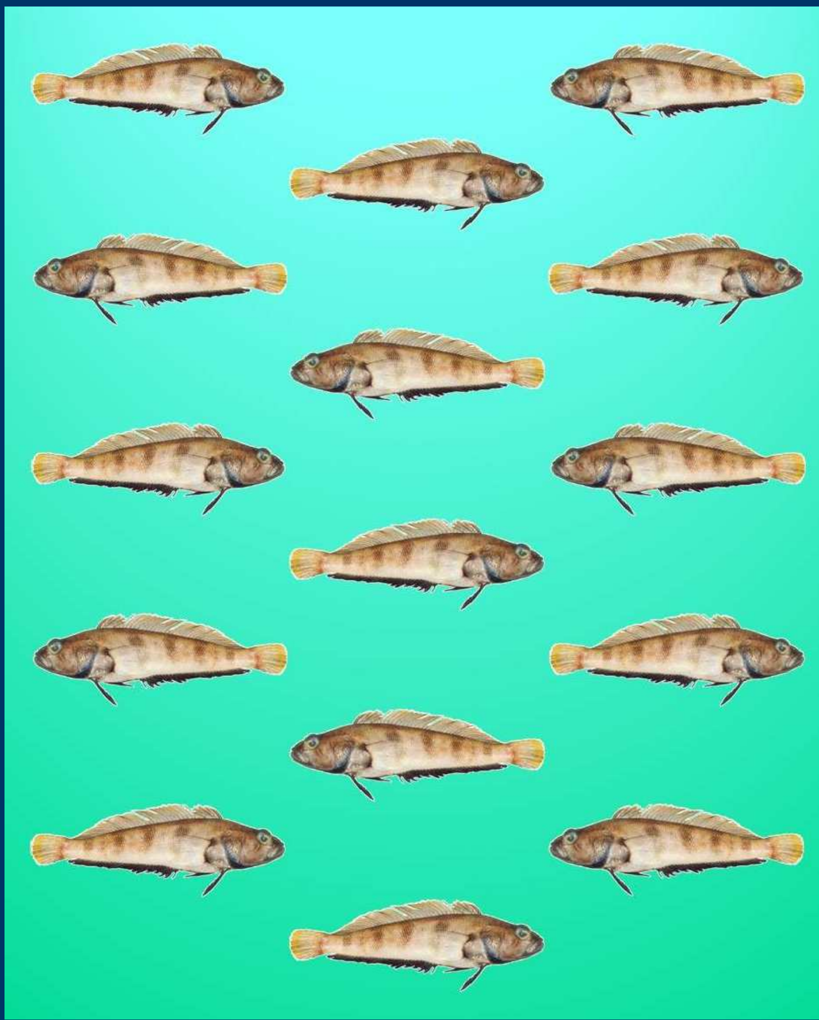
Stock Assessment

Rock Cod

Patagonotothen ramsayi



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Rock cod (*Patagonotothen ramsayi*) stock assessment

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Summary

Annual rock cod commercial catches and survey catches decreased in 2020 for respectively the sixth and fifth straight years. Following recommendations of the MacAlister Elliott & Partners external review, total allowable catch (TAC) calculation was revised according to the ICES category 3 - 2/3 rule for biomass indices, but constrained by a maximum of the average of the last three years' catches. The rock cod TAC for 2022 is accordingly set at 1266.0 tonnes.

Length-based indicators suggest that maximum sustainable yield is being achieved in the current finfish fishery, but conservation outcomes for immature and large rock cods are not clearly positive. Rock cod lengths at 50% adulthood have significantly decreased since about 2000. Median lengths have also decreased, but length distribution sampling in the fishery may be influenced by the recent decline of rock cod to commercial bycatch status.

Introduction

Rock cod *Patagonotothen ramsayi* (Regan) is a medium-sized benthopelagic species inhabiting the shelf edge and upper slope of the Falkland Islands (Brickle et al. 2006a, Laptikhovsky et al. 2013), where part of the total stock migrates mainly in spring and summer (Arkhipkin et al. 2012). Rock cod has long been a major bycatch component of Falkland trawl fisheries (Brickle et al. 2006a, La Mesa et al. 2016), as predators of rock cod are commercially important species such as toothfish, kingclip, hakes, and skates (Arkhipkin et al. 2003, Brickle et al. 2003, Nyegaard et al. 2004, Brickle et al. 2006b). Rock cod are also known to scavenge trawl discards (Laptikhovsky and Arkhipkin 2003), resulting in further overlap with the fisheries.

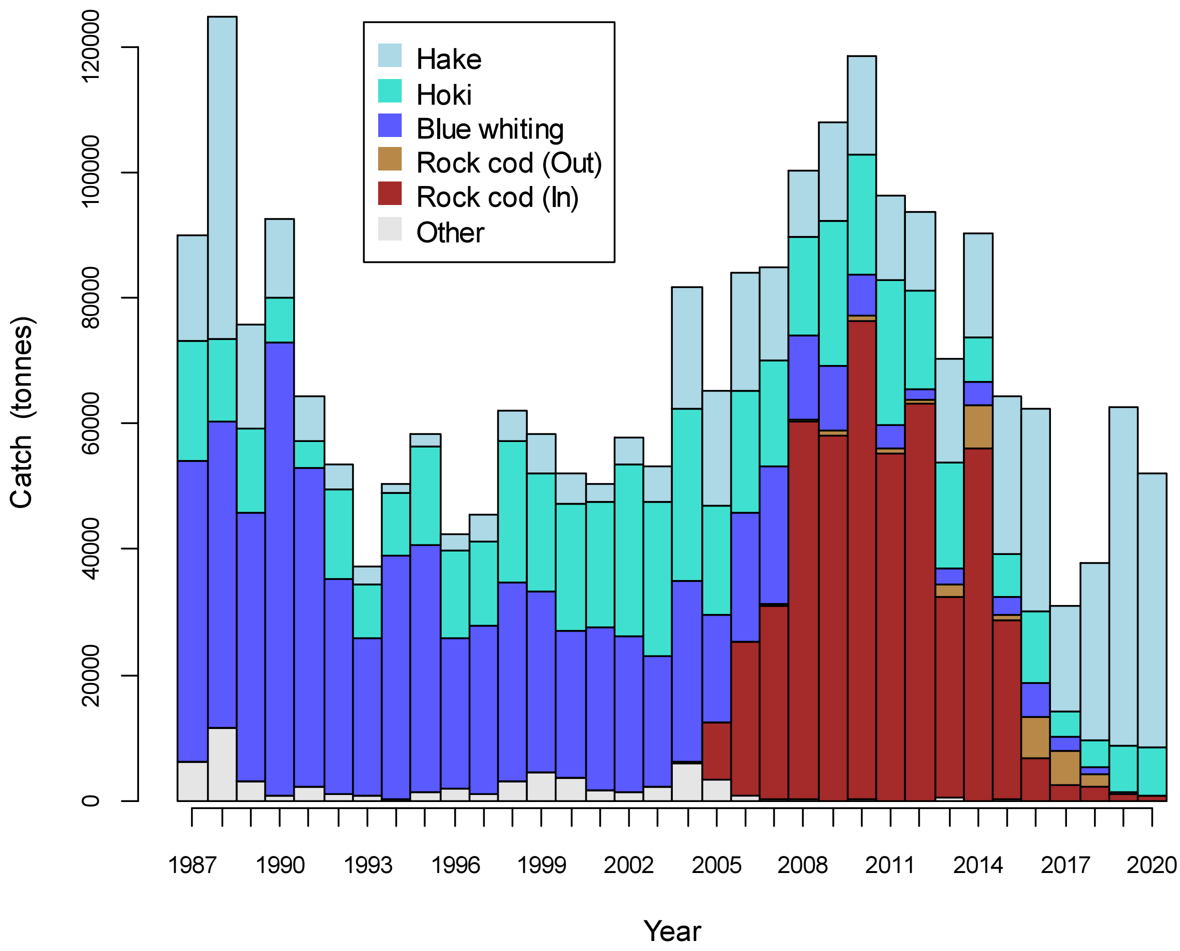


Figure 1. Annual commercial catches of rock cod and other major groundfish target species from FIFD catch reports, since 1987. Category 'other' is catch reported as such; i.e. unidentified species, not a pooled category of identified species. Rock cod (out) are rock cod caught outside the Falkland Islands conservation zones but reported to the FIFD (as required for Falkland-flagged vessels), and entered in the database as licence category "O". Hake, hoki, and blue whiting are totalled irrespective of licence category. Hake includes *Merluccius hubbsi* and the rarer *Merluccius australis*.

A project was funded by the European Union to commercialize rock cod (Brickle et al. 2005), and subsequent market development and redistribution of effort led to a 30-fold increase in catch rates of rock cod in the Falkland Islands fishery (Laptikhovsky et al. 2013). Rock cod catches are normally processed into headed and gutted frozen product. The flesh is white, with a firm, elastic texture and high nutritional value for human consumption (Gonzalez et al., 2007). Rock cod was never commercially reported before 2003, suggesting that this species comprised the bulk of 'other' catches in those years. Between 2006 and 2015 rock cod was the largest quantity of finfish catch in Falkland Islands fisheries, but has since decreased substantially (Figure 1). In a pattern commonly seen in other fisheries (Pauly et al. 1998), the increased use of rock cod had coincided with catch decreases of higher-value species. In 2015, the minimum cod end mesh size for finfish trawls was increased to 110 mm, largely as a measure to mitigate capture of undersized rock cod (Roux and Winter 2013).

Methods

In 2020, rock cod was included in the 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. Rock cod was advised at category 3, as a species for which survey-based assessments provide reliable indications of trends in stock metrics, such as total mortality, recruitment, and biomass (ICES 2018a). Additionally, MEP (2020) recommended that the rock cod category 3 assessment should be supported by a length-distribution method such as the length-based indicator (LBI) (ICES 2015).

Category 3

For category 3 the common assessment method uses a 2/3 rule, in which next year's advised total allowable catch (TAC) is based on trends in 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 last 3 years (MEP 2020). Year-to-year change is further limited to an 'uncertainty cap' of ±20% (ICES 2018a).

The program of parallel February groundfish and calamari pre-season surveys has been run continuously in all years starting 2015, to 2020 (Ramos and Winter 2020). Accordingly the 2/3 rule could be applied for the first time for 2020 as:

$$\text{TAC-3}_{2020} = \text{TAC-5}_{2019} \times \frac{\overline{\text{Surveys}_{2018\text{ to }2019}}}{\overline{\text{Surveys}_{2015\text{ to }2017}}},$$

where:

$$\text{TAC-5}_{2019} = \overline{\text{Catches}_{2016\text{ to }2018}},$$

then:

$$\text{TAC-3}_{2022} = \text{TAC-3}_{2020} \times \frac{\overline{\text{Surveys}_{2019\text{ to }2020}}}{\overline{\text{Surveys}_{2016\text{ to }2018}}}.$$

Note that the year now jumps from 2020 to 2022. Standard procedure is to inform *next* year's allowable catch with data up to the last completed year, i.e., the *previous* year, as licencing advice must be issued while the *current* year is still in progress.

LBI

ICES (2015, 2018b) recommends the LBI method which provides a suite of indicators based on combinations of catch-at-size distributions, life-history parameters L_{Inf}; the asymptotic average maximum body size (Haddon 2001), and L_{Mat}; the length at 50% maturity (Cope and Punt 2009). L_{Inf} and L_{Mat} parameters were assessed for males and females separately as rock cod growth and maturation are sexually dimorphic (Brickle et al. 2006a, 2006b). The proportions of females in each year's length-frequency samples were also examined.

L_{Inf} was calculated from the von Bertalanffy growth function, modelled to rock cod length and age data from the FIFD database with nonlinear least-squares fitting in R package 'fishmethods' (Nelson 2015). Variability of L_{Inf} and the other von Bertalanffy parameters was estimated by bootstrapping. Residuals of the von Bertalanffy model fit were randomly re-sampled with replacement, added back to the expected lengths; these newly generated data were re-fit to the von Bertalanffy function, and the 95% quantiles of 10,000 iterations retained as confidence intervals. Calculations were restricted to rock cod length and age data since 2014, as these data are considered reliable (Lee et al. 2018). Currently the most recent year of available length and age data is 2017, thus four years. Likelihood ratio tests with permutation analysis (Mooij et al. 1999) were run to examine whether L_{Inf} of individual years were significantly different compared to all years pooled[a]. If individual years were different, the linear regression was computed[b], weighted by inverse variance of each year's von Bertalanffy function (Marín-Martínez and Sánchez-Meca 2010), and L_{Inf} linear fit values for LBI parameterization were assigned from the closest year of the data set (i.e., years < 2014 took the 2014 value, years >2017 took the 2017 value). If individual years were not different, combined L_{Inf} of the four years were used.

L_{Mat} 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 stages 1 are always juvenile and stages 3 are always adult (B. Lee, FIFD, personal communication). Therefore, maturity assignment was simplified to a dichotomous classification of juvenile (0 - 1) or adult (3+), omitting stage 2. Rock cod maturities were taken sporadically by FIFD observers starting in 1995, and consistently from 2002. The aggregates of 50% adulthood lengths were plotted against years and trends calculated with LOESS smooths (degree = 2, span = 0.90), also 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.

LBI method indicators were applied to all years from which observer length measurements of rock cod were available and reported as random samples[c]: years 2002 to 2020. Because finfish trawls are restricted to larger meshes than calamari trawls, only

[a] Intermediate levels of pooling would also be computable, e.g., 2 or 3 consecutive years at a time, but it was not deemed relevant to extend the analysis to that level of resolution.

[b] With just four data the linear regressions had low potential for statistical significance, but this was taken into consideration assigning margins of error to the L_{Inf} estimates.

[c] FIFD database codes R and S.

observer length measurements taken in finfish-licensed fisheries were used[d], to avoid biasing length-frequency distributions if proportionally more samples are recorded from one fishery or another in different years. The procedure for identifying finfish-licensed observer samples is described in Appendix 1. 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[e] should be bigger than length at 50% maturity, for conservation of immature fish ($L_C / L_{Mat} > 1$).
2) Length at cumulative 25[th] percentile of catch numbers should be bigger than length at 50% maturity, for conservation of immature fish ($L_{25\%} / L_{Mat} > 1$).
3) Mean length of the largest 5% of individuals in the catch should be at least 80% of the asymptotic length, as a benchmark that enough large individuals are in the stock ($L_{max5\%} / L_{Inf} > 0.8$).
4) 'Mega-spawners' should comprise at least 30% of the catch (thus implicitly represent at least 30% of the stock), as large, old fish disproportionately benefit the resilience of the population (Froese 2004) ($P_{mega} > 0.3$).
   Mega-spawners are defined as individuals larger than optimum length (L_{Opt}) + 10%, where L_{Opt} itself 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 and 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 30,000× on the normal distribution each year's fit of L_{Inf} to the linear regression and L_{Mat} to the LOESS smooth. Indicators were scored against the 'traffic light' scale (ICES 2015) with reference criteria >1, >0.8, and >0.3 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[f]. Reference criterion ≈1 was green if the lower and upper 95% quantiles spanned 1, yellow if the lower and upper 95% quantiles spanned 0.9 without spanning 1 (cf. ICES 2015), and red otherwise. Reference criterion ≥1 was scored the same as >1, except that empirical values ≥1 were automatically green.

[d] Also excluding skate and *Illex* trawls. 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.

[e] Note that this parameter may be poorly defined if the catch length-frequency distribution is not smooth and unimodal.

[f] Note that this use of the margins of variability means that same empirical values may be scored different colours in different years.

Results

Catches

During 2020 a total of 807.0 tonnes rock cod were caught in the Falkland Islands zone; the lowest total since the start of consistent commercial reporting in 2005 (Figure 1). Compared to last year (Winter 2020), rock cod catches decreased more than four-fold in the A- and G-licence finfish trawl fisheries, but nearly doubled in the X-licence calamari fishery (Table 1). Among finfish target licences, of 748 A-licence catch reports in 2020, rock cod was the third-highest catch species on 7 catch reports. Of 506 G-licence catch reports in 2020, rock cod was the second-highest catch species on 3 catch reports. And of 735 W-licence catch reports in 2020, rock cod was the highest catch species on 8 and the second-highest on 25 catch reports.

Table 1. Falkland Islands rock cod catches by licence in 2019.

Licence		Rock cod catch	%
Code	Type	(Tonnes)	
A	Unrestricted finfish	18.8	2.3
G	Restricted finfish + *Illex*	42.2	5.2
W	Restricted finfish	254.7	31.6
F	Skate	2.8	0.3
C	Calamari 1st season	261.7	32.4
X	Calamari 2nd season	145.3	18.0
B	*Illex* squid	0.9	0.1
S	Surimi	0.0	0.0
L	Toothfish longline	0.0	0.0
E	Experimental	11.0	1.4
O	Out-of-zone	69.6	8.6
Total		807.0	100.0

Category 3

Annual commercial rock cod catches, corresponding to Figure 1 are summarized in Table A1. Only 'in-zone' catches are used as these catches represent license-allocated fishing effort. Based on the in-zone catches:

$$\text{TAC-5}_{2019} = \overline{\text{Catches}_{2016\text{ to }2018}} = \overline{6895.3, 2422.0, 2146.3} = 3821.2 \text{ tonnes.}$$

Together with the survey data in Table III of Ramos and Winter (2020):

$$\text{TAC-3}_{2020} = \text{TAC-5}_{2019} \times \frac{\overline{\text{Surveys}_{2018\text{ to }2019}}}{\overline{\text{Surveys}_{2015\text{ to }2017}}}$$

$$= 3821.2 \times \frac{\overline{87595.83, 377793.3}}{\overline{352570.42, 235339.08, 138641.20}} = 989.2 \text{ tonnes.}$$

Pursuant to the ±20% uncertainty cap:

$$\text{TAC-3}_{2020} = \text{TAC-5}_{2019} - 20\% \times \text{TAC-5}_{2019} = 3821.2 \times 0.80 = 3057.0 \text{ tonnes.}$$

$$\text{TAC-3}_{2022} = \text{TAC-3}_{2020} \times \frac{\overline{\text{Surveys}_{2019\text{ to }2020}}}{\overline{\text{Surveys}_{2016\text{ to }2018}}}$$

$$= 3057.0 \times \frac{\overline{377793.3, 22335.25}}{\overline{235339.08, 138641.20, 87595.83}} = 597.3 \text{ tonnes.}$$

Pursuant to the ±20% uncertainty cap:

$$\text{TAC-3}_{2022} = \text{TAC-3}_{2020} - 20\% \times \text{TAC-3}_{2020} = 3057.0 \times 0.80 = 2445.6 \text{ tonnes.}$$

However, TAC-3_{2022} is conspicuously higher than the 3-year catch average (TAC-5_{2022}) which, given that rock cod survey biomass is still on a declining trend (Ramos and Winter 2020), may be considered as a conservative alternative:

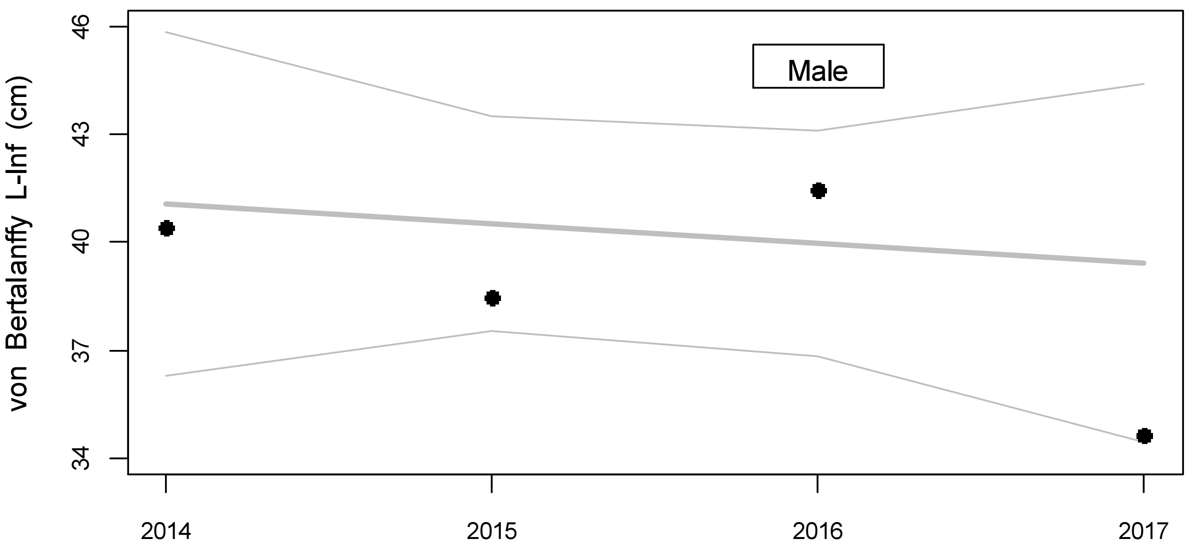
$$\text{TAC-5}_{2022} = \overline{\text{Catches}_{2018\text{ to }2020}} = \overline{2146.3, 925.2, 726.4} = 1266.0 \text{ tonnes.}$$

Again, note the two-year jump from 2020 to 2022.

LBI

L_{Inf} of the years 2014 – 2017 were significantly different ($p < 0.001$) by likelihood ratio, for both males and females. Yearly von Bertalanffy parameters are summarized in Table A2. Accordingly, L_{Inf} for LBI parameterization was set to the linear trends. Despite only four data, the decreasing trend was marginally significant ($p < 0.06$) for females (Figure 2). L_{Mat} between years 1995 and 2020 showed significantly decreasing trends from approximately 2005 for both males and females (Figure 3).

Figure 2 [below]. Asymptotic lengths (L_{Inf}) calculated according to the von Bertalanffy growth function for male (top) and female (bottom) rock cod, in years 2014 to 2017. Grey lines are linear regressions ± 95% confidence intervals.



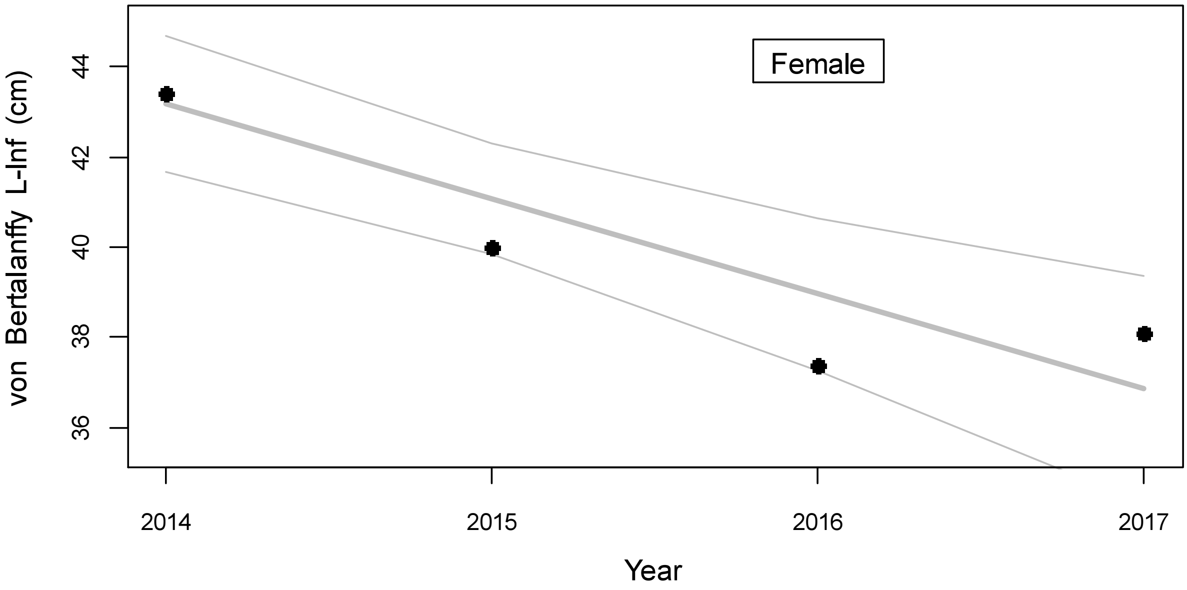
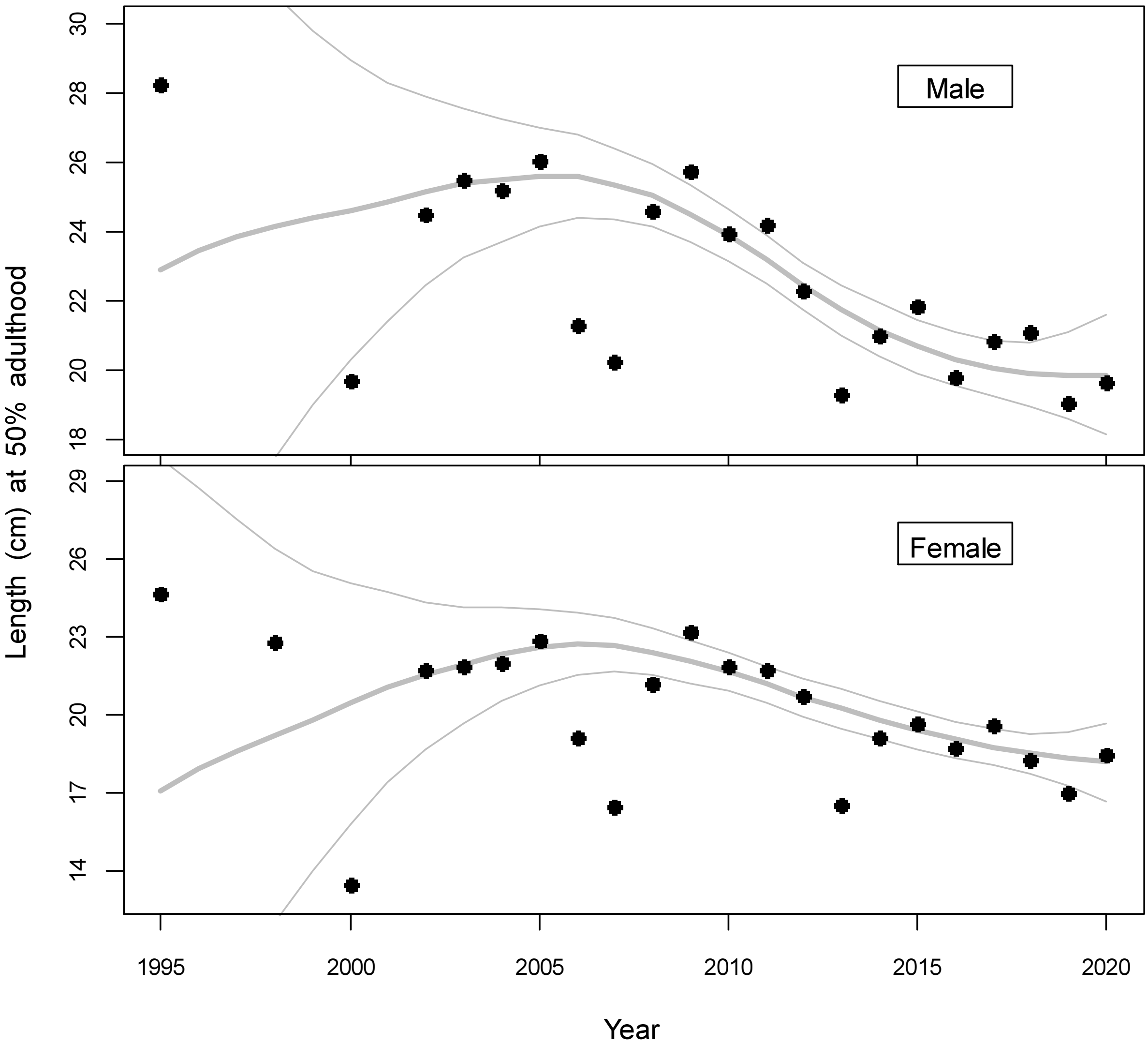


Figure 3 [below]. Lengths at 50% adulthood of male (top) and female (bottom) rock cod, 1995 to 2020. Grey lines are LOESS smooths ± 95% confidence intervals. Yearly data correspond to the 0.5 length intercepts in Figure A1.



A total of 348,157 rock cod lengths were randomly sampled in finfish trawls between 2002 and 2020; 165,001 male and 183,156 female. Resultant 'traffic light' scores for LBI method indicators are summarized in Tables 2 and 3.

Year 2002 can be discounted, as only 6 male and 11 female rock cod lengths were randomly sampled, at one station. Among years 2003 to 2020, indicator L_C / L_{Mat} appeared to fluctuate haphazardly, and may be inconsistent due to irregular length-frequency modes (Figure A2). $L_{25\%}$ / L_{Mat}, the other indicator for conservation of immature fish, showed a pattern of generally more successful outcomes in the range of years that had the highest catches of rock cod (2007 to 2014; Figure 1), whereby for males most of these years were yellow (around one, Table 2), and for females most of these years were green (greater than one, Table 3). Indicator $L_{max5\%}$ / L_{Inf}, for the conservation of large individuals, was consistently yellow for males and half yellow half green for females, with the five most recent years green. Indicator P_{mega}, for the presence of mega-spawners, was almost all yellow for males until 2015, the year when catches started to decline strongly (Figure 1), although only in 2008 the empirical proportion was above the threshold of 0.3 (Table 2). For females, P_{mega} has been constantly red (Table 3). L_{meanC} / L_{Opt}, the indicator for optimal yield, was green for males until 2014, the last year of very high rock cod catches, and mostly yellow for females. Both males and females were yellow in the most recent year 2020. L_{meanC} / $L_{F=M}$, the indicator for maximum sustainable yield, was also mostly green for males, and for females, mostly green except the four-year period from 2011 to 2014; roughly the end range of the period of high rock cod catches (Figure 1).

Table 2. Male rock cod indicators by year, with 'traffic light' scoring.

Ref.	Conservation				Optim. Yield	MSY
	L_C / L_{Mat} >1	$L_{25\%}$ / L_{Mat} >1	$L_{max5\%}$ / L_{Inf} >0.8	P_{mega} >0.3	L_{meanC} / L_{Opt} ≈1	L_{meanC} / $L_{F=M}$ ≥1
2002	0.68	0.72	0.56	0.00	0.72	0.86
2003	0.91	0.91	0.82	0.10	0.98	0.98
2004	0.82	0.86	0.81	0.11	0.97	1.02
2005	0.86	0.90	0.84	0.20	1.02	1.04
2006	0.78	0.90	0.83	0.16	0.97	1.05
2007	0.95	0.99	0.85	0.18	1.03	1.00
2008	1.00	1.04	0.86	0.33	1.08	1.02
2009	0.82	0.90	0.86	0.22	0.97	1.06
2010	0.84	0.88	0.85	0.11	0.95	1.03
2011	0.95	0.99	0.82	0.09	0.97	0.99
2012	0.98	1.03	0.83	0.14	0.99	1.01
2013	0.88	0.97	0.80	0.08	0.90	1.01
2014	1.09	0.99	0.79	0.05	0.98	0.97
2015	0.63	0.77	0.82	0.19	0.86	1.17
2016	0.89	0.94	0.82	0.08	0.87	0.99
2017	0.65	0.75	0.78	0.05	0.75	1.01
2018	0.91	0.91	0.80	0.07	0.88	0.98
2019	0.71	0.91	0.81	0.08	0.84	1.08
2020	0.71	0.86	0.82	0.08	0.79	1.03

Table 3. Female rock cod indicators by year, with ‘traffic light’ scoring.

Ref.	Conservation				Optim. Yield	MSY
	L_C / L_{Mat} >1	$L_{25\%}$ / L_{Mat} >1	$L_{max5\%}$ / L_{Inf} >0.8	P_{mega} >0.3	L_{meanC} / L_{Opt} ≈1	L_{meanC} / $L_{F=M}$ ≥1
2002	0.74	0.79	0.53	0.00	0.66	0.84
2003	0.96	1.00	0.77	0.04	0.88	0.96
2004	0.85	0.94	0.78	0.06	0.89	1.03
2005	1.02	1.02	0.79	0.12	0.97	0.99
2006	0.84	0.97	0.80	0.10	0.91	1.05
2007	0.97	1.06	0.81	0.14	0.95	1.01
2008	1.07	1.16	0.84	0.21	1.01	1.01
2009	0.91	1.00	0.84	0.17	0.93	1.03
2010	0.92	1.01	0.83	0.09	0.90	1.01
2011	1.04	1.08	0.78	0.05	0.92	0.97
2012	1.06	1.11	0.78	0.06	0.92	0.97
2013	0.94	1.04	0.77	0.06	0.86	0.99
2014	1.16	1.11	0.75	0.03	0.93	0.95
2015	0.67	0.93	0.81	0.13	0.88	1.21
2016	0.94	1.00	0.86	0.15	0.91	1.02
2017	0.69	0.85	0.87	0.11	0.86	1.12
2018	1.03	1.03	0.87	0.11	0.96	1.00
2019	0.93	1.04	0.87	0.13	0.96	1.07
2020	0.82	0.93	0.89	0.15	0.90	1.08

Conclusion

Length-based indicators (LBI) showed mixed results (Tables 2 and 3) in parallel with the trends of low catches and low survey indices. Traffic-light scores indicated that immature rock cod are not well protected – especially males, while large rock cod are protected – especially females, but *very* large rock cod are again not protected. Median rock cod lengths sampled in finfish-licensed fisheries have been significantly decreasing over the years (Figure 4), while length-frequency distribution spreads; the ranges between, e.g., the 25th quantile and the 75th quantile of lengths, have not varied significantly (Figure 5), thus size distributions have not become more truncated. MSY indicators showing strong (green) in recent years, despite decreasing lengths, imply that rock cod are maintaining productivity at smaller sizes, as well as maturity at smaller sizes (Figure 3). Contrary to the high $L_{max5\%}$ / L_{Inf} scores, these trends indicate that large rock cod are not protected.

The ambiguity of these signals invites caution about rock cod length distributions. The LBI method assumes equilibrium conditions (ICES 2018b), which would usually represent as annual length modes progressing in fairly regular order left to right (e.g., Gulland and Rosenberg 1992). However, recent years of the finfish-licenced rock cod length distributions have been irregular (Figure A2; since 2015), suggesting that as rock cod declined to a commercial bycatch, different parts of the stock may have been sampled haphazardly depending on the primary target catch.

Figure 4 [below]. Median lengths in finfish-licenced observer samples of male (top) and female (bottom) rock cod, 2002 to 2020. Grey lines are LOESS smooths ± 95% confidence intervals. Yearly data correspond to Figure A2.

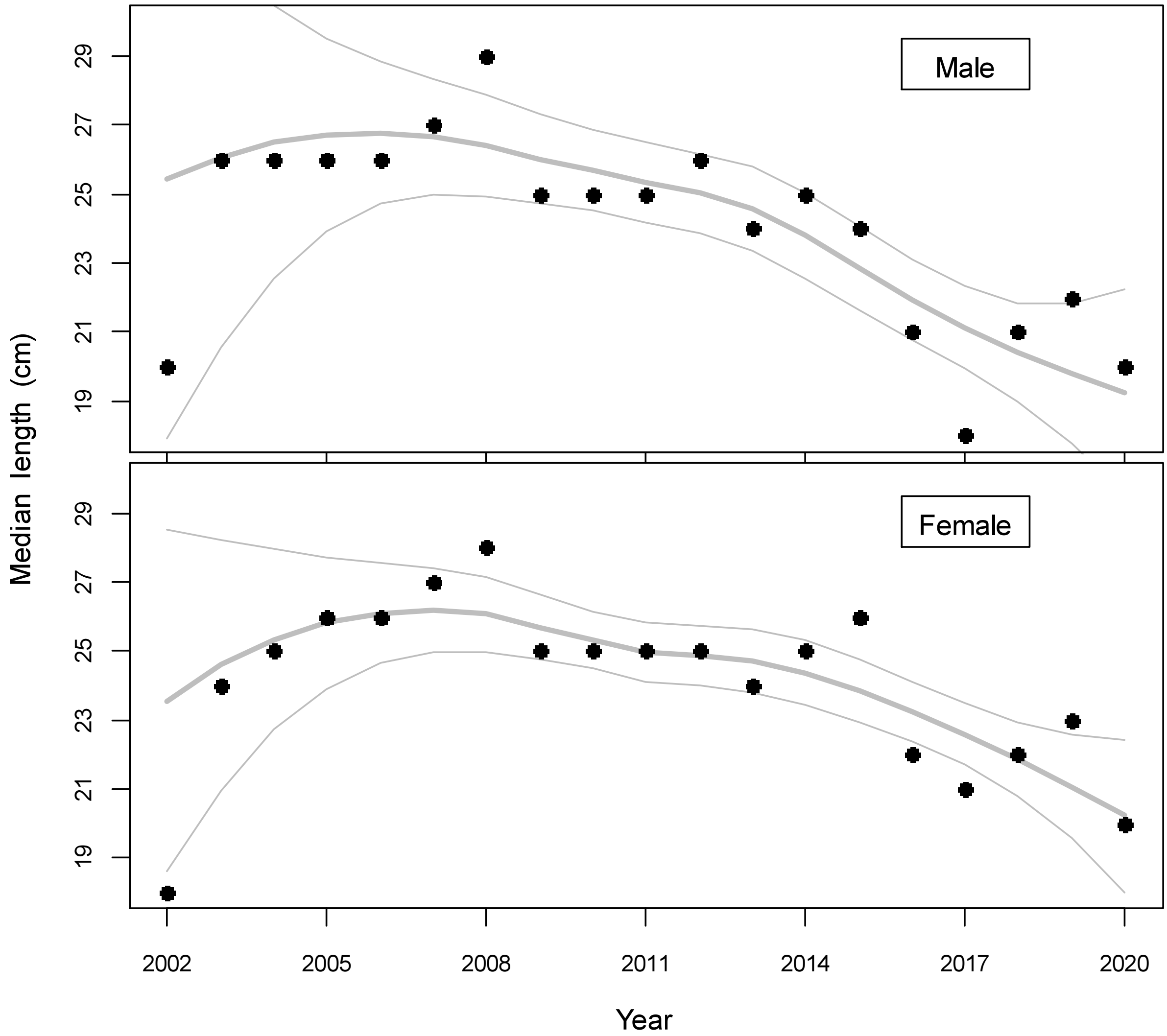
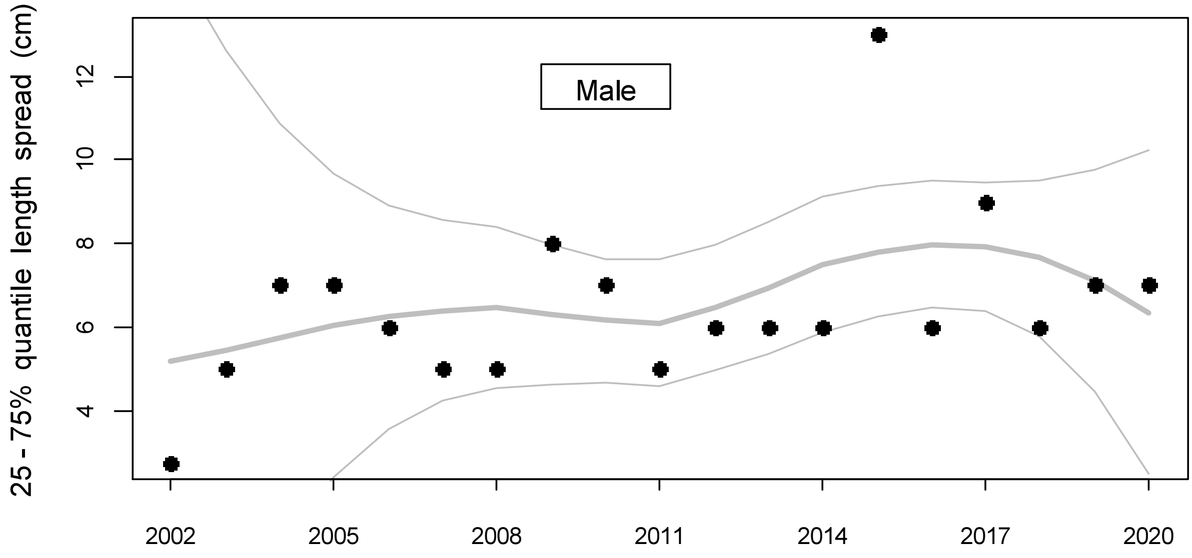
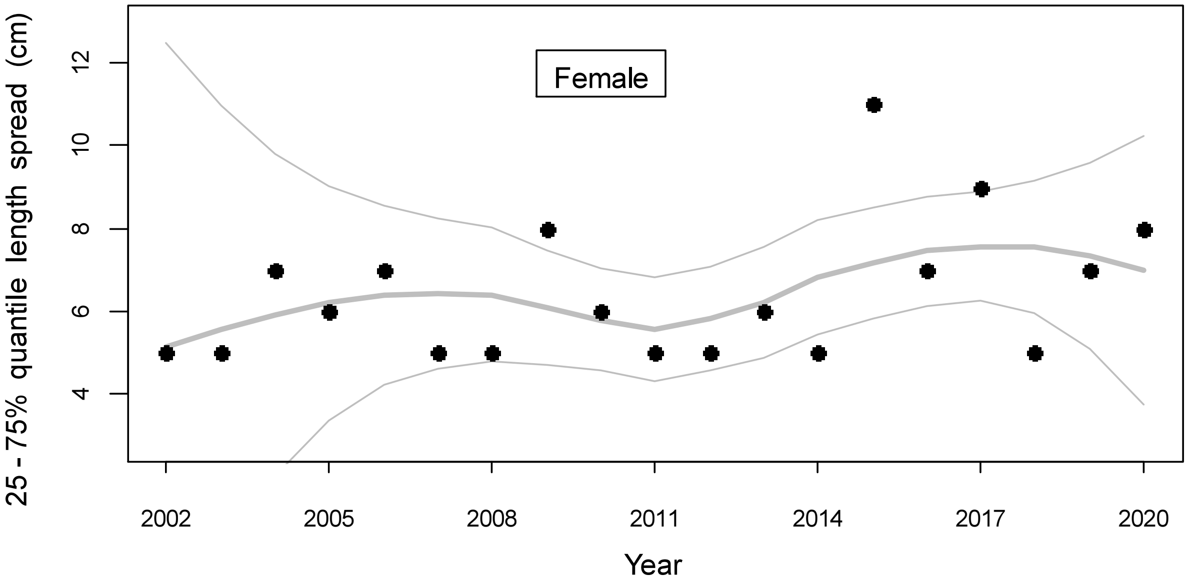


Figure 5 [below]. 25% to 75% quantile length spreads in finfish-licenced observer samples of male (top) and female (bottom) rock cod, 2002 to 2020. Grey lines are LOESS smooths ± 95% confidence intervals. Yearly data correspond to Figure A2.





Alternatively, male and female components of the stock may have been affected differently. Several of the traffic light scores showed distinct outcomes for males and females (Tables 2 and 3), and a slight but statistically significant trend was found in sex proportions from 2002 to 2020 (Figure 6). The proportion of females decreased until about 2008/2009, steadied between 2009 and 2011/2012 – the period of highest average rock cod catches – then decreased again after 2012 until about 2016. Males and females exhibit dissimilar behaviours such as spawning territoriality (Arkhipkin et al. 2013), and if conditions change to make one sex or the other more vulnerable the entire stock may be impacted.

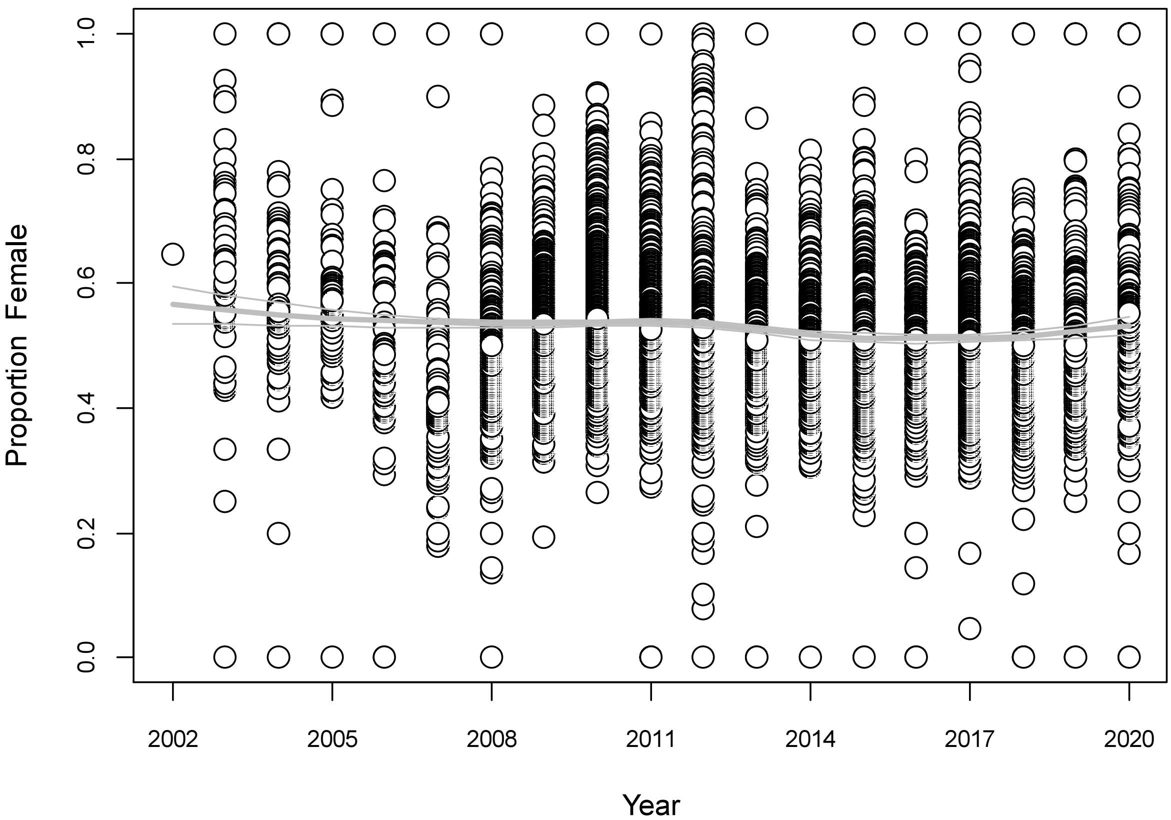


Figure 6 [previous page]. LOESS trend of average female proportion in finfish-licensed rock cod samples, 2002 to 2020. Circles (N = 3532) are individual observer stations.

The LBI results were thus not definitive, but together with the low catches and low survey indices point to the continuing need for conservative management of the rock cod stock. The trajectory of Falkland Islands rock cod catches also parallels that of Argentina (Table A3).

$TAC\text{-}5_{2022}$ = 1266.0 tonnes is equivalent to 2.15% of total Falkland Islands-licenced finfish catch taken in 2020, but higher than any annual rock cod catch total since 2018 (Table A1). Thus $TAC\text{-}5_{2022}$ fulfils the requirement of a conservative catch limit, but without undue risk of 'choking' other fishery targets.

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Appendix

A1. 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[g] (which still does not result in all samples getting matched).

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.

[g] 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.

Table A1. Falkland Islands commercial rock cod catches (excluding E licences) by year. Equivalent to the rock cod (out) and rock cod (in) bars in Figure 1, but restricted to the first year (1992) that any rock cod catch was reported.

Year	Rock cod catch (tonnes)		Year	Rock cod catch (tonnes)	
	Out-of-zone	In-zone		Out-of-zone	In-zone
1992	0.0	0.7	2007	35.1	30843.4
1993	0.0	0.0	2008	361.4	60162.9
1994	0.0	0.0	2009	806.4	57993.5
1995	0.0	0.0	2010	1019.9	76146.4
1996	0.0	0.0	2011	710.8	55272.6
1997	0.0	0.0	2012	611.0	63114.8
1998	0.0	0.0	2013	2020.2	31952.6
1999	0.0	0.0	2014	6809.9	56134.3
2000	0.0	0.0	2015	933.3	28537.7
2001	0.0	0.0	2016	6448.4	6895.3
2002	0.0	0.0	2017	5496.9	2422.0
2003	0.0	2.4	2018	2088.1	2146.3
2004	0.0	176.1	2019	26.7	925.2
2005	0.0	9043.7	2020	69.6	726.4
2006	0.0	24616.3			

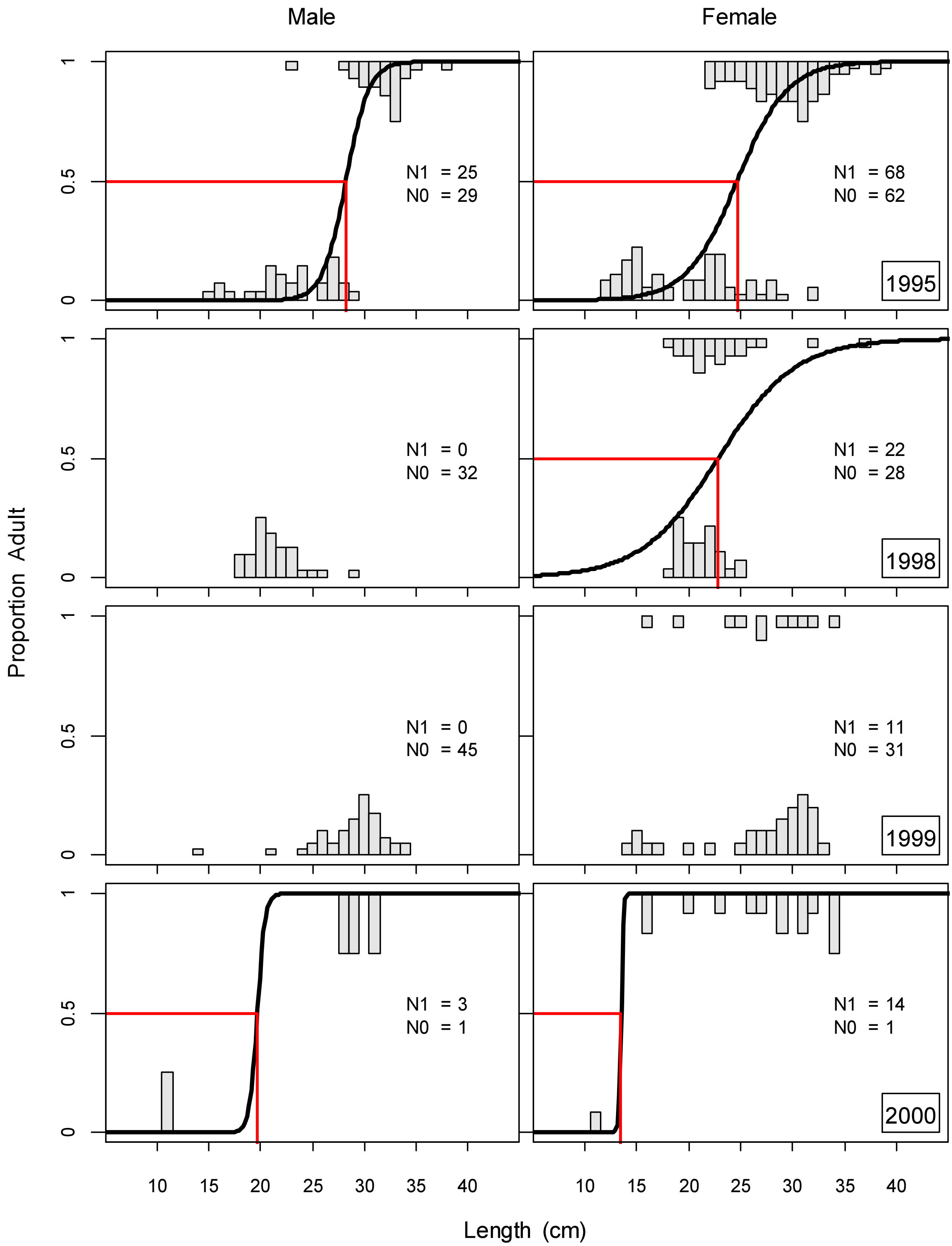
Table A2. Rock cod von Bertalanffy length-at-age parameters, by year and sex, and 95% confidence intervals of L_{Inf} (in cm).

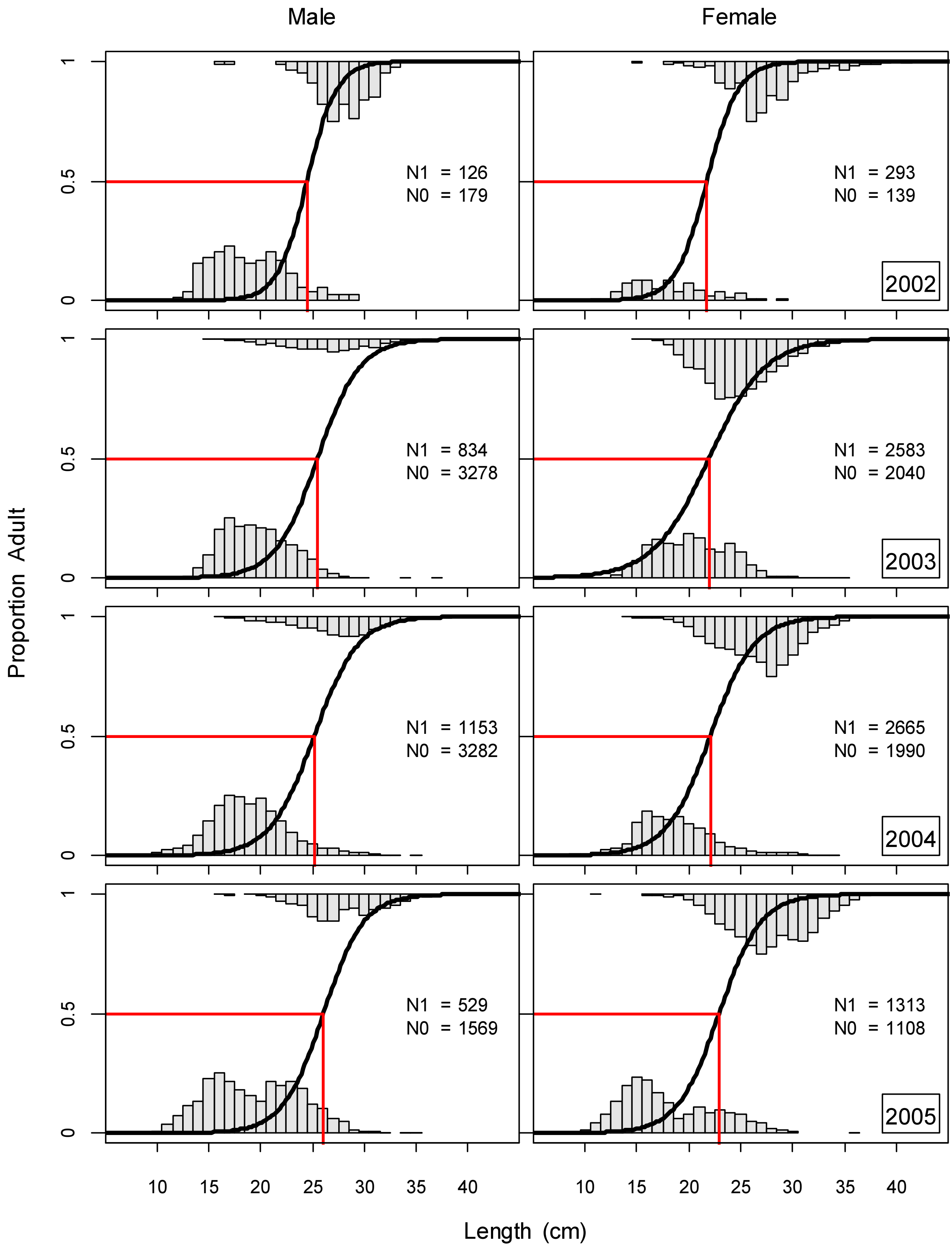
Sex	Year	N	k	t_0	L_{Inf}	
M	2014	85	0.206	–0.870	40.4	(36.5 – 46.4)
	2015	175	0.297	–0.497	38.5	(36.5 – 40.8)
	2016	167	0.199	–1.260	41.5	(36.8 – 49.9)
	2017	72	0.325	–0.238	34.7	(32.1 – 38.0)
F	2014	104	0.189	–0.771	43.4	(39.8 – 49.5)
	2015	163	0.245	–0.827	40.0	(38.2 – 42.1)
	2016	156	0.260	–1.068	37.4	(35.2 – 40.2)
	2017	83	0.250	–0.479	38.1	(36.0 – 40.9)

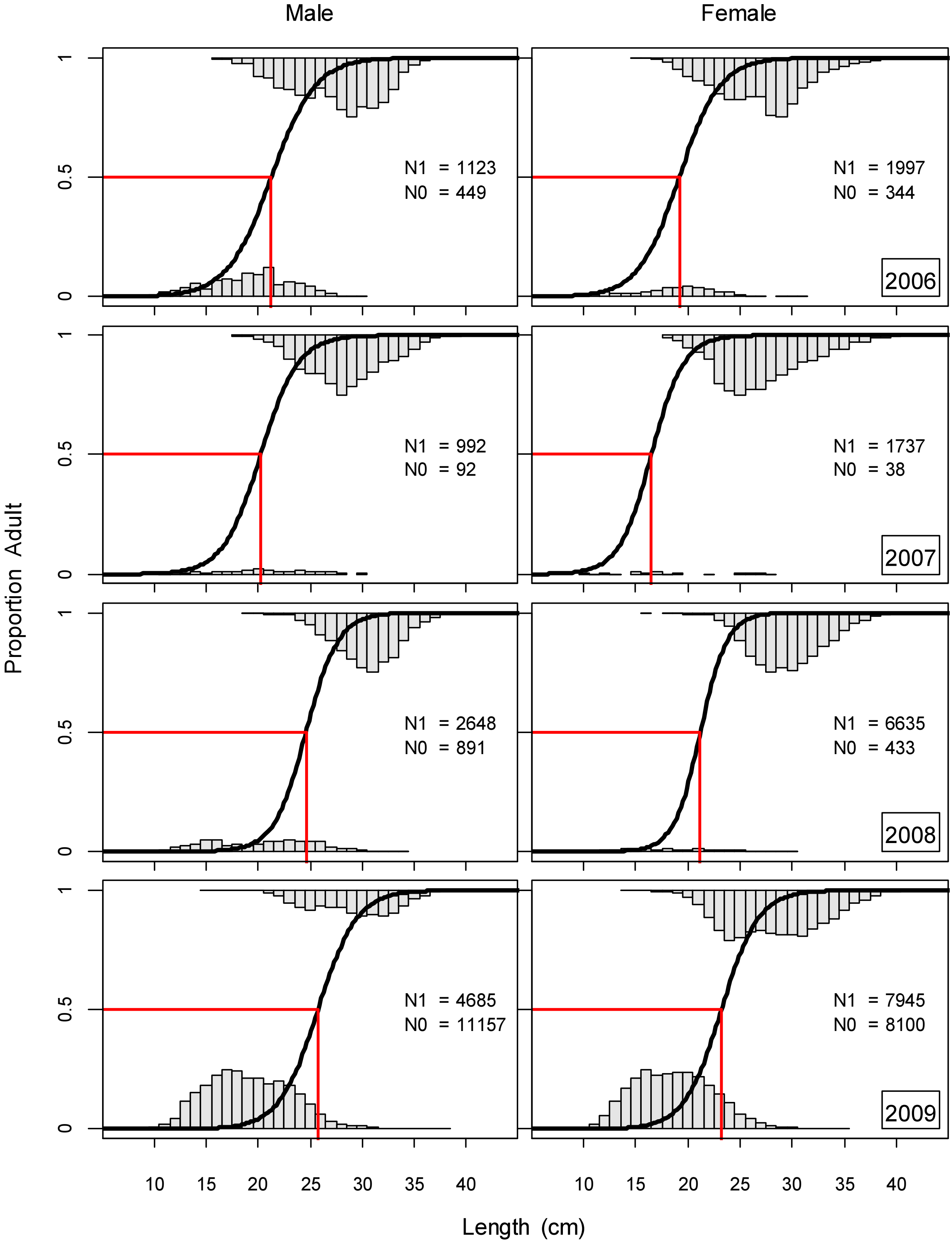
Table A3. Argentina commercial rock cod[h] catches by year, for the same range of years as Table A1. From Sánchez et al. 2012, Navarro et al. 2014, 2019, and the website of the Ministerio de Agricultura, Ganadería y Pesca[i] (Argentina).

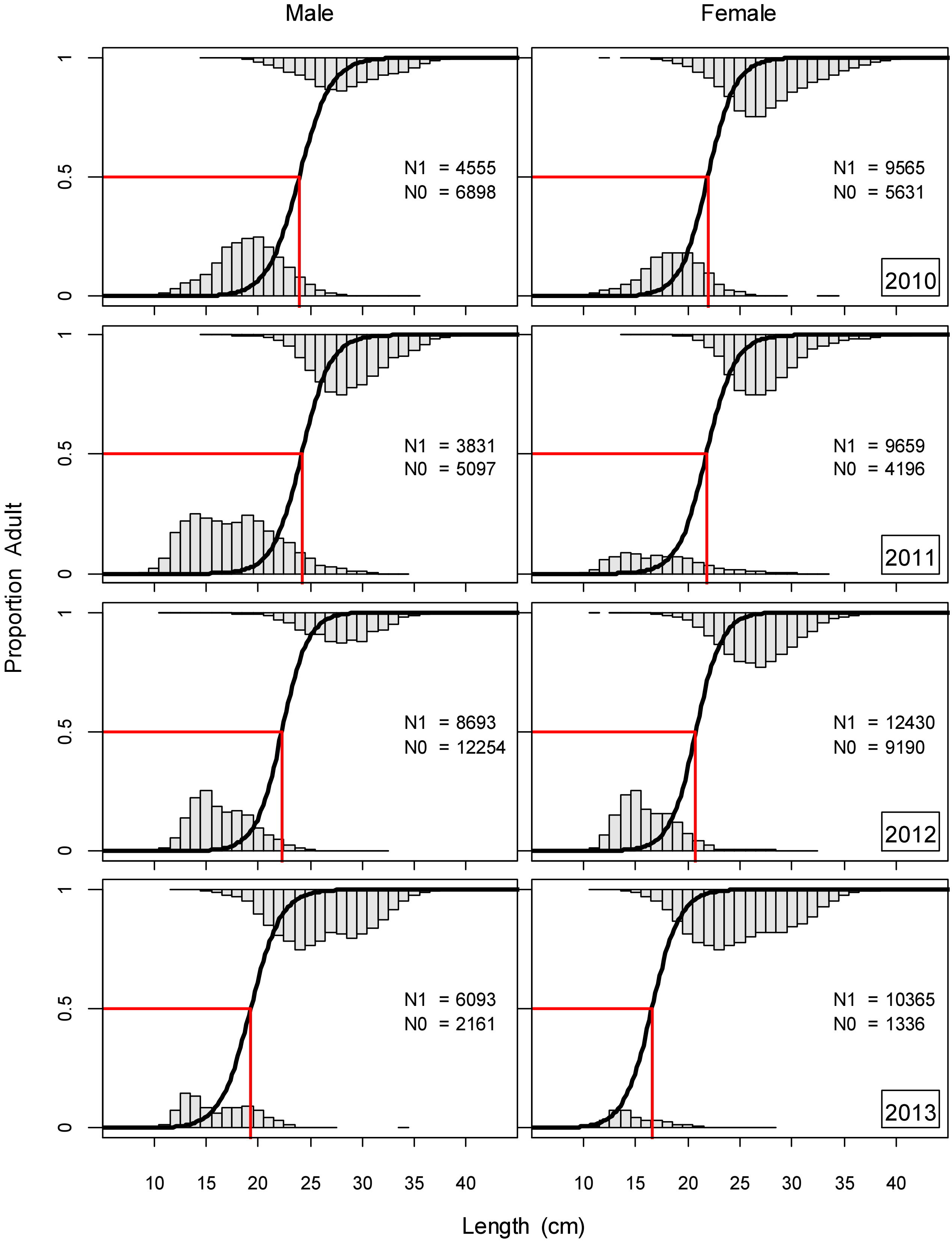
Year	Rock cod catch (tonnes)	Year	Rock cod catch (tonnes)
1992	0.0	2007	8354.8
1993	0.0	2008	12433.5
1994	0.1	2009	16645.5
1995	0.0	2010	9447.8
1996	0.0	2011	8575.4
1997	0.0	2012	7936.8
1998	0.0	2013	6517.9
1999	0.0	2014	6850.5
2000	0.2	2015	4273.1
2001	182.8	2016	909.5
2002	179.6	2017	1972.1
2003	258.8	2018	809.0
2004	468.7	2019	87.8
2005	4169.7	2020	101.8
2006	9842.2		

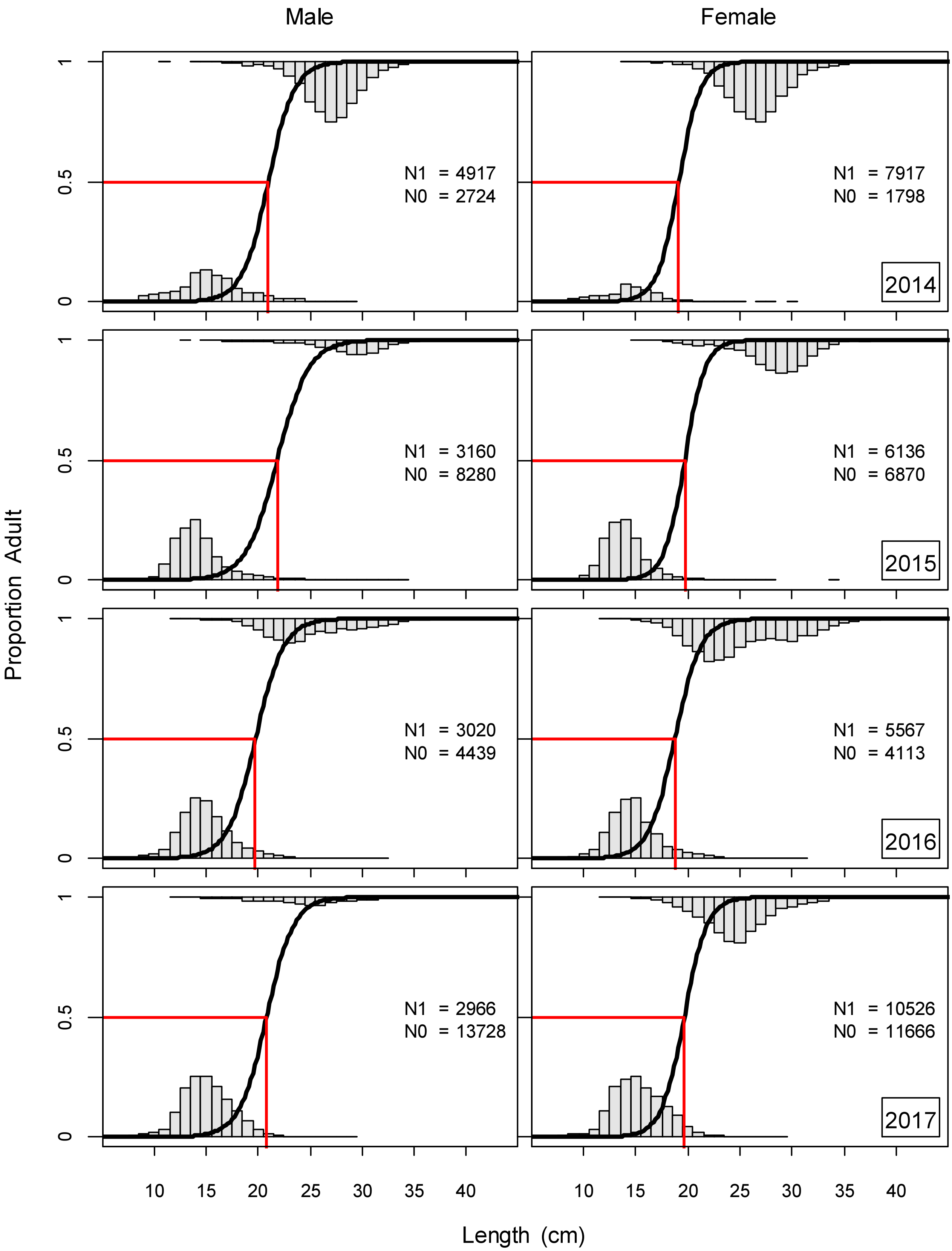
[h] Reported as Notothenia. While this is ostensibly the family Nototheniidae, not the species, Cousseau and Perrotta (2000) identify Notothenia as *Patagonotothen ramsayi*.
[i] www.magyp.gob.ar/sitio/areas/pesca_maritima/desembarques/


Male
Female
Proportion Adult
Length (cm)
N1 = 25
N0 = 29
N1 = 68
N0 = 62
1995
N1 = 0
N0 = 32
N1 = 22
N0 = 28
1998
N1 = 0
N0 = 45
N1 = 11
N0 = 31
1999
N1 = 3
N0 = 1
N1 = 14
N0 = 1
2000
0
0.5
1
10
15
20
25
30
35
40


Male
Female
Proportion Adult
Length (cm)
N1 = 126
N0 = 179
N1 = 293
N0 = 139
2002
N1 = 834
N0 = 3278
N1 = 2583
N0 = 2040
2003
N1 = 1153
N0 = 3282
N1 = 2665
N0 = 1990
2004
N1 = 529
N0 = 1569
N1 = 1313
N0 = 1108
2005


Male
Female
Proportion Adult
Length (cm)
N1 = 1123
N0 = 449
N1 = 1997
N0 = 344
2006
N1 = 992
N0 = 92
N1 = 1737
N0 = 38
2007
N1 = 2648
N0 = 891
N1 = 6635
N0 = 433
2008
N1 = 4685
N0 = 11157
N1 = 7945
N0 = 8100
2009


Male
Female
Proportion Adult
Length (cm)
N1 = 4555
N0 = 6898
N1 = 9565
N0 = 5631
2010
N1 = 3831
N0 = 5097
N1 = 9659
N0 = 4196
2011
N1 = 8693
N0 = 12254
N1 = 12430
N0 = 9190
2012
N1 = 6093
N0 = 2161
N1 = 10365
N0 = 1336
2013


Male
Female
Proportion Adult
Length (cm)
N1 = 4917
N0 = 2724
N1 = 7917
N0 = 1798
2014
N1 = 3160
N0 = 8280
N1 = 6136
N0 = 6870
2015
N1 = 3020
N0 = 4439
N1 = 5567
N0 = 4113
2016
N1 = 2966
N0 = 13728
N1 = 10526
N0 = 11666
2017

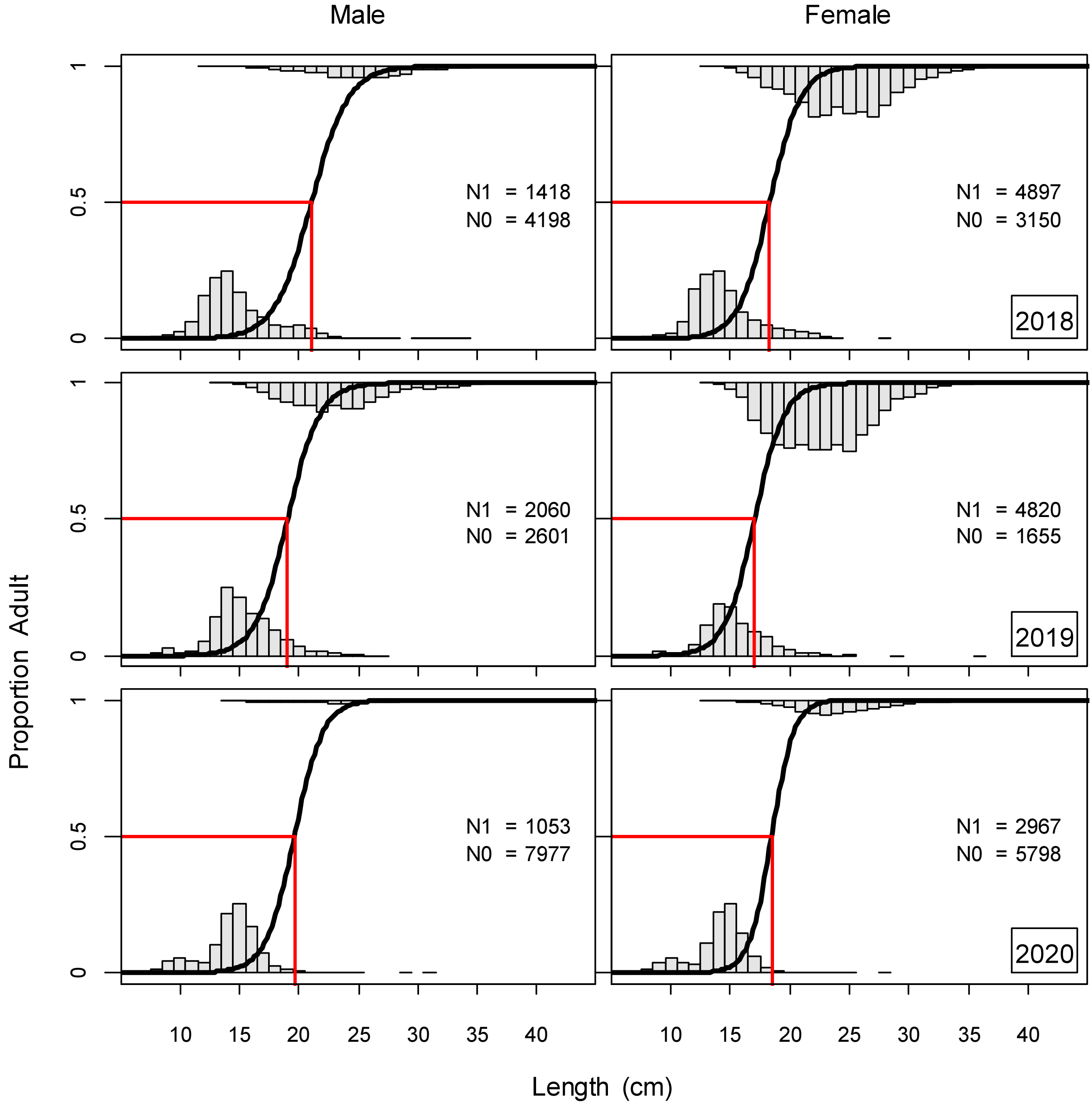
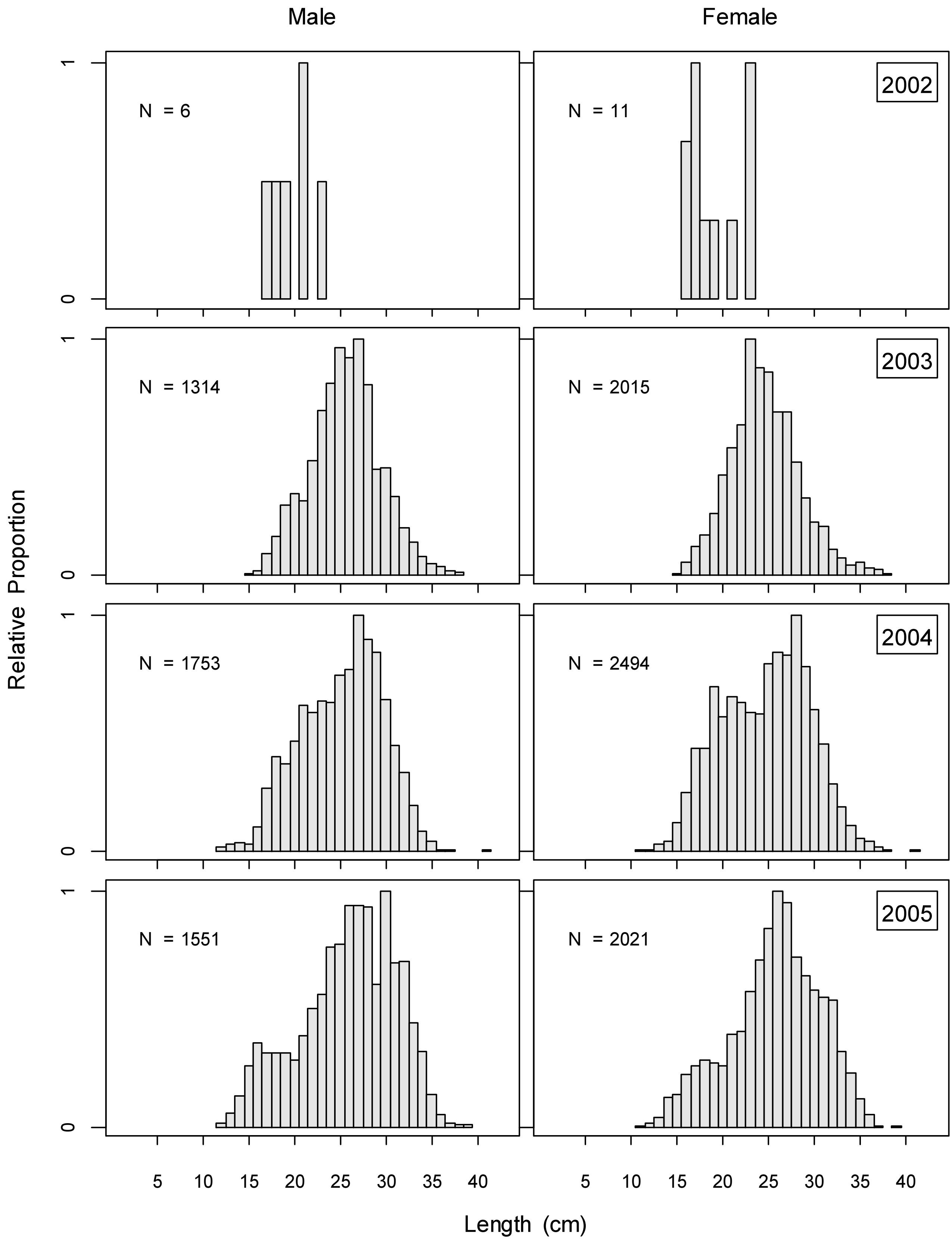
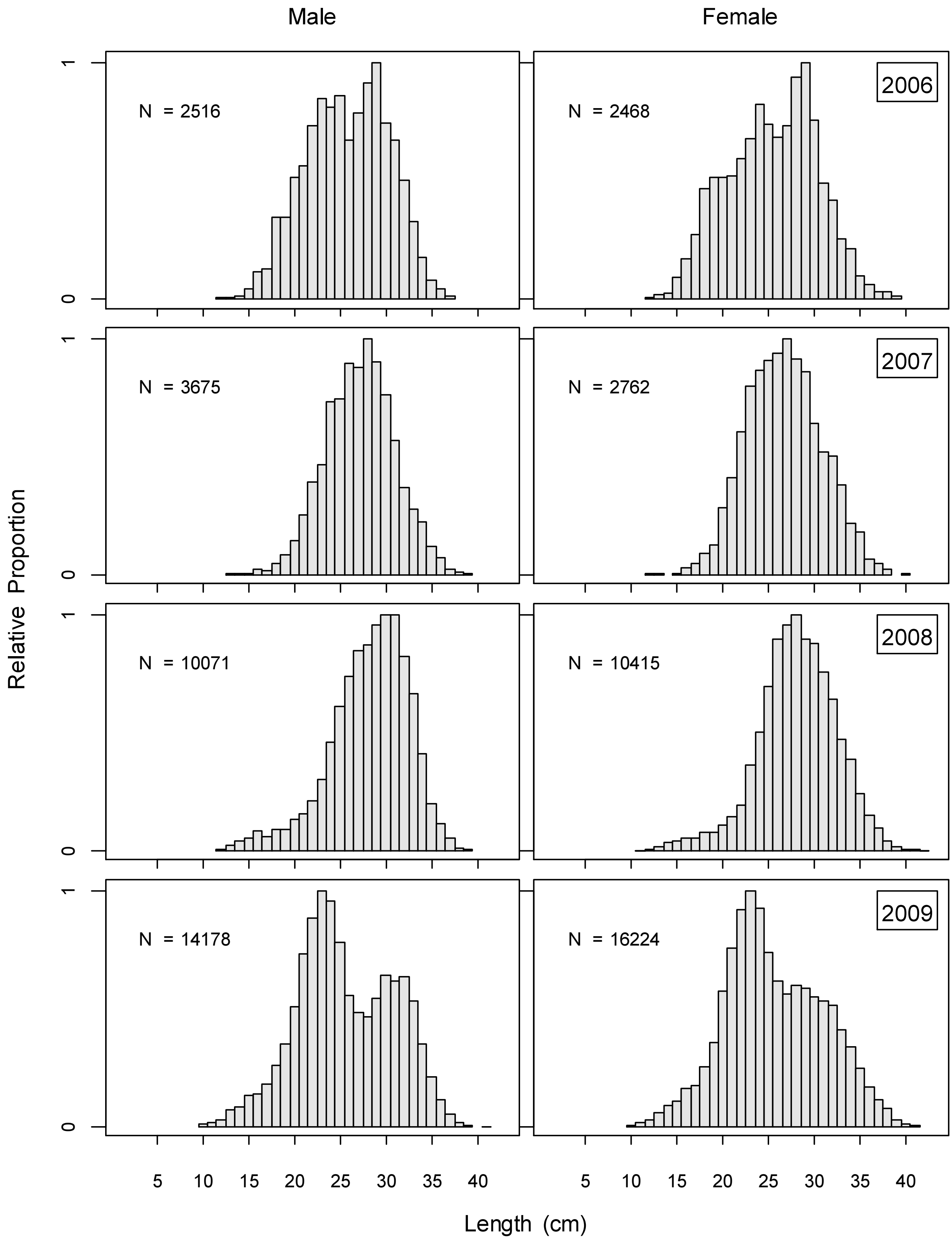
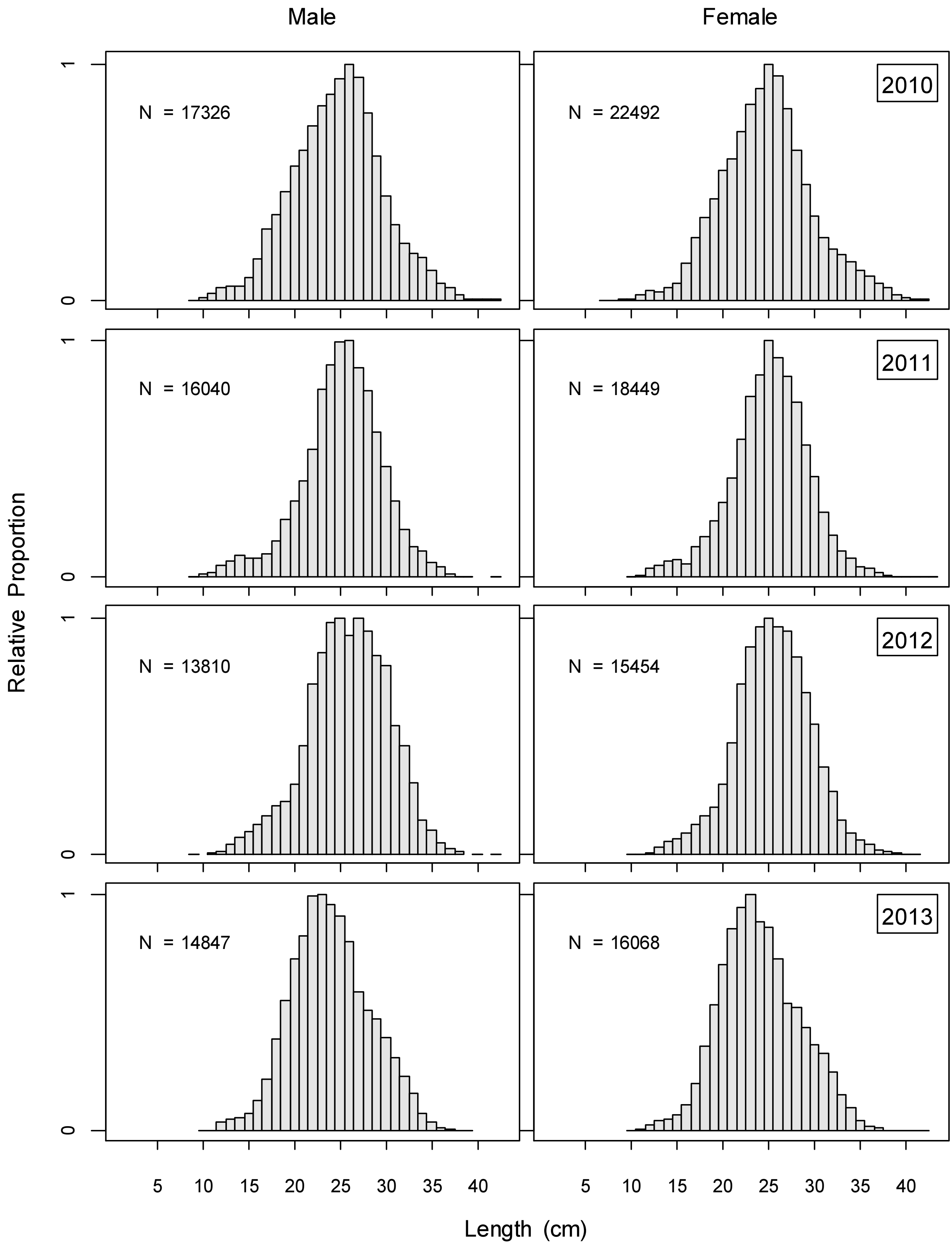


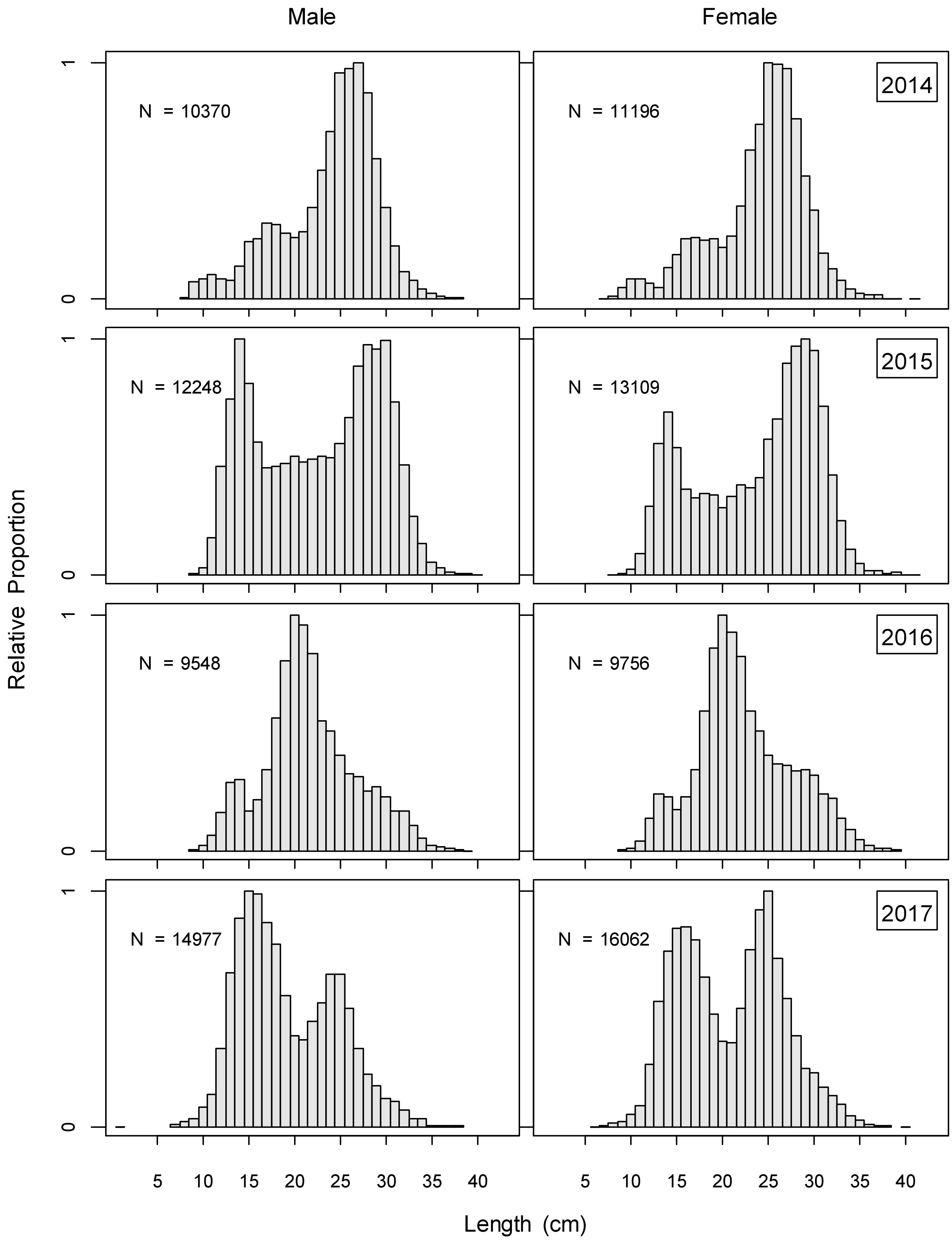
Figure A1. Binomial logistic regressions of juvenile (0) or adult (1) maturity vs. length. The regressions are omitted from data sets that were insufficient or failed to converge on plausible values. Grey bars: distributions scaled to sample numbers. Red lines: Length intercept of 50% adulthood, corresponding to Figure 3.


Male
Female
Relative Proportion
1
0
N = 6
N = 11
2002
N = 1314
N = 2015
2003
N = 1753
N = 2494
2004
N = 1551
N = 2021
2005
5 10 15 20 25 30 35 40
5 10 15 20 25 30 35 40
Length (cm)



Male
Female
2006
2007
2008
2009
N = 2516
N = 2468
N = 3675
N = 2762
N = 10071
N = 10415
N = 14178
N = 16224
Relative Proportion
0
1
5 10 15 20 25 30 35 40
Length (cm)


Male
Female
2010
2011
2012
2013
N = 17326
N = 22492
N = 16040
N = 18449
N = 13810
N = 15454
N = 14847
N = 16068
Relative Proportion
Length (cm)
0
1
5
10
15
20
25
30
35
40


Male
Female
Relative Proportion
N = 10370
N = 11196
2014
N = 12248
N = 13109
2015
N = 9548
N = 9756
2016
N = 14977
N = 16062
2017
0
1
5 10 15 20 25 30 35 40
Length (cm)

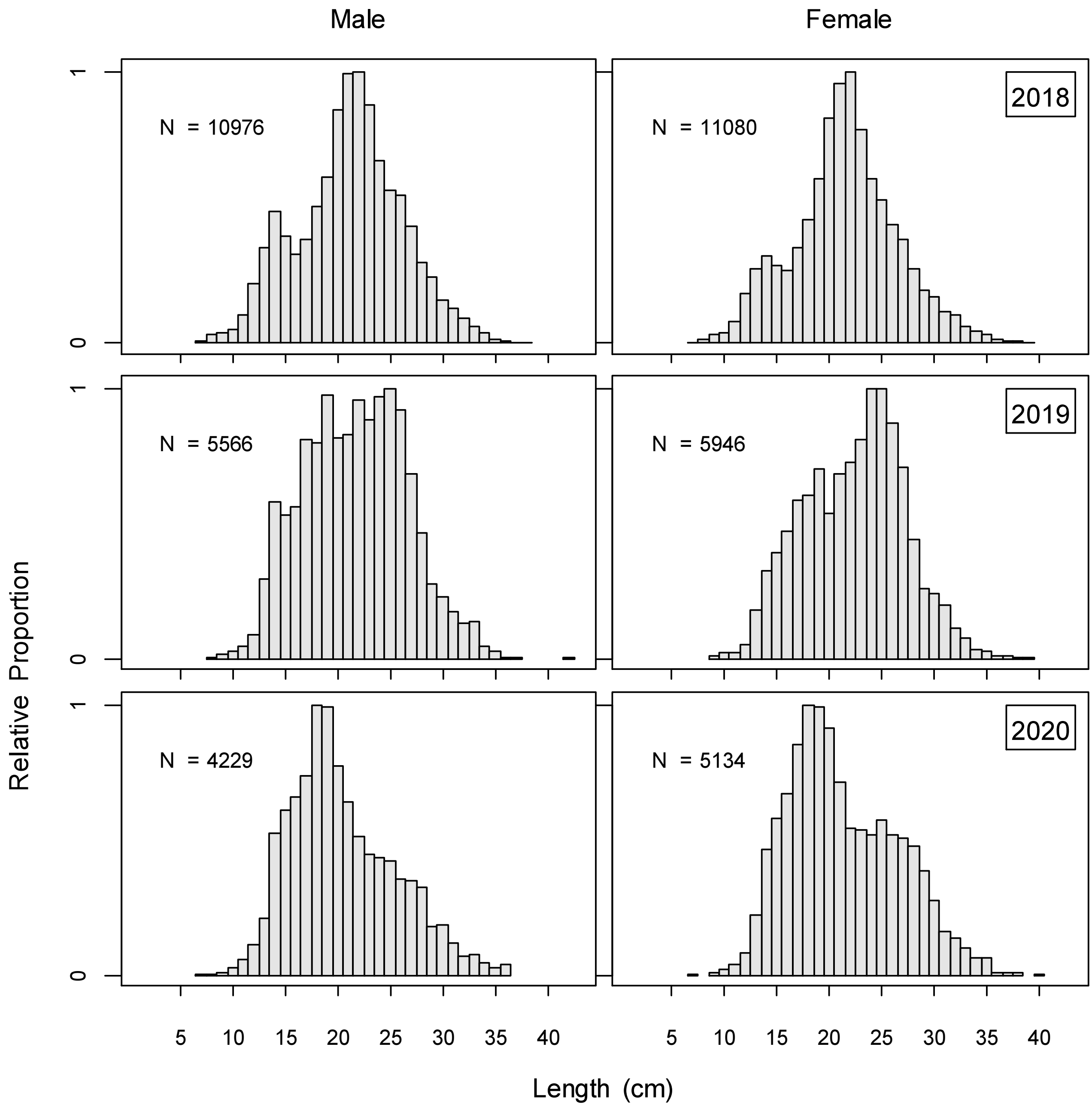


Figure A2. Randomly sampled rock cod lengths in finfish trawls. Note that numbers are not equivalent to Figure A1, as Figure A1 may include non-random samples and gear other than finfish trawls. Yearly numbers are summarized in Figures 4 and 5.