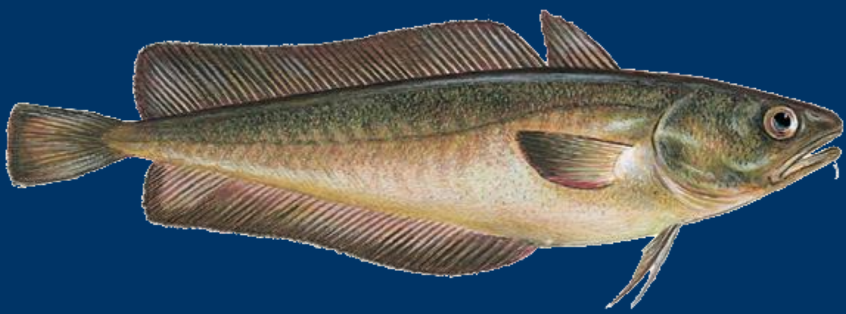
Stock Assessment of red cod (*Salilota australis*) in the Falkland Islands



Jorge E. Ramos, Andreas Winter

Natural Resources - Fisheries
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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

Commercial catches of red cod *Salilota australis* in Falkland Islands licenced fisheries were 1,414 tonnes (t) in 2020, the second lowest catch since 1990. Nearly 91% of commercial catches were by finfish licences (A–, G–, and W–). In 2020, commercial CPUE reached its lowest level (53 kg/h) since 1990, and CPUE from summer (February) research surveys had its lowest level (19 kg/h) since 2010.

Following recommendations of the MacAlister Elliott & Partners external review, Total Allowable Catch (TAC) calculation was revised 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. To reflect uncertainty, biomass estimates were weighted by their inverse variance. The red cod TAC for 2022 is accordingly set at 1,199 t.

Length-based indicators suggest that conservation of immature fish, large individuals, mega-spawners, optimal yield, and maximum sustainable yield was negative over the past decade. Asymptotic lengths (L_∞) increased significantly over most of the period 1988 to 2018 for both females and males. Length at 50% maturity was stable for most of the time series, and increased significantly since 2012 for males. Length frequencies shifted from large individuals (> 40 cm total length) that were dominant prior to 2009, to smaller individuals (< 40 cm total length) that became more common since 2009. Even smaller individuals < 30 cm total length were dominant from 2016 to 2020. Negative outputs for large individuals and for mega-spawners, and declines in lengths over the last decade may be explained by fishing vessels not targeting large and reproductive individuals during the reproductive months 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, and aggregates in dense spawning schools at depths between 180 m and 200 m; spawning aggregations occur in the periphery of two upwelling areas created by the cold-water Falkland Current in the west and south-west of the Falkland Islands (Arkhipkin et al. 2010). Spawning then takes place to the south and south-west of West Falkland between August and October (Brickle et al. 2011). After spawning, red cod migrates 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 (http://www.fig.gov.fk/fisheries/publications/fishery-statistics; Falkland Islands Government 2021), compared with the Argentina fishery (https://www.agroindustria.gob.ar/sitio/areas/pesca_maritima/desembarques/; 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 (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. A category 3 assessment framework was the primary recommendation for red cod (MEP 2020), 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, or surplus production methods. A Length-Based Indicator method (LBI) was used to provide a suite of indicators based on combinations of catch-at-size distributions, life-history parameters such as L_∞ (Haddon 2001) and L50 (length at 50% maturity; Cope & Punt 2009). For comparison with previous work (Winter 2018), the Optimized Catch Only Method (OCOM; Zhou et al. 2018) was also used to estimate yearly biomass, MSY, and TAC_{2022}. Detailed information on OCOM and its outputs are presented in Appendix I.

Commercial fishery data

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 2020 from the Falkland Islands (http://www.fig.gov.fk/fisheries/publications/fishery-statistics; Falkland Islands Government 2021), and Argentina (https://www.agroindustria.gob.ar/sitio/areas/pesca_maritima/desembarques/; 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 to 2020.

Commercial catches of red cod in Falkland Islands waters were examined by licence type for 2020. Catch-per-unit-effort (CPUE) was estimated as the sum of red cod catches divided by the sum of effort, per year and per month, from finfish (A–, G–, and W–) licences. Spatial distribution of the 2020 monthly CPUE average was estimated from the finfish licences that contributed most of the red cod catches.

Scientific surveys data

Biomass estimates and the spatial distribution of red cod were examined from austral summer scientific surveys (groundfish and pre-recruitment surveys) carried out in February 2010, 2011, and 2015 – 2021 in Falkland Islands waters (Ramos & Winter 2021). A trend of the biomass time series from 2010 to 2021 was calculated using LOESS (span = 0.75, degree = 2). Biomass ratios between the most recent February surveys (2021) 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 2021). Biomass estimates, the spatial distribution of red cod, and biomass ratios were also examined (following Ramos & Winter 2021) from scientific surveys carried out in austral winter, during July 2017 (Gras et al. 2017; Winter et al. 2017) and July 2020 (Randhawa et al. 2020; Winter et al. 2020).

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 last year's advice to generate this year's advice (MEP 2020). If implemented for the first time (i.e., there is no 'last year'), the rule needs to be instigated by a different criterion, such as category 5: average catches from the 3 previous years (MEP 2020). Year-to-year change is further limited to an 'uncertainty cap' of ± 20% (ICES 2018a).

Given that the program of February surveys has been run continuously in all years starting in 2015 (Ramos & Winter 2021), the 2/3 rule was applied for the first time for 2020, utilizing the February survey data from 2015 to 2019 and the (retrospective) category 5 TAC for year 2019. Category 5 TACs are based on in-zone catches, excluding experimental (E–licence) and out-of-zone catches (O–licence) (Appendix II). In the calculations, ratios of the 2/3 rule were computed from mean values of the February survey biomass estimates:

$$TAC\_5_{2019} = \overline{C_{2016\ to\ 2018}}$$

$$TAC\_3_{2020} = TAC\_5_{2019} \times \frac{\overline{B_{2018\ to\ 2019}}}{\overline{B_{2015\ to\ 2017}}}$$

Or limited to 20% reduction:

$$TAC\_3_{2020} = TAC\_5_{2019} \times 0.8$$

$$TAC\_3_{2021} = TAC\_3_{2020} \times \frac{\overline{B_{2019\ to\ 2020}}}{\overline{B_{2016\ to\ 2018}}}$$

Or limited to 20% reduction:

$$TAC\_3_{2021} = TAC\_3_{2020} \times 0.8$$

$$TAC\_3_{2022} = TAC\_3_{2021} \times \frac{\overline{B_{2020\ to\ 2021}}}{\overline{B_{2017\ to\ 2019}}}$$

Or limited to 20% reduction:

$$TAC\_3_{2022} = TAC\_3_{2021} \times 0.8$$

However, each year's survey biomass estimate is subject to more or less uncertainty depending on the distribution of catches (Ramos & Winter 2021). 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 30,000 randomized re-samples (2015 = 837479943.3; 2016 = 1040692565.0; 2017 = 331021938.9; 2018 = 800985291.6; 2019 = 462104093.5; 2020 = 35607219.6; 2021 = 54092395.5). TAC was calculated as follows:

$$TAC\_5_{2019} = \overline{C_{2016\ to\ 2018}}$$

$$TAC\_3_{2020} = TAC\_5_{2019} \times \frac{\left(\sum_{y=2018}^{2019} B_y \times {}^{1}/_{Var_y}\right) \Big/ \left(\sum_{y=2018}^{2019} {}^{1}/_{Var_y}\right)}{\left(\sum_{y=2015}^{2017} B_y \times {}^{1}/_{Var_y}\right) \Big/ \left(\sum_{y=2015}^{2017} {}^{1}/_{Var_y}\right)}$$

$$TAC\_3_{2021} = TAC\_3_{2020} \times \frac{\left(\sum_{y=2019}^{2020} B_y \times {}^{1}/_{Var_y}\right) \Big/ \left(\sum_{y=2019}^{2020} {}^{1}/_{Var_y}\right)}{\left(\sum_{y=2016}^{2018} B_y \times {}^{1}/_{Var_y}\right) \Big/ \left(\sum_{y=2016}^{2018} {}^{1}/_{Var_y}\right)}$$

Or limited to 20% reduction:

$$TAC\_3_{2021} = TAC\_3_{2020} \times 0.8$$

$$TAC\_3_{2022} = TAC\_3_{2021} \times \frac{\left(\sum_{y=2020}^{2021} B_y \times {}^{1}/_{Var_y}\right) \Big/ \left(\sum_{y=2020}^{2021} {}^{1}/_{Var_y}\right)}{\left(\sum_{y=2017}^{2019} B_y \times {}^{1}/_{Var_y}\right) \Big/ \left(\sum_{y=2017}^{2019} {}^{1}/_{Var_y}\right)}$$

Or limited to 20% reduction:

$$TAC\_3_{2022} = TAC\_3_{2021} \times 0.8$$

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

Length 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_∞ (Haddon 2001) and L50 (length at 50% maturity; Cope & Punt 2009). L_∞ 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 observer length measurements of red cod were available and reported as random samples (FIFD database codes R and S), i.e., years 2002 to 2020. Total lengths of up to one hundred individuals per trawl were measured to the lowest centimetre. Because finfish trawls are restricted to larger meshes than calamari trawls, only observer length measurements taken in finfish-licensed fisheries 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 were also excluded; while skate and *Illex* currently do not have different mesh allowances from finfish, their different targets could also relate to characteristically different length-frequency distributions of red cod.

The procedure for identifying finfish-licensed observer samples is described in Appendix III. 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_∞ > 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). $L_{Opt} = 3 \cdot L_\infty \cdot (3 + Mk^{-1})^{-1}$ (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 $(3 \cdot L_C + L_\infty)/4$.

Margins of variability of the six indicators were estimated by randomly re-sampling 30,000× on the normal distribution each year's fits of L_∞ and L50 to the LOESS smooths. Indicators were scored against the 'traffic light' scale (ICES 2015) with reference criteria >1 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, >0.8, and >0.3, yellow if 1, 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, <0.8, 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 for optimal yield was green if the lower and upper 95% quantiles spanned 1, yellow if the lower and upper 95% quantiles spanned 0.9 (the threshold used in ICES 2015) without spanning 1, and red otherwise. Reference criterion ≥1 for MSY was scored the same as >1, except that empirical values ≥1 were automatically green.

Length-age relationship

L_∞ was calculated from the von Bertalanffy growth function, modelled to red cod length and age data from the FIFD database with nonlinear least-squares fitting using the R package 'fishmethods' (Nelson 2019). Red cod length and age data were available for years 1988–2018, with status of age data advised 'with caution' (Lee et al. 2020) as verification of these ages is in progress. Variability of L_∞ and the other von Bertalanffy parameters was estimated by bootstrapping. Residuals of the von Bertalanffy model fit were randomly re-sampled with replacement, added back to the expected lengths; these newly generated data were re-fit to the von Bertalanffy function, and the 95% quantiles of 30,000 iterations retained as confidence intervals. Inter-annual trends of the von Bertalanffy parameters were calculated by LOESS (span = 0.90, degree = 2, weighted by inverse variance), and the LOESS smooth fits applied to the LBI indicators to mitigate unevenness over the time series.

Length at 50% maturity (L50)

Length at 50% maturity (L50) was calculated as the mid-point of the binomial logistic regression of maturity vs. length (Heino et al. 2002). Gonadal maturity is cyclical as fish pass through pre- to post-spawning phases, and definitive maturity assignments can only be made that stage 1 is immature, stage 3 is early developing, and stages 4 or higher are mature (Brickle et al. 2011). Therefore, maturity assignment was simplified to a dichotomous classification of juvenile (0 – 3) or adult (4+), omitting stage 2 (Winter 2018). Red cod maturities were available from all years 1993 to 2020, and data included in the analysis were from August through October, which are the reproductive months (Brickle et al. 2011). The aggregates of L50 were plotted against years and trends calculated with LOESS smooths (span = 0.90, degree = 2), also weighted by inverse variance of each year's binomial logistic regression.

Length frequencies

Length frequencies were examined yearly for females and males to describe patterns in length through time. Lengths of individuals sampled randomly (FIFD database codes R and S) on finfish bottom trawl vessels, i.e., A–, G–, and W– licences, were included in the analysis. Length frequencies were examined from 2002 to 2020 as 2002 was the first year in which length measurements could be cross-referenced with the licence. Unsexed individuals were excluded from the analysis.

Results

ICES advice rules

Commercial fishery data

Red cod catches in Falkland Islands waters have averaged 4,129 t per year since 1987, representing approximately 58% of the Falkland Islands and Argentine combined annual catch (Fig. 1).

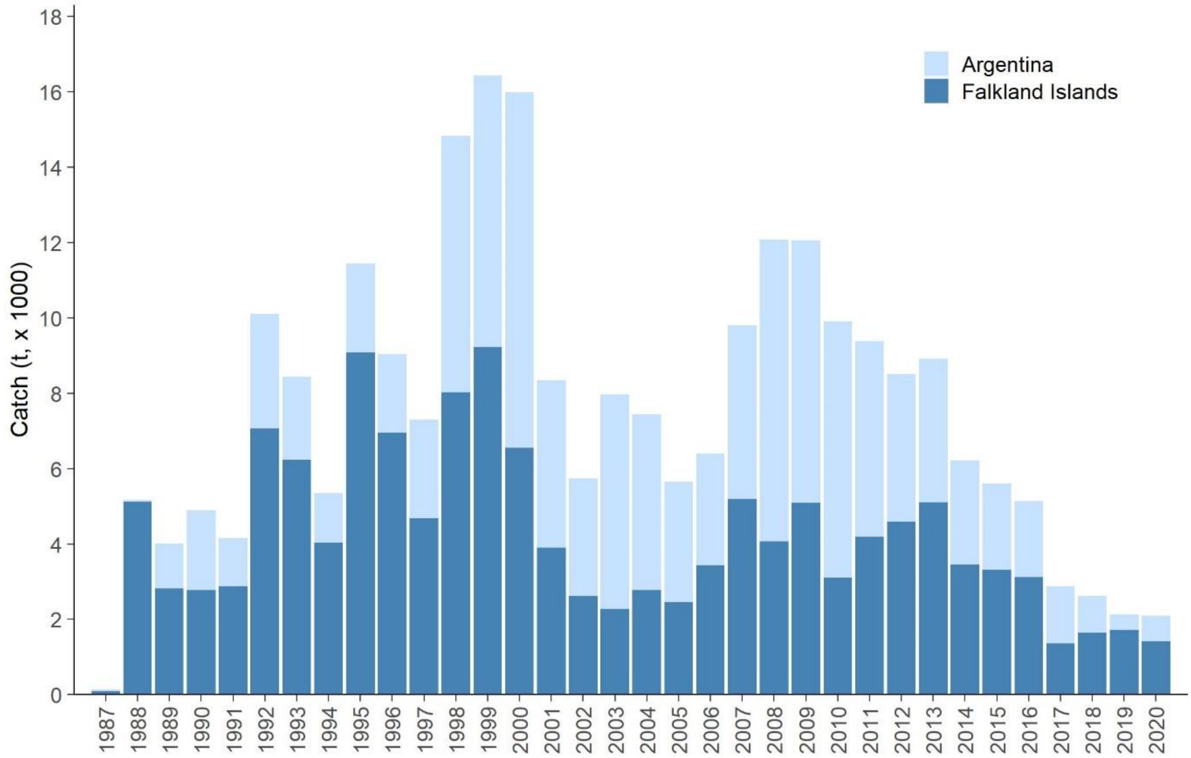

Fig. 1. Annual commercial catch of red cod in Falkland Islands and Argentine waters. Falkland Islands commercial catch data exclude experimental (E–licence) and out-of-zone (O–licence) licences.

Falkland Islands and Argentine red cod catches were positively associated (Fig. 2; Appendix II). The data suggest that red cod catches are determined by pulses of high abundance in the Southwest Atlantic, in particular in the Falkland Islands EEZ.

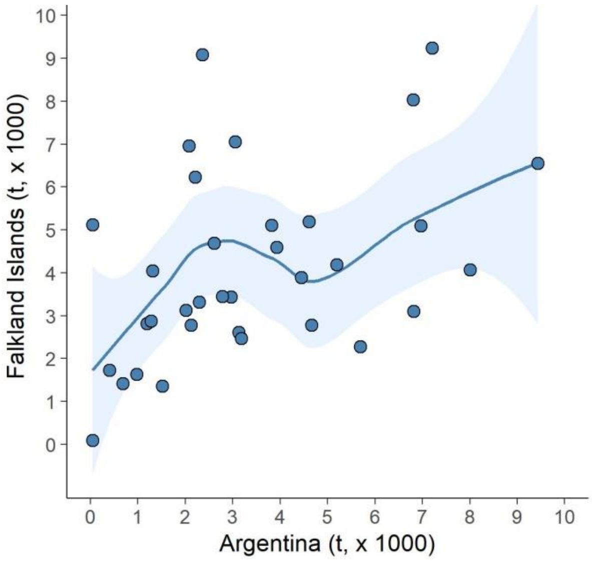

Fig. 2. Annual commercial catches of red cod, Falkland Islands vs. Argentina, from 1987 to 2020. Blue lines: LOESS smooths ± 95% confidence intervals.

During 2020 a total of 1,418 t of red cod were reported caught in Falkland Islands waters, of which 1,414 t were reported under commercial licences, i.e., excluding the experimental E–licence. The three finfish licences (A–, G– and W–licences) together accounted for 91% of the total red cod catch (Table I).

Table I. Catches by licence of red cod in Falkland Islands waters during 2020.

Licence	Target species	Catch (t)	Catch (%)
W	Restricted finfish	733.48	51.72
A	Unrestricted finfish	297.18	20.96
G	Restricted finfish and *Illex*	259.35	18.29
X	Calamari 2nd season	92.07	6.49
F	Skates and rays	29.41	2.07
E	Experimental	4.41	0.31
C	Calamari 1st season	1.90	0.13
B	*Illex* squid	0.36	0.03
L	Toothfish (longline)	0.00	0.00
S	Southern blue whiting and hoki	0.00	0.00
O	Outside Falkland Islands waters	0.00	0.00
Total		1,418.15	100.00

CPUE increased from 1990 to reach the highest CPUE in the time series in 1995 (176 kg/h), and remained relatively stable until 1999; CPUE then had a steep decline from 1999 to

2003 (63 kg/h). CPUE increased to 2012 and declined again to reach the lowest value in the time series in 2020 (53 kg/h) (Fig. 3).

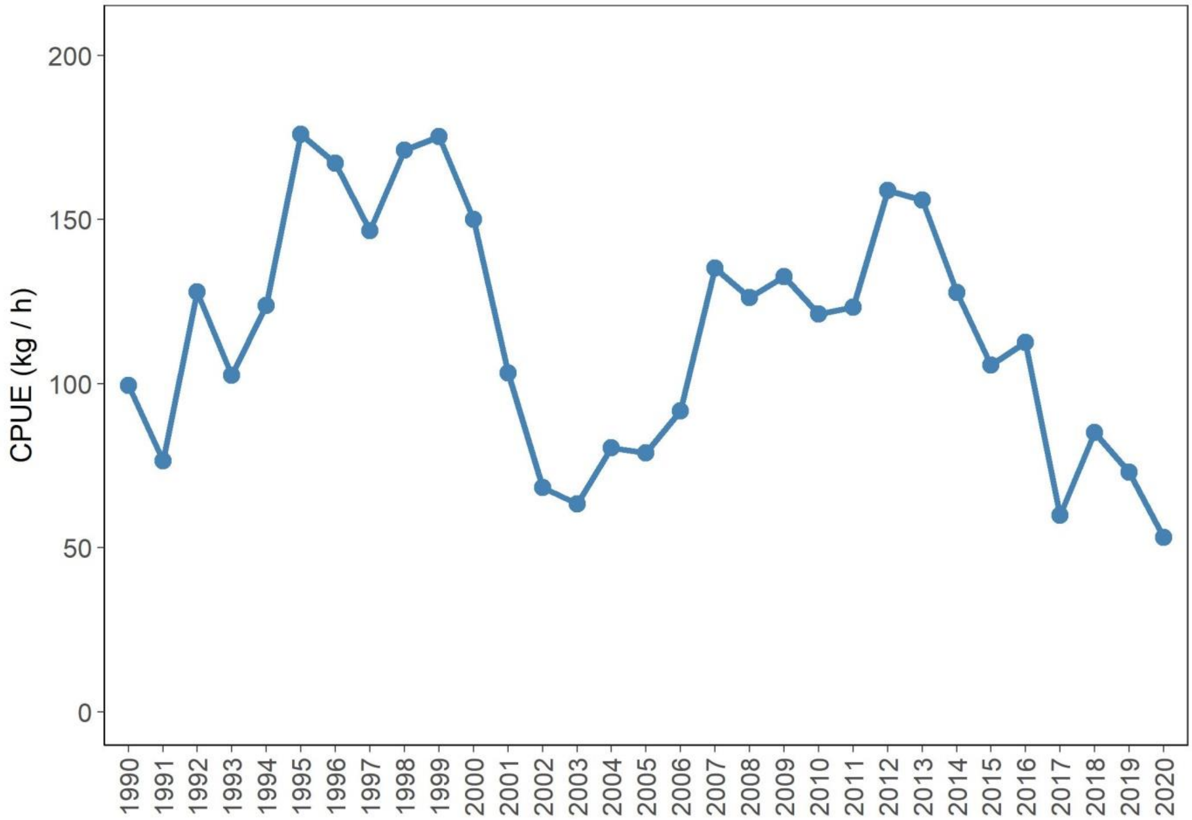

Fig. 3. Yearly CPUE of red cod in Falkland Islands waters, estimated from A–, G–, and W–licensed vessels.

Average monthly CPUE increased from January to March, and remained with the highest values during late summer and most of autumn (March through May). CPUE declined towards early winter (July) and increased again from late winter to early spring (August through October). The year 2020 had a different pattern from most other years mainly in January and February when the highest CPUE values were reported, followed by a steep drop in CPUE towards March (Fig. 4; Appendix IV). During 2020, 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 V).

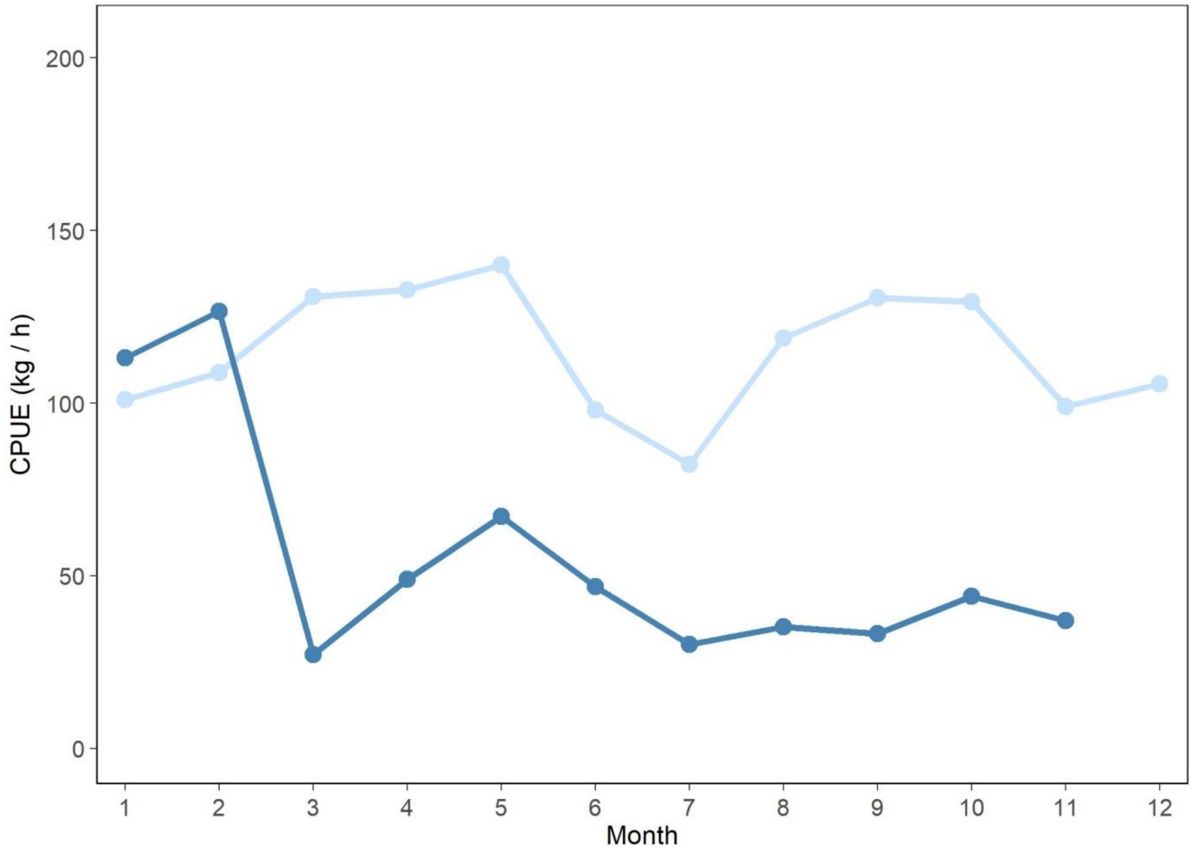

Fig. 4. Average monthly CPUE of red cod in Falkland Islands waters for 2020 (dark blue line), and since 1990 (light blue line), estimated from A–, G–, and W–licensed vessels.

Scientific surveys data

Summer surveys (February)

The biomass of red cod during the February surveys saw a declining trend, with the biomass in 2021 (34,341.38 t) being 26% of the biomass in 2010 (93,194.65 t; Table II; Fig. 5). However, only a total of 24,833 out of 30,000 paired re-samples had higher biomass estimate values in February 2010 than in February 2021 (82.8%), therefore the difference in biomass between 2021 and 2010 is considered not significant at $p > 0.05$. During the February 2015–2018 surveys, red cod were mainly aggregated to the west edge of the FICZ but their distribution spread to the north and south-west of West Falkland during the February 2019–2021 surveys (Appendix VI).

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	93194.65 (19743.66–150576.55)
	D. gahi	55	42.29	109.27	111.60	1.02	
	Total	142	59.33	196.79	13539.08	68.80	
2011	Groundfish	88	17.21	88.00	23099.27	262.49	161778.97 (41760.22–252434.63)
	D. gahi	58	40.04	110.63	440.27	3.98	
	Total	146	57.25	198.63	23539.54	118.51	
2015	Groundfish	89	16.72	90.17	20314.03	225.29	106878.11 (45428.59–160292.10)
	D. gahi	57	46.90	111.50	1495.40	13.41	
	Total	146	63.61	201.67	21809.43	108.15	
2016	Groundfish	90	17.64	91.42	18644.48	203.94	105369.24 (29467.04–154110.28)
	D. gahi	56	54.46	107.92	1302.61	12.07	
	Total	146	72.10	199.33	19947.08	100.07	
2017	Groundfish	90	18.52	92.00	11104.46	120.70	60319.76 (23204.51–89308.37)
	D. gahi	58	54.09	117.00	2717.14	23.22	
	Total	148	72.62	209.00	13821.59	66.13	
2018	Groundfish[a]	97	20.47	96.42	12733.50	132.07	55845.34 (19149.62–114403.45)
	D. gahi	59	36.87	100.83	567.39	5.63	
	Total	156	57.35	197.25	13300.89	67.43	
2019	Groundfish	79	17.22	79.00	10652.83	134.85	82793.68 (36684.05–116442.72)
	D. gahi	52	72.70	97.05	3029.02	31.21	
	Total	131	89.93	176.05	13681.85	77.72	
2020	Groundfish[a]	80	17.04	79.95	3334.18	41.70	22661.17 (11566.08–34435.10)
	D. gahi	59	86.80	112.52	373.27	3.32	
	Total	139	103.84	192.47	3707.45	19.26	
2021	Groundfish	80	16.34	79.48	5681.47	71.48	34341.38 (22268.63–50967.64)
	D. gahi	55	90.64	111.22	358.65	3.22	
	Total	135	106.99	190.70	6040.12	31.67	

[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.

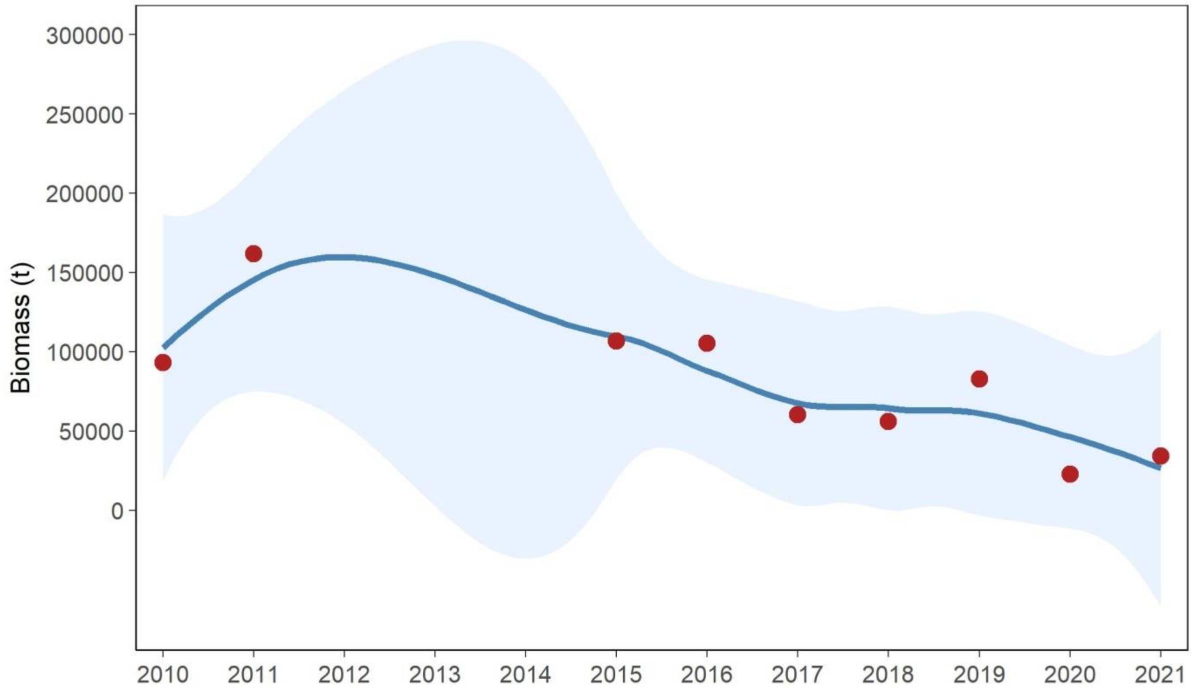

Fig. 5. Red cod biomass estimates (red) and smoothed biomass trend (LOESS; span = 0.75, degree = 2) from summer (February) surveys in Falkland Islands waters.

Winter surveys (July)

The estimated biomass of red cod in the July 2020 survey (39,641.18 t) was 3× greater than in the July 2017 survey (12,553.68; Table III). However, only 21,507 out of 30,000 paired re-samples had higher biomass estimate values in July 2020 than in July 2017 (71.7%), 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 Falkland Islands Conservation Zones, whereas in July 2020 red cod were mainly aggregated to the north-west (Appendix VII). 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	12553.68 (6753.62 – 17805.46)
	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	39641.18 (6081.36 – 74618.05)
	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.

ICES Category 3 Total Allowable Catch

Total Allowable Catch (TAC) for the year 2022 under the ICES category 3 assessment framework was estimated at 1,199 t. TACs for any given year were > 20% reduction from the preceding year TAC, and therefore an uncertainty cap was implemented (Table IV).

Table IV. Annual Total Allowable Catch (TAC) estimates in tonnes based on ICES categories 3 and 5 assessment frameworks, and using the 20% cap. The selected TAC for 2022 is indicated in bold font. *weighted by inverse variance of February surveys biomass estimates.

TAC	2/3 rule (t)	20% cap (t)	2/3 rule (t)*	20% cap (t)*
TAC_5_{2019}	2041	2041	2041	2041
TAC_3_{2020}	1557	1633	1874	1874
TAC_3_{2021}	1166	1306	748	1499
TAC_3_{2022}	561	1045	611	**1199**

Length analyses

Length Based Indicators

Yearly ‘traffic light’ length indicators for females and males are summarized in Tables V and VI, respectively. Indicator $L_C/L50$, for conservation of immature fish, had negative outcomes (red) from 2002 to 2020 for females. For males, this indicator fluctuated from 2002 to 2006 but it was negative most years since 2006, except for 2018. Indicator $L_{25\%}/L50$, also for conservation of immature fish, showed positive outcomes (green) early in the time series (2002–2008) for females and males. However, negative outcomes were common since 2009 for females, whereas males had negative outcomes since 2009, except for two positive outcomes in 2013 and 2018. Indicator $L_{max5\%}/L_{\infty}$, for the conservation of large individuals, fluctuated from 2002 to 2008 for females, and from 2002 to 2012 for males; negative outcomes were common over the last few years for both females and males. Indicator P_{mega}, for the presence of mega-spawners, was almost all negative for both females and males since 2002. Indicator L_{meanC}/L_{Opt}, for optimal yield, fluctuated between yellow and red from 2002 to 2005 for females, and from 2002 to 2008 for males. However, negative outcomes were common the rest of the time series. Indicator $L_{meanC}/L_{F=M}$, for maximum sustainable yield, was mostly green from 2002 to 2008 for females and from 2002 to 2009 for males; negative outcomes were common the rest of the years for both females and males.

Table V. Female red cod indicators by 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_{∞}) 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.

Ref.	Conservation				Optimal yield	MSY
	L_C / L50 >1	$L_{25\%}$ / L50 >1	$L_{max5\%}$ / L_{∞} >0.8	P_{mega} >0.3	L_{meanC} / L_{Opt} ≈1	L_{meanC} / $L_{F=M}$ ≥1
2002	0.90	1.13	0.85	0.15	0.89	1.19
2003	0.87	1.10	0.76	0.03	0.78	1.06
2004	0.89	1.12	0.86	0.22	0.88	1.19
2005	0.69	0.98	0.75	0.03	0.69	1.05
2006	0.87	1.10	0.80	0.07	0.79	1.09
2007	0.67	1.05	0.78	0.05	0.76	1.20
2008	0.71	1.21	0.79	0.12	0.83	1.29
2009	0.72	0.90	0.74	0.02	0.63	0.99
2010	0.67	0.85	0.72	0.02	0.59	0.96
2011	0.64	0.73	0.69	0.01	0.55	0.92
2012	0.80	0.87	0.72	0.02	0.58	0.89
2013	0.94	0.97	0.70	0.01	0.63	0.91
2014	0.63	0.76	0.62	0.00	0.52	0.88
2015	0.45	0.73	0.63	0.01	0.50	0.94
2016	0.48	0.74	0.62	0.00	0.50	0.94
2017	0.65	0.72	0.59	0.00	0.46	0.79
2018	0.83	0.99	0.65	0.00	0.58	0.90
2019	0.50	0.80	0.65	0.00	0.50	0.94
2020	0.67	0.91	0.60	0.00	0.52	0.89

Table VI. Male red cod indicators by 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_∞) 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

Ref.	Conservation				Optimal yield	MSY
	L_C / L50 >1	$L_{25\%}$ / L50 >1	$L_{max5\%}$ / L_∞ >0.8	P_{mega} >0.3	L_{meanC} / L_{Opt} ≈1	L_{meanC} / $L_{F=M}$ ≥1
2002	0.70	1.14	0.94	0.21	0.91	1.32
2003	0.96	1.08	0.79	0.05	0.81	1.02
2004	0.83	1.15	0.95	0.25	0.89	1.22
2005	1.20	1.13	0.76	0.03	0.84	0.96
2006	1.04	1.24	0.85	0.09	0.87	1.08
2007	0.76	1.08	0.88	0.13	0.83	1.21
2008	0.80	1.27	0.87	0.25	0.91	1.31
2009	0.72	0.99	0.82	0.08	0.69	1.07
2010	0.80	0.90	0.76	0.03	0.63	0.94
2011	0.60	0.81	0.73	0.02	0.58	0.97
2012	0.78	0.96	0.78	0.04	0.63	0.96
2013	0.86	1.08	0.72	0.02	0.65	0.97
2014	0.44	0.73	0.62	0.00	0.49	0.93
2015	0.51	0.70	0.65	0.01	0.50	0.91
2016	0.56	0.74	0.62	0.00	0.52	0.93
2017	0.75	0.78	0.60	0.00	0.49	0.80
2018	0.98	1.09	0.66	0.01	0.63	0.91
2019	0.57	0.76	0.68	0.01	0.52	0.94
2020	0.80	0.91	0.61	0.00	0.55	0.87

Length-age relationship

The length-age relationship of females and males pooled (n = 5,134) gave the following values: L_∞ = 100.59 cm, k = 0.0924, and t_0 = -0.7108 years. Length and age of females (n = 3,108) ranged from 10 cm to 93 cm, and from 1 year to 24 years, respectively. The length-age relationship of females gave the following values: L_∞ = 103.26 cm, k = 0.0915, and t_0 = -0.6309 years. Length and age of males (n = 2,026) ranged from 11 cm to 87 cm and from 1 year to 21 years, respectively. The length-age relationship of males gave the following values: L_∞ = 91.93 cm, k = 0.1014, and t_0 = -0.7827 years (Appendix VIII). Yearly von Bertalanffy parameters are summarized in Appendix IX. Asymptotic lengths (L_∞) increased significantly over most of the period 1988 to 2018 for both females and males (Fig. 6).

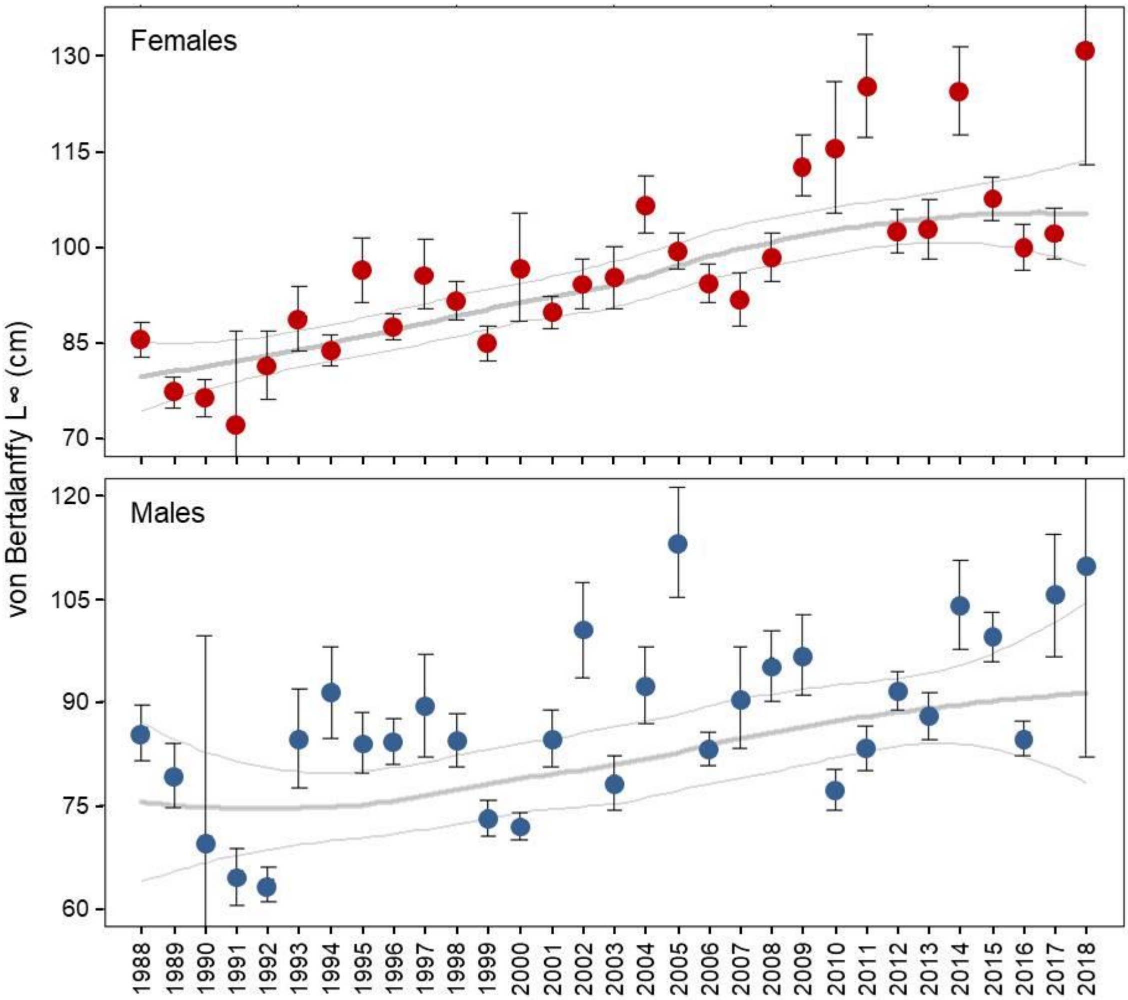

Fig. 6. Asymptotic lengths (L_∞) calculated according to the von Bertalanffy growth function for female and male red cod, 1988 to 2018, ± 1 standard error. Grey lines are LOESS smooths ± 95% confidence intervals.

Length at 50% maturity (L50)

Lengths at 50% maturity were relatively stable for both females and males since 1993. An increasing trend in L50 was detected for males since 2013; however, the number of mature males (stages 4 or more) sampled from August to October since 2017 is small (n_{2017} = 6; n_{2018} = 71; n_{2019} = 3; n_{2020} = 44), likely overestimating L50 during these years (Fig. 7). Concurrently, the proportions of red cod individuals sampled that were mature have been decreasing over the years (cf. N0 vs. N1; Appendix X). That trend is not strictly quantifiable, as observer samples in the early years (< 2002) were not verifiably random. However, the overall proportion of length/maturity sampled red cod that is random is > 90%.

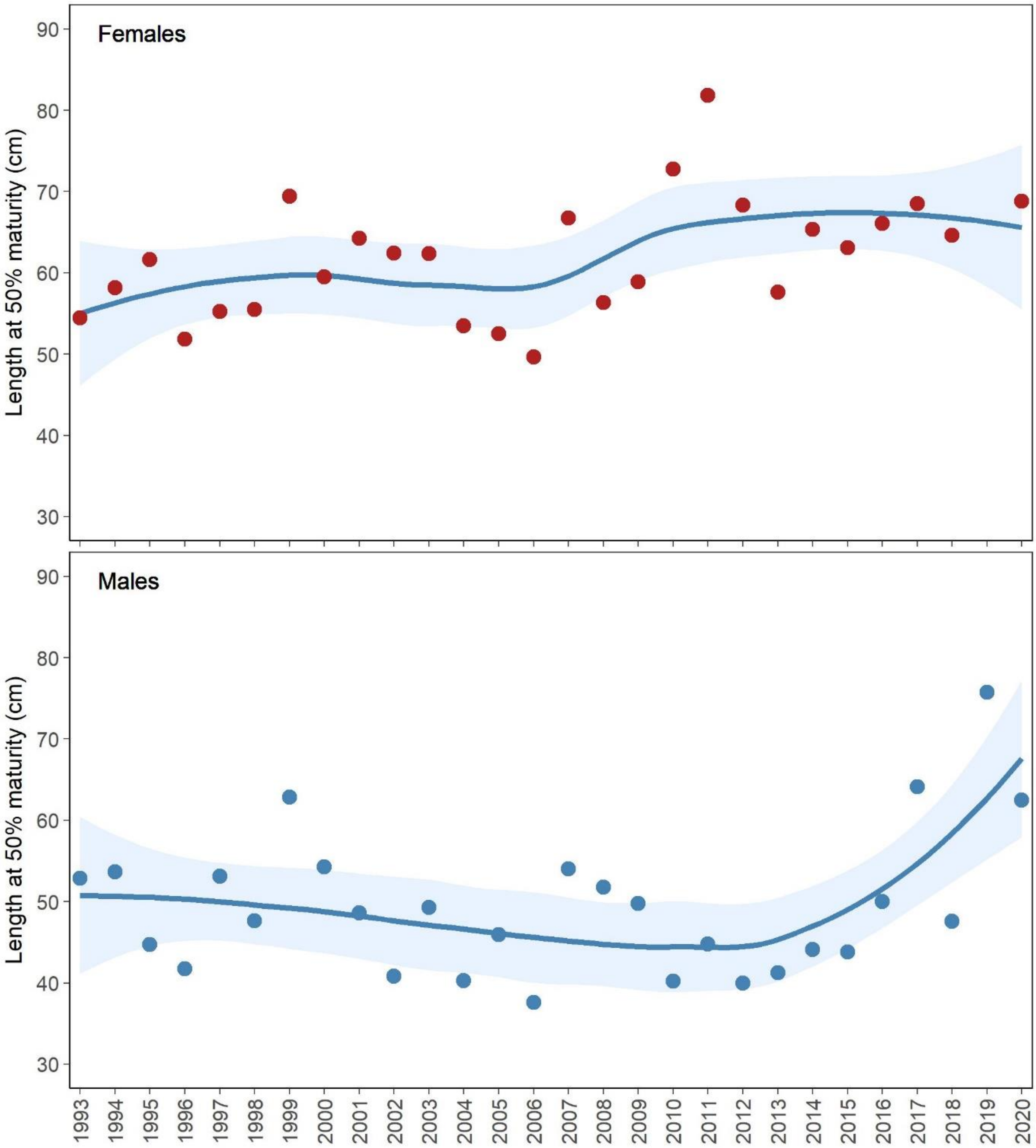

Fig. 7. Lengths at 50% maturity (L50) of female and male red cod, 1993 to 2020. Dark blue lines and light blue areas are the LOESS smooths ± 95% confidence intervals.

Length frequencies

Female red cod were in the range of sizes from 10 cm to 93 cm total length, and males ranged from 11 cm to 87 cm total length. Females and males were characterized by a few cohorts not discernible due to size overlap, with greater numbers of large individuals (mainly > 40 cm total length) from 2002 to 2008. Smaller individuals (mainly < 40 cm total length) became dominant since 2009. Over the last 5 years, from 2016 to 2020, females and males were mostly < 30 cm total length (Fig. 8; Appendix XI).

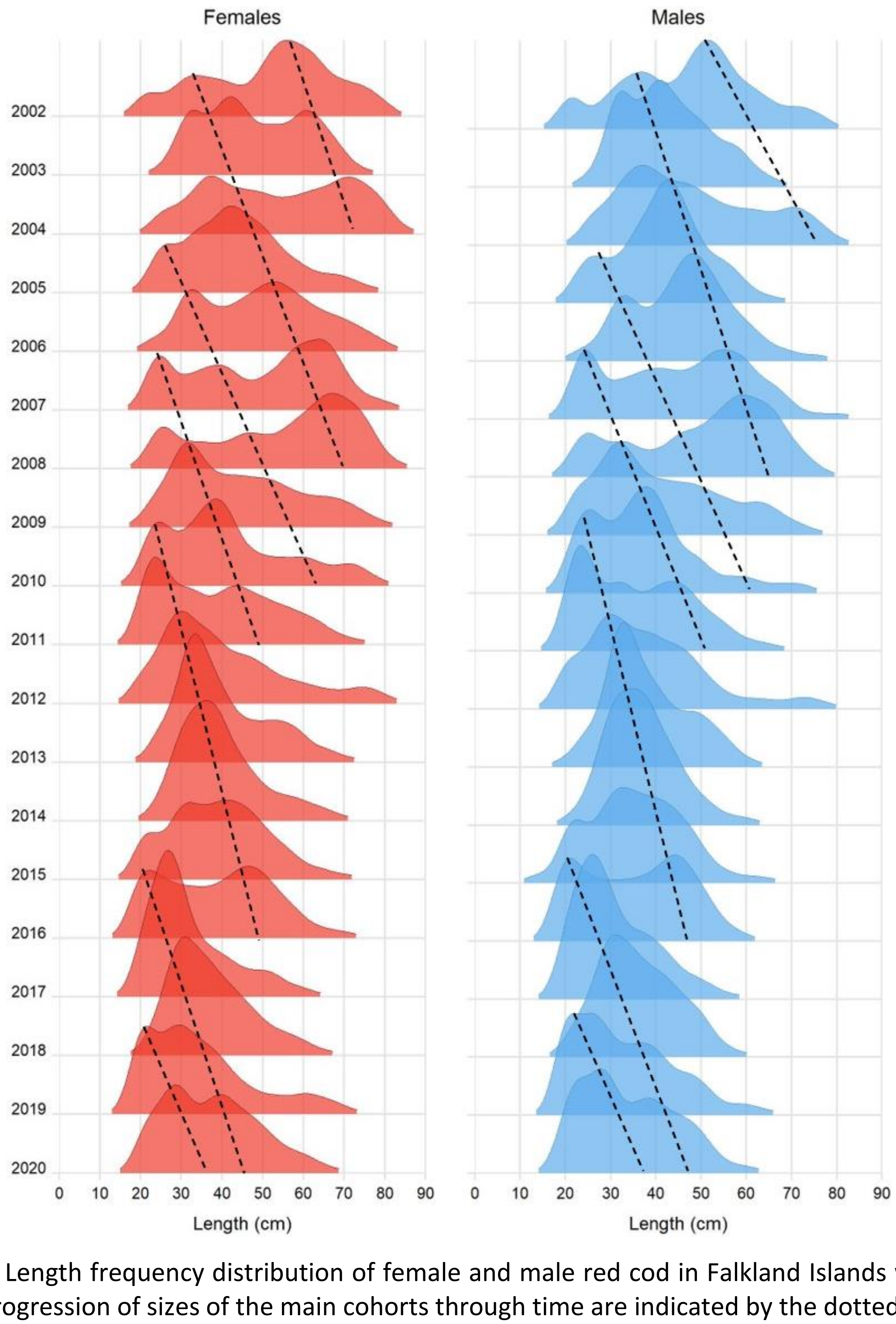

Fig. 8. Length frequency distribution of female and male red cod in Falkland Islands waters. The progression of sizes of the main cohorts through time are indicated by the dotted lines.

Conclusions

Length-based indicators suggest that MSY was strong from 2002 to 2008 when conservation for immature, and large individuals were positive (green). Conservation of immature individuals, large individuals, and mega-spawners was negative (red) over the past decade. Weak optimal yield and MSY over the last 10 years, and decline in body size suggest that red cod productivity has not been maintained. However, red cod spawning grounds were closed for fishing since 2010 and large individuals were not targeted (A. Arkhipkin *pers. comm.*). This may affect the LBI outputs for large individuals and for mega-spawners encountered over the past decade.

Abundance of red cod in Falkland Islands waters appears to be decreasing, as suggested by the declining trend of the commercial fishery CPUE, which is consistent with the biomass decline estimated using OCOM. However, part of the decrease in CPUE since 2015 can also be due to the fishery not targeting red cod during the reproductive months (August through October).

Nevertheless, 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. Therefore, based on the ICES category 3 assessment framework, a Total Allowable Catch of 1,199 t is recommended for red cod in the year 2022, which represents a decrease of 15% from the total commercial catch in 2020 (1,414 t).

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Appendix

Appendix I. Optimized Catch Only Method (OCOM)

Methods

OCOM was developed for data-poor fish stocks; this approach uses time series of catches and priors for the intrinsic population growth rate (r) derived from basic life history parameters, and 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). OCOM applies an optimization of the Graham-Schaefer surplus production model to search the potential parameter space (Schaefer 1954):

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

where B_y = biomass at the start of time step y; r = intrinsic growth rate; K = carrying capacity (equal to the initial biomass B_0 for a surplus production model); C_y = known catch during time-step y. Catches per year (C_y) were the sum of red cod annual catches in the Falkland Islands and Argentina. The Graham-Schaefer surplus production model has two unknown parameters, r and K. S = B_y/K, therefore K can be solved if prior information on r and S is available (Zhou et al. 2018).

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

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

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

To avoid negative values being sampled, a lognormal distribution was implemented in R Studio (RStudio Team 2021):

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

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

Natural mortality (M) was calculated from several published empirical life-history equations. Given the uncertainties in estimating M (Kenchington 2014), examining multiple estimators is recommended (Gunderson et al. 2003; Zhang & Megrey 2006; Brodziak et al. 2011):

$$\mathrm{M} = 4.899 \times t_{max}^{-0.916} = 4.899 \times 24^{-0.916} = 0.2666 \qquad \text{(Then et al. 2015)}$$

$$\mathrm{M} = 4.118 \times k^{0.73} \times L_{\infty}^{-0.33} = 4.118 \times 0.0924^{0.73} \times 100.59^{-0.33} = 0.1581 \qquad \text{(Then et al. 2015)}$$

$$\mathrm{M} = 1.82 \times k = 1.82 \times 0.0924 = 0.1683 \qquad \text{(Charnov et al. 2013)}$$

$$\mathrm{M} = \frac{4.3}{t_{max}} = \frac{4.3}{24} = 0.1792 \qquad \text{(Then et al. 2015)}$$

where t_{max} = maximum age, L_{∞} = asymptotic length, and k = rate by which L_{∞} is approached; maximum age was taken from the FIFD age-length database.

To solve K the prior distribution for stock saturation S was taken from Winter (2018), which was estimated using the length-based Bayesian biomass estimation method (LBB; Froese et al. 2018):

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

where $\mu_{B/B0}$ = 0.18 and $\sigma_{B/B0}$ = 0.0566. However, the LBB method has been criticized as potentially biased (Hordyk et al. 2019). An additional suite of saturation values was therefore tested between S = 0.12 and 0.24, to cover the plausible range for this stock (e.g., from February surveys B_{2020}/B_{2010} = 0.2431).

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 $B_{current} = B_{2020}$. MSY was also reported and was defined from the Graham-Schaefer production model as indicated in Hilborn & Walters (1992):

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

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

The biomass that can sustain MSY (B_{MSY}) was calculated following Schaefer (1954):

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

$0.5B_{MSY}$ is considered the biomass below which recruitment becomes impaired and the stock is in danger of collapsing (Froese et al. 2011). This reference point was based on the comparison of lower stock limits used in Europe (B_{pa} = precautionary reference point for spawning stock biomass) relative to B_{MSY} (Froese & Proelß 2010). $0.5B_{MSY}$ has been suggested as a limit reference point for closing target fisheries, and the default limit biomass below which additional measures must be activated (Froese et al. 2011), e.g., minimizing bycatch in other fisheries. Therefore, biomass estimates in 2020 were compared with $0.5B_{MSY.}$

OCOM Total Allowable Catch (TAC)

Historical catch is often used to estimate quota allocation on international and regional scales (Lynham 2014). Partition of the TAC between the Falkland Islands and Argentina may be considered as follows:

1) 10–, 5–, and 3–year average contributions (%) of the Falkland Islands relative to the combined catch of red cod in Falkland Islands and Argentina.
2) Equal share of the total catch limit of red cod between the Falkland Islands and Argentina, i.e. 50% each.

Results

Parameters estimated from the OCOM Graham-Schaefer production model based on the different mortality rates and saturation = 0.18 are summarized in Table AI-I. M = 0.1581 produced the most conservative MSY and was retained for testing with the suite of saturation values between S = 0.12 and S = 0.24. Different saturation values correlated inversely with the optimized value of K (Table AI-II), indicating that the algorithm used for these OCOM computations (Winter 2018) is not applicable without an accurately determined estimate of S.

Nevertheless, a reasonable corroboration is suggested with the ICES category 3 TAC. Input parameters M = 0.1581, F_{MSY} = 0.87, and S = 0.18 obtained K = 106,323 t, MSY = 7,305 t and the biomass time series in Fig. AI-III and Table AI-IV. With B_{MSY} = 0.5 K = 0.5 x 106,323 = 53,161.5 t, by proportion B_{2020}/B_{MSY} = 18,566 / 53,161.5 = 0.3492. Thus, the TAC of red cod should be approximately equivalent to 34.92% of MSY: 7,305 × 0.3492 = 2,550.91 t. Alternatives of the Falkland Islands partition of this TAC range from 1,275 to 1,796 t (Table AI-V), compared to the ICES category 3 TAC of 1,199 t (Table IV).

Table AI_I. OCOM Graham-Schaefer production model parameters and estimates of biomass and MSY for red cod, using commercial catch data from 1987 to 2020. M = mortality rate; r = intrinsic growth rate; K = carrying capacity; B_{1987} = biomass in 1987; B_{2020} = biomass in 2020; MSY = maximum sustainable yield. Medians with 95% confidence intervals in parentheses; selected outputs are indicated in bold font. Saturation S = 0.18.

	OCOM			
M	0.2666	**0.1581**	0.1683	0. 1792
r	0.4644 (0.1817 – 1.1932)	**0.2744** **(0.1071 – 0.6959)**	0.2909 (0.1141 – 0.7455)	0.3112 (0.1227 – 0.8026)
K	73,264 (35,841 – 136,820)	**106,323** **(53,793 – 179,061)**	102,437 (51,023 – 174,282)	97,722 (48,227 – 167,967)
B_{1987}	73,260 (37,697 – 136,797)	**106,330** **(53,866 – 179,056)**	102,417 (51,033 – 174,315)	97,745 (48,498 – 167,965)
B_{2020}	12,889 (4,270 – 30,421)	**18,566** **(5,810 – 41,321)**	17,597 (5,549 – 39,176)	16,930 (5,646 – 38,055)
B_{2020}/B_{1987}	0.1759 (0.1133 – 0.2224)	**0.1746** **(0.1079 – 0.2308)**	0.1718 (0.1087 – 0.2247)	0.1732 (0.1164 – 0.2266)
MSY	8,507 (6,214 – 10,691)	**7,305** **(4,772 – 9,359)**	7,445 (4,948 – 9,509)	7,608 (5,177 – 9,676)

Table AI_II. Outputs of the sensitivity analysis for the OCOM Graham-Schaefer production model using different saturation S values relative to the selected model with S = 0.18 for red cod stock, using commercial catch data from 1987 to 2020. M = mortality rate; r = intrinsic growth rate; K = carrying capacity; B_{1987} = biomass in 1987; B_{2020} = biomass in 2020; MSY = maximum sustainable yield. Medians with 95% confidence intervals in parentheses.

	OCOM						
S	0.12	0.14	0.16	**0.18**	0.20	0.22	0.24
M	0.1581	0.1581	0.1581	**0.1581**	0.1581	0.1581	0.1581
r	0.2775 (0.1078 – 0.6968)	0.2763 (0.1060 – 0.7058)	0.2758 (0.1093 – 0.6967)	**0.2744** **(0.1071 – 0.6959)**	0.2742 (0.1082 – 0.6914)	0.2764 (0.1072 – 0.7059)	0.2752 (0.1083 – 0.7059)
K	105,051 (53,739 – 174,251)	105,540 (53,214 – 176,758)	105,900 (53,756 – 176,784)	**106,323** **(53,793 – 179,061)**	106,712 (54,067 – 179,876)	106,301 (53,222 – 182,991)	106,814 (53,223 – 183,283)
B_{1987}	105,053 (53,709 – 174,162)	105,540 (53,247 – 176,756)	105,907 (53,816 – 176,784)	**106,330** **(53,866 – 179,056)**	106,699 (54,093 – 179,903)	106,314 (53,255 – 183,013)	106,822 (53,235 – 183,285)
B_{2020}	11,952 (1,052 – 30,009)	14,175 (2,633 – 33,756)	16,412 (4,530 – 36,742)	**18,566** **(5,810 – 41,321)**	20,635 (7,678 – 44,583)	22,593 (8,710 – 48,345)	24,858 (10,267 – 51,587)
B_{2020}/B_{1987}	0.1138 (0.0196 – 0.1723)	0.1343 (0.0495 – 0.1910)	0.1550 (0.0842 – 0.2078)	**0.1746** **(0.1079 – 0.2308)**	0.1933 (0.1419 – 0.2478)	0.2125 (0.1635 – 0.2642)	0.2327 (0.1929 – 0.2815)
MSY	7,290 (4,685 – 9,362)	7,292 (4,672 – 9,392)	7,298 (4,782 – 9,363)	**7,305** **(4,772 – 9,359)**	7,310 (4,855 – 9,349)	7,347 (4,871 – 9,393)	7,357 (4,920 – 9,392)

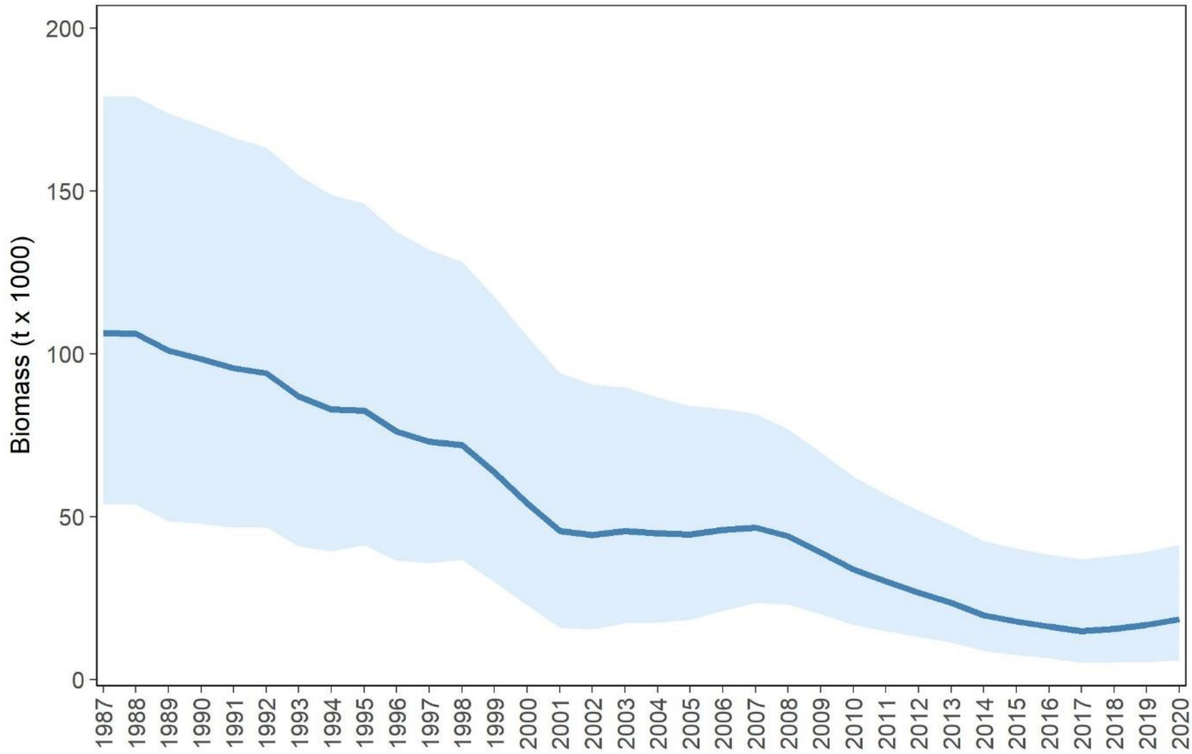


Fig. AI_III. Median and 95% confidence intervals of annual red cod stock biomass from 1987 to 2020 estimated from the OCOM Graham-Schaefer production model. The parameters were M = 0.1581; F_{MSY} = 0.87; S = 0.18; and $\sigma_{B/B0}$ = 0.0566.

Table AI_IV. OCOM total annual biomass estimates (median) and 95% lower and upper confidence intervals (LCI and UCI, respectively) from MCMC posterior distributions for red cod. Estimates considering Falkland Islands, Argentina and Chile, with natural mortality (M) = 0.1581

Year	Biomass (T)	LCI (t)	UCI (t)
1987	106,330	53,866	179,056
1988	106,193	53,696	178,921
1989	101,060	48,591	173,767
1990	98,427	47,858	170,316
1991	95,545	46,639	166,317
1992	94,066	46,803	163,427
1993	86,947	40,928	154,895
1994	82,865	39,301	148,714
1995	82,515	41,315	146,078
1996	76,140	36,540	137,523
1997	73,043	35,657	131,908
1998	72,034	36,721	128,319
1999	63,586	29,994	117,519
2000	54,183	22,791	105,370
2001	45,505	15,944	94,128
2002	44,298	15,405	90,623
2003	45,666	17,309	89,741
2004	44,848	17,514	86,568
2005	44,503	18,293	83,975

2006	45,951	21,050	83,113
2007	46,692	23,573	81,605
2008	44,034	22,993	76,848
2009	39,021	20,082	69,683
2010	33,737	16,791	62,310
2011	30,122	14,902	56,938
2012	26,629	13,054	51,901
2013	23,540	11,407	47,357
2014	19,630	8,718	42,500
2015	17,776	7,586	40,159
2016	16,250	6,502	38,230
2017	14,905	5,161	36,867
2018	15,601	5,265	37,885
2019	16,724	5,320	39,111
2020	18,566	5,810	41,321

Table AI_V. Total Allowable Catch (TAC) alternatives for red cod in Falkland Islands waters.

Criteria	Threshold	TAC (t)
1) Relative average contribution		
10-year (58.98%)	2,550.91 x 0.5898	1,504.52
5-year (63.91%)	2,550.91 x 0.6391	1,630.28
3-year (70.42%)	2,550.91 x 0.7042	1,796.35
2) Equal share		
50%	2,550.91 x 0.5	1,275.45

Appendix II. Annual commercial catches (t) of red cod reported in Falkland Islands (excluding E–licence; http://www.fig.gov.fk/fisheries/publications/fishery-statistics; Falkland Islands Government 2021) and Argentina (https://www.agroindustria.gob.ar/sitio/areas/pesca_maritima/desembarques/; Sánchez et al. 2012; Navarro et al. 2014, 2019).

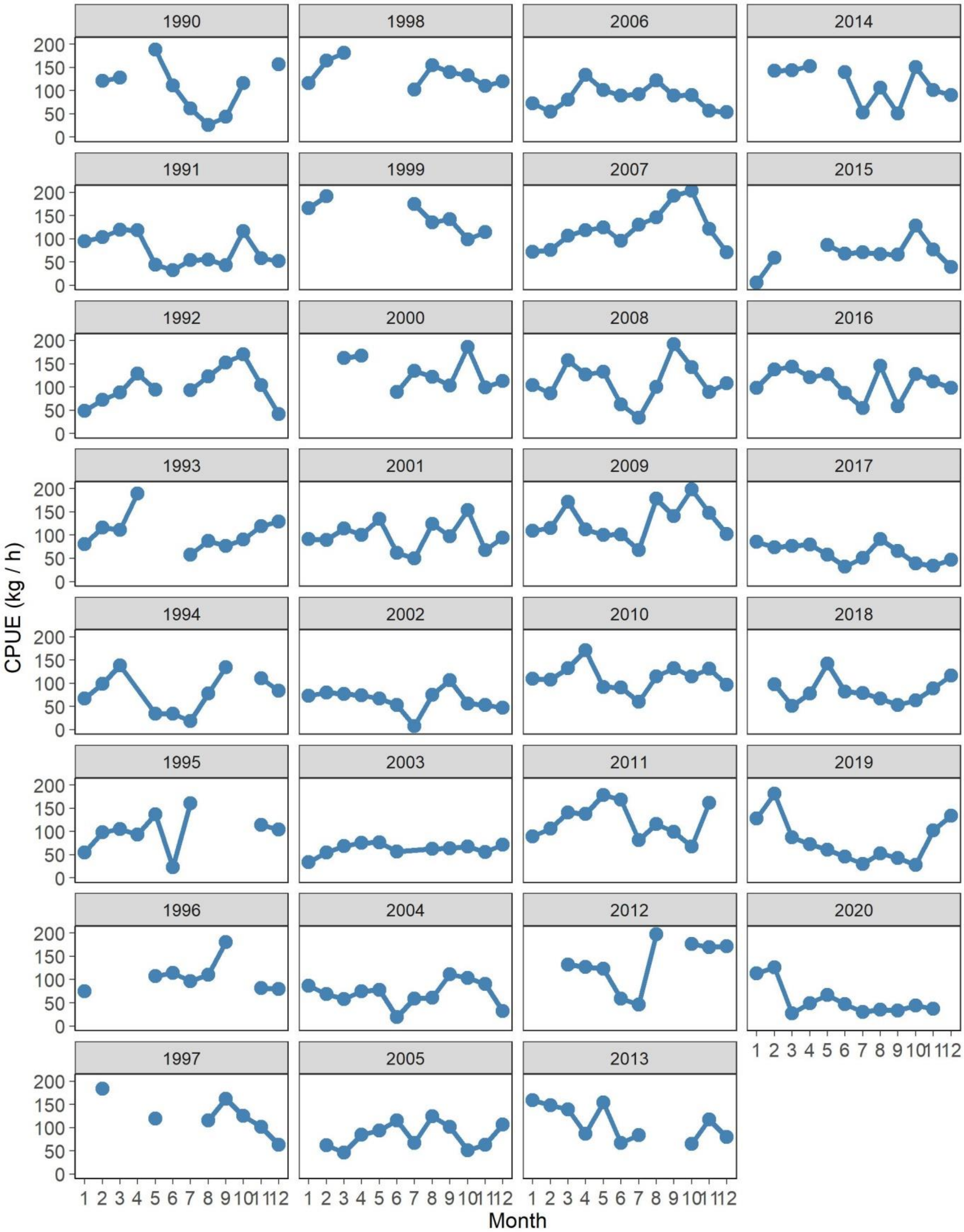
Year	Falkland Islands (t)	Argentina (t)
1987	88.0	46.9
1988	5,121.0	47.5
1989	2,817.0	1,186.0
1990	2,778.0	2,115.5
1991	2,880.0	1,272.2
1992	7,057.0	3,050.0
1993	6,231.0	2,207.3
1994	4,043.0	1,310.4
1995	9,085.0	2,359.3
1996	6,961.0	2,077.0
1997	4,691.0	2,610.4
1998	8,028.0	6,808.5
1999	9,235.0	7,202.9
2000	6,556.0	9,431.3
2001	3,896.0	4,449.0
2002	2,617.0	3,129.1
2003	2,284.0	5,689.1
2004	2,780.0	4,664.3
2005	2,465.0	3,185.5
2006	3,440.0	2,962.0
2007	5,192.0	4,609.8
2008	4,071.0	8,009.5
2009	5,094.0	6,962.7
2010	3,099.0	6,813.0
2011	4,184.0	5,190.7
2012	4,590.0	3,921.9
2013	5,103.0	3,814.9
2014	3,447.0	2,780.1
2015	3,312.0	2,289.2
2016	3,122.0	2,008.3
2017	1,363.0	1,511.2
2018	1,638.0	977.6
2019	1,725.0	396.6
2020	1,414.0	685.8

Appendix III. Identifying finfish-licenced observer samples.

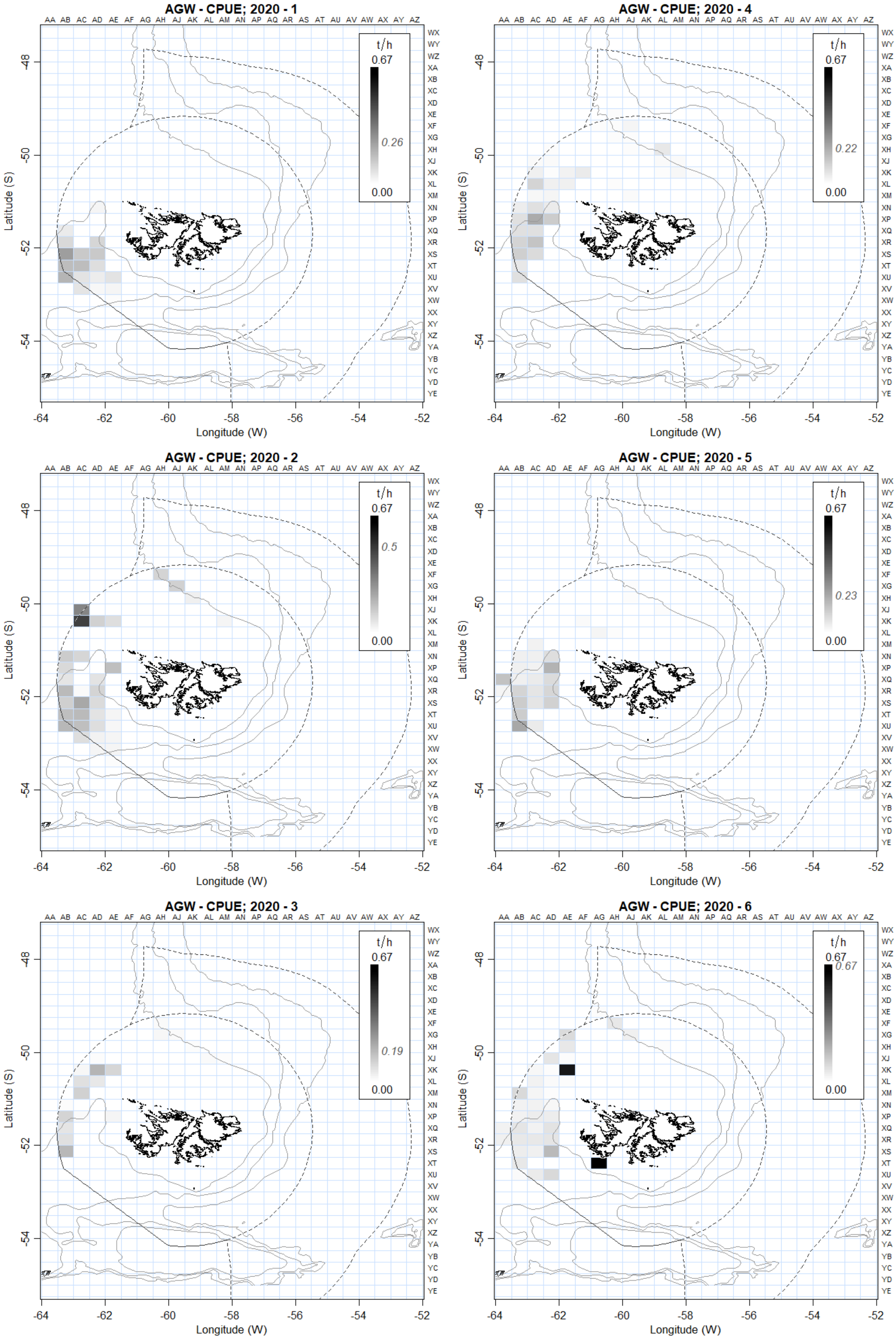
The FIFD observer database identifies samples by vessel, date, activity (fishing gear type), and observer station, but does not directly link to the licence that the vessel was operating under. If required, the licence must be cross-referenced from the catch report. In most cases, a catch report is recorded the same day by the same vessel, and the corresponding licence can be applied to the samples directly. In some cases however, a catch report is not recorded the same day and instead the nearest catch report by the same vessel either up to 3 days later or 1 day earlier is applied (which still does not result in all samples getting matched). The rationale being that a vessel will file its catch report when it has finished processing the trawl, which may be several days if it is a big haul or the factory is backed up; alternatively the observer might only sample a trawl the day after it was hauled.

Among positive licence matches, finfish trawl samples are those with activity codes B (bottom trawl), P (pelagic trawl) or S (semi-pelagic trawl), and licence codes A/Y (unrestricted finfish), G (*Illex* + restricted finfish), W/Z (restricted finfish), and S (surimi). Licence code E (experimental) may be any gear or catch target, and can therefore only be matched as finfish by checking against a survey report for that date range or, more expediently, evaluating the species composition that was caught. For this assessment, the criteria were used that a trawl E licence target was designated *Illex* if *Illex* comprised >50% of the catch within 1 day earlier and three days later, skate if skate comprised >50% of the catch within 1 day earlier and three days later, and calamari if calamari comprised >25% of the catch within 1 day earlier and three days later; otherwise finfish. The lower threshold for calamari reflected the outcome that calamari catch is often scarce in early days of pre-season surveys (e.g., Winter et al. 2019). As criteria of >50% *Illex* / skate vs. >25% calamari are non-exclusive, the additional rule was set that a catch composition was designated to that target which exceeded its threshold by the highest proportion. Finfish-designated E licence samples were then added to the commercial licence finfish samples.

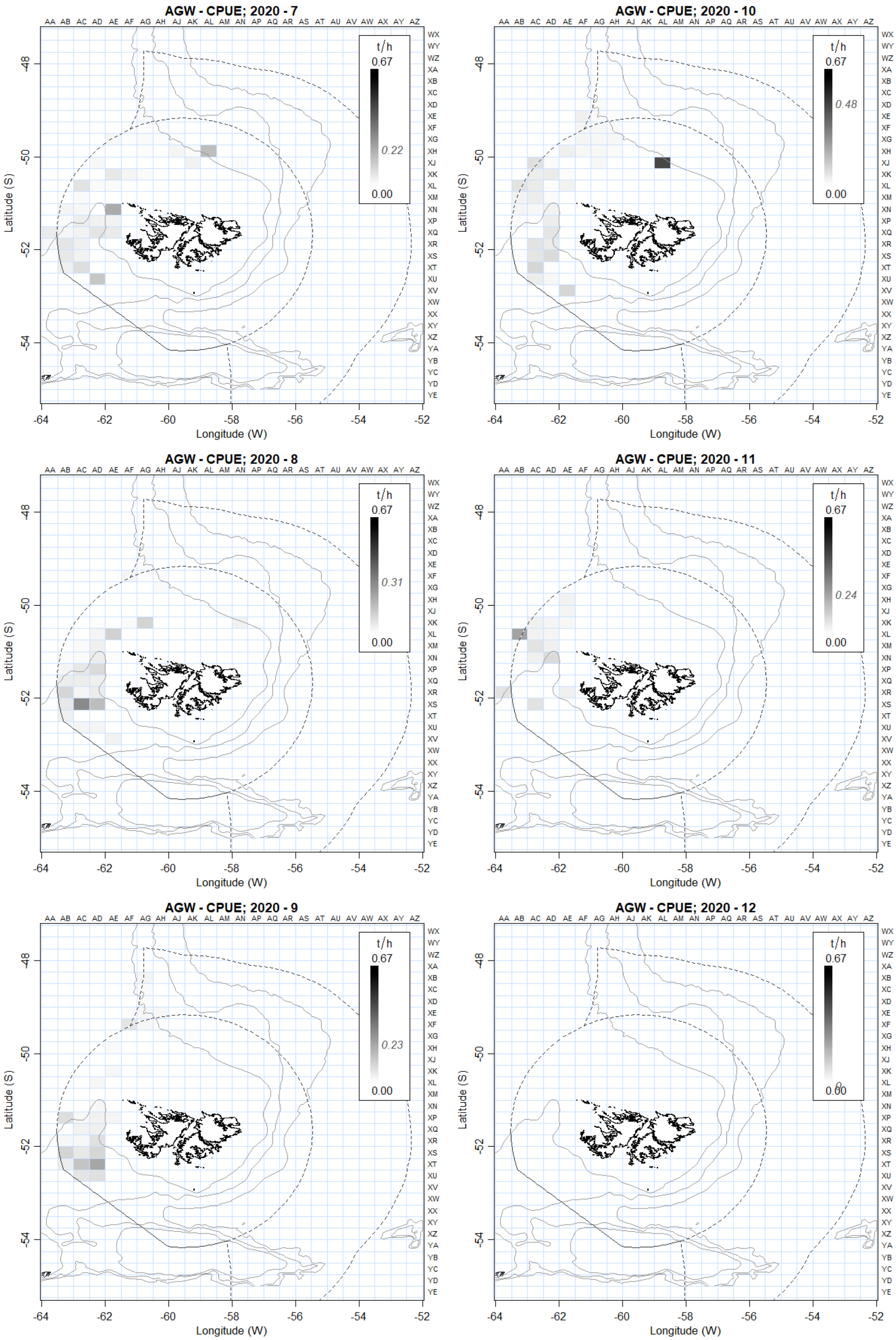
Appendix IV. Monthly CPUE of red cod in Falkland Islands waters from 1990 to 2020, estimated from A–, G–, and W–licensed vessels.



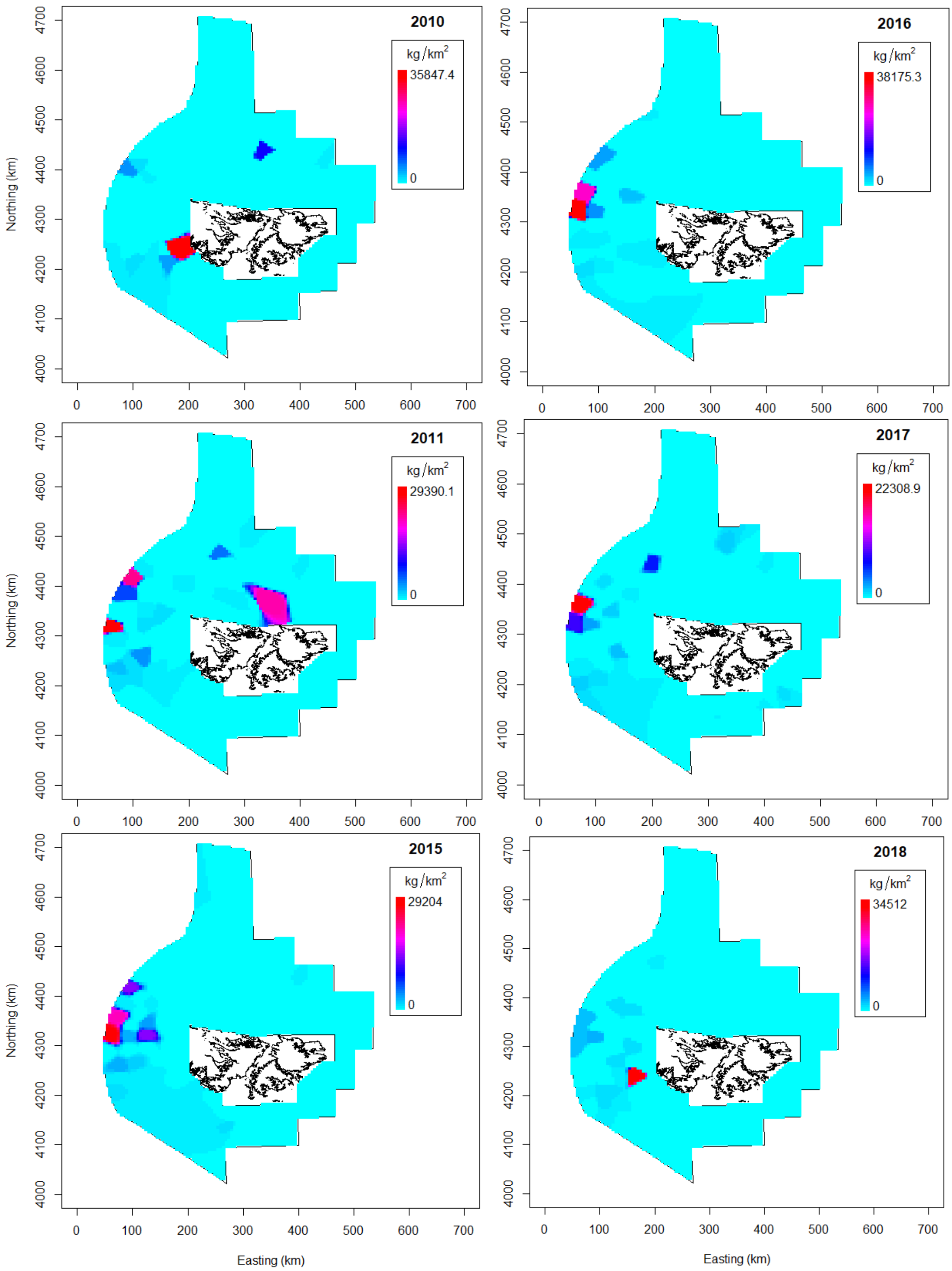
Appendix V. Monthly CPUE of red cod in Falkland Islands waters during 2020, estimated from A–, G–, and W–licensed vessels.



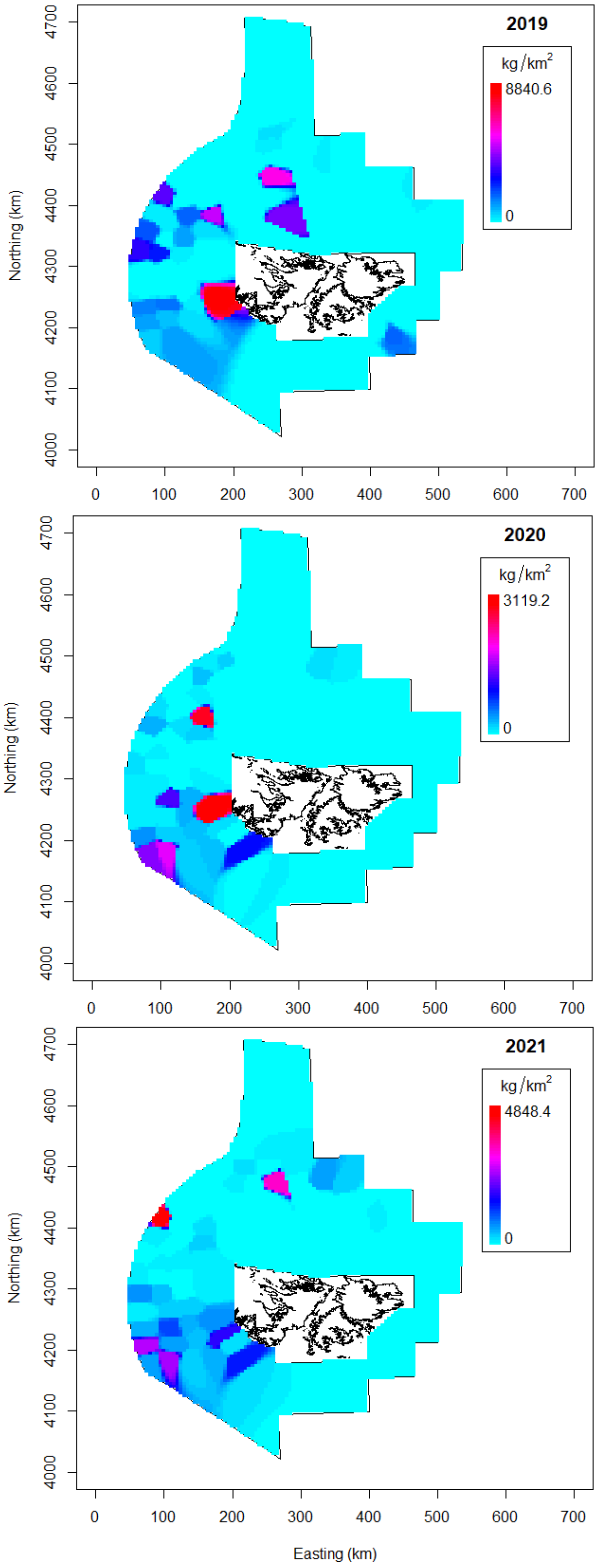
Appendix V. *continued…*



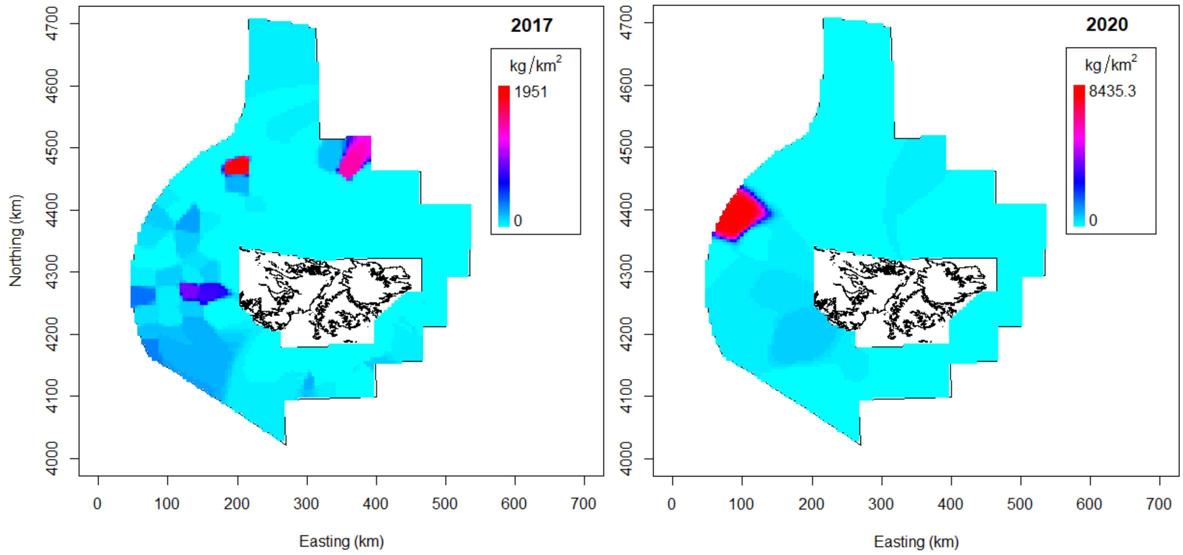
Appendix VI. Densities of red cod modelled by inverse distance weighting throughout the Falkland Islands fishing zone, in February 2010–2021.



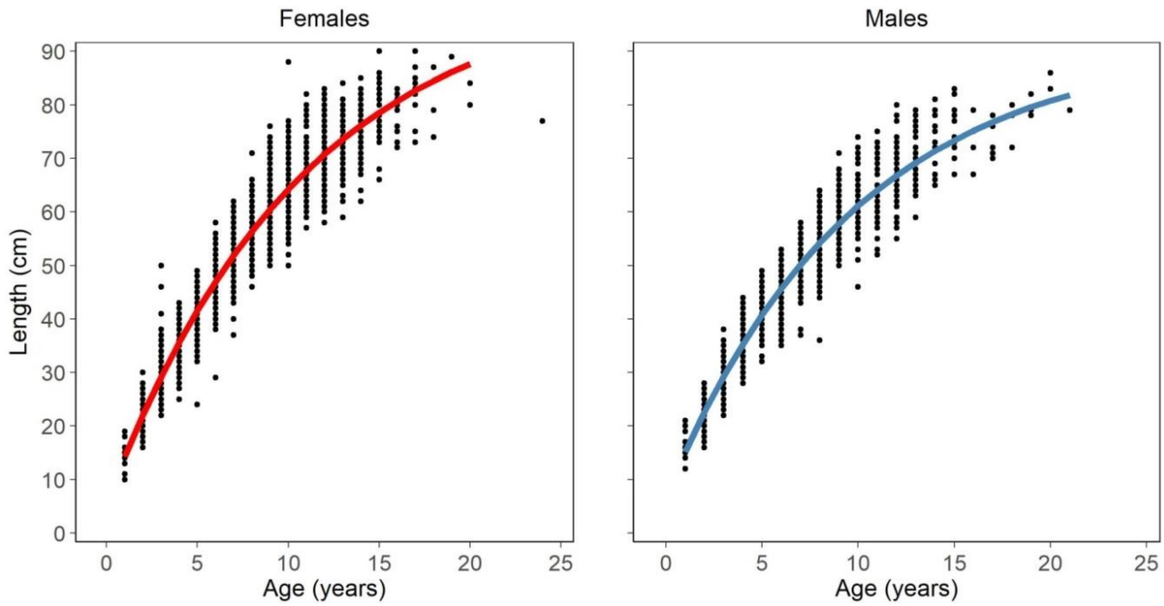
Appendix VI. *continued…*



Appendix VII. Densities of red cod modelled by inverse distance weighting throughout the Falkland Islands fishing zone, in July 2017 and July 2020.



Appendix VIII. von Bertalanffy age-length relationship of female and male red cod from the Falkland Islands.



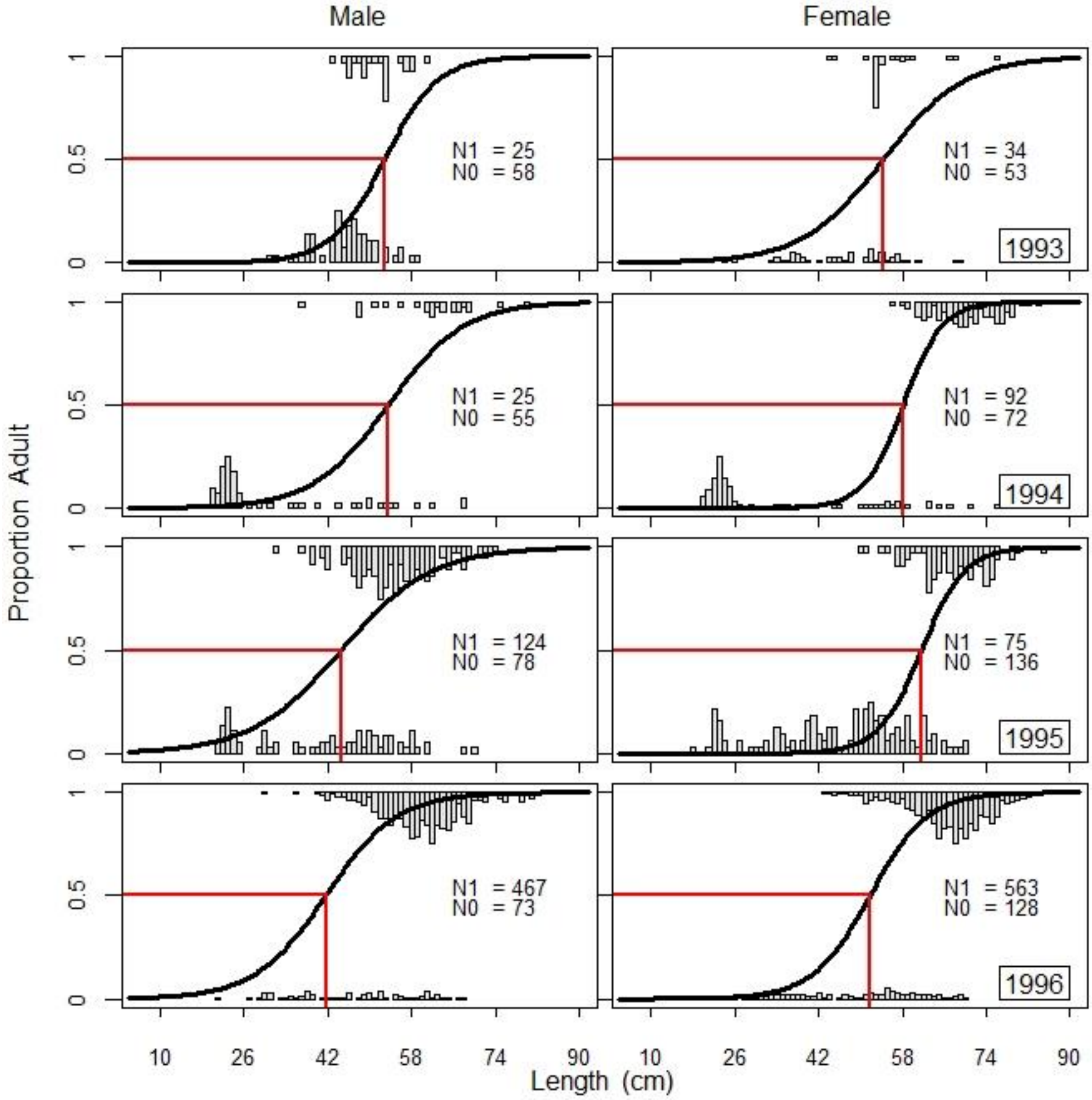
Appendix IX. Red cod von Bertalanffy length-at-age parameters for curvature (k), age of fish at length zero (t_0), and asymptotic length (L_∞), by year and sex, with 95% confidence intervals.

Sex	Year	N	k		t_0 (years)		L_∞ (cm)	
	1988	875	0.10	(0.09 - 0.11)	-1.40	(-1.76 - -1.09)	85.6	(80.9 - 91.6)
	1989	110	0.19	(0.15 - 0.24)	0.52	(0.03 - 0.92)	77.5	(73.3 - 83.3)
	1990	57	0.26	(0.17 - 0.37)	1.72	(0.26 - 2.63)	76.6	(72.6 - 83.8)
	1991	51	0.16	(0.07 - 0.26)	-0.32	(-4.33 - 1.41)	72.3	(66.0 - 94.6)
	1992	192	0.13	(0.09 - 0.17)	-0.61	(-1.76 - 0.19)	81.8	(74.8 - 94.6)
	1993	180	0.11	(0.08 - 0.14)	-0.79	(-1.65 - -0.15)	89.0	(81.8 - 101.0)
	1994	172	0.15	(0.13 - 0.18)	0.18	(-0.14 - 0.48)	84.0	(79.7 - 89.2)
	1995	406	0.10	(0.08 - 0.12)	-0.76	(-1.30 - -0.30)	96.7	(88.8 - 108.2)
	1996	573	0.13	(0.11 - 0.15)	-0.28	(-0.69 - 0.08)	87.7	(84.1 - 92.2)
	1997	205	0.11	(0.08 - 0.13)	-0.80	(-1.55 - -0.22)	95.8	(87.8 - 109.3)
	1998	531	0.13	(0.11 - 0.15)	0.20	(-0.21 - 0.56)	91.8	(87.0 - 98.3)
	1999	273	0.18	(0.14 - 0.22)	0.64	(-0.02 - 1.15)	85.0	(80.9 - 91.2)
	2000	288	0.09	(0.06 - 0.12)	-1.09	(-2.08 - -0.36)	97.1	(86.0 - 118.3)
	2001	259	0.14	(0.12 - 0.17)	0.04	(-0.47 - 0.44)	90.0	(85.8 - 95.7)
	2002	344	0.12	(0.09 - 0.14)	-0.21	(-0.80 - 0.28)	94.4	(88.2 - 103.2)
F	2003	202	0.11	(0.09 - 0.13)	-0.23	(-0.64 - 0.13)	95.4	(87.4 - 106.4)
	2004	368	0.09	(0.07 - 0.10)	-0.77	(-1.21 - -0.40)	106.9	(99.5 - 117.2)
	2005	500	0.10	(0.09 - 0.12)	-0.33	(-0.59 - -0.10)	99.6	(94.7 - 105.9)
	2006	342	0.11	(0.10 - 0.13)	-0.43	(-0.76 - -0.13)	94.6	(89.4 - 101.2)
	2007	144	0.10	(0.08 - 0.12)	-0.69	(-1.24 - -0.23)	91.9	(85.0 - 101.5)
	2008	393	0.10	(0.08 - 0.11)	-0.69	(-1.03 - -0.40)	98.6	(92.6 - 106.9)
	2009	467	0.08	(0.07 - 0.10)	-0.48	(-0.72 - -0.27)	112.9	(104.8 - 123.6)
	2010	278	0.08	(0.06 - 0.10)	-0.83	(-1.24 - -0.48)	115.7	(101.3 - 141.1)
	2011	418	0.07	(0.06 - 0.08)	-0.74	(-1.03 - -0.49)	125.5	(112.8 - 144.1)
	2012	252	0.09	(0.08 - 0.10)	-0.54	(-0.81 - -0.29)	102.5	(96.6 - 110.2)
	2013	247	0.09	(0.07 - 0.10)	-0.53	(-0.82 - -0.28)	102.9	(95.3 - 113.2)
	2014	552	0.07	(0.06 - 0.08)	-0.68	(-0.86 - -0.52)	124.6	(113.1 - 140.0)
	2015	517	0.09	(0.08 - 0.10)	-0.64	(-0.82 - -0.48)	107.8	(101.8 - 114.9)
	2016	430	0.10	(0.09 - 0.11)	-0.23	(-0.45 - -0.03)	100.1	(93.8 - 108.2)
	2017	313	0.10	(0.08 - 0.11)	-0.20	(-0.42 - -0.01)	102.2	(95.5 - 111.0)
	2018	181	0.06	(0.04 - 0.09)	-0.74	(-1.35 - -0.25)	131.3	(108.7 - 178.8)

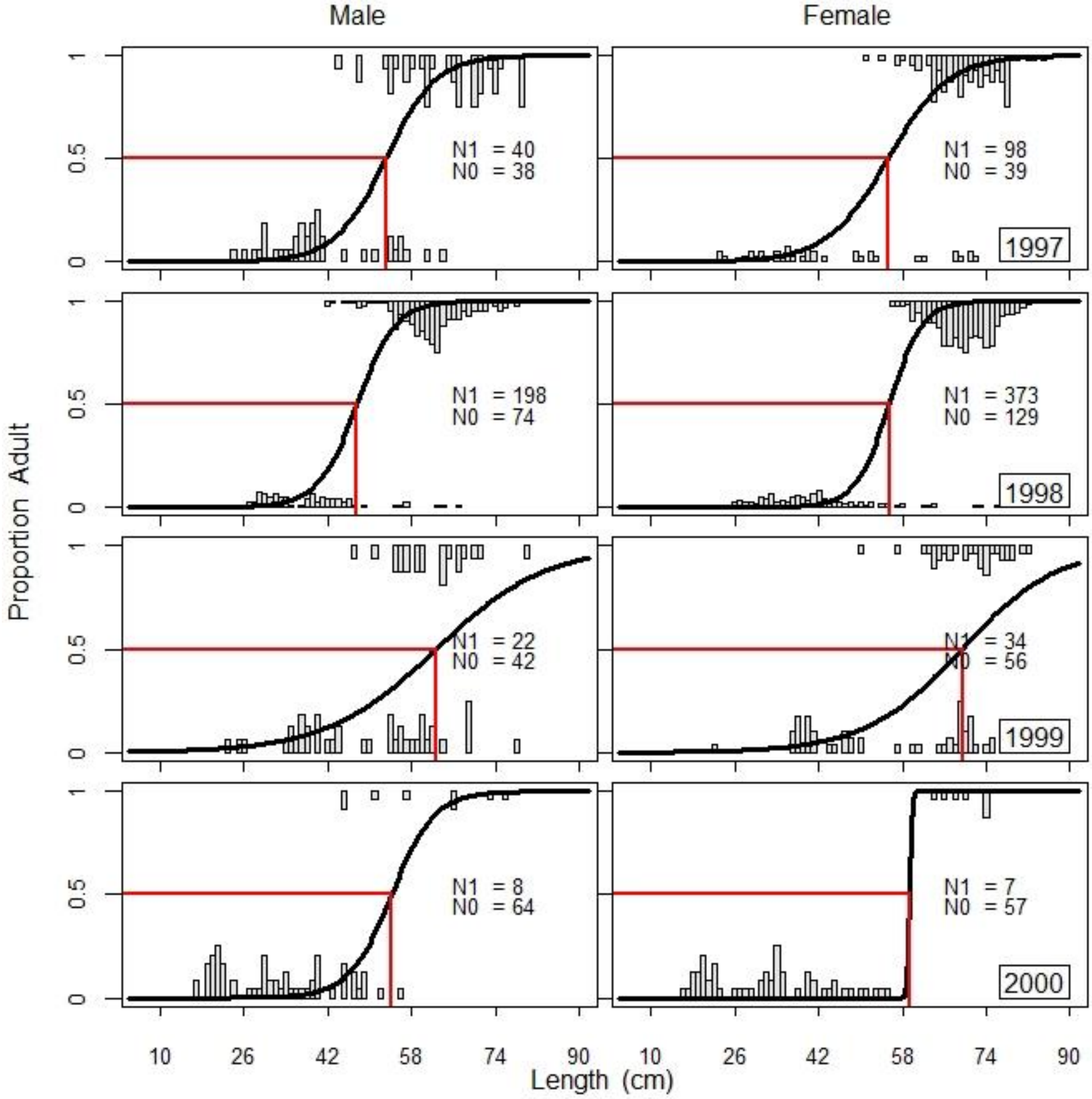
Sex	Year	N	k		t_0 (years)		L_∞ (cm)	
	1988	744	0.09	(0.07 - 0.10)	-1.98	(-2.44 - -1.59)	85.6	(79.2 - 95.1)
	1989	79	0.16	(0.11 - 0.21)	0.08	(-0.66 - 0.66)	79.4	(72.4 - 90.7)
	1990	48	0.19	(0.06 - 0.35)	-0.24	(-4.43 - 1.66)	69.9	(62.4 - 103.2)
	1991	50	0.20	(0.11 - 0.30)	-0.14	(-2.84 - 1.30)	64.8	(60.0 - 75.0)
	1992	160	0.20	(0.15 - 0.26)	-0.16	(-1.01 - 0.47)	63.6	(59.5 - 69.4)
	1993	158	0.11	(0.07 - 0.15)	-1.62	(-3.29 - -0.49)	84.8	(75.7 - 102.8)
	1994	99	0.12	(0.09 - 0.15)	-0.32	(-0.76 - 0.04)	91.5	(81.7 - 107.5)
	1995	336	0.12	(0.10 - 0.15)	-0.50	(-0.98 - -0.09)	84.2	(77.4 - 94.3)
	1996	433	0.12	(0.09 - 0.14)	-0.95	(-1.54 - -0.45)	84.2	(79.0 - 91.8)
	1997	143	0.11	(0.07 - 0.15)	-1.04	(-1.91 - -0.38)	89.5	(79.5 - 108.2)
	1998	240	0.13	(0.10 - 0.16)	-0.17	(-0.77 - 0.31)	84.4	(78.6 - 93.4)
	1999	186	0.21	(0.15 - 0.26)	0.29	(-0.58 - 0.91)	73.2	(69.4 - 79.5)
	2000	266	0.16	(0.13 - 0.19)	-0.32	(-0.90 - 0.14)	72.0	(68.7 - 76.5)
	2001	115	0.13	(0.10 - 0.16)	-0.63	(-1.37 - -0.06)	84.7	(78.4 - 94.0)
	2002	182	0.09	(0.06 - 0.11)	-1.36	(-2.14 - -0.75)	100.5	(90.5 - 117.5)

M	2003	146	0.15	(0.11 - 0.19)	0.01	(-0.50 - 0.43)	78.3	(71.6 - 87.4)
	2004	257	0.10	(0.07 - 0.12)	-1.06	(-1.80 - -0.54)	92.5	(85.2 - 106.3)
	2005	272	0.07	(0.06 - 0.09)	-1.20	(-1.70 - -0.78)	113.1	(100.5 - 132.3)
	2006	232	0.12	(0.10 - 0.14)	-0.97	(-1.34 - -0.64)	83.2	(78.7 - 88.5)
	2007	96	0.09	(0.06 - 0.12)	-1.17	(-1.89 - -0.60)	90.6	(80.0 - 109.0)
	2008	219	0.09	(0.07 - 0.11)	-1.08	(-1.50 - -0.72)	95.3	(87.1 - 107.0)
	2009	333	0.09	(0.07 - 0.11)	-0.78	(-1.15 - -0.49)	96.9	(88.6 - 109.3)
	2010	180	0.15	(0.12 - 0.17)	-0.25	(-0.54 - -0.01)	77.3	(72.4 - 84.1)
	2011	230	0.13	(0.11 - 0.14)	-0.37	(-0.60 - -0.17)	83.3	(77.9 - 90.4)
	2012	212	0.11	(0.10 - 0.12)	-0.37	(-0.62 - -0.15)	91.5	(86.7 - 97.6)
	2013	134	0.11	(0.09 - 0.13)	-0.30	(-0.56 - -0.07)	88.0	(82.3 - 95.7)
	2014	407	0.09	(0.08 - 0.11)	-0.44	(-0.60 - -0.30)	104.1	(93.7 - 119.1)
	2015	377	0.09	(0.08 - 0.11)	-0.66	(-0.83 - -0.50)	99.5	(93.3 - 107.3)
	2016	279	0.12	(0.10 - 0.13)	-0.42	(-0.65 - -0.22)	84.9	(80.3 - 90.2)
	2017	230	0.08	(0.06 - 0.10)	-0.73	(-1.07 - -0.43)	105.5	(92.3 - 127.0)
	2018	143	0.07	(0.04 - 0.11)	-0.99	(-1.83 - -0.39)	109.9	(88.1 - 174.5)

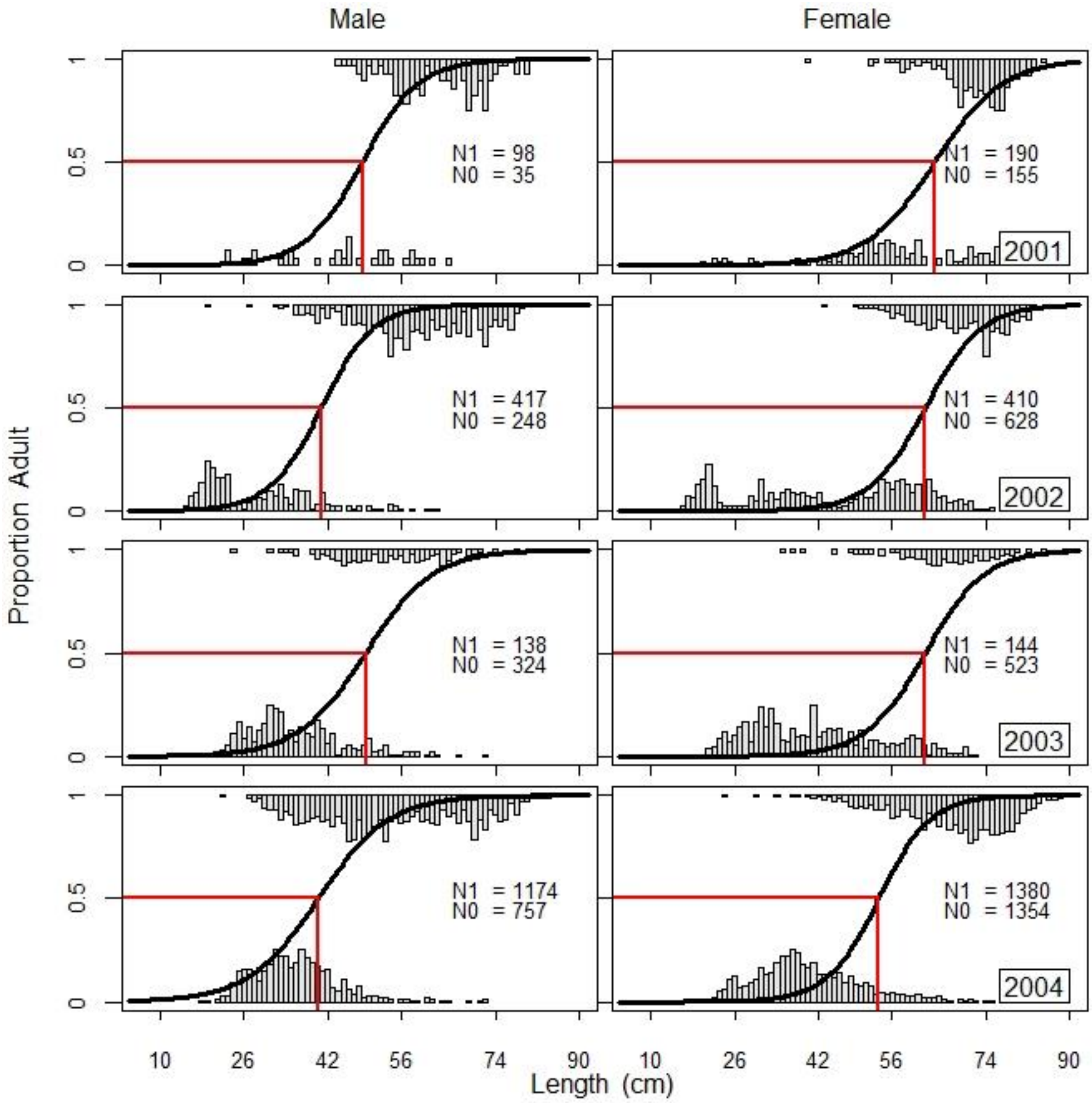
Appendix X. Binomial logistic regressions of juvenile (0) or adult (1) maturity vs. length for red cod. Grey bars: distributions scaled to sample numbers. Red lines: Length intercept of 50% adulthood, corresponding to Fig. 7.



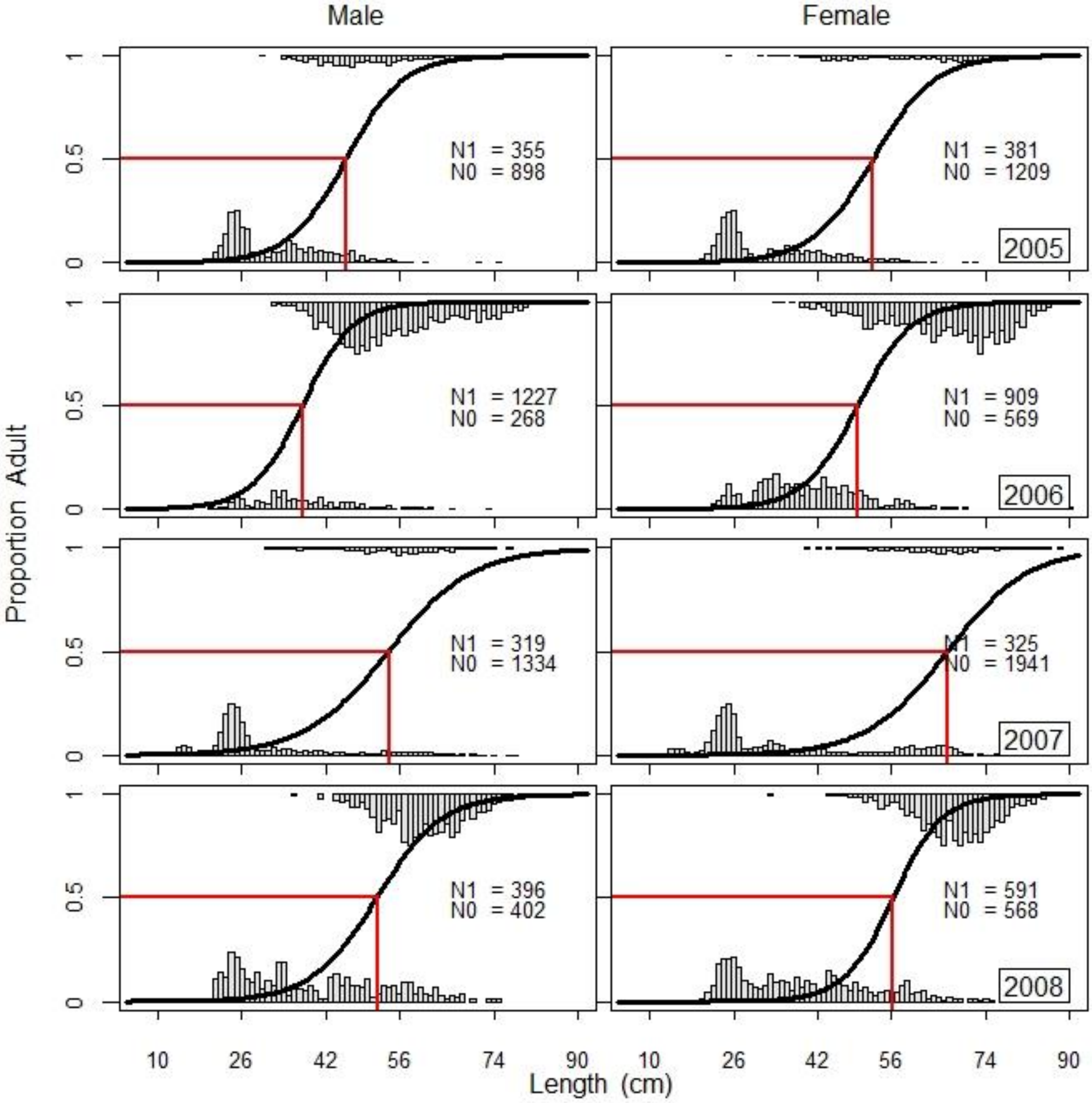
Appendix X. *continued…*



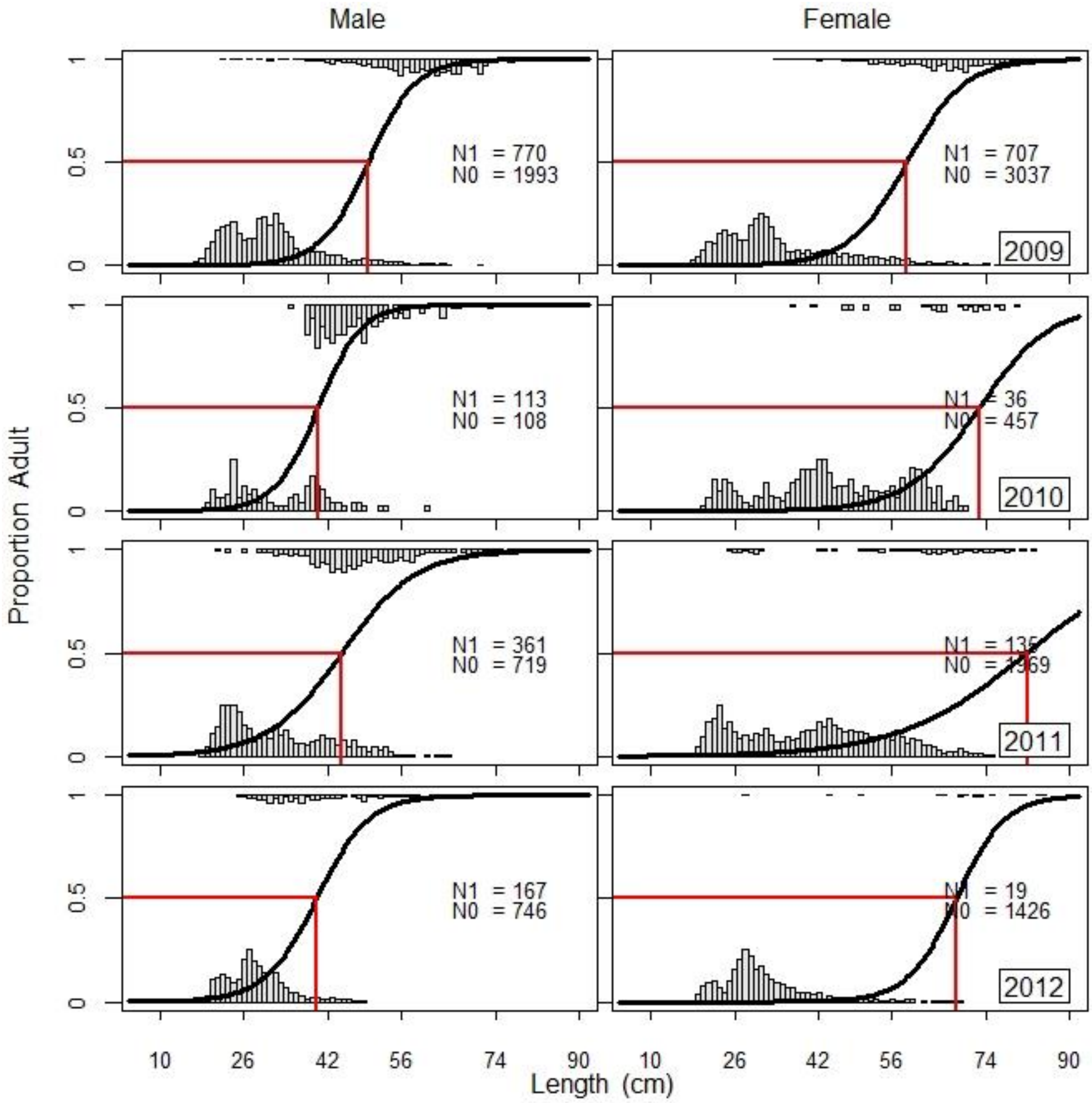
Appendix X. *continued…*



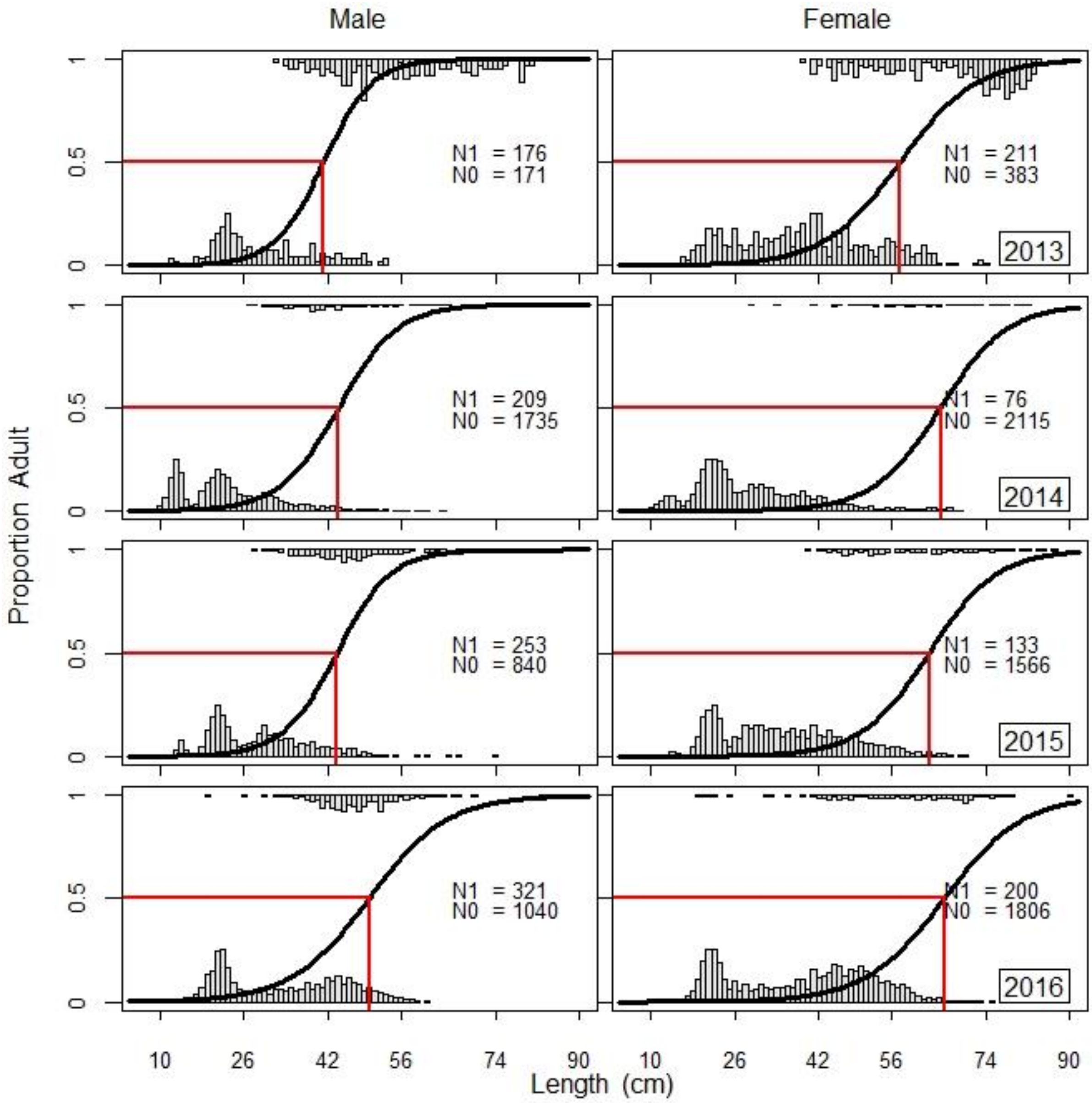
Appendix X. *continued…*



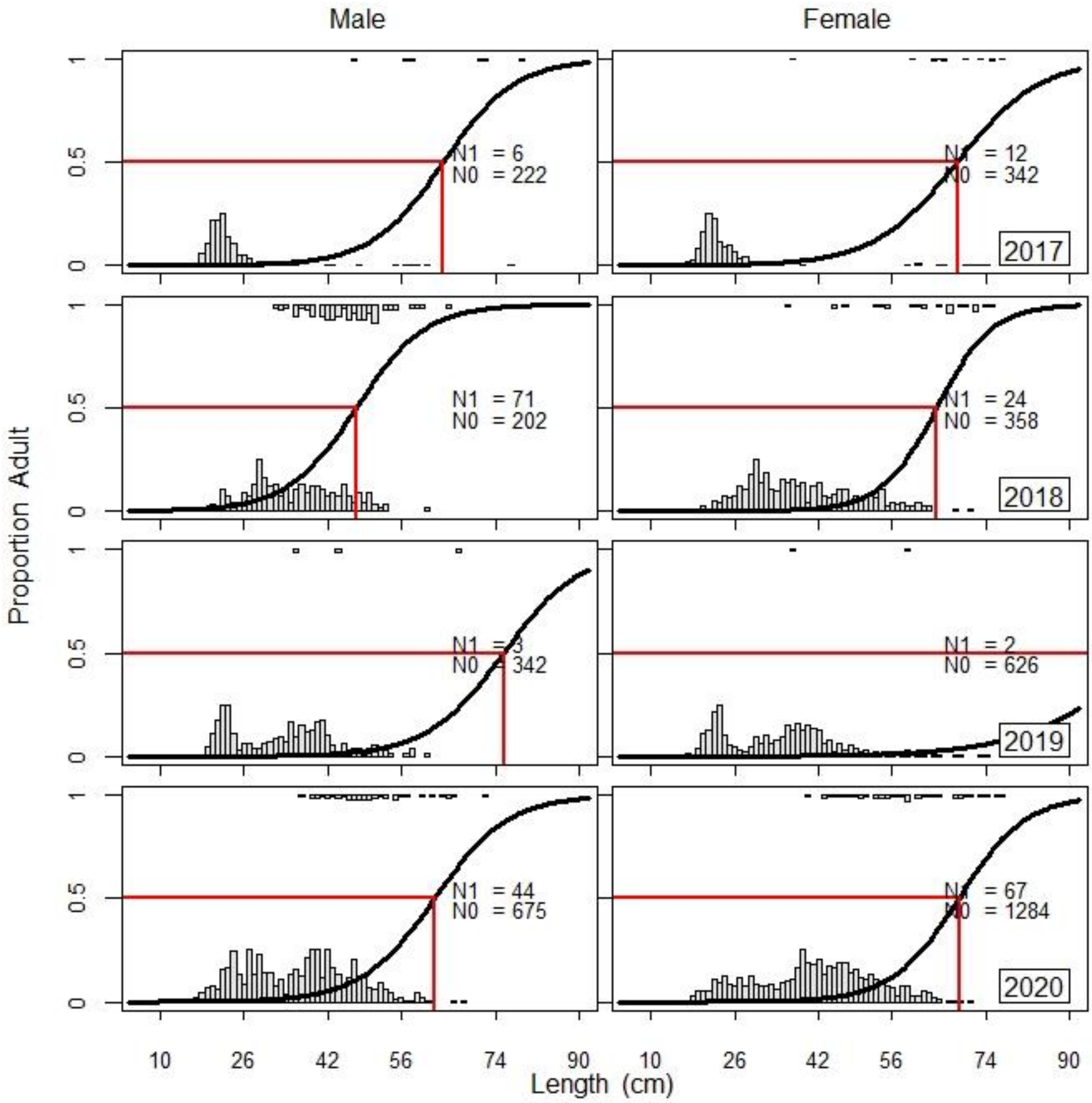
Appendix X. *continued…*



Appendix X. *continued…*



Appendix X. *continued…*



Appendix XI. Number of red cod individuals sampled for length frequency distributions.

Year	Females (n)	Males (n)
2002	1,769	1,231
2003	746	513
2004	3,441	2,425
2005	1,514	1,220
2006	2,078	1,666
2007	2,374	1,501
2008	1,704	1,075
2009	4,241	2,971
2010	1,652	1,021
2011	3,284	1,941
2012	2,001	1,388
2013	1,154	681
2014	1,309	925
2015	1,823	1,075
2016	3,254	2,357
2017	1,235	802
2018	1,813	1,183
2019	1,979	1,224
2020	3,546	2,240