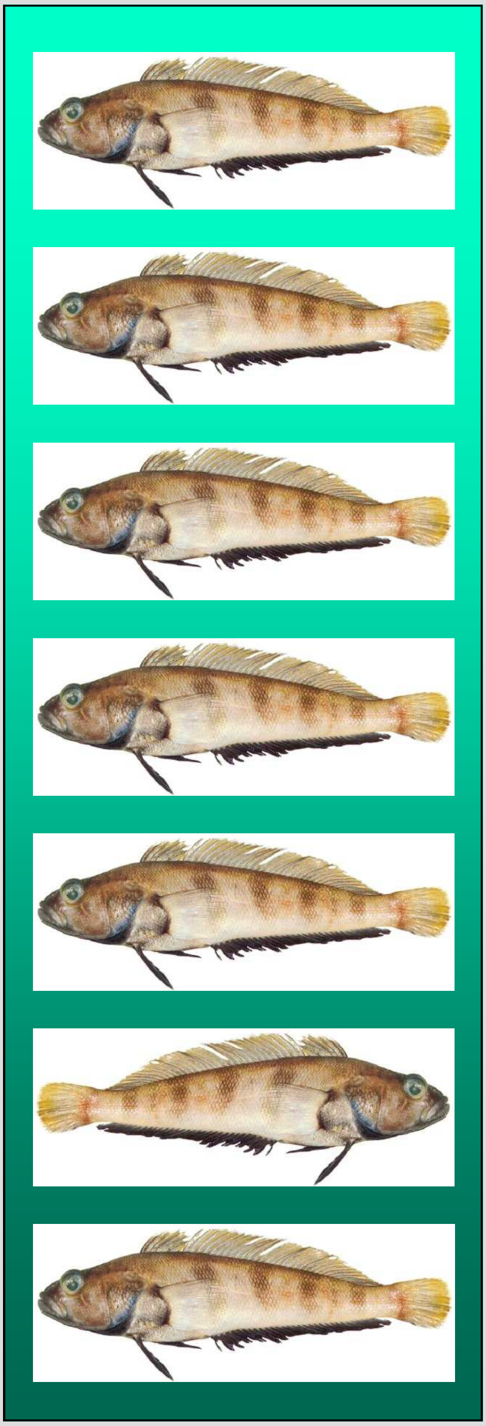

Stock assessment

Rock cod

(*Patagonotothen ramsayi*)

Andreas Winter

Natural Resources

Fisheries

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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.

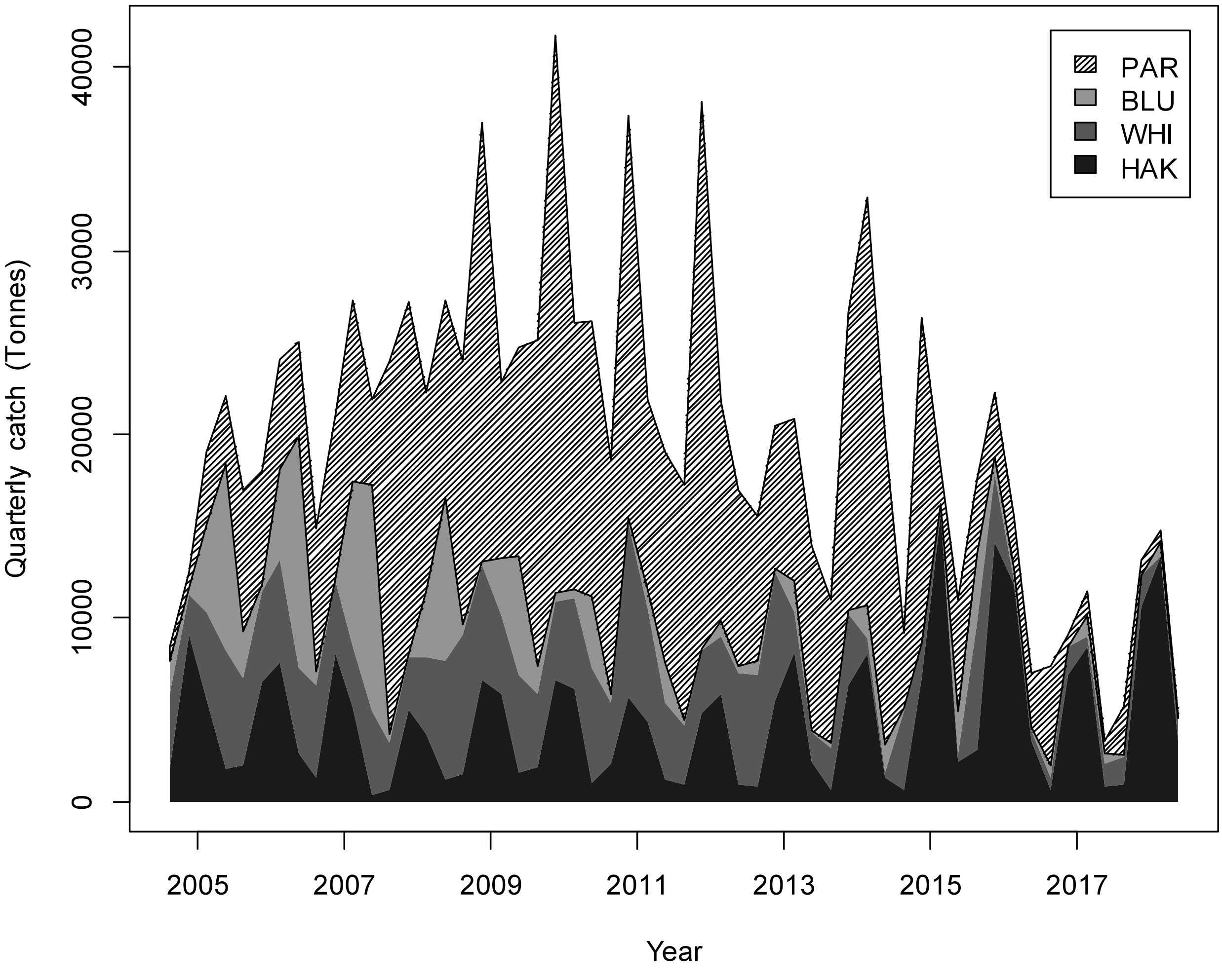

Figure 1. Quarterly catches in tonnes since 2005 in Falkland Islands fisheries of hake (HAK), hoki (WHI), blue whiting (BLU), and rock cod (PAR). The plot is stacked not superimposed; e.g., in 2nd quarter 2010, the highest peak, catch was HAK + WHI + BLU + PAR = 41695 t.

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 2018). In a pattern commonly seen in other fisheries (Pauly et al. 1998), the increased commercial use of rock cod coincided with catch decreases of higher-value species.

During 2018 a total of 2203 tonnes rock cod were caught in the Falkland Islands zone, with catch by licence distributions shown in Table 1. As during last year (Winter and Gras 2018), rock cod were predominantly taken in the calamari fisheries, where most (99.5%) are discarded. Among finfish target licences, of 772 A licence catch reports in 2018, rock cod was the highest catch species on 1 and the second-highest on 13 catch reports. Of 482 G licence catch reports in 2018, rock cod was the second-highest catch species on 73 catch reports, but never the highest. And of 423 W licence catch reports in 2018, rock cod was the highest catch species on 10 and the second-highest on 22 catch reports.

Table 1. Falkland Islands rock cod catches by licence in 2018.

Licence		Rock cod catch	%
Code	Type	(Tonnes)	
A	Unrestricted finfish	198.2	9.0
G	Restricted finfish + *Illex*	351.2	15.9
W	Restricted finfish	172.1	7.8
F	Skate	5.4	0.2
C	Calamari 1st season	814.8	37.0
X	Calamari 2nd season	604.6	27.4
B	*Illex* squid	0.1	0.0
S	Surimi	0.0	0.0
L	Toothfish longline	0.0	0.0
E	Experimental	56.8	2.6
Total		2203.1	100.0

Methods

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:

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

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 = 2018, the last complete year of data.

The Schaefer production model was again 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).

Rock cod biomass estimates were compiled from the six sets of trawl surveys that have, since 2010, been conducted synchronously in February over the groundfish fishing zone and the *D. gahi* fishing zone. Additionally, data from a survey in February 2007 were accessed and paralleled with that season's *D. gahi* survey 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).

For the current stock assessment, all biomass estimates were calculated from the survey trawl catch densities using an inverse distance weighting algorithm (Shepard 1968). Previous assessments had used kriging algorithms (Winter et al. 2010, Winter and Gras 2018), but with uneven results, and last year's assessment found that kriging estimates could not be computed jointly for most survey pairs which had different survey designs, trawl targets, and trawl gear (Winter and Gras 2018). Inverse distance weighting is a deterministic method of spatial prediction that can be more reliable than kriging for small data sets (Kravchenko 2003, Mueller et al. 2004). Biomass estimation and the inverse distance weighting algorithm are described in Appendix 1.

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. Thus the production model was modified as:

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

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 (approximately every other year K_{2005}, K_{2008}, K_{2010}, K_{2012}, K_{2014}, K_{2016}, K_{2018}), but optimized on a LOESS smooth prediction (span = 0.9) of these 7 years applied to all years 2005-2018.

The full model for this stock assessment thus optimized 9 parameters: K_{2005}, K_{2008}, K_{2010}, K_{2012}, K_{2014}, K_{2016}, K_{2018}, 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), 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 found by running the CMSY (catch-MSY) algorithm with Bayesian state-space implementation of the Schaefer model (BSM) (Froese et al. 2017). CMSY-BSM is a 'data-limited' method that sets broadly categorical prior ranges for a (general form – univariate K) Schaefer model based on species' resilience (Martell and Froese 2013, Froese et al. 2017). Resilience of rock cod has been reported as 'medium' (Froese and Pauly 2019). However, given the rapid stock decline observed in the Falkland Islands zone (Winter and Gras 2018), it was decided to use an input of 'low' resilience, corresponding to a prior r-range of 0.05 - 0.5 (Table 2 in Froese et al. 2017). Starting biomass, being uncertain, was given a wide range of 0.4 - 1.0 B_1/K ('medium' to 'high' in Table 3, Froese et al. 2017). The probability distribution of the BSM was computed by Markov Chain Monte Carlo with the Gibbs sampler JAGS (Froese et al. 2017). To reduce the spread of starting values, outputs of JAGS were sub-sampled by the criterion that 2018 biomass values had to be greater than the catch in 2018, and linear regression between JAGS biomass samples and the survey biomass estimates had to be significant ($p \leq 0.05$) with slope ≥ 0.20 and ≤ 10. All sub-sampled JAGS output parameters were tested in the modified Schaefer model (Equation 2) and the best optimal value retained. Carrying capacity was transformed from the univariate K in JAGS to K_{2005}, K_{2008}, K_{2010}, K_{2012}, K_{2014}, K_{2016} and K_{2018} in the modified Schaefer model by an index multiplier based on the inverse LOESS trend of annual hake catches. Hake was the one major finfish target to show a significant correlation with rock cod (Appendix 2). 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.

The basic objective function of model optimization was:

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

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

summed on the survey years t = 2007, 2010, 2011, 2015, 2016, 2017, 2018. 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 maximum K > 3× minimum K. The factor of 3× was chosen as it represents the approximate ratio of highest hake catch (2016; 32,101 t) over lowest hake catch (2008; 10,579 t); changes in hake catch being the argument for a flexible K trend (Appendix 2). 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 1.65 to increase the weight of the penalty. Thus the objective function for optimization became:

$$\left(\frac{n_t}{2} \cdot \log(2\pi)\right) + \left(n_t \cdot \log(\sigma)\right) + \frac{\sum_t^{survey}\left(\log\left(B_{optim\ t}\right) - \log\left(B_{survey\ t}\right)\right)^2}{2\sigma^2} + \max\left[0, \left(\left(\frac{\max\left(K_{t\ optim}\right)}{\min\left(K_{t\ optim}\right)}\right) - 3\right)\right] + 1.65 \times \begin{cases} \text{abs}(r - 0.8), & \text{if } r > 0.8 \\ 0, & \text{if } r \leq 0.8 \end{cases} \tag{4}$$

Uncertainty 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) 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 capacity estimates.

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).

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

$$\mathrm{MSY} = \frac{\mathrm{r} \cdot \mathrm{K}_{2018}}{4} \tag{5}$$

For comparative evaluation, 50% maturities-at-length 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 extensively collecting these measurements. The aggregates of 50% adulthood lengths were plotted against years and trends examined with LOESS smooths (degree = 2, span = 0.90). Males and females were analysed separately as rock cod growth and maturation are sexually dimorphic (Brickle et al. 2006a, 2006b).

Results

Table 2. Rock cod biomass estimates from parallel groundfish and *D. gahi* surveys in February. N = number of trawl stations per survey.

Year	N trawl stations		Biomass	95% CI	Sources
	Groundfish	*D. gahi*	(Tonnes)	(Tonnes)	
2007	36	64	1475571.3	544753.2 – 2592790.2	FIG 2007 Payá 2007
2010	86	55	765866.8	576328.5 – 983285.4	FIG 2010 Arkhipkin et al. 2010
2011	86	58	1248190.6	744046.6 – 2165233.7	FIG 2011 Winter et al. 2011
2015	89	57	361300.3	270298.0 – 470343.0	Gras et al. 2015 Winter et al. 2015
2016	89	57	238844.6	175801.1 – 314525.6	Gras et al. 2016 Winter et al. 2016
2017	90	59	137843.9	110687.9 – 170140.6	Gras et al. 2017 Winter et al. 2017
2018	97	59	94079.3	66646.6 – 125553.3	Gras et al. 2018 Winter et al. 2018a

Survey biomass estimates of rock cod ranged from 1,475,571 tonnes in 2007 to 94,079 tonnes in 2018, thus a decrease by 15.7× in 11 years (Table 2). Distributions in most February surveys showed localized high concentrations (Appendix Figure A3).

Optimized parameter values of the modified Schaefer production model are summarized in Table 3. Population growth rate r reverted to a relatively high estimate of 0.6985[1], suggesting that the species does have medium resilience (Froese and Pauly 2019), but with a large margin of uncertainty. Model biomass estimates of rock cod ranged from 1,266,424 tonnes in 2005 to 967,520 tonnes in 2011 before decreasing consistently from 2012 onwards. The trend is not monotonic: annual biomass was generally close to the annual carrying capacity K (compare Figures 2 and 3), and therefore effected a ratio (Equation 2) that was sometimes >1 and sometimes <1, causing the trend to fluctuate. The most recent four years showed close agreement between the Schaefer model estimates and the survey estimates on which they were tuned (Figure 2).

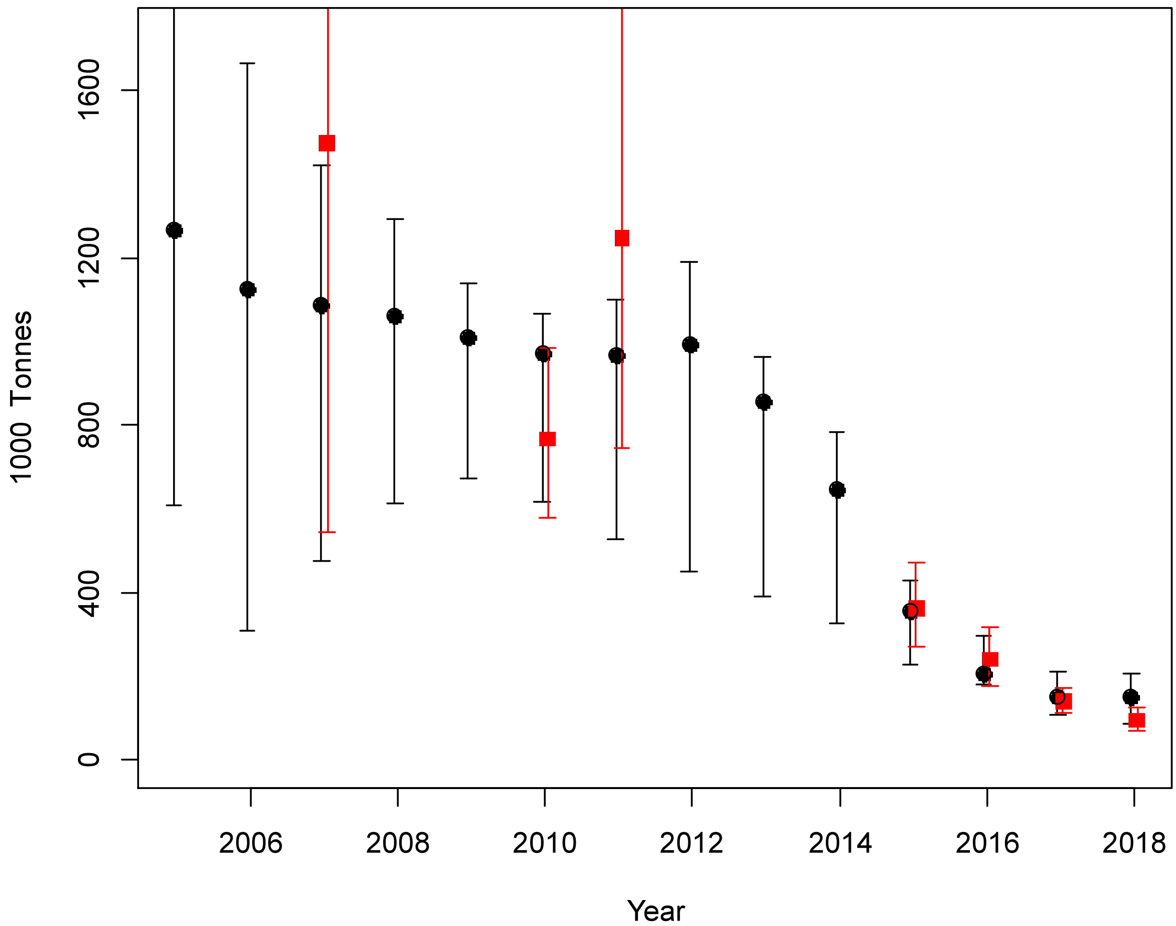

Figure 2. Annual estimates of rock cod biomass, 2005 to 2018. Red squares: area estimates from the parallel groundfish – *D. gahi* surveys. Black circles: optimized estimates from the modified Schaefer production model. Both sets of estimates with 95% confidence bars. Red squares are equivalent to the data in Table 2.

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[1] r = 0.6985 means the population is intrinsically capable of increasing by $e^{0.6985} - 1$ = 101% per year; in other words approximately doubling.

Table 3. Optimized parameter values of the modified Schaefer production model. K values for pertinent years correspond to Figure 3.

Parameter		Optimized value	95% CI
Carrying capacity	(K_{2005})	1083358 T	469226 – 1350754
Carrying capacity	(K_{2008})	1098891 T	615640 – 1268690
Carrying capacity	(K_{2010})	1036918 T	449742 – 1138634
Carrying capacity	(K_{2012})	1104510 T	480527 – 1265701
Carrying capacity	(K_{2014})	660780 T	360158 – 840094
Carrying capacity	(K_{2016})	239425 T	158168 – 343234
Carrying capacity	(K_{2018})	158722 T	93157 – 235237
Biomass in 1st year	(B_{2005})	1266424 T	607961 – 2823366
Population growth rate	(r)	0.6985	0.1216 – 1.3461
Maximum sustainable yield	(MSY)	27717 T	4236 – 50736

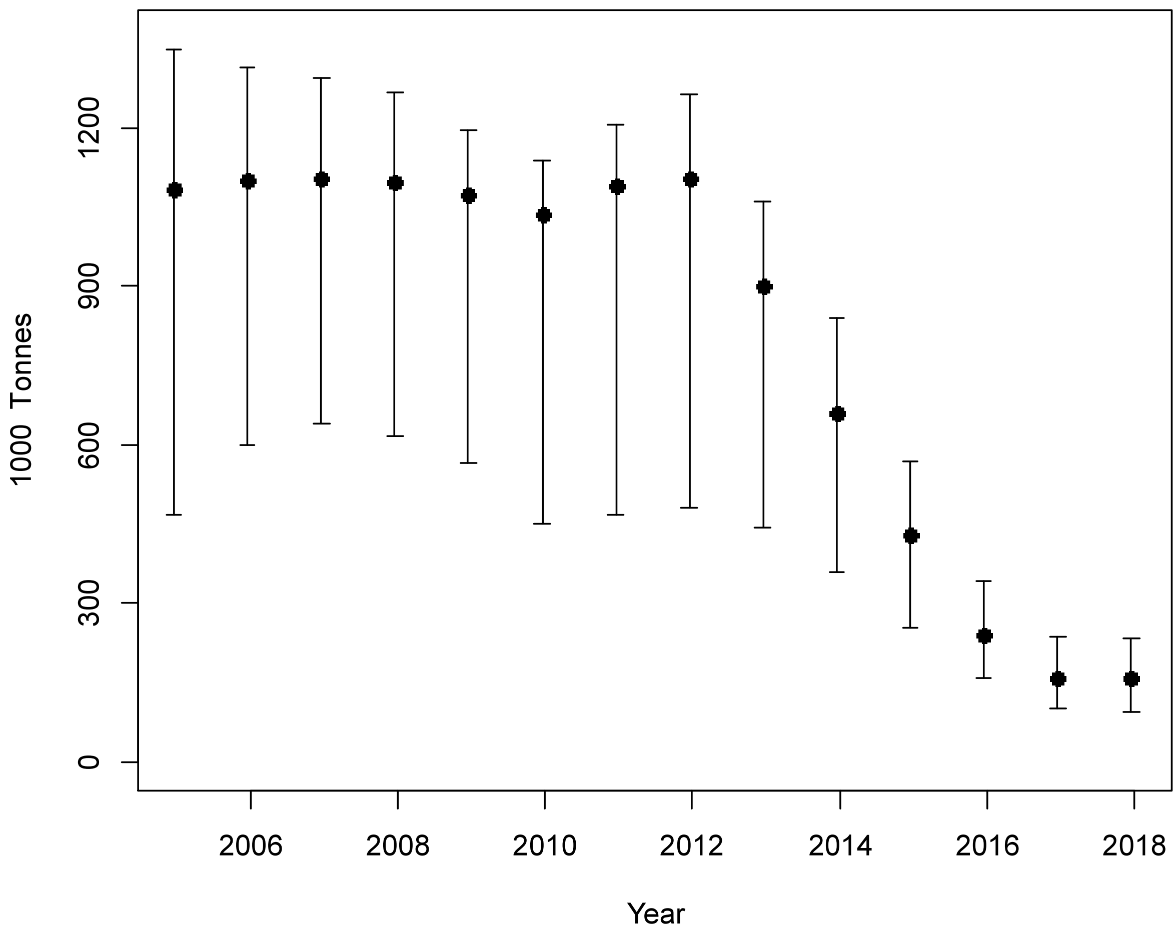


Figure 3. Annual population carrying capacity (K) optimized by the modified production model, with 95% confidence bars. Values in pertinent years correspond to Table 3.

The time series of B / B_{MSY} and F / F_{MSY} calculated from the modified Schaefer production model indicate that from 2005 to 2018, the rock cod population was never at a status below maximum sustainable yield (Table 4). This result is hard to reconcile with the finding that by any measure, the rock cod stock has decreased at least 8× since its highest levels prior to 2010 (Figure 2). A potentially biasing factor in the modelling result is that optimization tunes most strongly on the carrying capacity K, which accounts for most of the parameter inputs (Table 3). Even with a penalty function against >3, the model output obtained a ratio of maximum K / minimum K = 8.56 (Table 3, Figure 3).

Table 4. Rock cod fishing mortality (F) and biomass (B) time series in relation to maximum sustainable yield.

Year	B / B_{MSY}	F / F_{MSY}
2005	2.3380	0.0209
2006	2.0421	0.0633
2007	1.9658	0.0824
2008	1.9357	0.1642
2009	1.8797	0.1673
2010	1.8701	0.2288
2011	1.7735	0.1670
2012	1.8016	0.1845
2013	1.9054	0.1150
2014	1.9512	0.2803
2015	1.6549	0.2412
2016	1.7167	0.1871
2017	1.8890	0.1528
2018	1.8639	0.0831

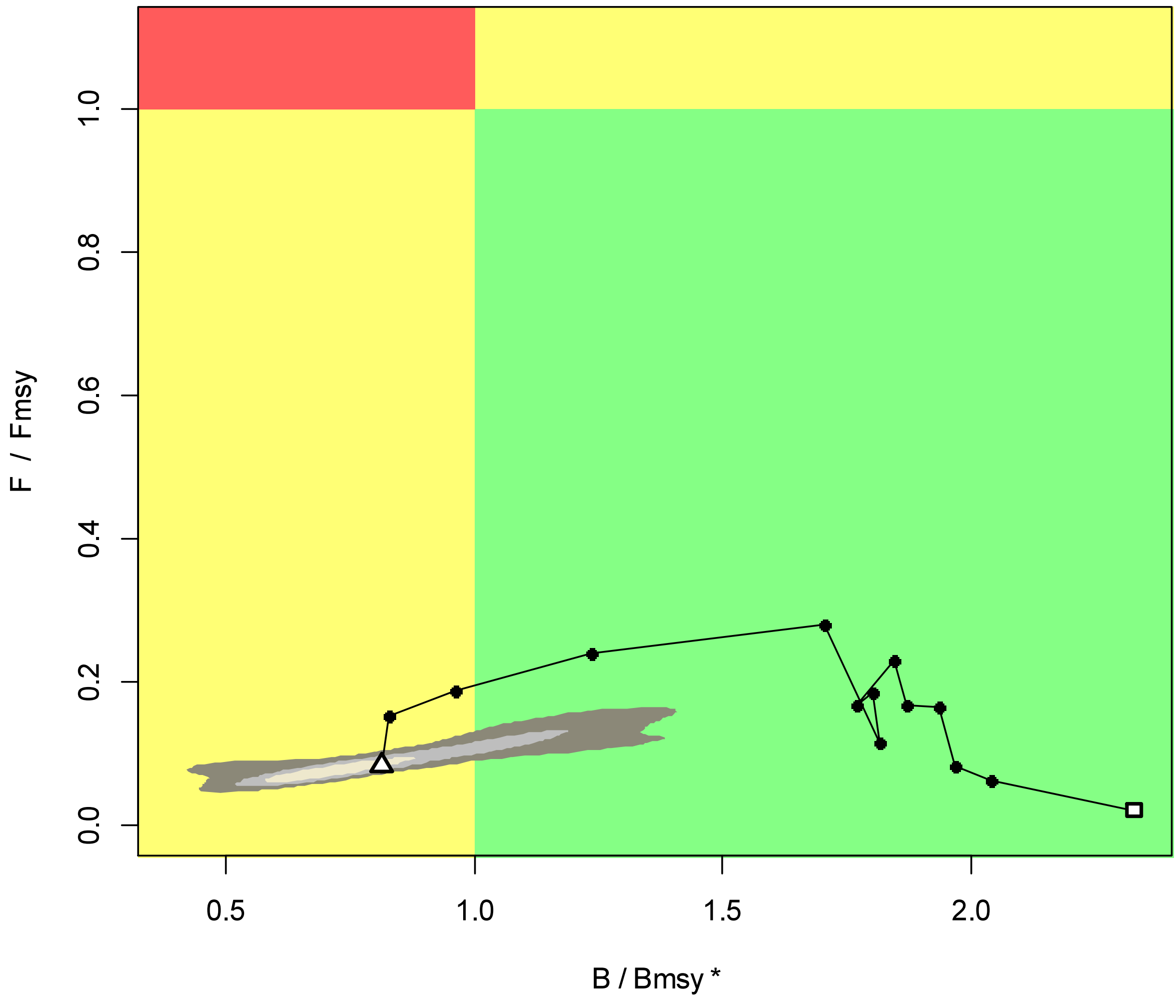
Accordingly, a hypothetical adjustment was calculated to bring the rate of K variation in line with its expectation:

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

where $$\text{max. diff} = \max(K_t) \times \left(\frac{\text{min Hake catch}_t}{\text{max Hake catch}_t}\right) - \min(K_t)$$

B / B_{MSY} re-calculated with the adjusted K_t (now designated B / B_{MSY}*) produced the Kobe plot shown in Figure 4. The trajectory proceeded from deep in the green field in 2005 – as typical for an un-fished or under-fished stock, to the yellow field in 2018 – indicative of a stock that is below maximum sustainable yield but not currently being over-fished. Notably, the trajectory never approached the threshold for overfishing ($F / F_{MSY} = 1$).

Figure 4 [next page]. Kobe plot of the B / B_{MSY}* vs. F / F_{MSY} time series from 2005 (square) to 2018 (triangle). Grey-shaded contours around the 2018 triangle are the 95%, 80%, and 50% credibility intervals of the estimate.



Length and maturity measurements nevertheless gave some evidence that fishing has influenced the rock cod stock. Lengths at 50% adulthood showed a significantly decreasing trend ($p < 0.05$) for males over the period 2003 to 2018, and a qualitatively similar although non-significant trend for females (Figure 5). 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.

Conclusion

The addition of 2007 to the index of rock cod biomass estimates produced a change in the time series profile of this stock. Rather than increasing rapidly since about the mid-2000s (Laptikhovsky et al. 2013, Winter and Gras 2018), it appears now that rock cod abundance was high for at least a number of previous years, before decreasing substantially to current levels (Figure 2). The caveat remains that the 2007 survey has a high margin of uncertainty (Table 2); having covered only part of the finfish area, but for a survey that was actually dedicated to skates it is notable that 50.36% of total catch was rock cod (FIG 2007). Two earlier bottom trawl surveys during February had also reported rock cod as the highest (2000; 31.25% of total, FIG 2000) and second-highest (2006; 25.42% of total, FIG 2006) catch[2].

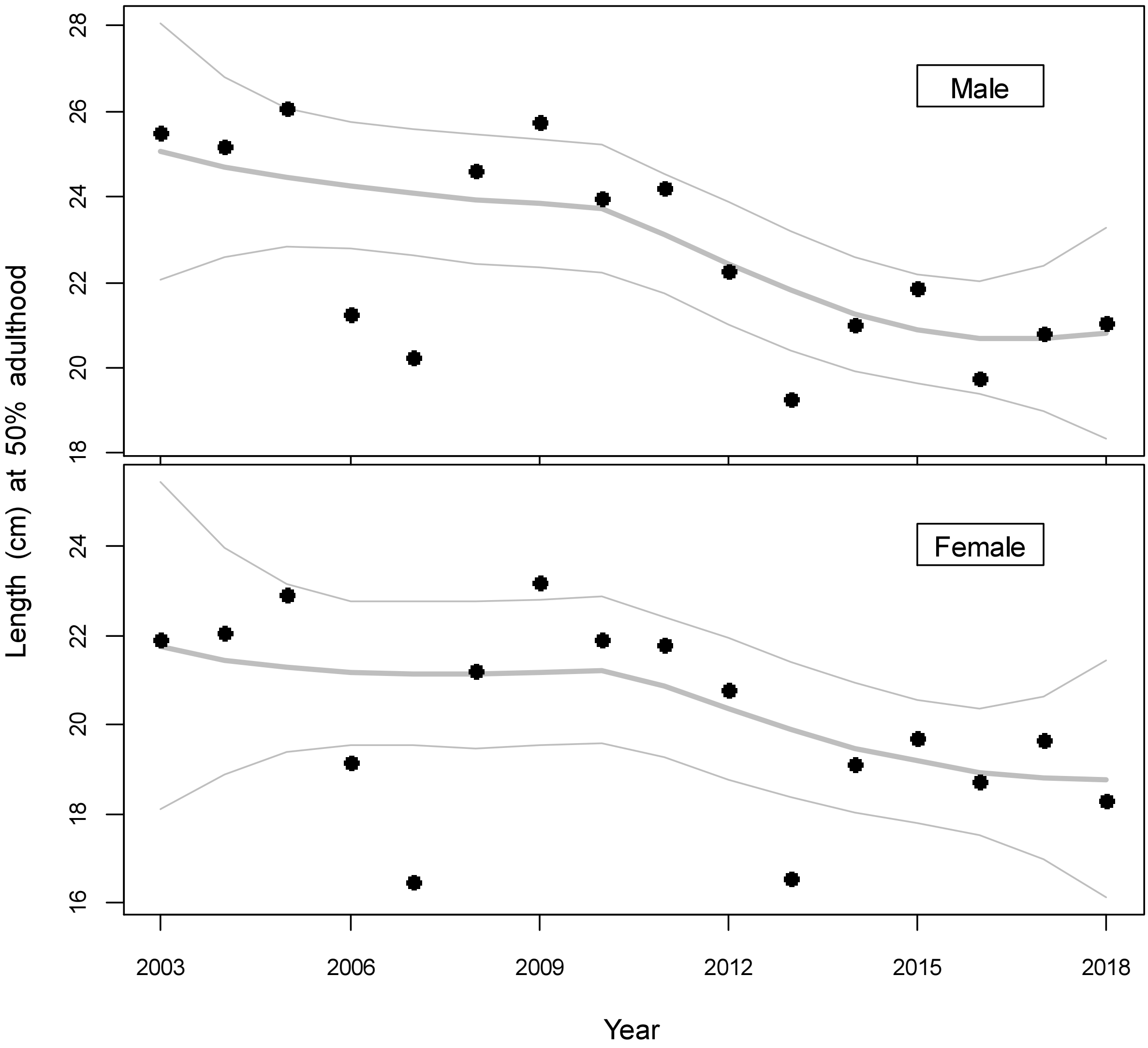


Figure 5. Lengths at 50% adulthood of male (top) and female (bottom) rock cod, 2003 to 2018. Grey lines are LOESS smooths ± 95% confidence intervals. Yearly data correspond to the 0.5 length intercepts in Figure A4.

From its current level, the rock cod stock has not shown signs of recovery despite low catches in the fishery (Table 1). With recent high catches of hake (H. Randhawa, FIFD, unpublished), calamari (Winter 2018, Winter et al. 2019) and intermittently *Illex* (FIS 2015), it may be hypothesized that the species assemblage has undergone a longer-term shift. To stabilize rock cod at its current level, it is recommended to limit fishing mortality at the rate that was last in the 'green zone'; in 2015 (Figure 4). In 2015, Falklands zone rock cod catch was recorded at 29086 tonnes (FIG 2018), non-significantly higher than the current estimated

[2] However, the 2000 and 2006 February surveys were not included in the stock assessment as they covered shelf areas south and east that did not include the main fishing grounds for rock cod.

MSY (Table 3), plus approx. 930 tonnes of out-of-zone catch. However, estimated carrying capacity K was 2.7× higher in 2015 (428,743 tonnes) than in 2018 (158,722 tonnes), suggesting, as a reference point, that current allowable catch be limited to (29086 + 930)/2.7 = 11,112 tonnes. Allowable catch should remain contingent on potential future progression of the carrying capacity.

References

Arkhipkin, A., Brickle. P., Laptikhovsky, V. 2003. Variation in the diet of the Patagonian toothfish, *Dissostichus eleginoides* (Perciformes: Nototheniidae), with size, depth and season around the Falkland Islands (Southwest Atlantic). Journal of Fish Biology 63: 428–441.

Arkhipkin, A., Brickle, P., Laptikhovsky, V., Winter, A. 2012. Dining hall at sea: feeding migrations of nektonic predators to the eastern Patagonian Shelf. Journal of Fish Biology 81: 882-902.

Arkhipkin, A., Winter, A., May, T. 2010. *Loligo gahi* stock assessment survey, First season 2010. Technical Document, FIG Fisheries Department, 13 p.

Bianchi, G., Gislason, H., Graham, K., Hill, L., Jin, X., Koranteng, K., Manickchand–Heileman, S., Payá, I., Sainsbury, K., Sanchez, F., Zwanenburg, K. 2000. Impact of fishing on size composition and diversity of demersal fish communities. ICES Journal of Marine Science 57: 558–571.

Brickle, P., Laptikhovsky, V., Pompert, J., Bishop, A. 2003. Ontogenetic changes in the feeding habits and dietary overlap between three abundant rajid species on the Falkland Islands' shelf. Journal of the Marine Biological Association of the UK 83: 1119-1125.

Brickle, P., Shcherbich, Z., Laptikhovsky, V., Arkhipkin, A. 2005. Scientific Report. Aspects of the biology of the Falkland Islands rockcod *Patagonotothen ramsayi* (Regan, 1913) on the southern Patagonian shelf. Directorate of Natural Resources, FIG, Stanley, 81 p.

Brickle, P., Laptikhovsky, V., Arkhipkin, A., Portela, J. 2006a. Reproductive biology of *Patagonotothen ramsayi* (Regan, 1913) (Pisces: Nototheniidae) around the Falkland Islands. Polar Biology 29: 570-580.

Brickle, P., Arkhipkin, A., Shcherbich, Z. 2006b. Age and growth of a sub-Antarctic notothenioid, *Patagonotothen ramsayi* (Regan 1913), from the Falkland Islands. Polar Biology 29: 633-639.

Carson, R.T., Granger, C.W.J., Jackson, J.B.C., Schlenker, W. 2009. Fisheries management under cyclical population dynamics. Environmental and Resource Economics 42: 379-410.

Chapman, E.J., Byron, C.J. 2018. The flexible application of carrying capacity in ecology. Global Ecology and Conservation 13: e00365.

Falkland Islands Government (FIG). 2000. Scientific Report, Fisheries Research Cruise ZDLH1-02-2000. Stanley, FIG Fisheries Department. 64 p.

Falkland Islands Government (FIG). 2006. Scientific Report, Fisheries Research Cruise ZDLH1-02-2006. Stanley, FIG Fisheries Department. 37 p.

Falkland Islands Government (FIG). 2007. Scientific Report, Fisheries Research Cruise ZDLH1-02-2007. Stanley, FIG Fisheries Department. 40 p.

Falkland Islands Government (FIG). 2010. Scientific Report, Fisheries Research Cruise ZDLT1-02-2010. Stanley, Fisheries Department, Directorate of Natural Resources, Falkland Islands Government, 31 p.

Falkland Islands Government (FIG). 2011. Scientific Report, Fisheries Research Cruise ZDLT1-02-2011. Stanley, Fisheries Department, Directorate of Natural Resources, Falkland Islands Government, 37 p.

Falkland Islands Government (FIG). 2018. Fisheries Department Fisheries Statistics, Volume 22, 2017. Stanley, FIG Fisheries Department, 68 p.

FIS 2015. 'Extraordinary' Illex squid season forecast. www.fis.com/fis/worldnews//worldnews.asp?l=e&id=75918&ndb=1

Froese, R., Demirel, N., Coro, G., Kleisner, K.M., Winker, H. 2017. Estimating fisheries reference points from catch and resilience. Fish and Fisheries 18: 506-526.

Froese, R., Pauly, D. (eds.) 2019. FishBase. World Wide Web electronic publication. www.fishbase.org, (02/2019).

Gonzalez, M.J., Gallardo, J.M., Brickle, P., Medina, I. 2007. Nutritional composition and safety of *Patagonotothen ramsayi*, a discard species from Patagonian shelf. International Journal of Food Science and Technology 42:1240-1248.

Gras, M. 2016. Linear models to predict the horizontal net opening of the DNR Fisheries Department bottom trawl. Technical Document, FIG Fisheries Department. 5 p.

Gras, M., Blake, A., Pompert, J., Jürgens, L., Visauta, E., Busbridge, T., Rushton, H., Zawadowski, T. 2015. Report of the 2015 rock cod biomass survey ZDLT1-02-2015. Stanley, Fisheries Department, Directorate of Natural Resources, Falkland Islands Government, 45 p.

Gras, M., Pompert, J., Blake, A., Boag, T., Grimmer, A., Iriarte, V., Sánchez, B, 2016. Report of the 2016 finfish and rock cod biomass survey ZDLT1–02–2016. Stanley, Fisheries Department, Directorate of Natural Resources, Falkland Islands Government, 72 p.

Gras, M., Pompert, J., Blake, A., Busbridge, T., Derbyshire, C., Keningale, B., Thomas, O. 2017. Report of the 2017 ground fish survey ZDLT1–02–2017. Stanley, Directorate of Natural Resources – Fisheries, Falkland Islands Government, 83 p.

Gras, M., Randhawa, H.S., Blake, A., Busbridge, T., Chemshirova, I., Guest, A. 2018. Report of the 2018 ground fish survey ZDLM3–02–2018. Stanley, Directorate of Natural Resources – Fisheries, Falkland Islands Government, 83 p.

Hilborn, R., Walters, C.J. 1992. Quantitative Fisheries Stock Assessment. Chapman and Hall, New York, 570 p.

Hilborn, R., Mangel, M. 1997. The Ecological Detective. Monographs in Population Biology 28, Princeton University Press, 315 p.

Hutchings, J. A. 2004. Chapter 7; Life histories of fish. In Handbook of Fish Biology and Fisheries, Vol. 1 (Hart, P. J. B. & Reynolds, J. D., eds), pp. 149–174. Oxford: Blackwell Science Ltd.

Kravchenko, A.N. 2003. Influence of spatial structure on accuracy of interpolation methods. Soil Science Society of America Journal 67: 1564–1571.

La Mesa M., Riginella E., Melli V., Bartolini F., Mazzoldi C. 2016. Biological traits of a sub-Antarctic nototheniid, *Patagonotothen ramsayi*, from the Burdwood Bank. Polar Biology 39: 103-111.

Laptikhovsky, V., Arkhipkin, A. 2003. An impact of seasonal squid migrations and fishing on the feeding spectra of subantarctic notothenioids *Patagonotothen ramsayi* and *Cottoperca gobio* around the Falkland Islands. Journal of Applied Ichthyology 19: 35-39.

Laptikhovsky, V., Arkhipkin, A., Brickle, P. 2013. From small bycatch to main commercial species: Explosion of stocks of rock cod *Patagonotothen ramsayi* (Regan) in the Southwest Atlantic. Fisheries Research 147: 399-403.

Martell, S., Froese, R. 2013. A simple method for estimating MSY from catch and resilience. Fish and Fisheries 14: 504-514.

Maunder, M. 2001. A general framework for integrating the standardization of catch per unit effort into stock assessment models. Canadian Journal of Fisheries and Aquatic Sciences 58: 795-803.

Maunder M, Aires-da-Silva, A. 2011. Evaluation of the Kobe plot and strategy matrix and their application to tuna in the EPO. Inter-American Tropical Tuna Commission Stock Assessment Report 12: 191-211.

Mueller, T.G., Pusuluri, N.B., Mathias, K.K., Cornelius, P.L., Barnhisel, R.I., Shearer, S.A. 2004. Map Quality for Ordinary Kriging and Inverse Distance Weighted Interpolation. Soil Science Society of America Journal 68: 2042-2047.

Nash, J.C., Varadhan, R. 2011. optimx: A replacement and extension of the optim() function. R package version 2011-2.27. http://CRAN.R-project.org/package=optimx

Nyegaard, M., Arkhipkin, A., Brickle, P. 2004. An alternating discard scavenger: variation in the diet of kingclip, *Genypterus blacodes* (Ophidiidae) around the Falkland Islands. Journal of Fish Biology 65: 666–682.

Pauly, D., Christensen, V., Dalsgaard, J., Froese, R., Torres, F. Jr. 1998. Fishing down marine food webs. Science 279:860-863.

Payá, I. 2007. *Loligo gahi* stock assessment survey, First season 2007. Technical Document, FIG Fisheries Department, 15 p.

Punt, A. E. 1990. Is B1 = K an appropriate assumption when applying an observation error production-model estimator to catch-effort data? South African Journal of Marine Science 9: 249-259.

Quinn II, T.J. 2003. Ruminations on the development and future of population dynamics models in fisheries. Natural Resource Modeling 16: 341-392.

Schaefer, M.B. 1954. Some aspects of the dynamics of populations important to the management of commercial marine fisheries. Bulletin of the IATTC 1: 27-56.

Seafish. 2010. Bridle angle and wing end spread calculations. Research and development catching sector fact sheet. www.seafish.org.

Shepard, D. 1968. A two-dimensional interpolation function for irregularly-spaced data. Proceedings of the 23rd ACM National Conference: 517-524.

Shin, Y.–J., Rochet, M.–J., Jennings, S., Field, J. G., Gislason, H. 2005. Using size–based indicators to evaluate the ecosystem effects of fishing. ICES Journal of Marine Science 62: 384–396.

Wang, J., Yu, W., Chen, X., Chen, Y. 2016. Stock assessment for the western winter-spring cohort of neon flying squid (*Ommastrephes bartramii*) using environmentally dependent surplus production models. Scientia Marina 80: 69-78.

Wang, J., Chen, X., Tanaka, K., Cao, J., Chen, Y. 2017. Environmental influences on commercial oceanic ommastrephid squids: a stock assessment perspective. Scientia Marina 81: 37-47.

Winter, A., Laptikhovsky, V., Brickle, P. Arkhipkin, A. 2010. Rock cod (*Patagonotothen ramsayi* (Regan, 1913)) stock assessment in the Falkland Islands. Fisheries Department, Falkland Islands Government, 12 p.

Winter, A., Davidson, D. Watson, M. 2011. *Loligo gahi* stock assessment survey, 1st season 2011. Technical Document, FIG Fisheries Department, 18 p.

Winter, A., Jones, J., Shcherbich, Z. 2015. *Loligo* stock assessment survey, 1st season 2015. Technical Document, FIG Fisheries Department, 16 p.

Winter, A., Zawadowski, T., Shcherbich, Z., Bradley, K., Kuepfer, A. 2016. Falkland calamari stock assessment survey, 1st season 2016. Technical Document, FIG Fisheries Department, 19 p.

Winter, A., Jones, J., Shcherbich, Z. Iriarte, V. 2017. Falkland calamari stock assessment survey, 1st season 2017. Technical Document, FIG Fisheries Department, 17 p.

Winter, A. 2018. *Doryteuthis gahi* stock assessment, 2nd season 2018. Technical Document, FIG Fisheries Department, 34 p.

Winter, A., Gras, M. 2018. Rock cod (*Patagonotothen ramsayi*) stock assessment. Technical Document, FIG Fisheries Department. 13 p.

Winter, A., Iriarte, V., Zawadowski, T. 2018a. *Doryteuthis gahi* stock assessment survey, 1st season 2018. Technical Document, FIG Fisheries Department, 20 p.

Winter, A., Zawadowski, T., Thomas, O. 2018b. *Doryteuthis gahi* stock assessment survey, 2nd season 2018. Technical Document, FIG Fisheries Department, 19 p.

Winter, A., Zawadowski, T., Tutjavi, V. 2019. *Doryteuthis gahi* stock assessment survey, 1st season 2019. Technical Document, FIG Fisheries Department, 18 p.

Zhou, S., Punt, A.E., Smith, A.D.M., Ye, Y., Haddon, M., Dichmont, C.M., Smith, D.C. 2018. An optimized catch-only assessment method for data poor fisheries. ICES Journal of Marine Science 75: 964-976.

Appendix 1

Biomass densities per species at each trawl station were calculated as the species catch weight divided by the trawl station area: trawl width × distance. For *D. gahi* squid surveys, trawl width was derived from the distance between trawl doors (Seafish 2010). For groundfish surveys, the triangulation method that derives trawl width from the distance between trawl doors is unsuitable because the geometry of the net is different. Since 2016 finfish survey trawl width has instead been measured directly from Marport sensors fitted to the extremities of the survey vessel's trawl net wings. Finfish surveys earlier than 2016 received trawl widths retroactively calculated using a linear function of either trawl net height or door distance (Gras 2016). The 2007 trawl survey had wing spread (net width) recorded in its database.

Yearly trawl biomass densities were extrapolated to the survey area combining the Loligo Box (31,296.9 km^2) and finfish zone (122,493.7 km^2), partitioned into grids of 5 km^2, using inverse distance weighting. Position coordinates were converted to WGS 84 projection in UTM sector 21. The basic inverse distance weighting algorithm assigns a value u to any grid location x that is the weighted average of a known scattered set of points $\mathrm{x_i}$ according to the inverse of the i points' distances from the grid location x:

$$u(\mathrm{x}) = \begin{cases} \dfrac{\sum_{i=1}^{N} w_i(\mathrm{x}) u_i}{\sum_{i=1}^{N} w_i(\mathrm{x})}, & \text{if } d(\mathrm{x}, \mathrm{x_i}) \neq 0 \\ u_i, & \text{if } d(\mathrm{x}, \mathrm{x_i}) = 0 \end{cases}$$

where

$$w_i(\mathrm{x}) = \frac{1}{d(\mathrm{x}, \mathrm{x_i})^p}$$

The power parameter *p* (a positive real number) adjusts the weight of points $\mathrm{x_i}$ as a function of distance; higher values of *p* put higher influence on the points $\mathrm{x_i}$ closest to a given interpolated point x. For this assessment, values of *p* were computationally optimized so that the coefficient of variation of the interpolated points x (the grids of 5 km^2) matched the coefficient of variation of the actual survey catches. Because some points may be more clustered than others, an isolation parameter was assigned attributing to points $\mathrm{x_i}$ more weight in proportion to being further away from any other point $\mathrm{x_i}$. Isolation parameters (*s*), per yearly survey, were calculated as the standardized mean of distances between each point $\mathrm{x_i}$ and all other points $\mathrm{x_j}$:

$$s(\mathrm{x_i}) = \overline{d(\mathrm{x_i}, \mathrm{x_j})}$$

, giving a revised inverse distance weighting factor as:

$$w_i(\mathrm{x}) = \left(\frac{s(\mathrm{x_i})}{d(\mathrm{x}, \mathrm{x_i})}\right)^p$$

A further adjustment was made to the calculation of distance. The distance *d*(x, $\mathrm{x_i}$) is inherently calculated as Euclidean (straight-line) distance. However, the survey area surrounds the Falkland Islands and between two remote points a fish or ship would have to travel a real distance longer than straight-line; circumnavigating the landmass. Therefore, an axial loop was drawn through the survey area (Figure A1 – an extension of the axial line through the Loligo Box used in Winter et al. 2018b), and *d*(x, $\mathrm{x_i}$) was defined as the longer of either the Euclidean distance between x and x_i, or the distance on the axial loop between its two points respectively closest to x and x_i.

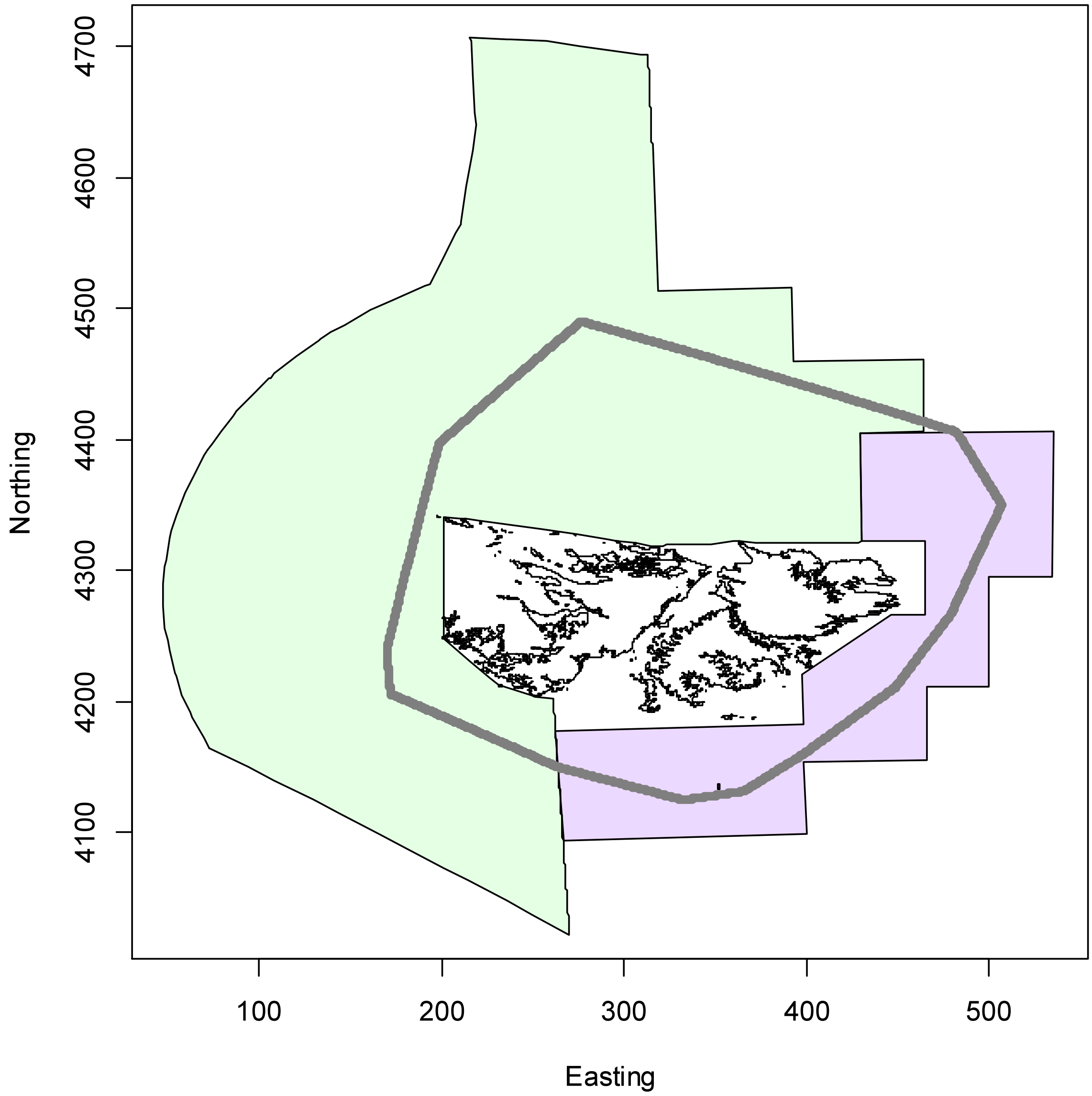


Figure A1. Survey area combining the finfish zone (green) and Loligo Box (mauve), with axial loop (dark grey) used to define relative distances for the inverse distance weighting algorithm.

Uncertainty of the biomass was estimated by a hierarchical bootstrap algorithm. For 30,000 iterations, survey trawls and their catches were first randomly re-sampled with replacement, whereby each year's finfish survey and parallel *D. gahi* survey were re-sampled separately so that both 'halves' of the survey area retained about the same relative coverage. Second, each re-sampled trawl was given a random uniform re-assignment of its coordinate position between start latitude and longitude and end latitude and longitude. Third, the isolation parameters were re-calculated for the randomized set of trawl data, and the inverse distance weighted algorithm re-applied. One iteration might thus re-sample any trawl twice or more, but each would have a slightly different position. 95% confidence intervals and standard deviations of the 30,000 bootstrap iterations were then used to infer the uncertainty.

Appendix 2.

Annual commercial catches of hake (*Merluccius hubbsi* and *Merluccius australis*), hoki (*Macruronus magellanicus*) and southern blue whiting (*Micromesistius australis*) in Falklands fisheries were compared with rock cod by LOESS smooth (degree = 2, span = 0.9), 2005 to 2018. These species represent the primary commercial finfish targets (FIG 2018).

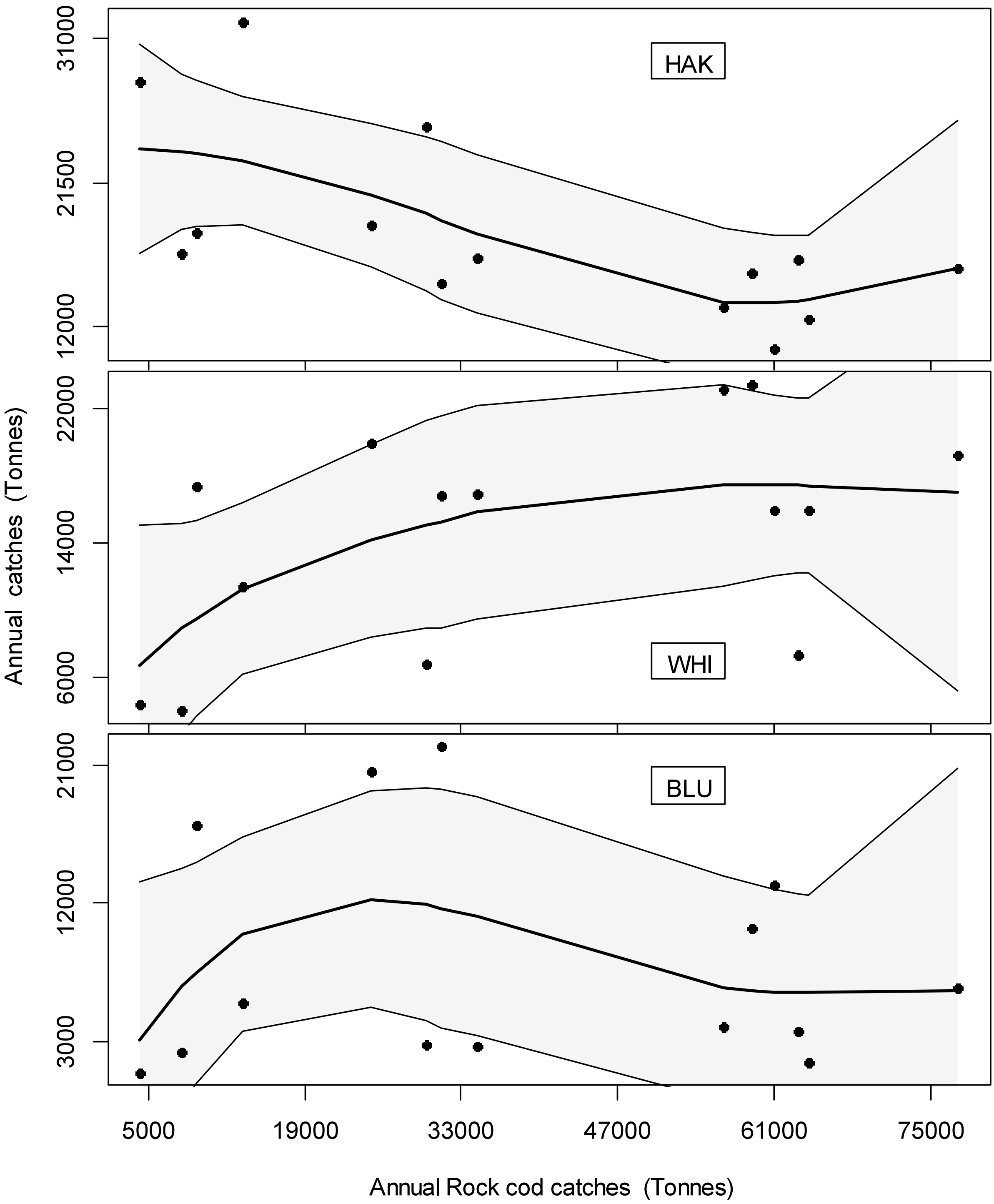
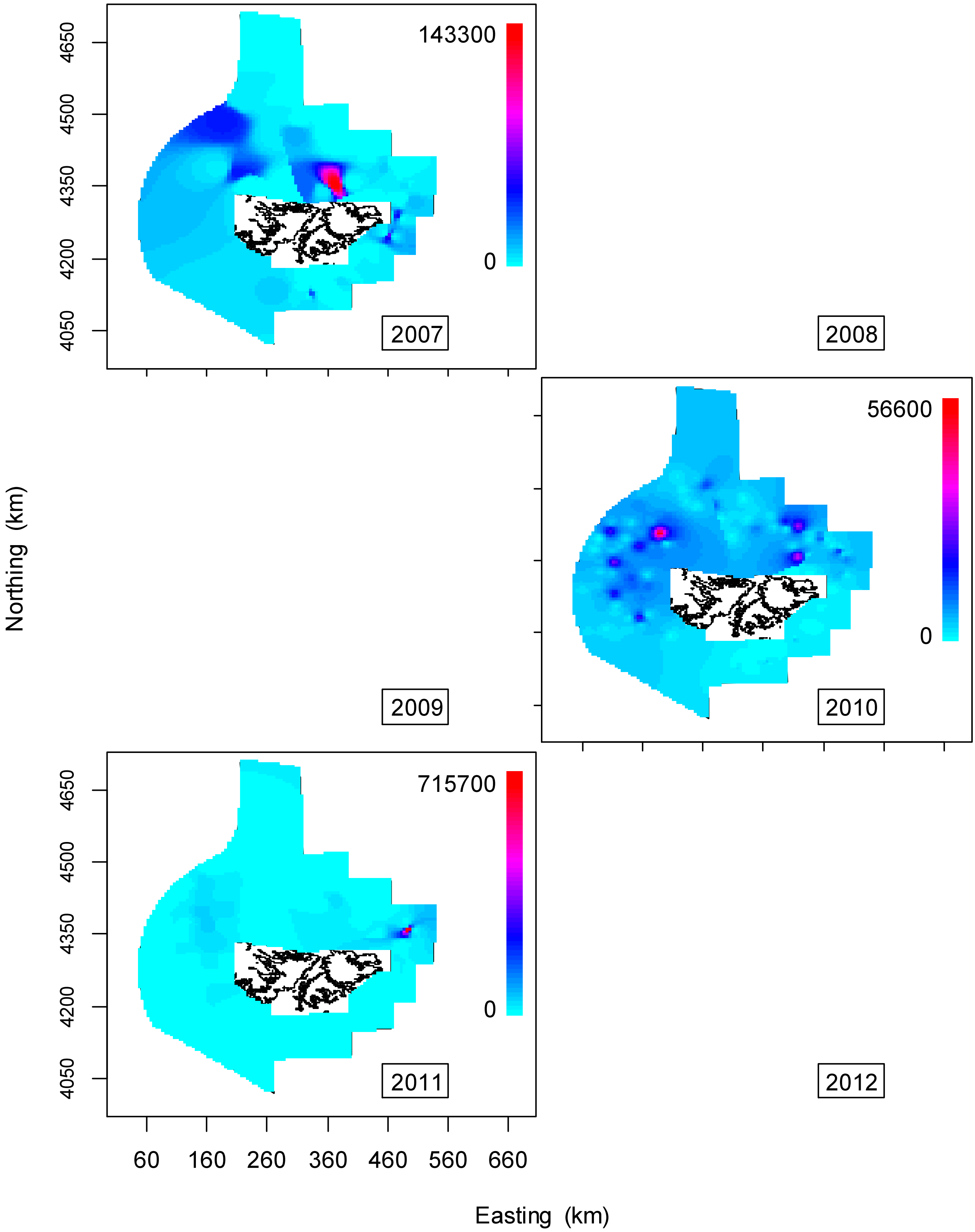


Figure A2. LOESS smooths of hake (HAK), hoki (WHI), and southern blue whiting (BLU) annual catches vs. rock cod annual catches, 2005 to 2018.

Appendix 3.



143300
0
2007
2008
56600
0
2009
2010
715700
0
2011
2012
4650
4500
4350
4200
4050
Northing (km)
60
160
260
360
460
560
660
Easting (km)

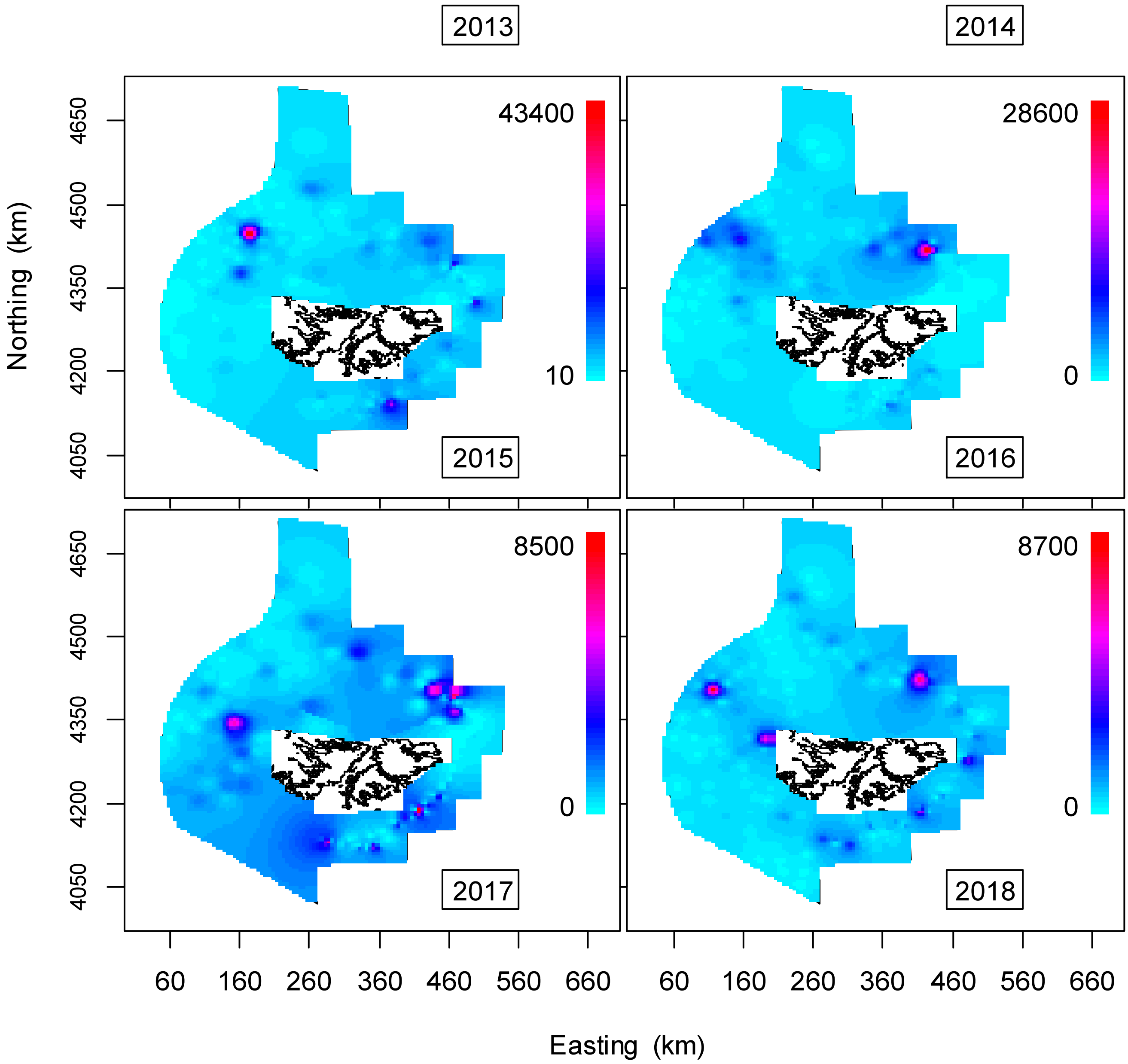
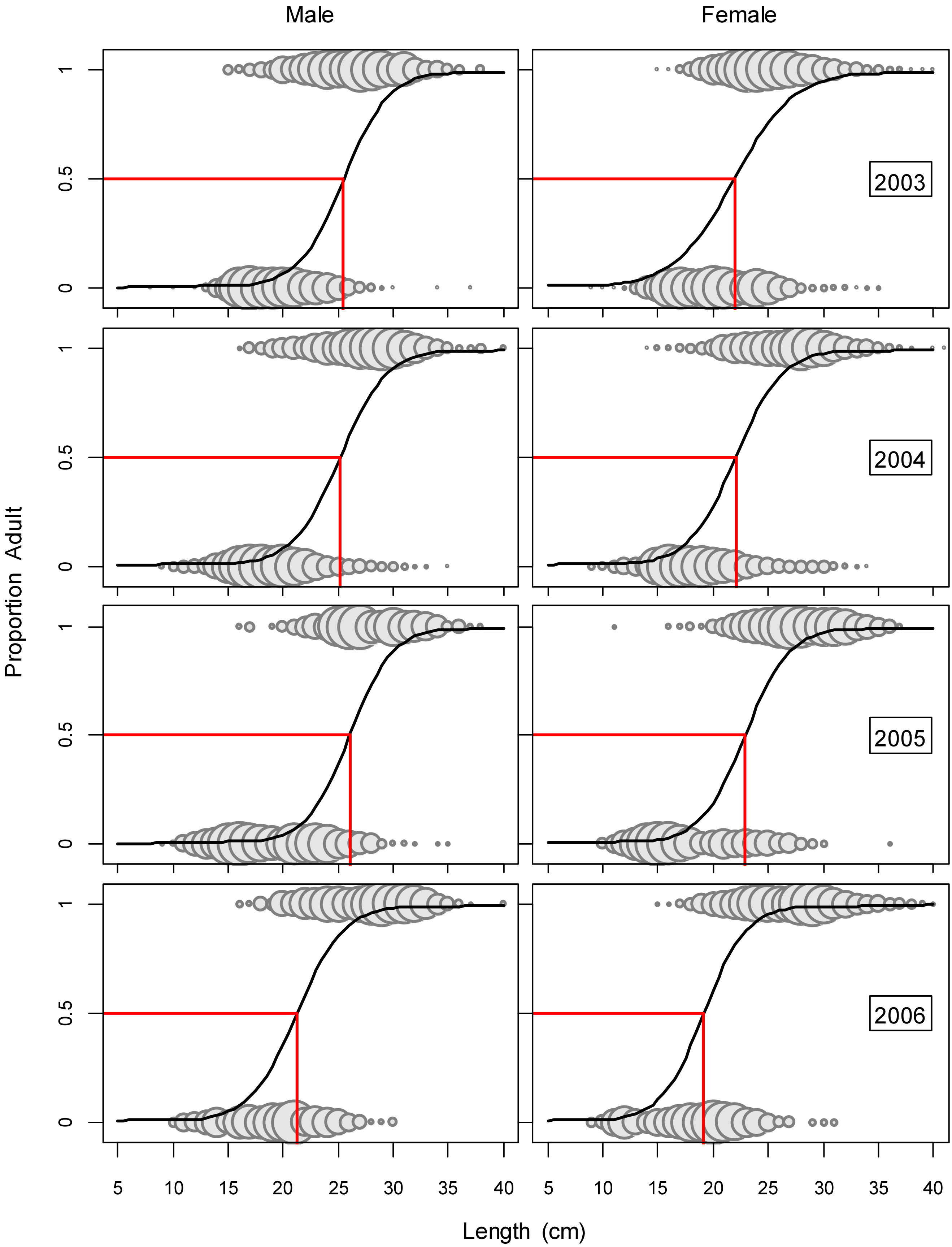
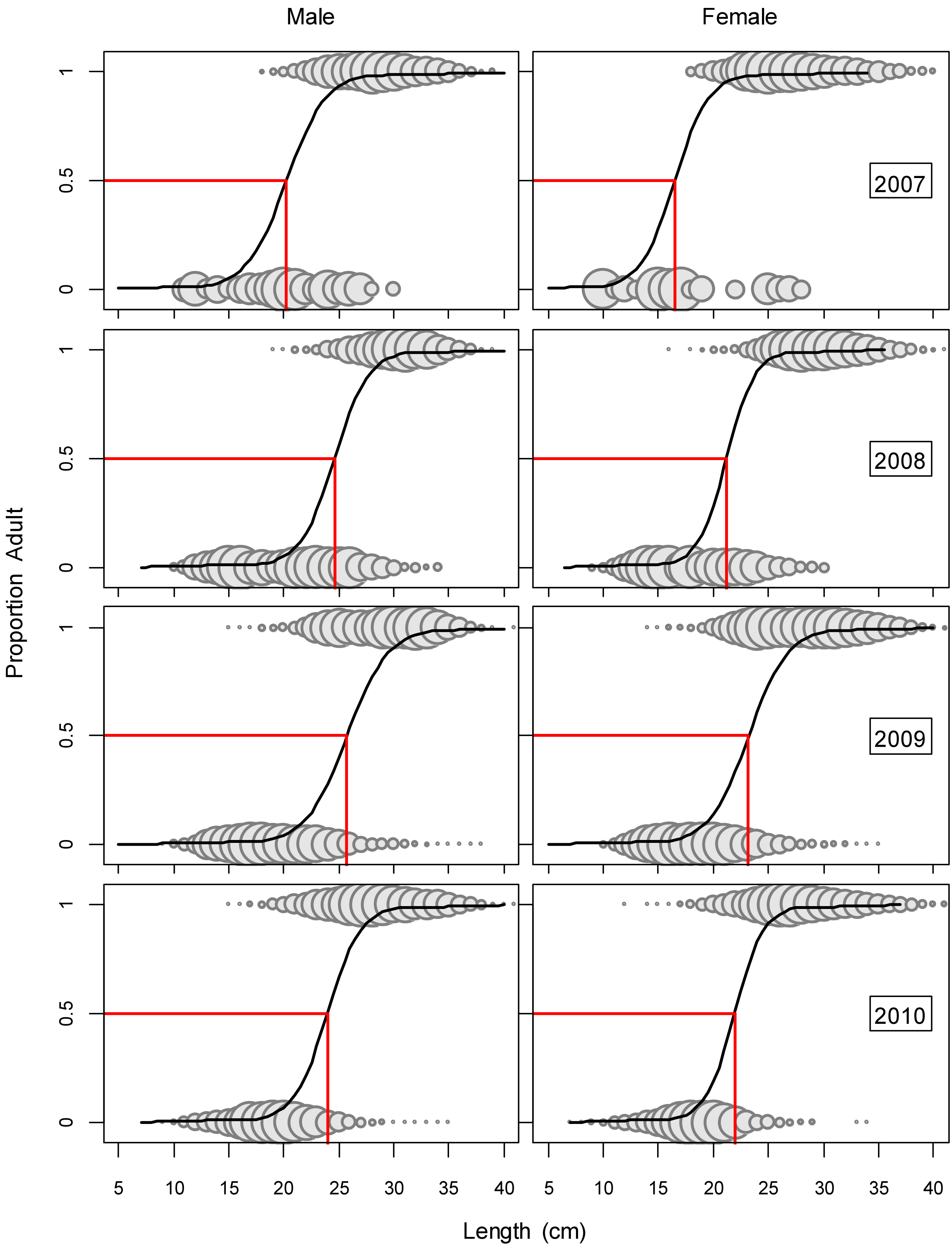


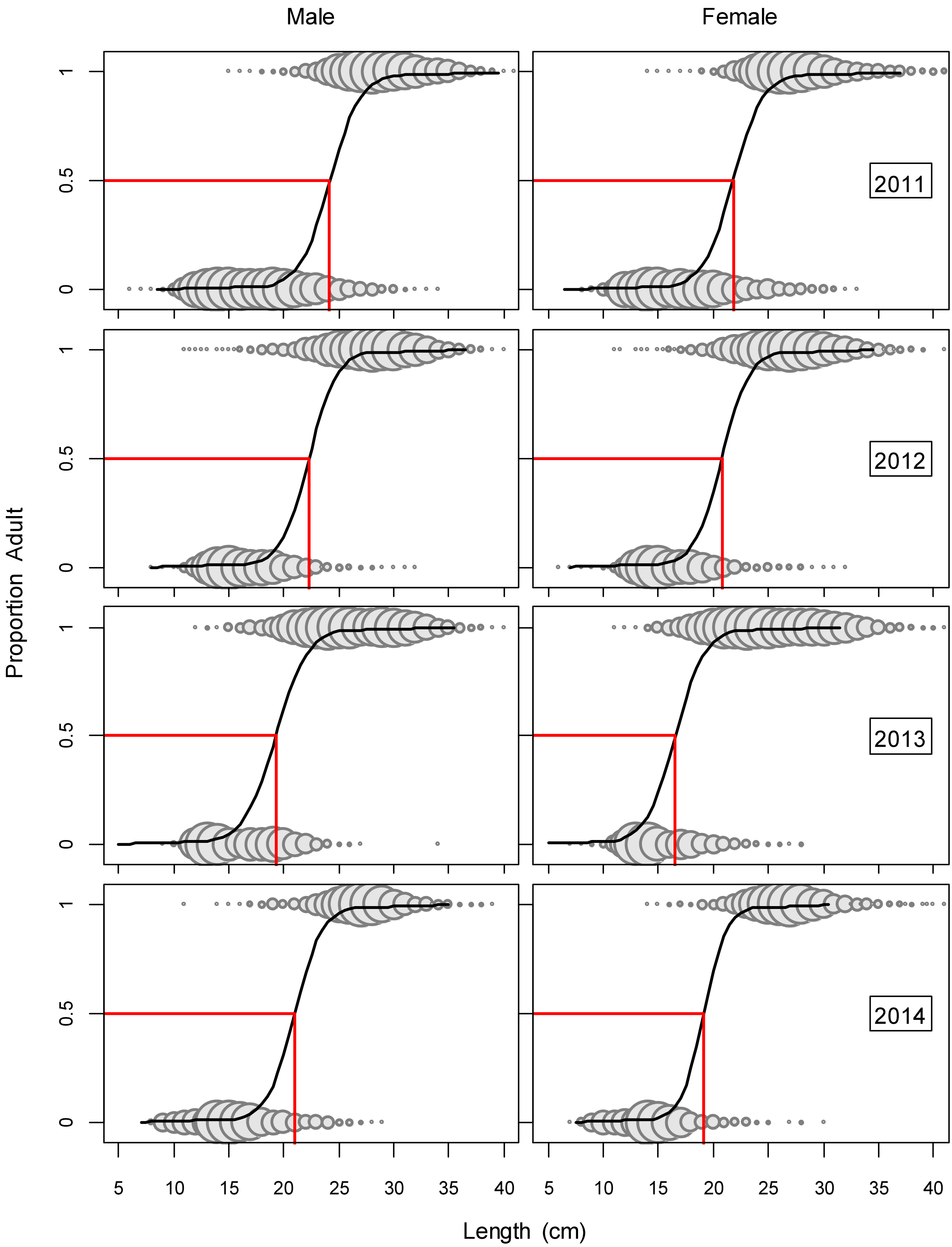
Figure A3. Modelled rock cod biomass density distributions in kg km^{-2} from February trawl surveys. Maximum and minimum densities shown on each graph.

Appendix 4.



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


Male
Female
Proportion Adult
Length (cm)
2007
2008
2009
2010
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

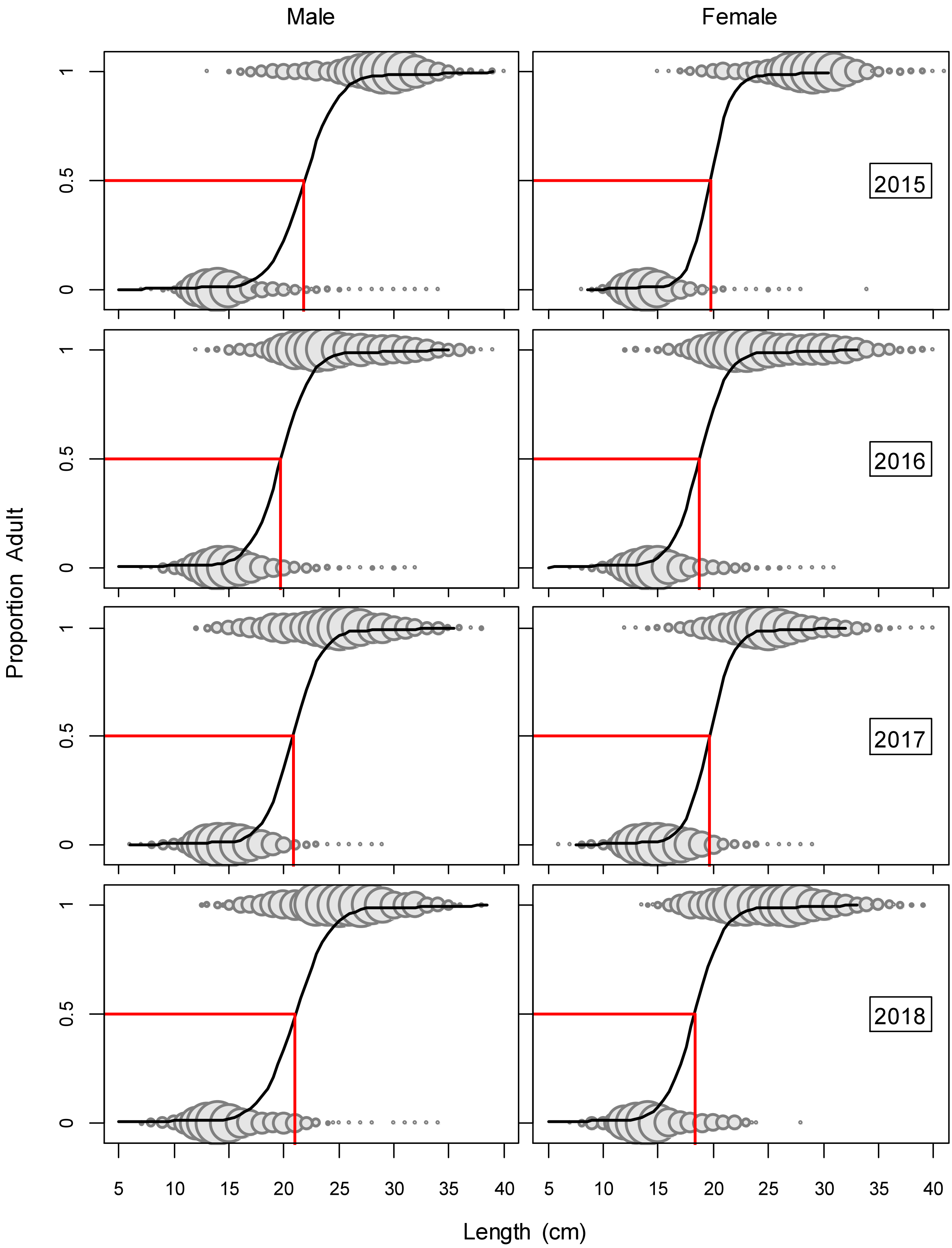


Figure A4. Binomial function GLMs of juvenile (0) or adult (1) maturity vs. length. Grey circles: scaled to sample numbers. Red lines: Length intercept of 50% adulthood, corresponding to Figure 5.