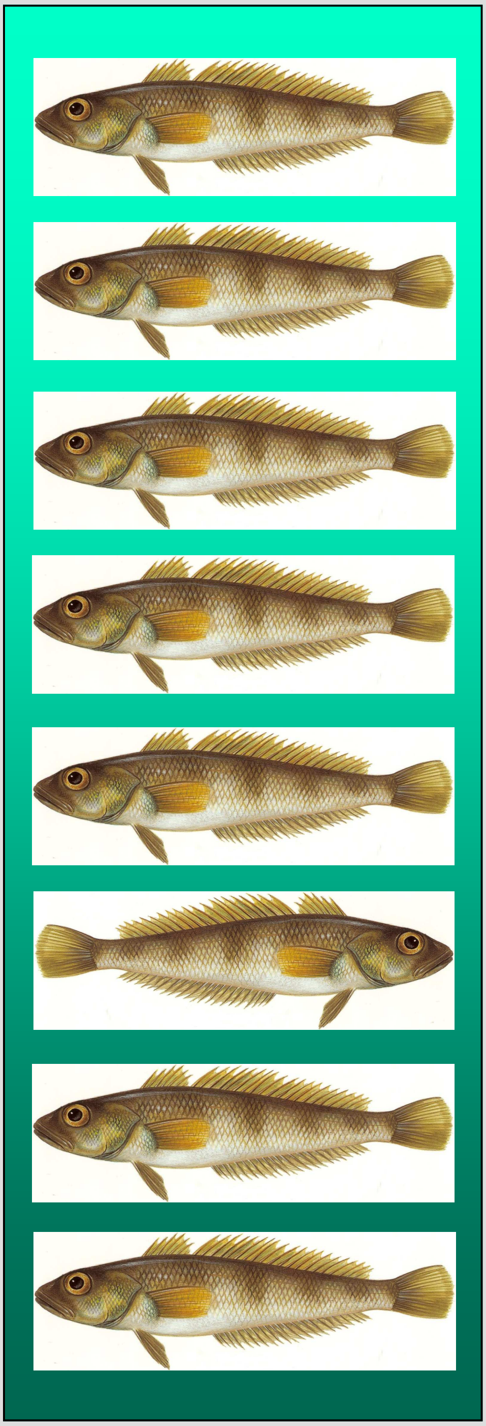

Stock assessment

Rock cod

(*Patagonotothen ramsayi*)

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Natural Resources

Fisheries

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Introduction

Rock cod *Patagonotothen ramsayi* 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). 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 (FIG 2017, Figure 1). 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.

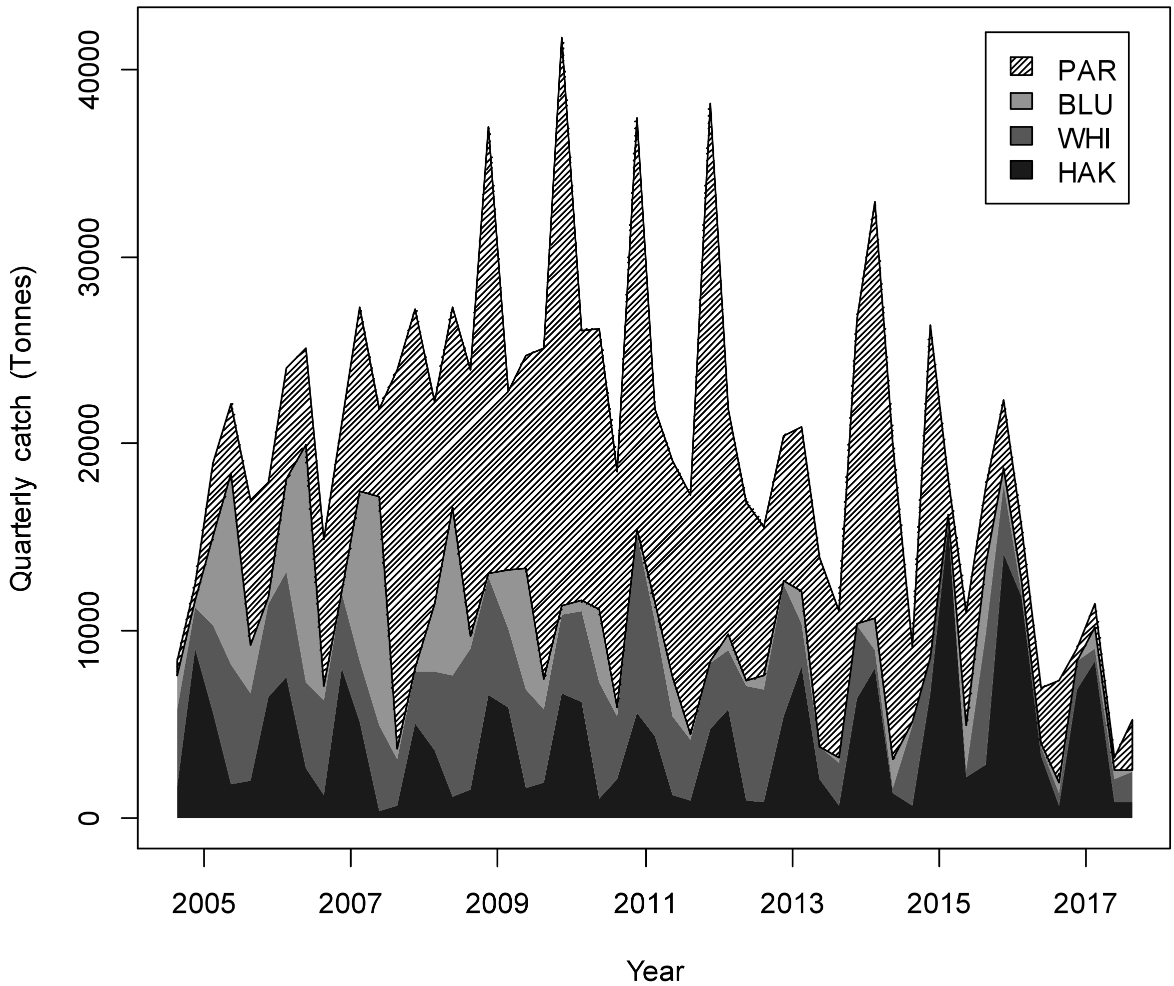

Figure 1. Quarterly catches in tonnes since 2005 in Falkland Islands fisheries of hake (HAK), hoki (WHI), blue whiting (BLU), and rock cod (PAR). The plot is stacked not superimposed; e.g., in 2nd quarter 2010, the highest peak, catch was HAK + WHI + BLU + PAR = 41695 t.

During 2017 a total of 2537 tonnes rock cod were caught in the Falkland Islands zone, with catch by licence distributions shown in Table 1. It is notable that in 2017 rock cod were primarily taken in the calamari fisheries where most (99%) are destined to be discarded. Among finfish target licences, of 727 A licence catch reports in 2017, rock cod was the highest catch species on 3 and the second-highest on 20 catch reports. Of 440 G licence catch reports in 2017, rock cod was the highest catch species on 2 and the second-highest on 41 catch reports. And of 603 W licence catch reports in 2017, rock cod was the highest catch species on 13 and the second-highest on 29 catch reports.

Table 1. Falkland Islands rock cod catches by licence in 2017.

Licence		Rock cod catch	%
Code	Type	(tonnes)	
A	Unrestricted finfish	180.0	7.1
G	Restricted finfish + *Illex*	247.9	9.8
W	Restricted finfish	170.2	6.7
F	Skate	4.8	0.2
C	Calamari 1st season	687.3	27.1
X	Calamari 2nd season	1129.2	44.5
B	*Illex* squid	2.7	0.1
S	Surimi	0.0	0.0
L	Toothfish longline	0.0	0.0
E	Experimental	115.1	4.5
Total		2537.1	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. The model is run from year t = 2005, when rock cod were starting to be recorded in catches as an identified species group (rather than 'other'). The model ends with year t = 2017, the last complete year of data.

The Schaefer production model has achieved inadequate results in the past two years, as catch indicators of rock cod have decreased strongly (FIFD 2017). The available data and length of time series do not yet support transition to an age-structured model for this species. Therefore, a modified version of the Schaefer production model is implemented to improve estimation, in particular with respect to two factors:

A) Index of relative abundance.
B) Carrying capacity.

An index of relative abundance is required to optimize the free parameters of the model; r, K, B_1 (stock biomass in the first year of the fishery), and q (catchability coefficient). Indices of relative abundance are typically constructed from the CPUE of fishing. However, CPUE only provides a reliable relative abundance index if fishing effort proceeds in a consistent pattern annually. In a commercial fishery, consistent effort is difficult to ascertain unless the species is the sole target of the fishery, not a mixed-species target or bycatch (Biseau 1998). Furthermore, catchability may change significantly over the course of a commercial fishery (Walters and Maguire 1996) or mask changing spatial distributions (Walters 2003). Targeting of rock cod in the Falkland Islands has undergone large fluctuations as the stock size fluctuated (Laptikhovsky et al. 2013, FIFD 2017). Attempts to standardize or subset commercial CPUE have not given good results. For this assessment, survey biomass estimates are used instead of commercial CPUE for the index of relative abundance. Since the start of commercial targeting of rock cod, five trawl surveys have been conducted over the grounds fished for rock cod, and timed to coincide with the *Doryteuthis gahi* squid surveys in February to provide a synchronous estimate of rock cod in the entire Falklands fishery zone (Winter et al. 2010). These five surveys were in 2010 (FIG 2010), 2011 (FIG 2011), 2015 (Gras et al. 2015), 2016 (Gras et al. 2016), and 2017 (Gras et al. 2017). Geostatistic estimates of rock cod biomass in these surveys have recently been revised and standardized to provide a consistent measure of abundance (Table 2, and see Appendix). Biomasses were transformed into a relative index ($B_{\text{relative } t}$) by dividing each survey year's biomass by the mean of the five survey years' biomass (Table 2).

Table 2. Geostatistic estimates of rock cod biomass (tonnes).

Year	Groundfish zone	*D. gahi* zone	Total	Index
2010	752836	38633	791470	1.414
2011	870932	386103	1257035	2.246
2015	237168	127602	364769	0.652
2016	230992	25958	256950	0.459
2017	95242	33043	128285	0.229

The carrying capacity in the general form of the Schaefer production model is defined by a single variable (K), as the population is assumed stationary (at equilibrium). However, the large inter-annual changes in commercial and survey rock cod catches indicate that the Falklands rock cod population is not at equilibrium. Carrying capacity may especially manifest disequilibrium in a production model as cumulative changes in 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). For this rock cod assessment model, carrying capacity was not correlated with environmental factors, but allowed to flex between years. The flexibility represented a surrogate for changes in habitat suitability for rock cod, or the encroachment of other species. Thus the production model became:

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

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 (every other year K_{2005}, K_{2007}, K_{2009}, K_{2011}, K_{2013}, K_{2015}, K_{2017}), but optimized on a LOESS smooth prediction (span = 0.9) of these 7 years applied to all years 2005-2017. The full model for this stock assessment thus optimized 10 parameters: K_{2005}, K_{2007}, K_{2009}, K_{2011}, K_{2013}, K_{2015}, K_{2017}, B_1, and q. 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), the assumption of $B_1 = K_{2005}$ would have been inappropriate.

The objective function of model optimization was:

$$\sum_{t}^{survey}\left(\log\left(B_{optim\ t}\right)-\log\left(\frac{B_{relative\ t}}{q_{optim}}\right)\right)^2 \tag{3}$$

summed on the survey years t = 2010, 2011, 2015, 2016, 2017. The objective function was augmented by penalty functions for K (in any year) ≤ 0, B_{2005} < catch in the first year, $B_{2005}/K_{2005} < 0.10$ or $B_{2005}/K_{2005} > 1.5$, $q < 0$ or >1, and $r < 0$ or $r > 0.8$.

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

$$MSY = \frac{rK_{2017}}{4} \tag{4}$$

Optimization was calculated in R programming package ‘optimx’ using the Nelder-Mead algorithm (Nash and Varadhan 2011). With 10 parameters, the model was susceptible to converging on non-global minima (Subbey 2018). Therefore a multi-step procedure was employed. The optimization was initiated with plausible values based on the last previous successful time-series model (FIFD 2015). After the initial optimization was run, values that had changed little from their initial values were tested over a range with all other values fixed, to see if any lower minimization could be achieved. The best minimization was then re-looped on itself through the optimization algorithm until the minimum value no longer decreased.

Variability of the model optimization was estimated by subtracting out the residuals of the model fit (per survey year; $B_{optim} - B_{relative}/q_{optim}$ as in equation 3), permuting the residuals and adding the permuted residuals back to the survey biomass estimates. Then, as before, the biomass estimates were transformed to a relative abundance index on which to optimize the production model. The usual procedure would be to randomize the permutations a large number of times (e.g., 10000×). However, with five surveys the total number of different permutations is only 5^5 = 3125. Therefore, each different permutation was run once. Of the 3125 permutations, 2395 converged successfully and were used to calculate 95% confidence intervals of the yearly biomass model estimates and the MSY.

Results and Conclusion

Final parameters of the modified production model are listed in Table 3. Rock cod biomass estimates from this model were in good agreement with the survey biomass estimates on which they were optimized, ranging from 1.9× as high in 2011 to 2.2× as high in 2010 and 2015 (Table 4). That model estimates were consistently higher than survey estimates may relate to the inclusion of out-of-zone data, which made up a substantial proportion of total rock cod catches particularly in the past 2 years. Accordingly, the model infers rock cod stock biomass more broadly throughout the area inhabited by the stock and availed to the fishery, whereas the survey estimate is restricted to the area delineated by the surveys (e.g., Gras et al. 2017).

Table 3. Optimized parameter values of the production model.

Parameter		Optimized value
Carrying capacity	(K_{2005})	2,468,051 t
Carrying capacity	(K_{2007})	542,588 t
Carrying capacity	(K_{2009})	8,950,168 t
Carrying capacity	(K_{2011})	282,761 t
Carrying capacity	(K_{2013})	3,355,025 t
Carrying capacity	(K_{2015})	763,442 t
Carrying capacity	(K_{2017})	227,484 t
Biomass in 1st year	(B_{2005})	148,790 t
Catchability coefficient	(q)	8.736 e-7
Population growth rate	(r)	0.8048

Table 4. Rock cod biomass estimates (tonnes) per year.

Year	Survey estimate	Model estimate
2005		148790
2006		253045
2007		418412
2008		691924
2009		1104042
2010	791470	1709140
2011	1257035	2397689
2012		2529431
2013		854174
2014		948876
2015	364769	784651
2016	256950	501037
2017	128285	265860

For the most recent year 2017, the model estimated a rock cod biomass of 265,860 tonnes, with a 95% confidence interval of 147,793 to 531,587 tonnes. The high overall variability margins of the model estimate are not surprising (Figure 2), as the model was optimized on only 5 independent data points (surveys in 2010, 2011, 2015, 2016, and 2017). It may be anticipated that the estimation will become tighter with more years of survey data. Maximum sustainable yield based on K_{2017} was 65,036 t with a 95% confidence interval of 14,116 to 116,620 t. This MSY should only be considered illustrative, given the caveats on MSY (Larkin 1977, Mangel et al. 2002), as the Falklands rock cod stock is not apparently at equilibrium. The value of 65,036 t does suggest, however, that current catch levels are not endangering the rock cod population.

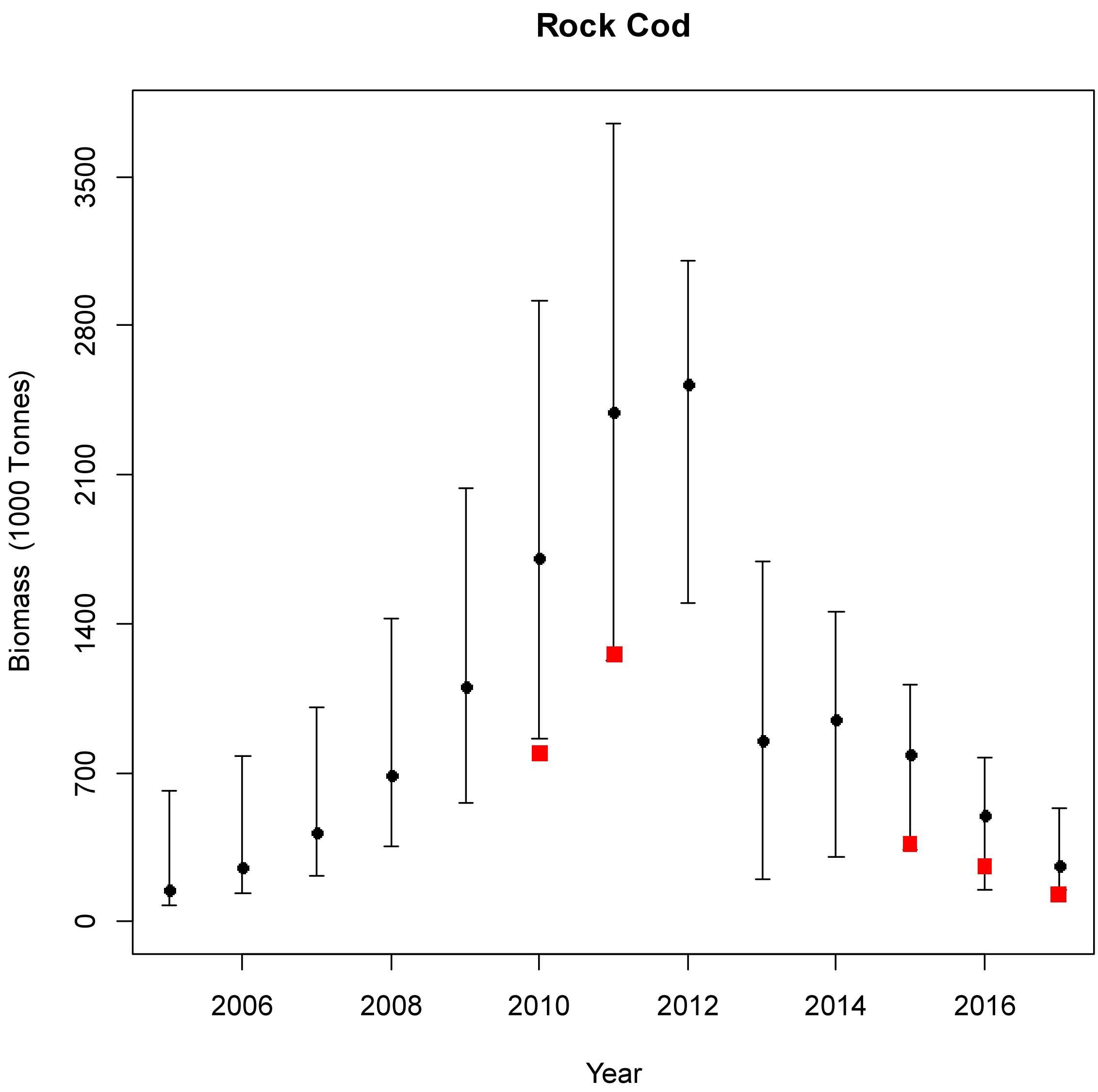

Figure 2. Annual estimates of rock cod biomass, 2005 to 2017. Red squares: geostatistic estimates from the joint groundfish – *D. gahi* surveys. Black circles: estimates from the modified production model, with 95% confidence intervals. Red squares and black circles are equivalent to the data in Table 4.

The variable carrying capacity (K) of this assessment optimized to a dome-shaped time series that peaked in 2009 at 4,601,678 tonnes, 3× higher than in 2005 and 14× higher than in 2017 (Figure 3). Expectedly, the increasing and decreasing trend of carrying capacity preceded the biomass trend (Figure 2) by several years. The carrying capacity was plotted against yearly catches of hoki (*Macruronus magellanicus*), hake (*Merluccius hubbsi* + *Merluccius australis*), and southern blue whiting (*Micromesistius australis*); the other major groundfish species of the Falkland Islands fisheries (Figure 4). Rock cod carrying capacity had a significant positive relationship with hoki catches (GAM, $p < 0.005$) and a significant negative relationship with hake catches (GAM, $p < 0.025$). Hakes, like rock cod, are near-bottom fish whereas hoki are pelagic (Arkhipkin et al. 2012), suggesting that habitat depreciates for rock cod with higher presence of hakes which are spatially proximate predators and competitors, but habitat improves for rock cod if the assemblage shifts towards hoki as the dominant fish, which are spatially more removed. Rock cod carrying capacity also had a positive relationship with blue whiting catches which are pelagic (Arkhipkin et al. 2012), but this relationship was not significant (Figure 4; GAM, $p > 0.100$). Yet, it is the decline of blue whiting that is often cited in connection with the strong increase of rock cod abundance since 2006 (Laptikhovsky et al. 2013). The absence of a significant relationship suggests that the pattern of blue whiting exploitation, occurring in both Argentina and the Falkland Islands, may have been too broad to show an influence on rock cod carrying capacity in the Falkland Islands.

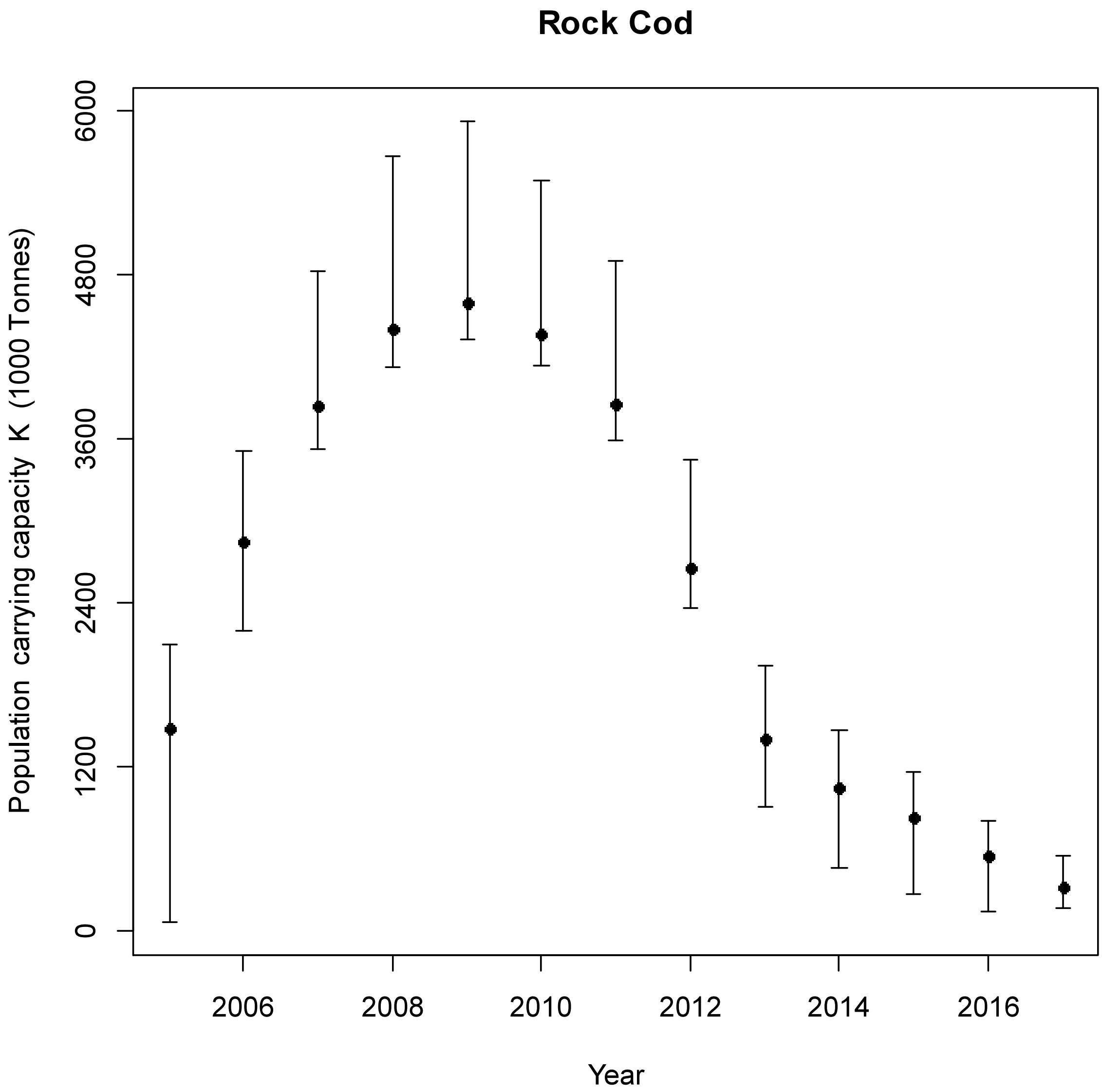

Figure 3. Yearly population carrying capacity (K) optimized by the modified production model, with 95% confidence bars. Note that these K values are not equivalent to those listed in Table 3; they are the LOESS smooth predictions of the K values in Table 3.

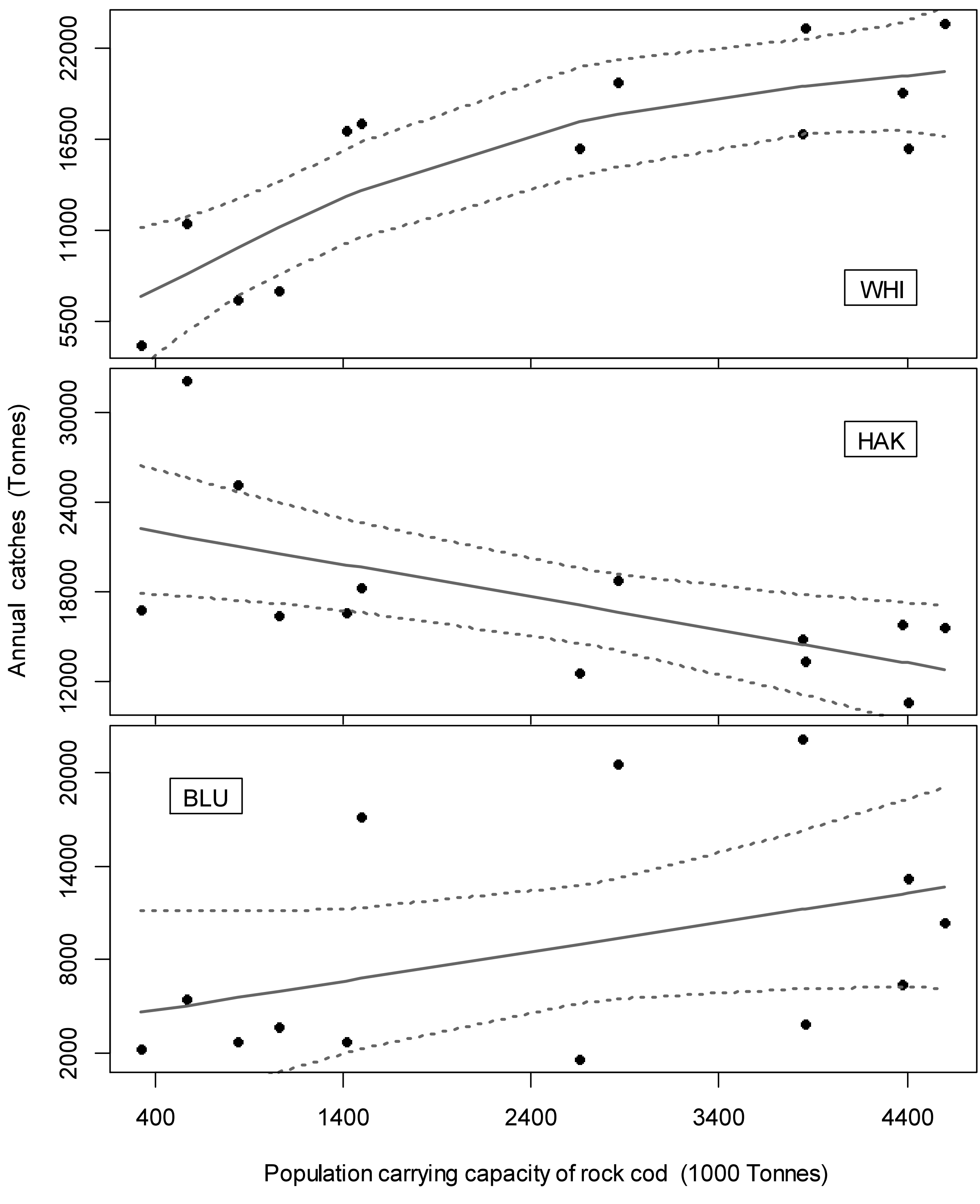

Figure 4. Relationships between model-optimized carrying capacity (K) of rock cod vs. annual catches of hoki (WHI), hakes (HAK), and blue whiting (BLU). X-axis values of these plots correspond to the Y-axis point values of Figure 3. Lines represent the generalized additive model (GAM)-fitted predictions ± 95% confidence intervals.

That rock cod has both increased then decreased precipitously since 2005 underscores a complex relationship with fishing pressure. While rock cod ceased being the primary finfish catch after 2015, reported out-of-zone rock cod catches in 2016 (6448 t) and 2017 (5497 t) were two of the three highest years on record. Partly, these out-of-zone catches will be due to fishers searching more aggressively in alternate areas. However, the out-of-zone catches may also be indicative of changing spatial population structure under the effect of fisheries (Fisher and Frank 2004, Ciannelli et al. 2013). Spatial population structure will be informed by continued monitoring of all commercial species in the Falkland Islands assemblage.

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Appendix

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).

Biomass density estimates were extrapolated to the survey area using geostatistical methods (Petitgas 2001). The finfish survey area was delineated at 122,493.7 km^2, and the *D. gahi* squid survey area was delineated at 31,296.9 km^2. Both were partitioned into survey area units of 1 km^2. For each survey, the best fitting spherical, exponential, or Cauchy semi-variogram model was selected. Geostatistic biomass estimates were computed separately for the groundfish survey and *D. gahi* surveys (Figure A1), as differences in survey design, trawl target, and trawl gear rendered the two surveys poorly compatible for a combined estimate computation (the initial 2010 joint survey program; Winter et al. 2010, had been an exception in this regard). The groundfish survey and *D. gahi* survey biomass estimates were then added together.

Uncertainty of the geostatistical biomass models was estimated by conditional simulation (Woillez et al. 2009). 10,000 conditional simulations were calculated for each of the groundfish survey area and *D. gahi* survey area mean densities, and randomly drawn with replacement 250,000×. For surveys prior to 2016, the groundfish survey random draws were multiplied by an additional uncertainty factor of the trawl width linear function. At each random draw of the conditional simulations, the trawl width model data (Gras 2016) were also randomly resampled, the linear function and resulting biomass densities recalculated and applied to the geostatistic model. The conditional simulations were used to verify stability of the geostatistic estimates.

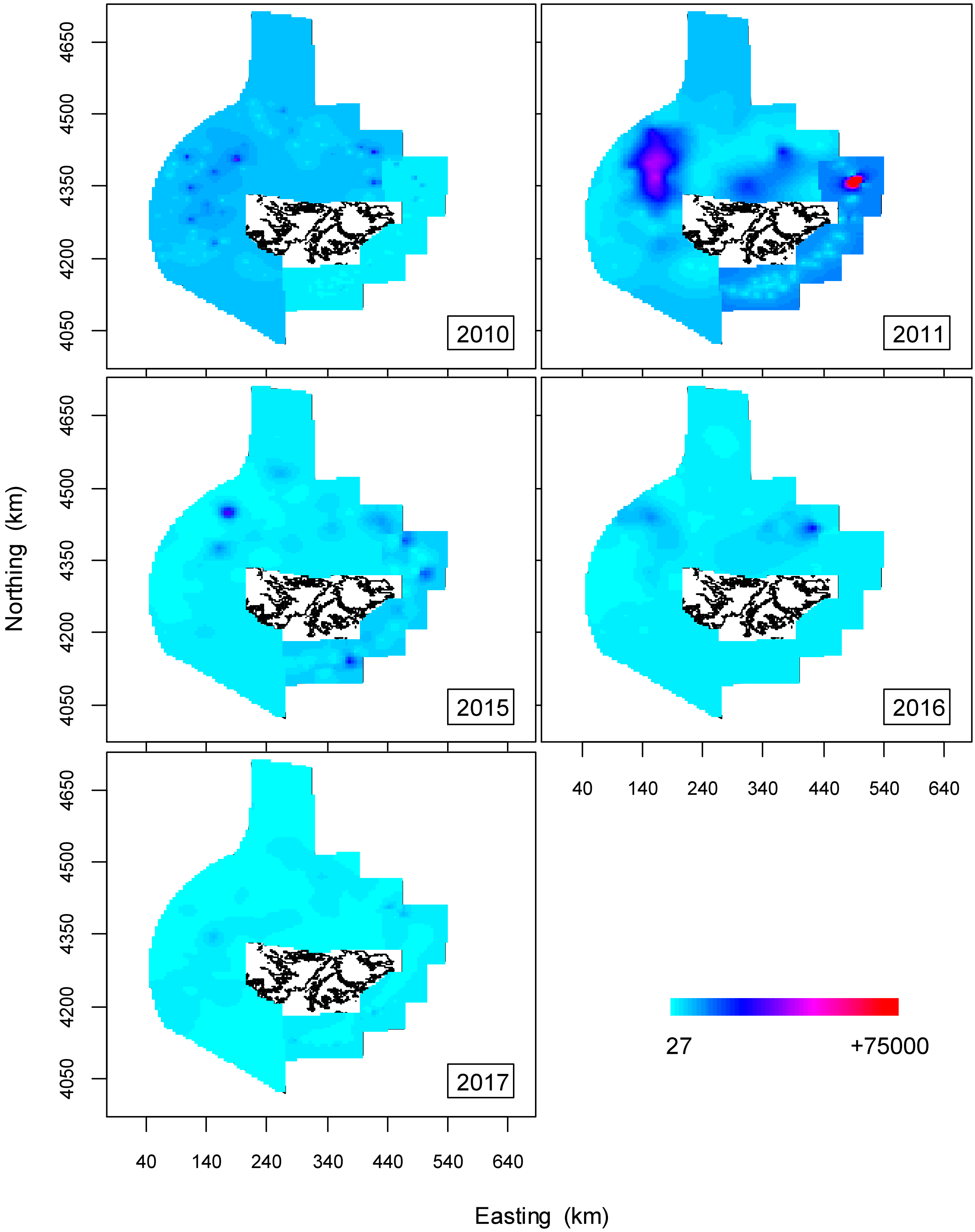

Figure A1. Geostatistic-modelled rock cod density distributions in kg km^{-2} of the five February trawl surveys since 2010.