Stock Assessment of rock cod (*Patagonotothen ramsayi*) in the Falkland Islands

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Summary

Commercial catches of rock cod *Patagonotothen ramsayi* in Falkland Islands licenced fisheries were 1,316 tonnes (t) in 2021, the sixth lowest catch reported since 1990. In 2021, calamari (C– and X–licences) vessels accounted for 82%, and finfish vessels (A–, G–, and W–licences) accounted for 12.5% of the total rock cod catch; 94% of the total rock cod catch was discarded.

Abundance has a declining trend. Annual commercial CPUE reached its lowest level (10 kg/h) in 2021. The biomass calculated from the 2022 austral summer (February) research surveys was 11.4% of the biomass calculated from the 2010 austral summer research surveys, and the biomass calculated from the 2020 austral winter (July) research surveys was 10.9% of the biomass calculated from the 2017 austral winter research surveys.

Length-based indicators suggest that conservation of immature fish, large individuals, mega-spawners, and optimal yield were of concern or negative through most of the time series. Asymptotic lengths (L_{Inf}) decreased since 2014, length at 50% maturity declined from 2003. Length frequency distributions show a shift in 2015, with the majority of individuals being > 20 cm total length before 2015 and < 20 cm total length since 2015. Rock cod was caught mainly at ages 2–3 years old, before reaching sexual maturity.

Following recommendations of the MacAlister Elliott & Partners external review, Total Allowable Catch (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. The ICES category 3 rule calculated a rock cod TAC for 2023 of 2,179 t. However, given the several weak length-based indicators, a more precautionary approach is recommended to limit rock cod TAC for the year 2023 to the same TAC as 2022: 1,266 t.

Introduction

Rock cod *Patagonotothen ramsayi* (Regan, 1913) is a medium-sized benthopelagic species that inhabits the shelf and upper slope at 50–500 m depth in the Southwest Atlantic (Brickle et al. 2006; Laptikhovsky et al. 2013). Part of the stock migrates into Falkland Islands waters in austral spring (October to December) and summer (January to March), to the northwest and north of the Falkland Islands Conservation Zone; in autumn (April to June), rock cod emigrates from Falkland Islands waters and remains in low abundances during austral winter (July to September) (Arkhipkin et al. 2012). Spawning occurs in austral autumn on the Argentine Shelf at 42°S, at the end of austral autumn and in part of austral winter at the shelf break in Falkland Islands waters, and in austral spring at the Burdwood Bank (Ekau 1982; Brickle et al. 2006). Most of the rock cod catch in the Southwest Atlantic is historically taken by the Falkland Islands fishery (Falkland Islands Government [a]; Falkland Islands Government *in prep.*), compared with the Argentina fishery (Argentine Government [b]; Sánchez et al. 2012; Navarro et al. 2014, 2019). Rock cod has long been a major bycatch component of Falkland trawl fisheries (Brickle et al. 2006; La Mesa et al. 2016), as predators of rock cod are commercially important species, i.e., toothfish, kingclip, hakes, and skates (Arkhipkin et al. 2003; Brickle et al. 2003; Nyegaard et al. 2004). Rock cod are also known to scavenge trawl discards (Laptikhovsky & Arkhipkin 2003), resulting in further overlap with the fisheries. With the decline of southern blue whiting *Micromesistius australis australis* and the simultaneous increase in abundance of rock cod in the 2000s, this species became the main commercial target in Falkland Islands waters (Laptikhovsky et al. 2013) with record catches from 2008 to 2014. Rock cod catches saw a steep decline from 2015 and have been bycatch in small quantities ever since[a].

Methods

ICES advice rules

In 2020, rock cod was included in the Falkland Islands Government finfish stock assessment and management review (MEP 2020). The MEP report recommended stock

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

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 rock 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. 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_{Inf} (Haddon 2001) and L50 (length at 50% maturity; Cope & Punt 2009).

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 rock cod catch data were examined from 1987 to 2021 from the Falkland Islands (Falkland Islands Government[a]; Falkland Islands Government *in prep.*), 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 rock cod from 1987 to 2021.

Commercial catches and discard of rock cod in Falkland Islands waters were examined by licence type for 2021. Catch per unit effort (CPUE) was estimated as the sum of rock cod catches divided by the sum of effort, per year and per month, from finfish (A–, G–, and W–) licences. Spatial distribution of the 2021 monthly CPUE average was estimated from the finfish vessels, and from the calamari (C– and X–licences) vessels that contributed most of the rock cod catches.

Survey biomass estimates

Biomass estimates and the spatial distribution of rock cod were examined from austral summer scientific surveys (groundfish and pre-recruitment surveys) carried out in February

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

2010, 2011, and 2015 – 2022 in Falkland Islands waters (Ramos & Winter 2022). A trend of the biomass time series from 2010 to 2022 was calculated using LOESS (span = 0.75, degree = 2). 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). Biomass estimates, the spatial distribution of rock cod, and biomass ratios were also examined (following Ramos & Winter 2022) 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 Total Allowable Catch (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 2022), 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 I). 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% change:

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

Then:

$$TAC\_3_{2021} = TAC\_3_{2020} \times \left.\frac{\overline{B_{2019\ to\ 2020}}}{\overline{B_{2016\ to\ 2018}}}\right| \pm 20\%$$

$$TAC\_3_{2022} = TAC\_3_{2021} \times \left.\frac{\overline{B_{2020\ to\ 2021}}}{\overline{B_{2017\ to\ 2019}}}\right| \pm 20\%$$

$$TAC\_3_{2023} = TAC\_3_{2022} \times \left.\frac{\overline{B_{2021\ to\ 2022}}}{\overline{B_{2018\ to\ 2020}}}\right| \pm 20\%$$

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 rock cod biomass were estimated from each year's 10,000 randomized re-samples (2015 = 1812238298.4; 2016 = 1086091193.4; 2017 = 252713155.1; 2018 = 247374890.8; 2019 = 101030944.9; 2020 = 16692274.9; 2021 = 28913954.4; 2022 = 350918441.5). TAC was calculated as follows:

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

$$TAC\_3_{2020} = TAC\_5_{2019} \times \left.\frac{\left(\sum_{y=2018}^{2019} B_y \times {}^{1}\!/_{Var_y}\right) \Big/ \left(\sum_{y=2018}^{2019} {}^{1}\!/_{Var_y}\right)}{\left(\sum_{y=2015}^{2017} B_y \times {}^{1}\!/_{Var_y}\right) \Big/ \left(\sum_{y=2015}^{2017} {}^{1}\!/_{Var_y}\right)}\right| \pm 20\%$$

$$TAC\_3_{2021} = TAC\_3_{2020} \times \left.\frac{\left(\sum_{y=2019}^{2020} B_y \times {}^{1}\!/_{Var_y}\right) \Big/ \left(\sum_{y=2019}^{2020} {}^{1}\!/_{Var_y}\right)}{\left(\sum_{y=2016}^{2018} B_y \times {}^{1}\!/_{Var_y}\right) \Big/ \left(\sum_{y=2016}^{2018} {}^{1}\!/_{Var_y}\right)}\right| \pm 20\%$$

$$TAC\_3_{2022} = TAC\_3_{2021} \times \left. \frac{\left(\sum_{y=2020}^{2021} B_y \times {}^{1}/_{Var_y}\right) \Big/ \left(\sum_{y=2020}^{2021} {}^{1}/_{Var_y}\right)}{\left(\sum_{y=2017}^{2019} B_y \times {}^{1}/_{Var_y}\right) \Big/ \left(\sum_{y=2017}^{2019} {}^{1}/_{Var_y}\right)} \right| \pm 20\%$$

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

Where 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_{Inf} (Haddon 2001) and L50 (length at 50% maturity; Cope & Punt 2009). L_{Inf} and L50 parameters were assessed for females and males separately as rock cod maturation is sexually dimorphic (Brickle et al. 2006).

LBI method was applied to all years from which observer length measurements of rock cod were available and reported as random samples (FIFD database codes R and S), i.e., years 2004 to 2021. 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 rock cod.

The procedure for identifying finfish-licensed observer samples is described in Appendix II. 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 by number (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 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 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

The von Bertalanffy growth function (R package 'fishmethods'; Nelson 2019) was used to fit rock cod length and age data from the FIFD database with nonlinear least-squares fitting. Calculations were made using only rock cod age data from the years 2014–2017, which are considered reliable (Lee et al. 2018, 2020). 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. The resulting von Bertalanffy parameters were used to predict ages for female and male length data collected randomly (FIFD database codes R and S). Variabilities of L_{Inf}, K, and t_0 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 trends of von Bertalanffy parameters were calculated by LOESS (span = 0.75, degree = 2).

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 and stages 3+ are always adult (B. Lee, FIFD, *pers. comm.*). Therefore, maturity assignment was simplified to a dichotomous classification of juvenile (0 – 1) or adult (3+), omitting stage 2 (Winter 2018). Rock cod maturities of randomly sampled individuals collected under finfish (A–, G–, W–) and experimental (E–) licences were available consistently from 2003 to 2021. Trends of L50 were calculated with LOESS smooths (span =

0.75, degree = 2), weighted by inverse variance of each year's binomial logistic regression. Previous assessments (e.g., Winter 2020) had shown these trends to be significant and the LOESS fits per year were used for LBI parameterization.

Length frequencies

Length frequencies were examined yearly for females and males to describe patterns in length through time. Lengths of individuals sampled randomly on finfish bottom trawl vessels, i.e., A–, G–, and W– licences, and the experimental E–licence, were included in the analysis. Length frequencies were examined from 2003 to 2021; unsexed individuals were excluded from the analysis.

Catch at age

Catch at age proportions were examined as a proxy for fishing pressure at each age class. Ideally, fishing pressure should be higher on age classes of mature individuals that have already reproduced. High fishing pressure on young and immature individuals is detrimental for the stock. The proportion of catch at age was calculated for females and males separately, and per year. Rock cod age data from the years 2014–2017 are considered reliable (Lee et al. 2018, 2020). Ages were extrapolated to the other years (2004 to 2021) from corresponding lengths of randomly sampled individuals, using von Bertalanffy growth function parameters calculated with the 2014–2017 data (in R package 'fishmethods'; Nelson 2019).

Natural mortality

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

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

$$\mathrm{M} = 4.118 \times \mathrm{K}^{0.73} \times \mathrm{L}_{\mathrm{Inf}}^{-0.33} \qquad \text{Eqn. 2}$$

where t_{max} = maximum age, K = rate by which L_{Inf} is approached, and L_{Inf} = asymptotic length. Eqn. 1 was prioritized over Eqn. 2 given that reliable rock cod age data are only available for years 2014–2017 (Lee et al. 2018, 2020), and Eqn. 1 does not require the age-derived parameters K and L_{Inf} . Then et al. (2015) further 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. However, outputs from both equations 1 and 2 were presented for comparison.

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

Results

Commercial catch and CPUE

Rock cod catches in Falkland Islands waters were negligible from 1987 to 2002, but since 2003 have represented approximately 74% of the Falkland Islands and Argentine combined annual catch (Fig. 1). Falkland Islands and Argentine rock cod annual catches were positively correlated (Fig. 2; Appendix I).

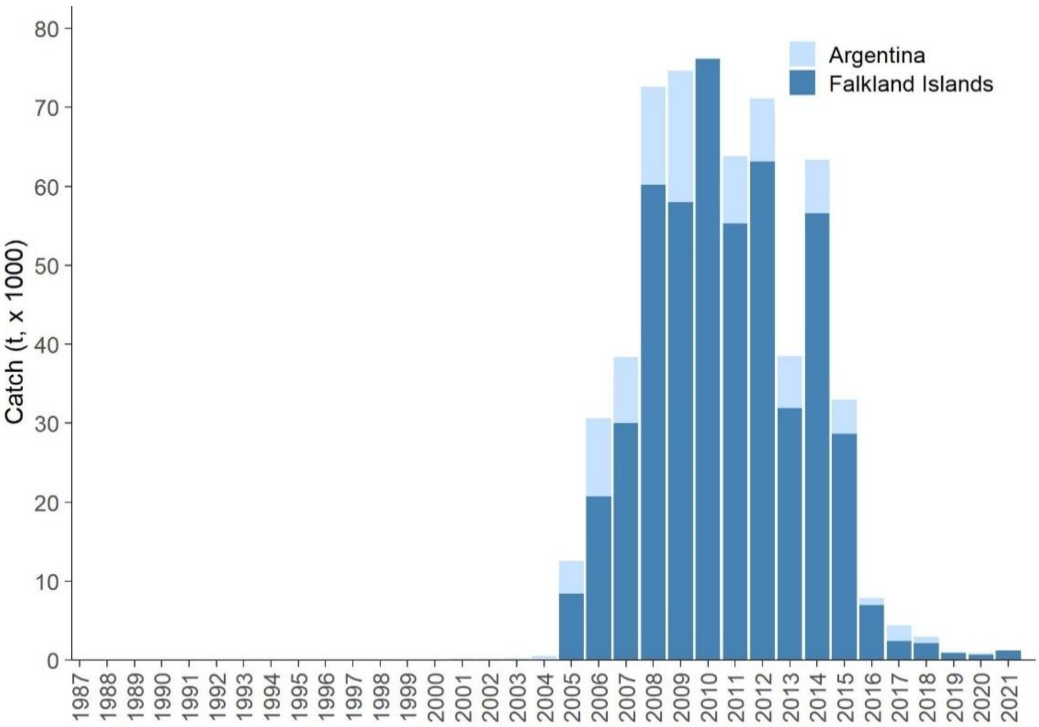

Fig. 1. Annual commercial catch of rock cod in Falkland Islands and Argentine waters. Falkland Islands commercial catch data exclude experimental (E–licence) and out-of-zone (O–licence) licences.

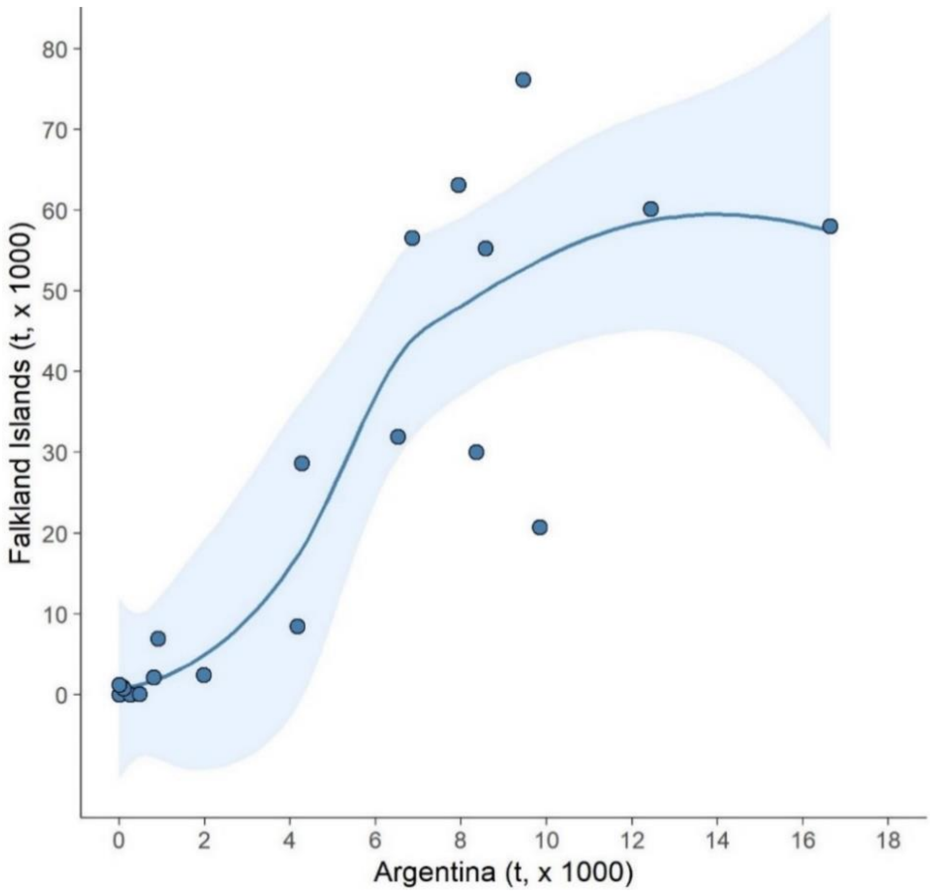

Fig. 2. Annual commercial catches of rock cod, Falkland Islands vs. Argentina, from 2003 to 2021. Blue lines: LOESS smooths ± 95% confidence intervals.

During 2021, a total of 1,400 t of rock cod were reported caught in Falkland Islands waters, of which 1,316 t were reported under commercial licences, i.e., excluding the experimental E–licence. Calamari (C– and X–licences) vessels accounted for 82% of the total rock cod catch, and finfish (A–, G– and W–licences) vessels accounted for 12% of the total rock cod catch. Nearly 94% of the rock cod catch in 2021 was reported discarded; particularly high amounts of discards occurred in calamari vessels (> 99%; Table I). Proportions of rock cod discards reported by the commercial fisheries have increased since 2010, i.e., 2010 = 22%; 2011 = 12%; 2015 = 14%; 2016 = 51%; 2017 = 79%; 2018 = 77%; 2019 = 58%; 2020 = 64%; 2021 = 94% (Falkland Islands Government *unpublished data*).

Table I. Catches by licence of rock cod in Falkland Islands waters during 2021.

Licence	Target species	Catch (t)	Catch (%)	Discard (t)	Proportion discarded (%)
C	Calamari 1st season	641.58	45.82	640.48	99.83
X	Calamari 2nd season	499.85	35.70	499.85	100.00
E	Experimental	83.88	5.99	83.30	99.30
W	Restricted finfish	60.44	4.32	27.27	45.12
A	Unrestricted finfish	57.56	4.11	44.25	76.87
G	Restricted finfish and *Illex*	56.41	4.03	26.24	46.50
B	*Illex* squid	0.37	0.03	0.37	100.00
F	Skates and rays	0.00	0.00	0.00	0.00
L	Toothfish (longline)	0.00	0.00	0.00	0.00
S	Southern blue whiting and hoki	0.00	0.00	0.00	0.00
O	Outside Falkland Islands waters	0.00	0.00	0.00	0.00
Total		1,400.09	100.00	1,321.76	94.40

CPUE increased from 2004 to 2008; CPUE were > 1,000 kg/h from 2008 to 2014, except for 2013 (700 kg/h). The highest CPUE in the time series was reported in 2010 (1,640 kg/h); CPUE then declined to reach the lowest value in 2021 (10 kg/h) since 2004 (Fig. 3).

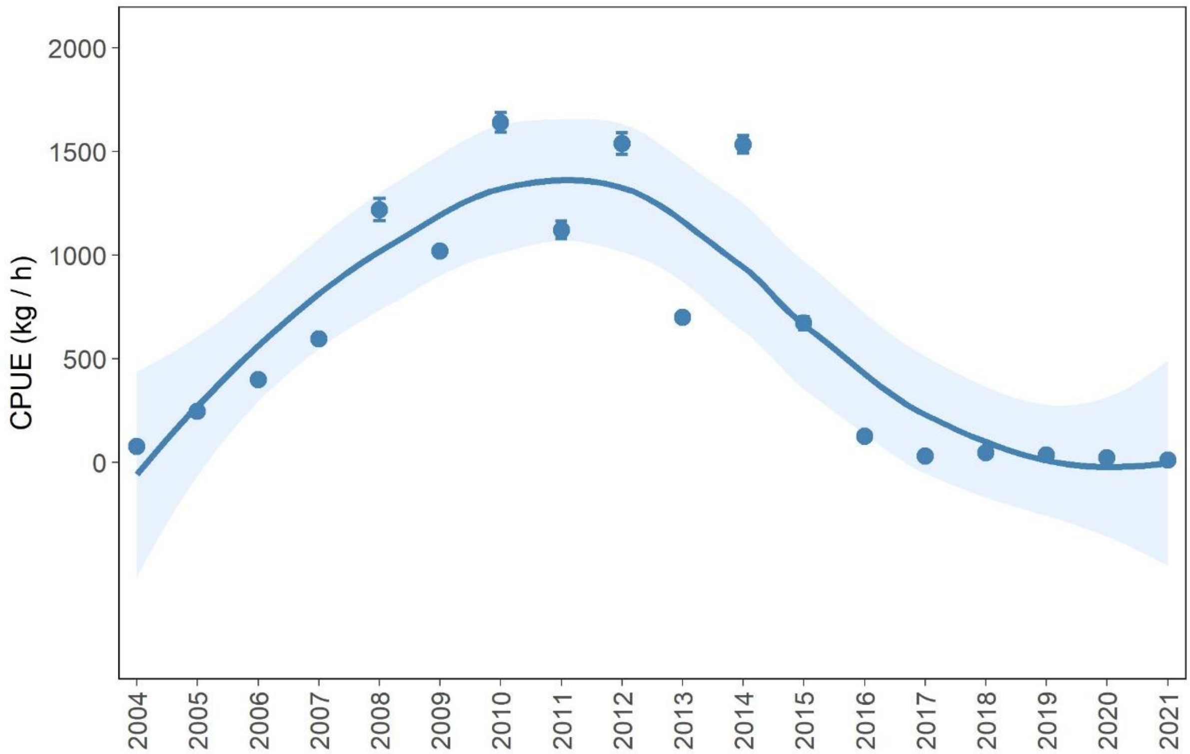

Fig. 3. Yearly CPUE ± 1 standard error of rock cod in Falkland Islands waters, estimated from finfish (A–, G–, and W–licences) vessels. Dark blue lines and light blue areas are the LOESS smooths ± 95% confidence intervals.

Average monthly CPUE by finfish (A–, G–, and W–licences) vessels from 2004 to 2020 ranged between 430 kg/h and 1,295 kg/h, with the highest value reported in May. CPUE increased from January through May, followed by a decline through September and a subsequent increase from October through December (Fig. 4). This pattern suggests that rock cod is more abundant in Falkland Islands waters during austral spring (October to December), summer (January to March), and part of autumn (April and May). The year 2021 had lower values compared with the average from 2004 to 2020; values ranged between 3 kg/h and 36 kg/h from March through December, with no fishing effort in January and February (Fig. 4; Appendix III). During 2021, rock cod were caught mainly to the west and northwest of West Falkland by finfish vessels (Appendix IV); however, most catches were by calamari (C– and X–licences) vessels along the 'Loligo Box' in the south and east (Appendix V).

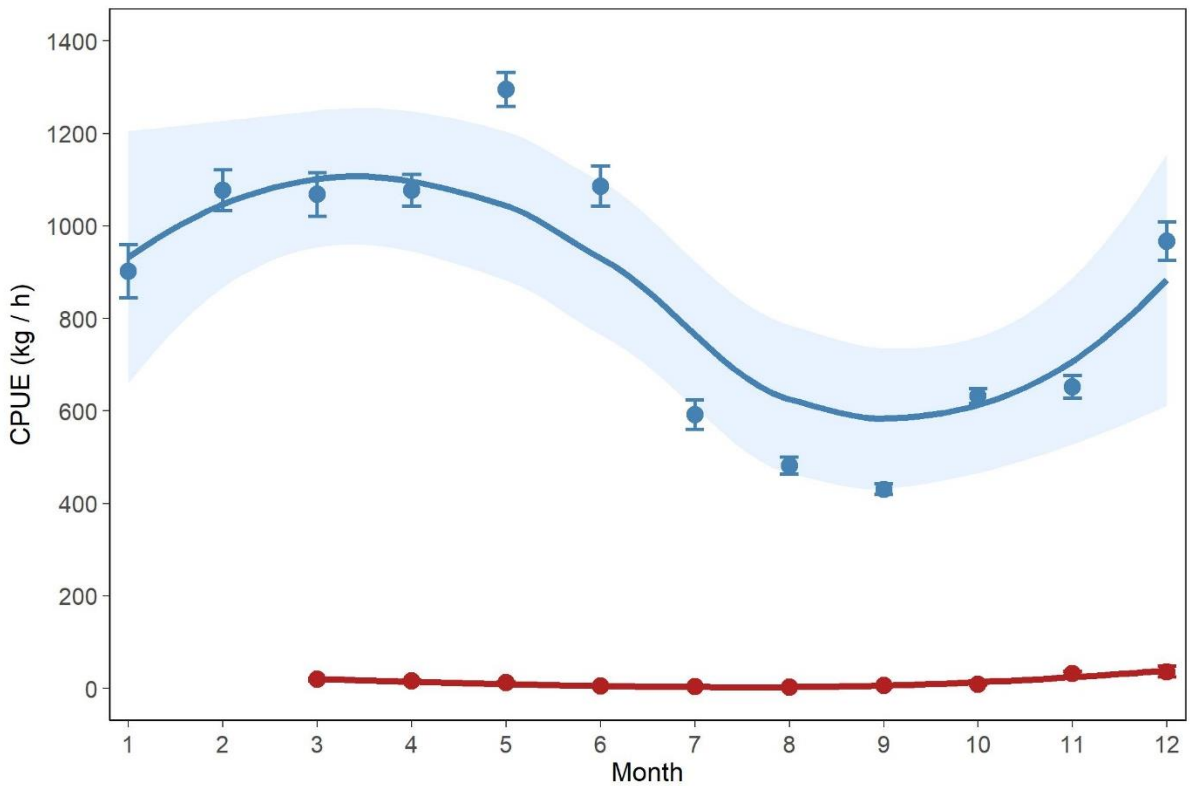

Fig. 4. Monthly CPUE ± 1 standard error of rock cod in Falkland Islands waters for 2021 (red dots), and from 2004 through 2020 (blue dots), calculated from finfish (A–, G–, and W–licences) vessels. Dark blue line and light blue areas are the LOESS smooths ± 95% confidence intervals.

Surveys biomass estimates

Summer surveys (February)

The biomass of rock cod during the February surveys have an overall declining trend, with the biomass in 2022 (93,177 t) being 11.4% of the biomass in 2010 (817,086 t; Fig. 5; Table II). However, biomass has been increasing again since 2020. All 10,000 out of 10,000 paired re-samples had higher biomass estimate values in February 2010 than in February 2022 (100%), therefore the difference in biomass between 2022 and 2010 is significant at $p < 0.05$. During the February 2010–2018 surveys, rock cod were distributed all over the FICZ, with aggregations mainly to the north. A shift was observed in 2019, 2020, and 2021 with aggregations occurring mainly to the south. In February 2022, rock cod occurred mainly to the north-west (Appendix VI).

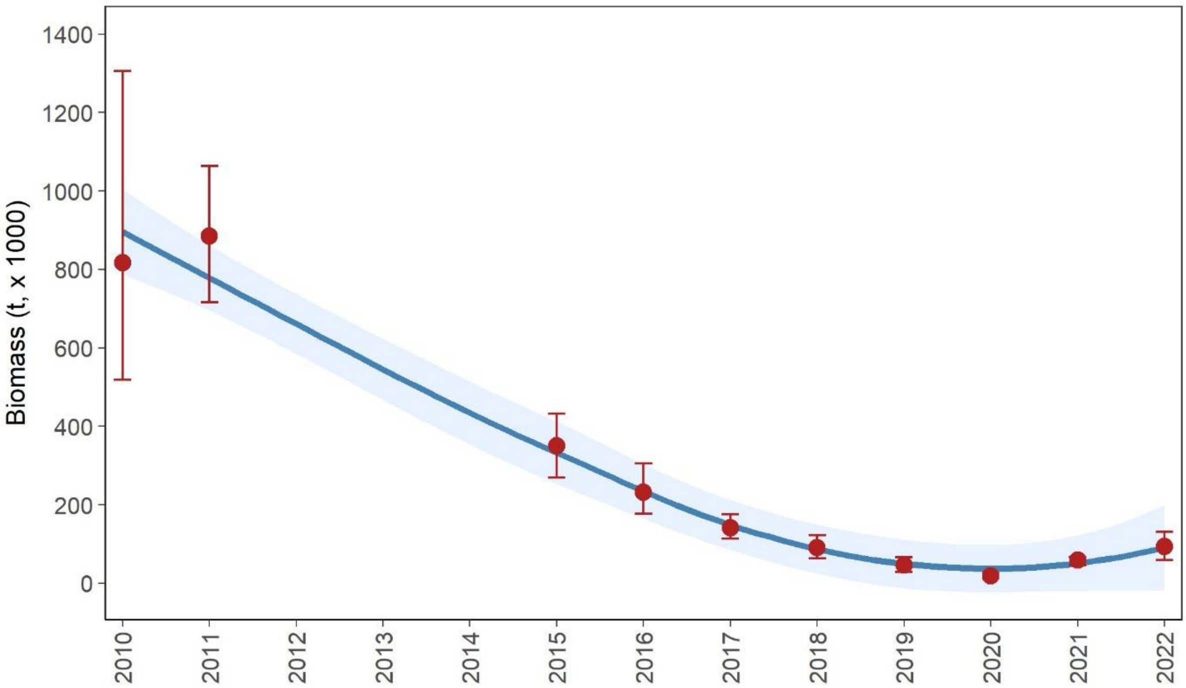

Fig. 5. Rock cod biomass estimates (red dots) ± 95% confidence intervals from February surveys in Falkland Islands waters. Note that groundfish February surveys were not conducted in 2012, 2013, and 2014. Dark blue lines and light blue areas are the inter-annual LOESS smooths ± 95% confidence intervals.

Table II. Summer (February) surveys catch and effort, and biomass estimates (mean ± 95% confidence intervals) of rock 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	108207.81	1236.43	817086.43 (519306.26–1306091.27)
	D. gahi	55	42.29	109.27	56383.16	516.01	
	Total	142	59.34	196.78	164590.97	836.41	
2011	Groundfish	88	17.21	88.00	116097.06	1319.28	884741.55 (716079.56–1064218.58)
	D. gahi	58	40.04	110.63	133286.83	1204.76	
	Total	146	57.26	198.63	249383.89	1255.50	
2015	Groundfish	89	16.72	90.17	31673.93	351.28	350913.41 (269667.68–432687.92)
	D. gahi	57	46.90	111.50	166598.20	1494.15	
	Total	146	63.61	201.67	198272.13	983.17	
2016	Groundfish	90	17.64	91.42	31656.88	346.29	232429.14 (177911.14–306135.45)
	D. gahi	56	54.46	107.92	45651.57	423.03	
	Total	146	72.10	199.33	77308.44	387.83	
2017	Groundfish	90	18.52	92.00	14525.72	157.89	141469.65 (113896.56–176351.05)
	D. gahi	58	54.09	117.00	61607.49	526.56	
	Total	148	72.62	209.00	76133.21	364.27	
2018	Groundfish[a]	97	20.47	96.42	11383.25	118.06	90679.85 (63308.48–122537.23)
	D. gahi	59	36.87	100.83	24538.99	243.36	
	Total	156	57.35	197.25	35922.24	182.12	
2019	Groundfish	79	17.22	79.00	2541.07	32.17	45669.16 (29040.32–66668.90)
	D. gahi	52	72.70	97.05	25390.83	261.63	
	Total	131	89.93	176.05	27931.90	158.66	
2020	Groundfish[a]	80	17.04	79.95	1774.02	22.19	19079.02 (11656.70–27065.20)
	D. gahi	59	86.80	112.52	9204.06	81.80	
	Total	139	103.84	192.47	10978.08	57.04	
2021	Groundfish	80	16.43	79.48	3807.52	47.90	59670.41 (45689.57–66885.68)
	D. gahi	55	90.65	111.22	53349.29	479.69	
	Total	135	107.07	190.70	57156.81	299.72	
2022	Groundfish	42	9.22	41.90	10993.69	262.38	93177.17 (58753.11–131454.56)
	D. gahi	60	86.75	119.08	19822.10	166.46	
	Total	102	95.97	160.98	30815.79	191.42	

[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 rock cod. Note that groundfish February surveys were not conducted in 2012, 2013, and 2014.

Winter surveys (July)

The estimated biomass of rock cod in the July 2020 survey (5,790 t) was 10% of the July 2017 survey (52,933; Table III). All 10,000 out of 10,000 paired re-samples had higher biomass estimate values in July 2017 than in July 2020 (100%), thus significant at $p < 0.05$. In July 2017, the main aggregations of rock cod were detected to the south in the Falkland Islands Conservation Zones, whereas in July 2020 rock cod were mainly aggregated to the north and northwest (Appendix VII).

Table III. Winter (July) surveys catch and effort, and biomass estimates (mean ± 95% confidence intervals) of rock 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	15.41	74	2003.33	27.07	52933.12 (32228.09 – 68987.56)
	D. gahi[a]	59	54.71	114	30906.69	271.11	
	Total	133	70.12	188	32910.02	175.05	
2020	Groundfish[b]	33	7.14	33	329.77	9.99	5790.28 (4128.66 – 7309.08)
	D. gahi	55	98.57	101	1176.93	11.62	
	Total	88	105.71	134	1506.70	11.22	

[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 rock 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

Ratios of the 2/3 rule were computed from mean values of the February survey biomass estimates:

$$TAC\_5_{2019} = \overline{6962.9 + 2414.7 + 2164.0} = 3847.20$$

$$TAC\_3_{2020} = 3847.20 \times \frac{\overline{90679.85 + 45669.16}}{\overline{350913.41 + 232429.14 + 141469.65}} = 1085.58$$

Or limited to 20% change:

$$TAC\_3_{2020} = 3847.20 \times 0.8 = 3077.76$$

Then:

$$TAC\_3_{2021} = \left. 3077.76 \times \frac{\overline{45669.16 + 19079.02}}{\overline{232429.14 + 141469.65 + 90679.85}} \right| \pm 20\% = 2462.21$$

$$TAC\_3_{2022} = \left. 2462.21 \times \frac{\overline{19079.02 + 59670.41}}{\overline{141469.65 + 90679.85 + 45669.16}} \right| \pm 20\% = 1969.77$$

$$TAC\_3_{2023} = \left. 1969.77 \times \frac{\overline{59670.41 + 93177.17}}{\overline{90679.85 + 45669.16 + 19079.02}} \right| \pm 20\% = 2178.86$$

To reflect uncertainty, TAC calculations using biomass estimates weighted by their inverse variance were:

$$TAC\_5_{2019} = \overline{6962.9 + 2414.7 + 2164.0} = 3847.20$$

$$TAC\_3_{2020} = 3847.20 \times \frac{\left(\frac{(90679.85 + 45669.16) \times (0.00000000415 + 0.0000000137)}{0.00000000415 + 0.0000000137}\right)}{\left(\frac{(350913.41 + 232429.14 + 141469.65) \times (0.000000000551 + 0.000000000783 + 0.00000000405)}{0.000000000551 + 0.000000000783 + 0.00000000405}\right)} \pm 20\% = 3077.76$$

$$TAC\_3_{2021} = 3077.76 \times \frac{\left(\frac{(45669.16 + 19079.02) \times (0.0000000137 + 0.0000000486)}{0.0000000137 + 0.0000000486}\right)}{\left(\frac{(232429.14 + 141469.65 + 90679.85) \times (0.000000000783 + 0.00000000405 + 0.00000000415)}{0.000000000783 + 0.00000000405 + 0.00000000415}\right)} \pm 20\% = 2462.21$$

$$TAC\_3_{2022} = 2462.21 \times \frac{\left(\frac{(19079.02 + 59670.41) \times (0.0000000486 + 0.0000000338)}{0.0000000486 + 0.0000000338}\right)}{\left(\frac{(141469.65 + 90679.85 + 45669.16) \times (0.00000000405 + 0.00000000415 + 0.0000000137)}{0.00000000405 + 0.00000000415 + 0.0000000137}\right)} \pm 20\% = 1969.77$$

$$TAC\_3_{2023} = 1969.77 \times \frac{\left(\frac{(59670.41 + 93177.17) \times (0.0000000338 + 0.000000000171)}{0.0000000338 + 0.000000000171}\right)}{\left(\frac{(90679.85 + 45669.16 + 19079.02) \times (0.00000000415 + 0.0000000137 + 0.0000000486)}{0.00000000415 + 0.0000000137 + 0.0000000486}\right)} \pm 20\% = 2363.72$$

ICES category 3 TAC calculations for the year 2023 are summarized in Table IV according to four versions of the algorithm: the 2/3 rule with or without 20% cap at each year, then either with or without 20% cap but inverse-variance weighted. The two 20% cap columns of Table IV correspond to the equations shown above.

Table IV. Annual Total Allowable Catches (TAC) in tonnes based on ICES categories 3 and 5 assessment frameworks, and using the 20% cap.

TAC	2/3 rule (t)	20% cap (t)	2/3 rule (t)*	20% cap (t)*
TAC_5_{2019}	3847	3847	3847	3847
TAC_3_{2020}	1086	3078	1268	3078
TAC_3_{2021}	643	2462	609	2462
TAC_3_{2022}	1047	1970	1223	1970
TAC_3_{2023}	2906	2179	4059	2364

*weighted by inverse variance of February surveys biomass estimates.

Length analyses

Length Based Indicators

Yearly ‘traffic light’ length indicators for females and males are summarized in Table V. Indicator L_C/L50, for conservation of immature fish, had negative outcomes (red) almost every year from 2004 to 2021 for females, except for 2007, 2008, 2011, and 2014. For males, this indicator was negative most years except for 2008 and 2014. Indicator $L_{25\%}$/L50, also for conservation of immature fish, fluctuated from 2004 to 2014 for females, with negative years from 2015 onwards except for 2019; for males, indicator $L_{25\%}$/L50 was negative most years except for 2008 and 2014. Indicator $L_{max5\%}/L_{Inf}$, for the conservation of large individuals, was positive in 2015 and 2016, and it was of concern (yellow) from 2017 onwards for females; for males, indicator $L_{max5\%}/L_{Inf}$ was positive most of the time series, except for 2004, 2017, and from 1019 to 2021 when it was of concern. Indicator P_{mega}, for the presence of mega-spawners, was negative most of the time series except from 2005–2006 to 2009 when it was of concern or positive. Indicator L_{meanC}/L_{Opt}, for optimal yield, was mostly positive for females and males before 2011; however, it became predominantly of concern or negative the rest of the time series. Indicator $L_{meanC}/L_{F=M}$, for maximum sustainable yield, was mostly positive through the time series for females and males.

Table V. Rock 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.

		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
F	2004	0.75	0.84	0.83	0.10	0.88	1.06
	2005	0.68	0.86	0.85	0.17	0.91	1.14
	2006	0.85	0.98	0.87	0.21	0.99	1.09
	2007	0.97	1.06	0.88	0.26	1.03	1.04
	2008	1.06	1.15	0.91	0.38	1.10	1.04
	2009	0.89	0.98	0.91	0.26	1.01	1.07
	2010	0.86	0.96	0.90	0.15	0.97	1.06
	2011	1.03	1.03	0.85	0.12	1.00	1.00
	2012	0.93	0.98	0.84	0.12	0.95	1.05
	2013	0.90	1.00	0.83	0.11	0.91	1.03
	2014	1.18	1.08	0.83	0.15	1.01	0.98
	2015	0.63	0.79	0.85	0.23	0.86	1.20
	2016	0.85	0.91	0.86	0.13	0.88	1.04
	2017	0.70	0.81	0.84	0.09	0.82	1.07
	2018	0.76	0.93	0.84	0.09	0.86	1.09
	2019	0.82	0.99	0.83	0.08	0.87	1.06
	2020	0.77	0.88	0.84	0.09	0.81	1.02
	2021	0.66	0.83	0.79	0.04	0.78	1.05

		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
M	2004	0.58	0.71	0.83	0.12	0.85	1.09
	2005	0.61	0.77	0.89	0.24	0.94	1.16
	2006	0.80	0.92	0.88	0.32	1.04	1.08
	2007	0.87	0.95	0.91	0.36	1.08	1.06
	2008	0.99	1.03	0.92	0.52	1.16	1.05
	2009	0.81	0.89	0.92	0.33	1.04	1.08
	2010	0.79	0.87	0.90	0.19	0.99	1.07
	2011	0.95	0.95	0.87	0.19	1.03	1.01
	2012	0.76	0.85	0.86	0.19	0.96	1.10
	2013	0.84	0.93	0.85	0.14	0.94	1.04
	2014	1.06	0.96	0.85	0.23	1.04	1.01
	2015	0.59	0.74	0.88	0.24	0.85	1.16
	2016	0.70	0.85	0.88	0.12	0.87	1.07
	2017	0.65	0.70	0.85	0.11	0.81	1.03
	2018	0.66	0.81	0.88	0.16	0.88	1.12
	2019	0.71	0.86	0.87	0.16	0.89	1.08
	2020	0.71	0.77	0.86	0.10	0.82	1.00
	2021	0.66	0.72	0.81	0.09	0.80	1.01

Length-age relationship

The likelihood ratio test did not find statistically significant differences in the von Bertalanffy growth models for females and males ($X^2_{(3,\ n\ =\ 1,434)}$ = 1.81, p = 0.613). However, given the sexual dimorphism of rock cod, von Bertalanffy growth model outputs are presented for females and males pooled, and separately (Appendix VIII). The length-age relationship of females and males pooled (n = 1,434) from 2014 to 2017 gave: L_{Inf} = 38.7 cm, K = 0.2560, and t_0 = -0.5185 years. Length and age of females (n = 733) ranged from 8 cm to 44 cm, and from 0 year to 15 years, respectively. The length-age relationship of females gave: L_{Inf} = 39.5 cm, K = 0.2387, and t_0 = -0.6328 years. Length and age of males (n = 700) ranged from 7 cm to 39 cm and from 0 year to 14 years, respectively. The length-age relationship of males gave: L_{Inf} = 37.97 cm, K = 0.2745, and t_0 = -0.4210 years (Appendix VIII). Yearly von Bertalanffy parameters are summarized in Appendix IX. Asymptotic lengths (L_{Inf}) were not significantly changing from 2004 to 2017, although showing a slightly declining trend from 2014 to 2017 (Fig. 6).

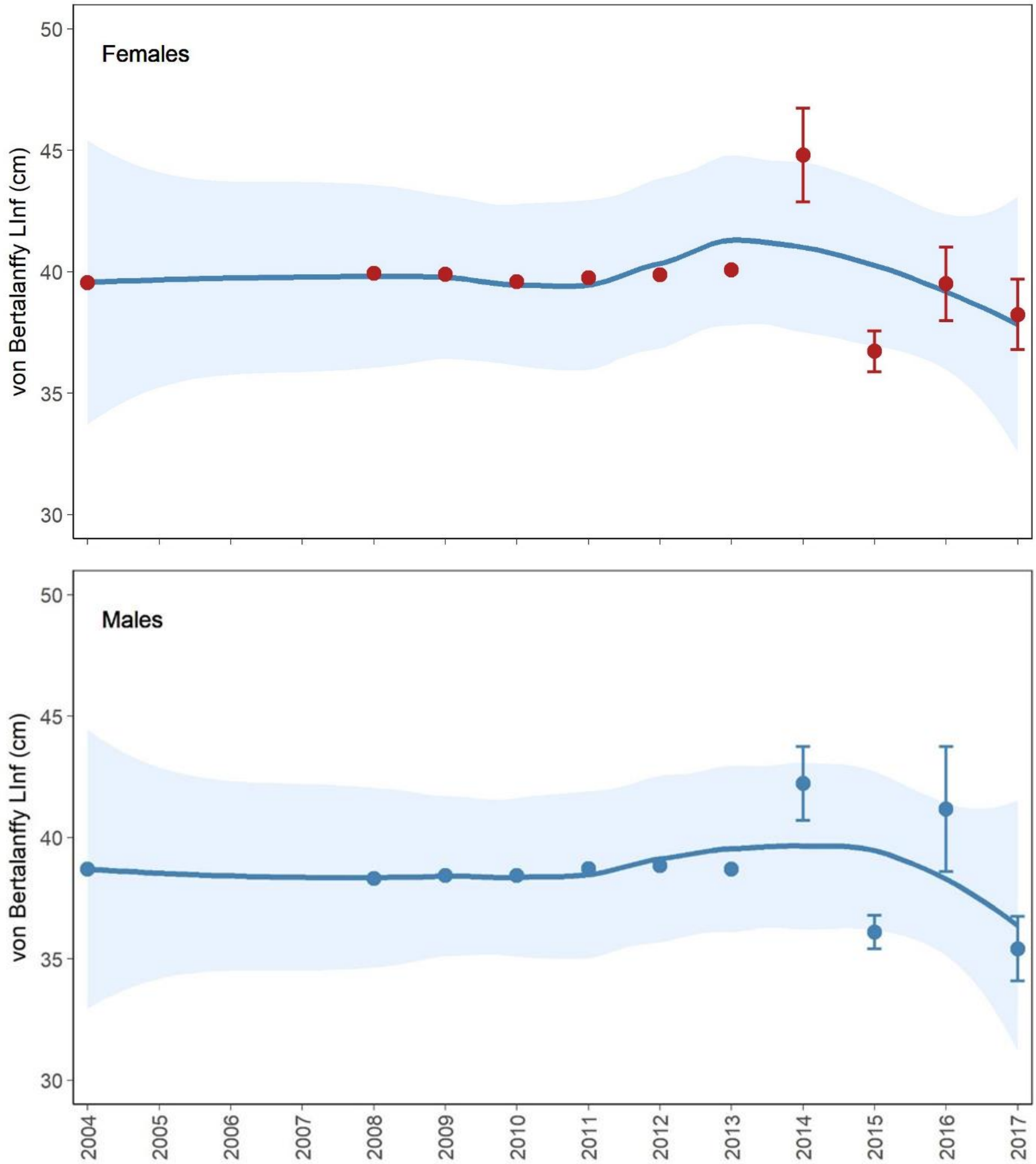

Fig. 6. Asymptotic lengths (L_{Inf}) ± 1 standard error calculated according to the von Bertalanffy growth function for female (red dots) and male (blue dots) rock cod, 2004 to 2017. Standard errors are presented for years 2014–2017, from which actual age data were used. L_{Inf} from 2004 to 2013 represent length-age extrapolations using the inversed von Bertalanffy equation. Dark blue lines and light blue areas are the LOESS smooths ± 95% confidence intervals.

Length at 50% maturity (L50)

Lengths at 50% maturity of females ranged from 16.9 cm in 2013 to 23.3 cm in 2009; L50 of males ranged from 18.5 cm in 2021 to 25.8 cm in 2005. The L50 fit was stable from 2003 to 2010, followed by a decline from 2011 through 2021 (Fig. 7; Appendixes X–XI).

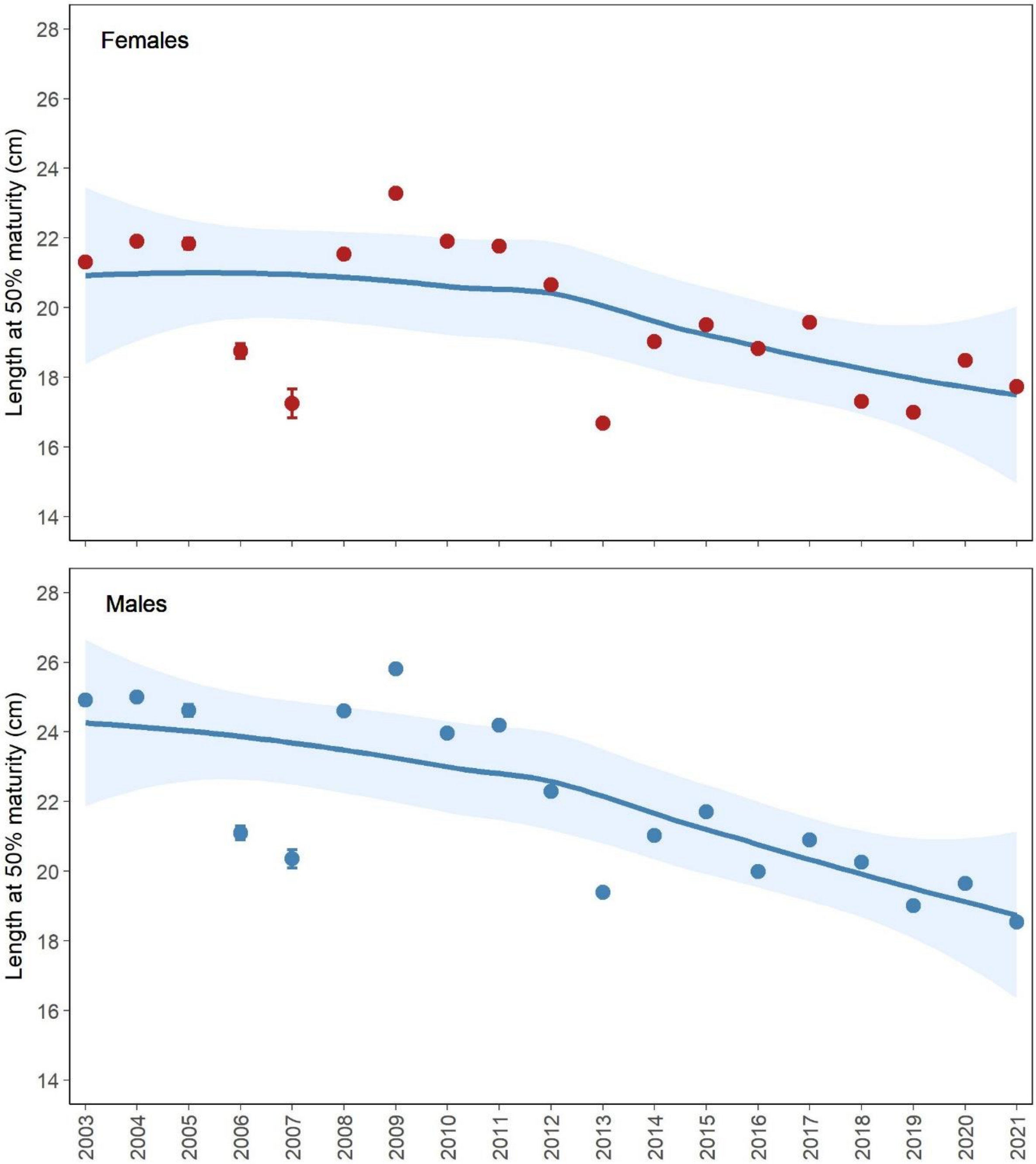

Fig. 7. Lengths at 50% maturity (L50) ± 1 standard error calculated for female (red dots) and male (blue dots) rock cod, 2003 to 2021. Dark blue lines and light blue areas are the LOESS smooths ± 95% confidence intervals.

Length frequencies

Female rock cod were in the range of sizes from 2 cm to 43 cm total length, and males ranged from 1 cm to 42 cm total length. Females and males were characterized by a few length-groups not discernible due to size overlap and had similar patterns in the length frequency distributions. An increase in modal length was found from 2003 to 2008; modal length declined in 2009, likely due to the presence of a new length-group and the removal of large individuals by the fishery. Modal length increased to 2014; it was variable from 2015 to 2018 and appeared to decline from 2018 to 2021 (Fig. 8; Appendix XII).

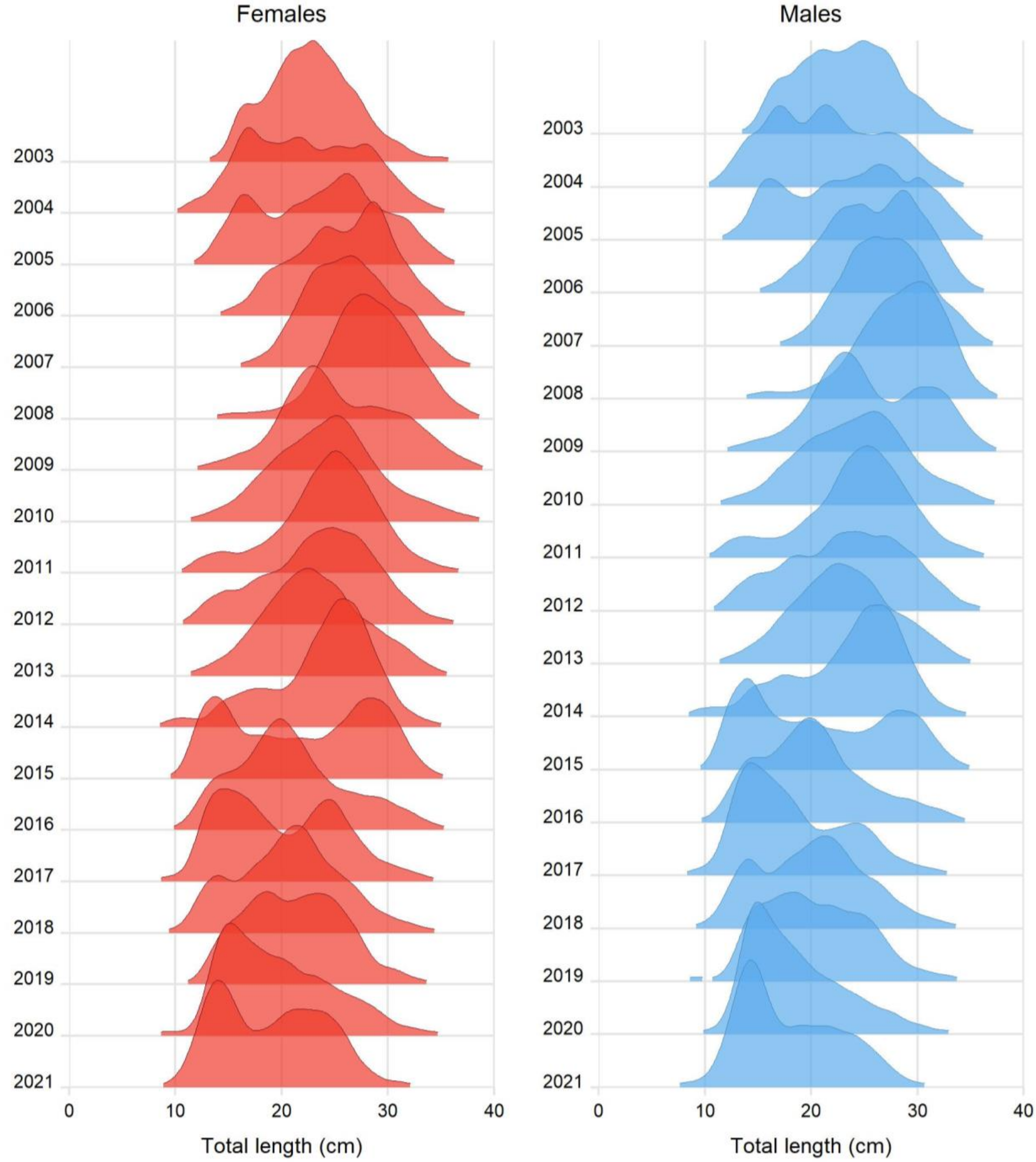

Fig. 8. Length frequency distribution of female and male rock cod in Falkland Islands waters.

Catch at age

Greater proportions of female and male rock cod have been consistently caught at ages 2–3 years old through the time series (Figs. 9 and 10); individuals of age 1 year old were also common in recent years.

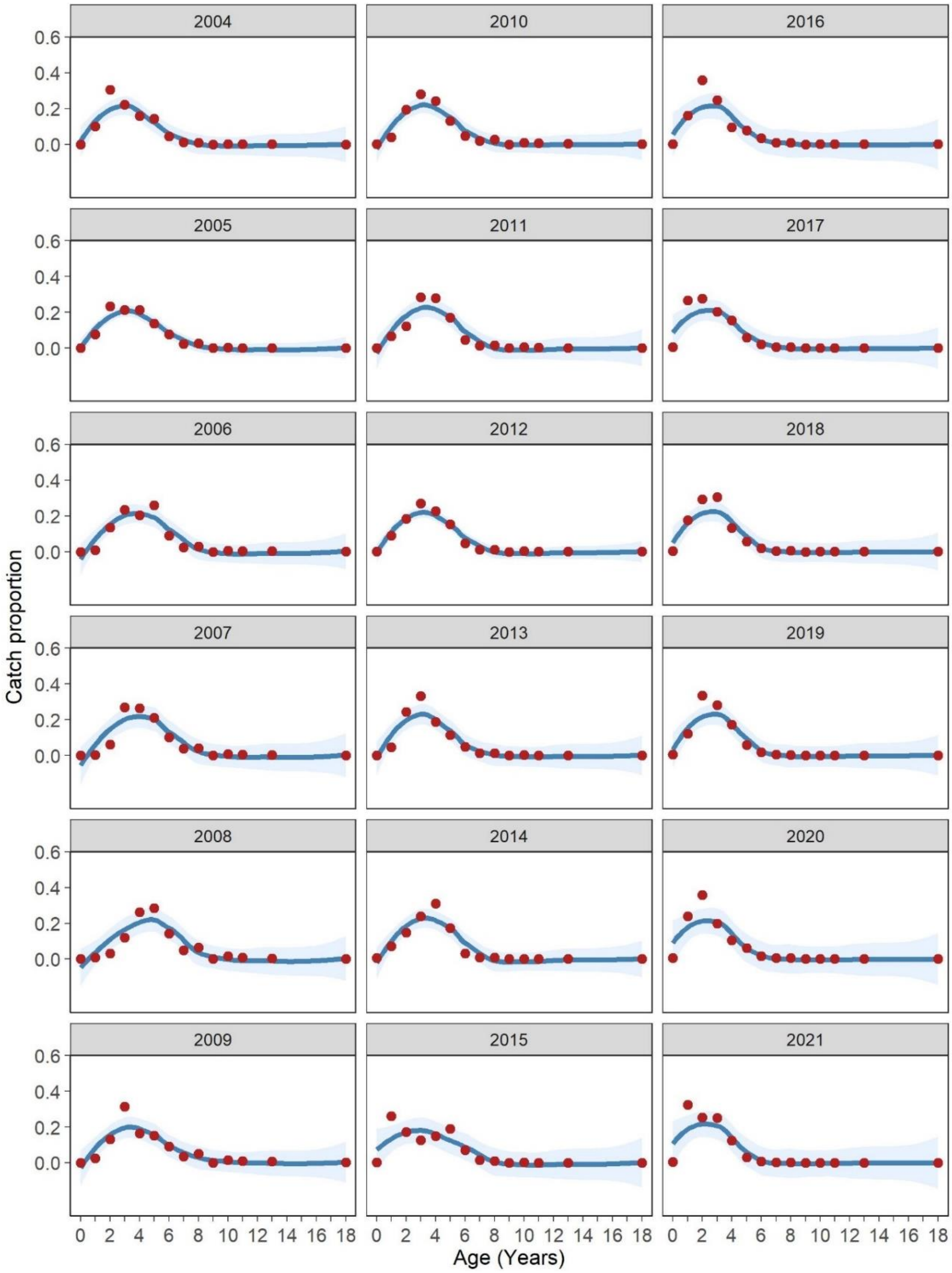

Fig. 9. Catch at age of female rock cod in Falkland Islands waters by finfish (A–, G–, and W–licences) and experimental (E–licence) vessels. Dark blue lines and light blue areas are the LOESS smooths ± 95% confidence intervals.

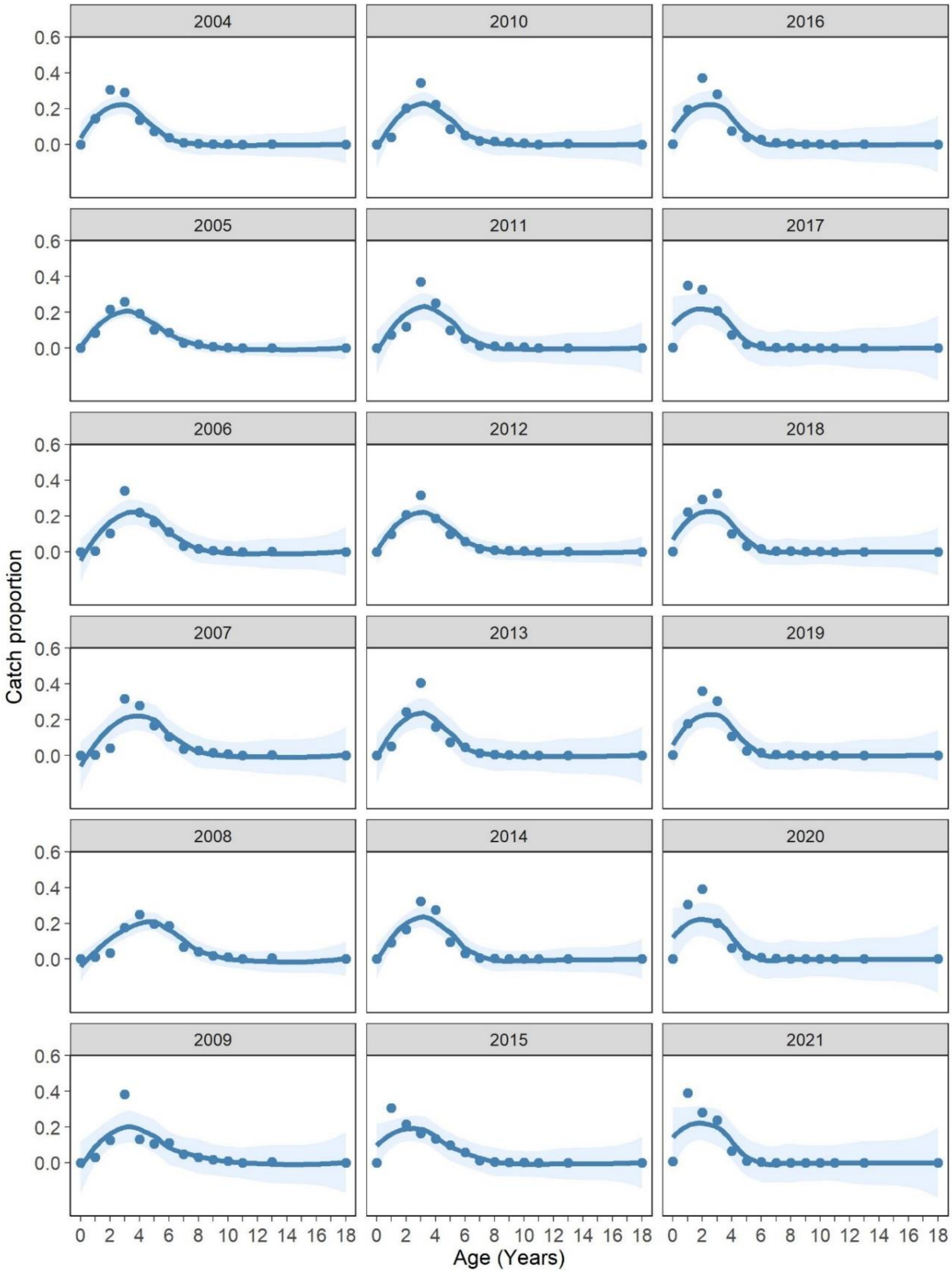

Fig. 10. Catch at age of male rock cod in Falkland Islands waters by finfish (A–, G–, and W–licences) and experimental (E–licence) vessels. Dark blue lines and light blue areas are the LOESS smooths ± 95% confidence intervals.

Natural mortality

Natural mortality (M) calculations obtained:

$$\mathrm{M} = 4.899\ \times \mathrm{t}_{\mathrm{max}}^{-0.916} = 4.899\ \times\ 15^{-0.916} =\ 0.4100 \qquad \text{Eqn. 1}$$

$$\mathrm{M} = 4.118 \times \mathrm{K}^{0.73} \times \mathrm{L}_{\mathrm{Inf}}^{-0.33} = 4.118\ \times 0.2560^{0.73} \times\ 38.7^{-0.33} = 0.4558 \qquad \text{Eqn. 2}$$

Eqn. 1 (M = 0.4100) was selected as the best estimate following the recommendations of Then et al. (2015).

Conclusions

Length-based indicators suggest that MSY was positive most of the time series. Conservation of immature individuals was negative most years, and conservation of large individuals was of concern since 2017. Conservation of mega-spawners was variable early in the time series but was consistently negative since 2010, likely due to the poor conservation of immature individuals that were removed by the fishery and resulted in a deficit of mature individuals afterwards. Weak scores on optimal yield since about 2011 and decline in body size (as seen by declining L_{Inf} from 2014 to 2017 and length frequency distributions) suggest that rock cod productivity has not been maintained. This is further supported by the decline in L50 since 2009, with smaller and lighter spawners producing fewer eggs (Koops et al. 2004; Brickle et al. 2006).

Trawl mesh experiments have led to the recommendation of 110 mm mesh codends and 40 mm square mesh panels to reduce the incidental catch of juvenile and undersized fish while retaining commercial size rock cod estimated at approximately 25 cm length (Roux et al. 2013). A 110 mm mesh codend is now a requirement in the Falkland Islands finfish fisheries. However, as most rock cod bycatch is currently in the calamari fisheries (C–, and X–licences), small individuals (< 25 cm total length) are still being caught in high proportions compared with larger individuals. Small individuals have not reached sexual maturity (Brickle et al. 2006) and are mostly discarded.

The proportion of rock cod discards by Falkland Islands fisheries reached 94.4% in 2021, having increased year after year with the shift of most catches from finfish target to calamari bycatch. Discard results in resource wasting, unreported catch, TACs not registering part of the catch, and stock overexploitation (Guillen et al. 2018). Further examination of catch selectivity by the different Falkland Islands fisheries may reduce fishing pressure on small individuals and benefit the current state of the rock cod stock. Several countries have implemented discard ban initiatives (Guillen et al. 2018; Soto-Oñate & Lemos-Nobre 2021), which may be worth exploring to prevent the waste of the resource and may be a channel of opportunities to make use of the bycatch that otherwise would be discarded.

Annual CPUE calculated from commercial fishery data suggests that the abundance of rock cod in Falkland Islands waters remains low after its considerable decrease since 2011, and it currently appears to be comparable to levels before 2005. The CPUE decrease of rock cod is concurrent with the CPUE increase of common hake (*Merluccius hubbsi*) (Ramos & Winter, *in prep.*), suggesting that CPUE of rock cod may have decreased in part due to the change of the fishery target from rock cod to common hake. Biomass estimates from the February scientific surveys followed a similar pattern to commercial CPUE, with a decline in abundance from 2010 to 2020, and a slight increase in abundance in 2021 and in 2022 from the previous year. Biomass estimates from the July scientific surveys also suggest a decline in abundance from 2017 to 2020.

Fishing mortality was not calculated in this study due to the limitation of accurate age data, which also impedes the estimation of parameters such as age at maturity and catch selectivity. However, with high catches for several years, and the subsequently declining trends in biomass and CPUE, it is reasonable to assume that fishing mortality has been substantial for several years. Natural mortality was estimated to be high (M = 0.41), which may be explained in part by rock cod being prey for large nektonic fishes (Arkhipkin et al. 2012). The potential impact of total mortality (natural mortality + fishing mortality) on the rock cod population should be taken into consideration.

The multiple analyses used in this study suggest that the rock cod stock is in poor state with respect to conservation criteria. Better reporting of the commercial by-catch and discard of rock cod should be of high importance in Falkland Islands fisheries. The most conservative version of the ICES category 3 – 2/3 rule proposes a Total Allowable Catch of 2,179 t. Given the several weak LBI indicators and trends observed, a more precautionary approach is recommended to limit rock cod TAC for year 2023 to the same TAC as 2022: 1,266 t (Winter 2021). A TAC of 1,266 t is within 4% of the actual commercial catch in the last completed year of fishing, 2021, and would represent a realistic objective for the fishery.

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Appendix

Appendix I. Annual commercial catches (t) of rock cod reported in Falkland Islands (excluding E–licence; Falkland Islands Government [a]; Falkland Islands Government *in prep.*) and Argentina (Argentine Government[b]; Sánchez et al. 2012; Navarro et al. 2014, 2019).

Year	Falkland Islands (t)	Argentina (t)
1987	NA	0.9
1988	NA	0.1
1989	NA	0
1990	NA	0
1991	0.0	0
1992	0.7	0
1993	NA	0
1994	NA	0.1
1995	NA	0
1996	NA	0
1997	NA	0
1998	NA	0
1999	NA	0
2000	NA	0.2
2001	NA	182.8
2002	NA	179.6
2003	2.4	258.8
2004	75.5	468.7
2005	8,438.6	4,169.7
2006	20,768.3	9,842.2
2007	30,028.3	8,354.8
2008	60,163.6	12,433.5
2009	57,995.9	16,645.5
2010	76,152.7	9,447.8
2011	55,271.7	8,575.4
2012	63,129.5	7,936.8
2013	31,958.6	6,517.9
2014	56,534.2	6,850.5
2015	28,684.7	4,273.1
2016	6,962.9	909.5
2017	2,414.7	1,972.1
2018	2,164.0	809
2019	933.0	87.8
2020	730.7	101.8
2021	1,316.2	2.9

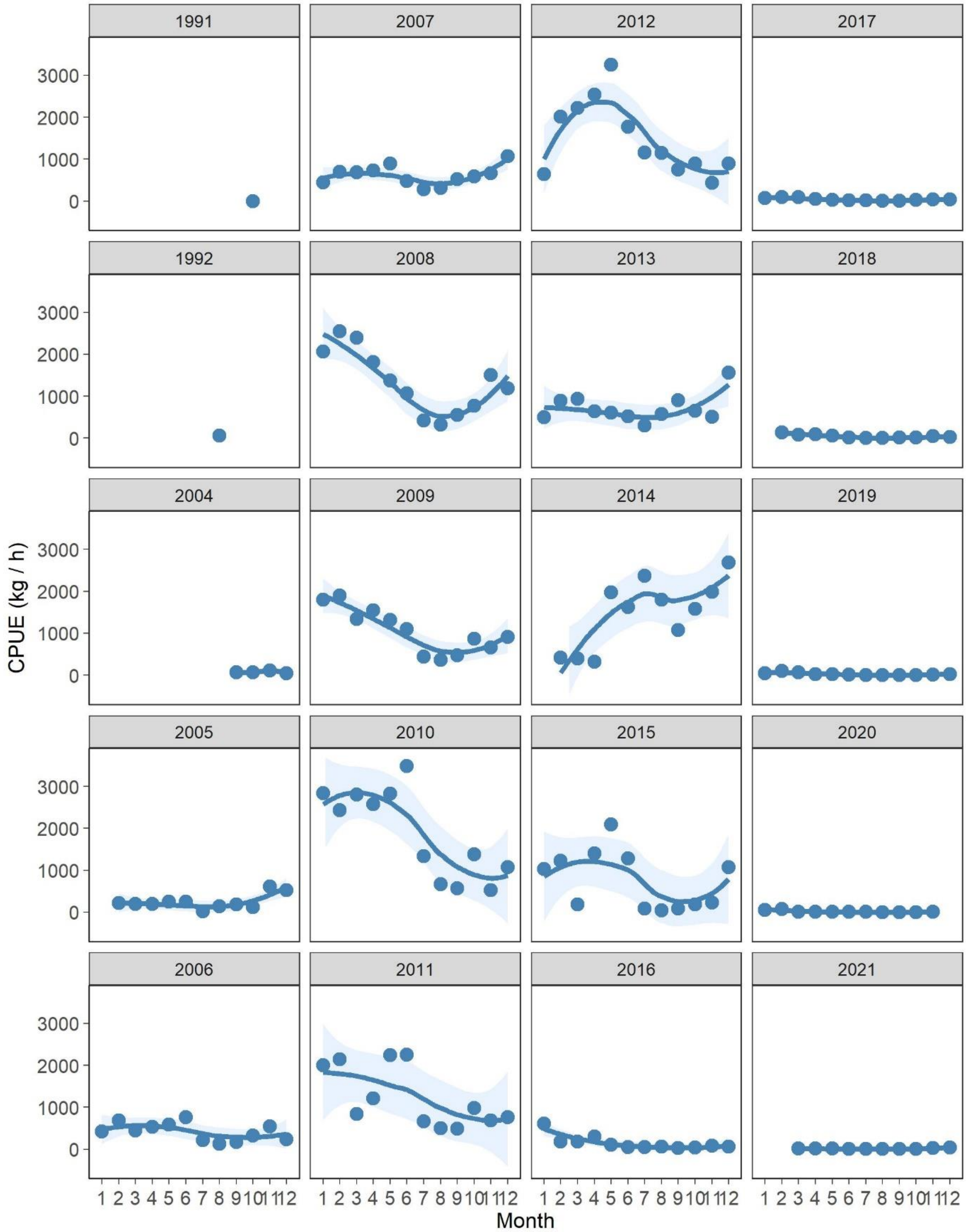
[a] http://www.fig.gov.fk/fisheries/publications/fishery-statistics
[b] https://www.agroindustria.gob.ar/sitio/areas/pesca_maritima/desembarques/

Appendix II. Identifying finfish-licenced observer samples.

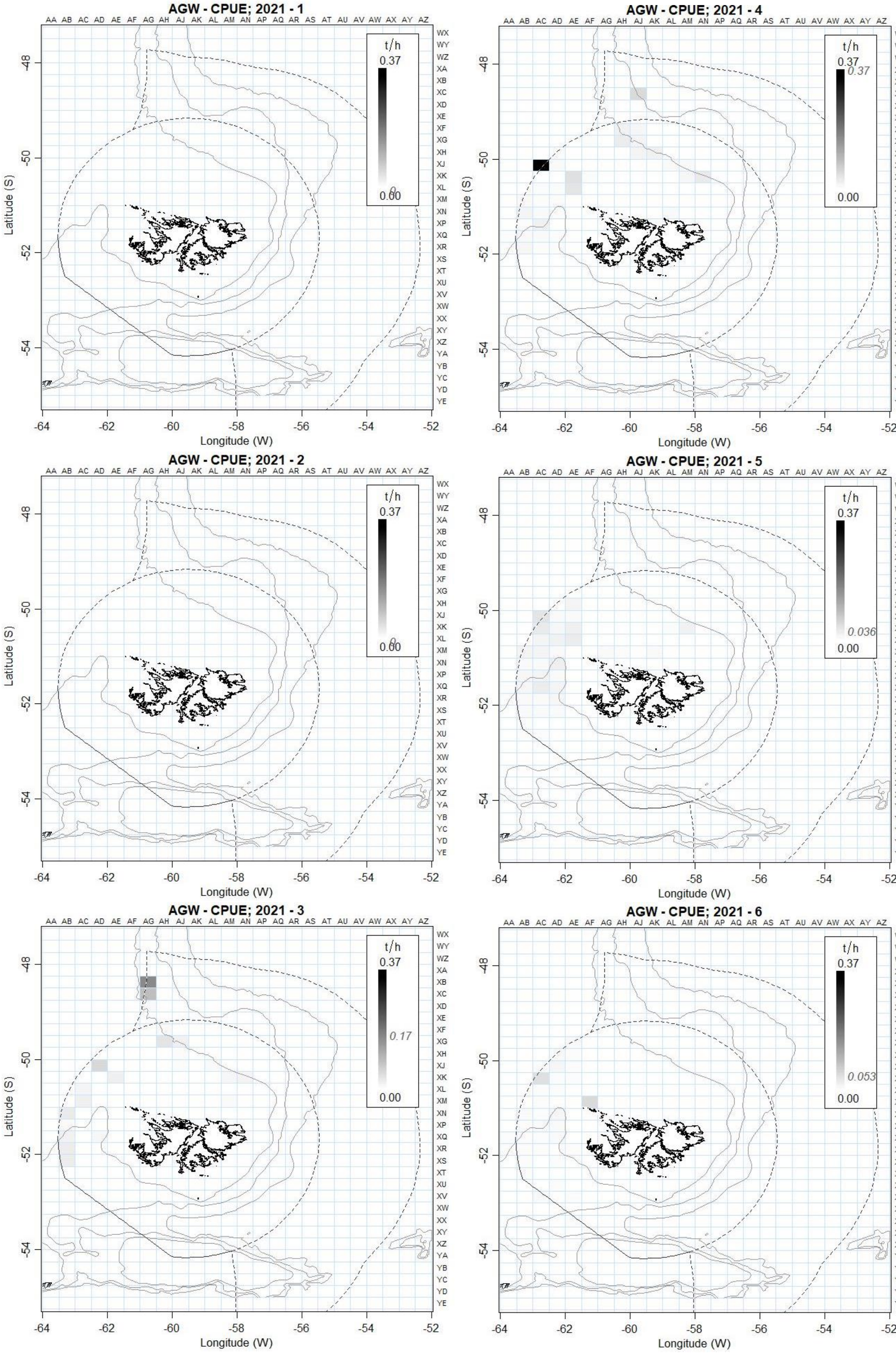
The FIFD observer database identifies samples by vessel, date, activity (fishing gear type), and observer station, but does not directly link to the licence that the vessel was operating under. If required, the licence must be cross-referenced from the catch report. In most cases, a catch report is recorded 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.

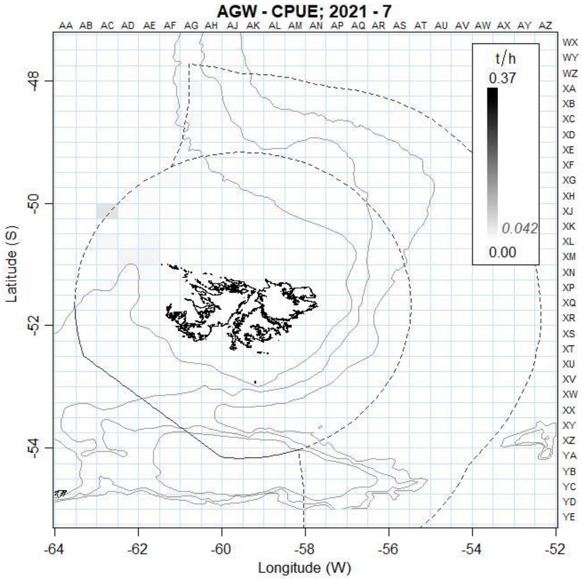
Appendix III. Monthly CPUE of rock cod in Falkland Islands waters from 1991 to 2021, estimated from A–, G–, and W–licensed vessels. Dark blue lines and light blue areas are the LOESS smooths ± 95% confidence intervals.

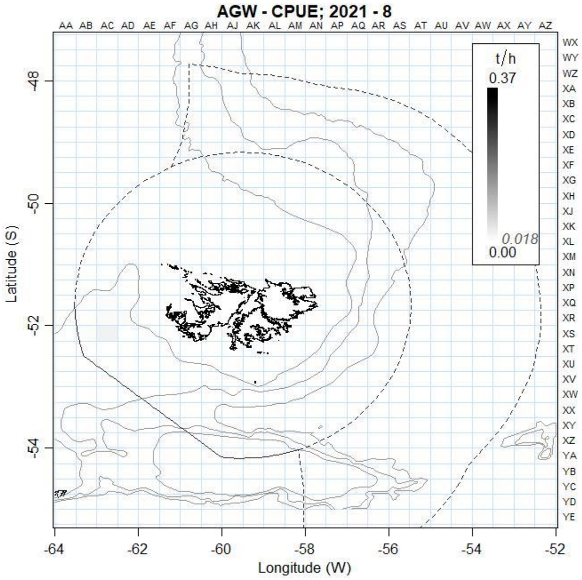


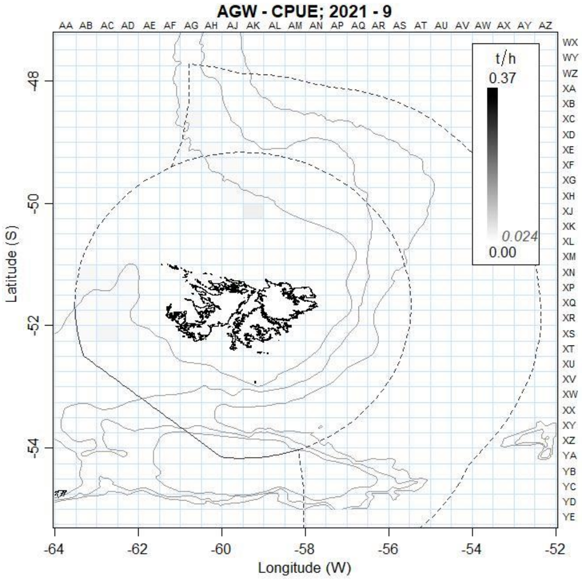
Appendix IV. Monthly CPUE of rock cod in Falkland Islands waters during 2021, estimated from A–, G–, and W–licensed vessels. Note there was no fishing effort during January and February under finfish licences.

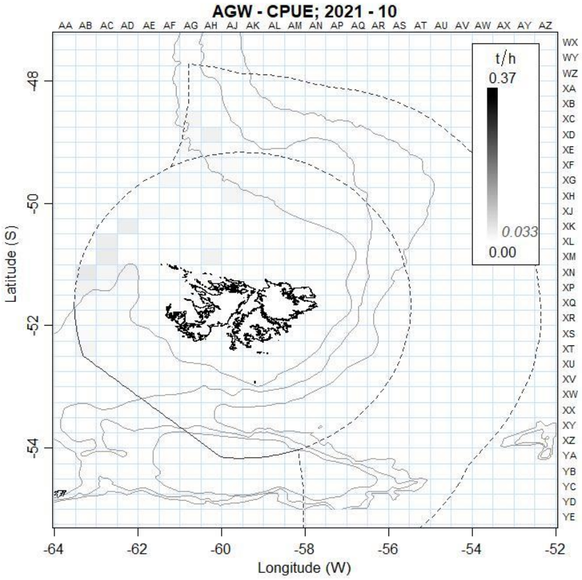


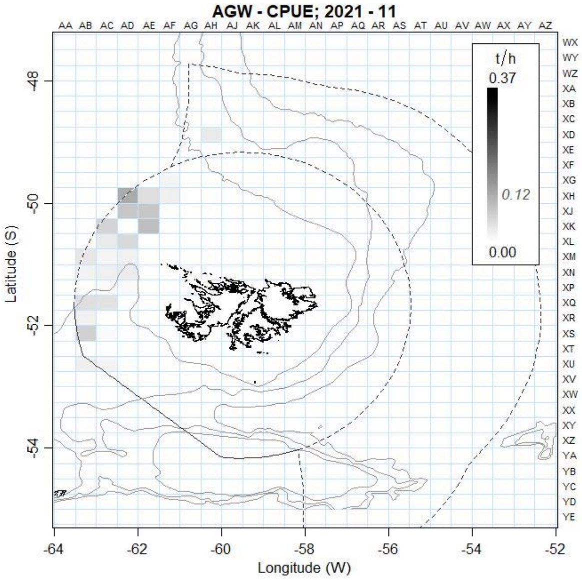
Appendix IV. *continued…*

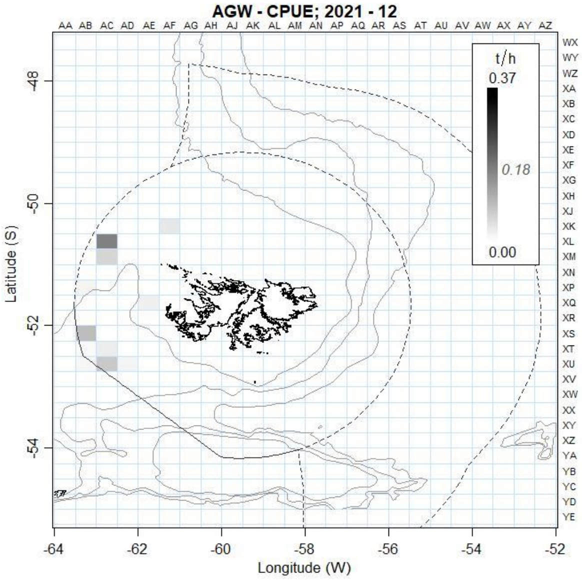




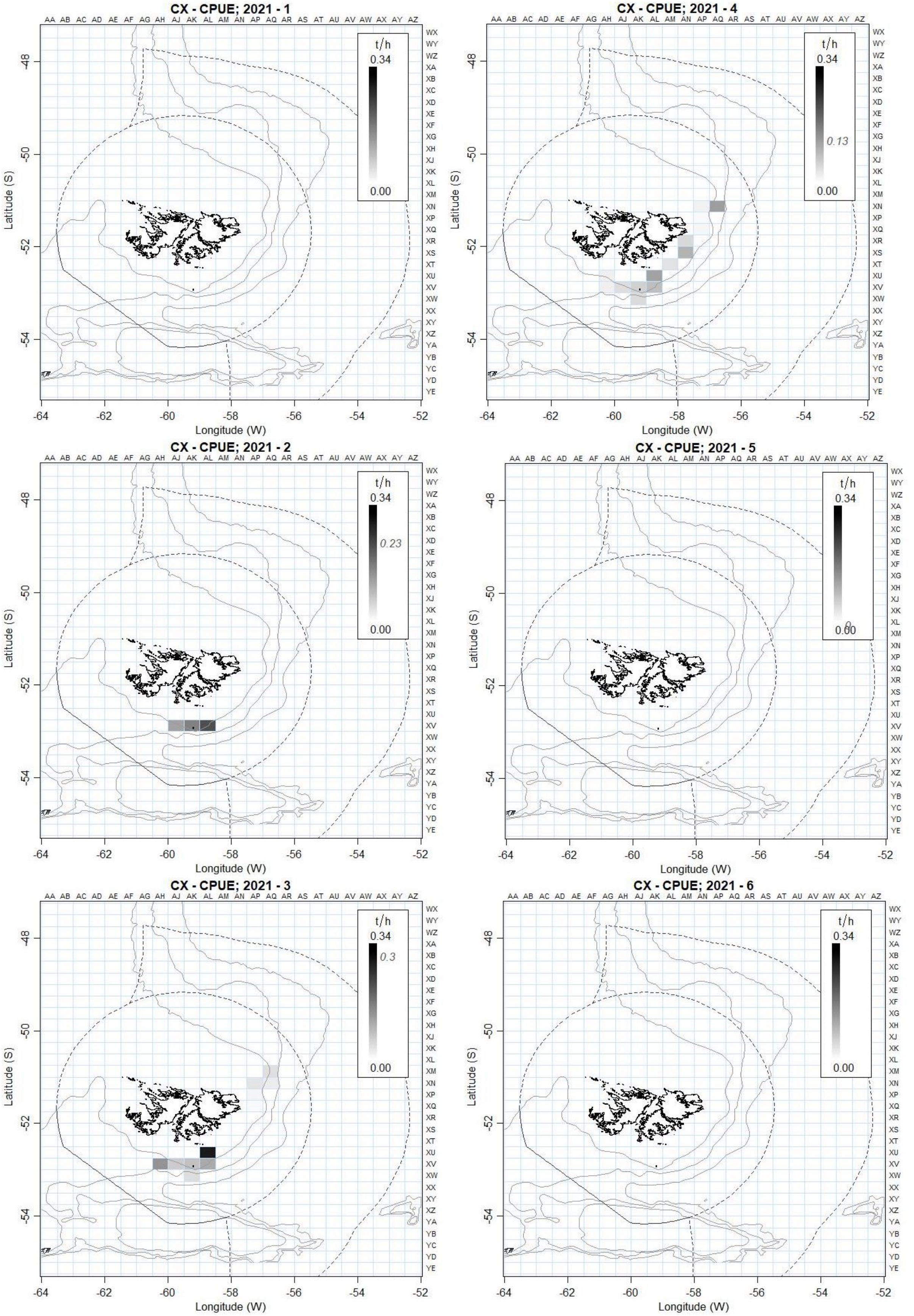




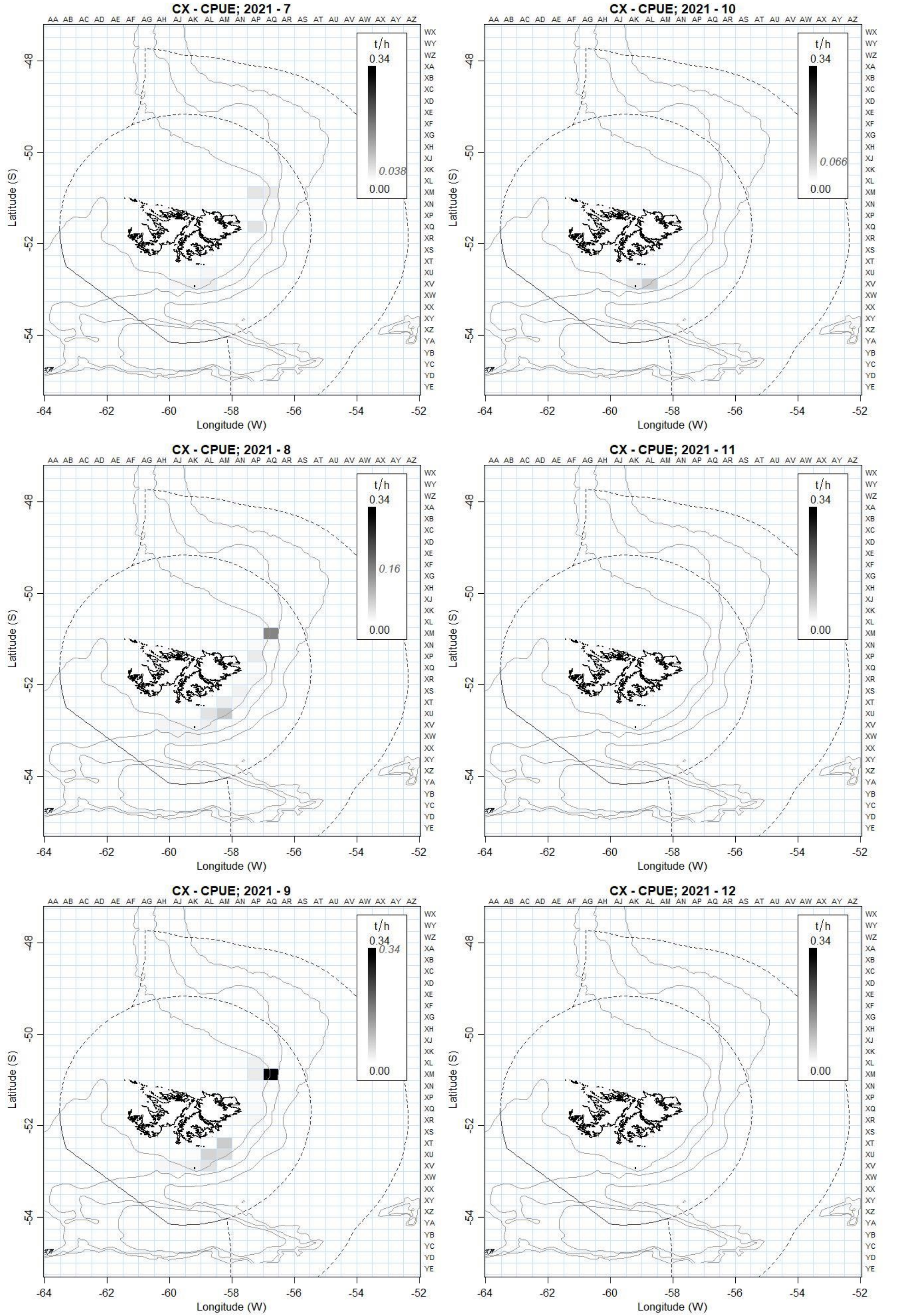




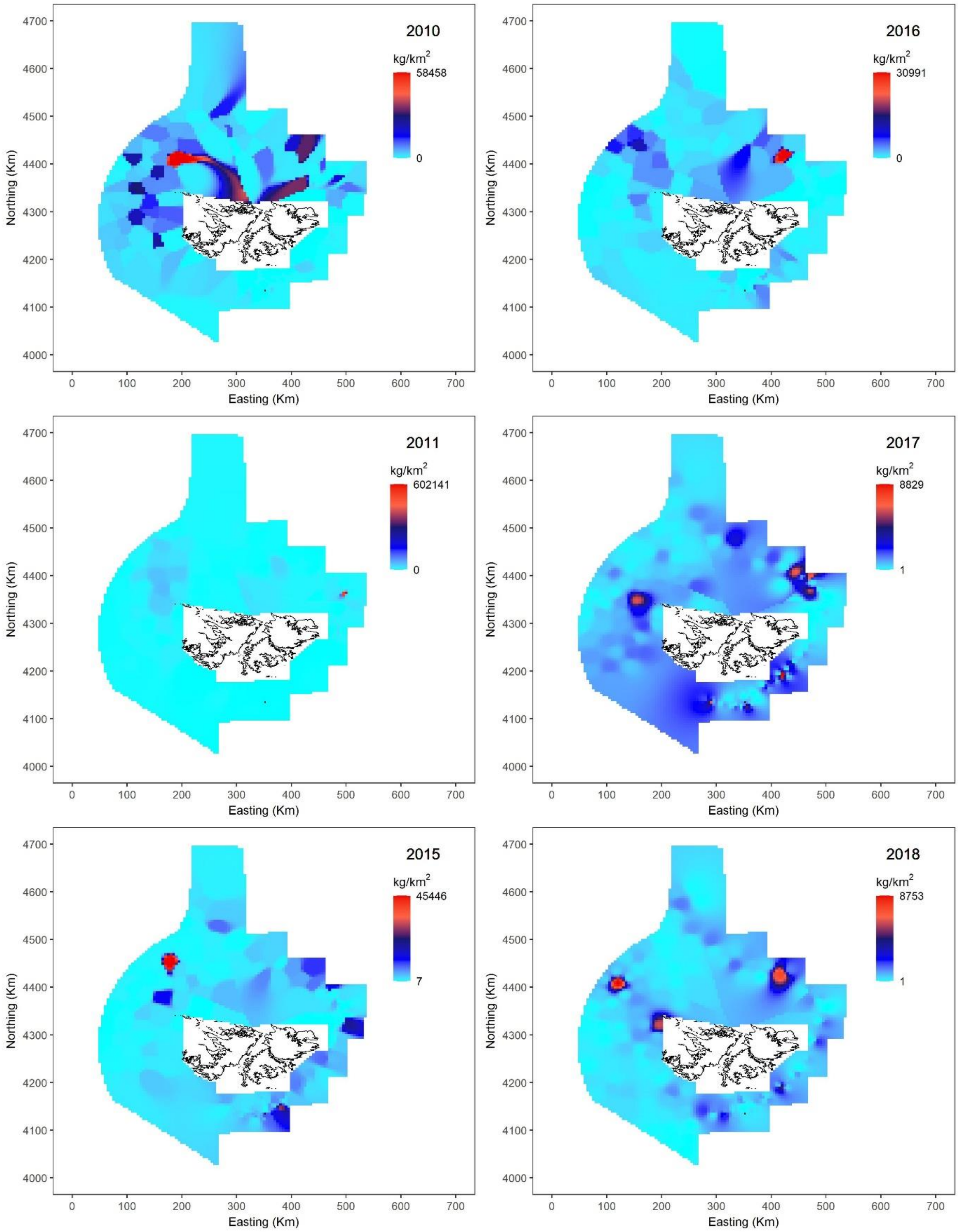
Appendix V. Monthly CPUE of rock cod in Falkland Islands waters during 2021, estimated from C–, and X–licensed vessels. Note there was no fishing effort during January, June, November and December under C– and X–licensed vessels.



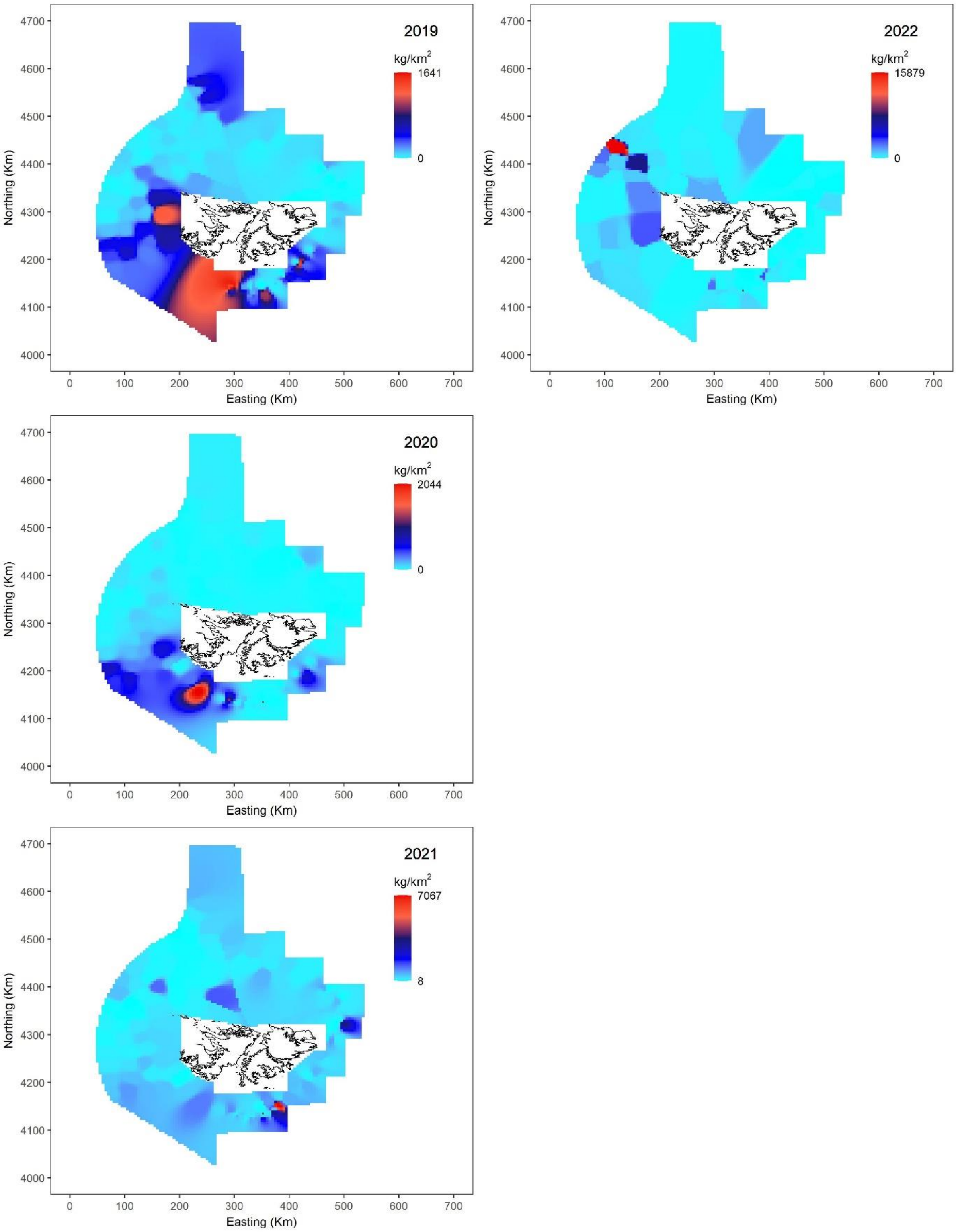
Appendix V. *continued…*



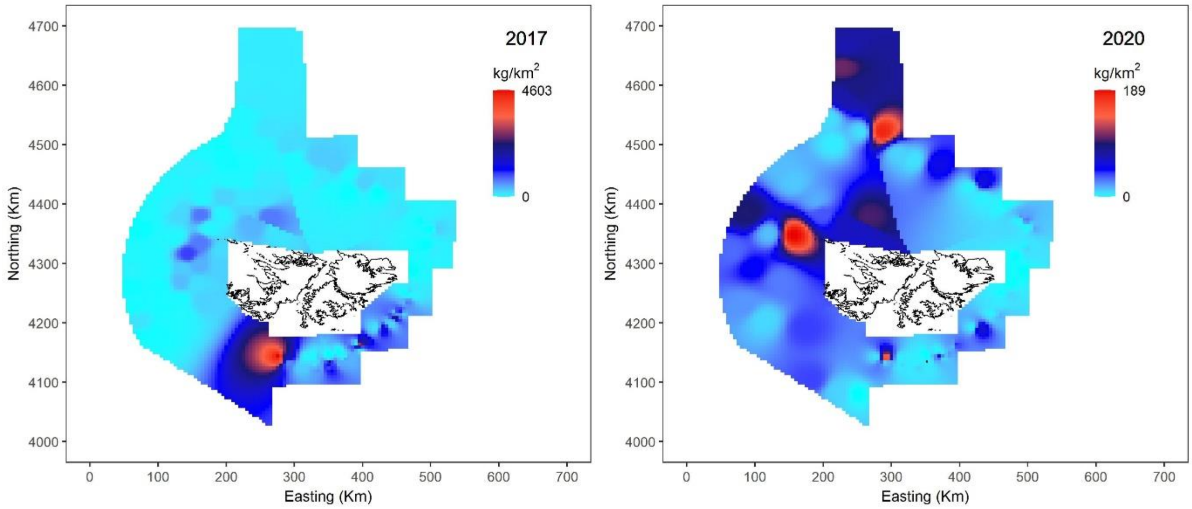
Appendix VI. Densities of rock cod modelled by inverse distance weighting throughout the Falkland Islands fishing zone, during the February 2010–2022 groundfish and pre-recruitment surveys.



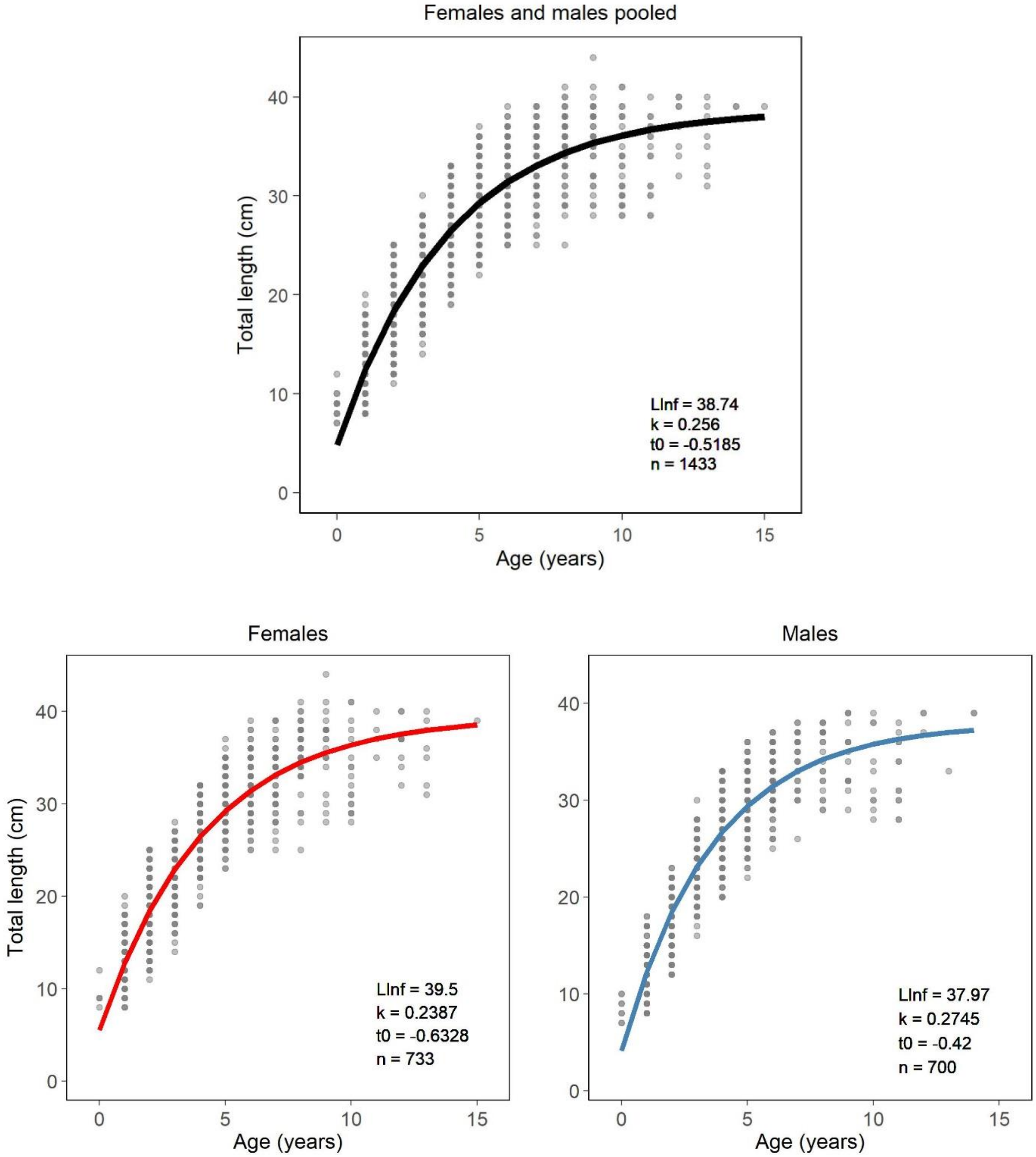
Appendix VI. *continued…*



Appendix VII. Densities of rock cod modelled by inverse distance weighting throughout the Falkland Islands fishing zone, during the July 2017 and July 2020 groundfish and pre-recruitment surveys.



Appendix VIII. von Bertalanffy age-length relationship of rock cod collected during 2014–2017 in Falkland Islands waters.

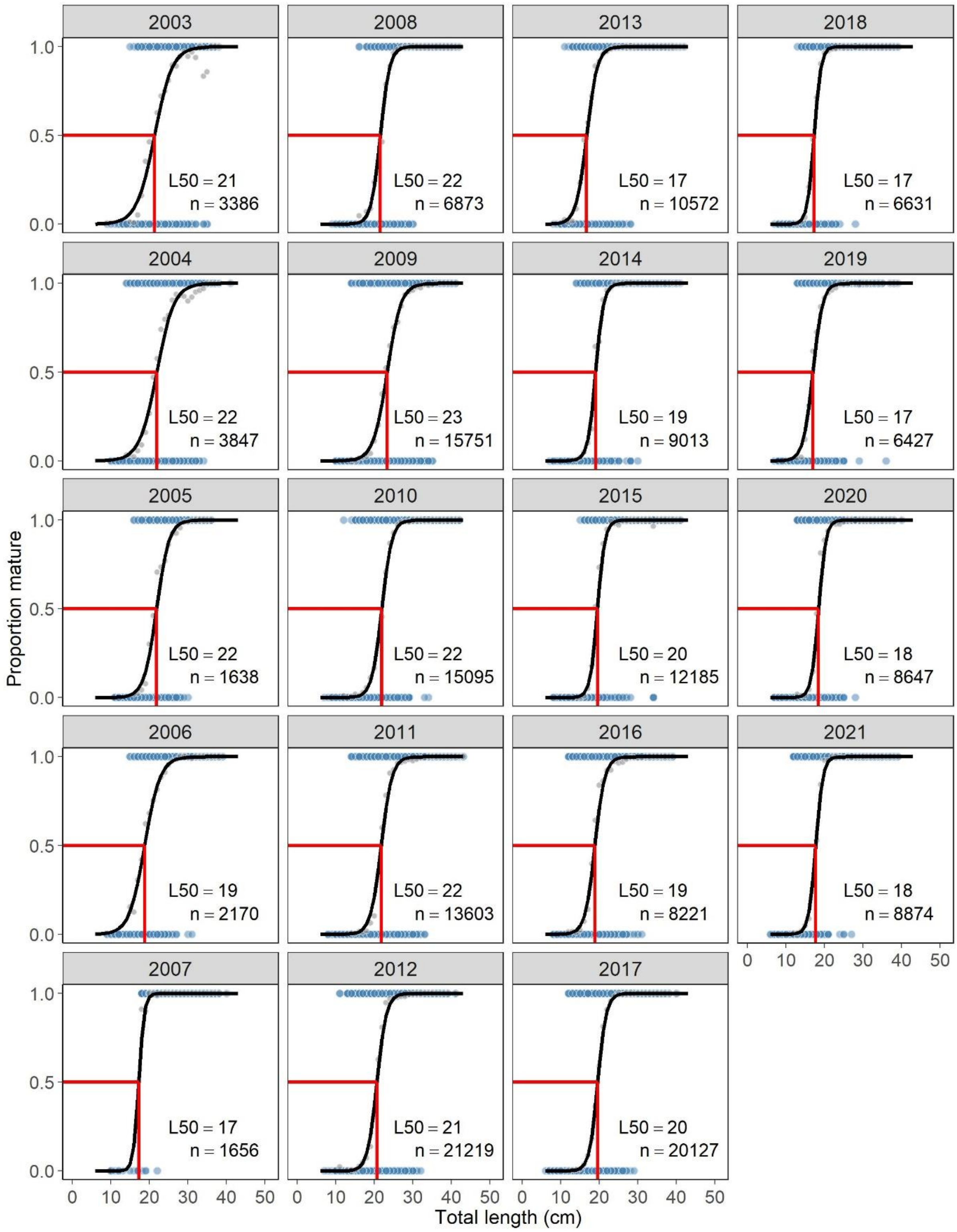


Appendix IX. Rock cod von Bertalanffy length-at-age parameters for curvature (K), age of fish at length zero (t_0), and asymptotic length (L_{Inf}), by year and sex, with 95% confidence intervals. Parameters were not calculated for 2005–2007 due to the limited rock cod age data during those years.

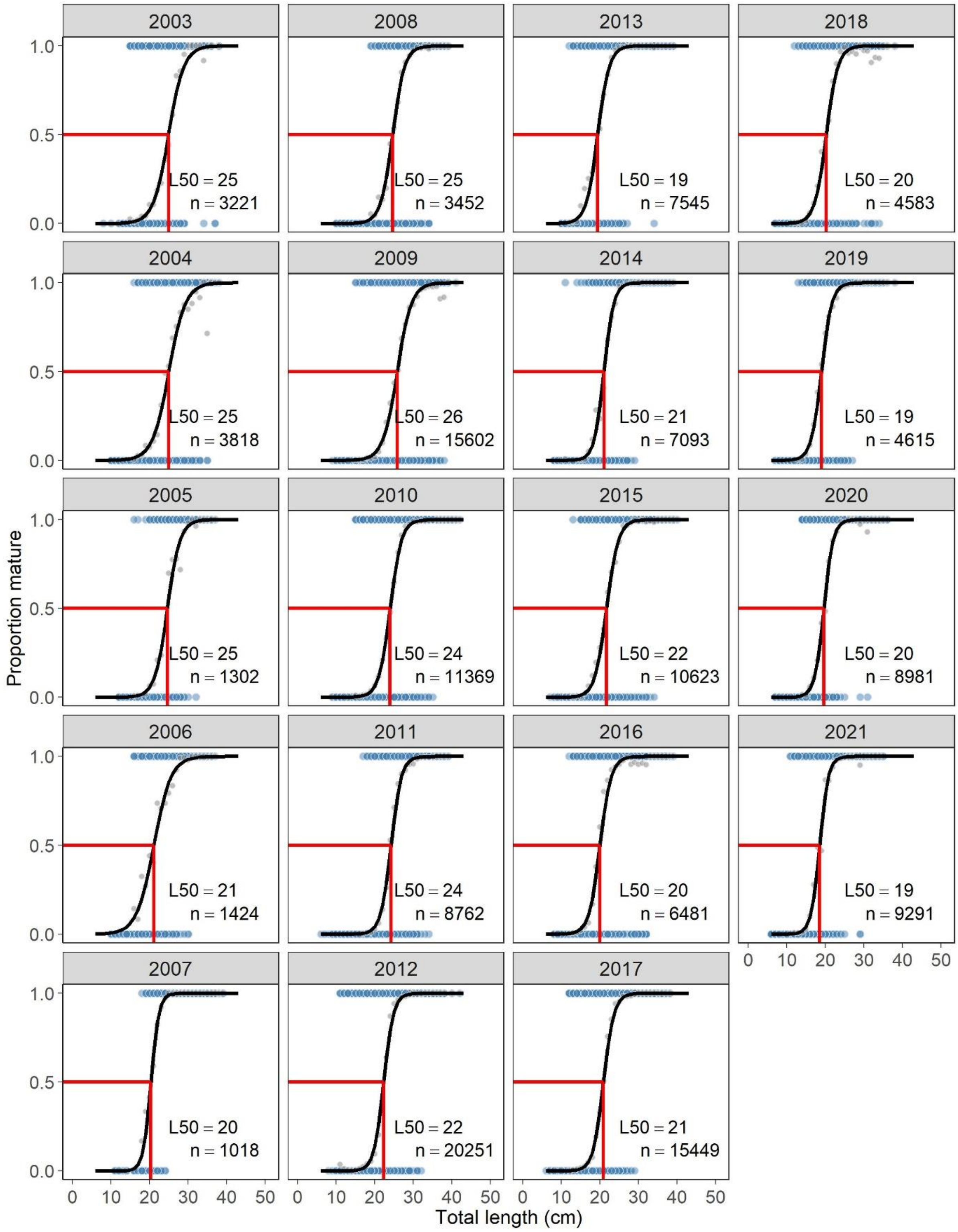
Sex	Year	n	K	t_0 (years)	L_{Inf} (cm)
	2004	124	0.235 (0.207 - 0.265)	-0.626 (-0.875 - -0.410)	39.551 (38.163 - 41.216)
	2008	233	0.216 (0.204 - 0.228)	-0.985 (-1.133 - -0.837)	39.930 (39.348 - 40.522)
	2009	386	0.222 (0.211 - 0.233)	-0.801 (-0.920 - -0.684)	39.888 (39.354 - 40.452)
	2010	163	0.230 (0.214 - 0.247)	-0.659 (-0.848 - -0.489)	39.590 (38.940 - 40.311)
	2011	248	0.226 (0.214 - 0.239)	-0.707 (-0.824 - -0.600)	39.760 (39.119 - 40.422)
F	2012	104	0.222 (0.206 - 0.240)	-0.752 (-0.950 - -0.570)	39.874 (39.057 - 40.730)
	2013	152	0.215 (0.202 - 0.229)	-0.849 (-0.982 - -0.721)	40.075 (39.383 - 40.815)
	2014	170	0.182 (0.145 - 0.219)	-0.541 (-0.888 - -0.263)	44.796 (41.690 - 49.348)
	2015	197	0.298 (0.247 - 0.357)	-0.774 (-1.150 - -0.456)	36.726 (35.233 - 38.514)
	2016	190	0.253 (0.198 - 0.313)	-0.668 (-1.065 - -0.359)	39.499 (37.013 - 42.979)
	2017	176	0.256 (0.203 - 0.315)	-0.158 (-0.537 - 0.141)	38.237 (35.793 - 41.495)

Sex	Year	n	K	t_0 (years)	L_{Inf} (cm)
	2004	113	0.265 (0.222 - 0.308)	-0.314 (-0.633 - -0.055)	38.707 (37.053 - 40.996)
	2008	223	0.261 (0.244 - 0.280)	-0.597 (-0.753 - -0.449)	38.316 (37.670 - 38.992)
	2009	347	0.258 (0.243 - 0.274)	-0.596 (-0.729 - -0.470)	38.443 (37.849 - 39.073)
	2010	163	0.258 (0.238 - 0.279)	-0.601 (-0.803 - -0.410)	38.426 (37.692 - 39.197)
	2011	224	0.249 (0.233 - 0.265)	-0.648 (-0.767 - -0.534)	38.722 (37.994 - 39.477)
M	2012	78	0.243 (0.216 - 0.272)	-0.752 (-0.997 - -0.534)	38.848 (37.529 - 40.202)
	2013	136	0.249 (0.232 - 0.268)	-0.620 (-0.759 - -0.482)	38.696 (37.943 - 39.457)
	2014	159	0.227 (0.189 - 0.270)	-0.324 (-0.535 - -0.136)	42.234 (39.633 - 45.568)
	2015	204	0.341 (0.288 - 0.403)	-0.431 (-0.750 - -0.164)	36.106 (34.863 - 37.548)
	2016	178	0.217 (0.159 - 0.279)	-0.844 (-1.227 - -0.545)	41.173 (37.335 - 47.248)
	2017	159	0.302 (0.239 - 0.370)	-0.130 (-0.464 - 0.126)	35.421 (33.143 - 38.390)

Appendix X. Binomial logistic regressions of juvenile (0) or adult (1) maturity vs. length for female rock cod. Red lines indicate the intercept for length at 50% adulthood, corresponding to Fig. 7. Gray dots indicate the proportion of mature individuals per size class.



Appendix XI. Binomial logistic regressions of juvenile (0) or adult (1) maturity vs. length for male rock cod. Red lines indicate the intercept for length at 50% adulthood, corresponding to Fig. 7. Gray dots indicate the proportion of mature individuals per size class.



Appendix XII. Number of rock cod individuals sampled for length frequency distributions.

Year	Females (n)	Males (n)
2002	11	6
2003	3,197	2,082
2004	3,753	3,644
2005	2,743	2,069
2006	2,271	2,363
2007	2,546	3,187
2008	10,290	9,867
2009	16,148	14,051
2010	25,858	20,195
2011	22,018	19,570
2012	24,885	23,840
2013	19,300	17,894
2014	13,215	12,326
2015	17,305	16,948
2016	14,022	15,000
2017	21,382	21,378
2018	14,504	15,128
2019	10,004	9,596
2020	9,544	9,161
2021	11,119	12,402