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STATUS UPDATE OF PACIFIC COD (*GADUS MACROCEPHALUS*) FOR WEST COAST VANCOUVER ISLAND (AREA 3CD), AND HECATE STRAIT AND QUEEN CHARLOTTE SOUND (AREA 5ABCD) IN 2020

Context

The last assessment for Pacific Cod (*Gadus macrocephalus*) in British Columbia (BC) was completed in 2018 (DFO 2019a; Forrest et al. 2020). Separate assessments were undertaken for stocks in Area 3CD (West Coast Vancouver Island, WCVI) and Area 5ABCD (consisting of Queen Charlotte Sound (QCS) and Hecate Strait (HS) combined) (Figure 1). Both the 3CD and 5ABCD stocks were assessed to be in the Cautious Zone (DFO 2009).

Fishery-independent synoptic bottom trawl surveys are conducted biennially in BC, usually occurring in even-numbered years for WCVI, and odd-numbered years in QCS and HS. However, due to the coronavirus disease 2019 (COVID-19) pandemic, the scheduled 2020 WCVI survey did not occur. The 2018 survey index for WCVI was very low, at approximately 26–27% of the magnitude of the 2014 and 2016 observations (Figure 2). The commercial catch per unit effort (CPUE) index has also decreased since 2016 (Figure 2). Catches in 2018 and 2019 in Area 3CD were also much lower than previous years (Table 1, Figure 3).

The previous advice (DFO 2019a) recommended assessment updates in each area be provided in years immediately following the biennial groundfish synoptic bottom trawl survey (i.e., when the most recent survey index point is available). However, given the low 2018 index of abundance in Area 3CD, coupled with the lack of updated survey information in 2020, Fisheries and Oceans Canada (DFO) Pacific Fisheries Management Branch has requested that DFO Pacific Science Branch assess the status of both BC Pacific Cod stocks in 2020 and recommend harvest advice for 2021 to inform the development of the 2020/2021 Integrated Fisheries Management Plan.

This Science Response reports results from the Science Response Process of October 2020 on the Stock Assessment Update of British Columbia Pacific Cod for Areas 3CD, and 5ABCD in 2020.

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).

This assessment provides science advice for the stocks in Queen Charlotte Sound combined with Hecate Strait (5ABCD) and West Coast Vancouver Island (3CD) (Figure 1). The choice to combine Areas 5AB and 5CD was made during the 2018 assessment (DFO 2019a), mainly due to poor model diagnostics and the lack of historical fishery-independent indices of abundance for the Area 5AB model in the 2013 assessment (Forrest et al. 2015). There is also no evidence for genetic distinction between these two stocks (Forrest et al. 2015).

Description of the fishery

Pacific Cod in BC are caught almost entirely in the groundfish bottom trawl fishery, which is part of BC's integrated groundfish fishery (DFO 2017). They are caught in small quantities in the groundfish longline fishery (around 0.5% of the total annual catch on average), which is also part of the integrated fishery. The depth range of capture in 5ABCD ranges from around 60–200 m, with data showing a shift to deeper depths since 1996 (Forrest et al. 2020). Currently, the majority of the BC Pacific Cod catch is taken in Area 5CD. Commercial catches also come from Area 5AB and Area 3CD. Near negligible catch is taken from the west coast of Haida Gwaii, Area 5E (< 0.5% of total average annual catch since 1985). The BC integrated fishery is subject to 100% at-sea and dockside monitoring. Since 1996, all bottom trawl vessels have carried observers who record the catch of each species and estimate quantities of released (discarded) fish.

Analysis and Response

Data

Data were extracted from DFO databases using methods described in Forrest et al. (2020). Biological data from fishery-independent and commercial fishery sources were available up until 2019. Catch data were updated to 2020, with data extrapolated from October 1, 2020 to the end of the fishing year (see below). For each area, models were fit to the following data: commercial catch, fishery-independent indices of abundance, commercial catch per unit effort (CPUE), and annual mean weight of fish in the commercial catch.

Commercial catch

Commercial catch data (Tables 1 and 2, Figures 3 and 4) 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 2020). Catch data prior to 1981 include catch by US vessels (Forrest et al. 2015, 2020). Fishing years are defined as beginning on April 1 for all years, and are referenced by starting year, e.g., fishing year 1957 runs from April 1, 1957 to March 31, 1958 (see Forrest et al. 2020).

Prior to the introduction of at-sea observer coverage in 1996, estimates of discards for the period 1956–1995 were obtained from fishing logbooks in the absence of at-sea observers. Pre-1996 discards are, therefore, a major source of uncertainty in this assessment. Estimates in years following the introduction of 100% at-sea observer coverage in 1996 are considered to be accurate. Pacific Cod can be legally discarded by trawlers in BC. However, on-board observers first estimate the quantity being discarded, which is counted against the quota. Therefore, in addition to greater accuracy in reporting of discards since 1996, incentives to avoid discarding have also been greater.

At the time of the assessment, the 2020 fishing year was incomplete. In order to provide projections for the 2021 fishing season, the 2020 catch (landings + discards) was extrapolated in each area, using the three-year average proportion of catch taken by September 30 (representing the end of the second quarter of the 2020 fishing year). This proportion was used to extrapolate from the catch at September 30, 2020 to a total estimated catch for the 2020 fishing year (Tables 1 and 2). In Area 3CD, the average proportion was 67.4% (average of 85.6%. 46.2% and 70.5% for the 2017, 2018, and 2019 fishing years, respectively). In area 5ABCD, the average proportion was 87.8% (average of 88.6%. 82.7% and 92.1% for the 2017, 2018, and 2019 fishing years, respectively). In Area 3CD, the average proportion of catch taken by September 30 has been inconsistent in recent years and therefore the 2020 extrapolation should be considered uncertain. However, the magnitude of the catch in the past three years has been low, and the 2020 catch is expected to have a minor impact on 2021 catch advice. In addition, 2020 catch patterns in both areas may be atypical due to the COVID-19 pandemic.

Canadian bottom trawl surveys

Survey indices (Table 3 and Figure 5) were calculated using a swept area analysis, documented in Appendix A of Forrest et al. (2020). Abundance in Area 3CD (Figure 1) is indexed by the WCVI Synoptic Survey. The survey was first conducted in 2004 and is conducted in alternating (even-numbered) years. Due to the COVID-19 pandemic there was no survey in 2020. Abundance in Area 5AB (Figure 1) is indexed by the QCS Synoptic Survey. The survey was first conducted in 2003 and 2004, and then in odd years since 2005. Abundance in Area 5CD (Figure 1) was indexed by the HS Multispecies Assemblage Survey in 1984, 1987, 1989, 1991, 1993, 1995, 1996, 1998, 2000, 2002, and 2003. Since 2005, it has been indexed in odd-numbered years by the HS Synoptic Survey. Details on spatial extent and depth strata of all surveys are provided in Appendix A of Forrest et al. (2020).

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 (Figures 7 and 8). The indices were developed using a Tweedie generalized linear mixed 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 (Figure 7). The modern-period GLMMs included predictors for depth, latitude, locality, month, vessel, and a locality-year interaction (Figure 8).

Annual mean weight in commercial catch

Annual mean weight in the commercial catch was calculated using the methodology decribed in Appendix C of Forrest et al. (2020). Commercial biological samples were available for calculating mean weight from 1956 to 2019. In the absence of available commercial biological samples for 2020, the annual mean weight for 2020 was assumed the same as 2019.

Stock assessment model

The current stock assessment model is a Bayesian delay-difference model (Deriso 1980), fit to survey indices, commercial CPUE, commercial catch data and commercial annual mean weights (Forrest et al. 2015, 2020). A full stock assessment history for both stocks is provided in Forrest et al. (2020). The current 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) (see also Tables 4 and 5, this document).

Forrest et al. (2015) and Forrest et al. (2020) used a model-averaging approach to construct decision tables based on combined posterior samples from several sensitivity cases. This was to address some of the key irresolvable uncertainties associated with the stock assessment. Major axes of uncertainty were 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). Details are provided in the model scenarios section. Other stock assessments that have used a model-averaging approach are 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 three assessments of BC *Sebastes* stocks (DFO 2019b, 2020a, 2020b).

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;
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 the 2018 assessment (DFO 2019a), historical reference points were used to assess stock status, where

1. The USR is the historical 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 5ABCD this is the estimated biomass in 2000. For Area 3CD it is the estimated biomass in 1986.
3. The LRR is the average fishing mortality rate 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 simulation-testing of historical reference points for the 5CD stock of Pacific Cod.

Model scenarios

Reference case models were established for Areas 3CD and 5ABCD to represent what were considered the most plausible choices across a range of assumptions for each stock. The Reference models for Areas 3CD and 5ABCD shared similar characteristics to each other in terms of data choices, prior probability distributions and fixed parameter settings. Key characteristics of the models are provided in Tables 4 and 5. For further details, see Forrest et al. (2020). These models served as the basis from which sensitivity scenarios were developed, altering alternative model assumptions one at a time. A set of model scenarios for each stock was agreed upon at the Canadian Science Advisory Secretariat (CSAS) Regional Peer Review (RPR) meeting for model averaging in the 2018 assessment (DFO 2019a). The same sets were used here (updated with catch data to 2020 and index data to 2019 where available). Full details on the model configurations and assumptions for each scenario are provided in Forrest et al. (2020).

Area 3CD

For Area 3CD, 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 $\ln(q)$ = $\ln(1.0)$;
3. Sc 2e Increase the standard deviation (SD) for synoptic survey $\ln(q)$ to 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 $\sigma_W = 0.15$.

Area 5ABCD

For Area 5ABCD, the scenarios 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 surveys $\ln(q)$ = $\ln(1.0)$ (pro-rated by depth-stratum areas of Area 5AB and 5CD);
3. Sc 2e Increase the standard deviation (SD) for synoptic survey $\ln(q)$ to 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 $\sigma_W = 0.15$.

Reference model results

Results are presented from the two reference case models, to demonstrate model performance and to provide comparison with the 2018 stock assessment. Advice, presented in the next section, is based on combined model results in each area.

For both areas, the joint posterior distribution for each model was 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 samples were dropped to allow for sufficient burn-in).

Model convergence was informed by visual inspection of trace and autocorrelation plots (not shown), and the statistics $\hat{R}$, the potential scale reduction statistic, which should approach 1.0 as the chains are consistent with convergence, and n_{eff}, which measures the effective number of MCMC independent samples after accounting for autocorrelation (Gelman and Rubin 1992; Gelman et al. 2014; see descriptions in Forrest et al. 2020).

Area 3CD

Reference case 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 6). 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 9. The reference model followed the trends of the two fishery-independent indices (Figure 9a and d), but did not closely fit the 2012, 2014 and 2016 data points in WCVI Synoptic survey (Figure 9a). This 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 9b), it did not capture all the peaks in the modern series (Figure 9c). Fits such as this tend to occur when there is no other information (such as age composition data or contrasting mean weight data) to help resolve large fluctuations in observed indices.

Forrest et al. (2015) and 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 a number of sensitivity analyses to treatment of the observation error parameter σ_O, one of which is included in the model-averaging set in each area (Sc 6b).

As in the 2018 assessment (Forrest et al. 2020), the model tended to underestimate annual mean weight, especially in the early part of the time series (Figure 10). This is most likely because most of the length measurements in this part of the time series came from fish classified as “keepers”, i.e., not released at sea (see Forrest et al. (2015) for discussion of this issue for the Area 5AB and 5CD stocks). Smaller, released 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 in each area (Sc 7b).

Reference model parameter estimates are shown in Table 6. Notably, the median estimated value of natural mortality, M, was 0.45 y^{-1} (0.41–0.49 y^{-1}) in the current assessment (Table 6), compared to 0.42 y^{-1} (0.39–0.46 y^{-1}) in 2018 (Forrest et al. 2020). Values in parentheses here and elsewhere refer to lower and upper bounds of the 95% credible interval. The larger 2020 estimates of M suggest that the model is partially explaining the decreased biomass through greater natural mortality, although there was considerable overlap between the current and 2018 credible intervals.

Area 5ABCD

As for Area 3CD, reference case model fits to the data were typical of all sensitivity cases. The model diagnostics were consistent with convergence, and posterior sample autocorrelation was relatively minor for most parameters (Table 7).

The MPD (mode of the posterior distribution) model fits to the five indices of abundance are shown in Figure 11. The model followed the general trends of the three fishery-independent indices, but could not fit some of the larger peaks (for example 2004 and 2005 peaks in the Queen Charlotte Sound Synoptic Survey, and the 2009 and 2013 peaks in the Hecate Strait Synoptic Survey, Figure 11b and c). Similarly, the model followed the major patterns in the two CPUE indices but did not capture all the peaks (Figure 11d and e). As in previous assessments, the model tended to underestimate annual mean weight, especially between 1970 and 2000 (Figure 12), likely for similar reasons described for Area 3CD.

Reference model parameter estimates are shown in Table 7. The range of the posterior estimate of M was was nearly identical in the current assessment, at 0.31 y^{-1} (0.28–0.34 y^{-1}), compared to 0.31 y^{-1} (0.28–0.35 y^{-1}) in the 2018 assessment (Forrest et al. 2020).

Indicators of current stock status

Management advice for both stocks is based on the results of the combined models described above in the model scenarios section. The RPR meeting held in October 2018 reviewed the Reference Case model and the suite of sensitivity runs described above, and concluded that no one model adequately represented the uncertainty associated with these stock assessments. Consequently, RPR participants agreed to adopt an approach that combined model runs to include a greater range of plausible uncertainties associated with these stocks.

Area 3CD

Posterior estimates of reference points and stock status from the combined model-averaged set are provided in Table 8. At the beginning of the 2021 fishing year, under the assumed 2020 catch level, median biomass is projected to be 14,099 t (6,008–47,920 t). Median fishing mortality for the 2020 fishing year is projected to be 0.006 y^{-1} (0.002–0.015 y^{-1}). The median estimated LRP and USR are estimated to be 8,603 t (3,134–28,435 t) and 28,436 t (12,254–84,756 t), respectively. The median estimated LRR is estimated to be 0.065 y^{-1} (0.021–0.187 y^{-1}). Median biomass in 2021 relative to the LRP and USR is estimated to be 1.64 (1.01–3.59) and 0.507 (0.313–0.962), respectively. Median fishing mortality relative to the LRR is estimated to be 0.083 (0.038–0.137) (Table 8).

The average posterior biomass and fishing mortality from the combined model-averaged set are shown in Figures 13 and 14. The estimated biomass range was very broad. Combined average posterior results from all models indicate that the stock in 2020 was just above the LRP (Figure 13). This is a notable decrease in estimated stock status (median B_{2021}/LRP = 1.64) compared to the 2018 assessment, where median B_{2019}/LRP was 2.07 (2.48–2.16)) (DFO 2019a). The estimated fishing mortality range was also broad (Figure 14), reflecting the range of biomass estimates. However, recent estimates of fishing mortality were well below the median LRR (Figure 14).

Area 5ABCD

Posterior estimates of reference points and stock status from the combined model-averaged set are provided in Table 9. At the beginning of the 2021 fishing year, under the assumed 2020 catch level, median biomass is projected to be 19,634 t (11,318–40,603 t). Median fishing mortality for the 2020 fishing year is projected to be 0.027 y^{-1} (0.013–0.049 y^{-1}). The median estimated LRP and USR are estimated to be 9,814 t (5,662–20,881 t) and 33,409 t (21,630–59,004 t), respectively. The median estimated LRR is estimated to be 0.15 y^{-1} (0.09–0.28 y^{-1}). Median biomass in 2021 relative to the LRP and USR is estimated to be 1.96 (1.40–3.11) and 0.59 (0.39–0.89), respectively. Median fishing mortality relative to the LRR is estimated to be 0.17 (0.11–0.27) (Table 9).

The average posterior biomass and fishing mortality from the combined model-averaged set are shown in Figures 15 and 16. As for Area 3CD, the estimated biomass range was very broad. Combined average posterior results from all models indicate that the stock in 2020 was above the LRP, within the Cautious Zone. The estimated fishing mortality range was also broad (Figure 16), reflecting the range of biomass estimates. Recent estimates of fishing mortality were well below the median LRR.

2021 harvest advice

Performance measures were calculated over a sequence of alternative 2021 projected catch levels and are based on posterior samples for a one-year projection to the beginning of 2022. Uncertainty enters the projections through parameter uncertainty propagated through the modeled time series and recruitment anomalies for the projection year. The following performance measures were evaluated:

1. $P(B_{2022} < B_{2021})$
2. $P(F_{2021} > F_{2020})$
3. $P(B_{2022} < LRP)$
4. $P(B_{2022} < USR)$
5. $P(F_{2021} > LRR)$

Decision tables were constructed for each area using the equally weighted combined posterior samples (see Forrest et al. 2020).

Area 3CD

For illustration, recent combined average posterior biomass with a one year projection under four alternative catch levels is shown in Figure 17.

The model-averaged decision table probabilities are presented in Table 10. In summary:

- $P(B_{2022} < B_{2021})$ ranged from 55% to 83% over the range of 2021 catch levels.
- $P(F_{2021} > F_{2020})$ ranged from < 1% to > 99%. The 2020 catch was extrapolated to be approximately 59 t, hence the probability increase between 50 t and 60 t.
- $P(B_{2022} < LRP)$ ranged from < 2% to 10%.
- $P(B_{2022} < USR)$ ranged from 97% to 98%.
- $P(F_{2021} > LRR)$ ranged from < 1% to 98%.

Under a 2021 catch of 500 tonnes (the 2019/20 TAC), there is a 4% probability that biomass in 2021 will be below the LRP (Table 10). However, assuming the 2021 catch is of a similar magnitude to the 2020 catch (approximately 59 t), the probability of the 2021 biomass being below the LRP is 2% (Table 10). The 2022 biomass is projected to be in the Cautious Zone (below the USR) with 97–98% probability under all 2021 catch scenarios tested, including zero catch.

The probability of the fishing mortality exceeding the LRR is less than 1% for all levels of catch up to 400 t. This probability is based on the maximum LRR (i.e., average estimated fishing mortality rate from 1956–2004). DFO's precautionary approach policy (DFO 2009) describes the removal reference (i.e., the LRR) as the maximum acceptable removal rate for the stock. The policy illustrates a harvest control rule with a linear decline in the LRR for stocks in the Cautious Zone. Such a harvest control rule has not been formally agreed upon for Pacific Cod and, therefore, the probabilities in Table 10 and in previous Pacific Cod advice (DFO 2015, 2019a) do not reflect any adjustment to the LRR when the stock is in the Cautious Zone. If such a harvest control rule were applied, as illustrated in DFO (2009), then probabilities of exceeding the LRR would be higher. It is recommended that a harvest control rule, which describes any adjustments to the LRR for stocks below the USR, should be agreed upon before the next assessment update.

Area 5ABCD

Recent combined average biomass with a one year projection under four alternative catch levels is shown in Figure 18.

The model-averaged decision table probabilities are presented in Table 11. In summary:

- $P(B_{2022} < B_{2021})$ ranged from 22% to 91% over the range of 2021 catch levels.
- $P(F_{2021} > F_{2020})$ ranged from < 1% to > 99%. The 2020 catch was extrapolated to be approximately 425 t, hence the probability increase between 400 t and 500 t.
- $P(B_{2022} < LRP)$ ranged from < 1% to 1%.
- $P(B_{2022} < USR)$ ranged from 98% to 99%.
- $P(F_{2020} > LRR)$ ranged from < 1% to 85%.

Under a 2021 catch of 950 tonnes (the 2018/19 TAC), there is less than 1% probability that biomass in 2021 will be below the LRP (Table 11). Assuming the 2021 catch is of a similar magnitude to the 2020 catch (approximately 425 t), the probability of the 2022 biomass being below the LRP is also less than 1% (Table 10). The 2022 biomass is projected to be in the Cautious Zone (below the USR) with 98%–99% probability under all 2021 catch scenarios tested, including zero catch.

The probability of the stock exceeding the LRR is less than 1% for all levels of catch up to 1400 t. As for Area 3CD, if the LRR were adjusted downward because the stock is in the Cautious Zone (DFO 2009), the probabilities of exceeding the LRR would be higher.

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 the set of model configurations included within the assessment 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 and gear selectivity;
2. Relatively short time series of fishery-independent abundance indices, which show no clear trend;
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 undergone decline since 2017, likely due to warming north Pacific

waters (Barbeaux et al. 2020), 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

This document updates the stock status of Pacific Cod stocks in Area 3CD and 5ABCD at the end of the 2020 fishing year, and provides 2021 catch advice in the form of decision tables. Currently, both stocks are assessed to be in the Cautious Zone, as was the case in the 2018 assessment (DFO 2019a). However, the Area 3CD stock is estimated to have declined in abundance and is estimated to be closer to the LRP than in the previous assessment.

A critical concern with this assessment is the lack of a WCVI synoptic survey update in 2020. It is recommended that this area be surveyed as soon as it is feasible, and that this advice be updated when the data are available. Further analysis of recent survey data including spatial and depth distribution of the stock, and analysis of biological data, such as condition of the fish over time (length-weight relationship) and spatial distribution of length data could also provide insights into possible causes of the apparent rapid decline in abundance. Other key research recommendations, which would improve understanding of stock and fishery dynamics for both stocks are provided in Forrest et al. (2020). A fully described harvest control rule should be agreed upon before the next assessment update.

Tables

Table 1. Reported catch (mt) of Pacific Cod in Area 3CD by Canada and the USA, 1956–2020. 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. The 2020 total catch estimate is extrapolated from the combined landings plus discards taken up to September 30, 2020 (see text). Therefore 2020 nominal landings and discards are not shown individually. Numbers are rounded for presentation.

Year	Canada landings	Canada released at sea	Canada total	USA	Total catch
1956	715	0	715	770	1,485
1957	1,117	0	1,117	558	1,675
1958	526	0	526	271	797
1959	416	0	416	510	926
1960	240	0	240	376	616
1961	284	0	284	232	516
1962	428	6	434	402	836
1963	838	2	840	345	1,185
1964	1,107	8	1,115	907	2,022
1965	1,608	8	1,616	1,088	2,704
1966	2,095	143	2,238	1,145	3,383
1967	1,202	0	1,202	623	1,825
1968	726	4	730	351	1,081
1969	796	2	798	147	945
1970	1,150	32	1,182	454	1,636
1971	3,585	120	3,705	1,319	5,024
1972	4,447	2	4,449	1,271	5,720
1973	2,457	1	2,458	627	3,085
1974	2,913	7	2,920	1,013	3,933
1975	2,854	24	2,878	1,359	4,237
1976	2,187	2	2,189	1,679	3,868
1977	1,608	49	1,657	1,344	3,001
1978	1,168	18	1,186	1,086	2,272
1979	1,530	13	1,543	741	2,284
1980	1,117	10	1,127	287	1,414
1981	1,518	4	1,522	0	1,522
1982	608	2	610	0	610
1983	883	0	883	0	883
1984	506	2	508	0	508
1985	440	0	440	0	440
1986	441	0	441	0	441
1987	1,400	2	1,402	0	1,402
1988	3,153	3	3,156	0	3,156
1989	1,958	3	1,961	0	1,961
1990	2,076	4	2,080	0	2,080
1991	2,971	0	2,971	0	2,971
1992	2,229	1	2,230	0	2,230
1993	2,091	2	2,093	0	2,093

Year	Canada landings	Canada released at sea	Canada total	USA	Total catch
1994	816	1	817	0	817
1995	252	4	256	0	256
1996	146	9	155	0	155
1997	135	10	145	0	145
1998	56	5	61	0	61
1999	75	8	83	0	83
2000	129	13	142	0	142
2001	342	16	358	0	358
2002	177	26	204	0	204
2003	458	41	499	0	499
2004	418	27	444	0	444
2005	265	29	294	0	294
2006	143	10	153	0	153
2007	55	13	68	0	68
2008	105	7	111	0	111
2009	365	56	422	0	422
2010	577	25	602	0	602
2011	502	9	511	0	511
2012	399	19	418	0	418
2013	361	29	389	0	389
2014	442	12	454	0	454
2015	445	3	449	0	449
2016	323	2	325	0	325
2017	164	1	165	0	165
2018	23	0	23	0	23
2019	43	4	47	0	47
2020	-	-	59	0	59

Table 2. Reported catch (mt) of Pacific Cod in Area 5ABCD by Canada and the USA, 1956–2020. 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. The 2020 total catch estimate is extrapolated from the combined landings plus discards taken up to September 30, 2020 (see text). Therefore 2020 nominal landings and discards are not shown individually. Numbers are rounded for presentation.

Year	Canada landings	Canada released at sea	Canada total	USA	Total catch
1956	1,666	0	1,666	2,063	3,729
1957	3,199	7	3,206	2,677	5,883
1958	3,275	0	3,275	3,549	6,824
1959	2,478	0	2,478	1,974	4,452
1960	2,029	0	2,029	951	2,980
1961	1,529	7	1,536	251	1,787
1962	2,138	3	2,141	310	2,451
1963	2,478	99	2,577	883	3,460
1964	6,568	86	6,654	1,009	7,663
1965	9,291	0	9,291	1,562	10,853
1966	9,409	199	9,608	1,362	10,970
1967	6,034	344	6,378	1,025	7,403
1968	4,325	107	4,432	606	5,038
1969	2,817	8	2,825	405	3,230
1970	1,267	1	1,268	198	1,466
1971	1,542	24	1,566	698	2,264
1972	3,642	0	3,642	1,667	5,309
1973	4,258	13	4,271	1,426	5,697
1974	6,005	66	6,071	1,539	7,610
1975	6,739	100	6,839	1,139	7,978
1976	5,796	52	5,848	635	6,483
1977	4,369	179	4,548	408	4,956
1978	4,078	125	4,203	159	4,362
1979	7,462	282	7,744	62	7,806
1980	5,487	75	5,562	10	5,572
1981	3,462	35	3,497	0	3,497
1982	3,089	29	3,118	0	3,118
1983	2,478	68	2,546	0	2,546
1984	2,113	8	2,121	0	2,121
1985	1,338	6	1,344	0	1,344
1986	4,019	112	4,131	0	4,131
1987	12,711	41	12,752	0	12,752
1988	8,020	8	8,028	0	8,028
1989	4,214	42	4,256	0	4,256
1990	4,242	233	4,475	0	4,475
1991	9,892	66	9,958	0	9,958
1992	7,087	35	7,122	0	7,122
1993	4,869	7	4,876	0	4,876
1994	1,757	2	1,759	0	1,759

Year	Canada landings	Canada released at sea	Canada total	USA	Total catch
1995	1,293	3	1,296	0	1,296
1996	1,270	92	1,362	0	1,362
1997	1,261	105	1,366	0	1,366
1998	982	59	1,041	0	1,041
1999	692	53	746	0	746
2000	553	28	581	0	581
2001	296	38	334	0	334
2002	382	104	487	0	487
2003	660	147	807	0	807
2004	833	130	963	0	963
2005	1,004	83	1,087	0	1,087
2006	872	32	904	0	904
2007	370	15	384	0	384
2008	309	7	316	0	316
2009	668	40	708	0	708
2010	1,452	48	1,500	0	1,500
2011	1,233	7	1,240	0	1,240
2012	870	12	882	0	882
2013	829	22	851	0	851
2014	904	18	922	0	922
2015	924	18	942	0	942
2016	529	5	534	0	534
2017	346	4	350	0	350
2018	254	5	259	0	259
2019	450	4	454	0	454
2020	-	-	425	0	425

Table 3. Pacific Cod survey data for Canadian trawl surveys in metric tons (without accounting for survey catchability). Positive sets refers to the number of trawl sets that caught Pacific Cod. OTHER HS MSA = Hecate Strait Multispecies Assemblage survey; 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.

Survey abbrev.	Year	Biomass	CV	Lower CI	Upper CI	Sets	Positive sets
OTHER HS MSA	1984	1142.4	0.30	606.6	1929.9	146	88
OTHER HS MSA	1987	3875.7	0.35	1501.2	6778.9	85	43
OTHER HS MSA	1989	4102.8	0.43	1318.5	7976.0	90	48
OTHER HS MSA	1991	1031.8	0.30	506.1	1679.0	97	59
OTHER HS MSA	1993	1255.6	0.24	719.9	1862.4	94	40
OTHER HS MSA	1995	1419.8	0.46	528.7	2880.5	101	52
OTHER HS MSA	1996	1418.5	0.26	793.2	2208.0	158	83
OTHER HS MSA	1998	4253.0	0.51	1223.7	9186.9	86	52
OTHER HS MSA	2000	436.1	0.20	283.7	622.8	105	54
OTHER HS MSA	2002	2025.9	0.27	1137.3	3203.6	91	66
OTHER HS MSA	2003	1288.7	0.21	808.3	1871.8	95	77
SYN HS	2005	1946.4	0.24	1192.6	2992.5	198	161
SYN HS	2007	586.6	0.22	359.5	856.2	132	72
SYN HS	2009	2460.8	0.45	744.7	4918.3	155	102
SYN HS	2011	1860.7	0.26	1083.4	2978.7	184	124
SYN HS	2013	2326.5	0.24	1443.3	3512.3	175	132
SYN HS	2015	956.6	0.21	598.9	1394.0	148	107
SYN HS	2017	1554.4	0.34	754.4	2792.0	138	107
SYN HS	2019	1752.1	0.37	832.3	3204.5	136	102
SYN QCS	2003	806.6	0.17	568.1	1092.1	233	101
SYN QCS	2004	1624.4	0.26	901.8	2550.5	230	118
SYN QCS	2005	1505.0	0.35	785.6	2705.1	224	125
SYN QCS	2007	434.5	0.25	245.5	665.9	255	105
SYN QCS	2009	565.5	0.24	335.1	859.5	233	95
SYN QCS	2011	1018.4	0.21	644.6	1473.9	251	98
SYN QCS	2013	928.3	0.15	680.9	1232.9	240	134
SYN QCS	2015	1122.3	0.29	644.0	1852.9	238	124
SYN QCS	2017	521.8	0.17	355.2	706.0	240	90
SYN QCS	2019	1004.0	0.13	782.6	1283.6	242	113
SYN WCVI	2004	1133.1	0.22	696.4	1652.4	89	54
SYN WCVI	2006	1156.0	0.22	689.1	1693.5	164	88
SYN WCVI	2008	512.6	0.40	233.1	986.2	159	65
SYN WCVI	2010	1577.4	0.17	1087.3	2128.2	136	100
SYN WCVI	2012	921.3	0.18	626.2	1279.6	151	94
SYN WCVI	2014	2149.4	0.20	1342.7	3076.3	146	110
SYN WCVI	2016	2026.8	0.19	1325.7	2877.8	140	99
SYN WCVI	2018	552.9	0.21	362.3	805.9	190	91

Table 4. Estimated and fixed parameters and prior probability distributions used in the Reference Case, Area 3CD. The survey catchability parameter for WCVI (q_1) was estimated with the prior probability distribution $Normal(ln(0.228), 0.3)$. The other survey catchability parameters 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 ($\Gamma_{k,t}$)	65	[-30, 3]	[-30, 3]
Log recruitment deviations (ω_t)	65	None	Normal($0, 2$)
Initial log recruitment deviations ($\omega_{init,t}$)	8	None	Normal($0, 2$)

Table 5. Estimated and fixed parameters and prior probability distributions used in the Reference Case, Area 5ABCD. The survey catchability parameters for QCS and HS (q_2 and q_3) were estimated with the prior probability distributions $Normal(ln(0.408), 0.3)$ and $Normal(ln(0.0654,), 0.3)$, respectively. The other survey catchability parameters 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)	5	None	See caption
Log fishing mortality values ($\Gamma_{k,t}$)	65	[-30, 3]	[-30, 3]
Log recruitment deviations (ω_t)	65	None	Normal($0, 2$)
Initial log recruitment deviations ($\omega_{init,t}$)	8	None	Normal($0, 2$)

Table 6. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of key parameters from the Reference Case, Area 3CD. 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	2,205	3,173	4,825	3,698	510	1.00
h	0.414	0.733	0.930	0.806	761	1.00
M	0.412	0.449	0.489	0.453	712	1.00
q_1	0.043	0.066	0.099	0.066	655	1.00
q_2	0.001	0.002	0.003	0.002	674	1.00
q_3	0.001	0.002	0.003	0.002	666	1.00
q_4	0.052	0.080	0.114	0.082	662	1.00

Table 7. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of key parameters from the Reference Case, Area 5ABCD. 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 = Hecate Strait Assemblage survey, q_2 = Queen Charlotte Sound Synoptic Survey, q_3 = Hecate Strait Synoptic Survey, q_4 = Commercial CPUE pre-1996, and q_5 = Commercial CPUE post-1995.

Parameter	2.5%	50%	97.5%	MPD	n_{eff}	$\hat{R}$
R_0	2,316	2,936	3,792	3,377	298	1.00
h	0.447	0.736	0.938	0.810	731	1.00
M	0.279	0.308	0.343	0.306	715	1.00
q_1	0.054	0.069	0.085	0.071	621	1.00
q_2	0.039	0.051	0.067	0.051	647	1.00
q_3	0.068	0.088	0.118	0.089	661	1.00
q_4	0.002	0.003	0.004	0.003	587	1.00
q_5	0.006	0.008	0.011	0.008	648	1.00

Table 8. Posterior (2.5th percentile, Median, and 97.5th percentile) of reference points for model-averaged Area 3CD. 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_{2021}	6008	14099	47920
F_{2020}	0.002	0.006	0.015
LRP (1986)	3134	8603	28435
USR (1956–2004)	12254	28436	84756
LRR (1956–2004)	0.021	0.065	0.187
B_{2021}/LRP	1.005	1.640	3.590
B_{2021}/USR	0.313	0.507	0.962
F_{2020}/LRR	0.038	0.083	0.137

Table 9. Posterior (2.5th percentile, Median, and 97.5th percentile) of reference points for model-averaged Area 5ABCD. 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_{2021}	11318	19634	40603
F_{2020}	0.013	0.027	0.049
LRP (2000)	5662	9814	20881
USR (1956–2004)	21630	33409	59004
LRR (1956–2004)	0.085	0.153	0.278
B_{2021}/LRP	1.395	1.960	3.110
B_{2021}/USR	0.385	0.592	0.887
F_{2020}/LRR	0.108	0.174	0.270

Table 10. Decision table with model averaging for Area 3CD. Models averaged are: 1a) Reference model 3CD, 2d) WCVISS ln(q) prior mean = ln(1.0), 2e) WCVISS ln(q) prior SD = 0.6, 3a) M prior mean = 0.4, SD = 0.1, 5a) kage = 3y and update FW parameters, 6b) Fix sigma O = 0.15 and 7b) Fix sigma W = 0.15.

2021 Catch(mt)	$P(B_{2022} < B_{2021})$	$P(F_{2021} > F_{2020})$	$P(B_{2022} <$ LRP)	$P(B_{2022} <$ USR)	$P(F_{2021} >$ LRR)
0	0.55	<0.01	0.02	0.97	<0.01
10	0.56	<0.01	0.02	0.97	<0.01
20	0.56	<0.01	0.02	0.97	<0.01
30	0.56	<0.01	0.02	0.97	<0.01
40	0.57	<0.01	0.02	0.97	<0.01
50	0.57	<0.01	0.02	0.97	<0.01
60	0.57	0.26	0.02	0.97	<0.01
70	0.58	0.94	0.02	0.97	<0.01
80	0.58	>0.99	0.02	0.97	<0.01
90	0.58	>0.99	0.02	0.97	<0.01
100	0.59	>0.99	0.02	0.97	<0.01
150	0.60	>0.99	0.02	0.97	<0.01
200	0.62	>0.99	0.03	0.97	<0.01
300	0.64	>0.99	0.03	0.98	<0.01
400	0.67	>0.99	0.03	0.98	<0.01
500	0.69	>0.99	0.04	0.98	0.06
600	0.71	>0.99	0.04	0.98	0.22
700	0.73	>0.99	0.05	0.98	0.42
800	0.75	>0.99	0.05	0.98	0.62
900	0.76	>0.99	0.06	0.98	0.77
1,000	0.77	>0.99	0.06	0.98	0.86
1,100	0.79	>0.99	0.07	0.98	0.91
1,200	0.80	>0.99	0.08	0.98	0.94
1,300	0.81	>0.99	0.08	0.98	0.96
1,400	0.82	>0.99	0.09	0.98	0.97
1,500	0.83	>0.99	0.10	0.98	0.98

*Table 11. Decision table with model averaging for Area 5ABCD. Models averaged are: 1a) Reference model 5ABCD, 2d) HSSS ln(q) prior mean = ln(1.0 * 0.35), QCSSS = ln(1.0 * 0.65), 2e) HSSS and QCSS ln(q) prior SD = 0.6, 3a) M prior mean = 0.4, SD = 0.1, 5a) kage = 3y and update FW parameters, 6b) Fix sigma O = 0.15 and 7b) Fix sigma W = 0.15.*

2021 Catch(mt)	$P(B_{2022} < B_{2021})$	$P(F_{2021} > F_{2020})$	$P(B_{2022} <$ LRP)	$P(B_{2022} <$ USR)	$P(F_{2021} >$ LRR)
0	0.22	<0.01	<0.01	0.98	<0.01
100	0.25	<0.01	<0.01	0.98	<0.01
200	0.29	<0.01	<0.01	0.98	<0.01
300	0.33	<0.01	<0.01	0.98	<0.01
400	0.37	0.03	<0.01	0.98	<0.01
500	0.42	0.97	<0.01	0.98	<0.01
600	0.46	>0.99	<0.01	0.98	<0.01
700	0.50	>0.99	<0.01	0.98	<0.01
800	0.55	>0.99	<0.01	0.98	<0.01
900	0.59	>0.99	<0.01	0.98	<0.01
1,000	0.62	>0.99	<0.01	0.98	<0.01
1,100	0.66	>0.99	<0.01	0.98	<0.01
1,200	0.69	>0.99	<0.01	0.99	<0.01
1,300	0.71	>0.99	<0.01	0.99	<0.01
1,400	0.74	>0.99	<0.01	0.99	<0.01
1,500	0.75	>0.99	<0.01	0.99	0.01
1,600	0.78	>0.99	<0.01	0.99	0.03
1,700	0.79	>0.99	<0.01	0.99	0.05
1,800	0.81	>0.99	<0.01	0.99	0.08
1,900	0.82	>0.99	<0.01	0.99	0.12
2,000	0.83	>0.99	<0.01	0.99	0.17
2,100	0.84	>0.99	<0.01	0.99	0.23
2,200	0.85	>0.99	<0.01	0.99	0.31
2,300	0.86	>0.99	<0.01	0.99	0.39
2,400	0.87	>0.99	<0.01	0.99	0.48
2,500	0.88	>0.99	<0.01	0.99	0.56
2,600	0.88	>0.99	<0.01	0.99	0.64
2,700	0.89	>0.99	<0.01	0.99	0.70
2,800	0.89	>0.99	<0.01	0.99	0.76
2,900	0.90	>0.99	<0.01	0.99	0.81
3,000	0.91	>0.99	0.01	0.99	0.85

Figures

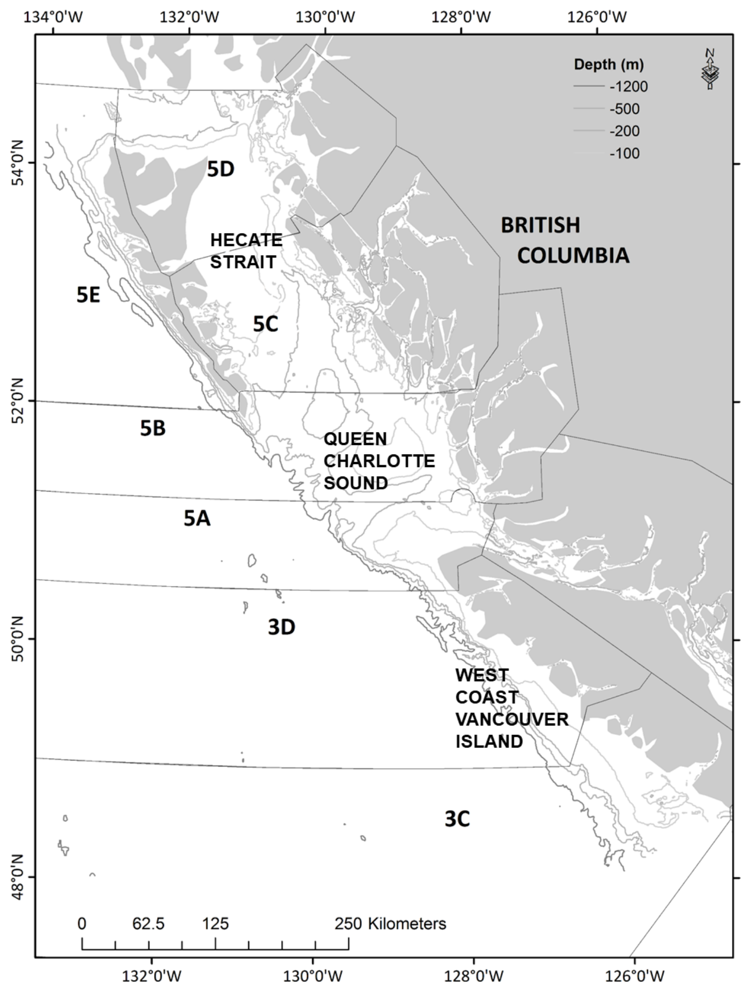

Figure 1. Map of the management areas 5AB (Queen Charlotte Sound), 5CD (Hecate Strait), and 3CD (West Coast Vancouver Island).

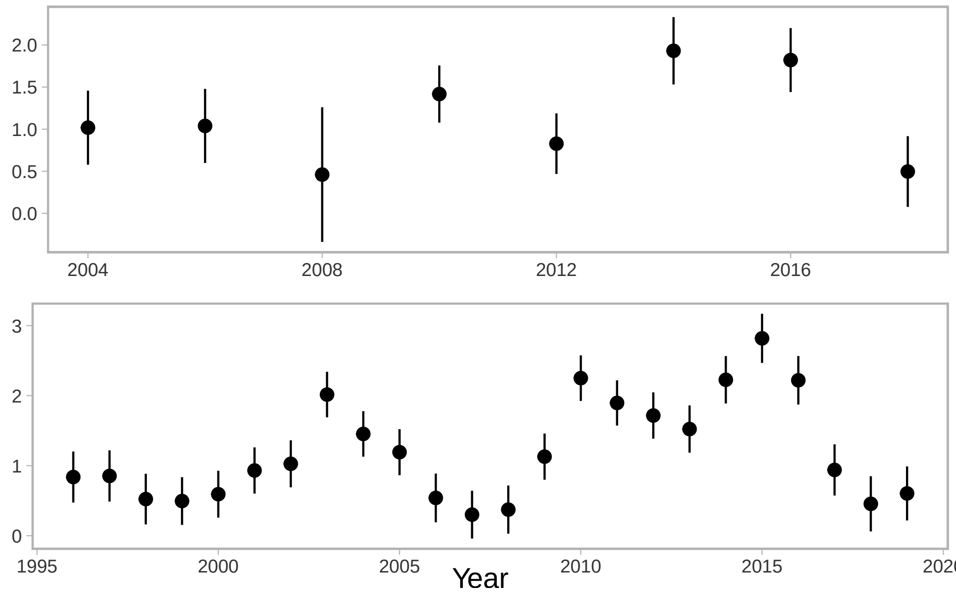

Figure 2. Top: Relative index of abundance from the West Coast Vancouver Island Synoptic Survey, centred by its geometric mean. Bottom: Commercial CPUE, centred by its geometric mean

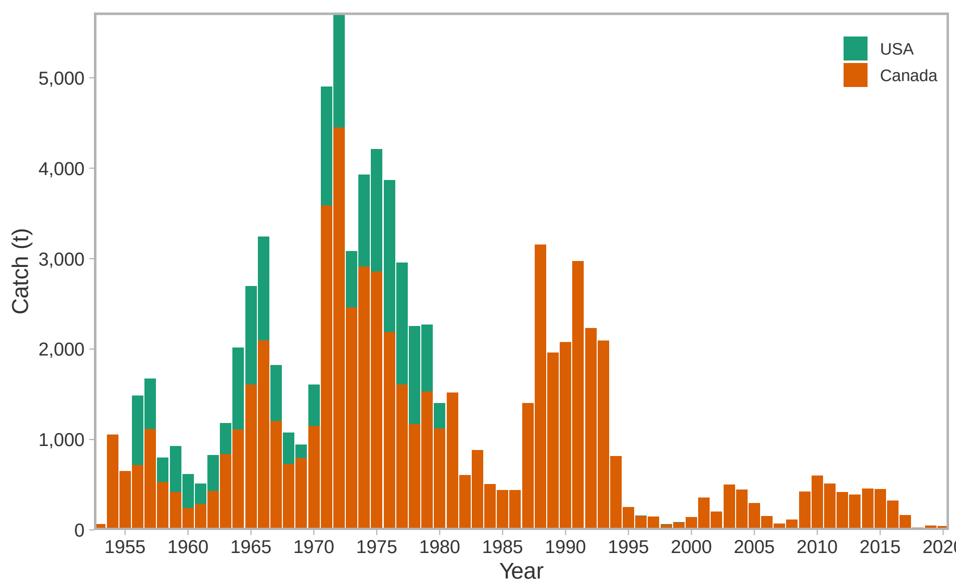

Figure 3. Catch for Area 3CD. Canadian catch includes at-sea releases.

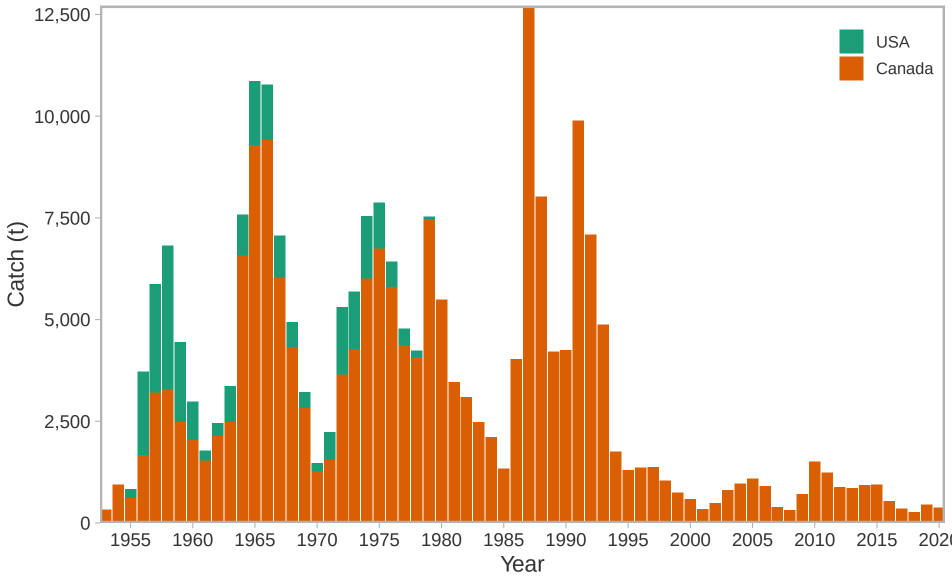

Figure 4. Catch for Area 5ABCD. Canadian catch includes at-sea releases.

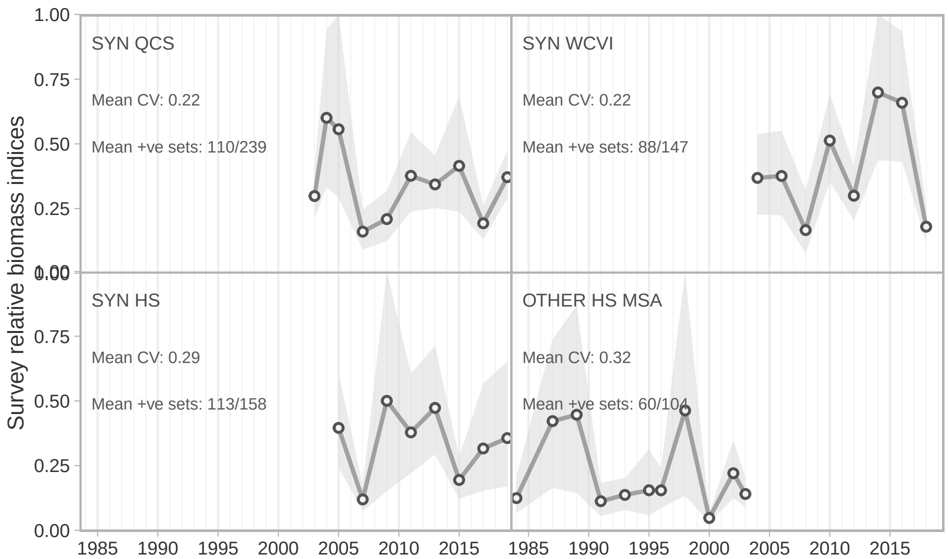

Figure 5. Pacific Cod survey data for Canadian trawl surveys. Shown is relative biomass and associated lower and upper confidence intervals. Positive sets refers to the number of trawl sets that caught Pacific Cod. SYN QCS = Queen Charlotte Sound synoptic bottom trawl survey; SYN WCVI = West Coast Vancouver Island synoptic bottom trawl survey; SYN HS = Hecate Strait synoptic bottom trawl survey; OTHER HS MSA = Hecate Strait Multispecies Assemblage survey.

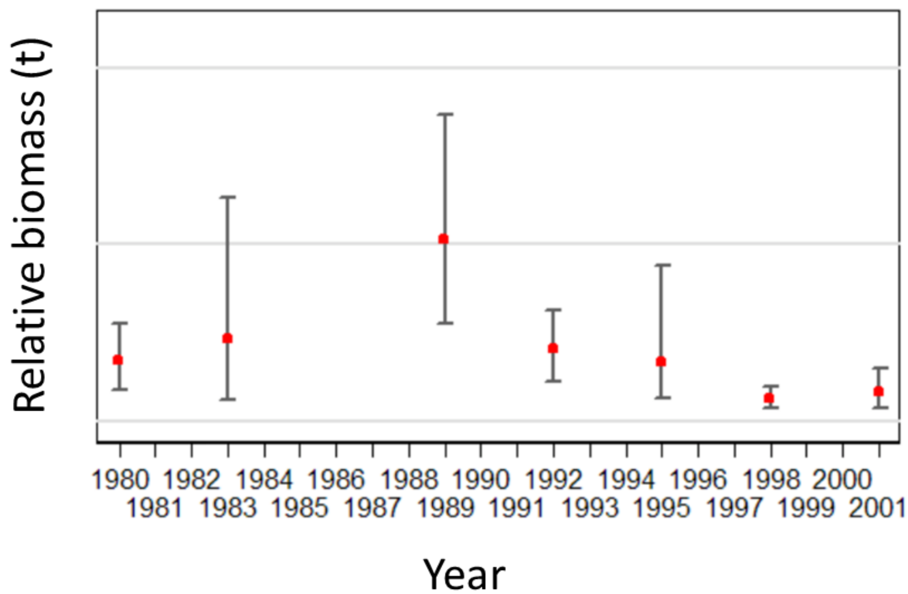

Figure 6. Biomass estimates for Pacific Cod in the International North Pacific Fisheries Commission Vancouver region (Canadian waters only) with 95% error bars estimated from 1000 bootstraps.

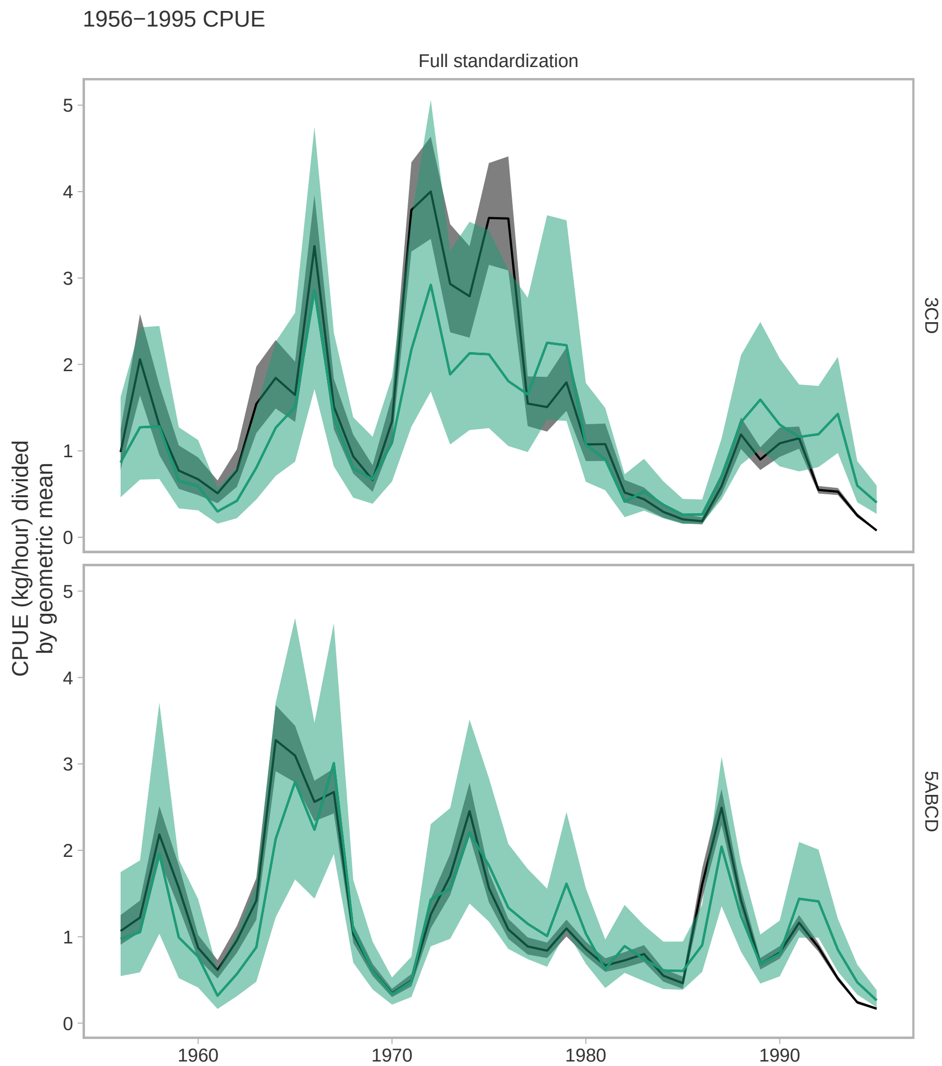

Figure 7. Commercial trawl CPUE standardization models for Area 3CD (top) and 5ABCD (bottom). The black line and shaded region indicate a CPUE index with only a year predictor. The coloured line and shaded ribbons shows a standardization model that includes all the predictors plus locality-by-year (space-time) random effects. Locality and locality-year interactions are fit as random effects and all other variables are fit as fixed effects.

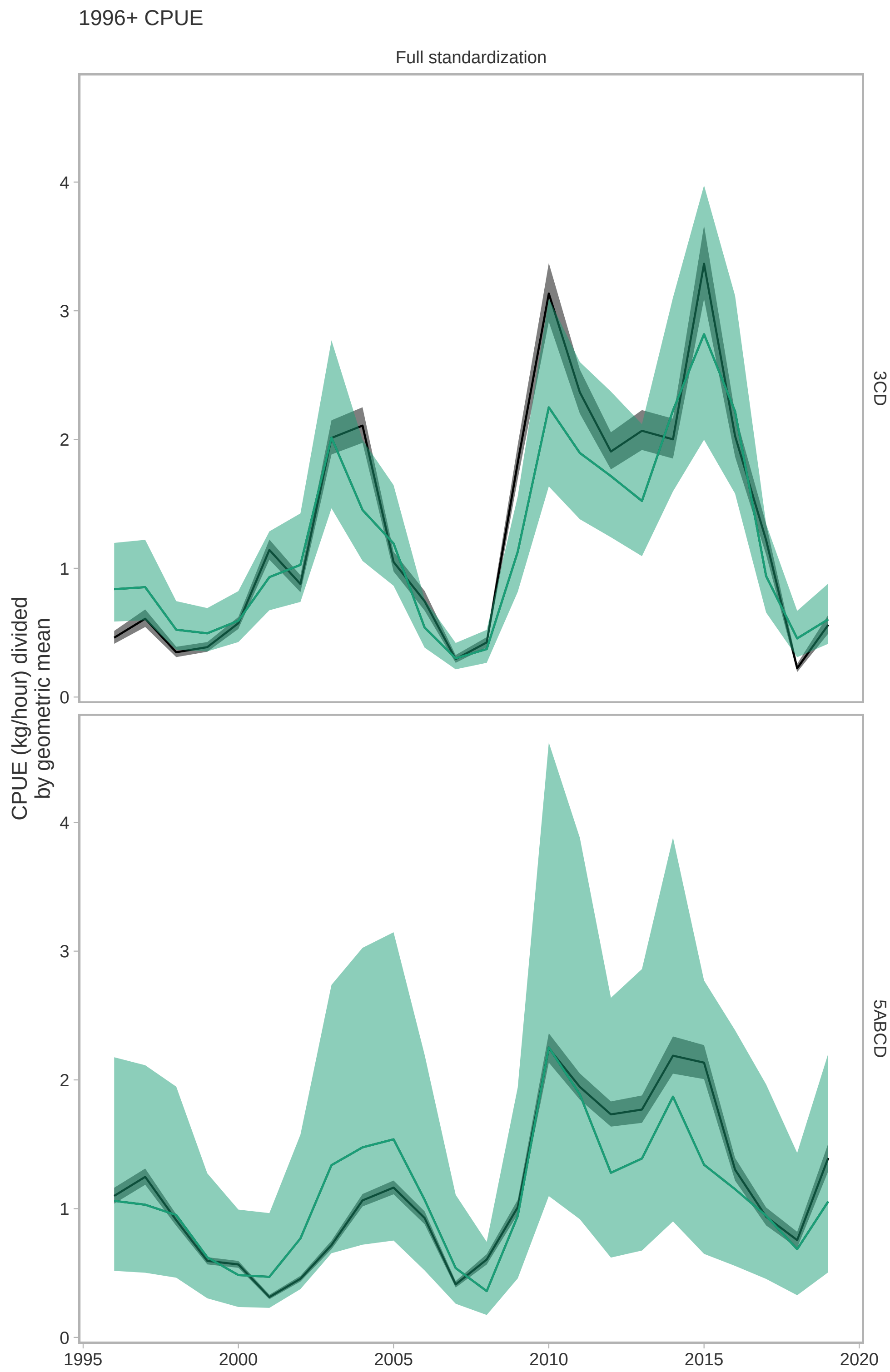

Figure 8. Same as Figure 7 but for the 1996 to 2019 data for Area 3CD (top) and 5ABCD (bottom). Locality, vessel, and locality-year interactions are fit as random effects and all other variables are fit as fixed effects.

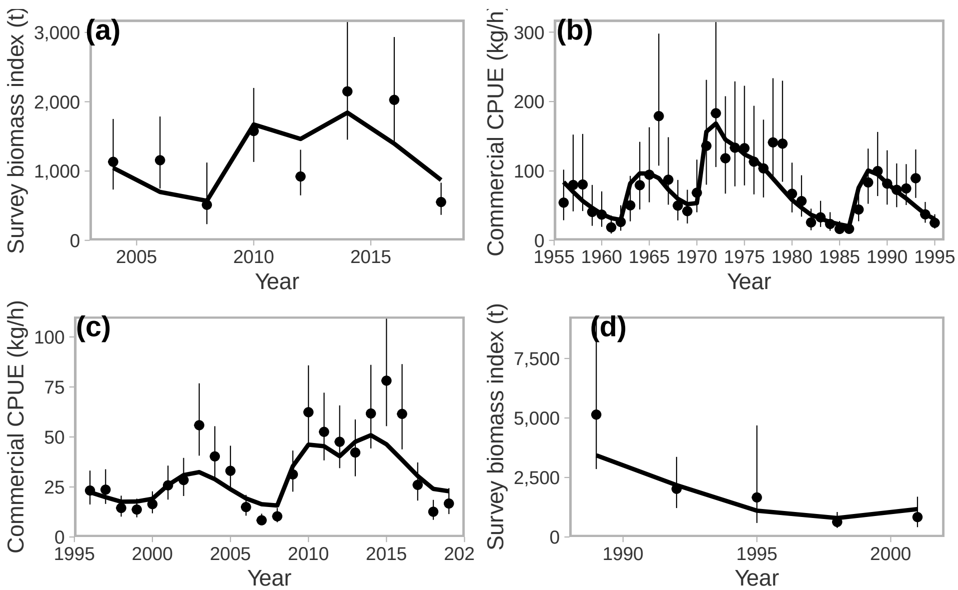

Figure 9. Reference model MPD fits to observed indices of abundance (points) for Area 3CD from: (a) the WCVI Synoptic Survey, (b) Commercial CPUE pre-1996, (c) Commercial CPUE post-1995, and (d) the NMFS Triennial Survey (Canadian portion). For clarity, only MPD results are shown.

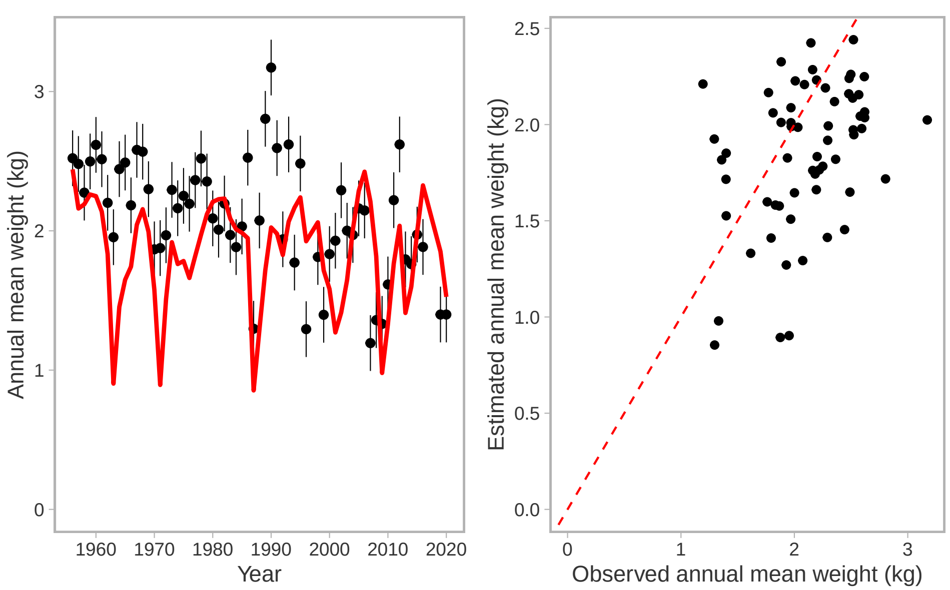

Figure 10. Reference model MPD fit to the mean weight data for Area 3CD. For clarity, only MPD results are shown.

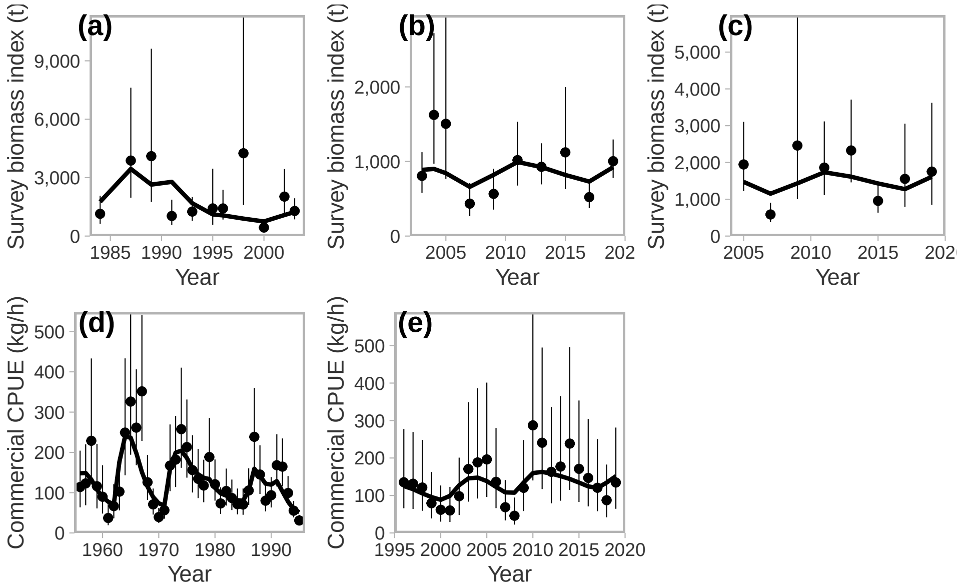

Figure 11. Reference model MPD fits to observed indices of abundance (points) for Area 5ABCD from: (a) the HS Assemblage survey, (b) the QCS Synoptic Survey, (c) the HS Synoptic Survey, (d) Commercial CPUE pre-1996, and (e) Commercial CPUE post-1995. For clarity, only MPD results are shown.

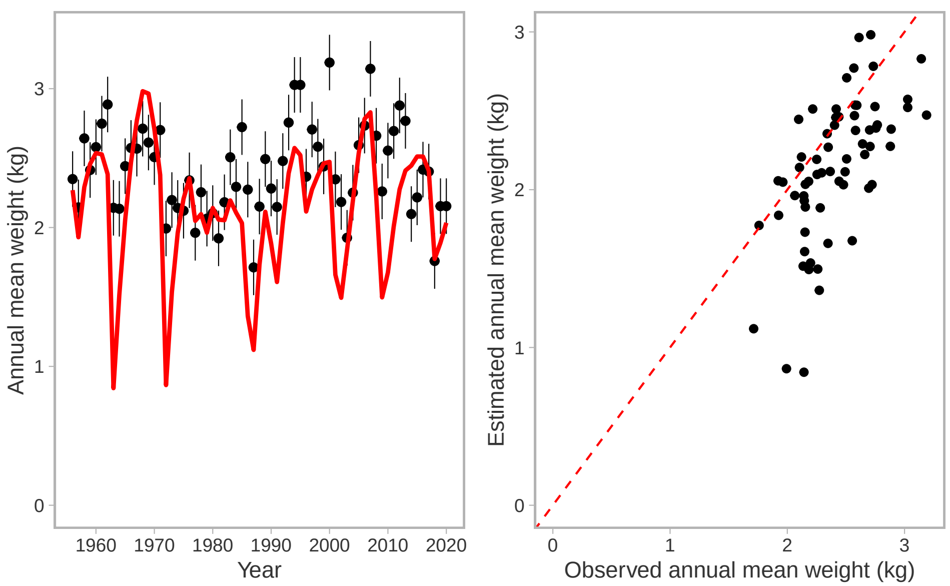

Figure 12. Reference model MPD fit to the mean weight data for Area 5ABCD. For clarity, only MPD results are shown

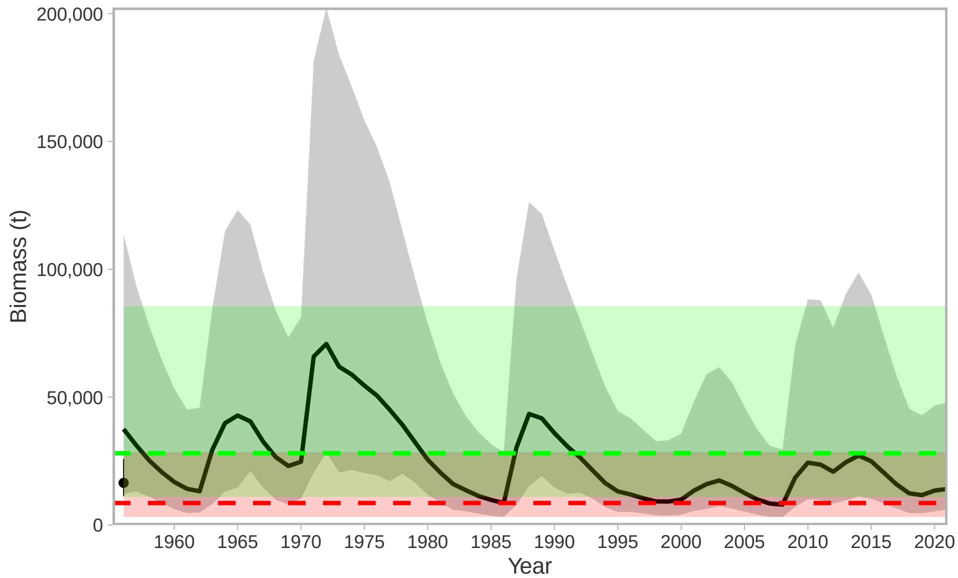

Figure 13. Combined posterior biomass for the model-averaged set for Area 3CD. Thick solid line shows the posterior median and the grey shaded region represents the 95% credible interval. Green dashed line shows the median USR; red dashed line shows the median LRP. Red and green shaded intervals represent the 95% credible interval of the LRP and USR, respectively.

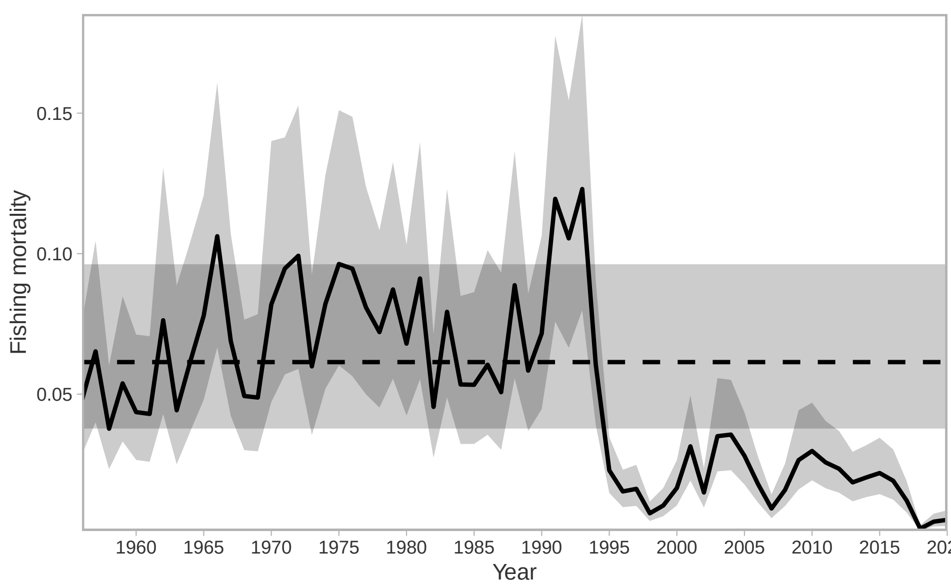

Figure 14. Combined posterior fishing mortality for the model-averaged set for Area 3CD. Thick solid line shows the posterior median and the shaded region represents the 95% credible interval. Black dashed line shows the median LRR and the horizontal shaded region represents the 95% credible interval.

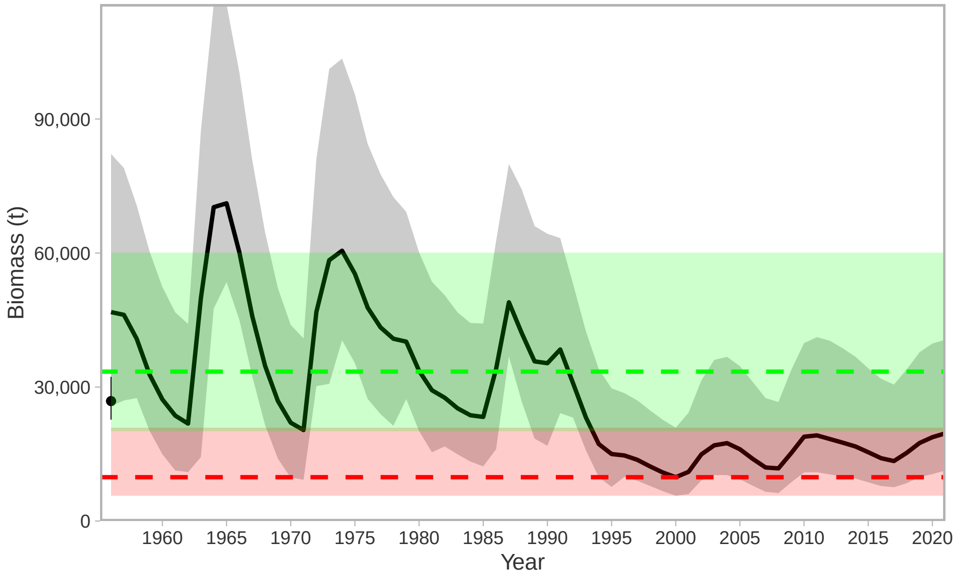

Figure 15. Combined posterior biomass for the averaged models, Area 5ABCD. Thick solid line shows the posterior median and the grey shaded region represents the 95% credible interval. Green dashed line shows the median USR; red dashed line shows the median LRP. Red and green shaded intervals represent the 95% credible interval of the LRP and USR, respectively.

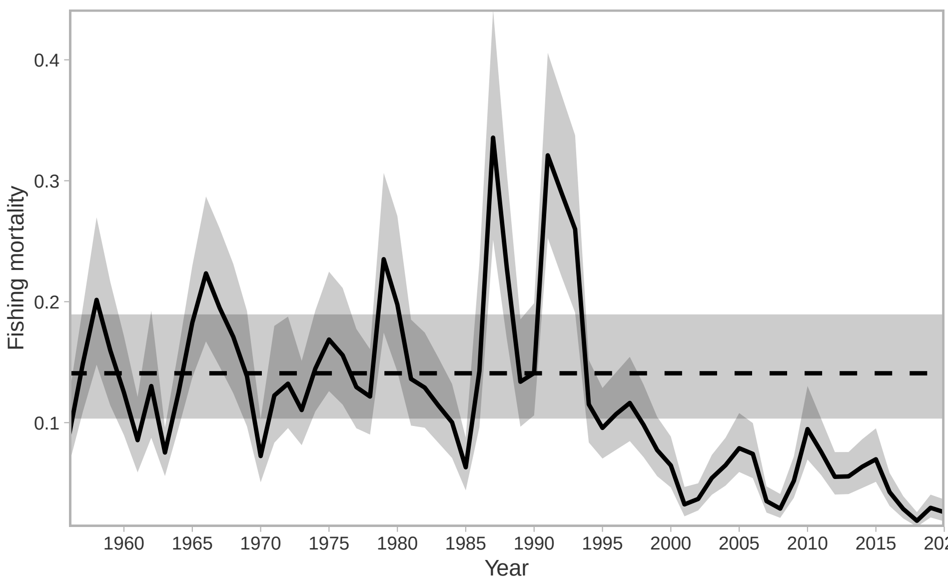

Figure 16. Combined posterior fishing mortality for the model-averaged set for Area 5ABCD. Thick solid line shows the posterior median and the shaded region represents the 95% credible interval. Black dashed line shows the median LRR and the horizontal shaded region represents the 95% credible interval.

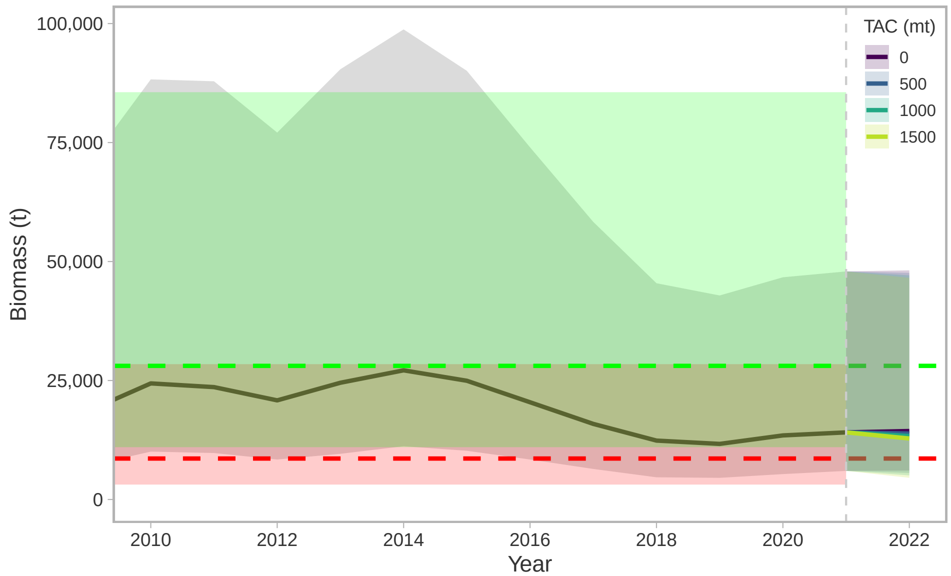

Figure 17. Combined posterior estimates of biomass for the model-averaged set for Area 3CD with projections (to the beginning of 2022). Thick black line shows the posterior median and the grey shaded region represents the 95% credible interval. Green dashed line shows the median USR; red dashed line shows the median LRP. Red and green shaded intervals represent the 95% credible interval of the LRP and USR, respectively. The coloured regions to the right of the vertical dashed line represent projections based on various 2021 catch levels. For clarity, years before 2010 are removed.

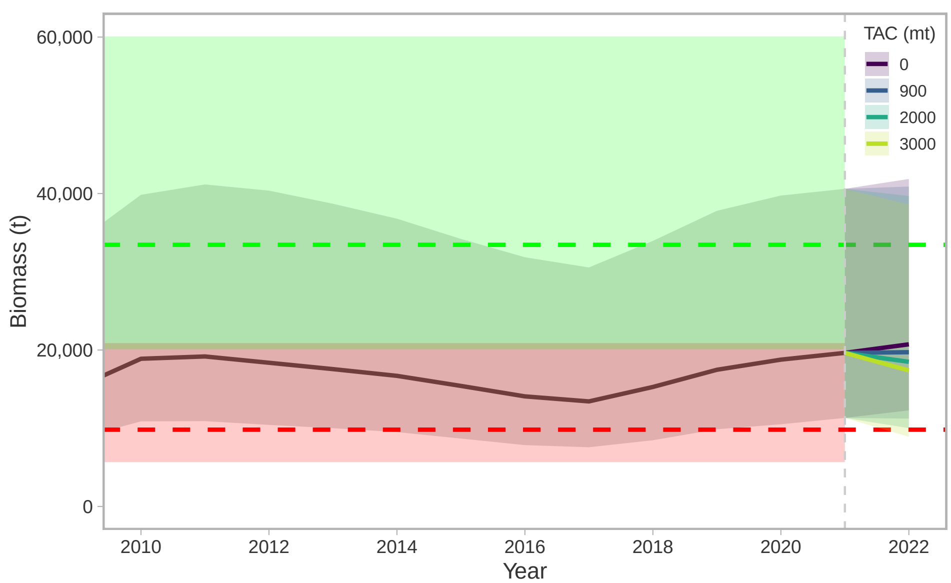

Figure 18. Same as Figure 17 but for Area 5ABCD.

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Approved by

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Regional Director
Science Branch, Pacific Region
Fisheries and Oceans Canada
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