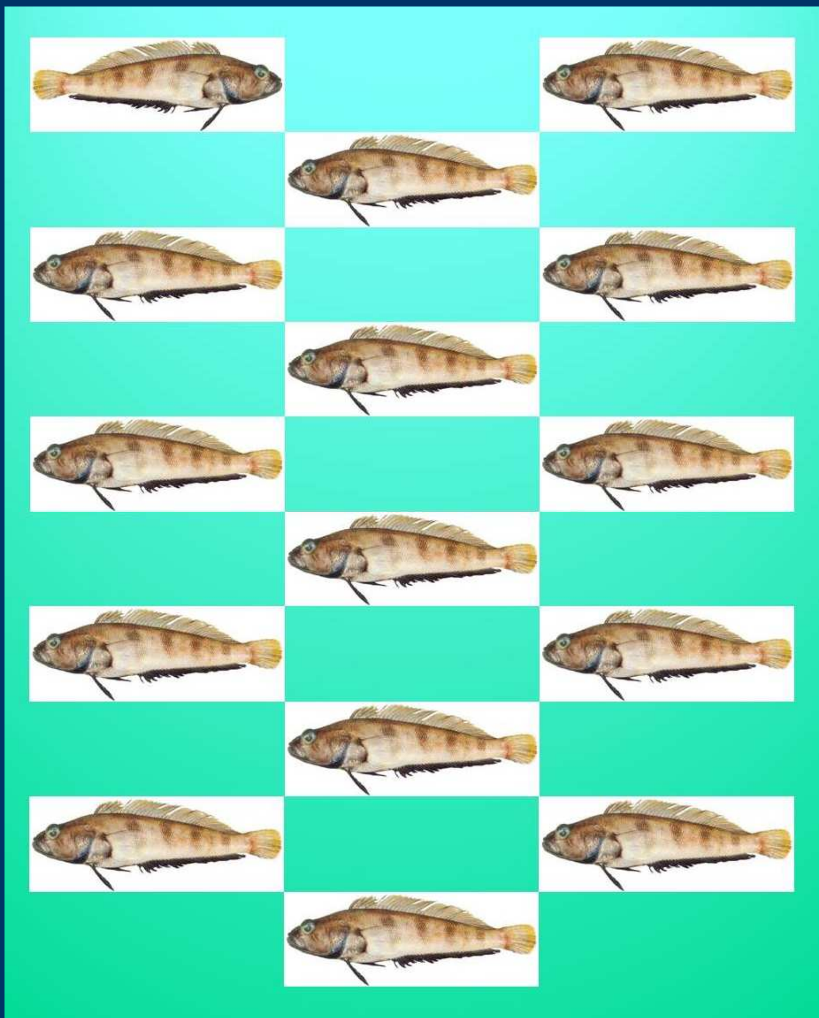
Stock Assessment

Rock Cod

Patagonotothen ramsayi



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Index

Abstract

Rock cod biomass in 2019 was estimated at 155,149 tonnes, using a Schaefer production model modified for variable carrying capacity. The production model time series beginning in 2005 (when rock cod were first species-identified consistently in Falkland Islands fishery catches) to 2019 indicated that biomass had been about level for the past two years. Maximum sustainable yield (MSY) of rock cod from the modified Schaefer production model was estimated at 34,330.4 tonnes. The February 2019 parallel groundfish and pre-season calamari surveys estimated a biomass of 37,793.3 tonnes rock cod in the combined survey area; the lowest estimate since the start of this survey series in 2010. Proportioning MSY to the ratio of the survey biomass estimate over the model biomass estimate gave a target total allowable catch of 8362.6 tonnes, higher than any annual reported catches since 2016. Despite current low impact of the commercial fisheries on rock cod, decreased lengths at 50% adulthood and qualitative overfishing indicators suggest that the stock is still depleted.

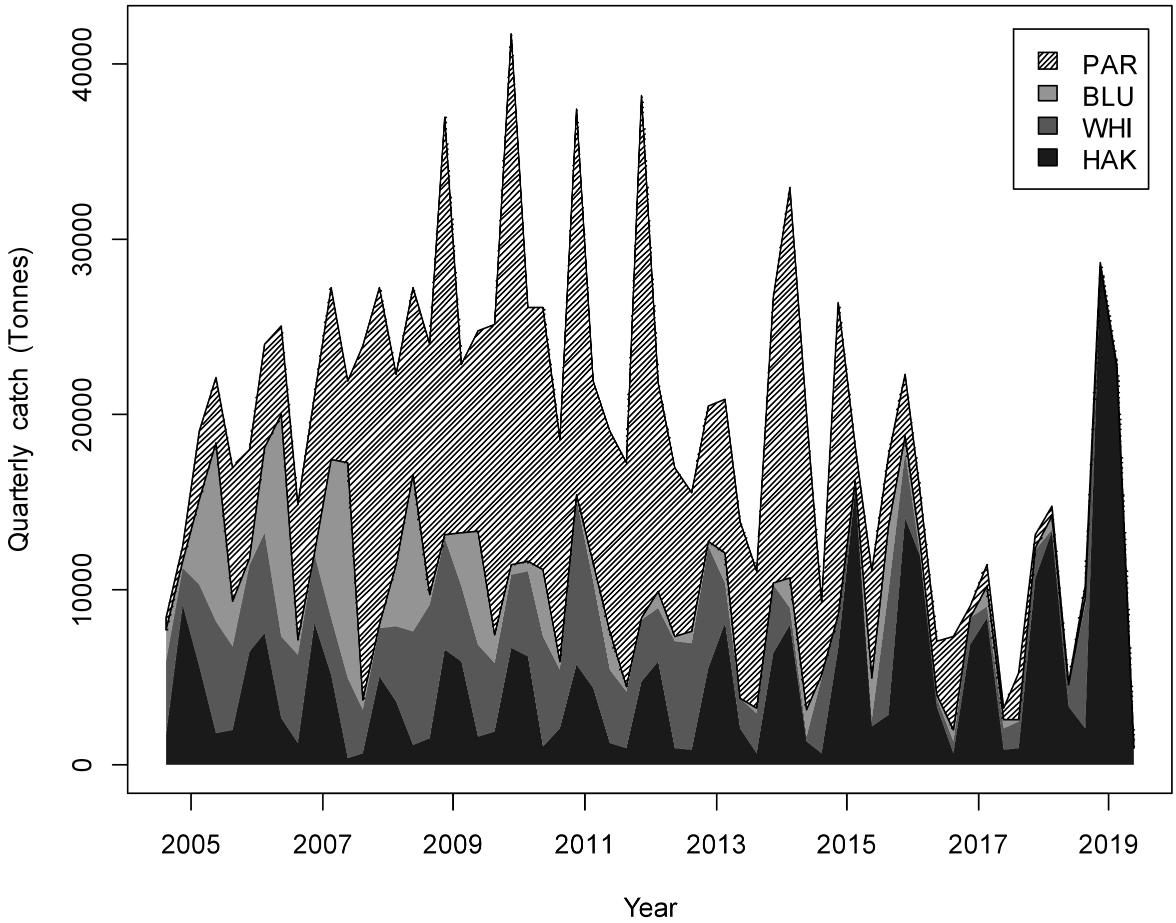
Introduction

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). 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.

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). Between 2006 and 2015 rock cod was the largest volume of finfish catch in Falkland Islands fisheries, but has since decreased substantially (Figure 1, FIG 2019). In a pattern commonly seen in other fisheries (Pauly et al. 1998), the increased commercial use of rock cod had coincided with catch decreases of higher-value species.

During 2019 a total of 970 tonnes rock cod were caught in the Falkland Islands zone, with catch by licence distributions shown in Table 1. Compared to last year (Winter 2019a), rock cod bycatches decreased considerably in the calamari fishery, and predominance shifted from calamari back to the finfish trawl fisheries, although rock cod catch increased only under W licence. Among finfish target licences, of 804 A-licence catch reports in 2019, rock cod was the highest catch species on 1 and the second-highest on 13 catch reports. Of 604 G-licence catch reports in 2019, rock cod was the highest catch species on 4 and the second-highest catch species on 34 catch reports. And of 762 W-licence catch reports in 2019, rock cod was the highest catch species on 2 and the second-highest on 16 catch reports.

Figure 1 [next page]. Quarterly catches in tonnes since 2005 in Falkland Islands fisheries of hake (HAK), hoki (WHI), blue whiting (BLU), and rock cod (PAR). The plot is stacked not superimposed; e.g., in 2nd quarter 2010, the highest peak, catch was HAK + WHI + BLU + PAR = 41695 t.



Methods
Production model

With annual catch data consistently available since 2005, the Falkland Islands rock cod stock has been modelled using a Schaefer production model (Schaefer 1954), expressed as a difference equation:

$$B_{t+1} = B_t + rB_t\left(1 - \frac{B_t}{K}\right) - C_t \tag{1}$$

where B_t and C_t are the stock biomass and catch in year t; r is the intrinsic population growth rate and K is the carrying capacity. Yearly catches (C_t) include out-of-zone commercial catch reports, as these are assumed to come from the same stock. The model is run from year t = 2005, when rock cod were starting to be recorded in catches as an identified species group (PAR or COX rather than 'other'). The model ends with year t = 2019, the last complete year of data. The Schaefer production model was optimized using survey biomass estimates – rather than commercial CPUE – for the index of abundance, and using a time-variable trend of carrying capacity (Winter and Gras 2018, Winter 2019a).

Rock cod biomass estimates were compiled from the seven sets of trawl surveys that have, since 2010, been conducted synchronously in February over the groundfish fishing zone and the *D. gahi* fishing zone (Ramos and Winter 2019). Additionally, data from a survey in February 2007 were accessed and paralleled with that season's *D. gahi* survey (Payá 2007) to extend back the available time series. The 2007 survey had been focused primarily on skates (Rajiformes) but covered much of the same area, and recorded the catch of significant quantities of rock cod (FIG 2007).

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

Licence		Rock cod catch	%
Code	Type	(Tonnes)	
A	Unrestricted finfish	107.2	11.0
G	Restricted finfish + *Illex*	207.6	21.4
W	Restricted finfish	273.9	28.2
F	Skate	0.1	0.0
C	Calamari 1st season	257.2	26.5
X	Calamari 2nd season	77.8	8.0
B	*Illex* squid	0.4	0.0
S	Surimi	0.0	0.0
L	Toothfish longline	0.0	0.0
E	Experimental	19.4	2.0
O	Other	26.7	2.7
Total		970.3	100.0

Biomass estimates used as the index of abundance were calculated from the survey trawl catch densities using inverse distance weighting (Shepard 1968), a deterministic method of spatial prediction that can be more reliable than kriging for small data sets (Kravchenko 2003, Mueller et al. 2004). Compared to last year (Winter 2019a), inverse distance weighting was implemented with an updated algorithm for calculating power factors (Ramos and Winter 2019), resulting in some changes to the previous biomass estimates.

The general form of the Schaefer production model defines carrying capacity K by a single variable, as the population is assumed stationary (at equilibrium). However, there is no theoretical basis for carrying capacity to be fixed (Carson et al. 2009, Chapman and Byron 2018), and disequilibrium may be especially manifest in a production model as cumulative changes of reproductive parameters, juvenile and adult survival, growth, and predator / prey interactions contribute to fluctuations in carrying capacity over time (Quinn 2003). Studies of other commercial fishery stocks have modified production models by assigning variable values to carrying capacity, correlated with environmental factors such as sea surface temperature and chlorophyll concentration (Wang et al. 2016, 2017). The large inter-annual changes in commercial and survey rock cod catches indicate that the Falklands rock cod population is not at equilibrium. Accordingly, carrying capacity was allowed to flex between years, representing a surrogate for changes in rock cod habitat suitability, or the encroachment of other species. Possible encroachment was examined by plotting catch correlations and LOESS smooths between rock cod and other major finfish targets hake (*Merluccius hubbsi* + *M. australis*), hoki (*Macruronus magellanicus*), and southern blue whiting (*Micromesistius australis*). The production model was thus modified as:

$$B_{t+1} = B_t + rB_t\left(1 - \frac{B_t}{K_t}\right) - C_t \qquad (2)$$

where K_t is the yearly carrying capacity. To prevent K_t from fluctuating too strongly, the model was parameterized with carrying capacity in 7 years (every 2[nd] or 3[rd] year K_{2005}, K_{2008}, K_{2010}, K_{2013}, K_{2015}, K_{2017}, K_{2019}), but optimized on a LOESS smooth prediction (span = 0.9) of these 7 years applied to all years 2005-2019.

The full model for this stock assessment thus optimized 9 parameters: K_{2005}, K_{2008}, K_{2010}, K_{2013}, K_{2015}, K_{2017}, K_{2019}, B_1, and r. Biomass in the first year of a fishery (here: $B_1 = B_{2005}$) is often assumed to equal the carrying capacity (Punt 1990, Hilborn and Mangel 1997, Maunder 2001), removing one free parameter to be optimized. However, unreported catches of rock cod were certainly taken before 2005, and together with the non-stationary profile of the rock cod stock (Laptikhovsky et al. 2013, Winter and Gras 2018, Winter 2019a), the assumption of $B_1 = K_{2005}$ would have been inappropriate.

Optimization was calculated in R programming package 'optimx' using the Nelder-Mead algorithm (Nash and Varadhan 2011). Starting values for optimization were set by re-entering the output values obtained from last year's assessment (Table 3 in Winter 2019a), but switching the carrying capacity of year 2018 as a starting value to 2019.

The objective function of model optimization was:

$$\left(\frac{n_t}{2} \cdot \log(2\pi)\right) + \left(n_t \cdot \log(\sigma)\right) + \frac{\sum_t^{survey}\left(\log(B_{optim\ t}) - \log(B_{survey\ t})\right)^2}{2\sigma^2} \tag{3}$$

where $$\sigma = \sqrt{\left(\log\left(\frac{B_{optim\ t}}{B_{survey\ t}}\right)\right)},$$

summed on the survey years t = 2007, 2010, 2011, 2015, 2016, 2017, 2018, 2019. This configuration of the objective function assumes that survey biomasses ($B_{survey\ t}$) are absolute biomasses, rather than a relative index. The model thereby loses some generality but becomes more stable by not having to optimize a catchability coefficient. To prevent K values from diverging excessively, a penalty function was added to the objective function to act against max K > 3× min K. To prevent growth rate r from diverging excessively, a penalty function was added to act against r > 0.8. The difference between r and 0.8 was multiplied by 2.625 to increase weight of the penalty[1]. Thus the objective function for optimization became:

$$\left(\frac{n_t}{2} \cdot \log(2\pi)\right) + \left(n_t \cdot \log(\sigma)\right) + \frac{\sum_t^{survey}\left(\log(B_{optim\ t}) - \log(B_{survey\ t})\right)^2}{2\sigma^2}$$
$$+ \begin{Bmatrix} \max(K_{t\ optim})/\min(K_{t\ optim}), & \text{if } \max(K_{t\ optim})/\min(K_{t\ optim}) > 3 \\ 0, & \text{if } \max(K_{t\ optim})/\min(K_{t\ optim}) \le 3 \end{Bmatrix}$$
$$+ 2.625 \times \begin{Bmatrix} abs(r - 0.8), & \text{if } r > 0.8 \\ 0, & \text{if } r \le 0.8 \end{Bmatrix} \tag{4}$$

Variability of the modified Schaefer production model was evaluated by randomly re-sampling from the normal distribution $N(\mu = \bar{x}_t, \sigma = sd_t)$ of each year's (t = 2007, 2010, 2011, 2015, 2016, 2017, 2018, 2019) survey biomass estimate, then substituting the set of re-samples for $B_{survey\ t}$ in Equation 4 and re-calculating the optimization. The re-sample routine was run 30,000× and 95% confidence intervals reported for annual biomass and carrying

[1] This penalty weight factor was determined empirically, over the range of 0.5 to 3.5, according to which weight gave the best combination of convergence of the optimization, r < 1, B < K, and B/B_{MSY} during the last 3 years.

capacity estimates. To stabilize the estimation, the median value of each year's 30,000 annual biomass and carrying capacity was retained as the final output value rather than the empirical optimization.

Maximum sustainable yield was defined according to the formulation of Hilborn and Walters (1992), applied to the most recent year for K:

$$\mathrm{MSY} = \frac{r \cdot K_{2019}}{4} \qquad (5)$$

Stock status time series from the modified Schaefer production model were visualized as Kobe plots of B / B_{MSY} on the x-axis vs. F / F_{MSY} on the y-axis (Maunder and Aires-da-Silva 2011). The ratio B / B_{MSY} is the measure of a population being in an overfished state, relative to its maximum sustainable yield (if B / B_{MSY} < 1), and the ratio F / F_{MSY} is the measure of overfishing currently ongoing (if F / F_{MSY} > 1). Values of B are the annual biomass estimates of the modified Schaefer production model; F is annual catch divided by B. B_{MSY} and F_{MSY} are fisheries reference points defined as B_{MSY} = K/2 and F_{MSY} = r/2 (Froese et al. 2017, Zhou et al. 2018).

Underreporting

An additional analysis was undertaken to estimate proportions of rock cod biomass that may have been unreported or underreported discard. Fishing vessels in Falkland Islands waters are required to record discard as part of their daily catch reports; however, discard self-reporting in fishing industries is generally a low priority and often imprecise (Lordan et al. 2011). For independent estimation, vessel-reported discard proportions can be measured against observer data (as available), in two ways: comparison of size distributions, and comparison of catch composition.

Commercial production usually prefers larger individual fish and squid (Batsleer et al. 2015), but in fisheries without legal minimum landing sizes the threshold of retention vs. discard sorting may be ad hoc. Roux and Winter (2013) estimated that the retention threshold for rock cod was about 25 cm total length until 2008, then decreased to about 23 cm total length with the fishery adapting to catches of smaller individuals. As a rough measure, the proportions[2] of rock cod reported discarded per year were compared to the proportions under 25/23 cm from random samples measured by observers.

Alternatively, vessels may discard any size rock cod (or other species) if it has no market value. In that case, size distributions are inconclusive but the ratio between the quantity of rock cod and other catch reported would differ from the ratio of catch composition measured by the observer. A comparison was calculated between the weight of rock cod in the vessel catch report and the weight of rock cod back-calculated from the proportion represented by rock cod in corresponding observer catch composition samples. Because vessels are not required to report all bycatch – only principal categories – the comparison was limited to that part of the observer catch composition sample comprising species that were in the vessel catch report itself[3].

Both types of comparison were calculated for years 2005 through 2019. All catch reports were retained that could be matched with observer samples taken the same day on the same vessel. Underreporting of rock cod would be suggested if the 'discard-size' proportion of rock cod in observer samples was higher than the actual discard proportion in the vessel

[2] Converted to biomass by the weight-length relationship $W = a \cdot L^b$ (Froese 2006).

[3] Catch code OTH (other) was excluded, and all skate species identified by observers were matched to the unspecified vessel reporting code RAY.

catch report, or if the rock cod weight back-calculated from the observer sample was higher than the rock cod weight in the vessel catch report. Comparisons were grouped by year and by licence type, whereby unrestricted finfish licences A and Y, restricted finfish licences W and Z, skate licences F and R, and calamari licences C and X were respectively grouped together. Error distributions of the observer vs. vessel report average differences were calculated by bootstrap resampling of the catch reports per year / licence type[4], and additionally for 'discard-size' proportions, by hierarchical bootstrap resampling of the lengths within observer samples.

Margins of rock cod catch inferred from observer samples, above what was reported as vessel catch, were averaged per year and licence, smoothed across years, and multiplied by the total numbers of licenced catch reports. The biomass calculations of equations 2 – 5 were then reprised with the extrapolated total margins of unreported rock cod catch added to the reported catches

Lengths at 50% adulthood

For comparative evaluation against the production model assessment, lengths at 50% adulthood were calculated from binomial logistic regressions of rock cod length vs. adulthood in each year. 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. Maturities-at-length were taken starting in 2003, 2 years before commercial rock cod data were consistently available, but FIFD observers had already started collecting these measurements. The aggregates of 50% adulthood lengths were plotted against years and trends examined with LOESS smooths (degree = 2, span = 0.90), weighted by inverse variance (Marín-Martínez and Sánchez-Meca 2010) of each year's binomial logistic regression. Males and females were analysed separately as rock cod growth and maturation are sexually dimorphic (Brickle et al. 2006a, 2006b).

Overfishing indicators

The three qualitative overfishing indicators proposed by Froese (2004) were tested for 2019 catches from the available age, length, and maturity measurements[5]: (1) % mature fish in catch, (2) % optimum-length fish in catch, and (3) % 'mega-spawners' in catch. Optimum length (L_{opt}) was calculated by the empirical equation:

$$\log(L_{opt}) = 1.0421 \cdot \log(L_{\infty}) - 0.2742 \tag{6}$$

(Froese and Binohlan 2000), where L_{∞} is asymptotic length according to the von Bertalanffy growth function, modelled to the rock cod data in R package 'fishmethods' (Nelson 2015). L_{opt} represents the length where the number of fish in a given unfished year-class × their mean individual weight is maximum; thus obtaining maximum yield and potential revenue. Mega-spawners are defined as fish 10% larger than L_{opt} (Froese 2004).

[4] Error calculation was limited to year / licence type groups comprising ≥5 catch reports.

[5] Available measurements being those fish landed on-board a ship where the observer can sample them. The potential bias is not addressed here that smaller fish may have higher escapement than larger fish, and that calamari licence fisheries allow smaller meshes than finfish licence fisheries. However, the analysis was restricted to random-sampled fish, i.e., FIFD sampling codes R and S.

Results

Production model

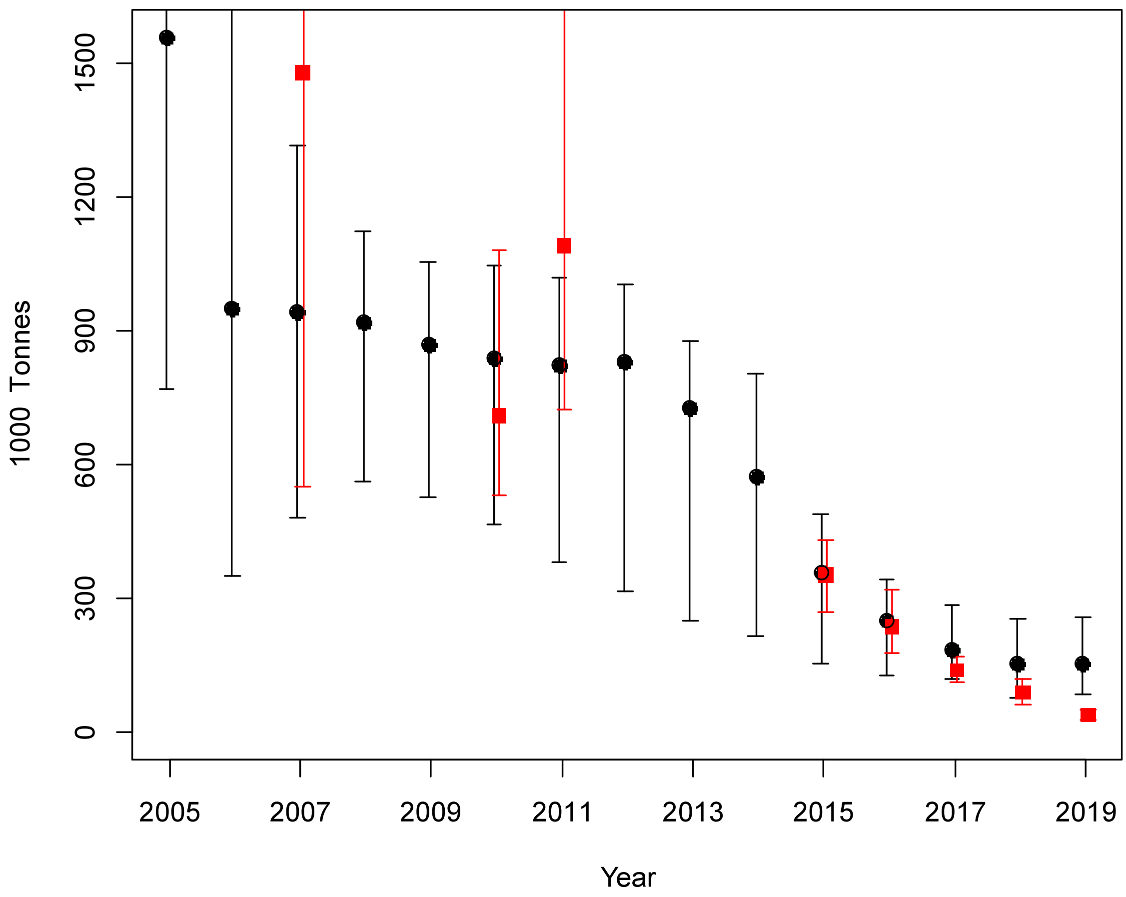
Survey biomass estimates of rock cod ranged from 1,481,537 tonnes in 2007 to 37,793 tonnes in 2019, thus a decrease by 39× in 12 years (Table 2). Distributions in most February surveys showed localized high concentrations (Appendix Figure A1).

Table 2. Rock cod biomass estimates from parallel groundfish and *D. gahi* surveys in February. N = number of trawl stations per survey. Except for year 2007, the data correspond to Tables 1 and A1 in Ramos and Winter (2019). Biomass estimates are equivalent to the red symbols in Figure 2.

Year	N trawl stations		Biomass	95% CI
	Groundfish	*D. gahi*	(Tonnes)	(Tonnes)
2007	36	64	1481537.0	548973.7 – 2767159.1
2010	87	55	709498.1	531586.2 – 1080580.6
2011	88	58	1090654.7	722624.3 – 1761468.5
2015	89	57	352569.7	269340.5 – 430392.5
2016	90	56	235339.1	178002.1 – 318431.2
2017	90	58	138641.1	111082.8 – 170695.2
2018	97	59	87595.8	61132.9 – 118475.9
2019	83	52	37793.3	27541.4 – 51384.4

Table 3. Annual biomass and carrying capacity estimates from the re-sampled optimizations of the modified Schaefer production model. Biomass estimates are equivalent to the black circles in Figure 2, carrying capacity estimates are equivalent to Figure 3.

Year	Biomass (T)		Carrying capacity K (T)	
	Median	95% CI	Median	95% CI
2005	1560012.5	768595.8 – 3667218.2	945600.1	189124.4 – 1126178.1
2006	952869.7	351758.2 – 1680813.2	947145.6	247213.0 – 1123272.1
2007	942862.8	479739.8 – 1318487.4	947898.2	233926.2 – 1124349.4
2008	921274.3	560333.6 – 1123819.6	944034.2	208984.8 – 1119925.5
2009	868873.6	526890.1 – 1055710.3	938006.6	217265.1 – 1124652.8
2010	840027.2	465900.6 – 1047765.4	930779.0	157045.2 – 1126048.9
2011	825630.6	380281.0 – 1018524.4	945794.3	185630.2 – 1117388.7
2012	831105.3	315832.2 – 1005746.1	927574.2	161944.9 – 1087346.9
2013	728497.1	250211.2 – 877086.9	790501.7	176508.8 – 944980.6
2014	572249.6	215465.3 – 803950.6	604949.8	140405.9 – 848960.2
2015	356520.1	154225.1 – 489877.9	425267.9	143987.6 – 574219.1
2016	248664.8	127795.1 – 343090.5	282618.6	142360.3 – 379130.2
2017	185895.3	117323.2 – 284621.1	210176.6	135544.2 – 324594.5
2018	154080.0	78463.8 – 253711.2	176071.5	92859.3 – 325512.9
2019	155149.0	82632.5 – 257801.3	177741.7	91047.6 – 387179.4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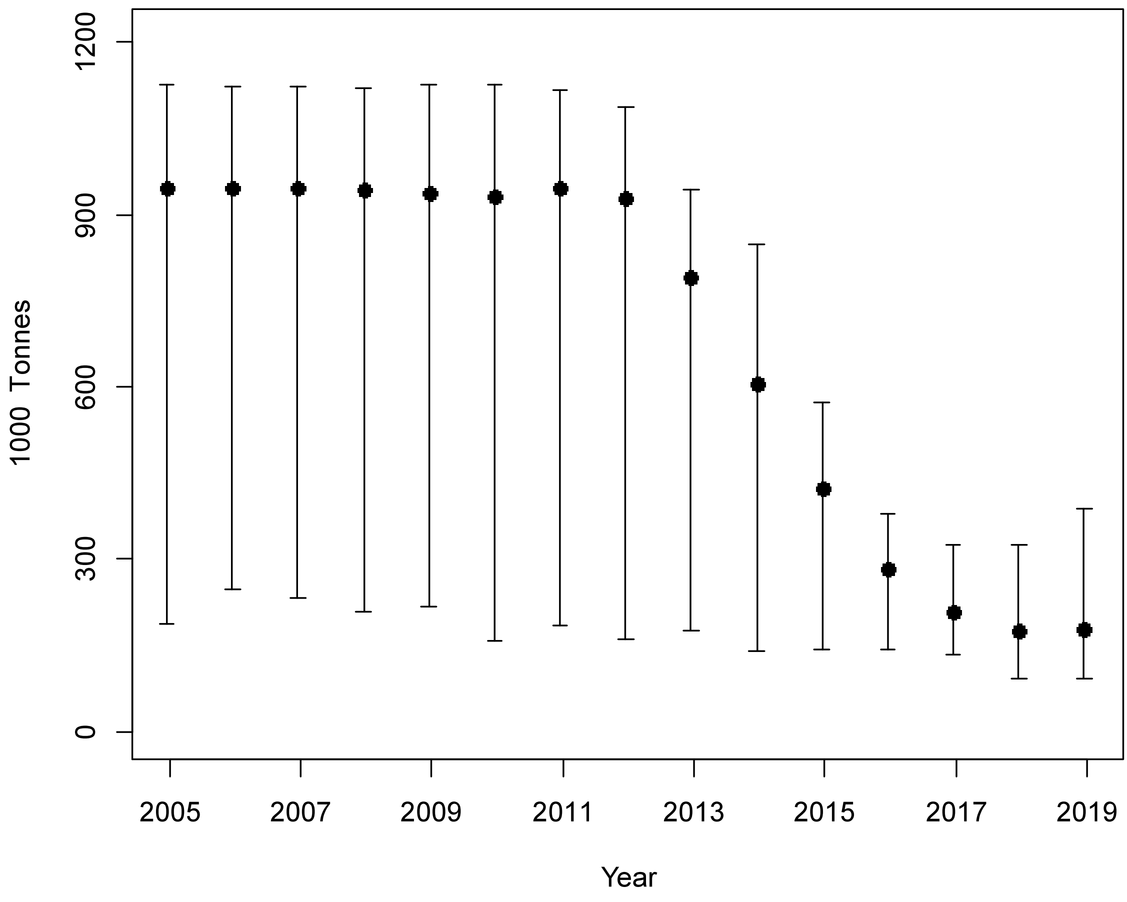
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Figure 2 [previous page, top]. Annual estimates of rock cod biomass, 2005 to 2019. Red squares: area estimates from the parallel groundfish – *D. gahi* surveys. Black circles: median optimized estimates from the modified Schaefer production model. Both sets of estimates with 95% confidence intervals. Red squares are equivalent to the data in Table 2, black circles are equivalent to the biomass data in Table 3.

Figure 3 [previous page, bottom]. Annual median population carrying capacity (K) optimized by the modified production model, with 95% confidence bars. Values are equivalent to Table 3.

Production model optimization yielded 29,867 stable convergences among the 30,000 iterations. Production model median biomass estimates of rock cod ranged from 1,560,012.5 tonnes in 2005 to 831,105.3 tonnes in 2012 before decreasing consistently from 2012 onwards (Figure 2, Table 3). Despite methodological changes, the 2010 biomass estimate obtained in this assessment is not significantly different from the 2010 biomass estimate calculated for the first systematic assessment of rock cod (Winter et al. 2010). Estimates of carrying capacity were generally 2% - 20% higher than the biomass in any year (except for the anomalous year 2005 (Figure 3, Table 3)), with a slightly increasing trend over time of the ratio K/B. Production model median biomass estimates were non-significantly different from the survey biomass estimates, in all years except the last one – 2019, which presented a very narrow confidence interval due to the consistently low rock cod catches obtained in that year's survey (Figure 2).

Optimized MSY parameter values of the modified Schaefer production model are summarized in Table 4. Population growth rate r resulted in a relatively high median estimate of 0.773[6], corresponding to the range of medium resilience (Froese et al. 2017) postulated by Froese and Pauly (2019), but with a large margin of uncertainty. Maximum sustainable yield (34,330 t) was estimated higher but not significantly different from last year (Winter 2019a).

Table 4. Parameter values for rock cod maximum sustainable yield.

Parameter		Median	95% CI
Population growth rate (yr^{-1})	r	0.773	0.039 – 0.835
2019 Carrying capacity (t)	K	177741.7	91047.6 – 387179.4
Maximum sustainable yield (t)	MSY	34330.4	1753.8 – 50890.6

The time series of B / B_{MSY} and F / F_{MSY} calculated from the modified Schaefer production model indicate that from 2005 to 2019, the rock cod population was never at a status below maximum sustainable yield (Table 5). This result is hard to reconcile with the finding that by any measure, the rock cod stock has decreased at least 10× since its highest levels prior to 2010 (Figure 2). A potentially biasing factor in the modelling result is that optimization tunes strongest on the carrying capacity K, which accounts for most of the parameter inputs (Equation 2). Even with a penalty function against >3, the model output obtained a ratio of maximum K / minimum K = 5.4 (Table 3, Figure 3).

Accordingly, a hypothetical adjustment was calculated to bring the rate of K variation in line with its expectation:

[6] r = 0.773 means the population is intrinsically (unrestrained by carrying capacity) capable of increasing by $e^{0.773} - 1$ = 116.6% per year.

$$\text{adjusted } K_t = K_t + \left(\text{max. diff} \times \left(\frac{(\max(K_t) - K_t)}{\max(K_t) - \min(K_t)}\right)\right)\Bigg|_{t=2005}^{t=2018} \quad (7)$$

where $\text{max. diff} = \max(K_t) \times \left(\frac{\text{min Hake fit catch}_t}{\text{max Hake fit catch}_t}\right) - \min(K_t)$. The ratio 'min Hake fit catch / max Hake fit catch' corresponds to the minimum and maximum of the LOESS smooth in the HAK plot of Figure 4.

Table 5. Rock cod fishing mortality (F) and biomass (B) time series in relation to maximum sustainable yield parameters.

Year	B / B_{MSY}	F / F_{MSY}
2005	3.2995	0.0153
2006	2.0121	0.0676
2007	1.9894	0.0858
2008	1.9518	0.1714
2009	1.8526	0.1759
2010	1.8050	0.2387
2011	1.7459	0.1769
2012	1.7920	0.1997
2013	1.8431	0.1224
2014	1.8919	0.2855
2015	1.6767	0.2170
2016	1.7597	0.1398
2017	1.7689	0.1119
2018	1.7502	0.0721
2019	1.7458	0.0162

Hake is the one major finfish target that showed a significant[7] and inverse annual catch correlation with rock cod; in contrast to hoki and southern blue whiting (Figure 4). Hakes, like rock cod, are near-bottom fish (Arkhipkin et al. 2012), suggesting that habitat depreciates for rock cod with higher presence of hakes which are spatially proximate predators and competitors.

B / B_{MSY} re-calculated with the adjusted K_t (now designated $B / B_{MSY}*$)[8] produced the Kobe plot shown in Figure 5. The trajectory proceeded from deep in the green field in 2005 – as typical for an un-fished or under-fished stock, to inside the yellow field in 2019 – indicative of a stock that is below maximum sustainable yield but not currently being over-fished. Concomitantly, the trajectory never approached the threshold for overfishing ($F / F_{MSY} = 1$, on the Y-axis).

[7] Significance threshold at the statutory 5% level, but adjusted with the Šidák correction to $1 - (1 - 0.05)^{(1/3)} = 1.695\%$ because correlation was tested in parallel on three separate species. This adjustment is equivalent to approx. 2.3875 standard deviations for the 98.305% confidence interval, compared to 1.96 standard deviations for the 95% confidence interval (Rohlf and Sokal 1981).

[8] Note that this is an ad-hoc adjustment for visualization only. As the production model optimizes r and K simultaneously, values of B and B_{MSY} cannot truly be adjusted independently of each other, and $B / B_{MSY}*$ is not equivalent to, e.g., a limit constraint on the K-ratio in the optimization.

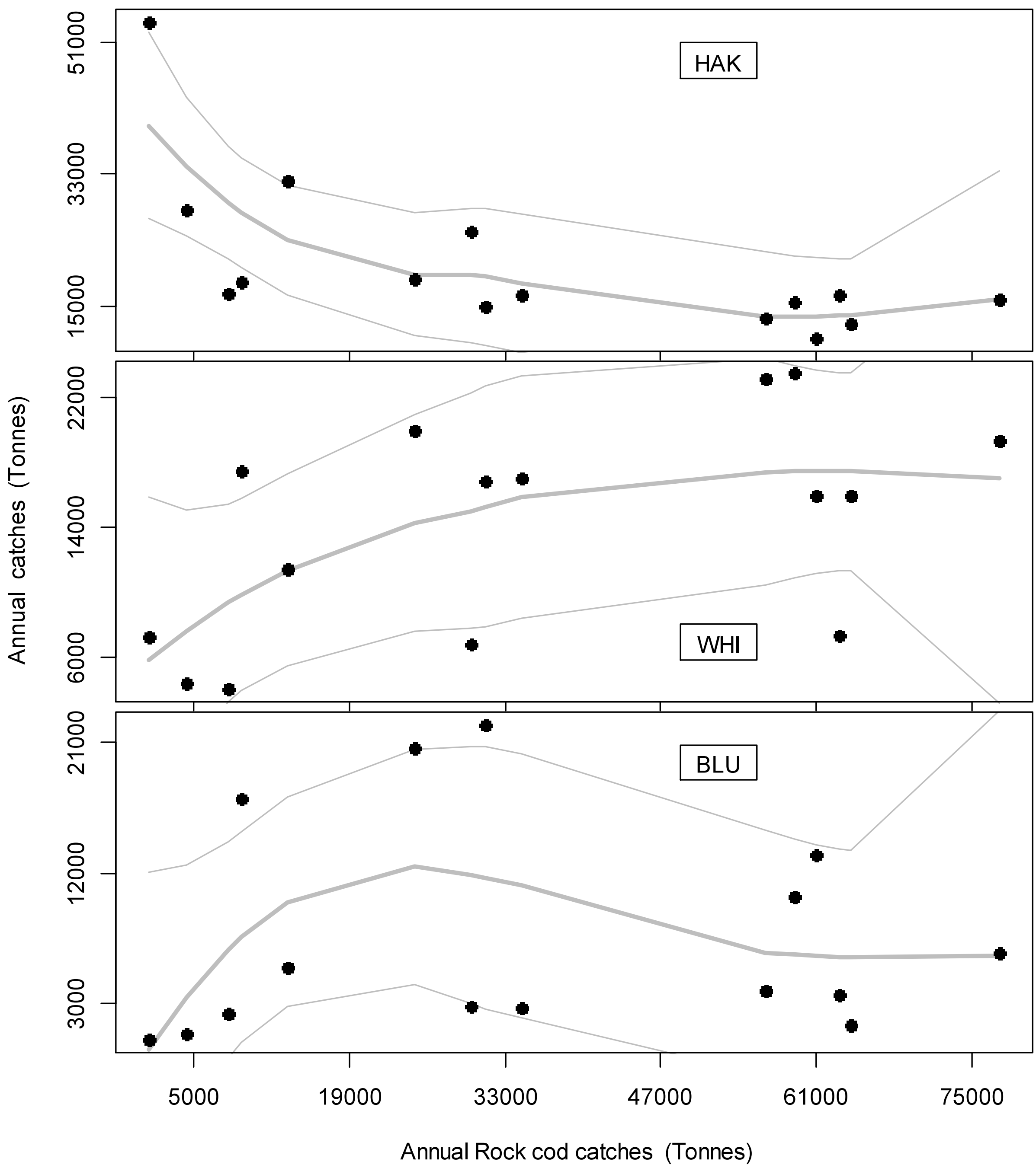
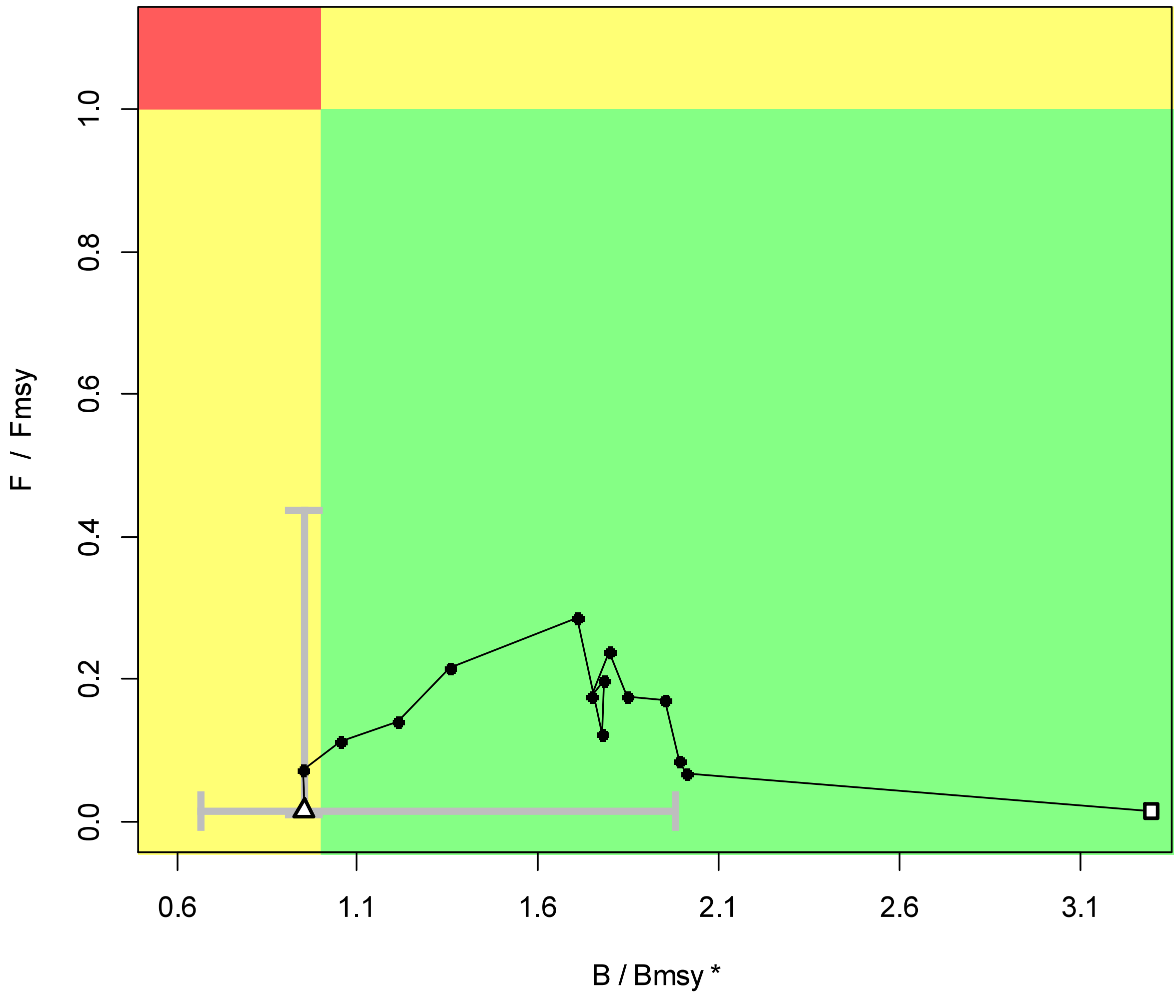


Figure 4. LOESS smooths (degree = 2, span = 0.90) ± Šidák-corrected 95% confidence intervals of hake (HAK), hoki (WHI), and southern blue whiting (BLU) annual catches vs. rock cod annual catches, 2005 to 2019.

Figure 5 [next page]. Kobe plot of the B / B_{MSY}* vs. F / F_{MSY} time series from 2005 (square) to 2019 (triangle). Grey brackets are the 95% confidence intervals of the 2019 triangle estimates.



Underreporting

A total of 2671 catch reports from 2005 to 2019 were matched with catch composition samples, of which 2590 also had rock cod length samples. Rock cod catch and discard proportions are summarized for the licence types comprising most rock cod catch: unrestricted finfish (A or Y licence) – Table 6, finfish + *Illex* (G licence) – Table 7, restricted finfish (W or Z licence) – Table 8, and calamari (C or X licence) – Table 9. Licence types for skate, *Illex*, and surimi licences, which catch minor quantities of rock cod, are in the appendix Tables A1 – A3. Tables 6 – 9 show a consistent pattern of observer samples in most years having a significantly lower proportion (negative difference) of 'discard-size' rock cod than the vessels' correspondingly reported discard proportions of their rock cod catches. The outcome implies that vessels discarded more rock cod than just undersized individuals, or that the 25/23 cm size thresholds were not accurate to begin with. In contrast, for half the years under A/Y and C/X licences (Tables 6 and 9), and a quarter of the years under G and W/Z licences (Tables 7 and 8), observer samples showed significantly higher average back-calculated rock cod weights than the corresponding vessel catch reports. Those differences are not absolutely definitive as other species could also be under- or misreported, but in the aggregate the differences suggest that some vessels recorded less rock cod than was actually in their catches.

Average rock cod catch tonnage differences (the second-last columns in Tables 6 to 9) are plotted in Figure 6, with LOESS smooth trends of the differences from 2005 to 2019.

Smoothed average differences per year are summarized in Table 10 with reported fishing days per licence, and the resulting extrapolated total estimates of unreported catch.

Table 6. Comparative metrics for rock cod discard (percentage) and catch (tonnes) from commercial vessel reports and from on-board observers, in the unrestricted finfish fishery (A or Y licence). Differences are Obs. – Com., followed by 95% confidence intervals of the difference when N ≥ 5. Note that N may be less for % discard than for catch; not all observer samples include size measurements. Red fields: significantly negative difference, green fields: significantly positive difference; significance is indicated by the confidence interval excluding zero.

Year	% PAR discard (size)					Avg. T PAR catch				
	N	Obs.	Com.	Difference		N	Obs.	Com.	Difference	
2005	2	15.6	26.1	-10.5,		2	16.06	13.62	2.45,	
2006	24	15.9	65.9	-50.1,	-68.4 to -28.0	24	5.62	4.52	1.10,	-1.09 to 2.99
2007	37	17.3	53.5	-36.2,	-54.1 to -17.5	56	10.18	5.89	4.29,	1.82 to 6.84
2008	38	2.8	38.6	-35.8,	-51.7 to -21.3	38	19.33	20.42	-1.08,	-4.39 to 2.18
2009	84	14.0	41.3	-27.4,	-34.0 to -21.6	86	17.31	14.93	2.38,	0.89 to 3.87
2010	81	9.8	39.9	-30.1,	-38.7 to -21.7	81	29.16	27.86	1.30,	-1.34 to 3.83
2011	46	7.1	19.4	-12.4,	-18.8 to -6.7	46	22.30	23.76	-1.46,	-3.07 to 0.01
2012	23	16.1	9.3	6.8,	-1.0 to 13.2	24	11.71	11.97	-0.26,	-2.24 to 1.33
2013	18	34.9	48.6	-13.7,	-36.8 to 7.8	18	4.70	3.74	0.96,	-0.38 to 2.74
2014	29	4.4	10.2	-5.8,	-9.3 to -2.8	29	17.76	13.96	3.80,	1.86 to 6.02
2015	23	3.6	12.0	-8.4,	-10.7 to -5.3	23	2.20	1.60	0.60,	0.03 to 1.47
2016	20	34.3	24.3	10.0,	-10.1 to 26.9	20	1.07	1.06	0.02,	-0.34 to 0.33
2017	51	16.2	37.3	-21.1,	-28.9 to -14.2	56	0.32	0.18	0.14,	0.06 to 0.25
2018	37	25.8	46.5	-20.7,	-40.6 to 5.2	38	0.35	0.23	0.12,	0.01 to 0.31
2019	27	19.7	75.8	-56.1,	-78.5 to -30.5	28	0.07	0.05	0.02,	0.01 to 0.03

Table 7. Comparative metrics for rock cod discard and catch from commercial vessel reports and from on-board observers, in the restricted finfish + *Illex* fishery (G licence). Description as for Table 6.

Year	% PAR discard (size)					Avg. T PAR catch				
	N	Obs.	Com.	Difference		N	Obs.	Com.	Difference	
2005	1	13.2				1	5.11	0.00	5.11,	
2006	6	15.6	16.0	-0.4,	-6.6 to 5.9	6	13.29	11.46	1.83,	-2.39 to 7.66
2007	11	12.1	23.7	-11.6,	-20.8 to -1.6	11	17.04	17.01	0.03,	-4.24 to 4.36
2008	40	2.2	5.8	-3.6,	-5.4 to -1.6	43	18.57	19.88	-1.31,	-3.40 to 0.70
2009	29	8.2	20.3	-12.1,	-17.4 to -7.0	29	23.43	22.63	0.8,	-2.59 to 4.08
2010	32	14.2	25.9	-11.7,	-17.5 to -6.3	33	30.56	26.94	3.62,	1.06 to 6.21
2011	26	13.3	10.0	3.3,	-0.4 to 7.0	28	42.88	42.22	0.66,	-1.98 to 3.28
2012	30	10.8	8.6	2.2,	-3.2 to 6.9	30	24.81	23.51	1.30,	-1.81 to 3.90
2013	5	43.7	43.3	0.4,	-19.8 to 31.1	5	7.61	8.72	-1.12,	-3.87 to 1.32
2014	10	1.4	2.8	-1.4,	-3.6 to 0.6	17	14.47	14.6	-0.13,	-4.78 to 4.38
2015	5	21.5	10.0	11.4,	-2.6 to 34.0	5	11.88	10.95	0.93,	-0.07 to 2.41
2016	30	14.5	20.8	-6.3,	-18.4 to 6.1	31	1.67	0.98	0.69,	0.20 to 1.26
2017	44	16.5	25.8	-9.4,	-16.6 to -2.5	44	1.00	0.43	0.57,	0.10 to 1.31
2018	25	30.7	44.4	-13.7,	-32.7 to 2.1	26	0.41	0.27	0.14,	0.03 to 0.27
2019	13	6.4	0.4	6.0,	1.9 to 12.6	13	0.08	0.09	-0.01,	-0.1 to 0.05

Table 8. Comparative metrics for rock cod discard and catch from commercial vessel reports and from on-board observers, in the restricted finfish fishery (W or Z licence). Description as for Table 6.

Year	% PAR discard (size)					Avg. T PAR catch				
	N	Obs.	Com.	Difference		N	Obs.	Com.	Difference	
2005	37	19.2	64.1	-44.9,	-59.4 to -16.8	38	4.81	2.19	2.61,	1.13 to 4.58
2006	21	31.4	43.5	-12.1,	-21.3 to -2.1	23	13.46	10.43	3.03,	0.57 to 5.34
2007	8	6.1	15.6	-9.5,	-15.4 to -0.1	8	16.86	13.67	3.19,	1.35 to 4.96
2008	88	2.4	8.3	-5.9,	-7.8 to -4.2	88	16.23	19.69	-3.46,	-5.66 to -1.23
2009	84	8.4	18.8	-10.4,	-18.7 to -3.6	84	18.72	17.00	1.72,	-0.49 to 3.84
2010	60	16.4	10.8	5.6,	1.5 to 9.5	61	16.22	17.37	-1.15,	-3.56 to 1.17
2011	50	9.1	9	0.2,	-5.0 to 4.2	51	15.13	14.77	0.36,	-1.40 to 2.02
2012	36	12.1	5.9	6.2,	2.8 to 9.8	37	24.64	23.56	1.08,	-0.75 to 2.88
2013	17	18.8	14.3	4.6,	-4.5 to 14.3	17	14.16	13.23	0.92,	-1.75 to 3.02
2014	33	1.8	5.5	-3.6,	-5.0 to -2.0	36	37.42	38.39	-0.97,	-4.60 to 2.21
2015	80	6.9	6.6	0.3,	-3.0 to 2.6	82	7.55	8.51	-0.97,	-2.21 to 0.13
2016	40	22.9	30.7	-7.7,	-18.7 to 2.1	40	2.43	0.98	1.46,	0.15 to 3.92
2017	4	3.4	0	3.4,		4	10.86	1.10	9.76,	
2018	27	7.1	33.4	-26.3,	-47.0 to -9.6	27	1.18	0.84	0.34,	-0.08 to 1.10
2019	14	16	10.2	5.8,	-6.2 to 16.6	15	0.31	0.26	0.05,	-0.02 to 0.15

Table 9. Comparative metrics for rock cod discard and catch from commercial vessel reports and from on-board observers, in the calamari fishery (C or X licence). Description as for Table 6.

Year	% PAR discard (size)					Avg. T PAR catch				
	N	Obs.	Com.	Difference		N	Obs.	Com.	Difference	
2005	33	51.6	99	-47.3,	-54.2 to -38.8	35	1.15	1.24	-0.08,	-0.83 to 0.54
2006	32	76.4	100	-23.6,	-33.4 to -13.7	32	6.73	4.14	2.59,	-0.36 to 6.20
2007	47	51.1	100	-48.8,	-54.9 to -42.2	48	5.69	5.51	0.19,	-0.93 to 1.30
2008	50	23.6	96.6	-73.0,	-79.9 to -64.4	51	6.82	4.81	2.01,	0.56 to 3.69
2009	119	41.2	98	-56.8,	-64.1 to -48.7	122	3.53	4.26	-0.73,	-2.12 to 0.41
2010	53	41.6	100	-58.4,	-66.0 to -49.4	53	7.77	4.95	2.82,	0.45 to 5.85
2011	63	40.4	92.7	-52.2,	-62.2 to -39.0	66	4.14	3.64	0.50,	-0.50 to 1.76
2012	104	55	98.9	-43.8,	-50.2 to -37.0	106	2.56	1.87	0.70,	0.27 to 1.22
2013	61	65.8	96.9	-31.0,	-37.3 to -23.6	63	2.44	1.61	0.82,	0.14 to 1.61
2014	58	55.6	98.9	-43.3,	-51.5 to -34.7	62	3.39	2.46	0.94,	-0.08 to 2.01
2015	67	71.9	95.7	-23.8,	-31.6 to -14.3	67	5.57	4.20	1.37,	0.59 to 2.19
2016	87	82.4	99.4	-17.0,	-21.7 to -12.5	90	3.20	2.33	0.87,	0.20 to 1.69
2017	174	68.1	98.1	-30.0,	-34.6 to -24.6	176	1.97	1.24	0.73,	0.47 to 1.01
2018	55	92.2	100	-7.8,	-11.3 to -4.8	55	0.95	0.61	0.35,	0.17 to 0.56
2019	75	73.6	100	-26.4,	-32.2 to -20.9	75	0.67	0.20	0.47,	0.04 to 1.29

Including the extrapolated total estimates of unreported catch in the modified Schaefer production model reduced the biomass estimate in each year, but by trivial, non-significant amounts (Figure 7, Table A4). The calculation of extrapolated unreported catch did not include some quantities that would have occurred in skate, *Illex*, and surimi fisheries (Tables A1 to A3), however; these fisheries take consistently low rock cod bycatches (Table 1 for 2019, data not shown for earlier years) that would have made little change to the biomass modelling outcome. The small effects shown in Figure 7, and correspondingly in Table 11 for MSY, reflect that rock cod catches were low proportions of estimated biomasses regardless, and putative underreporting does not, in any case, change the biomass index from the February surveys (Table 2).

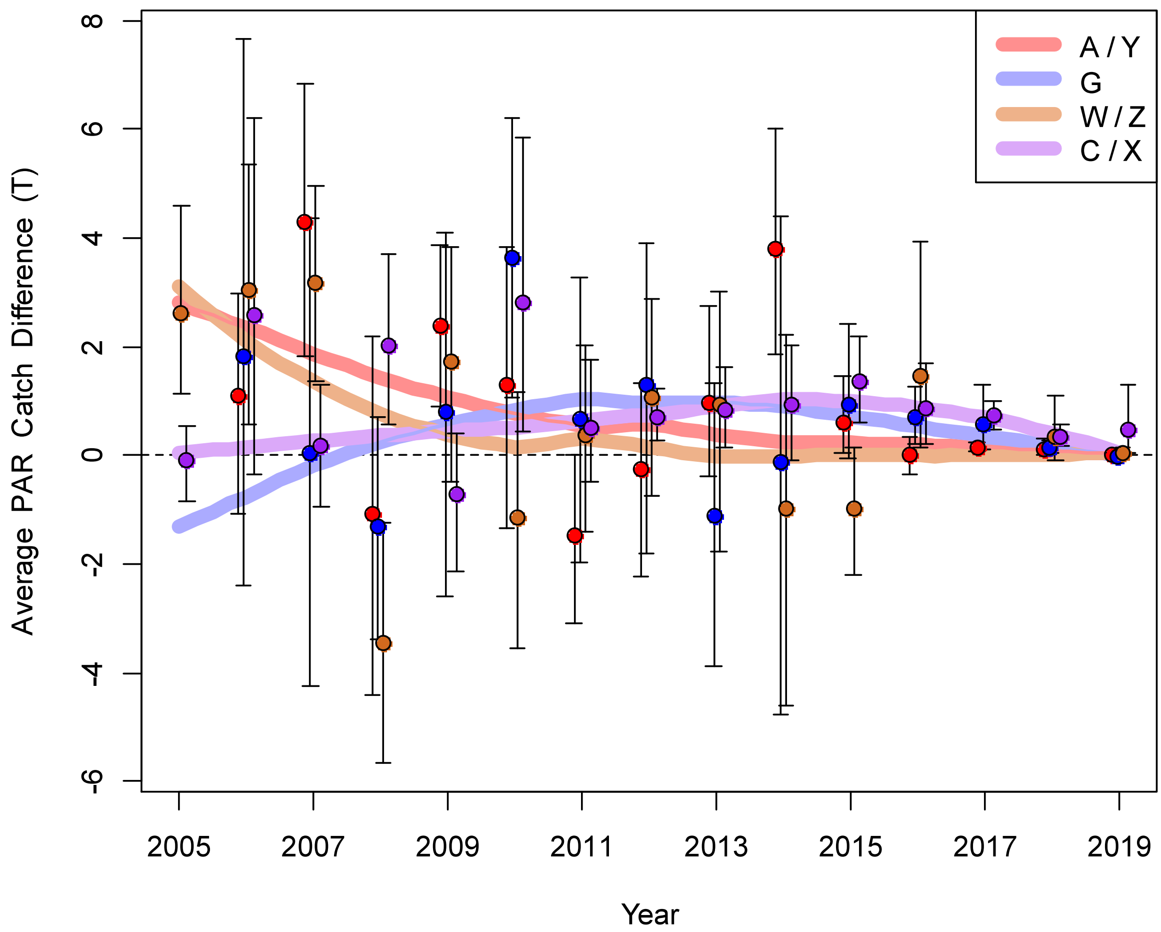


Figure 6. Average yearly rock cod catch differences between observer sample back-calculations and vessel reports, per licence type. LOESS smooths (degree = 2, span = 0.90) are weighted by the inverse variance of each year's rock cod catch difference.

Including the extrapolated total estimates of unreported catch in the modified Schaefer production model reduced the biomass estimate in each year, but by trivial, non-significant amounts (Figure 7, Table A4). The calculation of extrapolated unreported catch did not include some quantities that would have occurred in skate, *Illex*, and surimi fisheries (Tables A1 to A3), however; these fisheries take consistently low rock cod bycatches (Table 1 for 2019, data not shown for earlier years) that would have made little change to the biomass modelling outcome. The small effects shown in Figure 7, and correspondingly in Table 11 for MSY, reflect that catches were low proportions of estimated biomasses regardless, and putative underreporting does not, in any case, change the biomass index from the February surveys (Table 2).

Table 10 [next page]. Total N catch reports per licence type per year, and extrapolated unreported rock cod catch, in tonnes. Unreported catches (Unrep. T) per licence type are each year's LOESS smooth intercept (From Figure 6, but set at minimum zero) multiplied by the N catch reports N.

Year	A / Y		G		W / Z		C / X		Total
	N	Unrep. T	N	Unrep. T	N	Unrep. T	N	Unrep. T	Unreported
2005	760	2130.0	188	0.0	1532	4781.5	1786	48.3	6959.9
2006	1135	2684.7	529	0.0	1632	3449.9	1587	247.2	6381.8
2007	1290	2411.8	627	0.0	1631	2194.6	1743	458.5	5064.9
2008	1045	1500.8	945	224.3	1624	1251.2	1968	708.3	3684.6
2009	1107	1180.7	980	559.1	1672	634.4	1696	749.5	3123.7
2010	1093	845.9	961	805.3	1563	244.5	1934	1003.1	2898.8
2011	1089	573.1	824	850.7	1503	461.4	1870	1181.2	3066.3
2012	836	474.1	924	878.0	1483	212.3	1866	1397.3	2961.8
2013	849	326.9	863	827.4	1500	0.0	1978	1783.6	2937.8
2014	799	201.3	838	748.6	1529	0.0	1971	2012.8	2962.7
2015	788	181.6	905	649.0	1341	8.7	1615	1609.7	2449.0
2016	802	156.2	549	289.5	992	0.0	2024	1785.1	2230.8
2017	728	102.7	440	154.2	603	0.0	1997	1374.1	1631.1
2018	773	63.0	482	81.0	423	7.6	1952	790.6	942.2
2019	807	15.6	604	0.0	762	38.1	1588	50.2	103.9

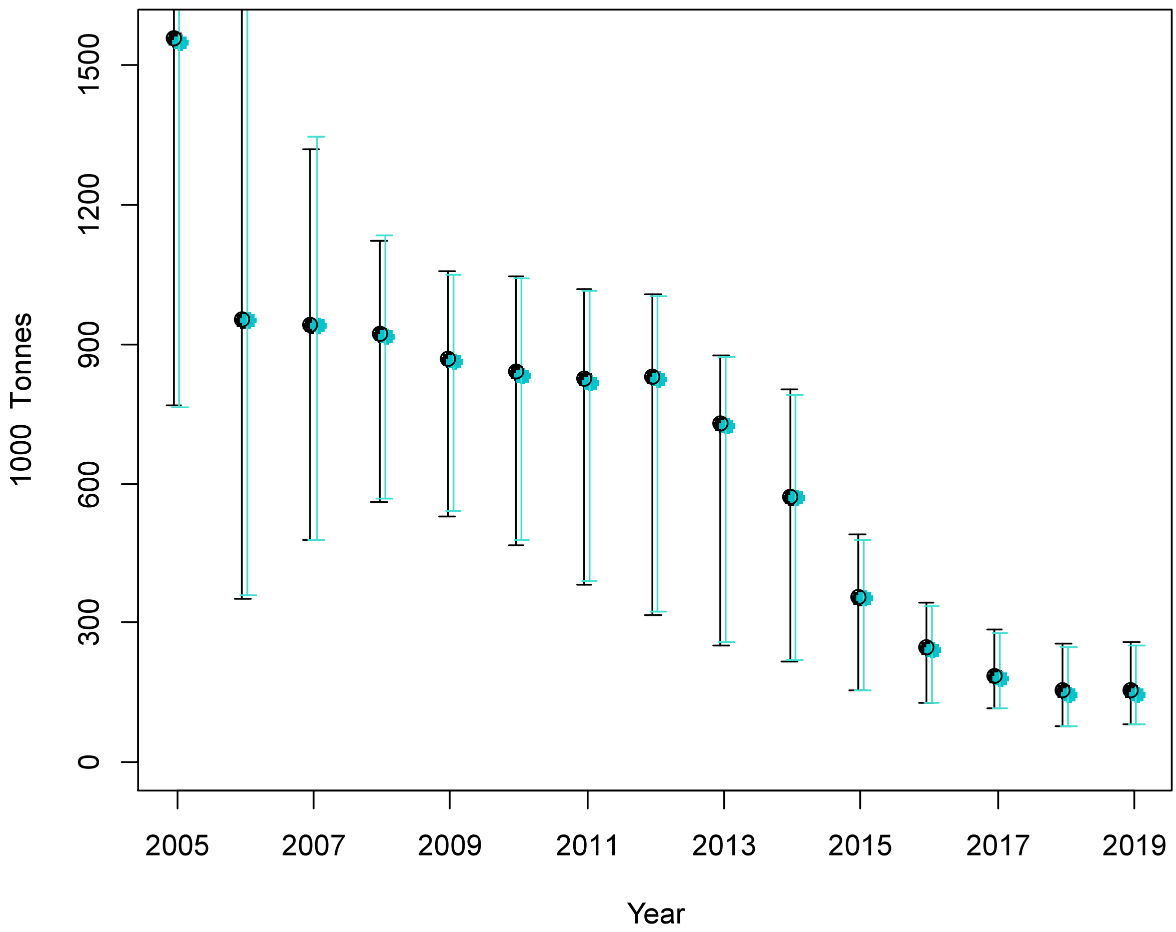


Figure 7. Annual estimates of rock cod biomass, 2005 to 2019. Black circles: median optimized estimates from the modified Schaefer production model, same as in Figure 2. Blue circles: median optimized estimates from the modified Schaefer production model, calculated with extrapolated unreported catches. Both sets of estimates with 95% confidence intervals.

Table 11. Parameter values for rock cod maximum sustainable yield, re-calculated with extrapolated estimates of unreported catch (compare to Table 4).

Parameter		Median	95% CI
Population growth rate (yr^{-1})	r	0.764	0.034 – 0.831
2019 Carrying capacity (t)	K	174380.3	89026.8 – 387032.9
Maximum sustainable yield (t)	MSY	33312.2	1456.4 – 49897.0

Lengths at 50% adulthood

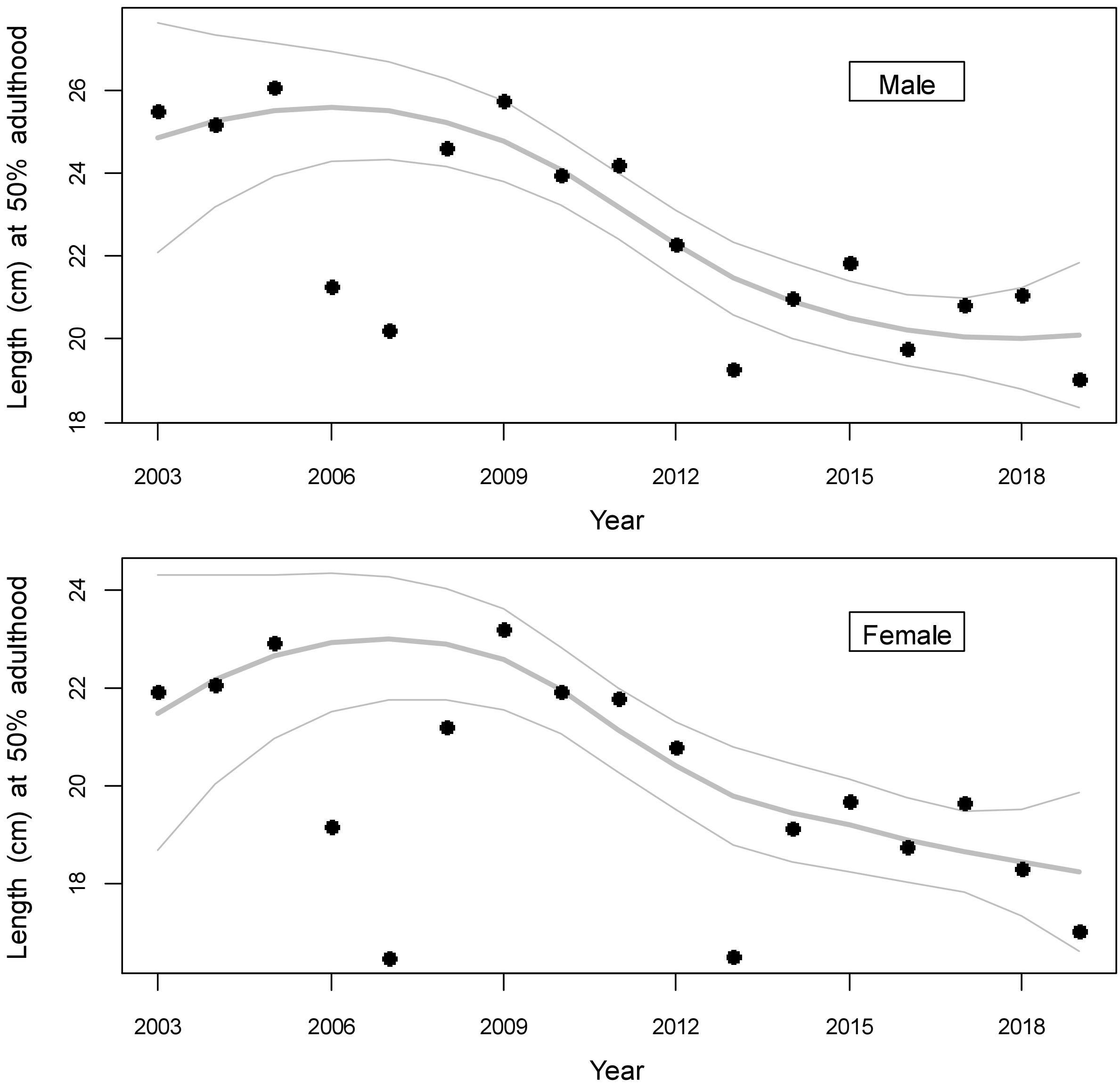


Figure 8. Lengths at 50% adulthood of male (top) and female (bottom) rock cod, 2003 to 2018. Grey lines are LOESS smooths ± 95% confidence intervals. Yearly data correspond to the 0.5 length intercepts in Figure A2.

Lengths at 50% adulthood showed a significantly decreasing trend ($p < 0.05$) for both males and females over the period 2003 to 2019 (Figure 8). Given this significant decrease, the age-length relationship was restricted to recent data. Figure 8 shows that for both males and females, variability has been non-significant between 2015 and 2019, and therefore age-length data from this bracket[9] were used to calculate the von Bertalanffy growth function (Figure 9), resulting in $L_\infty = 38.5$ cm. According to Equation 6, L_{opt} was then 34.1 cm, and the cut-off length for mega-spawners was 34.1 × 1.1 = 37.55 cm.

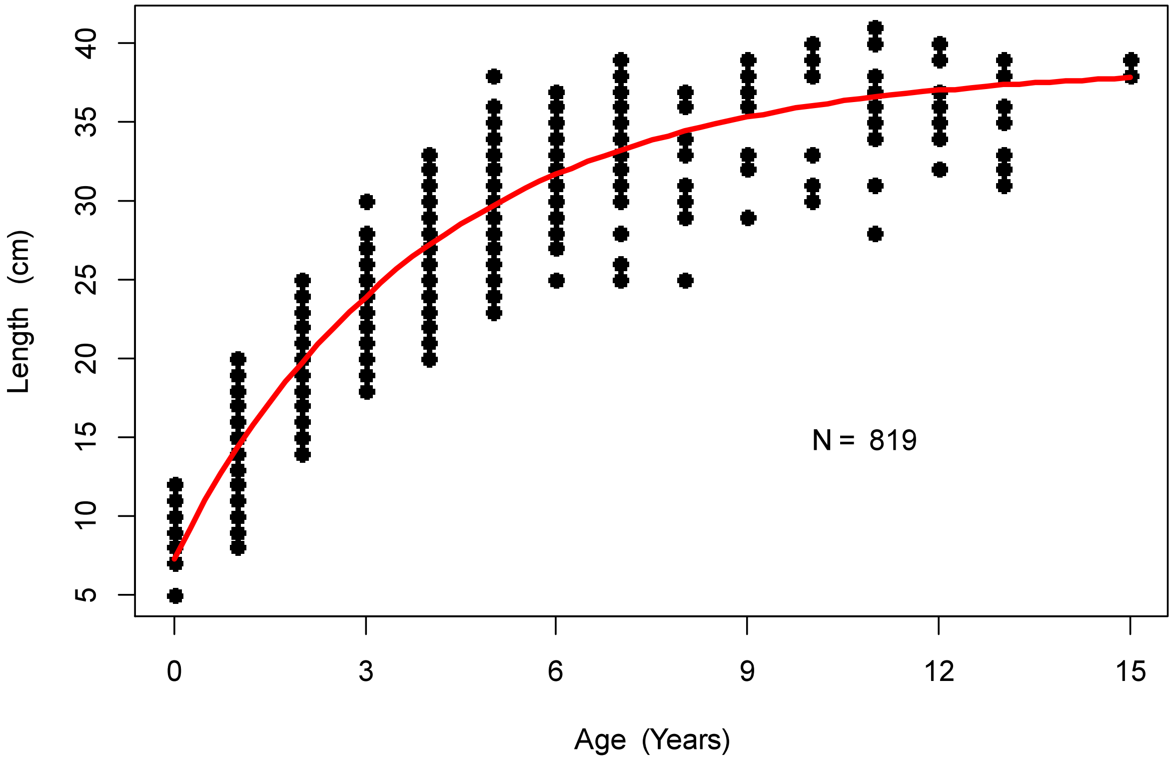


Figure 9. von Bertalanffy length-age relationship of Falkland Islands rock cod, 2015-2017.

Overfishing indicators

The three overfishing indicators of Froese (2004) are summarized in Table 12 by licence. For the 'mature' indicator (1), the target outcome would be 100% of fish caught (Froese 2004). Among the three finfish licences, W, which took substantially the most rock cod in 2019 (Table 1), had the lowest proportion of mature rock cod, and between the two calamari licences, C, which took 3× more rock cod than X (Table 1), also had a much lower proportion of mature rock cod. The maturity contrast between C and X (Table 12) is interesting in particular as both calamari fisheries are undertaken over the same restricted area with the same amount of effort. Differences between C and X in spatial effort distributions were not high in 2019 (Winter 2019b; 2019c), and as rock cod are relatively slow-growing fish (Brickle et al. 2016b), the results suggests an ontogenetic migration of the small, immature fish caught in C season no longer being in the area for X season. For the L_{opt} indicator (2), the target outcome would be all catch within ±10% of L_{opt}, and for the 'mega-spawner' indicator

[9] N = 819. No rock cod age data are yet available from years 2018 and 2019; thus it was years 2015, 2016, 2017.

(3), the target outcome would be at least 20% catch consisting of mega-spawners in fisheries that are managed without individual length restrictions (Froese 2004). No Falkland Islands fishery came close to these targets in 2019 (Table 12).

Table 12. By licence, proportions of sampled rock cod that were mature, within 10% of L_{opt}, and mega-spawners; i.e., >110% of L_{opt}, from commercial fisheries in 2019.

Licence		N	Overfishing indicators		
			Mature	L_{opt}	Mega-spawners
A	Unrestricted finfish	2863	0.906	0.033	0.000
G	Restricted finfish + *Illex*	621	0.850	0.135	0.000
W	Restricted finfish	1237	0.804	0.096	0.003
C	Calamari 1st season	4484	0.247	0.001	0.000
X	Calamari 2nd season	5130	0.975	0.001	0.000
B	*Illex* squid*	438	0.527	0.098	0.002

* Data taken from a trawler only.

Conclusion

The incongruously high biomass estimate in 2005 (Figure 2) reflects the difficulty of stabilizing this assessment in the (relatively) early years; before rock cod was commercially targeted or identifiably reported[10]. However, the overall time-trend of biomass estimates continues to support the inference that rock cod abundance was high in previous years before decreasing substantially to current levels.

February survey catches of rock cod decreased to a new low in 2019, indicative that the rock cod stock is not recovering despite ongoing low catches in the fishery. With recent high catches of hake (Winter 2019d), calamari (Winter 2019b), and intermittently *Illex* (FIS 2015), the hypothesis holds that the Falklands zone species assemblage has undergone a longer-term shift. To maintain the rock cod stock – sustainably – at least at its current level, catch should not exceed maximum sustainable yield. To enhance precaution, it is recommended that the ratio of MSY over biomass estimated from the production model be pro-rated to the more conservative survey biomass estimate, thus a total allowable catch of:

$$\text{TAC} = \frac{34330.4}{155149.0} \times 37793.3 = 8362.6 \text{ tonnes.}$$

The last time that an annual total licenced rock cod catch exceeded 8362.6 t was in 2015 (FIG 2019[11]); this TAC is therefore not likely to impose any constraint on Falkland Islands commercial fisheries at their presently allocated effort.

Nevertheless, length, maturity, and age measurements give evidence that fishing has influenced the rock cod stock. Decreasing size of maturity is a typical response to fishing pressure (Bianchi et al. 2000, Hutchings 2004, Shin et al., 2005) that would be unlikely to result from natural predation, as predators preferentially take small individuals. The poor outcome of the qualitative overfishing indicators should furthermore be taken into consideration for future appraisal of the rock cod stock.

[10] 2005 was the last year in which reported rock cod catch was <20,000 t until 2016 (FIG 2014, FIG 2019).

[11] The FIG 2019 catch statistics exclude licence type "O", but the calculations in this report do not; as they are catches on the same stock regardless.

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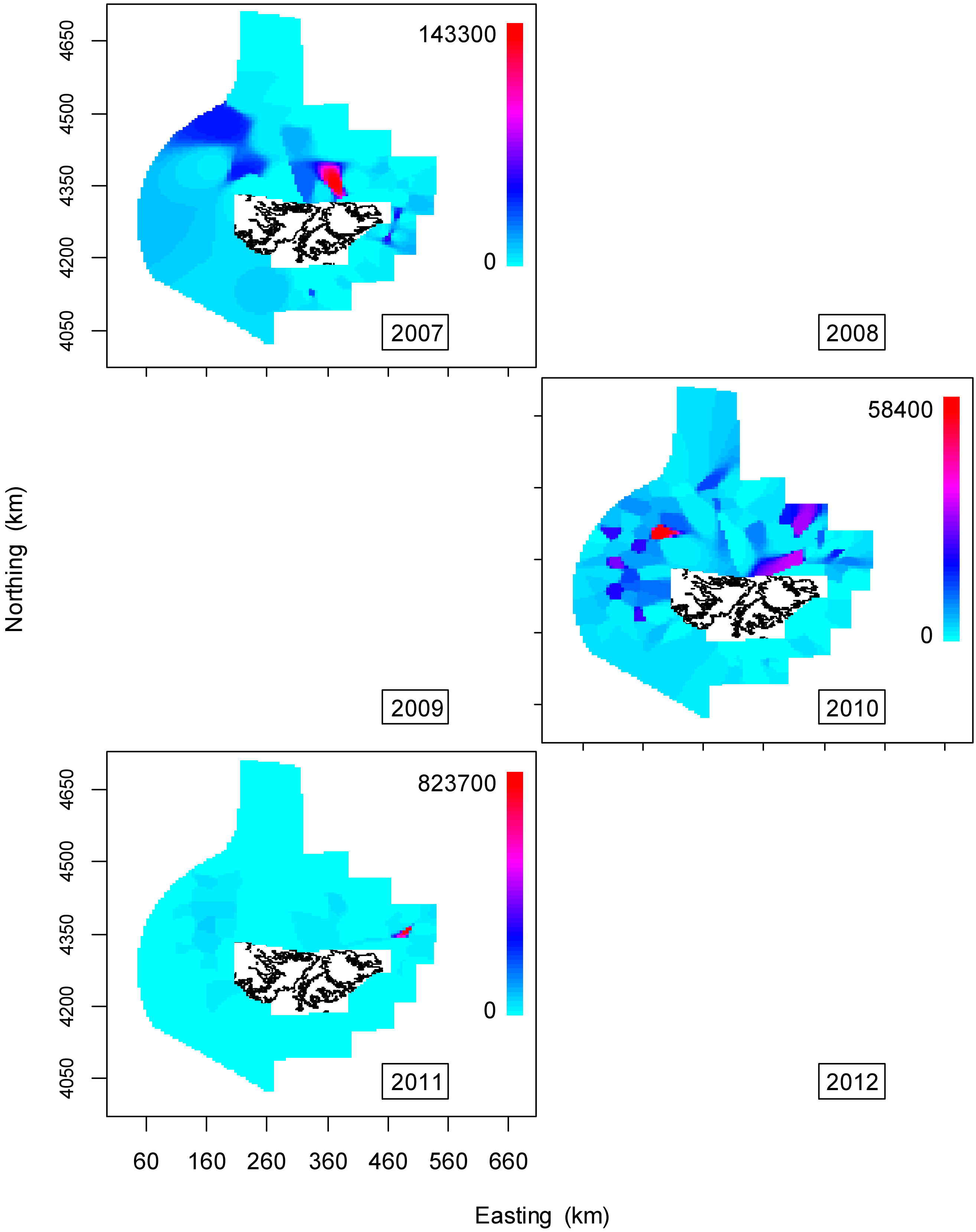
Appendix



143300
0
2007
2008
58400
0
2009
2010
823700
0
2011
2012
4650
4500
4350
4200
4050
Northing (km)
60
160
260
360
460
560
660
Easting (km)

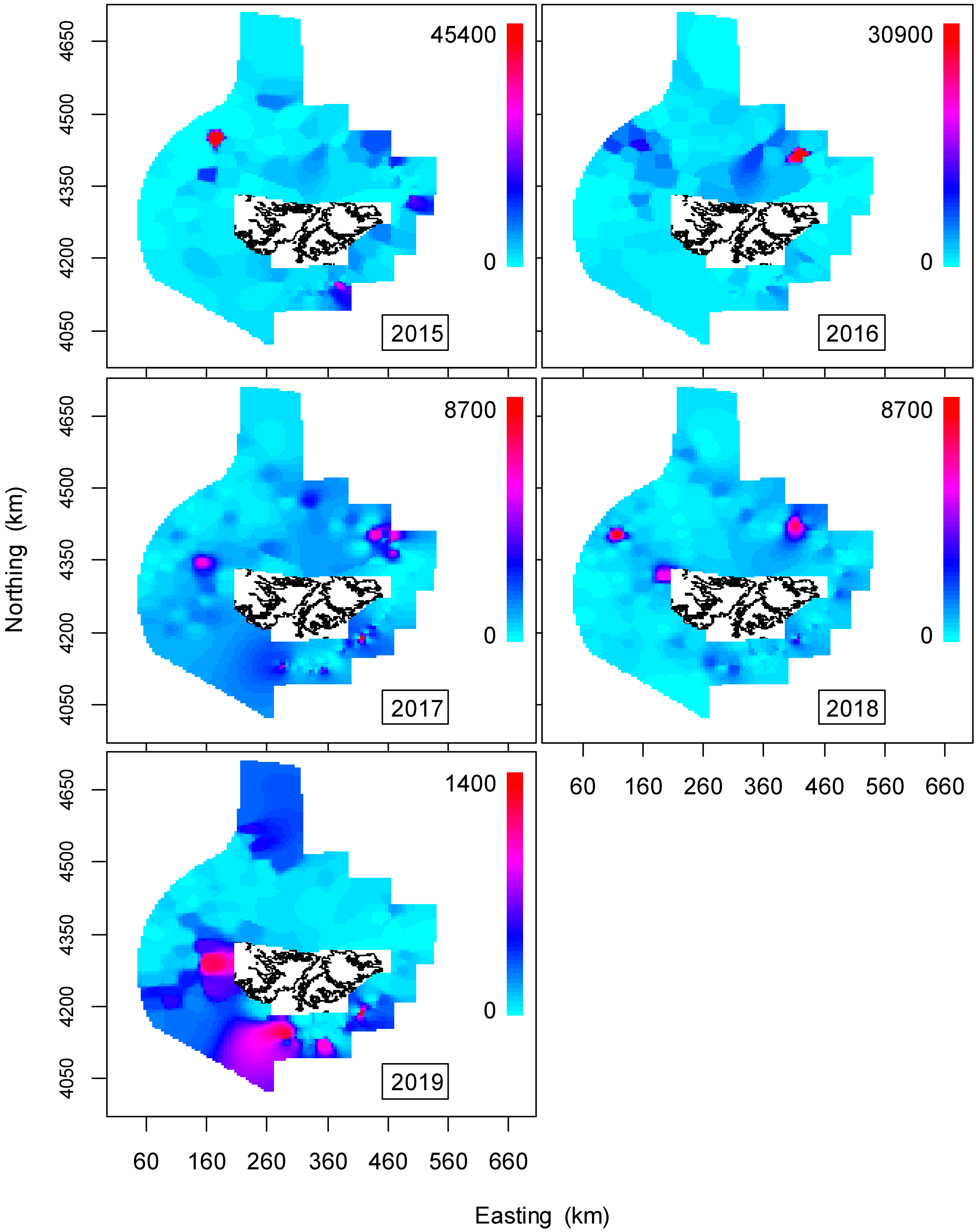
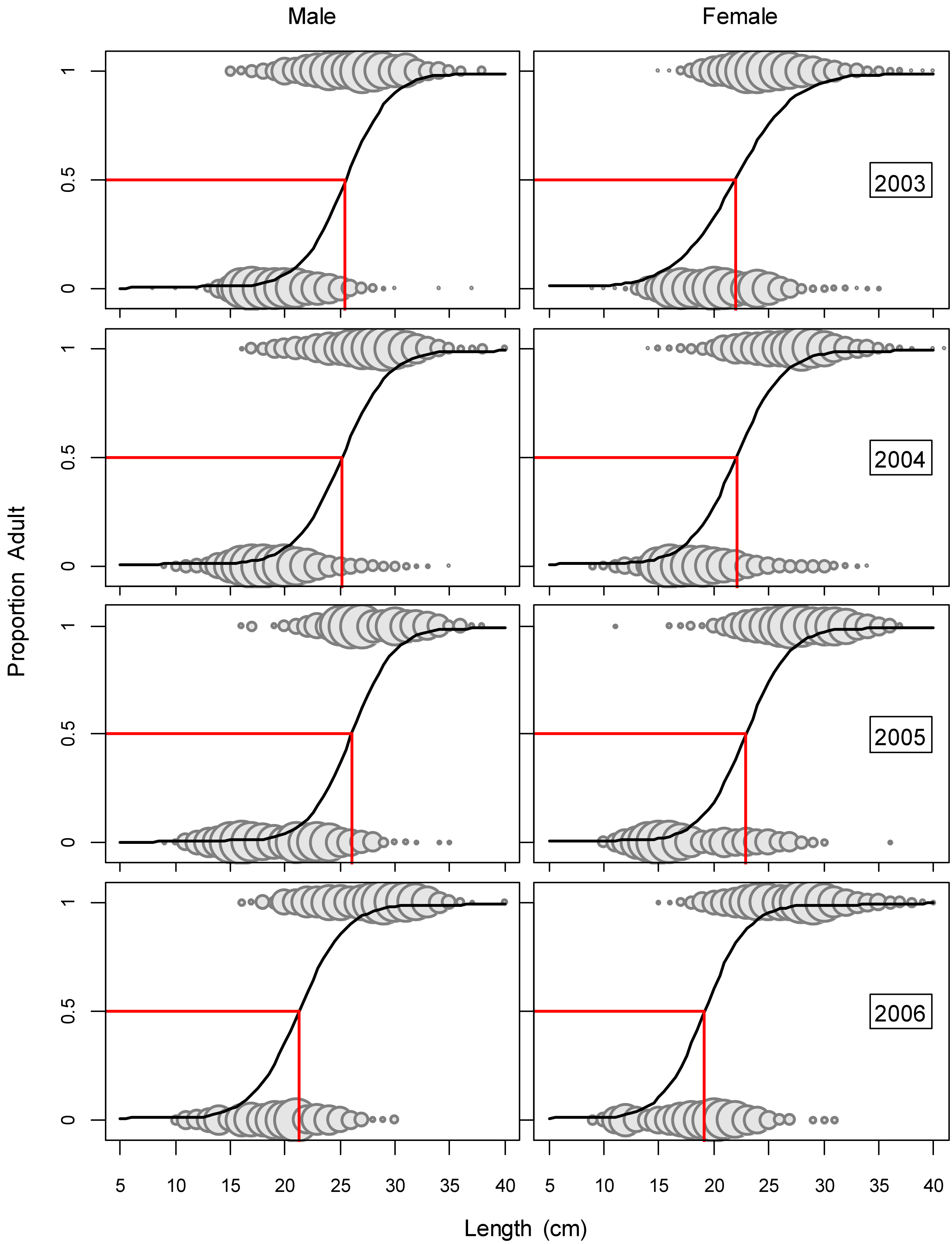
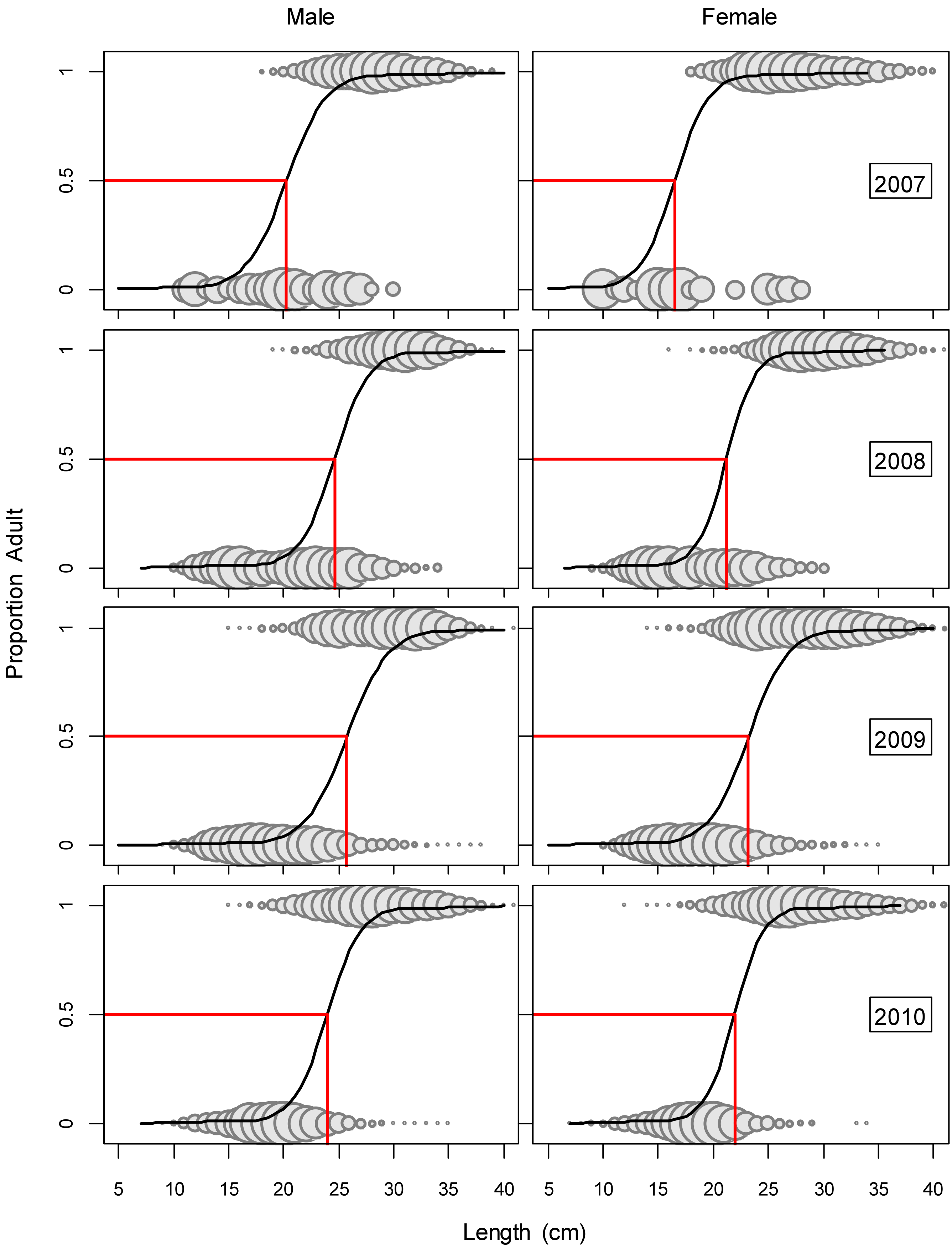
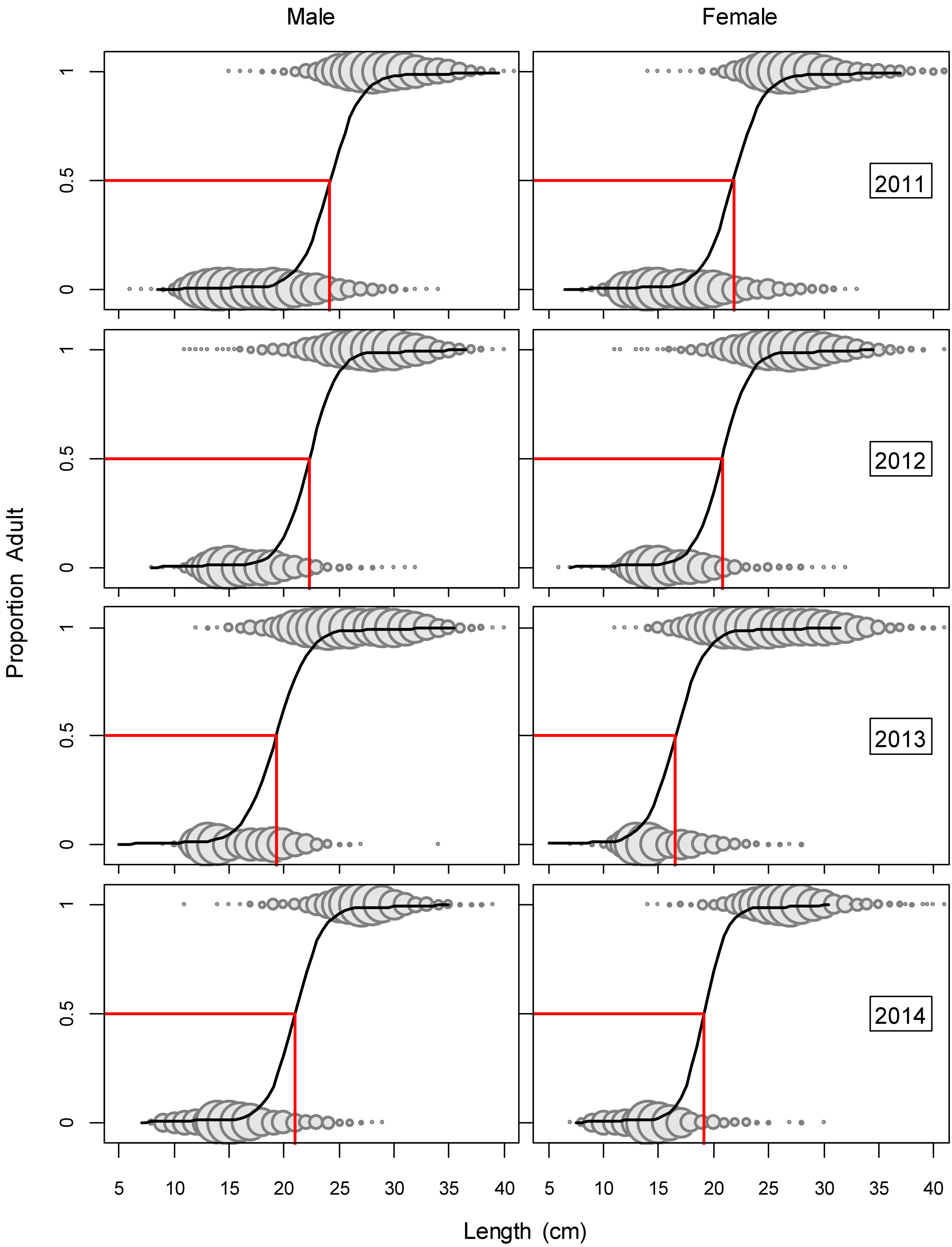


Figure A1. Modelled rock cod biomass density distributions in kg km^{-2} from February trawl surveys. Maximum and minimum densities shown on each graph.

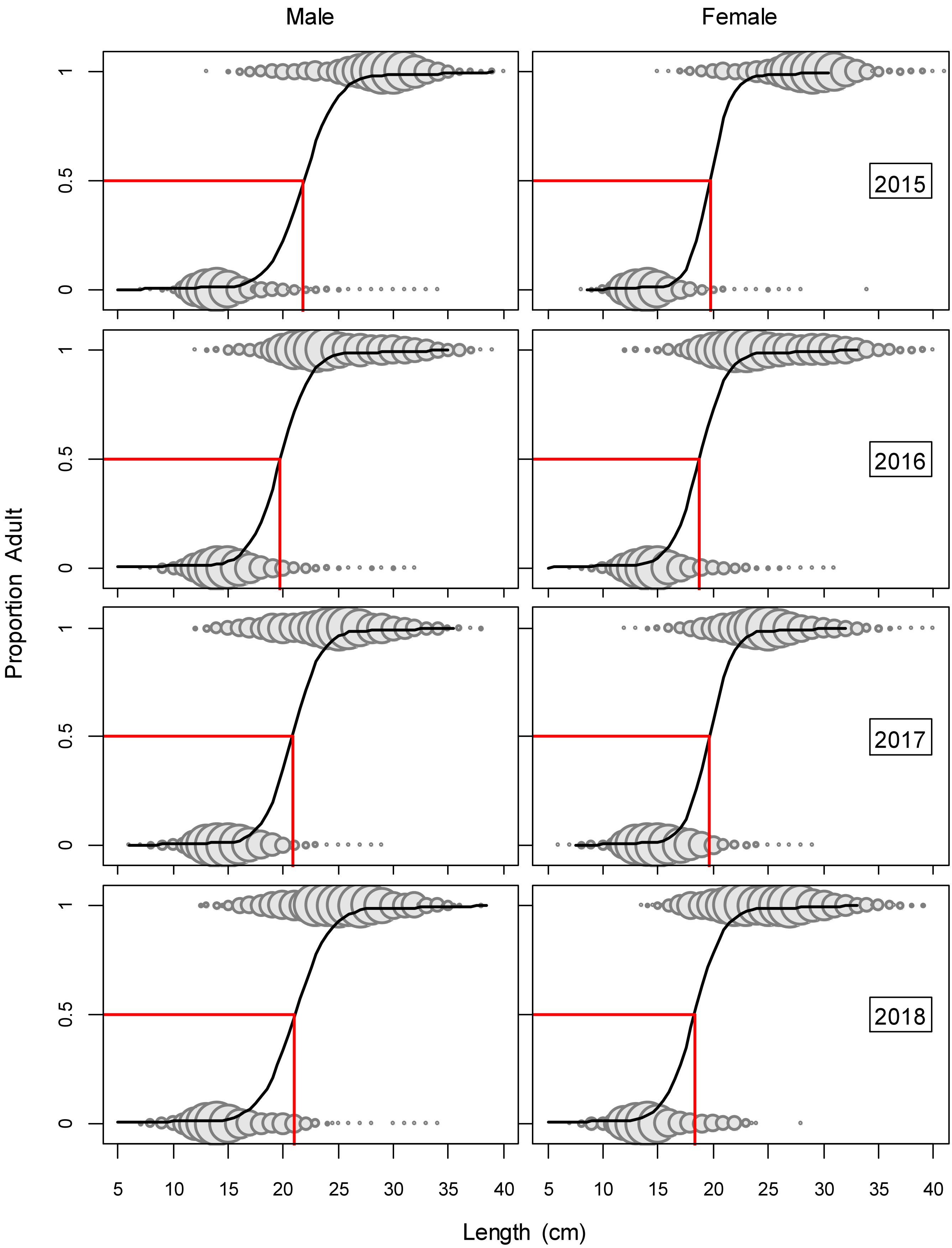

Male
Female
2003
2004
2005
2006
Proportion Adult
Length (cm)
0
0.5
1
5
10
15
20
25
30
35
40



Male
Female
2007
2008
2009
2010
Proportion Adult
Length (cm)
0
0.5
1
5
10
15
20
25
30
35
40



Male
Female
Proportion Adult
Length (cm)
2011
2012
2013
2014
0
0.5
1
5
10
15
20
25
30
35
40


Male
Female
Proportion Adult
2015
2016
2017
2018
Length (cm)
0
0.5
1
5
10
15
20
25
30
35
40

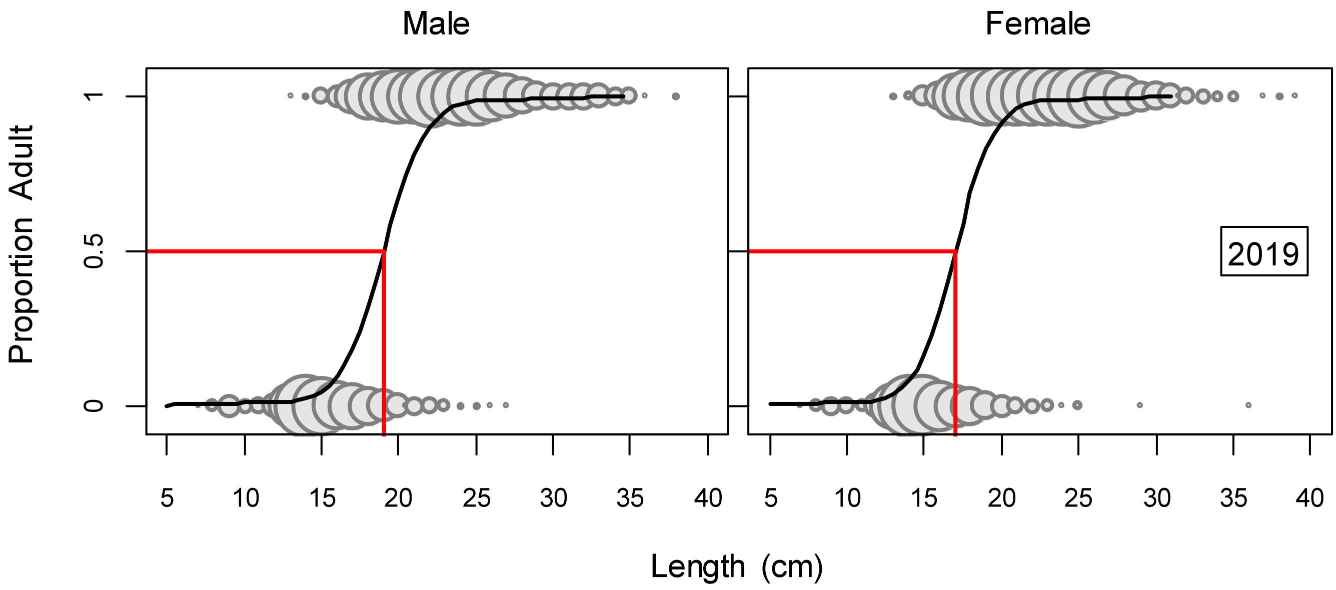


Figure A2. Binomial function GLMs of juvenile (0) or adult (1) maturity vs. length. Grey circles: scaled to sample numbers. Red lines: Length intercept of 50% adulthood, corresponding to Figure 6.

Table A1. Comparative metrics for rock cod discard and catch from commercial vessel reports and from on-board observers, in the skate fishery (F or R licence). Description as for Table 6.

Year	% PAR discard (size)				Avg. T PAR catch			
	N	Obs.	Com.	Difference	N	Obs.	Com.	Difference
2005	0				0			
2006	0				0			
2007	1	23.8	12.3	11.5,	1	21.92	20.29	1.63,
2008	0				0			
2009	11	9.3	7.6	1.8, -3.1 to 4.5	11	23.82	16.72	7.10, 4.88 to 9.35
2010	3	10.6	1.2	9.4,	3	17.62	11.24	6.38,
2011	3	2.5	8.1	-5.6,	3	8.47	8.42	0.05,
2012	1	0.0	3.3	-3.3,	1	21.78	12.24	9.54,
2013	0				0			
2014	2	13.1	31.3	-18.2,	2	2.03	2.24	-0.20,
2015	5	11.9	1.2	10.7, 2.7 to 16.0	5	3.21	5.63	-2.42, -8.25 to 1.1
2016	2	43.2	18.9	24.3,	2	8.61	3.65	4.96,
2017	0				0			
2018	2	43.4	100.0	-56.6,	2	0.05	0.01	0.04,
2019	0				0			

Table A2. Comparative metrics for rock cod discard and catch from commercial vessel reports and from on-board observers, in the *Illex* squid fishery (B licence). Description as for Table 6.

Year	% PAR discard (size)				Avg. T PAR catch			
	N	Obs.	Com.	Difference	N	Obs.	Com.	Difference
2005	10	33.8			11	6.59	0.00	6.59, 3.66 to 10.07
2006	0				0			
2007	0				0			
2008	0				0			
2009	0				0			
2010	0				1	0.00	0.00	0.00,
2011	1	2.4	100.0	-97.6,	1	0.10	0.07	0.03,
2012	1	4.1	51.4	-47.3,	1	1.49	2.24	-0.74,
2013	0				0			
2014	0				0			
2015	1	0.0	100.0	-100.0,	1	2.43	0.10	2.33,
2016	0				0			
2017	0				0			
2018	0				0			
2019	2	7.3	100.0	-92.7,	2	0.06	0.03	0.03,

Table A3. Comparative metrics for rock cod discard and catch from commercial vessel reports and from on-board observers, in the surimi fishery (S licence). Description as for Table 6.

Year	% PAR discard (size)				Avg. T PAR catch			
	N	Obs.	Com.	Difference	N	Obs.	Com.	Difference
2005	0				0			
2006	0				0			
2007	6	3.5	100.0	-96.5, -99.0 to -94.5	6	11.47	2.92	8.55, 1.69 to 19.08
2008	8	0.0			8	0.01	0.00	0.01, 0.00 to 0.01
2009	0				0			
2010	1	0.0			1	0.00	0.00	0.00,
2011	5	0.0			5	0.01	0.00	0.01, 0.00 to 0.02
2012	0				0			
2013	0				0			
2014	0				0			
2015	0				0			
2016	1	0.0	5.9	-5.9,	1	0.15	0.17	-0.02,
2017	0				0			
2018	0				0			
2019	0				0			

Table A4. Annual biomass and carrying capacity estimates from the re-sampled optimizations of the modified Schaefer production model, calculated with extrapolated unreported catches. Biomass estimates are equivalent to the blue circles in Figure 7.

Year	Biomass (T)		Carrying capacity K (T)	
	Median	95% CI	Median	95% CI
2005	1552799.0	765356.3 – 3756133.5	943826.2	177241.9 – 1124920.8
2006	952301.1	357589.9 – 1735935.4	947535.2	237682.6 – 1121602.4
2007	941274.4	478713.6 – 1348553.6	949211.8	221129.6 – 1122240.5
2008	920350.0	568998.7 – 1134937.1	946513.8	202911.8 – 1118236.4
2009	866144.5	539422.8 – 1048567.5	937863.4	209456.7 – 1122628.8
2010	832932.4	477129.5 – 1041116.2	927869.0	153317.7 – 1124289.6
2011	818295.8	391068.6 – 1014084.6	945918.8	186556.2 – 1117943.9
2012	825736.5	325460.7 – 1001692.1	931551.8	165013.1 – 1088582.6
2013	724286.9	257105.5 – 874077.2	789795.2	177907.4 – 942958.5
2014	569658.6	219169.2 – 790568.1	604318.8	136236.2 – 839459.0
2015	353013.8	155201.5 – 479003.5	423988.3	142479.7 – 565102.4
2016	243972.1	126711.3 – 336208.3	280594.3	142585.3 – 376550.7
2017	179584.4	114059.4 – 278154.1	207615.2	133730.9 – 324934.6
2018	146582.4	76939.4 – 245668.4	172738.6	91019.7 – 331162.5
2019	147508.8	79875.7 – 249831.6	174380.3	89026.8 – 387032.9