ASSESSMENT OF BRITISH COLUMBIA PACIFIC COD FOR AREAS 3CD AND 5ABCD IN 2018

Pacific Cod (Gadus macrocephalus).

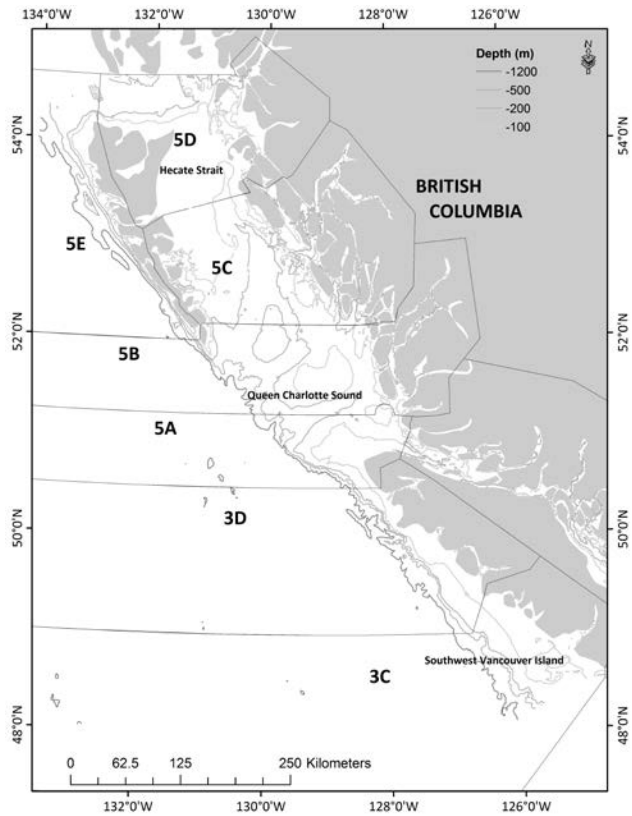

Figure 1. Pacific Cod assessment areas comprising Pacific Marine Fisheries Commission (PMFC) major areas.

Context

*Pacific Cod (*Gadus macrocephalus*) is a commercially important species of cod that occurs along the entire coast of British Columbia. Pacific Cod is a relatively short lived species (10-11 years, DFO 2015). The majority of catches are taken in Hecate Strait and Queen Charlotte Sound, where abundance is highest, although large catches have historically been taken off the West Coast of Vancouver Island. Pacific Cod are caught by the groundfish bottom trawl fishery and in small amounts by hook and line fisheries. Four stocks of Pacific Cod are defined for management purposes in BC: Strait of Georgia (4B); West Coast Vancouver Island (3CD); Queen Charlotte Sound (5AB); and Hecate Strait (5CD).*

Advice was requested by Fisheries and Oceans Canada (DFO) Fisheries Management on the current stock status for Pacific Cod in Areas 5AB, 5CD, and 3CD. Areas 5AB and 5CD were last assessed in 2014; Area 3CD was last assessed in 2001. Area 4B is not assessed in this document. This Science Advisory Report is from the October 10-11, 2018 regional peer review on the Assessment of British Columbia Pacific Cod for Areas 3CD, and 5ABCD in 2018. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

SUMMARY

- Pacific Cod (*Gadus macrocephalus*) is a commercially important, short-lived species that occurs along the entire coast of British Columbia (BC). It is primarily caught by the groundfish bottom trawl fishery and in small amounts by the hook and line fishery. The majority of catches are taken in Hecate Strait and Queen Charlotte Sound (Area 5ABCD, average 739.6 t/yr, 2013-2017). Although large catches were taken historically off the West Coast of Vancouver Island (Area 3CD), catches in recent years have been lower (average 363 t/yr, 2013-17).
- Four stocks of Pacific Cod are defined for management purposes in BC: Strait of Georgia (4B); West Coast Vancouver Island (3CD); Queen Charlotte Sound (5AB); and Hecate Strait (5CD). Historically each area has been assessed separately. For the purposes of this assessment, data from Areas 5AB and 5CD were combined into a single stock assessment, due to the lack of biological evidence for separate stocks and improved fits to the combined data compared to data from area 5AB alone. Area 3CD was assessed separately. Area 4B was not assessed at this time as there is no directed commercial fishery there.
- Pacific Cod is difficult to age, making statistical catch-age models inappropriate for this species. Therefore, stocks in Areas 5ABCD and 3CD were assessed using Bayesian delay-difference models. The models were fit to fishery-independent indices of abundance, mean annual weight in the commercial catch, and new standardized commercial catch-per-unit-effort (CPUE) indices that were developed using Tweedie generalized linear mixed effect models (GLMMs). Updated estimates of growth parameters were also incorporated into the models.
- The absolute scale of the estimated biomass in the two assessed areas, determined by estimated catchability (q) in the survey indices, was considered the major axis of uncertainty in this assessment. Several sensitivity analyses were done to evaluate the possible magnitude of this uncertainty. Relatedly, uncertainty in the relative biomass scales informed by catch and CPUE data between the historical (pre-1996) and modern (1995+) eras was also identified as a major axis of uncertainty, especially for Area 5ABCD.
- Due to uncertainty in model parameters, biological reference points based on equilibrium assumptions (e.g., maximum sustainable yield [MSY]) were not used. Instead, following the approach in previous stock assessments for Area 5CD, reference points were based on estimated historical biomass. For both stocks, the recommended upper stock reference (USR) is the average estimated biomass between 1956 and 2004; and the recommended limit reference point (LRP) is an agreed-upon undesirable low biomass state to be avoided (B_{2000} in Area 5ABCD; B_{1986} in Area 3CD). The recommended limit removal rate (LRR) is the average estimated fishing mortality between 1956 and 2004.
- For each of the two assessed stock areas, advice is provided as a decision table that summarizes the probability of breaching reference points over a range of fixed catch levels for a one-year projection using a model-averaging approach. The model- averaged decision tables were constructed using unweighted posterior samples from a reference case model and six sensitivity cases for each stock, to encompass the range of parameter uncertainty in the assessments.
- Model-averaged estimated biomass in Area 5ABCD declined after 2011, with a slight increase in the last two years of the time series. The model-averaged median estimate of 2018 biomass was above the median LRP but below the USR. Model-averaged estimated

annual recruitments were mostly below average during the last two decades of the time series.

- Model-averaged estimated biomass in Area 3CD declined after 2015. The model-averaged median estimate of 2018 biomass was above the median LRP but below the median USR. Model-averaged estimated annual recruitments were below average for most years in the last two decades in the time series.
- For Area 5ABCD, model-averaged biomass at the beginning of 2019 (B_{2019}) was projected to be 0.60 (0.39-1.01) of unfished biomass (B_0). For Area 3CD, model-averaged B_{2019} was projected to be 1.13 (0.78-1.73) of B_0. Proportions denote median (and 2.5 - 97.5 percentiles).
- It is recommended that the next assessment should occur after a suite of species, including Pacific Cod, is evaluated using a simulation-based management procedure approach for data limited and data moderate groundfish species, to be reviewed through the Canadian Science Advisory Secretariat (CSAS) in 2019/20. It is also recommended that any future updates to the current assessments should be done in years immediately following the biennial groundfish synoptic bottom trawl survey in each area (i.e., when the most recent survey index point is available).

INTRODUCTION

Biology and Stock Structure

Pacific Cod (*Gadus macrocephalus*) is a relatively short-lived, fast-growing member of the family Gadidae. Other common names in British Columbia (BC) include Grey Cod and Gray Cod. Populations of Pacific Cod are distributed from California, through waters off BC, the Gulf of Alaska and the Bering Sea to Russia, Korea, Japan and China. Maximum observed age in British Columbia is thought to be around 10-11 years, although the species is difficult to age. The maximum length recorded in British Columbia is 100 cm. Pacific Cod are demersal spawners, with spawning most likely occurring from February to March. Estimated population dynamics of BC Pacific Cod have been characterized by large apparent variations in abundance from the 1950s through the mid-1990s when the amplitude of variations in estimated abundance diminished markedly.

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). It is unclear whether these are biologically distinct populations. Recent genetic analyses have identified a distinction between North American and Asian Pacific Cod populations and have shown some evidence for distinction between Alaskan populations and those south of Dixon Entrance in British Columbia. There is also some evidence that fish taken off the coast of Washington and the West Coast of Vancouver Island may be distinct from fish sampled within the Strait of Georgia or Puget Sound. However, genetic linkages between stocks in BC and those in Alaska remain poorly understood.

Prey and Predators

Young Pacific Cod eat mainly marine invertebrates, including amphipods, krill, shrimp and crabs. At around 50-55 cm they also become piscivorous, with Pacific Sand Lance and Pacific Herring representing important components of their diet. Juvenile Sablefish and adult Pacific Hake have also been reported in the diet of Pacific Cod off the West Coast of Vancouver Island. Pacific Cod have been reported in the diets of Pacific Halibut, Pacific Spiny Dogfish, sea birds, seals and sea lions. It has been suggested that availability of Pacific Herring prey could be one driver of Pacific Cod production in Hecate Strait.

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. Currently, the majority of the BC fishery for Pacific Cod occurs in Hecate Strait and off southwest Vancouver Island. Pacific Cod are distributed throughout Hecate Strait, Queen Charlotte sound and off the west coast of Vancouver Island mainly at depths of 50-200m, although catches at greater depths have occurred.

Annual reported catches of Pacific Cod in Hecate Strait/Queen Charlotte Sound (5ABCD) and off the west coast of Vancouver Island (3CD) have shown considerable variability since the beginning of the time series in 1956 (Figure 2a, 2b). Bottom trawl fishing effort has been somewhat cyclic in all areas. In recent years of lower Pacific Cod quotas (post-2000), many fishing masters have reported active avoidance of Pacific Cod to prevent their individual quotas from being exceeded before catching available quotas for other species. Other factors, including changes in markets, participation in other fisheries, and avoidance of species such as Pacific Halibut, have also been identified as influencing effort in the Pacific Cod fishery.

Prior to 1988 the fishery was unrestricted with no established quota. Commencing in 1988, the fishery was managed using trip limits, then in 1992 an annual Total Allowable Catch (TAC) was introduced. This was followed by dockside monitoring, and the introduction of at-sea observers in 1996. Since 1996, the fishery has been subject to the following management measures: 100% at-sea monitoring using observers, 100% dockside monitoring, individual vessel accountability for all retained and released catch, individual transferable quotas, and reallocation of these quotas among vessels and groundfish sectors to cover catch of non-directed species (see DFO 2017). Pacific Cod can be legally discarded by trawlers in BC. However, on-board observers first estimate the quantity being discarded, assign it a discard mortality rate, and apply the resulting weight of fish attributable to fishing mortality against the vessel's Pacific Cod quota. The total 2018 TAC for Areas 5AB and 5CD combined was 950 metric tonnes (mt). The 2018 TAC for Area 3CD was 500 mt.

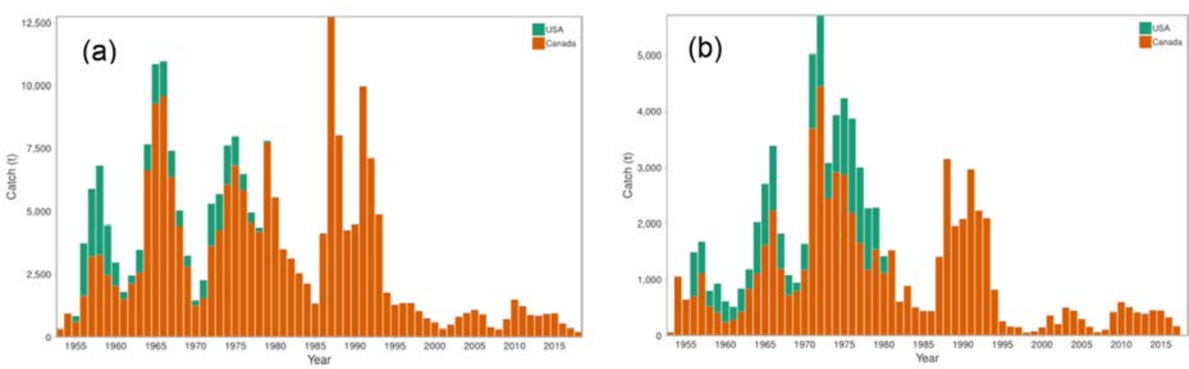

Figure 2: Pacific Cod catch records for the years 1956-2018 for (a) Area 5ABCD, and (b) Area 3CD. Canadian catch includes at-sea releases.

Ecosystem Considerations

In 2012, measures were introduced to reduce and manage the bycatch of corals and sponges in the BC groundfish bottom trawl fishery. These measures were developed jointly by the fishing industry and environmental non-governmental organisations, and include:

a. freezing the footprint of groundfish bottom trawl activities to reduce trawl fishery impacts on significant ecosystem components such as corals and sponges (Wallace et al. 2015);
b. establishing a combined bycatch conservation limit for corals and sponges; and
c. establishing an encounter protocol for individual trawl tows when the combined coral and sponge catch exceeds 20 kg.

These measures have been incorporated into Fisheries and Oceans Canada's (DFO's) Pacific Region Groundfish Integrated Fisheries Management Plan (DFO 2017).

ASSESSMENT

Sources of Data

Catch data were available from 1956 to 2018 (Figure 2), and included landings data from US (prior to 1981) and Canadian vessels, and estimates of at-sea releases (discards) from Canadian vessels. Prior to the introduction of 100% at-sea observer coverage in 1996, estimates of at-sea releases were obtained from fishing logbooks. Japanese and Soviet vessels also trawled in waters off BC in the late 1960s and early 1970s. These vessels were mainly targeting rockfish and were likely fishing at depths greater than 150 m. Bycatch of Pacific Cod in these fisheries is unknown. At the time of the assessment, the 2018 fishing year was incomplete. In order to provide projections for the 2019 fishing season, the 2018 catch was extrapolated in each area, based on average catches in the preceding years.

The stock assessment models for Areas 5ABCD and 3CD were fit to fishery-independent indices of abundance, mean annual weight in the commercial catch, and new standardized commercial catch-per-unit-effort (CPUE) indices that were developed using generalized linear mixed effect models (GLMMs) that assumed a Tweedie distribution. Updated estimates of growth parameters were also provided and incorporated into the models. Due to large changes in the databases and management of the fishery, separate commercial CPUE indices were developed for the "historical" period (prior to 1996) and the "modern" period (post-1995). Annual mean weights from the commercial fishery were calculated using a length-weight relationship applied to sampled commercial length data, using updated estimates of growth parameters.

Assessment Methodology

Pacific Cod stocks were assessed using Bayesian delay-difference models. The delay-difference model structure tracks the effects of recruitment, survival, and growth on biomass. This type of assessment modeling can perform well, as long as its major assumptions regarding constant growth, knife-edged maturity and fishery selectivity, and constant natural mortality are met. The models were conditioned on commercial catch data and fit to CPUE data, fishery-independent survey data, and annual estimated mean weights from the commercial fishery, as described above.

For each assessed stock, a reference case model and a set of sensitivity analyses were presented. For Area 5ABCD, the reference case model was fit to three fishery-independent abundance indices:

i. the Hecate Strait Multispecies Assemblage Trawl Survey;
ii. the Hecate Strait Synoptic Trawl Survey; and
iii. the Queen Charlotte Sound Synoptic Trawl Survey.

For Area 3CD, the reference model was fit to two fishery-independent abundance indices:

i. the West Coast Vancouver Island Synoptic Trawl Survey; and
ii. the US National Marine Fisheries Service (NMFS) Triennial Survey (in Canadian waters).

Reference case models for both stock areas assumed that the age of knife-edged recruitment to the fishery and spawning population occurred at age two years. This assumption was based on examination of available age and length data. Both reference case models were fit to two commercial CPUE indices ("historical" and "modern"). These indices were developed using GLMMs that assumed a Tweedie distribution and included a locality-year interaction term. Both reference case models used prior probability distributions for natural mortality (M), steepness of the Beverton-Holt stock-recruit relationship (h), and "catchability coefficients" (q), i.e., scaling parameters, for the synoptic survey indices. Prior probability distributions for M and h were based on those used in previous stock assessments for Pacific Cod. Prior probability distributions for survey catchability parameters were based on estimated values for other species in the same area (Area 5ABCD: Rock Sole (*Lepidopsetta* spp.); Area 3CD: Pacific Ocean Perch (*Sebastes alutus*)). Models were also fit to the annual mean weight in the commercial fishery data. Fixed values were assumed for observation and process error terms, and for the standard deviation used in the likelihood for the annual mean weight data. Fixed values were based on values used in previous assessments for Pacific Cod.

Sensitivity runs were done to evaluate the effect of certain model and data assumptions. These included:

- Exclusion of the locality-year interaction as a random effect in the commercial CPUE data in both the historical and modern periods.
- Exclusion of the commercial CPUE indices for the historical and/or modern periods.
- Exclusion of the NMFS Triennial Survey index for Area 3CD.
- Variation or removal of prior probability distributions for M, h, and the survey q parameters.
- Increasing the assumed age at knife-edged maturity and fishery selectivity to age three years.
- Evaluating the effects of the updated growth parameters (instead using parameters from the previous assessments of Pacific Cod).
- Variation in the assumed fixed value of observation and process errors in the model.
- Variation in the standard deviation used in the likelihood component for the annual mean weight data.
- Addition of an inflation factor to account for uncertainty in the total pre-1996 catch data.

The absolute scale of the estimated biomass in the two assessed areas, determined by estimated catchability (q) in the survey indices, was considered the major axis of uncertainty in this assessment. Several sensitivity analyses were done to evaluate the possible magnitude of this uncertainty. Relatedly, uncertainty in the relative scale of biomass between the historical and modern eras was also identified as an important axis of uncertainty, especially for Area 5ABCD.

Reference Points

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

i. an Upper Stock Reference point (USR);

ii. a Limit Reference Point (LRP); and

iii. a Limit Removal Rate (LRR).

Provisional values of USR = 0.8B_{MSY} and LRP = 0.4B_{MSY} are suggested in the absence of stock specific reference points, where B_{MSY} is the estimated long-term equilibrium biomass when the stock is fished at the fishing mortality rate corresponding to maximum sustainable yield (F_{MSY}).

Previous assessments found that estimates of MSY-based reference points, or those based on B_0, for Hecate Strait Pacific Cod are sensitive to uncertainties for natural mortality and stock-recruitment assumptions (e.g., Sinclair and Starr 2005; Forrest et al., 2015). The use of MSY-based or B_0- based reference points were therefore not supported for this stock. Alternative "historical" reference points based on metrics of estimated biomass were therefore applied in the current assessments for stocks in Areas 5ABCD and 3CD, based on the approach accepted in the previous assessments for Area 5CD Pacific Cod (Sinclair and Starr 2005; Forrest et al., 2015). The USR and LRR for both Areas 5ABCD and 3CD were defined as: USR = the estimated average biomass for the period 1956 to 2004; and LRR = the estimated average fishing mortality for the period 1956-2004.

Proposed LRPs represent agreed-upon undesirable biomass states to be avoided. For Area 5ABCD, the previous assessment of Area 5CD Pacific Cod (Forrest et al. 2015) recommended B_{1971} as the LRP, which represented a low biomass level from which the stock subsequently recovered to an above average level. During the 2018 regional peer review (RPR) meeting, reviewers and participants questioned whether 1971 truly represented an undesirable state, since estimated 1971 biomass was greater than any estimated biomass since 1995. RPR participants agreed that a more defensible undesirable biomass state occurred in the year 2000, which precipitated a large cut in TAC from 1,000 mt to 200 mt in 2001. Therefore B_{2000} is recommended as the LRP for Area 5ABCD. Authors and RPR participants agreed that more work is needed to develop biological reference points for Pacific Cod, particularly development of conservation and economic objectives for the stocks.

For Area 3CD, B_{1986} was selected as recommended LRP, representing a historically low (undesirable) biomass state from which the stock recovered to above average.

In summary, the recommended reference points for each stock are:

- Area 5ABCD

  USR = estimated average biomass for the period 1956 to 2004;

  LRP = a low biomass level agreed to be an undesirable state to avoid (B_{2000}); and

  LRR = estimated average fishing mortality for the period 1956-2004.

- Area 3CD

  USR = estimated average biomass for the period 1956 to 2004;

LRP = a low biomass level agreed to be an undesirable state to avoid (B_{1986}); and

LRR = estimated average fishing mortality for the period 1956-2004.

RESULTS

Model Averaging

Given large uncertainty in model results across the sensitivity cases for each stock, a model-averaging approach was used for presenting model results and harvest advice. Model-averaged estimates of biomass, recruitment, stock status and reference points were constructed using unweighted combined posterior samples from the reference case and six sensitivity cases (scenarios) for each stock, to encompass the range of parameter uncertainty in the assessments. Similarly, decision tables summarizing the probability of breaching reference points over a range of fixed catches for a one-year projection were constructed using the unweighted combined posterior samples from the model-averaged set. The set of sensitivity cases included in the model-averaging set was agreed upon and refined by RPR participants.

For Area 5ABCD, the scenarios (Sc) included in the model-averaging set were:

- Sc 1a Reference model
- Sc 2d Set the mean of the prior probability distribution for synoptic survey ln(q) = ln(1.0) (pro-rated by depth-stratum areas of Area 5AB and 5CD)
- Sc 2e Increase the standard deviation (SD) for synoptic survey ln(q) to 0.6.
- Sc 3a Set the parameters of the prior probability distribution for ln(M) to mean = ln(0.4), SD = 0.1
- Sc 5a Set knife-edged age at recruitment = 3 years
- Sc 6b Reduce the overall observation error term σO = 0.15
- Sc 7b Reduce the SD in the likelihood for the fit to average annual mean weight σW = 0.15

For Area 3CD, the scenarios (Sc) included in the model-averaging set were:

- Sc 1a Reference model
- Sc 2d Set the mean of the prior probability distribution for synoptic survey ln(q) = ln(1.0)
- Sc 2e Increase the standard deviation (SD) for synoptic survey ln(q) to 0.6.
- Sc 3a Set the parameters of the prior probability distribution for ln(*M*) to mean = ln(0.4), SD = 0.1
- Sc 5a Set knife-edged age at recruitment = 3 years
- Sc 6b Reduce the overall observation term σ_O = 0.15
- Sc 7b Reduce the SD in the likelihood for the fit to average annual mean weight σ_W = 0.15

Estimated Biomass and Stock Status

Model-averaged estimated biomass in Area 5ABCD declined after 2011, with a slight increase in the last two years of the time series (Figure 3a). The biomass at the beginning of 2019 (B_{2019}) was forecast to be 15,687 mt (8,701 mt – 33,340 mt), where numbers denote median (and 2.5 – 97.5 percentiles). The model-averaged median estimate of 2018 biomass was above the median LRP but below the median USR. Model-averaged estimated annual recruitments have been mostly below average for the past two decades (Figure 4a).

Model-averaged estimated biomass in Area 3CD has declined since 2015 (Figure 3b). B_{2019} was projected to be 16,817 mt (7,100 mt – 57,754 mt). The model-averaged median estimate of 2018 biomass was above the median LRP but below the median USR. Model-averaged estimated annual recruitments have been below average for most years in the past two decades, with the exception of 2009, 2013 and 2014 (Figure 4b).

Estimated stock status biomass levels and reference points from the model-averaged stock assessments of Area 5ABCD and 3CD are summarized in Table 1. For Area 5ABCD, model-averaged B_{2019} was projected to be 0.60 (0.39-1.01) of unfished biomass (B_0). For Area 3CD, model-averaged B_{2019} was projected to be 1.13 (0.78-1.73) of B_0. Proportions denote median (and 2.5 - 97.5 percentiles).

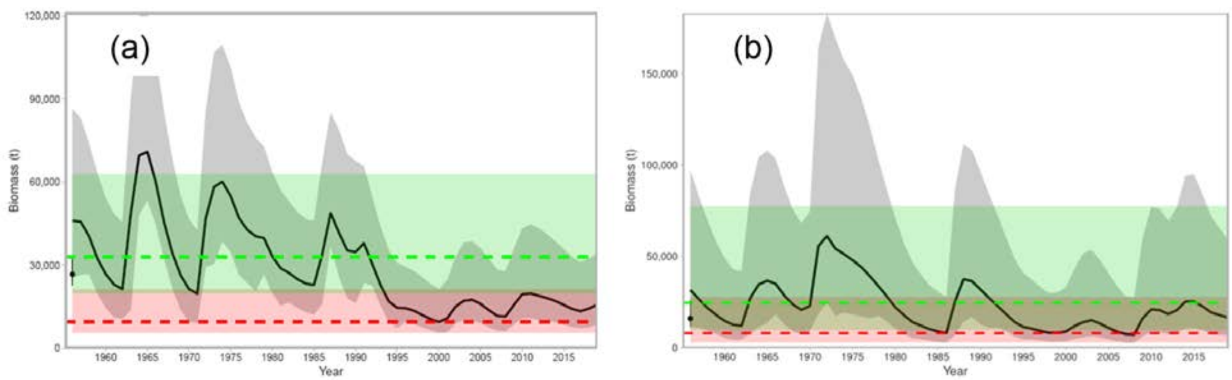

Figure 3. Model-averaged posterior estimated biomass (median and 95% credible interval) for (a) Area 5ABCD; and (b) Area 3CD. The dashed green lines show the USR, the dashed red lines show the LRP. The shaded areas around the reference point lines show the 95% credible intervals.

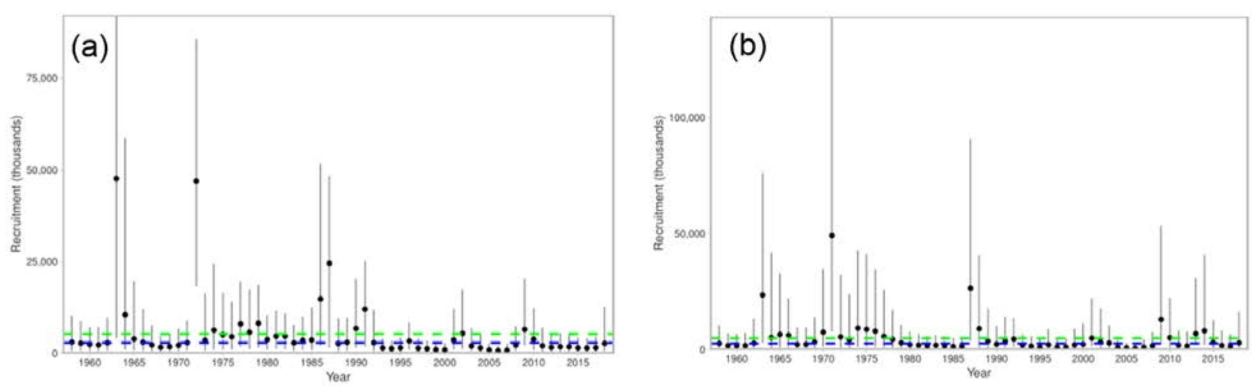

Figure 4. Model-averaged posterior estimated recruits (median and 95% credible interval) for (a) Area 5ABCD and (b) Area 3CD. The dashed green line is the median of the posterior medians and the dashed blue line is the mean of the posterior medians.

Table 1: Model-averaged posterior estimated biomass and reference points (2.5th, 50th, and 97.5th percentiles) for (left) Area 5ABCD and (right) Area 3CD. Biomass is in metric tonnes.

Reference Point	2.5%	50%	97.5%
B_0	18,872.55	26,072.95	39,743.86
B_{1956}	25,747.48	46,965.35	84,161.39
B_{2019}	8,701.41	15,687.40	33,339.51
B_{2019}/B_0	0.39	0.60	1.01
B_{2019}/B_{1956}	0.20	0.34	0.64
F_{2018}	0.01	0.02	0.04
LRP (2000)	5,563	9,762	20,781
USR (1956–2004)	20,048	33,780	61,615

Reference Point	2.5%	50%	97.5%
B_0	8,154.83	14,548.70	41,282.42
B_{1956}	11,727.18	32,454.22	94,423.73
B_{2019}	7,100.31	16,817.45	57,754.00
B_{2019}/B_0	0.78	1.13	1.73
B_{2019}/B_{1956}	0.32	0.53	0.98
F_{2018}	0.00	0.01	0.03
LRP (1986)	2,859	8,108	26,730
USR (1956–2004)	9,952	24,982	74,478

Harvest Advice

For each of the two areas, harvest advice is provided in a decision table, using a model-averaging approach. The decision tables summarize the probabilities of breaching reference points over a range of alternative 2019 catch levels (ranging from 0 mt to approximately three times the 2018 TAC for each area). The probabilities in the model-averaged decision tables were constructed using unweighted combined posterior samples from the reference case and six sensitivity cases (see Model averaging section). Model-averaged projected 2020 biomass over a selected range of 2019 catch levels for each area is shown in Figure 5.

Decision tables show estimated probabilities of:

- biomass decreasing between 2019 and 2020: $P(B_{2020}<B_{2019})$;
- fishing mortality in 2019 exceeding fishing mortality in 2018: $P(F_{2019}>F_{2018})$;
- biomass in 2020 being below the LRP: $P(B_{2020}<LRP)$;
- biomass in 2020 being below the USR: $P(B_{2020}<USR)$; and
- fishing mortality in 2019 exceeding the LRR: $P(F_{2019}>LRR)$.

The model-averaged decision table for Area 5ABCD for a range of projected 2019 catch levels (0 mt to 3,000 mt) is provided in Table 2. In summary:

- $P(B_{2020}<B_{2019})$ ranged from 12% to 89% over the range of 2019 catch levels.
- $P(F_{2019}>F_{2018})$ ranged from < 1% to > 99%. The 2018 catch was extrapolated to be approximately 200 mt, hence the probability increase between 200 mt and 300 mt
- $P(B_{2020}<LRP)$ ranged from <1% to 11%.
- $P(B_{2020}<USR)$ ranged from 98% to 99%.
- $P(F_{2019}>LRR)$ ranged from <1% to 95%.

The model-averaged decision table for Area 3CD for a range of projected 2019 catch levels (0 mt to 1500 mt) is provided in Table 3. In summary:

- $P(B_{2020}<B_{2019})$ ranged from 76% to 89% over the range of 2019 catch levels.
- $P(F_{2019}>F_{2018})$ ranged from < 1% to > 99%. The 2018 catch was extrapolated to be approximately 164 mt, hence the probability increase between 100 mt and 200 mt
- $P(B_{2020}<LRP)$ ranged from <1% to 1%.
- $P(B_{2020}<USR)$ ranged from 95% to 97%.
- $P(F_{2019}>LRR)$ ranged from <1% to 96%.

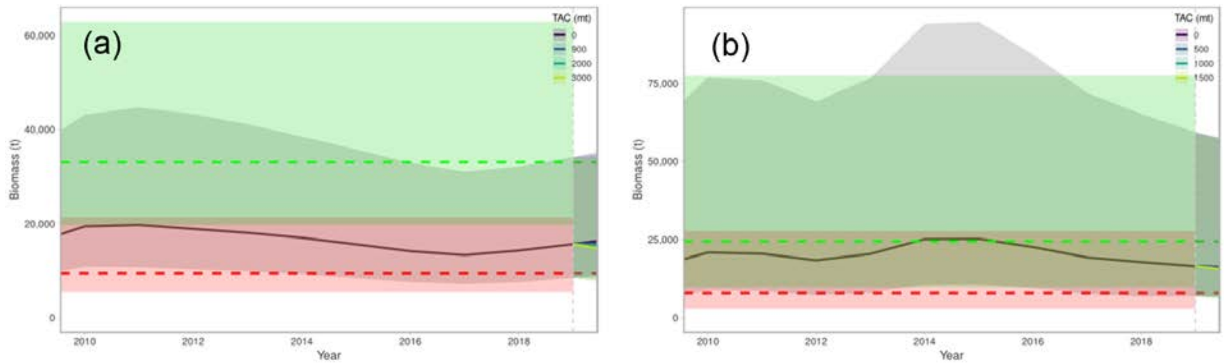

Figure 5. Model-averaged estimated biomass for 2010-2018 with projection to 2020 for (a) Area 5ABCD and b) Area 3CD. The dashed green lines show the USR, the dashed red lines show the LRP. The shaded areas around the reference point lines show the 95% credible intervals.

Table 2: Model-averaged decision table for Area 5ABCD.

2019 Catch (mt)	$P(B_{2020}<B_{2019})$	$P(F_{2019}>F_{2018})$	$P(B_{2020}<LRP)$	$P(B_{2020}<USR)$	$P(F_{2019}>LRR)$
0	0.12	<0.01	<0.01	0.98	<0.01
100	0.14	<0.01	<0.01	0.98	<0.01
200	0.17	<0.01	<0.01	0.99	<0.01
300	0.21	0.98	<0.01	0.99	<0.01
400	0.25	>0.99	<0.01	0.99	<0.01
500	0.29	>0.99	0.01	0.99	<0.01
600	0.34	>0.99	0.01	0.99	<0.01
700	0.38	>0.99	0.01	0.99	<0.01
800	0.43	>0.99	0.01	0.99	<0.01
900	0.47	>0.99	0.01	0.99	<0.01
1,000	0.52	>0.99	0.01	0.99	<0.01
1,100	0.56	>0.99	0.01	0.99	0.01
1,200	0.60	>0.99	0.02	0.99	0.02
1,300	0.63	>0.99	0.02	0.99	0.04
1,400	0.66	>0.99	0.02	0.99	0.08
1,500	0.69	>0.99	0.02	0.99	0.14
1,600	0.71	>0.99	0.03	0.99	0.22
1,700	0.74	>0.99	0.03	0.99	0.31
1,800	0.75	>0.99	0.03	0.99	0.40
1,900	0.78	>0.99	0.04	0.99	0.50
2,000	0.79	>0.99	0.04	0.99	0.58
2,100	0.81	>0.99	0.05	0.99	0.66
2,200	0.82	>0.99	0.05	0.99	0.73
2,300	0.83	>0.99	0.06	0.99	0.78
2,400	0.84	>0.99	0.07	0.99	0.83
2,500	0.85	>0.99	0.07	0.99	0.86
2,600	0.86	>0.99	0.08	0.99	0.89
2,700	0.87	>0.99	0.09	0.99	0.91
2,800	0.88	>0.99	0.09	0.99	0.93
2,900	0.89	>0.99	0.10	0.99	0.94
3,000	0.89	>0.99	0.11	0.99	0.95

Table 3: Decision table with model averaging for Area 3CD.

2019 Catch (mt)	$P(B_{2020}<B_{2019})$	$P(F_{2019}>F_{2018})$	$P(B_{2020}<LRP)$	$P(B_{2020}<USR)$	$P(F_{2019}>LRR)$
0	0.76	<0.01	<0.01	0.95	<0.01
100	0.77	<0.01	<0.01	0.95	<0.01
200	0.79	>0.99	<0.01	0.95	<0.01
300	0.80	>0.99	<0.01	0.96	<0.01
400	0.81	>0.99	<0.01	0.96	<0.01
500	0.82	>0.99	<0.01	0.96	<0.01
600	0.83	>0.99	<0.01	0.96	0.01
700	0.84	>0.99	<0.01	0.96	0.05
800	0.85	>0.99	<0.01	0.96	0.18
900	0.86	>0.99	0.01	0.96	0.36
1,000	0.87	>0.99	0.01	0.96	0.55
1,100	0.87	>0.99	0.01	0.96	0.71
1,200	0.88	>0.99	0.01	0.96	0.83
1,300	0.88	>0.99	0.01	0.97	0.90
1,400	0.89	>0.99	0.01	0.97	0.94
1,500	0.89	>0.99	0.01	0.97	0.96

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, results from seven alternative model configurations were used 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:

i. the lack of reliable age composition data for this species, which would provide additional information about recruitment strength and gear selectivity;

ii. relatively short time series of fishery-independent abundance indices, which show no clear trend;

iii. possible bias in the length frequency data prior to 1996, due to possible under-representation of lengths of fish that were caught but discarded at sea;

iv. a poor understanding of Pacific Cod stock structure in Pacific waters; and

v. 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.

A comparison of length-frequency data from the fishery with data from the surveys suggests that the survey selects younger fish than the fishery. Changes to management and fishery practices since the 1950s have almost certainly resulted in changes to fishery selectivity throughout the time series, due to changes in mesh size and potential changes in the spatial distribution of fishing effort (e.g. avoidance of known “hot spots” for Pacific Cod). Therefore, the delay-difference model’s assumption of time-invariant, knife-edged selectivity at age two years is almost certainly violated for this stock.

Furthermore, it is unclear whether Pacific Cod in each of the assessment areas are biologically distinct from other BC and/or Alaskan stocks, which has implications for conclusions based on local estimates of stock productivity and biomass. External drivers, including environmental influences (e.g., larval water transport) and predator-prey dynamics, have been suggested as mechanisms that affect Pacific Cod productivity, and provide additional uncertainty to understanding stock dynamics.

Feedback simulation modelling (a component of Management Strategy Evaluation) is recommended to evaluate the performance of alternative management procedures for Pacific Cod under a range of structural uncertainties (e.g., Forrest et al., 2018), including time-varying selectivity, alternative representations of stock structure and alternative drivers of productivity, such as environmental forcing.

OTHER CONSIDERATIONS

Environment

A number of studies have found correlations between recruitment and environmental indices for Pacific Cod in Hecate Strait. The current dominant hypothesis is an inverse relationship between recruitment and northward water transport of larvae. Northward water transport has been shown to be positively correlated with mean annual sea level at Prince Rupert during the spawning season, which in turn has been used as an explanatory variable for recruitment in previous studies.

It is not known how climate change will affect this species and the conclusions of this stock assessment. Although there is agreement that warmer temperature regimes will affect marine species, the exact nature of these effects is poorly understood.

CONCLUSIONS AND ADVICE

Despite large uncertainty in the assessments, biomass of Pacific Cod in Areas 5ABCD and 3CD is estimated to be declining following brief periods of rebuilding. In both areas recruitment is estimated to have been below the estimated long-term (56-year) average in most years for the past two decades.

The use of MSY-based and B_0-based reference points could not be supported for these stocks. Alternative “historical” reference points were used based on those accepted for the previous assessments or on the advice received during the RPR meeting.

Advice to managers is provided in decision tables (Tables 2 and 3) that summarize the probability of breaching reference points over a range of 2019 catches for a one-year projection. The decision tables use a model-averaging approach intended to integrate uncertainty captured in seven alternative model scenarios.

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SOURCES OF INFORMATION

This Science Advisory Report is from the October 10-11, 2018 regional peer review on the Assessment of British Columbia Pacific Cod for Areas 3CD, and 5ABCD in 2018. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

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