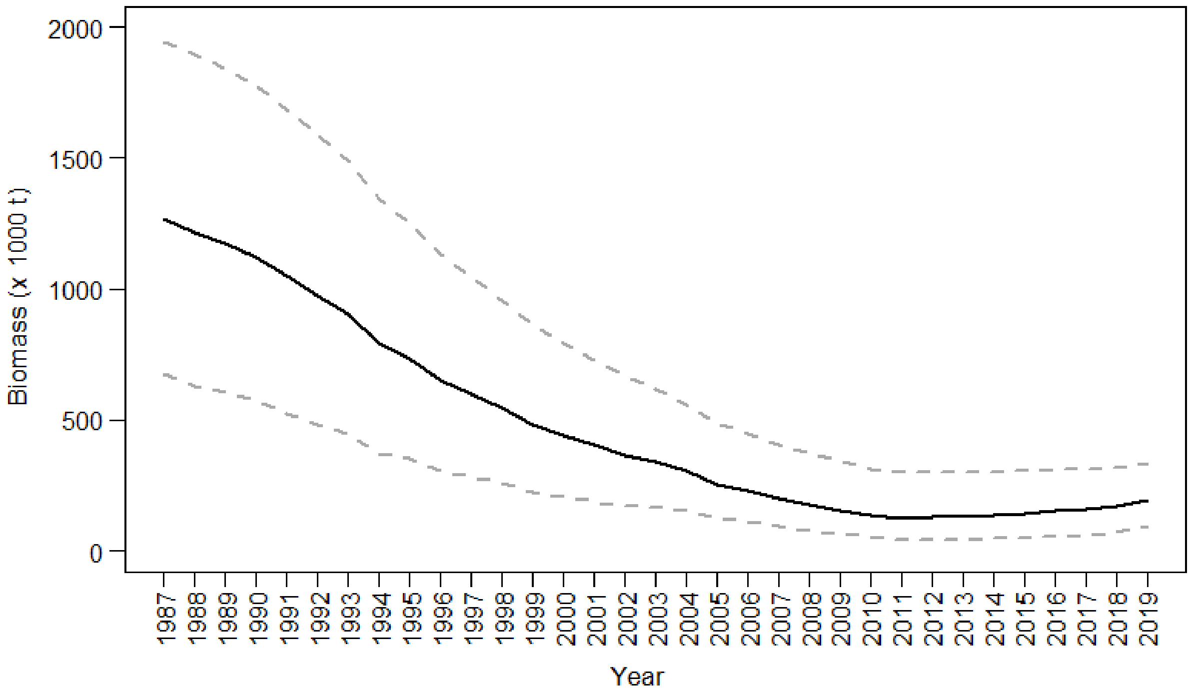

Fig. 4. Median and 95% confidence intervals of annual southern blue whiting stock biomass from 1987 to 2019 estimated from the OCOM Graham-Schaefer production model. The parameters were M = 0.15; F_{MSY} = 0.87; r (σ_r^2) = 0.2312; $\mu_{B/B0}$ = 0.1553; and $\sigma_{B/B0}$ = 0.0274.

The OCOM estimate of r (0.2624; 0.1025 – 0.6830, 95% CI) corresponds to 'low' and 'medium' resilience for southern blue whiting (Froese et al. 2017). Therefore, prior ranges of r for 'low' (0.05 – 0.5) and 'medium' (0.2 – 0.8) resilience were tested for CMSY. However, only the CMSY analysis using 'low' resilience found a representative number (n = 5,623) of viable trajectories for r-k pairs. Hence, outputs using 'medium' resilience are not presented. The depletion level estimated by OCOM: B_{2019}/B_{1987} = 0.1522 overlaps 'strong' depletion prior ranges (0.01 – 0.40) (Froese et al. 2019), and this was set for CMSY (Table III). The CMSY analysis suggests that there is reduced fishing pressure on SBW, and the stock is recovering from still too small biomass (Fig. 5).

Table III. CMSY parameters, and estimated biomass and MSY for the southern blue whiting stock commercial catches from 1987 to 2019, calculated with prior range of r = 0.05 – 0.5, and '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_{1987} = biomass in 1987; B_{2019} = biomass in 2019; MSY = maximum sustainable yield; B/B_{MSY} (2019) = ratio of the stock biomass in 2019 to the stock biomass that can produce maximum sustainable yield; F_{2019} = fishing mortality in 2019; F/F_{MSY} = ratio of fishing mortality to the fishing mortality rate at maximum sustainable yield. Medians with 95% confidence intervals in parentheses.

	CMSY
Resilience	Low
r	0.1405
	(0.1019 – 0.1936)
K	2,029,847
	(1,385,389 – 2,974,095)
F_{MSY}	0.0703
	(0.0509 – 0.0968)
B_{MSY}	1,014,923
	(692,694 – 1,487,047)
B_{1987}	1,458,200
	(1,203,711 – 1,661,075)
B_{2019}	440,861
	(33,670 – 1,056,785)
B_{2019}/B_{1987}	0.3023
	(0.0280 – 0.6362)
MSY	71,302
	(63,223 – 80,413)
B/B_{MSY} (2019)	0.3718
	(0.0898 – 0.7819)
F_{2019}	0.0404
	(0.0192 – 0.5271)
F/F_{MSY}	0.7727
	(0.3674 – 10.0901)

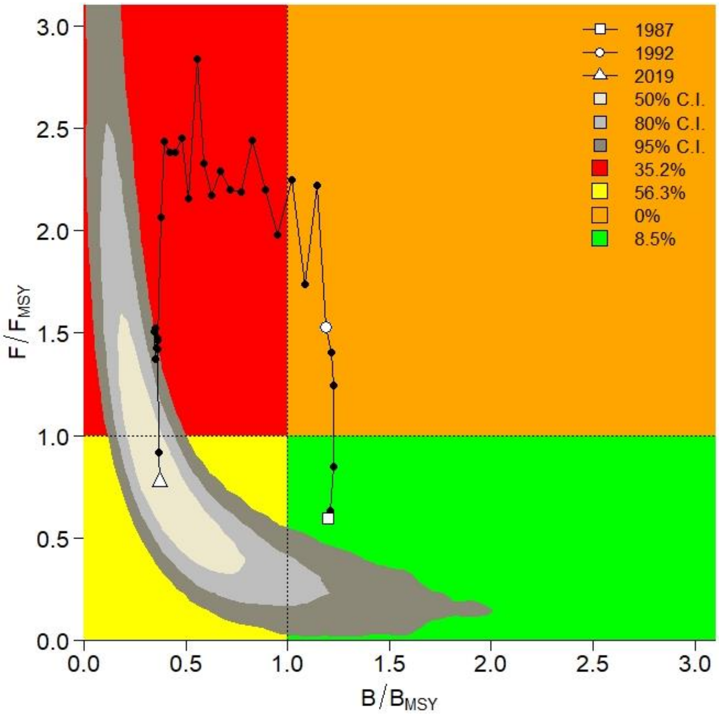

Fig. 5. Trajectory of relative stock size (B/B_{MSY}) over relative exploitation (F/F_{MSY}) estimated with the CMSY analysis under 'strong' depletion scenario for the southern blue whiting stock (SBW). The data point for 2019 is located in the yellow zone, which indicates reduced fishing pressure on the stock recovering from still too small biomass.

Catch limits

OCOM outputs estimated using M = 0.15 (Table II) were used to estimate catch limits for the Falkland Islands under criteria 2 and 3. B_{MSY} was estimated at 0.5 x 1,267,952 = 633,976 t from the OCOM estimate of K. By proportion with B_{2019}/B_{MSY} = 192,973 / 633,976 = 0.304, the present catch limit of the SBW should be 30.4% of the OCOM's MSY estimate: 83,158 × 0.304 = 25,280 t.

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

Table IV. Catch limit alternatives for southern blue whiting in Falkland Islands waters.

Criteria	Threshold	Catch limit (t)
1) Average catch		
10-year	3,034	3,034
5-year	2,405	2,405
3-year	1,273	1,273
2) Relative average contribution		
10-year (11.06%)	25,280 x 0.1106	2,796
5-year (9.78%)	25,280 x 0.0978	2,472
3-year (5.94%)	25,280 x 0.0594	1,502
3) Equal share		
33.3%	25,280 x 0.3333	8,426

Discussion

Since 1987, the Falkland Islands have contributed on average 26% of the total annual catch of SBW; this proportion has decreased to 11% in the last decade. Most SBW catches in Falkland Islands waters from 2010 to 2019 were from W–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 SBW during its spawning season in September and October in Falkland Islands waters. S–licensed vessels have not fished in Falkland Islands waters since 2017. However, restrictions to the Southeast of East Falkland between October and January may alleviate fishing pressure on this species when S–licence vessels resume fishing in Falkland Islands waters. The management of SBW also requires international collaboration given that mature individuals may be caught before they enter the FICZ and reach their spawning grounds in Falkland Islands waters, with detrimental effects on offspring production and consequently on yields for the nations that target this stock.

A declining trend in total biomass was found by OCOM from 1987 through 2010, with a period of stabilization and slow recovery from 2011. Stabilization and slow recovery is supported by the 'medium' resilience of southern blue whiting (Froese & Pauly 2019) and its estimated potential to increase the size of the population at about 30% per year. Accordingly, CMSY estimates suggest that fishing pressure has decreased and the stock is still recovering from still too small biomass.

Differences in annual total biomass estimates found in this study may be due to the source of the data required by OCOM and CMSY. OCOM uses total annual catch (i.e. aggregated of the Falkland Islands, Argentina, and Chile) and starting values for intrinsic population growth rate (r) and stock saturation (S). Intrinsic population growth rate is derived from basic life history parameters (Zhou et al. 2018) estimated from FIFD data, which may not be representative of the entire SBW. Stock saturation was taken from the Length-Based Bayesian biomass estimation method (LBB) implemented by Ramos & Winter (2019). LBB is a new approach that has proved useful for data poor stocks (Froese et al. 2018; Wang et al. 2020), although it has raised criticism due to its sensitivity and assumptions (Hordyk et al. 2019). CMSY uses total annual catch and ranges of values for r and depletion status (Froese et al. 2017). Both approaches provided comparable MSY estimates despite differences in biomass estimates. In OCOM and in CMSY, MSY is calculated as rK/4, where r is intrinsic population growth rate and K is carrying capacity (Froese et al. 2017; Zhou et al. 2018).

The various metrics of SBW indicate a need for precautionary management. Given that OCOM calculated conservative biomass and MSY estimates, the most conservative OCOM outputs were used to estimate catch limits for the Falkland Islands. The alternatives of catch limits for the Falkland Islands ranged from 1,273 t to 8,426 t. These alternatives represent hypothetical options, as other factors may be relevant to the catch limits. The catch limit for the Falkland Islands should take as reference the MSY suggested for the SBW (25,280 t), i.e. criterion 2. For instance, equal partition of the MSY between the three fisheries (33.33% each) that target the SBW resulted in 8,426 t. In contrast, catch limits estimated under criterion 2 ranged between 1,502 t and 2,796 t, which would reduce fishing pressure on this heavily depleted stock. The Falkland Islands Government has restricted S–licence allocations to 2,000 t annually, which contributes to lower SBW catches and therefore lower relative average contributions than would otherwise have been realized. Nevertheless, bycatch must be monitored closely given that the annual average catch (1,273 t) since the S–licence has not been used (2017–2019) in Falkland Islands waters already reached 46% to 85% of the catch limits estimated under the criterion 2 recommended.

OCOM total biomass for 2019 was estimated at 192,973 t (95,004 – 335,643 T; 95% CI) and was marginally below 0.5 B_{MSY} (316,988 t), suggesting that additional measures should be implemented. Accordingly, catch limit alternatives estimated in this study follow a more precautionary measure and thus are lower than the SBW catch limit (30,000 t) established in Argentina for 2019 (https://www.pescare.com.ar/establecen-la-captura-maxima-de-merluza-2019/). However, catch limits for the Falkland Islands may not achieve the recovery of this shared stock if further regulations are not implemented outside Falkland Islands waters. The management of SBW requires consideration of the migratory patterns, size and age distributions, size and age at maturity, reproductive seasons, spawning grounds, and other biological parameters across the Southeast Pacific and the Southwest Atlantic, with close collaboration between the nations involved.

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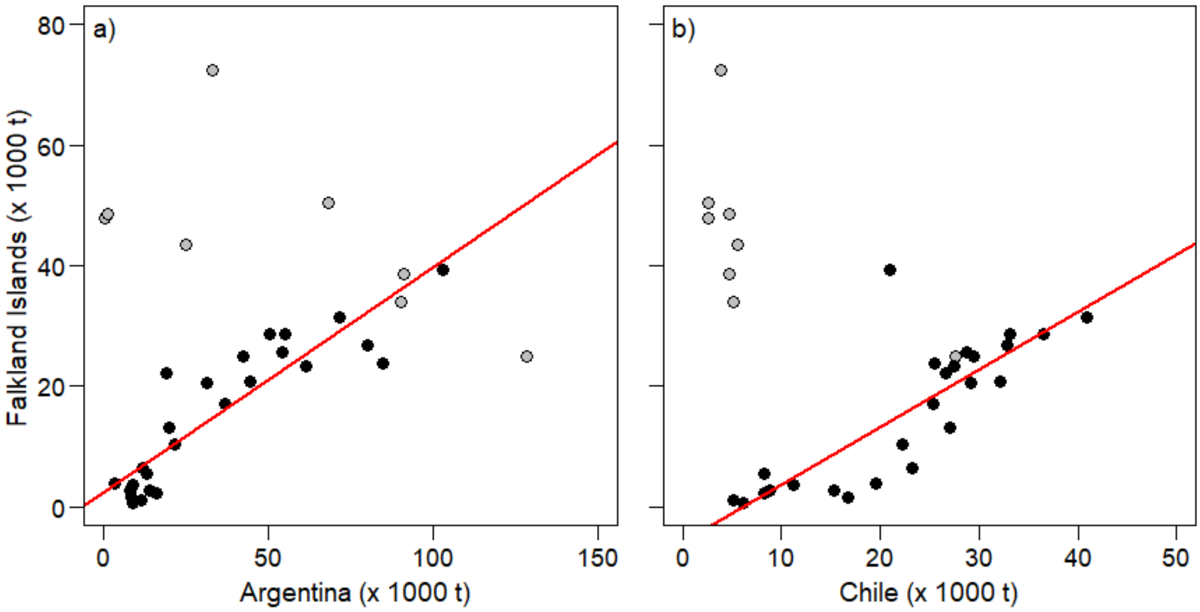
Appendixes

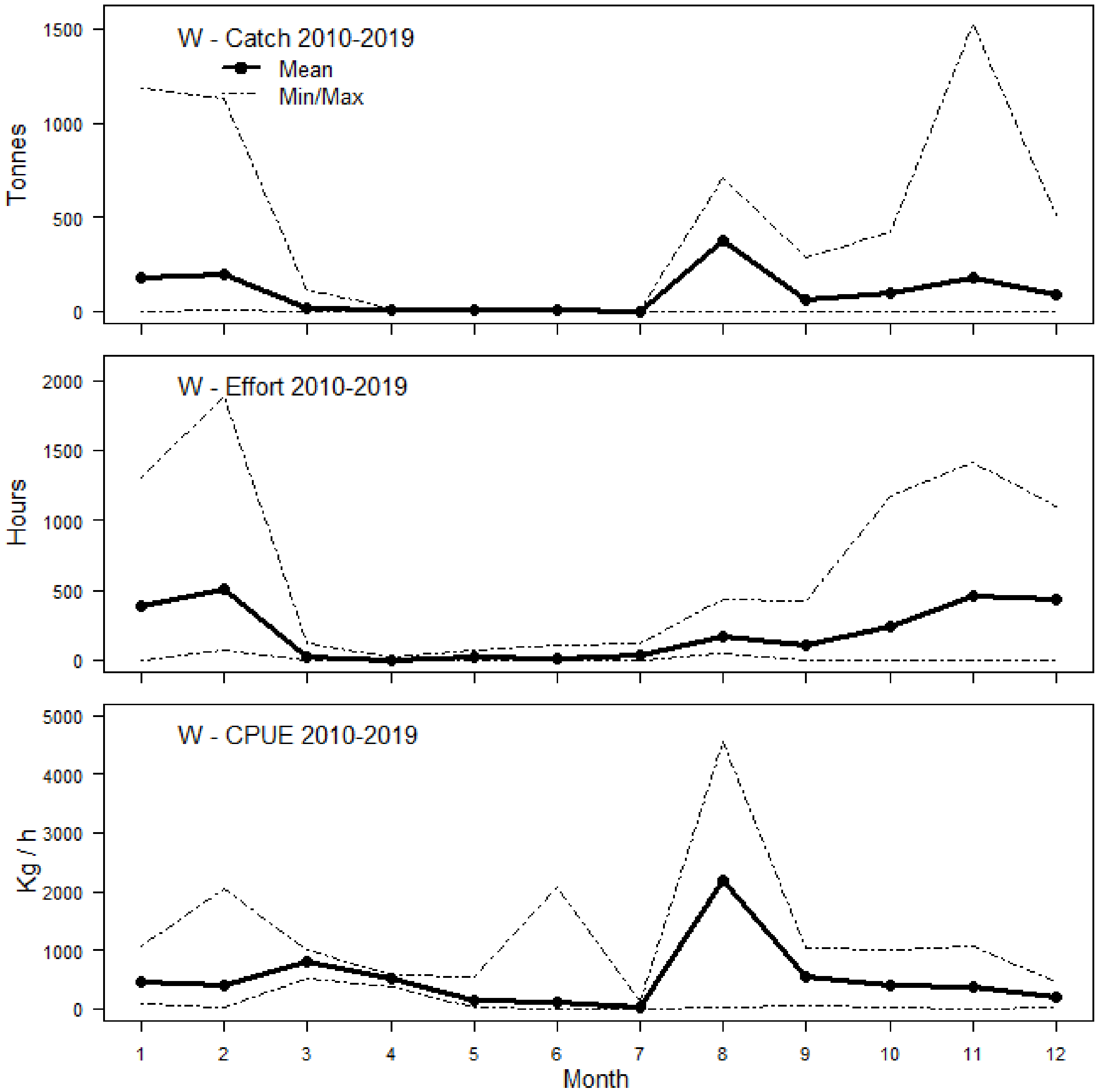
Appendix I. Commercial catches by year (t) of southern blue whiting in Chilean, Argentine and Falkland Islands waters. Catch data from Chile for the year 2019 is preliminary (R. Cespedes, IFOP, *pers. comm.*).

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
2019	6,075	8,639	518	15,232

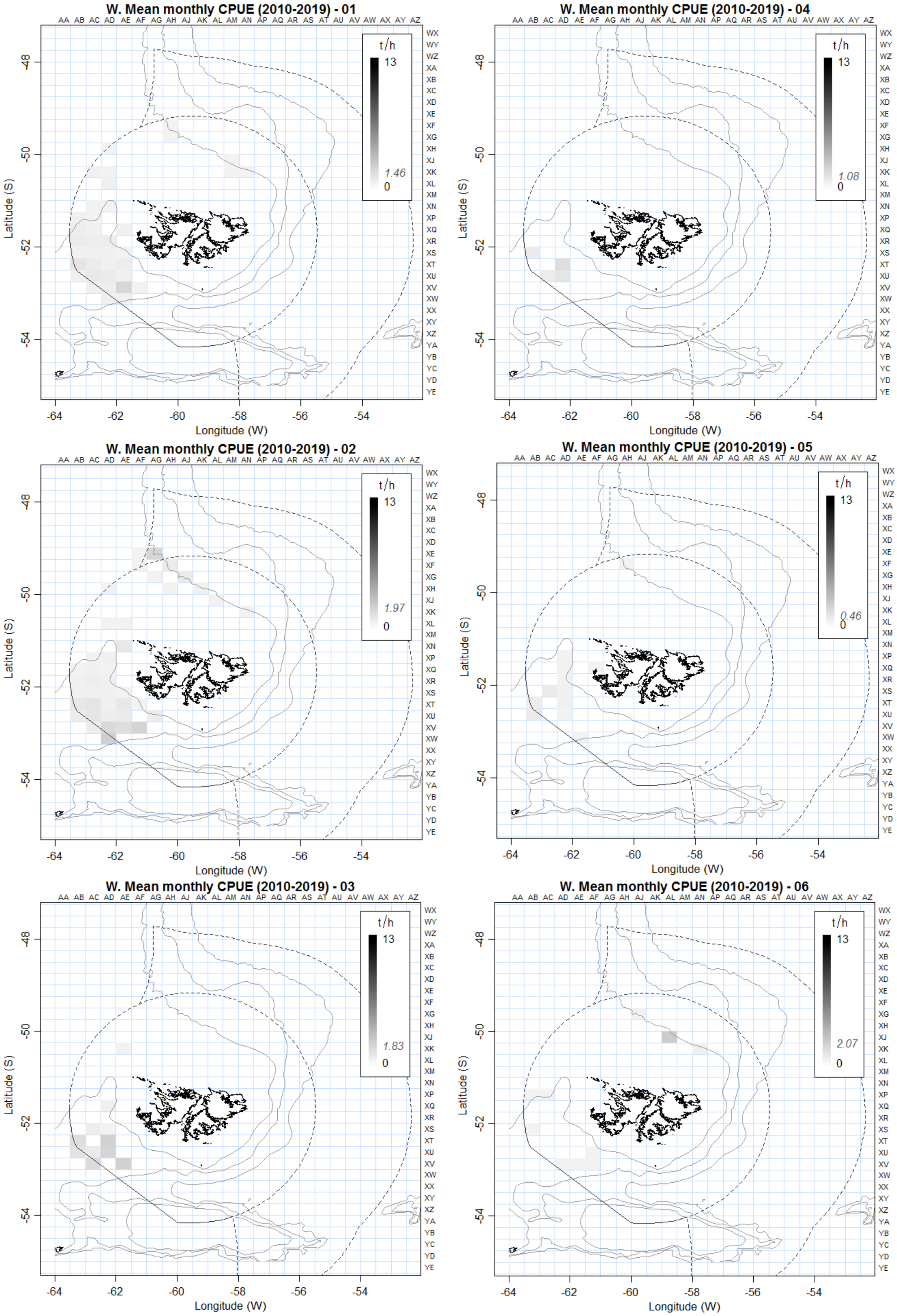
Appendix II. Correlation of southern blue whiting annual catches between a) Falkland Islands and Argentina from 1995 to 2019 ($r = 0.89$, $n = 25$, $p < 0.001$), and b) Falkland Islands and Chile from 1995 to 2019 ($r = 0.85$, $n = 25$, $p < 0.001$). Grey circles refer to catch data from 1987 to 1994. Black circles refer to catch data from 1995 to 2019.



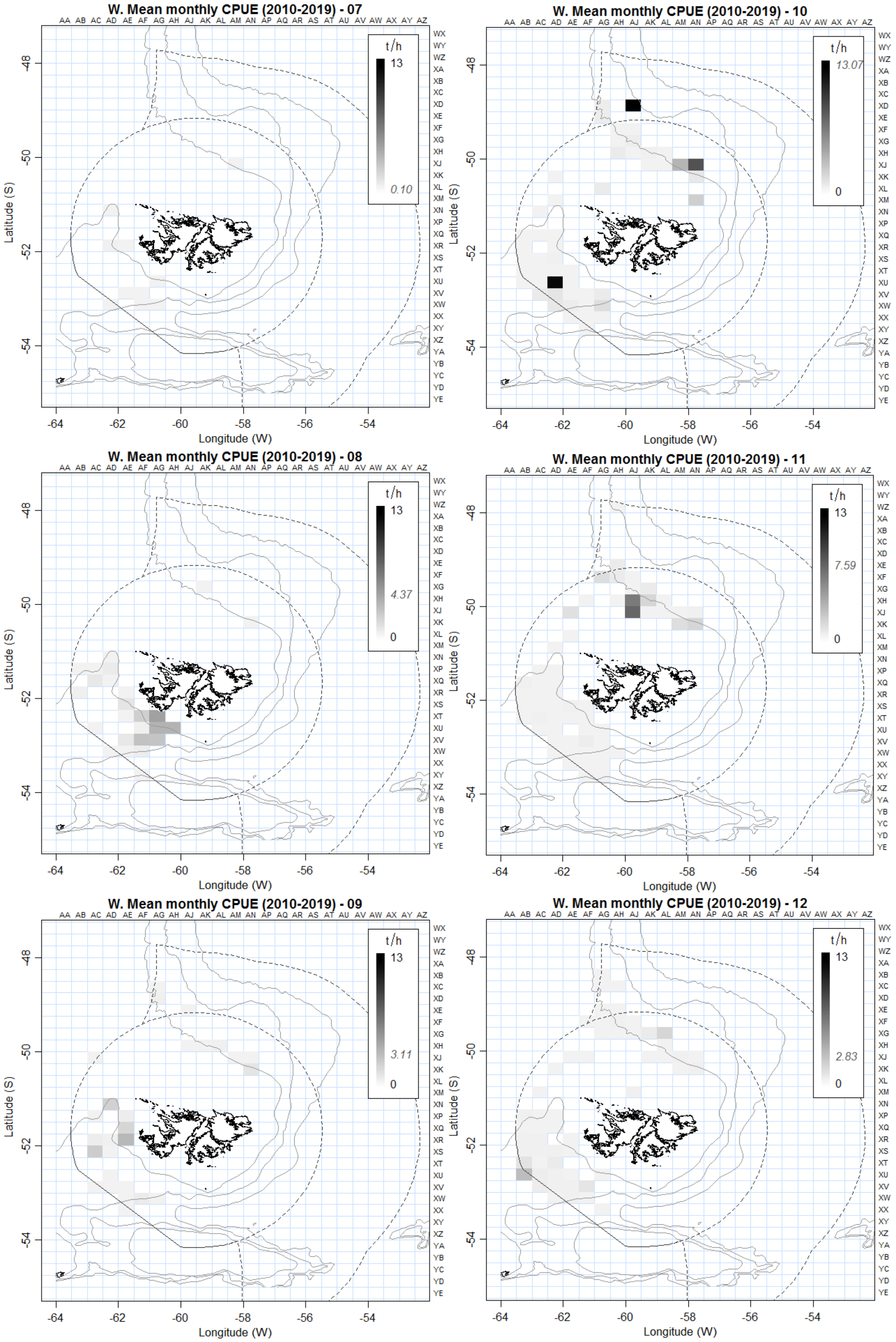
Appendix III. Mean monthly catch, effort and CPUE of the southern blue whiting stock by W–licensed vessels in Falkland Islands waters from 2010 to 2019.



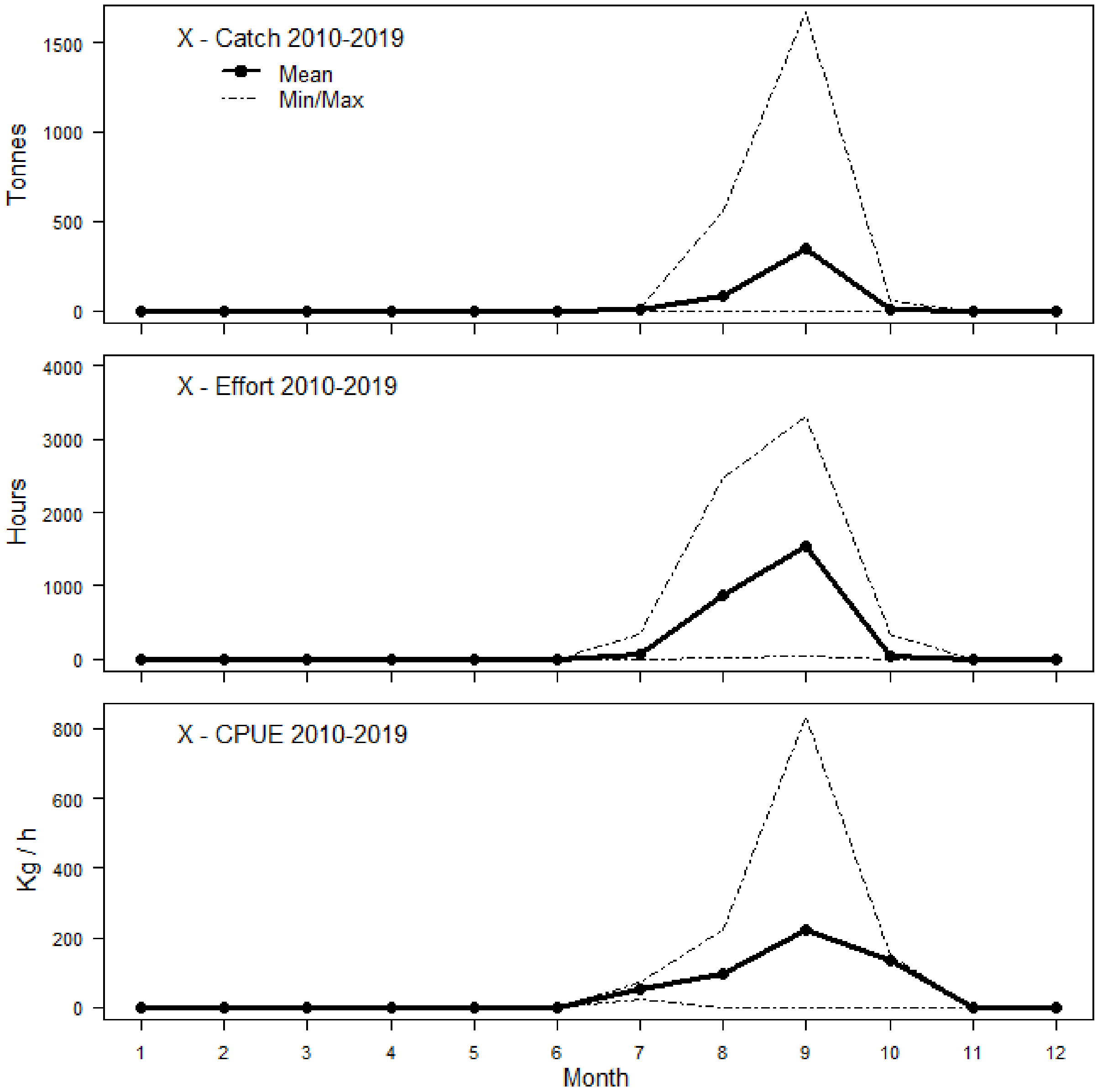
Appendix IV. Spatial distribution of mean monthly CPUE (t/h) of the southern blue whiting stock by W–licensed vessels in Falkland Islands waters from 2010 to 2019.



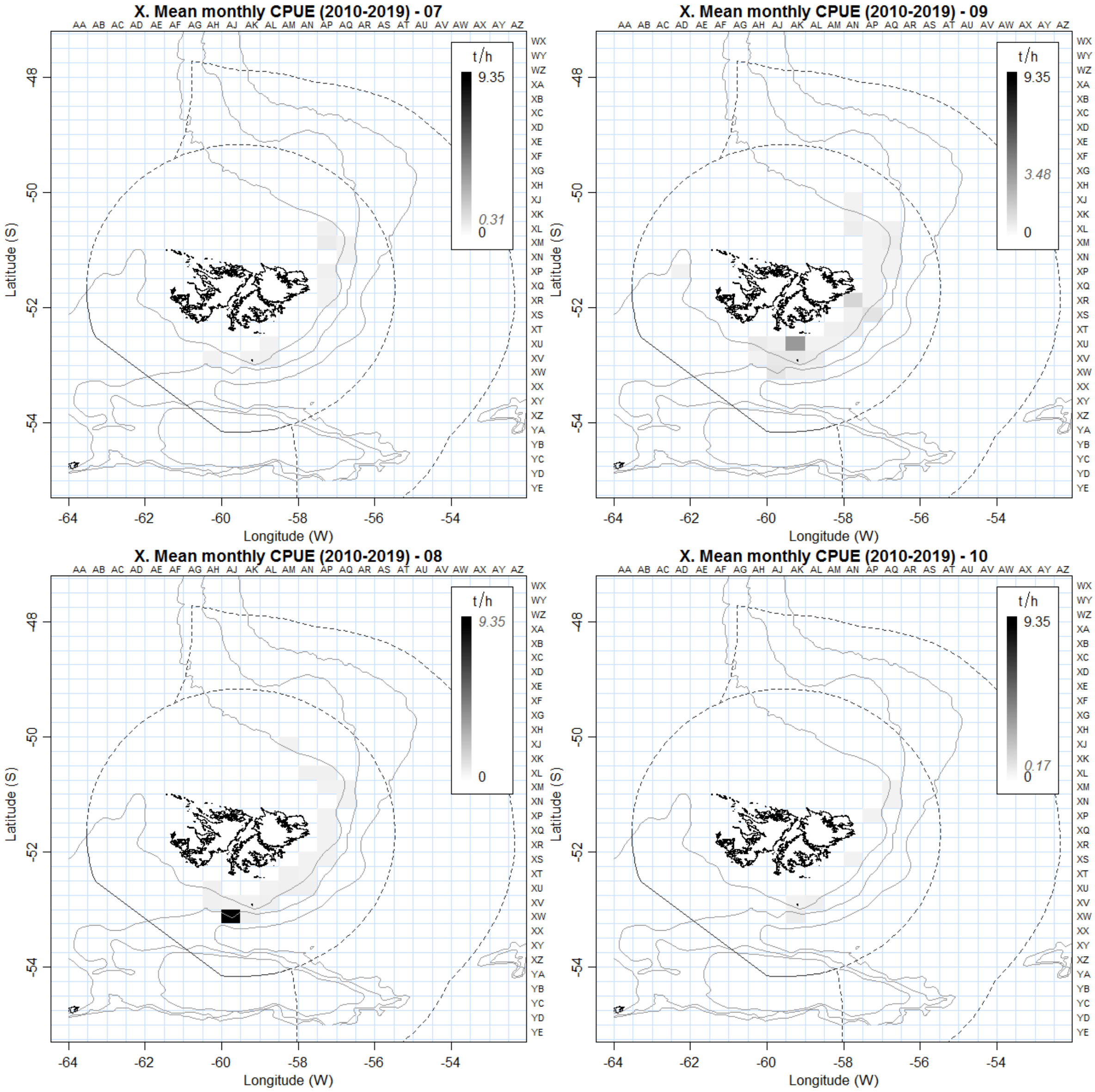
Appendix IV. *continued*



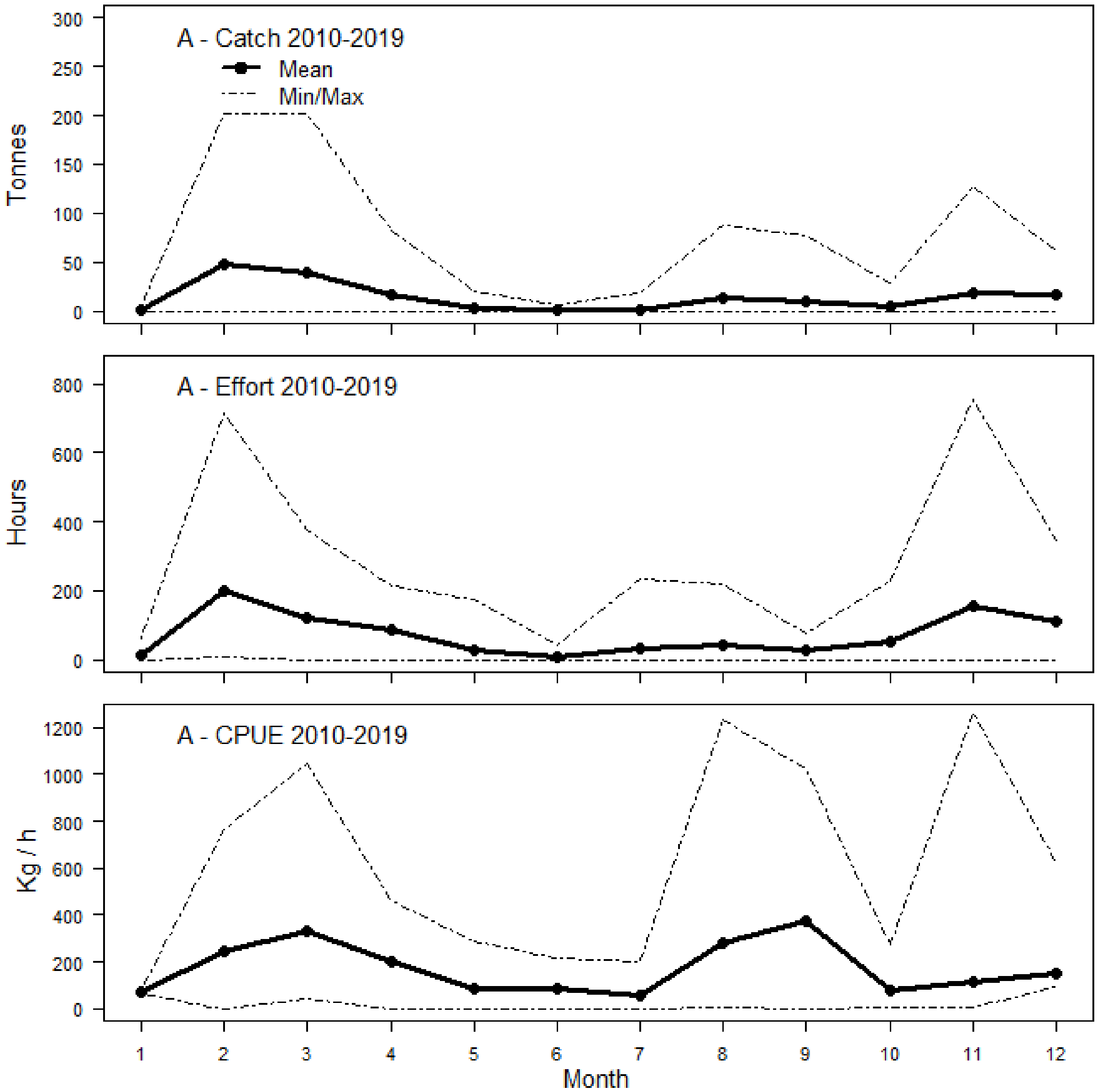
Appendix V. Mean monthly catch, effort and CPUE of the southern blue whiting stock by X–licensed vessels in Falkland Islands waters from 2010 to 2019.



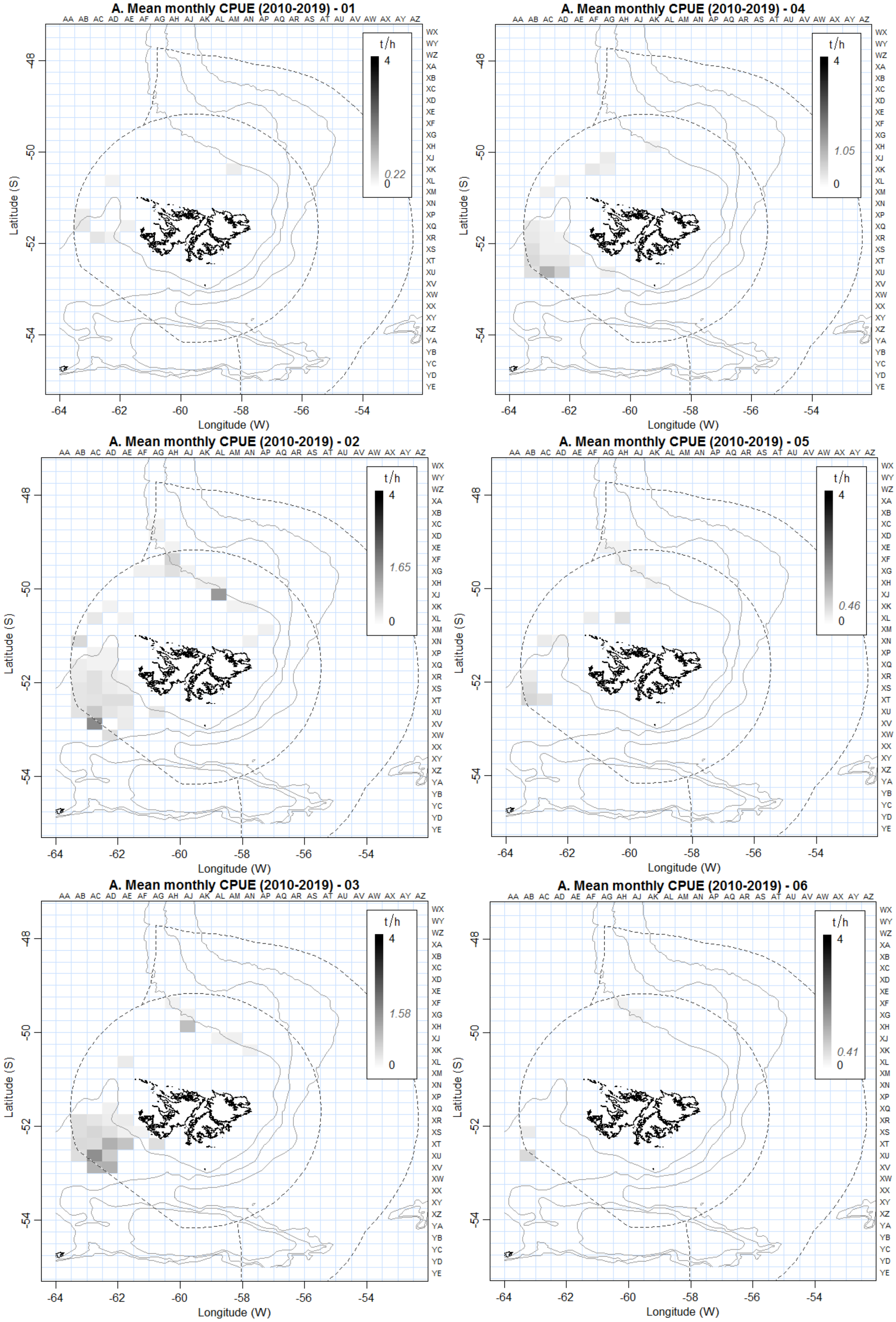
Appendix VI. Spatial distribution of mean monthly CPUE (t/h) of the southern blue whiting stock by X–licensed vessels in Falkland Islands waters from 2010 to 2019.



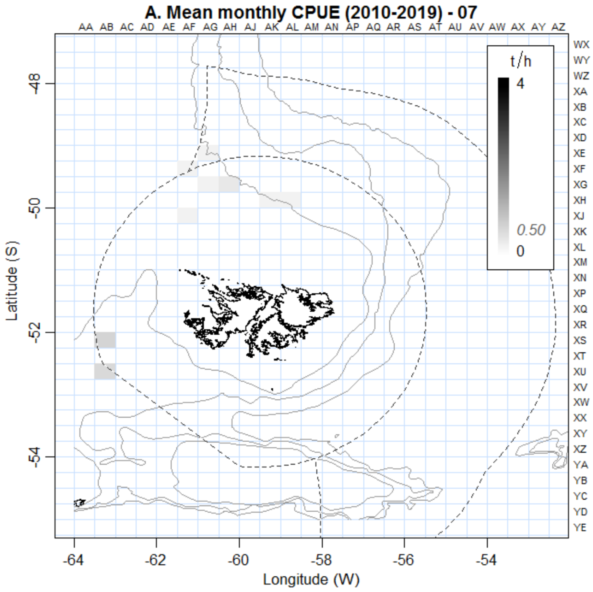
Appendix VII. Mean monthly catch, effort and CPUE of the southern blue whiting stock by A–licensed vessels in Falkland Islands waters from 2010 to 2019.

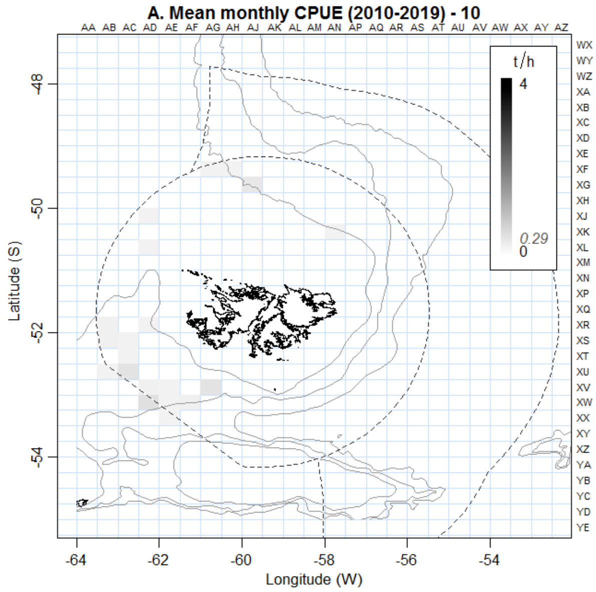


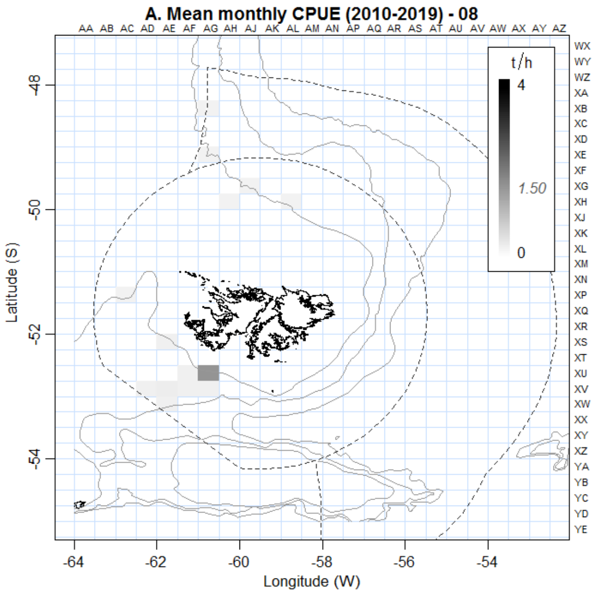
Appendix VIII. Spatial distribution of mean monthly CPUE (t/h) of the southern blue whiting stock by A–licensed vessels in Falkland Islands waters from 2010 to 2019.

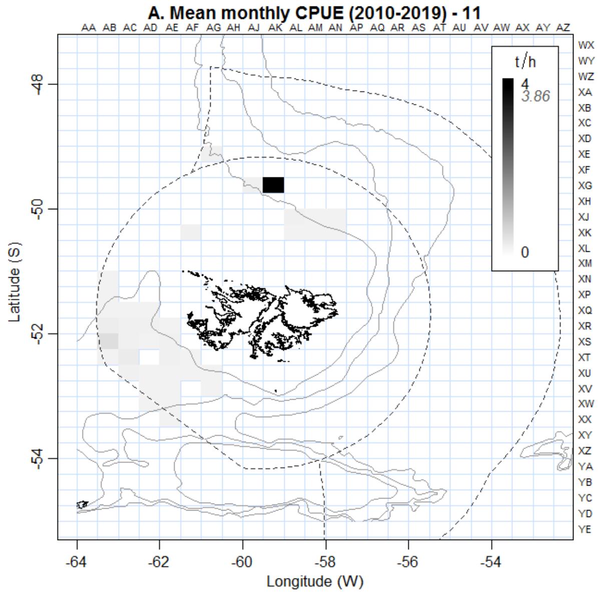


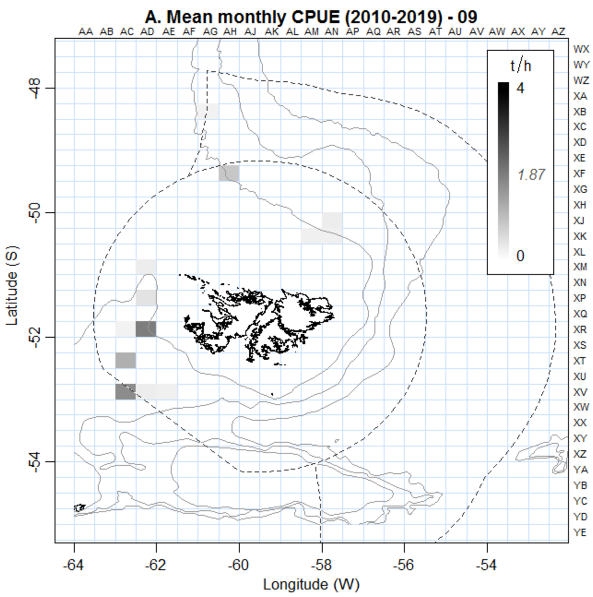
Appendix VIII. *continued*

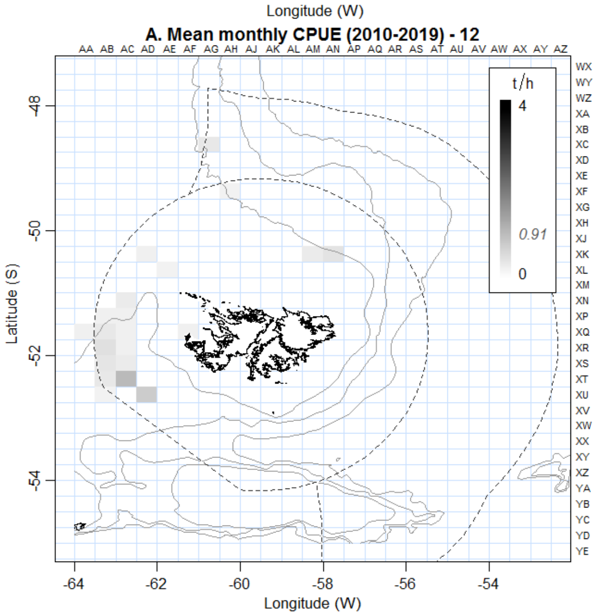




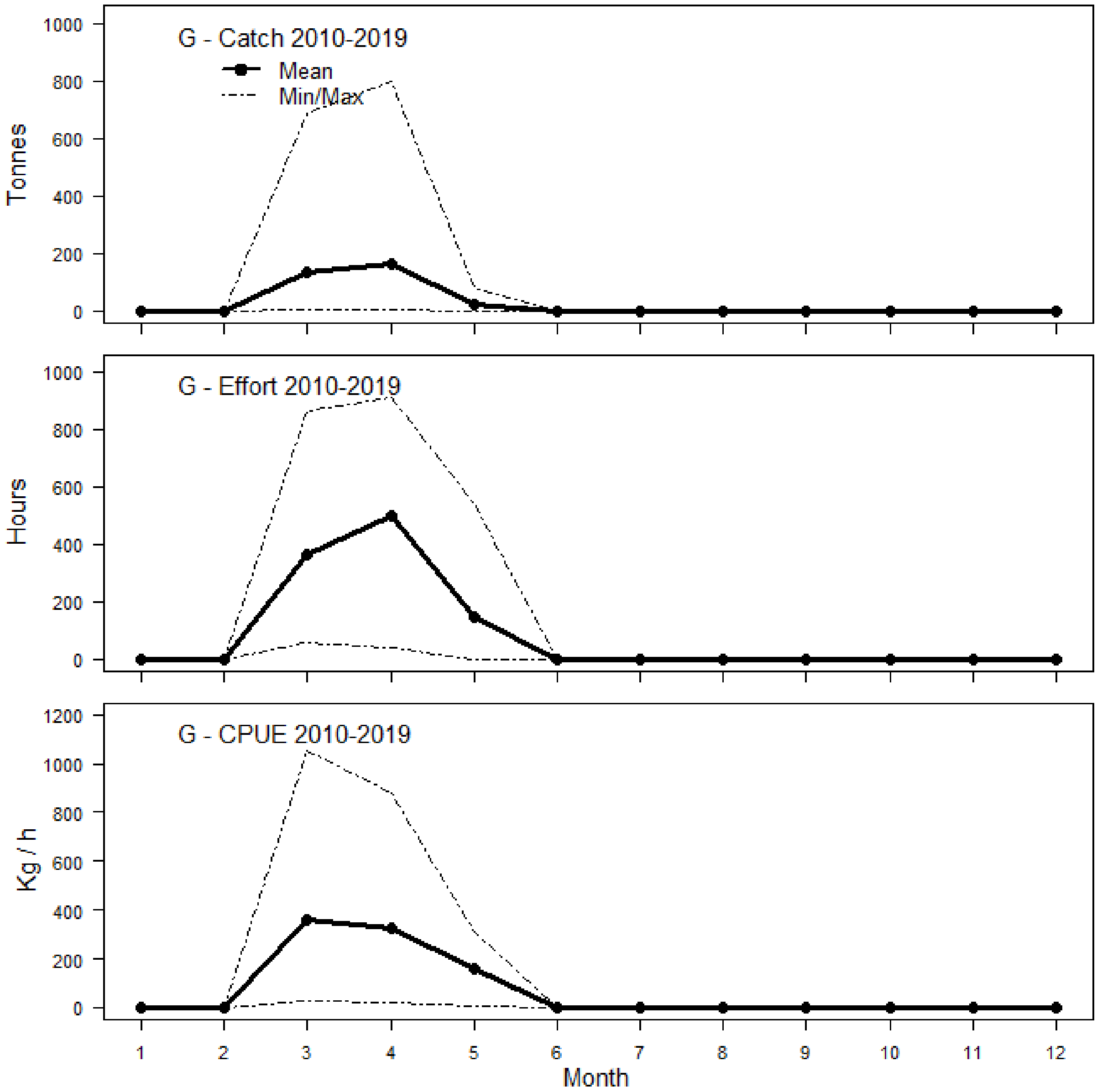




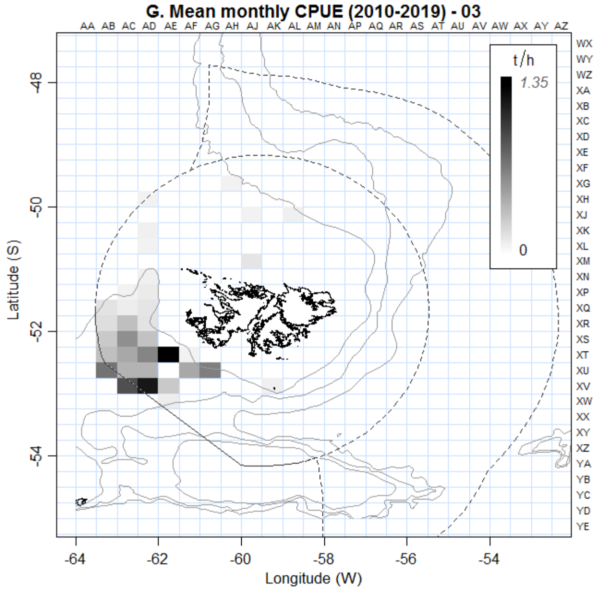


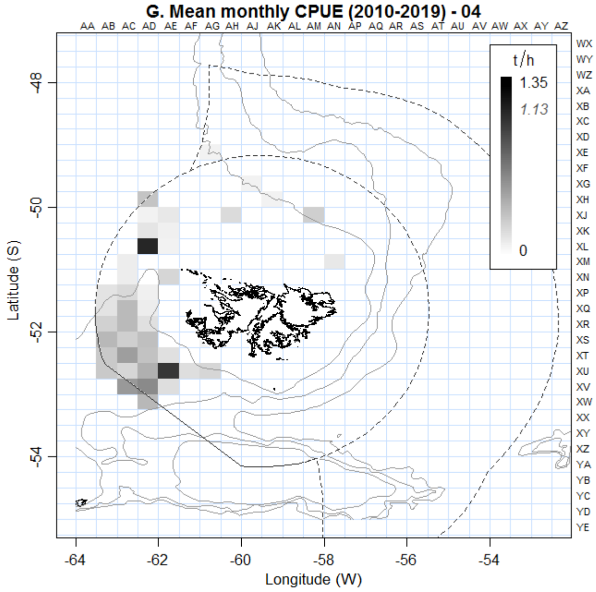


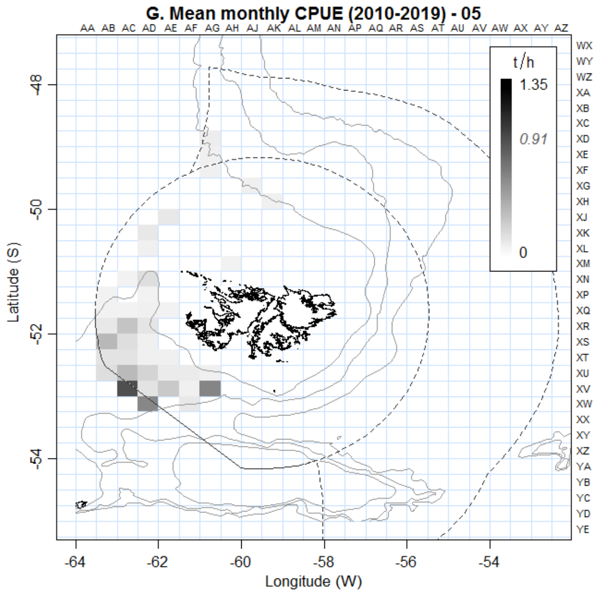
Appendix IX. Mean monthly catch, effort and CPUE of the southern blue whiting stock by G–licensed vessels in Falkland Islands waters from 2010 to 2019.



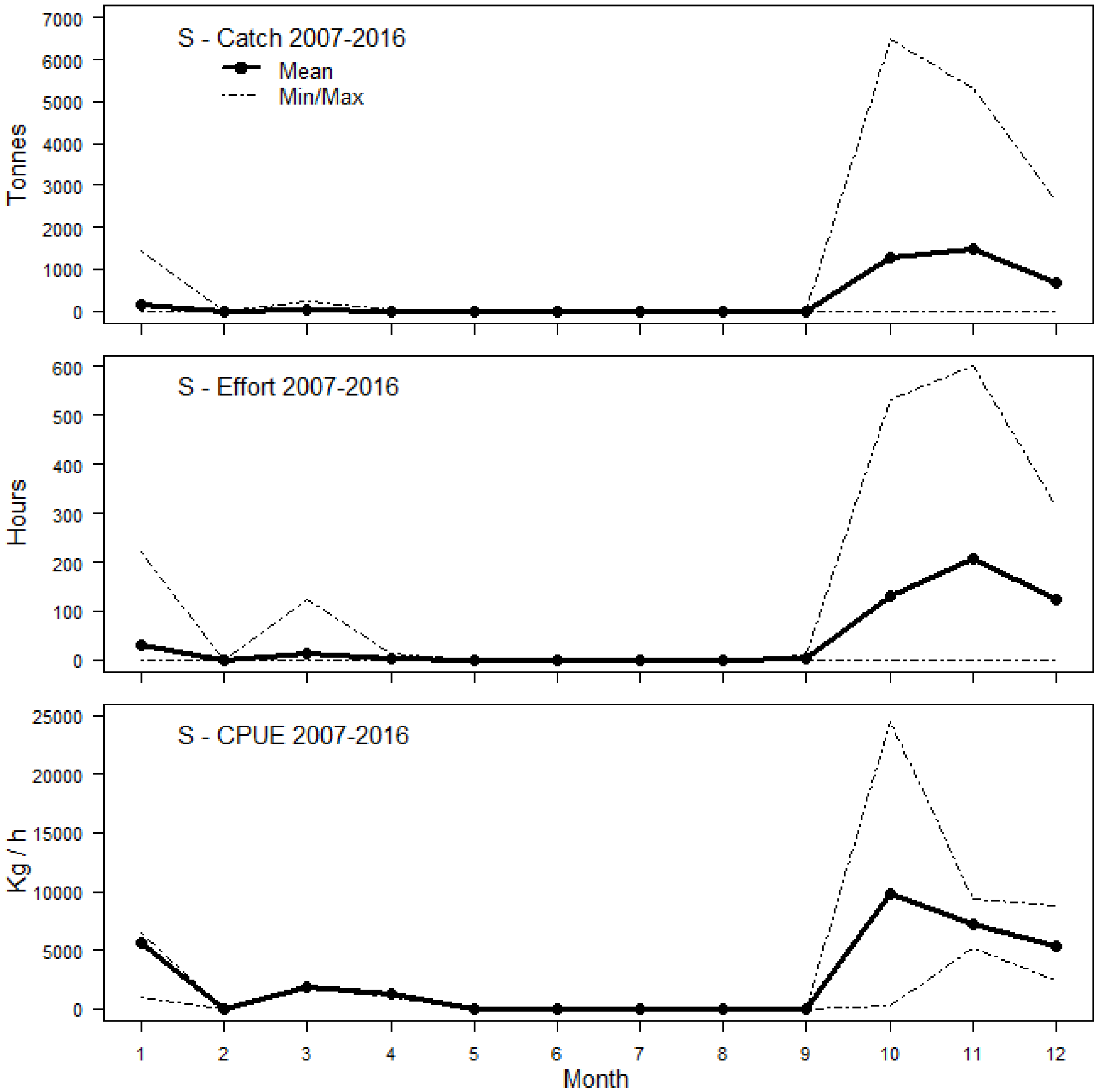
Appendix X. Spatial distribution of mean monthly CPUE (t/h) of the southern blue whiting stock by G–licensed vessels in Falkland Islands waters from 2010 to 2019.



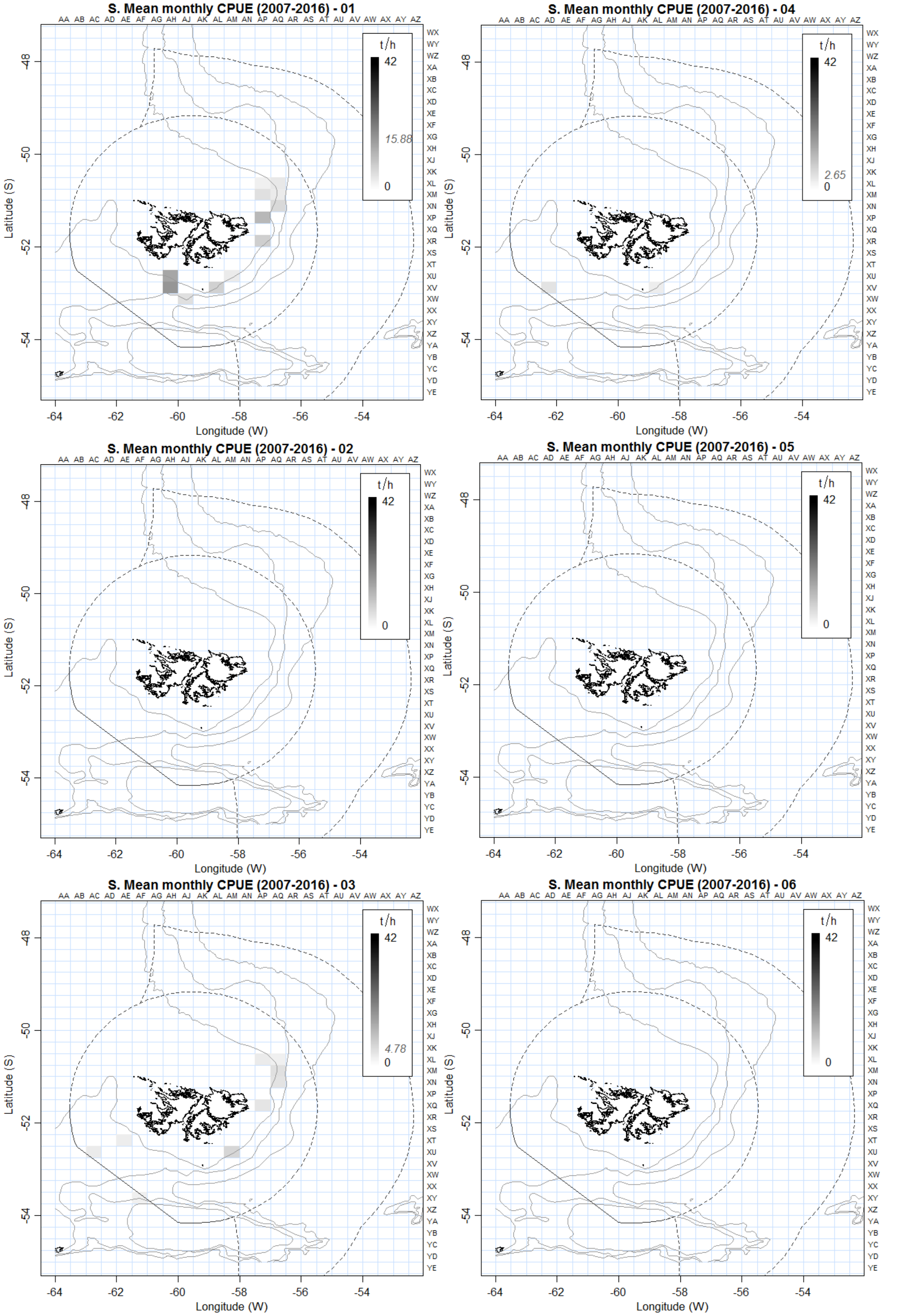




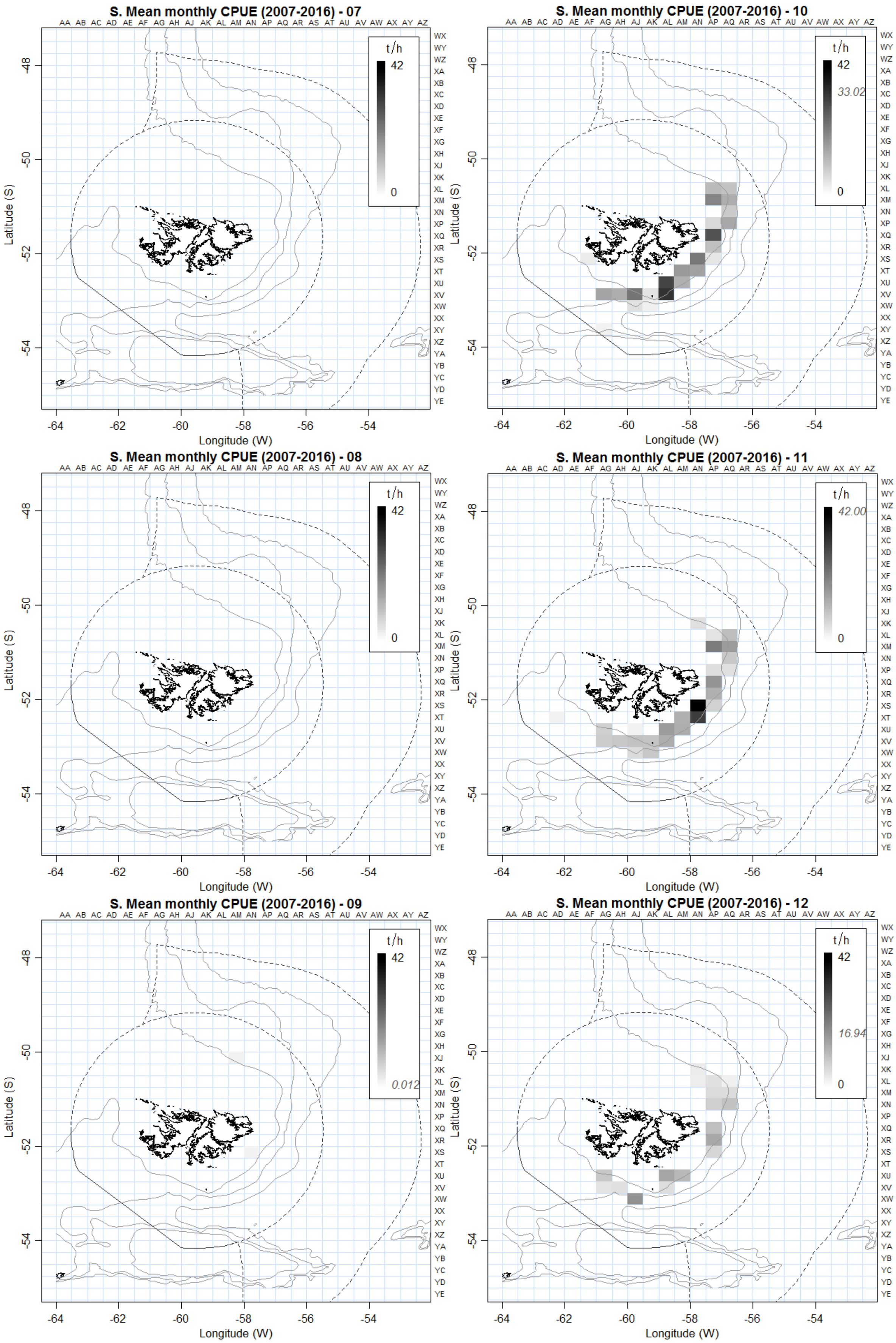
Appendix XI. Mean monthly catch, effort and CPUE of the southern blue whiting stock by S–licensed vessels in Falkland Islands waters from 2007 to 2016. S-licence was not used during 2017–2019.



Appendix XII. Spatial distribution of mean monthly CPUE (t/h) of the southern blue whiting stock by S–licensed vessels in Falkland Islands waters from 2007 to 2016. S-licence was not used during 2017–2019.



Appendix XII. *continued*



Appendix XIII. OCOM total annual biomass estimates (median) and 95% lower and upper confidence intervals (LCI and UCI, respectively) from MCMC posterior distributions for southern blue whiting. Estimates considering Falkland Islands, Argentina and Chile, with natural mortality (M) = 0.15

Year	Total biomass (MPD)	Total biomass (LCI)	Total biomass (UCI)
1987	1,267,857	677,928	1,944,171
1988	1,217,307	626,844	1,893,547
1989	1,175,398	604,016	1,843,973
1990	1,123,911	574,638	1,779,854
1991	1,048,225	524,978	1,686,455
1992	974,225	484,052	1,588,076
1993	904,025	449,042	1,489,261
1994	790,937	371,310	1,343,402
1995	734,545	351,464	1,251,380
1996	652,321	303,591	1,133,248
1997	601,577	284,182	1,047,862
1998	544,945	257,229	958,041
1999	482,467	222,222	863,109
2000	440,513	203,936	792,086
2001	403,890	189,138	729,099
2002	367,174	173,440	667,292
2003	338,817	164,799	615,824
2004	306,698	152,434	560,915
2005	255,761	121,190	489,180
2006	230,096	110,030	447,660
2007	198,541	92,011	403,083
2008	174,413	78,334	368,124
2009	153,859	65,462	338,463
2010	134,833	51,465	313,450
2011	125,114	42,462	299,175
2012	127,463	42,671	299,211
2013	130,561	43,362	300,677
2014	135,682	44,934	301,974
2015	144,131	49,409	307,355
2016	152,328	55,022	310,120
2017	160,498	61,477	313,783
2018	170,872	71,922	319,277
2019	192,973	95,004	335,643