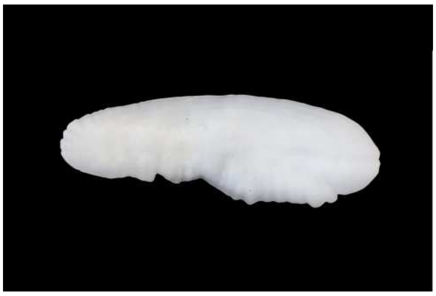
Stock assessment of hoki (*Macruronus magellanicus*) in the Falkland Islands



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Participating/Contributing Scientific Staff

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

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Summary

The Southwest Atlantic hoki stock was assessed with the optimized catch-only method (OCOM). The most conservative estimate by OCOM obtained a median MSY of 212,444 tonnes, and stock biomass in 2018 of 272,046 tonnes. The 2018 stock biomass was 12.6% of stock biomass in 1987 and 25.21% of the biomass that would provide MSY. The length-based Bayesian biomass estimation method (LBB) found that length at 50% catch (18 cm pre-anal length) was nearly 12 cm below the optimum length at catch (30 cm pre-anal length). Modal pre-anal lengths of females and males had statistically significant decreases from 2002 to 2018. Females had a statistically significant decrease in age at 50% maturity, and a non-significant declining trend in length at 50% maturity. Males had a statistically significant decrease in age and length at 50% maturity. Based on $B_{2018}/B_{MSY} = 0.2521$, it is recommended that the total catch limit of the Southwest Atlantic hoki stock should be 25.21% of MSY: 212,444 × 0.2521 = 53,557 t. In Falkland Islands waters, hoki is caught mainly from February to April under W and A licences, and from March to May under G licence, with most catches taking place in March. The recommended catch limit of hoki in Falklands waters ranged between 4,917 t and 17,851 t based on different criteria. Adjustment to catch restrictions for specific fishing licences in the Falkland Islands may aid further reductions of fishing pressure on hoki.

Introduction

Hoki *Macruronus magellanicus* (Löonberg, 1907; Merlucciidae) is a highly migratory pelagic-demersal fish that occurs in temperate shelf and slope waters of the Southeast Pacific (southern Chile) and Southwest Atlantic (Argentina and Falkland Islands) (Schuchert et al. 2010; Froese & Pauly 2019). The northern boundary of its distribution reaches 33°S in the Southwest Atlantic and 29°S in the Southeast Pacific, whereas the southern boundary extends to 57°S around Cape Horn (Wöhler & Giussi 2001). Hoki lives at 30–500 m depth and undergoes vertical migrations from pelagic to deep waters during the day and from deep to pelagic waters during the night (D'Amato & Carvahlo 2005; see Froese & Pauly 2019 and references there in). This species is one of the most abundant pelagic fish on the Patagonian shelf; however, it is not highly abundant in Falkland waters as the Falkland Island Conservation Zone is located at the edge of its distribution (Falkland Islands Government 2018).

From austral spring to autumn, *M. magellanicus* are dispersed throughout their feeding grounds on the Patagonian Shelf south of 48°S (Wöhler & Giussi 2001). Part of the stock migrates further north to spawn during winter; still a considerable proportion of adult fish skips spawning and remains on the feeding grounds during the spawning season (Rideout et al. 2005). The main spawning aggregations have been encountered in the vicinity of Guamin Island, Chile, between 43°S and 48°S (Payá et al. 2002). Smaller aggregations of spawning fish and juveniles have also been found in the Southwest Atlantic in the Gulf of San Matias and in the Gulf of San Jorge in Argentina (Wöhler & Giussi 2001), and also on the shelf edge east of the Falkland Islands (Giussi 1996). Larvae are present on either side of the Magellanic Strait (53°S), near Cape Horn (55°S), and farther north in coastal areas of the Atlantic Ocean (Niklitschek et al. 2014). After winter spawning, hoki migrates in spring to the slope areas of the Falkland Current Front (west of the Falkland Islands), where it preys upon myctophids (*Gymnoscopelus nicholsi*), amphipods (*Themisto gaudichaudii*) and squids (*Doryteuthis gahi*) (Brickle et al. 2009; Arkhipkin et al. 2012). In summer, hoki mainly occupies the warmer northern Falkland Islands' shelf (Brickle et al. 2009).

Recent studies suggest that hoki in the Southwest Atlantic and Southeast Pacific belong to the same population (McKeown et al. 2015). Connectivity between both areas appears to occur via migrations around Cape Horn and throughout the channels of Tierra del Fuego (Wöhler & Giussi 2001). Accordingly, genetic studies found that individuals from the Argentine coast, and near the west (52°S, 64°W) and southwest (54°18'S, 64°43'W) edge of the Falkland Island Conservation Zone belong to the same population (D'Amato & Carvalho 2005; D'Amato 2006). Therefore, for the purpose of this report hoki from the Falkland Islands, Argentina and Chile will be referred to as Southwest Atlantic hoki stock.

Hoki is one of the most important commercial species in Chile, where it is targeted by a bottom trawl fishery in the austral zone (43–57°S) and an industrial purse-seine fleet off central-south Chile (36–40°S) (Pino et al. 2004). In the Chilean fishery, hoki are caught at sizes between 29 and 118 cm total length (TL), and at ages up to 16 years, with fishing mortality estimated at 0.2668 for males and 0.2314 for females (Chong et al. 2007). Hoki stocks have strongly declined in Chile in recent years (Chong et al. 2007). In contrast, abundances in the South Atlantic increased during the period 1985–2001 (Wöhler et al. 2007). In Argentina, trawlers target hoki all year round in the Argentine Exclusive Economic Zone and in adjacent waters from 39°S to 56° S. Age at maturity has been estimated at 2.9–4 years old (Giussi & Wöhler 2001) and size at maturity at 56 cm total length (Gorini & Pájaro 2014). Fishing mortality in the Argentine hoki fishery was 0.31 in the year 2000; however, from 2001 and through 2009 it oscillated between 0.11 and 0.18 (CeDePesca 2010). In Falkland waters, hoki is targeted mainly by trawlers during spring, summer and autumn in deep waters to the Southwest (Falkland Islands Government 2018), with the main commercial catch at 100 and 200 m depth (Brickle et al. 2009). Currently, there is a no-fishing area for S-licensed pelagic trawlers 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 this species during 2017 and 2018 under S licence. The mean annual contribution of hoki to the Falkland Islands trawl fishery is approximately 9% by catch weight from 1987 to 2018 (Falkland Islands Government 2018).

Given that the Southwest Atlantic hoki stock is targeted by different inter-boundary fisheries, these must be accounted for stock assessment. Restricted access to catch and effort data 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 hoki resource, 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 Southwest Atlantic hoki stock 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 hoki in Chilean waters during 2018 was provided by Instituto del Fomento Pesquero (IFOP) on request given that the data were 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 three fisheries that share the Southwest Atlantic hoki stock.

Temporal and spatial patterns of hoki 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 Southwest Atlantic hoki stock.

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^2_r) = $\sigma^2_M + \sigma^2_e$. Measurement error in M (σ^2_M) = 0.23 and the process error in the relationship between M and F_{MSY} (σ^2_e) = 0.0012; hence, uncertainty of r (σ^2_r) = 0.2312 (Zhou et al. 2018).

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

$$M1 = 4.118 \cdot k^{0.73} \cdot L_{\infty}^{-0.33}$$

$$M2 = 1.82 \cdot k$$

$$M3 = \frac{4.3}{t_{max}}$$

where t_{max} = maximum age, L_{∞} = asymptotic pre-anal length, and k = rate by which L_{∞} is approached.

Maximum age was taken from the FIFD age-length database, and L_{∞} and k were taken from the von Bertalanffy equation used to examine the age-length relationship. 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

Pre-anal length (hereafter referred as 'length') and age data were collected on board commercial vessels that carried out bottom trawls (A, G and W licences) during spring (October, November, December), summer (January, February, March), and autumn (April, May, June) in Falkland Islands waters. Length data were taken from random samples, whereas age data were taken from random and non-random samples. Winter (July, August, September) data were excluded given that part of the hoki population emigrates from

Falkland waters during that season (Rideout et al. 2005; Arkhipkin et al. 2012), which may bias the length and age frequencies.

Length was measured to the nearest centimetre. The deposition of growth rings in otoliths was examined to determine the age of 4,059 individuals (2,370 females and 1,689 males). A total of 3,876 otoliths (2,283 females and 1,593 males) were processed at the Sea Fisheries Institute in Gdynia (Poland), 72 otoliths (42 females and 30 males) were processed in the Falkland Islands Fisheries Department (FIFD), and the source of age measurement of 111 otoliths (45 females and 66 males) was unknown.

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 length at 50% maturity from 2002 to 2018, and age at 50% maturity from 2001 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) during spring, summer and autumn, including licences variances during October. 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. Hoki length data from commercial vessels collected from 2000 to 2016 were suitable for the LBB analysis (length frequencies from 2010, 2017 and 2018 did not show the distribution required for LBB and were excluded); therefore, $B_{current} = B_{2016}$ and $B_0 = B_{2000}$. Length data from research cruises (i.e. E licence) conducted every February in 2010–2011, and 2015–2018 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 (Musick 1999). Monte Carlo simulations were used to select viable pairs of maximum intrinsic rate of population increase (r) and unexploited population size (carrying capacity: K) from parameter ranges that are plausible in relation to the depletion level shown by the catch time series. A prior range for r (0.28; 0.16 – 0.48 95% CI) was taken from Fishbase (Froese & Pauly 2019; https://www.fishbase.se/summary/Macruronus-magellanicus.html) corresponding to low resilience. A prior for depletion level was identified based on $B_{current}/B_0$ estimated with OCOM and LBB.

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.

Pairs of r-K were visualized in a scatterplot where CMSY searched for the most probable r. 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 area distribution of commercial and research hoki data from the Falkland Islands used for this stock assessment is indicated in Fig. 1.

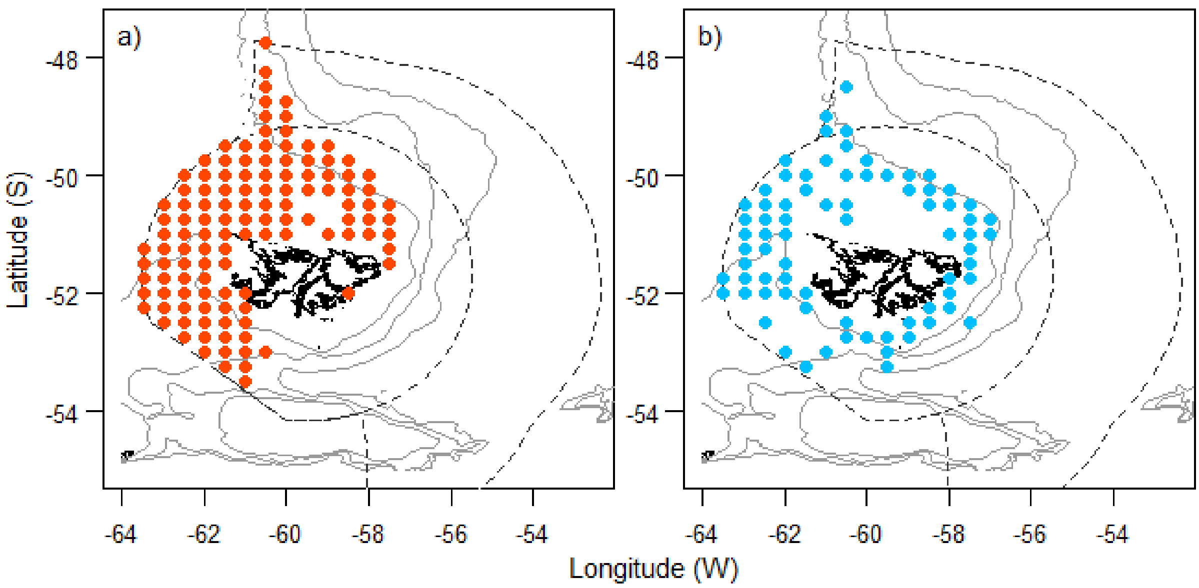

Fig. 1. Distribution of hoki catch and sampling data by a) commercial trawlers under A, G and W licences in red, and b) February research surveys under E licence in blue within the Falkland Islands Conservation Zones (FICZ and FOCZ). Dots indicate the mid-point of each grid square and represent catches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

Catch limits

Alternative catch limits for hoki in Falklands waters were examined based on average catch and on relative average contribution (%) by the Falkland Islands, Argentina and Chile over different periods of time (i.e. 10-, 5-, and 3-year average), and on equal share of the total catch of the Southwest Atlantic stock, i.e. 33.33%.

Results

Commercial catch

Catches of hoki in the Falkland Islands have averaged 15,340 t per year since 1987; catches had an increasing trend from 1987 to reach a maximum of 26,970 t in 2002, followed by a gradual decline to 4,438 t in 2018. Average annual catch was 13,262 t over the last ten years, whereas it was relatively low over the last 5 years (6,858 t). The Falkland Islands have the smallest annual contribution (10.7 ± 3.1%) to the total production of the Southwest Atlantic hoki stock over the last 10 years. Argentina and Chile contribute 49.8 ± 6.4% and 39.5 ± 4.7% of the catch, respectively. The annual mean catch in Argentina over the period 1987–2018 was 62,103 t, with a maximum of 124,638 t in 2006. Mean annual catch in Argentina was 58,338 t over the last 10 years, and 40,668 t over the last 5 years. Mean annual catch in Chile over the period 1987–2018 was 120,918 t; however, annual catch in Chile decreased considerably to a mean of 47,552 t over the last 10 years, and to a mean of 28,566 t over the last 5 years. The maximum catch in Chile in the time series was 375,446 t in 1996 followed by a declining trend to reach a minimum of 17,054 t in 2018 (Fig. 2; Appendix I). Annual hoki catches from Falkland Islands and Argentina had a significant positive correlation ($r = 0.68$, $n = 32$, $p < 0.001$), whereas Chilean and Falkland Islands catches were not significantly correlated ($r = 0.18$, $n = 32$, $p = 0.33$; Appendix II).

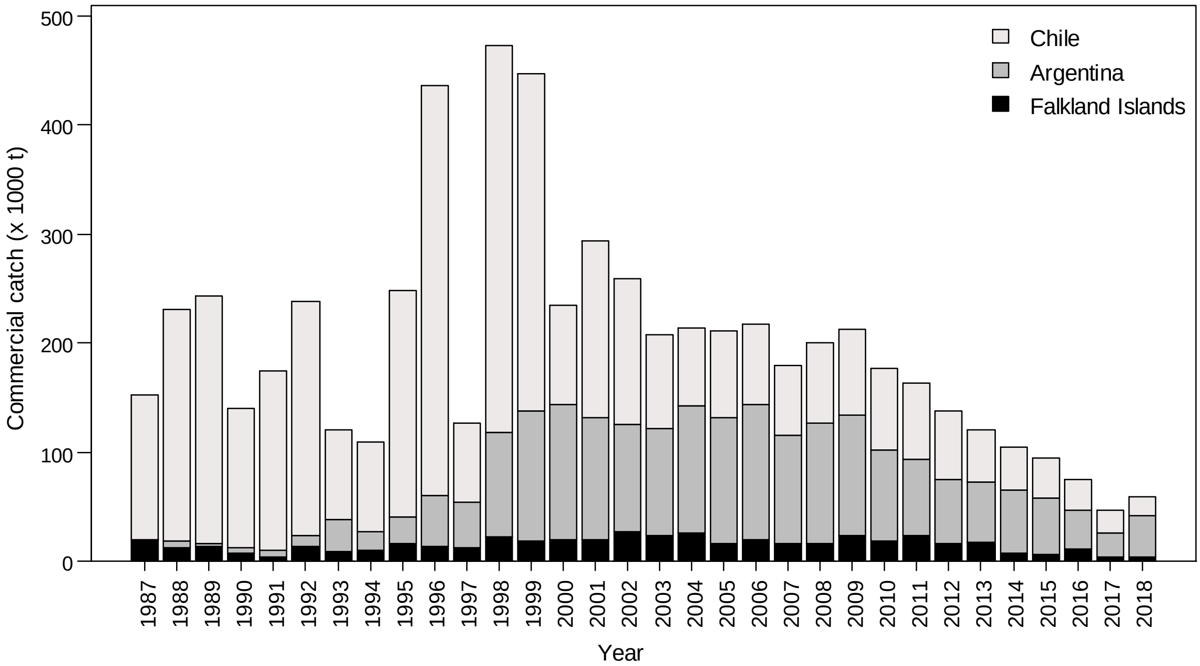

Fig. 2. Commercial total catch of the Southwest Atlantic hoki stock from 1987 to 2018. Catch data from Chile for the year 2018 are preliminary (R. Céspedes, IFOP, *pers. comm.*).

In 2018, approximately 53% of hoki catch in the Falkland Islands was under W licence. G-licensed vessels contributed 40% of the catch of hoki, whereas A-licensed vessels had a minor contribution (5%). The average over the period 2008 – 2018 had a similar pattern; W-licensed vessels contributed 39%, G-licensed vessels contributed 35%, and A-licensed vessels contributed 17% of the hoki catch (Table I). Hoki is caught mainly from February to April under W and A licences, and from March to May under G licence, with most of the catches occurring in March (Appendixes III–V). From February to April, most of the catch of hoki under W and A licences took place to the Southwest of the Falkland Islands. Catches were also observed to the north of West Falkland under W licences during those months. From March to May, catches under G licence were observed to the southwest of West Falkland, although a few grid squares with considerable catches were also detected to the north during April (Appendixes VI–VIII).

Table I. Catch of hoki 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	234	5.26	2,596	17.48
B	1	0.01	23	0.15
C	0	0.00	76	0.51
E	31	0.70	103	0.69
F	4	0.09	219	1.47
G	1,779	40.08	5,159	34.74
L	0	0.00	0	0.00
O	0	0.00	0	0.00
R	0	0.00	40	0.27
S	0	0.00	716	4.82
W	2,364	53.26	5,752	38.73
X	26	0.59	126	0.85
Y	0	0.00	0	0.00
Z	0	0.00	43	0.29
Total	4,439	100.00	14,852	100.00

Age-length relationship

The age-length relationship of females and males pooled gave the following values: L_∞ = 48.5 cm, k = 0.125, and t_0 = -2.08 years (Fig. 3a). Length and age of females ranged from 13 to 46 cm, and from 1 to 16 years respectively. The age-length relationship of females gave the following values: L_∞ = 51 cm, k = 0.119, and t_0 = -2.05 years (Fig. 3b). Length and age of males ranged from 12 to 43 cm and from 1 to 15 years, respectively. The age-length relationship of males gave the following values: L_∞ = 42.7 cm, k = 0.15, and t_0 = -2.0 years for males (Fig. 3c).

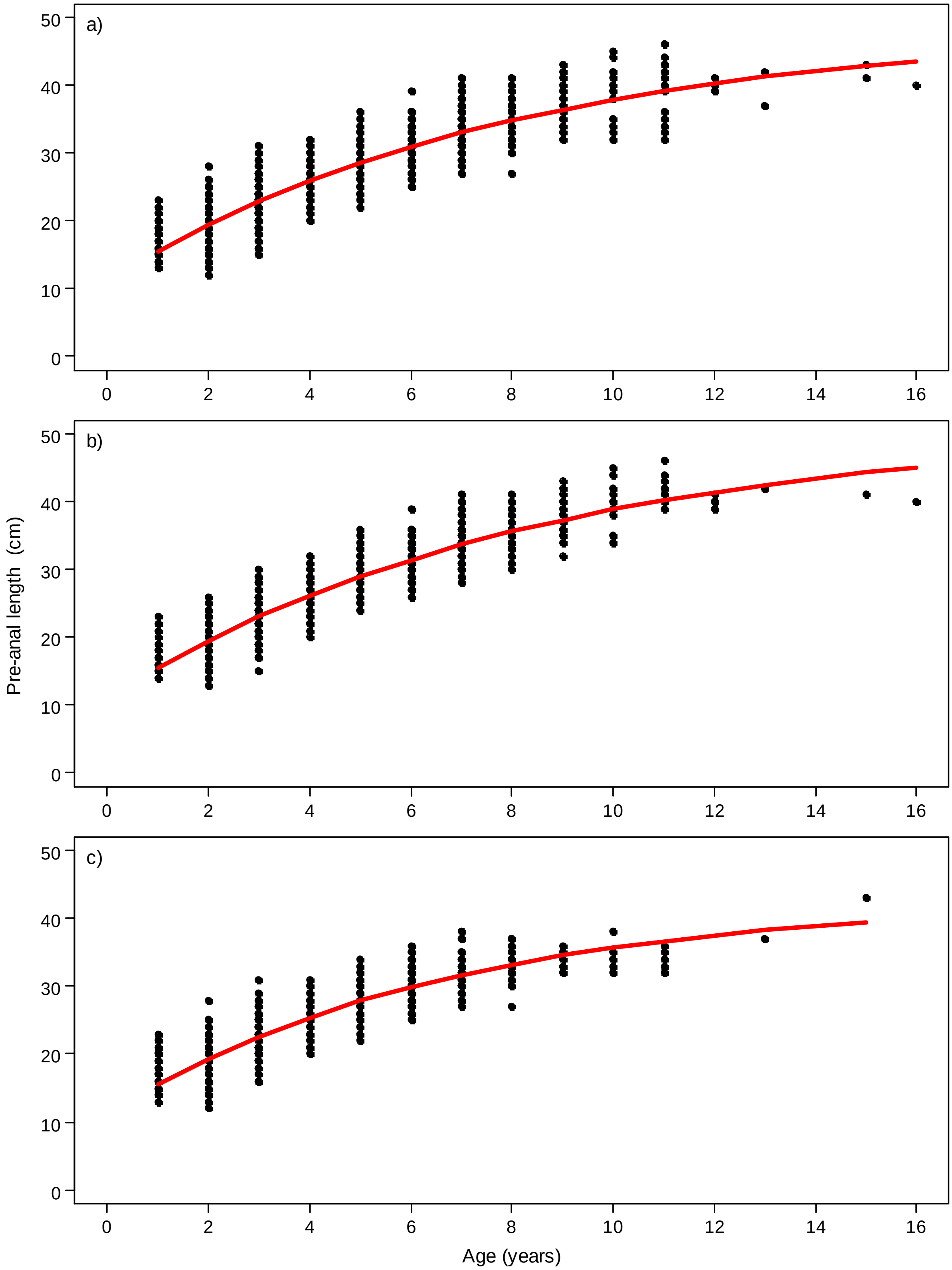

Fig. 3. von Bertalanffy age-length relationship of hoki from the Falkland Islands. a) Females and males pooled; b) females; c) males.

The range of female modal lengths was 16–30 cm during the period 2002–2018. Modal lengths significantly decreased at a rate of 4.6 mm per year ($p = 0.018$) from 2008 to 2018. Modal length had an overall decreasing trend with some cyclicality when length increased over a few consecutive years (e.g. 2004–2006) 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 IX). The range of male modal lengths was 16–28 cm during the period 2002–2018. Modal lengths significantly decreased at a rate of 3.6 mm per year ($p = 0.015$) from 2002 to 2018. Modal length again had an overall decreasing trend despite cohort cyclicality (e.g. 2004–2007, 2010–2013, and 2014–2016) (Fig. 4b; see length frequencies per year in Appendix X).

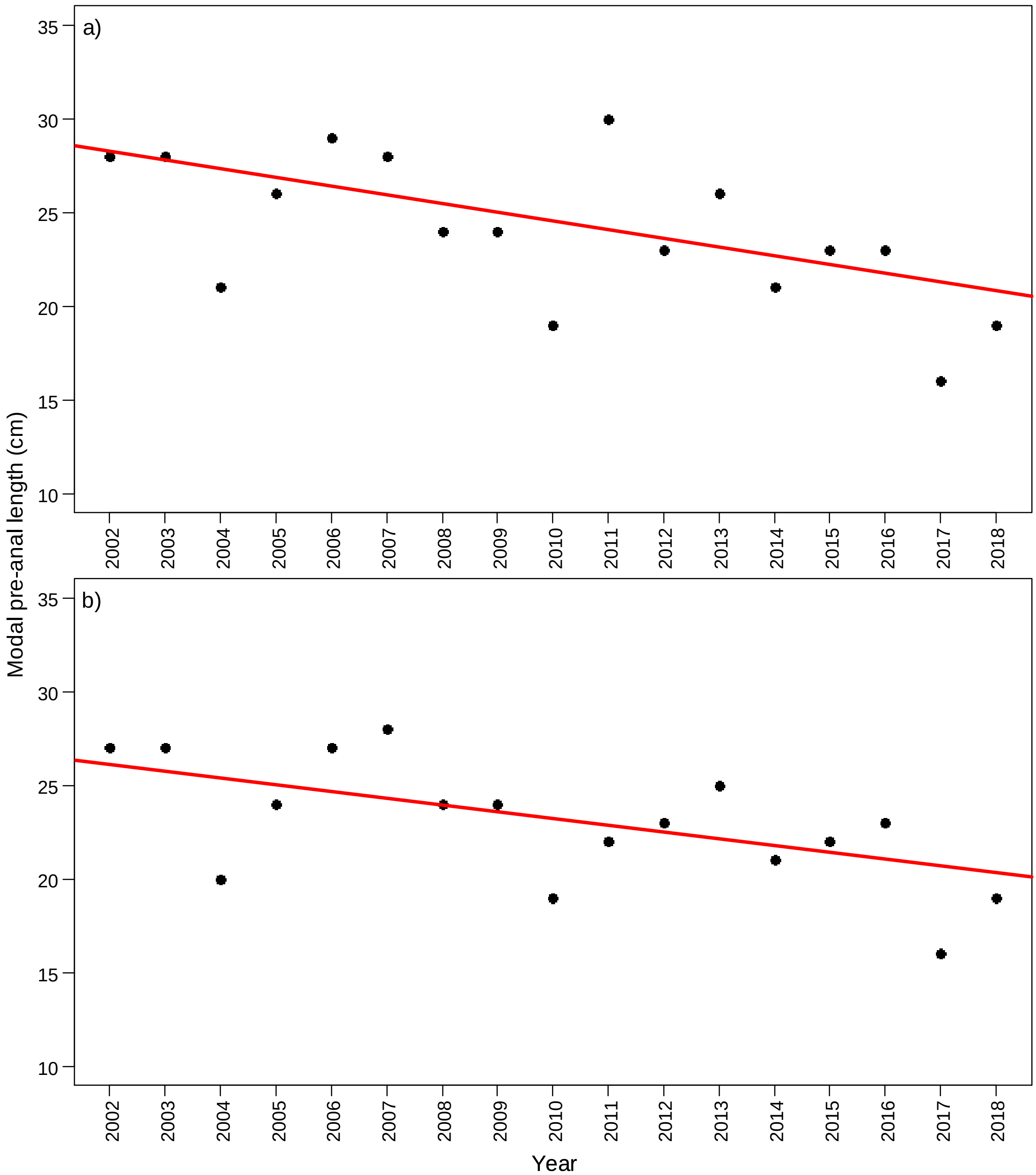

Fig. 4. Annual modes of hoki a) female and b) male pre-anal length in the Falkland Islands. Linear regression of modes vs. year (red line; regression weighted by the inverse RMSD of each year's LOESS function).

Age and length at maturity

Mean age at 50% maturity of females and males pooled was estimated at 2.9 years from 2001 to 2018. In females, a significant declining trend ($p = 0.025$) in annual average age at 50% maturity occurred at a rate of 0.06 years per year from 2002 to 2018 (Fig. 5a), with mean age at 50% maturity estimated at 2.8 years. In males, a statistically significant decline (p = 0.038) in annual average age at 50% maturity occurred at a rate of 0.05 years per year from 2001 to 2018 (Fig. 5b), with mean age at 50% maturity estimated at 3.0 years. Annual age at 50% maturity curves per year can be consulted in Appendixes XI–XII.

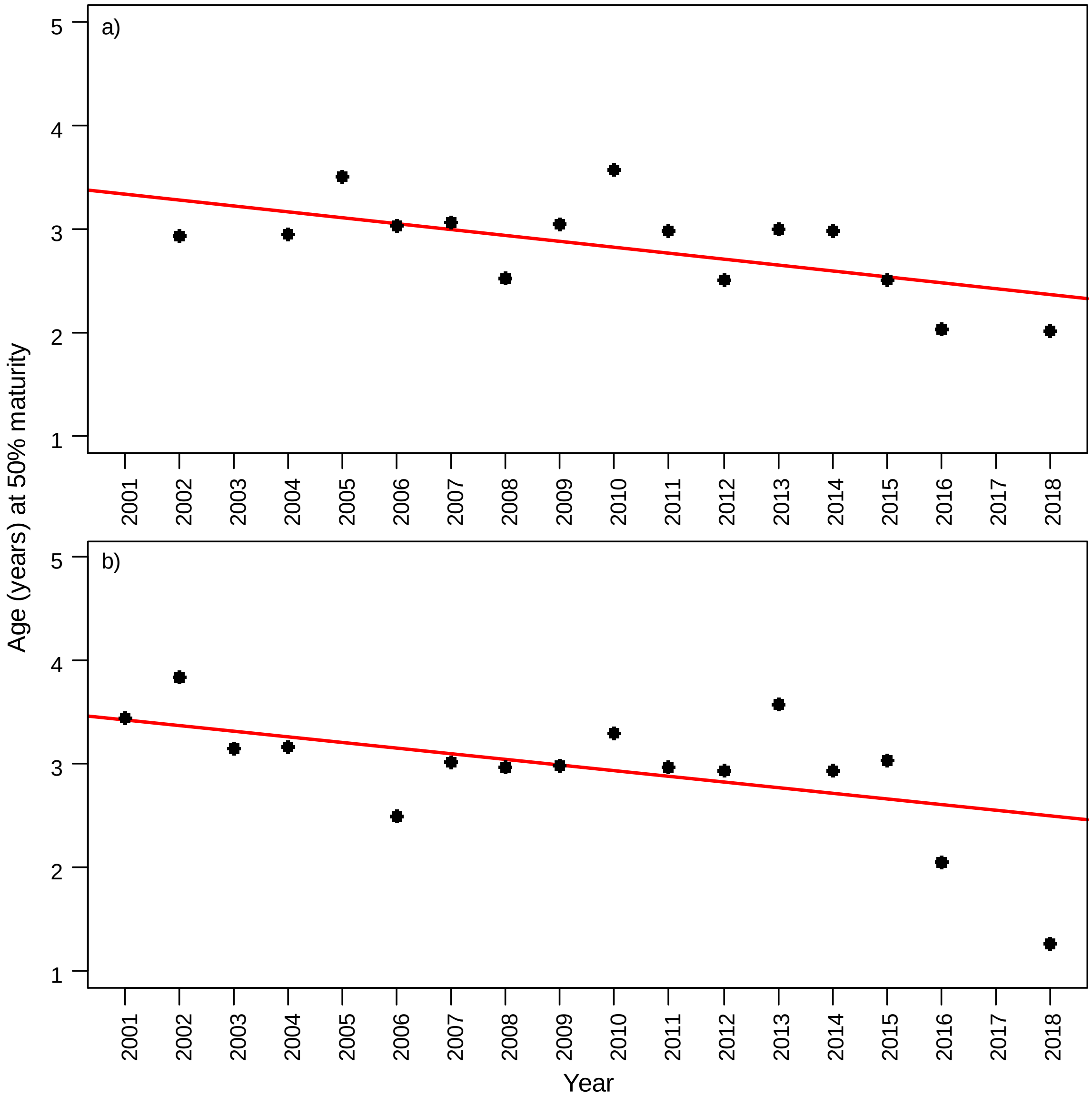

Fig. 5. Linear regression of age at 50% maturity of a) female and b) male hoki vs. year (regression weighted by the R^2 of each year's logistic function).

Mean length at 50% maturity of females and males pooled was estimated at 21.8 cm pre-anal length from 2002 to 2018. In females, a non-significant trend (p = 0.148) in annual average length at 50% maturity was observed (Fig. 6a), with mean length at 50% maturity estimated at 20.9 cm pre-anal length. In males, a statistically significant decline (p = 0.003) in annual average length at 50% maturity was observed at a rate of 2.0 mm per year from 2002 to 2018 (Fig. 6b), with mean length at 50% maturity estimated at 22.1 cm pre-anal length. Annual length at 50% maturity curves per year can be consulted in Appendixes XIII–XIV.

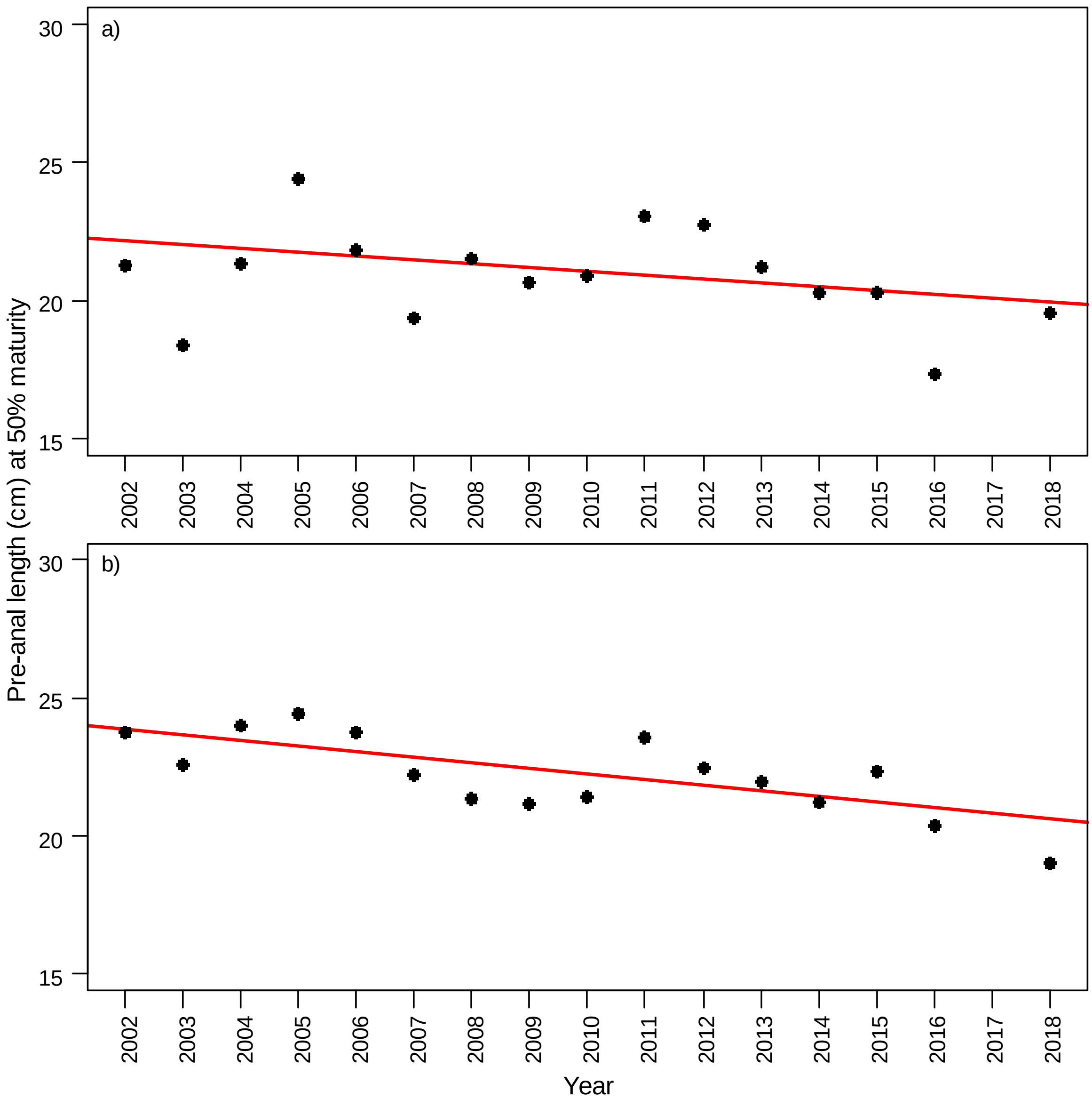

Fig. 6. Linear regression of length at 50% maturity of a) female and b) male hoki vs. year (regression weighted by the R^2 of each year's logistic function).

Biomass estimation

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

$$M1 = 4.118 \cdot k^{0.73} \cdot L_{\infty}^{-0.33} = 0.2507$$

$$M2 = 1.82 \cdot k = 0.2275$$

$$M3 = \frac{4.3}{t_{max}} = 0.2687$$

where t_{max} = 16 years; k = 0.125 cm · year^{-1}; L∞ = 48.5 cm.

Lengths of 92,178 individuals caught in commercial vessels were used for the LBB calculations. The biomass of hoki throughout the time series was below the biomass that can produce MSY, at B/B_0 = 0.084, and the ratio of observed biomass to the biomass that would provide maximum sustainable yield (B/B_{MSY}) was estimated in 0.23 (0.18 – 0.29; 95% CI). The biomass estimated for 2016 relative to the biomass estimated for 2002 (B_{2016}/B_{2002}) was 0.1272 ± 0.0170 SD (Table II; Appendix XV).

Table II. Summary of LBB parameters for hoki caught in Falkland waters from commercial length data, 2002 to 2016 except 2010. Lc50 = length at 50% 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; Lc = length at first 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.

LBB outputs across years			
Parameter	Output	Parameter	Output
Lc50	18.3 (18.0 – 18.7)	L95th	39.3
Lc/L_∞	0.37 (0.37 – 0.38)	$L95th/L_\infty$	0.8
Lc95	25.1	F/M	3.5 (3.0 – 4.2)
alpha	0.431 (0.414 – 0.443)	F/K	5.0 (4.6 – 5.6)
Lmean/Lopt	0.71	B/B_0	0.084 (0.066 – 0.110)
Lc/Lc_{opt}	0.61	B/B_{MSY}	0.23 (0.18 – 0.29)
LBB outputs for 2016			
Parameter	Output	Parameter	Output
L_∞	48.52 (47.52 – 49.33)	F/M	2.11 (1.81 – 2.62)
Lc	16.78 (16.61 – 17.01)	F/K	3.11 (2.82 – 3.49)
Lmean	23.84	B/B_0	0.1272 (0.1000 – 0.1600)

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

$$r1 \sim \exp(\text{norm}(\log(\mu_r), \sigma_r)) = \exp(\text{norm}(\log(2 \cdot 0.87 \cdot 0.2507), \text{sqrt}(0.2312)))$$

$$r2 \sim \exp(\text{norm}(\log(\mu_r), \sigma_r)) = \exp(\text{norm}(\log(2 \cdot 0.87 \cdot 0.2275), \text{sqrt}(0.2312)))$$

$$r3 \sim \exp(\text{norm}(\log(\mu_r), \sigma_r)) = \exp(\text{norm}(\log(2 \cdot 0.87 \cdot 0.2687), \text{sqrt}(0.2312)))$$

The prior distribution for stock saturation S was calculated in R Studio (RStudio Team 2016) based on B_{2016}/B_0 estimated with LBB:

$$S \sim \text{norm}(\mu_{B/B0}, \sigma_{B/B0}) = \text{norm}(0.1272, 0.0170)$$

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 = 0.2275) produced the lowest estimate of median MSY and therefore were selected over other OCOM estimates. Median intrinsic growth rate was estimated at 0.3937, equivalent to a potential 48% increase of the population per year by implementing $e^{0.3937} - 1$. Carrying capacity was 2,158,399 t (1,104,758 – 3,764,644 t; 95% CI). The biomass of hoki in 2018 was estimated at 272,046 t (132,140 – 517,214 t; 95% CI) and the MSY was estimated at 212,444 t (142,679 – 277,624 t; 95% CI). Accordingly, a continuous decrease in biomass was estimated from 1987 (2,158,251 t) to 2018 (272,046 t; Fig. 7), with the biomass of 2018 comprising 12.6% of the biomass in 1987 (B_{2018}/B_{1987} = 0.1260).

Table III. OCOM Graham-Schaefer production model parameters and estimates of biomass and MSY for the Southwest Atlantic hoki 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.

OCOM					
M	r	K	B_{1987}	B_{2018}	MSY
0.2507	0. 4386	2,004,445	2,004,759	255,114	219,830
	(0. 1711 – 1.1292)	(1,015,285 – 3,548,948)	(1,034,355 – 3,548,843)	(125,289 – 490,417)	(151,739 – 286,443)
0.2275	**0.3937**	**2,158,399**	**2,158,251**	**272,046**	**212,444**
	(0.1516 – 1.0052)	**(1,104,758 – 3,764,644)**	**(1,105,620 – 3,764,716)**	**(132,140 – 517,214)**	**(142,679 – 277,624)**
0.2687	0. 4671	1,919,137	1,918,590	243,863	224,087
	(0. 1807 – 1.2086)	(967,833 – 3,452,747)	(1,006,285 – 3,452,515)	(120,238 – 497,971)	(155,845 – 291,685)

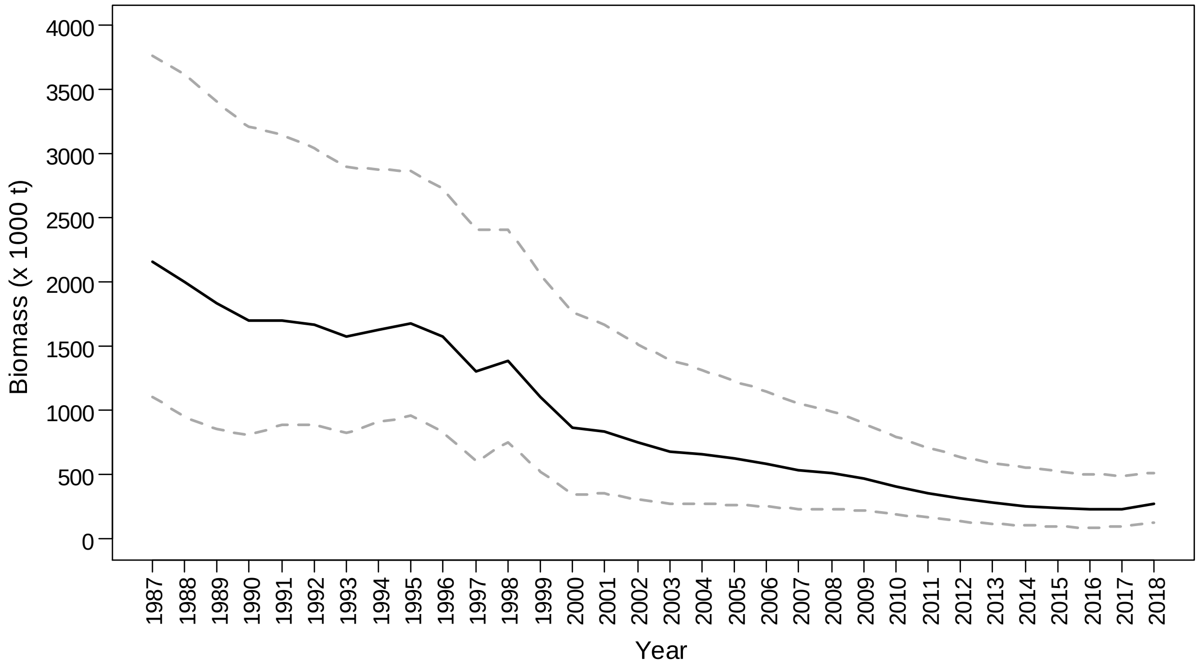

Fig. 7. Median and 95% confidence intervals of the Southwest Atlantic hoki stock annual biomass from 1987 to 2018 estimated from the OCOM Graham-Schaefer production model. The parameters were M = 0.2275; F_{MSY} = 0.87; r (σ_r^2) = 0.2312; $\mu_{B/B0}$ = 0.1272; and $\sigma_{B/B0}$ = 0.0170.

For CMSY analysis, the 'low' resilience of hoki corresponds to a prior r range of 0.05 – 0.50 (Froese et al. 2017). The depletion levels estimated by OCOM: B_{2018}/B_{1987} = 0.1260, and LBB: B_{2016}/B_{2002} = 0.1272 overlap both 'very strong' (0.01 – 0.20) and 'strong' (0.01 – 0.40) depletion prior ranges (Froese et al. 2019). Therefore, both prior depletion ranges were examined with CMSY (Table IV). The CMSY analysis suggests that hoki was caught below MSY from 1987 to 2018 (Fig. 8a). However, biomass declined gradually from the late 1990s to 2018 (Fig. 8b). Exploitation levels (F/F_{MSY}) had a variable but overall increasing trend (Fig. 8c). The hoki stock 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 hoki stock based shared commercial catch data from 1987 to 2018, calculated with either 'very strong' or '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	
Parameter	Very strong depletion	Strong depletion
r	0.239	0.278
	(0.119 – 0.483)	(0.162 – 0.478)
K	15,281,000	7,485,000
	(5,829,000 – 40,065,000)	(2,009,000 – 27,896,000)
F_{MSY}	0.0517	0.063
	(0.0256 – 0.1040)	(0.037 – 0.108)
B_{MSY}	7,641,000	3,743,000
	(2,914,000 – 20,033,000)	(1,004,000 – 13,948,000)
B_{2018}	1,652,000	848,000
	(205,000 – 4,479,000)	(93,500 – 2,182,000)
MSY	914,000	520,000
	(364,000 – 2,296,000)	(114,000 – 2,372,000)
B/B_{MSY} (2018)	0.216	0.227
	(0.027 – 0.586)	(0.025 – 0.583)
F_{2018}	0.0358	0.0697
	(0.013 – 0.289)	(0.0271 – 0.6320)
F/F_{MSY}	0.691	1.11
	(0.255 – 5.580)	(0.43 – 10.00)

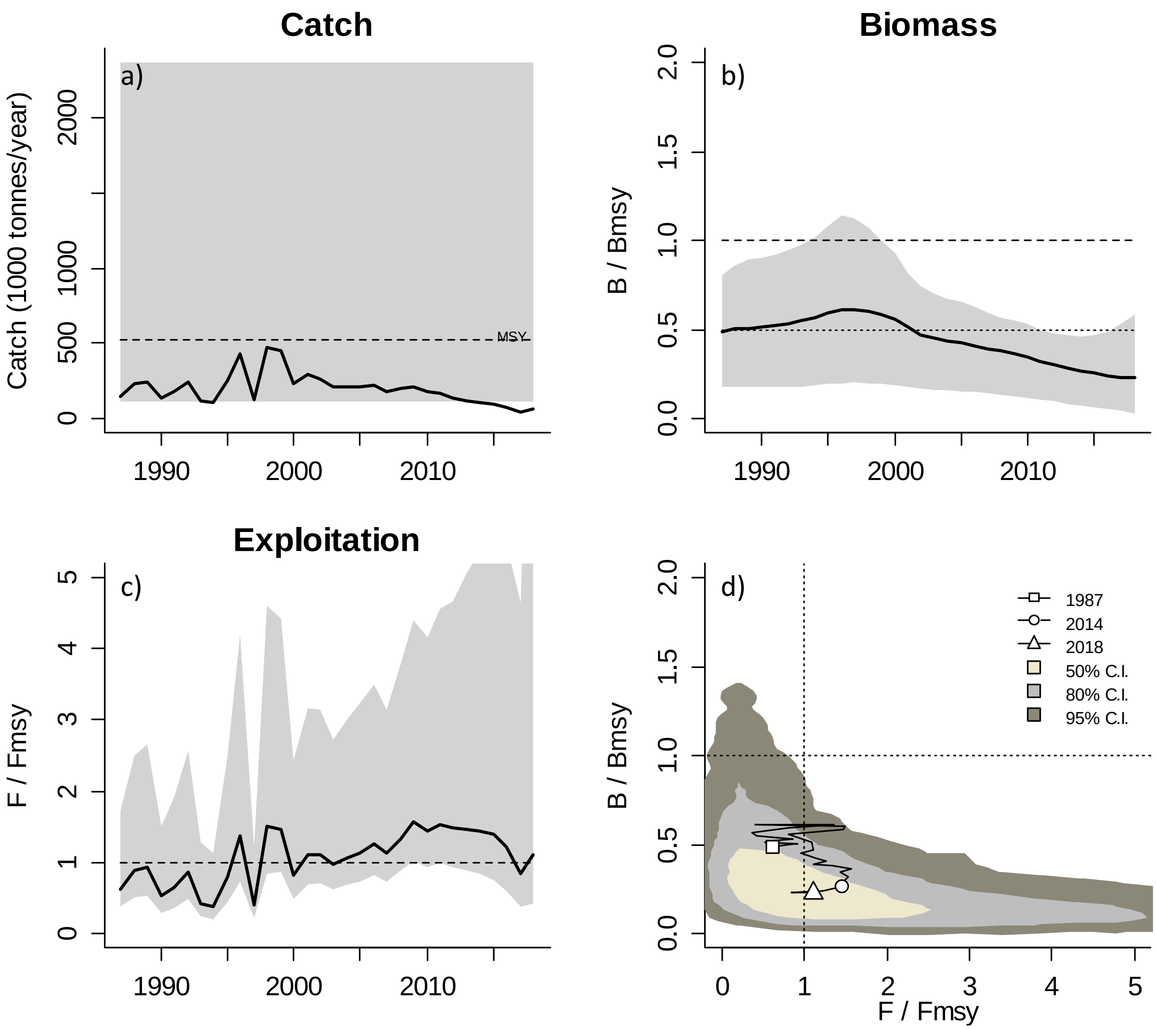

Fig. 8. Outputs of CMSY analysis for the Southwest Atlantic hoki stock. a) Hoki catches relative to the CMSY estimate of MSY, with indication of 95% confidence limits in grey; b) Relative total biomass (B/B_{MSY}), with the grey area indicating uncertainty; c) relative exploitation (F/F_{MSY}); d) Trajectory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

Conclusions

Since 1987, the Falkland Islands have contributed on average 9% to the total annual catch of the Southwest Atlantic hoki stock; this proportion has increased to 10.74% in the last decade. In Falkland Islands waters, most hoki catches were from W, G, and A licences respectively, whereas sporadic S-license fishing resulted in minor hoki catches since 2007.

The LBB analysis suggests that the 2016 stock size was nearly 13% of the "unexploited" stock size in 2002 (B_{2016}/B_{2002} = 0.1272) and 23% of the biomass that would provide maximum sustainable yield (B/B_{MSY} = 0.23). Based on the lowest estimate of mortality (M = 0.2275), OCOM provided the most precautionary estimate of MSY in 212,444 t. OCOM also detected a declining trend in hoki biomass over time, with relative stabilization in the most recent years. The finding of low stock biomass is supported by the low average length at 50% catch (18.3 cm pre-anal length) compared to the optimum length at catch (30 cm pre-anal length), and by the low resilience of the species (Froese & Pauly 2019); indication that the stock is being harvested at a rate that is outpacing growth rates in terms of overall weight or biomass. CMSY presented a number of contradictions; the estimated MSY has never been caught, but B/B_{MSY} was consistently < 1, indicating an overfished stock, and F/F_{MSY} was > 1 for nearly every year since 2002, indicating the continuation of overfishing. MSY would be greater than 60% of the total biomass in 2018, despite the species being identified with low resilience. On the basis of these outcomes CMSY was not considered an effective model for this data set, but will be re-examined in future assessments.

Although studies suggest that stocks can yield sustainable harvests at levels considered overfished (Hilborn 2010), and despite hoki not being the primary target in any Falkland Islands fishery, the various metrics of the Southwest Atlantic hoki stock indicate a need for precautionary management. According to the Schaefer model B_{MSY} = 0.5 K (Froese et al. 2017), B_{MSY} = 1,079,200 t from the OCOM estimate of K = 2,158,399 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} = 272,046 / 1,079,200 = 0.2521, the present catch limit of the Southwest Atlantic hoki stock should be 25.21% of the OCOM MSY estimate: 212,444 × 0.2521 = 53,557 t. Historical catch is often used to estimate quota allocation on international and regional scales (Lynham 2013). Catch limit alternatives for the Falkland Islands based on different criteria are presented in Table V.

Table V. Catch limit alternatives for hoki in Falkland Islands waters.

Criteria	Threshold	Catch limit (t)
Average catch		
10-year	13,261	13,261
5-year	6,858	6,858
3-year	6,684	6,684
Relative average contribution		
10-year (10.74%)	53,557 x 0.1074	5,749
5-year (9.18%)	53,557 x 0.0918	4,917
3-year (10.55%)	53,557 x 0.1055	5,652
Equal share		
33.3%	53,557 x 0.3333	17,851

The alternatives of catch limits for the Falkland Islands ranged from 4,917 t to 17,851 t, which is less than half the average annual catch from the other fisheries that target the Southwest Atlantic hoki stock. It is noted that 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 hoki 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 Southwest Atlantic hoki stock (53,557 t), and not only the average catch. For instance, equal partition of the MSY between the three fisheries (33.33% each) that target the Southwest Atlantic hoki stock resulted in 17,851 t. In contrast, catch limits estimated from the relative average contribution of the Falkland Islands to the total catch of the Southwest Atlantic hoki stock ranged between 4,917 t and 5,749 t. Important considerations must be taken into account to determine catch limits. 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 the Falkland Islands only. The Falkland Islands are located at the edge of the distribution of the Southwest Atlantic hoki stock, which may not be representative of the entire stock and thus may bias biomass estimates. Nonetheless, 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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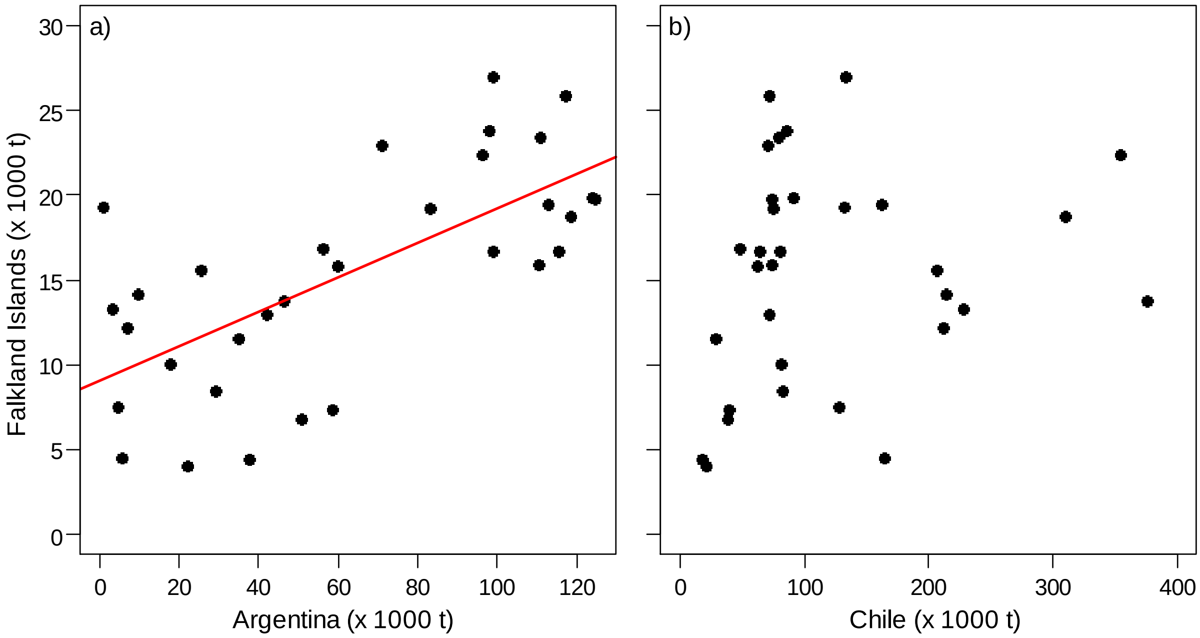
Appendix

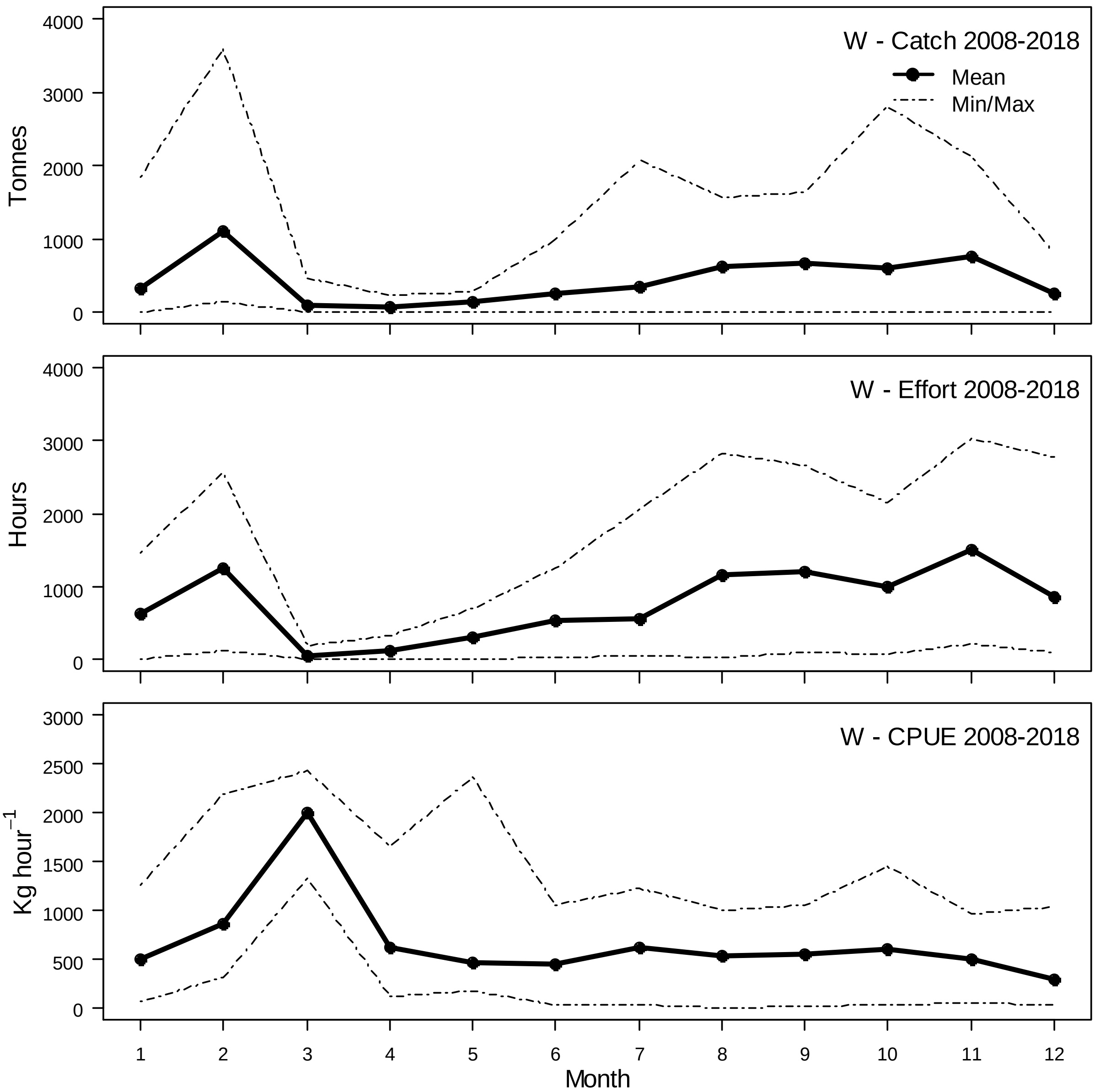
Appendix I. Historical commercial catch (t) of hoki in Falkland Islands, Argentine and Chilean waters. Catch data from Chile for the year 2018 are preliminary (R. Céspedes, IFOP, *pers. comm.*).

Year	Falkland Islands	Argentina	Chile	Total
1987	19,307	782	131,834	151,923
1988	12,209	6,952	211,624	230,785
1989	13,313	3,085	227,393	243,791
1990	7,553	4,353	128,002	139,908
1991	4,499	5,583	164,697	174,779
1992	14,188	9,534	214,324	238,046
1993	8,506	29,174	82,580	120,260
1994	10,064	17,472	81,310	108,846
1995	15,603	25,228	206,734	247,565
1996	13,813	46,241	375,446	435,500
1997	13,006	41,787	71,479	126,272
1998	22,378	96,218	354,184	472,780
1999	18,765	118,356	309,904	447,025
2000	19,831	123,926	91,333	235,090
2001	19,471	112,539	162,082	294,092
2002	26,970	98,865	133,418	259,253
2003	23,815	97,797	85,896	207,508
2004	25,905	116,965	71,177	214,047
2005	16,723	115,340	79,755	211,818
2006	19,769	124,638	73,421	217,828
2007	16,669	98,808	63,697	179,174
2008	15,908	110,269	73,567	199,744
2009	23,404	110,717	78,440	212,561
2010	19,227	82,855	74,330	176,412
2011	22,979	70,903	70,137	164,019
2012	15,867	59,595	62,175	137,637
2013	16,849	55,966	47,602	120,417
2014	7,392	58,396	39,345	105,133
2015	6,845	50,469	37,475	94,789
2016	11,562	34,946	28,108	74,616
2017	4,053	21,930	20,850	46,833
2018	4,438	37,598	17,054	59,090

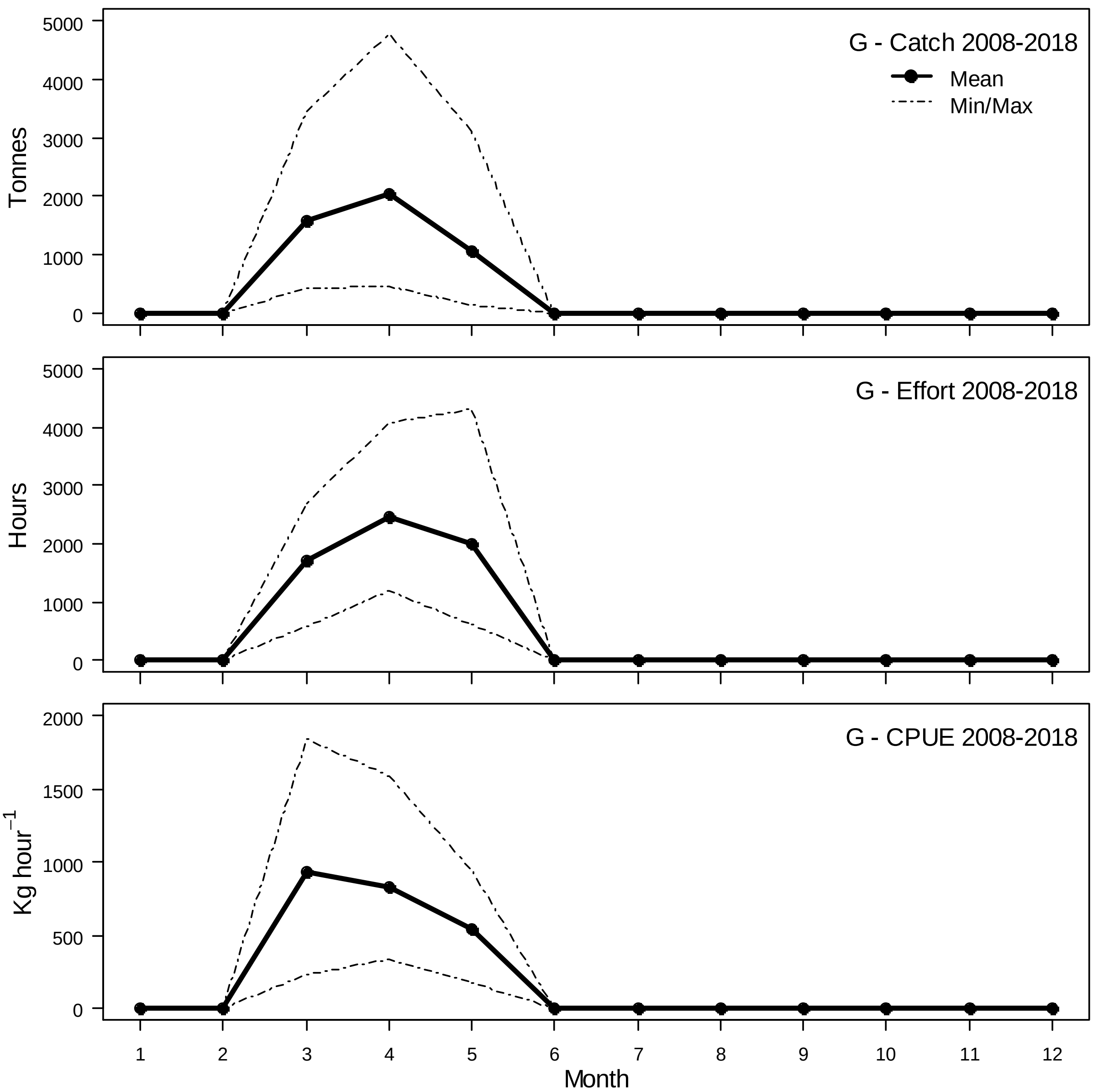
Appendix II. Correlation of hoki annual catches between fisheries. a) Correlation between Falkland Islands and Argentine hoki annual catches from 1987 to 2018 ($r = 0.68$, $n = 32$, $p < 0.001$). b) Correlation between Falkland Islands and Chilean hoki annual catches from 1987 to 2018 ($r = 0.18$, $n = 32$, $p = 0.33$).



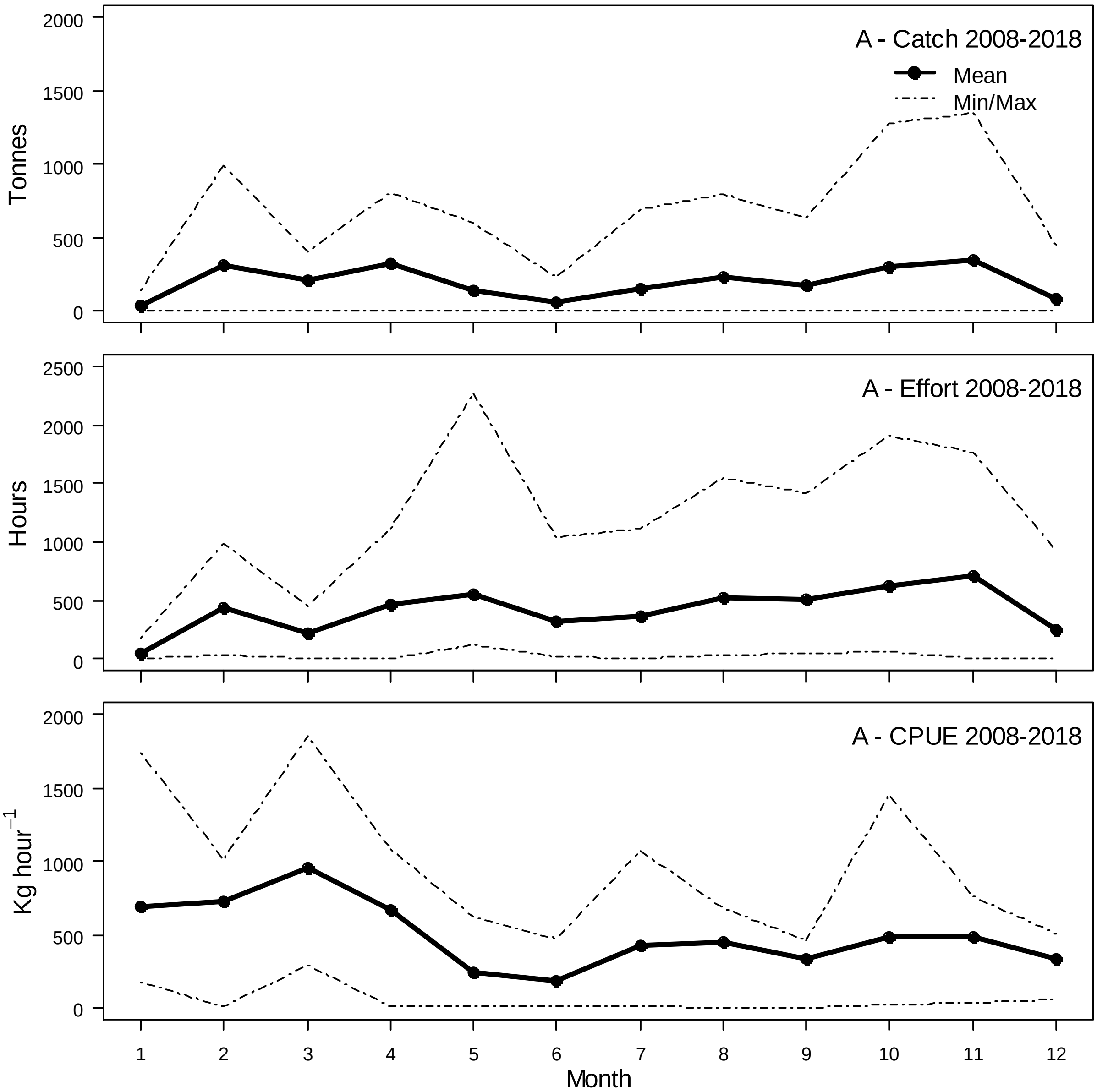
Appendix III. Mean monthly catch, effort and CPUE of hoki by W-licensed vessels in Falklands waters from 2008 to 2018.



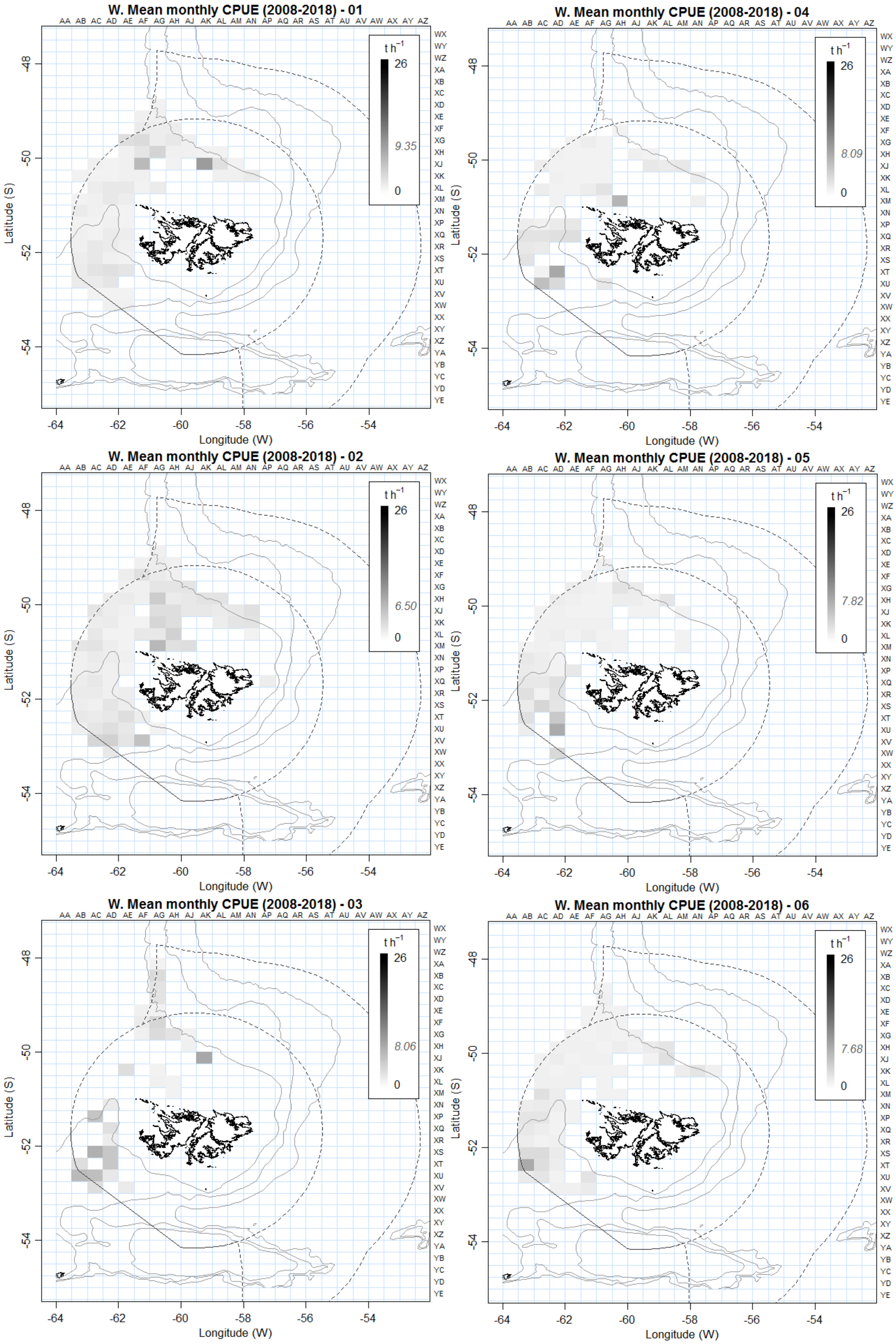
Appendix IV. Mean monthly catch, effort and CPUE of hoki by G-licensed vessels in Falklands waters from 2008 to 2018.

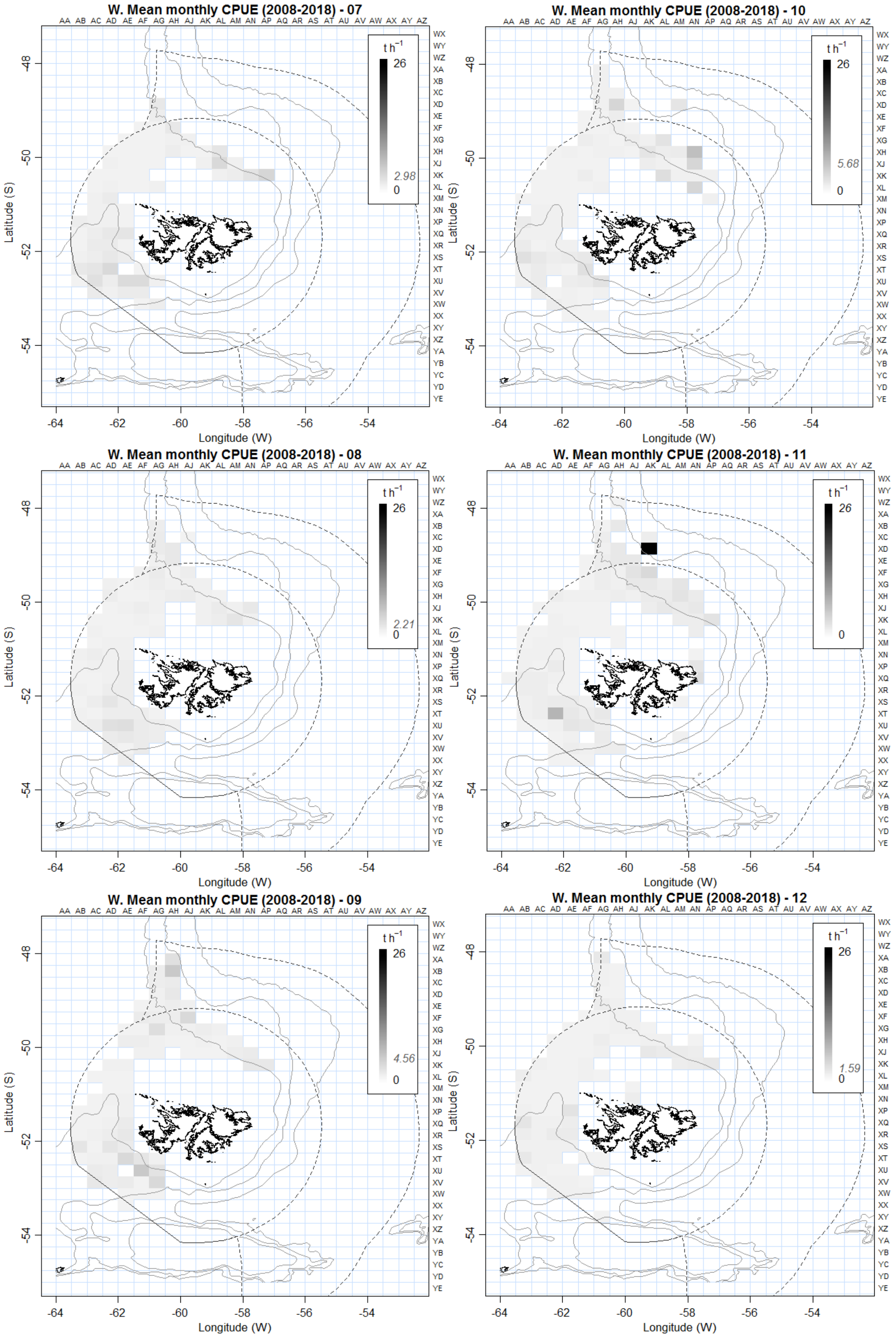


Appendix V. Mean monthly catch, effort and CPUE of hoki by A-licensed vessels in Falklands waters from 2008 to 2018.

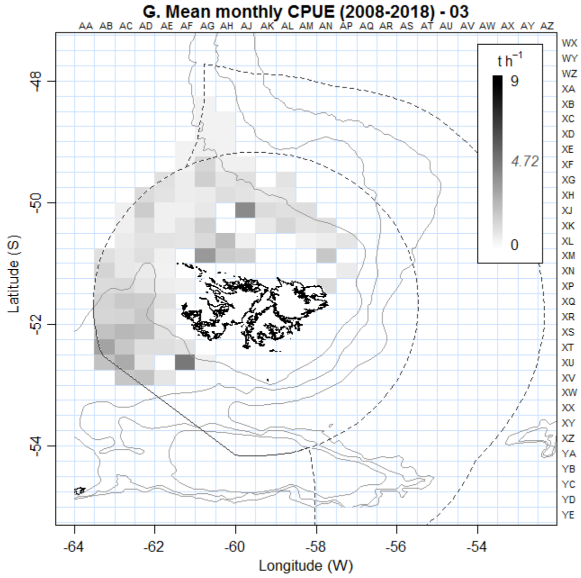


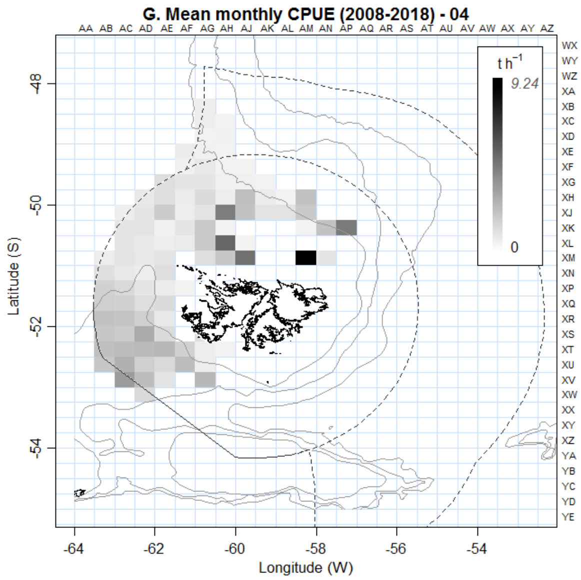
Appendix VI. Monthly spatial distribution of CPUE ($t \cdot h^{-1}$) of hoki by W-licensed vessels in Falklands waters from 2008 to 2018.

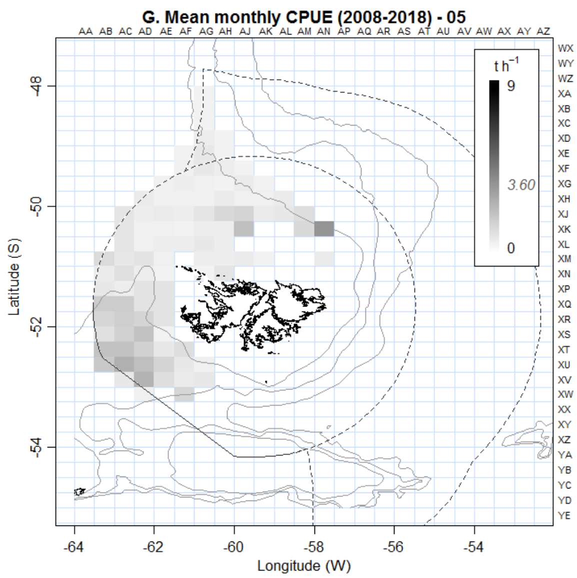



W. Mean monthly CPUE (2008-2018) - 07
W. Mean monthly CPUE (2008-2018) - 10
W. Mean monthly CPUE (2008-2018) - 08
W. Mean monthly CPUE (2008-2018) - 11
W. Mean monthly CPUE (2008-2018) - 09
W. Mean monthly CPUE (2008-2018) - 12
Latitude (S)
Longitude (W)
t h^{-1}
26
2.98
5.68
2.21
4.56
1.59
0

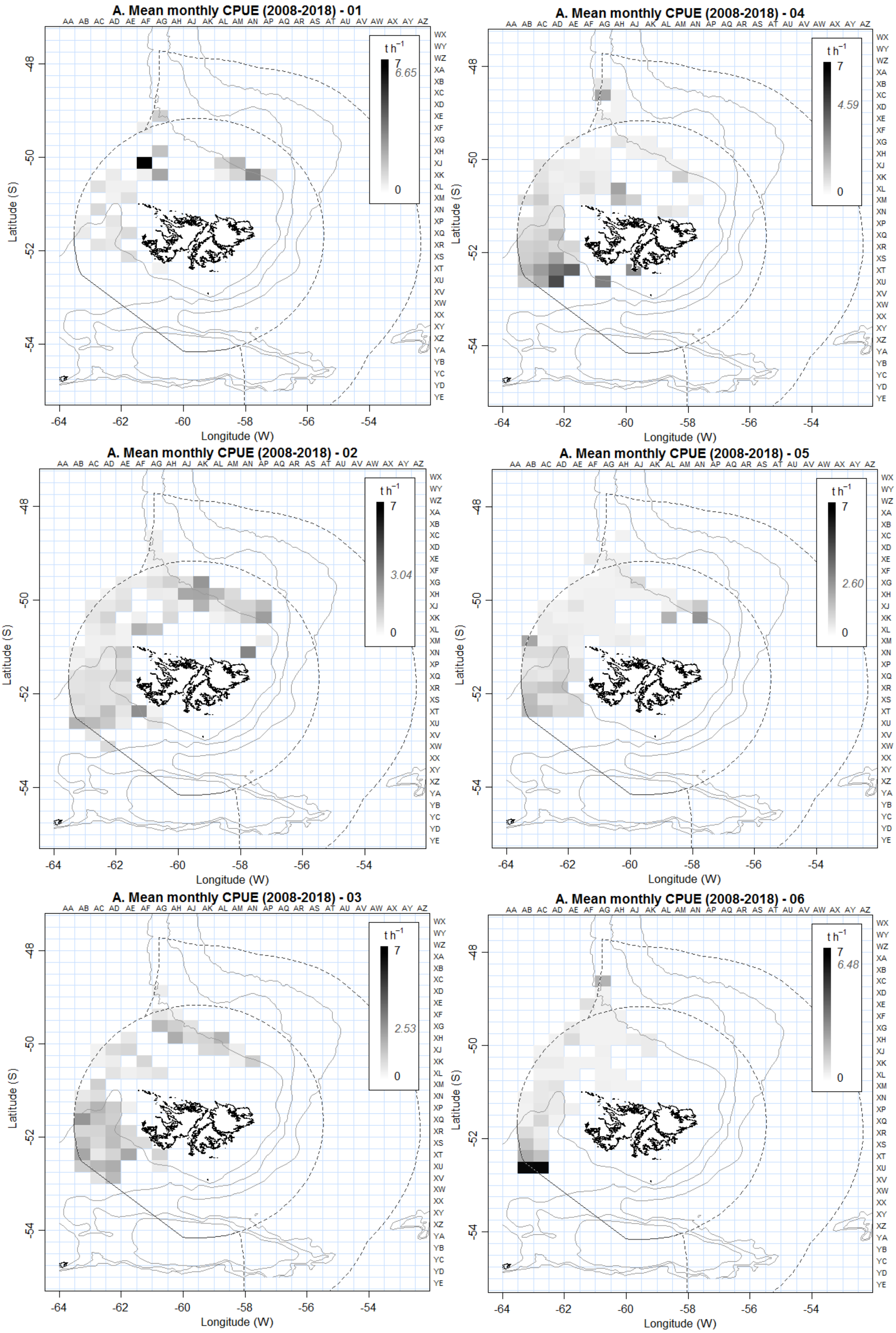
Appendix VII. Monthly spatial distribution of CPUE (t · h^{-1}) of hoki by G-licensed vessels in Falklands waters from 2008 to 2018. G-licensed vessels do not fish from June to February.

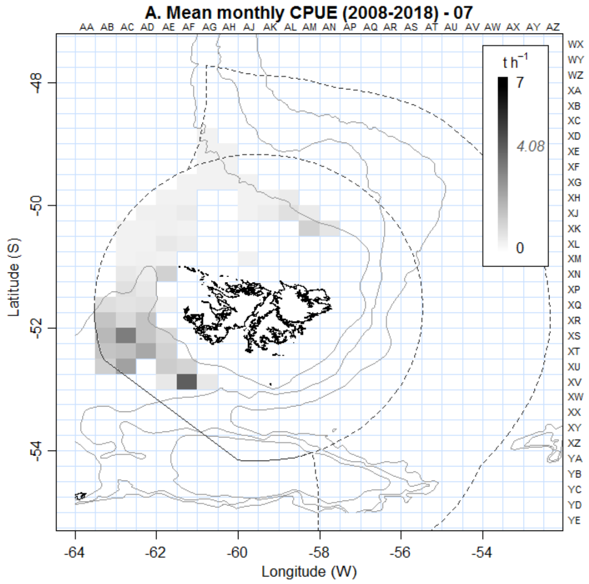


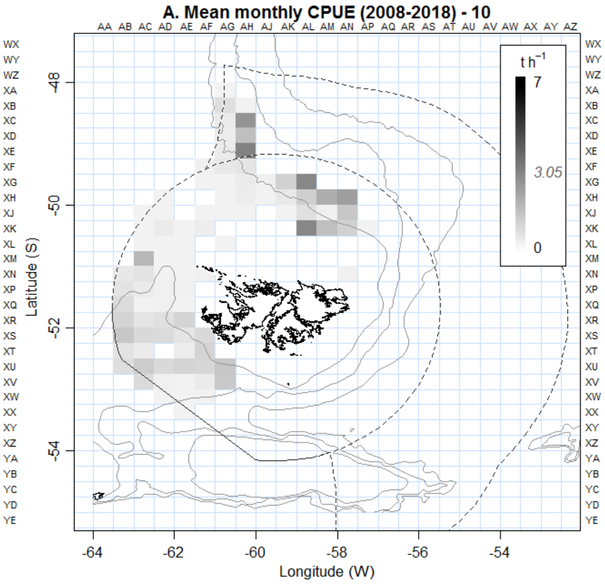


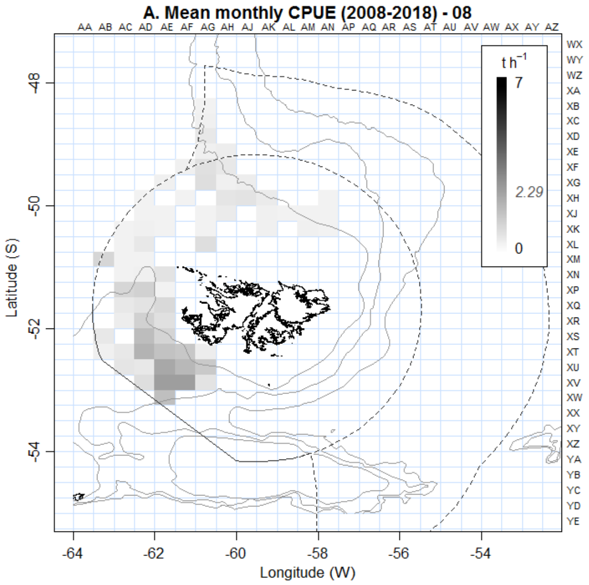


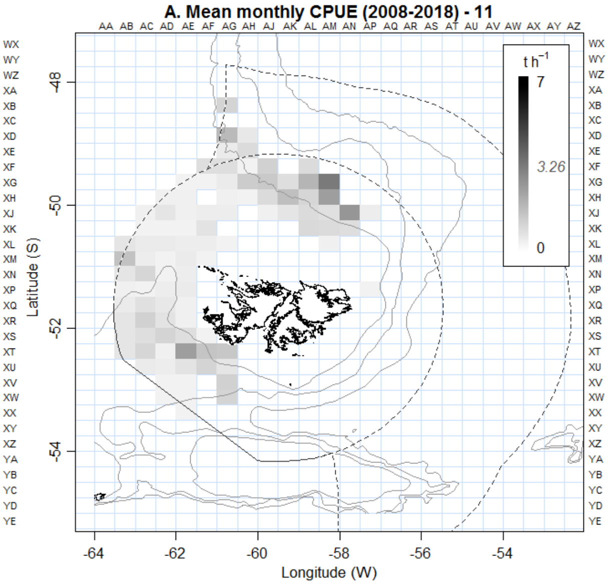
Appendix VIII. Monthly spatial distribution of CPUE ($t \cdot h^{-1}$) of hoki by A-licensed vessels in Falklands waters from 2008 to 2018.

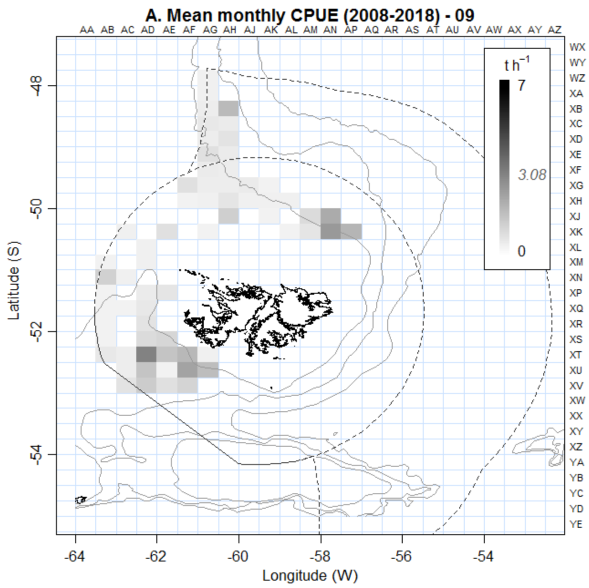


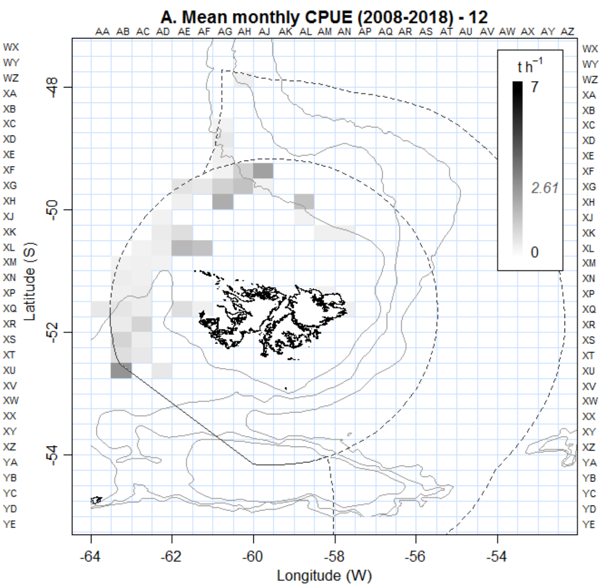

A. Mean monthly CPUE (2008-2018) - 07
t h^{-1}
7
4.08
0
Latitude (S)
Longitude (W)


A. Mean monthly CPUE (2008-2018) - 10
t h^{-1}
7
3.05
0
Latitude (S)
Longitude (W)

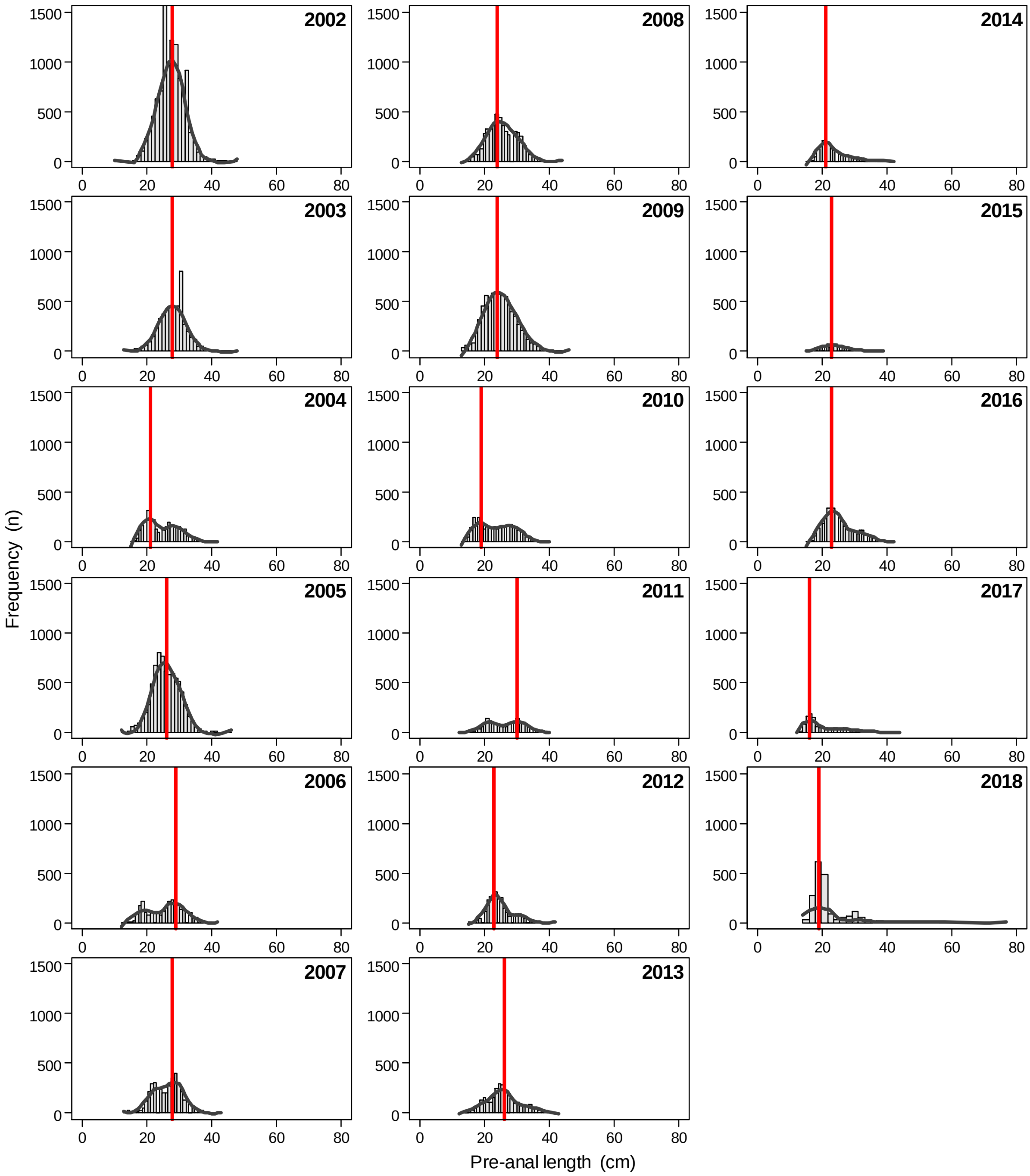

A. Mean monthly CPUE (2008-2018) - 08
t h^{-1}
7
2.29
0
Latitude (S)
Longitude (W)


A. Mean monthly CPUE (2008-2018) - 11
t h^{-1}
7
3.26
0
Latitude (S)
Longitude (W)

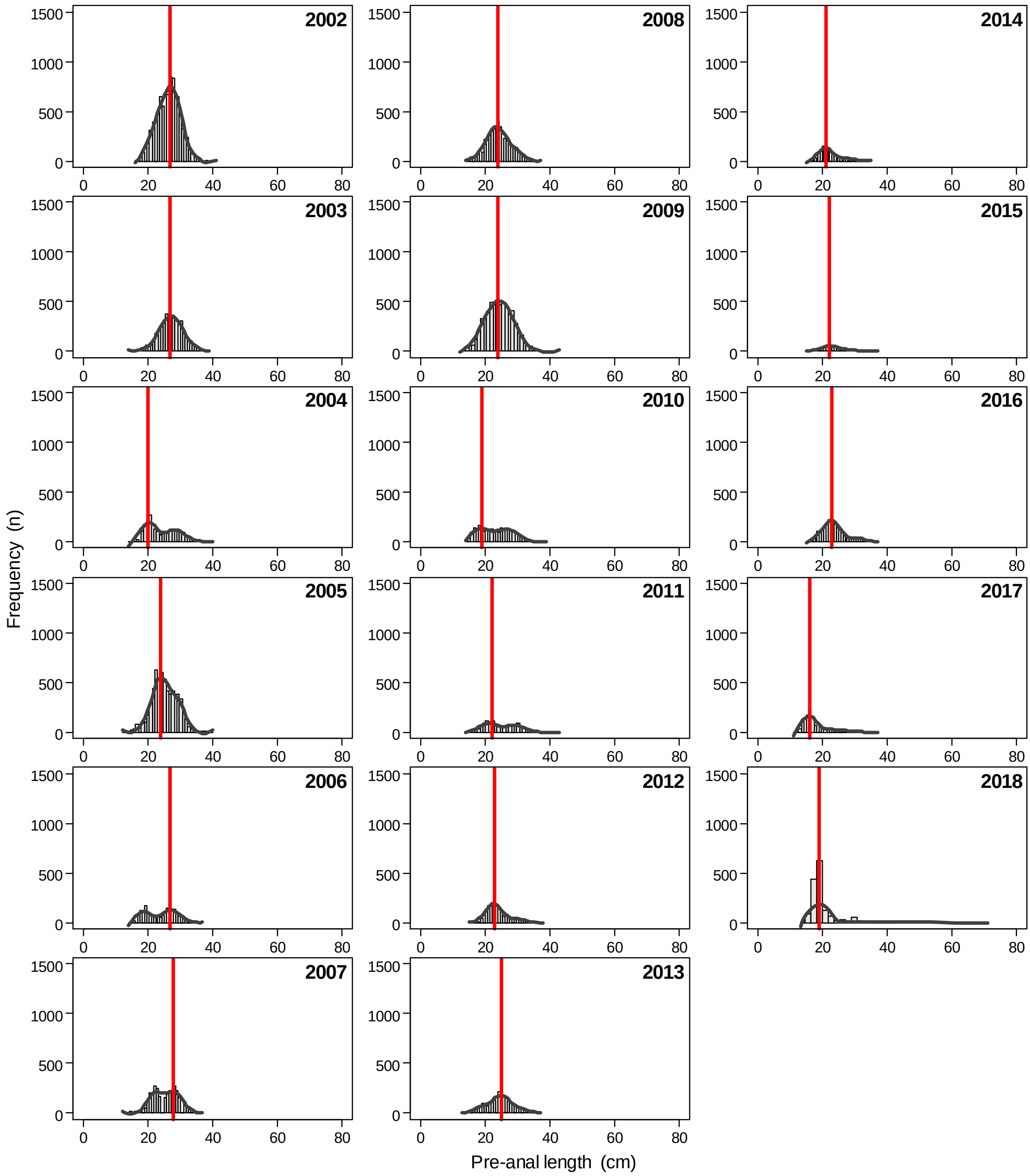

A. Mean monthly CPUE (2008-2018) - 09
t h^{-1}
7
3.08
0
Latitude (S)
Longitude (W)


A. Mean monthly CPUE (2008-2018) - 12
t h^{-1}
7
2.61
0
Latitude (S)
Longitude (W)

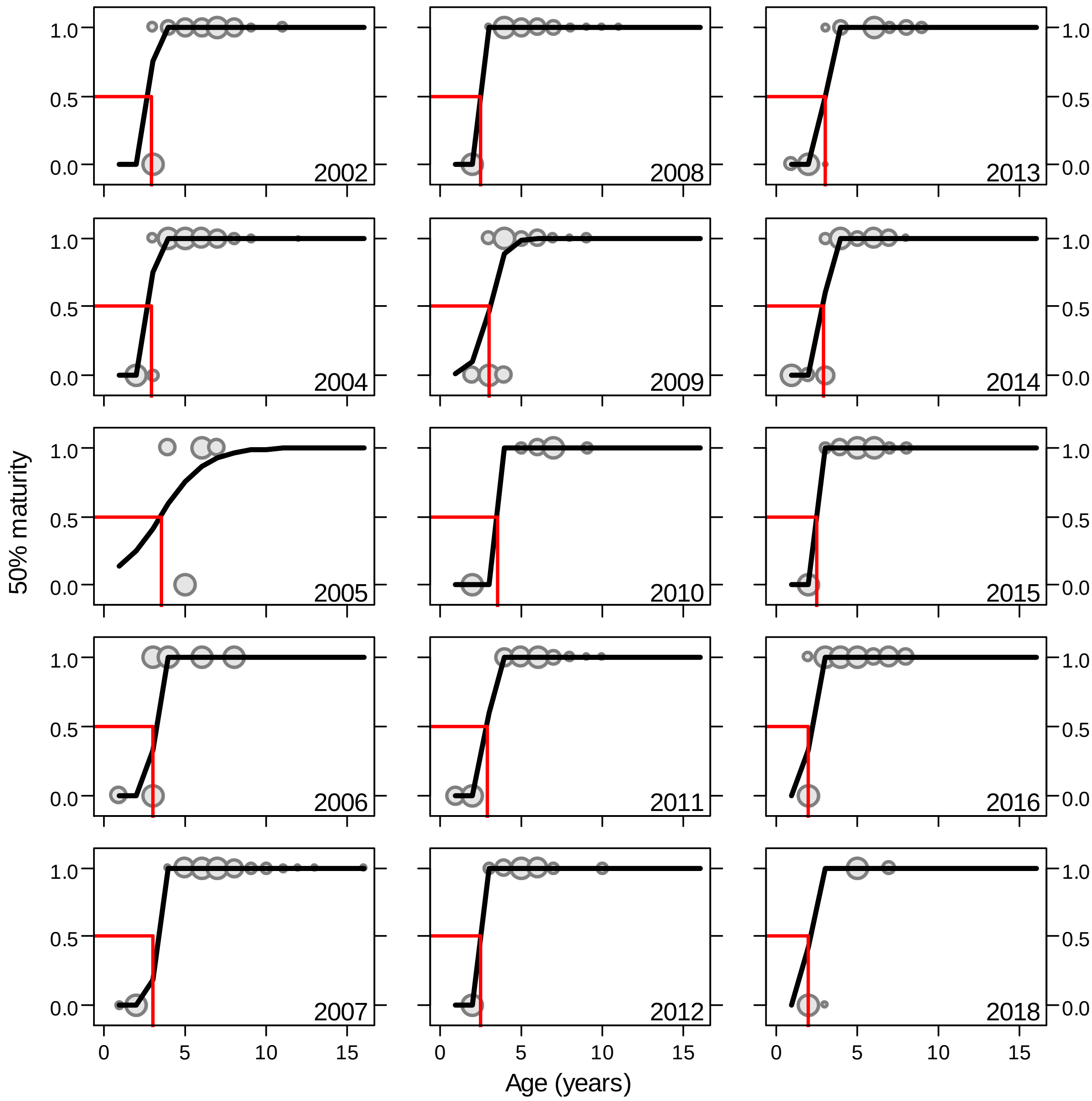
Appendix IX. Annual modes of female hoki pre-anal lengths in the Falkland Islands from 2002 to 2018. The modes (vertical red lines) are calculated from LOESS smooths over the length distributions to mitigate sampling fluctuations. n_{2002} = 10,532; n_{2003} = 4,917; n_{2004} = 2,744; n_{2005} = 7,508; n_{2006} = 2,580; n_{2007} = 3,744; n_{2008} = 4,699; n_{2009} = 7,500; n_{2010} = 2,871; n_{2011} = 1,513; n_{2012} = 2,308; n_{2013} = 2,739; n_{2014} = 1,459; n_{2015} = 651; n_{2016} = 3,146; n_{2017} = 1,128; n_{2018} = 1,900.



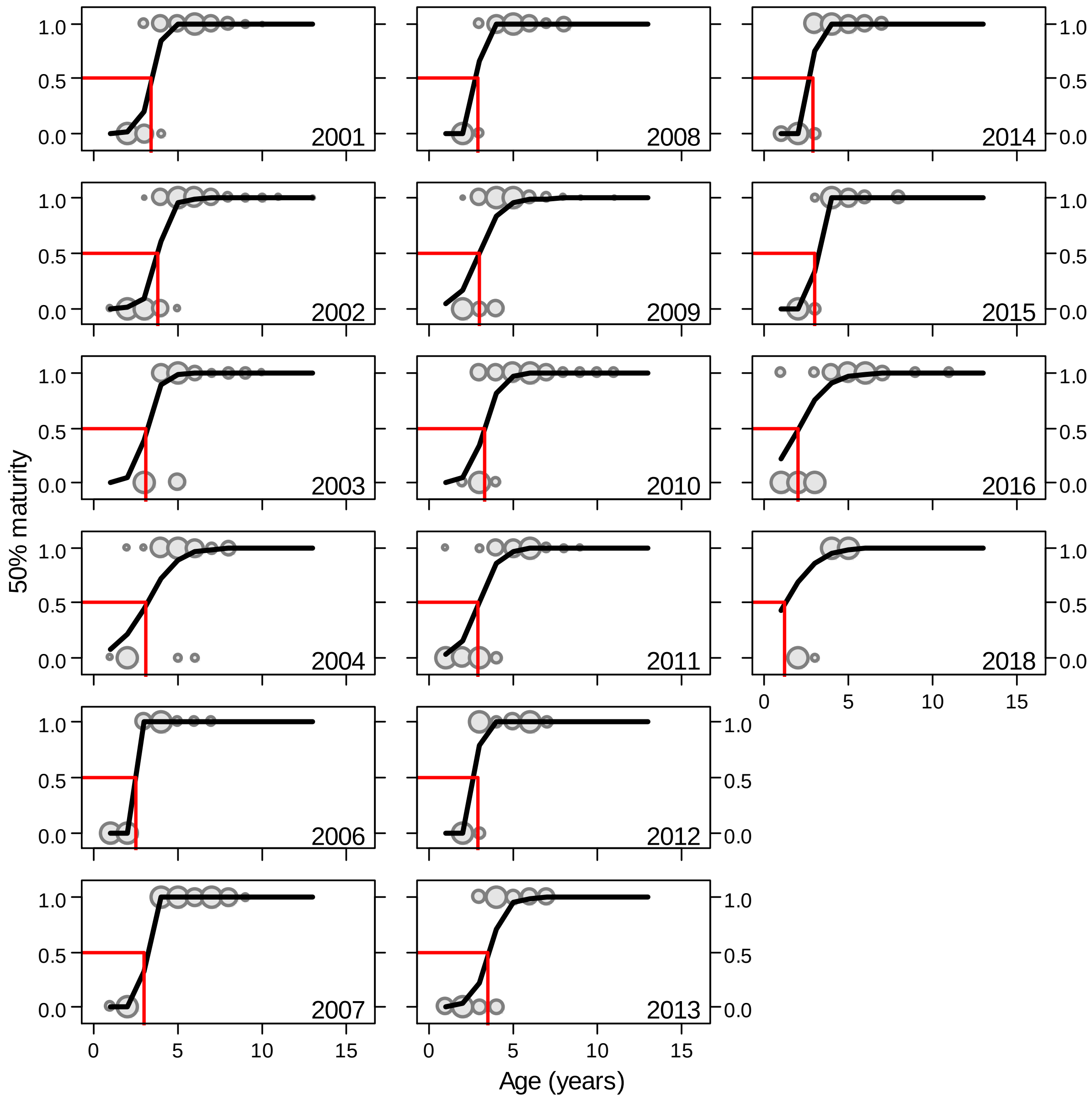
Appendix X. Annual modes of male hoki pre-anal lengths in the Falkland Islands from 2002 to 2018. The modes (vertical red lines) are calculated from LOESS smooths over the length distributions to mitigate sampling fluctuations. n_{2002} = 7,021; n_{2003} = 3,430; n_{2004} = 2,041; n_{2005} = 5,407; n_{2006} = 1,540; n_{2007} = 2,605; n_{2008} = 3,166; n_{2009} =5,812; n_{2010} = 1,990; n_{2011} = 1,146; n_{2012} = 1,430; n_{2013} = 1,735; n_{2014} = 905; n_{2015} = 480; n_{2016} = 1,691; n_{2017} = 1,129; n_{2018} = 1,564.



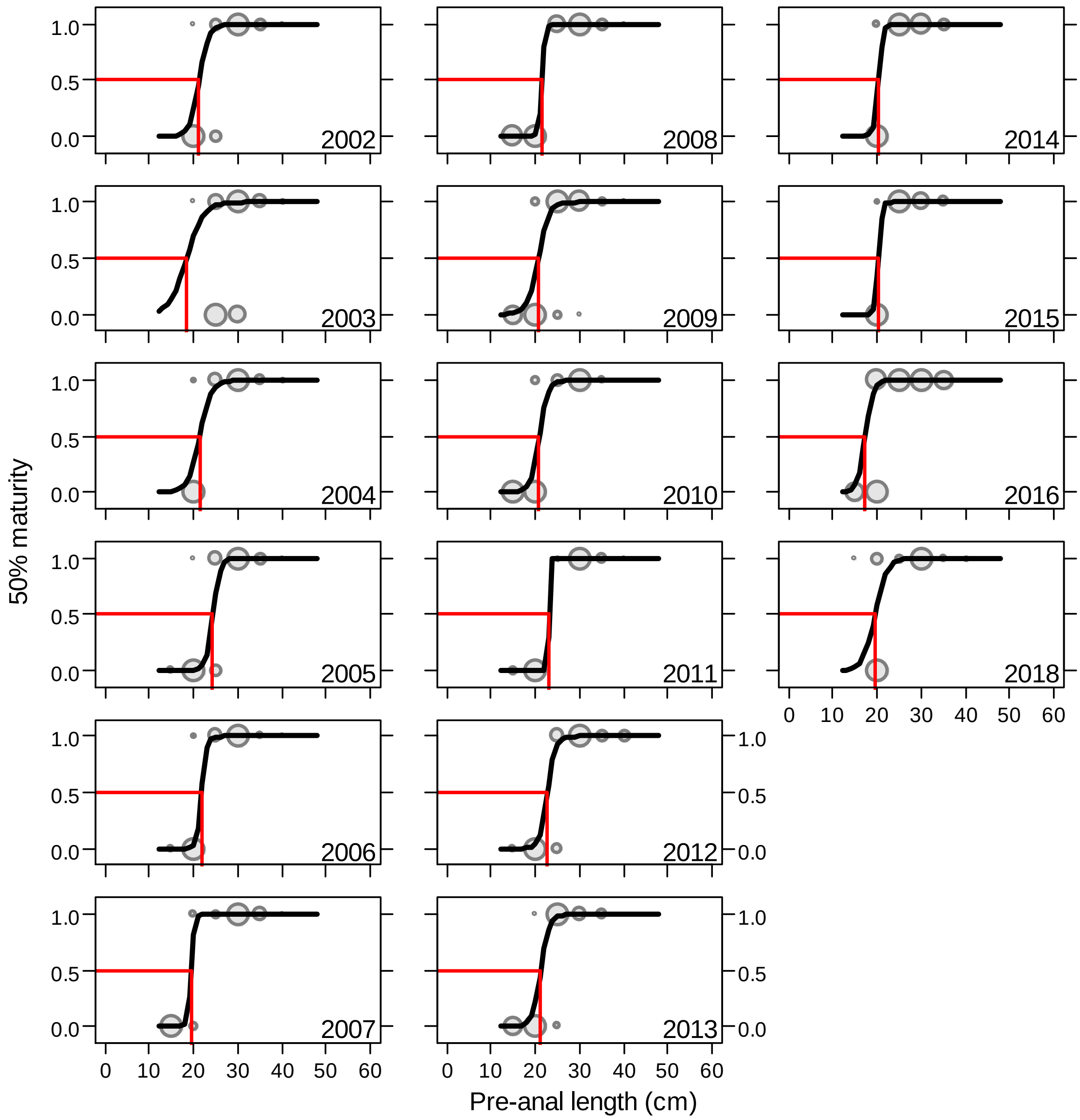
Appendix XI. Age at 50% maturity of female hoki in the Falkland Islands from 2002 to 2018. Logistic regressions were made for age vs. juvenile (0: maturity stages 0 and I) and adult (1: maturity stages III+).



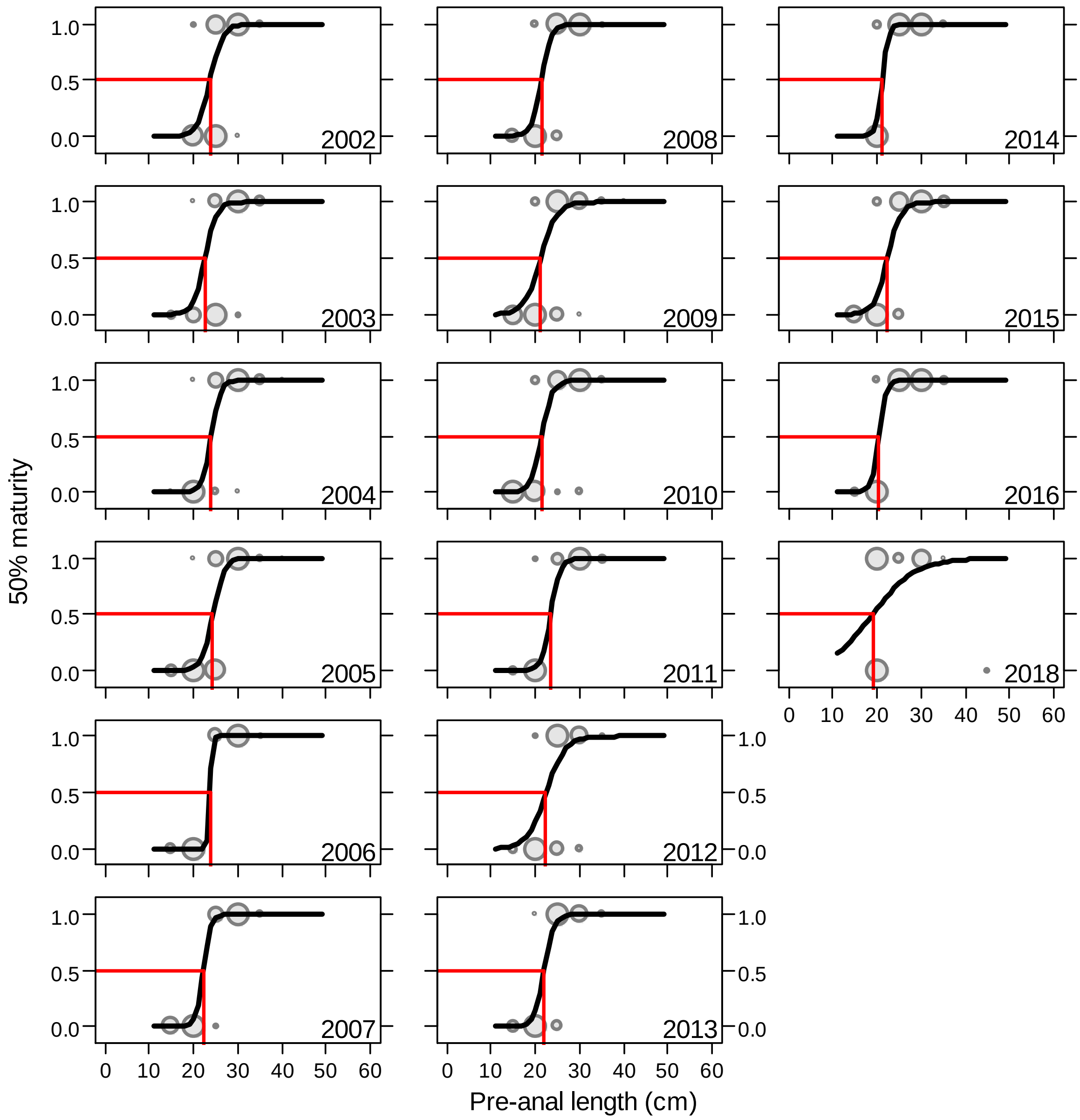
Appendix XII. Age at 50% maturity of male hoki in the Falkland Islands from 2001 to 2018. Logistic regressions were made for age vs. juvenile (0: maturity stages 0 and I) and adult (1: maturity stages III+).



Appendix XIII. Length at 50% maturity of female hoki in the Falkland Islands from 2002 to 2018. Logistic regressions were made for length vs. juvenile (0: maturity stages 0 and I) and adult (1: maturity stages III+).



Appendix XIV. Length at 50% maturity of male hoki in the Falkland Islands from 2002 to 2018. Logistic regressions were made for length vs. juvenile (0: maturity stages 0 and I) and adult (1: maturity stages III+).



Appendix XV. LBB implemented on hoki from Falkland Islands waters. a) accumulated length frequency data used to estimate priors Lc, L_∞, and Z/K; b) length frequency data for the first year in the time series (2002), and c) length frequency data for the last year in the time series (2016), 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 2016 (blue vertical line) are indicated.