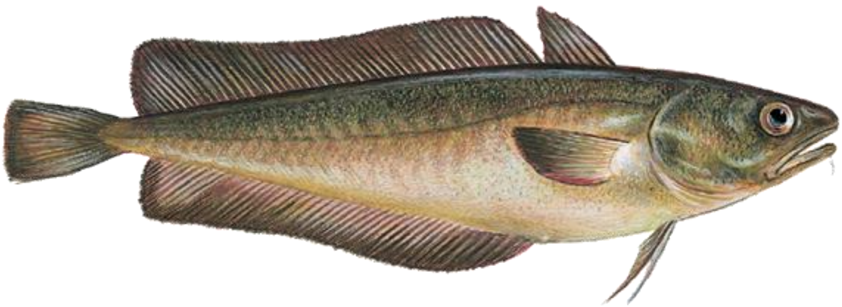
Stock Assessment of red cod (*Salilota australis*) in the Falkland Islands

SA - 2022 - BAC



Jorge E. Ramos, Andreas Winter

Natural Resources - Fisheries
Falkland Islands Government
Stanley, Falkland Islands

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Reviewed and approved on 1st of December of 2022 by:

Andrea Clausen
Director of Natural Resources
Falkland Islands

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Jorge E. Ramos*, Andreas Winter

Fisheries Department, Directorate of Natural Resources, Falkland Islands Government, Bypass Road, Stanley FIQQ 1ZZ, Falkland Islands

*jeramos@naturalresources.gov.fk

Summary

The red cod Total Allowable Catch (TAC) for 2023 is set at 1,439 tonnes (t). Following recommendations of the MacAlister Elliott & Partners external review, this TAC was calculated according to the ICES category 3 - 2/3 rule, in which next year's advised TAC is proportioned by the mean biomass estimate of the two most recent years divided by the mean biomass estimate of the three previous years.

Red cod commercial catches in Falkland Islands licenced fisheries were 1,187 t in 2021; below the average catch over the past 10 years.

Red cod commercial CPUE in the Falklands Interim Conservation Zone varied between 1990 and 2021, with the CPUE in 2020 and 2021 being the lowest in the time series.

Length-based indicators suggest that conservation of immature fish, large individuals, mega-spawners, optimal yield, and MSY have been poor for over a decade. Length and age analyses showed no significant change of asymptotic length from 2002 through 2019 and of length at 50% maturity of females from 1992 through 2021. Comparison of length at 50% maturity and catch at length revealed that red cod were mainly caught before reaching maturity, which can reduce stock sustainability. Poor indicators for large individuals and for mega-spawners, and the higher proportion of immature individuals within the catch over the past decade may be in part because of fishing vessels being prohibited from targeting spawning individuals since 2010.

Introduction

Red cod (*Salilota australis*, Moridae) is a demersal fish that inhabits shelf and slope subtropical, temperate and sub-Antarctic waters, at 30–1,000 m depth, of the Southeast Pacific (from 33°S to the southern tip of South America) and Southwest Atlantic (40°S to 55°S) in the Patagonian region of Chile and Argentina, and in Falkland Islands and Strait of Magellan waters (Cohen et al. 1990; Arkhipkin et al. 2010, 2012). However, no studies have addressed connectivity of this species between the Southeast Pacific and the Southwest Atlantic. Red cod carries out winter (July through September) migrations on the Patagonian Shelf in the Southwest Atlantic (Arkhipkin et al. 2010). Spawning aggregations occur at 180–200 m depths in the periphery of two upwelling areas created by the cold-water Falkland Current to the south and southwest of West Falkland between August and October (Arkhipkin et al. 2010; Brickle et al. 2011). After spawning, red cod migrate back to their feeding grounds (Arkhipkin et al. 2010). Based on the migratory behaviour of red cod in the region it is assumed that Falklands and Argentine fisheries catch the same stock. This species is considered a valuable by-catch by these two nations and most of the catch is historically taken by the Falkland Islands fishery (Falkland Islands Government[a]; Falkland Islands Government 2021), compared with the Argentina fishery (Argentine Government[b]; Sánchez et al. 2012; Navarro et al. 2014, 2019).

Methods

ICES advice rules

In 2020, red cod was included in a Falkland Islands Government finfish stock assessment and management review conducted by MacAlister Elliott & Partners Ltd, UK (MEP 2020). The MEP report recommended stock assessments for most commercial finfish species to be based on the ICES advice rules (ICES 2012, 2018a), referencing applicable categories of data availability and quality; for red cod, the advice was to calculate Total Allowable Catch (TAC) using the ICES category 3, as a species for which commercial landings data and abundance indices from surveys or the fishery are available. MEP (2020) also recommended exploring ancillary stock status information from ICES data limited methods such as length-based indicators. A Length-Based Indicator method (LBI) has been used since 2021 by the

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[a] http://www.fig.gov.fk/fisheries/publications/fishery-statistics
[b] https://www.agroindustria.gob.ar/sitio/areas/pesca_maritima/desembarques/

Falkland Islands Fisheries Department (FIFD) to provide a suite of indicators for several commercial finfish species based on combinations of catch-at-size distributions, and life-history parameters such as L_{Inf} (asymptotic length; Haddon 2001) and L50 (length at 50% maturity; Cope & Punt 2009). Otolith growth increments of Falkland Islands red cod have been read at the National Marine Fisheries Research Institute (MFRI) in Gdynia, Poland. Red cod age data in the FIFD database have been rated 'with caution' (Lee et al. 2020) but appear reliable; therefore, LBI was implemented.

ICES Category 3 Total Allowable Catch

For category 3 the common assessment method uses a 2/3 rule, in which next year's advised TAC is calculated taking into account the most recent five years of the index. By this rule, a ratio of the mean of the last two years over the mean of the first three years' index of the five-year series is multiplied against the current year TAC (Ramos & Winter 2021) to generate next year's TAC (MEP 2020). However, each year's survey biomass estimate is subject to more or less uncertainty depending on the distribution of catches (Ramos & Winter 2022). To reflect uncertainty, biomass estimates were weighted by their inverse variance (Marín-Martínez & Sánchez-Meca 2010). Variances of red cod biomass were estimated from each year's 10,000 randomized re-samples (2015 = 844641348.4; 2016 = 1008476074.0; 2017 = 322677148.5; 2018 = 823259842.4; 2019 = 485141808.8; 2020 = 34324611.8; 2021 = 54115516.4; 2022 = 4401033099.0). TAC is further limited to an 'uncertainty cap' of ± 20% (ICES 2018a) with respect of the TAC set for the current year (TAC_{2022} = 1,199 t; Ramos & Winter 2021). TAC was calculated as follows:

$$TAC\_3_{2023} = TAC\_3_{2022} \times \left. \frac{\left(\sum_{y=2021}^{2022} B_y \times {}^{1}/_{Var_y}\right) \Big/ \left(\sum_{y=2021}^{2022} {}^{1}/_{Var_y}\right)}{\left(\sum_{y=2018}^{2020} B_y \times {}^{1}/_{Var_y}\right) \Big/ \left(\sum_{y=2018}^{2020} {}^{1}/_{Var_y}\right)} \right| \pm 20\%$$

Where B = February surveys biomass (t), and Var = Variance of February surveys biomass.

Commercial catch and CPUE

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 red cod catch data were examined from 1987 to 2021 from the Falkland Islands (Falkland Islands Government[a]; Falkland Islands Government 2021), and Argentina (Argentine Government[b]; Sánchez et al. 2012; Navarro et al. 2014, 2019). LOESS (span = 0.75, degree = 2) was implemented to examine the pattern of the association between Falkland Islands and Argentina commercial annual catches of red cod from 1987 through 2021. Commercial catches and discard of red cod were examined by licence type for 2021 in the FICZ.

CPUE was calculated as the sum of red cod catches divided by the sum of effort (trawl hours); annual CPUE, monthly CPUE through the time series, and the monthly distribution of the CPUE in the FICZ during 2021 were examined. Annual CPUE was calculated from bottom trawl finfish (A–, G–, and W–licences) vessels with fishing activity through the FICZ from 1990 through 2021. Monthly CPUE was calculated from finfish vessels with fishing activity through the FICZ from 1990 through 2020, and for 2021. CPUE was calculated from A–, G–, and W–licences because these contribute most of the red cod catches throughout the years. LOESS (span = 0.75, degree = 2) was implemented to examine the patterns of annual and monthly CPUE.

Survey biomass estimates

Biomass estimates and the spatial distribution of red cod were examined from joint surveys (groundfish and Patagonian squid *Doryteuthis gahi* pre-season surveys) carried out in February 2010, 2011, and 2015 – 2022 in Falkland Islands waters (Ramos & Winter 2022). Biomass ratios between the most recent February surveys (2022) and the first February surveys (2010) were estimated as a proxy of the change in biomass over time. Significance of difference and 95% confidence intervals of the change in biomass were computed from the randomized re-samples of the survey biomass estimates (Ramos & Winter 2022). A trend of the biomass time series from 2010 to 2022 was calculated using LOESS (span = 1, degree = 2).

[a] http://www.fig.gov.fk/fisheries/publications/fishery-statistics
[b] https://www.agroindustria.gob.ar/sitio/areas/pesca_maritima/desembarques/

Biomass estimates, the spatial distribution of red cod, and biomass ratios were also examined following Ramos & Winter (2022) from joint surveys (groundfish and Patagonian squid pre-season surveys) carried out during July 2017 (Gras et al. 2017; Winter et al. 2017) and July 2020 (Randhawa et al. 2020; Winter et al. 2020). The July surveys were conducted for the primary purpose of assessing common hake (Gras et al. 2017; Randhawa et al. 2020), and are presented as an additional comparative proxy for abundance patterns, with the caveat that these would likely reflect variability in the migratory timing of red cod.

Length and age analyses

Length Based Indicators

ICES (2015, 2018b) recommends the LBI method which provides a suite of indicators based on combinations of catch-at-size distributions, life-history parameters such as L_{Inf} (asymptotic length; Haddon 2001) and L50 (length at 50% maturity; Cope & Punt 2009). L_{Inf} and L50 parameters were assessed for females and males separately as red cod have sexually dimorphic growth (Brickle et al. 2011; Chong Follert et al. 2017).

LBI method was applied to all years from which red cod length and age data were available and reported as random samples (FIFD database codes R and S), i.e., years 1992 to 2021 for length data, and years 2002 to 2019 for age data. Because finfish trawls are restricted to larger meshes than calamari trawls, only length and age data from finfish (A–, G–, and W–licences) and experimental (E–licence) vessels were used, to avoid biasing length-frequency distributions if proportionally more samples are recorded from one fishery or another in different years. Skate and *Illex* trawls also were excluded because their different targets could relate to characteristically different length-frequency distributions of red cod.

LBI method indicators were then selected and scored using Tables 2.1.1.4.1 and 2.1.2.2 in ICES (2015) as templates:

1) Length at half the modal catch length should be bigger than L50, for conservation of immature fish (L_C / L50 > 1). Note that length at half the modal catch length may be poorly defined if the catch length-frequency distribution is not smooth and unimodal.
2) Length at cumulative 25th percentile of catch numbers should be bigger than L50, for conservation of immature fish ($L_{25\%}$ / L50 > 1).

3) Mean length of the largest 5% of individuals in the catch should be at least 80% of the asymptotic length, as a benchmark that enough large individuals are in the stock ($L_{max5\%} / L_{Inf} > 0.8$).
4) 'Mega-spawners' should comprise at least 30% of the catch (thus implicitly represent at least 30% of the stock), as large, old fish disproportionately benefit the resilience of the population (Froese 2004) ($P_{mega} > 0.3$). Mega-spawners are defined as individuals larger than optimum length (L_{Opt}) + 10%, where L_{Opt} is described as the length at which growth rate is maximum (ICES 2015), or the length at which total biomass of a year-class reaches its maximum value (Froese & Binohlan 2000). $L_{Opt} = 3 \cdot L_{Inf} \cdot (3 + Mk^{-1})^{-1}$ (Beverton 1992), where M is instantaneous natural mortality, k is the rate of curvature of the von Bertalanffy growth function, and the ratio Mk^{-1} is set in WKLIFE V software (ICES 2015) at the standard constant of 1.5 (Jensen 1996).
5) Mean length of individuals larger than L_C (L_{meanC}) should be approximately equal to L_{Opt}, for optimal yield ($L_{meanC} / L_{Opt} \approx 1$).
6) L_{meanC} should be equal or bigger to the length-based proxy for MSY ($L_{F=M}$), for producing maximum sustainable yield ($L_{meanC} / L_{F=M} \geq 1$). $L_{F=M}$ implements the premise that MSY is attained when fishing mortality equals natural mortality (Froese et al. 2018), and in WKLIFE V software (ICES 2015) is computed as $(3 \cdot L_C + L_{Inf})/4$.

Margins of variability of the six indicators were estimated by randomly re-sampling 10,000× on the normal distribution each year's fits of L_{Inf} and L50. Indicators were scored against the 'traffic light' scale (ICES 2015) with reference criteria > 1.0 for conservation of immature fish, > 0.8 for conservation of large fish, and > 0.3 for conservation of mega-spawners. The score was green if the lower 95% quantile of the re-sampled iterations was > 1.0, > 0.8, and > 0.3, yellow if 1.0, 0.8, and 0.3 were between the lower and upper 95% quantiles, and red if the upper 95% quantile of the re-sampled iterations was < 1.0, < 0.8, and < 0.3. The use of the margins of variability means that same empirical values of indicators may be scored different colours in different years. Reference criterion ≈ 1.0 for optimal yield was green if the lower and upper 95% quantiles spanned 1.0, yellow if the lower and upper 95% quantiles spanned 0.9 (the threshold used in ICES 2015) without spanning 1.0, and red otherwise. Reference criterion ≥ 1.0 for MSY was scored the same as > 1.0, except that empirical values ≥ 1.0 were automatically green.

Length-age relationship

The von Bertalanffy growth function (R package 'fishmethods'; Nelson 2019) was used to fit all red cod length-at-age data from finfish and experimental vessels. Red cod length and age data were jointly available for years 2002–2019, with status of age data advised 'with caution' (Lee et al. 2020) as verification of these ages is required. Growth model parameters (L_{Inf}, k, and t_0) were calculated for females and males using nonlinear least square regression. A likelihood ratio test (R package 'fishmethods'; Nelson 2019) was used to test whether the von Bertalanffy growth function was significantly different between females and males. Variabilities of the growth model parameters were estimated by bootstrapping; residuals of the model fits were randomly re-sampled with replacement, added back to the expected lengths, and re-fit to the von Bertalanffy growth function. The 95% quantiles of 10,000 iterations were retained as confidence intervals. Inter-annual trend of von Bertalanffy L_{Inf} was calculated by LOESS (span = 0.75, degree = 2).

Length and age at 50% maturity

Overall and yearly length at 50% maturity (L50) was calculated as the mid-point of the binomial logistic regression of maturity ogives vs. length (Heino et al. 2002). Sex and maturity were identified following the fish maturity scale by 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. Maturity is cyclical as fish pass from post-spawning phase to resting phase, and definitive maturity assignments can only be made that stages I through III are immature, and stages IV+ are always adult; however, stage II can be uncertain as it can look macroscopically similar to maturity stage VIII (A. Arkhipkin, FIFD, *pers. comm.*). Therefore, maturity assignment was simplified to a dichotomous classification of 0) juvenile, including maturity stages I and III, and 1) adult, including maturity stages IV to VIII, omitting stage II. Annual L50s were calculated from randomly sampled individuals collected through the FICZ under finfish and experimental licences during the spawning season (August-October; Brickle et al. 2011), from 1992 through 2021. Trends of annual L50 were calculated with LOESS (span = 0.75, degree = 2). Overall and yearly age at 50% maturity (A50) was calculated for females and males separately, by predicting age corresponding to L50 using the inversed von Bertalanffy equation.

Catch at length

Yearly length frequency distributions, from 1990 through 2021, were examined for females and males to describe patterns in catch at length through time. Unsexed individuals were excluded from the analysis. Lengths of individuals sampled randomly and caught by finfish and the experimental vessels through the FICZ from January through December were included in the analysis. Yearly length frequencies were compared with yearly L50 to assess if the catch was mainly comprised of immature or mature individuals.

Natural mortality

Natural mortality (M) of red cod was calculated as an indicator to examine vulnerability of the stock. Natural mortality is the component of total mortality that is not caused by fishing, but by causes such as predation, diseases, senility, pollution, amongst other factors. Annual natural mortality refers to the proportion of fish dying during the year expressed as a fraction of the fish alive at the beginning of the year (FAO 1999), and was calculated using equation 1 following Then et al. (2015):

$$M = 4.899 \times t_{max}^{-0.916} \qquad \text{Eqn. 1}$$

where t_{max} = maximum age, taken as the oldest age reported in the FIFD database not considered an outlier. Then et al. (2015) recommended the use of the t_{max}-based estimator over other estimators based on cross-validation of prediction error, model residual patterns, model parsimony, and biological considerations.

All analyses were performed in RStudio (R Core Team 2021).

Results

ICES advice rules

ICES Category 3 Total Allowable Catch

TAC options for 2023 based on the current year TAC were calculated as follows:

TAC_3_{2022} = 1,199 tonnes.

ICES 2/3 rule weighted by inverse variances:

$$TAC\_3_{2022} \times \frac{\left(\frac{(35217.39 \times 1.85^{-8}) + (81176.73 \times 2.27^{-10})}{1.85^{-8} + 2.27^{-10}}\right)}{\left(\frac{(57422.88 \times 1.21^{-9}) + (83005.12 \times 2.06^{-9}) + (21889.98 \times 2.91^{-8})}{1.21^{-9} + 2.06^{-9} + 2.91^{-8}}\right)}$$

$$= 1582.35$$

20% cap:

$$TAC_{3_{2022}} + 20\% = 1438.8$$

Thus:

$$TAC\_3_{2023} = \text{Minimum}\ (1582.35, 1438.8) \ = 1438.8 \text{ tonnes}$$

Commercial catch and CPUE

Red cod catches in Falkland Islands waters have averaged 1,671 t per year since 1987, representing approximately 58% of the Falkland Islands and Argentine combined annual catch (Fig. 1). Falkland Islands and Argentine red cod catches were positively associated (Fig. 2; Appendix I).

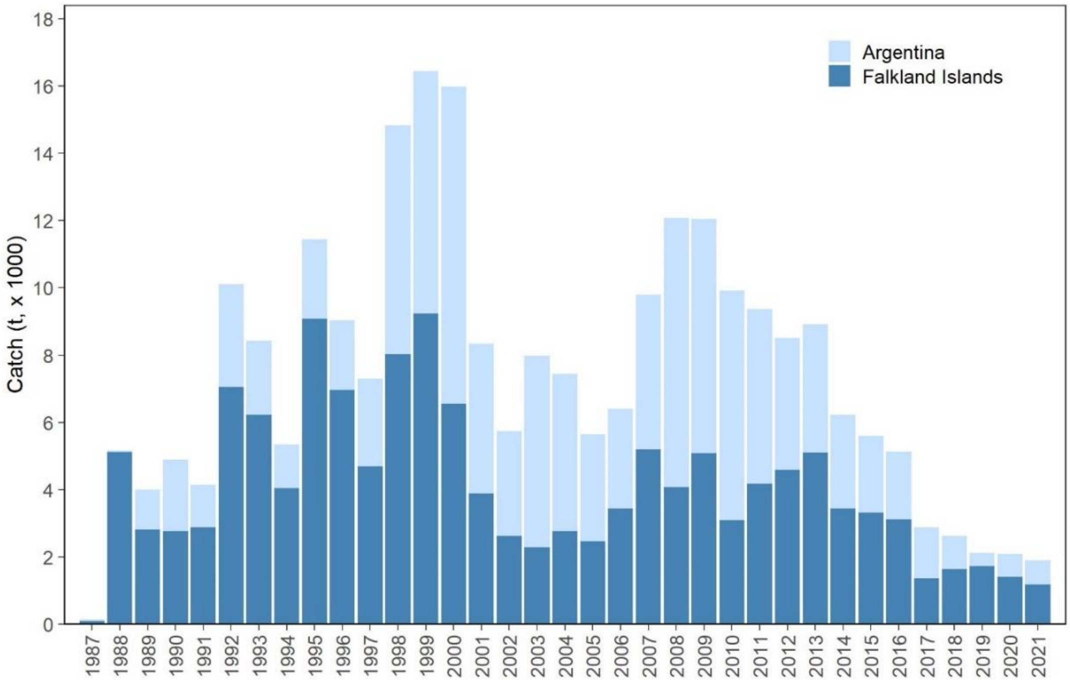


Fig. 1. Annual commercial catch of red cod in Falkland Islands, Argentine, and Chilean waters. Falkland Islands commercial catch data exclude experimental (E–licence) and out-of-zone (O–licence) licences from 1990; earlier than 1990 these licences were not designated.

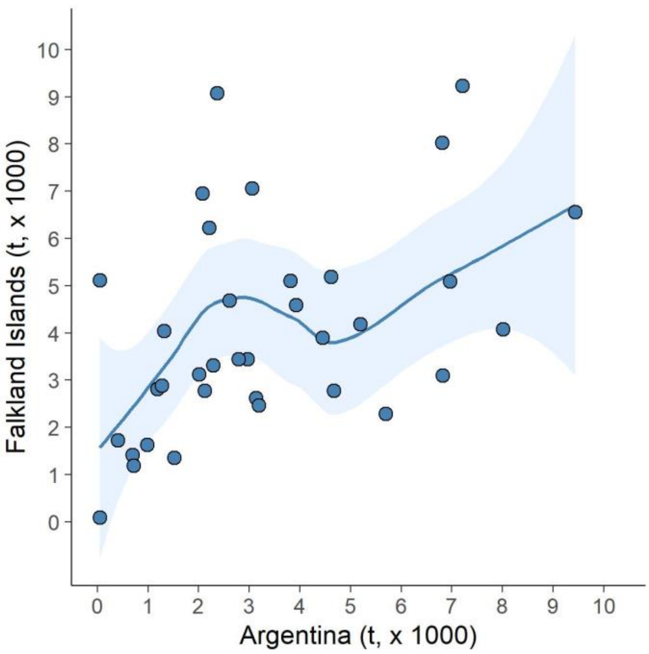


Fig. 2. Falkland Islands vs. Argentina annual commercial catches of red cod from 1987 to 2021, with LOESS smooth ± 95% confidence intervals (LOESS; span = 0.75, degree = 2).

From 1990 through 2021, approximately 90% of the annual red cod catch in the FICZ was from finfish licences (A–, G–, and W–licences). During 2021 a total of 1,194 t of red cod were reported caught in Falkland Islands waters, of which 1,187 t were caught under commercial licences, i.e., excluding the experimental E–licence. Approximately 44% of all Falkland Islands red cod catch was under W–licence, 27% was under A–licence, and 26% under G–licence in 2021; the three finfish licences (A–, G–, and W–licences) together accounted for 97% of the total red cod catch (Table I). Reported red cod discards were 1.5% of the total red cod catch in 2021; calamari vessels (C– and X–licences) discarded an average of 19% of their red cod catch, *Illex* vessels (B–licence) discarded 100%, and finfish vessels discarded an average of 0.8%.

Table I. Catch proportion of red cod by licence type in Falkland Islands waters during 2021.

Licence	Target species	Catch (t)	Catch (%)	Discard (t)	Proportion discarded (%)
W	Restricted finfish	524.579	43.93	7.702	1.47
A	Unrestricted finfish	321.875	26.96	2.767	0.86
G	Restricted finfish and *Illex*	313.785	26.28	0.609	0.19
C	Calamari 1st season	17.747	1.49	2.373	13.37
X	Calamari 2nd season	7.131	0.60	1.757	24.64
E	Experimental	7.015	0.59	0.931	13.27
B	*Illex* squid	1.440	0.12	1.440	100.00
F[a]	Skates and rays	0.000	0.00	0.000	0.00
L	Toothfish (longline)	0.000	0.00	0.000	0.00
S[a]	Southern blue whiting and hoki	0.000	0.00	0.000	0.00
O	Outside Falkland Islands waters	0.000	0.00	0.000	0.00
Total		1193.572	99.97	17.579	1.47

[a] F and S licenses were not fished during 2021.

Average CPUE ranged from 53 kg/h in 2020 to a maximum of 322 kg/h in 1996, although most values were below 250 kg/h. The CPUE trend showed two modes approximately 15 years apart; CPUE increased from 1990 to reach the highest CPUE in the time series in 1996 (322 kg/h), and declined towards 2003. CPUE increased again towards 2013 (232 kg/h) and declined to 55 kg/h in 2021 (Fig. 3).

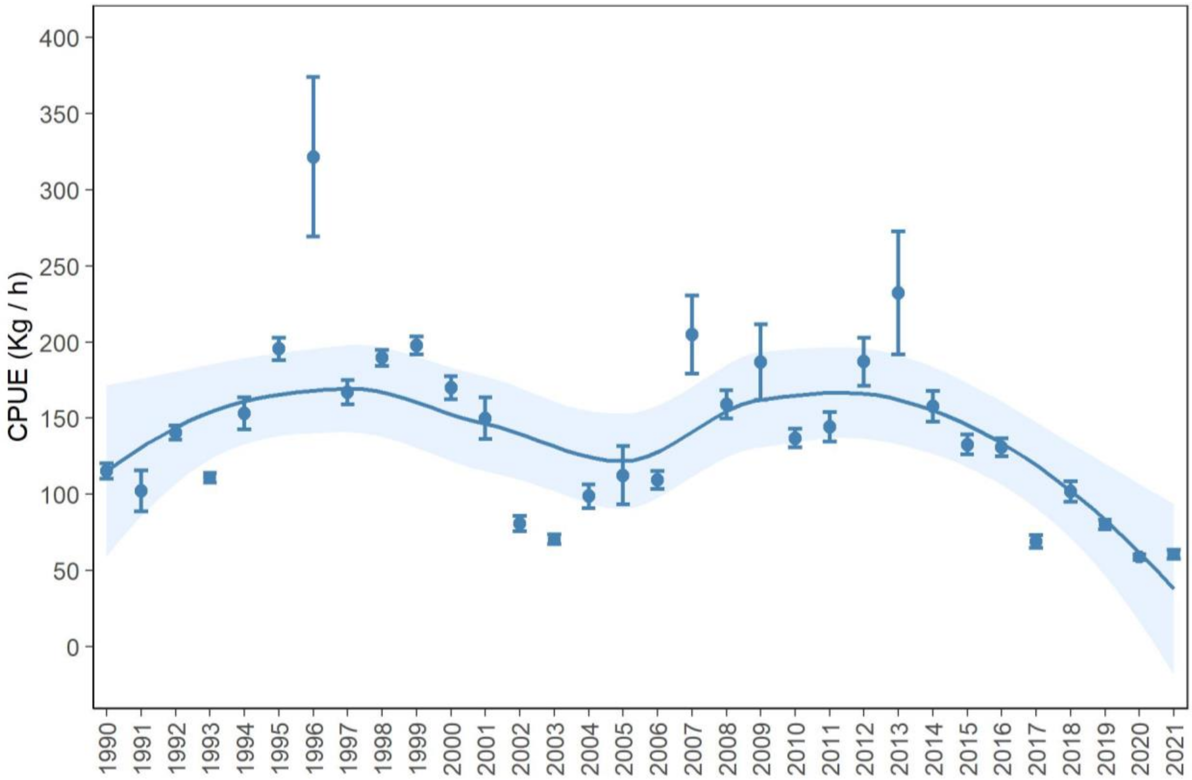


Fig. 3. Yearly CPUE ± 1 standard error of red cod in Falkland Islands waters from 1990 through 2021, calculated from finfish (A–, G–, and W–licences) vessels, with LOESS smooth ± 95% confidence intervals (LOESS; span = 0.75, degree = 2).

The monthly CPUE by finfish licences from 1990 through 2020 ranged between 82 kg/h and 140 kg/h; CPUE increased from January to March, and remained relatively high from March through May. CPUE declined towards July, and increased again from August through October. There was no fishing effort in January and February 2021, CPUE remained relatively similar from March through November and increased significantly in December (Fig. 4; Appendix II). During 2021, red cod were caught mainly to the west of West Falkland, between 50°S and 53°S, and between 62°W and 63°W; minor catches were also reported to the north in the FICZ (Appendix III).

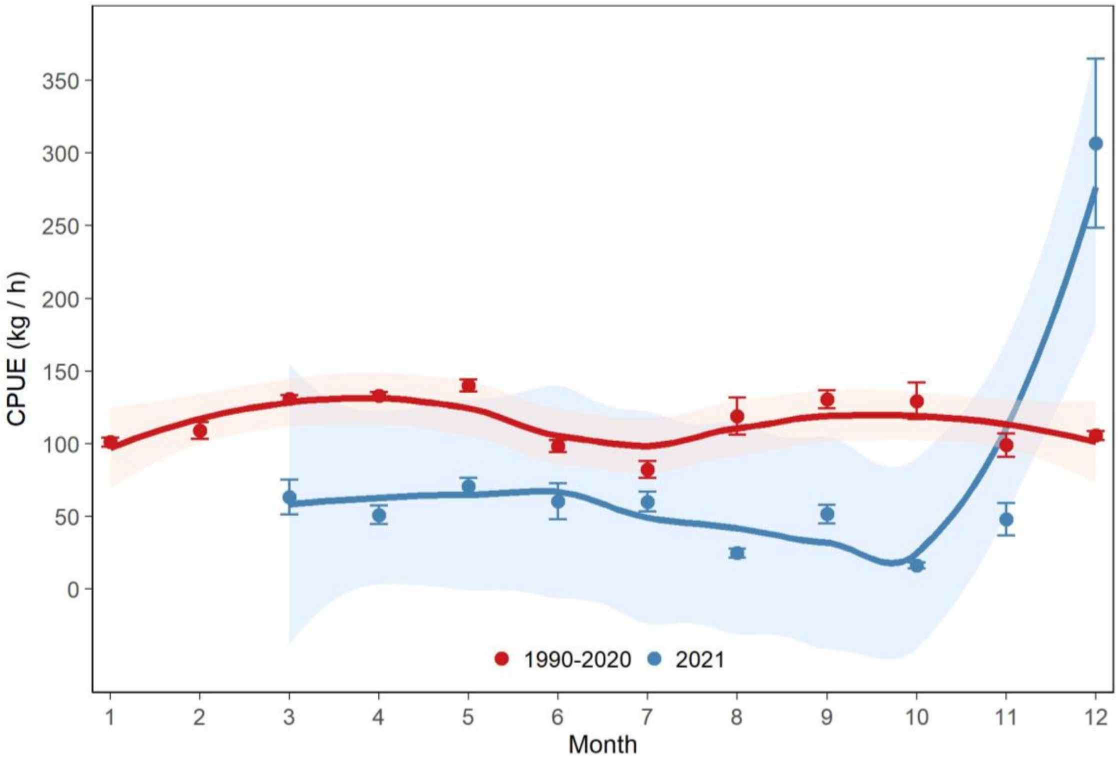


Fig. 4. Monthly average CPUE ± 1 standard error of red cod in Falkland Islands waters from 1990 through 2020 (red), and in 2021 (blue), calculated from finfish (A–, G–, and W–licences) vessels, with LOESS smooths ± 95% confidence intervals (LOESS; span = 0.75, degree = 2).

Surveys biomass estimates

Summer surveys (February)

The biomass of red cod during the February surveys did not change significantly from 2010 to 2022. The biomass of red cod in 2022 (81,176.73 t) was comparable to the biomass in 2010 (95,050.09 t; Table II; Fig. 5). Accordingly, only 5,776 out of 10,000 paired re-samples had higher biomass estimate values in February 2010 than in February 2022 (57.8%), therefore the difference in biomass between 2022 and 2010 is not significant at $p > 0.05$. During the February 2015–2018 surveys, red cod were mainly aggregated to the west edge of the FICZ. The aggregations were less dense and their distribution spread to the north and southwest of West Falkland during the February 2019–2022 surveys, with a decrease in the density of the aggregations compared with 2015–2018 (Appendix IV).

Table II. Summer (February) surveys catch and effort, and biomass estimates (mean ± 95% confidence intervals) of red cod in Falkland Islands waters.

Year	Survey	Trawls (n)	Swept area (km^2)	Effort (h)	Catch (kg)	CPUE (kg/h)	Biomass (t)
2010	Groundfish	87	17.04	87.52	13427.48	153.43	95050.09
	D. gahi	55	42.29	109.27	111.60	1.02	(18335.99–158897.80)
	Total	142	59.34	196.78	13539.08	68.80	
2011	Groundfish	88	17.21	88.00	23099.27	262.49	166617.50
	D. gahi	58	40.04	110.63	440.27	3.98	(39230.31–258711.16)
	Total	146	57.26	198.63	23539.54	118.51	
2015	Groundfish	89	16.72	90.17	20314.03	225.29	106244.23
	D. gahi	57	46.90	111.50	1495.40	13.41	(45278.81–160780.36)
	Total	146	63.61	201.67	21809.43	108.15	
2016	Groundfish	90	17.64	91.42	18644.48	203.95	102789.02
	D. gahi	56	54.46	107.92	1302.61	12.07	(28384.22–149860.74)
	Total	146	72.10	199.33	19947.08	100.07	
2017	Groundfish	90	18.52	92.00	11104.46	120.70	59568.95
	D. gahi	58	54.09	117.00	2717.14	23.22	(22863.35–86532.41)
	Total	148	72.62	209.00	13821.59	66.13	
2018	Groundfish[a]	97	20.47	96.42	12733.50	132.07	57422.88
	D. gahi	59	36.87	100.83	567.39	5.63	(19277.51–117355.42)
	Total	156	57.35	197.25	13300.89	67.43	
2019	Groundfish	79	17.22	79.00	10652.83	134.85	83005.12
	D. gahi	52	72.70	97.05	3029.02	31.21	(35235.62–119480.37)
	Total	131	89.93	176.05	13681.85	77.72	
2020	Groundfish[a]	80	17.04	79.95	3334.18	41.70	21889.98
	D. gahi	59	86.80	112.52	373.27	3.32	(10993.21–32014.04)
	Total	139	103.84	192.47	3707.45	19.26	
2021	Groundfish	80	16.43	79.48	5681.47	71.48	35217.39
	D. gahi	55	90.65	111.22	358.65	3.22	(22852.74–51663.11)
	Total	135	107.07	190.70	6040.12	31.67	
2022	Groundfish	42	9.22	41.90	9595.83	229.02	81176.73
	D. gahi	60	86.75	119.08	817.52	6.87	(34162.13–129660.26)
	Total	102	95.97	160.98	10413.34	64.69	

[a]An additional one-day transect of four trawls was taken in shallow inshore waters to sample for juvenile toothfish. These four trawls were not included in the analyses as their locations were not relevant to the distribution of red cod. Groundfish February surveys were not conducted in 2012, 2013, and 2014.

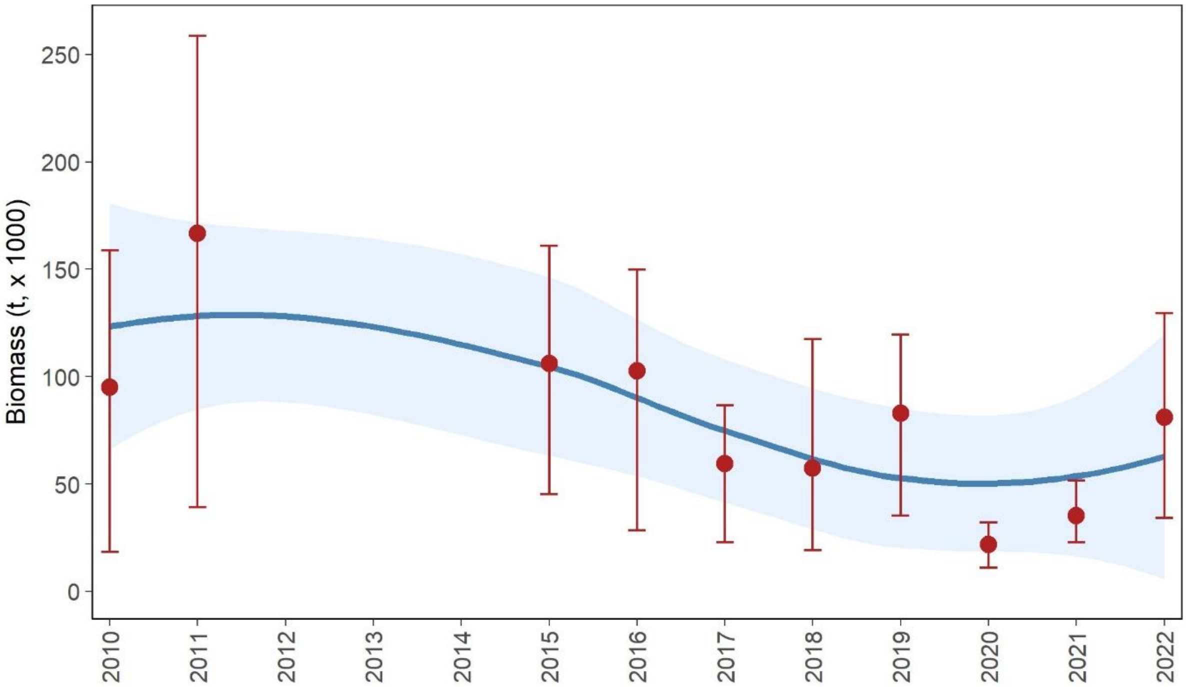


Fig. 5. Red cod biomass estimates (red dots) ± 95% confidence intervals from February surveys in Falkland Islands waters, with LOESS smooths ± 95% confidence intervals (LOESS; span = 1, degree = 2). No parallel February surveys (groundfish and Patagonian squid pre-season surveys) were conducted in 2012, 2013, and 2014.

Winter surveys (July)

The estimated biomass of red cod in the July 2020 survey (38,777 t) was 3× greater than in the July 2017 surveys (12,480; Table III). However, only 7,349 out of 10,000 paired re-samples had higher biomass estimate values in July 2020 than in July 2017 (73.5%), thus not significant at $p > 0.05$. In July 2017, aggregations of red cod were detected to the north and to the west in the FICZ, whereas in July 2020 red cod were mainly aggregated to the northwest limit of the FICZ (Appendix V). Differences in biomass estimates between February and July surveys are likely due to the migratory pattern of red cod.

Table III. Winter (July) surveys catch and effort, and biomass estimates (mean ± 95% confidence intervals) of red cod in Falkland Islands waters.

Year	Survey	Trawls (n)	Swept area (km^2)	Effort (h)	Catch (kg)	CPUE (kg/h)	Biomass (t)
2017	Groundfish	74	15.40	74	1784.05	24.11	12480.10 (6345.05 – 18207.66)
	D. gahi[a]	59	54.70	114	779.17	6.83	
	Total	133	70.10	188	2563.22	13.63	
2020	Groundfish[b]	33	7.14	33	2164.71	65.59	38776.73 (6143.58 – 68995.25)
	D. gahi	55	98.57	101	419.05	4.15	
	Total	88	105.71	134	2583.76	19.28	

[a]An additional one-day transect of four trawls was taken in shallow inshore waters to sample for juvenile toothfish. These four trawls were not included in analyses as their locations were not relevant to the distribution of red cod.
[b]Twelve additional trawls were conducted in high seas during the July 2020 survey; these trawls were not included in the analyses.
Note that no parallel July surveys (groundfish and Patagonian squid pre-season surveys) were conducted in 2018 and 2019.

Length and age analyses

Length Based Indicators

Yearly 'traffic light' length indicators for females and males are summarized in Table IV. Indicator $L_C/L50$, for conservation of immature fish, had positive outcomes (green) most years from 1992 to 2004, and had negative outcomes (red) most years from 2005 to 2021 for females. For males, this indicator was positive in 1996–1997, 2001–2002, and in 2008 but it was negative most years since 2003. Indicator $L_{25\%}/L50$, also for conservation of immature fish, had variable outcomes from 1992 to 2004 for females and males; however, negative outcomes were common since 2005. Indicator $L_{max5\%}/L_{Inf}$, for the conservation of large individuals, was of concern (yellow) from 2002 to 2009, 2013, and 2018–2019, and it was negative most years since 2010 for females. For males, this indicator was of concern most years from 2002 to 2021, except for 2005, 2012, 2014, and 2016 with negative outcomes. Indicator P_{mega}, for the presence of mega-spawners, was of concern most years from 2002 to 2008 for females, and in 2002 and 2008 for males; negative outcomes were common most years since 2009 for females, and since 2003 for males.

Indicator L_{meanC}/L_{Opt}, for optimal yield, had positive outcomes most years from 2002 to 2008 for females, and fluctuated between positive and of concern for males from 2002 to 2008; negative outcomes were common most years for both females and males since 2009. Indicator $L_{meanC}/L_{F=M}$, for maximum sustainable yield, was mostly positive from 2002 to 2021 for both females and males, except for a few years after 2009. Some LBI indicator outputs (Table IV) differ from the 2021 red cod stock assessment (Ramos and Winter 2021) due to length-age measurements from bottom trawl experimental (E–licence) being included in the current assessment, but not measurements from semi-pelagic trawls as in 2021.

Table IV. Red cod indicators by sex and year, with ‘traffic light’ scoring. L_C) Length at half the modal catch length; L50) Length at 50% maturity; $L_{25\%}$) Length at cumulative 25th percentile of catch; $L_{max5\%}$) Mean length of the largest 5% of individuals in the catch; L_{Inf}) Asymptotic average maximum body size; P_{mega}) Proportion of ‘Mega-spawners’ in the catch; L_{meanC}) Mean length of individuals larger than LC; L_{Opt}) Optimum length; $L_{F=M}$) Length-based proxy for MSY. Data were not available in some years (blank cells).

		Conservation				Optimal yield	MSY
Sex	Year	L_C / L50 >1	$L_{25\%}$ / L50 >1	$L_{max5\%}$ / L_{Inf} >0.8	P_{mega} >0.3	L_{meanC} / L_{Opt} ≈1	L_{meanC} / $L_{F=M}$ ≥1
	1992	0.70	0.88				
	1993	0.99	1.01				
	1994						
	1995	0.76	0.93				
	1996	1.12	1.18				
	1997	1.20	1.10				
	1998	1.27	1.16				
	1999						
	2000	0.37	0.45				
	2001	1.42	1.38				
	2002	1.28	1.22	0.75	0.04	0.99	0.97
	2003	1.19	1.03	0.74	0.04	0.96	0.95
	2004	1.16	1.12	0.85	0.30	1.07	1.05
	2005	0.50	0.85	0.83	0.12	0.78	1.18
F	2006	0.94	1.16	0.87	0.37	1.03	1.13
	2007	0.44	0.52	0.83	0.13	0.81	1.28
	2008	0.49	1.05	0.82	0.24	0.95	1.45
	2009	0.40	0.48	0.75	0.03	0.65	1.08
	2010			0.68	0.00	0.89	0.90
	2011	0.36	0.43	0.68	0.00	0.56	0.96
	2012	0.35	0.35	0.67	0.00	0.39	0.67
	2013	0.83	0.81	0.76	0.12	0.93	1.08
	2014	0.19	0.26	0.65	0.00	0.44	0.89
	2015	0.35	0.43	0.74	0.02	0.63	1.06
	2016	0.34	0.63	0.72	0.01	0.68	1.17
	2017						
	2018	1.04	0.96	0.72	0.00	0.93	0.95
	2019			0.67	0.00	0.50	0.80
	2020						
	2021	0.50	0.57				

Table IV. *continued…*

Sex	Year	Conservation L_C / L50 >1	$L_{25\%}$ / L50 >1	$L_{max5\%}$ / L_{Inf} >0.8	P_{mega} >0.3	Optimal yield L_{meanC} / L_{Opt} ≈1	MSY L_{meanC} / $L_{F=M}$ ≥1
	1992	0.88	0.88				
	1993	0.97	0.93				
	1994						
	1995						
	1996	1.14	1.16				
	1997	1.15	1.11				
	1998	0.96	0.98				
	1999						
	2000	0.89	0.89				
	2001	1.24	1.31				
	2002	1.27	1.20	0.91	0.36	1.12	1.05
	2003	0.75	0.95	0.77	0.05	0.80	1.03
	2004	0.72	0.91	0.87	0.19	0.85	1.13
	2005	0.56	0.86	0.71	0.01	0.71	1.05
M	2006	1.01	1.03	0.84	0.09	0.91	0.97
	2007	0.51	0.58	0.79	0.08	0.80	1.21
	2008	1.10	1.06	0.84	0.22	1.05	1.03
	2009	0.44	0.55	0.86	0.17	0.76	1.19
	2010	0.85	0.87	0.75	0.02	0.82	0.93
	2011	0.50	0.68	0.75	0.02	0.72	1.08
	2012	0.46	0.58	0.63	0.00	0.55	0.86
	2013	0.90	0.93	0.81	0.12	0.90	1.03
	2014	0.28	0.30	0.65	0.01	0.45	0.86
	2015	0.51	0.76	0.81	0.04	0.73	1.11
	2016	0.86	0.84	0.69	0.00	0.81	0.93
	2017						
	2018	0.69	0.78	0.67	0.01	0.74	0.94
	2019	0.46	0.71	0.61	0.01	0.64	0.97
	2020	0.78	0.72				
	2021	0.44	0.54				

Length-age relationship

The length-age relationship of females and males pooled (n = 8,283) gave the values: L_{Inf} = 100.77 cm, k = 0.0934, and t_0 = -0.5937 years. Length and age of females (n = 4,930) ranged from 9 cm to 90 cm, and from 1 year to 24 years, respectively. The length-age relationship of females gave the values: L_{Inf} = 103.79 cm, k = 0.0918, and t_0 = -0.5363 years. Length and age of males (n = 3,353) ranged from 9 cm to 86 cm and from 1 year to 22 years, respectively. The length-age relationship of males gave the values: L_{Inf} = 89.95 cm, k = 0.1070, and t_0 = -0.5984 years (Appendix VI). Yearly von Bertalanffy parameters are summarized in Appendix VII. Asymptotic lengths (L_{Inf}) did not change significantly from 2002 to 2019 (Fig. 6).

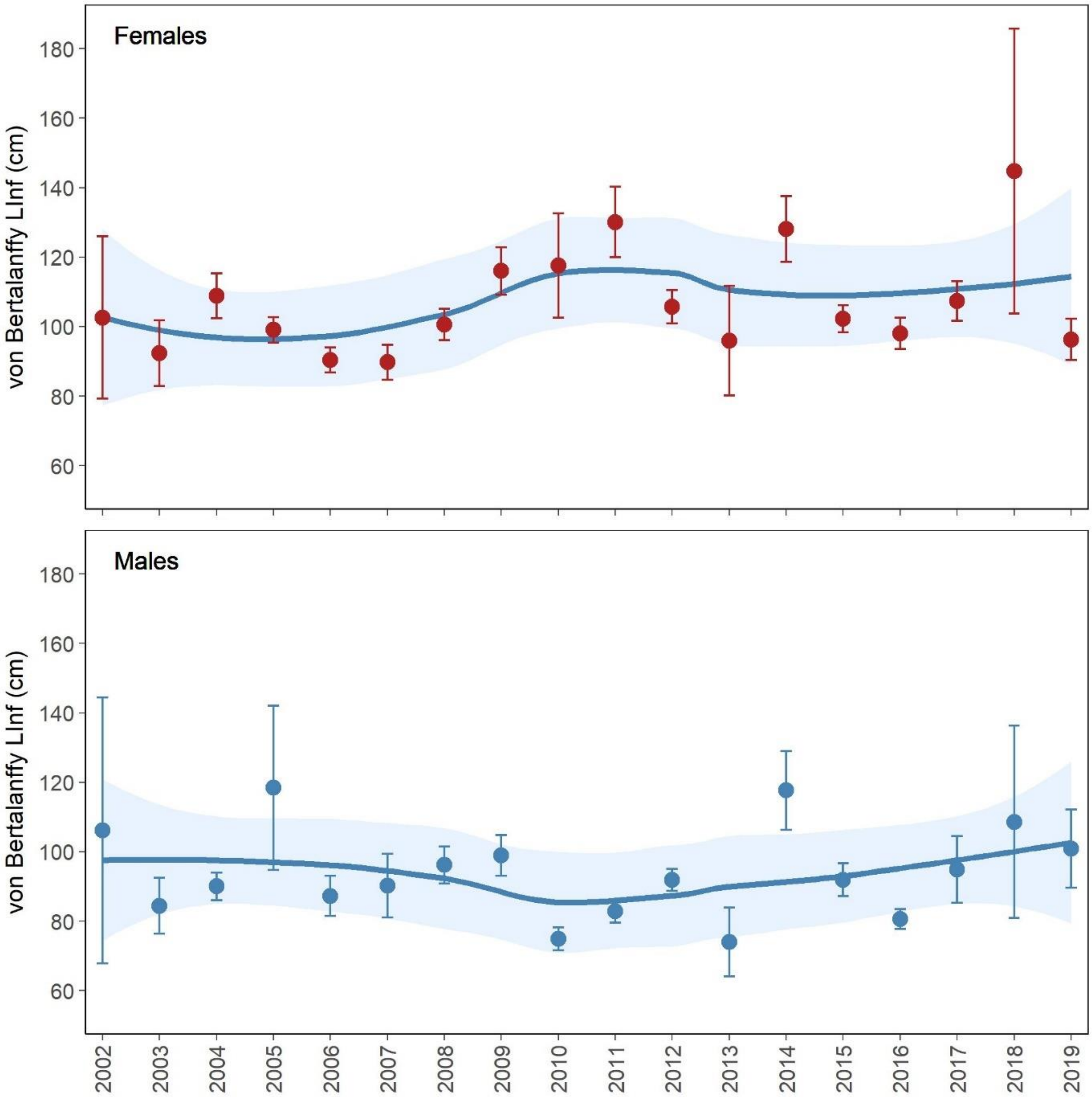


Fig. 6. Asymptotic lengths (L_{Inf}) ± 1 standard error calculated according to the von Bertalanffy growth function for female (red dots) and male (blue dots) red cod caught by finfish (A–, G–, and W–licences) and experimental (E–licence) vessels in the FICZ through the year, from 2002 through 2019, with LOESS smooths ± 95% confidence intervals (LOESS; span = 0.75, degree = 2).

Length and age at 50% maturity

Over the time series 1992–2021, length at 50% maturity (L50) of females was 50.9 ± 0.24 cm total length (n = 10,594) and age at 50% maturity (A50) was 6.8 years old; L50 of males was 44.5 ± 0.18 cm total length (n = 13,083) and A50 was 5.8 years old. Therefore, immature females are inferred as < 7 years old and mature females are inferred as ≥ 7 years old; immature males are inferred as < 6 years old and mature males are inferred as ≥ 6 years old. Annual L50 and A50 of females ranged from 33.6 cm and 3.7 years old in 2006 to 62.4 cm and 9.5 years old in 2011, respectively. Annual L50 and A50 of males ranged from 32.6 cm and 3.6 years old in 2006 to 68.7 cm and 12.9 years old in 2020. The L50 fit did not change significantly for females from 1992 through 2021 but it increased significantly for males in recent years (Fig. 7; Appendixes VIII–IX).

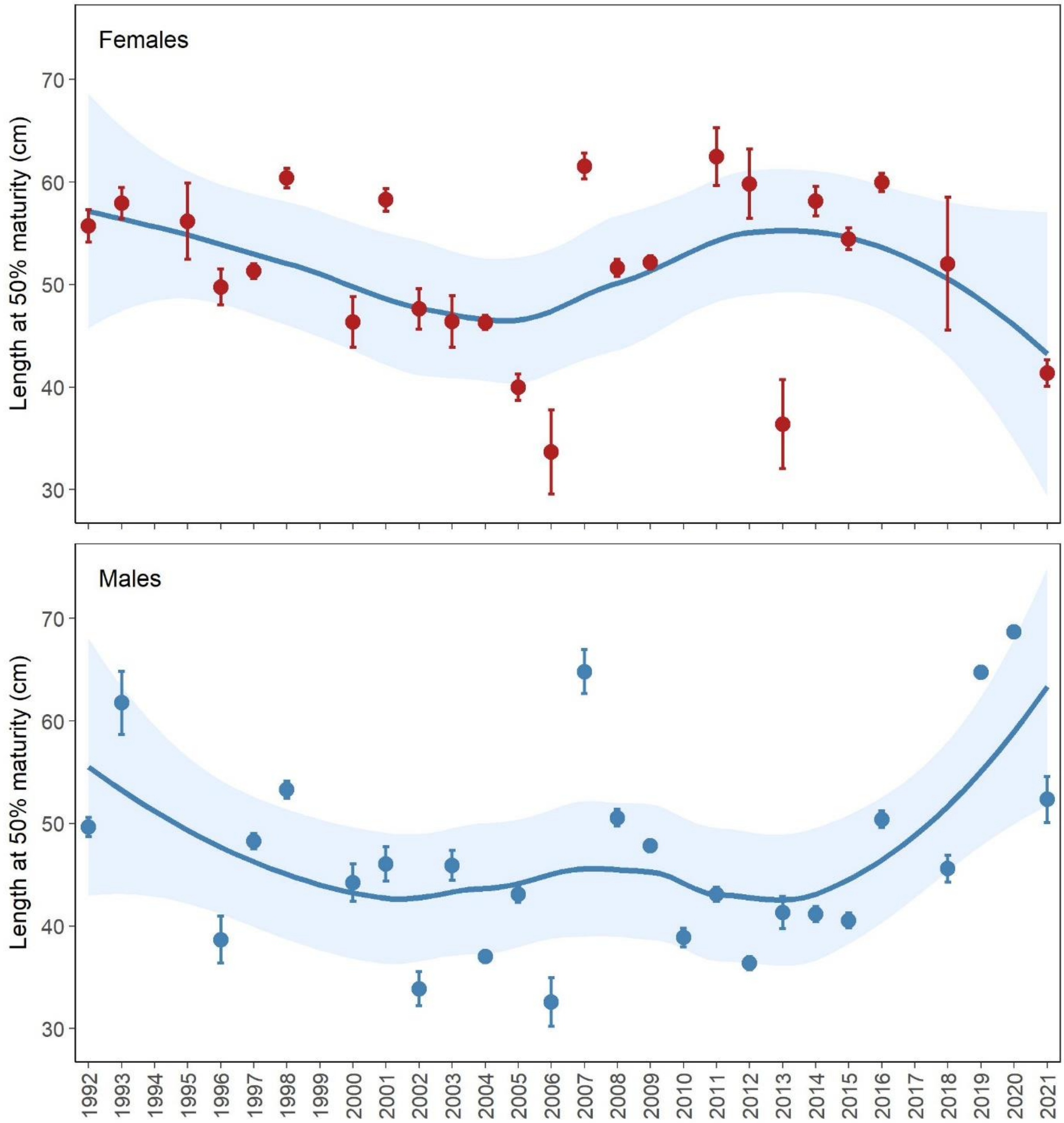


Fig. 7. Lengths at 50% maturity (L50) ± 1 standard error of female (red dots) and male (blue dots) red cod caught by finfish (A–, G–, and W–licences) and experimental (E–licence) vessels in the FICZ from August through October, from 1992 through 2021, with LOESS smooths ± 95% confidence intervals (LOESS; span = 0.75, degree = 2).

Catch at length

Female red cod (n = 85,555; 1990 to 2021) ranged from 9 cm to 97 cm total length, and males (n = 60,172; 1990 to 2021) ranged from 9 cm to 87 cm total length. Length-groups were not discernible due to size overlap most years. Females and males were mostly caught at > 40 cm total length from 2002 through 2008, smaller length-groups (< 40 cm total length) became dominant from about 2009 through 2021 (Fig. 8). The catch was mostly comprised of females and males at sizes ≤ L50 in 63% and 73% of the total number of years assessed (n = 32), respectively. Catch at length was ≥ L50 during a few years before 2008, and it was ≤ L50 from 2009 onwards (Fig. 8; Appendix X).

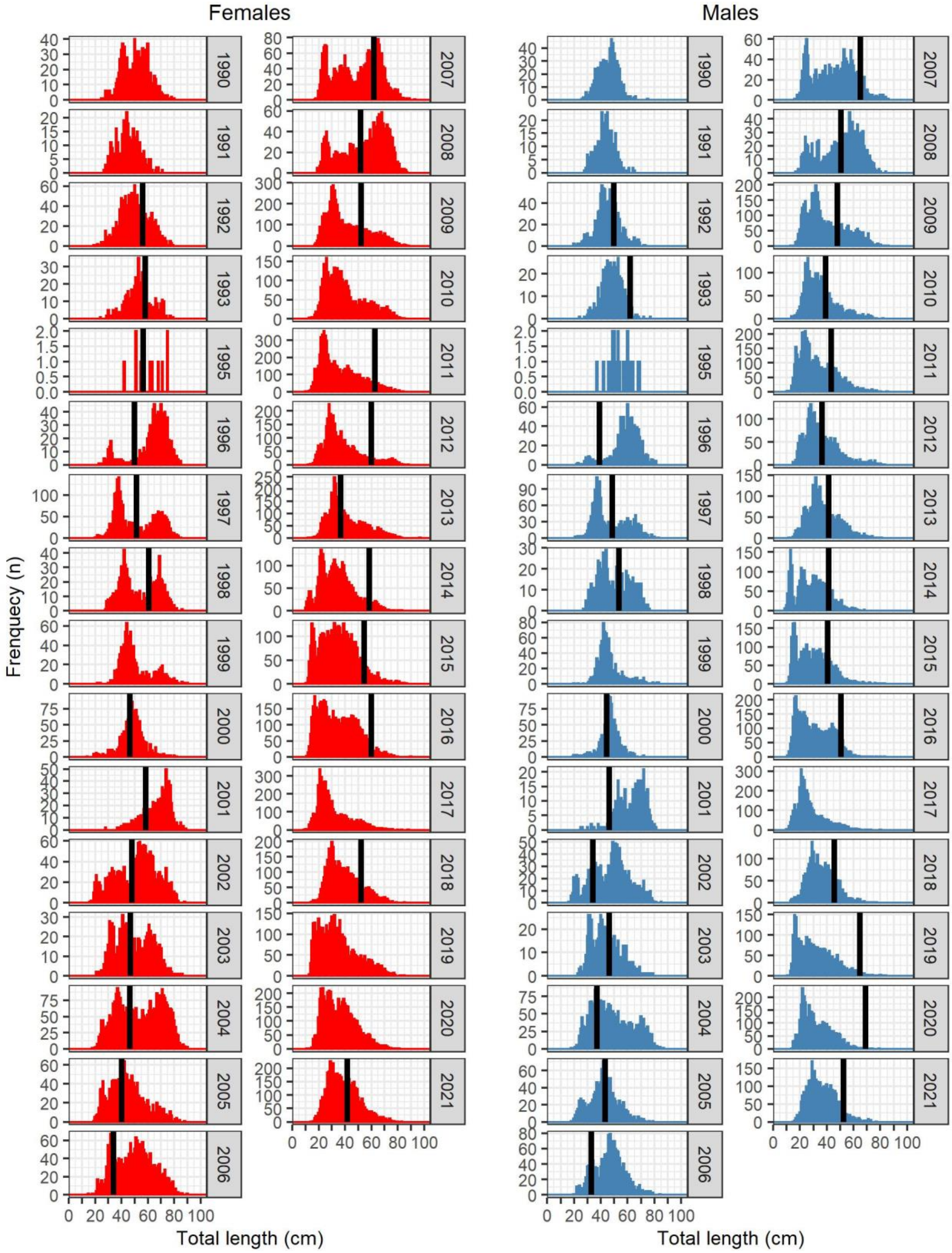


Fig. 8. Length frequency distribution of female and male red cod caught by finfish (A–, G–, and W–licences) and experimental (E–licence) vessels in the FICZ from 1990 through 2021. The black solid lines indicate the length at 50% maturity (L50). Note the gap in 1994 due to limited data.

Natural mortality

Equation 1 resulted in a natural mortality (M) calculation of:

$$M = 4.899 \times t_{max}^{-0.916} = 4.899 \times 24^{-0.916} = 0.2666$$

indicating that 26.6% of the stock dies per year not by fishing but due to natural causes such as predation, diseases, senility, amongst others.

Conclusions

Red cod Total Allowable Catch for 2023 was set at 1,439 t, calculated using the ICES category 3 framework, which represents an increase of 18% of the total commercial red cod catch in 2021 (1,186.6 t), and an increase of 20% of the TAC for 2022 (1,199 t).

Most of the red cod catch (97%) in Falkland Islands waters in 2021 was taken between the three finfish licences (A–, G–, and W–licences), with the greatest contribution to the catch by W–licence (44%).

Red cod commercial CPUE in the FICZ varied from 1990 to 2021; CPUE increased from 1990 through 1996, followed by a significant decline from 1997 through 2003. CPUE increased again towards 2013 and declined towards 2021. Intra-annually, the highest CPUE of red cod occurred from March through May, and from August through October.

February surveys biomasses showed no significant change in red cod abundance from 2010 through 2022; however, February surveys likely reflect variability in the migratory timing of this species. The 2017 and 2020 July surveys revealed comparable red cod biomasses, with overlapping confidence intervals.

Length-based indicators suggest that conservation of immature fish, large individuals, mega-spawners, and optimal yield were of concern or negative most years, whereas MSY was of concern or negative since about 2010. However, red cod spawning grounds to the south and southwest of West Falkland were closed for fishing since 2010 and large individuals were not targeted (A. Arkhipkin *pers. comm.*). This may have resulted in the decrease of CPUE during the months when spawning aggregations occur, i.e., August through October, which may also affect the LBI outcomes for large individuals and for mega-spawners encountered over the past decade.

The length and age analyses showed no significant change for L_{Inf} from 2002 to 2019, and of length at 50% maturity of females from 1992 to 2021. Comparison of length at 50% maturity and catch at length revealed that red cod were mostly caught before reaching maturity, which can reduce stock sustainability (Vasilakopoulos et al. 2011; Muluye et al. 2016; Ben-Hasan et al. 2021).

The multiple analyses used in this study suggest that the red cod stock is currently in poor condition and conservation measures should be implemented. Control of fishing pressure, and of by-catch and discard of small individuals of no commercial value should be of high importance in Falkland Islands fisheries given the trends detected.

References

Arkhipkin A, Brickle P, Laptikhovsky V (2010) The use of island water dynamics by spawning red cod, *Salilota australis* (Pisces: Moridae) on the Patagonian Shelf (Southwest Atlantic). Fisheries Research 105: 156–162. https://doi.org/10.1016/j.fishres.2010.03.022

Arkhipkin A, Brickle P, Laptikhovsky V, Winter A (2012) Dining hall at sea: feeding migrations of nektonic predators to the eastern Patagonian Shelf. Journal of Fish Biology 81: 882–902. https://doi.org/10.1111/j.1095-8649.2012.03359.x

Ben-Hasan A, Walters C, Hordyk A, Christensen V (2021) Alleviating Growth and Recruitment Overfishing through Simple Management Changes: Insights from an Overexploited Long-Lived Fish. Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science 13, 87–98. https://doi.org/10.1002/mcf2.10140

Beverton RJH (1992) Patterns of reproductive strategy parameters in some marine teleost fishes. Journal of Fish Biology 41: 137–160.

Brickle P, Laptikhovsky V, Arkhipkin A (2005) Reproductive strategy of a primitive temperate notothenioid *Eleginops maclovinus*. Journal of Fish Biology 66, 1044–1059. https://doi.org/10.1111/j.1095-8649.2005.00663.x

Brickle P, Laptikhovsky V, Arkhipkin A (2011) The reproductive biology of a shallow water morid (*Salilota australis* Günther, 1878), around the Falkland Islands. Estuarine, Coastal and Shelf Science 94: 102–110.

Chong Follert L, Contreras MF, Quiroz JC (2017) Biología reproductiva y aspectos poblacionales de la brótula (*Salilota australis*) en la zona sur-austral de Chile: consideraciones para el manejo de la pesquería. Latin American Journal of Aquatic Research 45: 787–796.

Cohen DM, Inada T, Iwamoto T, Scialabba N (1990) FAO species catalogue. Vol. 10. Gadiform fishes of the world (Order Gadiformes). An annotated and illustrated catalogue of cods, hakes, grenadiers and other gadiform fishes known to date. FAO Fish. Synop. 125(10). Rome: FAO. 442 p.

Cope JM, Punt AE (2009) Length-based reference points for data-limited situations: Applications and restrictions. Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science 1: 169–186.

Falkland Islands Government (1989) Fisheries Department Fisheries Report 87/88, Vol. 1. FIG Stanley, Fisheries Department. 45 p.

Falkland Islands Government (2021) Fisheries Department Fisheries Statistics, Vol. 25. FIG Stanley, Fisheries Department. 98 p.

FAO (1999) FAO Fisheries Technical Paper. No. 382. Rome, FAO. 113 p.

Froese R (2004) Keep it simple: three indicators to deal with overfishing. Fish and Fisheries 5: 86–91.

Froese R, Binohlan C (2000) Empirical relationships to estimate asymptotic length, length at first maturity and length at maximum yield per recruit in fishes, with a simple method to evaluate length frequency data. Journal of Fish Biology 56: 758–773.

Froese R, Winker H, Coro G, Demirel N, Tsikliras AC, Dimarchopoulou D, Scarcella G, Probst WN, Dureuil M, Pauly D (2018) A new approach for estimating stock status from length frequency data. ICES Journal of Marine Science 75: 2004–2015. https://doi.org/10.1093/icesjms/fsy078

Gras M, Pompert J, Blake A, Busbridge T, Boag T, Huillier JT, Concha F (2017) Report of the 2017 ground fish survey ZDLT1–07–2017. Fisheries Department, Directorate of Natural Resources, Falkland Islands Government, Stanley, Falkland Islands. 68 p.

Haddon M (2001) Modelling and quantitative methods in fisheries. Chapman & Hall/CRC, Boca Raton, Florida. 406 pp.

Heino M, Dieckmann U, Godø OR (2002) Measuring probabilistic reaction norms for age and size at maturation. Evolution 56: 669–678.

ICES (2012) ICES Implementation of Advice for Data limited Stocks in its 2012 Advice. http://www.ices.dk/sites/pub/Publication%20Reports/Expert%20Group%20Report/acom/2012/ADHOC/DLS%20Guidance%20Report%202012.pdf

ICES (2015) Report of the Fifth Workshop on the Development of Quantitative Assessment Methodologies based on Life-history Traits, Exploitation Characteristics and other

Relevant Parameters for Data-limited Stocks (WKLIFE V), 5–9 October 2015, Lisbon, Portugal. ICES CM 2015/ACOM: 56. 157 p.

ICES (2018a) General context of ICES advice. https://www.ices.dk/sites/pub/Publication%20Reports/Advice/2018/2018/Introduction_to_advice_2018.pdf

ICES (2018b) ICES technical guidelines. ICES reference points for stocks in categories 3 and 4. http://www.ices.dk/sites/pub/Publication%20Reports/Guidelines%20and%20Policies/16.04.03.02_Category_3-4_Reference_Points.pdf

Jensen AL (1996) Beverton and Holt life history invariants result from optimal trade-off of reproduction and survival. Canadian Journal of Fisheries and Aquatic Sciences 53: 820–822.

Lee B, Shcherbich Z, Randhawa H (2020) Towards the development of an ageing strategy for finfish in the Falkland Islands trawl fisheries. Technical Document, FIG Fisheries Department. 23 p.

Marín-Martínez F, Sánchez-Meca J (2010) Weighting by inverse variance or by sample size in random-effects meta-analysis. Educational and Psychological Measurement 70: 56–73.

MEP (2020) Annex 3: Review of Finfish Stock Assessments. Report for Falkland Islands Government. MacAlister Elliot & Partners Ltd. 47 p.

Muluye T, Tekle-Giorgis Y, Tilahun G (2016) The Extent of Immature Fish Harvesting by the Commercial Fishery in Lake Hawassa, Ethiopia. Momona Ethiopian Journal of Science 8, 37–49. https://doi.org/10.4314/mejs.v8i1.3

Navarro G, Rozycki V, Monsalvo M (2014) Estadísticas de la pesca marina en la Argentina. Evolución de los desembarques 2008-2013. Ministerio de Agricultura, Ganaderia y Pesca de la Nación. Buenos Aires, 144 p.

Navarro G, Rozycki V, Monsalvo M (2019) Estadísticas de la pesca marina en Argentina. Evolución de los desembarques 2012-2016. Secretaria de Gobierno de Agroindustria, 147 p.

Nelson GA (2019) Package ‘fishmethods’: Fishery science methods and models from published literature and contributions from colleagues. R package version 1.11-1.

Nikolsky GV (1963) *The Ecology of Fishes*. New York, USA: Adademic Press. In Brickle P, Laptikhovsky V, Arkhipkin A (2005) Reproductive strategy of a primitive temperate notothenioid *Eleginops maclovinus*. Journal of Fish Biology 66, 1044–1059. https://doi.org/10.1111/j.1095-8649.2005.00663.x

R Core Team (2021). RStudio: Integrated Development Environment for R. RStudio, PBC, Boston, MA URL http://www.rstudio.com/

Ramos JE, Winter A (2021) Stock assessment of red cod (*Salilota australis*) in the Falkland Islands. SA–2021–BAC. Fisheries Department, Directorate of Natural Resources, Falkland Islands Government, Stanley, Falkland Islands. 50 p.

Ramos JE, Winter A (2022) February bottom trawl survey biomasses of fishery species in Falkland Islands waters, 2010–2022. SA–2022–05. Fisheries Department, Directorate of Natural Resources, Falkland Islands Government, Stanley, Falkland Islands. 86 pp.

Randhawa HS, Blake A, Trevizan T, Brewin J, Evans D, Kairua T, Büring T (2020) Cruise Report ZDLT1-07-2020: 2020 Hake Demography Survey. Fisheries Department, Directorate of Natural Resources, Falkland Islands Government, Stanley, Falkland Islands. 135 p.

Sánchez R, Navarro G, Rozycki V (2012) Estadísticas de la pesca marina en la Argentina. Evolución de los desembarques 1898-2010. Ministerio de Agricultura, Ganaderia y Pesca de la Nación. Buenos Aires, 528 p.

Then AY, Hoenig JM, Hall NG, Hewitt DA (2015) Evaluating the predictive performance of empirical estimators of natural mortality rate using information on over 200 fish species. ICES Journal of Marine Science 72: 82 – 92.

Vasilakopoulos P, O'Neill FG, Marshall CT (2021) Misspent youth: does catching immature fish affect fisheries sustainability? ICES Journal of Marine Science 68, 1525–1534. https://doi.org/10.1093/icesjms/fsr075

Winter A, Ramos JE, Shcherbich Z, Tutjavi V, Matošević N (2020) 2020 2nd Season Assessment Survey Falkland calamari (*Doryteuthis gahi*). Technical Document, FIG Fisheries Department. 17 p.

Winter A, Shcherbich Z, Iriarte V, Derbyshire C (2017) *Doryteuthis gahi* Stock Assessment Survey, 2nd Season 2017. Technical Document, FIG Fisheries Department. 25 p.

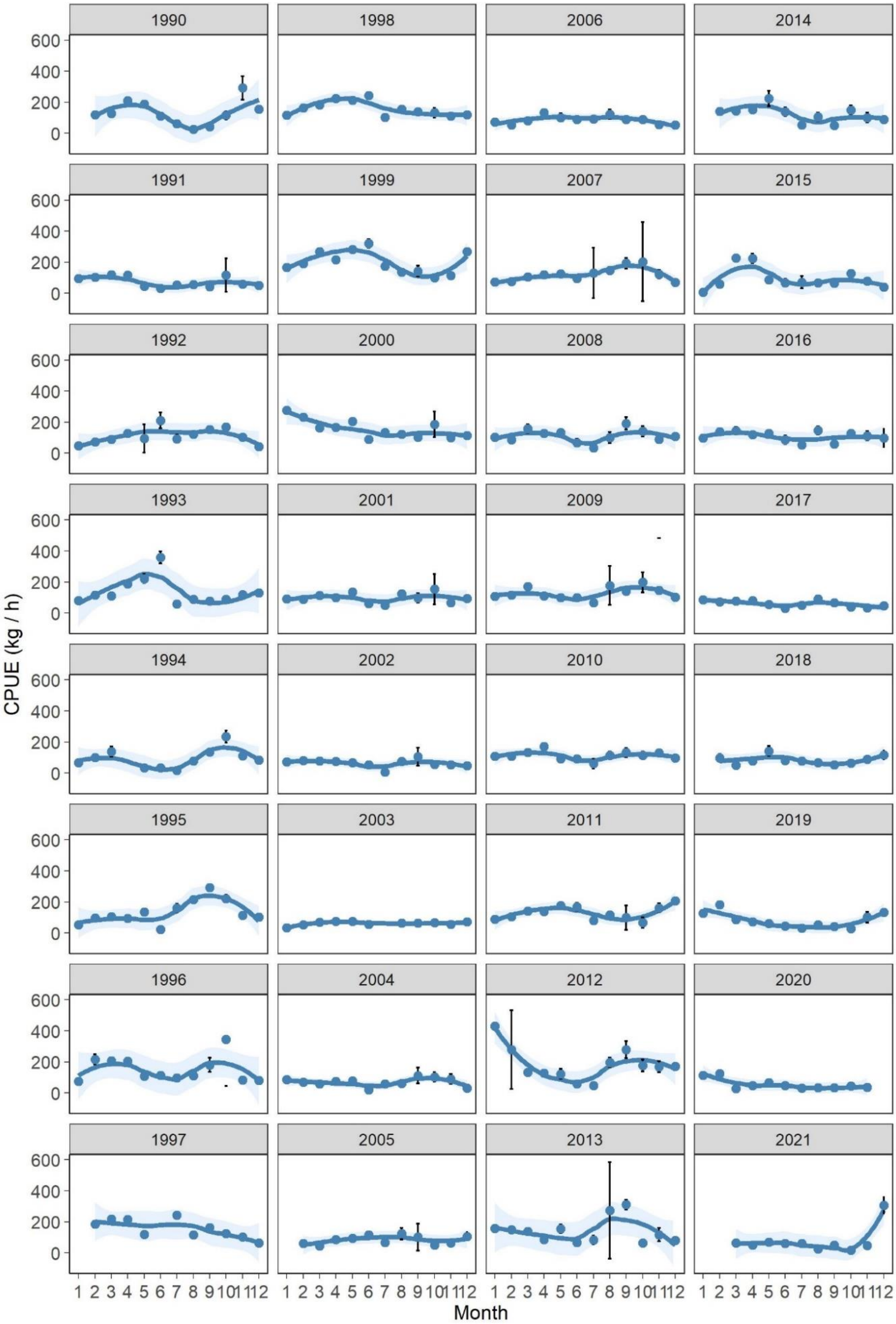
Appendix

Appendix I. Annual commercial catches (t) of red cod reported in Falkland Islands (excluding E–licence; Falkland Islands Government[e]; Falkland Islands Government 2021) and Argentina (Argentine Government[f]; Sánchez et al. 2012; Navarro et al. 2014, 2019).

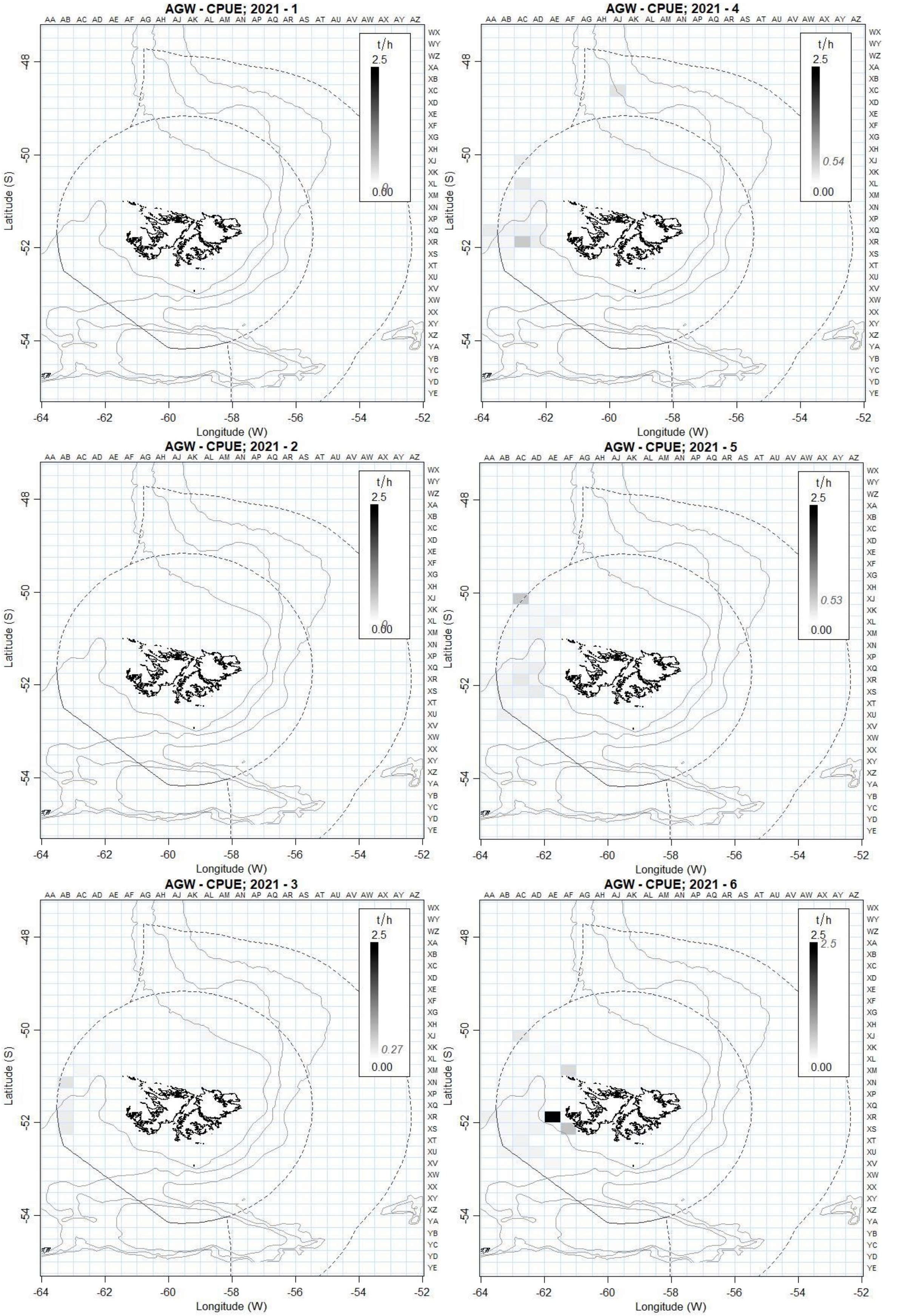
Year	Falkland Islands (t)	Argentina (t)
1987	88.0	46.9
1988	5121.0	47.5
1989	2817.0	1186.0
1990	2778.3	2115.5
1991	2879.6	1272.2
1992	7056.9	3050.0
1993	6230.6	2207.3
1994	4042.8	1310.4
1995	9085.0	2359.3
1996	6960.5	2077.0
1997	4691.3	2610.4
1998	8028.4	6808.5
1999	9234.9	7202.9
2000	6556.3	9431.3
2001	3896.2	4449.0
2002	2617.2	3129.1
2003	2283.9	5689.1
2004	2779.6	4664.3
2005	2465.1	3185.5
2006	3440.2	2962.0
2007	5191.6	4609.8
2008	4075.3	8009.5
2009	5093.7	6962.7
2010	3098.9	6813.0
2011	4184.2	5190.7
2012	4590.5	3921.9
2013	5103.4	3814.9
2014	3447.0	2780.1
2015	3312.4	2289.2
2016	3122.1	2008.3
2017	1363.0	1511.2
2018	1637.5	977.6
2019	1725.5	396.6
2020	1413.7	685.8
2021	1186.6	714.5

[e] http://www.fig.gov.fk/fisheries/publications/fishery-statistics
[f] https://www.agroindustria.gob.ar/sitio/areas/pesca_maritima/desembarques/

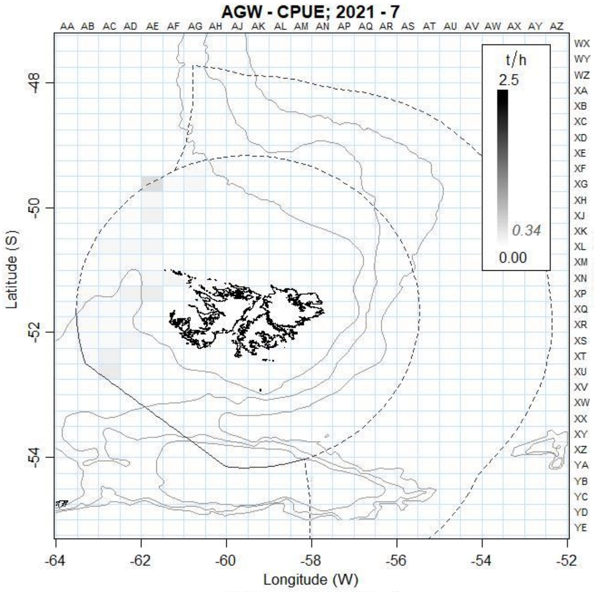
Appendix II. Monthly CPUE of red cod in Falkland Islands waters from 1990 to 2021, calculated from finfish (A–, G–, and W–licences) vessels, with LOESS smooths ± 95% confidence intervals (LOESS; span = 0.75, degree = 2).

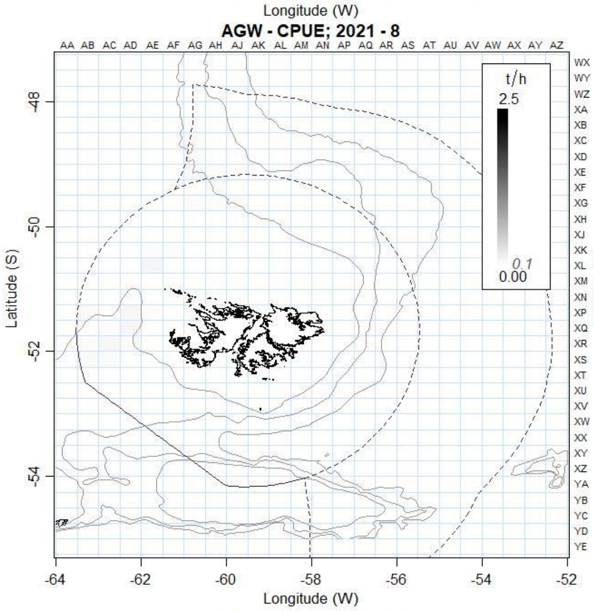


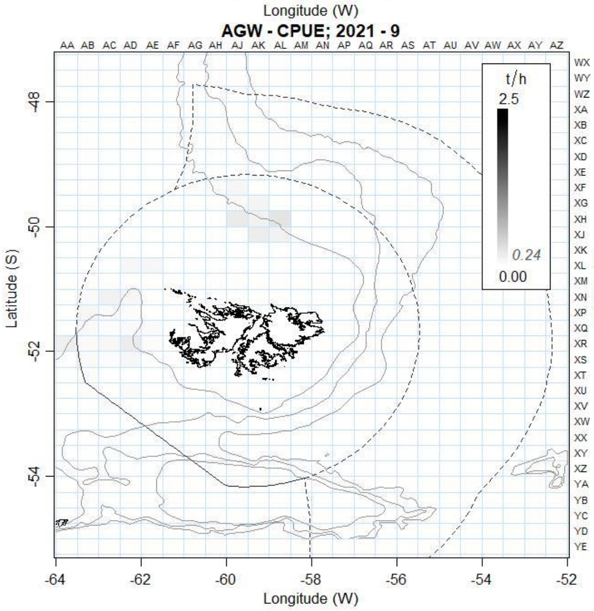
Appendix III. Monthly CPUE of red cod in Falkland Islands waters during 2021, calculated from finfish (A–, G–, and W–licences) vessels. There was no fishing effort during January and February under finfish licences.

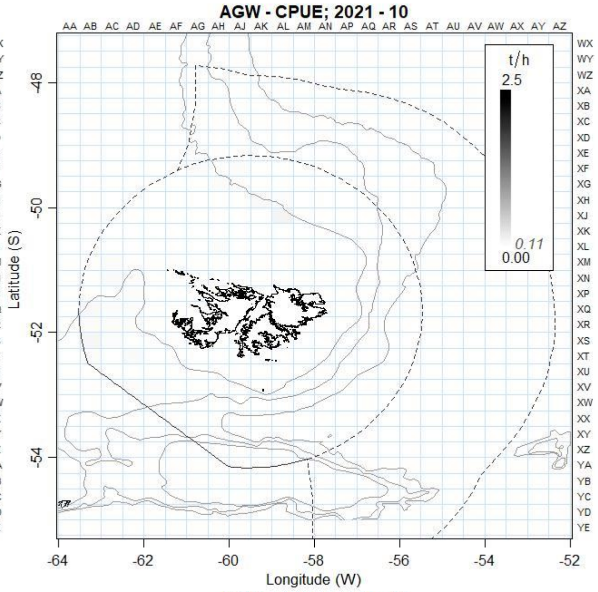


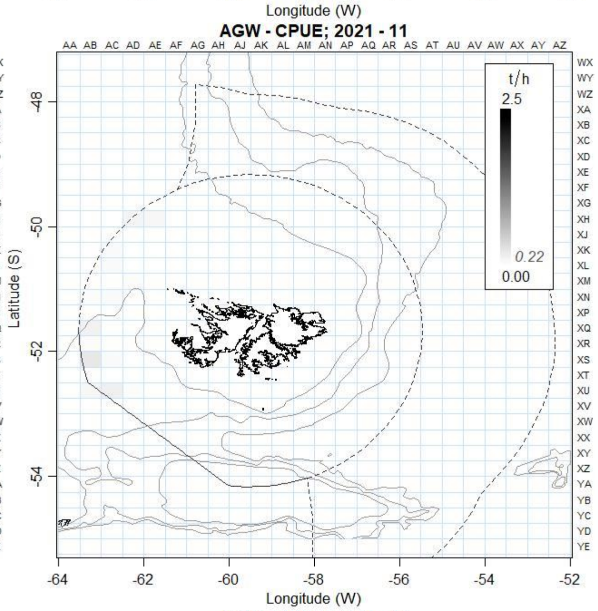
Appendix III. *continued…*

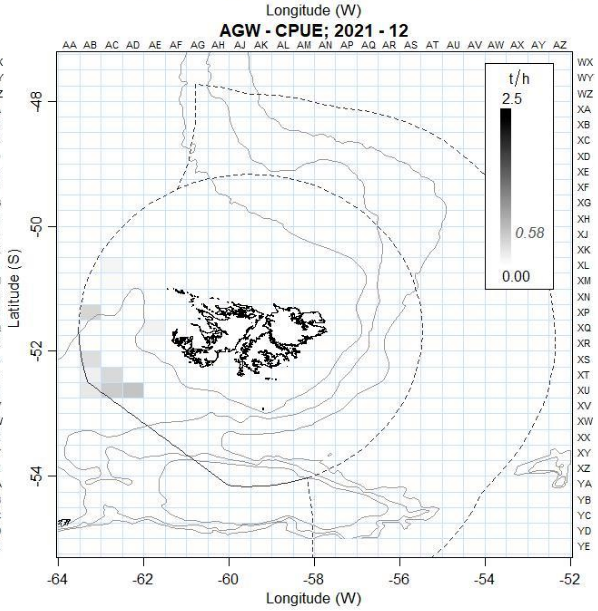




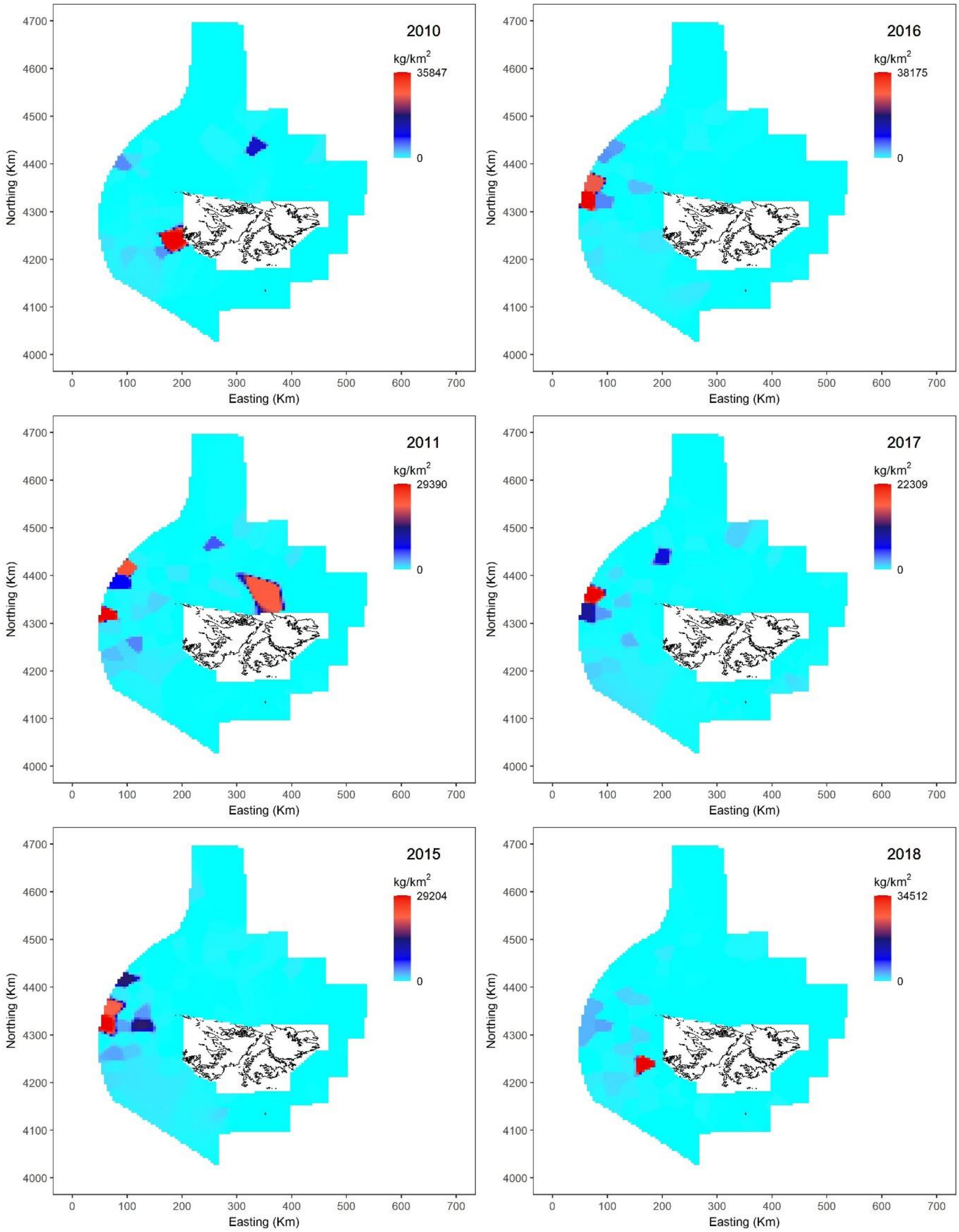




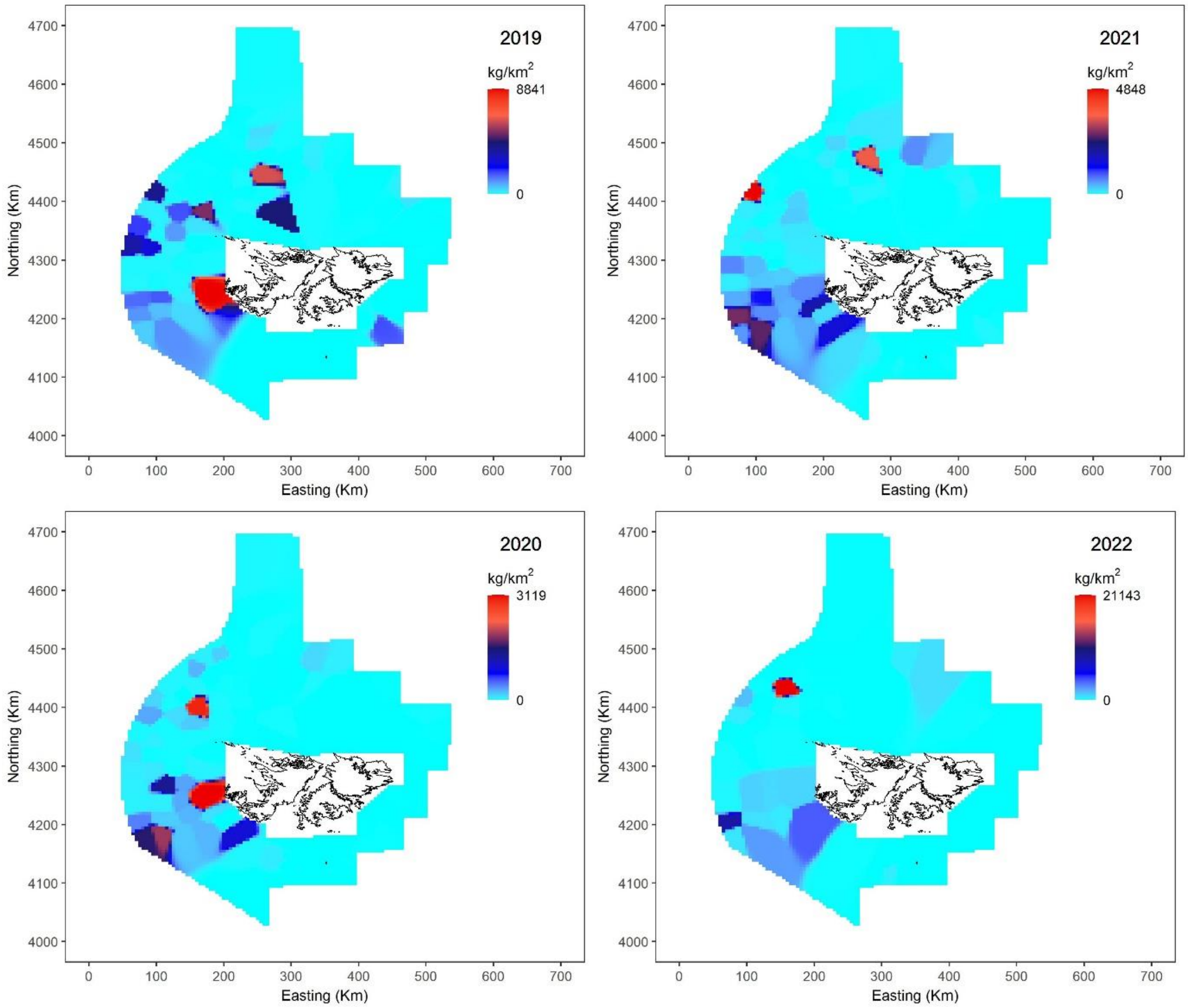




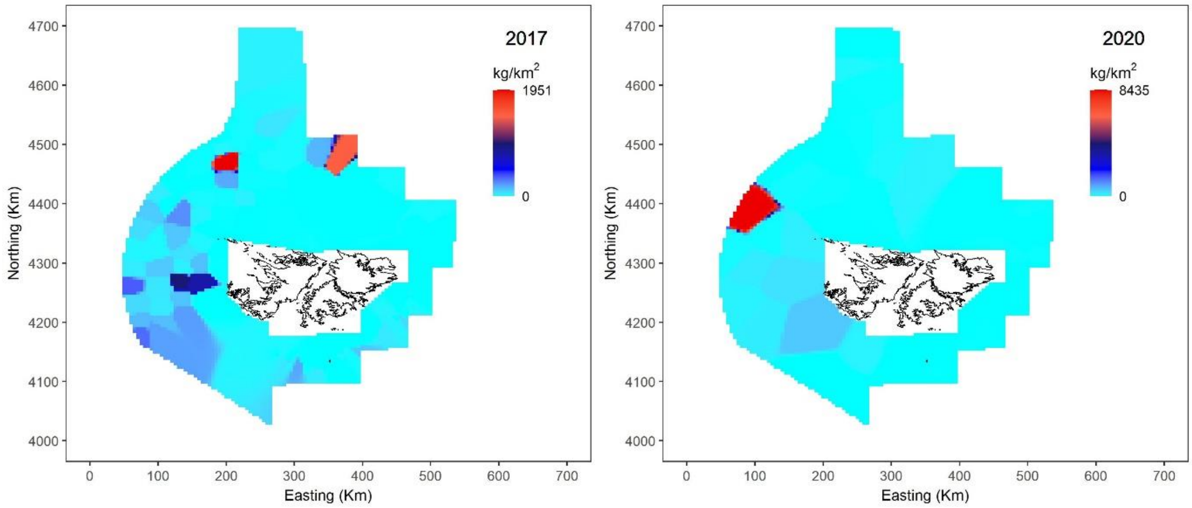
Appendix IV. Densities of red cod modelled by inverse distance weighting in the FICZ, during the February 2010–2022 groundfish and Patagonian squid pre-season surveys.



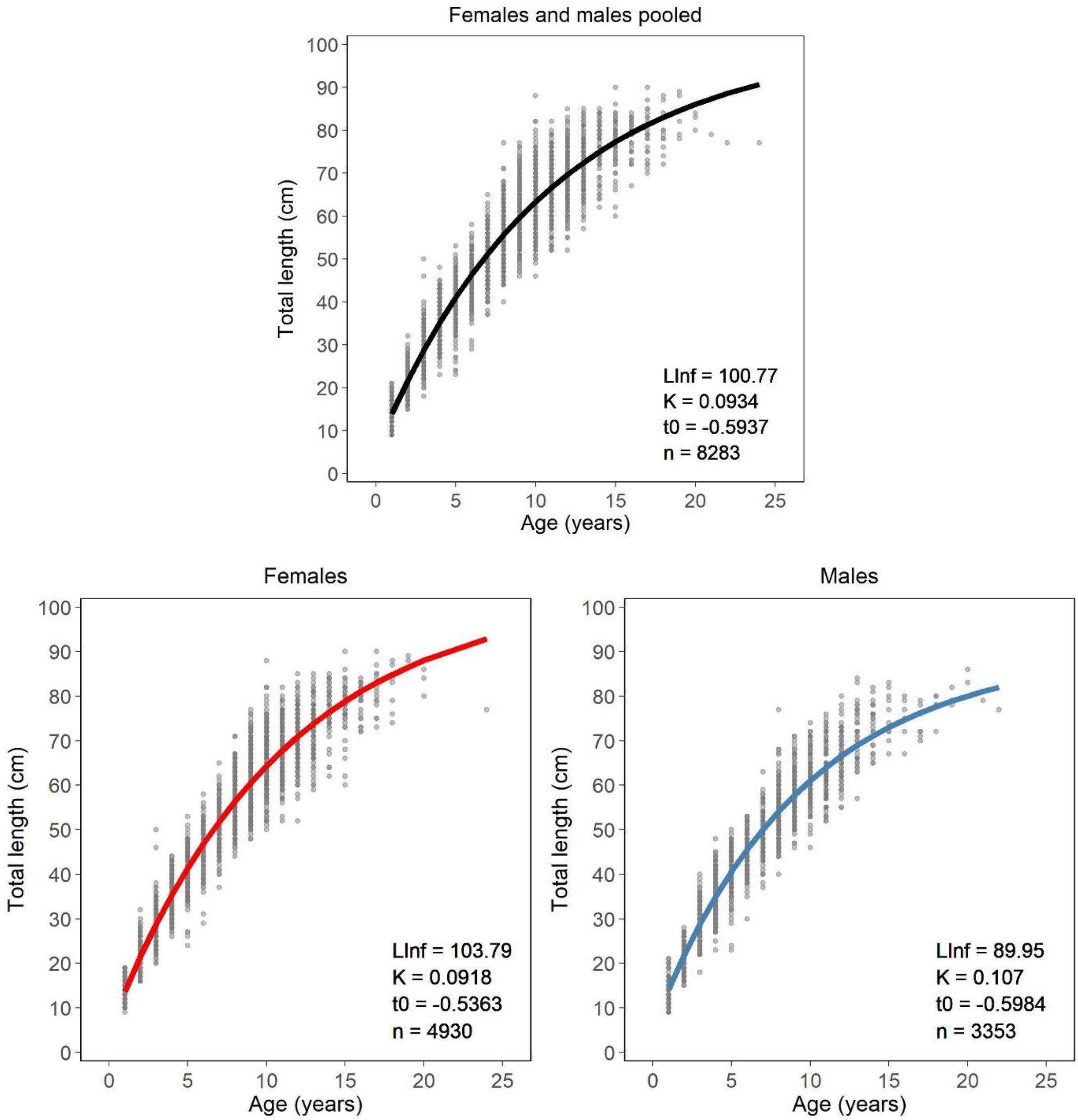
Appendix IV. *continued…*



Appendix V. Densities of red cod modelled by inverse distance weighting in the FICZ, during the July 2017 and July 2020 groundfish and Patagonian squid pre-season surveys.



Appendix VI. von Bertalanffy age-length relationship of female and male red cod collected in finfish (A–, G–, and W–licences) and experimental (E–licence) vessels in the FICZ. Age was determined by MFRI (n = 8,207) and FIFD (n = 76) staff.

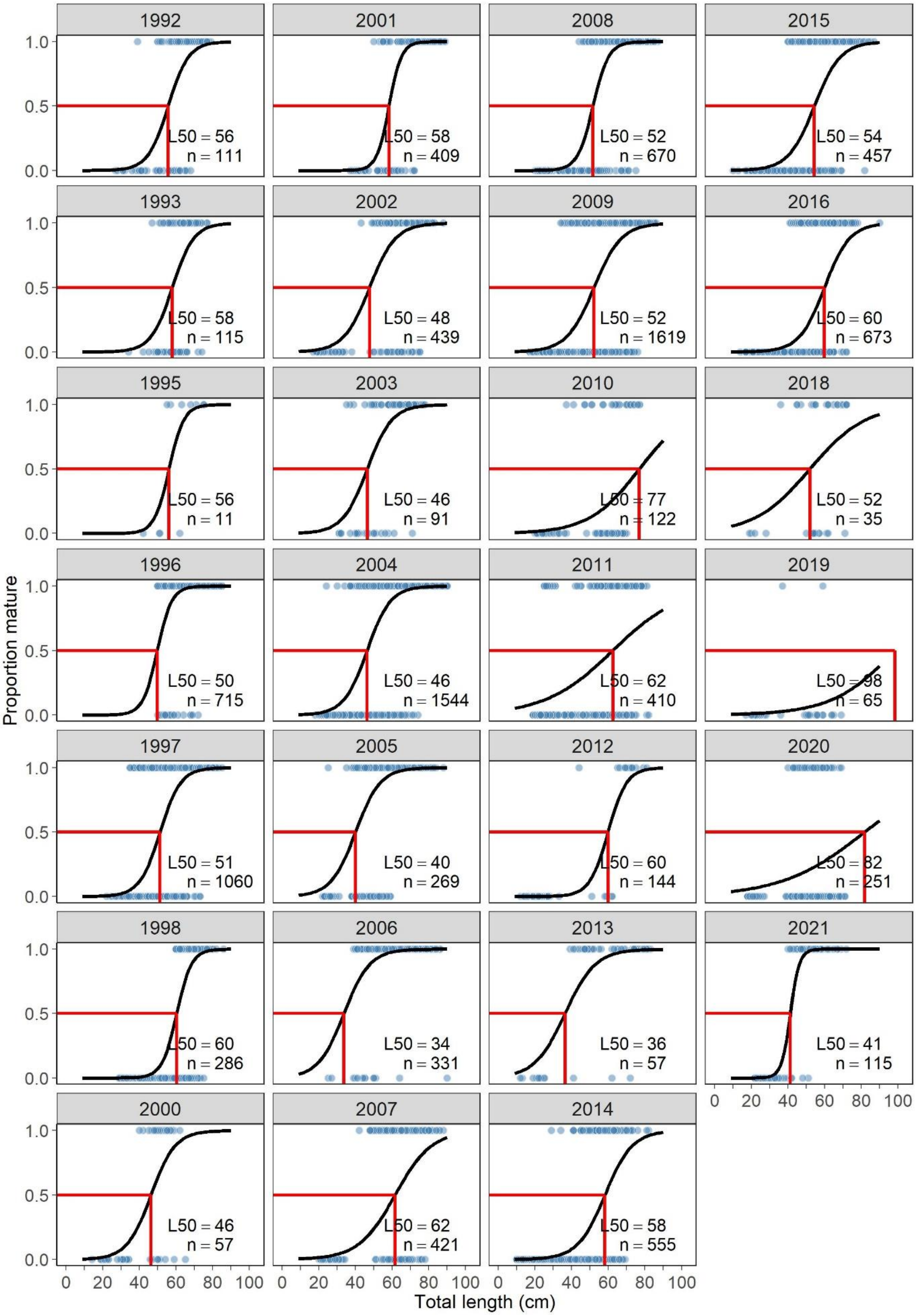


Appendix VII. Red cod von Bertalanffy length-at-age parameters for curvature (k), age of fish at length zero (t_0), and asymptotic length (L_{Inf}), by year and sex, with 95% confidence intervals. Red cod were collected in finfish (A–, G–, and W–licences) and experimental (E–licence) vessels in the FICZ.

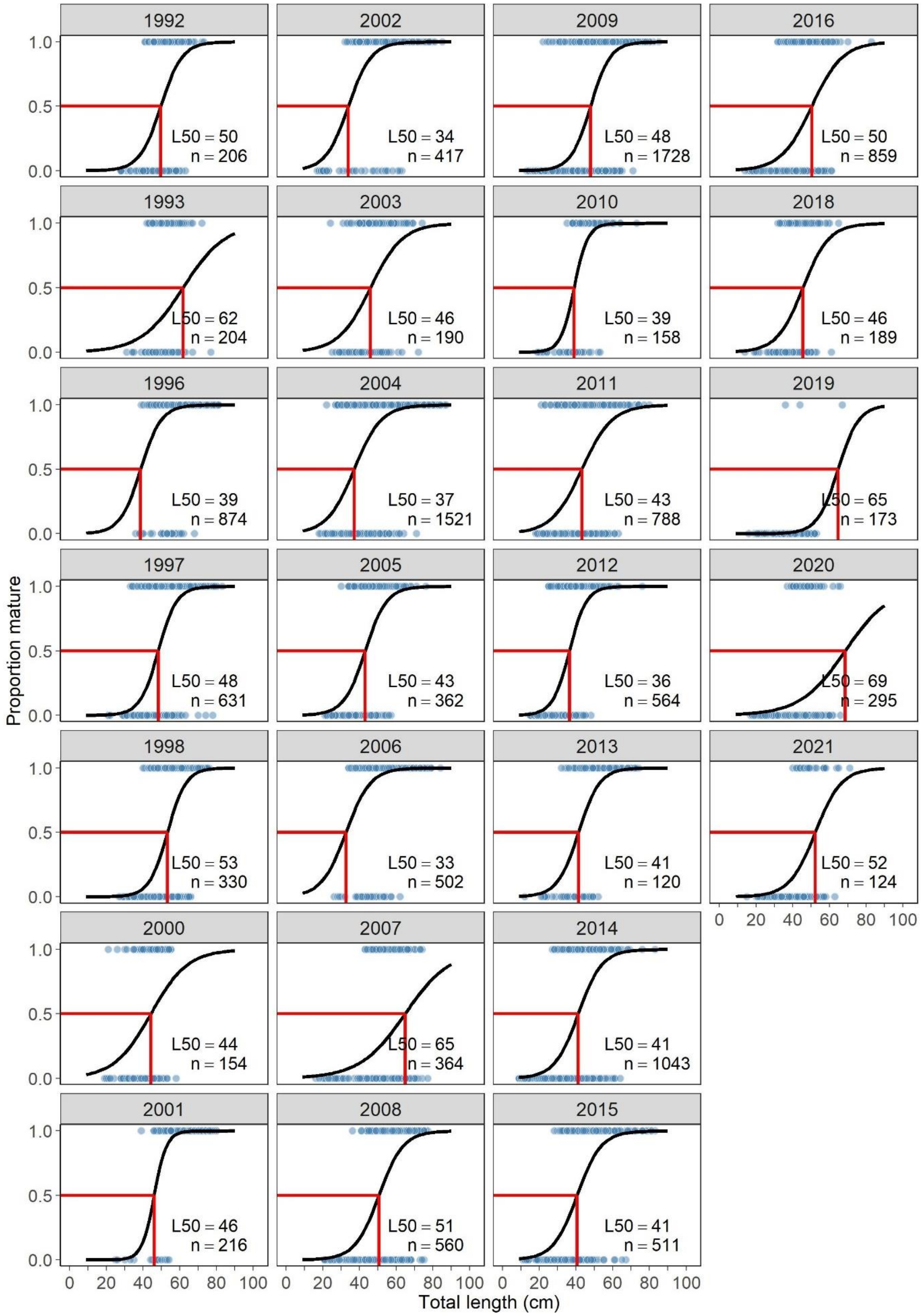
	Year	N	K		t_0 (years)		L_{Inf} (cm)	
	2002	76	0.091	(0.042 - 0.143)	-0.749	(-2.831 - 0.495)	102.6	(86.3 - 154.1)
	2003	123	0.110	(0.071 - 0.154)	-0.583	(-1.400 - 0.052)	92.3	(80.3 - 115.7)
	2004	281	0.085	(0.065 - 0.104)	-0.892	(-1.473 - -0.427)	108.9	(99.3 - 124.6)
	2005	241	0.105	(0.088 - 0.121)	-0.262	(-0.619 - 0.046)	99.1	(92.9 - 107.5)
	2006	172	0.123	(0.100 - 0.147)	-0.505	(-1.012 - -0.089)	90.4	(84.5 - 98.5)
	2007	74	0.113	(0.084 - 0.144)	-0.370	(-1.112 - 0.224)	89.7	(81.8 - 101.6)
	2008	334	0.092	(0.076 - 0.108)	-0.768	(-1.141 - -0.445)	100.6	(93.2 - 110.9)
	2009	336	0.077	(0.062 - 0.093)	-0.710	(-1.060 - -0.409)	116.0	(105.2 - 131.9)
	2010	204	0.075	(0.048 - 0.102)	-0.984	(-1.603 - -0.511)	117.6	(99.8 - 155.5)
F	2011	371	0.065	(0.050 - 0.080)	-0.869	(-1.218 - -0.568)	130.1	(114.7 - 153.8)
	2012	196	0.086	(0.071 - 0.101)	-0.618	(-0.988 - -0.296)	105.7	(97.7 - 116.8)
	2013	88	0.088	(0.050 - 0.126)	-0.865	(-1.663 - -0.302)	96.0	(79.9 - 136.8)
	2014	457	0.066	(0.053 - 0.081)	-0.719	(-0.935 - -0.524)	128.1	(113.1 - 150.3)
	2015	423	0.094	(0.081 - 0.106)	-0.589	(-0.792 - -0.41)	102.2	(95.6 - 111.0)
	2016	373	0.102	(0.085 - 0.119)	-0.222	(-0.465 - -0.007)	98.1	(90.5 - 108.3)
	2017	222	0.090	(0.074 - 0.106)	-0.283	(-0.527 - -0.067)	107.4	(97.9 - 120.5)
	2018	167	0.053	(0.025 - 0.081)	-0.946	(-1.714 - -0.35)	144.8	(111.4 - 246.9)
	2019	288	0.096	(0.074 - 0.119)	-0.724	(-1.156 - -0.354)	96.3	(87.1 - 110.3)

	Year	N	K		t_0 (years)		L_{Inf} (cm)	
	2002	62	0.081	(0.038 - 0.123)	-1.085	(-2.730 - -0.075)	106.2	(88.3 - 166.6)
	2003	91	0.112	(0.074 - 0.159)	-0.977	(-1.863 - -0.206)	84.4	(72.8 - 103.6)
	2004	193	0.105	(0.083 - 0.126)	-0.908	(-1.526 - -0.397)	90.0	(83.7 - 99.3)
	2005	159	0.065	(0.034 - 0.099)	-1.486	(-2.392 - -0.796)	118.4	(92.8 - 181.4)
	2006	130	0.104	(0.075 - 0.134)	-1.345	(-2.171 - -0.690)	87.3	(78.5 - 101.3)
	2007	48	0.101	(0.063 - 0.138)	-0.838	(-1.778 - -0.195)	90.2	(78.9 - 115.6)
	2008	195	0.090	(0.072 - 0.111)	-1.122	(-1.560 - -0.727)	96.2	(87.6 - 108.3)
	2009	226	0.086	(0.067 - 0.106)	-1.059	(-1.504 - -0.683)	98.9	(89.6 - 112.9)
	2010	123	0.160	(0.127 - 0.191)	-0.210	(-0.589 - 0.076)	74.9	(69.8 - 82.8)
M	2011	212	0.127	(0.107 - 0.147)	-0.346	(-0.599 - -0.125)	82.9	(77.4 - 90.3)
	2012	168	0.109	(0.093 - 0.125)	-0.370	(-0.669 - -0.110)	91.9	(86.5 - 98.9)
	2013	46	0.144	(0.083 - 0.208)	-0.311	(-1.057 - 0.208)	74.0	(62.7 - 100.1)
	2014	350	0.077	(0.058 - 0.097)	-0.521	(-0.713 - -0.355)	117.7	(101.0 - 145.5)
	2015	308	0.106	(0.088 - 0.124)	-0.568	(-0.759 - -0.395)	91.9	(84.0 - 102.8)
	2016	237	0.129	(0.111 - 0.148)	-0.319	(-0.571 - -0.093)	80.6	(75.7 - 86.7)
	2017	157	0.090	(0.062 - 0.119)	-0.683	(-1.094 - -0.346)	94.9	(81.6 - 119.3)
	2018	131	0.073	(0.036 - 0.111)	-0.971	(-1.849 - -0.343)	108.6	(86.3 - 176.2)
	2019	224	0.082	(0.054 - 0.112)	-1.134	(-1.810 - -0.611)	100.9	(86.6 - 128.3)

Appendix VIII. Binomial logistic regressions of juvenile (0) or adult (1) maturity ogives vs. length for female red cod sampled randomly in finfish (A–, G–, and W–licences) and experimental (E–licence) vessels in the FICZ. Red lines indicate the intercept for length at 50% adulthood, corresponding to Fig. 7.



Appendix IX. Binomial logistic regressions of juvenile (0) or adult (1) maturity ogive vs. length for male red cod sampled randomly in finfish (A–, G–, and W–licences) and experimental (E–licence) vessels in the FICZ. Red lines indicate the intercept for length at 50% adulthood, corresponding to Fig. 7.



Appendix X. Number of red cod individuals sampled for length frequency distributions, corresponding to individuals caught randomly by finfish (A–, G–, and W–licences) and experimental (E–licence) vessels through the year in the FICZ from 1990 to 2021.

Year	Females (n)	Males (n)
1990	821	679
1991	341	309
1992	1322	961
1993	469	489
1994	0	0
1995	11	21
1996	843	972
1997	2272	1527
1998	824	606
1999	900	884
2000	1297	1034
2001	701	345
2002	1819	1288
2003	814	551
2004	3500	2459
2005	1566	1243
2006	2078	1666
2007	2374	1506
2008	1704	1075
2009	5882	4268
2010	3775	2360
2011	7050	4445
2012	3793	2490
2013	4046	2594
2014	3163	2606
2015	4265	3101
2016	5723	4511
2017	5021	3951
2018	4033	2523
2019	4201	2795
2020	5668	3732
2021	5279	3181