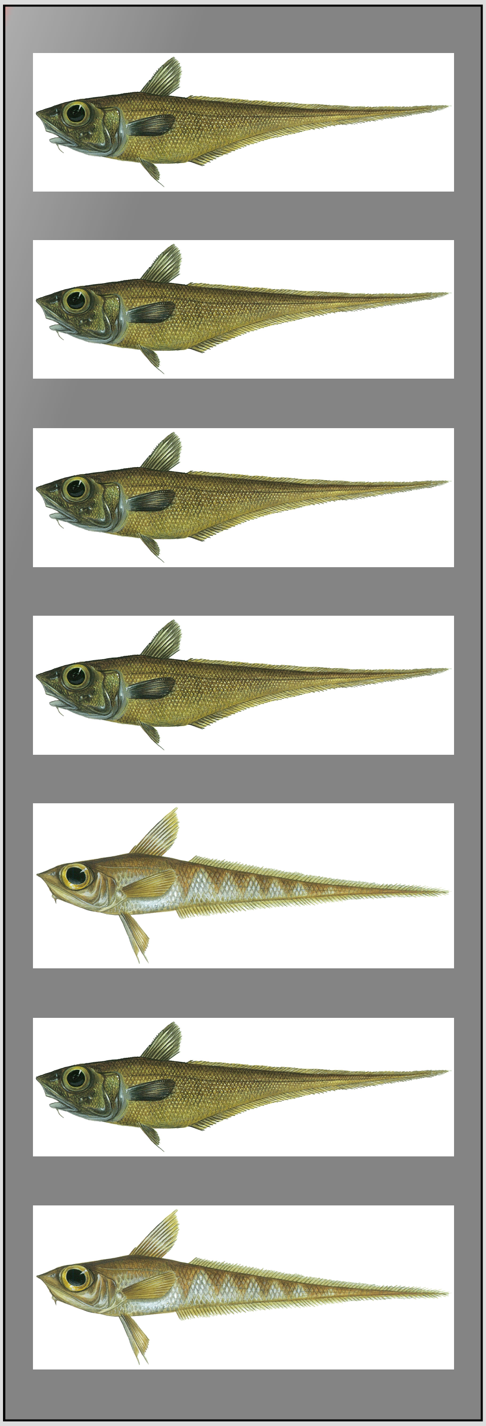

Stock assessment

Grenadier

(*Macrourus carinatus*)

(*Coelorinchus fasciatus*)

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Natural Resources

Fisheries

November 2018

Introduction

Two species of grenadier (Gadiformes, Macrouridae) are commonly caught in Falkland Islands trawl fisheries, *Macrourus carinatus* and *Coelorinchus fasciatus*. Grenadiers do not have licensed target status by the Falkland Islands Government (FIG 2018), but are currently designated bycatch under management rules. Initiation of a target fishery for *M. carinatus* is pending, and stock assessment is indicated as grenadiers represent a major component of the marine assemblage.

Macrourus carinatus (ridge-scaled rattail) is a bathy-demersal species inhabiting southern oceans in depth ranges of 200 – 1200 m (Froese and Pauly 2018), and a generalist predator feeding on a variety of gelatinous plankton, invertebrates, mesopelagic and benthic fish (Laptikhovsky 2005). A comparatively large grenadier (Laptikhovsky et al. 2008, Laptikhovsky 2011); *M. carinatus* has a history of exploitation in south-west Atlantic fisheries since the mid-1980s (Laptikhovsky et al. 2008, Sánchez et al. 2012). *M. carinatus* is commercial bycatch in Falklands fisheries, but with decreasing yields of other finfish, effort has increased in recent years targeting *M. carinatus* in deep-water trawls (Lee et al. in prep.).

Coelorinchus fasciatus (banded whiptail) is a smaller bathy-demersal species with similar geographic and depth distribution, and dietary habits (Froese and Pauly 2018). From New Zealand waters *C. fasciatus* has been reported as prey for kingclip (Mitchell 1984). In Falkland Islands fisheries >85% of identified *C. fasciatus* catch is recorded as discarded, but the identification is inconsistent. *C. fasciatus* does not have a reporting requirement in Argentine fisheries (Navarro et al. 2014).

Grenadier catches have been recorded in Falkland Islands trawl fisheries every year since 2004. However, >75% of Falklands commercial trawl reports do not identify the grenadier species, and only 1.3% of reports with any grenadier list grenadier as the highest catch. CPUE can therefore not be used as an index of relative abundance. The migratory behaviour of *M. carinatus* (Laptikhovsky 2011) suggests that the stock is shared with Argentina, and effort data are not available corresponding to Argentine catches. Accordingly, 'data-poor' methods were employed to assess *M. carinatus* and *C. fasciatus*, requiring only catch time series, length distributions, and some empirical life-history priors.

Methods

Assessment of either grenadier species required estimation of the total catch weight in each year (Figures and 2; last 10 years in Appendix Table 1). For Argentine catches (Sánchez et al. 2012, Navarro et al. 2014), and for Soviet catches from 1988 to 1991 (Laptikhovsky et al. 2008), all reported grenadier were assumed to be *M. carinatus*. For Falklands trawl catches reported as 'unidentified' grenadier, a species assignment of *M. carinatus* or *C. fasciatus* was made proportional to corresponding observer sample identifications.[1] Observer catch composition samples were categorized by year, and because studies indicate some depth distribution differences (Laptikhovsky et al. 2008, Froese and Pauly 2018), also categorized by 100 m depth strata. Catch composition samples were restricted to observers who had recorded both species at least once, to confirm that they could tell them apart, and the respective proportions summarized by year / depth category. Proportions were then multiplied by the catch weights of unidentified grenadier and added to the catch weights of grenadier that had been specifically reported as *M. carinatus* or *C. fasciatus* to begin with.

[1] All unidentified grenadier were assumed to be one or the other. The only other grenadier species identified in any observer samples was bigeye grenadier *Macrourus holotrachys*; occurring 61× less than *M. carinatus* and 8× less than *C. fasciatus*, which would be too sparse for consistent category assignment.

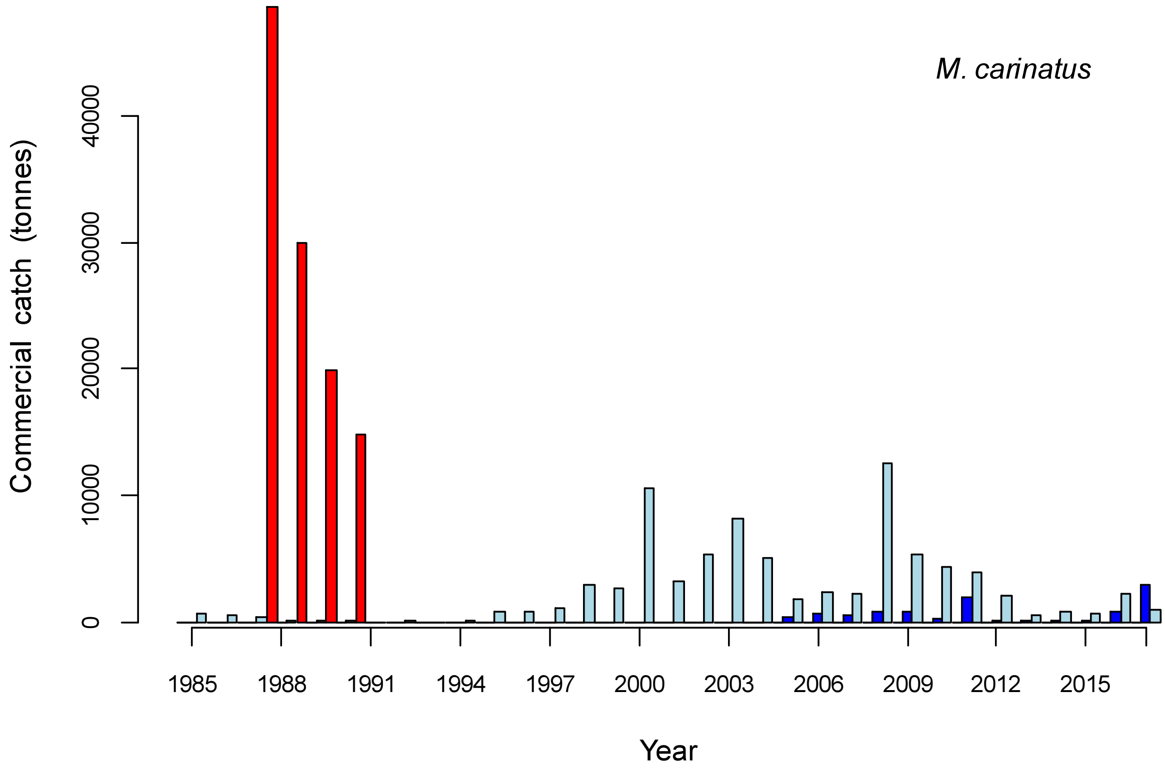

Figure 1. Commercial catches of *M. carinatus* reported in Falkland Islands (dark blue), Argentine (light blue), and Soviet fisheries (red), 1985 to 2017. Last 10 years are summarized in Appendix 1.

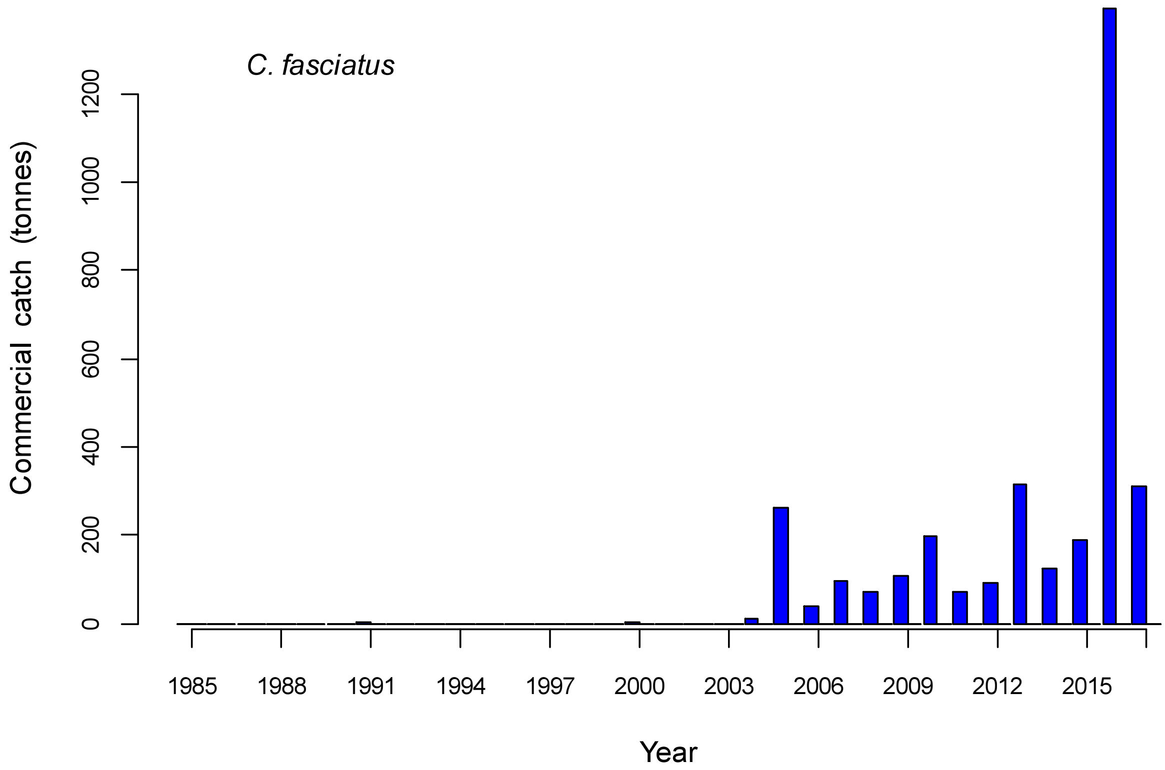

Figure 2. Commercial catches of *C. fasciatus* reported in Falkland Islands fisheries, 1985 to 2017. Last 10 years are summarized in Appendix Table 1.

OCOM

Catch time series were first applied to the optimized catch-only method (OCOM) (Zhou et al. 2018), which uses time series of catches and priors for population growth rate and carrying capacity based on the Schaefer surplus production model (Schaefer 1954):

$$B_{y+1} = B_y + r \cdot B_y \left(1 - \frac{B_y}{K}\right) - C_y$$

where B_y and C_y are the yearly biomass and catch totals, r is the population growth rate and K the carrying capacity. Population growth rate r was calculated from the generalized empirical relationship for gadiforms (Zhou et al. 2012):

$$r = 2 \cdot F_{MSY} = 2 \cdot 1.014 \cdot M$$

where M (natural mortality) was derived from several published empirical life-history equations, given the uncertainties in estimating M (Kenchington 2014):

$M = 4.899 \cdot t_{max}^{-0.916}$ (Then et al. 2015)

$M = 4.118 \cdot k^{0.73} \cdot L_{\infty}^{-0.33}$ (Then et al. 2015)

$M = 1.82 \cdot k$ (Charnov et al. 2013)

$M = \frac{1.65}{t_{mat}}$ (Jensen 1996)

$M = \frac{4.3}{t_{max}}$ (Kenchington 2014)

Parameters are t_{max} = maximum age, L_{∞} = asymptotic length, k = rate by which L_{∞} is approached, and t_{mat} = age at maturity. For *M. carinatus*, these parameters were obtained from Lee et al. (in prep.) (summarized in Table 1, and applied in Table 2). For *C. fasciatus*, these parameters were calculated from 256 length-age samples collected between years 1993 and 2004, aged by the Sea Fisheries Institute in Gdynia, Poland, and fitted to a von Bertalanffy growth function (for L_{∞} and k) and to a logistic regression (for t_{mat}) (summarized in Table 1, and applied in Table 2). For all equations, uncertainty of growth rate r (σ_r^2) was set by the empirical estimates in Zhou et al. (2018): measurement error of M σ_M^2 = 0.23 and process error of the relationship between M and F_{MSY} σ_e^2 = 0.0012; $\sigma_r^2 = \sigma_M^2 + \sigma_e^2$.

LBB

Carrying capacity K was derived from a different approach for evaluating data-poor stocks; the length-based Bayesian biomass estimation method (LBB) (Froese et al. 2018). LBB is based on the principle of calculating relative rates of natural mortality over somatic growth (M/k), and fishing mortality over somatic growth (F/k), which cancel out absolute values of time and biomass; reducing the data requirements to lengths only. M/k and F/k are used to derive indices of yield per recruit with and without fishing, and the ratio of these indices estimates current exploited biomass relative to unexploited biomass $B_{current}/B_0$ (Froese et al. 2018). K is then optimized by equivalence to B_0. LBB was run with the Gibbs sampler JAGS (sourceforge.net/projects/mcmc-jags/files/JAGS/4.x) through R package 'R2jags' (Su and

Yajima 2015). Uncertainty of the ratio B/B_0 was calculated from the MCMC of the Gibbs sampler (Froese et al. 2018).

Table 1. Individual growth parameters used to calculate natural mortality for *M. carinatus* (from Lee et al. in. prep.) and for *C. fasciatus* (from 256 observer samples; including 95% confidence intervals of the Von Bertalanffy growth parameters).

Parameter	*M. carinatus*	*C. fasciatus*	
t_{max}	53.00	24.00	
L_∞	28.87	11.22	(10.74 - 12.01)
k	0.082	0.194	(0.143 - 0.239)
t_{mat}	9.64	7.81	

Table 2. Priors for population growth rate r calculated with different empirical equations of natural mortality M and the parameters in Table 1, for *M. carinatus* and *C. fasciatus*.

M	*M. carinatus*	*C. fasciatus*
$4.899 \cdot t_{max}^{-0.916}$	0.2617	0.5406
$4.118 \cdot k^{0.73} \cdot L_\infty^{-0.33}$	0.4435	1.1350
$1.82 \cdot k$	0.3027	0.7153
$\frac{1.65}{t_{mat}}$	0.3471	0.4284
$\frac{4.3}{t_{max}}$	0.1645	0.3634

For *M. carinatus*, the LBB method was implemented with two alternate sets of length measurements[2]: 13572 length measurements from an experimental deep-water survey in 2011 (Monllor 2011), and 17357 length measurements from observer data collected in the commercial fisheries in 1994-1995 and 2002 to 2018 (Figure 3). Both sets are of interest as survey data may be higher resolution (taken with smaller-mesh trawls and/or more intensive sampling), whereas observer data from commercial fisheries may be coarser but have broader coverage. Observer data were taken from measurements that had been selected randomly. For spatial-temporal consistency, these data were restricted to grids that are open to either finfish (A, G, W) or calamari (C, X) licenses by current regulation, including September / October variances. Finfish vs. calamari lengths were re-weighted so that 96.5% of lengths were from finfish each year; the approximate average proportion over the past five years.

For *C. fasciatus*, the LBB method was implemented with 10075 length measurements from observer data collected in the commercial fisheries in 1991, 1993-1994, 1997, and 2001 to 2018. However, length distributions were biased by the inclusion of a few very large individual sizes in some years (Figure 3), which computationally implied that by 2017 the stock was depleted to 0.001 of virgin biomass (analysis not shown). As substantial catches of *C. fasciatus* continue to be taken (Figure 2), the implication is implausible and several of the

[2] For grenadier, all lengths are measured as pre-anal lengths.

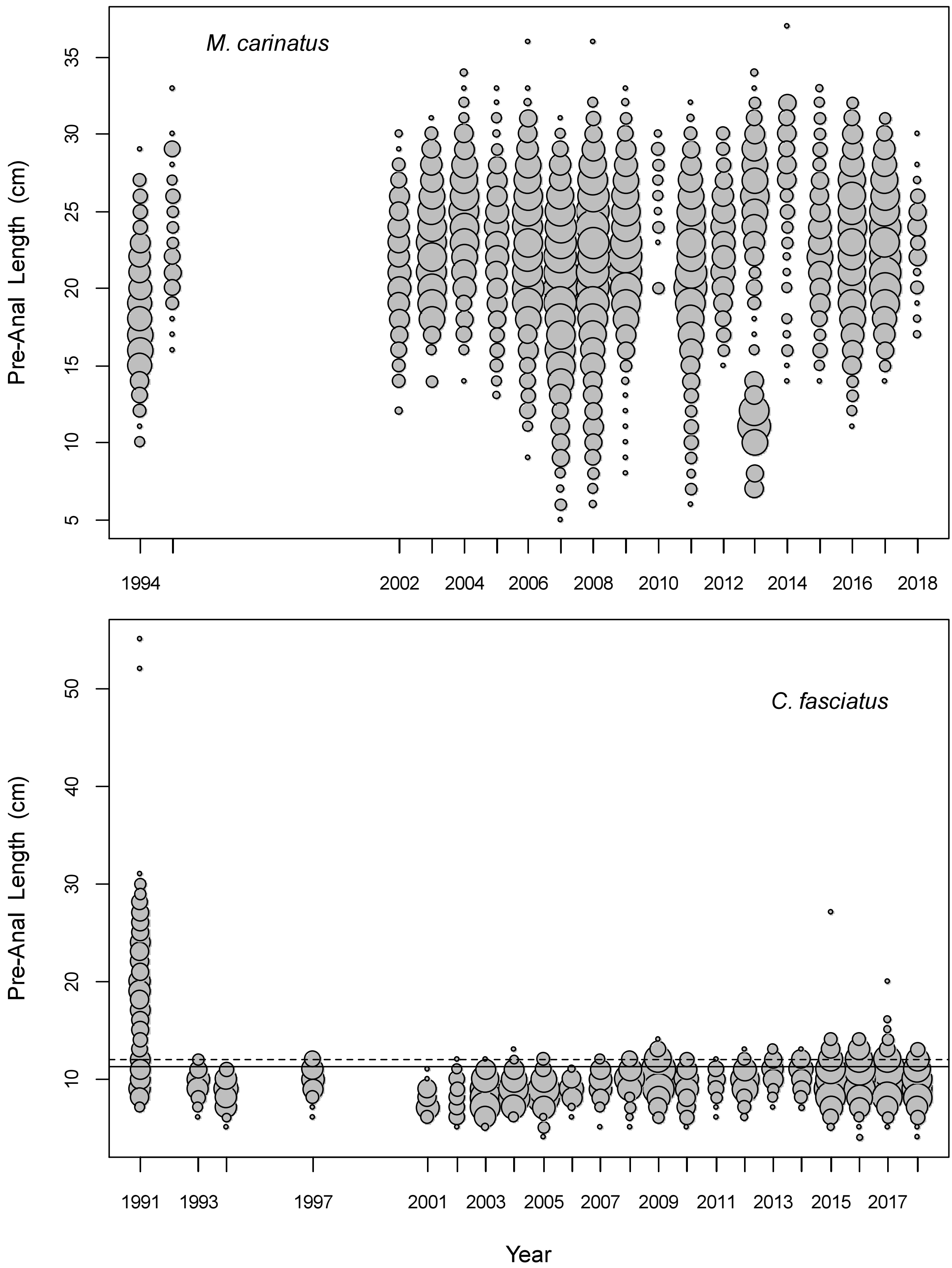

Figure 3. Distributions of commercial fishery observer-sampled length measurements per year of *M. carinatus* (top) and *C. fasciatus* (bottom). Symbols proportional to the log number of measurements per year. Horizontal lines on the *C. fasciatus* plot are the median and upper 95% confidence interval of L_∞ from the age-length relationship.

largest sizes were likely either misidentified species or total lengths entered as pre-anal lengths. An outlier test (Grubbs 1969) identified lengths in several years as >4 standard deviations from the mean; the threshold used in other fish measurement analyses (Kamikawa et al. 2015). Because categorical misidentifications could pertain to specimens other than those flagged as computational outliers (especially in 1991; Figure 3), *C. fasciatus* measurements were limited to those ≤ either the median or upper 95% confidence interval of L_∞ from the length-age estimation (Table 1).

OCOM + LBB

Time series of annual grenadier biomass were calculated by randomly drawing values of growth rate r and biomass ratio $B_{current}/B_0$ priors from their distributions (as above), and minimizing the difference between $B_{opt.\ current}$ / $B_{current}/B_0$ and carrying capacity K in the Schaefer production model[3]. Minimization was carried out in two steps. First, K was fixed equal to biomass in the first year of the time series (B_1). This commonly used assumption (Punt 1990) sets K as the single parameter to be optimized, which can therefore be searched efficiently over a wide range. Second, the initial optimized value of K was input as the prior for both K and B_1 in a Schaefer model with K and B_1 parameterized independently, and this model was optimized again. The second step was implemented because commercial fishing occurred in Falklands, Argentine, and out-of-zone waters before regular catch reporting, and $K = B_1$, while credible, cannot be explicitly verified for the time series. Random draws of r and $B_{current}/B_0$ were iterated and optimized 10000× (Zhou et al. 2018), and the medians and 95% confidence intervals computed for parameters r, K, B_1, $B_{current}$ and MSY (maximum sustainable yield); defined from a Schaefer production model as (Hilborn and Walters 1992):

$$\mathrm{MSY} = \frac{\mathrm{r} \cdot \mathrm{K}}{4}$$

Medians and 95% confidence intervals were weighted inverse to the optimum fit value (i.e., proportional to the likelihood) of each iteration.

CMSY

CMSY (catch – MSY), similarly to OCOM, uses catch time series and parameter priors to estimate fish populations on a Schaefer production model (Froese et al. 2017). Rather than empirically computed priors for growth rate r, however, CMSY sets broadly categorical prior ranges based on species' resilience (Martell and Froese 2013, Froese et al. 2017), where resilience is defined by the spawning stock biomass per recruit that corresponds to replacement fishing mortality (Musick 1999). The prior for carrying capacity K is based on the ratio of highest catch in the time series over growth rate r. Rather than optimizing r and K, CMSY uses a Monte Carlo algorithm to search pairs of r and K that do not crash the stock or exceed projected maximum biomass levels in relation to depletion criteria shown by the catch time series. Median biomass levels and confidence intervals are derived from the validated r and K pairs.

Both *M. carinatus* and *C. fasciatus* are characterized by 'low' resilience, with minimum population doubling time of 4.5 – 14 years[4] (Froese and Pauly 2018).

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[3] For the length measurement set from only the 2011 survey in LBB, $B_{current}$ (B_{2017}) was replaced by B_{2011}.
[4] Which, however, in the case of *M. carinatus* relates to a published maximum age of 19 years, considerably lower than the 53 years maximum age reported by Lee et al. (in prep.). For *C. fasciatus* few details are given in the reference how resilience was characterized.

Results

Total commercial fishery catches from the Falkland Islands, Argentina, and Soviet Union were examined for years 1985 to 2017. The first year of substantial reported catches of *M. carinatus* was 1988 (Figure 1). The first year of substantial reported catches of *C. fasciatus* was 2004, although intermittent minor quantities were reported as early as 1991 (barely visible on Figure 2). Grenadier trawl catches were likely taken in earlier years, but not taxonomically identified. To give a standardized overview the assessment time series of both *M. carinatus* and *C. fasciatus* were started in 1988.

Macrourus carinatus

The two alternate sets of length inputs to the LBB method resulted in similar ranges of carrying capacity, current biomass and MSY calculated from the OCOM (Table 3). Observer length distributions in the survey year 2011 were not notably different from other years (Figure 3). Using either alternate set the most precautionary MSY was, expectedly, obtained from the lowest estimate of natural mortality: $M = 4.3/t_{max} = 0.0811$. With $B_{2017}/B_0 = 0.515$, MSY at $M = 0.0811$ was 5744 tonnes, equivalent to 9.17% of the estimated 2017 biomass (Table 3). With $B_{2011}/B_0 = 0.272$, MSY at $M = 0.0811$ was 5158 tonnes, equivalent to 10.56% of the estimated 2017 biomass (Table 3). Given the high standard deviation of $B_{2017}/B_0 = 0.515$, OCOM estimates calculated from this ratio had much greater margins of uncertainty.

Table 3. *M. carinatus* OCOM + LBB Schaefer production model parameter estimates for different growth rate priors (Table 2) vs. two alternate calculations of $B_{current}/B_0$, and resulting calculations of year 2017 biomass and MSY. Medians and 95% confidence intervals in parentheses.

prior r	r	K	B_{1988}	B_{2017}	MSY
Commercial observer data: $B_{2017}/B_0 = 0.515 \pm 0.308$					
0.2617	0.263 (0.100 - 0.661)	106991 (85035 - 290407)	106018 (84417 - 291647)	52393 (0 - 259078)	7271 (4108 - 16767)
0.4435	0.433 (0.172 - 0.925)	93859 (78182 - 159042)	93110 (77850 - 158884)	46195 (0 - 140041)	10290 (5488 - 18974)
0.3027	0.301 (0.117 - 0.742)	102621 (82650 - 256556)	101680 (82147 - 257725)	50447 (0 - 230040)	7974 (4461 - 17405)
0.3471	0.342 (0.135 - 0.806)	99282 (81052 - 229987)	98430 (80608 - 225251)	49789 (0 - 202482)	8723 (4811 - 18045)
0.1645	0.164 (0.063 - 0.417)	130141 (94465 - 560881)	129380 (93663 - 559697)	62621 (0 - 523095)	5744 (0 - 18216)
2011 survey data: $B_{2011}/B_0 = 0.272 \pm 0.061$					
0.2617	0.260 (0.102 - 0.672)	106432 (84648 - 150571)	105453 (84115 - 149122)	54785 (24818 - 77866)	6907 (3839 - 14224)
0.4435	0.441 (0.175 – 0.996)	93293 (76647 - 121786)	92553 (76309 - 120688)	68272 (32193 - 79125)	10281 (5352 - 19105)
0.3027	0.304 (0.119 - 0.772)	101911 (81825 - 141645)	100986 (81360 - 140484)	58134 (27347 - 78512)	7756 (4218 - 15796)
0.3471	0.348 (0.135 - 0.859)	98496 (79616 - 134636)	97641 (79202 - 133485)	61534 (28688 - 78840)	8571 (4546 - 17108)
0.1645	0.167 (0.065 - 0.420)	123908 (94362 - 177784)	122755 (93579 - 175877)	48863 (21236 - 73576)	5158 (2843 - 9901)

The CMSY method obtained a substantially different set of parameters with the most probable carrying capacity >2.5× higher than was found for any estimate of LBB+OCOM, and population growth rate >1.6× higher than growth rates corresponding to precautionary MSYs with LBB+OCOM (compare Tables 3 and 4). MSY was much higher than the LBB+OCOM and equivalent to 43.86% of the estimated 2017 biomass (Table 4).

Table 4. *M. carinatus* CMSY Schaefer production model parameter estimates given 'low' resilience, and resulting calculations of year 2017 biomass and MSY. Medians and 95% confidence intervals in parentheses.

prior r	r	K	B_{1988}	B_{2017}	MSY
0.05 - 0.5	0.270 (0.159 - 0.459)	377246 (142e3 - 999e3)	144197 (106e3 - 181e3)	58019 (5997 - 268162)	25447 (10692 - 60564)

Coelorinchus fasciatus

LBB analyses restricted to lengths ≤ L_∞ gave a moderate B_{2017}/B_0 = 0.511 (coincidentally almost exactly equal to B_{2017}/B_0 = 0.515 for *M. carinatus*), but with a very high standard deviation. The resulting LBB+OCOM MSY, across different values of M, ranged implausibly from 50.74% to 167.72% (Table 5). Alternatively, LBB analyses restricted to lengths ≤ upper 95% confidence interval of L_∞ gave B_{2017}/B_0 = 0.436. The most precautionary MSY (with the lowest M = 0.1792) was 21.27% of the estimated 2017 biomass (Table 5).

prior r	r	K	B_{1988}	B_{2017}	MSY
Commercial observer data ≤ L_∞: B_{2017}/B_0 = 0.511 ± 0.901					
0.5406	0.544 (0.207 - 1.370)	1973 (765 - 36278)	1977 (723 - 35119)	320 (0 - 33937)	279 (83 - 4952)
1.1350	1.092 (0.435 - 2.440)	1692 (627 - 50003)	1690 (408 - 49880)	285 (0 - 45323)	478 (138 - 13942)
0.7153	0.712 (0.274 - 1.785)	1868 (696 - 38747)	1878 (487 - 38713)	313 (0 - 37449)	343 (104 - 7499)
0.4284	0.428 (0.166 - 1.089)	2131 (821 - 33458)	2127 (826 - 33113)	366 (0 - 31746)	232 (72 - 3715)
0.3634	0.363 (0.139 - 0.924)	2236 (859 - 34549)	2242 (886 - 34476)	408 (0 - 32505)	207 (63 - 3283)
Commercial observer data ≤ upper 95% of L_∞: B_{2017}/B_0 = 0.436 ± 0.200					
0.5406	0.540 (0.209 - 1.409)	2863 (1636 - 9076)	2864 (1638 - 8989)	1233 (80 - 7200)	392 (163 - 1469)
1.1350	1.109 (0.429 - 2.436)	2484 (1420 - 9427)	2484 (1411 - 9437)	1103 (66 - 8004)	707 (272 - 2874)
0.7153	0.716 (0.280 - 1.810)	2700 (1536 - 8295)	2699 (1532 - 8329)	1171 (79 - 6723)	491 (200 - 1763)
0.4284	0.423 (0.167 - 1.074)	3050 (1747 - 9891)	3054 (1747 - 9924)	1320 (86 - 8210)	331 (135 - 1209)
0.3634	0.362 (0.142 - 0.922)	3180 (1799 - 9747)	3177 (1804 - 9745)	1373 (96 - 7991)	292 (120 - 1061)

Table 5 [previous page]. *C. fasciatus* OCOM + LBB Schaefer production model parameter estimates for different growth rate priors (Table 2) vs. two alternate calculations of $B_{current}/B_0$, and resulting calculations of year 2017 red cod biomass and MSY. Medians and 95% confidence intervals in parentheses.

The CMSY method obtained an interesting contrast insofar as biomass was inferred to have increased from median estimates of 1780 t in 1988 to 3553 t in 2017 (albeit with confidence intervals that were not statistically significant), whereas the precautionary OCOM estimate showed quasi the reverse with 3177 t in 1988 to 1373 t in 2017 (compare Tables 5 and 6). MSY from the CMSY method was 9.46% of the estimated 2017 biomass (Table 6).

Table 6. *C. fasciatus* CMSY Schaefer production model parameter estimates given 'low' resilience, and resulting calculations of year 2017 biomass and MSY. Medians and 95% confidence intervals in parentheses.

prior r	r	K	B_{1988}	B_{2017}	MSY
0.05 - 0.5	0.282 (0.163 - 0.487)	4765 (1604 - 14155)	1780 (560 - 5352)	3553 (1076 - 9923)	336 (116 - 974)

Conclusion

Grenadiers are characterized by low productivity (Devine et al. 2012), slow recovery from exploitation (Baker et al. 2009), and low capacity to survive bycatch discarding (Rodgveller et al. 2010). *M. carinatus* and *C. fasciatus* have been assigned as respectively 'moderate' and 'moderate to high' vulnerability to fishing (Froese and Pauly 2018). Previous assessments of *M. carinatus* have been sporadic and locally restricted (van Wijk et al. 2000, Laptikhovsky et al. 2008, Payá 2009); while a study of the congeneric roughhead grenadier *M. berglax* suggests that that fish has a geographically expansive range (Coscia et al. 2018). The population of *C. fasciatus* has not been previously assessed.

These indications require conservative management of grenadier stocks. For *M. carinatus*, the most conservative MSY was 5158 tonnes, corresponding to M = 0.0811 and r = 0.1645 with the LBB+OCOM (Table 3). MSY corresponding to M = 0.0811 may be the most plausible anyway, as species with maximum ages >30 years are expected to have M <0.10 (Norse et al. 2012). MSY = 5158 t has been exceeded three times in the past ten years; in 2008 (13281 t), 2009 (6151 t) and in 2011 (5752 t) (Table A1). In this assessment calculations apply to total catch on the stock, and assuming that Falklands and Argentine fisheries take about half each, MSY = 5158 t is comparable to MSY = 3567 t calculated by Payá (2009) for the Falklands fishery only.

For *C. fasciatus*, the most conservative MSY (given a plausible MSY/B_{2017} ratio) was 292 tonnes, corresponding to M = 0.1792 and r = 0.3634 with the LBB+OCOM (Table 5). The resulting ratio of MSY/B_0 = 9.2% was higher than the 2-3% advised for deep-water species (Large et al. 2003). MSY = 292 t has also been exceeded three times in the past ten years; in 2013 (316 t), 2016 (1394) and 2017 (313 t) (Table A1).

A common outcome of both the *M. carinatus* and *C. fasciatus* assessments was high variability in all parameter estimates. Assessments of macrourids are challenging as relatively low commercial interest in these fish underlies questionable identifications and limited data; for example, the study of a north-east Atlantic grenadier fishery found that discard sizes changed throughout the period of the fishery, compromising the extrapolation of discard estimates (Pawlowski and Lorance 2009). High variability was evident particularly in the contrasting information from the LBB+OCOM vs. CMSY methods. Alternate methods are recommended to test the uncertainty of assessment models (Hill et al. 2007, Millar et al. 2015), and future work will be applied to examine sensitivities of the alternate 'data-poor' LBB, OCOM and CMSY methods for grenadier.

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Appendix

Table A1. Annual grenadier catches (tonnes) of the past 10 years. Catches correspond to Figures 1 and 2.

Year	*Macrourus carinatus*			*Coelorinchus fasciatus*
	Falkland I.	Argentina	Total	Falkland I.
2008	738.5	12542.5	13281.0	72.6
2009	772.9	5377.8	6150.7	109.9
2010	179.9	4329.2	4509.1	198.8
2011	1890.2	3862.2	5752.4	70.7
2012	82.0	2026.5	2108.5	93.0
2013	123.8	564.0	687.8	315.8
2014	35.9	844.9	880.8	123.7
2015	103.9	652.7	756.6	188.6
2016	826.8	2233.1	3059.9	1394.3
2017	2857.0	926.9	3783.9	312.6