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**Pacific Region**

**Canadian Science Advisory Secretariat**
**Science Advisory Report 2015/027**

# ASSESSMENT OF PACIFIC COD (*GADUS MACROCEPHALUS*) FOR QUEEN CHARLOTTE SOUND (AREA 5AB) IN 2013

*Pacific Cod (Gadus macrocephalus). Credit: Fisheries and Oceans Canada (DFO).*

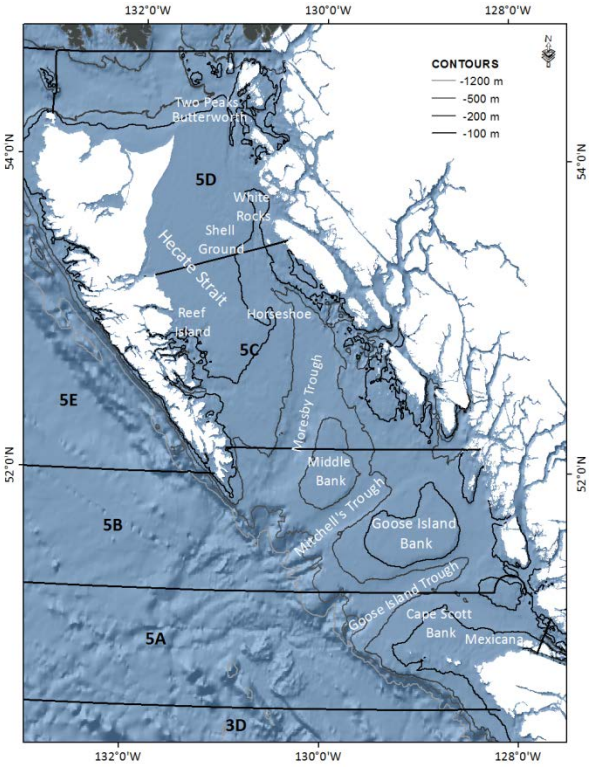


*Figure 1. Pacific Marine Fisheries Commission major management areas north of Vancouver Island (indicated by straight black lines). Key Pacific Cod fishing locations are indicated in white text. This assessment refers to Area 5AB only.*

## Context

*Pacific Cod (Gadus macrocephalus) is a commercially important species of cod that occurs along the entire coast of British Columbia. It is primarily caught by the groundfish trawl fishery and occasionally by the hook and line fishery, with most catch being taken from Hecate Strait (Area 5CD). This assessment refers to Queen Charlotte Sound (Area 5AB). The Hecate Strait stock was assessed in 2013. Advice was requested by Fisheries Management (FM) on the current stock status and potential yields for Pacific Cod in the waters of British Columbia.*

*This Science Advisory Report is from the December 8th, 2014 Pacific Cod (Gadus macrocephalus) Assessment for Queen Charlotte Sound (5AB), British Columbia in 2013. 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 species of cod that occurs along the entire coast of British Columbia (BC). It is primarily caught by the groundfish trawl fishery and occasionally by the hook and line fishery. The majority of catches are taken in Hecate Strait (Area 5CD, ~700 t in 2013) and Queen Charlotte Sound (Area 5AB, ~180 t in 2013), although large catches were taken historically off the west coast of Vancouver Island (Area 3CD).
- This advisory report refers to the Queen Charlotte Sound (5AB) stock after revisions to the 2013 assessment.
- Pacific Cod stocks in BC are difficult to assess, primarily due to the relatively short time series of fishery-independent indices of abundance, changes in fishery selectivity over time, and historical changes in management and fishery operations. Historical management changes include the transition to quotas (between the early 1990s and 1997), the introduction of 100% at-sea observer coverage (February 1996), and several voluntary and regulation mesh-size changes. There are very few survey age composition data for this difficult-to-age species, and no age composition data from the commercial fishery.
- The status of the Pacific Cod populations in 5AB was assessed using a Bayesian delay-difference model fit to fishery-independent survey data, commercial catch-per-unit-effort data, commercial catch data, and estimates of annual mean weights from the trawl fishery.
- Despite large uncertainty, biomass in 5AB is estimated to have been stable since 2001 on, but is estimated to be below the historical average.
- Advice to managers is provided in a decision table that summarizes the probability of breaching reference points at a range of fixed catches for a one-year projection. Due to model sensitivity to a number of model assumptions, the table uses a model-averaging approach intended to integrate results across a range of alternative model assumptions.
- Estimates of fishery reference points based on maximum sustainable yield (MSY) were very sensitive to model assumptions, and differed substantially among model sensitivity cases. Unfished biomass ($B_0$) was also sensitive to model assumptions. The use of reference points based on MSY and $B_0$ are consequently not supported for this stock.
- Alternative reference points based on estimates of average historical biomass, similar to those adopted for Pacific Cod in Area 5CD, were explored. However, the history-based reference points were problematic for Area 5AB because the historical period chosen (1956-2004) occurred during a time when fleet behaviour differed significantly from recent years. Currently, many vessels in Area 5AB actively avoid Pacific Cod due to low quotas. This was not the case in the historical period, when vessels actively targeted Pacific Cod. Using a more recent period to define the history-based reference points was also problematic, as the resulting estimates of average biomass were very low and were considered to be inconsistent with a precautionary decision-making framework. The historical biomass-based reference points were therefore rejected for use in Area 5AB.
- Estimated fishing mortality rates were fairly constant over the whole time series and were reasonably robust across a range of model assumptions. Therefore, a provisional, model-averaged reference point based on the average estimated fishing mortality for the period 1956-2004 ($F_{avg(1956\text{-}2004)}$) was adopted.
- A suggested harvest strategy in the short-term is therefore to continue harvesting at the current levels (200 t), which currently results in approximately $F = 0.3$, until a limit condition triggers a catch reduction strategy. A suitable trigger for precautionary action could occur when any new index point in the QCS Synoptic survey (after 2013) falls below 50% of the mean survey indices

prior to the new index point. Additionally, the stock assessment should be updated on an annual or biennial basis to evaluate the probability that the *F*-based reference point has been breached.

# INTRODUCTION

## Biology and Stock Structure

Pacific Cod (*Ga*dus 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, throughout BC waters and into the Gulf of Alaska, Bering Sea, Russia, Korea, Japan and China. Maximum observed age in BC is approximately 10-11 years; maximum length recorded in BC is 100 cm. Pacific Cod is a demersal spawner, with spawning most likely occurring from February to March. Population dynamics of Pacific Cod in BC have been characterized by large apparent variations in abundance since the 1950s.

Four stocks of Pacific Cod are defined for management purposes along the BC coast: Strait of Georgia (4B); West Coast Vancouver Island (3CD); Queen Charlotte Sound (5AB); and Hecate Strait (5CD), although it is unclear whether these groupings form biologically distinct populations. Recent genetic analyses have identified a distinction between North American and Asian Pacific Cod populations, and have shown some evidence for a distinction between Alaskan populations and those south of Dixon Entrance in BC. There is also some evidence that fish off the coast of Washington and off the west coast of Vancouver Island may be distinct from those sampled within the Strait of Georgia or Puget Sound. However, genetic linkages between stocks in BC and Alaska remain poorly understood.

## 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 2014). Currently, the majority of the BC fishery for Pacific Cod occurs in Hecate Strait (Figure 1). In Queen Charlotte Sound (QCS), this species is caught mainly around the edge of Goose Island Bank in Area 5B and off Cape Scott and on Mexicana Banks, north of Vancouver Island, in Area 5A (Figure 1). The depth range of capture is approximately 60-160 m.

Annual reported catches of Pacific Cod in QCS have shown considerable variability since the beginning of the time series in 1956 (Figure 3a, Tables 1 and 2). The estimated proportion of the total catch taken by the American fleet was 50% from 1956 to 1980. Japanese and Soviet vessels also trawled in waters off BC in the late 1960s and early 1970s. These vessels were mainly targeting rockfish (*Sebastes* spp.) and likely fishing at depths greater than 150 m. The bycatch of Pacific Cod in these fisheries remains unknown. Given uncertainty in foreign catches and discards in the earlier parts of the time series, total catch estimates should be considered underestimates prior to 1996.

Total effort of all trawl vessels has declined in 5AB since peaking in 1995 (Figure 3b). In recent years of lower Pacific Cod quotas, many fishing masters have reported active avoidance of Pacific Cod to prevent their quota being exceeded before catching available quotas of other species. Other factors including changes in markets, introduction of individual quotas, participation in other fisheries, and avoidance of species such as Pacific Halibut (*Hippoglossus stenolepis*), have been identified as factors influencing effort in the Pacific Cod fishery.

Since 1995, the fishery has been subject to the following management measures: 100% at-sea monitoring; 100% dockside monitoring; individual vessel accountability for all retained and released catch; individual transferable quotas; and reallocation of these quotas among vessels (DFO 2014). Pacific Cod can be legally discarded by trawlers in BC. However, on-board observers first estimate the quantity being discarded and assign an estimated discard mortality rate, which is counted against the vessel's Pacific Cod quota.

In 2012, measures were introduced to reduce and manage the bycatch of corals and sponges by the BC groundfish bottom trawl fishery. These measures were developed jointly by DFO, the fishing industry and environmental non-governmental organizations. They include: limiting the footprint of groundfish bottom trawl activities; establishing a combined bycatch conservation limit for corals and sponges; and defining encounter protocols. These measures have been incorporated into DFO's Pacific Region Integrated Fisheries Management Plan for Groundfish (DFO 2014).

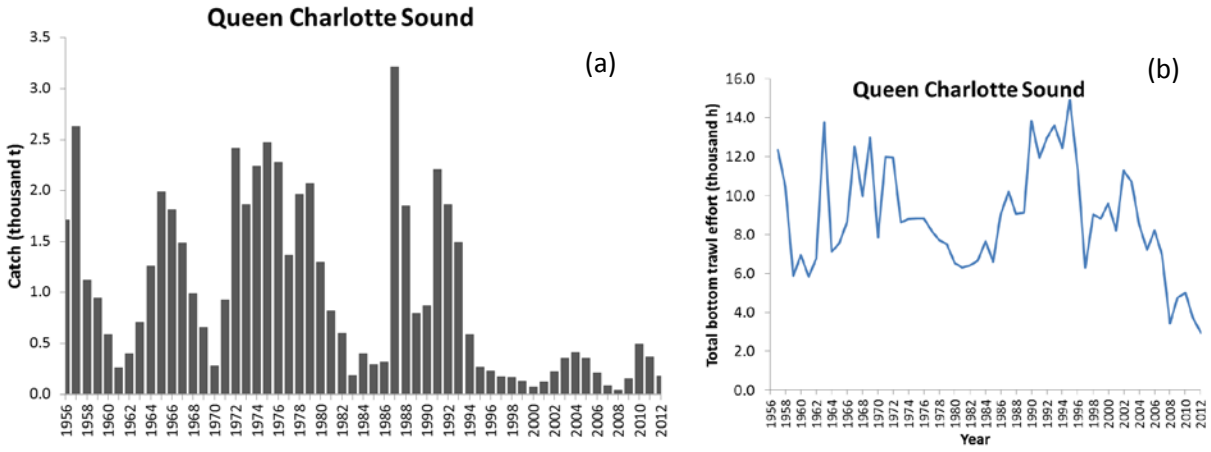


*Figure 2 (a) Total catches (thousand tonnes) of Pacific Cod during the period 1956-2012 in Queen Charlotte Sound. Catches represent the sum of landings from US and Canadian vessels, and estimated at-sea releases from Canadian vessels. Landings from US vessels ceased after 1978. (b) Annual trends in total bottom trawl fishing effort (thousands of hours) in Queen Charlotte Sound.*

## ASSESSMENT

The status of the Pacific Cod population in QCS was assessed using a Bayesian delay-difference model. The delay-difference model structure tracks the effects of recruitment, survival, and growth on biomass, without requiring an explicitly age-structured framework, and can perform well as long as its major assumptions regarding constant growth, knife-edged fishery selectivity and constant natural mortality are met. The model was conditioned on commercial catch data and fit to commercial catch-per-unit-effort (CPUE) data; fishery-independent survey data; and annual estimated mean weights from the commercial fishery.

A Reference Case model and a set of sensitivity analyses were reviewed. Model sensitivity was tested to alternative weightings of the index of abundance data, values of fixed variance parameters, and prior probability distributions used for key model parameters, notably natural mortality. Advice to managers is provided using a decision table that summarizes the probability of breaching fishing mortality-based reference points (see below) for a range of fixed catches over a one-year projection. Due to model sensitivity to a number of model assumptions, the decision table uses a model-averaging approach intended to integrate results across alternative model assumptions.

The model was fit to an index of CPUE data derived from key Pacific Cod fishing locations, recognizing a number of problems associated with the use of commercial CPUE data as an index of abundance. Primary among these are changes in management regime from an unrestricted fishery to the introduction of TACs (1992-1996) and Individual Vessel Quotas (IVQs, 1997-present) as well as several voluntary and mandatory increases in net mesh size. The CPUE time series used in the model spanned the period 1956 to 1995, the year before the introduction of 100% at-sea observer coverage in the fishery.

One suitable fishery-independent abundance index series was available for the assessment: the Queen Charlotte Sound synoptic groundfish trawl survey (conducted in 2003, 2004, and then biennially from 2005 to 2013). Annual mean weights from the commercial fishery were estimated using sampled commercial length data and published estimates of growth parameters.

## Reference Points

The DFO decision-making framework (DFO 2009) requires stock status to be characterized using the best available reference points, defaulting to a limit reference point of $0.4B_{MSY}$ and an upper stock reference point of $0.8B_{MSY}$, where $B_{MSY}$ is the estimated long-term equilibrium biomass when the stock is fished at maximum sustainable yield (MSY).

Large uncertainties in the parameters for natural mortality and steepness of the stock-recruit relationship have resulted in substantial uncertainties in MSY-based reference points for Pacific Cod in previous assessments (e.g., Sinclair and Starr 2005). In the current assessment, estimates of fishery reference points based on MSY were very sensitive to model assumptions, and differed substantially among model sensitivity cases. Estimated equilibrium unfished biomass ($B_0$) was also sensitive to model assumptions. The use of reference points based on MSY or $B_0$ were therefore not supported for this stock.

Alternative "history-based" reference points were developed for the first time for the Area 5AB stock, which paralleled reference points established for the 5CD stock (DFO 2015), which in turn were based on those established by Sinclair and Starr (2005) for Area 5CD and accepted by the participants of the 2005 Groundfish Subcommittee Meeting (Fargo 2005). The set of "history-based" reference points explored were:

(i) an Upper Stock Reference (USR) point based on the estimated average biomass for the period 1956 to 2004;

(ii) a Limit Reference Point (LRP) defined as the estimated minimum biomass from which the stock recovered to an above-average biomass level (in Area 5AB, the estimated biomass in 1985); and

(iii) a Limit Removal Rate (LRR) calculated as the estimated average fishing mortality for the period 1956-2004.

*Table 1. Provisional reference points from the Reference Case model as 2.5, 25, 50, 75 and 97.5 percentiles. Medians ($50^{th}$ percentiles) are highlighted in bold. $F_{2013}$ is the fishing mortality in 2013 and $F_{avg}$ = average fishing mortality from 1956-2004 (and 1956-2012).*

| Reference point | 2.5% | 25% | 50% | 75% | 97.5% |
|---|---|---|---|---|---|
| $F_{2013}$ | 0.111 | 0.226 | **0.289** | 0.373 | 0.616 |
| $F_{avg[1956-2004]}$ | 0.210 | 0.272 | **0.305** | 0.337 | 0.411 |
| $F_{avg[1956-2012]}$ | 0.207 | 0.269 | **0.305** | 0.341 | 0.420 |

The history-based reference points were problematic for Area 5AB because the historical period chosen (1956-2004) occurred during a time when fleet behaviour differed significantly from that in recent years. Currently, many vessels in Area 5AB actively avoid Pacific Cod due to low quotas there. This was not the case in the historical period, when vessels actively targeted Pacific Cod. Using a more recent period to define the history-based reference points was also problematic, as the resulting estimates of average biomass were very low and were considered to be inconsistent with a precautionary decision-making framework. The historical biomass-based reference points were therefore rejected for use in Area 5AB. On the other hand, estimated fishing mortality rates were fairly

constant over the whole time series (Table 1) and were reasonably robust across a range of model assumptions. Therefore, a provisional, model-averaged reference point based on the average estimated fishing mortality for the period 1956-2004 ($F_{avg(1956-2004)}$) was adopted (Table 2).

## Model Results

Despite large uncertainty, Pacific Cod biomass in Queen Charlotte Sound is estimated by the Reference Case model to have been below the historical average since the mid-1990s, and biomass is currently estimated to be below the median biomass minimum, $B_{1985}$ (Figure 3a). The biomass at the beginning of 2014 ($B_{2014}$) was estimated to be 1,328 t (582 t – 3,601 t), where numbers denote median estimates (2.5-97.5 percentiles) from the Bayesian posterior results (Figure 3b). It is possible that estimated low biomasses in recent years are informed by low catches resulting from active avoidance of Pacific Cod by the fleet, discussed above.

Model estimates of biomass and current stock status were explored and found to be very sensitive to a number of model assumptions. Results were most sensitive to assumptions about the prior probability distribution for log natural mortality, the influence of the mean weight data, reducing the overall standard deviation in observation residuals, and including recent commercial CPUE data (1996 on) as an index of abundance. Sensitivity analyses were done to explore the effects of these assumptions. Posterior results from the Reference Case and the four sensitivity analyses were combined and incorporated into model-averaged advice to managers.

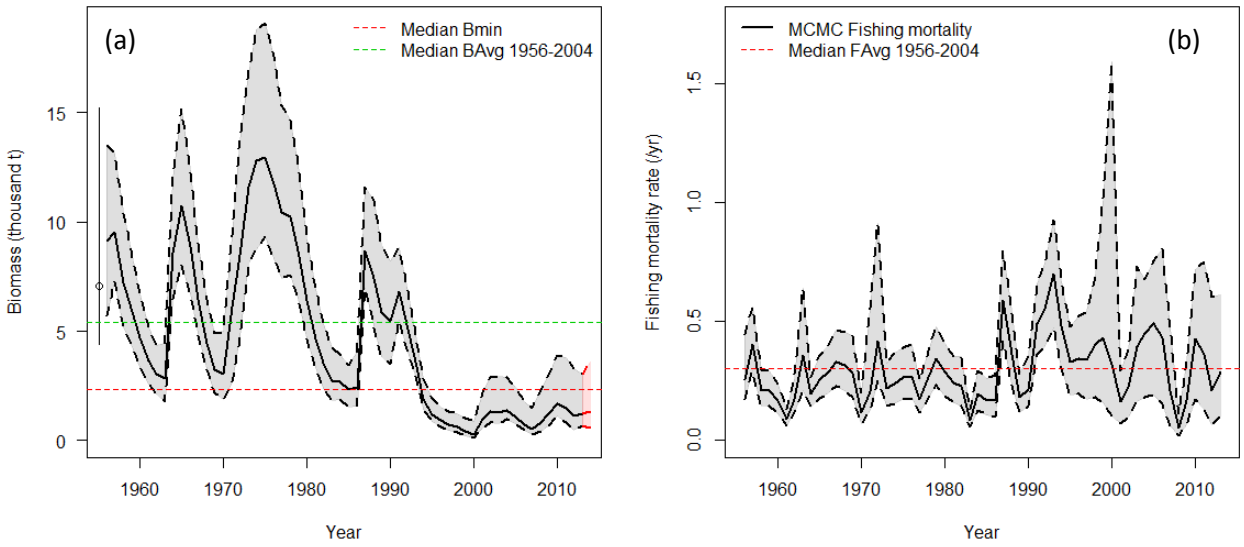


*Figure 3. (a) Estimates of biomass (1000 t) for the Reference Case model, shown as medians (solid line) and 95% credibility intervals (2.5 to 97.5 percentiles in grey), with the 2014 projected biomass in red. Estimated equilibrium unfished biomass, $B_0$, shown as median (open circle) and 95% credibility interval. Horizontal lines are median estimates of the USR (green) and LRP (red). (b) Estimates of fishing mortality for the Reference Case model with 95% credibility intervals. The median estimate of the proposed LRR, $F_{avg[1956-2004]}$ is shown as a red broken line.*

## Harvest Advice

Harvest advice is given in the form of a decision table that summarizes the probability of breaching fishing mortality-based reference points for a range of fixed catch levels that were projected for one year (Table 2). Due to the model's sensitivity to a number of assumptions, the table uses a model-

averaging approach intended to integrate uncertainty among the five alternative model configurations, including the Reference Case (Figure 3b).

Table 2 shows estimated probabilities of the expected fishing mortality in 2014 ($F_{2014}$) exceeding that for the current year ($F_{2013}$) and for the average over 1956-2004 ($F_{avg}$) for a range of projected catch levels in 2014. Probabilities represent the proportion of the posterior samples of $F_{2014}$ from the five model configurations that exceeded each fishing mortality-based reference point. The model used log recruitment anomalies in 2015 drawn randomly from a normal distribution.

From the projections, the probability of $F_{2014} > F_{2013}$ ($P(F_{2014} > F_{2013})$) under a 2014 catch level of 600 t (current TAC) is estimated to be 0.998 and $P(F_{2014} > F_{avg})$ is estimated to be 0.877 (Table 2). If 2014 catch is closer to that taken in 2013 (200 t), the probabilities of the projected fishing mortality rate exceeding the reference rates are lower: $P(F_{2014} > F_{2013}) = 0.077$ and $P(F_{2014} > F_{avg}) = 0.201$. The Area 5AB assessment of Pacific Cod estimated biomass-based reference points (see above) but these were not accepted for advice to managers. Instead, the following was suggested: continue harvesting at the current levels (200 t), which is estimated to result in $F \sim 0.3$, until a limit condition triggers a catch reduction strategy. The trigger recommended was to monitor the QCS Synoptic survey for any new index point (after 2013, see Figure 4) that falls below 50% of the mean survey indices prior to the new index point. Additionally, the stock assessment should be updated on an annual or biennial basis to evaluate the probability that the *F*-based reference point has been breached.

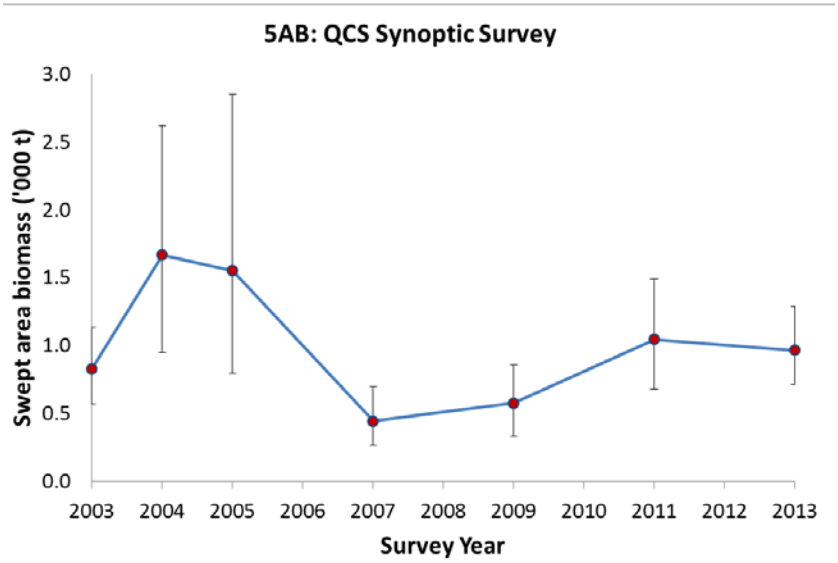


*Figure 4. Queen Charlottes Sound Synoptic survey series featuring indices of abundance measured as estimated swept area biomass. Error bars show 95% credibility intervals from 1,000 bootstrapped runs.*

*Table 2. "Model-averaged" decision table using performance measures based on provisional fishing mortality-based reference points expressed as the probability that the performance measure (indicated at the top of the column) will occur given the catch in the first column. $F_{2014}$ is the fishing mortality in 2014; $F_{avg}$ is the average fishing mortality from 1956 to 2004. Catches starred show approximate 2013 catch (~200 t) and current TAC (600 t).*

| | Fishing mortality-based | |
|---|---|---|
| **2014 Catch (t)** | **P($F_{2014} > F_{2013}$)** | **P($F_{2014} > F_{avg}$)** |
| 0 | 0.000 | 0.000 |
| 50 | 0.000 | 0.002 |
| 100 | 0.000 | 0.016 |
| 150 | 0.005 | 0.069 |
| ***200** | **0.077** | **0.201** |
| 250 | 0.418 | 0.363 |
| 300 | 0.736 | 0.517 |
| 350 | 0.882 | 0.634 |
| 400 | 0.933 | 0.714 |
| 450 | 0.961 | 0.774 |
| 500 | 0.976 | 0.817 |
| 550 | 0.984 | 0.848 |
| ***600** | **0.988** | **0.877** |
| 650 | 0.991 | 0.895 |
| 700 | 0.994 | 0.911 |
| 800 | 0.997 | 0.935 |
| 900 | 0.998 | 0.954 |
| 1000 | 0.999 | 0.968 |

## Sources of Uncertainty

Uncertainty in the estimated parameters and weights assigned to various data components was explicitly addressed using a Bayesian approach and the use of a model-averaged decision table. However, dealing with uncertainty in this way only reflects the set of model configurations included within the assessment. Additional uncertainties in this assessment stem from:

(i) the lack of reliable age composition data;

(ii) a relatively short series of fishery-independent abundance indices, which shows no clear trend;

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

(iv) a poor understanding of the relationship between commercial CPUE data and abundance and how it has changed over the course of the fishery.

The latter factor (iv) is a large contributor to the structural uncertainty in this assessment, particularly given the significant changes in management regime, market forces, fishing behaviour, and gear efficiencies that are known to have occurred, as well as being the only source of abundance information before 2003.

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 in 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 the Queen Charlotte Sound stock is biologically distinct from other BC and/or Alaskan stocks, which obscures the meaning of reference points based on local estimates of stock productivity parameters. External drivers, including environmental influences (e.g., larval water transport) and predator-prey dynamics, have been demonstrated to affect Pacific Cod productivity, and provide additional uncertainty to understanding stock dynamics and the best approach to management.

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, including time-varying selectivity, alternative representations of stock structure and alternative drivers of productivity, such as environmental forcing.

## Ecosystem Considerations

Pacific Cod is an omnivore, with a diet mainly consisting of marine invertebrates, including amphipods, krill, shrimp and crabs. At around 50-55 cm, Pacific Cod can also become piscivorous, with Pacific Sand Lance (*Ammodytes hexapterus*) and Pacific Herring (*Clupea pallasi*) forming important components of the diet. Juvenile Sablefish (*Anoplopoma fimbria*) and adult Pacific Hake (*Merluccius productus*) have also been reported in the diet of Pacific Cod off the west coast of Vancouver Island. Pacific Cod is preyed on by Pacific Halibut, Spiny Dogfish (*Squalus acanthias*), sea birds, seals and sea lions. Anecdotal reports describe a large increase in the Pinniped population, which could provide significant predation pressure.

## CONCLUSIONS AND ADVICE

The status of the Queen Charlotte Sound (5AB) population of Pacific Cod (*Gadus macrocephalus*) was assessed using a delay difference model. Despite large uncertainty, biomass and recruitment are estimated to have been below the historical average since the mid-1990s, and biomass is currently estimated to be below the median biomass minimum in 1985. Model estimates of biomass and stock status were very sensitive to prior assumptions about natural mortality, variance in the mean weight data, and the goodness of fit to the indices of abundance, particularly the commercial CPUE data. There is considerable concern that the 5AB fishery switched from a directed fishery to an avoidance fishery after the implementation of Individual Vessel Quotas in 1997, and the influence that this has had on the model's interpretation of catch and CPUE data.

Harvest advice appears in the form of a decision table that summarizes the probability of breaching fishing-mortality based reference points for a range of fixed catch levels. Due to model sensitivity to a number of assumptions, the decision table uses model-averaging to integrate uncertainty among five model configurations. A suggested harvest strategy in the short-term is to continue harvesting at current levels (~200 t), approximating $F = 0.3$, until a limit condition triggers a catch reduction strategy. A suitable trigger for precautionary action would occur when any new index point in the QCS Synoptic survey (after 2013) falls below 50% of the mean survey indices prior to the new index point. Additionally, the stock assessment should be updated on an annual or biennial basis to evaluate the probability that the *F*-based reference point has been breached.

## SOURCES OF INFORMATION

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