Fisheries and Oceans Canada / Pêches et Océans Canada
Ecosystems and Oceans Science / Sciences des écosystèmes et des océans

Pacific Region

Canadian Science Advisory Secretariat
Science Response 2024/003

STATUS UPDATE OF PACIFIC COD (*GADUS MACROCEPHALUS*) OFF THE WEST COAST OF VANCOUVER ISLAND IN 2023

Context

The 2020 assessment for Pacific Cod (*Gadus macrocephalus*) in British Columbia (BC) found the Area 3CD stock (West Coast Vancouver Island: WCVI; Figure 1) to be in the Cautious Zone with 97–98% probability, with 2–10% probability of being in the Critical Zone, over all catch scenarios considered (DFO 2021). This followed a notable reduction in the 2018 WCVI synoptic bottom trawl survey index (approximately 26–27% of the 2014 and 2016 observations (Table 1; Figure 2)). Given the low index point in 2018, the 2020 Science Response recommended updating the assessment following the 2020 WCVI synoptic bottom trawl survey. However, due to the COVID-19 pandemic, the scheduled 2020 WCVI survey was postponed to 2021, returning to its regular biennial schedule in 2022. Both the 2021 and 2022 index points were lower than the 2018 observation (Table 1). Catches since 2018 have also been lower than in previous years (Table 2; Figure 3). The commercial catch-per-unit-effort (CPUE) index decreased substantially in 2018 but has since increased, following increases in commercial catch (Figure 4).

A Request for Science Information and Advice (RSIA) for Pacific Cod was issued in 2022 for both the 3CD and 5ABCD (Hecate Strait and Queen Charlotte Sound) stocks. The stock assessment model (see Analysis and Response) is fitted to commercial and survey indices of abundance, commercial catch, and an index of mean weight, derived from commercial length samples (Forrest et al. 2020). However, due to the COVID-19 pandemic and a subsequent shift towards at-sea electronic monitoring, there has been no at-sea biological sampling on commercial trawl vessels since 2019. This change follows a trend of reduced biological length sampling of Pacific Cod on commercial vessels that began around 2015 (Appendix A).

The 2022 RSIA therefore had two steps: 1) an assessment of the potential sensitivity of the stock assessment to missing length data from the commercial fishery; and 2) a stock status update with updated catch advice for both stocks. The RSIA advised to only proceed to Step 2 if the missing length data were “deemed to not be of significance to the quality and rigour of the scientific advice”. Using the 2020 assessment model, the authors presented several sensitivity analyses to the Pacific Cod Technical Working Group (TWG) to evaluate alternative methods for updating the commercial mean weight index. This included a generalized linear model (GLM) for predicting the commercial mean weight index from a survey mean weight index derived from WCVI survey samples. The TWG found that the GLM provided acceptable predictions of the commercial mean weight index for the Area 3CD stock. However, the TWG decided that a similar GLM applied to the 5ABCD stock did not produce predictions consistent enough with the commercial mean weight index in overlapping years to be used in an assessment. Because of this issue with the 5ABCD commercial mean weight index and limited staff resources, Step 2 did not proceed.

The Pacific Groundfish Management Unit has not requested updated catch advice for 2023. However, given the three low index points in 2018, 2021, and 2022, Fisheries and Oceans Canada (DFO) Science Branch has issued a RSIA requesting a stock status update for the Area 3CD stock to ensure all three of these index points are considered in a timely evaluation of stock status. While the last assessment found that there was low probability (2%–10%) of the stock falling below its limit reference point (LRP) in 2022 under all considered catch scenarios (DFO 2021), the stock has failed to rebound under low estimated fishing mortality rates.

The Fish Stocks provisions (FSP) of Canada's *Fisheries Act* require that a rebuilding plan be developed for major fish stocks that have declined to or below their LRP. While the FSP only apply to major stocks prescribed in the *Fishery (General) Regulations*, guidance has been provided that states that, for stocks not subject to the FSP (such as Pacific Cod), DFO's Precautionary Approach (PA) Policy (DFO 2009) still applies:

"[. . .] under the [PA] policy, the requirement to develop a rebuilding plan is triggered once the stock declines to, or below, its LRP. However, in keeping with the 2009 PA Policy, if a fish stock is decreasing and approaching the LRP, management measures must encourage stock growth and arrest preventable declines, and the development of a rebuilding plan should be initiated sufficiently in advance to ensure that the plan is ready to be implemented if a stock declines to its LRP."

For the purpose of triggering a rebuilding plan, the guidance provides the following definitions of whether a stock is at or below its LRP:

"[A stock] is considered to be at or below its LRP if the terminal year stock status indicator is estimated to be at or below the LRP with a greater than 50% probability or if the projected stock status indicator falls below the LRP with a greater than 50% probability under a zero catch scenario in a 1-year projection, unless an alternative method or probability is defined in a stock-specific precautionary approach framework."

This Science Response reports results from the regional peer review of October 20, 2023, on the Status Update of Pacific Cod (*Gadus macrocephalus*) for West Coast Vancouver Island in 2023. Since there has been no request for catch advice, this is a stock status update only. The update uses the same model configurations as the 2018 and 2020 assessments (Forrest et al. 2020; DFO 2021), including model-averaged stock status based on the same seven sensitivity scenarios as in 2018 and 2020. Due to the ongoing absence of commercial length samples, this update uses the GLM developed in 2022 to update the last five years of the annual commercial mean weight index, based on values from a new survey mean weight index. The survey mean weight index and the GLM are described in Appendices B and C.

Background

Pacific Cod (or Grey Cod) is a relatively short-lived (~10–13 *y*), fast-growing member of the family Gadidae. It is distributed throughout the North Pacific Ocean, and throughout the waters of BC, typically in depth ranges up to 200 m. Four stocks of Pacific Cod are defined for management purposes on the BC coast: Strait of Georgia (4B), West Coast Vancouver Island (3CD), Queen Charlotte Sound (5AB), and Hecate Strait (5CD) (Figure 1). This document provides a stock status update for the 3CD stock only.

Description of the fishery

Pacific Cod in BC are caught almost entirely in the groundfish bottom trawl fishery, mainly in 50–200 m depth zones (Forrest et al. 2020). Most catch is taken in Area 5CD (Forrest et al. 2020), with smaller catches from Areas 5AB and 3CD, with near negligible catch taken from the west coast of Haida Gwaii, Area 5E (< 0.5% of total average annual catch since 1985). Pacific Cod are also caught in small quantities in the groundfish longline fishery (around 0.5% of the total annual catch on average).

The BC groundfish integrated fishery, which includes the bottom trawl fishery, is subject to 100% at-sea and dockside monitoring (DFO 2023). Between 1996 and 2019, all bottom trawl vessels carried observers who recorded the catch of each species and estimated quantities of released (discarded) fish. Since the COVID-19 pandemic, the fishery has shifted towards electronic monitoring on trawl vessels, which has impacted the availability of commercial biological samples (Appendix A).

Analysis and Response

Data

Data were extracted from DFO databases using methods described in Forrest et al. (2020). Data from fishery-independent and commercial fishery sources were available up until March 31, 2023 and all time series were updated using currently available data. Minor differences in the time series compared to those presented in previous assessments are due to routine updates and corrections in the databases.

For each area, models were fit to the following data: commercial catch, fishery-independent indices of abundance, commercial catch per unit effort (CPUE), and an index of mean weight of fish in the commercial catch.

Commercial catch

Commercial catch data (Table 2 and Figure 3) were extracted from three different databases held by DFO: *GFCatch* (Canadian trawl landings, 1954–1995); *PacHarvTrawl* (Canadian trawl landings, 1996 to March 31, 2007); and *GFFOS* (Canadian trawl landings, April 1, 2007 to March 31, 2022). Catch data prior to 1981 include catch by US vessels (Forrest et al. 2020). Fishing years are defined as beginning on April 1 for all years, and are referenced by starting year, e.g., the fishing year 1957 runs from April 1, 1957 to March 31, 1958.

Prior to the introduction of at-sea observers in 1996, estimates of discards were obtained from fishing logbooks. Pre-1996 discards are therefore a major source of uncertainty in this assessment. Estimates in years following the introduction of 100% at-sea monitoring in 1996 are considered to be accurate. Pacific Cod can be legally discarded by trawlers in BC. However, between 1996 and 2019, on-board observers first estimated the quantity being discarded and this was counted against the vessel's quota. Discard estimates are still counted against the vessel's quota, but the estimates are now made via the electronic monitoring system and fisher logbooks (DFO 2023). In addition to providing greater accuracy in reporting of discards since 1996, counting discards against the vessel's quota provides greater incentives to avoid discarding.

Canadian bottom trawl surveys

Survey indices (Table 1 and Figure 2) were calculated using a swept area analysis (a stratified random analysis), documented in Appendix A of Forrest et al. (2020). Abundance in Area 3CD (Figure 1) is indexed by the WCVI synoptic bottom trawl survey. The survey was first conducted in 2004 and is conducted in alternating (even-numbered) years. Due to the COVID-19 pandemic, the 2020 survey was postponed to 2021 then resumed its even-numbered years schedule in 2022.

For comparison, survey indices in Queen Charlotte Sound and Hecate Strait are also shown in Table 1 and Figure 2.

NMFS Triennial Survey (in Canadian waters)

An additional relative abundance index for Area 3CD was developed using data from the National Marine Fisheries Service (NMFS) Triennial survey, which operated off the lower half of WCVI between 1980 and 2001 (Figure 6). See Appendix A of Forrest et al. (2020) for details.

Commercial CPUE

Standardized commercial CPUE indices were developed for the historical (1956–1995) and modern (1996–2019) periods (Figure 4). The indices were developed using a Tweedie generalized linear mixed effects model (GLMM) described in detail in Appendix B of Forrest et al. (2020). The historical-period GLMMs included predictors for depth, locality, month, and a locality-year interaction. The modern-period GLMMs included predictors for depth, latitude, locality, month, vessel, and a locality-year interaction.

Commercial mean weight index

The commercial mean weight index between 1956 and 2016 was calculated using commercial length samples, with the methodology described in Appendix C of Forrest et al. (2020). Commercial biological samples were available for calculating mean weight from 1956 to 2019 (excluding 2018).

There has been no biological sampling on commercial trawl vessels since 2019, and a decline in commercial sampling of Pacific Cod that began around 2015 (Appendix A). In Area 3CD, only four biological samples were taken in 2017 (total 300 fish), no samples were taken in 2018, and only two samples were taken in 2019 (total 360 fish). The samples in 2017 and 2019 were taken from a limited area, especially in 2019 (Figure 5). The 2017 mean weight value was anomalously high (3.024 kg) and, given that it was only based on four samples, it was not used in the 2018 or 2020 stock assessments (Forrest et al. 2020; DFO 2021). Due to lack of data, the 2020 assessment used the 2019 mean weight value for both 2019 and 2020, although this approach was not ideal, as the 2019 index point was based on only two samples from the same location.

In the absence of representative biological samples for the last years of the index, a GLM was developed to predict the commercial mean weight index from a mean weight index derived from length samples from WCVI synoptic survey (Appendices B and C).

The GLM predicts values for the commercial mean weight index only for years when there was a survey (i.e., predicted commercial index values were generated for even-numbered years from 2004 to 2018, then 2021 and 2022; Appendix C: Figure 21). Therefore, a decision had to be made about how to include the GLM-derived index values, since there were no GLM-derived values for 2017, 2019 or 2020.

For consistency with previous assessments, the decision was to use the commercial mean weight index derived directly from commercial length samples for the years 1956–2016. Since neither of the previous assessments have used the 2017 index point, it was also omitted from this assessment update. For 2018–2022, the model uses the 2018, 2021 and 2022 mean weight index values derived from the GLM (Appendix C: Figure 21). Values for 2019 and 2020 were interpolated between 2018 and 2021 (Appendix D: Table 9, Sc. 1 Reference). See Appendix D for a brief presentation of model sensitivity to these choices.

Stock assessment model

The stock assessment model is a Bayesian delay-difference model (Deriso 1980), fit to survey indices, commercial CPUE indices, commercial catch data, and the commercial mean weight index. The model is fully described in Appendix D of Forrest et al. (2020). All fixed parameters and prior probability distributions for model parameters in the current assessment were the same as those reported in Forrest et al. (2020).

Joint posterior distributions were numerically approximated using the Markov Chain Monte Carlo (MCMC) routines built into AD Model Builder (Metropolis-Hastings algorithm) (Fournier et al. 2012). Posterior samples were drawn every 5,000 iterations from a chain of length 10 million, resulting in 2,000 posterior samples. The first 1,000 of these samples were dropped to allow for sufficient burn-in.

Reference points

The DFO Fishery Decision-making Framework Incorporating the Precautionary Approach (PA) Policy (DFO 2009) requires stock status to be characterized using three reference points:

1. An Upper Stock Reference point, USR;
2. A Limit Reference Point, LRP; and
3. A Limit Removal Rate, LRR.

The USR and LRP define the threshold of three biomass-based stock status zones defined under the PA Policy (DFO 2009): Critical Zone (below the LRP); Cautious Zone (above the LRP and below the USR); and Healthy Zone (above the USR).

As in previous assessments (DFO 2019a, 2021), historical reference points were used to assess stock status, where:

1. The USR is the mean of the biomass estimates from 1956–2004;
2. The LRP is the lowest estimated biomass agreed upon as an undesirable state to be avoided. For Area 3CD this is the estimated biomass in 1986; and
3. The LRR is the mean of the fishing mortality rate estimates from 1956–2004.

See Forrest et al. (2020) for the history of the choice to use historical reference points for Pacific Cod. See also Forrest et al. (2018) for an evaluation of historical reference points for the 5CD stock of Pacific Cod.

Model scenarios

A model-averaging approach was used to estimate stock status based on combined posterior samples from several sensitivity cases, as in the two previous assessments (DFO 2019a, 2021). In a model-averaging approach, several models, each representing a different but plausible state of nature, were developed and the posterior samples were combined across all scenarios to provide the probabilities of stock status. This approach captures the effects of key uncertainties and averages them into the results, as opposed to using a single best model with separate sensitivity analyses to explore the impact of uncertainties on the results. Other stock assessments that have used a model-averaging approach are Pacific Cod in Areas 5AB and 5CD (Forrest et al. 2015), Pacific Hake (Stewart et al. 2011), Pacific Halibut (Stewart and Hicks 2016), BC Shortspine Thornyhead (Starr and Haigh 2017), BC Walleye Pollock (Starr and Haigh 2021) and several assessments of BC *Sebastes* stocks (e.g., DFO 2019b, 2020a, 2020b).

Major axes of uncertainty for Pacific cod are catchability (q) in the indices of abundance, the magnitude of natural mortality (M), age at recruitment to the fishery, and the magnitude of observation errors in the surveys and mean weight (Forrest et al. 2020). A Reference model was first established to represent what were considered to be the most plausible model choices across a range of assumptions. Key characteristics of the Reference model are provided in Table 3. The Reference model served as the basis from which alternative scenarios were developed, altering key model assumptions one at a time.

The set of seven model scenarios for model-averaging was agreed upon at the Canadian Science Advisory Secretariat (CSAS) Regional Peer Review (RPR) meeting in 2018 (DFO 2019a). The same set was used again in the 2020 stock assessment update (DFO 2021) and is used again here. All models were updated with catch and index data to the end of the 2022 fishing year, with updates to the annual mean weight index described above. Full details on the model configurations and assumptions for each scenario are provided in Forrest et al. (2020).

The scenarios (Sc) included in the model-averaging set were:

1. Sc 1a: Reference model;
2. Sc 2d: Set the mean of the prior probability distribution for synoptic survey $\ln(q)$ = $\ln(1.0)$, i.e., $\ln(q) \sim \mathcal{N}(0, 0.3)$;
3. Sc 2e: Increase the standard deviation (SD) for synoptic survey $\ln(q)$ to 0.6, i.e., $\ln(q) \sim \mathcal{N}(ln(0.228), 0.6)$;
4. Sc 3a: Set the parameters of the prior probability distribution for $\ln(M) \sim \mathcal{N}(\ln(0.4), 0.1)$;
5. Sc 5a: Set knife-edged age at recruitment = 3 years;
6. Sc 6b: Reduce the overall observation error term $\sigma_O = 0.15$; and
7. Sc 7b: Reduce the SD in the likelihood for the fit to average annual mean weight $\sigma_W = 0.15$,

where scenario numbers reflect the original scenario numbers from the 2018 assessment (Forrest et al. 2020).

Reference model results

Reference model results are presented to demonstrate model performance and to provide comparison with the 2020 stock assessment update. Stock status, presented in the next section, is based on combined, averaged posterior model results.

Model convergence was informed by visual inspection of trace and autocorrelation plots (not shown), and two statistics: 1) the potential scale reduction statistic $\hat{R}$, which should approach 1.0 as the chains are consistent with convergence; and 2) the effective number of MCMC independent samples after accounting for autocorrelation n_{eff} (Gelman and Rubin 1992; Gelman et al. 2014).

Reference model parameter estimates are shown in Table 4. Reference model fits to the data were generally typical of all sensitivity cases. The model diagnostics were consistent with convergence, and posterior sample autocorrelation was relatively minor for most parameters (Table 4). Model fits to the catch were near perfect by design (standard deviation in log likelihood was set to 0.05) and are not shown. Model fits to the four indices of abundance are shown in Figure 7. The reference model followed the trends of the two fishery-independent indices (Figure 7a and d), but did not closely fit the 2012, 2014, and 2016 data points in the WCVI Synoptic survey (Figure 7a). This lack of fit is likely because of large differences between low points (2012 and 2018) and high points (2014 and 2016) in the survey observations. Similarly, while the model closely followed the major patterns in the historical CPUE index (Figure 7b), it did not capture all the peaks in the modern series (Figure 7c). Fits such as this tend to occur when there is no other information (such as age composition data) to help resolve large fluctuations in observed indices. Forrest et al. (2020) considered goodness of fit to the indices of abundance to be a primary driver of uncertainty in their assessments, as estimates of productivity parameters were sensitive to how well the model fit observed peaks in the indices. They presented several sensitivity analyses to treatment of the observation error parameter σ_O, one of which is included in the model-averaging set here (Sc 6b).

As in the 2020 assessment (DFO 2021), the model tended to underestimate annual mean weight, especially in the early part of the time series (Figure 8). This result is most likely because most of the length measurements in this part of the time series came from fish classified as "keepers", i.e., landed (see Forrest et al. (2015) for discussion of this issue for the Area 5AB and 5CD stocks). Smaller, discarded fish are therefore likely underrepresented in the annual mean weight data prior to the introduction of at-sea observers in 1996. A scenario with a smaller value of σ_W, which controls the fit to the mean weight in the likelihood function, is included in the model-averaging set (Sc 7b).

Sensitivity model results

Sensitivity of posterior recruitment estimates to the settings in the seven scenarios are shown in Figure 9. Sensitivity of posterior biomass estimates are shown in Figure 10. As in previous assessments, the model was most sensitive to the assumed mean and standard deviation in the prior for survey catchability (q) (Sc 2d and 2e).

Indicators of current stock status

Model-averaged posterior reference point estimates are provided in Table 5. Model-averaged posterior estimates for biomass and fishing mortality are shown in Figures 11 and 12, respectively.

While fishing mortality is estimated to be well below the limit removal reference, Table 6 shows a 23% probability (i.e., about 1 out of 4 chance) that the biomass at the beginning of 2023 was below the LRP and >99% probability that the stock was below the USR. See also Figures 13 and 14, noting that the models estimated just over 50% probability of the stock being below the LRP in 2021 (Figure 14).

Table 7 shows a 16% probability (i.e., about 3 out of 20 chance) that the stock would be below the LRP at the beginning of 2024 under a zero catch policy.

Sources of uncertainty

Uncertainty due to estimated parameters and the weights assigned to various data components was explicitly addressed using a Bayesian approach. For provision of advice, posterior results from seven alternative model configurations were combined to generate decision tables. However, this approach only captures uncertainty associated with this set of model configurations and may underestimate greater structural uncertainties. Additional uncertainties in this assessment stem from:

1. The lack of reliable age composition data for this species, which would provide additional information about recruitment strength, M, and gear selectivity. Reliable age composition data would also allow for better estimates of age at recruitment to the fishery;
2. Relatively short time series of fishery-independent abundance indices;
3. Uncertainty in the magnitude of pre-1996 discarding and foreign catches. Underestimation of historical discards could lead to an underestimation of stock productivity;

4. Bias in the length frequency data prior to 1996, due to likely under-representation of lengths of fish that were caught but released at sea;

5. A poor understanding of Pacific Cod stock structure in Pacific waters. For example, connectivity between stocks of Pacific Cod in BC and Alaska is not well understood. Pacific Cod stocks in the Gulf of Alaska have declined since 2017, likely due to warming north Pacific waters (Barbeaux et al. 2020; Laurel et al. 2023), and it is unknown whether there is any relationship between drivers of abundance of these stocks and stocks in BC; and

6. A poor understanding of the relationship between commercial CPUE data and abundance, and how this relationship has been affected over the course of management changes in the fishery.

Conclusions

Model-averaged estimates of biomass resulted in a 23% probability that the stock was below the LRP at the beginning of 2023, and a 16% probability that the stock would be below the LRP at the beginning of 2024 under zero catches. Therefore, the stock does not currently meet the threshold of 50% probability of being below the LRP required under the rebuilding guidance to trigger a rebuilding plan (see Context) and is currently considered to be in the Cautious Zone under the PA policy. However, these findings may invoke the requirement that “management measures must encourage stock growth and arrest preventable declines, and the development of a rebuilding plan should be initiated sufficiently in advance to ensure that the plan is ready to be implemented if a stock declines to its LRP.” Current fishing mortality is estimated to be low ($<$ 0.02 y^{-1}) but increasing slightly, with an approximate 70% increase in commercial catch between 2021 and 2022.

There are uncertainties in the scale of the model-estimated biomass, given large uncertainties in survey catchability. Reducing the estimated scale of the biomass would not necessarily influence the estimate of stock status, which is based on historical reference points that rescale with biomass. However, estimates of fishing mortality would increase with lower estimates of biomass.

Other Pacific Cod populations (notably in Alaska) have undergone large declines since the marine heatwave of 2015 and 2016 (e.g., Barbeaux et al. 2020; Laurel and Rogers 2020). However, survey indices of abundance in other areas of BC (Hecate Strait, Queen Charlotte Sound and West Coast Haida Gwaii) have not shown similar declines (Figure 2). There has not been a thorough analysis of potential causes for the current decline in the Area 3CD Pacific Cod stock, which may be related to climate change-mediated effects on egg/larval/juvenile (Abookire et al. 2022; Laurel et al. 2023) or adult (Barbeaux et al. 2020) life stages, fish movement, fishing, or other factors. We recommend that resources be allocated to investigate alternative hypotheses for changes in abundance of Pacific Cod in BC waters.

The loss of commercial biological samples from the commercial trawl fishery threatens the long-term viability of the current delay-difference model as a primary tool for assessing BC Pacific Cod populations. Given the poor power of the GLM for predicting a commercial mean weight index for the Area 5ABCD population (DFO unpublished report), there is already no clear path forward for that stock. We acknowledge that a new dockside biosampling program is currently in the pilot stage, with the intention expanding it to a full coastwide program following successful implementation of the pilot program. While this is a welcome development, further analysis will be required to explore potential biases occurring due to continuing lack of samples from fish discarded at sea. Therefore, in the ongoing absence of an at-sea commercial biological sampling program, we recommend resources be allocated to investigating and comparing other approaches for providing catch advice for Pacific Cod stocks, which may also be advantageous, given the uncertainties inherent in this model. Alternative approaches may include length-based methods (e.g., Haist and Fournier 1995, 1998), or more data-limited approaches, such as adjusting annual total allowable catches (TACs) based on changes in the survey indices. Versions of the latter approach are used by the International Council for the Exploration of the Sea (ICES) for data-limited (Category 3) stocks (ICES 2022). In Canada, survey-based data-limited methods have been simulation-tested in the Groundfish Management Procedure Framework (Anderson et al. 2021) and in Huynh et al. (2020). Exploration of non-age structured models that allow for time-varying productivity (e.g., Mildenberger et al. 2019) may also be informative.

Acknowledgments

The authors are grateful to Paul Starr (Canadian Groundfish Research and Conservation Society) and the Pacific Cod Technical Working Group for technical assistance with development of the Generalized Linear Model used to derive the mean weight index.

Tables

Table 1. Pacific Cod survey data for Canadian trawl surveys in metric tonnes (mt) (without accounting for survey catchability). Positive sets refers to the number of trawl sets that caught Pacific Cod. SYN HS = Hecate Strait synoptic bottom trawl survey; SYN QCS = Queen Charlotte Sound synoptic bottom trawl survey; SYN WCVI = West Coast Vancouver Island synoptic bottom trawl survey. Indices for the QCS and HS synoptic surveys are not included in this assessment but are shown for comparison.

Survey abbrev.	Year	Biomass	CV	Lower CI	Upper CI	Sets	Positive sets
SYN HS	2005	1860.8	0.23	1167.8	2836.9	198	161
SYN HS	2007	559.2	0.20	352.9	812.8	132	72
SYN HS	2009	2340.8	0.44	757.1	4651.7	155	102
SYN HS	2011	1784.6	0.26	1078.8	2804.5	184	124
SYN HS	2013	2220.8	0.22	1380.9	3337.0	175	132
SYN HS	2015	920.4	0.21	595.5	1360.0	148	107
SYN HS	2017	1485.8	0.34	732.8	2598.3	138	107
SYN HS	2019	1662.6	0.38	772.4	3129.0	135	101
SYN HS	2021	2088.7	0.39	1028.7	3922.0	116	91
SYN QCS	2003	815.1	0.16	565.6	1082.3	228	99
SYN QCS	2004	1613.2	0.26	932.6	2577.6	229	117
SYN QCS	2005	1498.3	0.35	744.9	2716.4	221	122
SYN QCS	2007	434.5	0.26	248.9	702.5	255	105
SYN QCS	2009	560.2	0.25	312.5	861.1	230	93
SYN QCS	2011	1018.3	0.21	631.5	1485.8	248	97
SYN QCS	2013	907.9	0.15	656.7	1200.0	236	131
SYN QCS	2015	1122.3	0.29	646.0	1884.7	238	124
SYN QCS	2017	522.2	0.17	365.5	719.0	239	90
SYN QCS	2019	1004.0	0.13	767.9	1259.6	242	113
SYN QCS	2021	1157.1	0.13	913.5	1463.1	193	126
SYN WCVI	2004	1133.1	0.22	691.8	1636.1	88	54
SYN WCVI	2006	1156.0	0.23	687.8	1699.8	164	88
SYN WCVI	2008	512.6	0.40	234.0	1022.0	159	65
SYN WCVI	2010	1577.4	0.16	1091.9	2098.3	136	100
SYN WCVI	2012	921.3	0.18	622.3	1267.5	151	94
SYN WCVI	2014	2149.4	0.21	1296.9	3156.3	146	110
SYN WCVI	2016	2026.8	0.20	1303.8	2888.2	140	99
SYN WCVI	2018	552.9	0.20	369.4	779.9	190	91
SYN WCVI	2021	431.7	0.17	300.6	581.8	169	86
SYN WCVI	2022	500.0	0.13	377.1	643.3	126	79

Table 2. Reported catch (mt) of Pacific Cod in Area 3CD by Canada and the USA, 1956–2022. The reported releases at sea (discards) for the period 1956–1995 are likely unrepresentative of true discarding because the estimates were taken from logbooks in the absence of observers. Discard estimates since 1996 are based on at-sea observations and are considered to be more representative of true discarding. Numbers are rounded for presentation.

Year	Landings	Released at sea	Total	USA	Total catch
1956	714.6	0.0	714.6	770	1,484.6
1957	1,116.6	0.0	1,116.6	558	1,674.6
1958	526.3	0.0	526.3	271	797.3
1959	416.0	0.0	416.0	510	926.0
1960	240.4	0.0	240.4	376	616.4
1961	284.1	0.0	284.1	232	516.1
1962	428.0	6.0	434.0	402	836.0
1963	838.4	2.0	840.4	345	1,185.4
1964	1,107.5	8.0	1,115.5	907	2,022.5
1965	1,607.9	8.0	1,615.9	1,088	2,703.9
1966	2,095.3	143.0	2,238.3	1,145	3,383.3
1967	1,201.8	0.0	1,201.8	623	1,824.8
1968	726.2	4.0	730.2	351	1,081.2
1969	795.8	2.0	797.8	147	944.8
1970	1,150.1	32.0	1,182.1	454	1,636.1
1971	3,585.0	120.0	3,705.0	1,319	5,024.0
1972	4,446.8	2.0	4,448.8	1,271	5,719.8
1973	2,457.2	1.0	2,458.2	627	3,085.2
1974	2,912.6	7.0	2,919.6	1,013	3,932.6
1975	2,853.8	24.0	2,877.8	1,359	4,236.8
1976	2,187.4	2.0	2,189.4	1,679	3,868.4
1977	1,608.3	49.0	1,657.3	1,344	3,001.3
1978	1,168.5	18.0	1,186.5	1,086	2,272.5
1979	1,530.0	13.0	1,543.0	741	2,284.0
1980	1,117.1	10.0	1,127.1	287	1,414.1
1981	1,517.6	4.0	1,521.6	0	1,521.6
1982	607.6	2.0	609.6	0	609.6
1983	883.4	0.0	883.4	0	883.4
1984	506.2	2.0	508.2	0	508.2
1985	440.2	0.0	440.2	0	440.2
1986	440.7	0.0	440.7	0	440.7
1987	1,399.7	2.0	1,401.7	0	1,401.7
1988	3,153.2	3.0	3,156.2	0	3,156.2
1989	1,958.3	3.0	1,961.3	0	1,961.3
1990	2,076.2	4.0	2,080.2	0	2,080.2
1991	2,970.8	0.0	2,970.8	0	2,970.8
1992	2,229.4	1.0	2,230.4	0	2,230.4
1993	2,090.5	2.0	2,092.5	0	2,092.5
1994	815.5	1.0	816.5	0	816.5
1995	251.8	4.0	255.8	0	255.8
1996	145.6	9.2	154.7	0	154.7
1997	135.3	10.1	145.4	0	145.4

Year	Landings	Released at sea	Total	USA	Total catch
1998	55.7	4.8	60.5	0	60.5
1999	75.2	7.7	82.9	0	82.9
2000	129.5	12.8	142.3	0	142.3
2001	341.5	16.1	357.6	0	357.6
2002	177.2	26.4	203.6	0	203.6
2003	457.9	41.4	499.3	0	499.3
2004	417.6	26.8	444.4	0	444.4
2005	265.2	28.6	293.8	0	293.8
2006	142.7	10.5	153.2	0	153.2
2007	55.0	12.9	67.9	0	67.9
2008	104.6	6.6	111.2	0	111.2
2009	365.5	56.1	421.6	0	421.6
2010	577.3	24.6	601.8	0	601.8
2011	501.7	9.4	511.1	0	511.1
2012	399.4	18.5	417.9	0	417.9
2013	360.7	28.7	389.4	0	389.4
2014	442.1	11.9	454.0	0	454.0
2015	445.3	3.5	448.8	0	448.8
2016	323.4	2.1	325.5	0	325.5
2017	163.8	0.8	164.6	0	164.6
2018	22.7	0.3	22.9	0	22.9
2019	43.0	4.0	47.0	0	47.0
2020	45.6	3.7	49.2	0	49.2
2021	79.2	1.3	80.5	0	80.5
2022	134.9	0.5	135.4	0	135.4

Table 3. Estimated and fixed parameters and prior probability distributions used in the Reference model. The survey catchability parameter for WCVI (q_1) was estimated with the prior probability distribution $\mathrm{Normal}(\ln(0.228), 0.3)$. The other survey catchability parameters (Table 4) were estimated without priors.

Parameter	Number estimated	Bounds [low, high]	Prior (mean, SD) (single value = fixed)
Log recruitment ($ln(R_0)$)	1	[1, 12]	Uniform
Steepness (h)	1	[0.2, 1]	Beta($\alpha = 5.83333, \beta = 2.5$)
Natural mortality ($ln(M)$)	1	[-2.302585, 0]	Normal($ln(0.5), 0.1$)
Variance ratio (ρ)	0	Fixed	0.059
Total inverse variance (ϑ^2)	0	Fixed	1.471
Survey catchability (q_k)	4	None	See caption
Log fishing mortality values ($\Gamma_{k,t}$)	67	[-30, 3]	[-30, 3]
Log recruitment deviations (ω_t)	67	None	Normal($0, 2$)
Initial log recruitment deviations ($\omega_{init,t}$)	8	None	Normal($0, 2$)

Table 4. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of key parameters from the Reference model. R_0 is in thousands of fish. $\hat{R}$ is the potential scale reduction statistic and n_{eff} is the effective number of simulation draws (see text). q_1 = West Coast Vancouver Island Synoptic Survey, q_2 = Commercial CPUE pre-1996, q_3 = Commercial CPUE post-1995, and q_4 = NMFS Triennial Survey (Canadian portion).

Parameter	2.5%	50%	97.5%	MPD	n_{eff}	$\hat{R}$
R_0	1,961	2,801	4,147	3,331	401	1.00
h	0.430	0.733	0.943	0.789	831	1.00
M	0.402	0.437	0.475	0.441	386	1.00
q_1	0.042	0.062	0.090	0.060	702	1.00
q_2	0.002	0.002	0.003	0.002	792	1.00
q_3	0.001	0.002	0.003	0.002	701	1.00
q_4	0.058	0.084	0.119	0.084	815	1.00

Table 5. Posterior (2.5th percentile, Median, and 97.5th percentile) model-averaged estimates of reference points. Biomass is in tonnes. All values are rounded. Ratios were calculated using full posterior distributions and cannot be calculated directly from the table.

Reference point	2.5%	50%	97.5%
B_{2023}	4584	10451	35428
F_{2022}	0.005	0.018	0.042
LRP (1986)	4443	8863	27213
USR (1956–2004)	16430	28547	81114
LRR (1956–2004)	0.022	0.064	0.115
B_{2023}/LRP	0.773	1.161	1.695
B_{2023}/USR	0.251	0.361	0.505
F_{2022}/LRR	0.194	0.279	0.413

Table 6. Model-averaged stock status at the beginning of 2023. See text for scenarios used in model-averaging.

P(B2023 < LRP)	P(B2023 < USR)	P(F2022 > LRR)
0.23	>0.99	<0.01

Table 7. Probabilities of stock breaching reference points under TAC = 0 for a one-year projection, from the model averaging.See text for scenarios used in model-averaging.

2023 Catch (mt)	P(B2024 < B2023)	P(B2024 < LRP)	P(B2024 < USR)
0	0.34	0.16	>0.99

Figures

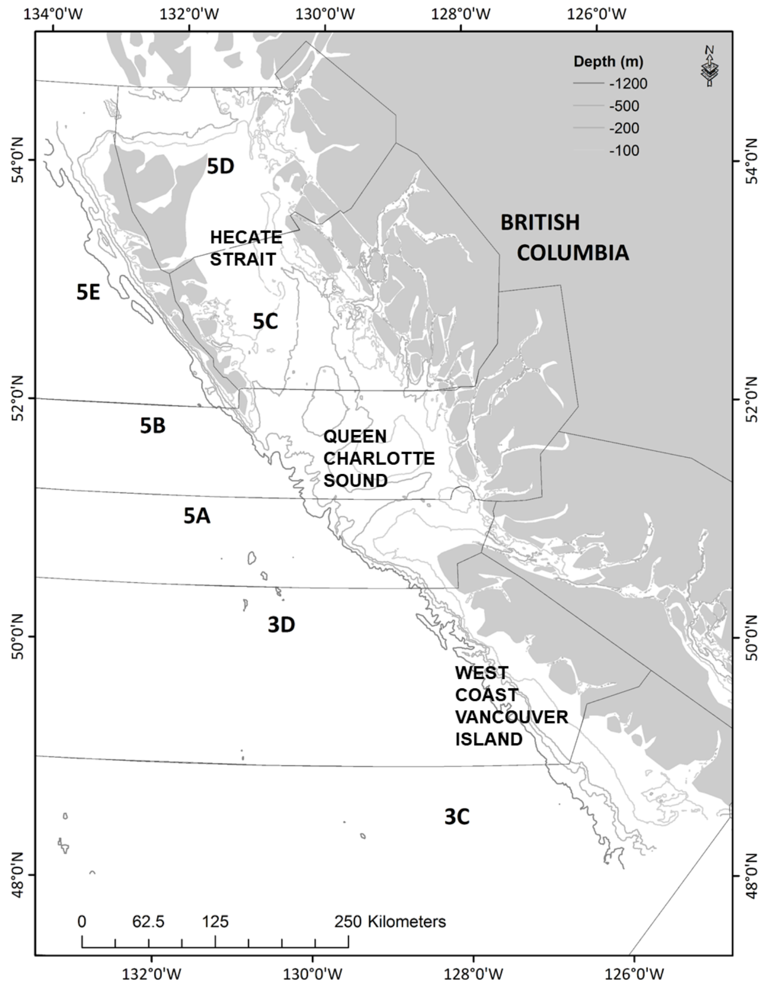

Figure 1. Map showing the management areas 3CD (West Coast Vancouver Island), 5AB (Queen Charlotte Sound), 5CD (Hecate Strait) and 5E (West Coast Haida Gwaii).

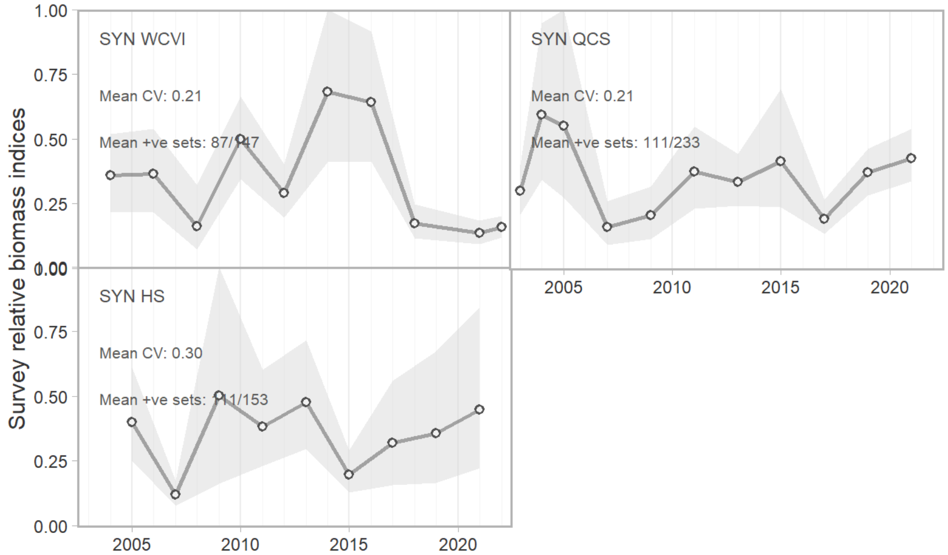

Figure 2. Pacific Cod survey data for Canadian trawl surveys showing relative biomass and associated lower and upper confidence intervals. Positive sets refers to the number of trawl sets that caught Pacific Cod. SYN WCVI = West Coast Vancouver Island synoptic bottom trawl survey; SYN QCS = Queen Charlotte Sound synoptic bottom trawl survey; SYN HS = Hecate Strait synoptic bottom trawl survey. Indices for the QCS and HS synoptic surveys are not included in this assessment but are shown for comparison.

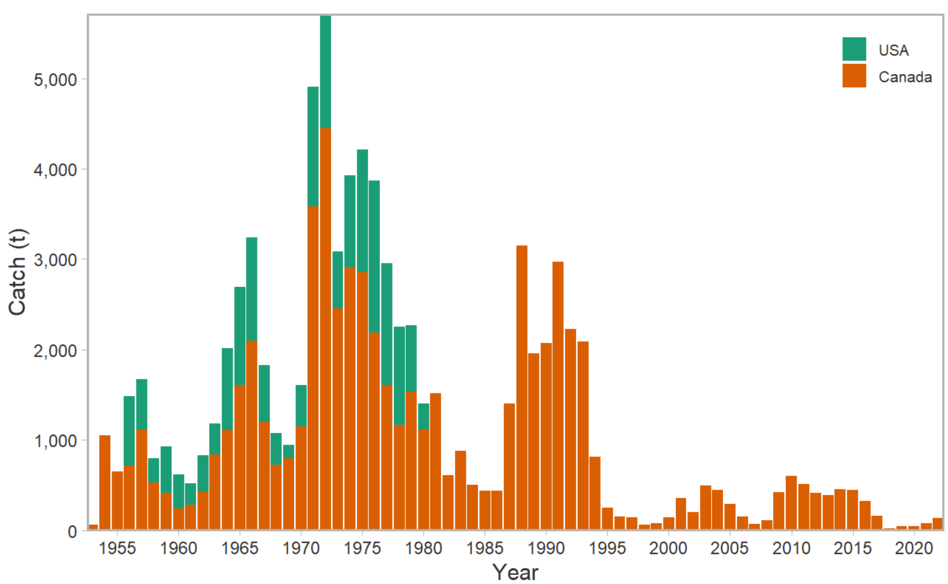

Figure 3. Catch for Area 3CD. Canadian catch includes at-sea discards.

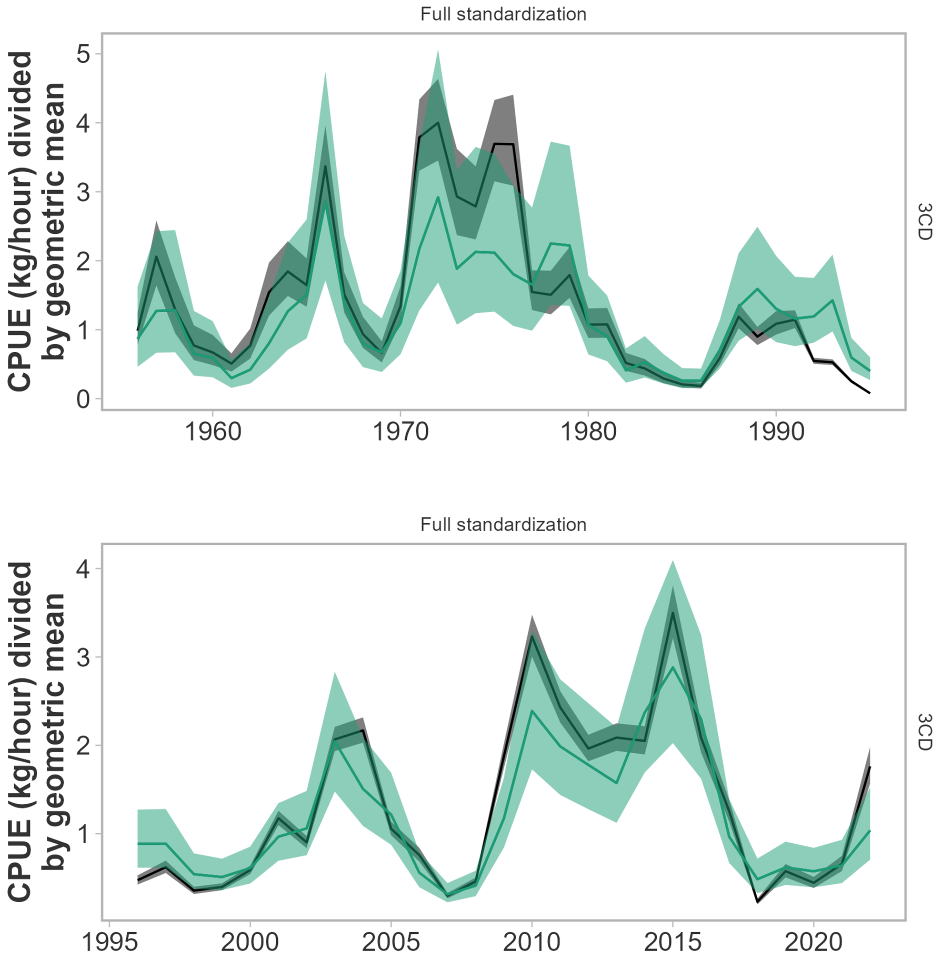

Figure 4. Commercial trawl CPUE standardization models for the historical period, 1956–1995 (top) and the modern period, 1996–2022 (bottom). The black line and shaded region indicate a CPUE index with only a year predictor (shown for comparison, not used in this assessment). The green line and shaded region shows a standardization model that includes all the predictors plus locality-by-year (space-time) random effects. Locality and locality-year interactions are fit as random effects and all other variables are fit as fixed effects.

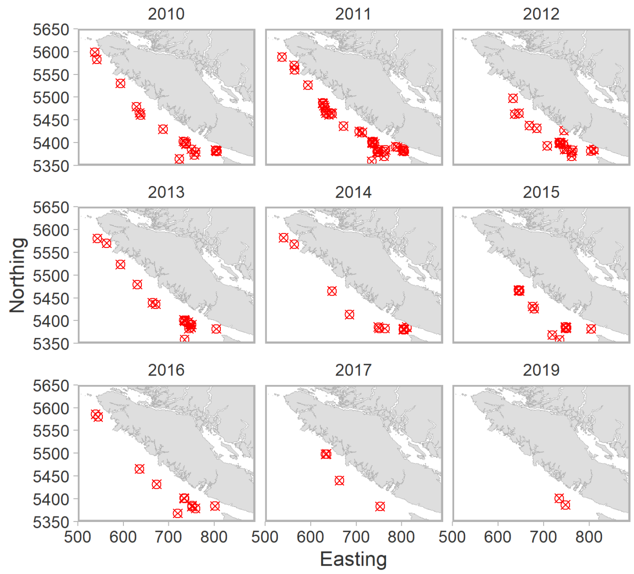

Figure 5. Location of Pacific Cod commercial biological samples by year. The total number of fish sampled in 2017 was 300. The total number sampled in 2019 was 360. See Appendix A for number of samples in other years.

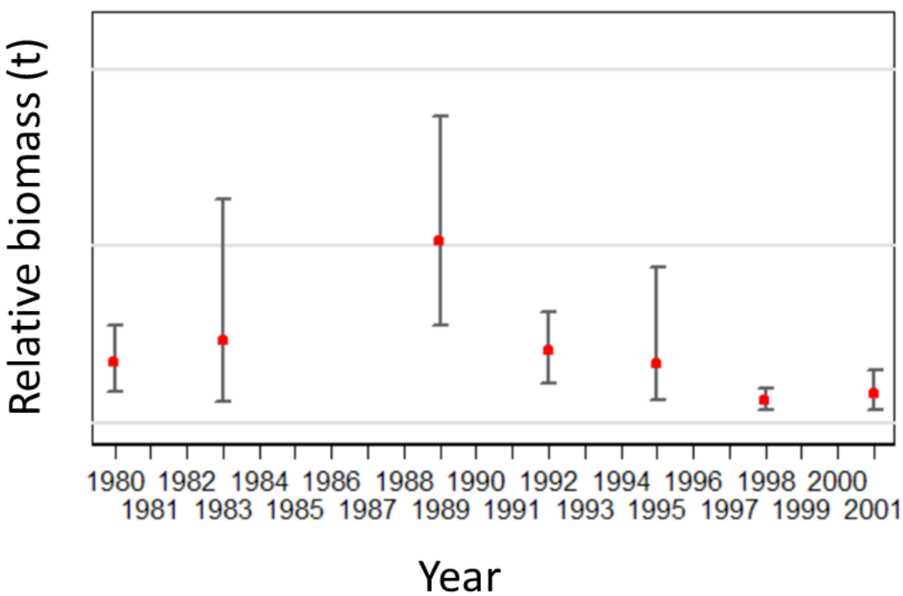

Figure 6. Biomass estimates for Pacific Cod from the NMFS Triennial Survey in the International North Pacific Fisheries Commission Vancouver region (Canadian waters only) with 95% error bars estimated from 1000 bootstraps.

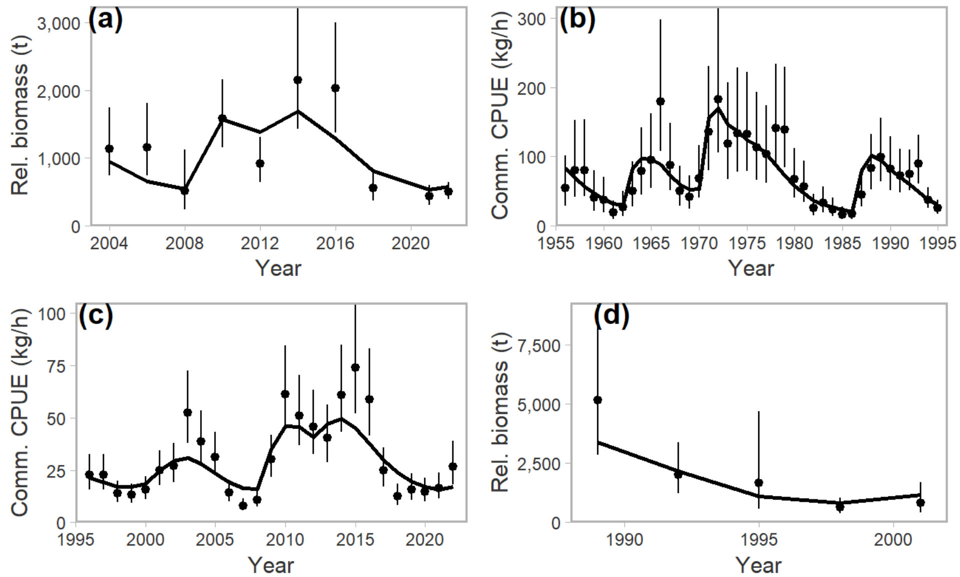

Figure 7. Reference model MPD fits to observed indices of abundance (points) from: (a) the WCVI Synoptic Survey, (b) Commercial CPUE pre-1996, (c) Commercial CPUE post-1995, and (d) the NMFS Triennial Survey (Canadian portion). For clarity, only MPD results are shown.

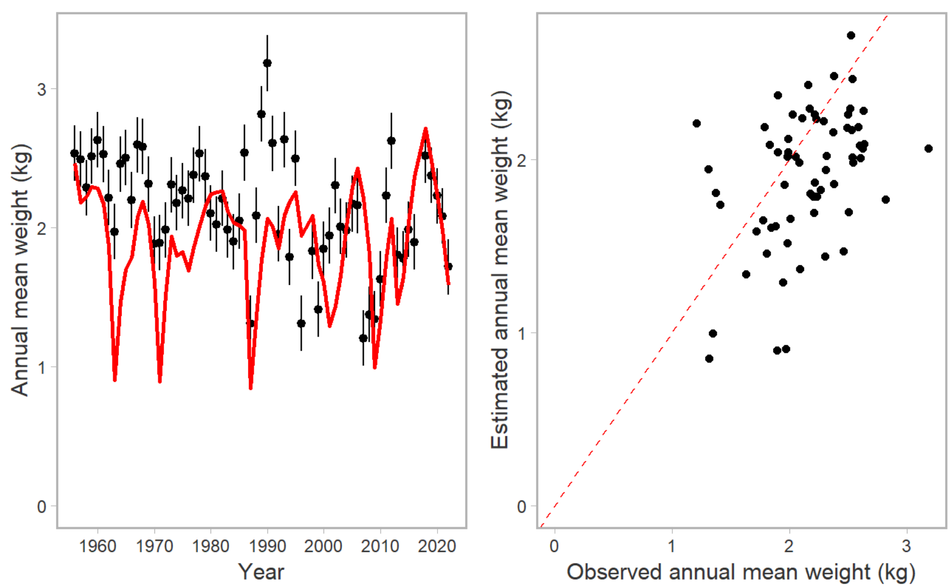

Figure 8. Reference model MPD fit to the mean weight index. For clarity, only MPD results are shown.

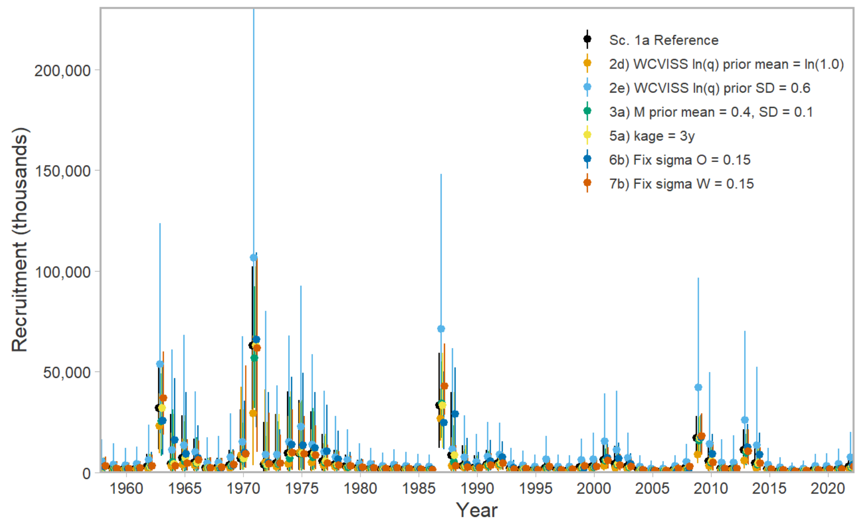

Figure 9. Sensitivity of recruitment estimates to the seven sensitivity cases used for model-averaging. Points shows the posterior medians and the bars represent the 95% credible interval. All models use the same commercial mean weight index used in the Reference model (see Table 9 for values since 2010).

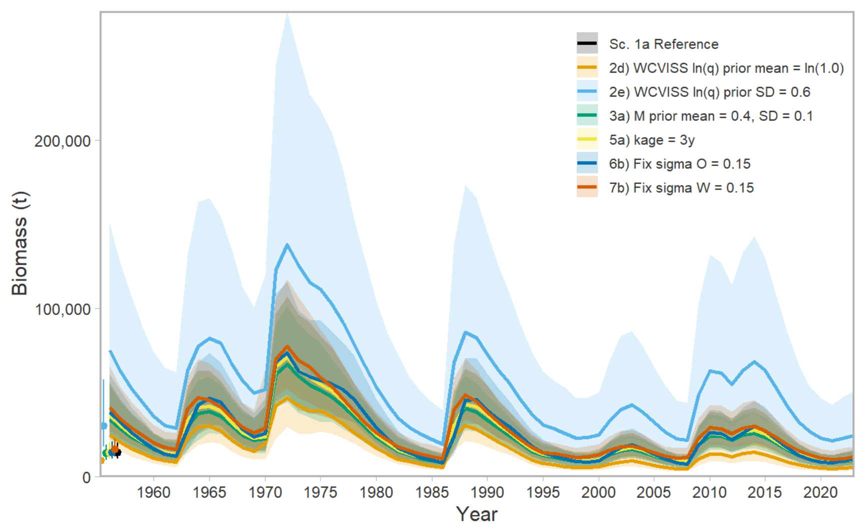

Figure 10. Sensitivity of biomass estimates to the the seven sensitivity cases used for model-averaging. Thick solid lines represent posterior medians and shaded regions represent 95% credible intervals. All models use the same commercial mean weight index used in the Reference model (see Table 9 for values since 2010).

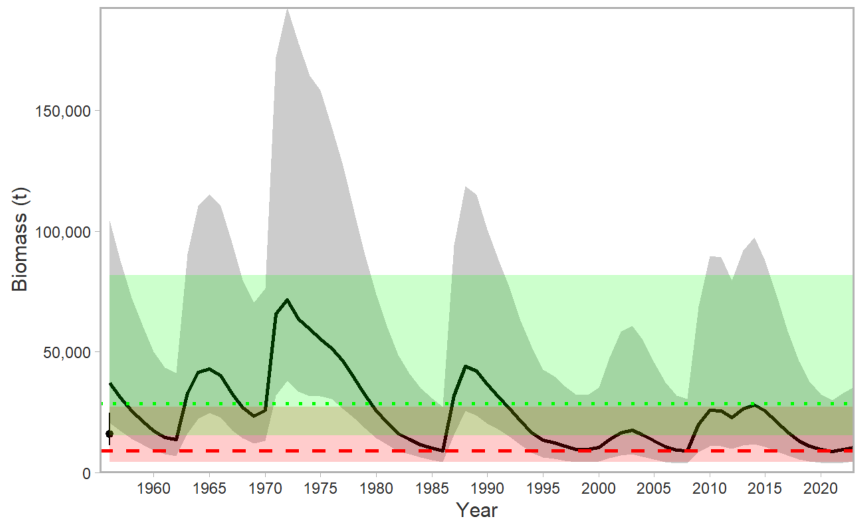

Figure 11. Combined posterior biomass for the model-averaged set. Thick solid line represents the posterior median and the grey shaded region represents the 95% credible interval. Green dotted line shows the median USR; red dashed line shows the median LRP. Red and green shaded intervals represent the 95% credible intervals of the LRP and USR, respectively.

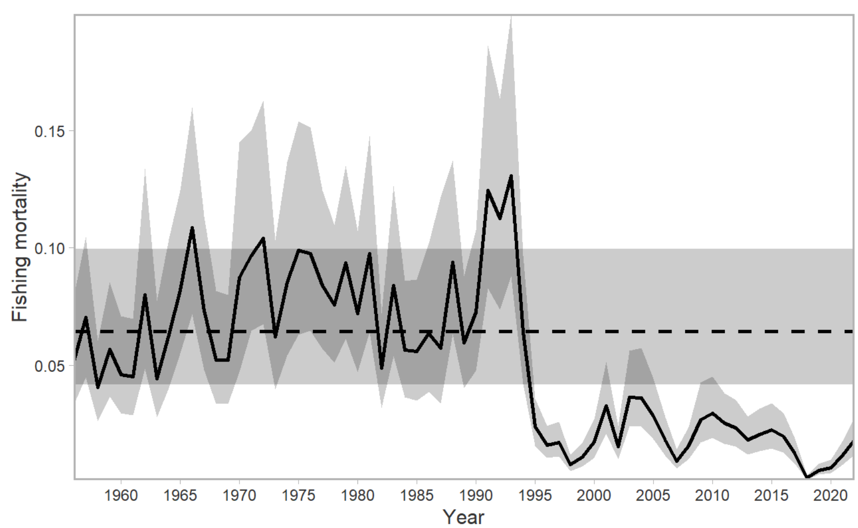

Figure 12. Combined posterior fishing mortality for the model-averaged set. Thick solid line shows the posterior median and the shaded region represents the 95% credible interval. Black dashed line shows the median LRR and the horizontal shaded region represents the 95% credible interval.

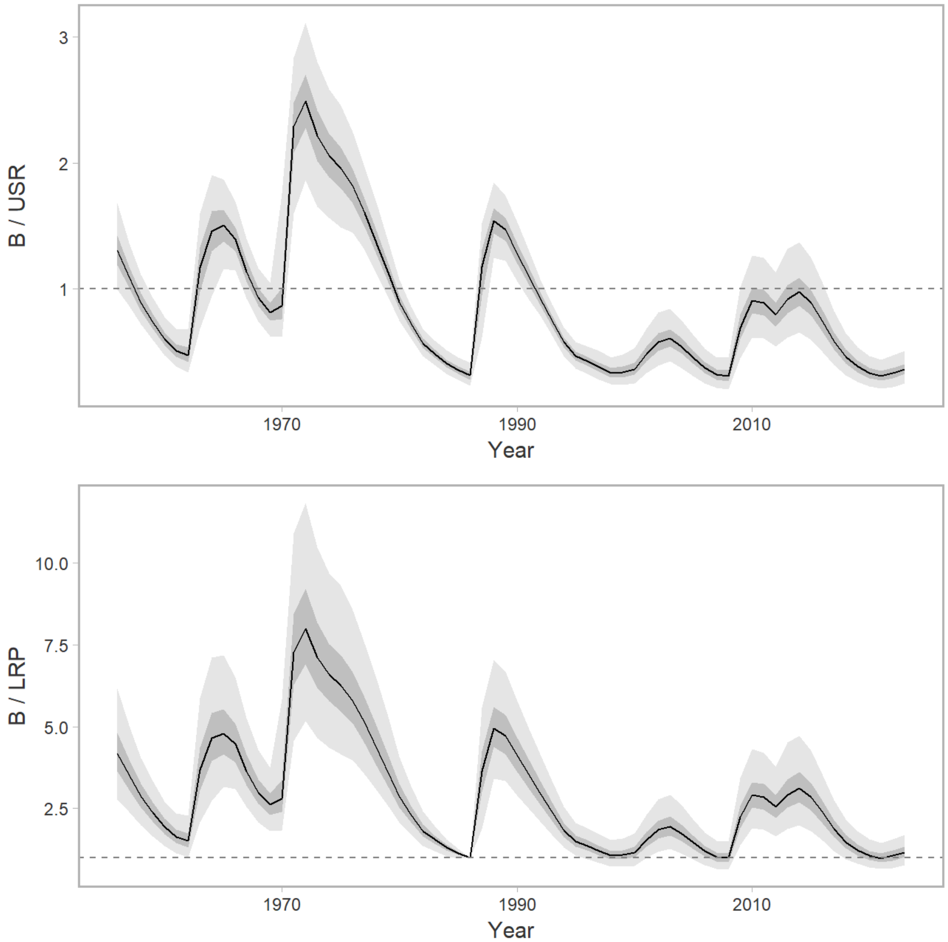

Figure 13. Combined posterior biomass relative to the USR and the LRP for the model-averaged set. Thick solid line shows the posterior median and the grey shaded regions represent the 50% and 95% credible intervals. Horizontal dashed line represents a ratio of 1.

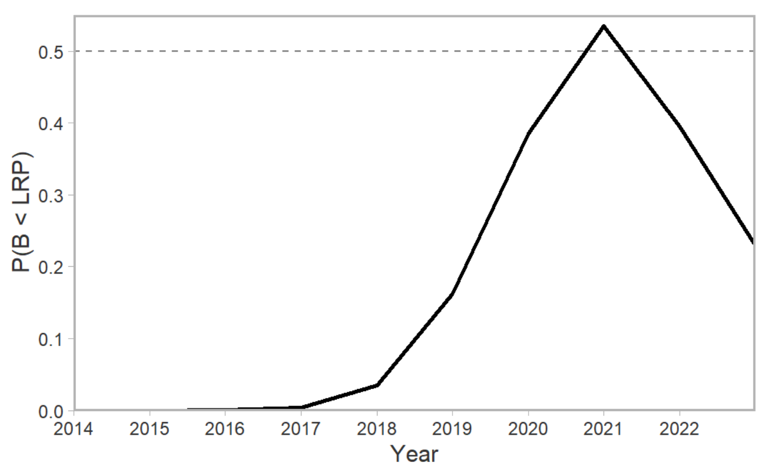

Figure 14. Probability of biomass being below the LRP from 2014 to 2023. The horizontal dashed line shows a threshold of 0.5 probability.

Contributors

Name	Affiliation	Role
Robyn Forrest	DFO Science, Pacific Region	Author
Sean Anderson	DFO Science, Pacific Region	Author
Ian Stewart	International Pacific Halibut Commission	Reviewer
Daniel Ricard	DFO Science, Gulf Region	Reviewer
Dana Haggarty	DFO Science, Pacific Region	Steering Committee
Steven Schut	DFO Science, Pacific Region	Steering Committee

Approved by

Andrew Thomson
Regional Director
Science Branch, Pacific Region
Fisheries and Oceans Canada
November 30, 2023

Sources of Information

Abookire, A.A., Litzow, M.A., Malick, M.J., and Laurel, B.J. 2022. Post-settlement abundance, condition, and survival in a climate-stressed population of Pacific cod. Canadian Journal of Fisheries and Aquatic Sciences 79(6): 958–968.

Anderson, S.C., Forrest, R.E., Huynh, Q.C., and Keppel, E.A. 2021. A management procedure framework for groundfish in British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2021/007. vi + 139.

Barbeaux, S.J., Holsman, K., and Zador, S. 2020. Marine heatwave stress test of ecosystem-based fisheries management in the Gulf of Alaska pacific cod fishery. Front. Mar. Sci. 7.

Deriso, R.B. 1980. Harvesting strategies and parameter estimation for an age-structured model. Can. J. Fish. Aquat. Sci. 37(2): 268–282.

DFO. 2009. A fishery decision-making framework incorporating the Precautionary Approach. (last reportedly modified 23 March, 2009, however, figures have since changed).

DFO. 2019a. Assessment of British Columbia Pacific Cod for areas 3CD, and 5ABCD in 2018. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2019/008.

DFO. 2019b. Widow Rockfish (*Sebastes entomelas*) stock assessment for British Columbia in 2019. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2019/044.

DFO. 2020a. Bocaccio (*Sebastes paucispinis*) stock assessment for British Columbia in 2019, including guidance for rebuilding plans. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2020/025.

DFO. 2020b. Rougheye/Blackspotted Rockfish (*Sebastes aleutianus/melanostictus*) Stock Assessment for British Columbia in 2020. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2020/047.

DFO. 2021. Status update of British Columbia Pacific Cod (*Gadus macrocephalus*) for West Coast Vancouver Island (area 3CD) and Hecate Strait and Queen Charlotte Sound (area 5ABCD) in 2020. DFO Can. Sci. Advis. Sec. Sci. Resp. 2021/002.

DFO. 2023. Pacific Region Integrated Fisheries Management Plan, Groundfish. Effective February 21, 2023. Version 3.1

Forrest, R.E., Rutherford, K.L., Lacko, L., Kronlund, A.R., Starr, P.J., and McClelland, E.K. 2015. Assessment of Pacific Cod (*Gadus macrocephalus*) for Hecate Strait (5CD) and Queen Charlotte Sound (5AB) in 2013. DFO Can. Sci. Advis. Sec. Res. Doc. 2015/052. xii + 197 p.

Forrest, R.E., Holt, K.R., and Kronlund, A.R. 2018. Performance of alternative harvest control rules for two Pacific groundfish stocks with uncertain natural mortality: Bias, robustness and trade-offs. Can. J. Fish. Aquat. Sci. 206: 259–286.

Forrest, R.E., Anderson, S.C., Grandin, C.J., and Starr, P.J. 2020. Assessment of Pacific Cod (*Gadus macrocephalus*) for Hecate Strait and Queen Charlotte Sound (Area 5ABCD), and West Coast Vancouver Island (Area 3CD) in 2018. DFO Can. Sci. Advis. Sec. Res. Doc. 2020/070. v + 216 p.

Fournier, D.A., Skaug, H.J., Ancheta, J., Ianelli, J., Magnusson, A., Maunder, M.N., Nielsen, A., and Sibert, J. 2012. AD Model Builder: Using automatic differentiation for statistical inference of highly parameterized complex nonlinear models. Optim. Methods Softw. 27: 233–249.

Gelman, A., Carlin, J.B., Stern, H.S., Dunson, D.B., Vehtari, A., and Rubin, D.B. 2014. Bayesian Data Analysis. Third Ed. Chapman & Hall, Boca Raton, FL.

Gelman, A., and Rubin, D.B. 1992. Inference from Iterative Simulation Using Multiple Sequences. Statistical Science 7(4): 457–472.

Haist, V., and Fournier, D. 1995. Hecate strait Pacific Cod assessment for 1995 and recommended yield options for 1996. PSARC Working Paper G: 95–3 p.

Haist, V., and Fournier, D. 1998. Hecate strait Pacific Cod assessment for 1998 and recommended yield options for 1999. PSARC Working Paper G: 98–3 p.

Huynh, Q.C., Hordyk, A.R., Forrest, R.E., Porch, C.E., Anderson, S.C., and Carruthers, T.R. 2020. The interim management procedure approach for assessed stocks: Responsive management advice and lower assessment frequency. Fish and Fisheries 21(3): 663–679.

ICES. 2022. ICES technical guidance for harvest control rules and stock assessments for stocks in categories 2 and 3. In Report of ICES Advisory Committee, 2022. ICES Advice 2022, Section 16.4.11.

Laurel, B.J., Abookire, A., Barbeaux, S.J., Almeida, L.Z., Copeman, L.A., Duffy-Anderson, J., Hurst, T.P., Litzow, M.A., Kristiansen, T., Miller, J.A., Palsson, W., Rooney, S., Thalmann, H.L., and Rogers, L.A. 2023. Pacific cod in the Anthropocene: An early life history perspective under changing thermal habitats. Fish and Fisheries: faf.12779.

Laurel, B.J., and Rogers, L.A. 2020. Loss of spawning habitat and prerecruits of Pacific cod during a Gulf of Alaska heatwave. Canadian Journal of Fisheries and Aquatic Sciences 77(4): 644–650.

McCullagh, P., and Nelder, J.A. 1989. Generalized linear models. Chapman & Hall, New York.

Mildenberger, T.K., Berg, C.W., Pedersen, M.W., Kokkalis, A., and Nielsen, J.R. 2019. Time-variant productivity in biomass dynamic models on seasonal and long-term scales. ICES Journal of Marine Science: fsz154.

Starr, P.J., and Haigh, R. 2017. Stock assessment of the coastwide population of Shortspine Thornyhead (*Sebastolobus alascanus*) in 2015 off the British Columbia coast. DFO Can. Sci. Advis. Sec. Res. Doc. 2017/015. ix + 174 p.

Starr, P.J., and Haigh, R. 2021. Walleye Pollock (*Theragra chalcogramma*) stock assessment for British Columbia in 2017. DFO Can. Sci. Advis. Sec. Res. Doc. 2021/004. vii + 265 p.

Stewart, I.J., Forrest, R.E., Grandin, C.J., Hamel, O.S., Hicks, A.C., Martell, S.J.D., and Taylor, I.G. 2011. Status of the Pacific hake (whiting) stock in U.S. and Canadian waters in 2011. Joint U.S. and Canadian Hake Technical Working Group.

Stewart, I.J., and Hicks, A.C. 2016. Assessment of the Pacific halibut (*Hippoglossus stenolepis*) stock at the end of 2016. International Pacific Halibut Commission Report of Assessment and Research Activities: 365–394.

Appendix A. Changes in commercial length sampling

The commercial groundfish bottom trawl fishery is subject to industry-funded, comprehensive 100% at-sea and dockside monitoring programs. Since 2020, there have been no independent at-sea observers deployed on vessels, and therefore the required 100% at-sea monitoring is now achieved through the use of an Electronic Monitoring (EM) system, where multiple cameras are deployed on trawl vessels to capture all activities related to the catching, sorting and discarding of fish. While this has resulted in a fairly seamless continuation of catch data streams, it has resulted in complete cessation of at-sea commercial biosampling. However, even before the switch to EM, there had been a reduction in samping for Pacific Cod, summarized below.

Table 8. Summary of commercial length samples since 1996 for Area 3CD. Mean lengths are not weighted by catch and are presented to visualise declines in sampling effort since 2015.

Year	Num samples	Num lengths	Raw mean length	SD length	SE length
1996	1	174	49.32	5.74	0.44
1998	1	262	54.85	6.85	0.42
1999	6	748	42.56	15.24	0.56
2000	5	927	47.21	17.06	0.56
2001	21	2950	49.14	12.83	0.24
2002	22	2493	56.29	13.95	0.28
2003	22	2658	49.14	13.04	0.25
2004	47	5895	53.29	11.08	0.14
2005	55	6738	53.85	13.33	0.16
2006	11	1099	54.79	11.83	0.36
2007	8	625	38.38	13.32	0.53
2008	10	1076	50.30	9.34	0.28
2009	19	1926	45.19	13.48	0.31
2010	20	2321	48.32	10.88	0.23
2011	43	3907	55.90	9.70	0.16
2012	25	2266	55.95	14.85	0.31
2013	20	1893	49.24	12.94	0.30
2014	17	1373	54.72	10.85	0.29
2015	12	1233	54.69	10.73	0.31
2016	11	882	52.02	11.07	0.37
2017	4	300	63.44	9.46	0.55
2019	2	360	49.56	8.36	0.44

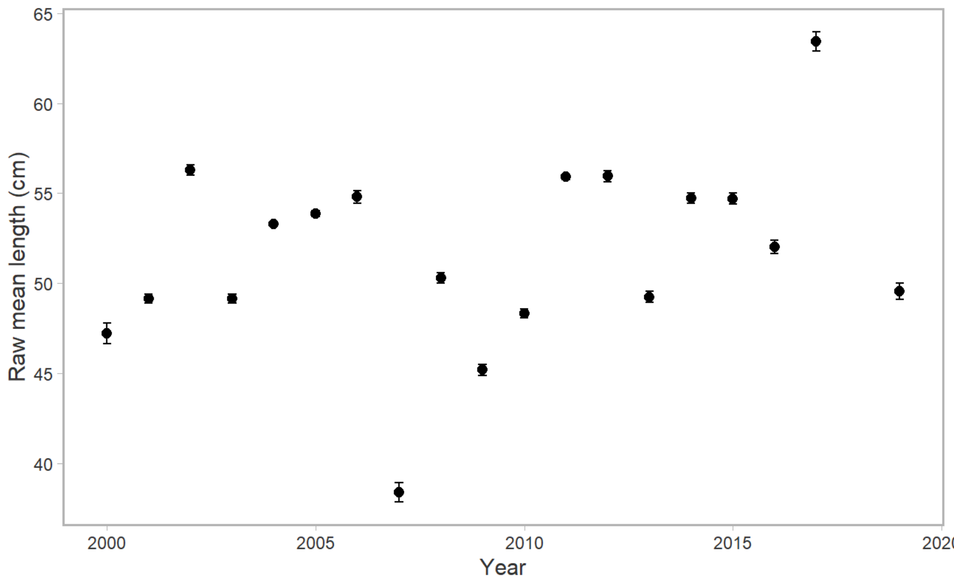

Figure 15. Summary of raw mean lengths in commercial catches since 2000 for Area 3CD, showing the anomalously high value in 2017. Mean lengths are unweighted by catch. Dots represent means and vertical line segments represent plus/minus one standard error (some hidden behind dots).

Appendix B. Developing a survey mean weight index

Methods

For the commercial mean weight index, we followed the steps in Appendix C of Forrest et al. (2020), which described the methodology for weighting the commercial length samples to produce a commercial mean weight index, weighted by sequential quarter and catch weight.

We adapted the approach for the West Coast Vancouver Island Synoptic Survey by replacing weighting by sequential quarter, which was done for the commercial samples, with weighting by depth stratum (Equations 3 and 4). This was done because the survey is depth-stratified.

Note that for the survey mean weight index, we derived weights of individual fish from the measured lengths, using published length-weight parameters (Forrest et al. 2020) rather than using weights that were directly measured (Equation 1). We decided to use weights derived from measured lengths because far more fish were measured than were weighed. This also follows the approach used for the commercial mean weight index.

The calculation of the survey mean weight index was done in the following steps. For simplicity, we have dropped year subscripts.

1. For each specimen i, in each Sample ID j, in each depth stratum s, convert individual length ($L_{i,j,s}$) to weight ($W_{i,j,s}$):

$$W_{i,j,s} = \alpha {L_{i,j,s}}^{\beta} \tag{1}$$

where α and β are constant length-weight parameters, where the values of the length-weight parameters are $\alpha = 0.00000765616$ and $\beta = 3.08$.

2. Calculate the mean weight (W_j) in each sample ID j, in each depth stratum s:

$$W_{j,s} = \frac{\sum\limits_{i=1}^{N_{j,s}} w_{i,j,s}}{N_{j,s}} \tag{2}$$

where $N_{j,s}$ is the number of weights $W_{i,j,s}$ in sample ID j and depth stratum s.

3. Calculate the mean weight (W_s) for each depth stratum s, weighted by the sample weights $S_{j,s}$:

$$W_s = \frac{\sum\limits_{j=1}^{N_s} W_{j,s} S_{j,s}}{\sum\limits_{j=1}^{N_s} S_{j,s}} \tag{3}$$

where N_s is the number of samples in depth stratum s.

4. Calculate the annual survey mean weight (W), weighted by the catch C_s in each stratum s:

$$W = \frac{\sum\limits_{s=1}^{K} W_s C_s}{\sum\limits_{s=1}^{K} C_s} \tag{4}$$

where K is the number of depth strata surveyed in that year.

Results

The commercial mean weight index, calculated using the methods in Appendix C of Forrest et al. (2020) is shown in Figure 16, which also shows the two index values that were removed due to low sampling effort (2017 and 2019, see Appendix A).

Figure 17 shows the relationship between directly observed weights (from weighing individual fish) vs calculated weights (obtained from Equation 1). Figure 18 compares the commercial mean weight index (Figure 16) with the survey mean weight index obtained from Equations 1–4.

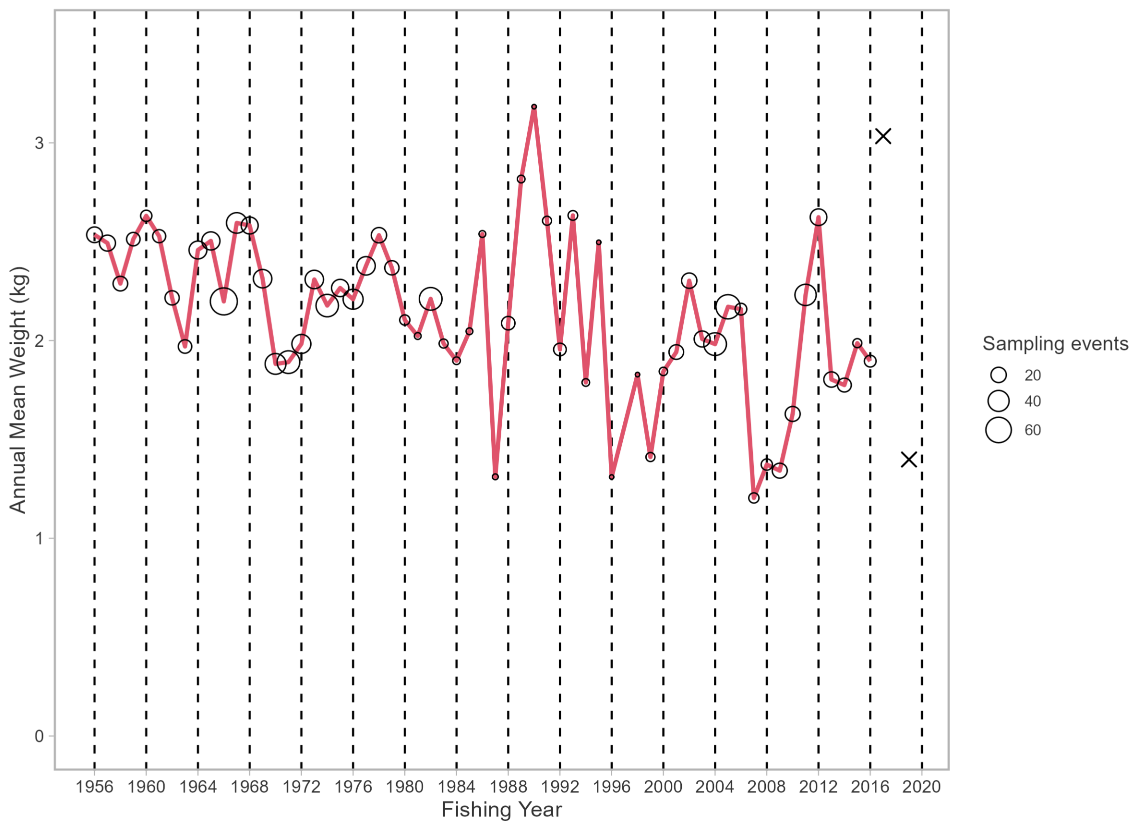

Figure 16. Time series of commercial mean weight series, calculated using methods shown in Forrest et al. (2020). Area of the circles indicates the number of sampling events. Black crosses indicate the 2017 and 2019 index values, which were removed from further analysis due to low sample sizes (see Appendix A).

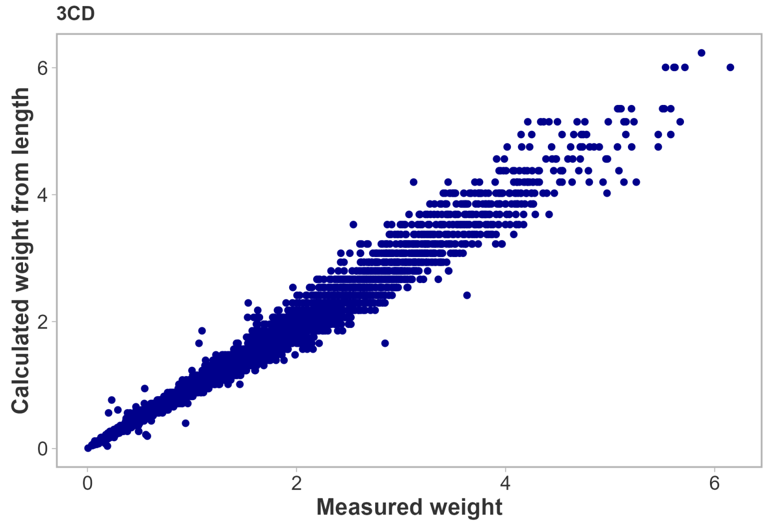

Figure 17. Observed vs. calculated weights from the WCVI survey; all years, all depth strata.

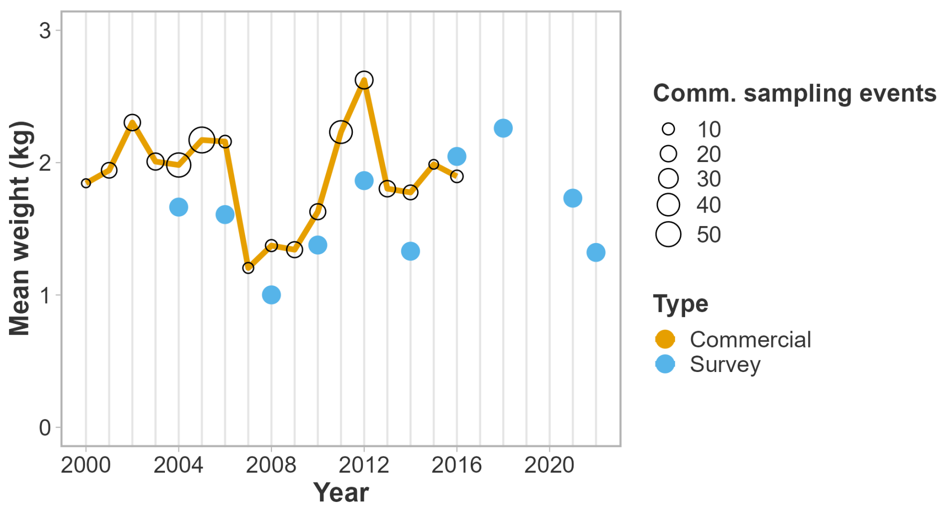

Figure 18. Comparison of the commercial mean weight index (line) and survey mean weight index (points). Area of the commercial circles indicates the number of sampling events. To aid visualization, the commercial mean weight index is truncated to begin in 2000.

Appendix C. Generalized Linear Model to predict commercial mean weight index

Methods

We used a GLM with gamma-distributed observations and a log link (McCullagh and Nelder 1989 p. 292), to estimate commercial mean weights (y_t) in year t from the survey mean weights (W_t) calculated in Appendix B. Our model was fit as

$$y_t \sim \mathrm{Gamma}(\phi, \mu_t/\phi), \tag{5}$$

$$\log(\mu_t) = \beta_0 + \beta_1 \log(W_t), \tag{6}$$

where μ_t represents the expected value at time t, β_0 and β_1 represent an intercept and slope, ϕ represents the gamma shape parameter, and the term μ_t/ϕ represents the gamma scale. The shape parameter can be reparameterized into the coefficient of variation (CV) as $\phi = 1/\mathrm{CV}^2$ or $\mathrm{CV} = 1/\sqrt{\phi}$.

Results

Figure 19 shows the commercial mean weight index plotted against the survey mean weight index, with the linear regression line. The GLM estimated an intercept (β_0) of 0.34 (95% CI: 0.13–0.57), or 1.41 kg (95% CI: 1.14–1.76 kg) in natural space (Figure 19). The model estimated β_1 as 0.75 (95% CI: 0.25–1.17), meaning a 1% increase in survey mean weight was associated with a 0.75% (95% CI: 0.25%–1.17%) increase in commercial mean weight (Figure 19). The CV was estimated as 0.12. A quantile-quantile plot of residuals transformed to have a Normal(0, 1) distribution if the model were consistent with the data did not reveal any substantial deviations from the expectation (Figure 20).

Figure 21 shows time series of all three indices: the survey mean weight index, the observed commercial mean weight index, and the predicted commercial mean weight index from the GLM, indicating good agreement between the commercial and survey mean weight indices. The predicted commercial mean weights fit the observed commercial mean weights almost perfectly between 2004 and 2010, and in 2014. The predictions underestimated the observed commercial index in 2012 and overestimated the commercial index in 2016.

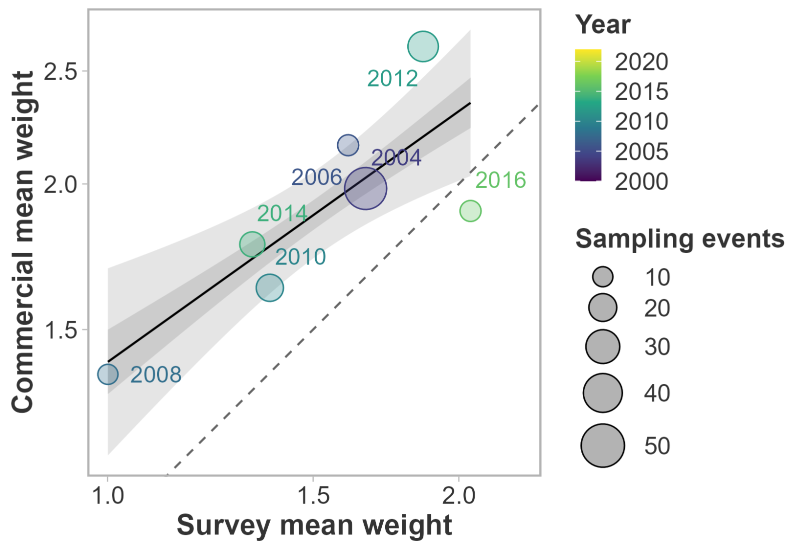

Figure 19. Commercial mean weight index vs. survey mean weight index. The solid line indicates the GLM mean; the dark and light grey shading indicates 50% and 95% confidence intervals. The area of the circles indicates the number of sampling events and the colour indicates the year. The diagonal line indicates a one-to-one relationship.

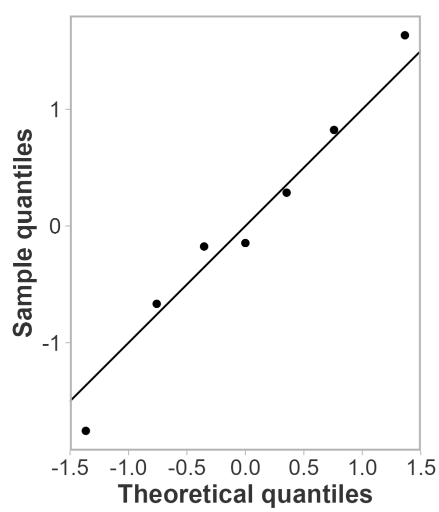

Figure 20. Quantile-quantile plot of the GLM predicting commercial mean weight from survey mean weight. The residuals have been transformed to be Normal(0, 1) if the model were consistent with the data. The line indicates the one-to-one line.

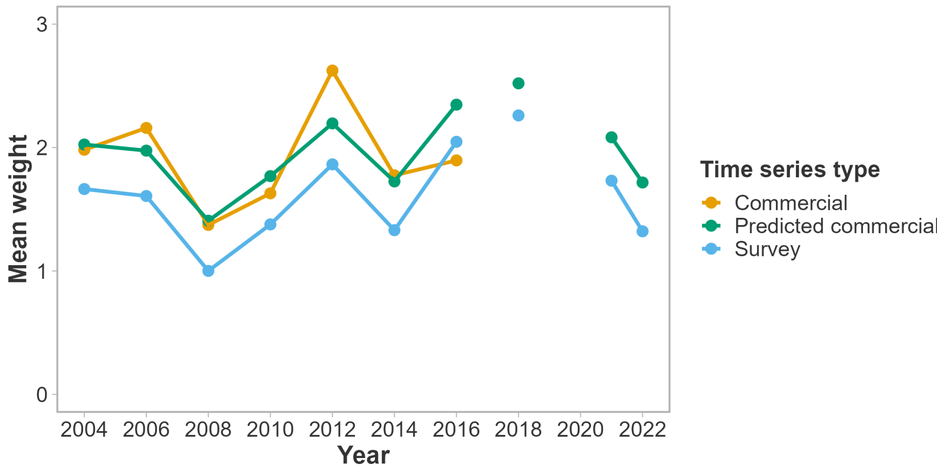

Figure 21. Comparison of the survey mean weight index, observed commercial mean weight index, and predicted commercial mean weight index from the GLM. For visualization purposes, the observed commercial mean weight index is truncated to begin in 2004, which is the year of the first WCVI Synoptic Survey.

Appendix D. Model sensitivity to treatment of the mean weight index

Four scenarios were evaluated to investigate the sensitivity of the stock assessment model to different treatments of the commercial annual mean weight index. All models were based on the Reference model. All scenarios used the commercial annual mean weight index derived from commercial length samples for the years 1956–2016. There was no 2017 index point in any scenario, as in previous assessments.

The four different scenarios are:

Sc. 1a Reference: For 2018–2022, use the GLM predicted values for 2018, 2021 and 2022. Use linear interpolation between 2018 and 2021 to fill in values for 2019 and 2020. This scenario was used as the basis for all models for evaluation of stock status in 2023 (see main body of this document).

Sc. 2: For 2018–2022, use the GLM predicted values for 2018, 2021 and 2022. Do not include interpolated values for 2019 and 2020.

Sc. 3: For the last seven years of the time series, use the same approach as in the 2020 assessment (DFO 2021), i.e, use the commercial mean weight index values for 2016, 2019 and 2020, where the 2020 value was set the same as the 2019 value. Continue to use the 2019 value for 2021 and 2022.

Sc. 4: Same as Sc. 3 but do not include any values for 2021 and 2022.

Values of the index since 2010 are provided in Table 9.

Table 9. Comparison of mean weight values used in the four commercial mean weight index scenarios. For clarity, the series is truncated to start in 2010.

Year	Sc. 1a Reference	Sc. 2	Sc. 3	Sc. 4
2010	1.629	1.629	1.629	1.629
2011	2.231	2.231	2.231	2.231
2012	2.624	2.624	2.624	2.624
2013	1.803	1.803	1.803	1.803
2014	1.775	1.775	1.775	1.775
2015	1.987	1.987	1.987	1.987
2016	1.896	1.896	1.896	1.896
2017	NA	NA	NA	NA
2018	2.520	2.520	NA	NA
2019	2.375	NA	1.399	1.399
2020	2.229	NA	1.399	1.399
2021	2.083	2.083	1.399	NA
2022	1.717	1.717	1.399	NA

Maximum posterior density (MPD) model fits to the commercial mean weight index from the four scenarios are shown in Figure 8 and Figures 22 to 24. As in the Reference model (Figure 8), fits to the mean weight index in the alternative scenarios were generally poor for the early part of the time series, with the models tending to underestimate observed mean weight for years prior to at-sea monitoring.

The models that used the GLM index values from 2018 onwards (Sc. 1a Reference and 2) fit the commercial mean weight index well (Figures 8 and 22). The fit was similar for scenarios both with and without interpolation in 2019–2020. The models without GLM values (Sc. 3 and 4) had a poor fit to the commercial mean weight index from 2018 onwards (Figures 23 and 24). In these scenarios, the model-predicted commercial mean weights followed a similar pattern to those in Sc. 1 and 2, with a peak in 2018, followed by a decline.

This pattern is consistent with predicted recruitment from all four models (Figure 25), which estimated low recruitment between 2016 and 2018. A population with fewer recruits is expected to have a higher than average mean weight of individuals. The models estimated an increase in recruitment between 2019 and 2022, which would explain the subsequent estimated decline in commercial mean weight. All four models showed a similar recruitment pattern, from which we infer that the other data sources in the model had a greater influence on model likelihoods than the commercial mean weight index, i.e., the declines in the survey index, commercial catches and commercial CPUE all pointed to low recruitment and higher mean weight in 2018 (Figures 2 to 4). Based on this finding, we suggest that the survey mean weight index, used to derive the commercial index in Sc. 1 and 2, is consistent with the other data sources and better indexes underlying mean weight patterns than simply extrapolating the mean weight index from 2019, as in Sc. 3 and 4.

Posterior biomass estimates from the four scenarios are shown in Figure 26, indicating that all four models estimated a similar pattern in biomass. Given the consistency of the GLM-derived commercial mean weight index with other data sources, and the small differences in biomass estimates among scenarios, the first scenario (Sc. 1a Reference) was used as the Reference model, and as the basis for the other six models in the model-averaged set.

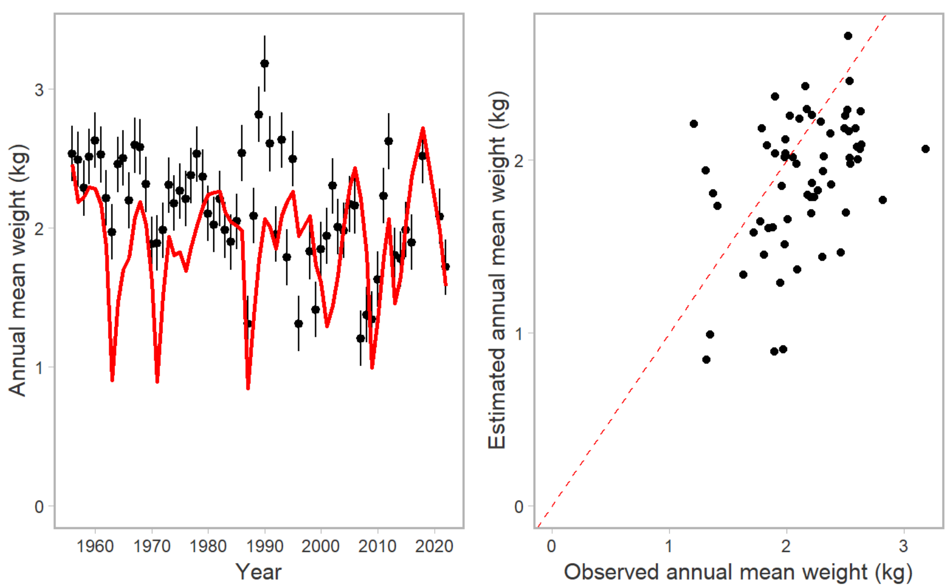

Figure 22. Scenario 2 model MPD fit to the mean weight data. See Methods for scenario descriptions.

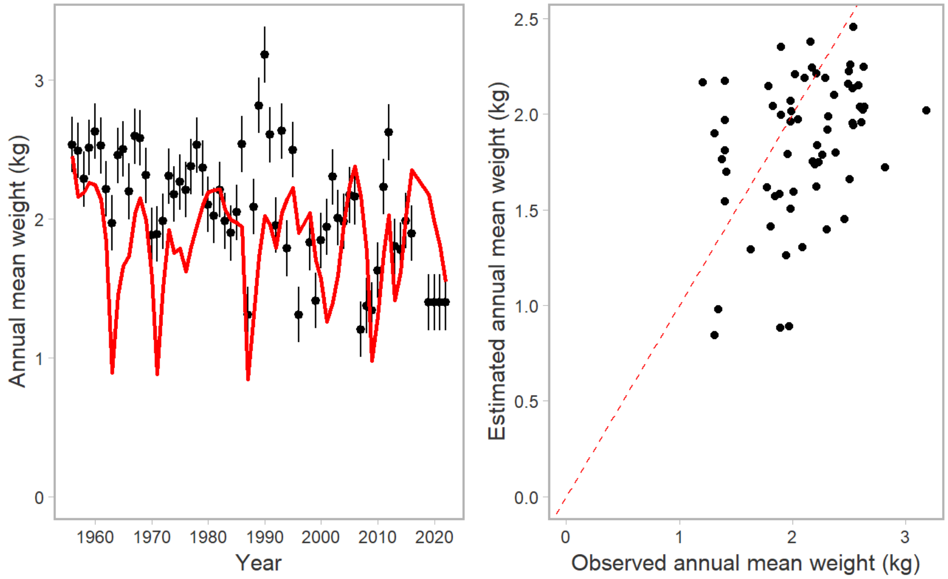

Figure 23. Scenario 3 model MPD fit to the mean weight data. See Methods for scenario descriptions.

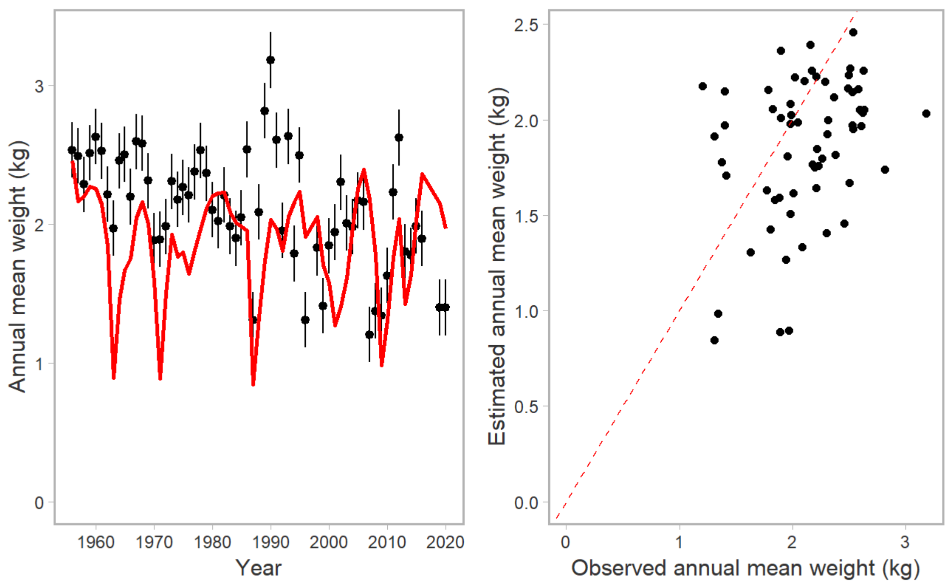

Figure 24. Scenario 4 model MPD fit to the mean weight data. See Methods for scenario descriptions.

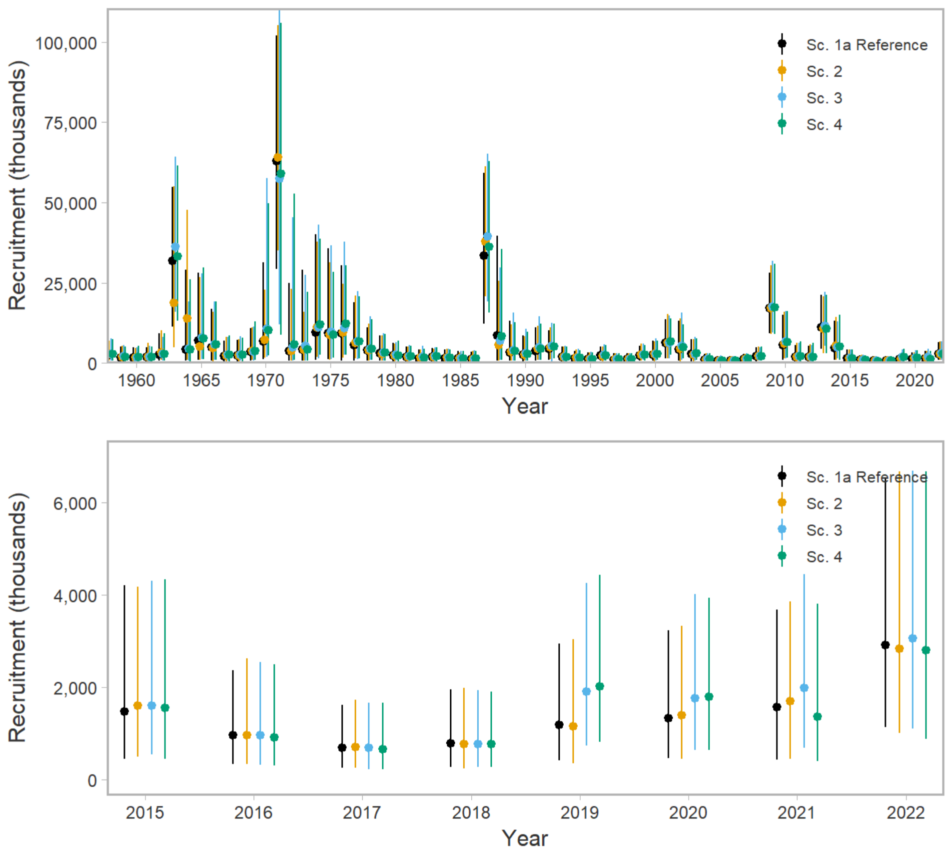

Figure 25. Sensitivity of recruitment estimates to commercial mean weight scenarios. Points shows the posterior medians and the bars represent the 95% credible intervals. See Methods for scenario descriptions. The lower panel is zoomed in to 2015–2022.

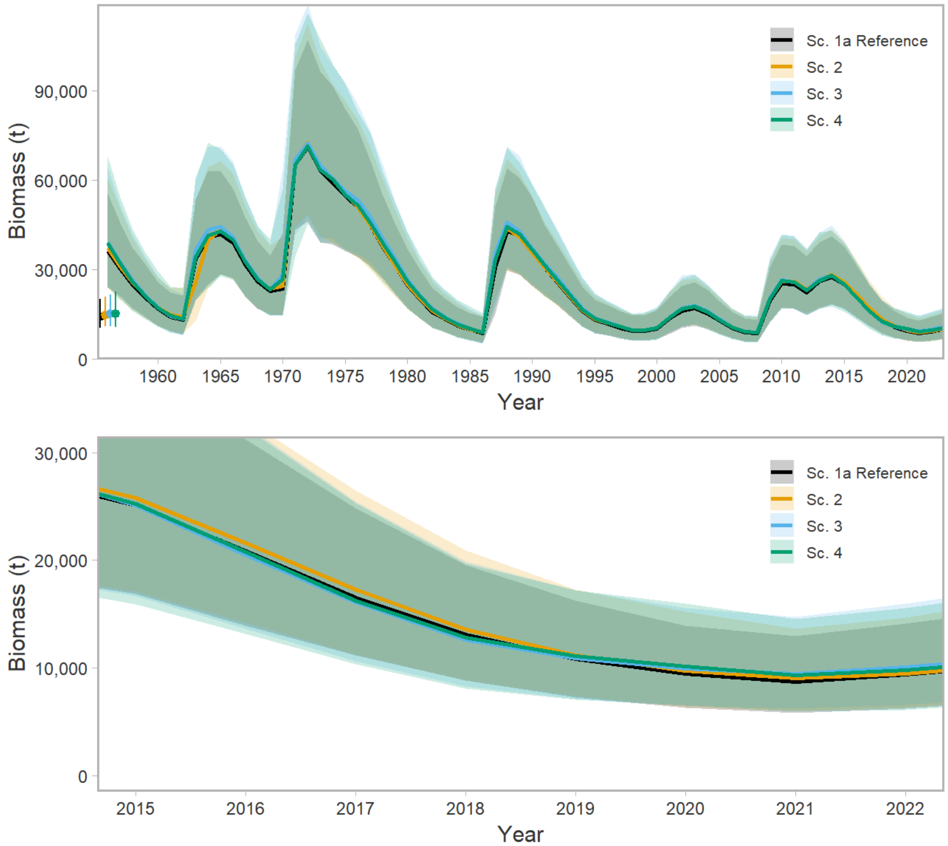

Figure 26. Sensitivity of biomass estimates to commercial mean weight scenarios. Thick solid lines shows posterior medians and the grey shaded regions represent 95% credible intervals. See Methods for scenario descriptions. The lower panel is zoomed in to 2015–2022.

This Report is Available from the:

Centre for Science Advice (CSA)
Pacific Region
Fisheries and Oceans Canada
3190 Hammond Bay Rd.
Nanaimo, BC V9T 6N7

E-mail: DFO.PacificCSA-CASPacifique.MPO@dfo-mpo.gc.ca
Internet address: www.dfo-mpo.gc.ca/csas-sccs/

ISSN 1919-3769
ISBN 978-0-660-69206-7 Cat No. Fs70-7/2024-003E-PDF

Correct Citation for this Publication:

DFO. 2024. Status Update of Pacific Cod (*Gadus macrocephalus*) off the West Coast of Vancouver Island in 2023. DFO Can. Sci. Advis. Sec. Sci. Resp. 2024/003.

Aussi disponible en français :

*MPO. 2024. Mise à jour sur l’état des stocks de morues du Pacifique (*Gadus macrocephalus*) au large de la côte ouest de l’île de Vancouver en 2023. Secr. can. des avis sci. du MPO. Rép. des Sci. 2024/003.*