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Pacific Region

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Science Advisory Report 2023/002

CANARY ROCKFISH *(SEBASTES PINNIGER)* STOCK ASSESSMENT FOR BRITISH COLUMBIA IN 2022

*Canary Rockfish (*Sebastes pinniger*)*
Credit: Terri Bonnet, DFO

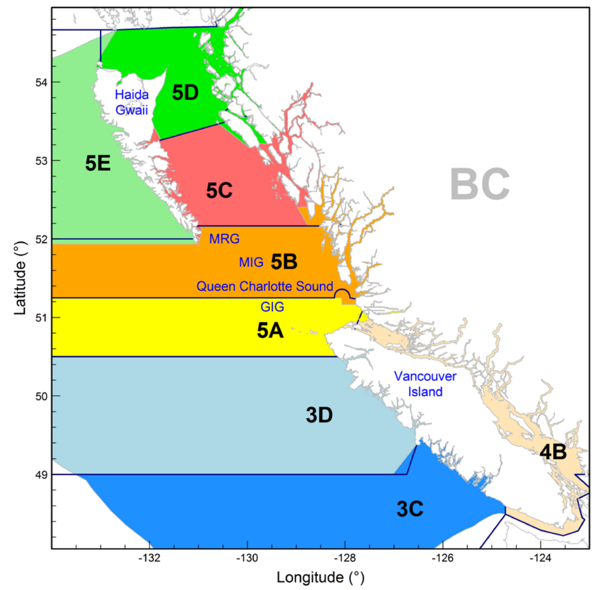

Figure 1. Canary Rockfish assessment areas comprising Pacific Marine Fisheries Commission (PMFC) major areas outlined with solid lines and used in this assessment. The Groundfish Management Unit area boundaries, based on [Pacific Fisheries Management Areas](), are superimposed as coloured polygons for comparison. This assessment is for PMFC areas 3CD+5ABCDE (excludes 4B).

Context

This is the third model-based stock assessment for Canary Rockfish (CAR, Sebastes pinniger*) after an initial assessment in 2007 using the Awatea model platform, followed by an update in 2009. CAR is almost exclusively fished by the commercial trawl fleet (83% bottom and 13% midwater), with minor amounts (4%) caught by the other gear types (primarily hook and line). The Committee on the Status of Endangered Wildlife in Canada (COSEWIC) assessed the species as 'Threatened' in 2007, but the 2007 stock assessment determined the coastwide stock status to be in the Fisheries and Oceans Canada (DFO) Cautious zone, followed by an update in 2009 placing the stock in the Healthy zone for the most credible model runs. The species ranges from the Gulf of Alaska southward to northern Baja California. In British Columbia (BC), the apparent area of highest concentration occurs on the west coast of Vancouver Island (3CD), particularly in the northern part (3D), but catches are also relatively high in Queen Charlotte Sound (5AB). This species also occurs at the top end of Graham Island and Dixon Entrance (5D). An important feature of the CAR age data is the abundance of older males and the lack of older females (female ages higher than 40 years are rare). The oldest observed ages are 84 for males and 77 for females.*

DFO Fisheries Management requested that DFO Science Branch assess CAR relative to reference points that are consistent with Decision-making Framework Incorporating the Precautionary Approach (DFO 2009a), and provide advice on the implications of various harvest strategies on projected stock status. This quantitative age-structured stock assessment model provided harvest advice for use over the next 10 years.

*This Science Advisory Report is from the September 7-8, 2022 regional peer review on Canary Rockfish (*Sebastes pinniger*) stock assessment for British Columbia in 2022. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.*

SUMMARY

- The Canary Rockfish (CAR) stock assessment evaluates a British Columbia (BC) coastwide population harvested by two fisheries, one using combined bottom and midwater trawl gear and the other using non-trawl gear. Bottom trawl catches are predominant (83% by weight over the period 1996 to 2021), followed by midwater trawl (13%) and hook and line (4%). Analyses of biology and distribution did not support separate regional stocks for CAR.
- The CAR stock was assessed using an annual two-sex catch-at-age model, implemented in a Bayesian framework to quantify uncertainty of estimated and derived parameters. The analysis platform adopted was the National Oceanic and Atmospheric Administration's (NOAA) Stock Synthesis 3. A base run that estimated natural mortality (M) and steepness (h) fit the available data credibly and was considered sufficient to model the population.
- This stock assessment was primarily informed by six CAR abundance series from fishery independent surveys, and a catch per unit effort (CPUE) abundance series. While the CAR survey abundance series had large relative errors, they did not contradict the commercial CPUE index series. Additionally, age frequency data from the commercial trawl fishery (36 years) and three survey series (23 years) were used.
- The median (with 5th and 95th percentiles) female spawning biomass at the beginning of 2023 (B_{2023}) was estimated to be 0.78 (0.57, 1.05) of the equilibrium unfished female spawning biomass (B_0). Also, B_{2023} was estimated to be 3.04 (1.92, 4.89) times the equilibrium female spawning biomass at maximum sustainable yield, B_{MSY}.
- There was an estimated probability of 1 that $B_{2023} > 0.4B_{MSY}$ and a probability of 1 that $B_{2023} > 0.8B_{MSY}$ (i.e., of being in the Healthy zone). The probability that the exploitation rate in 2022 was below that associated with MSY was 1 for the combined commercial fisheries.
- Advice to managers was presented in the form of decision tables using the suggested reference points from Fisheries and Oceans Canada's (DFO) Decision Making Framework Incorporating the Precautionary Approach (PA) (DFO 2009a). The decision tables provided ten-year projections across a range of constant catches up to 2000 tonnes/year. The recent five year (2017–2021) average catch was 789 t.
- The CAR stock was projected to remain above the limit reference point (LRP, $0.4B_{MSY}$) and upper stock reference (USR, $0.8B_{MSY}$) with a probability of >0.99 over the next 10 years at catch levels ≤1500 t/y. Catches ≤1250 t/y were predicted to keep the harvest rate below the harvest rate limit (u_{MSY}) in 10 years with probability >95%.
- Reference points for long-lived, low productivity species are uncertain. Advice relative to MSY reference points was deemed appropriate for CAR; however, other B_0 benchmark metrics were presented in the assessment document.

- It is recommended that a full re-assessment occurs in no more than 10 years, subject to the availability of new information. During intervening years, the trend in abundance can be tracked by commercial fishery CPUE and, less reliably (because of the high relative error), by the fishery independent surveys used in this stock assessment.

INTRODUCTION

Canary Rockfish (CAR, *Sebastes pinniger*) range from the Gulf of Alaska southward to northern Baja California, typically at depths between 100 and 230 m. In British Columbia (BC), the apparent area of highest concentration occurs on the west coast of Vancouver Island, particularly in the northern part of the west coast (PMFC areas 3D and 3C in Figure 1), but catches are also relatively high in Queen Charlotte Sound (PMFC areas 5A and 5B in Figure 1). This species also occurs at the top end of Graham Island, but the bottom topography in this area precludes much trawling at depths below 180 m.

In 2007, the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) assessed the coastal population of CAR in BC as ‘Threatened’. The primary evidence cited for this evaluation was an 86% decline over 30 years in the combined west coast Vancouver Island shrimp survey and the US National Marine Fisheries Service (NMFS) Triennial survey. In 2007, the coastwide CAR population was modelled using a fixed value for M=0.06 for males and females up to age 14, after which the female M was increased to 0.12 (Stanley et al. 2009). Steepness h was fixed to contrasting values (0.55, 0.7). The 2007 stock assessment concluded that the population was in DFO’s ‘Cautious zone’ (i.e., $0.4B_{\text{MSY}} \leq B_{2007} < 0.8B_{\text{MSY}}$) . This stock assessment was updated in 2009 with three more years of catch data and three additional trawl survey observations (DFO 2009b). This update included an additional model run that estimated h (median=0.79) using a prior based on a 2010 review of west coast rockfish steepness parameter estimates. The 2009 updated assessment concluded that CAR stock status was in DFO’s ‘Healthy zone’ ($B_{2009} \geq 0.8B_{\text{MSY}}$) for the models with the higher (and considered more realistic) steepness values.

In 2011, a decision was made not to list Canary Rockfish under Schedule 1 of the *Species at Risk Act* (SARA). While DFO continued to manage this species under the *Fisheries Act*, actions to address conservation concerns were outlined in the order not to list (SI/2011-56, July 6, 2011). In 2019, Bill-C-68 was enacted to amend the *Fisheries Act* with the Fish Stocks provisions, prompting a national review of the approximately 180 stocks using Sustainability Surveys with the aim to include the majority of those stocks in regulation over the next five years. Canary Rockfish are one of 18 groundfish stocks in the Pacific Region being considered for prescription in the Regulations.

The present assessment covered all of the BC outer coast, including Pacific Marine Fisheries Commission (PMFC) major areas (3CD and 5ABCDE, Figure 1). The available biological data were examined for evidence of stock separation among three regions: north (5DE), central (5ABC), and south (3CD). The split between 5DE and more southerly regions has previously shown differences in size and/or growth rate in other BC finfish populations. While some differences (growth, size, and composition taken by gear type) between areas were found, the differences were generally small and not always consistent across years, sexes or gear type. Furthermore, CAR data from 5DE were sparse and this part of the BC coast only accounted for a relatively small proportion of the catch (3.5%, mean from 1996–2021). Consequently, the authors elected to make the same single stock assumption that had been made by Stanley et al. (2009).

ASSESSMENT

The stock assessment used Stock Synthesis 3 (SS3, Methot and Wetzel 2013) to reconstruct CAR with an annual catch-at-age model, tuned to six fishery-independent trawl survey series, a bottom trawl CPUE series, annual estimates of commercial catch (Figure 2) since 1935, and age composition data from survey series (23 years of data from three surveys) and the commercial fishery (36 years of data). The model started from an assumed equilibrium state in 1935, the survey data covered the period 1967 to 2021 (although not all years were represented), and the CPUE series provided an annual index from 1996 to 2021.

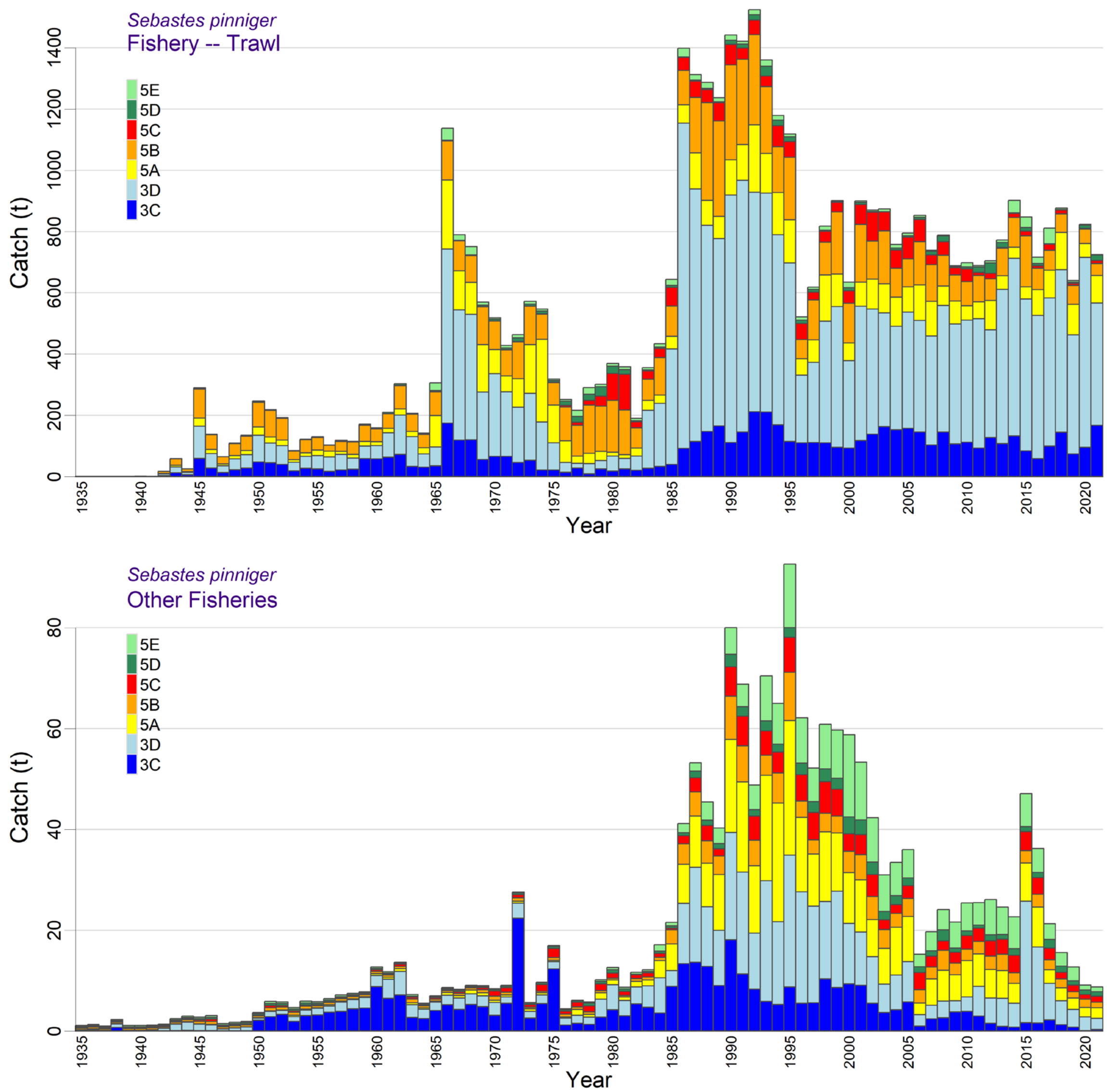

Figure 2. Reconstruction of Canary Rockfish catch, from 1935 to 2021 used in the stock assessment model. The 2022 catch was assigned a value of 780 t, based on feedback from industry, and split into 767 t for Trawl and 13 t for Other.

In this assessment, the Dirichlet-Multinomial was used for fitting age frequency data, which is a model-based method for estimating effective sample size (Thorson et al. 2017). This distribution incorporates an additional parameter per 'fleet', which governs the ratio of nominal ('input') and effective (‘output’) sample size for each composition data set, accomplishing the weighting as part of the estimation procedure. In previous assessments, weighting the composition data was achieved through either the mean-age method of Francis (2011) or the harmonic mean method of McAllister and Ianelli (1997; also see Methot et al. 2021). The use of the Dirichlet-Multinomial (DM) in SS3 proved useful for this species, although it failed for the 2021 Yellowmouth Rockfish assessment (Starr and Haigh 2022). One of the shortcomings of the DM method is its inability to scale sample sizes higher than those supplied.

The two-sex model was implemented in a Bayesian framework (using the Markov Chain Monte Carlo [MCMC] ‘No U-Turn Sampling’ procedure) to estimate one base run model which estimated separate natural mortalities for each sex and the stock-recruitment steepness parameter. This model also estimated average recruitment (based on the annual year class deviations over the period 1950-2012) and selectivities for the three surveys with age composition data and the commercial trawl fleet. Selectivities were fixed for the remaining three surveys and the ‘other’ commercial fishery. Fourteen sensitivity analyses were performed relative to the base run to test the effect of alternative model assumptions.

The base run was used to calculate a distribution of maximum sustainable yield (MSY) and other reference points that incorporated the combined uncertainty associated with the estimated primary parameters after downweighting the commercial CPUE by adding process error determined from a smoothing analysis. Ten-year projections were performed on the base run over a range of constant catches to estimate probabilities of breaching reference points. Advice to managers was presented as decision tables that provided probabilities of exceeding reference points consistent with the 2009 DFO Precautionary Approach: 0.4B_{MSY}; 0.8B_{MSY}, as well as remaining below the harvest rate at MSY (u_{MSY}) for 2023 through 2032 for a range of constant catch levels.

Figure 3 shows the estimated annual spawning biomass (mature females only) relative to spawning biomass at MSY for the coastwide CAR stock estimated by the base run, with the biomass trajectory declining from 1935 to 1995. The year 1996 marked the introduction of the 100% onboard observer program followed by the implementation of an individual vessel quota system in 1997. Biomass, beginning with 1996, ceased to decline, and, beginning in the early 2000s, began to increase.

Recruitment of age-0 fish showed relatively consistent recruitment across years, with the top four recruitment years being 2010, 2003, 2014, and 2006 (Figure 4). The base run population trajectory, spanning the period from 1935 to 2023, estimated median spawning biomass B_t in years t = 1935, 2023, and 2033 (assuming a constant catch of 750 t/y) to be 13,908, 10,760, and 11,010 tonnes, respectively. The median stock biomass will remain above the USR for the next 10 years at annual catches equal to all catches used in catch projections (Figure 3). Exploitation rates have largely stayed below u_{MSY} for much of the history of the fishery (Figure 4).

The estimated median equilibrium MSY (with 5th and 95th percentiles) was 1,305 tonnes (948, 1,886), compared to the average catch over the last five years (2017-2021) of 789 tonnes (Table 1). The estimated beginning-year spawning biomass in 2023 (B_{2023}) relative to equilibrium unfished biomass, B_{2023}/B_0 = 0.78 (0.57, 1.05), and to equilibrium spawning biomass that would support the MSY, B_{2023}/B_{MSY} = 3.04 (1.92, 4.87). Median exploitation rate in 2022 was low at 0.022 (0.013, 0.032, Table 1). The estimated current-year exploitation rate relative to that at MSY was u_{2022}/u_{MSY} = 0.27 (0.15, 0.47) for the commercial fishery (Figure 5, Table 1).

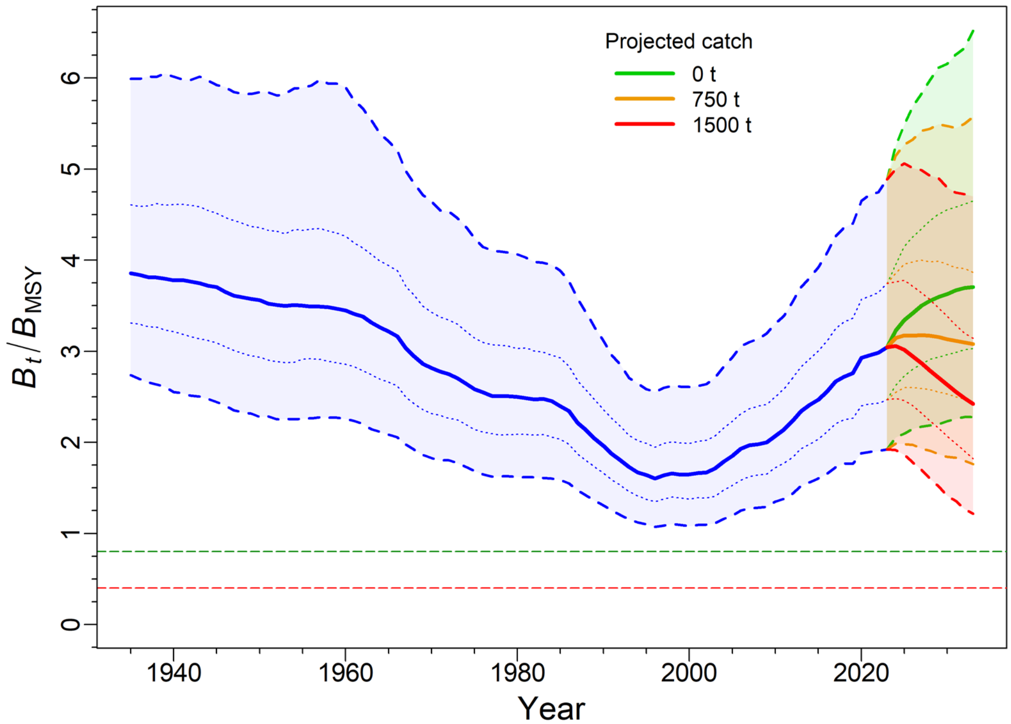

Figure 3. Estimates of spawning biomass B_t relative to B_{MSY} from the model posteriors (2,000 samples) of the CAR base run. The median biomass trajectory appears as a solid curve surrounded by a 90% credibility envelope (quantiles: 0.05, 0.95) in blue and delimited by dashed lines for years t=1935 - 2023; projected biomass using constant catch appears in green (no catch), orange (750 t/y), and red (1500 t/y) for years t=2024 - 2033 (10 years). Also shown is the 50% credibility interval (quantiles: 0.25 - 0.75) delimited by dotted lines.

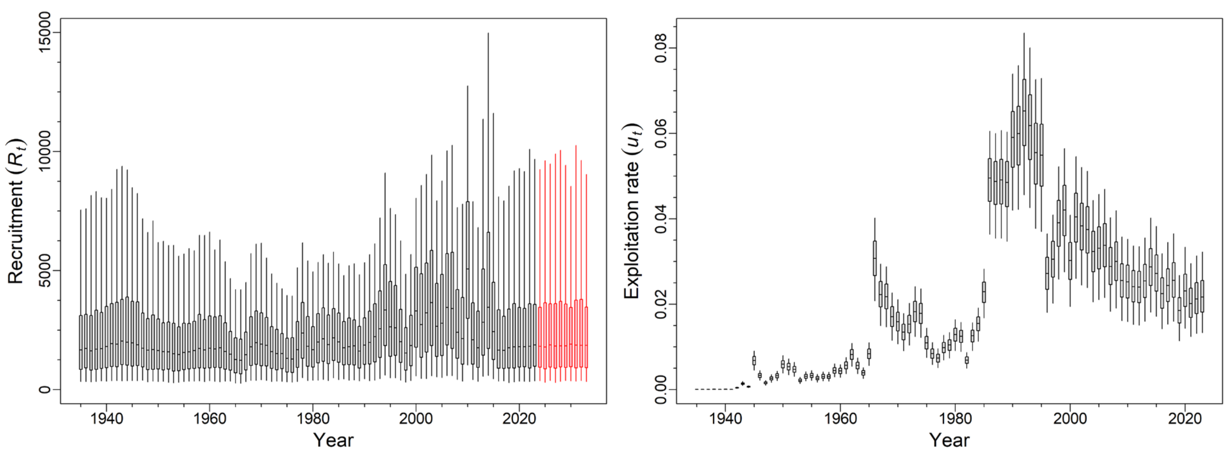

Figure 4. Base run marginal posterior distributions of annual recruitment (age-0 fish, left, including projected recruitment in red) and exploitation rate (right) for CAR. Boxplots give the 0.05, 0.25, 0.5, 0.75 and 0.95 quantiles from MCMC results.

Table 1. Quantiles of MCMC-derived quantities from 2,000 samples for the base run. Definitions: B_0 – unfished equilibrium spawning biomass (mature females in B_{1935}), B_{2023} – spawning biomass at the start of 2023, u_{2022} – exploitation rate (ratio of total catch to vulnerable biomass) in the middle of 2022, u_{max} – maximum exploitation rate (calculated for each sample as the maximum exploitation rate from 1935-2022), B_{MSY} – equilibrium spawning biomass at MSY (maximum sustainable yield), u_{MSY} – equilibrium exploitation rate at MSY. All biomass values (including MSY) are in tonnes. The average catch over the last 5 years (2017-21) was 775 t by trawl and 13.5 t for the 'other' fishery.

Quantity	5%	25%	50%	75%	95%
B_0	10,354	12,218	13,908	15,994	20,295
B_{2023}	7,275	9,071	10,761	12,886	17,637
B_{2023} / B_0	0.5703	0.6848	0.7780	0.8757	1.0450
u_{2022}	0.0134	0.0181	0.0217	0.0256	0.0323
u_{max}	0.0456	0.0572	0.0653	0.0727	0.0836
MSY	948	1,152	1,305	1,496	1,886
B_{MSY}	2,149	2,886	3,580	4,475	5,964
$0.4B_{MSY}$	860	1,154	1,432	1,790	2,385
$0.8B_{MSY}$	1,720	2,309	2,864	3,580	4,771
B_{2023} / B_{MSY}	1.9240	2.4680	3.0430	3.7440	4.8860
B_{MSY} / B_0	0.1670	0.2170	0.2593	0.3019	0.3652
u_{MSY}	0.0511	0.0683	0.0812	0.0949	0.1141
u_{2022} / u_{MSY}	0.1514	0.2128	0.2700	0.3419	0.4744

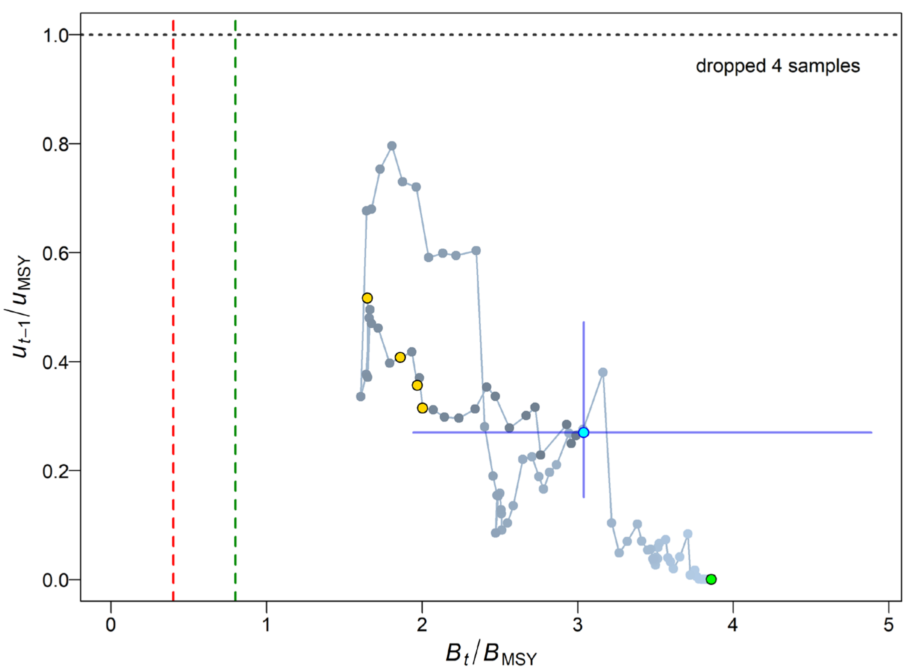

Figure 5. Phase plot through time of the medians of the ratios B_t/B_{MSY} (the spawning biomass at the start of year t relative to B_{MSY}) and fishing pressure u_{t-1}/u_{MSY}: (representing the exploitation rate in the middle of year t-1 relative to u_{MSY}) for the combined fishery (trawl+other) for the CAR base run. The filled green circle is the equilibrium starting year (1935). Years then proceed from lighter shades through to darker with the final year (t=2023) as a filled cyan circle, with the blue cross lines representing the 0.05 and 0.95 quantiles of the posterior distributions for the final year. Previous assessment year (1999, 2005, 2007, 2009) are indicated by gold circles. Red and green vertical dashed lines indicate the PA provisional LRP = $0.4B_{MSY}$ and USR = $0.8B_{MSY}$, and the horizontal grey dotted line indicates u_{MSY}. Four MCMC samples with estimated u_{MSY}=0 were dropped.

Reference Points

Figure 6 shows the stock status for the CAR base run relative to the adopted DFO (2009a) limit and upper stock reference points of $0.4B_{MSY}$ and $0.8B_{MSY}$, respectively. These PA reference points define the 'Critical', 'Cautious' and 'Healthy' zones. The CAR base run spawning biomass at the beginning of 2023 was estimated to be above the limit reference point (LRP) with probability $P(B_{2022} > 0.4B_{MSY}) = 1$, and above the upper stock reference (USR) point with probability $P(B_{2022} > 0.8B_{MSY}) = 1$ (i.e., no probability of being in the Cautious or Critical zones based on the set of MCMC posterior samples).

MSY-based reference points estimated within a stock assessment model can be sensitive to model assumptions about natural mortality and stock recruitment dynamics (Forrest et al. 2018). As a result, other jurisdictions use reference points that are expressed in terms of B_0 rather than B_{MSY} (Edwards et al. 2012; New Zealand Ministry of Fisheries 2011). Therefore, the reference points of $0.2B_0$ and $0.4B_0$ are also presented in Table 3, but are presented for information rather than as an alternative to the B_{MSY} reference points specified by the DFO PA decision making framework (DFO 2009a). These reference points, for example, are default values used in New Zealand respectively as a 'soft limit', below which management action needs to be taken, and a 'target' biomass for low productivity stocks, a mean around which the biomass is expected to vary. The 'soft limit' is equivalent to the Upper Stock Reference (USR, $0.8B_{MSY}$) in the DFO PA Sustainable Fisheries Framework while a 'target' biomass is not specified by the DFO PA Framework.

A second component of the DFO PA decision making framework (DFO 2009a) concerns the relationship of the exploitation rate relative to that associated with MSY under equilibrium conditions (u_{MSY}). The rule specifies that the exploitation rate should not exceed u_{MSY} when the stock is in the Healthy zone. Exploitation rates should be reduced to levels < u_{MSY} when the stock drops into the Cautious zone, with the allowable level of exploitation while in the Cautious zone dependent on the distance below the USR; exploitation should be kept to the lowest level possible when in the Critical zone. The phase plot of the time-evolution of spawning biomass and exploitation rate for the modelled fishery in MSY space (Figure 5) shows that the CAR stock has been in the Healthy zone from 1935 to the present.

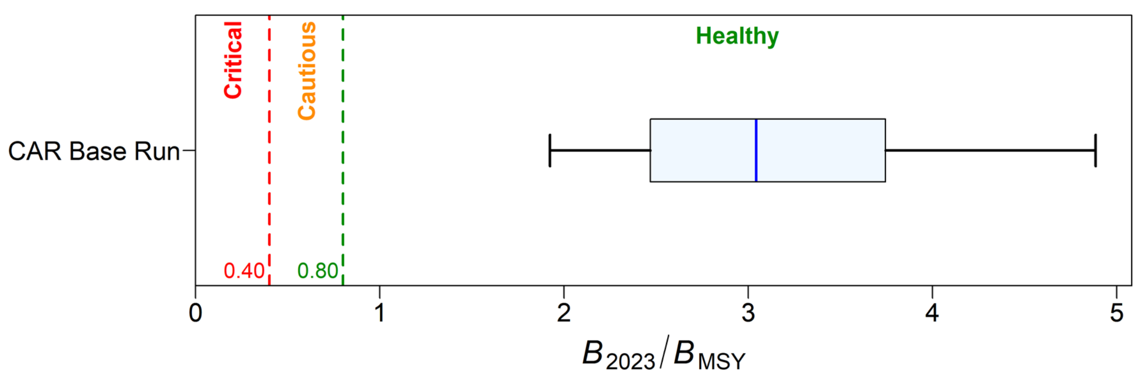

Figure 6. Stock status of the CAR base run relative to the DFO Precautionary Approach (PA) reference points of $0.4B_{MSY}$ and $0.8B_{MSY}$ for t=2023. Boxplots show the 0.05, 0.25, 0.5, 0.75 and 0.95 quantiles from the MCMC posterior.

Projection Results and Decision Tables

Ten-year projections with the first projection year labelled 2024 (reported as the biomass at the beginning of 2024 – which is the same as the biomass at the end of 2023 in the tables and figures), were made over a range of constant catch levels (0–2000 tonnes in 250 t increments;

Table 2 and Table 3). This time frame was considered adequate for advice to managers before the next stock assessment of this species. Note that the projection uncertainty increases as the number of projection years increase. While all projections should be treated with caution, projections for rockfish beyond 10 years should be treated with additional caution because they assume recruitment to vary about the average (from 1950 to 2012) while Figure 4 shows that historical CAR recruitments were initially low with larger recruitments occurring after the early 1990s. Consequently, simple average recruitment may not be an accurate representation of recruitment for this species (see projected recruitment in Figure 4). However, this issue may not be as problematic as for other *Sebastes* (rockfish) species which have generally low annual recruitment interspersed with large recruitment spikes (e.g., Bocaccio, *S. paucispinis*). The short-term (up to 10 years) projections in Table 2 are also more credible because they are primarily determined from year classes estimated during the model reconstruction and should be more reliable, particularly in the first half of the projection period.

The decision tables (Table 2 and Table 3) give the probabilities of the spawning biomass exceeding the biomass reference points or harvest rates remaining below u_{MSY} in each projection year for each catch level. These tables assume that catches will be held constant, with no consequent reduction of the exploitation rate even if a stock reaches the Cautious or Critical zones. The accuracy of the projections is predicated on the model being correct. Uncertainty in the parameters is explicitly addressed using a Bayesian approach but reflects only the specified model and weights assigned to the various data components.

Assuming that a catch of 750 t (close to the recent 5-year mean) will be taken each year for the next 10 years, Table 2 shows that a manager would be >99% certain that both B_{2028} and B_{2033} lie above the LRP of $0.4B_{\text{MSY}}$, >99% certainty that both B_{2028} and B_{2033} lie above the USR of $0.8B_{\text{MSY}}$, and >99% certainty that both u_{2028} and u_{2033} lie below u_{MSY} for the base run. Generally, it is up to managers to choose the preferred catch levels or harvest levels (if available) using risk levels acceptable to stakeholders. For example, it may be desirable to be 95% certain that B_{2033} exceeds an LRP whereas exceeding a USR might only require a 50% probability. Assuming this risk profile, a catch policy of <=2,000 t/y satisfies the LRP constraint in Table 2. Assuming that u_{MSY} is a target exploitation rate, all catch policies <= 1,250 t/y have a probability greater than 95% of the harvest rate remaining below u_{MSY} in 10 years, whereas catch policies <=2,000 t/y would have a probability greater than 50%.

Table 2. Decision tables for the PA reference points 0.4B_{MSY}, 0.8B_{MSY}, and u_{MSY} for current year (labelled as 2023) and 10-year projections for a range of constant catch policies (in tonnes) using the base run. Values are the probability (proportion of 1,996[1] MCMC samples with four bad samples dropped) of the female spawning biomass at the start of year t being greater than the B_{MSY} reference points, or the exploitation rate of vulnerable biomass in the middle of year t-1 being less than the u_{MSY} reference point. For reference, the average catch over the last 5 years (2017-2021) was 789 t.

P(B_t >0.4B_{MSY})

Catch policy	Projection year (start)									
	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
0	1	1	1	1	1	1	1	1	1	1	1
250	1	1	1	1	1	1	1	1	1	1	1
500	1	1	1	1	1	1	1	1	1	1	1
750	1	1	1	1	1	1	1	1	1	1	1
1000	1	1	1	1	1	1	1	1	1	1	1
1250	1	1	1	1	1	1	1	1	1	1	1
1500	1	1	1	1	1	1	1	1	1	1	1
1750	1	1	1	1	1	1	1	1	1	1	>0.99
2000	1	1	1	1	1	1	1	1	>0.99	>0.99	>0.99

P(B_t >0.8B_{MSY})

Catch policy	Projection year (start)										
	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
0	1	1	1	1	1	1	1	1	1	1	1
250	1	1	1	1	1	1	1	1	1	1	1
500	1	1	1	1	1	1	1	1	1	1	1
750	1	1	1	1	1	1	1	1	1	1	1
1000	1	1	1	1	1	1	1	1	1	1	1
1250	1	1	1	1	1	1	1	1	1	1	1
1500	1	1	1	1	1	1	1	1	>0.99	>0.99	>0.99
1750	1	1	1	1	1	1	>0.99	>0.99	>0.99	0.99	0.98
2000	1	1	1	1	1	>0.99	>0.99	0.99	0.99	0.97	0.95

P(u_t <u_{MSY})

Catch policy	Projection year (start)										
	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
0	1	1	1	1	1	1	1	1	1	1	1
250	1	1	1	1	1	1	1	1	1	1	1
500	1	1	1	1	1	1	1	1	1	1	1
750	1	1	1	1	1	1	1	1	1	1	1
1000	1	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
1250	1	0.99	0.99	0.99	0.99	0.99	0.98	0.98	0.97	0.97	0.96
1500	1	0.97	0.97	0.96	0.95	0.93	0.92	0.91	0.90	0.88	0.87
1750	1	0.93	0.91	0.89	0.87	0.85	0.83	0.81	0.78	0.75	0.73
2000	1	0.86	0.83	0.79	0.77	0.73	0.70	0.66	0.63	0.60	0.57

[1] Excluded four outlier samples that generated errors in projected amounts.

Table 3. Decision tables for the $0.2B_0$ and $0.4B_0$ reference points presented for information purposes for the current year (labelled as 2023) and 10-year projections for a range of constant catch policies (in tonnes) using the base run. Values are the probability (proportion of 1,996 MCMC samples, with four bad samples dropped) of the female spawning biomass at the start of year t being greater than the B_0 reference points. For reference, the average catch over the last 5 years (2017-2021) was 789 t.

P(Bt >$0.2B_0$)

Catch policy										Projection year (start)	
	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
0	1	1	1	1	1	1	1	1	1	1	1
250	1	1	1	1	1	1	1	1	1	1	1
500	1	1	1	1	1	1	1	1	1	1	1
750	1	1	1	1	1	1	1	1	1	1	1
1000	1	1	1	1	1	1	1	1	1	1	1
1250	1	1	1	1	1	1	1	1	1	1	1
1500	1	1	1	1	1	1	1	1	1	>0.99	>0.99
1750	1	1	1	1	1	1	1	>0.99	>0.99	>0.99	0.99
2000	1	1	1	1	1	1	>0.99	>0.99	0.99	0.98	0.96

P(B_t >$0.4B_0$)

Catch policy										Projection year (start)	
	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
0	1	1	1	1	1	1	1	>0.99	1	1	1
250	1	>0.99	1	1	>0.99	>0.99	>0.99	>0.99	>0.99	1	1
500	1	>0.99	1	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	1	1
750	1	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
1000	1	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	0.99	0.99	0.98	0.98
1250	1	>0.99	>0.99	>0.99	>0.99	0.99	0.99	0.98	0.97	0.96	0.95
1500	1	>0.99	>0.99	>0.99	0.99	0.99	0.98	0.96	0.94	0.92	0.88
1750	1	>0.99	>0.99	0.99	0.99	0.97	0.95	0.92	0.88	0.84	0.80
2000	1	>0.99	>0.99	0.99	0.98	0.95	0.91	0.86	0.80	0.76	0.70

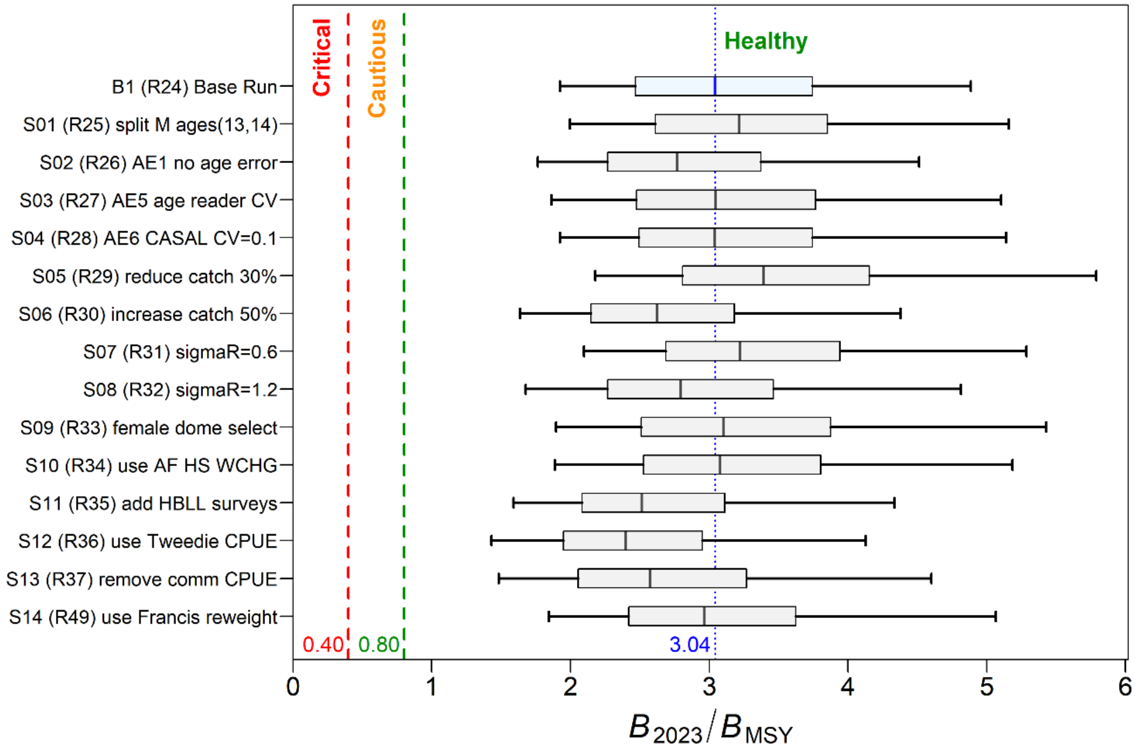

Figure 7. Stock status of the 14 CAR sensitivity runs compared to the base run relative to the DFO Precautionary Approach (PA) provisional reference points of $0.4B_{MSY}$ and $0.8B_{MSY}$ for t=2023. Boxplots show the 0.05, 0.25, 0.5, 0.75 and 0.95 quantiles from the MCMC posterior. The vertical dotted blue line depicts the base run median.

Sources of Uncertainty and Model Sensitivity Runs

Only one spatial stock of CAR has been identified along the BC coast, based on data that only show small differences in biology (lengths, growth rate) among gear types and regional sub-areas, but this may change with the accumulation of more data. Only one trawl fishery was modelled, but, because selectivities may differ between the bottom and midwater trawl fisheries, these fisheries may need to be modelled separately in future stock assessments. However, splitting the trawl fishery into separate fleets was not possible in this stock assessment because there were inadequate data to do so reliably. It is also possible that the trawl fishery selectivity may have evolved over the model reconstruction period, possibly contributing to the slight upward trend in recruitment that can be seen in Figure 4 (left panel). However, this issue can be best explored in the next CAR stock assessment.

Uncertainty in the base run estimated parameters was explicitly addressed using a Bayesian approach, with credibility intervals and probabilities provided for all quantities of interest. These intervals and probabilities are only valid for the specified model using the weights assigned to the various data components for the base run. The Bayesian approach also relies on the prior belief about each estimated parameter.

Structural uncertainty in this stock assessment was addressed by 14 sensitivity runs, all taken to the MCMC level, which explored plausible alternatives to the assumptions made in the base run (Table 4). None of these runs contradicted the base run conclusions. Furthermore, the base run MCMC uncertainty encompassed much of the MCMC uncertainty estimated for these sensitivity runs (e.g., see Figure 7).

The authors noted that natural mortality (*M*) was a key uncertainty for this species, especially as it appears to differ between the two sexes. This species exhibits a divergence in the apparent *M* for males from females which can be seen in age distributions, where there is a long tail of males past age 60 but the females are nearly absent by age 40. The previous BC CAR stock assessment approached this issue by hypothesizing that female *M* doubled at age 14 (Stanley et al. 2009). The most recent United States (US) CAR stock assessment (Thorson and Wetzel 2016) adopted a similar approach by assuming that female *M* increased relative to the male *M*, also at age 14.

Table 4. Sensitivity runs used to test a range of base run assumptions. All sensitivity runs were taken to MCMC to generate 2000 samples that were used to generate posterior distributions for all estimated parameters.

Sensitivity	Run	Description
S01	25	split *M* between ages 13 and 14 for estimation of *M* for young and mature fish
S02	26	apply no ageing error correction
S03	27	use smoothed ageing error from age-reader CVs
S04	28	use constant-CV ageing error (CV=10%)
S05	29	reduce commercial catch (1965-1995; foreign + unobserved domestic) by 30%
S06	30	increase commercial catch (1965-1995; foreign + unobserved domestic) by 50%
S07	31	reduce sigmaR (σ_R) to 0.6 from 0.9
S08	32	increase sigmaR (σ_R) to 1.2 from 0.9
S09	33	use female dome-shaped selectivity
S10	34	use age frequency data from HS & WCHG synoptic surveys
S11	35	add HBLL North & South (longline) surveys
S12	36	use CPUE fitted by Tweedie distribution
S13	37	remove commercial CPUE series
S14	49	use Francis mean-age reweighting instead of using the Dirichlet-Multinomial

This stock assessment used three approaches to investigate the problem of differential female *M* in this population.

- The approach used in the base run was to estimate separate *M* values for each sex while not allowing the selectivity functions to have descending right-hand limbs. That is, all fish remained fully selected by the fishery or the survey once maximum selectivity was reached. This run estimated the male median *M* to be 0.065 and the median female *M* to be 0.093.
- Sensitivity run S01 emulated the approach used by the 2007 and 2009 BC stock assessments by estimating separate *M* values for both males and females based on age, with the first estimate applied to ages less than or equal to 13 years (young fish) and the second estimate for ages 14 and older (mature fish)[2]. The mature male *M* was estimated to be 0.069 (median), rising from a median estimate of 0.054 for the young males, indicating that the age frequency (AF) data supported similar (and low) *M* values for both male age brackets. The mature female *M* estimate rose from a median of 0.061 for young females to 0.145, which were similar to the assumed fixed values (0.06 and 0.12) used in the 2007 and 2009 BC CAR stock assessments.
- Finally, sensitivity run S09 estimated single *M* values for each sex while allowing the right-hand limbs of the fishery and survey selectivities to descend for females, thus creating a cryptic population of mature females that had reduced vulnerability for older females and

[2] The SS3 platform appeared to be unable to estimate a single *M* parameter for males while estimating two female *M* parameters; consequently a second *M* parameter was estimated for each sex.

which served as an alternative explanation for the lack of older females in the age distributions. This approach worked well, with the estimated selectivity functions showing pronounced descending right-hand limbs for the trawl fishery and for five of the surveys while estimating the median *M* for males at 0.069 and for females at 0.086.

Run 24 was selected as the base run because it fit the available AF data well and required the fewest assumptions. Runs S01 and S09 fit the AF data marginally better but were less parsimonious in terms of number of estimated parameters than used by the base run. While all three runs were well into the Healthy zone (Figure 7), the base run had the lowest estimated stock depletion among the three alternative runs (Figure 8), with its median estimate of B_{2023}/B_0 equalling 0.78 while the median estimates for the same ratio were 0.94 for S01 and 0.84 for S09.

The use of commercial CPUE as an index of abundance has been avoided in some BC rockfish stock assessments, primarily due to potential biases that might result from shifts in vessel behaviour that do not reflect stock abundance. However, CPUE based on the bycatch of the evaluated species in the BC bottom trawl fishery have been used in several recent rockfish stock assessments (e.g., Bocaccio, Widow, *S. entomelas*; Redstripe, *S. proriger*). CAR is sometimes a target species as well as a bycatch species, but is more likely to be taken in conjunction with other rockfish and groundfish species. The CPUE models include the incidence of zero tows as well as the tows which captured the species, which improves the capacity of the model to track abundance. In general, there is confidence that zero tows have been recorded reasonably well as a result of the high level of observer coverage in the BC bottom trawl fishery, at least up until 2020. However, the shift to electronic monitoring resulting from the cessation of the at-sea observer programme due to COVID-19 pandemic concerns may have changed the reporting of zero tows. It is not known how this change has affected the reporting of zero tows, which may have improved because all captured rockfish are now required to be retained.

Two runs relating to CPUE were included in the suite of CAR sensitivity runs:

- Sensitivity run S13 dropped the CPUE series and estimated a stock size about 8% smaller than the base run. Given that the catch series is the same for the two models, the stock depletion for S13 was lower than for the base run, with the median estimate of B_{2023}/B_0 dropping from 0.78 for the base run to 0.67 for S13 (Figure 8).
- Sensitivity run S12 substituted a CPUE series based on the Tweedie distribution, a single distribution that emulates a compound Poisson-gamma distribution (Anderson et al. 2019). This CPUE series differed from the delta-lognormal series used in the base run with the final years ending at a relatively lower level for the Tweedie series. These differences may have arisen due to differences in the data selection procedure plus the Tweedie model handles zero catch observations differently. A second Tweedie series, which included a year-location interaction term that was closer to the delta-lognormal CPUE series, was also available. The series which did not use this interaction term was used because it showed the greatest contrast with the delta-lognormal series. The S12 sensitivity run estimated a stock size about 8% smaller than the base run and an even lower stock depletion estimate compared to sensitivity run S13. The median estimate of B_{2023}/B_0 dropped from 0.78 for the base run to 0.63 for S12. This run was the most pessimistic of all the sensitivity runs (Figure 8).

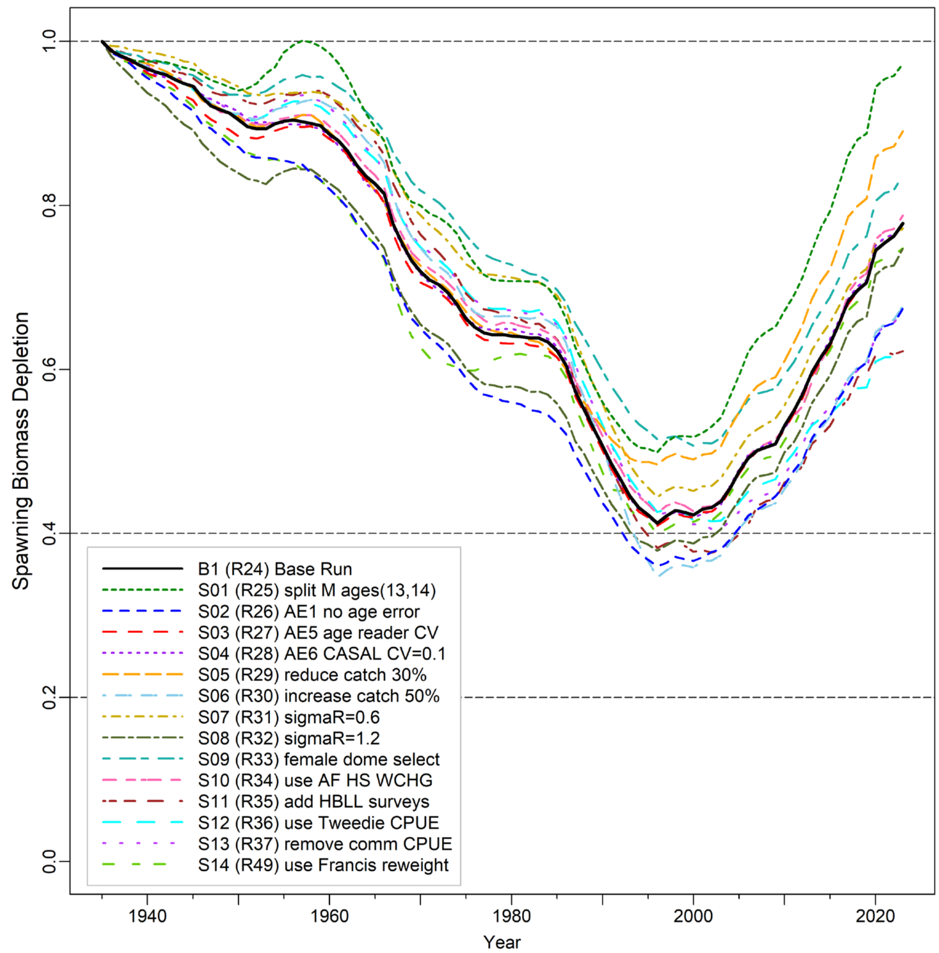

Figure 8. Model trajectories of median spawning biomass as a proportion of unfished equilibrium biomass (B_t/B_0) for the base run of the composite base run and 14 sensitivity runs. Horizontal dashed lines show reference points used by other jurisdictions: $0.2B_0$, $0.4B_0$, and B_0.

Adding the Hardbottom longline (HBLL) survey series to the model (S11) also resulted in a more pessimistic run, with the median estimate of B_{2023}/B_0 dropping from 0.78 for B1 to 0.62 for S11. However, these surveys do not monitor the full spatial range of the CAR population and operate in shallower waters and over rocky reefs, areas not fished by the trawl fishery. These surveys appear to miss smaller juveniles due to the large hook sizes used, and do not capture larger/older adults because these fish move out of the shallow waters into the deeper waters fished by the trawl fleet.

More effort was expended on investigating the impact of ageing error in this stock assessment than was done for previous rockfish assessments, with three sensitivity runs addressing this issue in addition to the base run. Ageing error was introduced into all models (except the model which dropped ageing error) using a smoothed function rather than the highly variable information based on the individual observations at each age.

- The base run used an ageing error series (AE3) that resulted from a function of smoothed standard deviations (SD) derived from coefficient of variances (CVs) of length-at-age. This function overlapped with the AE5 series (see next bullet) up to age 20, and then stayed high right up to age 60.

- Sensitivity run S03 implemented the AE5 series (smoothed SD derived from reader error CVs) which dropped away from the AE3 series, reaching zero around age 60. Stock status estimates generated by this run were nearly identical to the base run, with the median estimates for B_0, B_{2023} and B_{2023}/B_0 being the same as for the base run.
- Sensitivity run S04 implemented a constant 10% error at all ages. The stock status estimates from this run were also similar to the base run, with very similar median estimates for B_0, B_{2023} and B_{2023}/B_0 compared to the base run.
- Sensitivity run S02 dropped ageing error entirely. This run diverged from the base run, with B_0 estimated to be 27% greater than for the base run and B_{2023} was 10% greater than for the base run while B_{2023}/B_0 dropped to median 0.67 compared to the base run median of 0.78.

While S02 (no ageing error) diverged from the base run, the runs which applied ageing error all returned similar estimates for stock status, perhaps due to the similar standard deviations for younger ages (<25 y). However, even the ‘no ageing error’ run did not materially change the advice, with these runs all estimated to be well into the Healthy zone.

Raising (S08) or lowering (S07) the standard deviation of recruitment residuals (σ_R) affected the estimate of B_0, where the median estimate rose by 13% for S08 and dropped by 11% for S07. However, the estimates of B_{2023}/B_0 were similar to the base run, with the median estimate for S07 at 0.77 and at 0.75 for S08 compared to the base run median estimate of 0.78.

Sensitivity run S14, which emulated the base run but used the alternative (to the Dirichlet-Multinomial) Francis (2011) weighting procedure for age frequencies, returned a slightly lower median for B_{2023}/B_0 (0.748 compared to 0.754). The distribution of B_{2023}/B_{MSY} was also slightly lower for this run (Figure 7). These differences are small, indicating that the stock assessment results appear to be relatively insensitive to the weighting procedure used for the age frequency data.

Ecosystem Considerations and Climate Change

DFO groundfish fisheries managers have worked in consultation with science, industry and non-government organisations to implement measures in the commercial trawl fishery to protect bottom habitat, foster biodiversity, and ensure that these fisheries remain sustainable. These actions, described below, will benefit all species affected by this fishery.

In 2012, measures were introduced to reduce and manage the bycatch of corals and sponges by the BC groundfish bottom trawl fishery. These measures were developed jointly by industry and environmental non-governmental organisations, and include limiting the footprint of groundfish bottom trawl activities to manage the trawl fishery impacts on significant ecosystem components such as corals and sponges, establishing a combined bycatch conservation limit for corals and sponges, and establishing an encounter protocol. These measures also restrict access by bottom trawling to less than one-half of the available benthic habitat (stratified by area and depth) on the BC coast. These measures have been incorporated into DFO’s Pacific Region Groundfish Integrated Fisheries Management Plan.

To further mitigate ecosystem risk, all BC commercial groundfish fisheries are subject to the following management measures: 100% at-sea monitoring[3], 100% dockside monitoring, individual vessel accountability for all retained and released catch, individual transferable

[3] This requirement was met by 100% onboard observers from 1996 up to March 2020; beginning in April 2020, a replacement scheme based on electronic monitoring was implemented to accommodate changes resulting from the COVID-19 pandemic.

quotas, and reallocation of these quotas between vessels and fisheries to cover catch of non-directed species (see aforementioned Management Plan). These measures ensure that impacts on non-target species, ‘Endangered, Threatened and Protected’ (ETP) species, and biogenic habitat components (coral and sponge) are well monitored.

In addition to the fishery dependent ecosystem and fishery monitoring, DFO, in collaboration with industry partners, conducts a suite of fishery independent random depth-stratified surveys (using bottom trawl, demersal hook and line, and trap gears), which provide comprehensive coast wide coverage biennially of most offshore benthic habitats between the depths of 50 and 500 m. This suite of surveys provides an important source of information with very high specificity ensuring that ecosystem components vulnerable to fishing gears are monitored. While assessments and harvest options for groundfish species in the Pacific region are primarily provided on a single species basis, the fishery is managed in a multi-species context wherein many single species quotas are managed simultaneously. Additionally, freezing the footprint of the trawl fishery reduces the likelihood of impacts from the activities of the commercial bottom trawl fleet expanding into new benthic habitats.

This stock assessment included runs which incorporated an environmental index series in an exploratory analysis. The Pacific Decadal Oscillation (PDO) series was used for this exploration, primarily because it had been previously compared to the recruitment series estimates for Pacific Ocean Perch (see Appendix F in Haigh et al. 2018). However, it was difficult to evaluate the exploratory work in this stock assessment because it was found that the degree to which the model used the environmental information was governed by the relative weight given to the series. This was because parts of the environmental series were in conflict with some of fisheries data used in this stock assessment, leading to a deterioration in the fit to the fisheries data and consequent changes to the model predictions presented in Figure 6 and Table 1. The weight given to the PDO series was arbitrary, dependent on how much credibility was given to the series and the amount of effect that was judged to be sufficient. The main difficulty was that, unlike the equivalent issue between compositional data and biomass data, there existed no functional relationship in the model between the environmental series and the model dynamics.

It is not known how climate change will affect this species or the conclusions made by this stock assessment. Although there is agreement that warmer temperature regimes and changes to other environmental variables such as dissolved oxygen will likely affect marine species, the exact nature of these effects is poorly understood. Previous attempts at incorporating climate variables into stock assessments (e.g., Haigh at al. 2018) have proved unsuccessful, largely due to low contrast in the introduced series, a too-short time series, or overly simplistic (or unrealistic) functional models. Warmer temperatures may affect recruitment processes, natural mortality, and growth, any of which may affect stock resilience, productivity, and status relative to reference points which may in turn alter the perception of consequences associated with varying harvest levels relative to stock status. As well, reference points which rely on equilibrium conditions will shift because changing temperature regimes imply a change in productivity and consequently a different equilibrium level. Understanding the effect of climate change in a marine context will require additional monitoring and analyses.

CONCLUSIONS AND ADVICE

In common with stock assessments for other BC rockfish, this stock assessment depicts a slow-growing, low productivity stock. Unlike several of the more recent BC *Sebastes* stock assessments, we were able to obtain credible estimates for M, for both males and females. This meant that it was not necessary to construct a complex synthetic composite stock to cover an appropriate range of values for this parameter.

This stock assessment put the current (beginning 2023) CAR population in the DFO PA Healthy zone and predicted it will stay in the Healthy zone over the next 10 years at catch levels up to 2000 t/y). Fourteen sensitivity runs, which explored a wide range of alternative model assumptions, reached similar conclusions, with no sensitivity run contradicting the base run conclusions.

The decision tables provided guidance to the selection of short-term catch recommendations and described a range of possible future outcomes over the projection period at fixed levels of annual catch. The accuracy of these projections is predicated on the model being correct and are only available for the base run. Uncertainty in the parameters was explicitly addressed using a Bayesian approach but reflected only the specified model and estimated weights assigned to the various data components.

It is recommended that a full re-assessment occur in no more than 10 years, subject to the availability of new information. During intervening years the trend in abundance can be tracked by commercial fishery CPUE and, less reliably (because of the high relative error), by the fishery independent surveys used in this stock assessment. The groundfish synopsis report (Anderson et al. 2019; DFO 2022) summarises these trends and can be used as a tracking tool.

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SOURCES OF INFORMATION

This Science Advisory Report is from the September 7-8, 2022 regional peer review on Canary Rockfish (*Sebastes pinniger*) stock assessment for British Columbia in 2022. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

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