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 1,213 tonnes (t) in 2022, the sixth lowest catch since the first catch report of rock cod in 1992. In 2022, the calamari (C–, and X–licences) fishery accounted for 73%, and the finfish fishery (A–, G–, and W–licences) accounted for 23% of the total rock cod catch; 91% of the total rock cod catch was discarded.

Abundance has a declining trend. Annual commercial CPUE in the finfish fishery reached its lowest level (10 kg/h) in 2021. The biomass calculated from the 2023 summer (February) research surveys was 8% of the biomass calculated from the 2010 summer research surveys.

Length-based indicators suggest that conservation of immature fish, large individuals, and mega-spawners were of concern or negative most of the time series, and optimal yield was negative mainly in recent years.

Lengths at 50% maturity have declining trends since 2003. The calamari fishery caught smaller rock cod compared with the finfish fishery, and most rock cod were caught before reaching length at 50% maturity. The finfish fishery caught males before reaching length at 50% maturity in most years.

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 2024 of 1,519 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. 2006a; Laptikhovsky et al. 2013). Part of the stock migrates into Falkland Islands waters in spring[a] (October to December) and summer (January to March), to the northwest and north of the Falkland Islands Conservation Zone (FICZ) (Arkhipkin et al. 2012). In autumn (April to June), rock cod emigrates from Falkland Islands waters and remains in low abundances during winter (July to September) (Arkhipkin et al. 2012). Spawning occurs in autumn on the Argentine Shelf at 42°S, at the end of autumn and in part of winter at the shelf break in Falkland Islands waters, and in spring at the Burdwood Bank (Ekau 1982; Brickle et al. 2006a).

Analysis of population/stock structure have revealed contrasting patterns for rock cod (Shaw 2011; Brickle et al. 2021). Mitochondrial DNA sequencing showed no significant population genetic differentiation or stock structure between samples taken from the southern and northern Falkland Islands shelf (Shaw 2011). Analysis of parasite communities showed separation between the southern Falkland Islands shelf and the high seas to the north. Trace element analysis in otolith cores showed overlap between the southern and northern Falkland Islands shelf, and between the northern Falkland Islands shelf and the high seas to the north, but no overlap between the southern Falkland Islands shelf and the high seas to the north, probably due to intermixing during the larval phase. Trace element analysis in otolith edges suggested stock separation between the southern Falkland Islands shelf, the northern Falkland Islands shelf, and the high seas to the north (Brickle et al. 2021).

Most of the rock cod catch in the Southwest Atlantic is historically taken by the Falkland Islands fisheries (Falkland Islands Government[b]; Falkland Islands Government 2023), compared with the Argentina fisheries (Argentine Government[c]; 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. 2006a,b; 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

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

discards (Laptikhovsky & Arkhipkin 2003), resulting in further overlap with the fisheries. With the decline of southern blue whiting *Micromesistius australis* and the simultaneous increase in abundance of rock cod in the 2000s, this species became the main commercial target for the finfish fishery in the FICZ (Laptikhovsky et al. 2013) with record catches from 2008 to 2014. Incidental rock cod catches in the calamari (Patagonian squid *Doryteuthis gahi*) fishery were comparably lower since 2005. However, after the steep rock cod decline the calamari fishery has contributed most rock cod catches despite the small quantities in the FICZ since 2016[a].

Methods

ICES advice rules

In 2020, rock cod was included in a Falkland Islands Government finfish stock assessment and management review conducted by MacAlister Elliott & Partners Ltd, UK (MEP 2020). The MEP report recommended stock assessments for most commercial finfish species to be based on the ICES advice rules (ICES 2012, 2018a), referencing applicable categories of data availability and quality. 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 supplementary 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} (asymptotic length; Haddon 2001) and L50 (length at 50% maturity; Cope & Punt 2009).

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 the current TAC (Ramos &

Winter 2022a) to generate next year's TAC (MEP 2020). However, each year's survey biomass estimate is subject to more or less uncertainty depending on the distribution of catches (Ramos & Winter 2023). 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; 2023 = 2810261388.1). TAC was calculated as follows:

$$TAC\_3_{2024} = TAC\_3_{2023} \times \left. \frac{\left(\sum_{y=2022}^{2023} B_y \times {}^{1}\!/_{Var_y}\right) \Big/ \left(\sum_{y=2022}^{2023} {}^{1}\!/_{Var_y}\right)}{\left(\sum_{y=2019}^{2021} B_y \times {}^{1}\!/_{Var_y}\right) \Big/ \left(\sum_{y=2019}^{2021} {}^{1}\!/_{Var_y}\right)} \right| \pm 20\%$$

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

Commercial catch and CPUE

Commercial fishing around the Falkland Islands was not distinguished from other parts of the Southwest Atlantic prior to 1982 and catch data by species were recorded systematically from 1987 only (Falkland Islands Government 1989). Rock cod catch records span from 2003 onwards for the Falkland Islands. Therefore, total rock cod catch data were examined from 2003 to 2022 from the Falkland Islands (Falkland Islands Government[a]; Falkland Islands Government 2023), and Argentina (Argentine Government[b]; Sánchez et al. 2012; Navarro et al. 2014, 2019). LOESS (span = 0.75, C.I. = 0.95) was implemented to examine the pattern of the association between Falkland Islands and Argentina commercial annual catches of rock cod from 2003 to 2022.

Commercial annual catch and discard, and catch at depth were examined for the finfish (A–, G–, and W–licences) and for the calamari (C–, and X–licences) fisheries. Catch at depth

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

was examined to identify the depths where rock cod were caught during the years it was targeted, as well as to identify the depths that can potentially be avoided to reduce fishing pressure on the stock. Commercial catches and discard of rock cod in the FICZ were examined by licence type for 2022. Catch per unit effort (CPUE) was estimated as the sum of rock cod catches divided by the sum of effort. Annual CPUE, monthly CPUE through the time series, and the monthly distribution of the CPUE in the FICZ during 2022 were examined. Annual and monthly CPUE was calculated for the finfish and for the calamari fisheries. Spatial distribution of the 2022 monthly CPUE average was examined for the finfish and for the calamari fisheries. Catch and associated biological data were not recorded by licence type before July 2007. Therefore, inference of the most probable target fishery before July 2007 was conducted following the criteria explained in Appendix I.

Survey biomass estimates

Biomass estimates and the spatial distribution of rock cod were examined from joint summer surveys (groundfish and Patagonian squid *Doryteuthis gahi* pre-season surveys) carried out in February 2010, 2011, and 2015 – 2023 in Falkland Islands waters (Ramos & Winter 2023). A trend of the biomass time series from 2010 to 2023 was calculated using LOESS (span = 0.75, C.I. = 0.95).

Biomass estimates, the spatial distribution of rock cod, and biomass ratios were also examined following Ramos & Winter (2023) from joint surveys carried out in winter, during July 2017 (groundfish survey, Gras et al. 2017; Patagonian squid pre-season surveys, Winter et al. 2017), July 2020 (hake survey, Randhawa et al. 2020; Patagonian squid pre-season survey, Winter et al. 2020), and July 2022 (groundfish survey, Lee et al. 2022; Patagonian squid pre-season surveys, Winter & Skeljo 2022). The July surveys were conducted for the primary purpose of assessing common hake *Merluccius hubbsi* (Gras et al. 2017; Randhawa et al. 2020), and are presented as an additional comparative proxy for abundance patterns, with the caveat that these would likely reflect variability due to the migratory timing of rock cod (Arkhipkin et al. 2012).

Length and age analyses

Length Based Indicators

ICES (2015, 2018b) recommends the LBI method which provides a suite of indicators for population status based on combinations of catch-at-size distributions, life-history parameters such as L_{Inf} (asymptotic length; Haddon 2001) and L50 (length at 50% maturity; Cope & Punt 2009). L_{Inf} and L50 parameters were assessed for females and males separately as rock cod maturation is sexually dimorphic (Brickle et al. 2006a).

LBI method was applied to all years from which rock cod length (total length) and age data were available and reported as random samples (FIFD database codes R and S), i.e., years 2003 to 2022 for length data, and years 2003, and 2011 to 2018 for age data. In this report, only directly measured ages were used and not age calculated from length data using the von Bertalanffy age-length relationship, as was done in last year's report (Ramos & Winter 2022a), therefore resulting in LBI outputs for a smaller range of years. Because finfish trawls are restricted to larger meshes than calamari trawls, only length and age data from finfish and experimental (E–licence) vessels with fishing activity to the north and west in the FICZ 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 excluded because, although using larger meshes like the meshes used in finfish trawls, their different targets could relate to characteristically different length-frequency distributions of rock cod.

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

1) Length at half the modal catch length should be bigger than L50, for conservation of immature fish (L_C / L50 > 1). Note that length at half the modal catch length may be poorly defined if the catch length-frequency distribution is not smooth and unimodal.
2) Length at cumulative 25th percentile of catch numbers should be bigger than L50, for conservation of immature fish ($L_{25\%}$ / L50 > 1).
3) Mean length of the largest 5% of individuals in the catch should be at least 80% of the asymptotic length, as a benchmark that enough large individuals are in the stock ($L_{max5\%}$ / L_{Inf} > 0.8).
4) 'Mega-spawners' should comprise at least 30% of the catch 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). $L_{Opt} = 3 \cdot L_{Inf} \cdot (3 + Mk^{-1})^{-1}$ (Beverton 1992), where M is instantaneous natural mortality, k is the rate of curvature of the von Bertalanffy growth function, and the ratio Mk^{-1} is set in WKLIFE V software (ICES 2015) at the standard constant of 1.5 (Jensen 1996).

5) Mean length of individuals larger than L_C (L_{meanC}) should be approximately equal to L_{Opt}, for optimal yield ($L_{meanC} / L_{Opt} \approx 1$).
6) L_{meanC} should be equal or bigger to the length-based proxy for MSY ($L_{F=M}$), for producing maximum sustainable yield ($L_{meanC} / L_{F=M} \geq 1$). $L_{F=M}$ implements the premise that MSY is attained when fishing mortality equals natural mortality (Froese et al. 2018), and in WKLIFE V software (ICES 2015) is computed as $(3 \cdot L_C + L_{Inf})/4$.

Margins of variability of the six indicators were estimated by randomly re-sampling 10,000× on the normal distribution each year's fits of L_{Inf} and L50. Indicators were scored against the 'traffic light' scale (ICES 2015) with reference criteria >1 for conservation of immature fish, >0.8 for conservation of large fish, and >0.3 for conservation of mega-spawners. The score was green if the lower 95% quantile of the re-sampled iterations was >1.0, >0.8, and >0.3, yellow if 1.0, 0.8, and 0.3 were between the lower and upper 95% quantiles, and red if the upper 95% quantile of the re-sampled iterations was <1.0, <0.8, and <0.3. The use of the margins of variability means that same empirical values of indicators may be scored different colours in different years. Reference criterion ≈1.0 for optimal yield was green if the lower and upper 95% quantiles spanned 1.0, yellow if the lower and upper 95% quantiles spanned 0.9 (the threshold used in ICES 2015) without spanning 1.0, and red otherwise. Reference criterion ≥1.0 for MSY was scored the same as >1.0, except that empirical values ≥ 1.0 were automatically green.

Length-age relationship

The von Bertalanffy growth function (R package 'fishmethods'; Nelson 2019) was used to fit rock cod length and age data from finfish (A–, G–, and W–) and experimental (E–) licences with fishing activity at the north and west in the FICZ, and from calamari (C–, and X–) and experimental (E–) licences with fishing activity in the 'Loligo Box' to the east in the FICZ.

Rock cod length and age data were jointly available for years 2003–2019, which are considered reliable (Lee et al. 2018, 2020; B. Lee, FIFD, *pers. comm.*). 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 between males in the finfish and calamari fisheries. Variabilities of the growth model parameters were estimated by bootstrapping; residuals of the model fits were randomly re-sampled with replacement, added back to the expected lengths, and re-fit to the von Bertalanffy growth function. The 95% quantiles of 10,000 iterations were retained as confidence intervals. Inter-annual trends of von Bertalanffy L_{Inf} were calculated by LOESS (span = 0.75, C.I. = 0.95). Age was not re-calculated from length data using the von Bertalanffy age-length relationship, as per last year report (Ramos & Winter 2022a), therefore resulting in LInf calculations for a smaller range of years.

Length at 50% maturity

Length at 50% maturity (L50) was calculated as the mid-point of the binomial logistic regression of maturity vs. length (Heino et al. 2002). Sex and maturity were identified following the fish maturity scale by Brickle et al. (2006a; modified from Nikolsky 1963): I) immature; II) resting; III) early developing; IV) late developing; V) ripe; VI) running; VII) spent; VIII) recovering spent. Gonadal maturity is cyclical as fish pass from post-spawning phase to resting phase, and definitive maturity assignments can only be made that stage I is immature and stages III+ are always adult (B. Lee, FIFD, *pers. comm.*). Therefore, maturity assignment was simplified to a dichotomous classification of 0) juvenile, including maturity stages I, and 1) adult, including maturity stages III to VIII, omitting stage II (Winter 2018). Assuming stock structure subdivided by area (Brickle et al. 2021) and distinct biological characteristics, annual L50s were calculated from randomly sampled individuals collected under finfish and experimental licences with fishing activity north and west in the FICZ, and from calamari and experimental licences with fishing activity in the 'Loligo Box' to the east in the FICZ. Samples were consistently available from 2003 to 2022. Trends of L50 were calculated with LOESS smooths (span = 0.75, C.I. = 0.95), weighted by inverse variance of each year's binomial logistic regression. Previous assessments had shown these trends to be statistically significant (e.g., Winter 2020) and the LOESS fits per year were used for LBI parameterization.

Length frequency distribution

Yearly length frequency distributions, from 2003 through 2022, were examined for females and males to describe the size of rock cod caught in the finfish and calamari fisheries separately. Unsexed individuals were excluded from the analysis. Lengths of individuals sampled randomly and collected under finfish and experimental licences with fishing activity north and west in the FICZ, and from calamari and experimental licences with fishing activity in the 'Loligo Box' to the east in the FICZ were examined separately. Yearly length frequencies were compared with yearly L50 to assess if the catch was mainly comprised of immature or mature individuals.

Data analyses were conducted in R programming language (R Core Team 2021).

Results

ICES advice rules

ICES Category 3 Total Allowable Catch

TAC options for 2024 based on the current year TAC were calculated as follows:

$$\mathrm{TAC\_3}_{2024} = \underset{\mathrm{Min}}{\overset{\mathrm{Max}}{}}\left(\left(\mathrm{TAC\_3}_{2023}\right) \times \frac{\left(\overline{\mathrm{B}_{2022\ \mathrm{to}\ 2023}}\right)}{\left(\overline{\mathrm{B}_{2019\ \mathrm{to}\ 2021}}\right)}, \left(\mathrm{TAC\_3}_{2023}|_{20\%}\right) \right)$$

Where

$$\mathrm{TAC\_3}_{2023} = 1266\ \mathrm{tonnes}$$

and ICES 2/3 rule weighted by inverse variances:

$$\left(\overline{\mathrm{B}_{2022\ \mathrm{to}\ 2023}}\right) = \left(\sum_{y\,=\,2022}^{2023} \mathrm{B}_y \times \frac{1}{\mathrm{Var}_y}\right) \Big/ \left(\sum_{y\,=\,2022}^{2023} \frac{1}{\mathrm{Var}_y}\right) =$$

$$\frac{(93177.2 \times\ 1.71^{-10}) + (64729.1 \times 3.55^{-10})}{1.71^{-10} + 3.55^{-10}} = 73963\ \mathrm{tonnes}$$

$$\left(\overline{\mathrm{B}_{2019\ \mathrm{to}\ 2021}}\right) = \left(\sum_{y\,=\,2019}^{2021} \mathrm{B}_y \times \frac{1}{\mathrm{Var}_y}\right) \Big/ \left(\sum_{y\,=\,2019}^{2021} \frac{1}{\mathrm{Var}_y}\right) =$$

$$\frac{(45669.2 \times 1.37^{-8}) + (19079 \times 4.86^{-8}) + (59670.4 \times 3.38^{-8})}{1.37^{-8} + 4.86^{-8} + 3.38^{-8}} = 37146\ \mathrm{tonnes}$$

Thus,

$$\text{TAC\_3}_{2024} = 1266 \times \frac{73963}{37146} = 2520.75 \text{ tonnes}$$

Applying the 20% cap:

$$\text{TAC\_3}_{2024} = \text{TAC\_3}_{2023} + 20\% = 1519.20 \text{ tonnes}$$

Note that the year jumps from 2022 to 2024. Standard procedure is to inform next year's allowable catch with data up to the last completed year, i.e., the previous year (2022), as licencing advice must be issued while the current year is still in progress.

Commercial catch and CPUE

Rock cod catches in Falkland Islands waters were negligible from 1987 to 2004, but since 2005 have represented approximately 83% of the Falkland Islands and Argentine combined annual catch (Fig. 1). Falkland Islands and Argentine rock cod annual catches were positively correlated (Fig. 1 inside panel; Appendix II).

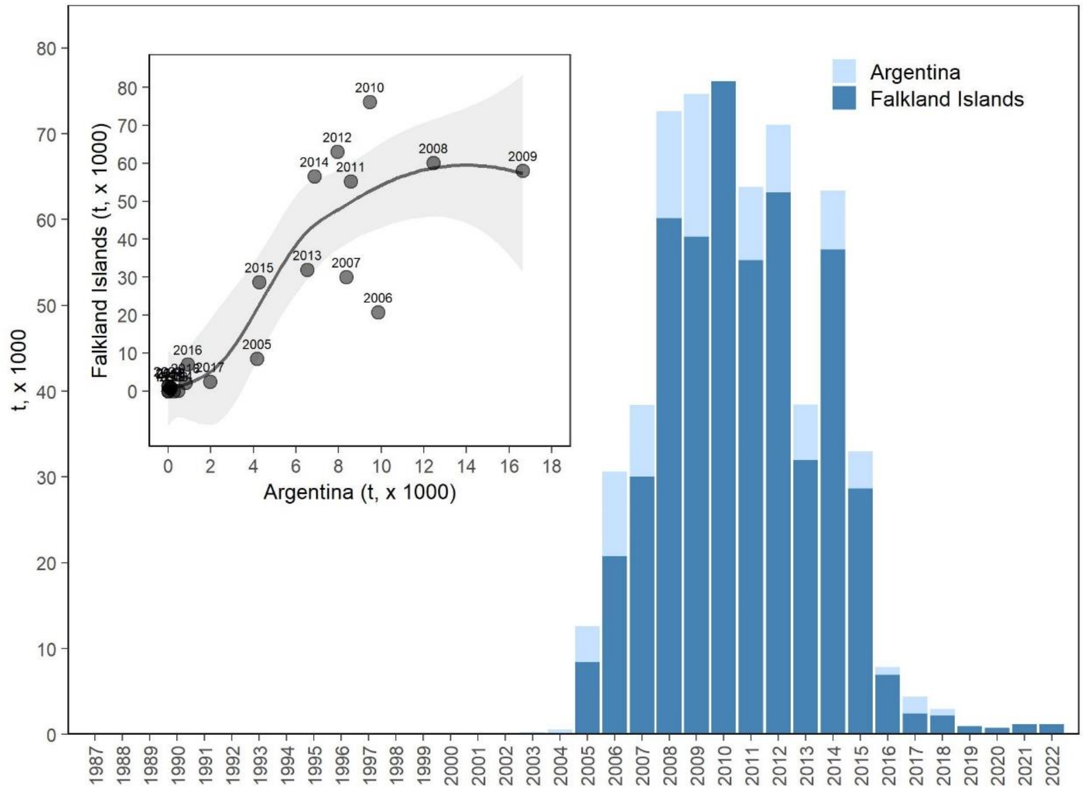

Fig. 1. Annual commercial catch of rock cod in Falkland Islands and Argentine waters. Falkland Islands catch data exclude experimental (E–licence) and out-of-zone (O–licence) licences. Inside panel shows the association between Falkland Islands and Argentine annual commercial catches of rock cod, with LOESS smooth ± 95% confidence intervals (LOESS; span = 0.75, C.I. = 0.95).

In the FICZ, the finfish fishery targeted rock cod over the period 2005–2015, and contributed an annual average of 89% of the total rock cod catch. However, fishing pressure by the finfish fishery decreased as rock cod abundance declined, and this proportion decreased since 2016 to an annual average of 37% per year. With the decrease of rock cod catches by the finfish fishery, the calamari fishery became the main contributor to the total rock cod catch with an annual average of 63%. From 2005 to 2015, the finfish fishery had an annual average rock cod catch of 36,289 t and the calamari fishery had an annual average rock cod catch of 3,486 t. From 2016 to 2022, the finfish fishery annual average rock cod catch decreased to 918 t and the calamari fishery annual average rock cod catch decreased to 1,295 t (Fig. 2 top panel).

Proportions of rock cod discards reported by the finfish fishery were on average 16% from 2005 to 2015, and 33% from 2016 to 2022. Proportions of rock cod discards reported by the calamari fishery were on average 94% from 2005 to 2015, and 100% from 2016 to 2022 (Fig. 2 bottom panel).

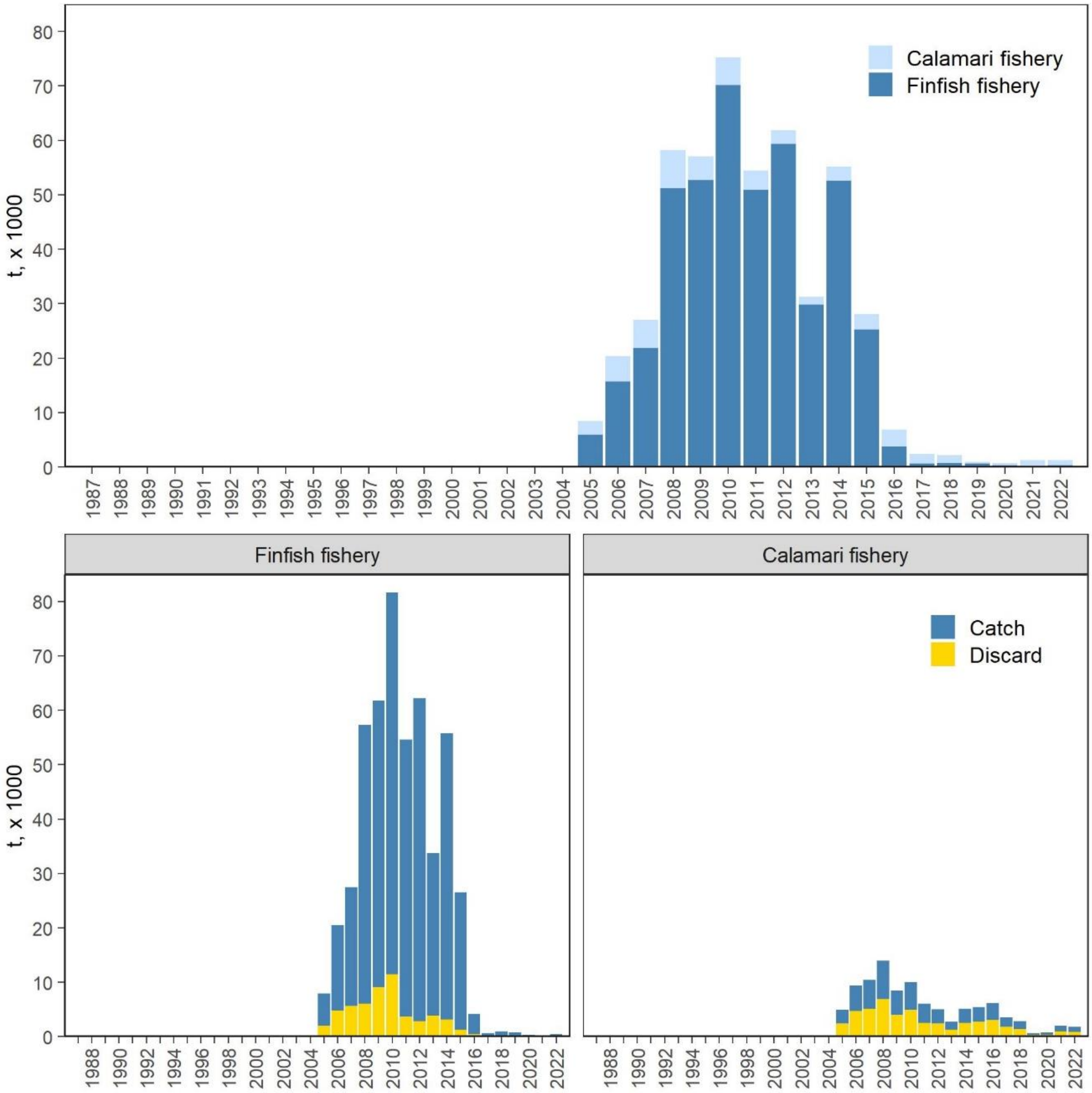

Fig. 2. Annual commercial catch of rock cod in Falkland Islands finfish (A–, G–, and W–licences) and calamari (C–, and X–licences) fisheries (top panel), and annual catch and discard by fishery (bottom panel).

A higher proportion of rock cod catches was observed in shallow bottom trawls (<200 m depth) from 2006 (95%) to 2015 (87%), which are the years with higher rock cod catches in the finfish fishery in the time series examined (Fig. 2). Rock cod catch proportions in shallow bottom trawls decreased to an annual average of 53% from 2016 to 2022 (Fig. 3), years when rock cod catches were negligible in the finfish fishery (Fig. 2). The opposite pattern was observed in the calamari fishery; rock cod catch proportions were lower at shallow bottom trawls in 2005 (9%) and increased to reach the highest proportion (89%) in 2022 (Fig. 3).

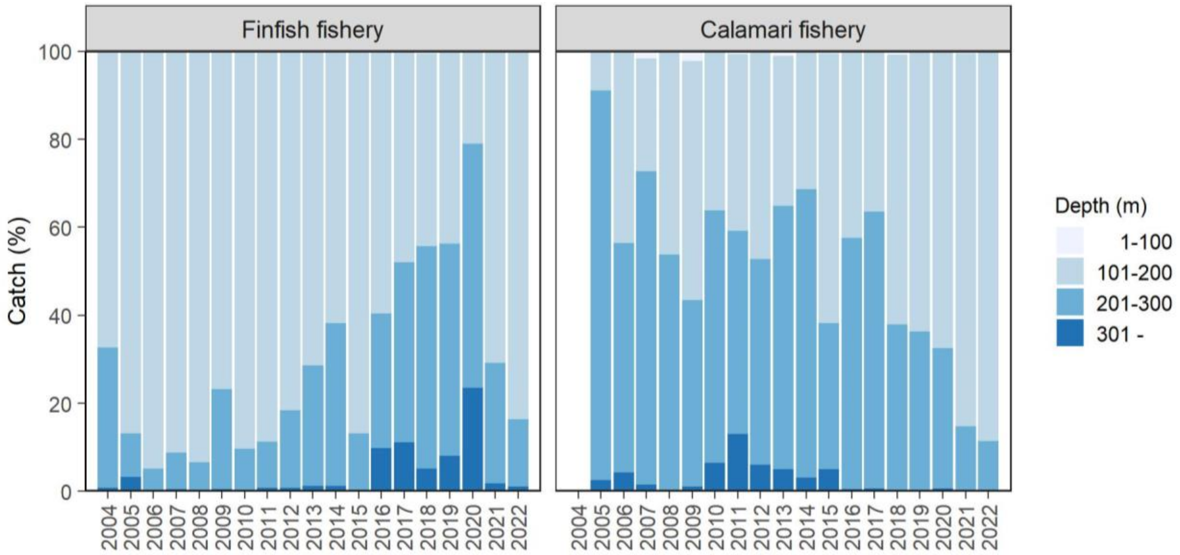

Fig. 3. Annual commercial catch of rock cod at depth in Falkland Islands finfish (A–, G–, and W–licences) and calamari (C–, and X–licences) fisheries.

In the finfish fishery, 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; CPUE in 2022 was 17 kg/h (Fig. 4). In the calamari fishery, CPUE had the highest value in 2007 with 309 kg/h and declined to reach the lowest value in 2020 (16 kg/h); the CPUE in 2022 was 29 kg/h (Fig. 4).

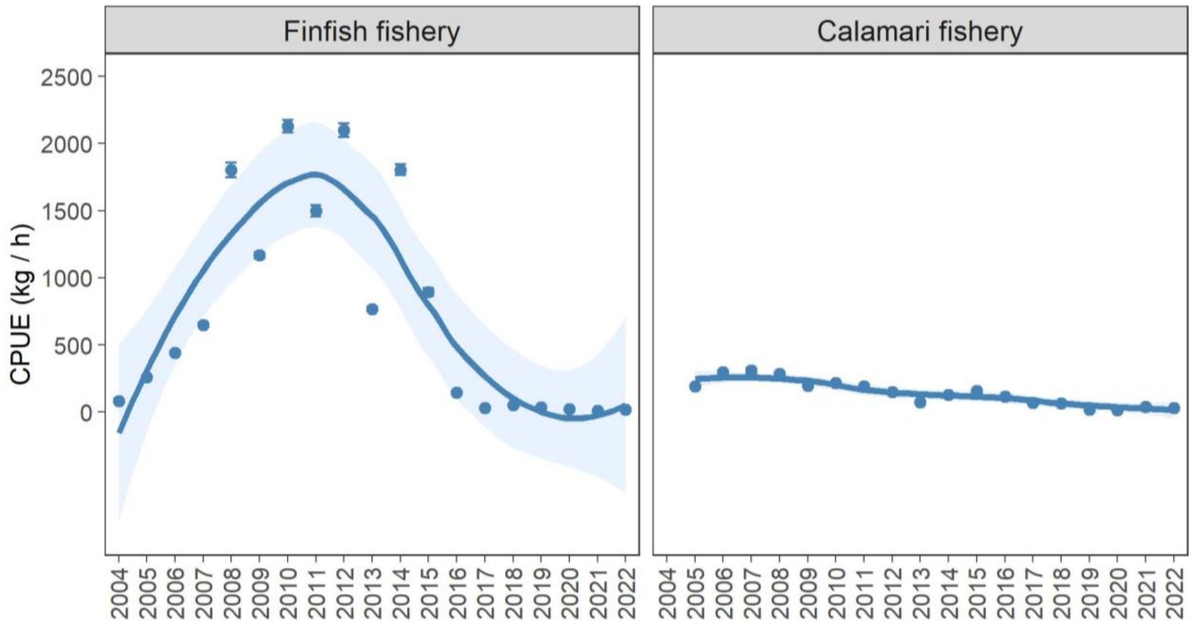

Fig. 4. Annual CPUE (mean ± SE) of rock cod in Falkland Islands finfish (A–, G–, and W–licences) and calamari (C–, and X–licences) fisheries.

Average monthly CPUE in the finfish fishery over the period of heavy fishing on rock cod, from 2007 to 2015, ranged between 641 kg/h and 2,351 kg/h. Higher CPUE was observed in the first half of the year, and the highest value was calculated for May. CPUE increased from January through May, followed by a decline through September. CPUE increased again from October through December but did not reach the levels observed in the first half of the year (Fig. 5; Appendix III). This pattern suggests that rock cod is more abundant in Falkland Islands waters during summer (January to March) and autumn (April to June). In the calamari fishery, CPUE ranged between 176 kg/h and 216 kg/h, with relatively higher values in the second fishing season under X–licence (Fig. 5; Appendix IV).

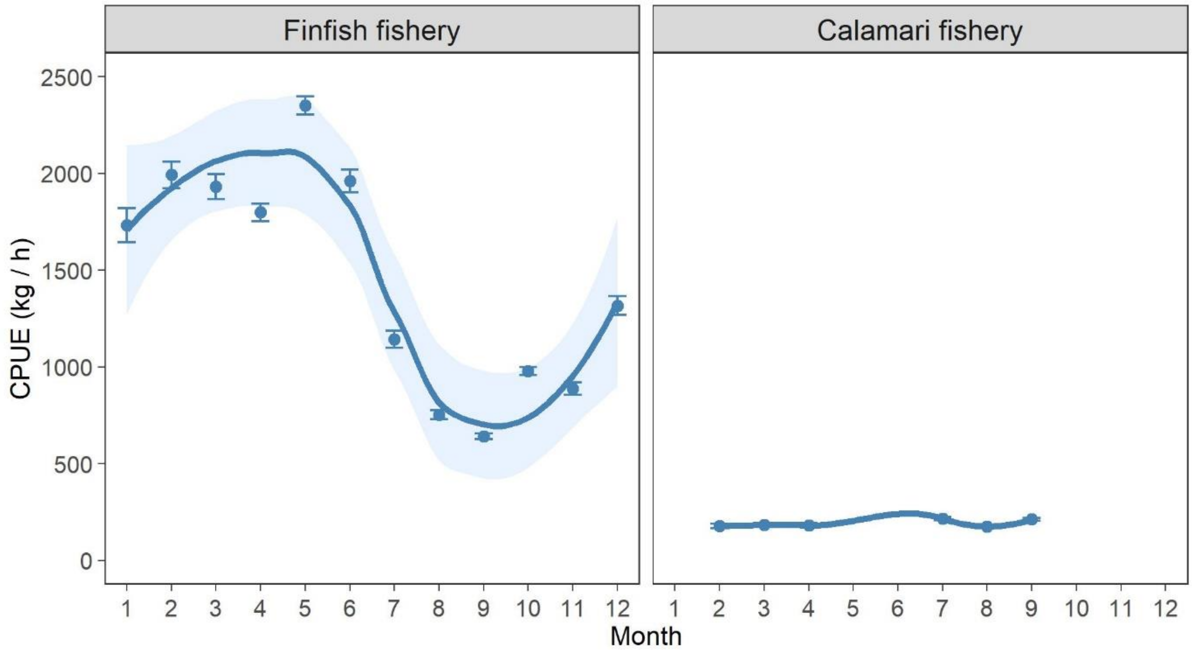

Fig. 5. Monthly CPUE (mean ± SE) of rock cod in the Falkland Islands finfish (A–, G–, and W– licences) and calamari (C–, and X– licences) fisheries.

During 2022, a total of 1,269 t of rock cod were reported caught in Falkland Islands waters, of which 1,213 t were reported under commercial licences, i.e., excluding the experimental E–licence. The calamari fishery (C–, and X–licences) accounted for 73% of the total rock cod catch, mostly in the south of the ‘Loligo Box’ (Appendix V). The finfish fishery (A–, G– and W–licences) accounted for 23% of the total rock cod catch, mainly to the west and north-west of West Falkland (Appendix VI). Nearly 91% of the rock cod catch in 2022 was reported discarded; discard proportions were considerably high in calamari vessels (>99%; Table I).

Table I. Catches by licence of rock cod in Falkland Islands waters during 2022.

Licence	Target species	Catch (t)	Catch (%)	Discard (t)	Proportion discarded (%)
C	Calamari 1st season	570.30	44.94	570.25	99.99
X	Calamari 2nd season	352.05	27.74	352.05	100.00
A	Unrestricted finfish	165.52	13.04	121.31	73.29
G	Restricted finfish and *Illex*	95.27	7.51	40.01	42.00
E	Experimental	55.76	4.39	55.76	99.99
W	Restricted finfish	29.92	2.36	14.43	48.23
B	*Illex* squid	0.19	0.01	0.19	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		1,269.00	100.00	1,153.99	90.94

Surveys biomass estimates

Summer surveys (February)

The biomass of rock cod during the February surveys have an overall declining trend, reaching its minimum in 2020 (19,079 t), with the biomass in 2023 (64,729 t) being 8% of the biomass in 2010 (817,086 t; Fig. 6; Table II). 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 2022 and 2023, the highest concentrations of rock cod occurred mainly to the north-west (Appendix VII).

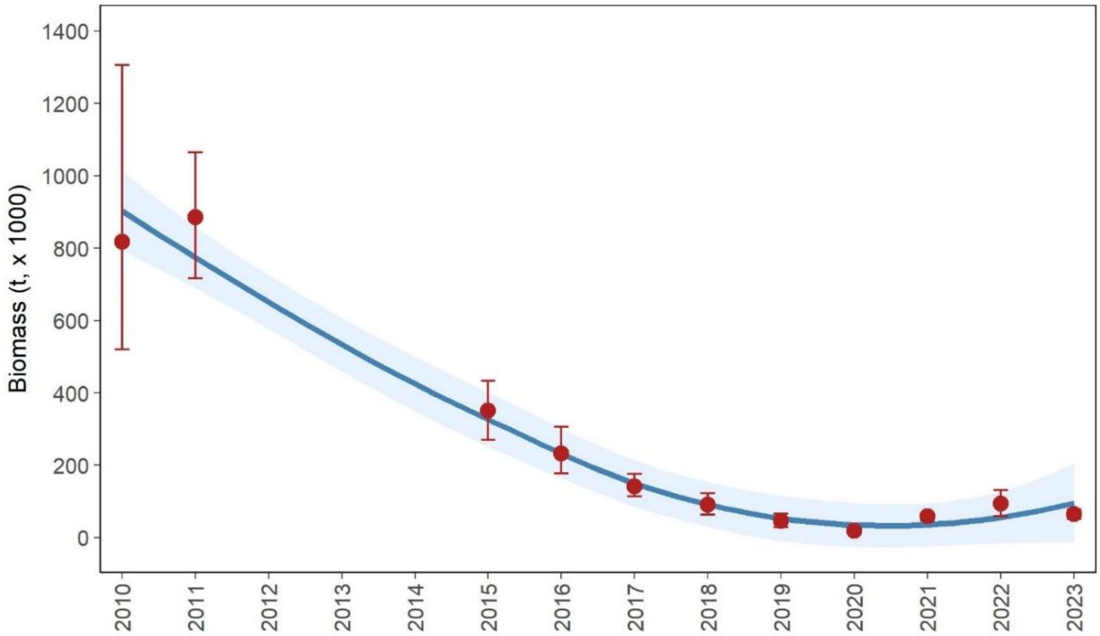

Fig. 6. Rock cod biomass estimates (red dots) ± 95% confidence intervals from February surveys in Falkland Islands waters. Note that groundfish February surveys were not conducted in 2012, 2013, and 2014. Dark blue lines and light blue areas are the inter-annual LOESS smooths ± 95% confidence intervals (LOESS; span = 0.75, C.I. = 0.95).

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	24539.00	243.36	
	Total	156	57.35	197.25	35922.25	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	16.48	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	107.13	190.70	57156.81	299.72	
2022	Groundfish	42	9.23	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	95.99	160.98	30815.79	191.42	
2023	Groundfish	84	18.57	83.77	10243.33	122.28	64729.11 (51235.90–78204.69)
	D. gahi	61	93.67	120.08	25969.85	216.27	
	Total	145	112.24	203.85	36213.18	177.65	

[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 2017 survey (52,933 t) was 97% of the July 2022 survey (54,746; Table III). A total of 5,223 out of 10,000 paired re-samples had higher biomass estimate values in July 2022 than in July 2017 (52%), thus not 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 2022 rock cod were mainly aggregated to the north-west (Appendix VIII). It must be noted that rock cod emigrates from Falkland Islands waters and remains in low abundances during winter (July to September) (Arkhipkin et al. 2012), and biomass calculations based on July surveys would likely reflect variability in the migratory timing of rock cod.

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	74.00	2003.33	27.07	52933.12 (32228.09 – 68987.56)
	D. gahi[a]	59	54.71	114.00	30906.69	271.11	
	Total	133	70.12	188.00	32910.02	175.05	
2020	Groundfish[b]	33	7.14	33.02	329.77	9.99	5789.94 (4128.66 – 7309.08)
	D. gahi	55	98.57	101.25	1176.93	11.62	
	Total	88	105.71	134.27	1506.70	11.22	
2022	Groundfish	62	12.28	61.62	6261.71	101.62	54746.30 (20465.10 – 91728.50)
	D. gahi	59	74.35	118.00	13828.36	117.19	
	Total	121	86.63	179.62	20090.07	111.85	

[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.

Length and age analyses

Length Based Indicators

Yearly 'traffic light' length indicators for females and males are summarized in Table IV. Indicator $L_C/L50$, for conservation of immature fish, had negative outcomes (red) almost every year from 2003 to 2022 for females, except for 2007, 2008, 2011, and 2014 mainly with positive values (green). For males, this indicator was negative most years except for 2008, which was of concern (yellow). Indicator $L_{25\%}/L50$, also for conservation of immature fish, fluctuated from 2003 to 2014 for females, with negative outcomes from 2015 onwards. For males, indicator $L_{25\%}$/L50 was negative most years except for 2007 and 2008. Indicator $L_{max5\%}/L_{Inf}$, for the conservation of large individuals, was positive in 2003, and from 2014 to 2017, and it was of concern from 2011 to 2013, and in 2018 for females. For males, indicator $L_{max5\%}/L_{Inf}$ was of concern most years from 2011 to 2018, except for 2015 and 2016 when it was positive. Indicator P_{mega}, for the presence of mega-spawners, was negative most of the time series except for 2003 and 2015 with positive outcomes, and in 2011 and 2014 with values of concern for females. For males, indicator P_{mega} was of concern most of the time series, with negative outcomes in 2015, 2017 and 2018. Indicator L_{meanC}/L_{Opt}, for optimal yield, was of concern or negative most years for females, and it was negative for males in 2015, 2017, and 2018. Indicator $L_{meanC}/L_{F=M}$, for maximum sustainable yield, was mostly positive through the time series for females and males. Limited availability of age data prevented LBI calculations from 2004 to 2010, and from 2019 to 2022.

Table IV. 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.

Sex	Year	Conservation				Optimal yield	MSY
		L_C / L50	$L_{25\%}$ / L50	$L_{max5\%}$ / L_{Inf}	P_{mega}	L_{meanC} / L_{Opt}	L_{meanC} / $L_{F=M}$
		>1	>1	>0.8	>0.3	≈1	≥1
	2003	0.82	0.96	1.08	0.51	1.17	1.16
	2004	0.69	0.83				
	2005	0.63	0.76				
	2006	0.88	0.97				
	2007	1.01	1.05				
	2008	1.14	1.19				
	2009	0.62	0.80				
	2010	0.77	0.91				
F	2011	1.12	0.98	0.82	0.07	0.99	0.97
	2012	0.63	0.77	0.73	0.02	0.74	1.06
	2013	0.95	1.00	0.75	0.03	0.85	1.00
	2014	1.23	1.18	0.85	0.20	1.05	0.99
	2015	0.62	0.73	0.99	0.41	0.93	1.21
	2016	0.68	0.79	0.97	0.24	0.90	1.13
	2017	0.69	0.79	0.85	0.09	0.81	1.06
	2018	0.64	0.75	0.82	0.07	0.78	1.09
	2019	0.75	0.91				
	2020	0.76	0.76				
	2021	0.65	0.71				
	2022	0.71	0.76				

Sex	Year	Conservation				Optimal yield	MSY
		L_C / L50	$L_{25\%}$ / L50	$L_{max5\%}$ / L_{Inf}	P_{mega}	L_{meanC} / L_{Opt}	L_{meanC} / $L_{F=M}$
		>1	>1	>0.8	>0.3	≈1	≥1
	2003	0.68	0.72	0.79	0.05	0.79	0.96
	2004	0.61	0.70				
	2005	0.60	0.64				
	2006	0.79	0.83				
	2007	0.91	0.98				
	2008	1.03	0.99				
	2009	0.56	0.69				
	2010	0.66	0.75				
M	2011	0.52	0.74	1.14	0.50	1.12	1.37
	2012	0.59	0.72	0.90	0.24	0.87	1.13
	2013	0.61	0.89	0.78	0.08	0.83	1.16
	2014	0.72	0.82	0.88	0.28	0.99	1.19
	2015	0.59	0.64	0.95	0.23	0.81	1.05
	2016	0.64	0.68	1.00	0.21	0.88	1.07
	2017	0.64	0.68	0.85	0.06	0.75	0.93
	2018	0.59	0.64	0.80	0.05	0.67	0.93
	2019	0.65	0.75				
	2020	0.71	0.71				
	2021	0.62	0.67				
	2022	0.69	0.69				

Length-age relationship

The likelihood ratio test found statistically significant difference in von Bertalanffy growth models between males in the finfish fishery and males in the calamari fishery ($X^2_{(3,\, n = 1{,}789)}$ = 10.56, p = 0.014). However, there was no statistically significant difference between females in the finfish fishery and females in the calamari fishery ($X^2_{(3,\, n = 1{,}983)}$ = 5.39, p = 0.145). There was statistically significant difference in von Bertalanffy growth models between females and males in the calamari fishery ($X^2_{(3,\, n = 1{,}110)}$ = 10.02, p = 0.018) but not in the finfish fishery ($X^2_{(3,\, n = 2{,}662)}$ = 0.84, p = 0.840). Given the sexual dimorphism of rock cod, von Bertalanffy growth model outputs are presented for females and males pooled, and separately, for each fishery (Table V; Appendix IX). Yearly von Bertalanffy parameters are summarized in Appendix X. Asymptotic lengths (L_{Inf}) had a statistically significant change for females but not for males from 2003 to 2018; however, there was a data gap from 2004 to 2010 (Fig. 7).

Table V. Rock cod von Bertalanffy growth model outputs. L_{Inf} = asymptotic length, K = curvature, t_0 = age of fish at length zero, N = Number of samples.

	Finfish fishery			Calamari fishery		
Parameter	Females	Males	Pooled	Females	Males	Pooled
L_{Inf}	40.48	38.94	39.80	42.82	40.58	42.15
K	0.2148	0.2423	0.2260	0.1566	0.1677	0.1581
t_0	-0.811	-0.7400	-0.7921	-1.4584	-1.4700	-1.4944
N	1,422	1,240	2,662	561	549	1,110
Length (cm), range	7–44	8–44	7–44	8–41	7–40	7–41
Age (years), range	0–17	0–14	0–17	0–15	0–13	0–15

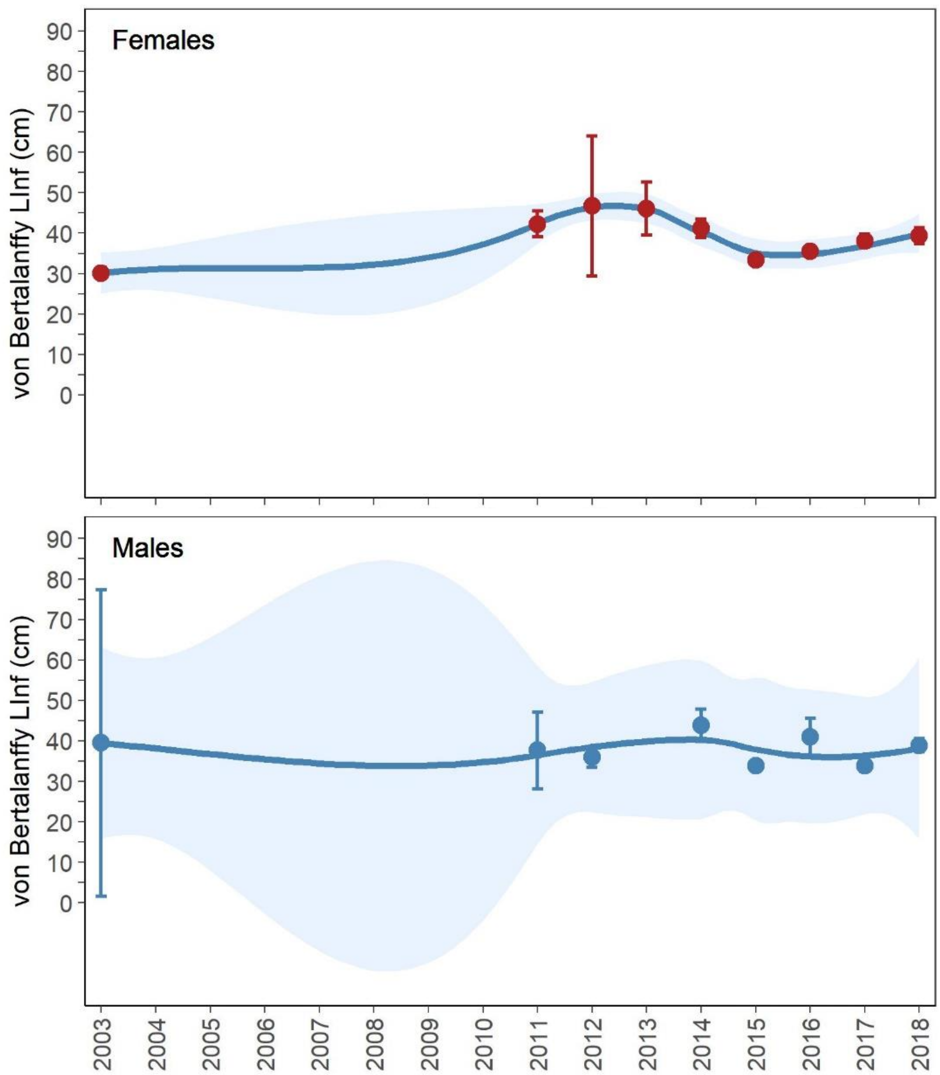

Fig. 7. Asymptotic lengths (L_{Inf}) ± 1 standard error calculated according to the von Bertalanffy growth function for female (red dots) and male (blue dots) rock cod caught by finfish (A–, G–, and W–licences) and experimental (E–licence) licences with fishing activity at the north and west in the FICZ through the year, from 2011 through 2018, with LOESS smooths ± 95% confidence intervals (LOESS; LOESS; span = 0.75, C.I. = 0.95).

Length at 50% maturity

Length at 50% maturity (L50) of females ranged from 17.7 cm in 2012 to 23.7 cm in 2005 in the finfish fishery (Appendixes XI–XII), and from 14.9 cm in 2007 to 24.7 cm in 2009 in the calamari fishery (Appendixes XIII–XIV). Length at 50% maturity of males ranged from 18.1 cm in 2022 to 26.7 cm in 2005 in the finfish fishery, and from 17.4 cm in 2019 to 27.0 cm in 2009 in the calamari fishery. Only males had statistically significant declining trends in L50 from 2003 to 2022 (Fig. 8).

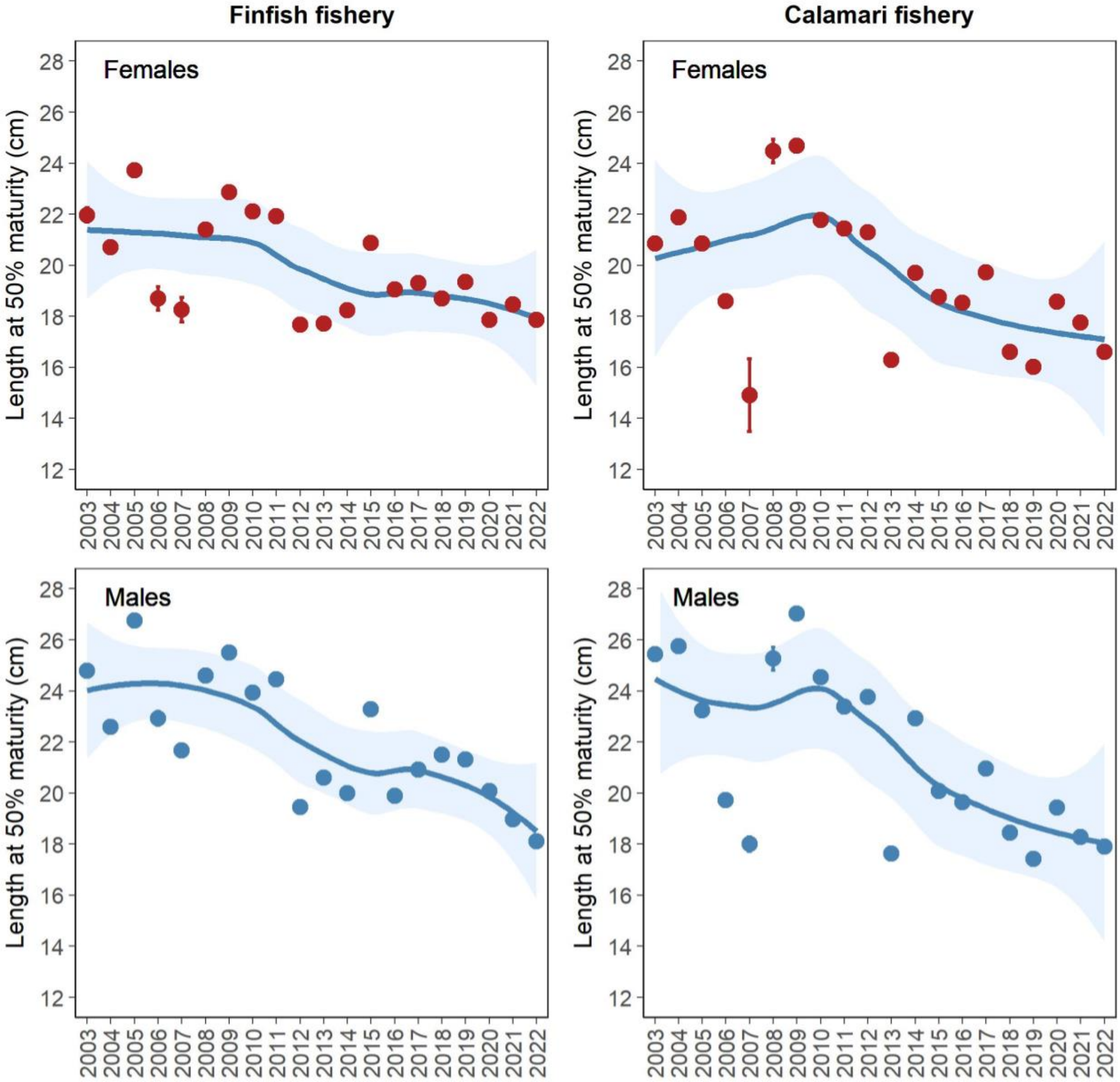

Fig. 8. Lengths at 50% maturity (L50) ± 1 standard error of female (red dots) and male (blue dots) rock cod in the finfish fishery (A–, G–, and W–licences + experimental E–licence in the finfish area) and in the calamari fishery (C–, and X–licence + experimental E–licence in the 'Loligo Box'), 2003 to 2022, with LOESS smooths ± 95% confidence intervals (LOESS; span = 0.75, C.I. = 0.95).

Length frequency distribution

Overall, larger individuals were more frequently caught in the finfish fishery compared with the calamari fishery (Fig. 9).

In the finfish fishery, female rock cod were caught in the range of sizes from 2 cm to 43 cm, and males ranged from 6 cm to 42 cm. Females and males were characterized by a few length-groups not distinguishable due to size overlap, and had similar patterns in the length frequency distributions. Increase in modal length was observed from 2003 to 2008, from 2009 to 2015, from 2016 to 2019, and from 2020 to 2022 (Fig. 9). These periodic increases and resets in modal length are likely due to the presence of new length-groups and due to the removal of large individuals by the fishery. Female rock cod were mostly caught at sizes larger than L50 in 16 out of the 20 years examined from 2003 to 2022, and males were mostly caught at sizes larger than L50 in 9 out of the 20 years examined (Fig. 9).

In the calamari fishery, female rock cod were in the range of sizes from 5 cm to 41 cm, and males ranged from 1 cm to 39 cm. 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. Increase in modal length was observed from 2003 to 2008, from 2009 to 2014, from 2015 to 2019, and from 2020 to 2022 (Fig. 10). These periodic increases and resets in modal length are likely due to the presence of new length-groups and due to the removal of large individuals by the fishery. Female rock cod were mostly caught at sizes larger than L50 in 2 out of the 20 years examined from 2003 to 2022 (10%), and males were mostly caught at sizes larger than L50 in only 5% of the years examined (Fig. 10). The number of individuals sampled for length frequency in the finfish and in the calamari fisheries are indicated in Appendix XV.

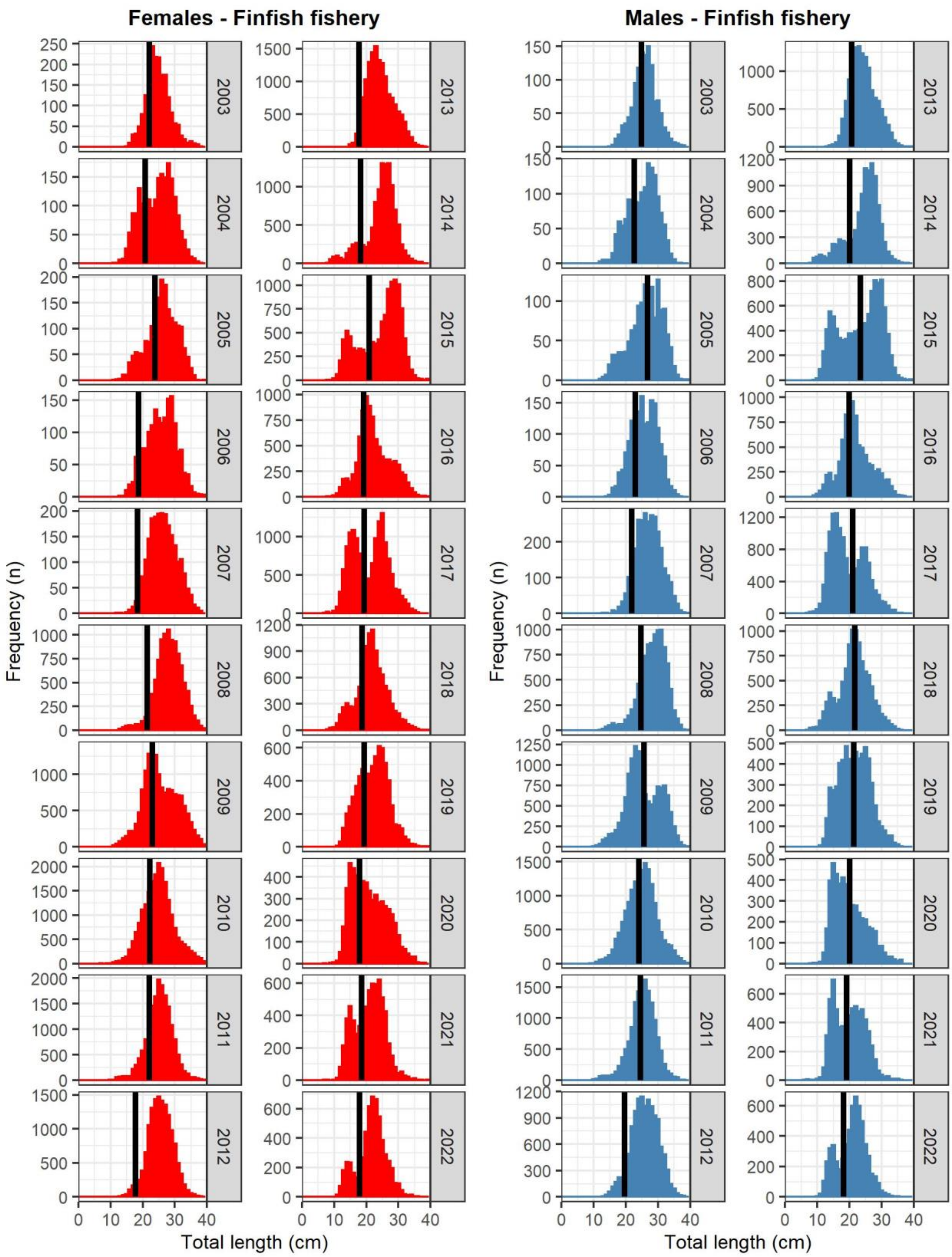

Fig. 9. Length frequency distribution of female and male rock cod in Falkland Islands finfish fishery (A–, G–, W–licences, and experimental E–licence in the finfish area). The black vertical line indicates length at 50% maturity.

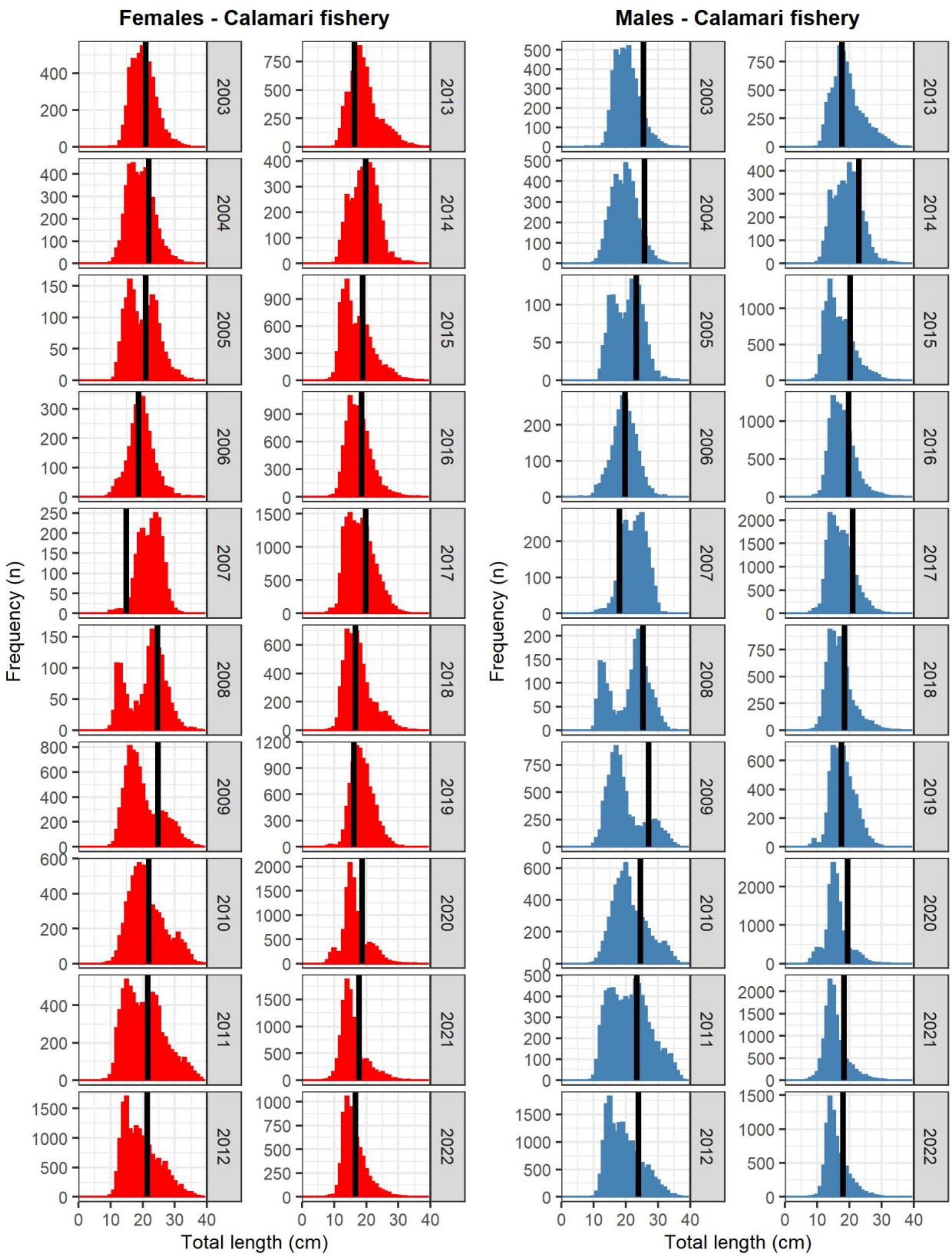

Fig. 10. Length frequency distribution of female and male rock cod in Falkland Islands calamari fishery (C–, X–licences, and experimental E–licence in the 'Loligo Box'). The black vertical line indicates length at 50% maturity.

Conclusions

Length-based indicators suggest that MSY was positive most years from 2011 to 2018. Conservation of immature individuals was negative most years, and conservation of large individuals was mainly of concern for males. Conservation of mega-spawners was mainly negative or of concern, possibly due to changes in recruitment or changes in the fishery no longer targeting rock cod. Weak scores on optimal yield and the negative trends in L50, with smaller and lighter spawners likely producing fewer eggs (Koops et al. 2004; Brickle et al. 2006a), suggest that rock cod productivity has not been maintained.

LBI appears to be appropriate to assess rock cod, as it was found to perform better for long-lived species with low individual growth rates such as this species (e.g., see Brickle et al. 2006b), and when implementing fishery-dependent indicators than fishery-independent indicators (Kell et al. 2022). LBI was also found to be useful at indicating trends rather than at quantifying exploitation level; for instance, performance can vary depending on whether the stock was being overfished or recovering (Kell et al. 2022). Rock cod was overfished in recent years (Winter 2020) and despite currently not being targeted in the FICZ, low abundances calculated in recent years and negative biological trends (e.g., declining trends in L50) suggest that this stock is in poor state.

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, most rock cod bycatch is currently in the calamari fishery (C–, and X–licences), and small individuals (<25 cm) are still being caught in high proportions compared with larger individuals, as revealed by the length frequency distribution per fishery described in this study. Moreover, small individuals have not reached sexual maturity (Brickle et al. 2006a) and are mostly discarded.

The proportion of rock cod discards by Falkland Islands fisheries increased year after year with the shift of rock cod being targeted by the finfish fishery to being mainly caught as bycatch in the calamari fishery. 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 a channel of opportunities to make use of the bycatch that otherwise would be discarded dead.

Annual CPUE calculated from commercial fishery data suggests that the abundance of rock cod in Falkland Islands waters has remained at low levels since 2016. The CPUE decrease of rock cod is concurrent with the CPUE increase of common hake (*Merluccius hubbsi*) (Ramos & Winter 2022b), 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. However, biomass estimates from the fisheries independent February scientific surveys followed a similar pattern to commercial CPUE, with a decline in abundance from 2010 to 2023 but a slight increase in abundance in 2021 and in 2022 from the previous year. This pattern is consistent with the biomass estimates from the July scientific surveys that suggest a decline in abundance from 2017 to 2020, followed by an increase in 2022.

The multiple analyses used in this study suggest that the rock cod stock is in poor state with respect to conservation criteria. Accurate reporting of the commercial bycatch 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 for 2024 of 1,519 t.

Recommendations

Rock cod age data is limited and prevents calculations of L_{Inf} for several years, required for LBI. More age data should be provided from 2004 to 2010, and from 2019 to 2022; revision of rock cod age data currently available in the FIFD database is also required for 2003, 2012, and 2013.

The accuracy of rock cod bycatch reporting has been questioned by FIFD observers and scientists. Rock cod bycatch reporting may depend circumstantially on how much rock cod is being caught and whether it risks triggering a move-on rule.

Calamari licence (C–, and –X licences) conditions should include rock cod in the definition of bycatch, which would implicate a move-on rule or spatio-temporal closure in this fishery.

Conservation measures options should be discussed at FIFD and implemented for the conservation of immature rock cod.

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Appendix

Appendix I. Target fishery inference at date before July 2007. Developed and implemented by Alex Blake, FIFD.

Prior to July 2007, fishing licences used were not routinely reported to FIFD. Whilst vessels generally only had one active licence, there were occasions when vessels had multiple licences available, which prevents comparability of catch data by licence, and therefore, by fishery before and after July 2007. Therefore, a method was originally implemented in MS Access, linked to SQL Server FishDev Database (AVB procedure), where licences were not recorded as part of the Daily Report between 1990 and June 2007. The only information available is from the licence database, which records the licences that each vessel had. Target fishery inference (equivalent to assigning the licence that was most likely used) before July 2007 was previously performed by using a script that loops through records with null licence entry, and on each loop it would append licence in the following order:

1) O licence was assigned to vessels with effort type out of the FOCZ,
2) B licence was assigned to jiggers,
3) L licence was assigned to longliners,
4) Vessels with a single licence were assigned that licence,
5) E licence was assigned to vessels with multiple licences, including experimental E licence,
6) C/X licence was assigned to vessels with multiple licences, including C/X licence, depending on the date the fishing season was opened,
7) B licence was assigned to vessels other than jiggers with multiple licences, including B licence,
8) G licence was assigned to vessels with multiple licences, including G licence,
9) A/Z licence was assigned to vessels with multiple licences, including A/Z licence (all Finfish first/second season),
10) F/R licence was assigned to vessels with multiple licences, including F/R licence (Rays first/second season),
11) S licence was assigned to vessels with multiple licences, including S licence (all Finfish first/second season),
12) W/Y licence was assigned to vessels with multiple licences, including W/Y licences (restricted Finfish first/second season).

However, this approach is considered simplistic in that it only infers the licence used based on the order of catch value, and was therefore improved in R programming language (R Core Team 2021) due to the capabilities of R, which allowed examining multiple factors at the same time. There are 263,206 daily reports where fishing is indicated but licence was not recorded. Licence at day was assigned using the following criteria in a hierarchical order:

1) Licence was assigned where vessels only had one active licence (n = 256,983 daily reports); this included all the jiggers, and left 6,223 fishing days without a licence,
2) E licence was assigned if a vessel had E licence (240 daily reports),
3) B licence was assigned if the vessel was in a combination of ‘Trawl and Jig Time’ unit effort type, and jigging effort >0 (93 daily reports),
4) C/X licence was assigned depending on the fishing season if the vessel had C/X licence, and with catch report grid corresponding to the ‘Loligo Box’ (2,909 daily reports),

5) C/X licence was assigned if the vessel had C/X licence and the maximum catch was *Doryteuthis gahi*, reported in grid squares that are adjacent to the 'Loligo Box' (75 daily reports),
6) F/R licence was assigned if the vessel had F/R licence and caught >40% skate (25 daily reports),
7) B licence was assigned if a vessel had B licence and the maximum catch was *Illex argentinus* (417 daily reports),
8) G licence was assigned if a vessel had G licence and the maximum catch was *I. argentinus* (132 daily reports),
9) A/Y licence was assigned if a vessel had A/Y licence and the maximum catch was hake (219/15 daily reports, respectively),
10) W/Z licence was assigned if a vessel had W/Z licence and the maximum catch was restricted to finfish (1,189/157 daily reports, respectively),
11) At this point there were a significant number of reports where the predominant catch was restricted finfish. However, no W licence was available and G licence was inferred, which allowed restricted finfish to be caught.
12) There were three daily reports where the vessel was fishing but had no catch, in these cases the licence was assigned to match the licence used in the previous and following day (which were the same),
13) Following the previous checks, a number of catch reports had eliminated some possible licences and the one remaining licence was assigned irrespective of the catch; these were A/Y licences where the predominant catch was not hake (186 daily reports),
14) There were four daily reports where the vessel had B and G licences, and the predominant catch was restricted finfish (G licence). Two vessels assumed to be fishing pelagically were inferred to be using B licence based on the knowledge of the vessels fishing pelagically for *Illex*, these vessels nevertheless obtained significant catches of *Micromesistius australis*.
15) At this point no vessel had more than two active licences; therefore, if a vessel had a B or G licence but did not catch *I. argentinus*, then the other active licence was assigned (A/Y, W/Z) (167 daily reports),
16) There were 20 daily reports remaining, with the predominant catch not covered by an available licence. For these records, the highest catch on an available licence was calculated, and that licence applied:

Major catch	Licence available	Number daily
Hake	W/Z, and B/G	8
Loligo	A/Y, B/G, and W/Z	11
RAY	A/Y, B/G, and W/Z	1

Differences between the VBA procedure and the R procedure:

The R procedure takes into account mainly the catch, and also the location of C/X licences.

Overall, there are 2,364 daily records that are different between the two data sets. The biggest difference between the two data sets is that 15,402 tonnes total catch that were assigned to B licence under the VBA procedure are assigned to W licence under the R procedure. A total of 910 daily reports, of which 897 were from trawlers and 13 were from vessels under a combination of licences with trawl time but no jig time, have higher finfish catches than *I. argentinus*; overall, the licences caught 13,369 tonnes of restricted finfish against 1,065 tonnes of *I. argentinus*.

The next largest change is that 12,356 tonnes (total catch) that were assigned to G licence under the VBA procedure, are assigned to A (8,185 tonnes) or W (4,171 tonnes) under the R procedure.

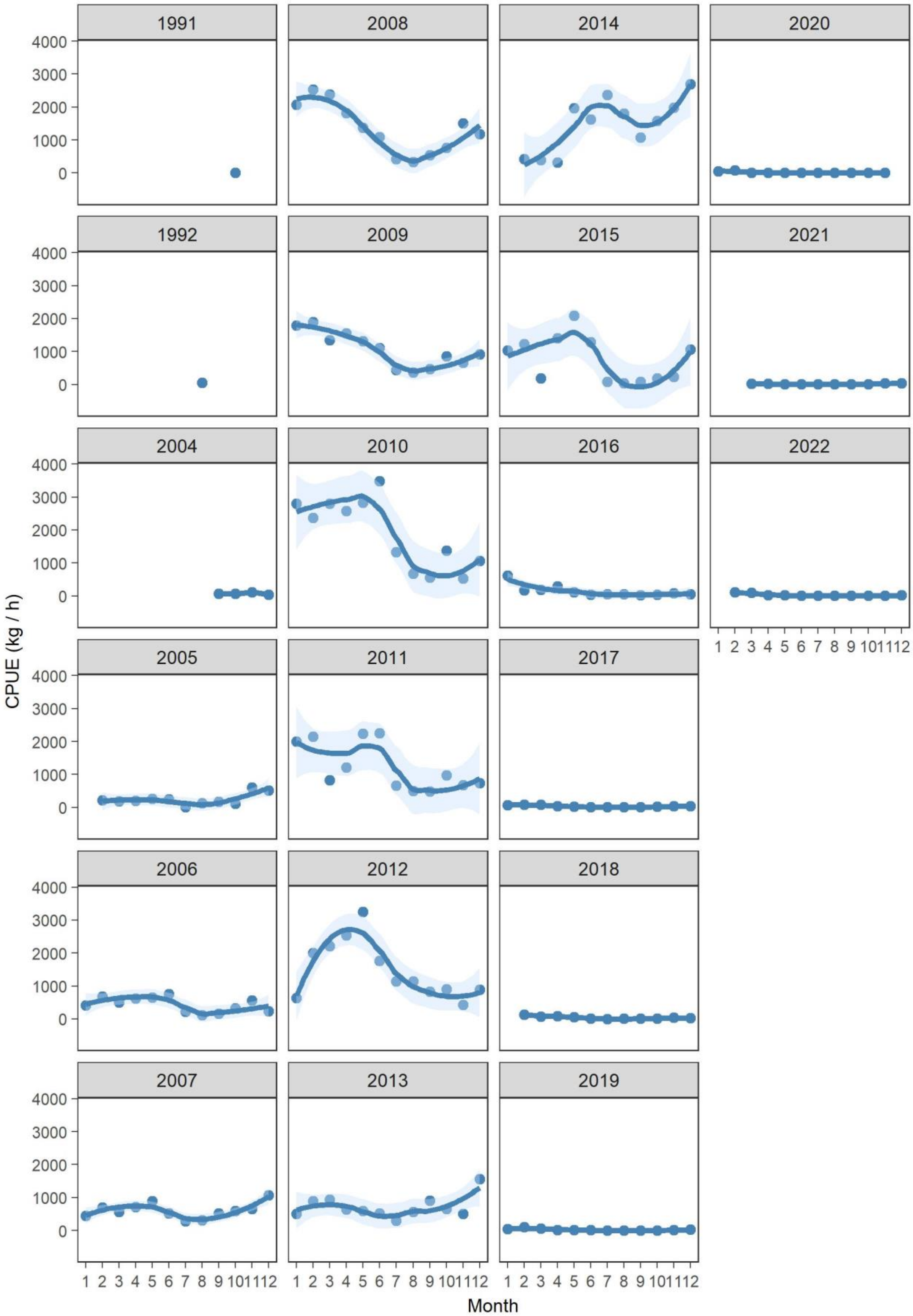
All the differences were recorded in ComparisonLicenceAssigned.csv (Available upon request to Alex Blake, FIFD). The improved approach (R procedure) was implemented from April 2023 to infer licence at day prior to July 2007.

Appendix II. Annual commercial catches (t) of rock cod reported in Falkland Islands (excluding E–licence; Falkland Islands Government[a]; Falkland Islands Government 2023) and Argentina (Argentine Government[b]; Sánchez et al. 2012; Navarro et al. 2014, 2019).

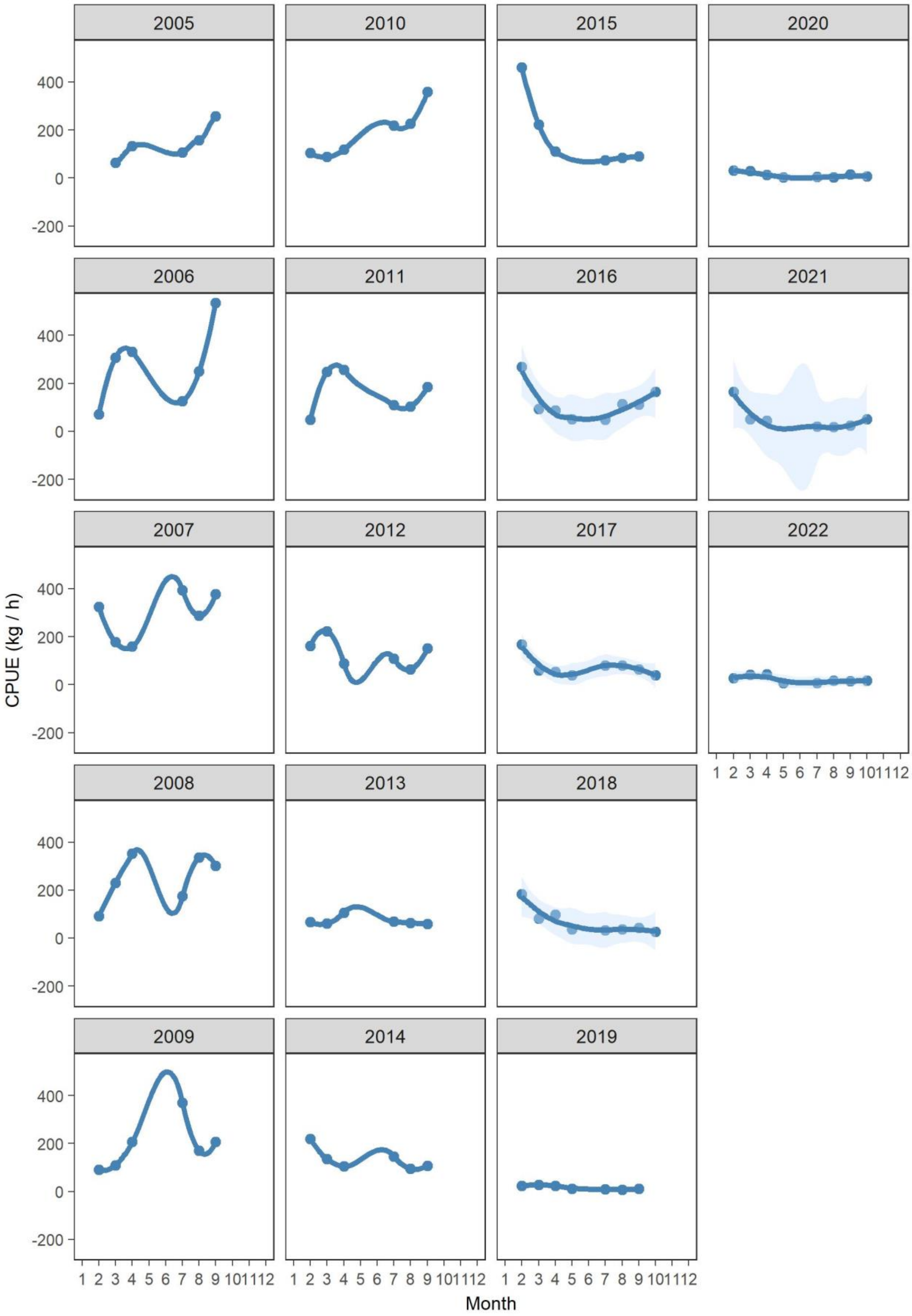
Year	Falkland Islands (t)	Argentina (t)
1987	NA	0.9
1988	NA	0.1
1989	NA	0
1990	NA	0
1991	0.0	0
1992	0.7	0
1993	NA	0
1994	NA	0.1
1995	NA	0
1996	NA	0
1997	NA	0
1998	NA	0
1999	NA	0
2000	NA	0.2
2001	NA	182.8
2002	NA	179.6
2003	2.4	258.8
2004	75.5	468.7
2005	8,438.6	4,169.7
2006	20,768.3	9,842.2
2007	30,028.3	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	1,208.0	3.2
2022	1,213.2	7.5

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

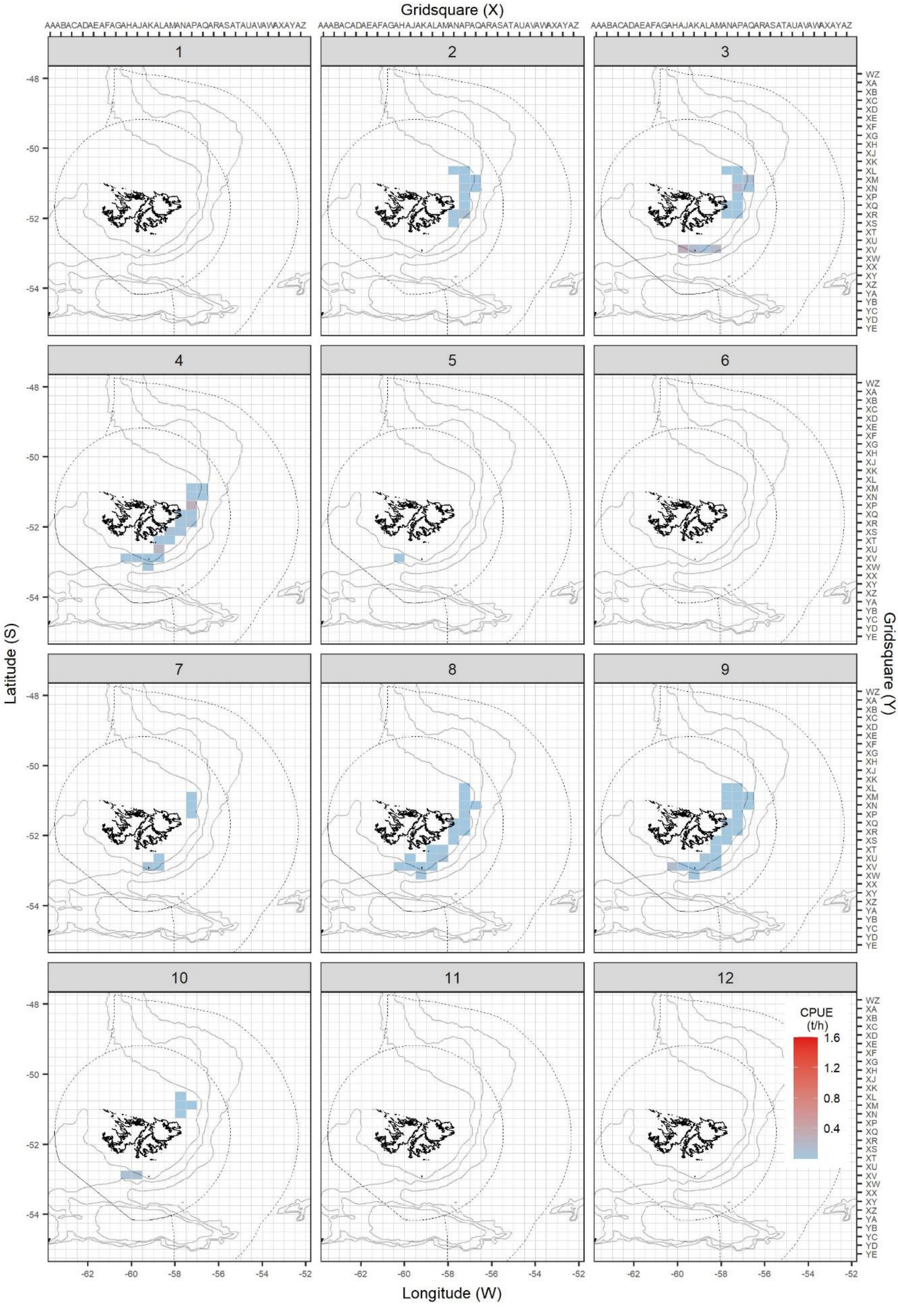
Appendix III. Monthly CPUE of rock cod in the Falkland Islands finfish fishery (A–, G–, and W–licences) from 1991 to 2022, with LOESS smooths ± 95% confidence intervals (LOESS; span = 0.75, C.I. = 0.95).



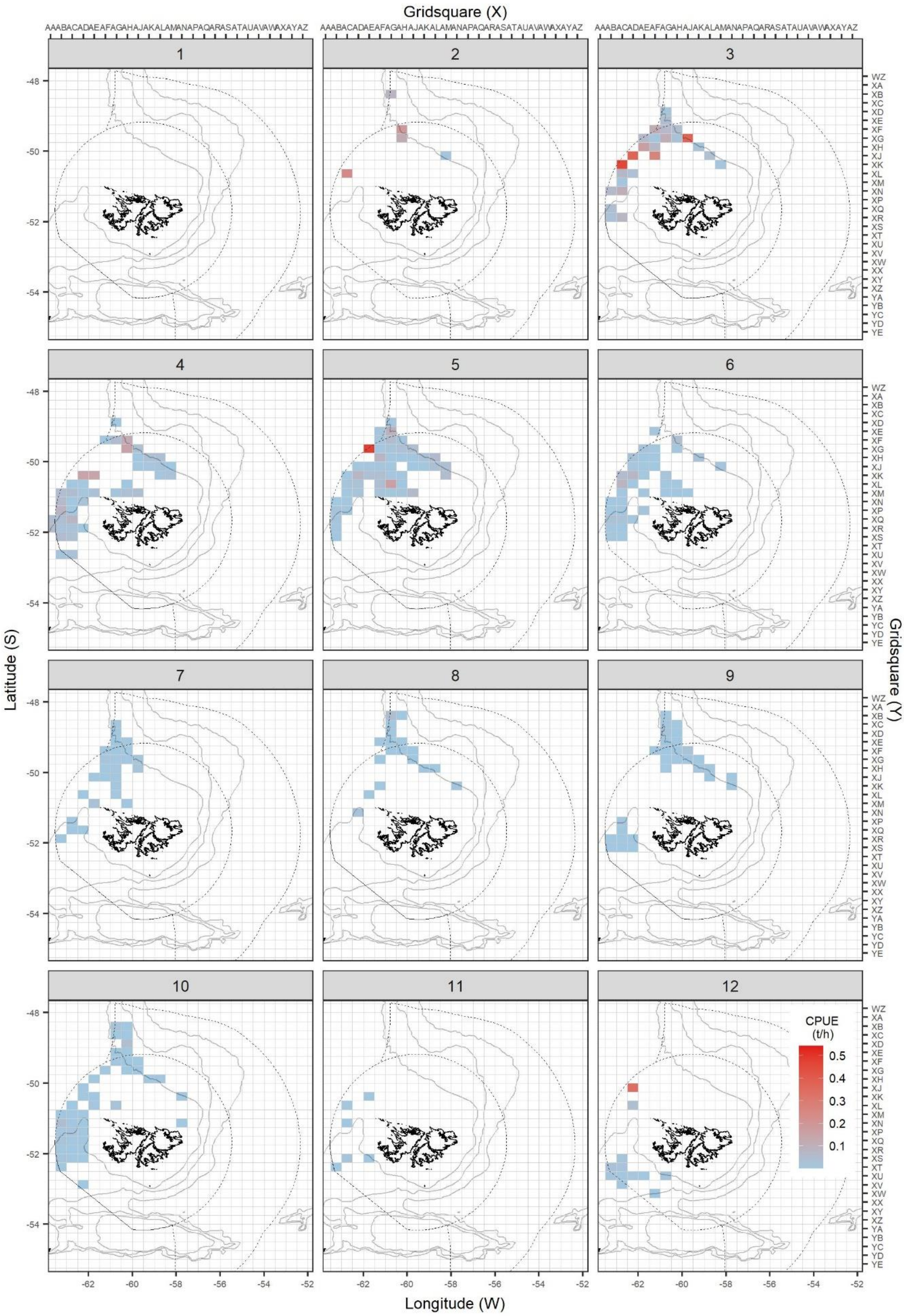
Appendix IV. Monthly CPUE of rock cod in the Falkland Islands calamari fishery (C–, and X– licences) from 1991 to 2022, with LOESS smooths ± 95% confidence intervals (LOESS; span = 0.75, C.I. = 0.95).



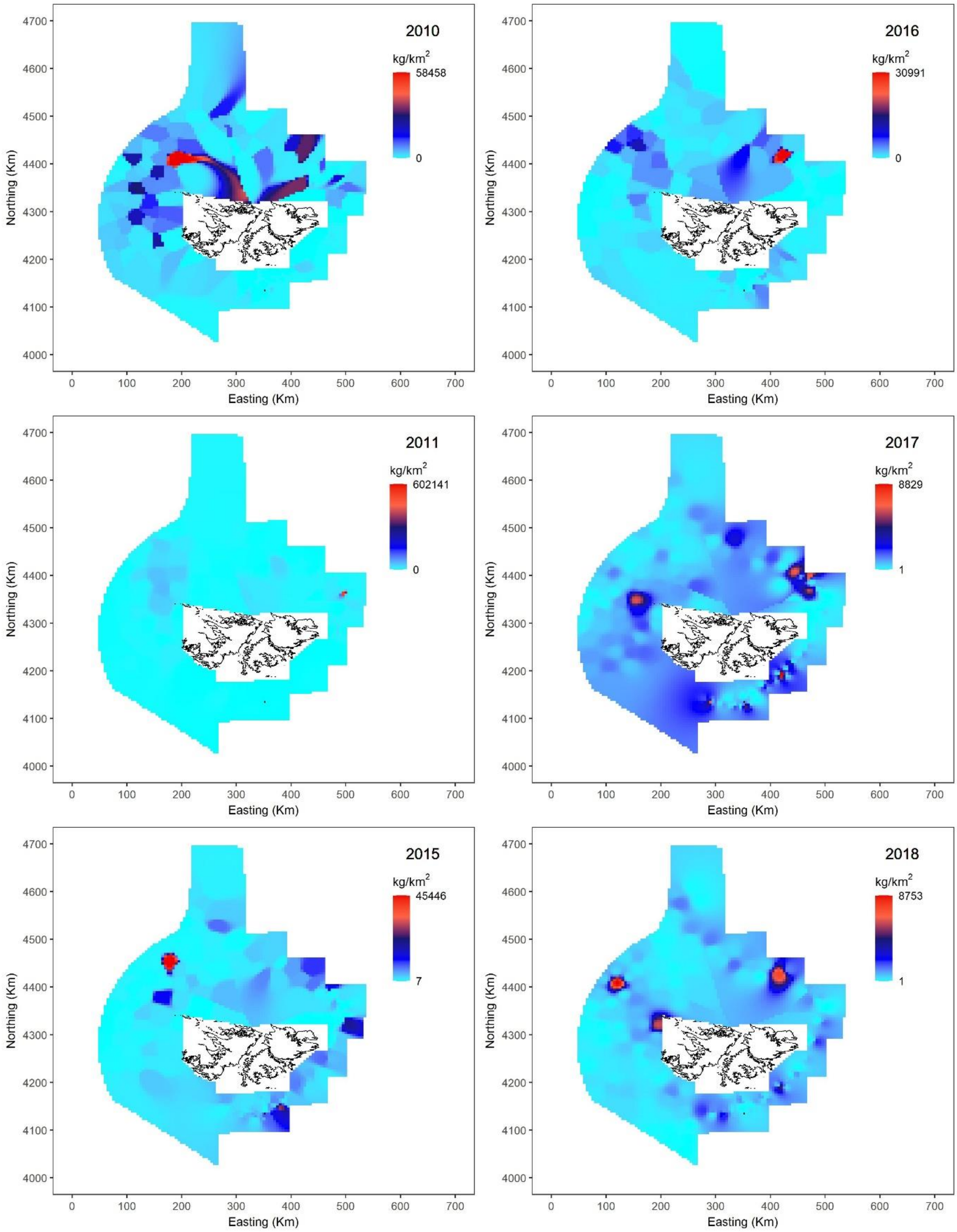
Appendix V. Monthly CPUE of rock cod in the Falkland Islands calamari fishery (C–, and X–licences) during 2022. Note that there was no fishing effort during January, June, November and December under calamari licences.



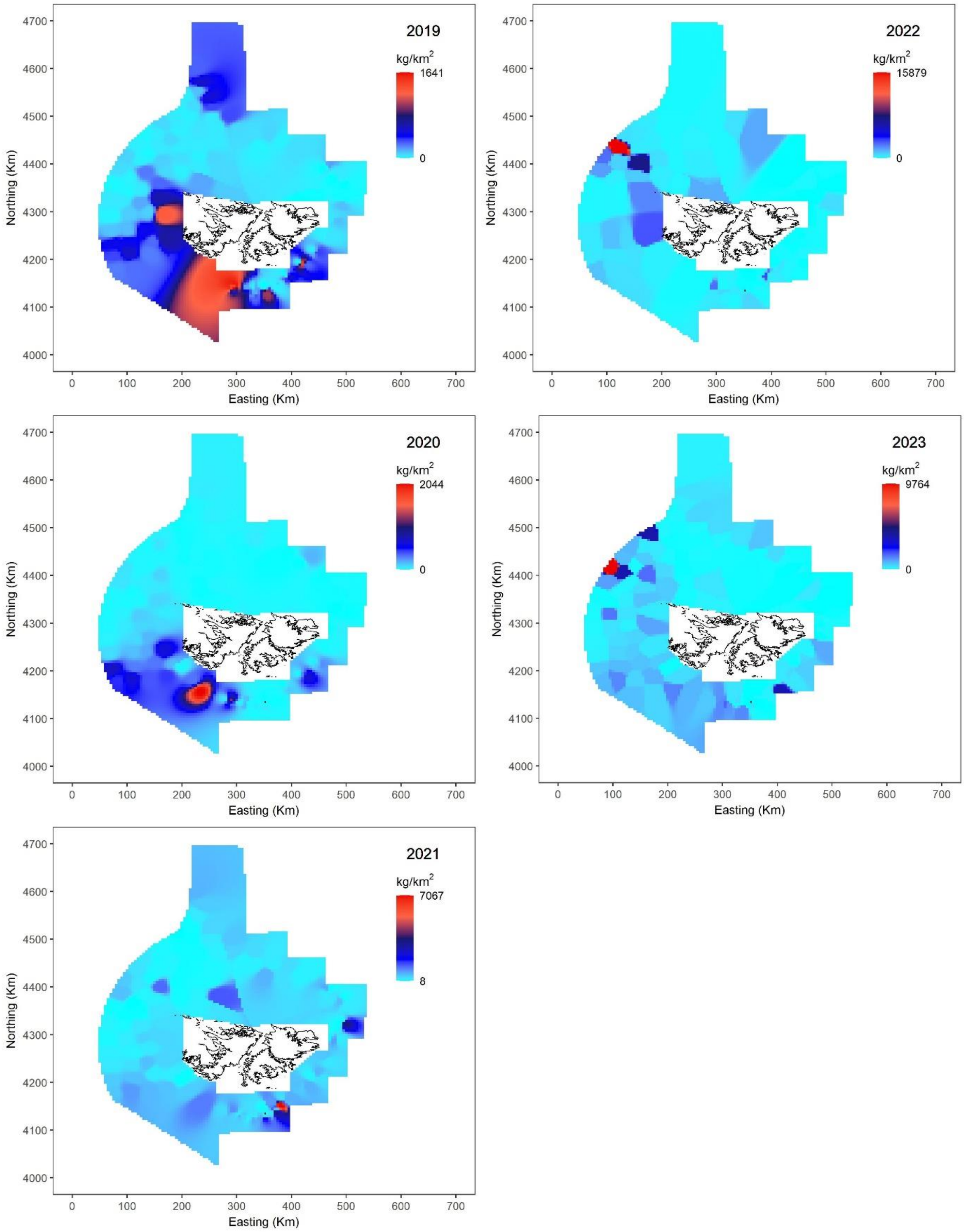
Appendix VI. Monthly CPUE of rock cod in the Falkland Islands finfish fishery (A–, G–, and W–licences) during 2022. Note that there was no fishing effort during January under finfish licences.



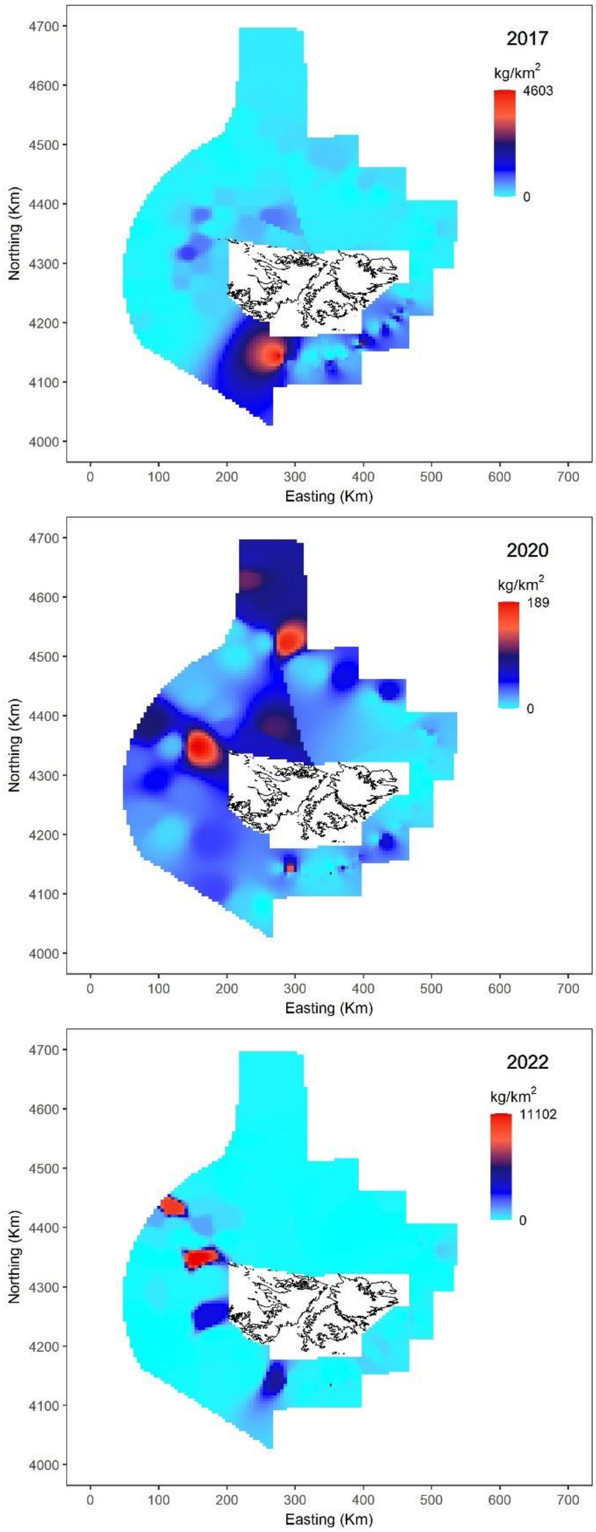
Appendix VII. Densities of rock cod modelled by inverse distance weighting throughout the Falkland Islands fishing zone, during the February 2010–2023 groundfish and pre-season surveys.



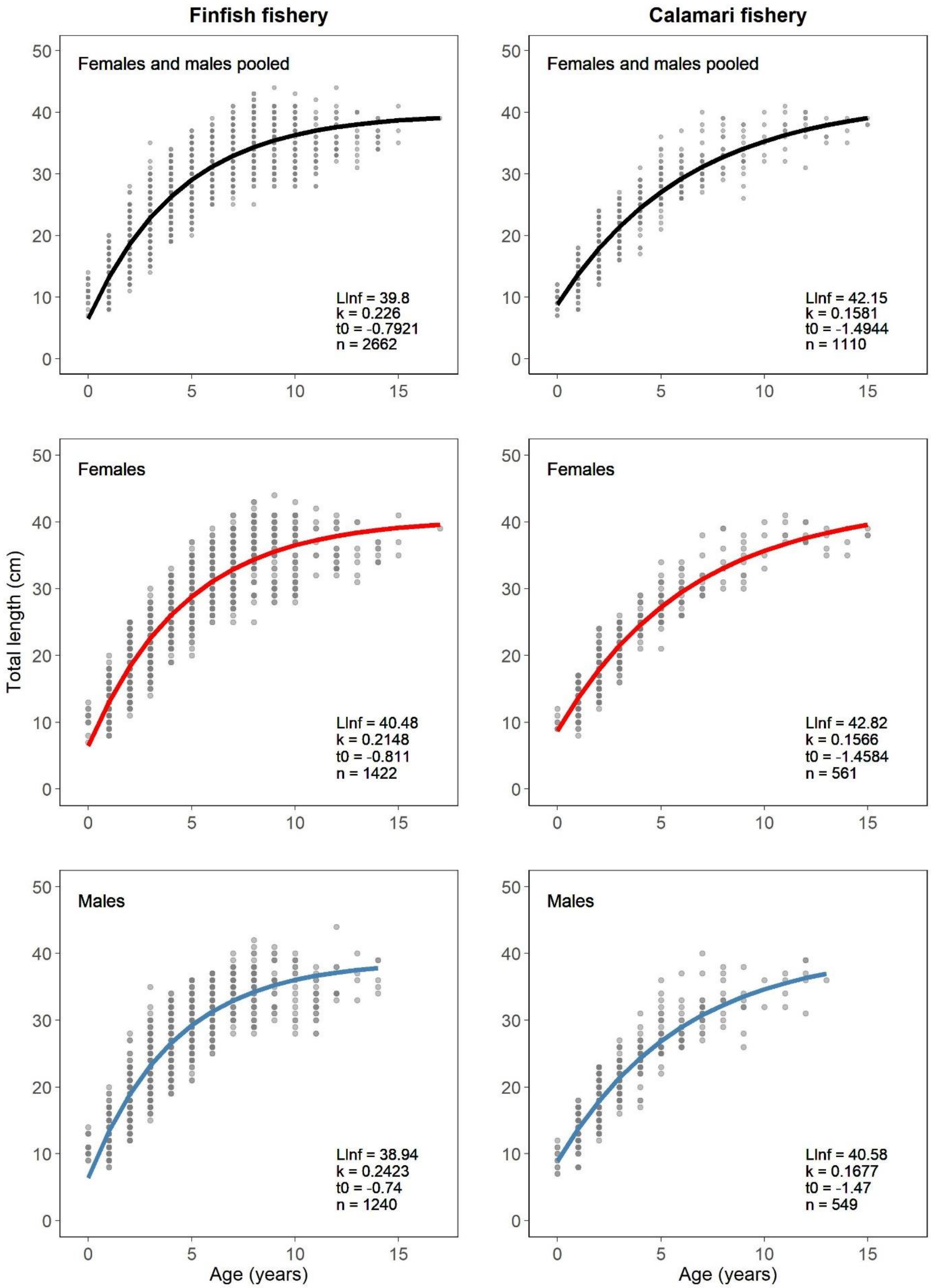
Appendix VII. *continued…*



Appendix VIII. Densities of rock cod modelled by inverse distance weighting throughout the Falkland Islands fishing zone, during the July 2017, July 2020, and July 2022 groundfish and pre-season surveys.



Appendix IX. von Bertalanffy age-length relationship of rock cod collected in the Falkland Islands finfish and calamari fisheries.

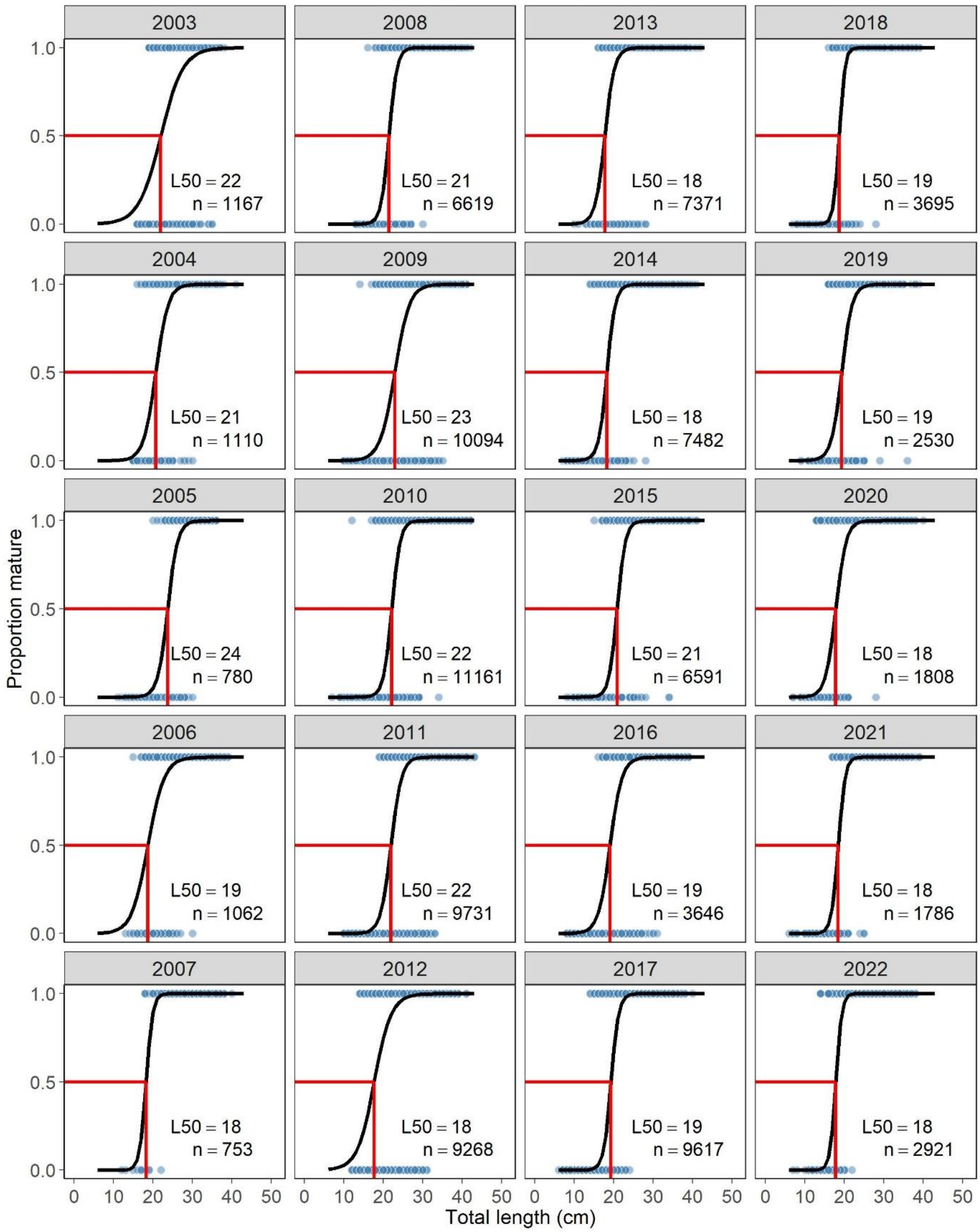


Appendix X. Rock cod von Bertalanffy length-at-age parameters for curvature (K), age of fish at length zero (t_0), and asymptotic length (L_{Inf}), by year and sex, with 95% confidence intervals. Parameters were not calculated for 2005–2007 due to the limited rock cod age data during those years.

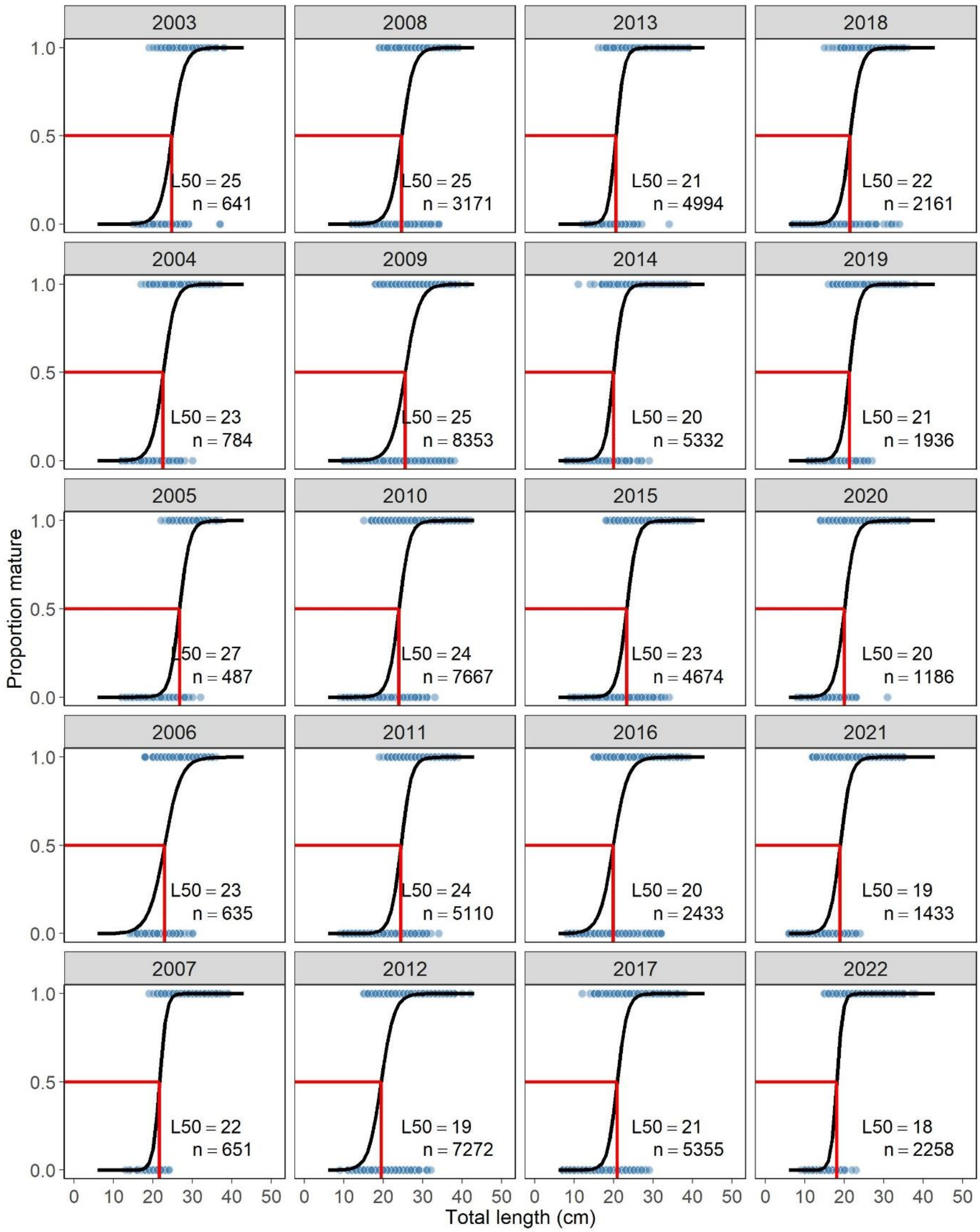
Sex	Year	n	K	t_0 (years)	L_{Inf} (cm)
	2003	61	0.396 (0.22 - 0.58)	-0.334 (-1.98 - 0.44)	30.1 (28.60 - 33.60)
	2011	145	0.164 (0.11 - 0.23)	-1.620 (-2.70 - -0.86)	42.3 (37.60 - 50.30)
	2012	87	0.133 (0.06 - 0.22)	-2.223 (-3.66 - -1.35)	46.7 (38.10 - 74.60)
	2013	43	0.173 (0.09 - 0.26)	-0.115 (-1.53 - 0.69)	46.1 (40.70 - 62.00)
F	2014	88	0.205 (0.15 - 0.26)	-0.496 (-0.91 - -0.19)	41.2 (37.80 - 46.60)
	2015	165	0.407 (0.33 - 0.50)	-0.430 (-0.78 - -0.15)	33.4 (32.00 - 35.20)
	2016	146	0.336 (0.24 - 0.44)	-0.331 (-0.89 - 0.07)	35.5 (33.40 - 38.60)
	2017	163	0.252 (0.19 - 0.32)	-0.212 (-0.66 - 0.14)	38.1 (35.40 - 42.00)
	2018	56	0.245 (0.17 - 0.32)	-0.590 (-1.19 - -0.18)	39.4 (36.40 - 44.30)

Sex	Year	n	K	t_0 (years)	L_{Inf} (cm)
	2003	28	0.117 (0.02 - 0.28)	-3.833 (-8.57 - -1.19)	39.5 (30.70 - 131.10)
	2011	143	0.239 (0.09 - 0.43)	-1.142 (-3.33 - -0.07)	37.6 (32.50 - 55.60)
	2012	69	0.303 (0.18 - 0.44)	-0.832 (-1.78 - -0.25)	35.9 (32.40 - 42.10)
	2013	29	0.014 (0.01 - 0.24)	-4.761 (-5.80 - -0.69)	197.6 (35.10 - 398.30)
M	2014	112	0.214 (0.14 - 0.29)	-0.360 (-0.91 - -0.19)	43.8 (38.60 - 54.00)
	2015	168	0.407 (0.33 - 0.49)	-0.327 (-0.78 - -0.15)	33.9 (32.60 - 35.40)
	2016	142	0.224 (0.14 - 0.32)	-0.696 (-0.89 - 0.07)	40.9 (36.10 - 51.30)
	2017	146	0.343 (0.26 - 0.44)	-0.009 (-0.66 - 0.14)	33.8 (31.60 - 36.70)
	2018	52	0.265 (0.21 - 0.33)	-0.860 (-1.19 - -0.18)	38.9 (35.90 - 42.30)

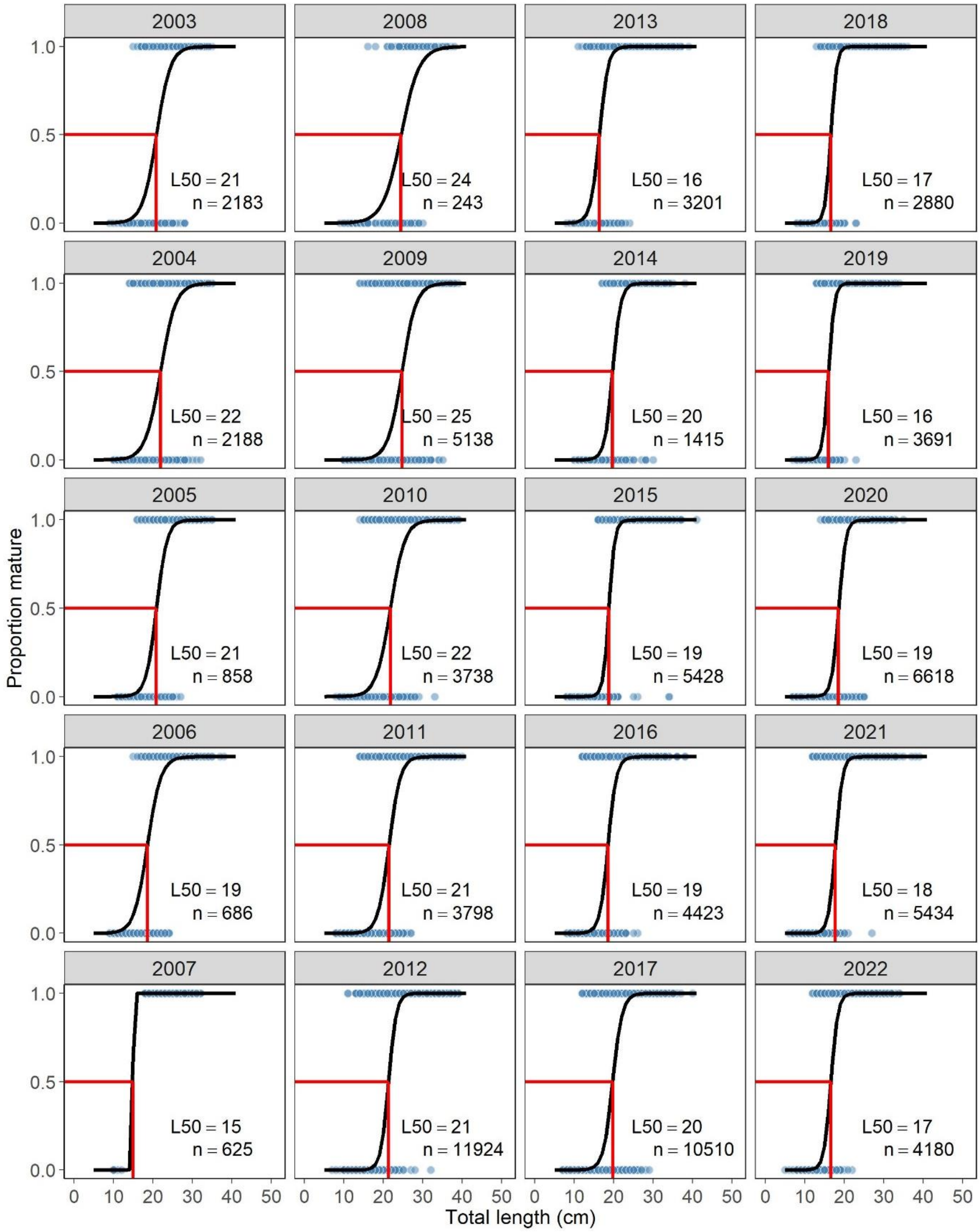
Appendix XI. Binomial logistic regressions of juvenile (0) or adult (1) maturity vs. length for female rock cod in the Falkland Islands finfish fishery (A–, G–, W–licences, and experimental E–licence in the finfish area). The red line indicates the intercept for length at 50% adulthood, corresponding to Fig. 8.



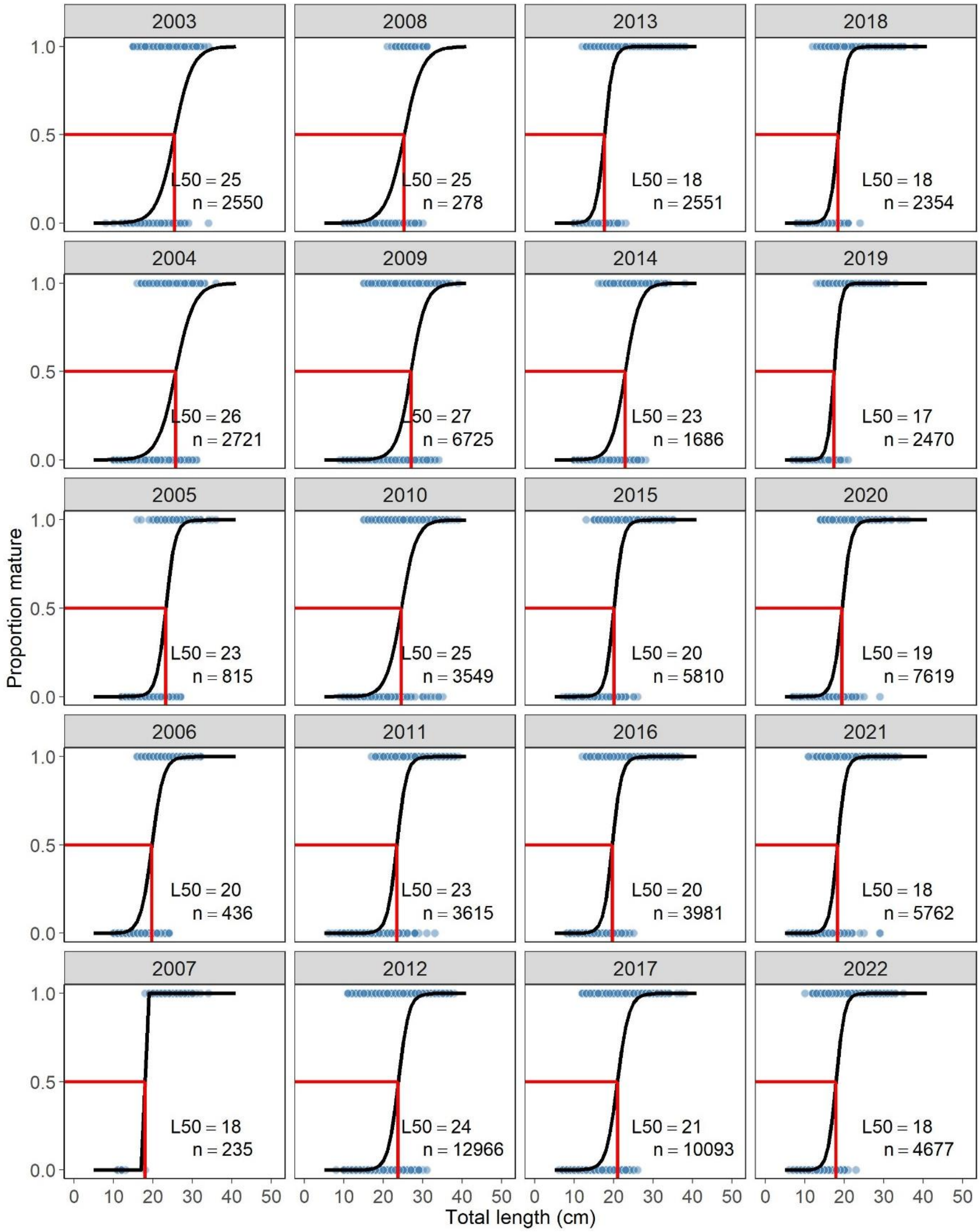
Appendix XII. Binomial logistic regressions of juvenile (0) or adult (1) maturity vs. length for male rock cod in the Falkland Islands finfish fishery (A–, G–, W–licences, and experimental E–licence in the finfish area). The red line indicates the intercept for length at 50% adulthood, corresponding to Fig. 8.



Appendix XIII. Binomial logistic regressions of juvenile (0) or adult (1) maturity vs. length for female rock cod in the Falkland Islands calamari fishery (C–, X–licences, and experimental E–licence in the 'Loligo Box'). The red line indicates the intercept for length at 50% adulthood, corresponding to Fig. 8.



Appendix XIV. Binomial logistic regressions of juvenile (0) or adult (1) maturity vs. length for male rock cod in the Falkland Islands calamari fishery (C–, X–licences, and experimental E–licence in the 'Loligo Box'). The red line indicates the intercept for length at 50% adulthood, corresponding to Fig. 8.



Appendix XV. Number of rock cod individuals sampled for length frequency distributions in the Falkland Islands finfish (A–, G–, W–licences, and experimental E–licence in the finfish area) and calamari (C–, X–licences, and experimental E–licence in the 'Loligo Box') fisheries.

	Finfish fishery		Calamari fishery	
Year	Females (n)	Males (n)	Females (n)	Males (n)
2003	1,901	1,233	5,076	4,795
2004	2,052	1,503	4,665	4,643
2005	1,914	1,446	1,707	1,471
2006	1,717	1,697	2,829	2,371
2007	2,225	2,997	2,266	2,793
2008	10,273	9,864	1,613	2,025
2009	15,660	13,483	8,105	8,392
2010	21,321	16,028	6,823	6,551
2011	17,064	14,517	7,701	7,610
2012	14,123	12,354	17,188	18,287
2013	14,599	12,832	7,880	7,993
2014	11,220	10,084	4,143	4,425
2015	11,870	10,662	9,528	11,316
2016	9,282	9,015	9,116	11,148
2017	14,869	13,447	16,604	19,219
2018	10,520	10,158	6,247	7,521
2019	6,954	6,408	9,262	6,279
2020	5,908	5,107	11,306	14,039
2021	6,918	7,167	10,728	12,721
2022	5,844	5,949	6,716	8,296