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Assessment of Pacific Cod (*Gadus macrocephalus*) for Hecate Strait and Queen Charlotte Sound (Area 5ABCD), and West Coast Vancouver Island (Area 3CD) in 2018

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

The status of two stocks of Pacific Cod (*Gadus macrocephalus*) in Hecate Strait/Queen Charlotte Sound (Area 5ABCD) and West Coast Vancouver Island (Area 3CD) was assessed using Bayesian delay-difference models. The models were fit to fishery-independent indices of abundance and new standardized commercial catch-per-unit-effort (CPUE) indices that were developed using Tweedie generalized linear mixed effect models (GLMMs). New analyses of growth and maturity were also done and incorporated into the models.

Model estimates of biomass and stock status in both management areas were sensitive to prior assumptions about natural mortality and survey scaling parameters, variance in the mean weight data, and the goodness of fit to the indices of abundance, particularly the commercial CPUE data. Harvest advice was produced in the form of decision tables that summarized the probability of breaching reference points in 2019 over a range of fixed 2018 catch levels. Due to model sensitivity to a number of assumptions, these stocks were assessed using a model-averaging approach which combined the posterior distributions from seven alternative model configurations for each stock.The resulting distributions were used to assess the historical biomass trajectories, current stock status and decision tables based on catch projections appropriate to each stock.

Reference points based on historical reconstruction of long-term average biomass and fishing mortality were accepted in 2013 for the Area 5CD Pacific Cod stock. “Historical” reference points were recommended because uncertainty in estimates of productivity parameters implied large uncertainty in reference points based on maximum sustainable yield (MSY). On the basis of the previous acceptance of historical reference points for Area 5CD Pacific Cod, the current assessment applies the same approach for the Areas 5ABCD and 3CD stocks. For both stocks, an upper stock reference point (USR) is defined as estimated average biomass during the period 1956-2004. A limit reference point (LRP) is defined as the lowest estimated biomass agreed to be an undesirable state to avoid (occurred in year 2000 in Area 5ABCD, and in 1986 in Area 3CD). For both stocks, a limit removal rate (LRR) is defined as estimated average fishing mortality during the period 1956–2004.

Biomass in Area 5ABCD is estimated to have been on a declining trajectory since 2011, following declining trends in abundance indices, despite low estimated fishing mortality rates over the same period. Median posterior estimates of biomass are estimated to be between the median LRP and median USR for Area 5ABCD. Recruitment is estimated to have been below average for the past two decades.

Biomass in Area 3CD is estimated to have been on a declining trajectory since 2015 after following an increasing trend from a historical low level of biomass between 1998 and 2014. These trends are consistent with the available biomass indices, including a recent downturn in the WCVI synoptic survey and the CPUE series. Median posterior estimates of biomass are estimated to be above the median LRP but below the USR for Area 3CD. Recruitment is estimated to have been below average for most years in the past two decades, with above average peaks in 2009, 2013 and 2014.

1 INTRODUCTION

1.1 STOCK STRUCTURE AND LIFE HISTORY

Pacific Cod (*Gadus macrocephalus*) is a relatively short-lived, fast-growing member of the family Gadidae. A common name in British Columbia (BC) is grey cod (or gray cod). Stocks of Pacific Cod are distributed from California, throughout the waters of BC, Gulf of Alaska and the Bering Sea to Russia, Korea, Japan and China (Hart 1973). Maximum observed age in British Columbia is around 10–11 years (Westrheim 1996, this document), while a maximum age of approximately 13 years has been reported for Alaskan stocks (Roberson 2001). Maximum length recorded in British Columbia is 100 cm (Hart 1973), although some larger specimens have been observed in Alaska and Russia (Westrheim 1996). In recent Synoptic trawl surveys in BC, the maximum recorded length was 93 cm (Appendix A, Table C.1). Pacific Cod are demersal spawners, with several studies reporting that spawning most likely occurs during February to March. A comprehensive review of the biology, life history and distribution of Pacific Cod in BC is provided by Westrheim (1996).

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 study focuses on the stocks in Queen Charlotte Sound combined with Hecate Strait (5ABCD), and the West Coast Vancouver Island (3CD) (Figure 1).

Recent genetic analyses have identified a distinction between North American and Asian Pacific Cod stocks, and have shown some evidence for distinction between Alaskan stocks and those south of Dixon Entrance in British Columbia (reviewed in Forrest et al. 2015). There is also 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, linkages, if any, among stocks in BC and those in Alaska remain poorly understood. To date it is uncertain whether genetic stock structure exists within BC waters (Forrest et al. 2015). Genetic samples have been collected from spawning grounds in Hecate Strait and Queen Charlotte Sound since the 2013 assessment but these have not yet been analyzed.

The choice to provide science advice for combined areas 5AB and 5CD in a single stock assessment was due mainly to poor model diagnostics and the lack of historical fishery-independent indices of abundance for Area 5AB (Forrest et al. 2015). There is also no evidence for genetic distinction between these two stocks. Provision of science advice for Areas 5ABCD combined should not imply that the areas should be managed as a single area, which is a choice for fishery managers in consultation with fishing industry members and other interested parties.

1.2 ECOSYSTEM CONSIDERATIONS

Population dynamics of Pacific Cod in BC have been characterized by large estimated variations in abundance (e.g., Sinclair et al. 2001, Forrest et al. 2015), although the causes are not clear. Hypotheses for apparent cyclic abundance in Hecate Strait include predator-prey cycles (Walters et al. 1986), density-dependent growth and mortality (Fournier 1983), and northward water transport of larvae (Tyler and Westerheim 1986, Tyler and Crawford 1991). Natural mortality has been estimated as high as 0.6–0.65 y^{-1} in some stock assessments (e.g., Fournier 1983, Sinclair and Starr 2005) although lower estimates (~0.4 y^{-1}) have also been obtained (Sinclair et al. 2001, Forrest et al. 2015). The combination of apparently volatile dynamics with short life span and high natural mortality suggests periods of over/under harvest could result if harvest strategies are not robust to these features. Also, in the context of the BC integrated groundfish fishery, constraints imposed by quotas for other species and economic considerations can mean that a single-species approach does not necessarily dictate the best harvest strategy.

1.2.1 PREY AND PREDATORS

Pacific Cod are omnivores, eating a diet of mainly marine invertebrates, including amphipods, euphausiids, shrimp and crabs. At around 50–55 cm they also become piscivorous, with Pacific Sand Lance (*Ammodytes hexapterus*) and Pacific Herring (*Clupea pallasi*) becoming important components of the diet (Westrheim 1996). 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 Ware and McFarlane (1986). Pacific Cod have been reported in the diets of Pacific Halibut (*Hippoglossus stenolepis*), North Pacific Spiny Dogfish (*Squalus suckleyi*), sea birds, seals and sealions (Westrheim 1996).

Walters et al. (1986) demonstrated a Pacific Cod-Herring predator-prey interaction in Hecate Strait, in contrast to Ware and McFarlane (1986). Simulation models developed by Walters et al. (1986) concluded that availability of Pacific Herring prey could be an important driver of Pacific Cod production in Hecate Strait, and, similarly, that Pacific Cod predation could be a significant driver of Pacific Herring abundance. These authors acknowledged that there are alternative hypotheses for cycles in abundance of Pacific Cod and Pacific Herring (e.g., environmental forcing; see below) and suggested that large-scale management experiments may be the only way to distinguish among competing hypotheses.

1.2.2 ENVIRONMENT

Several studies have investigated linkages between recruitment and environmental indices for Pacific Cod in Hecate Strait (see Westrheim (1996) for review). The dominant hypothesis is an inverse relationship between recruitment and northward advection of larvae (Tyler and Westerheim 1986, Tyler and Crawford 1991). Northward advection 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 by a number of authors (Fournier 1983, Sinclair 1999, Sinclair and Crawford 2005, Sinclair and Starr 2005). However, recent updates of the analyses by Tyler and Crawford (1991) failed to find a continuing correlation between Prince Rupert Sea level and recruitment of Pacific Cod in Hecate Strait (R. Forrest, Pacific Biological Station, unpublished data).This could in part be due to low quotas (and therefore lower catches) since 2001, contributing to low stock assessment estimates of recruitment in recent years (Forrest et al. 2015).

1.2.3 OTHER SPECIES

Other species caught with Pacific Cod include Arrowtooth Flounder (*Atheresthes stomias*), Yellowtail Rockfish (*Sebastes flavidus*), Pacific Ocean Perch (*S. alutus*), Lingcod (*Ophiodon elongatus*), Silvergray Rockfish (*S. brevispinis*), English Sole (*Parophrys vetulus*) and Big Skate (*Raja binoculata*) (Forrest et al. 2015). Vessels catching Pacific Cod must hold quota for all quota species encountered (DFO 2017). Since 1996, there has been 100% at-sea observer coverage on commercial bottom trawl vessels in BC. At-sea releases are recorded by observers and counted against the vessel's quota, according to agreed-upon discard mortality rates.

1.3 FISHERIES

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 also caught in very small quantities in the groundfish longline fishery (around 0.5% of the total annual catch on average), also part of the integrated fishery. Currently, the majority of the BC Pacific Cod catch is taken from Hecate Strait (Area 5CD), where it is one of the principal target species of the trawl fishery (Figures 4,6 and 8). Commercial catches also come from Queen Charlotte Sound (Area 5AB) and the west coast of Vancouver Island (Area 3CD). Near negligible catch is also taken from the west coast of Haida Gwaii, Area 5E (< 0.5% of total average annual catch since 1985).

Pacific Cod are distributed throughout Hecate Strait (Area 5CD) at depths mainly less than 150 m. Pacific Cod density appears to be highest over the Two Peaks/Butterworth, White Rocks, Shell Ground, Reef Island, and Horseshoe fishing grounds (Appendices A and B, Forrest et al. 2015). In Queen Charlotte Sound (Area 5AB), Pacific Cod are caught mainly off Cape Scott and Mexicana Banks, north of Vancouver Island, in Area 5A, and around the edge of Goose Island Bank in Area 5B (Appendix A and B, Forrest et al. 2015). The depth range of capture in 5ABCD ranges from around 60–200 m, with data showing a shift to deeper depths since 1996 (Appendix B, Figure B.5). The transition to deeper fishing grounds reflects a larger proportion of catches coming from deeper waters in Queen Charlotte Sound in more recent years (Figures 4 and 6). Annual reported catches of Pacific Cod in both Hecate Strait and Queen Charlotte Sound have shown considerable variability since the beginning of the time series in 1956 (Figure 2). The depth range of catches off West Coast Vancouver Island (Area 3CD) is similar to Area 5ABCD, with the majority of catch coming from 50–200 m depth zones (Appendix B, Figure B.5). See Sinclair et al. (2001) for description of changes in historical depth ranges of the fishery. See also Appendix B. Historical catches in Area 3CD have shown a similarly variable pattern to Area 5ABCD (Figure 8).

Prior to the introduction of at-sea observer coverage in 1996, estimates of at-sea releases (discards) for the period 1956–1995 were obtained from fishing logbooks. These estimates are considered an underestimate of the actual releases (Tables 1 and 2). Estimates in years following the introduction of 100% at-sea observer coverage in 1996 can be considered to be accurate. Since 1996, the proportions of estimated discards have been considerably higher than in years before at-sea observers (Tables 1 and 2), especially in Queen Charlotte Sound, largely as a result of reduced total catches and TACs (Table 3). Pacific Cod can be legally discarded by trawlers in BC. However, on-board observers first estimate the quantity being discarded. Therefore, in addition to greater accuracy in reporting of discards since 1996, incentives to avoid discarding have also been greater.

Japanese and Soviet vessels also trawled in waters off BC in the late 1960s and early 1970s. These vessels were mainly targeting rockfish and likely at depths greater than 150 m. The bycatch of Pacific Cod in these fisheries is, however, 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 fishing effort of bottom trawl vessels has declined in all areas in recent years. A detailed analysis of catch per unit effort (CPUE) is provided in Appendix B. As noted by Sinclair (1999), there are a number of problems with the use of commercial catch per unit effort as an index of biomass for Pacific Cod. Changes in the management regime from an unrestricted fishery prior to 1992, to the introduction of TACs (1992–1996) and then to Individual Vessel Quotas (IVQs) (1997-present), as well as several increases in mesh size (Forrest et al. 2015, their Table 5), have affected the underlying relationship between commercial CPUE and abundance, and the relationship between fishing effort and fishing mortality. In recent years of lower Pacific Cod quotas (Table 3), many fishing masters report actively avoiding Pacific Cod to prevent their Pacific Cod quota being exceeded before catching available quotas for other species. In the present assessment CPUE series are split into pre- and post-1996 series, and generalized linear mixed affect models are used to attempt to standardize the indices (Appendix B).

1.4 ASSESSMENT HISTORY

A number of methods have been used to assess Pacific Cod in Hecate Strait since the 1980s. Fournier (1983) developed an age-structured model and used it to test for evidence of age-dependent trends in natural mortality, density-dependent natural mortality and catchability, and also for evidence of an environmental factor affecting recruitment. Evidence was found for a relationship between mean sea level at Prince Rupert and recruitment, and also for density-dependent natural mortality. Natural mortality was estimated to be 0.65 y^{-1} by Fournier (1983). This author cautioned about the possibility of confounding among model parameters and systematic data biases that could influence conclusions from the analysis. Estimates of age were obtained from length-frequency analysis (Foucher and Fournier 1982).

Pacific Cod are one of the most difficult Pacific groundfish species to age. Annual rings (annuli) in otoliths, other bony structures and scales are difficult to distinguish from interannual growth checks (Beamish 1981, Chilton and Beamish 1982, Roberson 2001, Johnston and Anderl 2012). In British Columbia, age compositions have been estimated using length-based approaches, scales, otoliths and, currently, dorsal fin ray sections, although all methods present difficulties. In the absence of reliable direct age data, length-based approaches were used to assess the Hecate Strait stock during the 1990s (e.g., Haist and Fournier 1995, 1998). In the last of these, Haist and Fournier (1998) suggested that the stock had reached an historic low in 1996, followed by a slight rebound.

Sinclair (1999) used a simple surplus production model fit to a commercial CPUE index to assess the Area 5CD stock in 2000. This author cited significant structural changes in the fishery during the 1990s resulting in changes in quality and comparability of fishery-dependent data available for the analysis. Changes included voluntary increases in mesh size in the commercial fishery and introduction of individual vessel quotas (IVQs) in 1997 as discussed above. Given the large structural differences between the previous length-based models and the surplus production model, Sinclair (1999) noted that results were remarkably comparable until 1994, with three estimated peaks in abundance occurring in 1965, 1974–5 and 1986–7. The two approaches diverged significantly after 1994, with the length-based Multifan model (Haist and Fournier 1998) estimating an increase in biomass while the surplus production model estimated a decline. The differences were interpreted to be due to differences in the indices of abundance used to tune the models, as well as structural model differences.

Sinclair et al. (2001) developed a delay-difference model (Deriso 1980, Schnute 1985) containing a Ricker stock-recruit function to assess Pacific Cod in Areas 3CD and 5CD. Recruitment was assumed to be knife-edged at age 2 years. A report card summary of information available for the stock was also developed. The delay-difference model provided a better statistical fit to the data than the previously-applied surplus production model (Sinclair 1999). However, biomass estimates followed a similar trend and magnitude. The 2001 Area 3CD stock was updated in 2002 (Starr et al. 2002), using the same delay-difference model developed the previous year (Sinclair et al. 2001) and adding data from DFO's shrimp trawl survey. The authors of the 2002 assessment noted that the estimated MSY-based reference points F_{MSY} and B_{MSY} were not well estimated (Starr et al. 2002).

The Area 5CD assessment was updated in 2004 (Sinclair and Starr 2005), using a similar delay-difference model to that used by Sinclair et al. (2001), but using a Beverton-Holt stock-recruit function. Model fits were presented with alternative combinations of fixing or estimating natural mortality (M) and the steepness parameter of the stock-recruit function, h (Mace and Doonan 1988). They reported similar fits and biomass estimates for both scenarios but noted very different estimates of equilibrium MSY-based management parameters under alternative combinations of fixed and estimated h and M. They proposed "history-based" reference points, based on estimated historical biomass and fishing mortality, due to unreliability of MSY-based reference points. The Area 5AB and 5CD stocks were last assessed in 2013 (Forrest et al. 2015) using a new delay-difference model with a Beverton-Holt stock-recruit function and the assumption of knife-edged selectivity at 2 y. The model had some minor structural differences from the previous assessment, although bridging analyses showed these to have a relatively minor effect (Forrest et al. 2015, their Appendix A). The 2013 assessment adopted the same historical reference points that had been used in 2004 and these were accepted during peer review for Area 5CD (DFO 2015a). However, no reference points were accepted for Area 5AB (DFO 2015b). Key uncertainties noted by Forrest et al. (2015) were:

1. Uncertainty in fixed variance parameters, particularly the assumed observation error in the surveys, and the objective function component of the fit to annual mean weights;
2. Reliability of commercial CPUE as an index of abundance, and effects on CPUE of management changes post-1996;
3. Uncertainty in the prior probability distribution used for natural mortality M;
4. Uncertainty in the growth function (model parameters and assumptions of stationarity);
5. The possibility of violating the assumption of knife-edged recruitment at age 2 years, given evidence for younger fish in the length composition data from the commercial fishery; and
6. Uncertainty in stock structure.

Sensitivity to the first three of these uncertainties was partially addressed in Forrest et al. (2015) through the presentation of sensitivity analyses and alternative "model-averaged" decision tables for Areas 5AB and 5CD. The fourth and fifth uncertainties are partially addressed in the current assessment through the addition of extra sensitivity analyses comparing the previous and updated growth parameters, and comparing results with the assumption of knife-edged selectivity (Section 7). The sixth is still a key uncertainty for Pacific Cod. In the current assessment, data from Areas 5AB and 5CD are combined, under the assumption that Pacific Cod in Queen Charlotte Sound and Hecate Strait belong to a single stock.

2 DATA SOURCES

2.1 DATABASES

Data were extracted from a number of different databases:

GFBio: Biological samples and research cruise database. Groundfish Section, Marine Ecosystems and Aquaculture Division, Science Branch, Fisheries and Oceans Canada, Pacific Biological Station. This data archive includes most of the groundfish specimen data collected since the 1950s. It therefore includes data from a variety of sources (port and at-sea commercial sampling, research survey sampling), collected using a variety of sampling methods.

GFCatch: Canadian trawl landings, 1954–1995 (Rutherford 1999).

PacHarvTrawl: Canadian trawl landings, 1996 to March 31, 2007. SQL Server database, Groundfish Section, Marine Ecosystems and Aquaculture Division, Science Branch, Fisheries and Oceans Canada, Pacific Biological Station.

GFFOS: Canadian trawl landings, April 1, 2007 to 2017. View of the Fisheries and Oceans Canada (DFO) Fishery Operations (FOS) database. Groundfish Section, Marine Ecosystems and Aquaculture Division, Science Branch, Fisheries and Oceans Canada, Pacific Biological Station.

2.2 CATCH DATA

Groundfish fisheries were managed by calendar year until 1996. Beginning in 1997–98 the fishing year changed to April 1–March 31. In 2010–2011 the fishing year was changed again to February 21 to February 20. Throughout this document, as in Forrest et al. (2015), 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. These definitions were used consistently in all calculations involving commercial catch data, including development of the commercial CPUE index (Appendix B) and calculation of annual average mean weight in the catch (Appendix C). Landings data are presented separately for Canada and the USA (Tables 1 and 2). Combined USA-Canada landings data were obtained from the Pacific Marine Fisheries Commission reports for 1956–1981 and the USA landed portion was determined by subtracting the Canadian landed amount from the combined total for each year. In cases where the difference was negative, the USA landed amount was set to zero. Canadian data were obtained from the GFCatch database for the period 1954–1995 (Rutherford 1999); from the PacHarvest database for the period 1996-March 31, 2007; and from the Fisheries and Oceans Canada (DFO) FOS database for the period April 1, 2007 until the present. The annual size compositions of commercial catches and landings were estimated from port samples and at-sea samples collected by observers archived in the GFBio database (Appendix C).

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. For Area 5ABCD, the three year average proportion of catch taken by September 30 (88.4%) was used to extrapolate from the catch at September 30, 2018 to the total estimated catch for the 2018 fishing year (Table 1). For Area 3CD, the 2018 catch to September 30 was anomolously low for reasons that were unclear but that could have been related to the fishing industry delaying opportunities to catch Pacific Cod. Therefore, the total catch for the 2018 fishing year was extrapolated to be the same as the catch for 2017 (Table 2).

2.3 INDICES OF ABUNDANCE

Stock assessment models in Area 5ABCD were fit to three fishery-independent survey indices (Hecate Strait Multispecies Assemblage Survey, Hecate Strait Synoptic Survey and Queen Charlotte Sound Synoptic Survey) and two commercial CPUE indices derived from commercial bottom trawl catch and effort data (pre-1996 and post-1995).

Stock assessment models in Area 3CD were fit to two fishery-independent survey indices (West Coast Vancouver Island Synoptic Survey and NMFS Triennial Survey in Canada) and two commercial CPUE indices derived from commercial bottom trawl catch and effort data (pre-1996 and post-1995).

The fishery-independent indices of abundance were developed using swept-area analyses. Descriptions of the surveys and details of the analyses are provided in Appendix A.

The commercial CPUE indices were standardized for depth, fishing locality, month, vessel, and latitude, when available, using generalized linear mixed models (GLMMs), based on a Tweedie distribution. Details are provided in Appendix B.

2.4 BIOLOGICAL DATA

Updates to estimated growth, maturity and annual mean weights in commercial catches are provided in Appendix C.

We note that due to the near neglible quantities of catch taken in Area 5E (average <0.5% of total catch since 1985), and from the commercial groundfish longline fishery (around 0.5% of total catch since 1985), data from Area 5E and from the longline fishery are excluded from this assessment.

3 STOCK ASSESSMENT MODEL

All models presented in this document are Bayesian models implemented in AD Model Builder (Fournier et al. 2012). The models are based on the Integrated Statistical Catch Age Model (iSCAM), first reported in Martell et al. (2011). A major modification by the authors of Forrest et al. (2015) and this assessment is inclusion of delay-difference calculations. The model in its present formulation is fully described in Appendix D. Two major differences between the current model and the previous assessment (Forrest et al. 2015) are:

1. The current model estimates only one average recruitment parameter (R_0). The models in Forrest et al. (2015) and Martell et al. (2011) estimated three average recruitment parameters:
   - R_0, average unfished recruitment used in derivation of stock-recruit parameters;
   - R_{Init}, initial average recruitment used to initialize the age structure in the first year; and
   - R_{Avg}, average recruitment for the time series.

The decision to use just one average recruitment parameter was made because there is little to no information for estimating three parameters in the delay-difference model, which contains no explicit age composition information.

Also, the von Bertalanffy growth parameters have been updated in the current assessment for both stocks, to reflect more recent age and length data. Details are provided in Appendix C.

The reference models for the Area 5ABCD and 3CD assessments are discussed in more detail in Section 5.

4 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. A Reference Removal Rate;

2. A Limit Reference Point (LRP);

3. An Upper Stock Reference point (USR).

In the current assessment, these reference points are incorporated into the decision tables, where projected probabilities of breaching the reference points are reported. I.e., reference points are not incorporated into a formal harvest control rule.

Provisional values of $USR = 0.8B_{MSY}$ and $LRP = 0.4B_{MSY}$ are suggested in the absence of stock-specific reference points (DFO 2009). The framework specifies a limit reference removal rate of F_{MSY}. We refer to the reference removal rate as the limit removal rate (LRR) throughout this document. The PA policy also endorses "history-based" proxies based on estimated average spawning biomass and fishing mortality over a productive historical period (DFO 2009).

As already noted, large uncertainties in the productivity parameters *M* and *h* have resulted in substantial uncertainties in MSY-based reference points for Hecate Strait Pacific Cod in previous assessments (Starr et al. 2002, Sinclair and Starr 2005, Forrest et al. 2015). Given uncertainty in productivity parameters for this stock, Sinclair and Starr (2005) suggested using alternative reference points based on the reconstructed history of the stock, i.e., "history-based" reference points. They recommended the Limit Reference Point to be the minimum spawning biomass from which the stock recovered to above average levels. This was estimated to have occurred in 1971 (i.e., $LRP = B_{1971}$). Sinclair and Starr (2005) suggested long-term average Biomass (B_{Avg}) as a candidate proxy Upper Stock Reference and long-term average harvest rate (U_{Avg}) as a proxy for the reference removal rate.

Sinclair and Starr (2005) and Forrest et al. (2015) acknowledged that the absolute estimate of biomass in 1971 is dependent on model formulation, but found that most model formulations agreed that 1971 was the year in which the stock was lowest and subsequently recovered to above average levels. Therefore, they recommended the LRP be set at B_{1971}, as estimated by the assessment model. The Groundfish Subcommittee of PSARC (Fargo 2005) subsequently recommended the use of B_{1971} as the LRP for the Hecate Strait stock and it was again accepted as LRP by a Regional Peer Review (RPR) process in 2014 (DFO 2015a) for Area 5CD. Concurrently, long-term average Biomass (B_{Avg}) between 1956 and 2004, and long-term average fishing mortality (F_{Avg}) for the same period were accepted by the RPR for the Area 5CD USR and LRR, respectively (DFO 2015a).

While there was no precedent for reference points in Queen Charlotte Sound, the minimum stock size from which the biomass was estimated to have recovered to an above average level occurred in 1985 (Forrest et al. 2015). These authors proposed B_{1985} as the LRP for the Queen Charlotte Sound, with average biomass and fishing mortality for the period 1956–2004 as the USR and LRR, respectively. However, the RPR did not accept any reference points for the Queen Charlotte Sound (Area 5AB) Pacific Cod stock (DFO 2015b). The main reason cited was that the fishery in Area 5AB had become an "avoidance" fishery for Pacific Cod (to avoid breaching the Pacific Cod TAC before TACs for other groundfish species had been realized). Therefore the RPR participants felt that post-1996 estimates of abundance, which were largely informed by low catches, could not be assumed to accurately reflect abundance.

Forrest et al. (2018) simulation-tested a set of alternative reference points for Hecate Strait Pacific Cod and Rock Sole (*Lepidopsetta* spp.). They found that the "history-based" reference points (or operational control points, OCPs) that had been used for Pacific Cod in 2013 (Forrest et al. 2015) were robust to stock assessment biases because they scaled in the same direction as bias in estimates of biomass and fishing mortality. However, they were not necessarily good proxies for MSY-based reference points and tended to produce more precautionary catch recommendations than reference points based on B_{MSY}, B_0 and the spawning potential ratio (SPR; Clark (1991)). While the "history-based" reference points outperformed others in terms of long-term conservation outcomes, there were sometimes large trade-offs in terms of catch and catch stability (Forrest et al. 2018). Reference points based on estimated B_0 performed similarly to the "history-based" reference points but tended to have better trade-off properties (Forrest et al. 2018).

Some of the reference point concerns with the 5AB model may have been addressed by combining data for Areas 5AB and 5CD in the present stock assessment. Therefore we suggest using the same USR for Area 5ABCD as had been used for Area 5CD in (Forrest et al. 2015). During the review meeting for this assessment, it was decided by reviewers and attendees to modify the LRP to be the lowest estimated biomass agreed to be an undesirable state to avoid. The change in definition led to using 2000 as the low-biomass year and therefore the limit reference point for this assessment (i.e., $LRP = B_{2000}$).

In the absence of accepted reference points for Area 3CD, we suggest implementing the same approach. The LRP was kept as the biomass in 1986, as in the previous assessment, as it was agreed that moving it to a more recent time period would have a negligible effect.

In addition to the LRR, LRP and USR discussed above, two benchmark measures are also included: (i) F_{2017} and (ii) B_{2018}. Projected biomass and fishing mortality relative to these benchmarks are included in the decision tables to show whether: (i) fishing mortality is projected to increase or decrease under alternative projected 2018 catch levels; and whether biomass is projected to increase or decrease under alternative projected 2018 catch levels.

Suggested reference points and benchmarks for both areas are provided in Section 13.5.

5 REFERENCE CASE MODELS

Reference Case models were established for Areas 5ABCD and 3CD to show model response under what were considered the most plausible choices across a range of assumptions for each stock. These models served as the basis from which sensitivity runs were made, altering alternative hypotheses one step at a time. Most of these sensitivity runs altered assumptions that the current model configuration and data availability were not able to reliably exclude from consideration. Consequently, these Reference Case models should not be considered to be the "best available information" from which management advice can be provided. Instead, a model averaging approach (see below) was adopted that combined model results across a range of plausible assumptions, which in turn was used to provide management advice.

The Reference Case models for Areas 5ABCD and 3CD shared similar characteristics in terms of data choices, prior probability distributions and fixed parameter settings. For brevity, both reference case models are described in this section, with differences explained as necessary. The Bayesian delay-difference model is fully described in Appendix D.

The joint posterior distribution for each model was numerically approximated using the Markov Chain Monte Carlo 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). We assessed consistency with chain convergence by visual inspection of trace plots and autocorrelation plots and through calculating the potential scale reduction statistic

$\hat{R}$ and the effective number of simulation draws n_{eff} via the R package Stan (Stan Development Team 2018).

The potential scale reduction statistic (Gelman and Rubin 1992) is a common metric used in Bayesian statistics to assess chain convergence (Gelman et al. 2014, Hobbs and Hooten 2015, Stan Development Team 2017). The statistic measures the ratio of the average variance of MCMC samples within each chain to the variance of the samples across chains. As $\hat{R}$ approaches 1.0, the chains are consistent with convergence. In our case, we only had a single chain for each model run, but in following the advice of Gelman et al. (2014), we first divided the chain in two, effectively treating the first and second half as separate chains. Following the notation of Hobbs and Hooten (2015), we can calculate $\hat{R}$ for a given parameter θ as follows. For $j = 1, ..., m$ chains (two half chains here), we calculate the mean of the variances w as:

$$w = \frac{1}{m} \sum_{j=1}^{m} \mathrm{var}\left(\theta_j\right) \tag{1}$$

where θ_j is defined as $\theta_j = \frac{1}{K-1} \sum_{n=1}^{K} \left(\theta_{kj} - \overline{\theta}_j\right)^2$ across $k = 1, ..., K$ iterations. We then define the among-chain variance b as:

$$b = \frac{K}{m-1} \sum_{j=1}^{m} \left(\overline{\theta}_j - \overline{\overline{\theta}}\right)^2 \tag{2}$$

where $\overline{\overline{\theta}} = \frac{1}{m} \sum_{j=1}^{m} \overline{\theta}_j$. The variance of a stationary distribution of θ is then calculated as a weighted mean $\sigma_\theta^2 = \left(1 - \frac{1}{K}\right) w + \frac{1}{K} b$, and we can define the potential scale reduction factor as $\hat{R} = \sqrt{\frac{\sigma_\theta^2}{w}}$.

The statistic n_{eff} measures the effective number of MCMC independent samples after accounting for autocorrelation. For brevity we do not define the full calculation here, but it is available in Gelman et al. (2014) pp. 286–287 or Stan Development Team (2017) pp. 373–376.

5.1 DATA CHOICES

Both models were fit to observed catch data, observed average annual mean weight in the commercial catch, and fishery-independent and -dependent indices of abundance. Details on objective function components of the model are provided in Appendix D.

Data sources for observed catch data were described in Section 2, with values in Tables 1 and 2 and Figures 2 to 7 for Area 5ABCD, and Figures 8 to 9 for Area 3CD.

Fishery independent swept area abundance indices are documented in Appendix A, including biomass estimates, CVs and years covered.

For Area 5ABCD, these are:

1. the Hecate Strait Multispecies Assemblage Survey;
2. the Queen Charlotte Sound Synoptic Survey;
3. the Hecate Strait Synoptic Survey.

For Area 3CD, these are:

1. the West Coast Vancouver Island Synoptic Survey;
2. the NMFS Triennial Survey (in Canada).

Fishery dependent indices are fully documented in Appendix B. In each area, the CPUE time series are standardized GLMMs, with separate analyses for the periods before and after the introduction of 100% observer coverage in 1996, which resulted in large improvements in estimates of catch, discards and general data reliability. The two periods are referred to as: historical (1956–1995) and modern (1996–2017) (Appendix B).

Details on the calculation of average annual mean weight in the commercial fishery are provided in Appendix C. Inclusion of average annual mean weight data is intended to provide information about recruitment in the absence of age-composition data. This is dependent on the underlying assumption of the delay-difference model (Appendix D) that selectivity, growth and natural mortality are constant and knife-edged throughout the time period covered by the model (1956–2017). It is important to note that lower average annual mean weight in the commercial data could indicate a recruitment event, but could also have other causes including smaller proportions of older/larger fish due to fishing or natural mortality, changes in the spatial distribution of the fishery, or changes in growth.

5.2 PRIOR PROBABILITY DISTRIBUTIONS AND FIXED VARIANCE PARAMETERS

The prior probability distributions for leading parameters in the Area 5ABCD and 3CD Reference Case models are provided in Tables 4 and 5. Graphic presentation of prior probability distributions is provided in Figures 10 and 11. Model sensitivities to prior assumptions are tested in Section 7.

5.3 LEADING PARAMETERS

A broad, uniform prior probability distribution was used for $\ln(R_0)$, reflecting an ignorance the scale of the stock.

A beta distribution was used as a prior for steepness with shape parameters that resulted in a distribution with mean = 0.7 and SD = 0.15. These parameter choices resulted in a distribution with little to no probability density for values less than 0.2 (Figure 10), implying that no transformation was necessary. This is the same prior probability distribution accepted for use in the previous stock assessment (Forrest et al. 2015). Sinclair and Starr (2005) fixed steepness at 0.75 in one of their "preferred" scenarios. In their other "preferred" scenario, the mode of the joint posterior distribution (MPD) estimate of steepness was 0.53. The prior probability distribution chosen here encompasses both of these values.

A normal distribution was used for $\ln(M)$ with mean = $\ln(0.5)$ and SD = 0.1, as was used in Forrest et al. (2015). Sinclair and Starr (2005) obtained MPD estimates of *M* of 0.596 and 0.567 in their two "preferred" scenarios, whereas Forrest et al. (2015) obtained MPD estimates of 0.393 y^{-1} and 0.426 y^{-1} for Areas 5CD and 5AB, respectively. A bridging analysis done by Forrest et al. (2015) suggested that *M* could be considerably lower, depending on the values of other fixed or estimated parameters, and there has been considerable variability of estimates of *M* for Pacific cod throughout its assessment history (Fournier 1983, Haist and Fournier 1998, Sinclair et al. 2001).

5.4 SURVEY SCALING PARAMETERS (CATCHABILITY)

Broad uniform prior probability distributions were used for the scaling parameter q_k for indices *k*:

1. Hecate Strait Multispecies Assemblage Survey;
2. NMFS Triennial Survey; and
3. Commercial CPUE indices.

These priors reflected ignorance of the scale of the survey index relative to the stock. The Hecate Strait Multispecies Assemblage (HSMA) Survey was never designed as a stratified random trawl survey. Instead, it was a grid survey with one fixed location station per grid. Sinclair (2000) assigned each station to a depth stratum and analyzed the data as if the survey used a stratified random design. Because of this post-hoc stratification approach, the relationship between the survey index and the Pacific Cod stock is unknown. The National Marine Fisheries Service (NMFS) Triennial Survey ventured into Canadian waters seven times in the period 1980 to 2001. The survey was a random transect design, using a random start and then progressing up the west coast of the United States and Canada at 50 nm intervals. Each transect was stratified by depth and stations along the transect were selected randomly. The extent that the Triennial survey extended into Canada varied by survey, but the data were analyzed as if the survey had the same areal coverage in every year (see Appendix A). This survey was included in the current 3CD stock assessment to provide fishery independent biomass information in the 1980s and 1990s. However, as for the HSMA survey, the relationship between the survey index and the 3CD Pacific Cod stock is not known. The commercial CPUE indices are standardized catch rates (Appendix B) with an unknown relationship to stock abundance.

Normal distributions were used for $\ln(q_k)$ for indices *k* =:

1. Queen Charlotte Sound Synoptic Survey;
2. Hecate Strait Synoptic Survey; and
3. West Coast Vancouver Island Synoptic Survey.

The choice of prior probability distribution for survey scaling parameters has the potential for large impacts on stock assessment outcomes. We therefore present a number of alternative prior formulations as sensitivity analyses for the following informative prior probability distributions in Section 7.

5.4.1 Survey scaling parameters for Area 5ABCD

We used informative prior probability distributions for the two synoptic surveys based on median posterior estimates of *q* from the most recent stock assessment for Rock Sole (Holt et al. 2016). This was done to constrain the tendency in the models towards estimating implausibly high stock sizes. Rock sole is a flatfish species occupying a similar (although slightly shallower) depth range to Pacific Cod. Holt et al. (2016) obtained median posterior estimates of q = 0.6280 for Area 5AB and q = 0.1869 for Area 5CD. They did not use an informative prior probability distribution for *q*. The CV of their estimates was around 0.3. For our combined Area 5ABCD assessment we pro-rated these values according to the relative areas of habitat in Areas 5AB and 5CD. Adding up the areas of all the surveyed depth strata in each area gave a ratio of approximately 0.65:0.35 (5AB:5CD). Therefore the following values were used as means for the normal prior probability distributions for $\ln(q_k)$, for

1. *k* = Queen Charlotte Sound Synoptic Survey: mean $\ln(q_k) = \ln(0.6280 \cdot 0.65)$ = -0.895998; and
2. *k* = Hecate Strait Synoptic Survey: mean $\ln(q_k) = \ln(0.1869 \cdot 0.35)$ = -2.727539;

For both synoptic surveys, the standard deviation of the normal prior probability distribution for $\ln(q_k)$ was set to 0.3 in log space.

5.4.2 Survey scaling parameters for Area 3CD

As for Area 5ABCD, we used an informative prior probability distribution for the West Coast Vancouver Island Synoptic Survey based on a median posterior estimate from a recent assessment. Again this was done to constrain the very large stock size estimates made by the model when a uniform prior was applied. There have been fewer recent stock assessments focused on Area 3CD only and none for species in the same depth range as Pacific Cod. Here we used a normal prior probability distribution for $\ln(q_k)$ with mean set to the median posterior estimate of *q* from the most recent assessment for Area 3CD Pacific Ocean Perch (*Sebastes alutus*) (Edwards et al. 2013), i.e., mean $\ln(q_k)$ = $\ln(0.228)$ = -1.47841. The standard deviation of the normal prior probability distribution for $\ln(q_k)$ was set to 0.3 in log space, as for Area 5ABCD. Pacific Ocean Perch occurs in a deeper depth range than Pacific Cod, but it is a major target species for the trawl fishery and may therefore be informative about catchability in this area. Edwards et al. (2013) did not use an informative prior probability distribution for *q*.

5.5 FIXED VARIANCE PARAMETERS

The errors in variables approach used to partition process and observation error is described in detail in Appendix D. Briefly, The key variance parameter is the inverse of the total variance, i.e., total precision ϕ^{-2} (Martell et al. 2011). This parameter can be fixed or estimated, and was fixed here. The total variance is partitioned into observation and process error components by the model parameter ρ, which represents the proportion of the total variance that is due to observation error (Punt and Butterworth 1993, Deriso et al. 2007). These parameters are used to derive the observation error component of the total variance (σ_O, Eq. D.22) and the process error term (σ_R, Eq. D.23), which enters the objective function in the log likelihood function for the recruitment residuals (Eq. D.35).

Forrest et al. (2015) found it was not possible to obtain plausible estimates of the variance term ϕ^{-2} for their Base Case model. Any attempt to estimate ϕ^{-2} resulted in estimates of σ_R close to 2.0 and estimates of σ_O close to 1.5, with extremely poor fits to the indices of abundance, particularly the commercial CPUE data. It was therefore necessary to fix ϕ^{-2} and ρ to give fixed values of σ_O and σ_R. Sinclair and Starr (2005) also used fixed variance parameters in their assessment of Area 5CD Pacific Cod. Forrest et al. (2015) used values of ϕ^{-2} and ρ that resulted in σ_O = 0.25 and σ_R = 0.8. Preliminary model runs with the current dataset found that σ_O = 0.25 resulted in poor fits to the synoptic survey indices of abundance, especially in Area 5ABCD. Therefore in the current assessment σ_O was reduced to 0.2 in both Reference Case models. Sensitivity tests are provided in Section 7.

In addition to the overall observation error term σ_O, annual index points for each index of abundance series were weighted by annual CVs, using a multiplicative weighting approach fully described in Appendix D.

As for the previous stock assessment for Pacific Cod (Forrest et al. 2015), fixed variance components were used for the likelihood components for annual catch (σ_C) and average annual mean weight (σ_W). Problems with interpreting the mean weight data were discussed in Forrest et al. (2015), their Appendix C. These problems stem from changes over time in the sample sizes of different categories of length data, i.e., sorted and unsorted categories, and lack of data for smaller fish before observers measured fish at sea. Concerns about the use of the mean weight data were also recorded in the review of the 2005 assessment (Fargo 2005). This issue was acknowledged by Sinclair and Starr (2005), who noted that the mean weight series was necessary for estimation of model parameters but was down-weighted in the objective function. As in Forrest et al. (2015), σ_W was set to 0.2 in the Reference Case models. Because the model assumes observed catches are known without error, σ_C was set to a small value, i.e., σ_C = 0.05. However, sensitivity tests to these assumptions are provided in Section 7.

6 RESULTS

6.1 AREA 5ABCD: QUEEN CHARLOTTE SOUND AND HECATE STRAIT

The model diagnostics were consistent with convergence (Figure 12) and posterior sample autocorrelation was minor for most parameters (Figure 13). The value of $\hat{R}$ was ~ 1.00 for all parameters (Table 8).

The MPD model fits to the five indices of abundance are shown in Figure 14. 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 2013 peak in the Hecate Strait Synoptic Survey, Figure 14). Similarly, the model followed the major patterns in the two CPUE indices but did not capture all the peaks (Figure 14).

Forrest et al. (2015) considered goodness of fit to the indices of abundance to be a primary driver of uncertainty in their assessment, 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, some of which are explored in the current assessment (Section 7).

Model fit to the average annual weight in the commercial fishery (Figure 15) was slightly better than in the 2013 assessment (Forrest et al. 2015, their Figure 37), which tended to underestimate annual mean weight. However, the current model also tended to underestimate annual mean weight, especially between 1970 and 2000. The slightly improved fit compared to the previous assessment is likely partly due to the updated growth parameters used in the current model compared to the previous assessment (see Section 7). The effects of alternative values of σ_W are evaluated in Section 7.

Model fit to the total commercial catch is shown in Figure 16. Model fits are almost perfect due to the setting σ_C = 0.05 in the objective function (Appendix D). This was done so that the model was essentially conditioned on the catch data, which was assumed to be known with very little error, even though pre-1996 discard rates are uncertain.

Posterior probability distributions of estimated parameters are provided in Figure 17 and Table (8). The median, 2.5th percentile and 97.5th percentile posterior parameter estimates, and MPD estimates, are provided in Table 8. With the exception of steepness, the posterior estimates did not appear to be strongly influenced by the prior probability distributions. The posterior probability distribution for steepness was very similar to the prior probability distribution (Figure 17), implying that there is little information about this parameter in the available data. This is common in many stock assessments and was also noted in the previous stock assessments for Areas 5AB and 5CD (Forrest et al. 2015). Sensitivity to the prior distribution assumed for steepness is tested in Section 7.

Posterior probability estimates of $\ln(M)$ tended to be lower than the prior values (Figure 17), with a posterior median estimate of 0.346 y^{-1}, which is slightly lower than the median posterior estimate of 0.393 y^{-1} obtained by Forrest et al. (2015) for the Area 5CD stock. As noted above, Forrest et al. (2015) reported that posterior estimates of M were strongly influenced by the fit to the index of abundance data. Therefore the value assumed for σ_O likely has a stronger influence on estimates of M than the prior probability distribution for $\ln(M)$. This is discussed further in Section 7.

Survey scaling parameters (q_k) were strongly positively correlated with each other, especially the two synoptic surveys q_2 and q_3 in Figure 18, which were linearly correlated. This implies that changing the prior probability distribution for one of these parameters will strongly affect the other, and correspondingly, the scale of estimated biomass in the model. Because the two synoptic surveys occur in mostly the same years, it appears that the model had little leeway to change the ratio of their relative scales (see Section 7). Survey scaling parameters were negatively correlated with M. R_0 was also positively correlated with M, implying that there is limited information in the data to estimate both parameters independently, as they scale together when the estimated scale of the stock changes (Figure 18).The estimated a posterior distribution for the Queen Charlotte Sound q was well outside of the prior while the posterior distribution for the Hecate St synoptic survey scaling parameter was shifted but still within the compass of the prior distribution (Figure 17). These results indicate that the prior for the QC Sound synoptic survey may not be appropriate for this species/survey combination, especially given the strong linear correlation between the two synoptic surveys (q_2 and q_3 in Figure 18).

Estimates of reference points and benchmarks are provided in Table 9.

Median posterior estimated biomass B_t (with 95% credibility interval) is shown in Figure 19, with values in Table 10. Of note is the estimated downturn in estimated biomass since 2011. This is in contrast to the 2013 assessment (Forrest et al. 2015, their Figure 16), which projected an increase in biomass for 2014. In the current assessment, this downturn is driven by a decreasing trend in the synoptic surveys since 2013, as well as in the modern CPUE index (Figure 14). Also of note compared to the previous assessment is the lower estimate of B_0, which is now estimated to be lower than the 1956 stock biomass, with a smaller confidence interval (Figure 19). This is due to the structural change in the current assessment, where all average recruitment parameters are now set to the same estimated value (see Section 3), and may also be a function of the reduction in biomass driven by the drop in biomass indices.

Median posterior estimated relative biomass (B_t/B_0) (with 95% credibility interval) is shown in Figure 20 and Table 11. Median posterior estimated age-2 recruits and recruitment deviations (with 95% credibility interval) are shown in Figure 21 and Table 12. Recruitment is estimated to have been below average since 1990, with negative recruitment deviations since 2010.This is likely to be the primary reason that this stock is not doing well, in spite of low estimated fishing mortalities (Figure 22).

Median posterior estimated fishing mortality (F_t) is shown in Figure 22. Fishing mortality in 2017 was low compared to the historical period, with the posterior median estimated to be 0.03 y^{-1} (Tables 9 and 13).

We ran a retrospective analysis, sequentially removing the terminal year of data for four years to show the effects of each year's data (Figure 23). Results clearly show the effects of the biennial synoptic surveys on terminal estimates of biomass. Removing four years of data reverted the model back to its 2013 state, with an increase in biomass as was projected in the previous assessment for the Area 5CD stock (Forrest et al. 2015). Adding the 2014 data had little effect on the model as there were no Area 5AB or 5CD surveys in 2014. However, adding the 2015 data resulted in a lowering of estimated terminal biomass, because of a large drop in the 2015 Hecate Strait Synoptic Survey index (Figure 14).

6.2 AREA 3CD: WEST COAST VANCOUVER ISLAND

The model diagnostics were consistent with convergence (Figure 24) and posterior sample autocorrelation was minor for most parameters (Figure 25).The value of $\hat{R}$ was 1.00 for all parameters (Table 15).

The MPD model fits to the four indices of abundance are shown in Figure 26. The model fit the two fishery-independent indices quite closely (Figure 26 a and d), but did not fit the 2012 data point in the West Coast Vancouver Island Synoptic Survey. Similarly, the model followed the major patterns in the two CPUE indices but did not capture all the peaks (26 b and c).

As for Area 5ABCD, the model tended to underfit average annual weight in the commercial fishery (Figure 27). The effects of alternative values of σ_W are evaluated in Section 7.

Model fit to the total commercial catch is shown in Figure 28.

Posterior probability distributions of estimated parameters are provided in Figure 29 and Table 15. The median, 2.5th percentile and 97.5th percentile posterior parameter estimates, and MPD estimates, are provided in Table 15. As for Area 5ABCD, with the exception of steepness, the posterior estimates did not appear to be strongly influenced by the prior probability distributions. The posterior probability distribution for steepness, however, was very similar to the prior probability distribution (Figure 29), implying that there is little information about this parameter in the available data. Sensitivity to the prior distribution assumed for steepness is tested in Section 7.

As for Area 5ABCD, posterior probability estimates of $\ln(M)$ tended to be lower than the prior values (Figure 29), with a posterior median estimate of 0.413 y^{-1}. This is higher than the median posterior estimate of 0.346 y^{-1} obtained for the Area 5ABCD stock (Table 15), and very similar to the value of 0.42 y^{-1} obtained by Sinclair et al. (2001) for the Area 3CD stock.

Survey scaling parameters (q_k) were strongly positively correlated with each other (Figure 30). As for Area 5ABCD, the survey scaling parameters were negatively correlated with M, implying that there is limited information in the data to distinguish between a small productive stock or a larger, less productive stock (Figure 30). Interestingly, R_0 was positively correlated with M. As for the QC Sound synoptic survey, the estimated posterior distribution for the WCVI synoptic survey scaling parameter was outside of the prior (Figure 29).

Estimates of reference points and benchmarks are provided in Table 16.

Median posterior estimated biomass B_t (with 95% credibility interval) is shown in Figure 31, with values in Table 17. Biomass is estimated to have been on a declining trajectory since 2015. This followed an increasing trend from a historical low level of biomass between 1998 and 2014. The stock is estimated to have increased in abundance since 2008, consistent with an increasing trend in observed abundance in the West Coast Vancouver Island Synoptic Survey since 2010, as well as a general increase in the modern CPUE index since 2008 (Figure 26). The downturn in estimated biomass in 2017 is consistent with a slight drop in the West Coast Vancouver Island Synoptic Survey index and a large decrease in the modern CPUE index in 2017.

Median posterior estimated relative biomass (B_t/B_0) (with 95% credibility interval) is shown in Figure 32 and Table 18. Median posterior estimated age-2 recruits and recruitment deviations (with 95% credibility interval) are shown in Figure 33 and Table 19. Recruitment is estimated to have been below average for most years in the past two decades, with above average peaks in 2009, 2013 and 2014.

Median posterior estimated fishing mortality (F_t) is shown in Figure 34. Fishing mortality in

2017 is estimated to be very low, with the posterior median estimated to be 0.01 y^{-1} (Tables 16 and 20), reflecting low catches during the past decade (Figure 16) and an apparent growth in biomass (Figure 31).

We ran a retrospective analysis, sequentially removing the terminal year of data for four years to show the effects of each year's data (Figure 35). Results were not so systematic as for Area 5ABCD (Figure 35) and the relative magnitude of the bias was smaller. The largest effect was the addition of the 2017 data which caused the terminal biomass estimate to shift notably, most likely due to the large drop in the modern CPUE index in 2017 (Figure 26).

7 SENSITIVITY ANALYSES

We present a number of sensitivity analyses to show the influence of certain data sources, fixed parameters and prior probability distributions on model outcomes for the Area 5ABCD and 3CD Reference Case models. Prior probability distributions for leading parameters are provided in Tables 4 and 5. Fixed parameters are provided in Section 5.

For both stocks, we tested sensitivity of the model outputs to the following data and assumptions:

1. Inclusion of a locality-year interaction as a random effect in the commercial CPUE data (historical period: pre-1996 and modern period: post-1995)
2. Inclusion of commercial CPUE indices for the historical and modern periods.
3. Inclusion of the NMFS Triennial Survey index for Area 3CD
4. The prior probability distribution for $\ln(q)$
5. The prior probability distribution for $\ln(M)$
6. The prior probability distribution for steepness
7. The assumption of knife-edged selectivity and maturity at age 2
8. The updated growth parameters
9. The assumed fixed value of observation error σ_O
10. The assumed fixed value of σ_R
11. The assumed fixed value of σ_W
12. The influence of the pre-1996 annual mean weight data
13. The assumption of perfectly-known pre-1996 catch data

Results are presented under these headings below. In all sensitivity runs, as for the Reference Case models, 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.

7.1 SC 1B AND SC 1C. EXCLUSION OF A LOCALITY-YEAR INTERACTION AS RANDOM EFFECT IN COMMERCIAL CPUE INDICES

The reference case models were fit to historical and modern commercial CPUE indices that included a locality-year interaction as random effect (see Appendix B, Equations B.1 to B.5). Two sensitivity analyses are shown to illustrate the effect of omitting the locality-year interaction term (Equation B.4) from both historical and modern indices:

Sc 1b. Use equations without the interaction term to create CPUE indices for the historical and modern periods. Use the annual CVs resulting from the analysis as annual weighting terms in objective function of delay difference model (Equations D.24, D.25).

Sc 1c. Use equations without the interaction term to create CPUE indices for the historical and modern periods **and** double the annual CVs resulting from the analysis. Input the doubled CVs as weighting terms in objective function of delay difference model (Equations D.24, D.25).

Sc 1c was done because the annual CVs of the CPUE indices with omitted locality-year interactions were very small (less than 0.1 in some years). Annual CVs were doubled to address concerns that the objective function of the delay-difference model may have been giving the CPUE indices too much weight.

Resulting posterior estimates of biomass, recruitment, and fishing mortality compared to the Reference Case models are shown in Figures 36 to 39 for Area 5ABCD, and Figures 66 to 69 for Area 3CD. Removing the locality-year random effect interaction did not have a major effect on the biomass, recruitment, or fishing mortality posteriors. Of these sensitivity tests, removing the locality-year random effect interaction without artificially doubling the CV had the largest effect — this sensitivity analysis lowered the absolute estimate of biomass slightly and somewhat narrowed the credible intervals.

7.2 SC 1D TO 1F. EXCLUSION OF COMMERCIAL CPUE INDICES

A sensitivity analysis was done where the modern CPUE index was removed from the model altogether (Sc 1d). This was to address concerns that CPUE in the post-IVQ period (post-1995) may not be a good index of abundance, as some skippers reported avoiding Pacific Cod when quotas were low, especially in Area 5AB (Forrest et al. 2015). For comparison, to illustrate the effect of the historical CPUE index on model output, the historical CPUE index was removed (Sc 1e). Finally, to show the overall influence of the commercial CPUE data on model outcomes, both commercial CPUE indexes were removed (Sc 1f):

Sc 1d. Remove modern CPUE index from the model. Historical index includes locality-year interaction term as a random effect.

Sc 1e. Remove historical CPUE index from the model. Modern index includes locality-year interaction term as a random effect.

Sc 1f. Remove both CPUE indices from the model.

Resulting posterior estimates of biomass, recruitment, and fishing mortality compared to the Reference Case models are shown in Figures 36 to 39 for Area 5ABCD and Figures 66 to 69 for Area 3CD. For clarity biomass trajectories without Sc 1e and 1f are provided in Figures 37 and 67.

Removing the modern CPUE index from the model had little effect on the biomass, recruitment, or fishing mortality posteriors (Figures 37 and 67). However, removing the historical CPUE index had a large effect on the posterior estimates — especially the biomass estimates — substantially increasing the estimates of biomass prior to approximately 1970 (Figures 36 and 66). A similar strong influence of historical CPUE was noted by Forrest et al. (2015) who included a no-CPUE model run in their final model averaged decision tables.

7.3 SC 1G. EXCLUSION OF THE NMFS TRIENNIAL SURVEY INDEX FOR AREA 3CD

For Area 3CD only, a sensitivity analysis was done where the NMFS Triennial Survey index was removed from the model:

Sc 1g (Area 3CD only). Remove NMFS Triennial Survey index from the model.

Resulting posterior estimates of biomass, recruitment and fishing mortality compared to the Reference Case models are included in Figures 67 to 69.There was very little impact on the biomass trajectory compared to the reference case in this sensitivity run.

7.4 SC 2A AND 2B. PRIOR PROBABILITY DISTRIBUTION FOR SURVEY SCALING PARAMETERS (CATCHABILITY)

The absolute scale of the estimated biomass in the two assessed areas, determined by estimated catchability (q) in the survey indices, is considered the major axis of uncertainty in this assessment. For 5ABCD, six sensitivity analyses are shown to illustrate the effect of the normal prior probability distributions assumed for $\ln(q)$ for the QCS and HS Synoptic Surveys (see Sections 5.4.1 and 5.4.2 for Reference Case details:

Sc 2a. The mean of the QCS Synoptic Survey prior was set to the same mean as for the HS Synoptic Survey, and was then pro-rated according to relative areas, i.e., mean $\ln(q)$ = $\ln(0.1869 \cdot 0.65)$.

Sc 2b. No prior was used for q for either the QCS and HS Synoptic Surveys.

Four additional analyses were done to bracket the considerable uncertainty in the scale of the stock.

Sc 2c. The means of the QCS and HS Synoptic Survey priors were set to ln(0.5), and were then pro-rated according to relative areas, i.e.,for Queen Charlotte Sound mean $\ln(q)$ = $\ln(0.5 \cdot 0.65)$; and for Hecate Strait mean $\ln(q)$ = $\ln(0.5 \cdot 0.35)$.

Sc 2d. The means of the QCS and HS Synoptic Survey priors were set to ln(1), and were then pro-rated according to relative areas, i.e.,for Queen Charlotte Sound mean $\ln(q)$ = $\ln(0.65)$; and for Hecate Strait mean $\ln(q)$ = $\ln(0.35)$.

Sc 2e. The SDs of the QCS and HS Synoptic Survey priors were set to 0.6.

Sc 2f. The SDs of the QCS and HS Synoptic Survey priors were set to 1.0.

For 3CD, six sensitivity analyses are shown to illustrate the effect of the normal prior probability distribution assumed for $\ln(q)$ for the WCVI Synoptic Survey:

Sc 2a. The SD of the WCVI Synoptic Survey was set to the same SD as the value estimated by Edwards et al. (2013) for Pacific Ocean Perch, i.e., SD = 0.448.

Sc 2b. No prior was used for q for the WCVI Synoptic Survey.

As for Area 5ABCD, four additional analyses were done to bracket the considerable uncertainty in the scale of the stock.

Sc 2c. The mean of the WCVI Synoptic Survey prior was set to ln(0.5).

Sc 2d. The mean of the WCVI Synoptic Survey prior was set to ln(1).

Sc 2e. The SD of the WCVI Synoptic Survey prior was set to 0.6.

Sc 2f. The SD of the WCVI Synoptic Survey prior was set to 1.0.

Models were moderately sensitive to choice of the parameters used for the normal prior for $\ln(q)$

(Sc 2a; Figures 40 and 70). For clarity, estimated biomass biomass trajectories without Sc 2b is provided for Area 3Cd in Figure 71. Essentially, lowering the value of the mean (Area 5ABCD), or increasing the variance (Area 3CD) resulted in lower estimates of q (Tables 21 and 31), leading to larger estimates of biomass (Figures 40 and 71) and recruitment (Figures 41 and 72).

Notably, removing the informative prior in Sc 2b resulted in very low estimates of q for these surveys (Tables 22 and 32),leading to very large and uncertain estimates of biomass (Figures 40 and 70) and recruitment (Figures 41 and 72). This was extremely pronounced for Area 3CD (Table 32 and Figure 70) For both areas, increased estimates of biomass led to decreased estimates of F_t (Figures 42 and 73).

Given model sensitivity to priors assumed for survey $ln(q)$, and the tendency of the estimates to run to very low values without prior constraint, it seems justified to use a prior probability distribution informed by age-structured assessments for groundfish species caught in the same areas with the same gear, even though those estimates are conditional on the assumptions inherent in those models. Synoptic survey *q* should be considered a major source of uncertainty in this assessment and we suggest inclusion of Sc 2a (both areas) in the ensemble of models for model-averaged decision tables (Section 13.5).

7.5 SC 3A TO 3C. PRIOR PROBABILITY DISTRIBUTION FOR *M*

Three sensitivity analyses are shown to illustrate the effect of the parameters of the normal prior distribution assumed for $\ln(M)$:

Sc 3a. The mean was held at the Reference Case value of 0.5, while the standard deviation was increased to 0.2.

Sc 3b. The mean was reduced to 0.4 and the standard deviation was held at the Reference Case value of 0.1.

Sc 3c. The mean was reduced to 0.4 and the standard deviation was increased to 0.2.

Resulting posterior estimates of biomass, recruitment and fishing mortality compared to the Reference Case models are shown in Figures 43 to 45 for Area 5ABCD and Figures 74 to 76 for Area 3CD. Resulting parameter estimates are provided in Tables 23 to 25 for Area 5ABCD and Tables 33 to 35 for Area 3CD.

For Area 5ABCD, respective median posterior estimates of *M* for Sc 3a, 3b and 3c were 0.324 y^{-1}, 0.287 y^{-1} and 0.298 y^{-1}. These values are compared to the median posterior Reference Case estimate of *M* = 0.346 y^{-1}.

For Area 3CD, respective median posterior estimates of *M* for Scenarios 3a, 3b and 3c were 0.392 y^{-1}, 0.391 y^{-1} and 0.398 y^{-1}. These values are compared to the median posterior Reference Case estimate of *M* = 0.413 y^{-1}.

For Area 5ABCD, all sensitivity runs resulted in lower estimates of biomass than the Reference Case model (Figure 43).This was not surprising, given that all had lower posterior median estimates of *M*. Differences in estimated biomass among scenarios were smaller for Area 3CD, although all were slightly lower than for the Reference Case model (Figure 74).

We suggest inclusion of Sc 3b (both areas) in the ensemble of models for model-averaged decision tables (Section 13.5), as this scenario resulted in the biggest difference in estimated biomass in both areas.

7.6 SC 4A AND SC 4B. PRIOR PROBABILITY DISTRIBUTION FOR STEEPNESS

Two sensitivity analyses were done to illustrate the effect of the prior probability distribution assumed for steepness in the reference case model:

Sc 4a. Use a uniform prior for steepness bounded between 0.21 and 0.999.

Sc 4b. Use a beta prior for steepness with mean = 0.85 and sd = 0.15.

Resulting posterior estimates of biomass, recruitment and fishing mortality compared to the Reference Case models are shown in Figures 46 to 48 for Area 5ABCD, and Figures 77 to 79 for Area 3CD. Resulting parameter estimates are provided in Tables 26 to 27 for Area 5ABCD and Tables 36 to 37 for Area 3CD.

For Area 5ABCD, respective median posterior estimates of *h* for Scenarios 4a and 4b were 0.479 and 0.883. For Area 3CD, respective median posterior estimates of *h* for Scenarios 4a and 4b were 0.497 and 0.889. This was compared compared to 0.744 for the Area 5ABCD Reference Case and 0.747 for the Area 3CD Reference Case.

Despite the very large range in median posterior estimates of *h* among scenarios for both areas, there was almost no discernible effect on estimated biomass and recruitment, especially for Area 3CD (Figures 46 and 77). Model insensitivity to the prior probability distribution for *h* explains in part why the posterior probability distribution so closely matched the prior for both models (Figures 17 and 29).

Differences in model sensitivity to the prior for *h* in the current assessment vs. the previous assessment for Area 5CD can be explained by changes in the treatment of average recruitment. The model used in Forrest et al. (2015), estimated R_0 as a separate parameter to average annual recruitment (R_{Avg}). As a result, when Forrest et al. (2015) tested a uniform prior for *h*, while biomass estimates were unaffected, their posterior estimates of B_0 became very large (Forrest et al. 2015, their Figures 33 and 34). They described poor model convergence for most parameters and noted the model's tendency to sample very low estimates of steepness coincident with the very large estimates of $\ln(R_0)$. This suggests there was very little information in the data for estimation of a separate $\ln(R_0)$ parameter in the absence of age-composition data, suggesting that it may be preferable to combine average and unfished recruitment, as has been done in the current assessment.

7.7 SC 5A AND 5B. THE ASSUMPTION OF KNIFE-EDGED SELECTIVITY AND MATURITY AT AGE 2, AND EFFECTS OF UPDATING THE GROWTH PARAMETERS

The Reference Case delay-difference models assumed knife-edged selectivity and maturity at age 2 *y* (i.e., age at recruitment k = 2, Table D.1). New analysis of age and maturity data suggest age at 50% maturity could be closer to 3 *y* for BC Pacific Cod (Appendix C). A sensitivity analysis (Sc 5a) was done to illustrate the effect of assuming that fish recruit to the fishery and mature at age 3 *y*:

Another sensitivity analysis (Sc 5b) was done to illustrate the effects of reverting back to the von Bertalanffy growth parameters used in the previous Area 5CD assessments (Sinclair and Starr 2005, Forrest et al. 2015), which were also used by Sinclair et al. (2001) in the last assessment for Area 3CD. These previous stock assessments used the von Bertalanffy parameters that Westrheim (1996) reported for Area 3CD, (L_{inf} = 89.48 cm; K_{VB} = 0.307 y^1; and a_0 = -0.116 *y*).

The current Area 5ABCD assessment used values of growth parameters estimated in Appendix C using survey age and length data from the Hecate Strait and Queen Charlotte Sound Synoptic Surveys (L_{inf} = 95.51 cm; K_{VB} = 0.19 y^1; and a_0 = -0.81 y). The current Area 3CD assessment used values of growth parameters estimated in Appendix C using survey age and length data from the West Coast Vancouver Island Synoptic Survey (L_{inf} = 82.59 cm; K_{VB} = 0.26 y^1; and a_0 = -0.67 y). For both areas, the new values of the growth rate K_{VB} were much lower than used in the previous assessments.The delay-difference model in Sc 5b used Ford-Walford parameters W_k, α_g and ρ_g (Appendix D) derived from previous growth parameters used in (Sinclair et al. 2001, Sinclair and Starr 2005, Forrest et al. 2015).

In summary, the two new scenarios are:

Sc 5a. Set $k = 3y$ and update weight at recruitment W_k and Ford-Walford parameters accordingly.

Sc 5b. Run the model using the von Bertalanffy growth parameters that were used in the previous stock assessment (Forrest et al. 2015).

Resulting posterior estimates of biomass, recruitment and fishing mortality compared to the Reference Case models are shown in Figures 49 to 51 for Area 5ABCD and Figures 80 to 82 for Area 3CD. Fits to the average annual mean weight in the commercial fishery for Scenarios 5a and 5b are shown in Figures 52 and 83.

Not surprisingly, the Area 5ABCD model was sensitive to both the age at knife-edged selectivity and the growth parameters (Figure 49). For Sc 5a, the model estimated much lower biomass, especially for the historical period. This is expected since this scenario does not include age-2 fish. The fit to the average annual mean weight for Sc 5a (Figure 52 a) was better for the historical portion of the time series than for the Reference Case model, which tended to greatly underfit in some years (Figure 15). However, it should be remembered that prior to 1996, many observations of small fish were missing from the commercial length data, as only landed fish were measured (Appendix C and Forrest et al. (2015), their Appendix C). Therefore, the current Reference Case model is estimating mean weights that were probably present in the catch but not recorded.

For Sc 5b in Area 5ABCD, estimates of biomass were lower than for the Reference Case, especially for the historical period (Figure 49), with smaller peaks in biomass in the 1970s and 1990s. The von Bertalanffy growth rate used by Forrest et al. (2015) and Sinclair and Starr (2005) was larger than that in the Reference Case model, indicating a more productive stock. Therefore large peaks in catches could be explained by lower biomass in Sc 5b, due to greater stock productivity. Recent estimates of biomass were, however, more similar to the Reference Case (Figure 49). Fits to the annual average mean weight for Sc 5b (Figure 52 b) were similar to fits in the Reference Case model (Figure 15).

For Area 3CD, results were broadly similar to those in Area 5ABCD, although differences in biomass between the Reference Case and the two scenarios were more distinct (Figure 80). The fit to the average annual mean weight data was very poor for Sc 5a, and fairly similar to the Reference Case model for Sc 5b (Figure 83). As for Area 5ABCD, the growth rate used in the Reference Case model was lower than that used in Sc 5b. Therefore the model needed to explain catches of a less productive stock with a larger historical biomass.

7.8 SC 6A - 6C. ASSUMED FIXED VALUE OF OBSERVATION ERROR σ_O

The observation error parameter was σ_O was fixed at 0.2 in the Reference Case models (Section 5.5). Three sensitivity analyses were done to explore the impacts of changing this value:

Sc 6a. Fix σ_O = 0.10.

Sc 6b. Fix σ_O = 0.15.

Sc 6c. Fix σ_O = 0.25.

Resulting posterior estimates of biomass, recruitment and fishing mortality compared to the Reference Case models are shown in Figures 53 to 55 for Area 5ABCD and Figures 84 to 86 for Area 3CD.

MPD index fits for the HSMAS, HSSS and QCSS surveys are shown in Figures 56 to 58. MPD index fits for the Area 5ABCD commercial CPUE indices are shown in Figures 59 and 60.

MPD index fits for the WCVISS and Triennial Survey are shown in Figures 87 and 88. MPD index fits for the Area 3CD commercial CPUE indices are shown in Figures 89 and 90.

Confidence intervals shown on the plots are derived from the observed data (see Appendices A and B) and are unaffected by the value of σ_O.

As expected, decreasing the value of σ_O resulted in closer fits to indices of abundance in both areas. In Area 5ABCD, reducing σ_O also caused a reduction in estimated historical biomass, especially Sc 6a, although recent estimates of biomass were similar among scenarios (Figure 53). In Area 3CD, results were less pronounced (Figure 84), with more similar index fits among scenarios (Figure 88).

Productivity parameters *M* and *h* were sensitive to changes in σ_O, as were scale parameters R_0 and catchability parameters *q* (Tables 28 to 30 for Area 5ABCD, and Tables 38 to 40 for Area 3CD).

7.9 SC 6C. ASSUMED FIXED VALUE OF PROCESS ERROR σ_R

The process error parameter was σ_R was fixed at 0.8 in the Reference Case models (Section 5.5), as this stock appears to have had very variable recruitment throughout the history of the fishery. One sensitivity analysis was done to test the effect of increasing the assumed value of σ_R:

Sc 6d. Fix σ_R = 1.0.

There was very little discernible difference in the estimated biomass, recruitment and fishing mortality between the Reference Case model and Sc 6d (Figures 53 to 55 for Area 5ABCD and Figures 84 to 86 for Area 3CD).

7.10 SC 7A. ASSUMED FIXED VALUE OF σ_W

Given the uncertainties in interpreting the mean weight time series (see Section 5) and its potential to provide direct information for scaling the stock size, two sensitivity analysis was done to illustrate the effect of the fixed value of σ_W:

Sc 7a. Fix σ_W = 0.4.

Sc 7b. Fix σ_W = 0.15.

Resulting posterior estimates of biomass, recruitment and fishing mortality compared to the Reference Case models are shown in Figures 61 to 63 for Area 5ABCD and Figures 91 to 93 for Area 3CD.

Increasing σ_W in Sc 7a resulted in a large reduction in estimated biomass in both areas (Figures 61 and 91), but very poor fits to the average annual mean weight data (Figures 64a and 94a). Decreasing σ_w in Sc 7b did not have a noticeable effect on estimated biomass (Figures 61 and 91) or fits to the mean weight data (Figures Figures 64b and 94b). Confidence intervals shown on the plots arise from the observed data and are unaffected by the value of σ_W.

7.11 SC 7C. HISTORICAL ANNUAL MEAN WEIGHT IN THE COMMERCIAL CATCH

The annnual mean weight data are known to be biased prior to 1996 due to lack of samples of fish released at sea. For both stocks, a sensitivity analysis was done with pre-1996 annual mean weight data removed, to illustrate the influence of these data on the model.

Sc 7c. Remove observed annual mean weight data prior to 1996.

This scenario is essentially a more extreme case of Sc 7a. Removing the pre-1996 mean weight data resulted in much lower estimates of biomass (Figures 61 and 91), especially in the early parts of the time series. Notably for Area 5ABCD, removing these data also resulted in an implausibly large spike (> 15 */y*) in the credible interval for fishing mortality in 1991 (Figure 63). For Area 3CD, there were large peaks in estimated fishing mortality throughout the historical period (Figure 93).

7.12 SC 8A AND 8B. ASSUMPTION OF PERFECTLY-KNOWN HISTORICAL CATCH

For each stock, two sensitivity analyses were done, where pre-1996 commercial catch data were inflated by a fixed amount. These were done mainly to bracket the uncertainty in the model due to uncertain historical discarding and, to a lesser extent, foreign catches in the early part of the time series. These scenarios are not intended to represent real estimates of historical discarding. Reconstruction of the historical catch data, in collaboration with the fishing industry, is recommended as an area of future research.

Sc 8a. Inflate pre-1996 catches by 25%.

Sc 8b. Inflate pre-1996 catches by 50%.

As expected, inflating the historical commercial catch data inflated estimates of historical biomass by a similar magnitude (Figures 65 and 95), as the models needed more biomass to explain the observed catch. We note that RPR industry participants felt that unreported discards were not significant for this species due to the nature of fishing operations during the historical period.

8 COMBINED COMPOSITE MODEL

The Regional Peer Review meeting held in October 2018 reviewed the Reference Case model and the suite of sensitivity runs described above, coming to the conclusion that no one model adequately represented the uncertainty associated with this stock assessment. Consequently, the meeting agreed to adopt an approach that combined model runs to include a greater range of plausible uncertainties associated with this species in each area.

Forrest et al. (2015) used a model-averaging approach to construct decision tables based on combined posterior samples from several different sensitivity cases. This was to address some of the key irresolvable uncertainties associated with the stock assessment. A similar approach was used in the 2011 assessment of Pacific Hake (Stewart et al. 2011), where two structurally different stock assessment models were judged by the Pacific Fishery Management Council's Scientific and Statistical Committee to be equally plausible. A similar “ensemble” approach is used in the annual assessments of Pacific Halibut, where four structurally distinct models are used in construction of the decision table (Stewart and Hicks 2016). Two recent BC groundfish stock assessments (Shortspine Thornyhead (Starr and Haigh 2017) and Walleye Pollock (Starr and Haigh 2020)), which were based on the same iscam delay-difference model have also adopted this approach.

For Area 5ABCD, the following seven models were selected because they represent stock hypotheses and sources of uncertainty which cannot be ruled out given the current model structure and the availability of data:

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 $\ln(M)$ to $\mathcal{N} \sim (0.4, 0.1)$;
5. Sc 5a Set knife-edged age at recruitment = 3 years
6. Sc 6b Reduce the overall observation error term $\sigma_O = 0.15$
7. Sc 7b Reduce the SD in the likelihood for the fit to average annual mean weight $\sigma_W = 0.15$

Posterior estimates of biomass from the six sensitivity cases are shown together in Figure 96. The combined posterior estimates of biomass are shown in Figure 97. Projected biomass from the model-averaged set is shown in Figure 98.

For Area 3CD, the following seven models were selected because they represent stock hypotheses and sources of uncertainty which cannot be ruled out given the current model structure and the availability of data:

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 $\ln(M)$ to $\mathcal{N} \sim (0.4, 0.1)$;
5. Sc 5a Set knife-edged age at recruitment = 3 years
6. Sc 6b Reduce the overall observation error term $\sigma_O = 0.15$
7. Sc 7b Reduce the SD in the likelihood for the fit to average annual mean weight $\sigma_W = 0.15$

Posterior estimates of biomass from the model-averaged set are shown together in Figure 99. The combined posterior estimates of biomass are shown in Figure 100. Projected biomass from the model-averaged set is shown in Figure 101.

9 MODEL-AVERAGED REFERENCE POINTS AND DECISION TABLES

Reference points were calculated for each area using model-averaged blended posteriors as described above. The results are shown in Table 41 for Area 5ABCD and Table 44 for Area 3CD. Biomass and recruitment posterior medians with credible intervals and MPD values are also provided in Tables 42 and 43 for Area 5ABCD and Tables 45 and 46 for Area 3CD.

Performance measures were calculated over a sequence of alternative 2019 projected catch levels and are based on posterior samples for a one-year projection to the end of 2020. Uncertainty enters the projections through parameter uncertainty propagated from the modeled time series, and recruitment anomalies for the projection year, which were drawn randomly from a normal distribution, $\mathcal{N}(0, \sigma_R^2)$. The following performance measures were evaluated:

1. $P(B_{2020} < B_{2019})$
2. $P(F_{2019} > F_{2018})$
3. $P(B_{2020} < LRP)$
4. $P(B_{2020} < USR)$
5. $P(F_{2019} > LRR)$

where

1. USR (Upper Stock Reference) is the historical mean of the biomass estimates from 1956–2004.
2. LRP (Limit Reference Point) 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. LRR (Limit Removal Rate) is the average fishing mortality rate from 1956–2004.

For more information on reference points, see Section 4.

The above performance measures are intended to present probabilities of "undesirable" states under alternative 2019 projected catch levels. For example, an "undesirable" biomass-based performance measure occurs when the 2020 projected biomass is below the LRP, i.e., $B_{2020}/LRP < 1$. An "undesirable" fishing mortality-based performance measure occurs when projected 2019 fishing mortality is above the reference point, i.e., $F_{2019}/LRR > 1$.

Probabilities of such states are measured as the proportion of thinned, burned-in posterior samples that meet the criteria above (i.e., proportion of posterior samples < 1 for biomass-based performance measures; and proportion of posterior samples > 1 for fishing mortality-based performance measures). Note that MPD results are not used in development of advice.

Decision tables summarizing the probability of breaching reference points over a range of fixed catches for a one-year projection were constructed for each area using the unweighted combined posterior samples from a set of six sensitivity cases, plus the reference case (the "model-averaged" set). For each performance measure, under each alternative 2019 catch level, vectors of 1,000 burned-in posterior samples from each of the seven models were combined into a single vector of 7,000 samples. Probabilities of performance measures were then calculated from the combined samples.

9.1 AREA 5ABCD

The "Model-Averaged" decision table probabilities are presented in Table 47. 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%.

Under a 2019 catch level of 900 mt, close to the 2017 TAC, there is an estimated 1% probability that the 2020 biomass will be below the LRP and a 99% probability that the 2019 biomass will be below the USR.

9.2 AREA 3CD

The “Model-Averaged” decision table probabilities for Area 3CD are presented in Table 48. 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%.

Under a 2019 catch level of 500 mt, close to the 2017 TAC, there is an estimated 18% probability that the 2020 biomass will be below the LRP and a 99% probability that the 2020 biomass will be below the USR.

10 SUMMARY AND RESEARCH RECOMMENDATIONS

We presented the alternative, model averaged decision tables for Areas 5ABCD and 3CD in an attempt to more comprehensively incorporate substantial structural uncertainty in the assessments into advice for fishery managers and stakeholders. 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. However, we emphasize that there are major structural uncertainties that we have not been able to address in this assessment. These include, but are not limited to:

1. The effects of the assumption of constant selectivity over each of the two time periods in the trawl fishery. This assumption is unlikely to be correct, given the known variations in mesh size regulations and in fishing behaviour;
2. The effect of the assumption that recruitment to the fishery, surveys and the spawning biomass is knife-edged at age 2 years. Knife-edge recruitment is a structural assumption associated with the delay-difference model. Addressing this uncertainty would involve adopting another modelling approach;
3. The impact of uncertainty in stock structure in understanding patterns in abundance;
4. The impact of uncertainty in the magnitude of historical discarding and foreign catches;
5. The impact of change in onboard observer coverage and representativeness of length samples from the commercial catch.This issue is particularly important when interpreting sorted samples taken from landed catch relative to unsorted samples taken from catch as it comes on board.
6. There was a substantial change in the quality of the catch/effort data available to this assessment beginning in 1996. Before 1996, data were self-reported by fishers with uncertain

reliability. Tow-by-tow data only began in 1991, which meant that the catch location and depth can only be approximately known before 1991. Before 1991, effort and catch were combined on a daily basis within defined spatial "localities", again with unknown reliability. This meant that the analyses performed on the pre-1996 catch/effort data had fewer available variables for standardizing the "abundance" effect compared to the post-1995 data. As well, all fisher-dependent data (both before and after 1996) are affected by economic and other non-biological considerations for which it is difficult or impossible to standardize. Consequently, CPUE data need to be viewed as potentially biased and possibly misleading. This is an important uncertainty because both area stock assessments are highly dependent on the pre-1996 CPUE series, as indicated by sensitivity runs 1e and 1f, which estimate much larger stock sizes in the absence of the pre-1996 CPUE series. On the other hand, there is little sensitivity to the removal of the post-1995 CPUE data for either stock, likely because of the presence of the co-occurring fishery- independent surveys.

Uncertainty is therefore under-represented in this assessment. We make a number of research recommendations to help reduce uncertainties for BC Pacific Cod stocks:

1. Investigate application of a length-based model to characterize possible changes in selectivity in the trawl fishery, particularly the impact of changing mesh size regulations and recognizing that length samples prior to 1996 under-represent smaller length classes.
2. Investigate possible mixing between stock areas within and outside of British Columbia. Genetic samples have been collected from spawning fish in Hecate Strait and Queen Charlotte Sound but these data have not yet been analyzed. Other sources of information could also be considered, such as comparing trends in Alaskan waters, comparing trends with other BC commercial fisheries, otolith microchemistry or similarities/differences in other biological factors among areas.
3. Explore the application of geostatistical tools to coast-wide geospatial data for developing indices of abundance and better capturing spatio-temporal characteristics of the stock.
4. Work with the fishing industry to improve understanding of the magnitude of historical foreign catch and discards, and drivers of changes in fishing effort during the historical period, which may improve understanding of the relationship between commercial CPUE and abundance, and to better characterize uncertainty due to historical changes in the fishery.
5. Continue to develop feedback simulation models for this species (Carruthers and Hordyk 2018, Forrest et al. 2018) to evaluate, *inter alia*, costs and benefits of including age-composition data in developing advice for this species, given the current paucity of available ageing data, the expense of preparing fin-sections and the uncertainty associated with age readings. Such analyses could also be used to evaluate relative performance of the delay-difference model and alternative data-rich and/or data-limited assessment methods.

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13 TABLES

Table 1. Reported catch (mt) of Pacific Cod in Area 5ABCD by Canada and the USA, 1953–2018. Catch in 2018 was extrapolated based on the average proportion caught by September 30 in the previous three years (see text). The reported discards for the period 1953–1995 are unrepresentative of true discarding because the estimates were taken from logbooks. Discard estimates since 1996 are based on at-sea observations and are considered to be more representative of true discarding.

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	3,207	2,677	5,884
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	1,537	251	1,788
1962	2,138	3	2,140	310	2,450
1963	2,478	99	2,577	883	3,460
1964	6,568	86	6,655	1,009	7,664
1965	9,291	0	9,291	1,562	10,853
1966	9,409	199	9,609	1,362	10,971
1967	6,034	344	6,377	1,025	7,402
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	6,072	1,539	7,611
1975	6,739	100	6,840	1,139	7,979
1976	5,796	52	5,848	635	6,483
1977	4,369	179	4,547	408	4,955
1978	4,077	125	4,202	159	4,361
1979	7,459	282	7,741	62	7,803
1980	5,485	75	5,560	10	5,570
1981	3,454	35	3,488	0	3,488
1982	3,087	29	3,116	0	3,116
1983	2,477	68	2,545	0	2,545
1984	2,113	8	2,121	0	2,121
1985	1,338	6	1,343	0	1,343
1986	4,019	112	4,132	0	4,132
1987	12,711	41	12,752	0	12,752
1988	8,020	8	8,027	0	8,027
1989	4,214	42	4,256	0	4,256
1990	4,242	233	4,475	0	4,475
1991	9,892	66	9,957	0	9,957
1992	7,087	35	7,123	0	7,123
1993	4,869	7	4,876	0	4,876

Table 1. Reported catch (mt) of Pacific Cod in Area 5ABCD by Canada and the USA, 1953–2018. Catch in 2018 was extrapolated based on the average proportion caught by September 30 in the previous three years (see text). The reported discards for the period 1953–1995 are unrepresentative of true discarding because the estimates were taken from logbooks. Discard estimates since 1996 are based on at-sea observations and are considered to be more representative of true discarding. (continued)

Year	Canada landings	Canada released at sea	Canada total	USA	Total catch
1994	1,757	2	1,759	0	1,759
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	60	1,042	0	1,042
1999	692	53	746	0	746
2000	553	28	581	0	581
2001	296	39	334	0	334
2002	382	109	491	0	491
2003	660	150	810	0	810
2004	833	130	963	0	963
2005	1,004	83	1,087	0	1,087
2006	872	32	904	0	904
2007	370	15	385	0	385
2008	309	7	316	0	316
2009	669	40	709	0	709
2010	1,452	49	1,501	0	1,501
2011	1,233	7	1,240	0	1,240
2012	871	12	883	0	883
2013	829	22	851	0	851
2014	904	18	922	0	922
2015	924	18	943	0	943
2016	529	5	534	0	534
2017	346	4	350	0	350
2018	230	0	230	0	230

Table 2. *Reported catch (mt) of Pacific Cod in Area 3CD by Canada and the USA, 1953–2018. Catch in 2018 was set the same as 2017 (see text). The reported discards for the period 1953–1995 are unrepresentative of true discarding because the estimates were taken from logbooks. Discard estimates since 1996 are based on at-sea observations and are considered to be more representative of true discarding.*

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	2,239	1,145	3,384
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	1,658	1,344	3,002
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	1,521	0	1,521
1982	608	2	610	0	610
1983	883	0	884	0	884
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	1,962	0	1,962
1990	2,076	4	2,080	0	2,080
1991	2,971	0	2,971	0	2,971
1992	2,229	1	2,231	0	2,231
1993	2,091	2	2,093	0	2,093
1994	816	1	816	0	816
1995	252	4	255	0	255

Table 2. Reported catch (mt) of Pacific Cod in Area 3CD by Canada and the USA, 1953–2018. Catch in 2018 was set the same as 2017 (see text). The reported discards for the period 1953–1995 are unrepresentative of true discarding because the estimates were taken from logbooks. Discard estimates since 1996 are based on at-sea observations and are considered to be more representative of true discarding. (continued)

Year	Canada landings	Canada released at sea	Canada total	USA	Total catch
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	27	204	0	204
2003	458	45	503	0	503
2004	418	29	446	0	446
2005	265	29	295	0	295
2006	143	10	153	0	153
2007	55	13	68	0	68
2008	105	7	111	0	111
2009	365	56	421	0	421
2010	577	25	602	0	602
2011	503	9	512	0	512
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	164	0	164
2018	164	0	164	0	164

Table 3. Summary of TACs by area. IFMP = Integrated Fishery Management Plan

Year	3CD	5AB	5CDE	Total	Source
2018-19	500	250	700	1,450	IFMP
2017-18	500	250	700	1,450	IFMP
2016-17	500	200	700	1,400	IFMP
2015-16	500	400	1,200	2,100	IFMP
2014-15	500	590	1,200	2,290	IFMP
2013-14	500	590	1,200	2,290	IFMP
2012-13	500	590	1,200	2,290	IFMP
2011-12	500	590	1,200	2,290	IFMP
2010-11	500	390	800	1,690	IFMP
2009-10	500	390	800	1,690	IFMP
2008-09	500	390	800	1,690	IFMP
2007-08	500	390	800	1,690	IFMP
2006-07	500	390	800	1,690	IFMP
2005-06	500	390	800	1,690	GMU Trawl TAC xls
2004-05	500	390	400	1,290	GMU Trawl TAC xls
2003-04	500	260	400	1,160	GMU Trawl TAC xls
2002-03	240	260	200	700	GMU Trawl TAC xls
2001-02	694	260	200	1,154	GMU Trawl TAC xls
2000-01	694	260	1,000	1,954	GMU Trawl TAC xls
1999-00	694	260	1,000	1,954	GMU Trawl TAC xls
1998-99	694	260	1,000	1,954	GMU Trawl TAC xls
1997-98	694	260	1,620	2,574	GMU Trawl TAC xls
1996-97	bycatch only	bycatch only	bycatch only	0	CSAS ResDoc 2015/052

Table 4. Prior probability distributions, their parameters and initial values used in the Area 5ABCD Reference Case model. 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	Initial value	Lower bound	Upper bound	Distribution	P1	P2	Estimated	Basis
$ln(R_0)$	8.49	1.00	12.00	Uniform	1.00	15.00	Yes	Noninformative
h	0.75	0.20	1.00	Beta	5.83	2.50	Yes	Informative Previous assessment
$ln(M)$	-0.69	-2.30	0.00	Normal	-0.69	0.10	Yes	Informative Previous assessment
$ln(\bar{R})$	8.90	–	–	–	–	–	No	No prior Fixed parameter
$ln(R_{init})$	9.54	–	–	–	–	–	No	No prior Fixed parameter
ρ	0.06	–	–	–	–	–	No	No prior Fixed parameter
κ	1.47	–	–	–	–	–	No	No prior Fixed parameter
q_1	–	–	–	–	–	–	Yes	Noninformative Technical necessity
$ln(q_2)$	–	–	–	Normal	-0.90	0.30	Yes	Noninformative Technical necessity
$ln(q_3)$	–	–	–	Normal	-2.73	0.30	Yes	Noninformative Technical necessity
q_4	–	–	–	–	–	–	Yes	Noninformative Technical necessity
q_5	–	–	–	–	–	–	Yes	Noninformative Technical necessity

Table 5. Prior probability distributions, their parameters and initial values used in the Area 3CD Reference Case model. 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	**Initial value**	**Lower bound**	**Upper bound**	**Distribution**	**P1**	**P2**	**Estimated**	**Basis**
$ln(R_0)$	8.49	1.00	12.00	Uniform	1.00	15.00	Yes	Noninformative
h	0.75	0.20	1.00	Beta	5.83	2.50	Yes	Informative Previous assessment
$ln(M)$	-0.69	-2.30	0.00	Normal	-0.69	0.10	Yes	Informative Previous assessment
$ln(\bar{R})$	8.90	–	–	–	–	–	No	No prior Fixed parameter
$ln(R_{init})$	9.54	–	–	–	–	–	No	No prior Fixed parameter
ρ	0.06	–	–	–	–	–	No	No prior Fixed parameter
κ	1.47	–	–	–	–	–	No	No prior Fixed parameter
$ln(q_1)$	–	–	–	Normal	-1.48	0.30	Yes	Noninformative Technical necessity
q_2	–	–	–	–	–	–	Yes	Noninformative Technical necessity
q_3	–	–	–	–	–	–	Yes	Noninformative Technical necessity
q_4	–	–	–	–	–	–	Yes	Noninformative Technical necessity

Table 6. Reference points for the Reference Case 5ABCD and 3CD models.

Reference point	**Definition**	**Role**
B_{Min}	Lowest estimated biomass agreed to be an undesirable state to avoid (B_{2000} in 5ABCD; B_{1986} in 3CD)	LRP
B_{Avg}	Average biomass for the period 1956-2004	USR
F_{Avg}	Average fishing mortality for the period 1956-2004	LRR
B_{2018}	Biomass in 2018	Benchmark
F_{2017}	Fishing mortality in 2017	Benchmark

13.1 MODEL RESULTS: AREA 5ABCD

Table 7. Estimated and fixed parameters and prior probablilty distributions used in the Reference Case, Area 5ABCD.

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	Normal($0.5, 1$)
Log fishing mortality values ($\Gamma_{k,t}$)	63	[-30, 3]	[-30, 3]
Log recruitment deviations (ω_t)	63	None	Normal($0, 2$)
Initial log recruitment deviations ($\omega_{init,t}$)	8	None	Normal($0, 2$)

Table 8. 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. B_0 is in tonnes. $\hat{R}$ 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	2,331	2,989	3,902	3,400	611	1.00
h	0.432	0.727	0.931	0.800	767	1.00
M	0.280	0.312	0.347	0.309	749	1.00
B_0	23,167	27,265	32,755	31,281	450	1.00
q_1	0.054	0.068	0.086	0.071	879	1.00
q_2	0.038	0.050	0.066	0.050	970	1.00
q_3	0.065	0.086	0.114	0.087	972	1.00
q_4	0.002	0.003	0.004	0.003	760	1.00
q_5	0.006	0.008	0.011	0.008	958	1.00

Table 9. Posterior (2.5th percentile, Median, and 97.5th percentile) of reference points for Area 5ABCD. Biomass is in tonnes.

Reference Point	2.5%	50%	97.5%
B_0	23,167.35	27,265.30	32,755.25
B_{1956}	37,539.58	50,217.05	67,959.41
B_{2019}	11,348.04	15,949.75	26,144.53
B_{2019}/B_0	0.45	0.58	0.92
B_{2019}/B_{1956}	0.22	0.32	0.53
F_{2018}	0.01	0.02	0.03
LRP (2000)	7,728	10,642	14,719
USR (1956–2004)	27,931	36,423	48,099

Table 10. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of biomass (t) for the Reference Case, Area 5ABCD.

Year	2.5%	50%	97.5%	MPD
1956	37,540	50,217	67,959	45,179
1957	39,125	49,415	64,880	45,319
1958	34,214	43,655	57,501	40,341
1959	26,990	35,555	48,035	32,611
1960	21,923	29,725	41,177	27,147
1961	18,376	25,756	36,583	23,397
1962	16,352	23,741	34,725	21,490
1963	44,167	56,542	73,891	54,181
1964	60,565	76,396	98,583	73,288
1965	61,363	75,834	97,665	72,428
1966	51,665	64,235	83,301	60,719
1967	38,723	49,456	67,102	46,209
1968	28,963	37,750	51,664	35,061
1969	21,959	29,493	41,325	27,148
1970	17,852	24,356	34,856	22,340
1971	16,245	22,708	32,759	20,700
1972	37,584	51,225	66,072	48,618
1973	48,431	64,454	83,932	61,107
1974	51,298	66,297	85,363	62,438
1975	47,350	60,590	78,658	56,875
1976	39,882	52,304	69,580	48,770
1977	36,214	47,778	62,422	44,451
1978	34,976	45,172	58,545	41,795
1979	34,581	43,413	55,299	40,794
1980	28,155	36,461	47,681	34,132
1981	24,647	32,138	42,381	29,987
1982	23,284	29,955	39,071	28,257
1983	21,278	27,615	36,465	26,090
1984	19,659	26,095	35,068	24,752
1985	18,535	25,400	35,589	24,311
1986	25,269	39,126	54,220	31,882
1987	42,585	52,710	66,423	48,706
1988	36,226	46,178	59,125	43,430
1989	29,867	39,727	52,206	37,312
1990	28,728	39,203	50,525	36,419
1991	33,336	41,097	50,857	39,139
1992	26,776	32,944	41,233	31,348
1993	19,898	25,167	32,102	23,728
1994	14,585	18,944	24,944	17,829
1995	12,700	16,600	21,838	15,587
1996	12,048	15,648	20,615	14,874
1997	10,944	14,421	19,073	13,844
1998	9,709	12,876	17,368	12,492
1999	8,519	11,589	15,897	11,312

Year	2.5%	50%	97.5%	MPD
2000	7,728	10,642	14,719	10,431
2001	8,691	12,248	17,431	11,724
2002	11,820	15,877	21,431	15,241
2003	13,507	17,941	24,109	17,464
2004	13,768	18,068	24,586	17,669
2005	12,670	16,761	22,969	16,500
2006	11,043	14,707	20,235	14,581
2007	9,509	12,893	17,573	12,802
2008	9,259	12,820	18,098	12,705
2009	12,087	16,627	22,450	16,327
2010	14,695	19,781	26,487	19,492
2011	15,161	20,307	27,357	19,936
2012	14,617	19,806	26,706	19,340
2013	14,026	18,895	25,359	18,526
2014	13,332	17,789	23,980	17,531
2015	12,243	16,431	22,410	16,281
2016	11,046	15,044	20,654	14,984
2017	10,459	14,219	19,472	14,344
2018	10,596	14,797	21,965	14,941
2019	11,348	15,950	26,145	16,502

Table 11. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of biomass relative to B_0 for the Reference Case, Area 5ABCD.

Year	2.5%	50%	97.5%	MPD
1956	1.39	1.84	2.42	1.44
1957	1.42	1.81	2.31	1.45
1958	1.27	1.60	2.04	1.29
1959	1.02	1.31	1.69	1.04
1960	0.84	1.09	1.43	0.87
1961	0.71	0.94	1.27	0.75
1962	0.64	0.87	1.17	0.69
1963	1.58	2.08	2.70	1.73
1964	2.18	2.79	3.65	2.34
1965	2.20	2.78	3.61	2.32
1966	1.87	2.36	3.04	1.94
1967	1.44	1.82	2.35	1.48
1968	1.09	1.39	1.82	1.12
1969	0.83	1.08	1.44	0.87
1970	0.68	0.90	1.19	0.71
1971	0.63	0.83	1.10	0.66
1972	1.38	1.88	2.40	1.55
1973	1.77	2.37	3.09	1.95
1974	1.87	2.43	3.15	2.00
1975	1.72	2.22	2.83	1.82
1976	1.47	1.92	2.46	1.56
1977	1.34	1.76	2.22	1.42
1978	1.27	1.66	2.09	1.34
1979	1.26	1.59	2.02	1.30
1980	1.03	1.34	1.72	1.09
1981	0.91	1.18	1.50	0.96
1982	0.88	1.11	1.38	0.90
1983	0.81	1.02	1.27	0.83
1984	0.76	0.96	1.20	0.79
1985	0.71	0.93	1.21	0.78
1986	0.94	1.42	1.93	1.02
1987	1.55	1.94	2.39	1.56
1988	1.33	1.70	2.14	1.39
1989	1.11	1.46	1.87	1.19
1990	1.09	1.43	1.81	1.16
1991	1.23	1.51	1.82	1.25
1992	0.98	1.21	1.47	1.00
1993	0.74	0.92	1.15	0.76
1994	0.54	0.70	0.88	0.57
1995	0.48	0.61	0.76	0.50
1996	0.45	0.57	0.72	0.48
1997	0.42	0.53	0.66	0.44
1998	0.37	0.48	0.60	0.40
1999	0.33	0.43	0.54	0.36

Year	2.5%	50%	97.5%	MPD
2000	0.30	0.39	0.50	0.33
2001	0.34	0.45	0.61	0.37
2002	0.45	0.58	0.74	0.49
2003	0.52	0.66	0.83	0.56
2004	0.52	0.66	0.83	0.56
2005	0.49	0.61	0.77	0.53
2006	0.43	0.54	0.69	0.47
2007	0.37	0.47	0.61	0.41
2008	0.37	0.47	0.60	0.41
2009	0.46	0.61	0.78	0.52
2010	0.56	0.72	0.93	0.62
2011	0.58	0.74	0.97	0.64
2012	0.56	0.72	0.92	0.62
2013	0.54	0.69	0.88	0.59
2014	0.51	0.65	0.82	0.56
2015	0.47	0.60	0.76	0.52
2016	0.43	0.55	0.70	0.48
2017	0.41	0.53	0.66	0.46
2018	0.42	0.55	0.76	0.48
2019	0.45	0.58	0.92	0.53

Table 12. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of recruitment (thousands) for the Reference Case, Area 5ABCD.

Year	2.5%	50%	97.5%	MPD
1958	672	3,024	9,169	2,959
1959	703	2,685	7,563	2,874
1960	672	2,513	6,439	2,510
1961	644	2,365	6,113	2,407
1962	708	2,687	7,878	2,828
1963	40,312	59,872	81,698	58,977
1964	733	4,102	21,643	4,511
1965	805	3,455	14,979	4,032
1966	758	2,911	8,934	3,168
1967	597	2,125	6,121	2,396
1968	538	1,713	4,290	1,816
1969	573	1,938	4,660	1,980
1970	748	2,429	6,022	2,460
1971	815	2,931	8,118	3,117
1972	32,466	52,036	71,439	50,882
1973	756	3,722	21,390	3,658
1974	849	5,091	18,812	5,790
1975	1,136	4,852	15,313	5,708
1976	975	4,580	14,720	4,878
1977	2,035	8,140	19,896	8,908
1978	1,217	5,980	16,951	6,080
1979	1,133	6,743	17,758	7,978
1980	805	3,838	10,564	4,043
1981	1,195	4,936	11,328	5,106
1982	1,159	4,346	9,538	4,528
1983	781	2,926	7,490	3,071
1984	1,006	3,708	8,822	4,020
1985	933	3,655	12,501	4,203
1986	3,174	26,923	46,120	15,293
1987	2,646	15,909	45,970	29,024
1988	654	2,942	9,884	2,716
1989	702	3,184	10,467	3,159
1990	1,169	7,942	19,922	7,944
1991	2,476	11,324	22,877	12,453
1992	609	2,517	7,435	2,688
1993	404	1,499	3,536	1,566
1994	418	1,313	2,961	1,381
1995	450	1,653	3,879	1,679
1996	852	2,681	5,805	2,941
1997	409	1,425	3,443	1,483
1998	407	1,288	2,996	1,313
1999	287	1,000	2,419	1,119
2000	326	1,045	2,523	1,112
2001	1,366	4,691	9,995	4,241

Year	2.5%	50%	97.5%	MPD
2002	908	4,791	11,026	5,305
2003	595	2,064	5,443	2,223
2004	447	1,295	3,304	1,422
2005	343	895	2,048	956
2006	283	756	1,779	828
2007	309	892	2,105	958
2008	922	2,509	5,811	2,569
2009	3,071	7,355	12,959	7,216
2010	951	3,661	8,686	3,824
2011	634	2,067	5,280	2,127
2012	528	1,586	3,964	1,733
2013	526	1,656	3,946	1,764
2014	595	1,685	3,904	1,790
2015	455	1,434	3,431	1,534
2016	495	1,368	3,060	1,512
2017	454	1,527	3,805	1,713
2018	638	2,637	11,811	3,110

Table 13. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of fishing mortality, F, for the Reference Case, Area 5ABCD.

Year	2.5%	50%	97.5%	MPD
1956	0.07	0.09	0.12	0.10
1957	0.11	0.15	0.19	0.16
1958	0.15	0.20	0.26	0.22
1959	0.11	0.16	0.21	0.17
1960	0.09	0.12	0.17	0.14
1961	0.06	0.08	0.12	0.09
1962	0.08	0.13	0.19	0.14
1963	0.05	0.07	0.10	0.08
1964	0.10	0.12	0.16	0.13
1965	0.14	0.18	0.23	0.19
1966	0.16	0.22	0.28	0.23
1967	0.14	0.19	0.26	0.21
1968	0.12	0.17	0.23	0.18
1969	0.09	0.14	0.19	0.15
1970	0.05	0.07	0.10	0.08
1971	0.08	0.12	0.18	0.14
1972	0.10	0.13	0.18	0.13
1973	0.08	0.11	0.15	0.11
1974	0.11	0.14	0.19	0.15
1975	0.13	0.17	0.22	0.18
1976	0.11	0.16	0.21	0.17
1977	0.10	0.13	0.17	0.14
1978	0.09	0.12	0.16	0.13
1979	0.18	0.23	0.31	0.25
1980	0.15	0.19	0.27	0.21
1981	0.10	0.13	0.18	0.14
1982	0.10	0.13	0.17	0.14
1983	0.08	0.11	0.15	0.12
1984	0.07	0.10	0.14	0.10
1985	0.05	0.06	0.09	0.07
1986	0.09	0.13	0.22	0.16
1987	0.24	0.33	0.42	0.36
1988	0.17	0.22	0.30	0.24
1989	0.10	0.13	0.18	0.14
1990	0.11	0.14	0.20	0.15
1991	0.25	0.32	0.41	0.34
1992	0.22	0.29	0.37	0.31
1993	0.19	0.26	0.34	0.27
1994	0.08	0.11	0.15	0.12
1995	0.07	0.09	0.13	0.10
1996	0.08	0.11	0.14	0.11
1997	0.08	0.12	0.16	0.12
1998	0.07	0.10	0.14	0.10
1999	0.06	0.08	0.11	0.08

Year	2.5%	50%	97.5%	MPD
2000	0.05	0.07	0.09	0.07
2001	0.02	0.03	0.05	0.03
2002	0.03	0.04	0.05	0.04
2003	0.04	0.05	0.07	0.06
2004	0.05	0.06	0.09	0.07
2005	0.06	0.08	0.11	0.08
2006	0.05	0.07	0.10	0.08
2007	0.03	0.04	0.05	0.04
2008	0.02	0.03	0.04	0.03
2009	0.04	0.05	0.07	0.05
2010	0.07	0.09	0.13	0.09
2011	0.05	0.07	0.10	0.07
2012	0.04	0.05	0.07	0.05
2013	0.04	0.05	0.07	0.05
2014	0.05	0.06	0.09	0.06
2015	0.05	0.07	0.10	0.07
2016	0.03	0.04	0.06	0.04
2017	0.02	0.03	0.04	0.03
2018	0.01	0.02	0.03	0.02

13.2 MODEL RESULTS: AREA 3CD

Table 14. Estimated and fixed parameters and prior probablilty distributions used in the Reference Case, Area 3CD.

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	Normal($0.5, 1$)
Log fishing mortality values ($\Gamma_{k,t}$)	63	[-30, 3]	[-30, 3]
Log recruitment deviations (ω_t)	63	None	Normal($0, 2$)
Initial log recruitment deviations ($\omega_{init,t}$)	8	None	Normal($0, 2$)

Table 15. 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. B_0 is in tonnes. $\hat{R}$ 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	2,037	2,904	4,482	3,325	367	1.00
h	0.445	0.740	0.937	0.804	831	1.00
M	0.388	0.424	0.462	0.422	564	1.01
B_0	11,424	15,402	22,448	17,761	322	1.00
q_1	0.048	0.076	0.112	0.075	620	1.00
q_2	0.002	0.002	0.003	0.002	587	1.01
q_3	0.001	0.002	0.003	0.002	624	1.00
q_4	0.058	0.089	0.127	0.091	609	1.01

Table 16. Posterior (2.5th percentile, Median, and 97.5th percentile) of reference points for Area 3CD. Biomass is in tonnes.

Reference Point	2.5%	50%	97.5%
B_0	11,423.86	15,402.35	22,448.25
B_{1956}	23,756.87	35,234.00	57,756.57
B_{2019}	11,312.86	17,801.35	29,917.46
B_{2019}/B_0	0.90	1.14	1.65
B_{2019}/B_{1956}	0.32	0.50	0.84
F_{2018}	0.01	0.01	0.02
LRP (1986)	5,774	8,912	14,678
USR (1956–2004)	17,489	26,816	43,182

Table 17. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of biomass (t) for the Reference Case, Area 3CD.

Year	2.5%	50%	97.5%	MPD
1956	23,757	35,234	57,757	31,778
1957	19,801	29,285	48,327	26,795
1958	16,115	23,942	39,300	22,103
1959	13,431	20,020	33,135	18,587
1960	10,792	16,449	27,236	15,375
1961	9,004	14,144	23,709	13,201
1962	8,383	14,014	28,491	12,424
1963	13,787	27,042	47,639	31,612
1964	23,414	37,284	58,988	37,600
1965	26,342	39,744	62,142	37,962
1966	25,665	37,788	58,784	35,418
1967	20,376	31,218	50,116	29,108
1968	16,550	26,041	41,489	24,217
1969	14,529	22,714	37,580	21,438
1970	14,465	23,958	41,730	22,397
1971	41,218	62,166	99,762	60,998
1972	44,117	68,541	110,837	66,165
1973	38,441	60,528	99,436	57,945
1974	37,818	56,630	92,818	54,581
1975	33,965	52,760	84,116	50,212
1976	31,682	48,792	77,775	46,471
1977	28,690	43,170	67,219	40,962
1978	24,445	36,670	57,767	34,881
1979	20,459	30,375	47,893	28,911
1980	16,302	24,185	38,513	23,040
1981	13,057	19,640	31,376	18,704
1982	10,184	15,538	24,909	14,778
1983	8,740	13,303	21,837	12,696
1984	7,369	11,225	18,441	10,752
1985	6,415	9,926	16,470	9,478
1986	5,774	8,912	14,678	8,483
1987	13,268	29,212	49,404	30,768
1988	27,433	40,950	62,176	39,675
1989	26,803	39,281	61,183	37,402
1990	23,868	34,622	53,493	32,723
1991	20,627	29,786	46,118	28,203
1992	17,346	24,909	38,569	23,812
1993	13,604	19,950	31,223	19,273
1994	10,095	15,376	24,546	14,901
1995	8,210	12,452	19,915	12,203
1996	7,514	11,284	17,650	11,144
1997	6,626	10,000	15,861	9,963
1998	6,008	8,965	14,116	8,934
1999	6,050	9,092	13,895	9,029

Year	2.5%	50%	97.5%	MPD
2000	6,455	9,846	16,067	9,761
2001	8,278	12,759	20,615	12,966
2002	9,856	14,935	24,281	15,093
2003	10,479	15,548	24,539	15,606
2004	9,354	13,792	21,983	13,951
2005	7,790	11,548	18,226	11,671
2006	6,265	9,508	15,065	9,575
2007	5,339	8,190	12,919	8,271
2008	5,221	7,856	12,221	8,055
2009	11,095	17,514	27,807	17,364
2010	14,944	22,134	34,650	22,295
2011	14,606	21,889	34,900	22,125
2012	12,934	19,838	32,019	20,040
2013	14,237	22,252	35,026	22,234
2014	17,547	26,621	42,069	26,924
2015	17,618	26,742	43,090	27,030
2016	15,949	24,191	39,377	24,541
2017	13,739	21,029	33,358	21,281
2018	12,072	19,252	31,307	19,420
2019	11,313	17,801	29,917	18,380

Table 18. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of biomass relative to B_0 for the Reference Case, Area 3CD.

Year	2.5%	50%	97.5%	MPD
1956	1.67	2.30	3.19	1.79
1957	1.45	1.90	2.59	1.51
1958	1.18	1.55	2.07	1.24
1959	0.99	1.29	1.72	1.05
1960	0.80	1.07	1.42	0.87
1961	0.69	0.92	1.24	0.74
1962	0.64	0.90	1.56	0.70
1963	0.89	1.75	2.94	1.78
1964	1.58	2.42	3.49	2.12
1965	1.87	2.60	3.45	2.14
1966	1.87	2.43	3.17	1.99
1967	1.53	2.00	2.62	1.64
1968	1.26	1.68	2.19	1.36
1969	1.08	1.48	1.94	1.21
1970	1.13	1.54	2.32	1.26
1971	2.95	4.03	5.51	3.43
1972	3.13	4.37	6.09	3.73
1973	2.81	3.94	5.35	3.26
1974	2.72	3.69	4.88	3.07
1975	2.54	3.43	4.48	2.83
1976	2.38	3.15	4.15	2.62
1977	2.12	2.76	3.66	2.31
1978	1.86	2.36	3.13	1.96
1979	1.55	1.96	2.56	1.63
1980	1.20	1.56	2.05	1.30
1981	0.98	1.27	1.64	1.05
1982	0.78	1.01	1.30	0.83
1983	0.66	0.87	1.10	0.71
1984	0.56	0.73	0.95	0.61
1985	0.50	0.64	0.84	0.53
1986	0.44	0.58	0.77	0.48
1987	0.91	1.95	2.88	1.73
1988	1.98	2.64	3.52	2.23
1989	2.01	2.57	3.22	2.11
1990	1.79	2.26	2.82	1.84
1991	1.56	1.94	2.41	1.59
1992	1.32	1.62	2.01	1.34
1993	1.06	1.29	1.59	1.09
1994	0.80	0.99	1.23	0.84
1995	0.65	0.81	0.99	0.69
1996	0.60	0.73	0.89	0.63
1997	0.53	0.65	0.80	0.56
1998	0.47	0.58	0.70	0.50
1999	0.46	0.58	0.73	0.51

Year	2.5%	50%	97.5%	MPD
2000	0.49	0.64	0.85	0.55
2001	0.62	0.83	1.10	0.73
2002	0.77	0.97	1.24	0.85
2003	0.82	1.00	1.26	0.88
2004	0.73	0.90	1.12	0.79
2005	0.62	0.75	0.93	0.66
2006	0.50	0.61	0.76	0.54
2007	0.43	0.53	0.67	0.47
2008	0.41	0.51	0.65	0.45
2009	0.86	1.13	1.49	0.98
2010	1.15	1.44	1.82	1.26
2011	1.14	1.42	1.78	1.25
2012	1.03	1.29	1.60	1.13
2013	1.10	1.43	1.84	1.25
2014	1.39	1.73	2.20	1.52
2015	1.39	1.73	2.18	1.52
2016	1.26	1.57	1.99	1.38
2017	1.09	1.36	1.72	1.20
2018	0.97	1.23	1.72	1.09
2019	0.90	1.14	1.65	1.03

Table 19. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of recruitment (thousands) for the Reference Case,Area 3CD.

Year	2.5%	50%	97.5%	MPD
1958	622	2,524	7,271	2,577
1959	501	1,783	5,098	1,880
1960	449	1,697	5,102	1,750
1961	528	1,883	5,536	1,887
1962	738	3,446	19,285	2,893
1963	2,762	19,896	48,184	29,916
1964	805	9,661	42,306	4,380
1965	904	5,635	24,637	6,990
1966	901	4,698	18,083	6,176
1967	598	2,310	7,819	2,538
1968	609	2,368	6,793	2,599
1969	759	3,343	9,764	3,712
1970	1,536	7,267	27,502	7,437
1971	32,106	57,538	101,254	58,367
1972	767	3,902	21,314	4,095
1973	800	4,371	18,950	4,555
1974	1,369	9,693	31,309	11,672
1975	1,209	8,438	30,194	9,626
1976	1,664	9,358	29,047	10,167
1977	1,198	5,360	17,227	5,971
1978	852	3,809	12,218	4,132
1979	746	2,679	8,398	2,926
1980	591	2,116	5,611	2,311
1981	555	1,966	5,007	2,013
1982	538	1,542	3,871	1,628
1983	595	1,878	4,325	1,882
1984	599	1,631	3,878	1,656
1985	482	1,405	3,500	1,446
1986	405	1,359	3,573	1,388
1987	9,808	30,938	55,144	33,056
1988	882	8,612	37,426	7,177
1989	691	3,194	11,561	3,864
1990	655	2,466	8,133	2,838
1991	948	3,831	10,402	4,217
1992	872	3,950	9,415	4,492
1993	480	1,674	4,438	1,809
1994	454	1,523	3,758	1,569
1995	346	1,111	2,887	1,221
1996	697	1,950	4,378	2,130
1997	289	989	2,830	1,069
1998	385	1,194	2,749	1,220
1999	796	2,271	5,154	2,359
2000	892	2,688	6,963	2,688
2001	1,261	5,407	11,758	5,954

Year	2.5%	50%	97.5%	MPD
2002	965	3,884	9,799	3,952
2003	616	2,323	5,970	2,442
2004	285	917	2,360	1,028
2005	251	719	1,708	746
2006	214	637	1,482	700
2007	436	1,101	2,528	1,178
2008	680	1,770	3,908	1,948
2009	8,289	14,881	25,242	14,492
2010	983	4,430	11,732	5,174
2011	476	1,860	5,127	2,007
2012	433	1,669	4,668	1,865
2013	2,755	8,260	16,928	8,226
2014	3,011	8,806	19,378	9,539
2015	679	2,765	8,092	2,932
2016	490	1,778	5,133	2,087
2017	440	1,524	4,732	1,739
2018	637	2,685	11,897	3,284

Table 20. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of fishing mortality, F, for the Reference Case, Area 3CD.

Year	2.5%	50%	97.5%	MPD
1956	0.03	0.05	0.08	0.06
1957	0.04	0.07	0.11	0.08
1958	0.03	0.04	0.06	0.05
1959	0.04	0.06	0.09	0.06
1960	0.03	0.05	0.07	0.05
1961	0.03	0.05	0.07	0.05
1962	0.04	0.08	0.13	0.09
1963	0.03	0.05	0.11	0.05
1964	0.04	0.07	0.11	0.07
1965	0.05	0.09	0.13	0.09
1966	0.07	0.12	0.18	0.12
1967	0.05	0.07	0.12	0.08
1968	0.03	0.05	0.08	0.06
1969	0.03	0.05	0.08	0.06
1970	0.05	0.09	0.15	0.09
1971	0.06	0.10	0.16	0.11
1972	0.06	0.11	0.17	0.11
1973	0.04	0.06	0.10	0.07
1974	0.05	0.09	0.14	0.09
1975	0.06	0.10	0.16	0.11
1976	0.06	0.10	0.16	0.11
1977	0.06	0.09	0.14	0.09
1978	0.05	0.08	0.12	0.08
1979	0.06	0.10	0.15	0.10
1980	0.05	0.07	0.11	0.08
1981	0.06	0.10	0.15	0.10
1982	0.03	0.05	0.08	0.05
1983	0.05	0.08	0.13	0.09
1984	0.03	0.06	0.09	0.06
1985	0.03	0.06	0.09	0.06
1986	0.04	0.06	0.10	0.07
1987	0.04	0.06	0.14	0.06
1988	0.06	0.10	0.15	0.10
1989	0.04	0.06	0.09	0.07
1990	0.05	0.08	0.11	0.08
1991	0.08	0.13	0.19	0.14
1992	0.07	0.12	0.17	0.12
1993	0.08	0.14	0.21	0.14
1994	0.04	0.07	0.11	0.07
1995	0.02	0.03	0.04	0.03
1996	0.01	0.02	0.03	0.02
1997	0.01	0.02	0.03	0.02
1998	0.01	0.01	0.01	0.01
1999	0.01	0.01	0.02	0.01

Year	2.5%	50%	97.5%	MPD
2000	0.01	0.02	0.03	0.02
2001	0.02	0.03	0.05	0.03
2002	0.01	0.02	0.03	0.02
2003	0.03	0.04	0.06	0.04
2004	0.03	0.04	0.06	0.04
2005	0.02	0.03	0.05	0.03
2006	0.01	0.02	0.03	0.02
2007	0.01	0.01	0.02	0.01
2008	0.01	0.02	0.03	0.02
2009	0.02	0.03	0.05	0.03
2010	0.02	0.03	0.05	0.03
2011	0.02	0.03	0.04	0.03
2012	0.02	0.03	0.04	0.03
2013	0.01	0.02	0.03	0.02
2014	0.01	0.02	0.03	0.02
2015	0.01	0.02	0.03	0.02
2016	0.01	0.02	0.03	0.02
2017	0.01	0.01	0.01	0.01
2018	0.01	0.01	0.02	0.01

13.3 SELECTED SENSITIVITY RESULTS: AREA 5ABCD

Table 21. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of key parameters for Sc 2a (mean of the QCS Synoptic Survey was set to the same mean as for the HS Synoptic Survey), Area 5ABCD. R_0 is in thousands of fish. B_0 is in tonnes.

Parameter	2.5%	50%	97.5%	MPD	n_{eff}	$\hat{R}$
R_0	2,776	3,604	4,775	4,104	307	1.00
h	0.462	0.746	0.942	0.810	769	1.00
M	0.294	0.326	0.357	0.324	597	1.00
B_0	25,940	30,652	37,185	35,115	376	1.00
q_1	0.042	0.056	0.071	0.058	542	1.00
q_2	0.027	0.037	0.050	0.038	673	1.00
q_3	0.046	0.064	0.087	0.065	678	1.00
q_4	0.002	0.003	0.003	0.003	608	1.00
q_5	0.005	0.006	0.008	0.006	655	1.00

Table 22. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of key parameters for Sc 2b (uniform priors for synoptic survey catchability), Area 5ABCD. R_0 is in thousands of fish. B_0 is in tonnes.

Parameter	2.5%	50%	97.5%	MPD	n_{eff}	$\hat{R}$
R_0	4,017	8,216	17,782	8,550	143	1.02
h	0.449	0.726	0.938	0.802	903	1.00
M	0.324	0.372	0.408	0.368	141	1.02
B_0	34,607	56,364	111,382	59,712	149	1.02
q_1	0.011	0.023	0.047	0.027	98	1.02
q_2	0.006	0.014	0.027	0.015	104	1.02
q_3	0.010	0.024	0.047	0.026	105	1.02
q_4	0.001	0.001	0.002	0.001	94	1.02
q_5	0.001	0.002	0.005	0.003	102	1.02

Table 23. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of key parameters for Sc 3a (mean ln(M)=ln(0.5), SD=0.2), Area 5ABCD. R_0 is in thousands of fish. B_0 is in tonnes.

Parameter	2.5%	50%	97.5%	MPD	n_{eff}	$\hat{R}$
R_0	2,109	2,695	3,519	3,012	266	1.01
h	0.459	0.748	0.941	0.813	843	1.00
M	0.260	0.293	0.324	0.287	640	1.01
B_0	23,270	27,168	32,007	31,222	211	1.00
q_1	0.058	0.074	0.092	0.078	375	1.00
q_2	0.040	0.053	0.069	0.054	490	1.00
q_3	0.068	0.092	0.120	0.093	490	1.00
q_4	0.003	0.003	0.004	0.004	356	1.00
q_5	0.007	0.009	0.011	0.009	467	1.00

Table 24. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of key parameters for Sc 3b (mean ln(M)=ln(0.4), SD=0.1), Area 5ABCD. R_0 is in thousands of fish. B_0 is in tonnes.

Parameter	**2.5%**	**50%**	**97.5%**	**MPD**	n_{eff}	$\hat{R}$
R_0	1,635	2,114	2,771	2,369	313	1.00
h	0.503	0.783	0.953	0.839	1026	1.00
M	0.211	0.251	0.293	0.242	289	1.00
B_0	23,394	27,376	31,808	32,200	293	1.01
q_1	0.069	0.088	0.113	0.093	402	1.00
q_2	0.045	0.062	0.083	0.064	594	1.00
q_3	0.077	0.105	0.142	0.110	610	1.00
q_4	0.003	0.004	0.005	0.004	305	1.00
q_5	0.008	0.010	0.014	0.011	565	1.00

Table 25. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of key parameters for Sc 3c (mean ln(M)=ln(0.4), SD=0.2), Area 5ABCD. R_0 is in thousands of fish. B_0 is in tonnes.

Parameter	**2.5%**	**50%**	**97.5%**	**MPD**	n_{eff}	$\hat{R}$
R_0	1,657	2,178	2,776	2,450	409	1.00
h	0.503	0.772	0.947	0.836	924	1.00
M	0.217	0.257	0.294	0.249	540	1.00
B_0	23,218	27,134	31,409	31,966	309	1.00
q_1	0.068	0.086	0.106	0.091	597	1.00
q_2	0.046	0.060	0.082	0.063	793	1.00
q_3	0.078	0.104	0.142	0.107	791	1.00
q_4	0.003	0.004	0.005	0.004	549	1.00
q_5	0.008	0.010	0.013	0.011	739	1.00

Table 26. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of key parameters for Sc 4a (Uniform prior for steepness), Area 5ABCD. R_0 is in thousands of fish. B_0 is in tonnes.

Parameter	**2.5%**	**50%**	**97.5%**	**MPD**	n_{eff}	$\hat{R}$
R_0	2,397	3,053	3,986	3,445	197	1.01
h	0.207	0.333	0.885	0.590	115	1.02
M	0.288	0.321	0.353	0.313	411	1.01
B_0	21,972	26,735	32,014	31,196	86	1.00
q_1	0.050	0.065	0.081	0.070	504	1.00
q_2	0.037	0.050	0.066	0.051	593	1.00
q_3	0.065	0.087	0.115	0.088	571	1.00
q_4	0.002	0.003	0.004	0.003	292	1.01
q_5	0.006	0.008	0.011	0.008	582	1.00

Table 27. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of key parameters for Sc 4b (beta prior for steepness with mean = 0.85 and SD = 0.15), Area 5ABCD. R_0 is in thousands of fish. B_0 is in tonnes.

Parameter	2.5%	50%	97.5%	MPD	n_{eff}	$\hat{R}$
R_0	2,362	2,996	3,816	3,386	255	1.01
h	0.644	0.889	0.994	0.973	359	1.00
M	0.279	0.311	0.346	0.308	570	1.00
B_0	23,299	27,412	32,203	31,339	175	1.01
q_1	0.054	0.069	0.086	0.071	482	1.00
q_2	0.037	0.049	0.065	0.050	798	1.00
q_3	0.064	0.085	0.113	0.086	805	1.00
q_4	0.002	0.003	0.004	0.003	365	1.00
q_5	0.006	0.008	0.011	0.008	774	1.00

Table 28. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of key parameters for Sc 6a (σ_O = 0.1), Area 5ABCD. R_0 is in thousands of fish. B_0 is in tonnes.

Parameter	2.5%	50%	97.5%	MPD	n_{eff}	$\hat{R}$
R_0	2,333	2,876	3,605	3,280	932	1.00
h	0.534	0.800	0.952	0.852	709	1.00
M	0.368	0.404	0.443	0.409	1076	1.00
B_0	15,181	17,412	19,846	19,421	520	1.00
q_1	0.070	0.086	0.103	0.088	968	1.00
q_2	0.042	0.053	0.066	0.054	962	1.00
q_3	0.075	0.095	0.118	0.096	955	1.00
q_4	0.004	0.004	0.005	0.005	969	1.00
q_5	0.008	0.009	0.012	0.010	973	1.00

Table 29. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of key parameters for Sc 6b (σ_O = 0.15), Area 5ABCD. R_0 is in thousands of fish. B_0 is in tonnes.

Parameter	2.5%	50%	97.5%	MPD	n_{eff}	$\hat{R}$
R_0	2,237	2,797	3,594	3,228	368	1.02
h	0.478	0.765	0.952	0.832	601	1.02
M	0.301	0.337	0.374	0.341	428	1.02
B_0	19,559	22,571	26,240	25,424	266	1.00
q_1	0.060	0.077	0.093	0.081	530	1.02
q_2	0.040	0.051	0.067	0.054	599	1.00
q_3	0.069	0.090	0.117	0.094	596	1.00
q_4	0.003	0.004	0.004	0.004	194	1.04
q_5	0.007	0.009	0.011	0.009	582	1.00

Table 30. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of key parameters for Sc 6c (σ_O = 0.25), Area 5ABCD. R_0 is in thousands of fish. B_0 is in tonnes.

Parameter	**2.5%**	**50%**	**97.5%**	**MPD**	n_{eff}	$\hat{R}$
R_0	2,515	3,214	4,074	3,693	353	1.00
h	0.383	0.679	0.929	0.767	894	1.01
M	0.270	0.300	0.330	0.297	637	1.00
B_0	25,646	31,076	38,190	36,353	199	1.00
q_1	0.048	0.061	0.078	0.064	598	1.00
q_2	0.036	0.048	0.063	0.048	685	1.00
q_3	0.062	0.082	0.109	0.082	690	1.00
q_4	0.002	0.003	0.003	0.003	604	1.00
q_5	0.006	0.008	0.010	0.008	647	1.00

13.4 SELECTED SENSITIVITY RESULTS: AREA 3CD

Table 31. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of key parameters for Sc 2a (sd of the WCVI Synoptic Survey was set to the same sd as for the QCS and HS Synoptic Surveys), Area 3CD. R_0 is in thousands of fish. B_0 is in tonnes.

Parameter	2.5%	50%	97.5%	MPD	n_{eff}	$\hat{R}$
R_0	2,663	4,330	7,555	4,945	359	1.00
h	0.443	0.741	0.937	0.807	711	1.00
M	0.394	0.432	0.471	0.436	481	1.00
B_0	14,449	22,241	38,513	25,256	293	1.00
q_1	0.027	0.046	0.080	0.047	400	1.00
q_2	0.001	0.002	0.003	0.002	410	1.01
q_3	0.001	0.001	0.002	0.001	390	1.00
q_4	0.033	0.058	0.095	0.060	402	1.01

Table 32. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of key parameters for Sc 2b (uniform priors for synoptic survey catchability), Area 3CD. R_0 is in thousands of fish. B_0 is in tonnes.

Parameter	2.5%	50%	97.5%	MPD	n_{eff}	$\hat{R}$
R_0	12,036	59,688	154,665	109,795	873	1.00
h	0.447	0.736	0.941	0.801	806	1.01
M	0.427	0.460	0.496	0.468	805	1.00
B_0	59,562	278,932	731,890	507,724	856	1.00
q_1	0.001	0.003	0.015	0.002	483	1.00
q_2	0.000	0.000	0.001	0.000	469	1.00
q_3	0.000	0.000	0.000	0.000	476	1.00
q_4	0.002	0.004	0.020	0.003	462	1.00

Table 33. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of key parameters for Sc 3a (mean ln(M)=ln(0.5), SD=0.2), Area 3CD. R_0 is in thousands of fish. B_0 is in tonnes.

Parameter	2.5%	50%	97.5%	MPD	n_{eff}	$\hat{R}$
R_0	1,726	2,490	3,728	2,856	317	1.00
h	0.458	0.751	0.958	0.806	690	1.00
M	0.361	0.399	0.438	0.399	665	1.00
B_0	10,765	14,295	20,629	16,518	255	1.00
q_1	0.052	0.082	0.122	0.082	632	1.00
q_2	0.002	0.003	0.004	0.003	664	1.00
q_3	0.001	0.002	0.003	0.002	650	1.00
q_4	0.066	0.099	0.139	0.100	657	1.00

Table 34. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of key parameters for Sc 3b (mean ln(M)=ln(0.4), SD=0.1), Area 3CD. R_0 is in thousands of fish. B_0 is in tonnes.

Parameter	2.5%	50%	97.5%	MPD	n_{eff}	$\hat{R}$
R_0	1,650	2,527	4,007	2,850	144	1.01
h	0.448	0.749	0.945	0.806	864	1.00
M	0.355	0.400	0.444	0.399	335	1.00
B_0	10,612	14,581	20,963	16,503	125	1.01
q_1	0.053	0.081	0.124	0.082	401	1.01
q_2	0.002	0.003	0.004	0.003	338	1.01
q_3	0.001	0.002	0.003	0.002	412	1.01
q_4	0.064	0.098	0.143	0.100	335	1.01

Table 35. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of key parameters for Sc 3c (mean ln(M)=ln(0.4), SD=0.2), Area 3CD. R_0 is in thousands of fish. B_0 is in tonnes.

Parameter	2.5%	50%	97.5%	MPD	n_{eff}	$\hat{R}$
R_0	1,764	2,590	3,959	2,946	358	1.00
h	0.454	0.740	0.949	0.806	741	1.00
M	0.364	0.406	0.449	0.404	476	1.00
B_0	10,790	14,683	21,189	16,763	292	1.00
q_1	0.051	0.080	0.121	0.080	543	1.00
q_2	0.002	0.003	0.004	0.003	697	1.00
q_3	0.001	0.002	0.003	0.002	590	1.00
q_4	0.062	0.095	0.137	0.098	592	1.00

Table 36. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of key parameters for Sc 4a (Uniform prior for steepness), Area 3CD. R_0 is in thousands of fish. B_0 is in tonnes.

Parameter	2.5%	50%	97.5%	MPD	n_{eff}	$\hat{R}$
R_0	1,981	2,896	4,298	3,322	466	1.00
h	0.248	0.479	0.970	0.270	93	1.04
M	0.383	0.421	0.460	0.427	546	1.01
B_0	11,478	15,498	21,613	17,470	392	1.01
q_1	0.052	0.077	0.117	0.080	663	1.00
q_2	0.002	0.002	0.003	0.002	608	1.00
q_3	0.001	0.002	0.003	0.002	715	1.00
q_4	0.061	0.089	0.129	0.090	738	1.00

Table 37. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of key parameters for Sc 4b (beta prior for steepness with mean = 0.85 and SD = 0.15), Area 3CD. R_0 is in thousands of fish. B_0 is in tonnes.

Parameter	**2.5%**	**50%**	**97.5%**	**MPD**	n_{eff}	$\hat{R}$
R_0	1,948	2,912	4,606	3,317	247	1.02
h	0.573	0.878	0.991	0.975	277	1.00
M	0.384	0.426	0.465	0.422	530	1.00
B_0	11,229	15,329	22,832	17,725	218	1.04
q_1	0.048	0.074	0.110	0.075	667	1.01
q_2	0.002	0.002	0.003	0.003	679	1.00
q_3	0.001	0.002	0.003	0.002	660	1.01
q_4	0.056	0.086	0.126	0.091	628	1.00

Table 38. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of key parameters for Sc 6a (σ_O = 0.1), Area 3CD. R_0 is in thousands of fish. B_0 is in tonnes.

Parameter	**2.5%**	**50%**	**97.5%**	**MPD**	n_{eff}	$\hat{R}$
R_0	2,660	4,129	6,366	4,734	494	1.01
h	0.540	0.784	0.953	0.834	866	1.00
M	0.521	0.565	0.611	0.583	433	1.00
B_0	10,117	14,674	21,521	16,220	518	1.00
q_1	0.046	0.073	0.114	0.073	507	1.00
q_2	0.001	0.002	0.003	0.002	570	1.00
q_3	0.001	0.002	0.003	0.002	508	1.00
q_4	0.054	0.081	0.122	0.083	552	1.00

Table 39. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of key parameters for Sc 6b (σ_O = 0.15), Area 3CD. R_0 is in thousands of fish. B_0 is in tonnes.

Parameter	**2.5%**	**50%**	**97.5%**	**MPD**	n_{eff}	$\hat{R}$
R_0	2,298	3,244	4,991	3,759	423	1.00
h	0.496	0.773	0.941	0.821	453	1.01
M	0.431	0.472	0.510	0.478	486	1.00
B_0	11,084	14,887	21,411	16,867	360	1.00
q_1	0.047	0.074	0.110	0.074	590	1.00
q_2	0.001	0.002	0.003	0.002	528	1.01
q_3	0.001	0.002	0.003	0.002	583	1.00
q_4	0.055	0.085	0.119	0.086	575	1.00

Table 40. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of key parameters for Sc 6c (σ_O = 0.25), Area 3CD. R_0 is in thousands of fish. B_0 is in tonnes.

Parameter	2.5%	50%	97.5%	MPD	n_{eff}	$\hat{R}$
R_0	1,905	2,763	4,038	3,095	384	1.01
h	0.440	0.728	0.937	0.798	583	1.00
M	0.356	0.392	0.427	0.394	651	1.00
B_0	12,004	16,452	22,722	18,235	286	1.01
q_1	0.049	0.075	0.118	0.077	660	1.01
q_2	0.002	0.002	0.004	0.003	664	1.00
q_3	0.001	0.002	0.003	0.002	665	1.01
q_4	0.061	0.090	0.134	0.094	694	1.00

13.5 MODEL-AVERAGED REFERENCE POINTS AND DECISION TABLES

Table 41. Posterior (2.5th percentile, Median, and 97.5th percentile) of reference points for model-averaged Area 5ABCD. Biomass is in 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

Table 42. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of biomass (t) for model-averaged Area 5ABCD.

Year	2.5%	50%	97.5%	MPD
1956	37,540	50,217	67,959	45,179
1957	39,125	49,415	64,880	45,319
1958	34,214	43,655	57,501	40,341
1959	26,990	35,555	48,035	32,611
1960	21,923	29,725	41,177	27,147
1961	18,376	25,756	36,583	23,397
1962	16,352	23,741	34,725	21,490
1963	44,167	56,542	73,891	54,181
1964	60,565	76,396	98,583	73,288
1965	61,363	75,834	97,665	72,428
1966	51,665	64,235	83,301	60,719
1967	38,723	49,456	67,102	46,209
1968	28,963	37,750	51,664	35,061
1969	21,959	29,493	41,325	27,148
1970	17,852	24,356	34,856	22,340
1971	16,245	22,708	32,759	20,700
1972	37,584	51,225	66,072	48,618
1973	48,431	64,454	83,932	61,107
1974	51,298	66,297	85,363	62,438
1975	47,350	60,590	78,658	56,875
1976	39,882	52,304	69,580	48,770
1977	36,214	47,778	62,422	44,451
1978	34,976	45,172	58,545	41,795
1979	34,581	43,413	55,299	40,794
1980	28,155	36,461	47,681	34,132
1981	24,647	32,138	42,381	29,987
1982	23,284	29,955	39,071	28,257
1983	21,278	27,615	36,465	26,090
1984	19,659	26,095	35,068	24,752
1985	18,535	25,400	35,589	24,311
1986	25,269	39,126	54,220	31,882
1987	42,585	52,710	66,423	48,706
1988	36,226	46,178	59,125	43,430
1989	29,867	39,727	52,206	37,312
1990	28,728	39,203	50,525	36,419
1991	33,336	41,097	50,857	39,139
1992	26,776	32,944	41,233	31,348
1993	19,898	25,167	32,102	23,728
1994	14,585	18,944	24,944	17,829
1995	12,700	16,600	21,838	15,587
1996	12,048	15,648	20,615	14,874
1997	10,944	14,421	19,073	13,844
1998	9,709	12,876	17,368	12,492
1999	8,519	11,589	15,897	11,312

Year	2.5%	50%	97.5%	MPD
2000	7,728	10,642	14,719	10,431
2001	8,691	12,248	17,431	11,724
2002	11,820	15,877	21,431	15,241
2003	13,507	17,941	24,109	17,464
2004	13,768	18,068	24,586	17,669
2005	12,670	16,761	22,969	16,500
2006	11,043	14,707	20,235	14,581
2007	9,509	12,893	17,573	12,802
2008	9,259	12,820	18,098	12,705
2009	12,087	16,627	22,450	16,327
2010	14,695	19,781	26,487	19,492
2011	15,161	20,307	27,357	19,936
2012	14,617	19,806	26,706	19,340
2013	14,026	18,895	25,359	18,526
2014	13,332	17,789	23,980	17,531
2015	12,243	16,431	22,410	16,281
2016	11,046	15,044	20,654	14,984
2017	10,459	14,219	19,472	14,344
2018	10,596	14,797	21,965	14,941
2019	11,348	15,950	26,145	16,502

Table 43. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of recruitment (thousands) model-averaged Area 5ABCD.

Year	2.5%	50%	97.5%	MPD
1958	672	3,024	9,169	2,959
1959	703	2,685	7,563	2,874
1960	672	2,513	6,439	2,510
1961	644	2,365	6,113	2,407
1962	708	2,687	7,878	2,828
1963	40,312	59,872	81,698	58,977
1964	733	4,102	21,643	4,511
1965	805	3,455	14,979	4,032
1966	758	2,911	8,934	3,168
1967	597	2,125	6,121	2,396
1968	538	1,713	4,290	1,816
1969	573	1,938	4,660	1,980
1970	748	2,429	6,022	2,460
1971	815	2,931	8,118	3,117
1972	32,466	52,036	71,439	50,882
1973	756	3,722	21,390	3,658
1974	849	5,091	18,812	5,790
1975	1,136	4,852	15,313	5,708
1976	975	4,580	14,720	4,878
1977	2,035	8,140	19,896	8,908
1978	1,217	5,980	16,951	6,080
1979	1,133	6,743	17,758	7,978
1980	805	3,838	10,564	4,043
1981	1,195	4,936	11,328	5,106
1982	1,159	4,346	9,538	4,528
1983	781	2,926	7,490	3,071
1984	1,006	3,708	8,822	4,020
1985	933	3,655	12,501	4,203
1986	3,174	26,923	46,120	15,293
1987	2,646	15,909	45,970	29,024
1988	654	2,942	9,884	2,716
1989	702	3,184	10,467	3,159
1990	1,169	7,942	19,922	7,944
1991	2,476	11,324	22,877	12,453
1992	609	2,517	7,435	2,688
1993	404	1,499	3,536	1,566
1994	418	1,313	2,961	1,381
1995	450	1,653	3,879	1,679
1996	852	2,681	5,805	2,941
1997	409	1,425	3,443	1,483
1998	407	1,288	2,996	1,313
1999	287	1,000	2,419	1,119
2000	326	1,045	2,523	1,112
2001	1,366	4,691	9,995	4,241

Year	2.5%	50%	97.5%	MPD
2002	908	4,791	11,026	5,305
2003	595	2,064	5,443	2,223
2004	447	1,295	3,304	1,422
2005	343	895	2,048	956
2006	283	756	1,779	828
2007	309	892	2,105	958
2008	922	2,509	5,811	2,569
2009	3,071	7,355	12,959	7,216
2010	951	3,661	8,686	3,824
2011	634	2,067	5,280	2,127
2012	528	1,586	3,964	1,733
2013	526	1,656	3,946	1,764
2014	595	1,685	3,904	1,790
2015	455	1,434	3,431	1,534
2016	495	1,368	3,060	1,512
2017	454	1,527	3,805	1,713
2018	638	2,637	11,811	3,110

Table 44. Posterior (2.5th percentile, Median, and 97.5th percentile) of reference points for model-averaged Area 3CD. Biomass is in tonnes.

Reference point	2.5%	50%	97.5%
B_0	8,154.83	14,548.70	41,282.42
B_{1956}	11,727.18	32,454.25	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

Table 45. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of biomass (t) for model-averaged Area 3CD.

Year	2.5%	50%	97.5%	MPD
1956	23,757	35,234	57,757	31,778
1957	19,801	29,285	48,327	26,795
1958	16,115	23,942	39,300	22,103
1959	13,431	20,020	33,135	18,587
1960	10,792	16,449	27,236	15,375
1961	9,004	14,144	23,709	13,201
1962	8,383	14,014	28,491	12,424
1963	13,787	27,042	47,639	31,612
1964	23,414	37,284	58,988	37,600
1965	26,342	39,744	62,142	37,962
1966	25,665	37,788	58,784	35,418
1967	20,376	31,218	50,116	29,108
1968	16,550	26,041	41,489	24,217
1969	14,529	22,714	37,580	21,438
1970	14,465	23,958	41,730	22,397
1971	41,218	62,166	99,762	60,998
1972	44,117	68,541	110,837	66,165
1973	38,441	60,528	99,436	57,945
1974	37,818	56,630	92,818	54,581
1975	33,965	52,760	84,116	50,212
1976	31,682	48,792	77,775	46,471
1977	28,690	43,170	67,219	40,962
1978	24,445	36,670	57,767	34,881
1979	20,459	30,375	47,893	28,911
1980	16,302	24,185	38,513	23,040
1981	13,057	19,640	31,376	18,704
1982	10,184	15,538	24,909	14,778
1983	8,740	13,303	21,837	12,696
1984	7,369	11,225	18,441	10,752
1985	6,415	9,926	16,470	9,478
1986	5,774	8,912	14,678	8,483
1987	13,268	29,212	49,404	30,768
1988	27,433	40,950	62,176	39,675
1989	26,803	39,281	61,183	37,402
1990	23,868	34,622	53,493	32,723
1991	20,627	29,786	46,118	28,203
1992	17,346	24,909	38,569	23,812
1993	13,604	19,950	31,223	19,273
1994	10,095	15,376	24,546	14,901
1995	8,210	12,452	19,915	12,203
1996	7,514	11,284	17,650	11,144
1997	6,626	10,000	15,861	9,963
1998	6,008	8,965	14,116	8,934
1999	6,050	9,092	13,895	9,029

Year	2.5%	50%	97.5%	MPD
2000	6,455	9,846	16,067	9,761
2001	8,278	12,759	20,615	12,966
2002	9,856	14,935	24,281	15,093
2003	10,479	15,548	24,539	15,606
2004	9,354	13,792	21,983	13,951
2005	7,790	11,548	18,226	11,671
2006	6,265	9,508	15,065	9,575
2007	5,339	8,190	12,919	8,271
2008	5,221	7,856	12,221	8,055
2009	11,095	17,514	27,807	17,364
2010	14,944	22,134	34,650	22,295
2011	14,606	21,889	34,900	22,125
2012	12,934	19,838	32,019	20,040
2013	14,237	22,252	35,026	22,234
2014	17,547	26,621	42,069	26,924
2015	17,618	26,742	43,090	27,030
2016	15,949	24,191	39,377	24,541
2017	13,739	21,029	33,358	21,281
2018	12,072	19,252	31,307	19,420
2019	11,313	17,801	29,917	18,380

Table 46. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of recruitment (thousands) model-averaged Area 3CD.

Year	2.5%	50%	97.5%	MPD
1958	622	2,524	7,271	2,577
1959	501	1,783	5,098	1,880
1960	449	1,697	5,102	1,750
1961	528	1,883	5,536	1,887
1962	738	3,446	19,285	2,893
1963	2,762	19,896	48,184	29,916
1964	805	9,661	42,306	4,380
1965	904	5,635	24,637	6,990
1966	901	4,698	18,083	6,176
1967	598	2,310	7,819	2,538
1968	609	2,368	6,793	2,599
1969	759	3,343	9,764	3,712
1970	1,536	7,267	27,502	7,437
1971	32,106	57,538	101,254	58,367
1972	767	3,902	21,314	4,095
1973	800	4,371	18,950	4,555
1974	1,369	9,693	31,309	11,672
1975	1,209	8,438	30,194	9,626
1976	1,664	9,358	29,047	10,167
1977	1,198	5,360	17,227	5,971
1978	852	3,809	12,218	4,132
1979	746	2,679	8,398	2,926
1980	591	2,116	5,611	2,311
1981	555	1,966	5,007	2,013
1982	538	1,542	3,871	1,628
1983	595	1,878	4,325	1,882
1984	599	1,631	3,878	1,656
1985	482	1,405	3,500	1,446
1986	405	1,359	3,573	1,388
1987	9,808	30,938	55,144	33,056
1988	882	8,612	37,426	7,177
1989	691	3,194	11,561	3,864
1990	655	2,466	8,133	2,838
1991	948	3,831	10,402	4,217
1992	872	3,950	9,415	4,492
1993	480	1,674	4,438	1,809
1994	454	1,523	3,758	1,569
1995	346	1,111	2,887	1,221
1996	697	1,950	4,378	2,130
1997	289	989	2,830	1,069
1998	385	1,194	2,749	1,220
1999	796	2,271	5,154	2,359
2000	892	2,688	6,963	2,688
2001	1,261	5,407	11,758	5,954

Year	2.5%	50%	97.5%	MPD
2002	965	3,884	9,799	3,952
2003	616	2,323	5,970	2,442
2004	285	917	2,360	1,028
2005	251	719	1,708	746
2006	214	637	1,482	700
2007	436	1,101	2,528	1,178
2008	680	1,770	3,908	1,948
2009	8,289	14,881	25,242	14,492
2010	983	4,430	11,732	5,174
2011	476	1,860	5,127	2,007
2012	433	1,669	4,668	1,865
2013	2,755	8,260	16,928	8,226
2014	3,011	8,806	19,378	9,539
2015	679	2,765	8,092	2,932
2016	490	1,778	5,133	2,087
2017	440	1,524	4,732	1,739
2018	637	2,685	11,897	3,284

*Table 47. 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.*

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	0.01	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 48. 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.

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

14 FIGURES

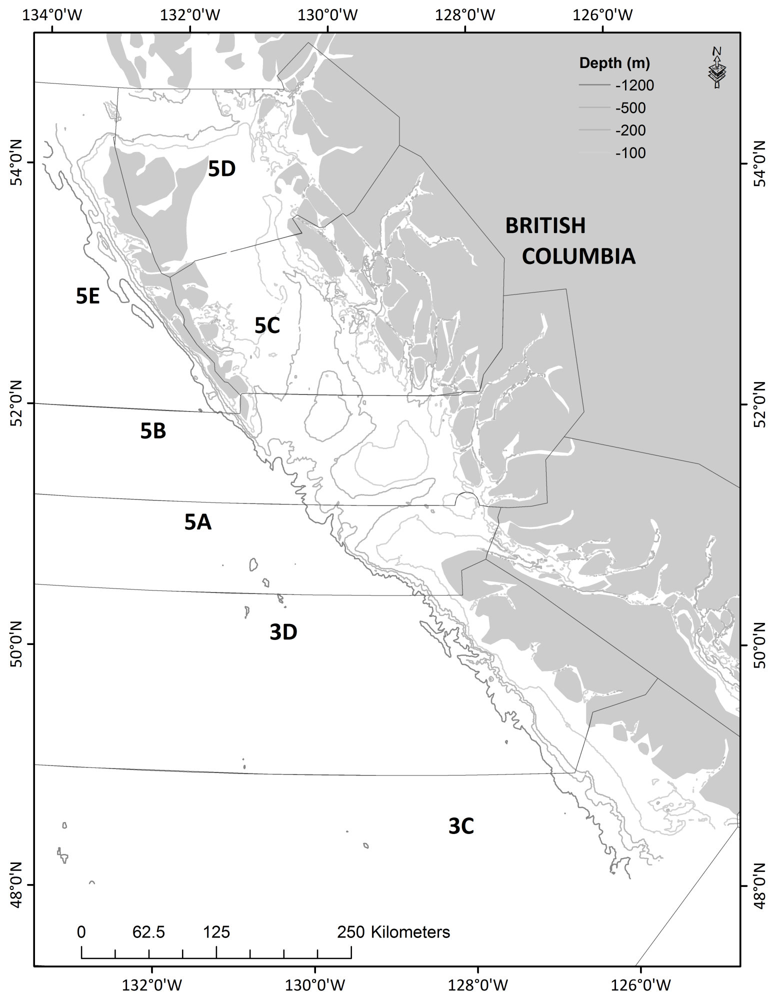

Figure 1. Map of the management areas 5AB (Queen Charlotte Sound), 5CD (Hecate Strait), and 3CD (West Coast Vancouver Island).

14.1 CATCH: AREA 5ABCD

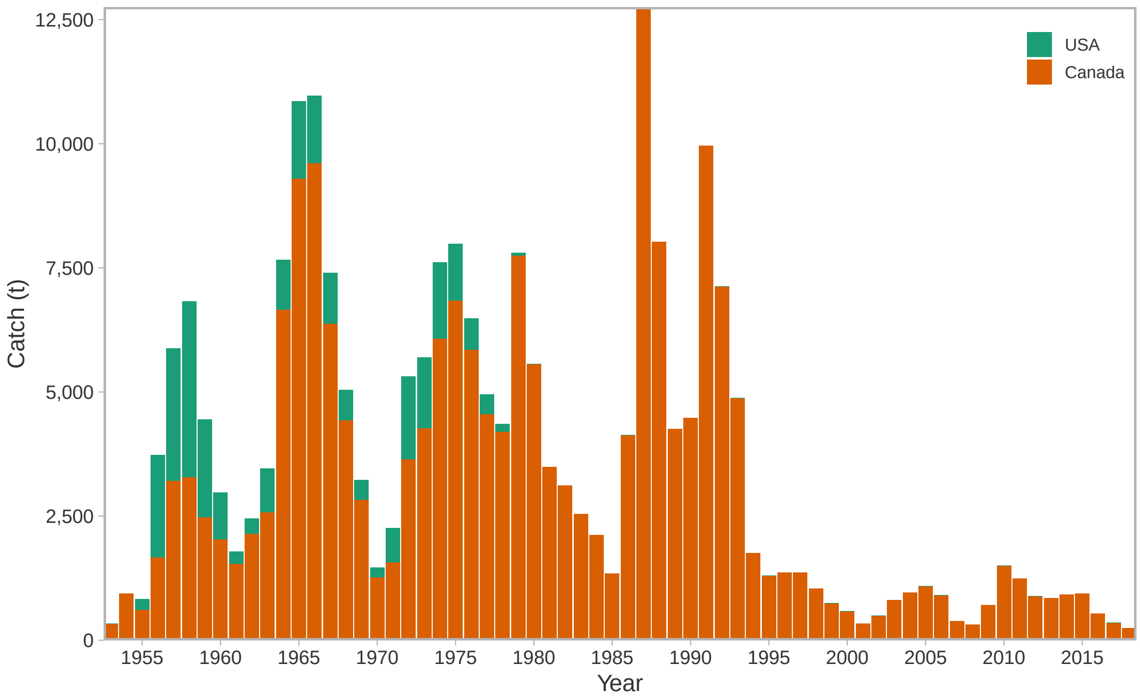

Figure 2. Catch for Area 5ABCD. Canadian catch includes at-sea releases.

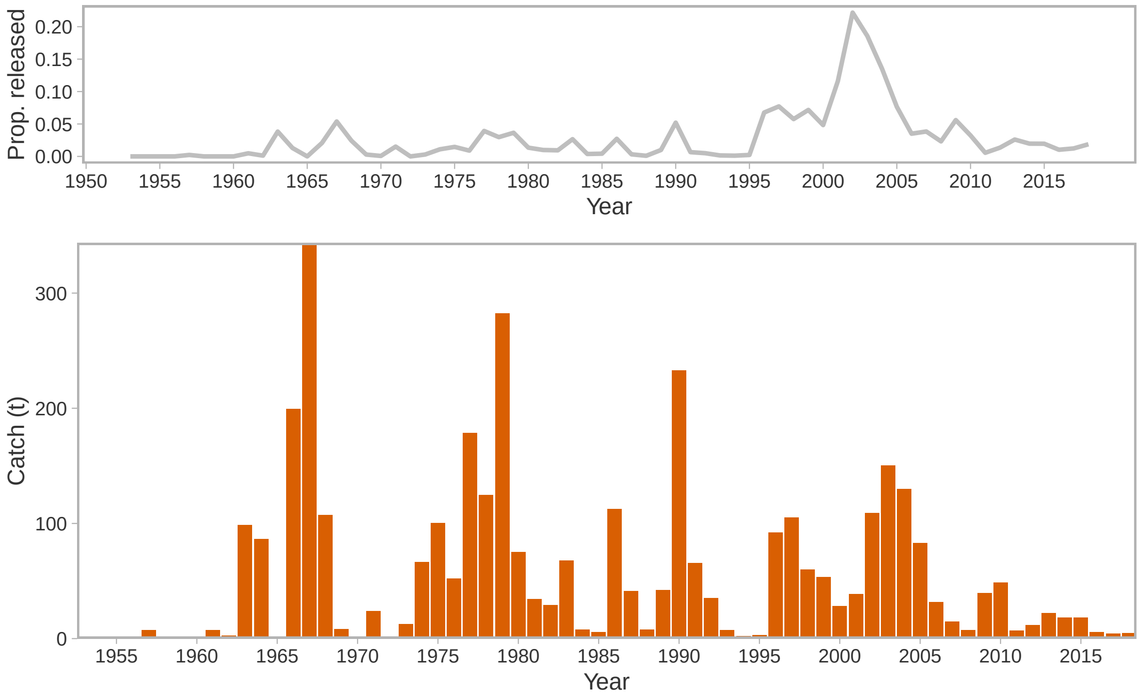

Figure 3. Estimated at-sea releases of Pacific Cod by bottom trawlers for Area 5ABCD.

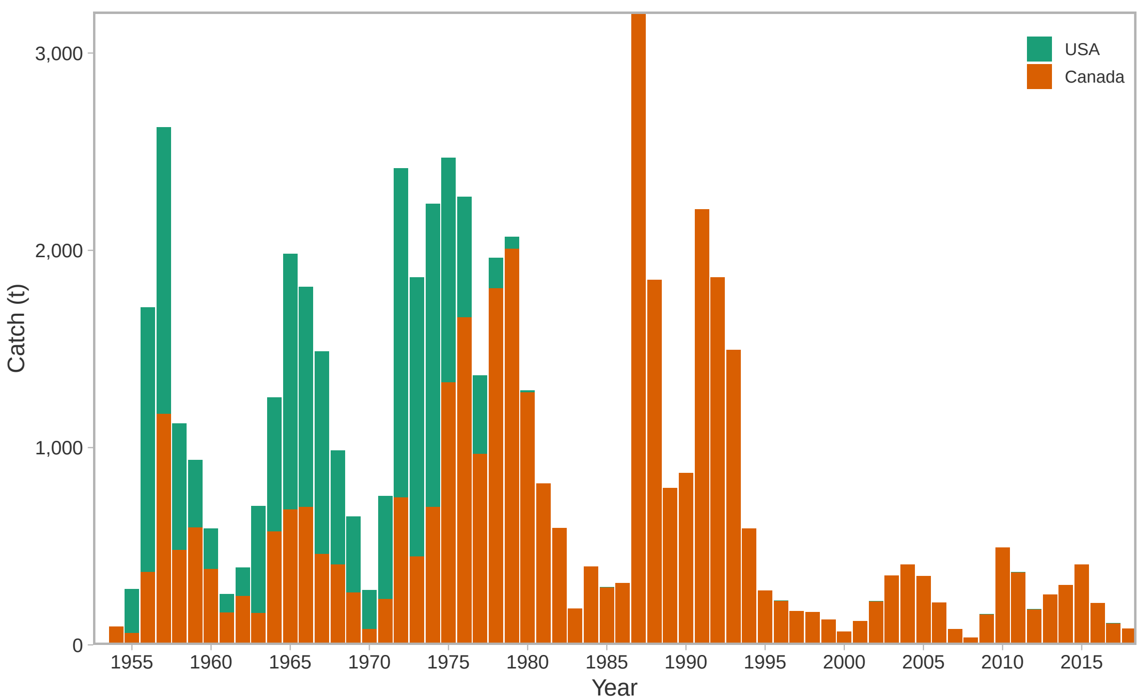

Figure 4. Catch for Area 5AB. Canadian catch includes at-sea releases.

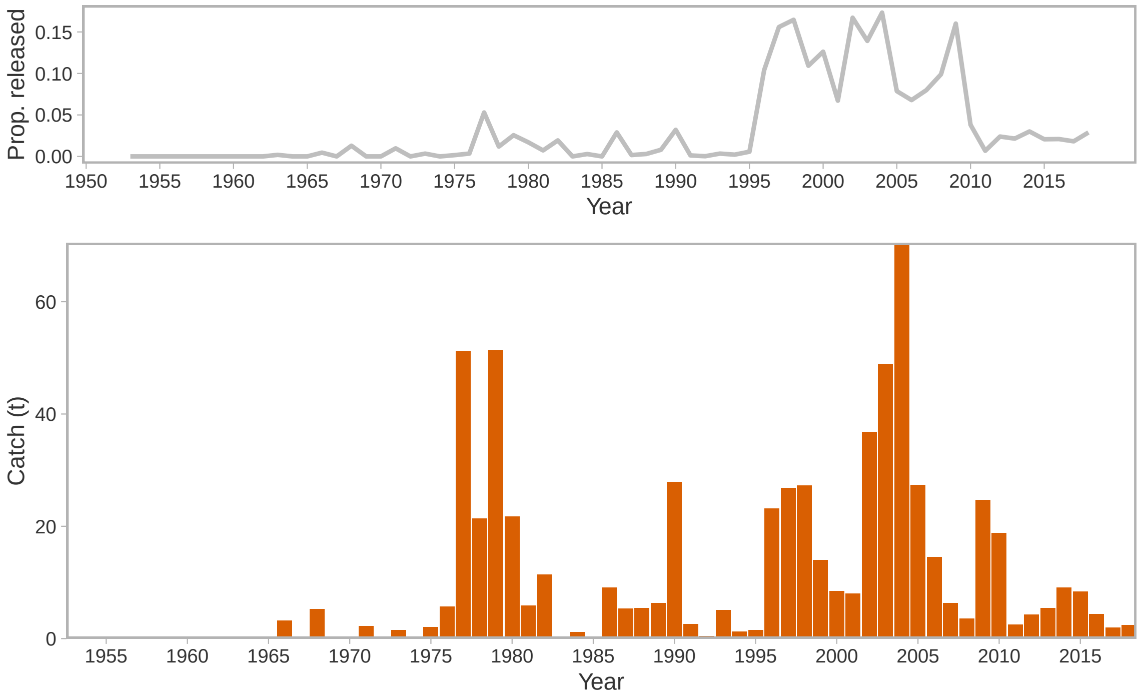

Figure 5. Estimated at-sea releases of Pacific Cod by bottom trawlers for Area 5AB.

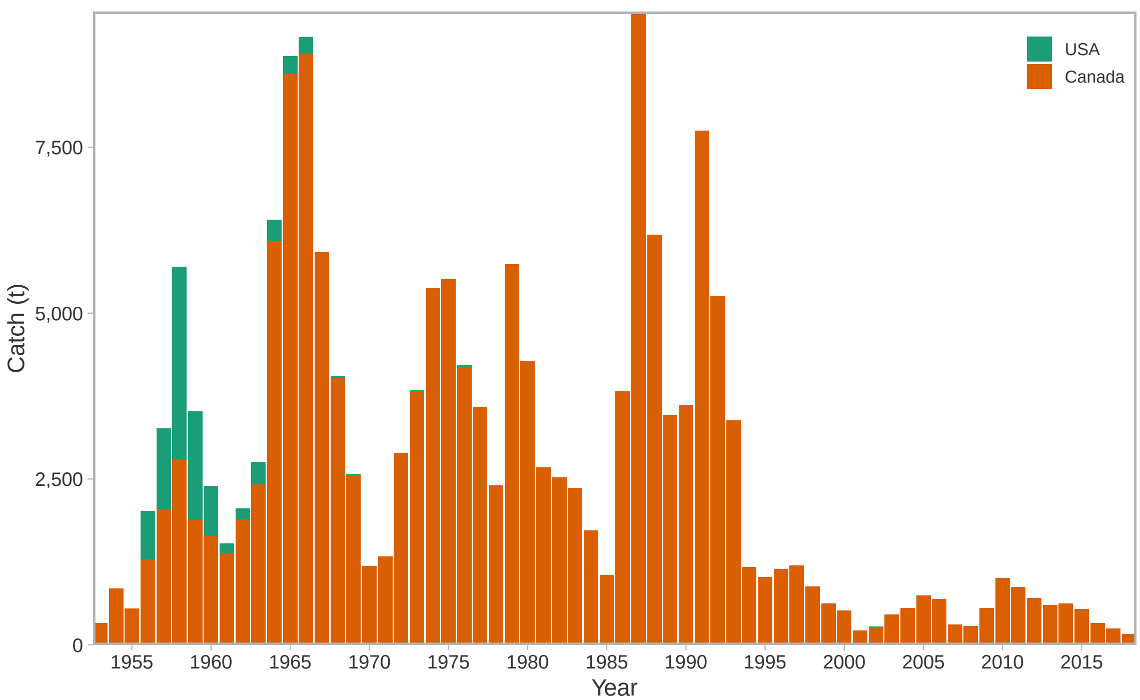

Figure 6. Catch for Area 5CD. Canadian catch includes at-sea releases.

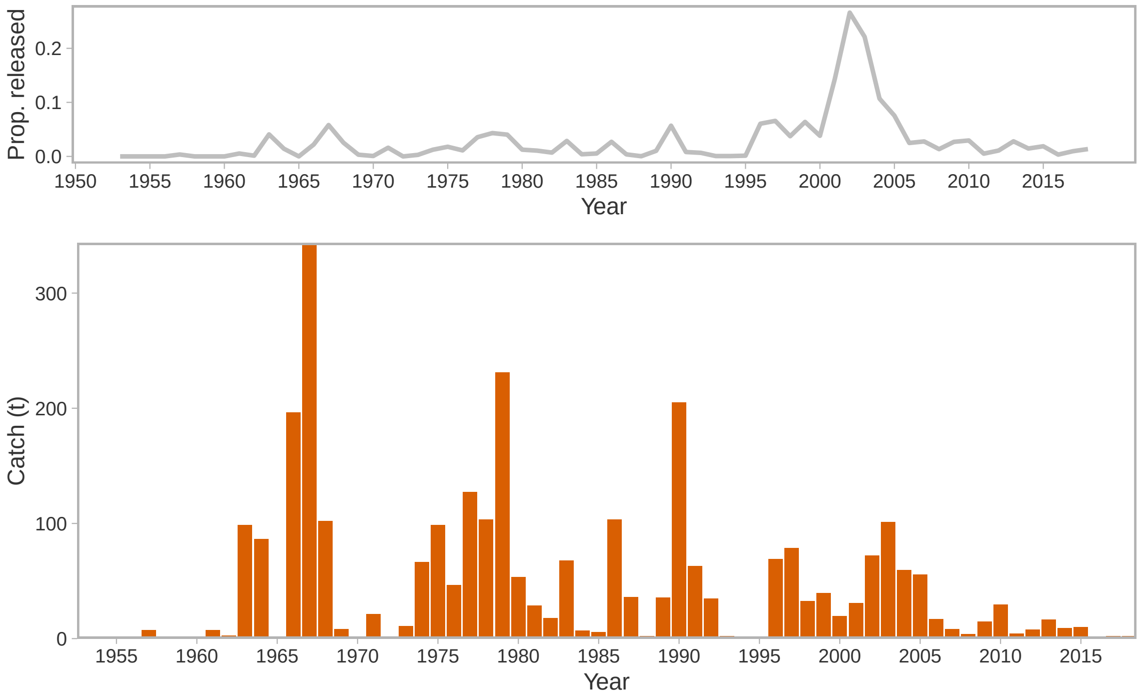

Figure 7. Estimated at-sea releases of Pacific Cod by bottom trawlers for Area 5CD.

14.2 CATCH: AREA 3CD

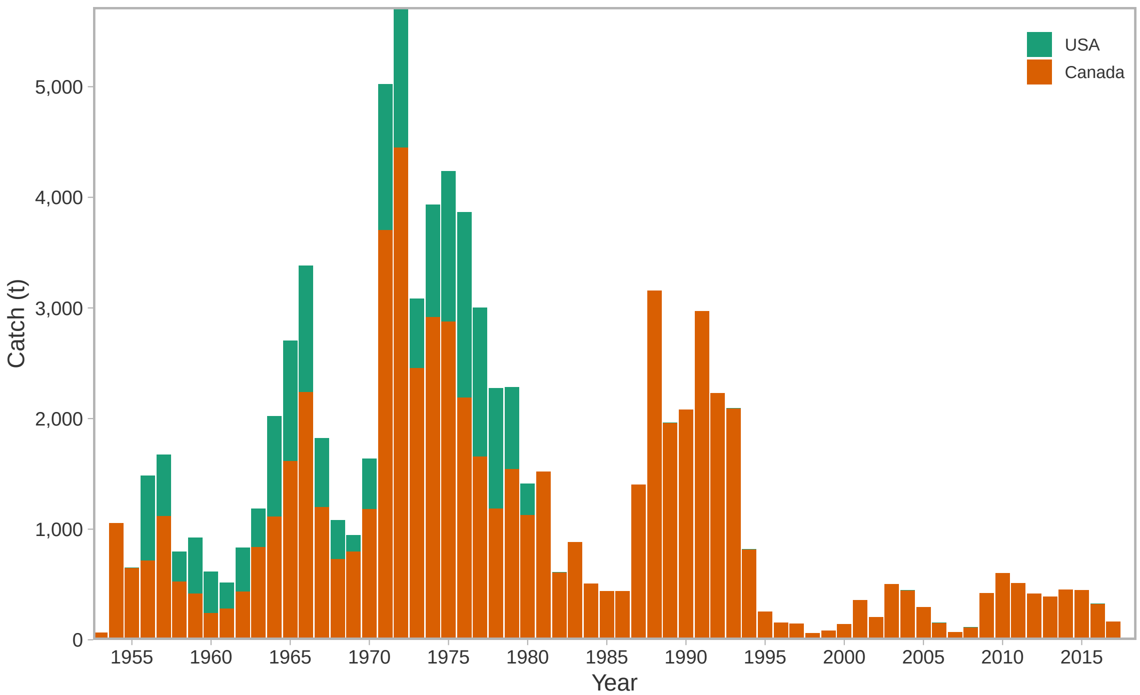

Figure 8. Catch for Area 3CD. Canadian catch includes at-sea releases.

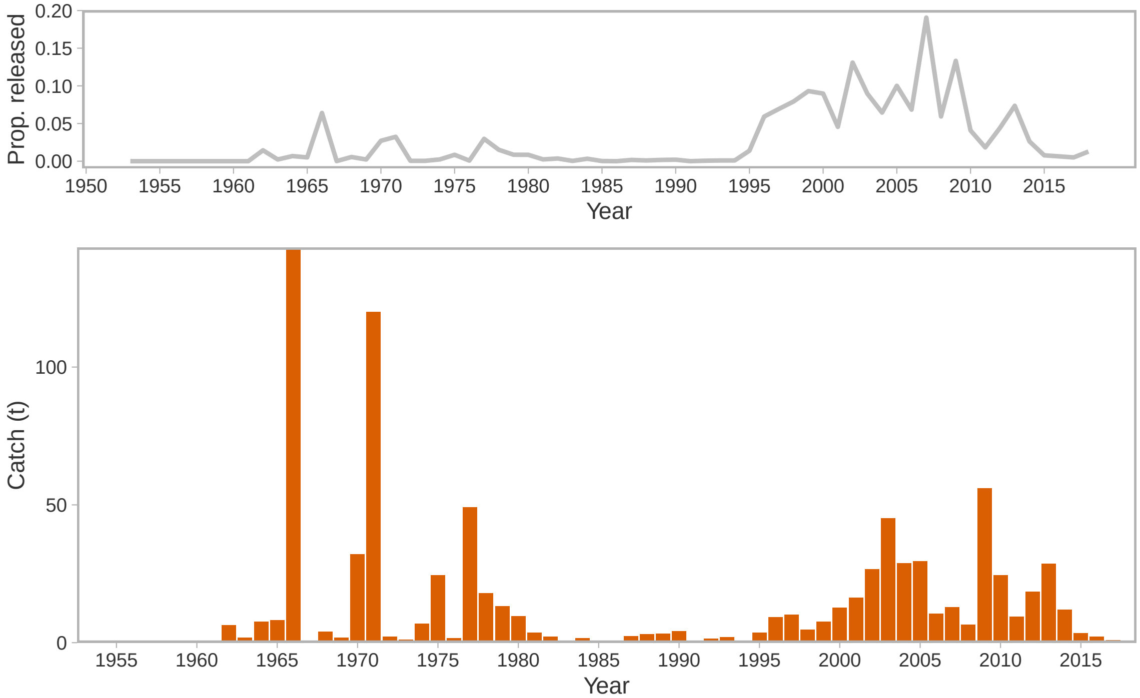

Figure 9. Estimated at-sea releases of Pacific Cod by bottom trawlers for Area 3CD.

14.3 PRIOR PROBABILITY DISTRIBUTIONS

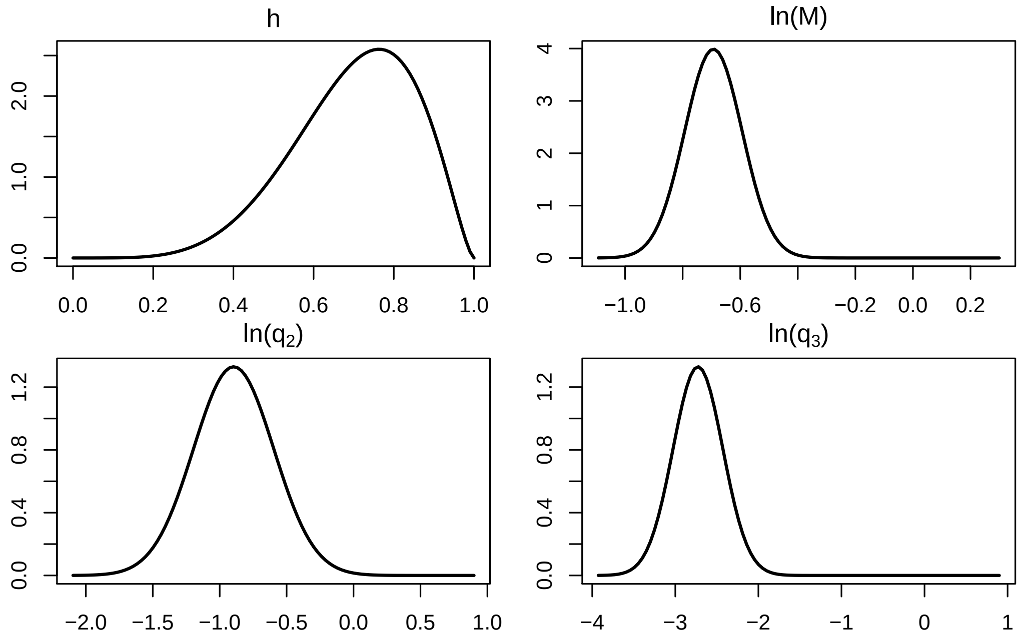

Figure 10. Prior probability distributions used in the Area 5ABCD reference model. q_1 = Hecate Strait Assemblage survey, q_2 = Queen Charlotte Sound Synoptic Survey, q_3 = Hecate Strait Synoptic Survey, q_4 = Commercial CPUE pre-1996, and q_5 = Commercial CPUE post-1995.

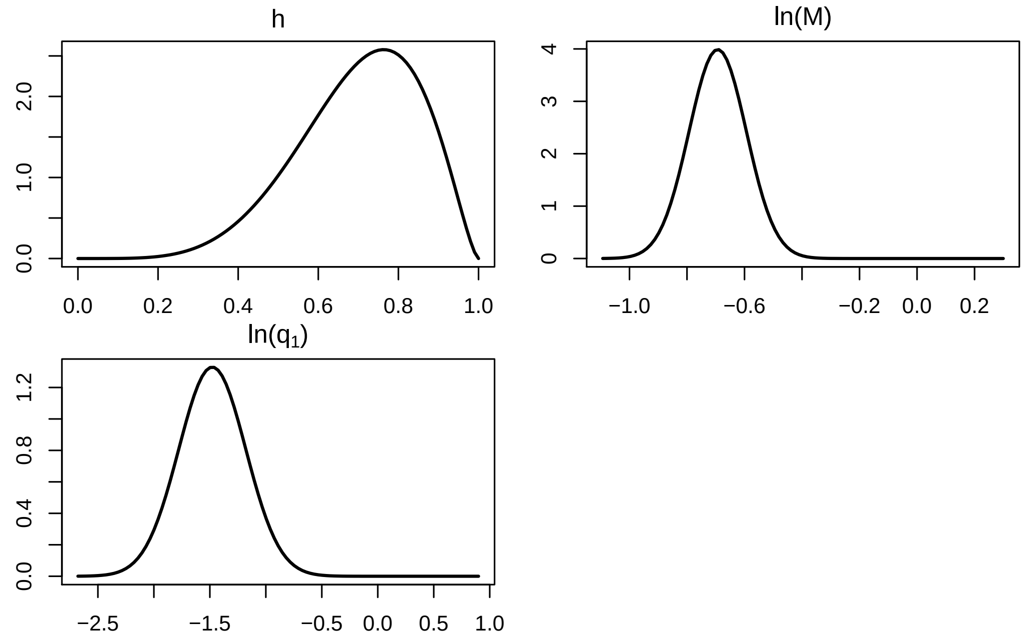

Figure 11. Prior probability distributions used in the Area 3CD reference model. q_1 *= West Coast Vancouver Island Synoptic Survey,* q_2 *= Commercial CPUE pre-1996,* q_3 *= Commercial CPUE post-1995, and* q_4 *= NMFS Triennial Survey (Canadian portion).*

14.4 MODEL RESULTS: AREA 5ABCD

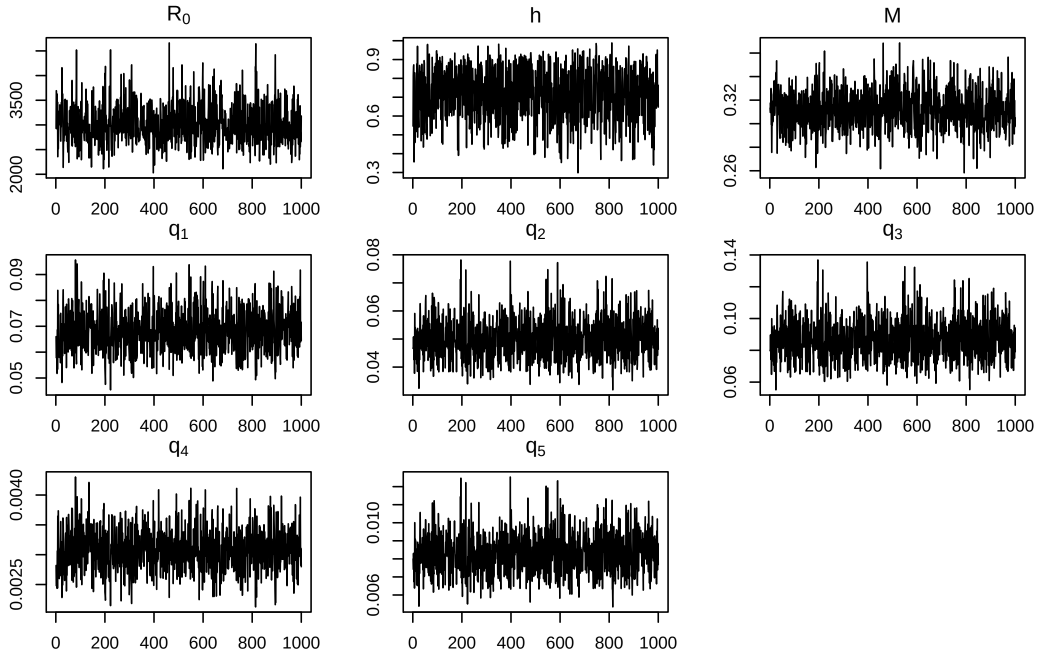

Figure 12. Traceplots of posterior samples for the Area 5ABCD reference model. q_1 *= Hecate Strait Assemblage survey,* q_2 *= Queen Charlotte Sound Synoptic Survey,* q_3 *= Hecate Strait Synoptic Survey,* q_4 *= Commercial CPUE pre-1996, and* q_5 *= Commercial CPUE post-1995.*

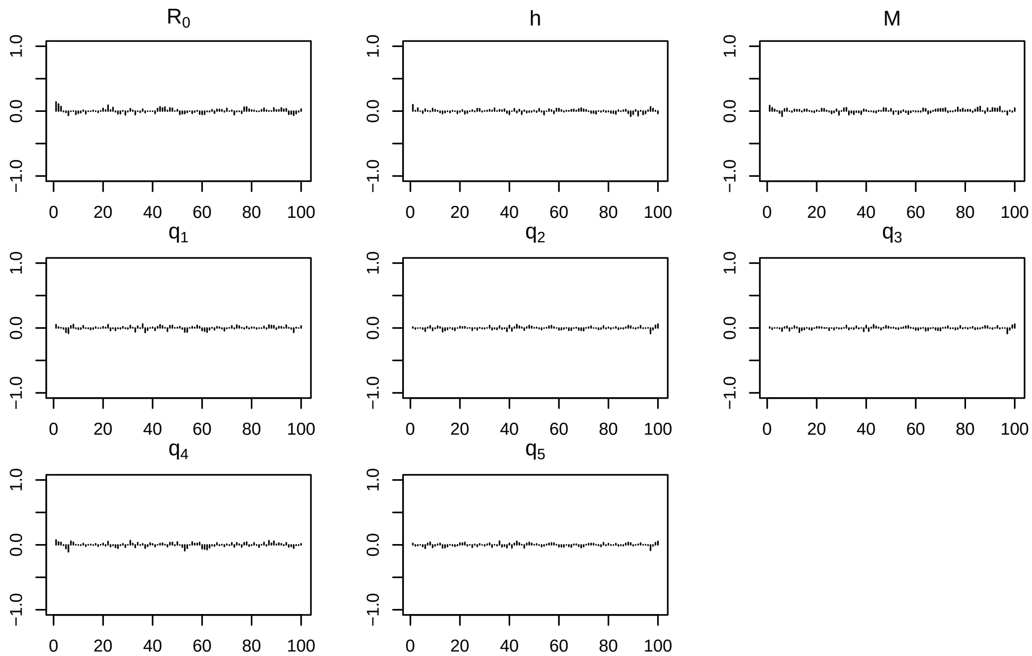

Figure 13. Autocorrelation plots for the Area 5ABCD reference model. q_1 = Hecate Strait Assemblage survey, q_2 = Queen Charlotte Sound Synoptic Survey, q_3 = Hecate Strait Synoptic Survey, q_4 = Commercial CPUE pre-1996, and q_5 = Commercial CPUE post-1995.

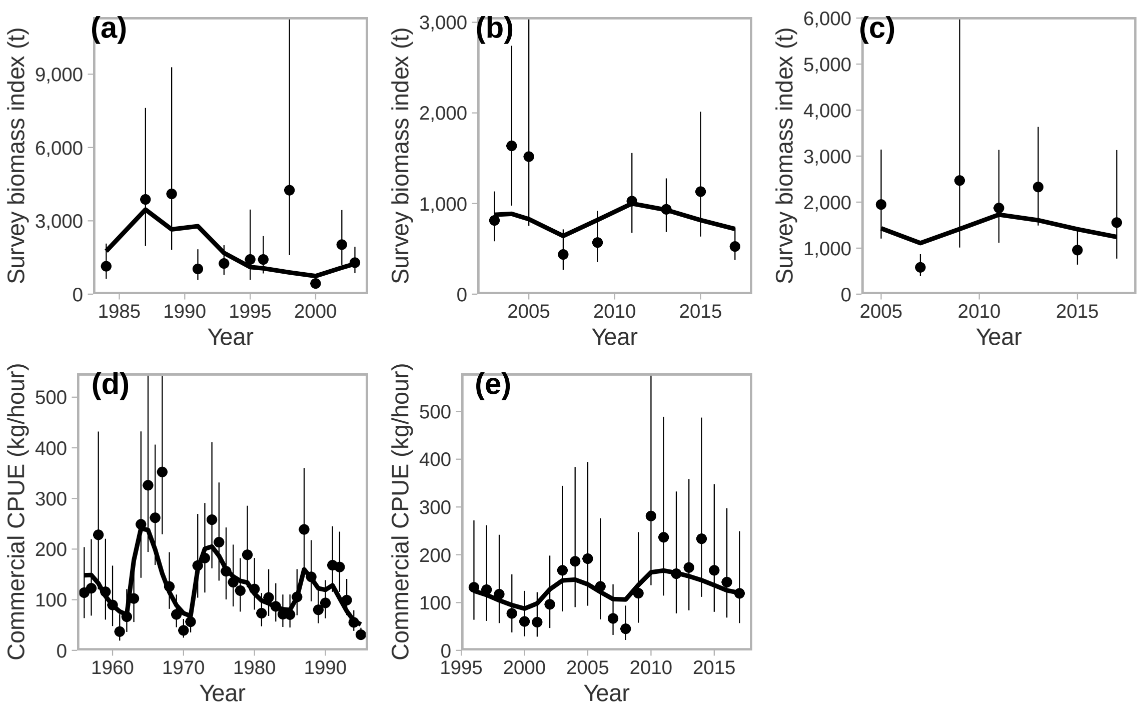

Figure 14. MPD fits to observed indices of abundance (points) for the Area 5ABCD reference model from: (a) the Hecate Strait Assemblage survey, (b) the Queen Charlotte Sound Synoptic Survey, (c) the Hecate Strait Synoptic Survey, (d) the Commercial CPUE pre-1996, and (e) the Commercial CPUE post-1995. For clarity, only MPD results are shown

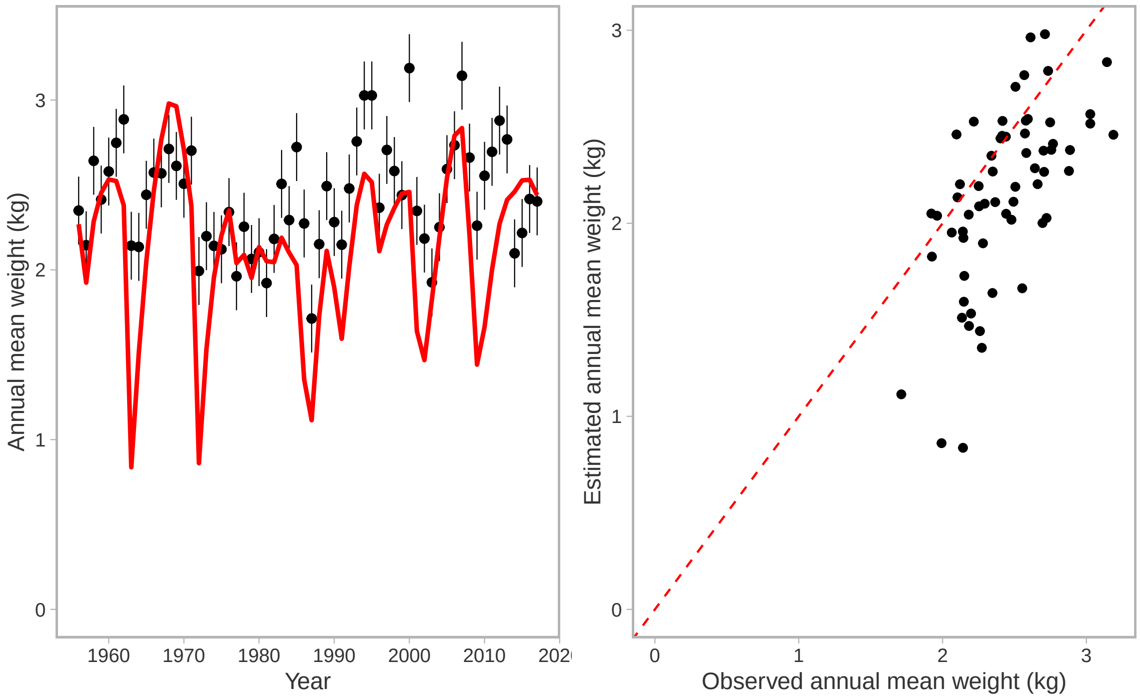

Figure 15. MPD fit to the mean weight data for Area 5ABCD reference model. For clarity, only MPD results are shown

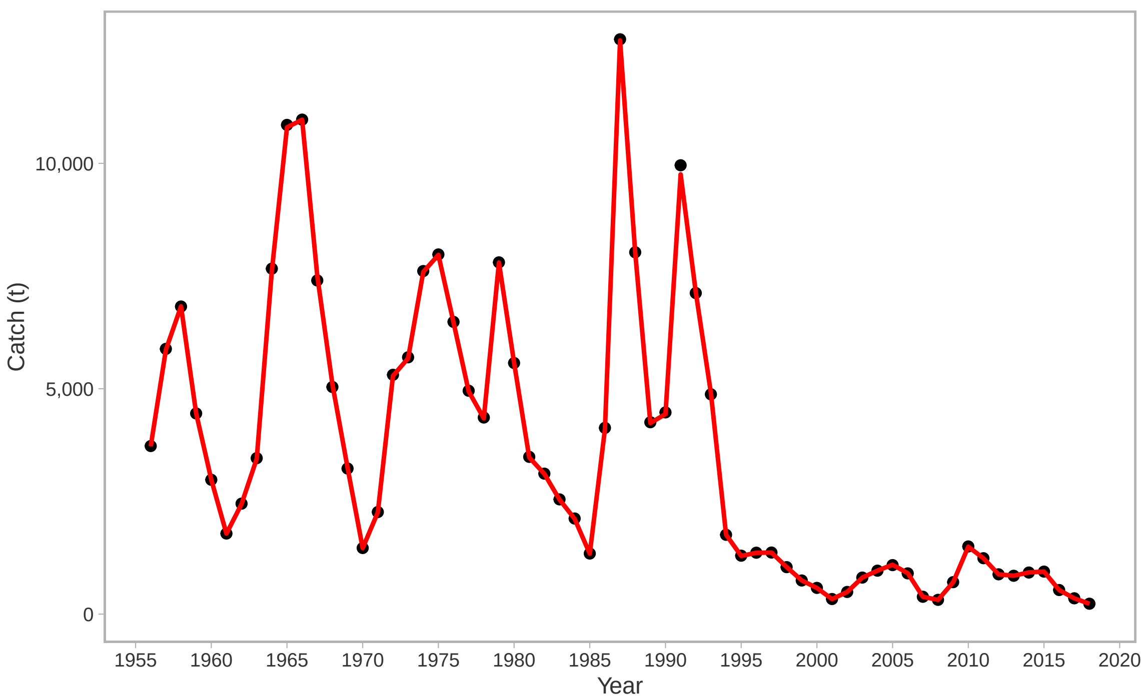

Figure 16. MPD fit to the catch data for Area 5ABCD reference model. For clarity, only MPD results are shown

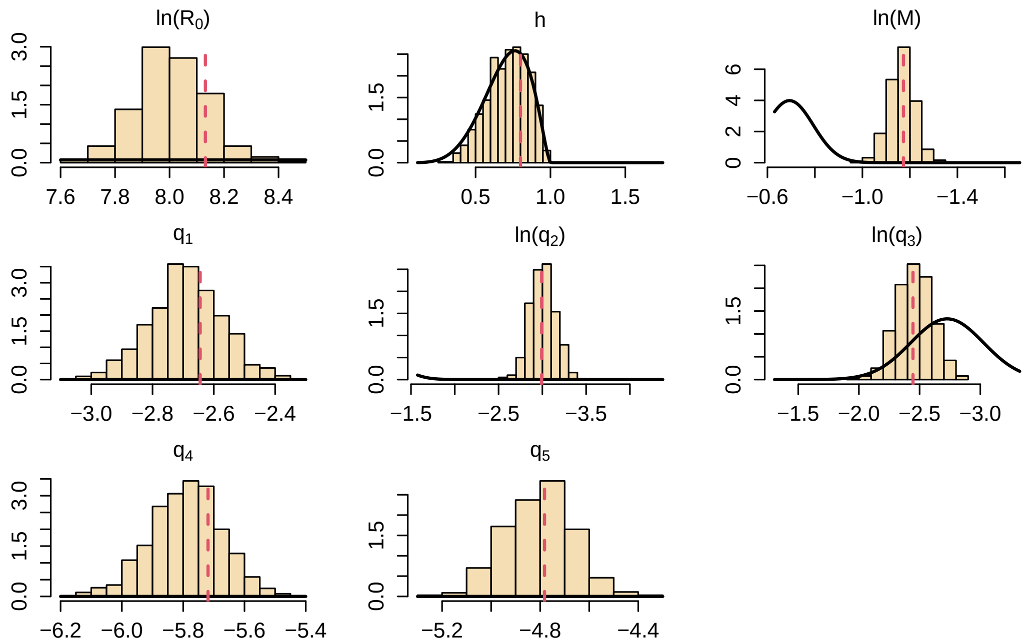

Figure 17. Histograms of posterior samples with prior probability distributions (lines) used in the Area 5ABCD reference model. MPD estimate shown as vertical dashed line. Note that both the Queen Charlotte Sound and Hecate Strait Synoptic Surveys used normal prior distributions on $ln(q)$, see Figure 10 for full distribution. 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.

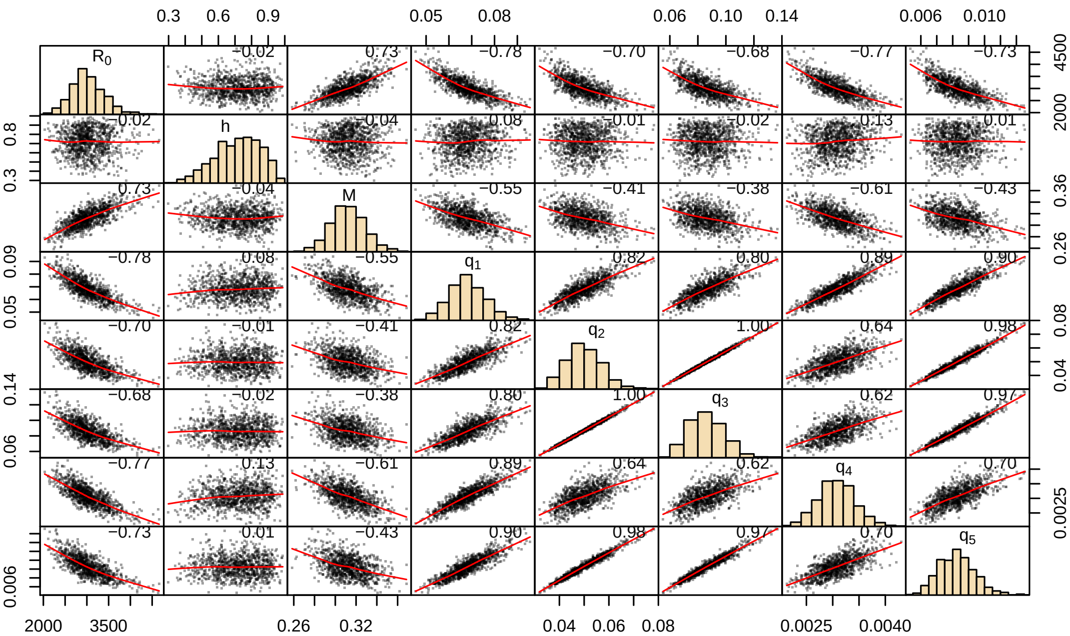

Figure 18. Pairs plots of posterior samples for the Area 5ABCD reference model. $\bar{R} = R_{Avg}$, q_1 *= Hecate Strait Assemblage survey,* q_2 *= Queen Charlotte Sound Synoptic Survey,* q_3 *= Hecate Strait Synoptic Survey,* q_4 *= Commercial CPUE pre-1996, and* q_5 *= Commercial CPUE post-1995.*

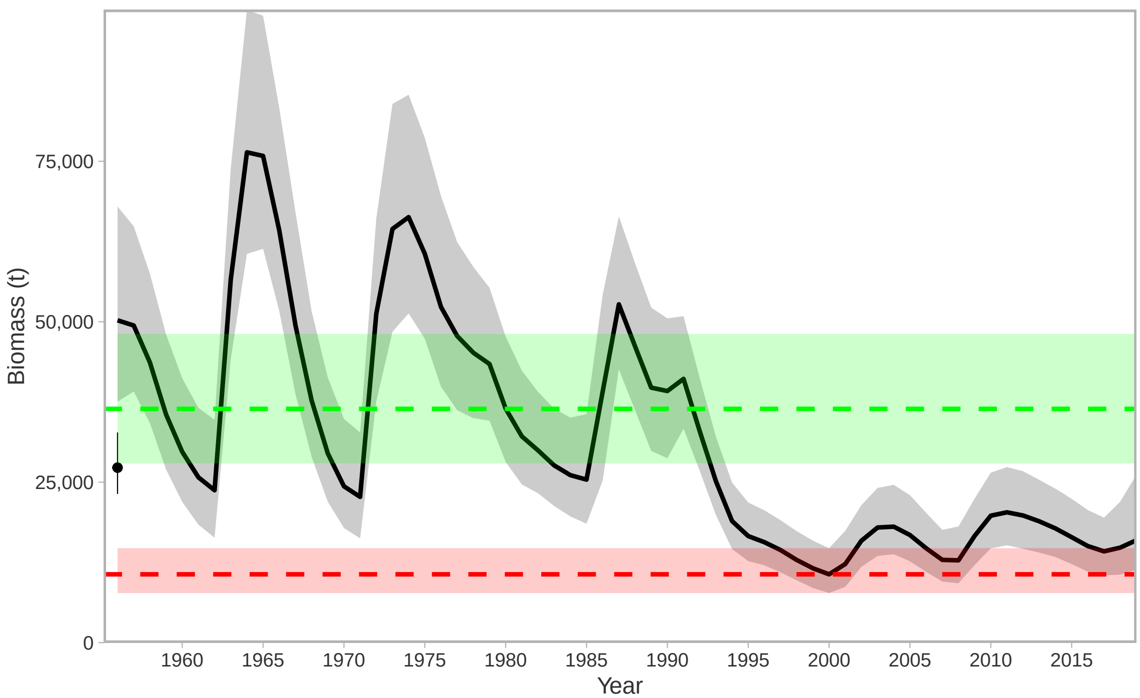

Figure 19. Posterior estimated biomass for the Reference Model, Area 5ABCD. The green dashed line shows the median Upper Stock Reference (USR) which is the mean biomass estimate for the years 1956–2004. The red dashed line shows the median Limit Reference Point (LRP) which is the lowest estimated biomass agreed to be an undesirable state to avoid, in this case it is the biomass estimate for 2000.

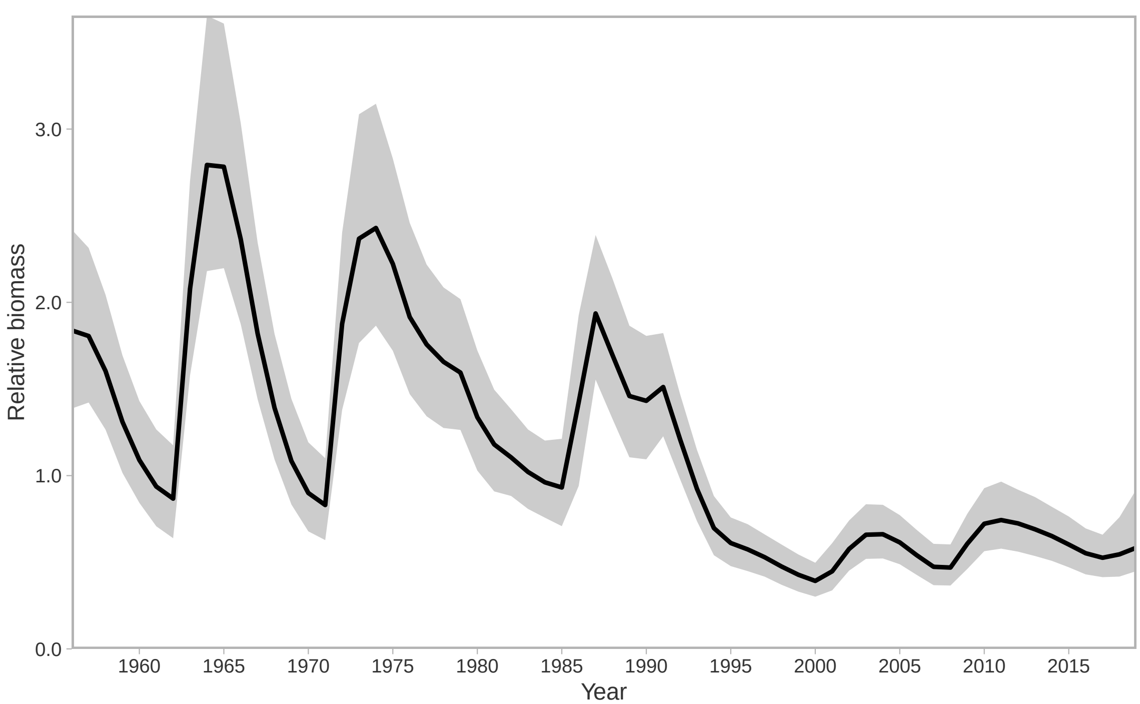

Figure 20. Relative biomass for the Reference Model, Area 5ABCD.

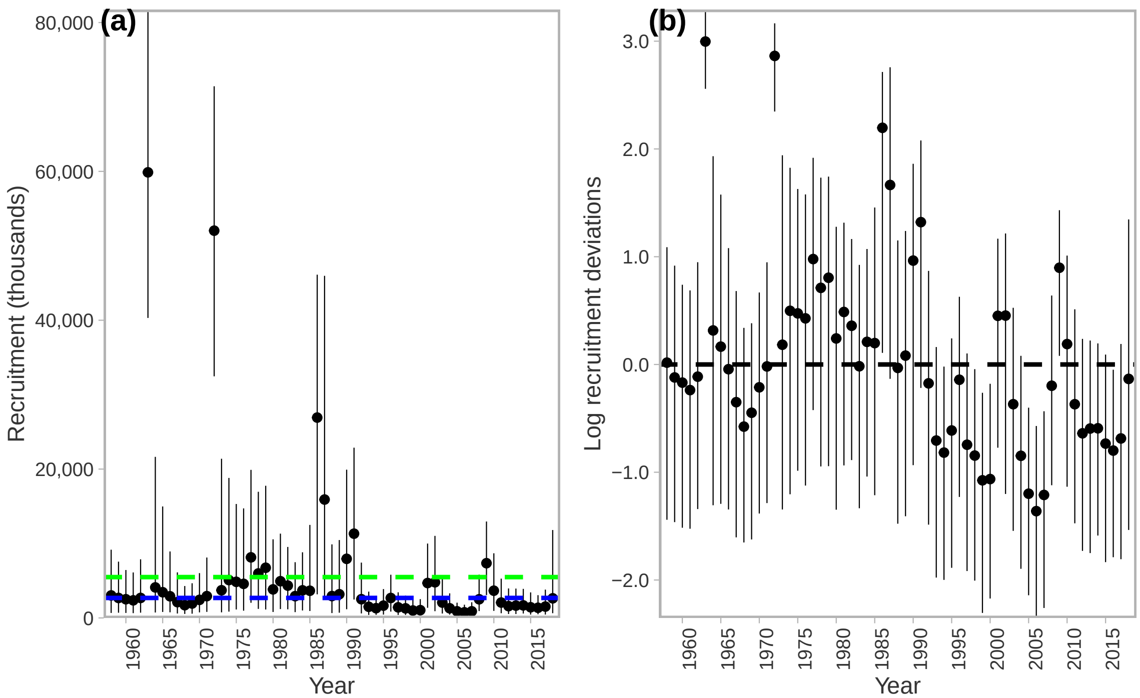

Figure 21. Recruitment (a) and recruitment deviations (b) for the Reference Model, Area 5ABCD. The green dashed line shows the mean of the MCMC posterior medians, the blue dashed line shows the median of the MCMC posterior medians.

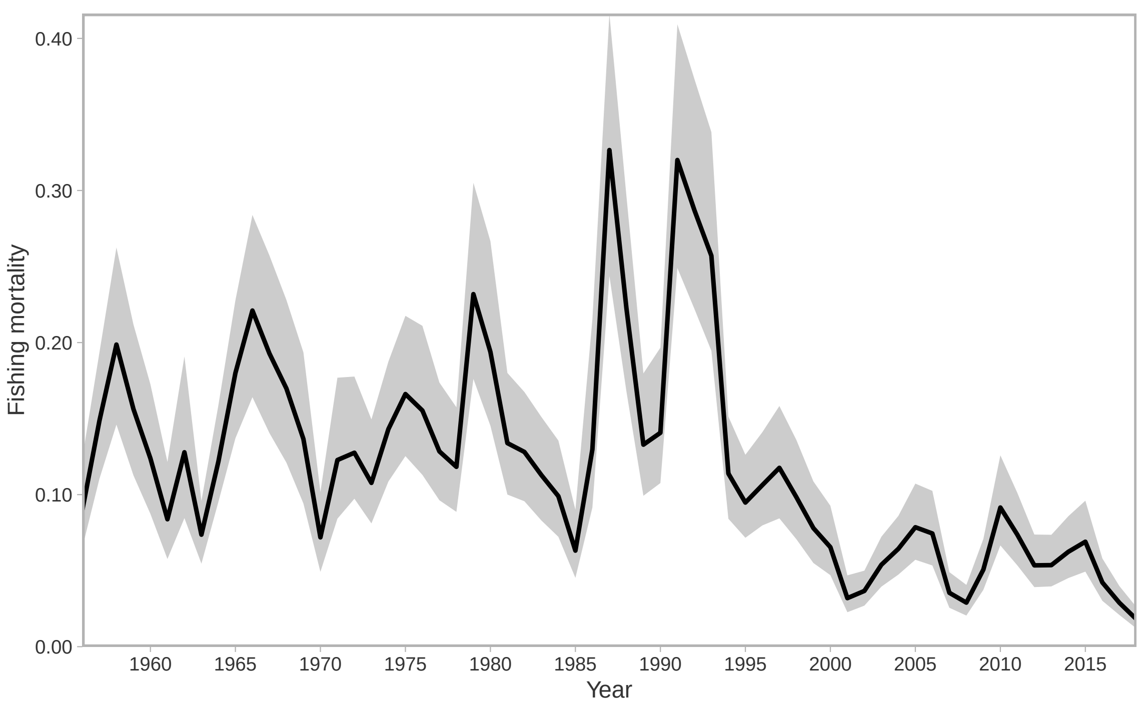

Figure 22. Fishing mortality for the Reference Model, Area 5ABCD.

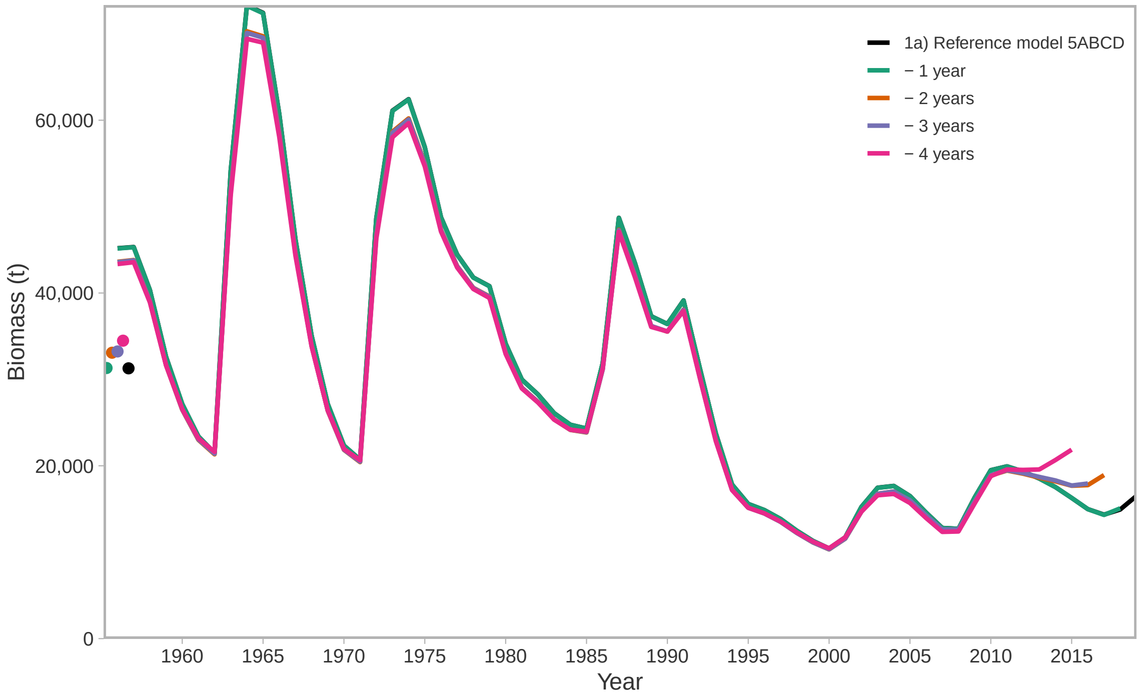

Figure 23. Retrospective biomass for the Reference Model, Area 5ABCD.

14.5 MODEL RESULTS: AREA 3CD

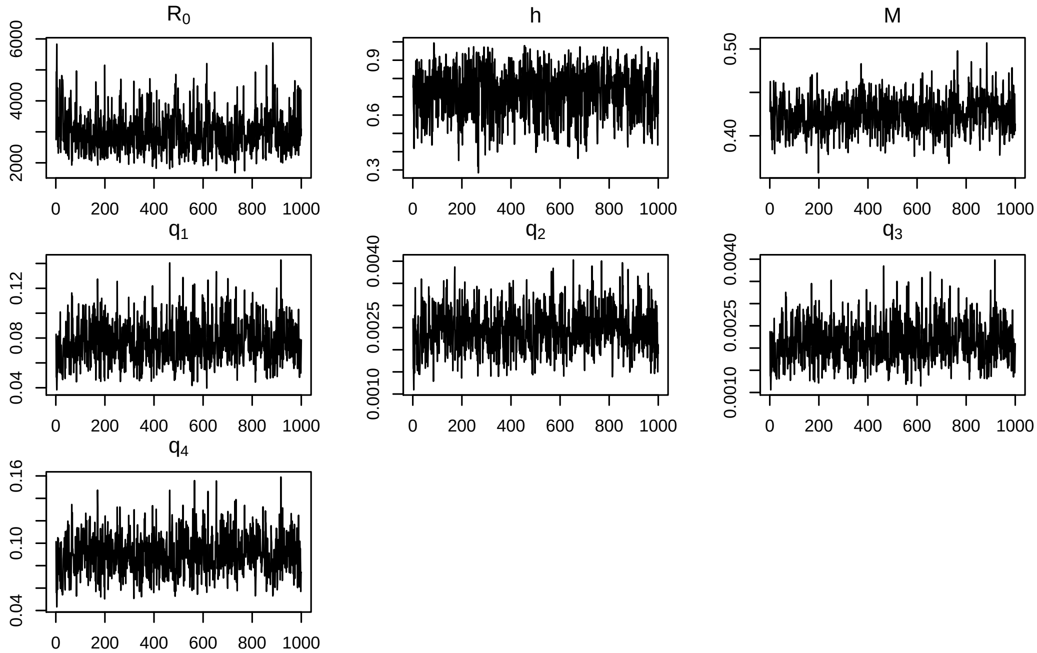

Figure 24. Traceplots of posterior samples for the Area 3CD reference model. q_1 *= West Coast Vancouver Island Synoptic Survey,* q_2 *= Commercial CPUE pre-1996,* q_3 *= Commercial CPUE post-1995, and* q_4 *= NMFS Triennial Survey (Canadian portion).*

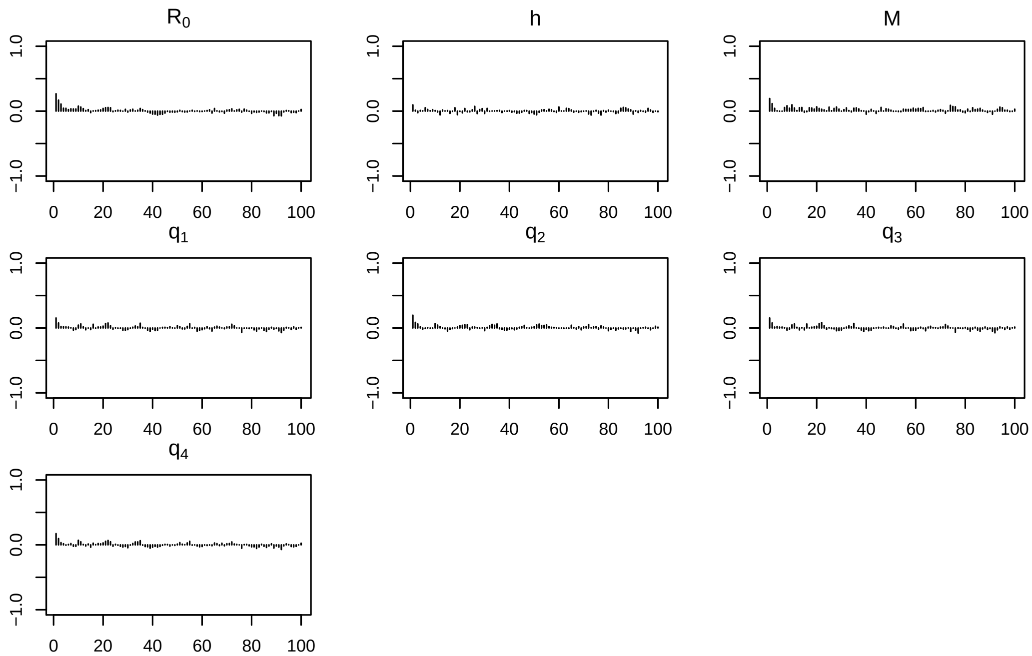

Figure 25. Autocorrelation plots for the Area 3CD reference model. q_1 = West Coast Vancouver Island Synoptic Survey, q_2 = Commercial CPUE pre-1996, q_3 = Commercial CPUE post-1995, and q_4 = NMFS Triennial Survey (Canadian portion).

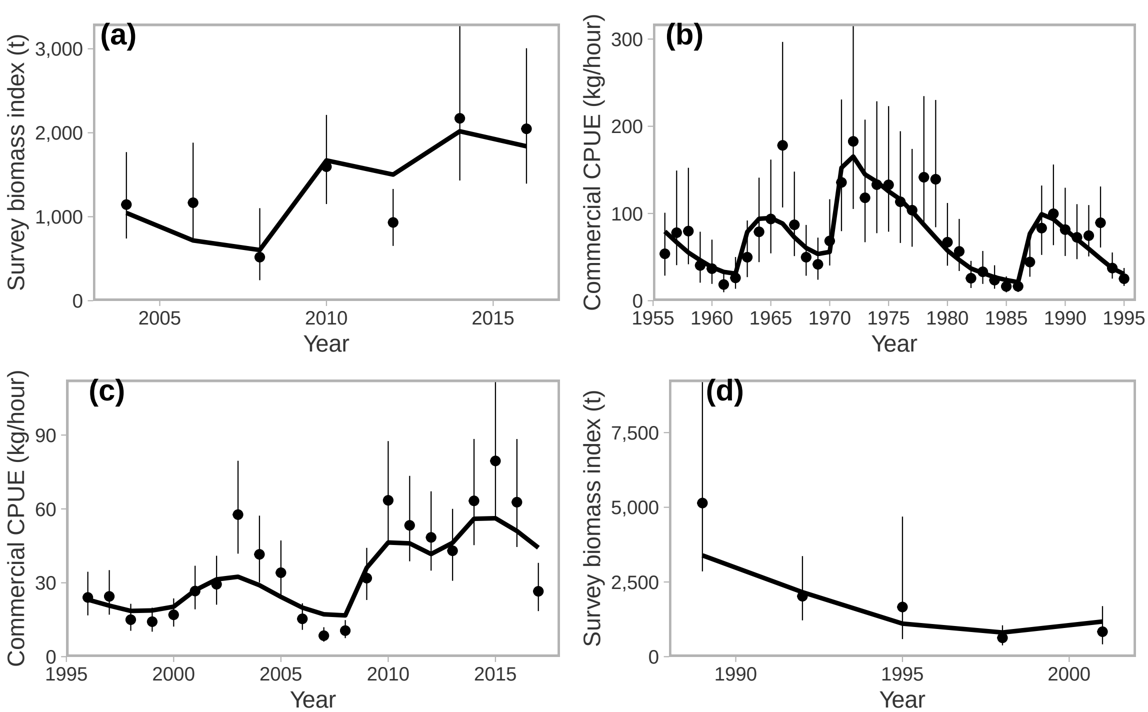

Figure 26. MPD fits to observed indices of abundance (points) for the Area 3CD reference model from: (a) the West Coast Vancouver Island Synoptic Survey, (b) the Commercial CPUE pre-1996, (c) the Commercial CPUE post-1995, and (d) the NMFS Triennial Survey (Canadian portion).

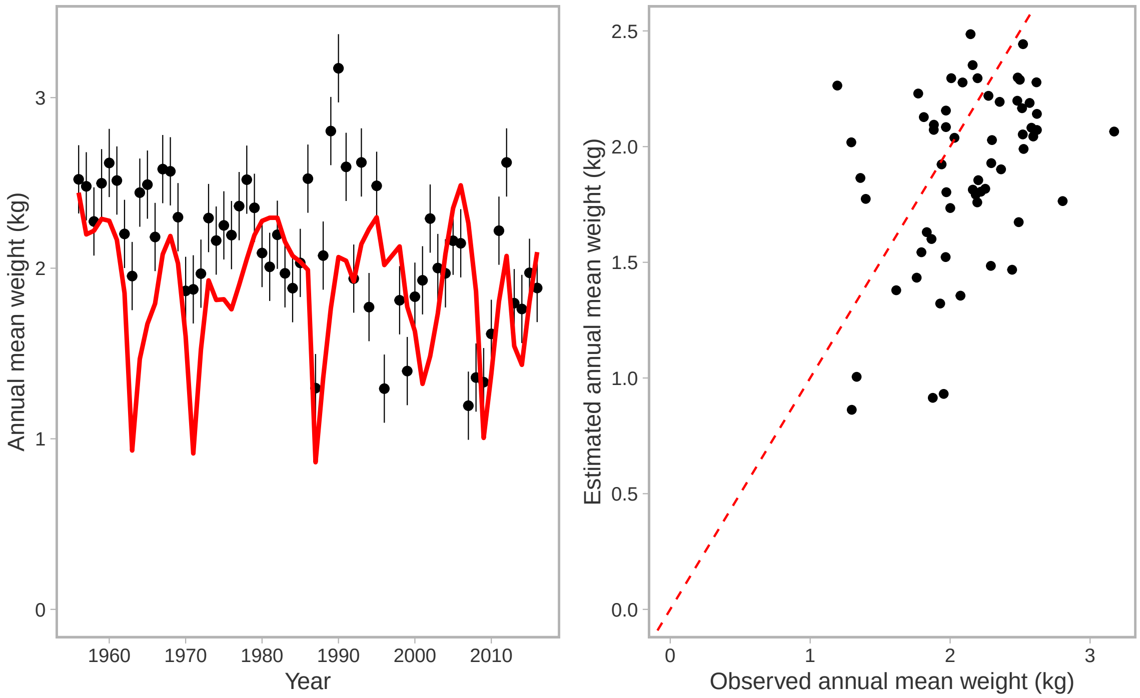

Figure 27. MPD fit to the mean weight data for Area 3CD reference model.

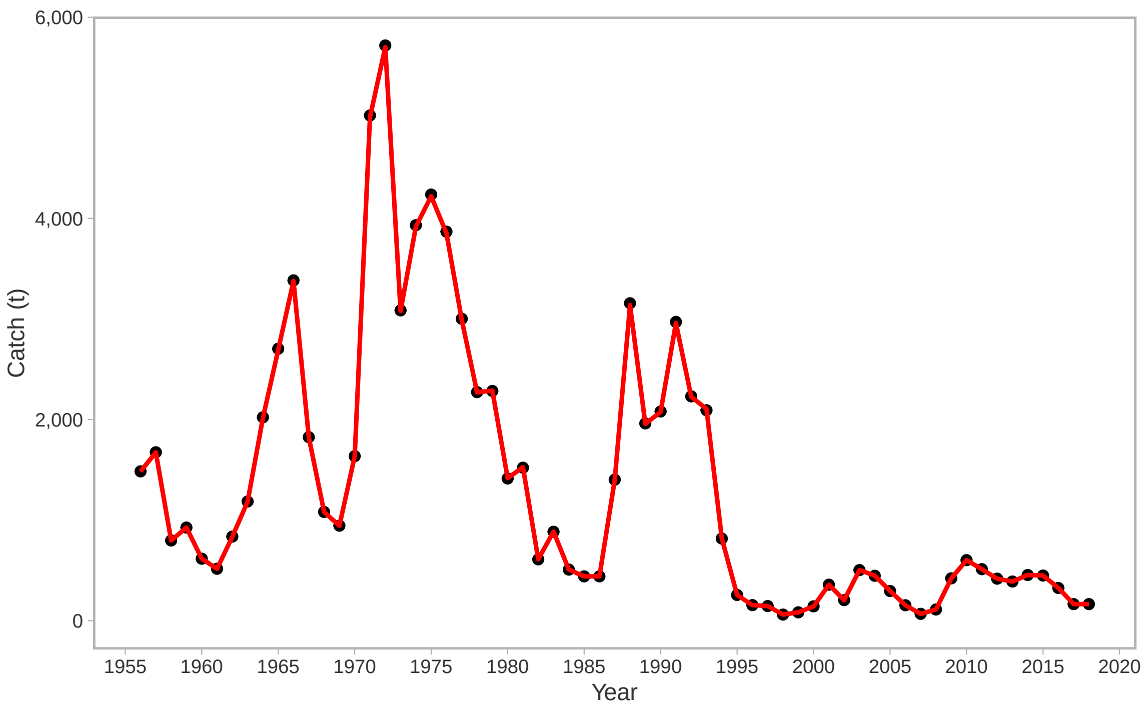

Figure 28. MPD fit to the catch data for Area 3CD reference model.

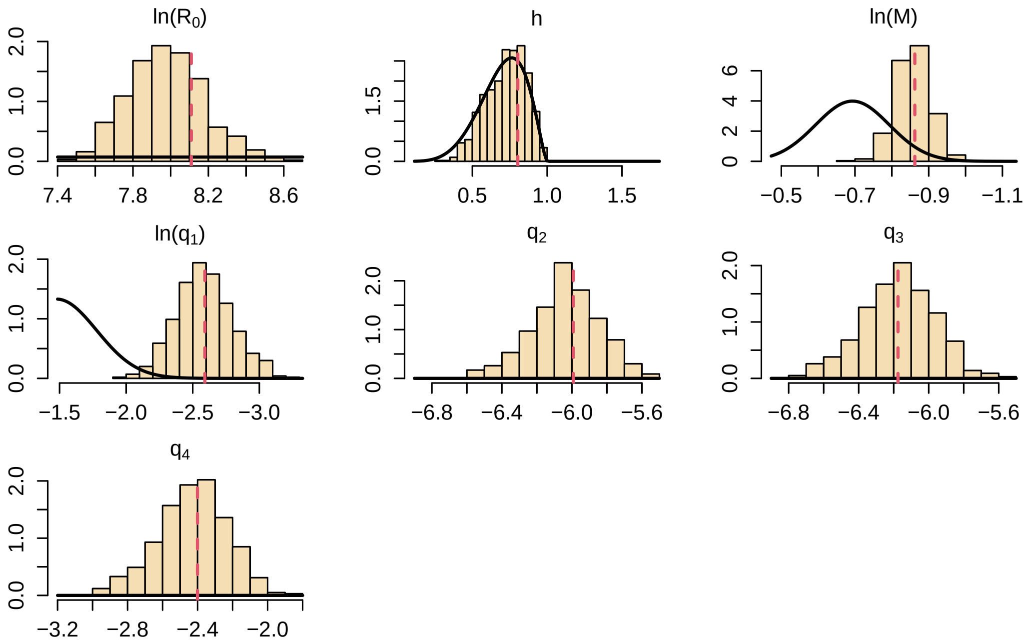

Figure 29. Histograms of posterior samples with prior probability distributions (lines) used in the Area 3CD reference model. MPD estimate shown as vertical dashed line. Note that the West Coast Vancouver Island Synoptic Survey used a normal prior distribution on $ln(q)$, see Figure 11 for full distribution. 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).

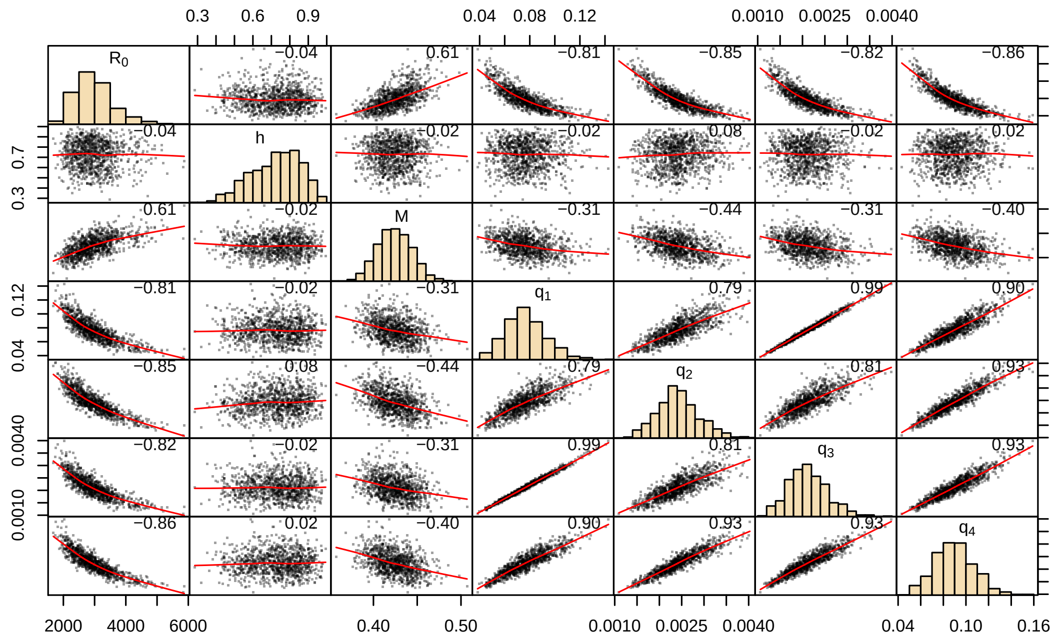

Figure 30. Pairs plots of posterior samples for the Area 3CD reference model. q_1 = West Coast Vancouver Island Synoptic Survey, q_2 = Commercial CPUE pre-1996, q_3 = Commercial CPUE post-1995, and q_4 = NMFS Triennial Survey (Canadian portion).

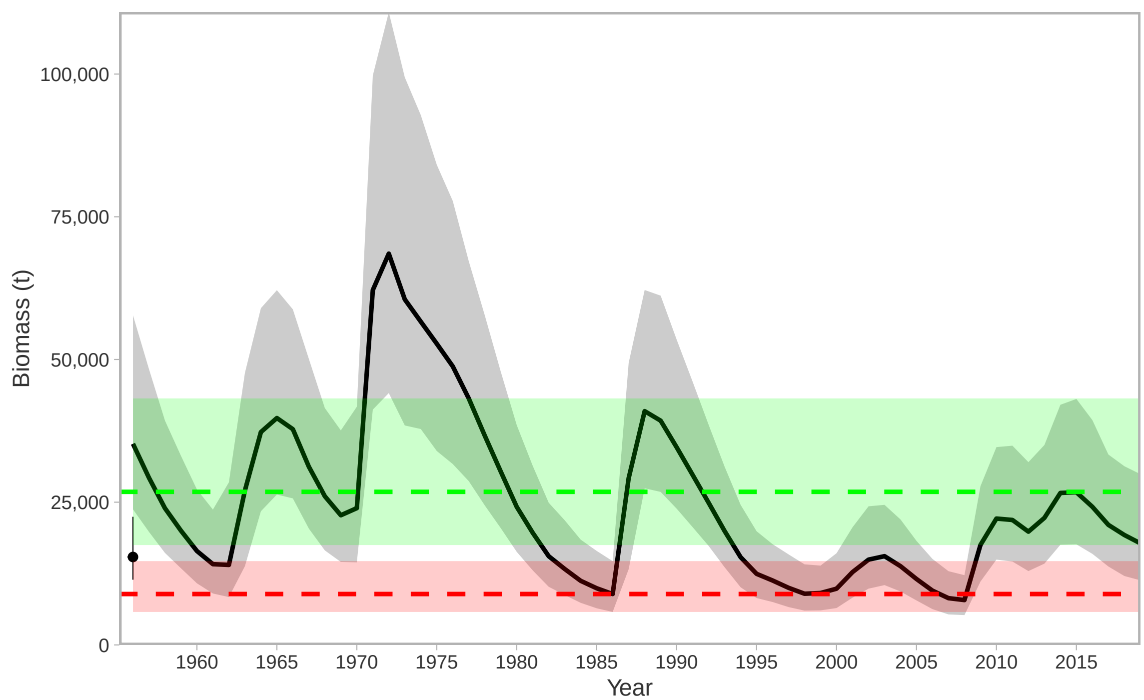

Figure 31. Posterior estimated biomass for the Reference Model, Area 3CD. The green dashed line shows the median Upper Stock Reference (USR) which is the mean biomass estimate for the years 1956–2004. The red dashed line shows the median Limit Reference Point (LRP) which is the lowest estimated biomass agreed to be an undesirable state to avoid, in this case it is the biomass estimate for 1986.

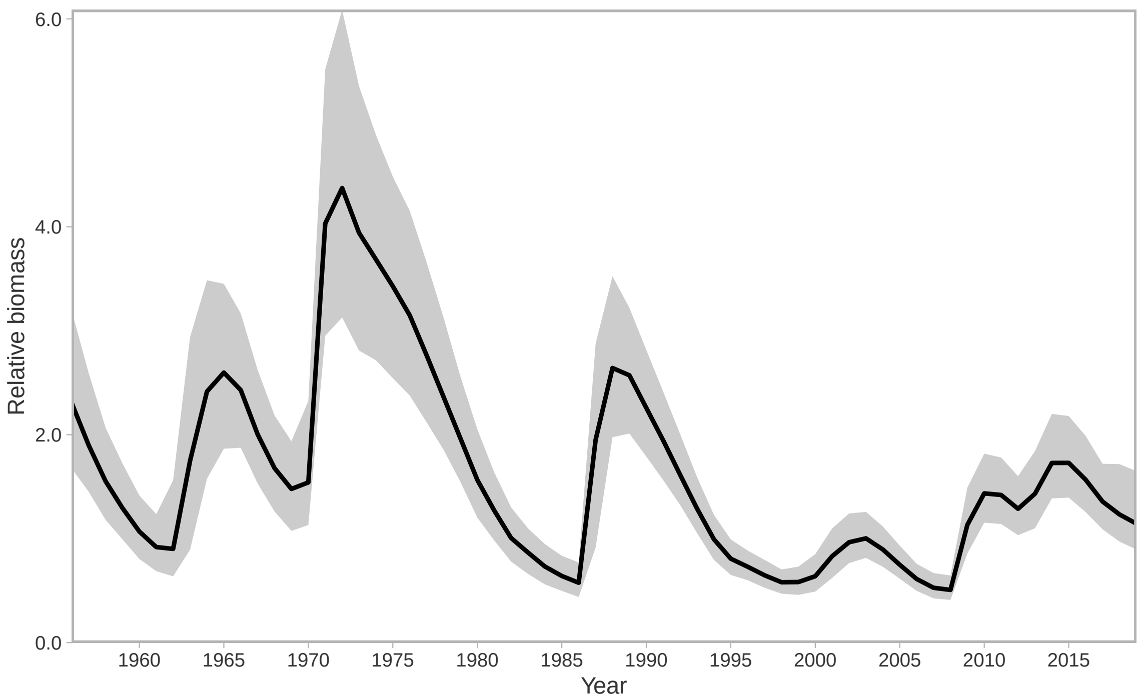

Figure 32. Relative biomass for the Reference Model, Area 3CD.

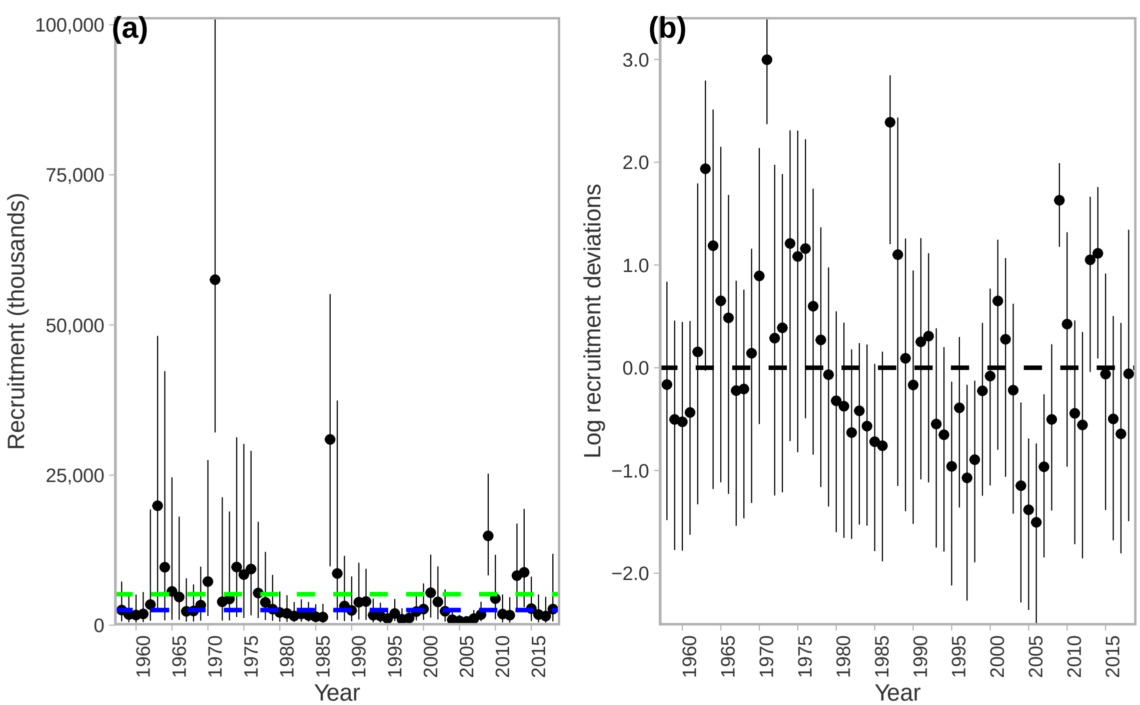

Figure 33. Recruitment (a) and recruitment deviations (b) for the Reference Model, Area 3CD. The green dashed line shows the mean of the MCMC posterior medians, the blue dashed line shows the median of the MCMC posterior medians.

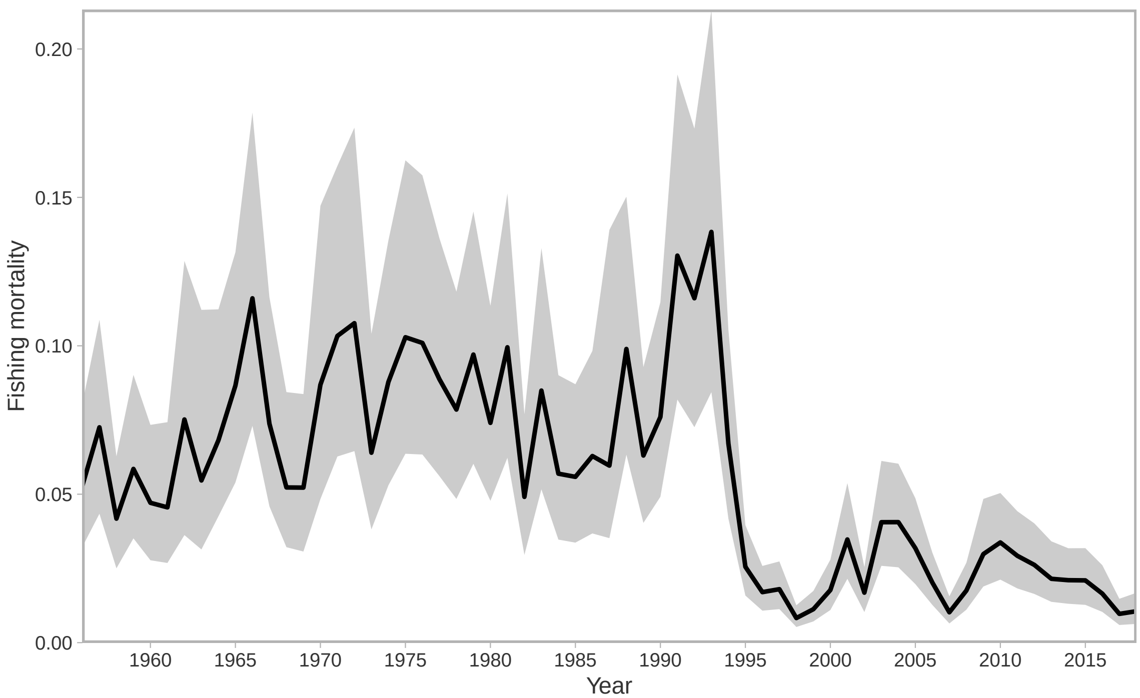

Figure 34. Fishing mortality for the Reference Model, Area 3CD.

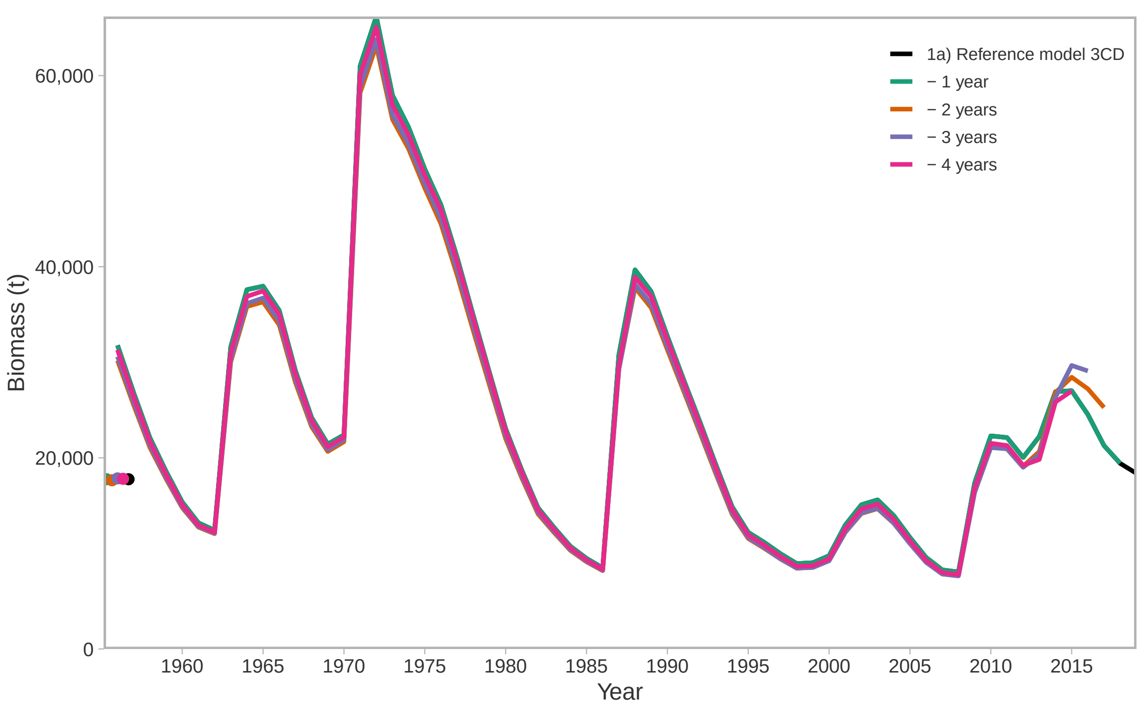

Figure 35. Retrospective biomass for the Reference Model, Area 3CD.

14.6 SENSITIVITY ANALYSES: AREA 5ABCD

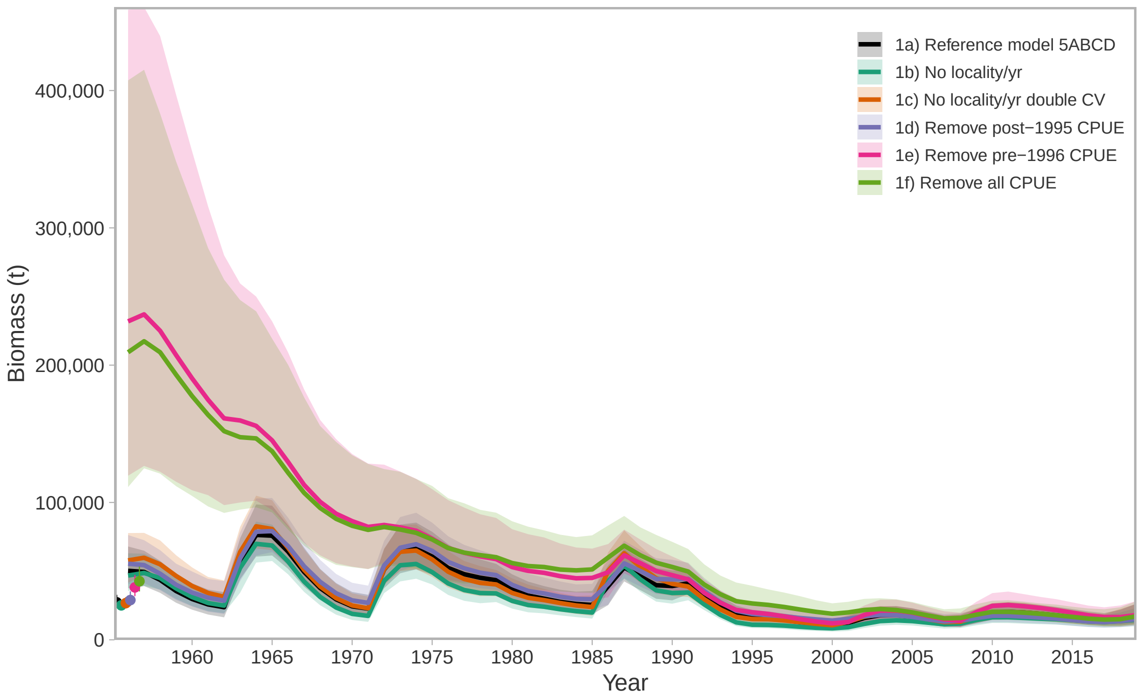

Figure 36. Sensitivity of biomass estimates to removing the year/locality interaction term from the commercial CPUE indices and using the annual CVs resulting from the analysis as the annual weighting terms in the objective function for two CV options, and to removal of the CPUE indices, Area 5ABCD.

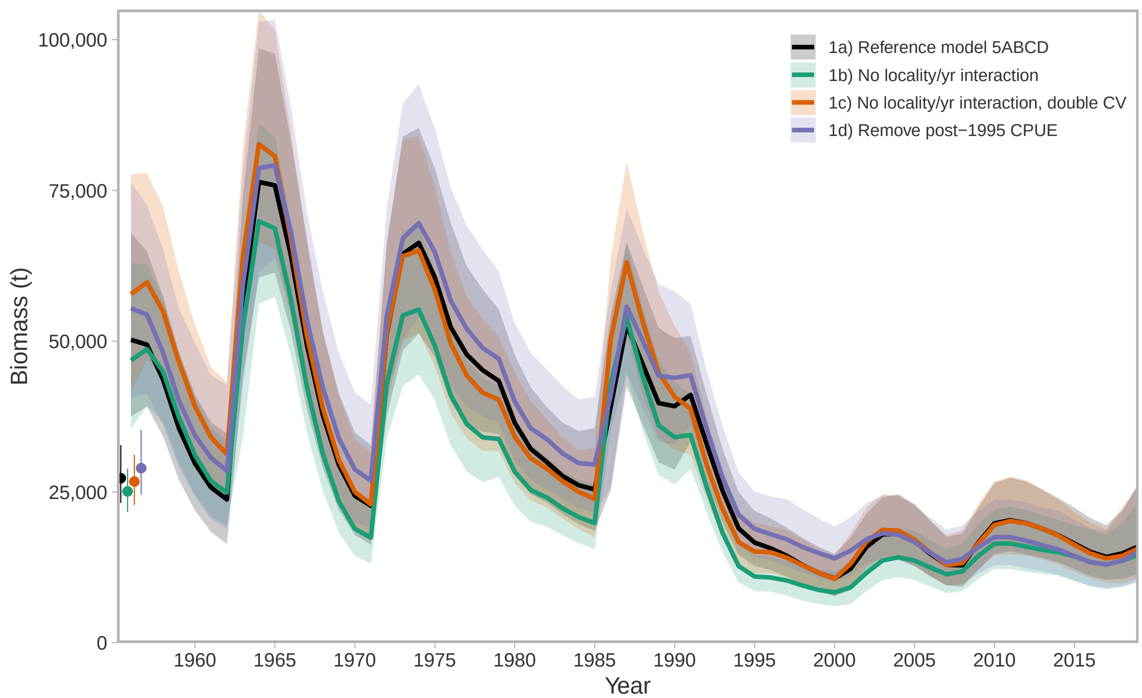

Figure 37. Sensitivity of biomass estimates to removing the year/locality interaction term from the commercial CPUE indices and using the annual CVs resulting from the analysis as the annual weighting terms in the objective function for two CV options, and to removal of post-1995 CPUE indices, Area 5ABCD.

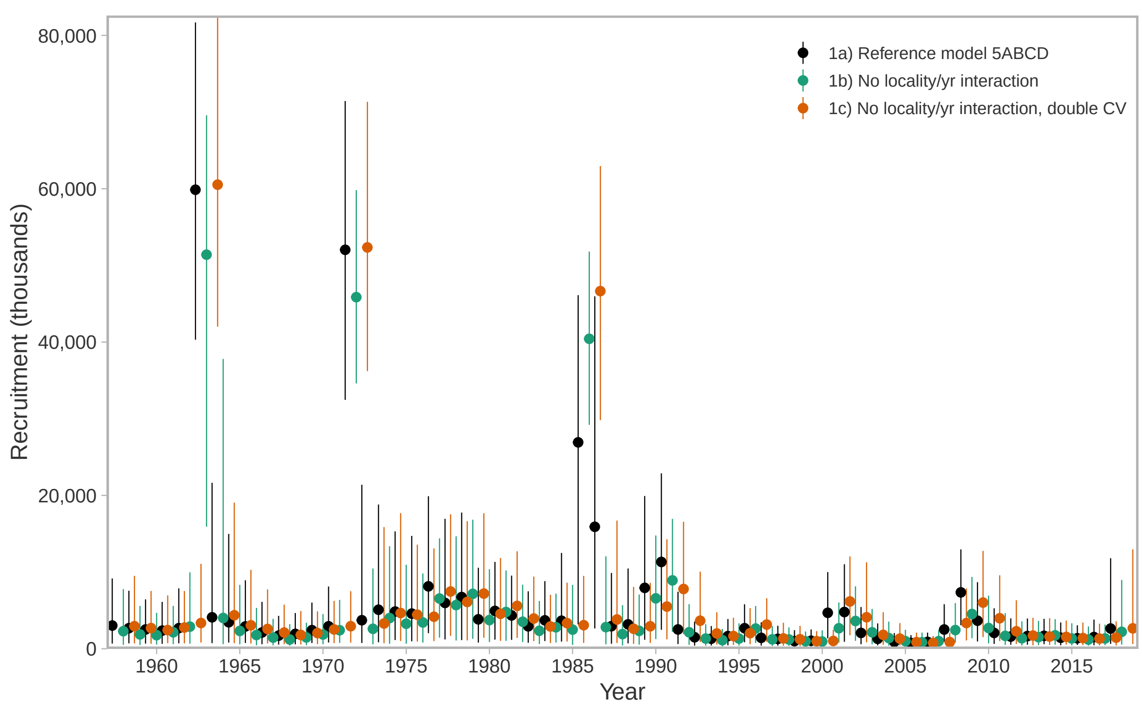

Figure 38. Sensitivity of recruitment estimates to removing the year/locality interaction term from the commercial CPUE indices and using the annual CVs resulting from the analysis as the annual weighting terms in the objective function for two CV options, Area 5ABCD.

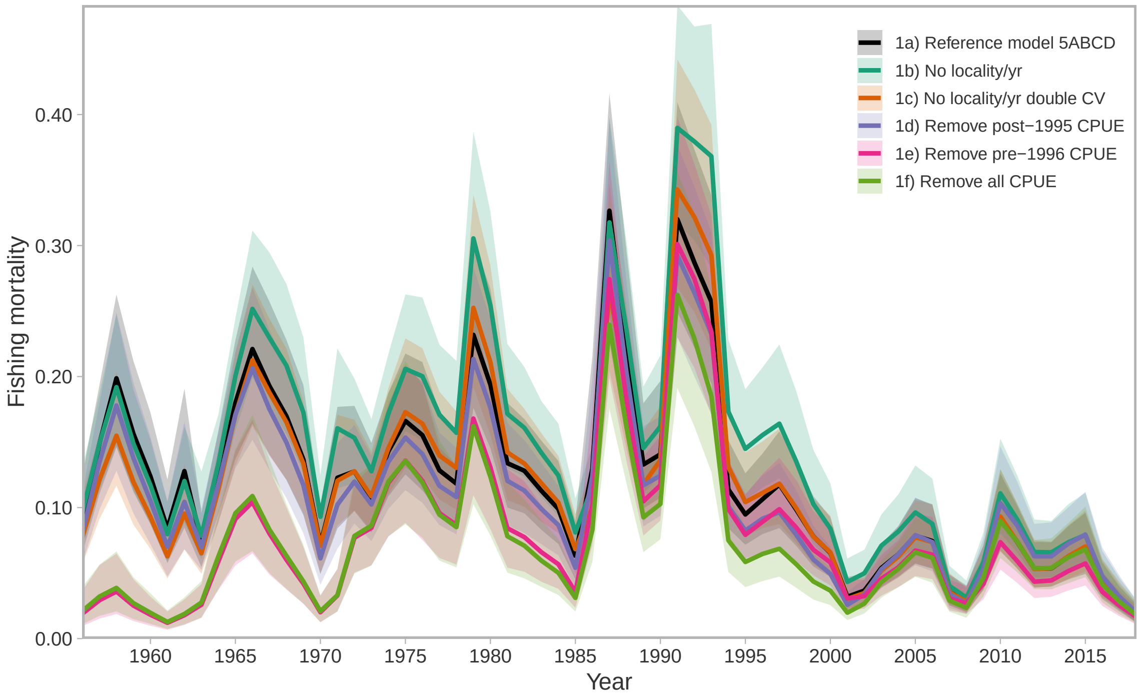

Figure 39. Sensitivity of fishing mortality estimates to removing the year/locality interaction term from the commercial CPUE indices and using the annual CVs resulting from the analysis as the annual weighting terms in the objective function for two CV options, and to removal of the CPUE indices, Area 5ABCD.

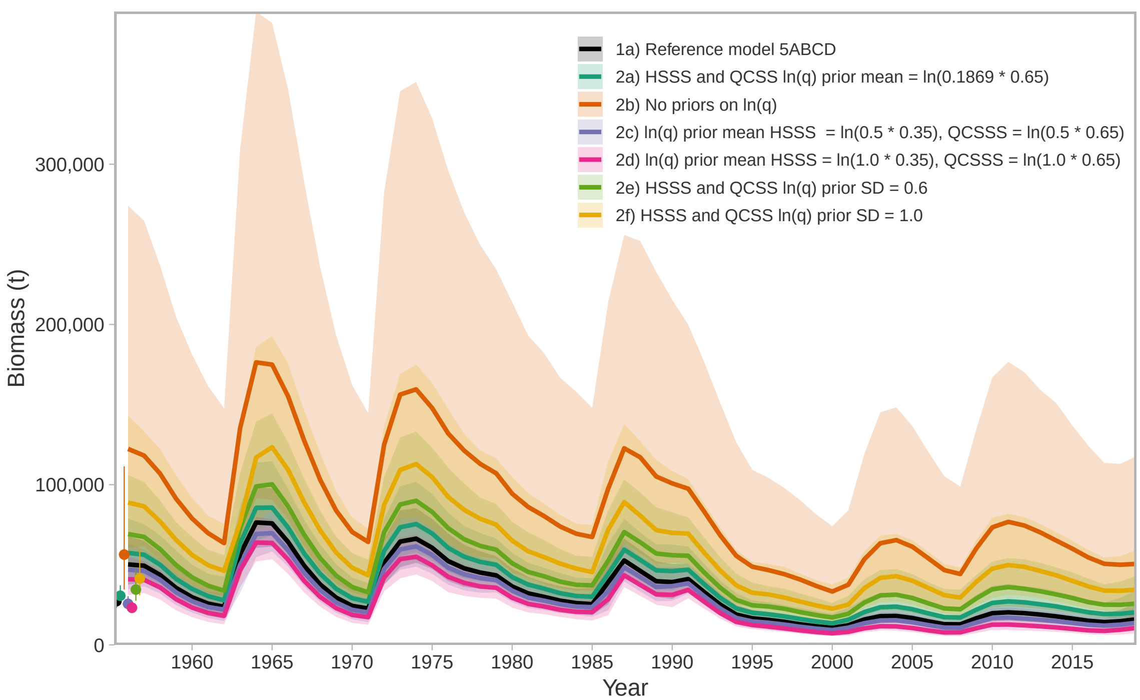

Figure 40. Sensitivity of biomass estimates to the mean of the catchability, q, being set equal for the QCS and HSS surveys, and to a uniform prior being used for both surveys, Area 5ABCD.

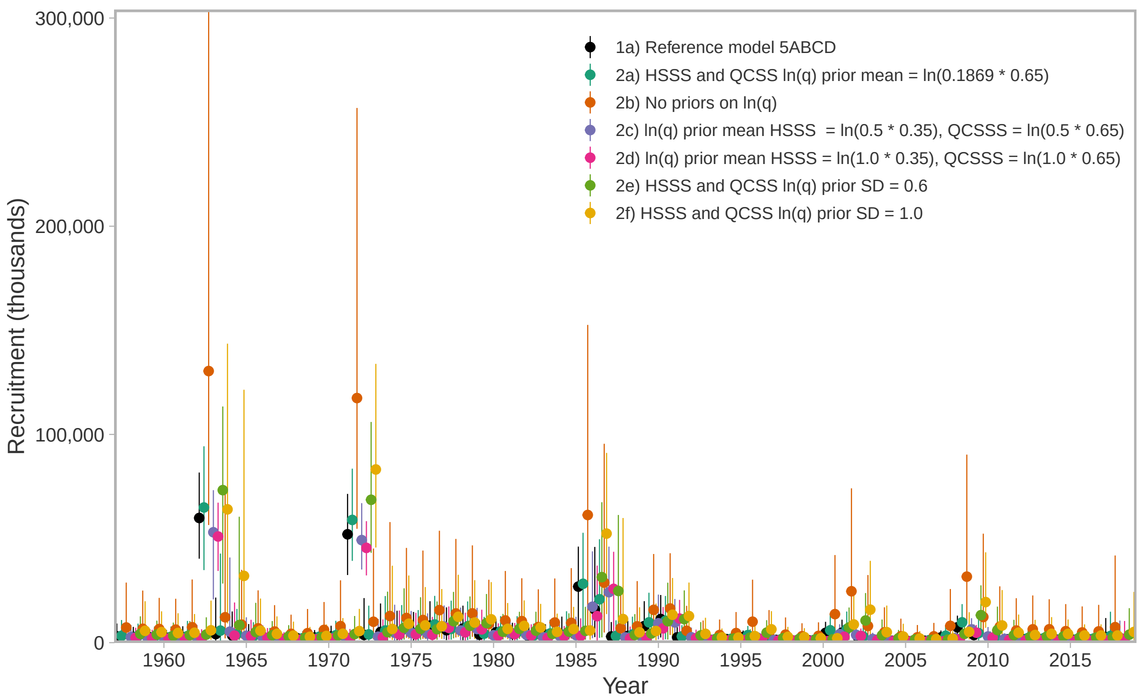

Figure 41. Sensitivity of recruitment estimates to the mean of the catchability, q, being set equal for the QCS and HSS surveys, and to a uniform prior being used for both surveys, Area 5ABCD.

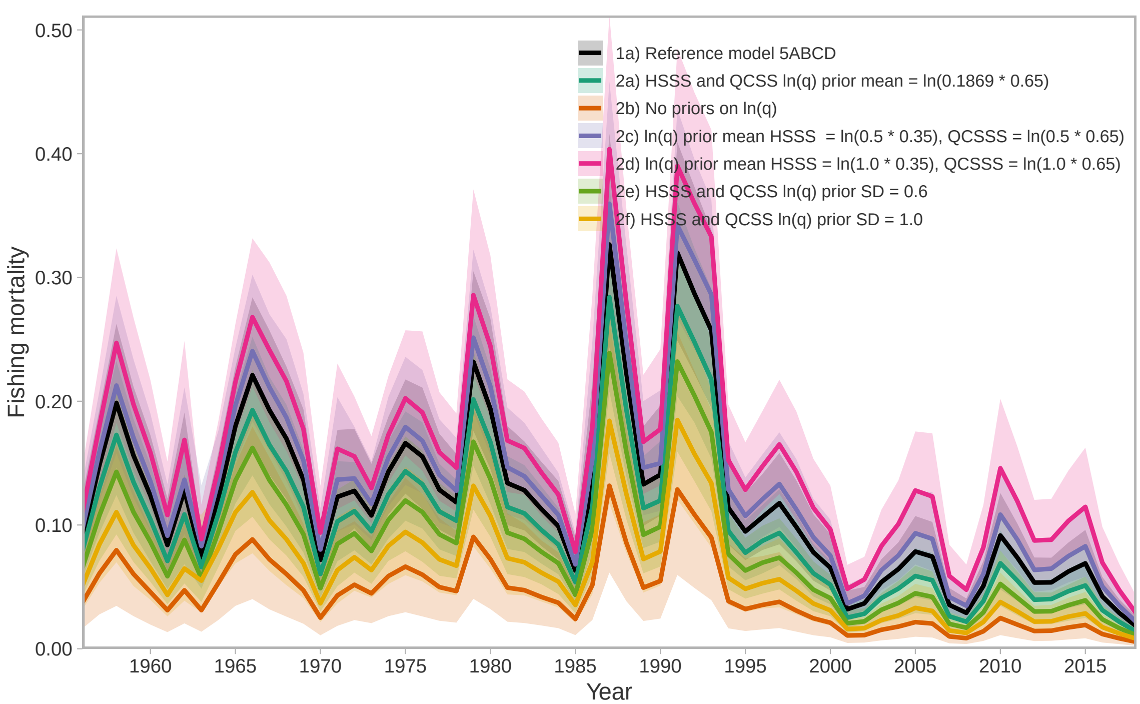

Figure 42. Sensitivity of fishing mortality estimates to the mean of the catchability, q, being set equal for the QCS and HSS surveys, and to a uniform prior being used for both surveys, Area 5ABCD.

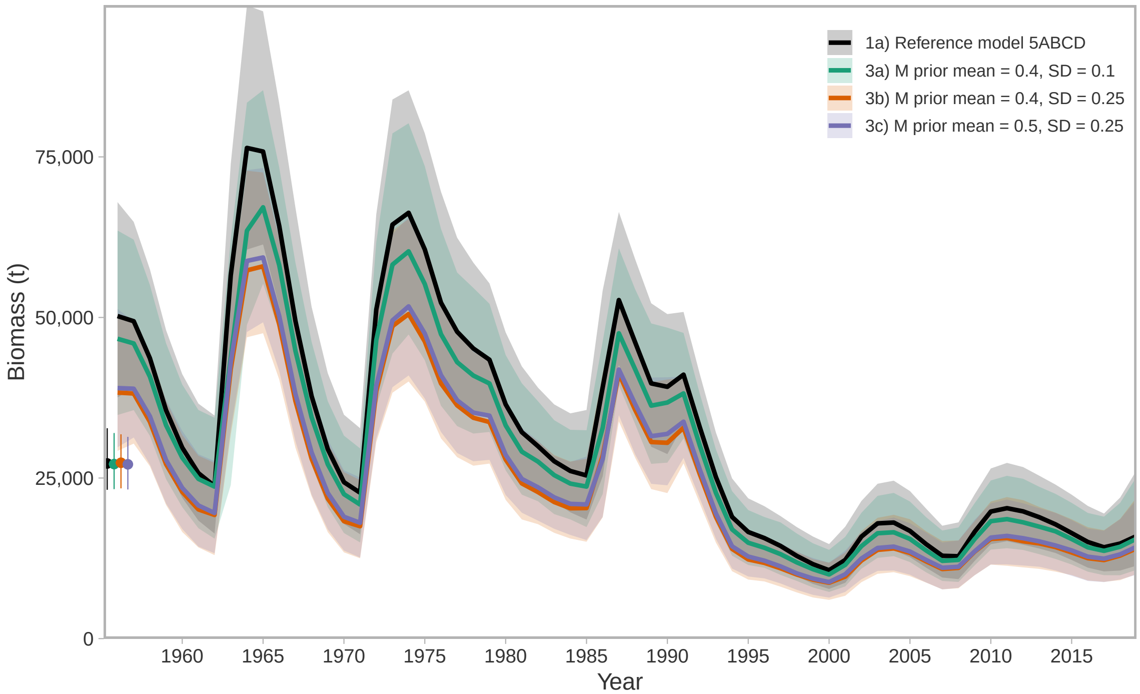

Figure 43. Sensitivity of biomass estimates to the parameters on the normal prior for natural mortality, M, Area 5ABCD.

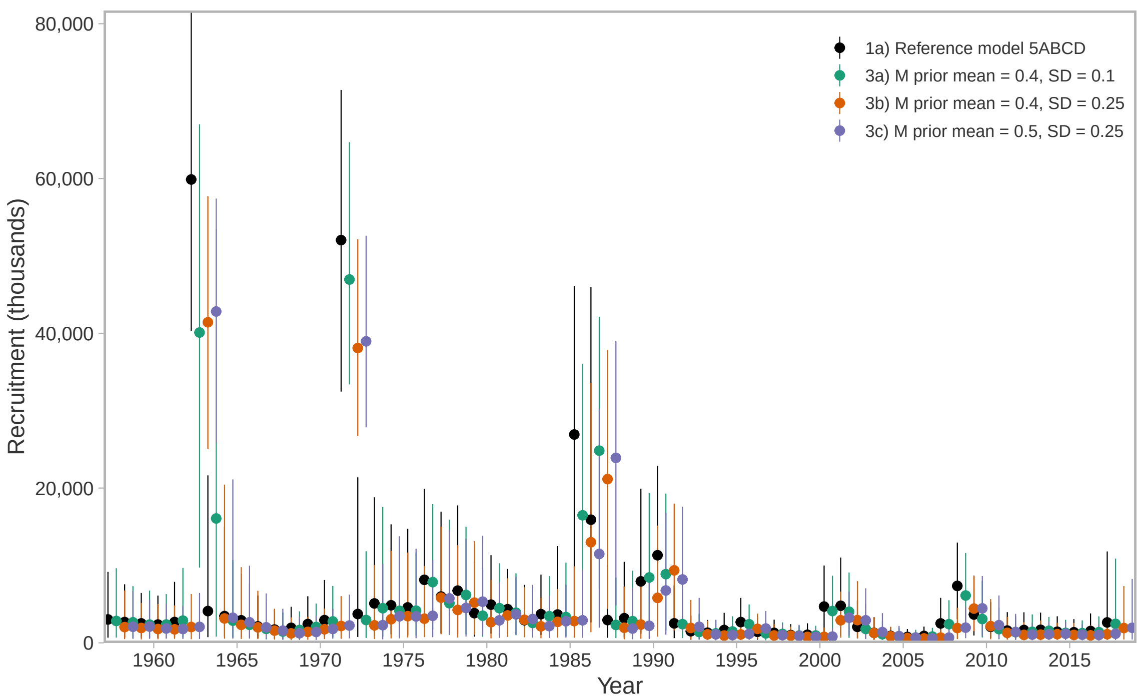

Figure 44. Sensitivity of recruitment estimates to the parameters on the normal prior for natural mortality, M, Area 5ABCD.

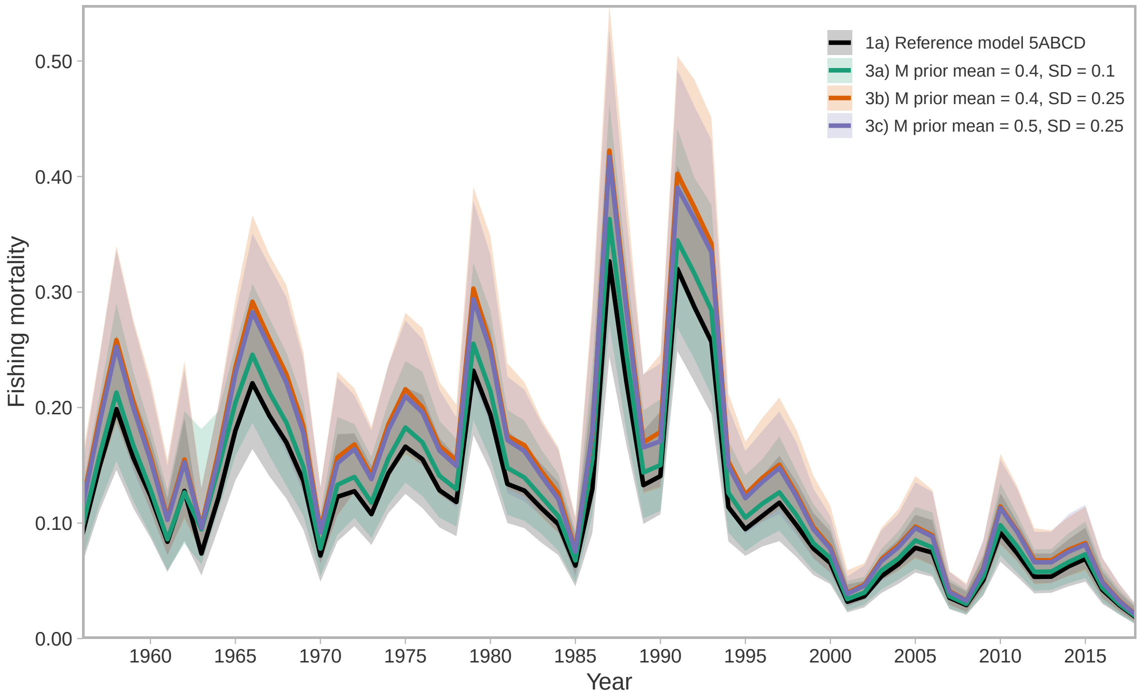

Figure 45. Sensitivity of fishing mortality estimates to the parameters on the normal prior for natural mortality, M, Area 5ABCD.

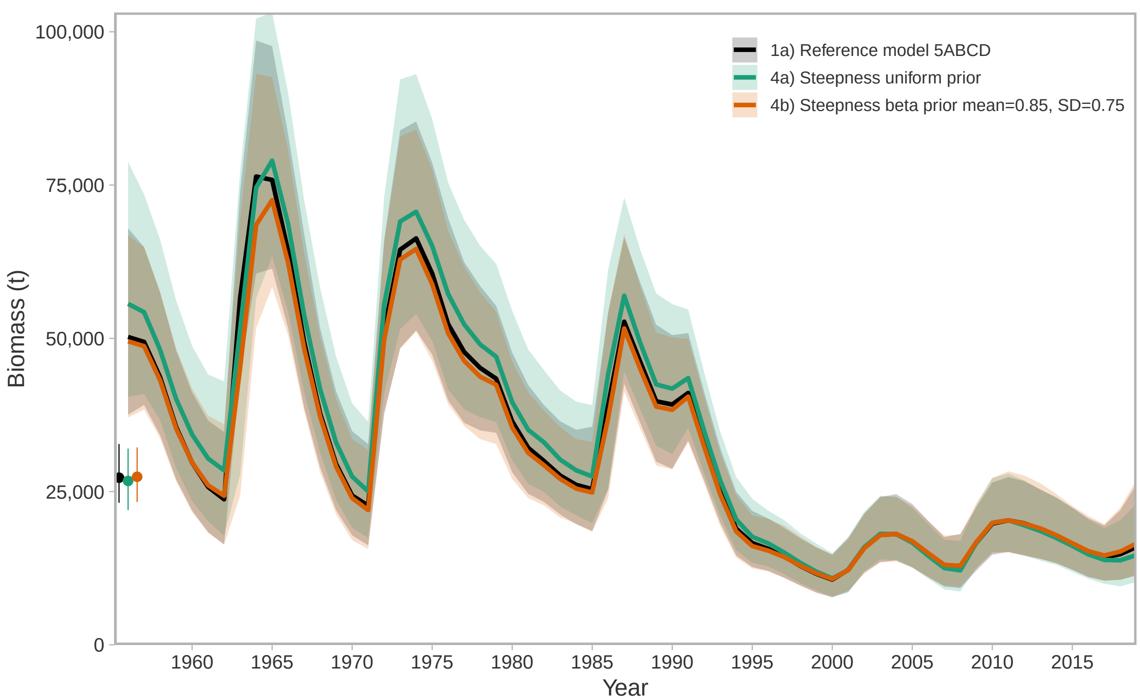

Figure 46. Sensitivity of biomass estimates to the prior probability distribution for steepness, including using a bounded uniform prior and a beta prior, Area 5ABCD.

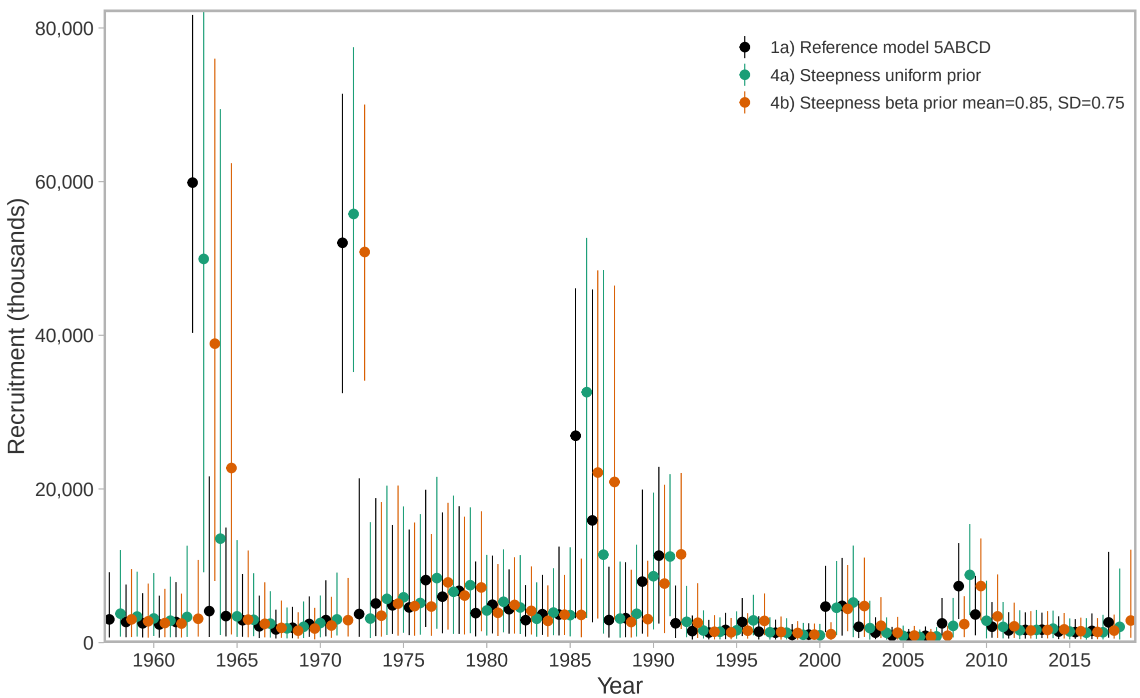

Figure 47. Sensitivity of recruitment estimates to the prior probability distribution for steepness, including using a bounded uniform prior and a beta prior, Area 5ABCD.

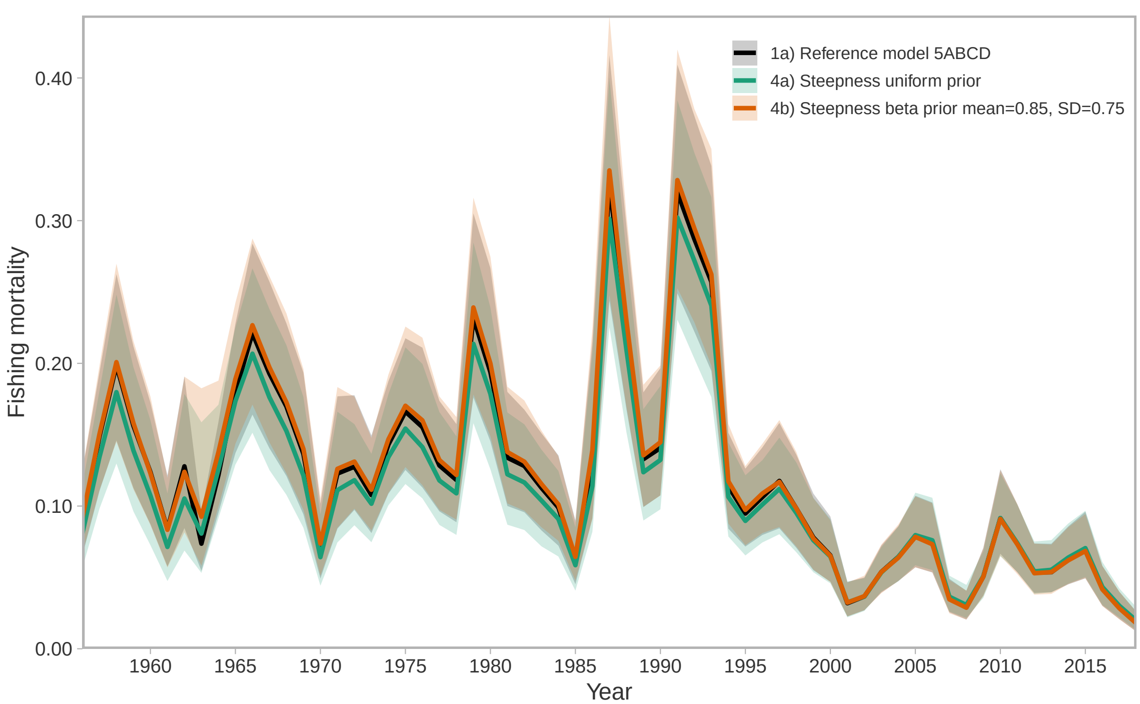

Figure 48. Sensitivity of fishing mortality estimates to the prior probability distribution for steepness, including using a bounded uniform prior and a beta prior, Area 5ABCD.

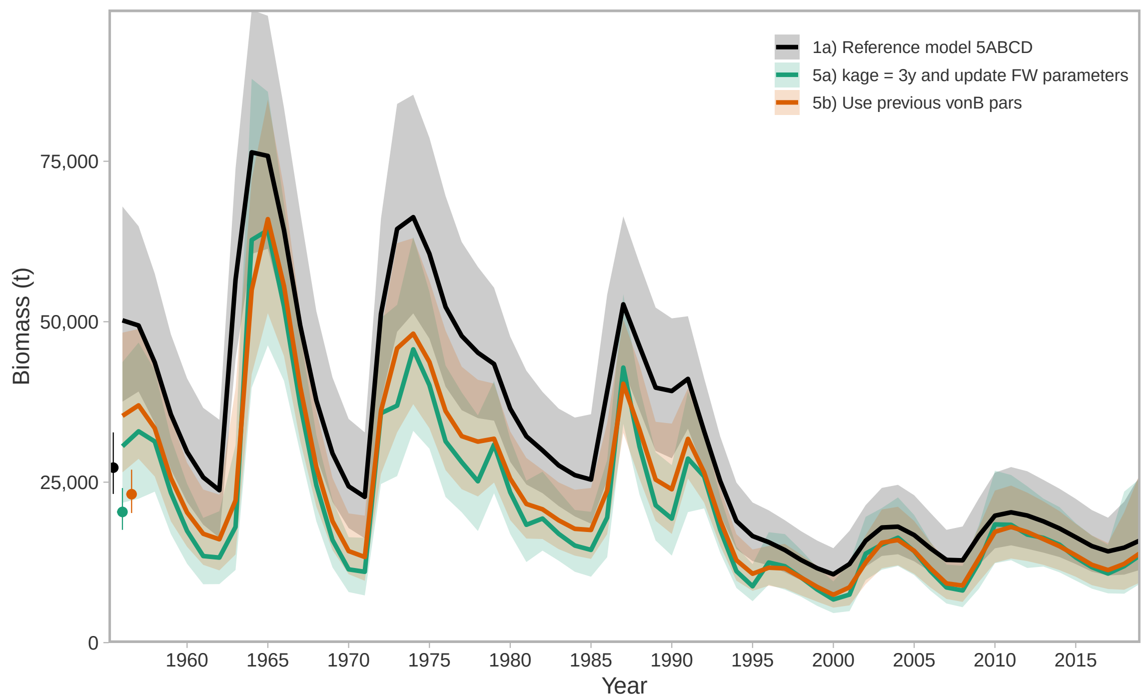

Figure 49. Sensitivity of biomass estimates to setting $k_{age} = 3y$ and update the Ford-Walford parameters accordingly, and to using the growth parameters used in the previous stock assessment, Area 5ABCD.

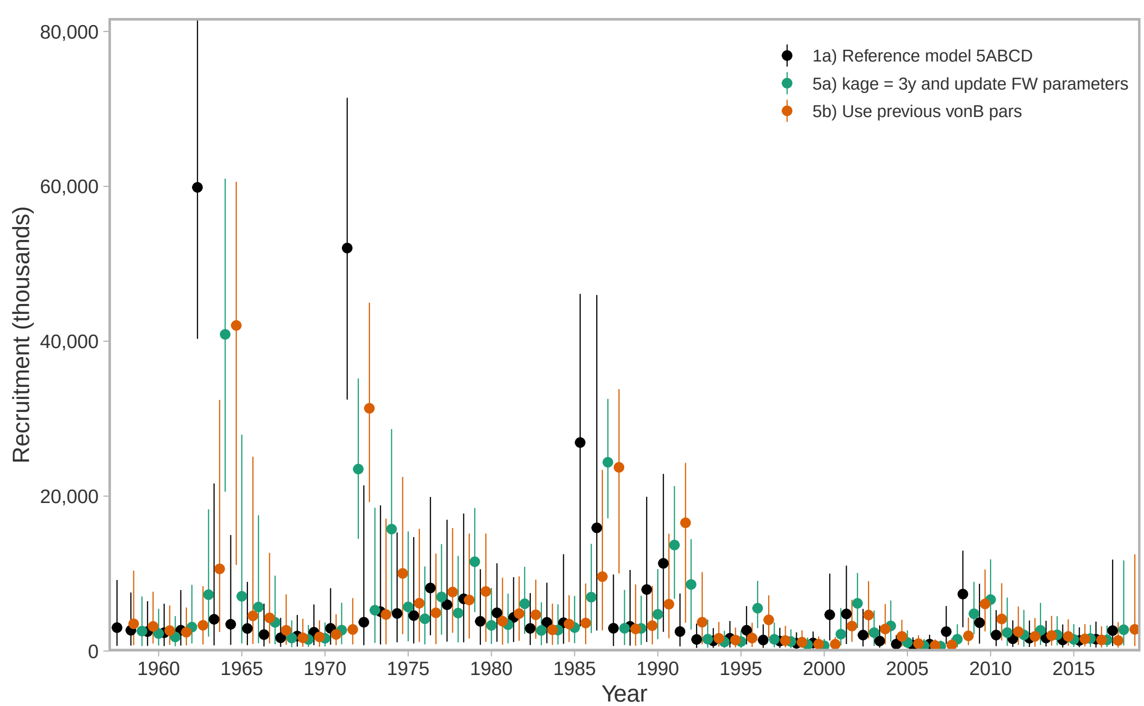

Figure 50. Sensitivity of recruitment estimates to setting $k_{age} = 3y$ and update the Ford-Walford parameters accordingly, and to using the growth parameters used in the previous stock assessment, Area 5ABCD.

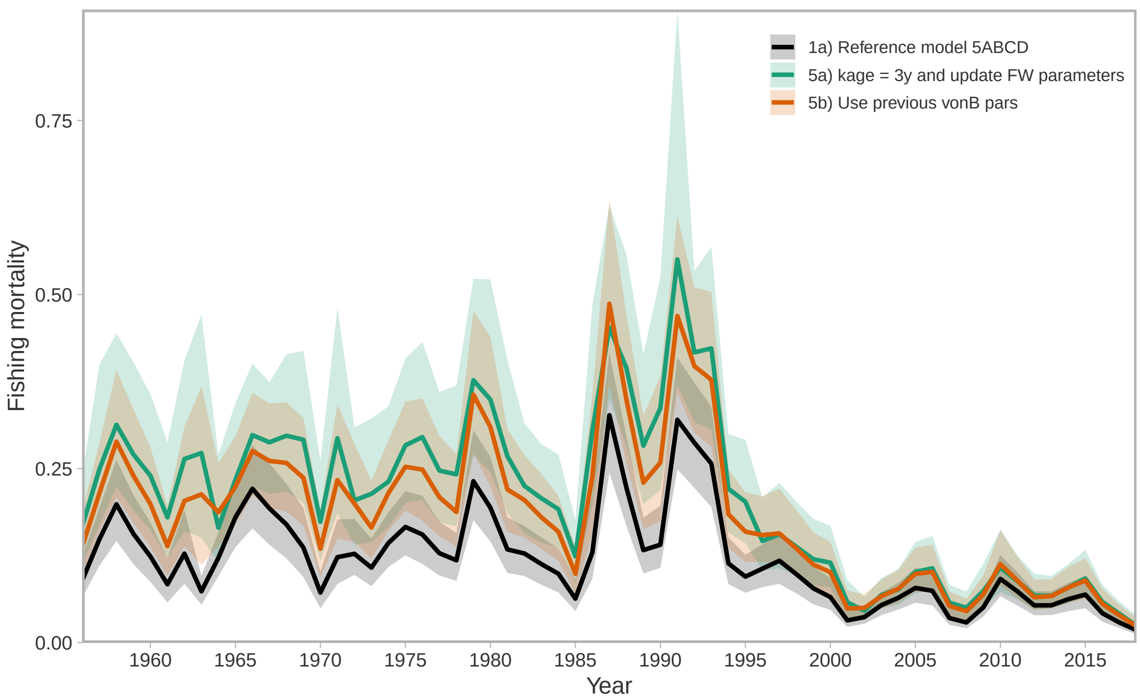

Figure 51. Sensitivity of fishing mortality estimates to setting $k_{age} = 3y$ and update the Ford-Walford parameters accordingly, and to using the growth parameters used in the previous stock assessment, Area 5ABCD.

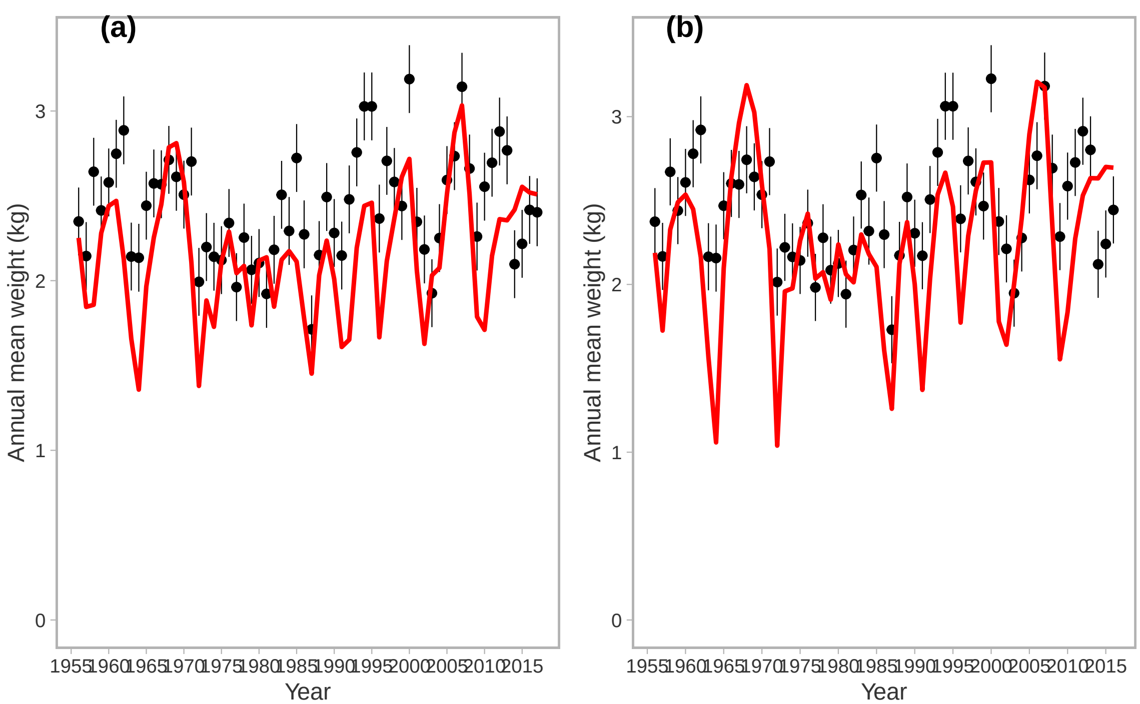

Figure 52. MPD fits to the average annual mean weights for (a) the Sensitivity to setting $k_{age} = 3y$ and update the Ford-Walford parameters accordingly, and (b) to using the growth parameters used in the previous Area 5CD stock assessment. Area 5ABCD.

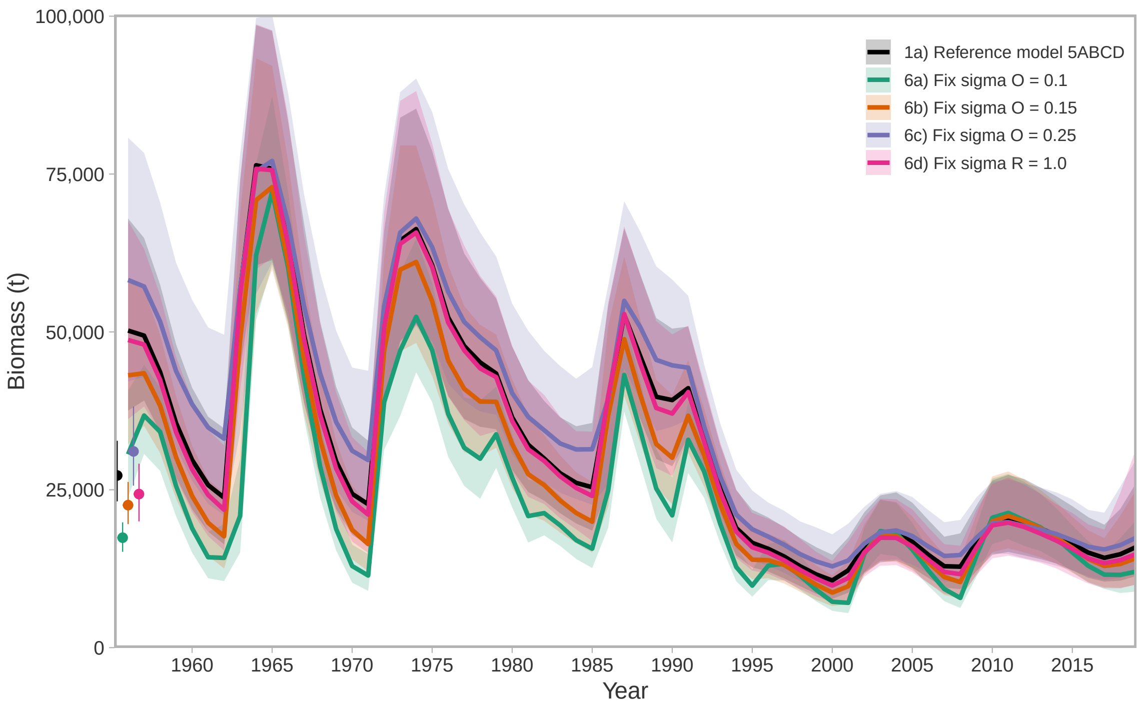

Figure 53. Sensitivity of biomass estimates to the assumed value of observation and process errors, Area 5ABCD.

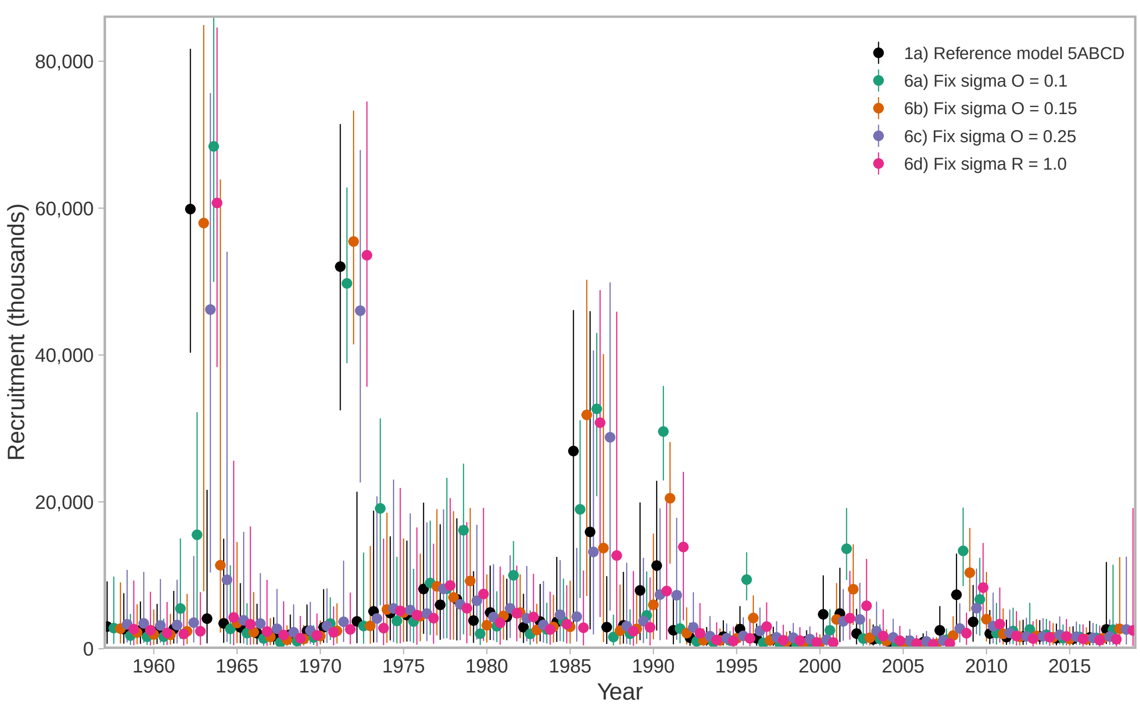

Figure 54. Sensitivity of recruitment estimates to the assumed value of observation and process errors, Area 5ABCD.

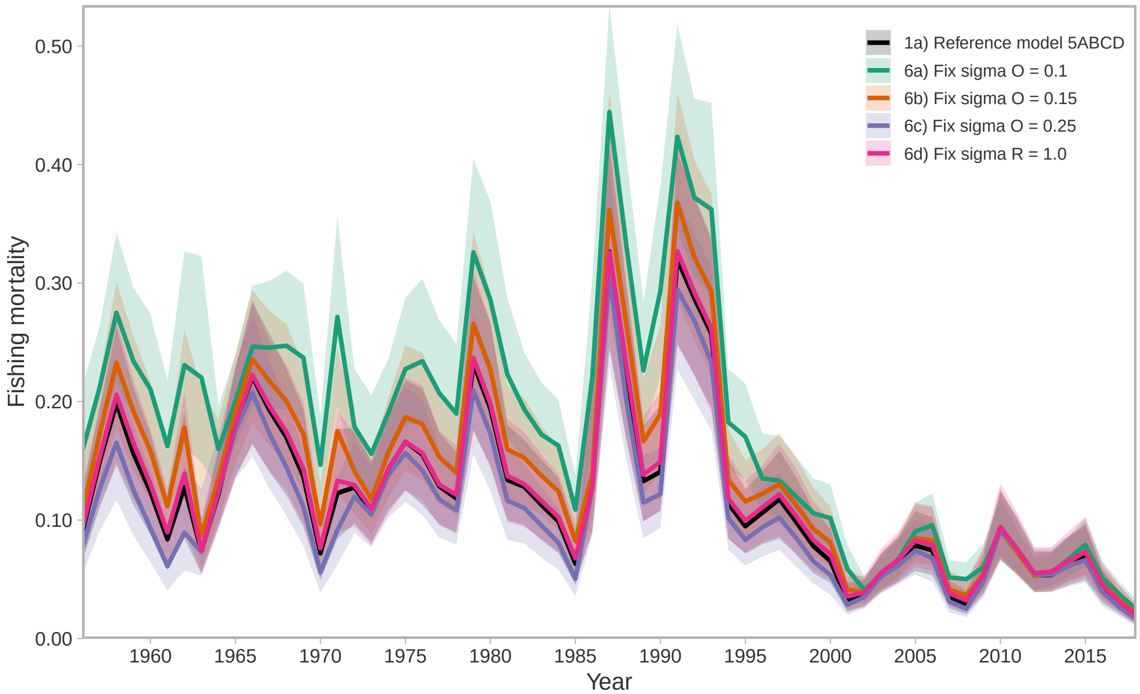

Figure 55. Sensitivity of fishing mortality estimates to the assumed value of observation and process errors, Area 5ABCD.

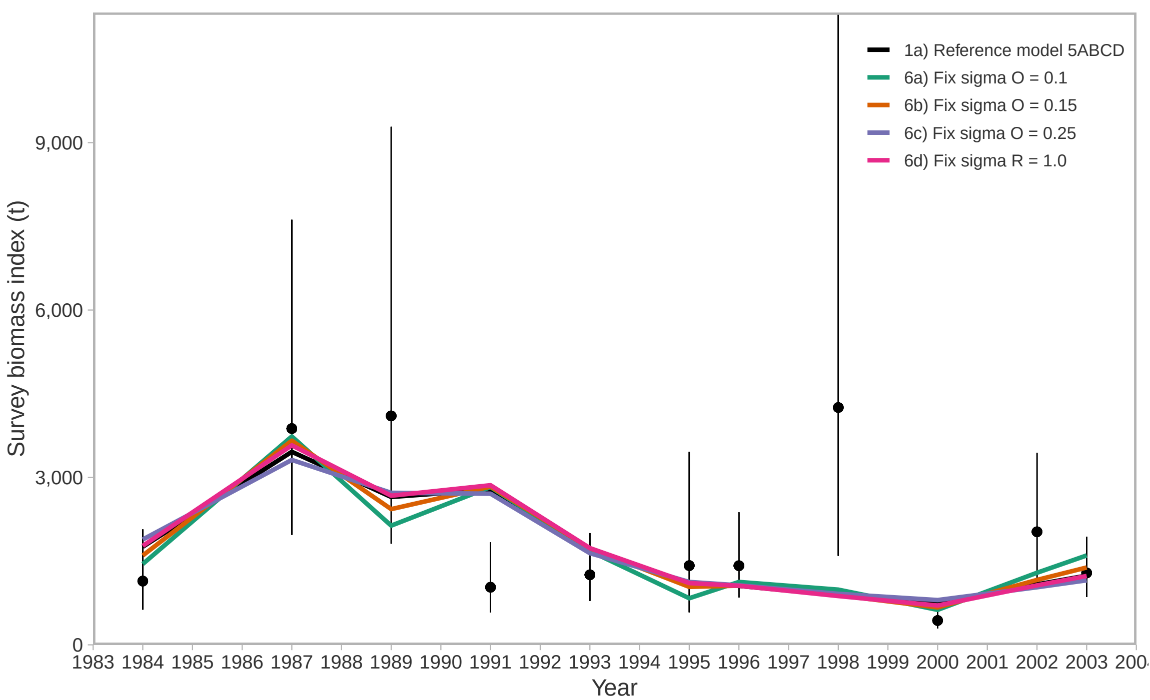

Figure 56. MPD index fits showing sensitivity to the assumed value of observation and process errors, HSMAS, Area 5ABCD.

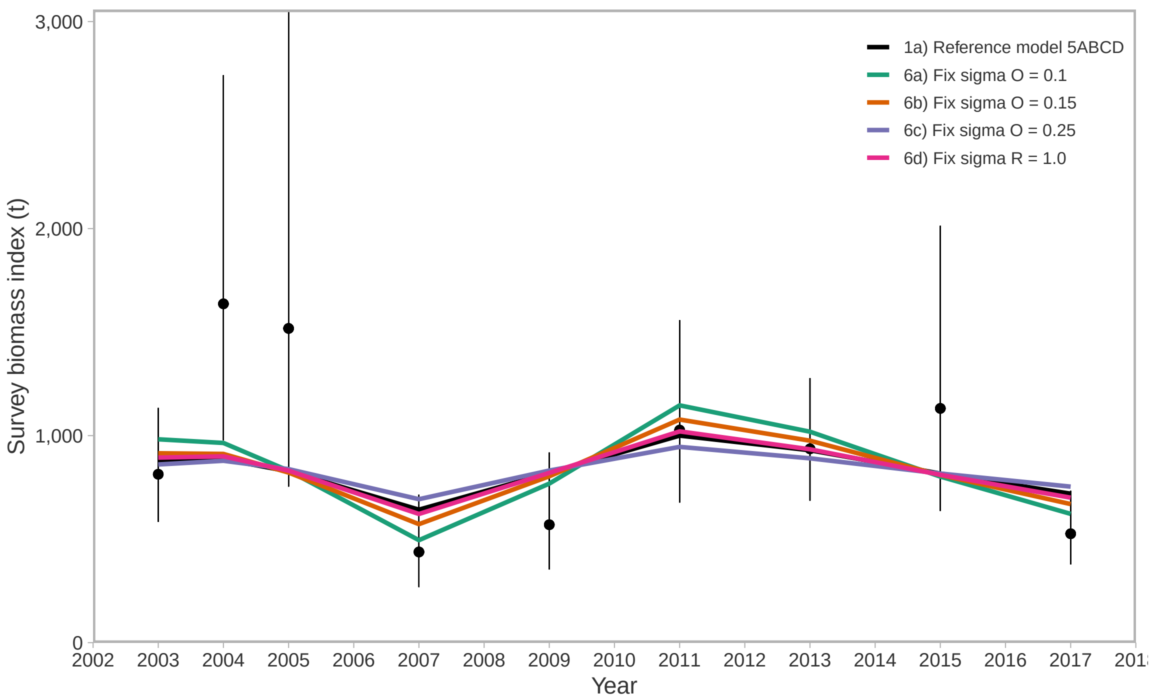

Figure 57. MPD index fits showing sensitivity to the assumed value of observation and process errors, QCSS, Area 5ABCD.

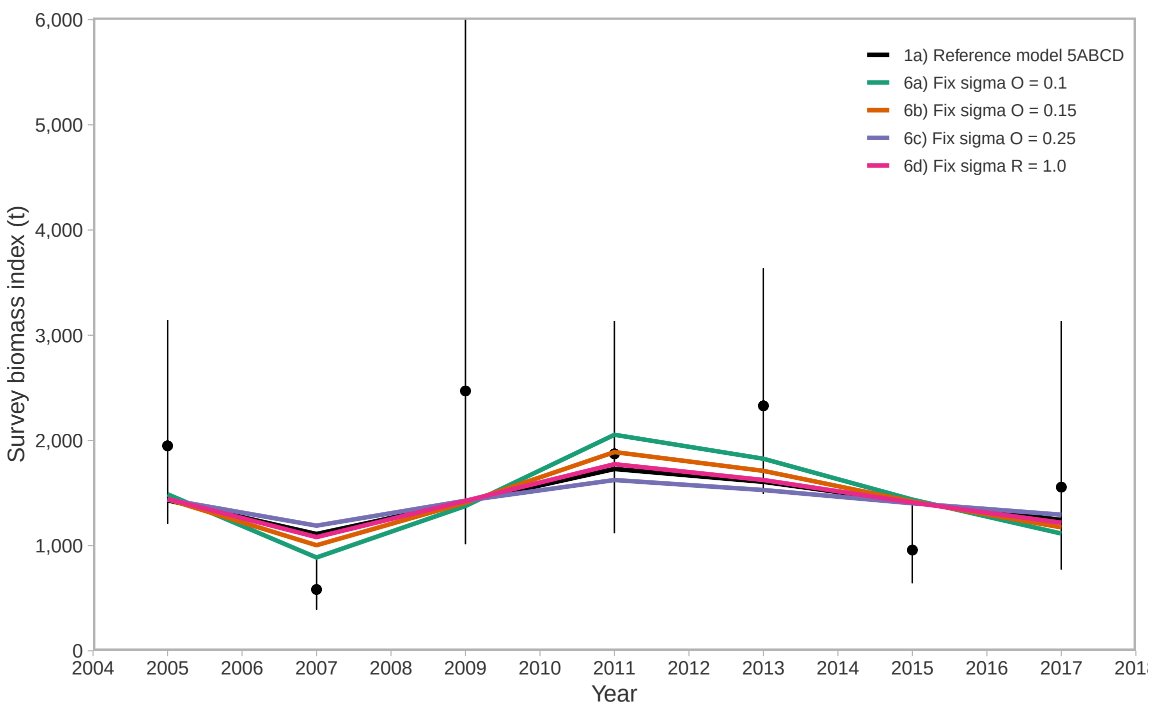

Figure 58. MPD index fits showing sensitivity to the assumed value of observation and process errors, HSSS, Area 5ABCD.

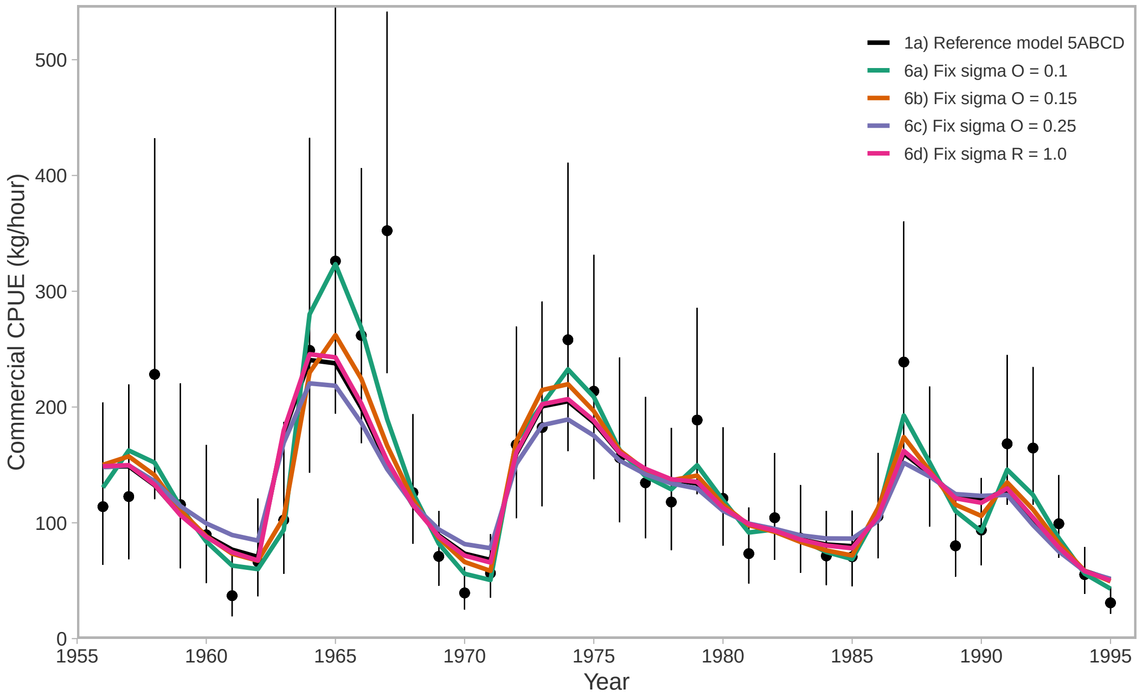

Figure 59. MPD index fits showing sensitivity to the assumed value of observation and process errors, commercial CPUE pre-1996, Area 5ABCD.

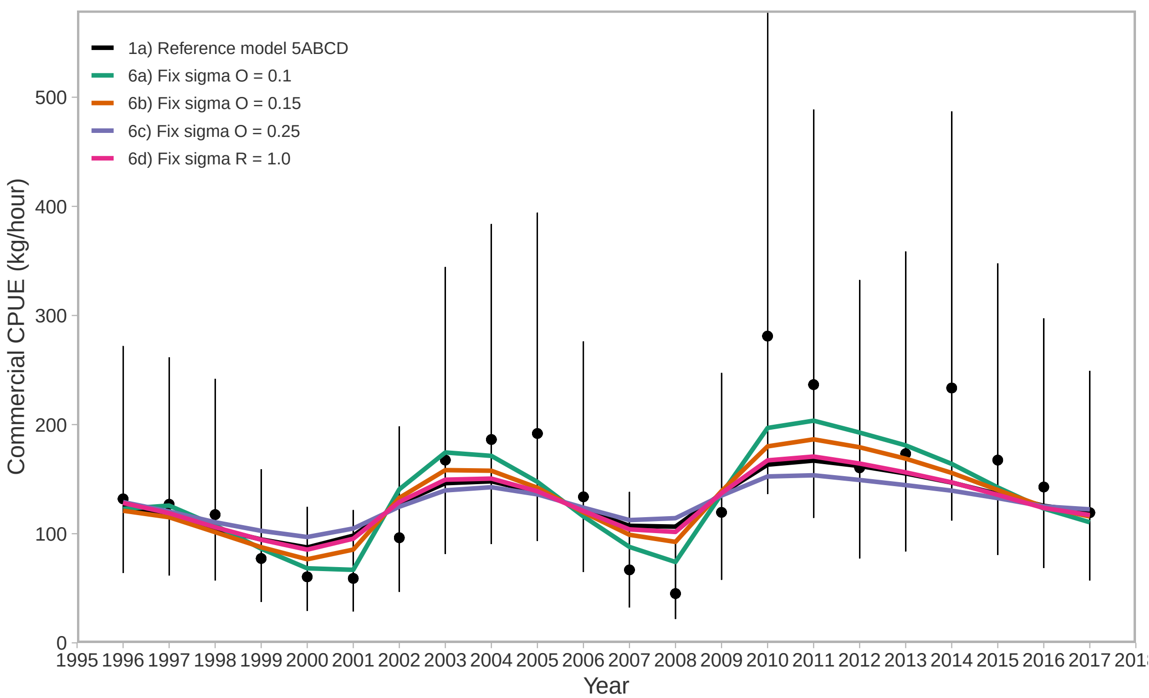

Figure 60. MPD index fits showing sensitivity to the assumed value of observation and process errors, commercial CPUE post-1995, Area 5ABCD.

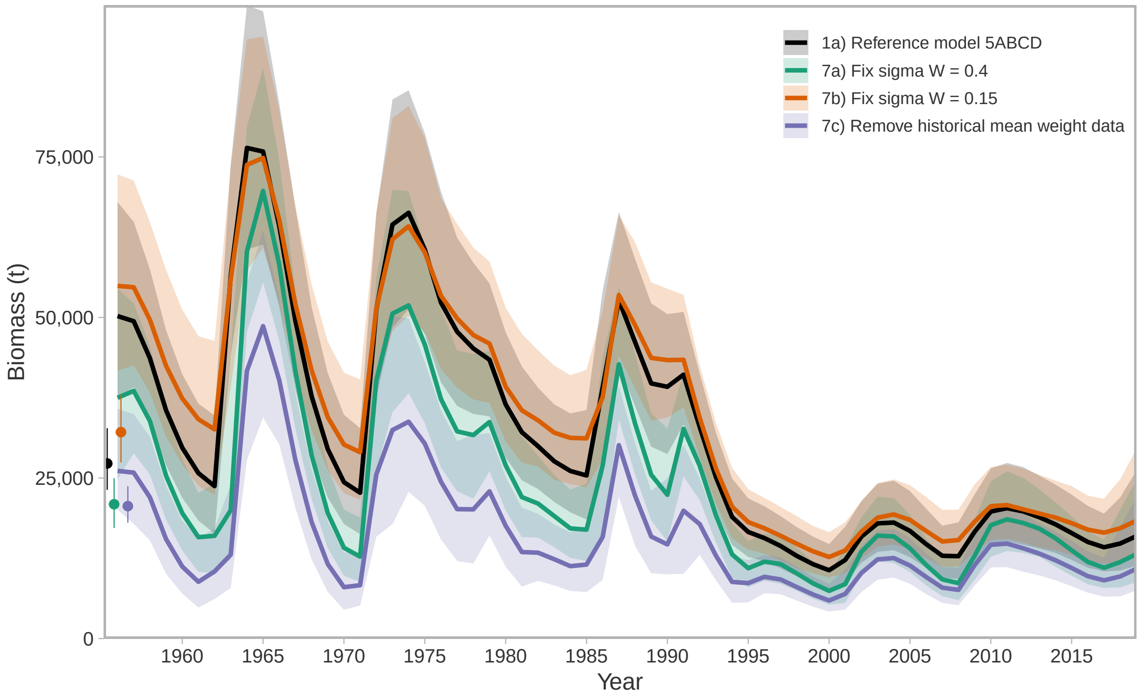

Figure 61. Sensitivity of biomass estimates to the assumed value of σ_W, Area 5ABCD.

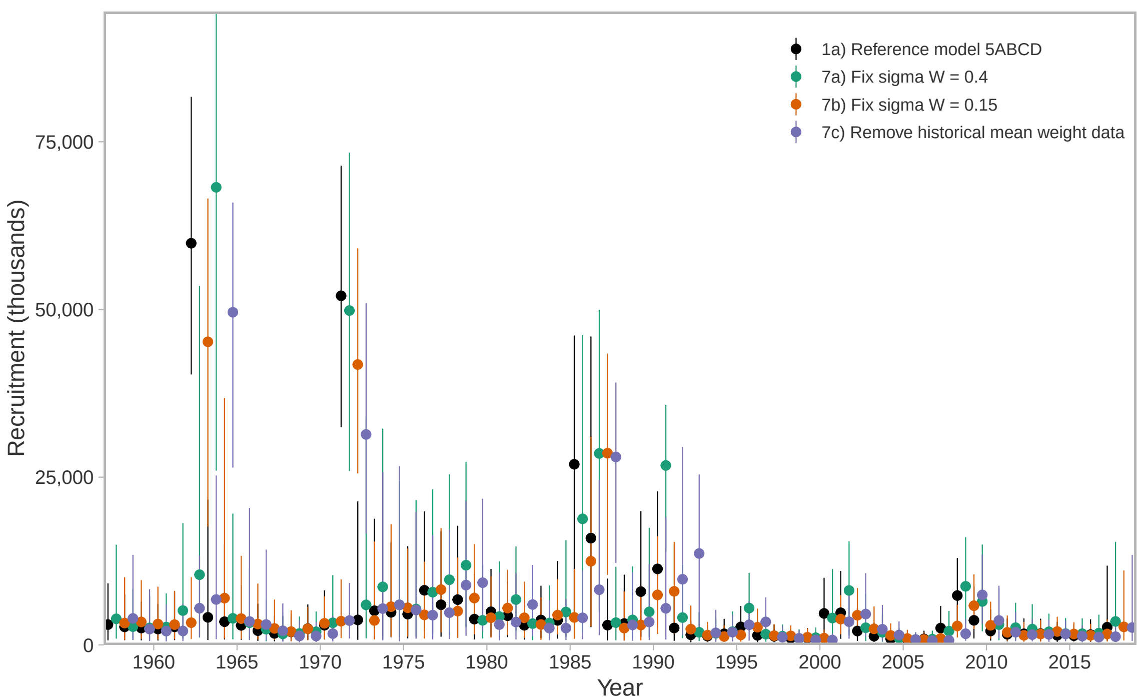

Figure 62. Sensitivity of recruitment estimates to the assumed value of σ_W, Area 5ABCD.

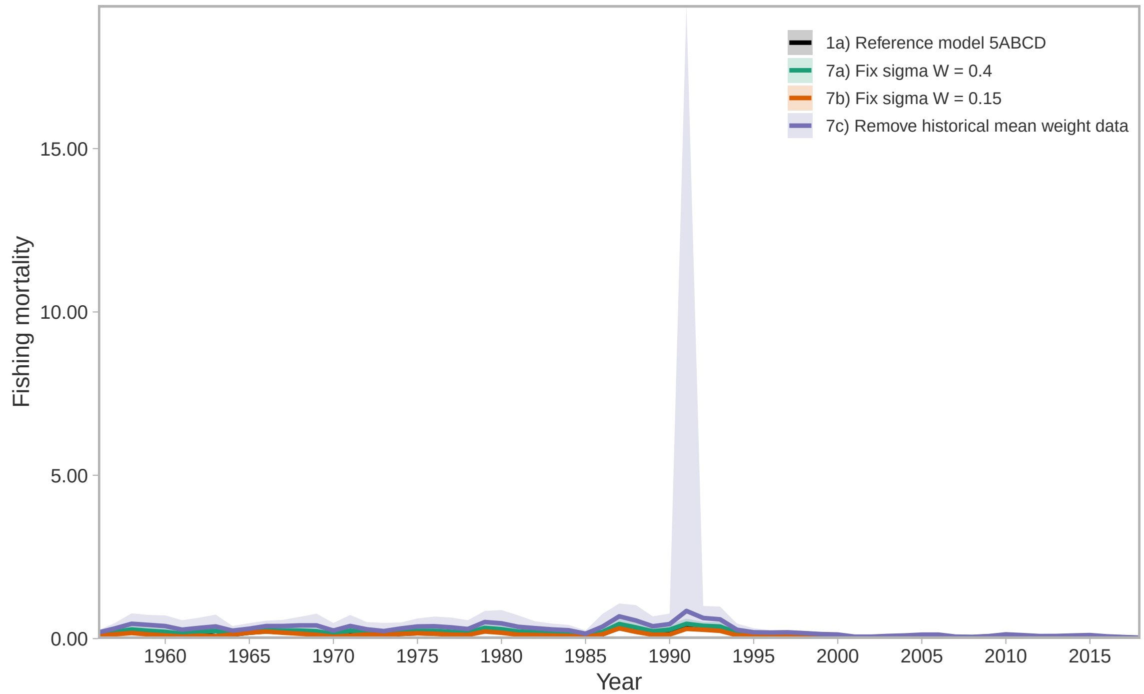

Figure 63. Sensitivity of fishing mortality estimates to the assumed value of σ_W, Area 5ABCD.

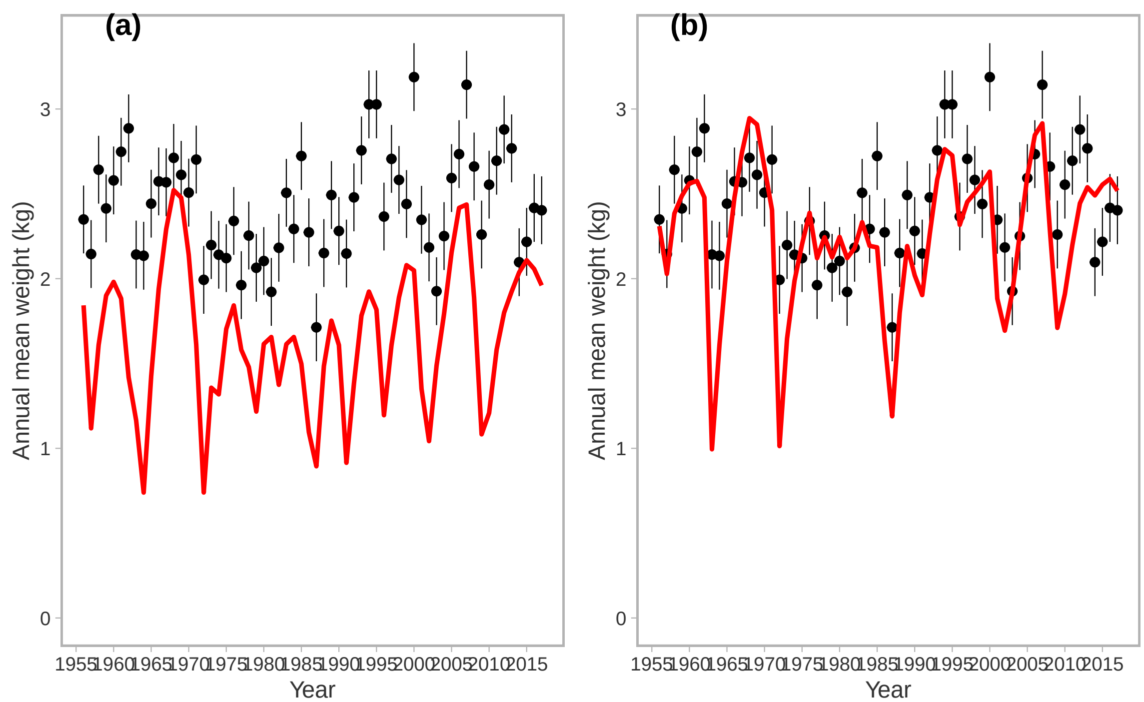

Figure 64. MPD fits to the average annual mean weights showing sensitivity to the assumed value of σ_W for (a) σ_W = 0.4 and (b) σ_W = 0.15, Area 5ABCD.

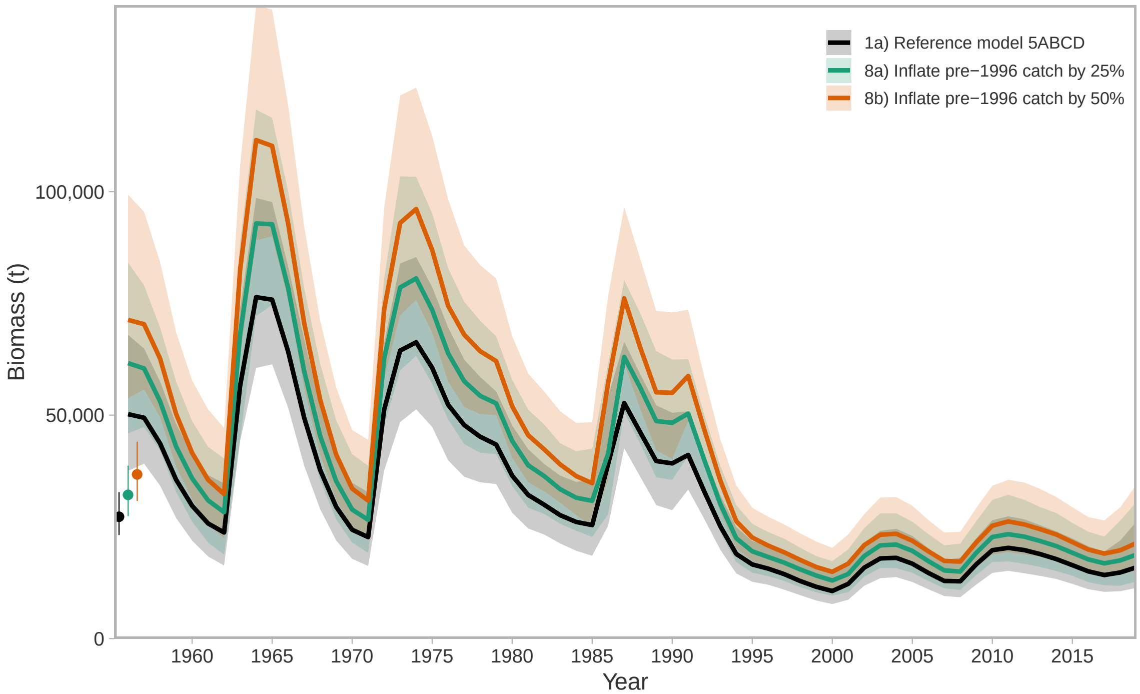

Figure 65. Sensitivity of biomass estimates to inflating the historical catch data, Area 5ABCD

14.7 SENSITIVITY ANALYSES: AREA 3CD

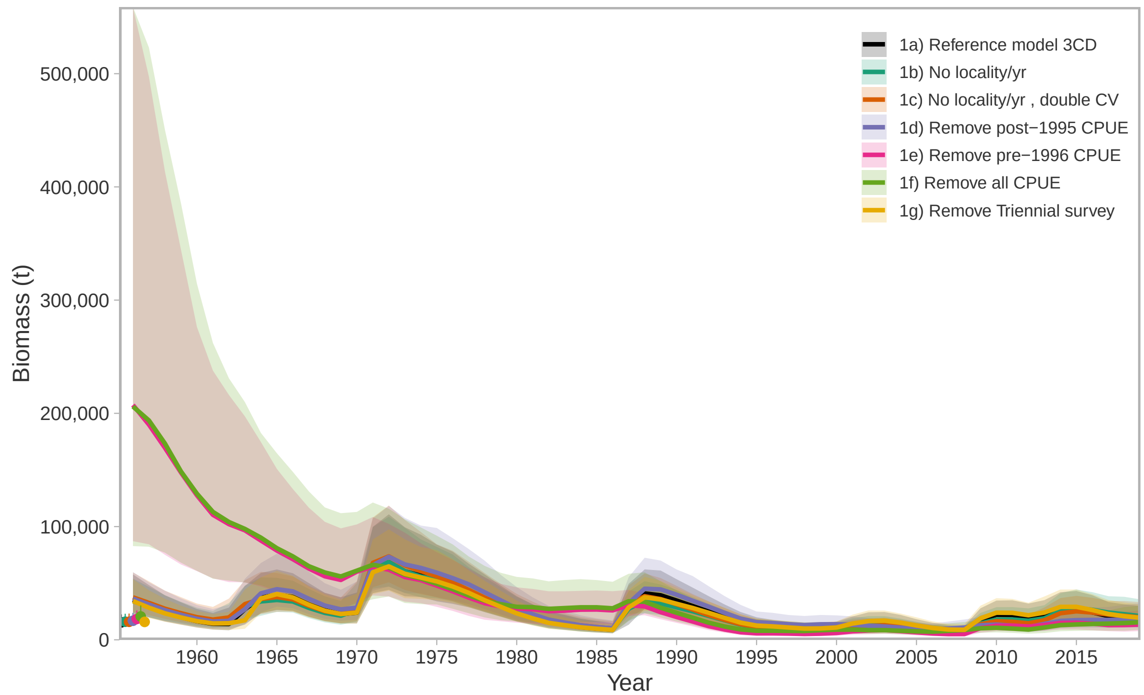

Figure 66. Sensitivity of biomass estimates to removing the year/locality interaction term from the commercial CPUE indices and using the annual CVs resulting from the analysis as the annual weighting terms in the objective function for two CV options, to removal of the CPUE indices, and to the removal of the Triennial survey index, Area 3CD.

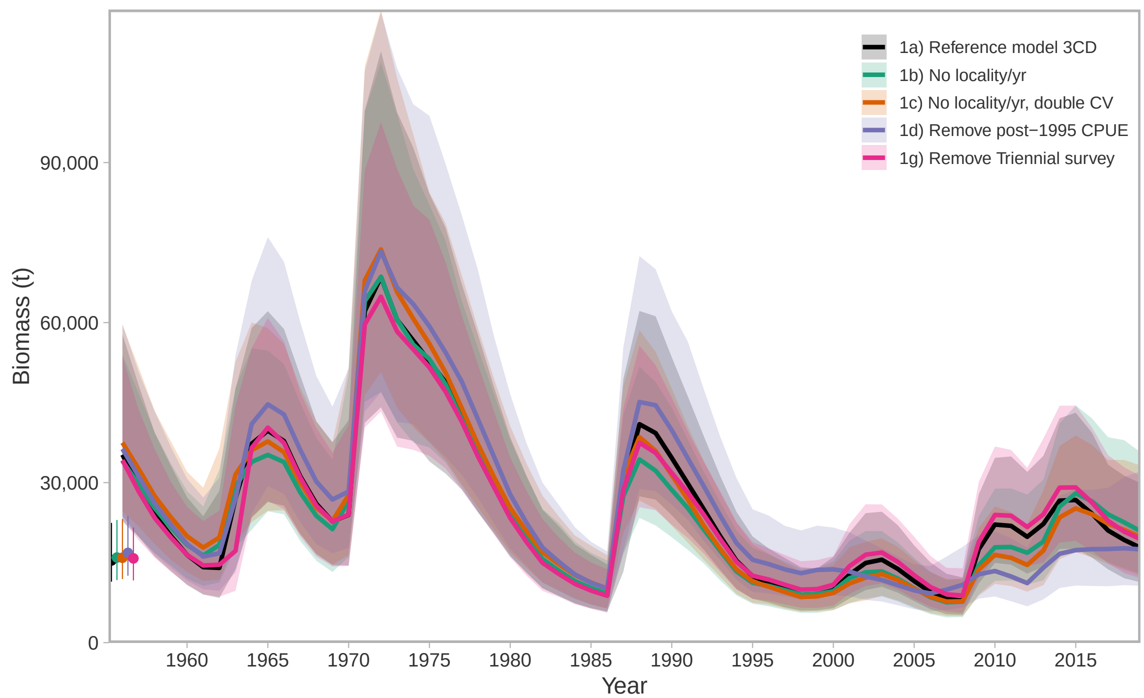

Figure 67. Sensitivity of biomass estimates to removing the year/locality interaction term from the commercial CPUE indices and using the annual CVs resulting from the analysis as the annual weighting terms in the objective function for two CV options, and to removal of post-1995 CPUE indices, Area 3CD.

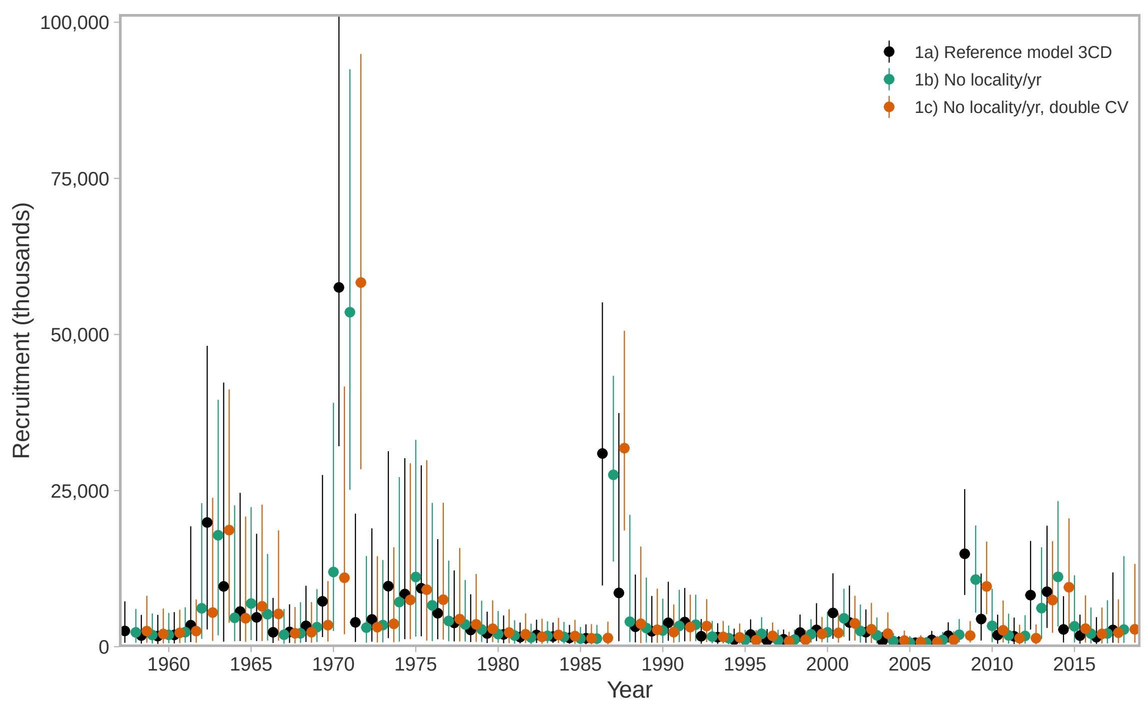

Figure 68. Sensitivity of recruitment estimates to removing the year/locality interaction term from the commercial CPUE indices and using the annual CVs resulting from the analysis as the annual weighting terms in the objective function for two CV options, Area 3CD.

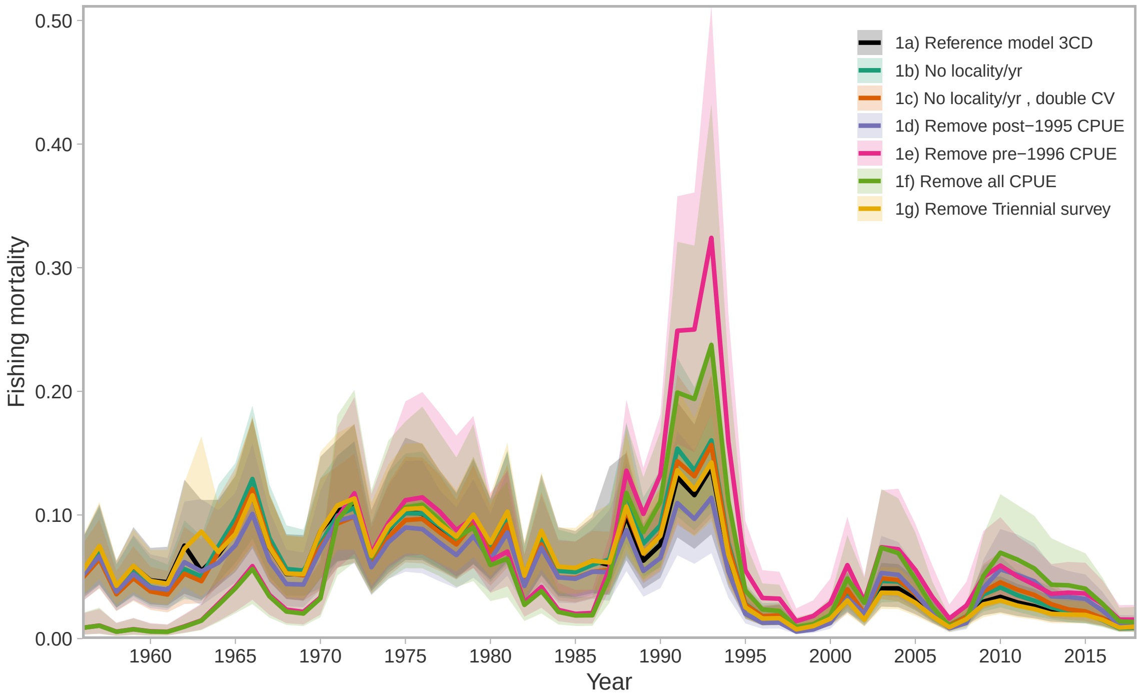

Figure 69. Sensitivity of fishing mortality estimates to removing the year/locality interaction term from the commercial CPUE indices and using the annual CVs resulting from the analysis as the annual weighting terms in the objective function for two CV options, Area 3CD.

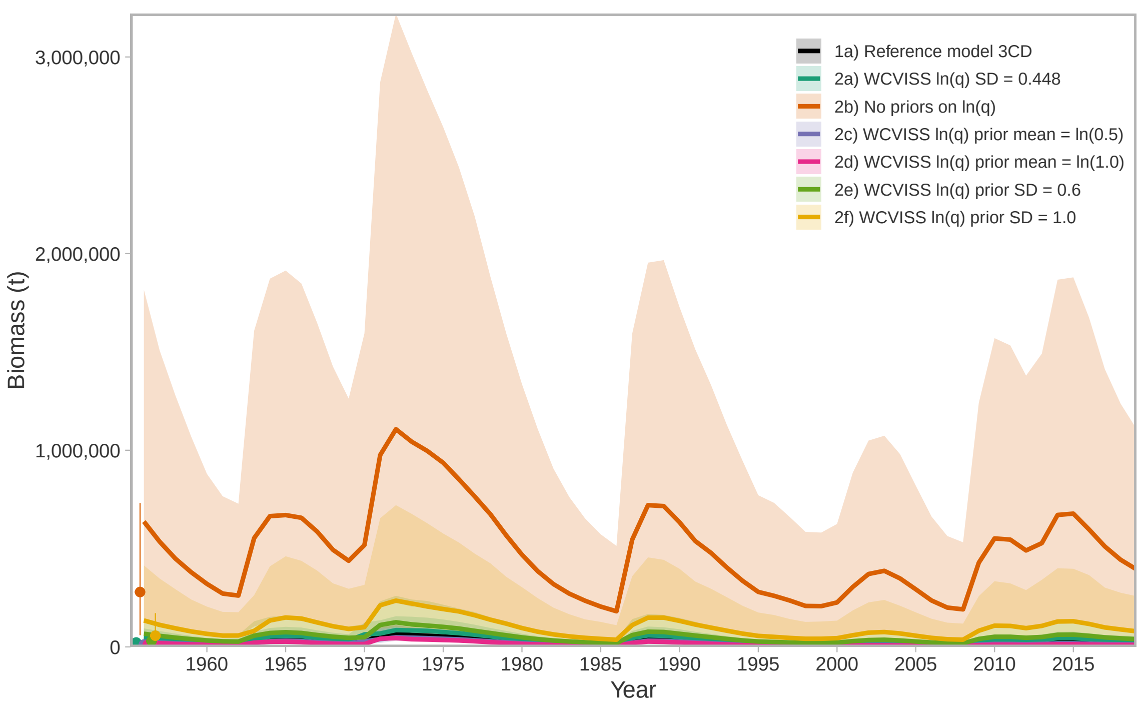

Figure 70. Sensitivity of biomass estimates to the SD for the WCVIS survey being set equal to the SD for the QCS and HSS surveys, and to a uniform prior being used for the WCVIS survey, Area 3CD.

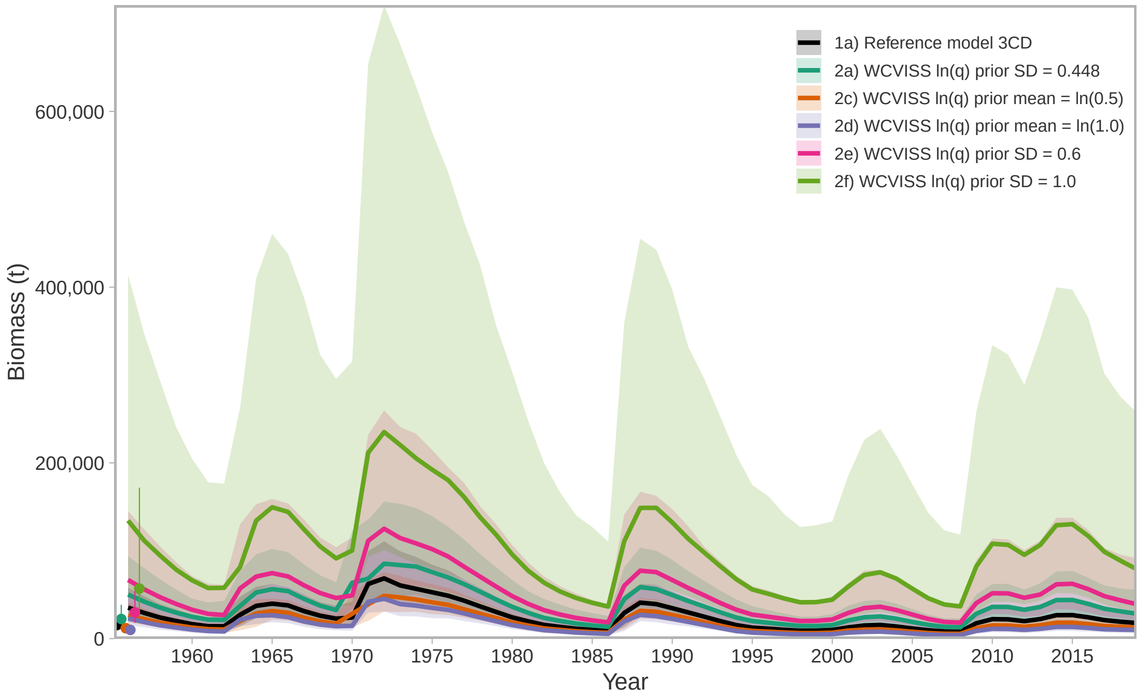

Figure 71. Sensitivity of biomass estimates to the SD for the WCVIS survey being set equal to the SD for the QCS and HSS surveys, Area 3CD.

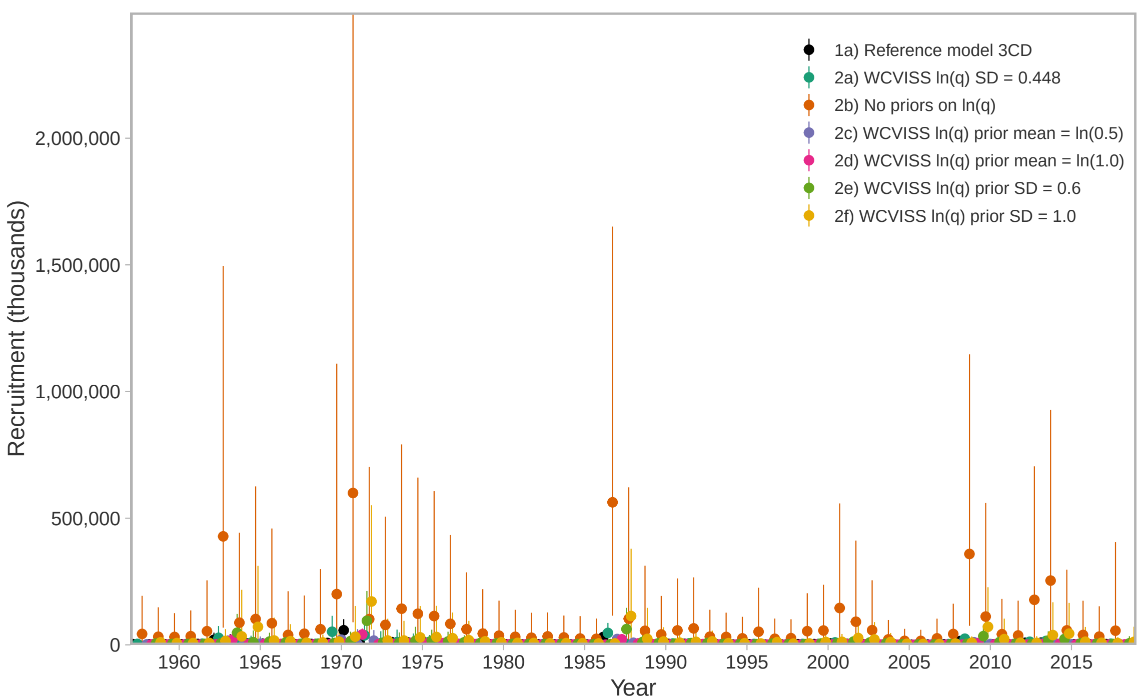

Figure 72. Sensitivity of recruitment estimates to the SD for the WCVIS survey being set equal to the SD for the QCS and HSS surveys, and to a uniform prior being used for the WCVIS survey, Area 3CD.

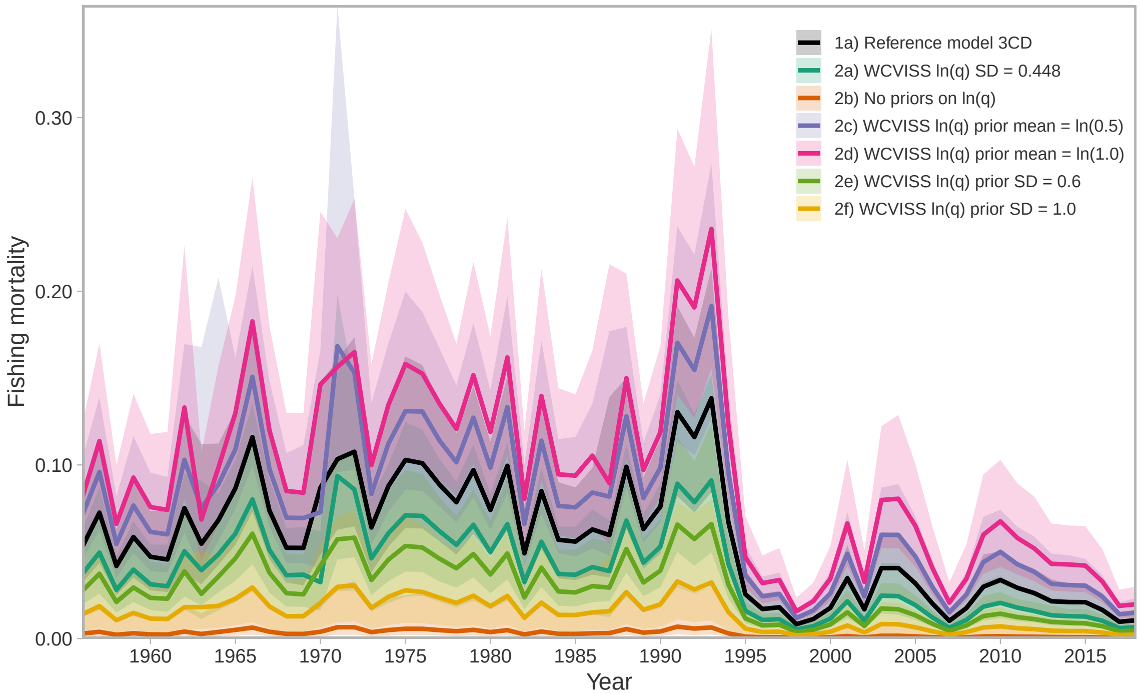

Figure 73. Sensitivity of fishing mortality estimates to the SD for the WCVIS survey being set equal to the SD for the QCS and HSS surveys, and to a uniform prior being used for the WCVIS survey, Area 3CD.

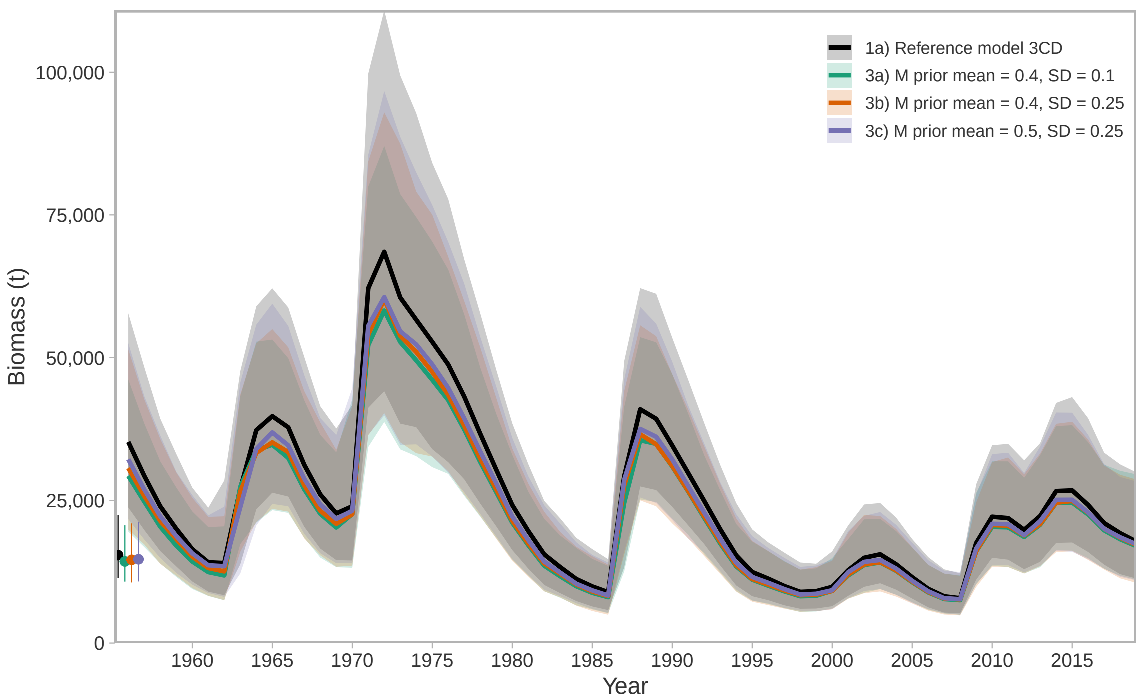

Figure 74. Sensitivity of biomass estimates to the parameters on the normal prior for natural mortality, M, Area 3CD.

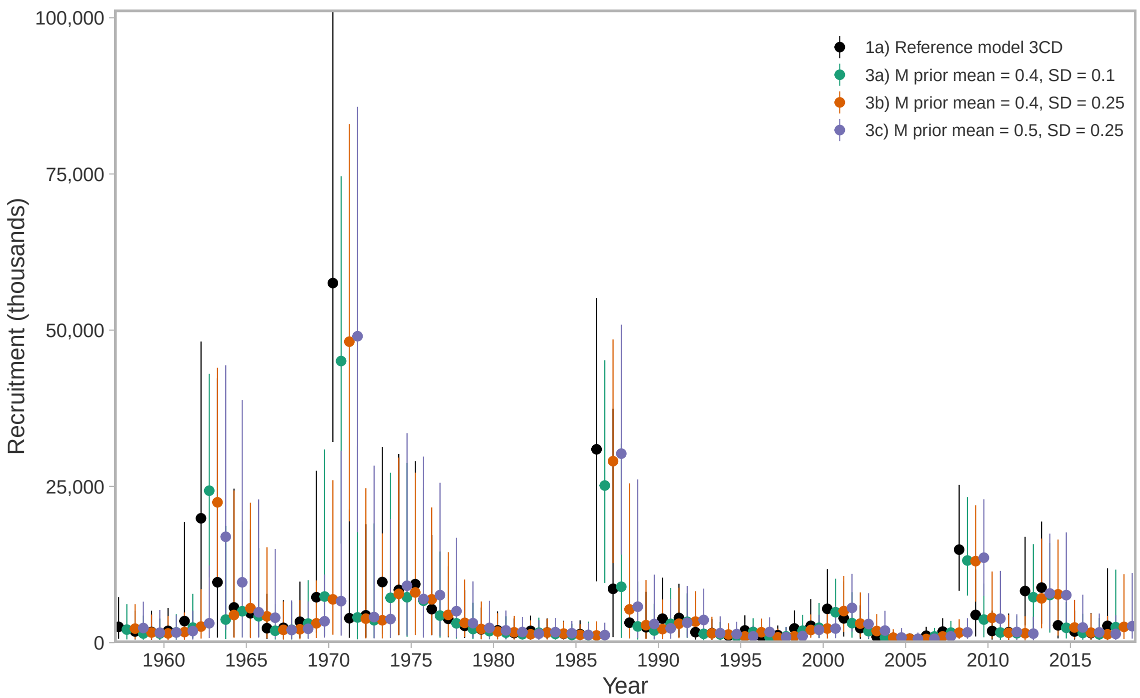

Figure 75. Sensitivity of recruitment estimates to the parameters on the normal prior for natural mortality, M, Area 3CD.

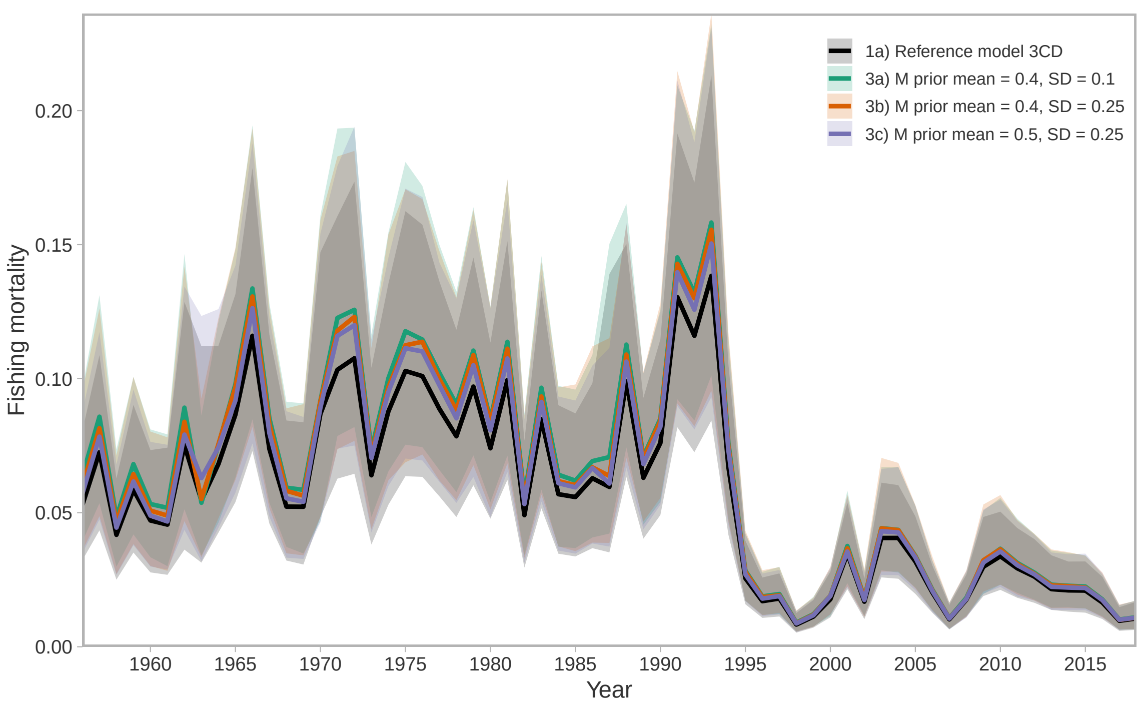

Figure 76. Sensitivity of fishing mortality estimates to the parameters on the normal prior for natural mortality, M, Area 3CD.

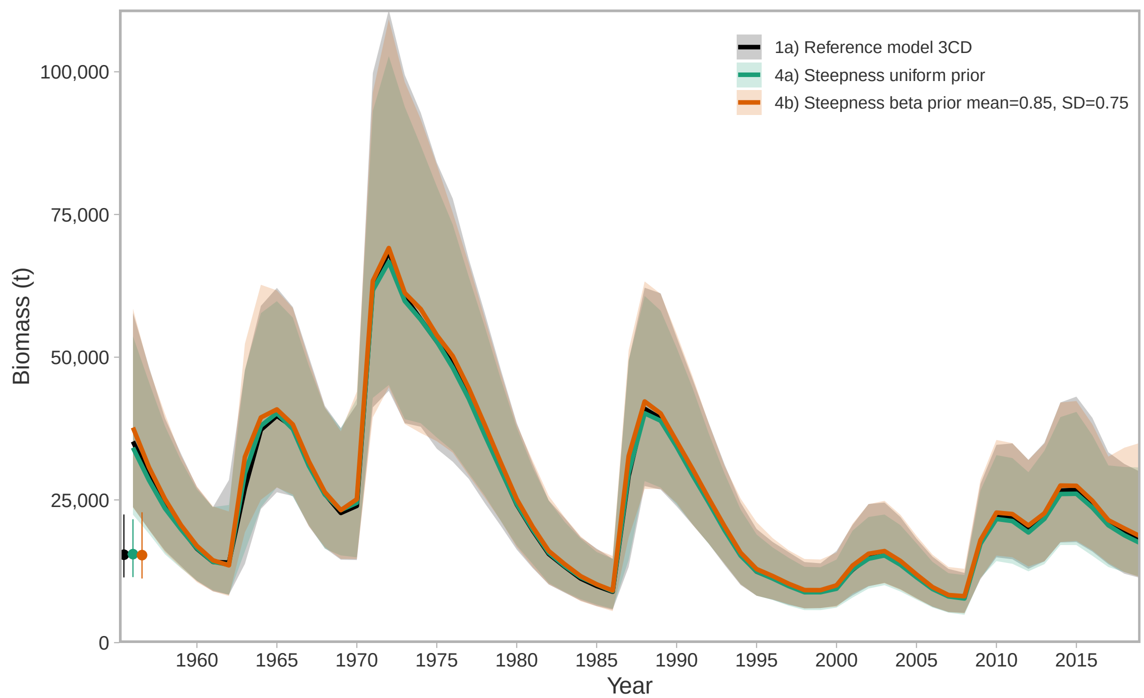

Figure 77. Sensitivity of biomass estimates to the prior probability distribution for steepness, including using a bounded uniform prior and a beta prior, Area 3CD.

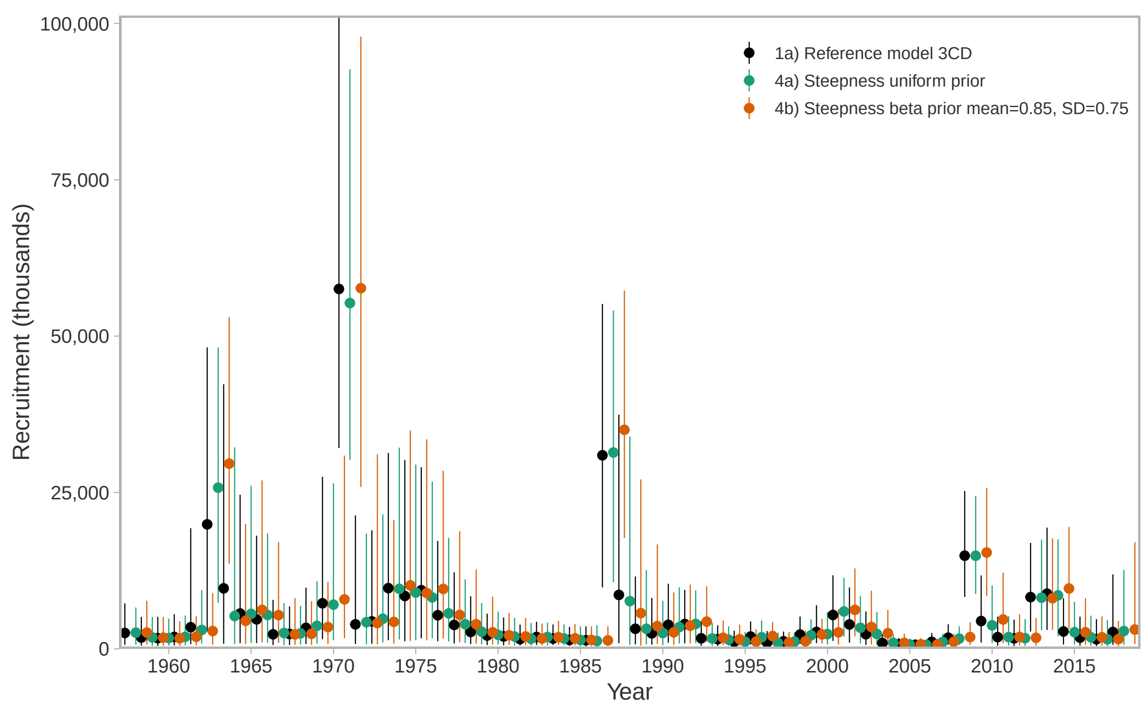

Figure 78. Sensitivity of recruitment estimates to the prior probability distribution for steepness, including using a bounded uniform prior and a beta prior, Area 3CD.

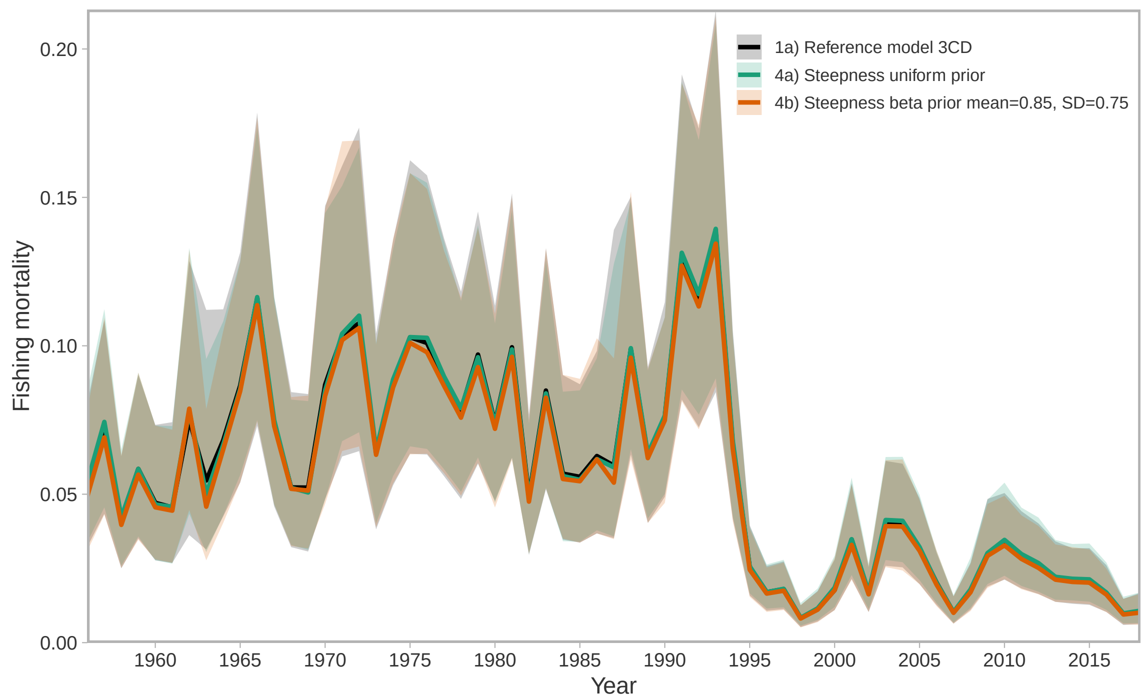

Figure 79. Sensitivity of fishing mortality estimates to the prior probability distribution for steepness, including using a bounded uniform prior and a beta prior, Area 3CD.

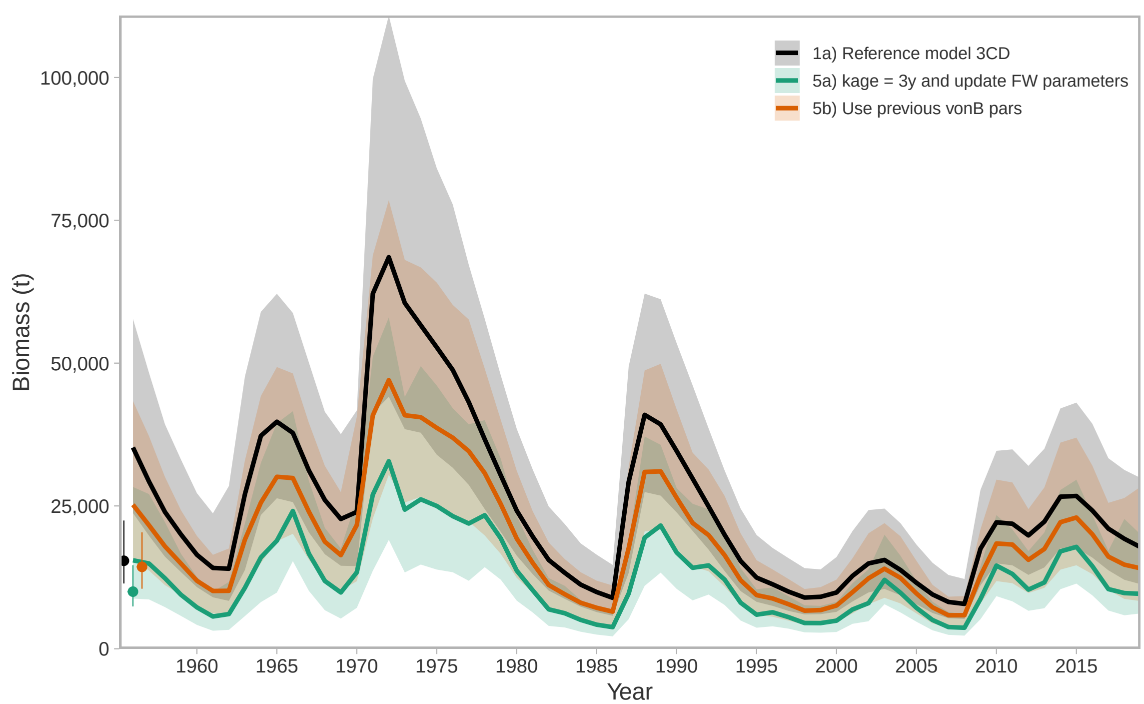

Figure 80. Sensitivity of biomass estimates to setting $k_{age} = 3y$ and update the Ford-Walford parameters accordingly, and to using the growth parameters used in the previous stock assessment, Area 3CD.

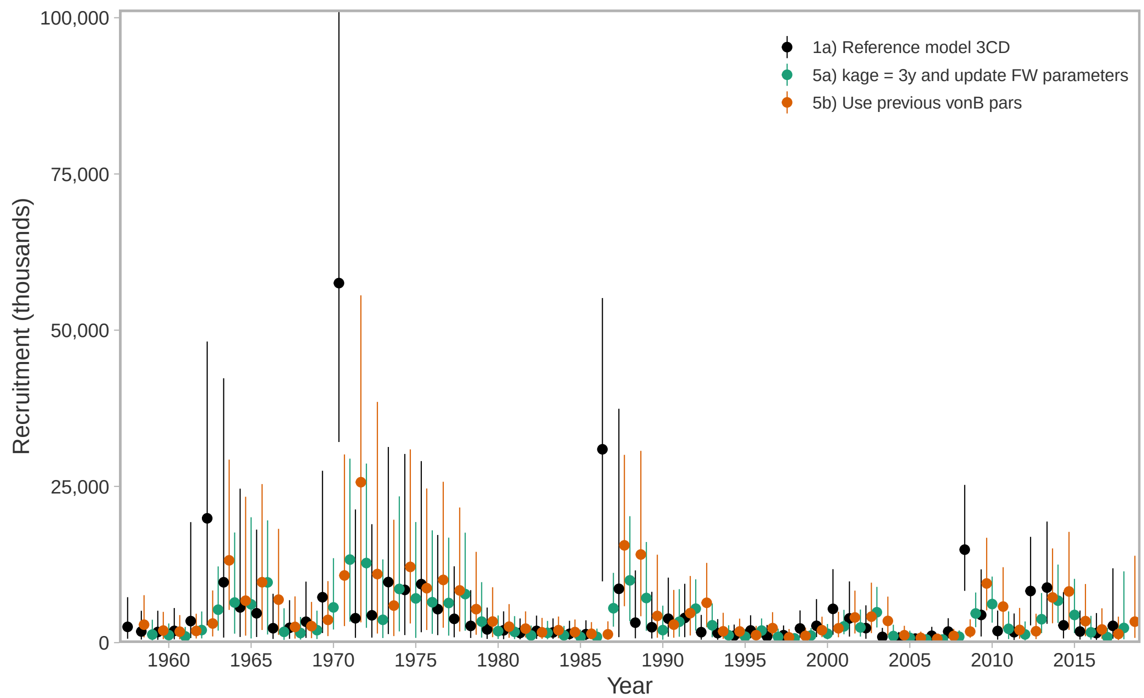

Figure 81. Sensitivity of recruitment estimates to setting $k_{age} = 3y$ and update the Ford-Walford parameters accordingly, and to using the growth parameters used in the previous stock assessment, Area 3CD.

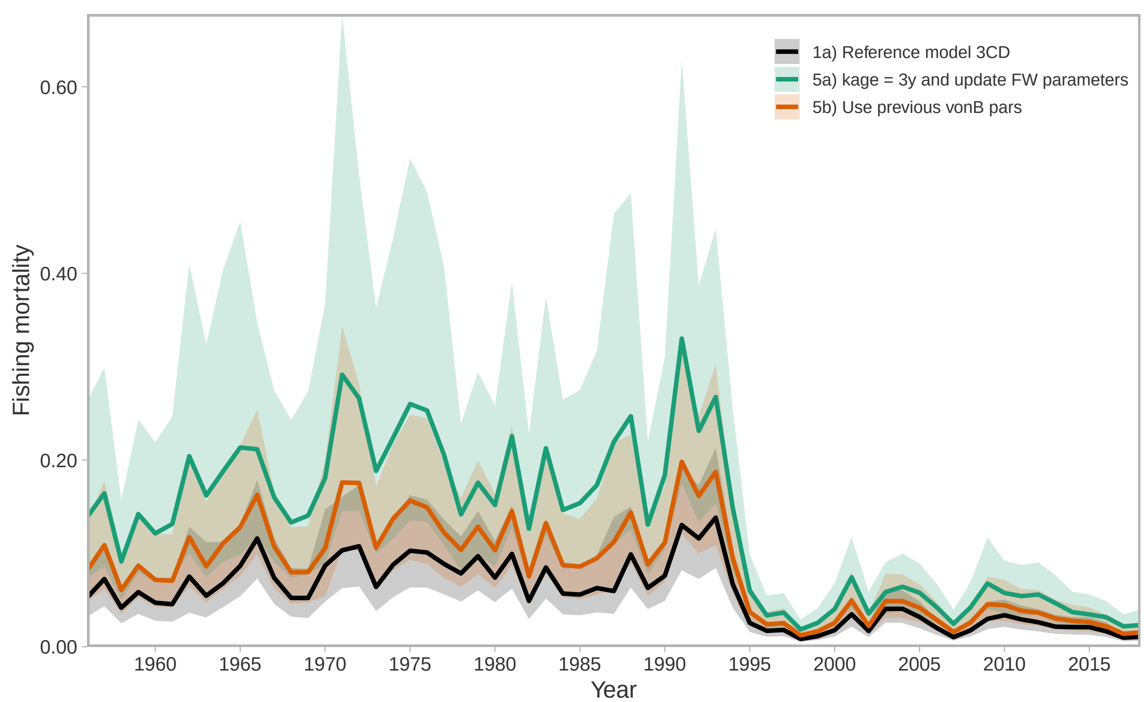

Figure 82. Sensitivity of fishing mortality estimates to setting $k_{age} = 3y$ and update the Ford-Walford parameters accordingly, and to using the growth parameters used in the previous stock assessment, Area 3CD.

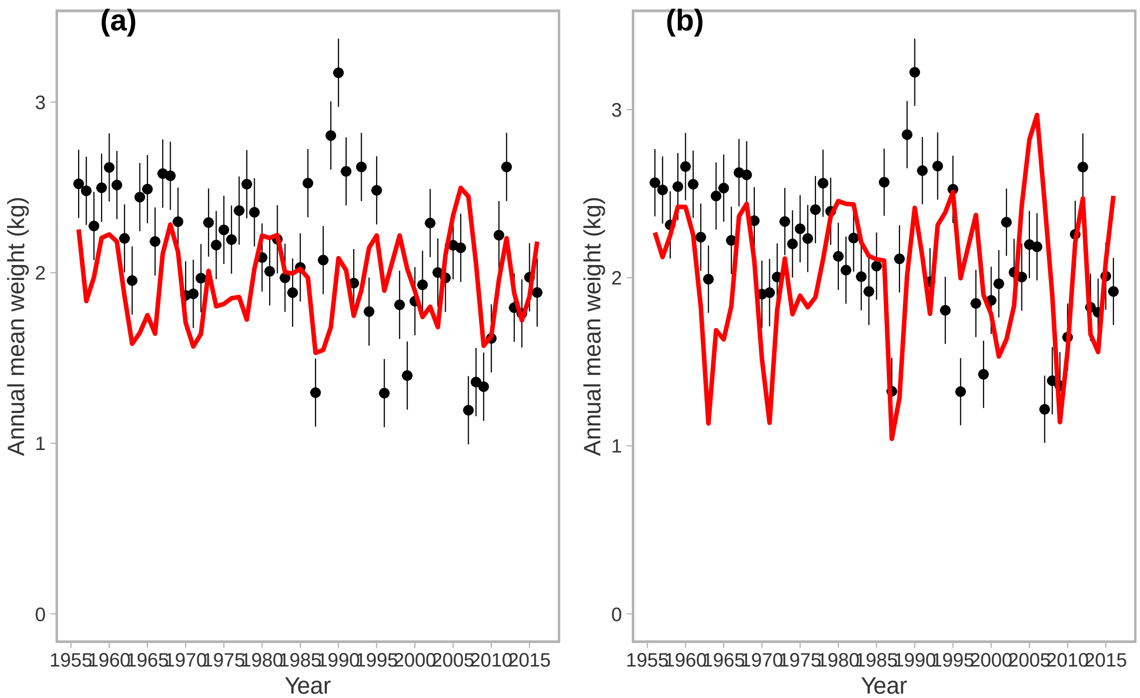

Figure 83. MPD fits to the average annual mean weights for (a) the Sensitivity to setting $k_{age} = 3y$ and update the Ford-Walford parameters accordingly, and (b) to using the growth parameters used in the previous Area 5CD stock assessment. Area 3CD.

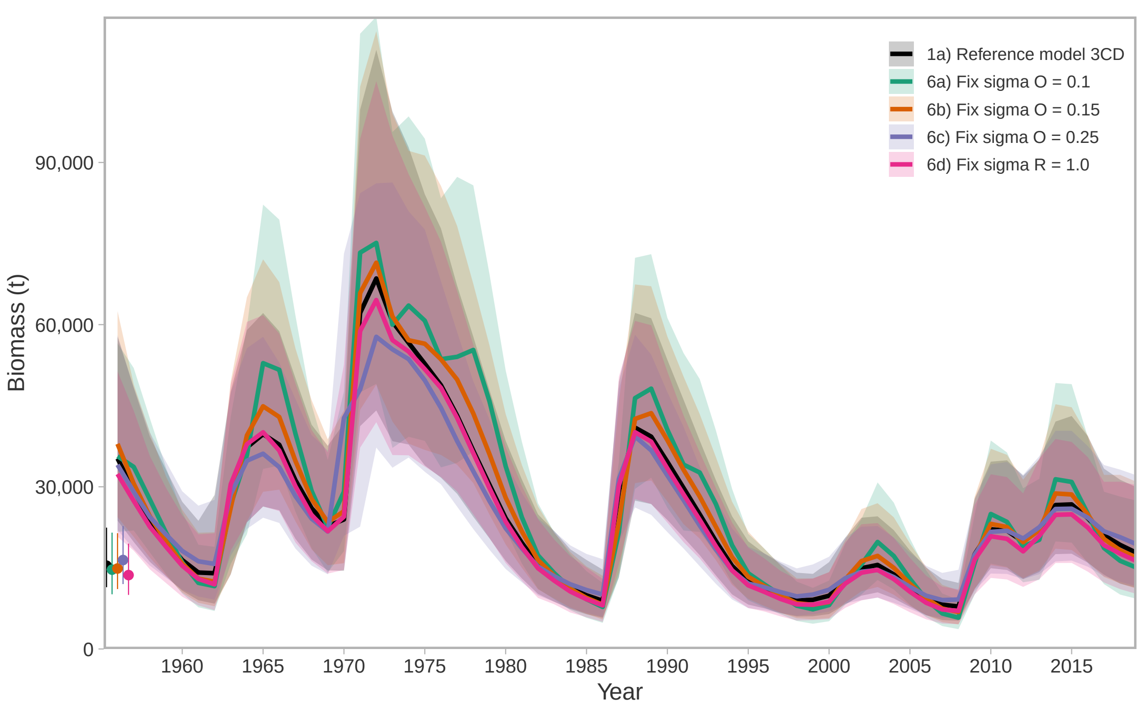

Figure 84. Sensitivity of biomass estimates to the assumed value of observation and process errors, Area 3CD.

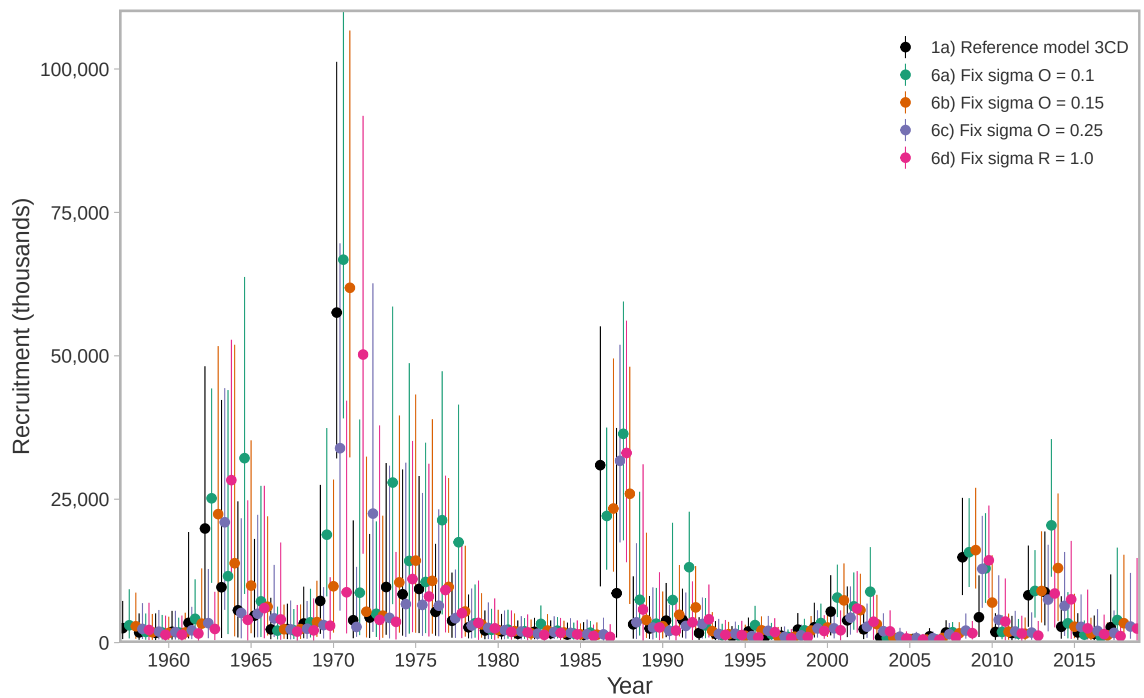

Figure 85. Sensitivity of recruitment estimates to the assumed value of observation and process errors, Area 3CD.

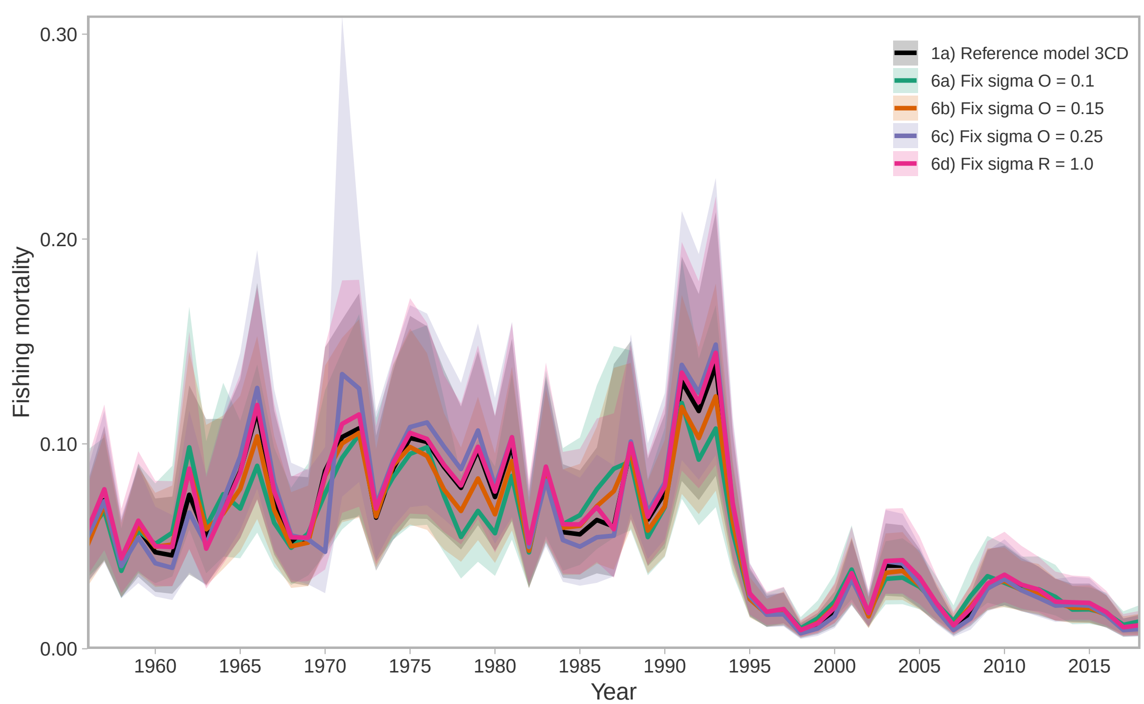

Figure 86. Sensitivity of fishing mortality estimates to the assumed value of observation and process errors, Area 3CD.

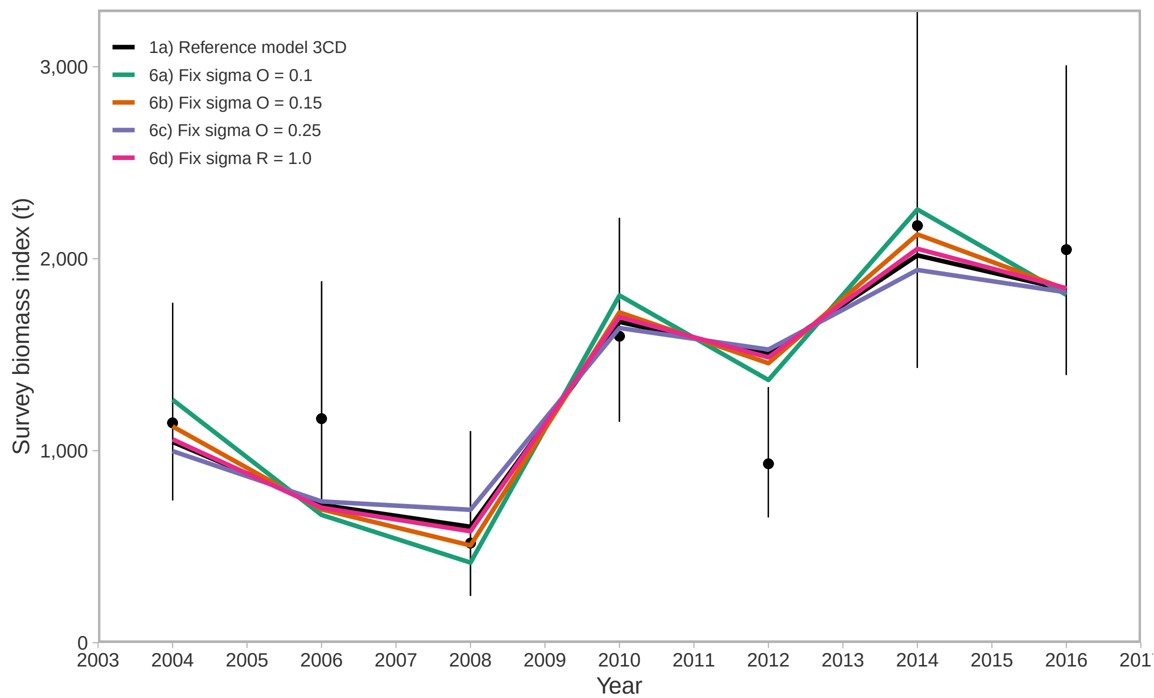

Figure 87. MPD index fits showing sensitivity to the assumed value of observation and process errors, WCVISS, Area 3CD.

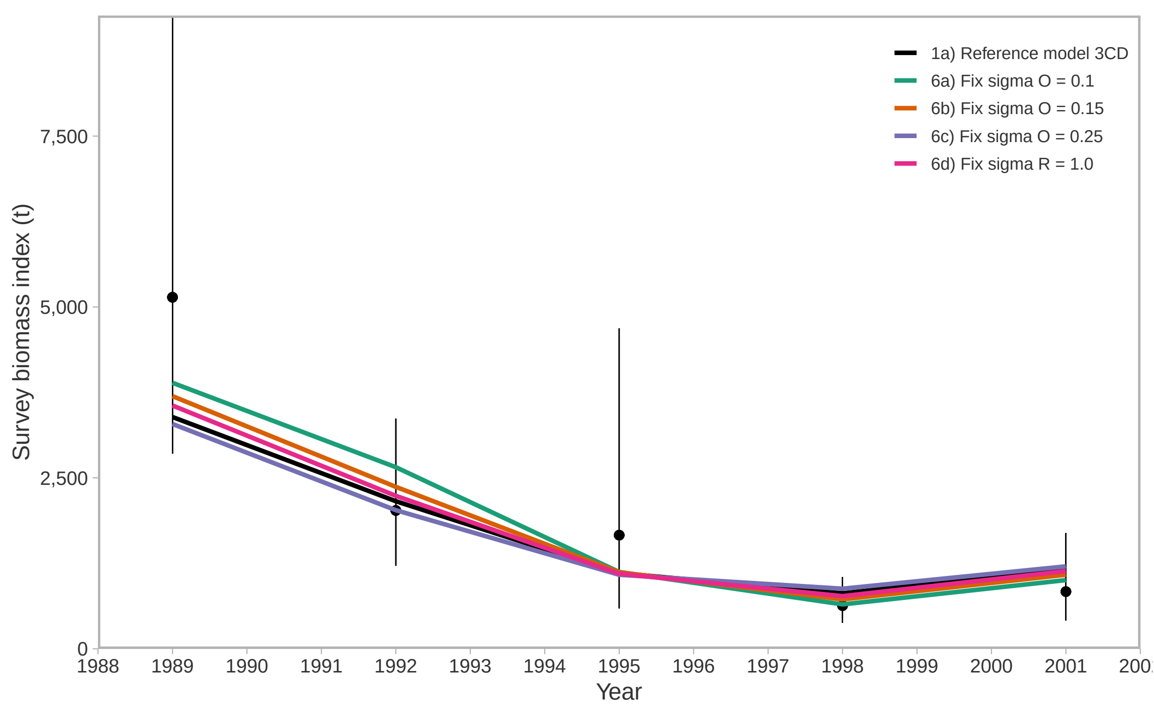

Figure 88. MPD index fits showing sensitivity to the assumed value of observation and process errors, NMFS Triennial survey, Area 3CD.

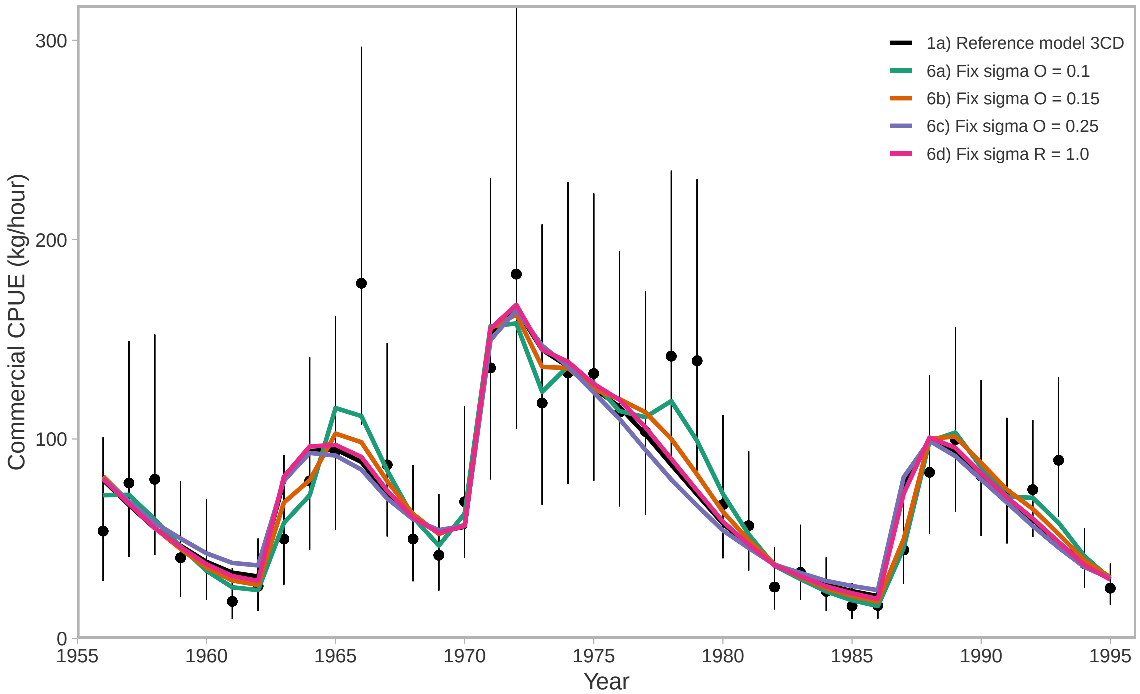

Figure 89. MPD index fits showing sensitivity to the assumed value of observation and process errows, commercial CPUE pre-1996, Area 3CD.

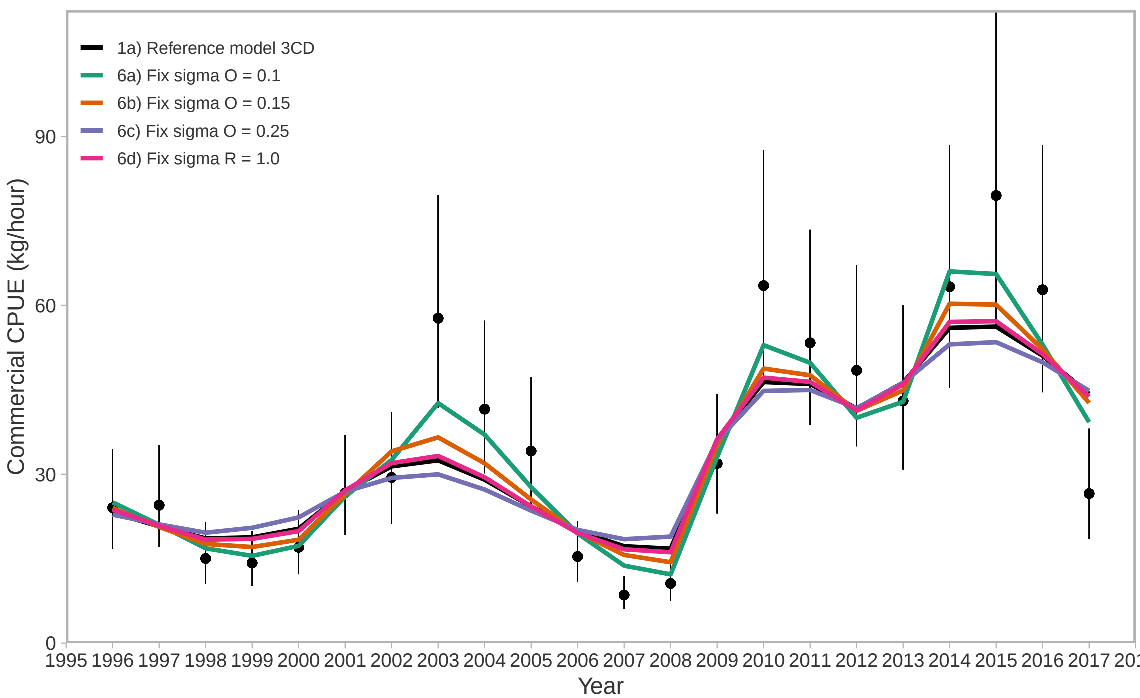

Figure 90. MPD index fits showing sensitivity to the assumed value of observation and process errors, commercial CPUE post-1995, Area 3CD.

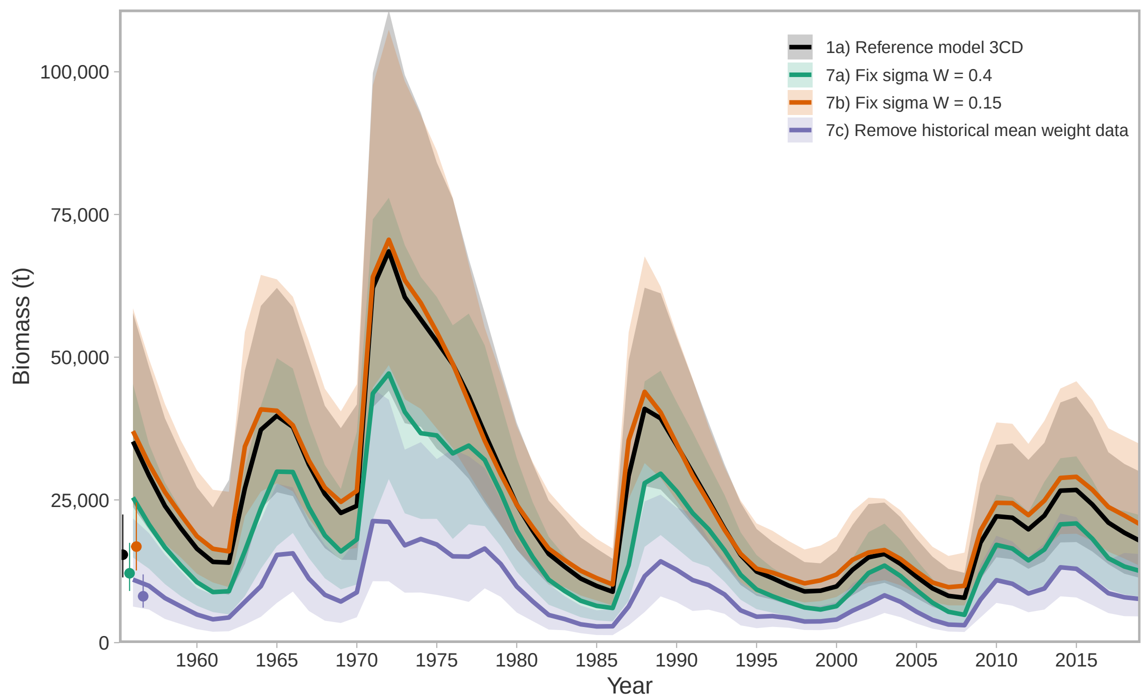

Figure 91. Sensitivity of biomass estimates to the assumed value of σ_W, Area 3CD.

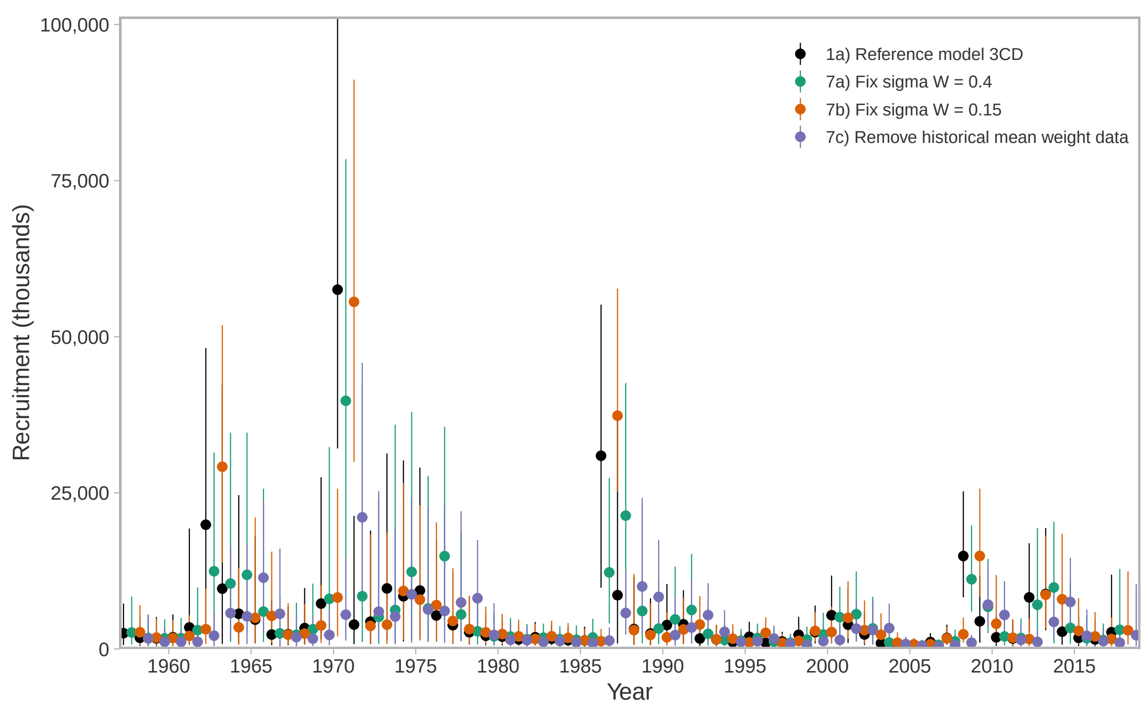

Figure 92. Sensitivity of recruitment estimates to the assumed value of σ_W, Area 3CD.

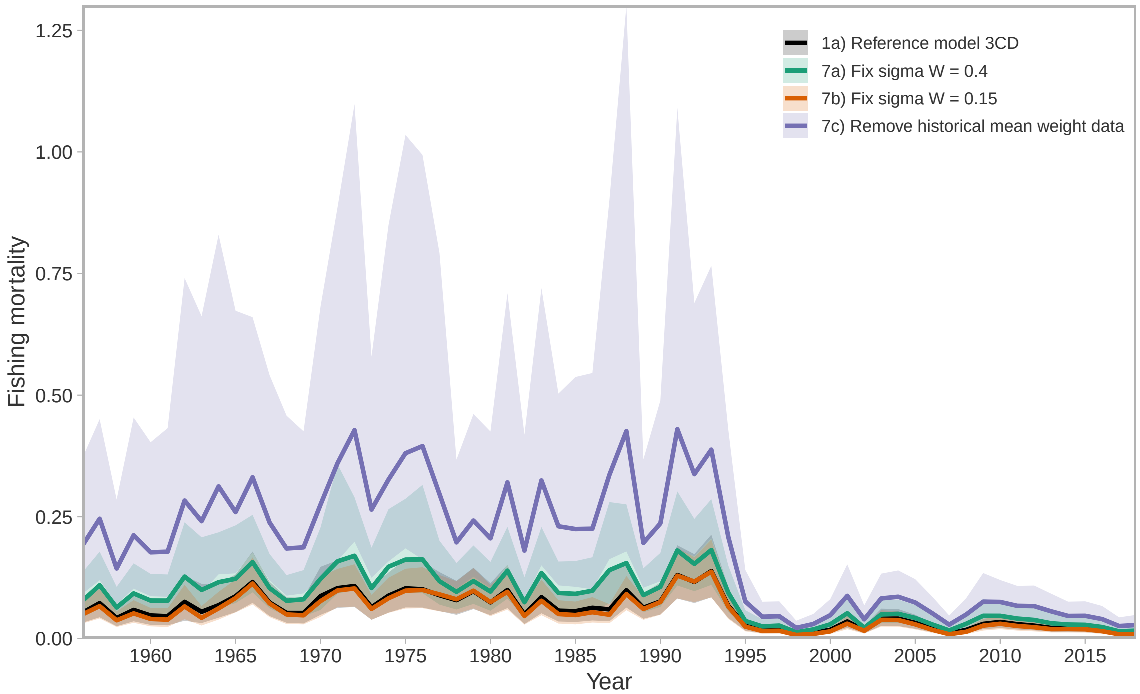

Figure 93. Sensitivity of fishing mortality estimates to the assumed value of σ_W, Area 3CD.

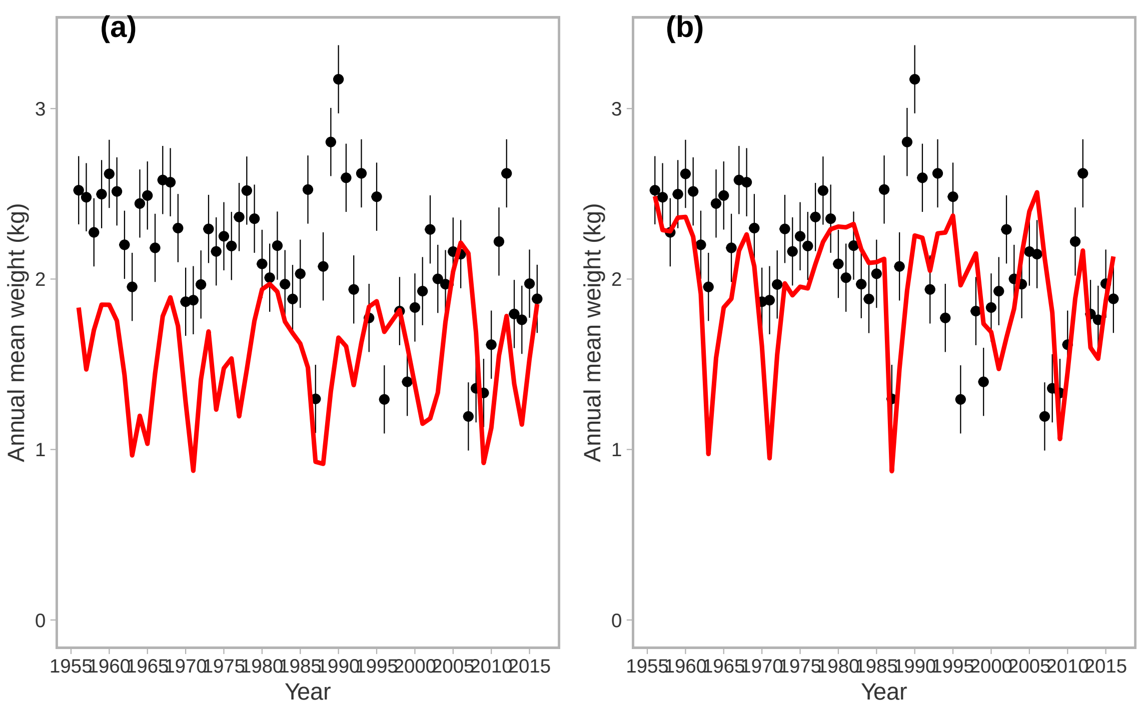

Figure 94. MPD fits to the average annual mean weights showing sensitivity to the assumed value of σ_W for (a) σ_W = 0.4 and (b) σ_W = 0.15, Area 3CD.

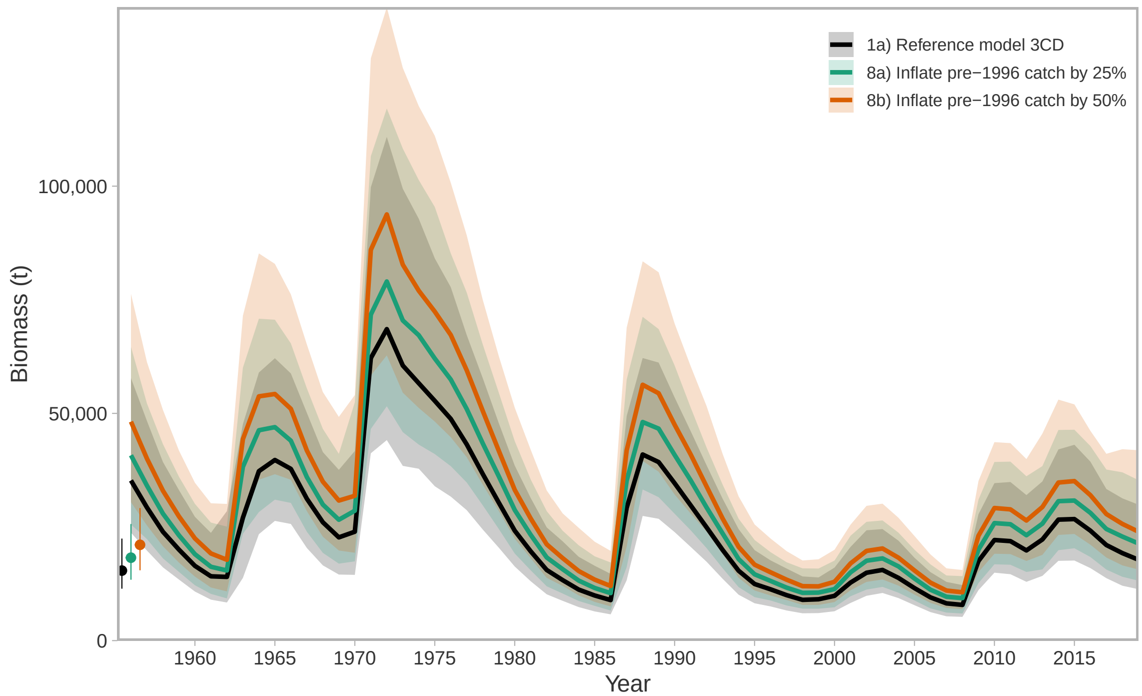

Figure 95. Sensitivity of biomass estimates to inflating the historical catch data, Area 3CD

14.8 MODEL-AVERAGED BIOMASS AND PROJECTIONS

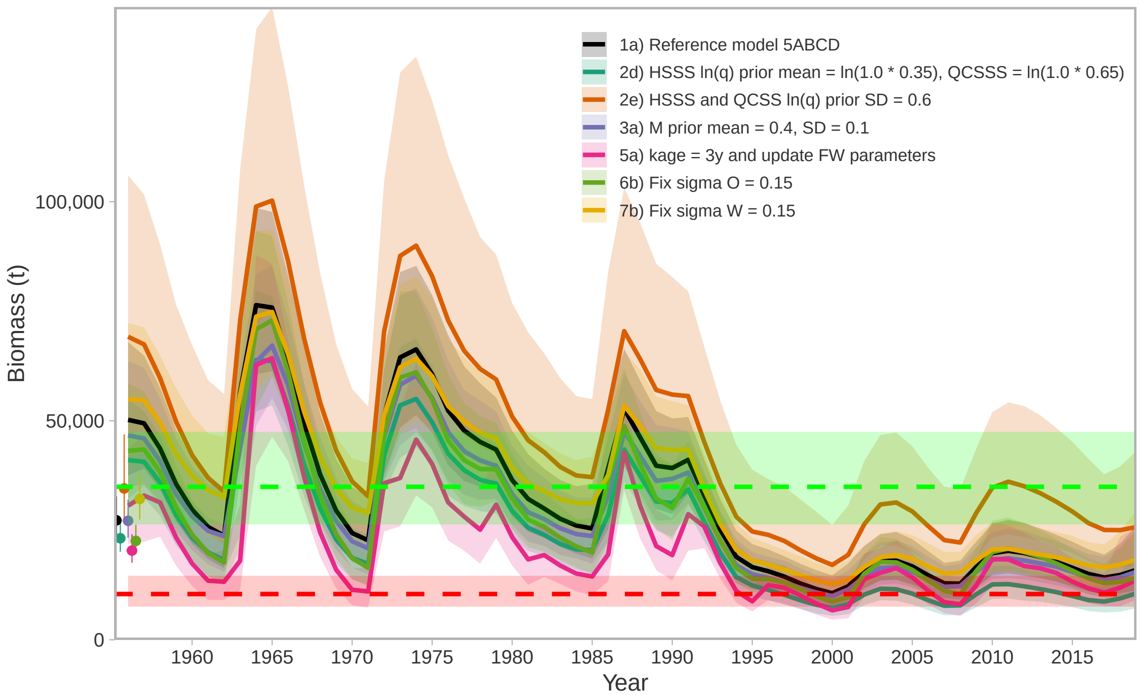

Figure 96. Posterior estimates of biomass for the model-averaged set for Area 5ABCD. The green dashed line shows the median Upper Stock Reference (USR) which is the mean biomass estimate for the years 1956–2004. The red dashed line shows the median Limit Reference Point (LRP) which is the lowest estimated biomass agreed to be an undesirable state to avoid, in this case it is the biomass estimate for 2000.

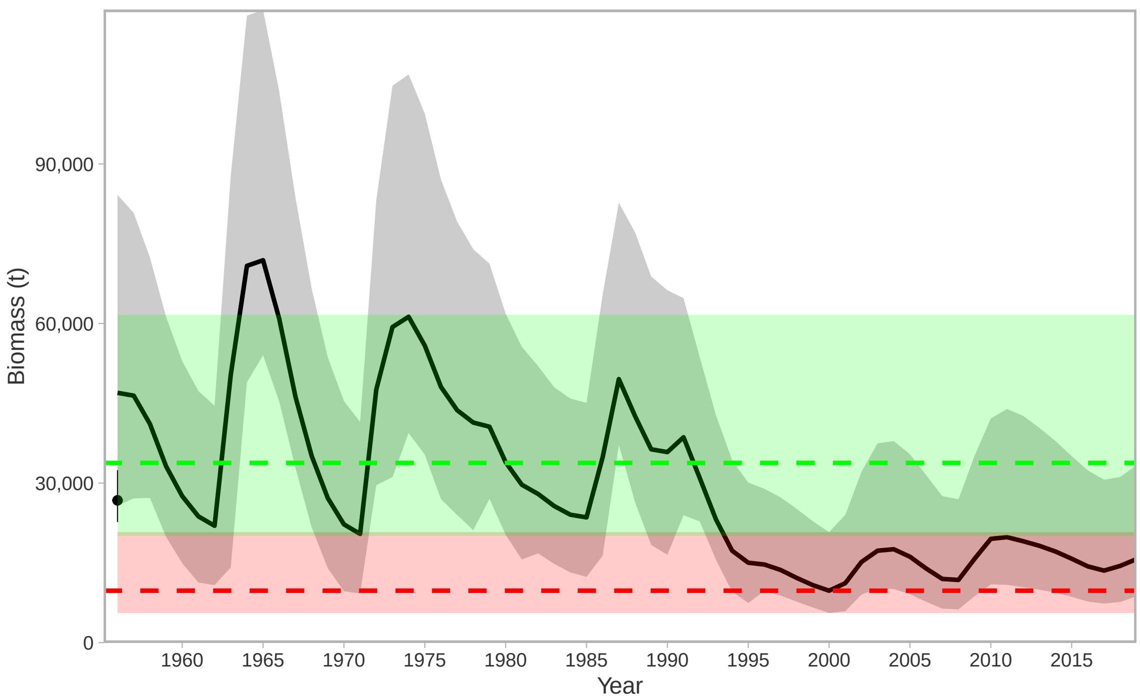

Figure 97. Combined posterior biomass for the averaged models, Area 5ABCD. The green dashed line shows the median Upper Stock Reference (USR) which is the mean biomass estimate for the years 1956–2004. The red dashed line shows the median Limit Reference Point (LRP) which is the lowest estimated biomass agreed to be an undesirable state to avoid, in this case it is the biomass estimate for 2000.

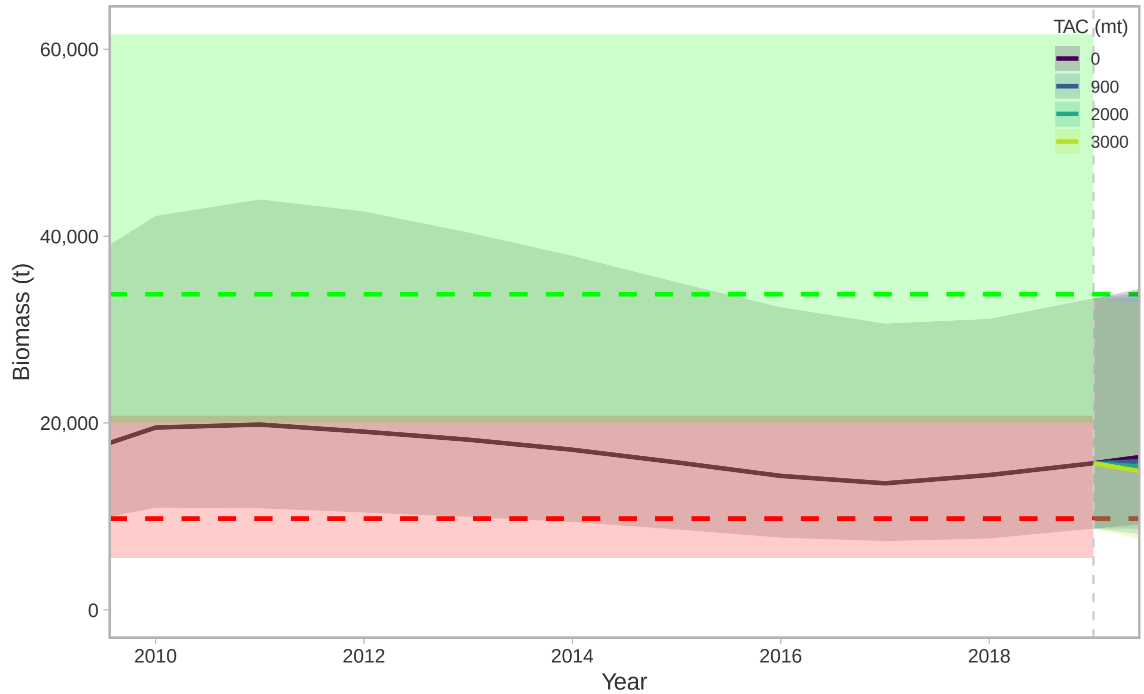

Figure 98. Combined posterior estimates of biomass for the model-averaged set for Area 5ABCD with projections (to the end of 2019). The upper horizontal green dashed line shows the median Upper Stock Reference (USR) which is the mean biomass estimate for the years 1956–2004. The lower horizontal red dashed line shows the median Limit Reference Point (LRP) which is the lowest estimated biomass agreed to be an undesirable state to avoid, in this case it is the biomass estimate for 2000. The coloured regions to the right of the vertical line represent projections based on various TACs. The line represents the posterior median and the shaded region represents the 95% credible interval. For clarity, years before 2010 are removed.

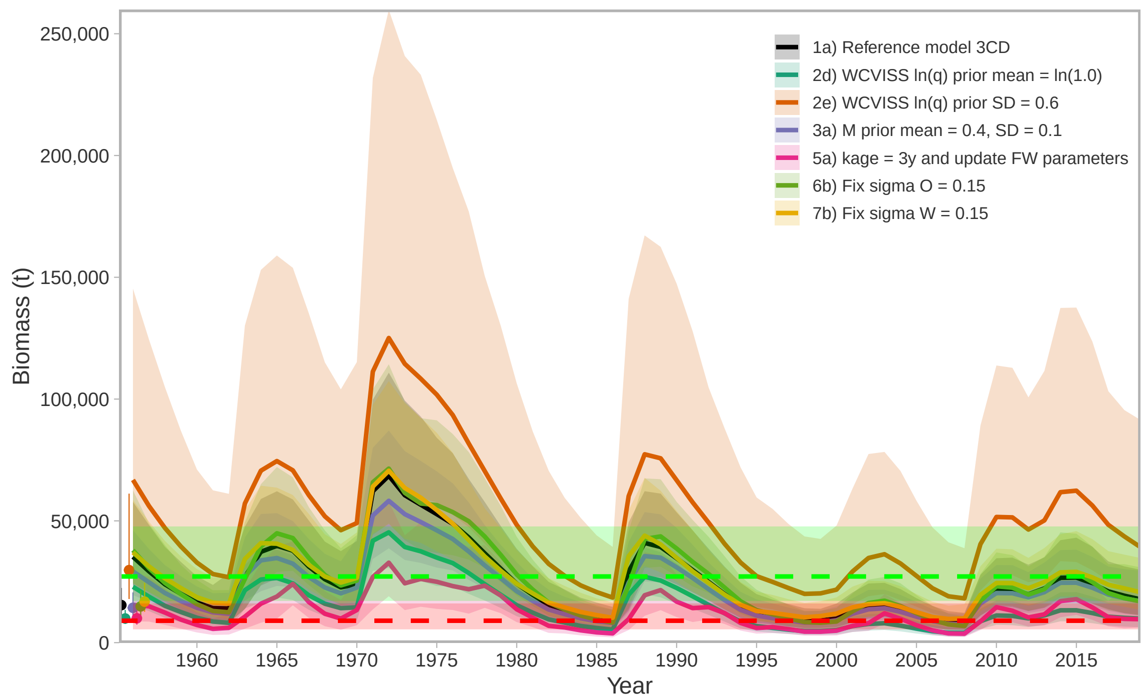

Figure 99. Posterior estimates of biomass for the model-averaged set for Area 3CD. The green dashed line shows the median Upper Stock Reference (USR) which is the mean biomass estimate for the years 1956–2004. The red dashed line shows the median Limit Reference Point (LRP) which is the lowest estimated biomass agreed to be an undesirable state to avoid, in this case it is the biomass estimate for 1986.

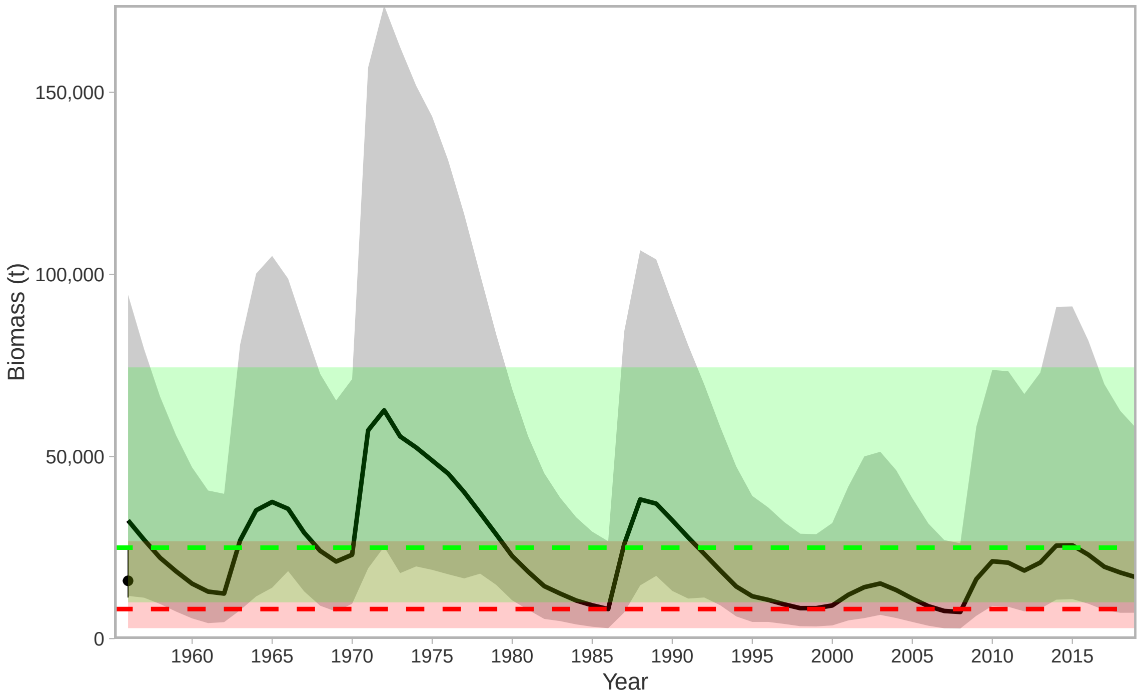

Figure 100. Combined posterior biomass for the model-averaged set for Area 3CD. The green dashed line shows the median Upper Stock Reference (USR) which is the mean biomass estimate for the years 1956–2004. The red dashed line shows the median Limit Reference Point (LRP) which is the lowest estimated biomass agreed to be an undesirable state to avoid, in this case it is the biomass estimate for 1986.

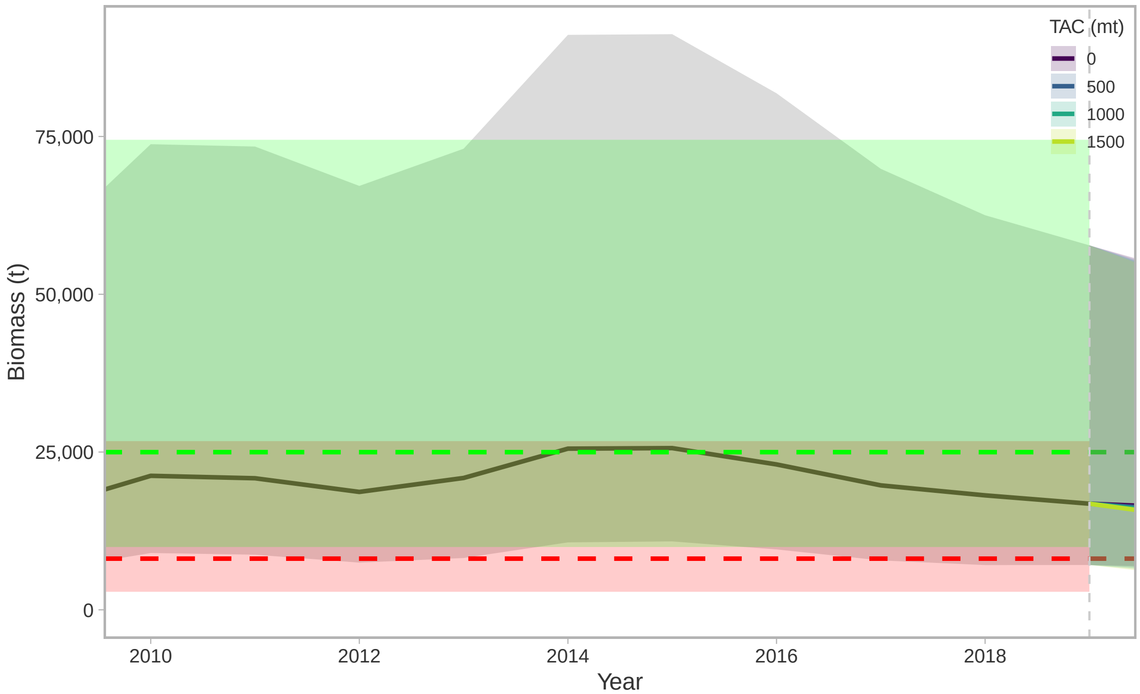

Figure 101. Combined posterior estimates of biomass for the model-averaged set for Area 3CD with projections (to the end of 2019). The upper horizontal green dashed line shows the median Upper Stock Reference (USR) which is the mean biomass estimate for the years 1956–2004. The lower horizontal red dashed line shows the median Limit Reference Point (LRP) which is the lowest estimated biomass agreed to be an undesirable state to avoid, in this case it is the biomass estimate for 2000. The coloured regions to the right of the vertical line represent projections based on various TACs. The line represents the posterior median and the shaded region represents the 95% credible interval.For clarity, years before 2010 are removed.

APPENDIX A. FISHERY-INDEPENDENT INDICES OF ABUNDANCE

A.1 CANADIAN SURVEYS

A.1.1 HECATE STRAIT ASSEMBLAGE SURVEY

A series of multi-species groundfish bottom trawl surveys was conducted in Hecate Strait in May-June of 1984, 1987, 1989, 1991, 1993, 1995, 1996, 1998, 2000, 2002, and 2003 Westrheim et al. (1984), Fargo et al. (1984), Fargo et al. (1988), Wilson et al. (1991), Hand et al. (1994), Workman et al. (1996), Workman et al. (1997), Choromanski et al. (2002)) (Figure A.1. The results up to 2000 were reported in the 2001 assessment (Sinclair et al. 2001) and results from 2002 and 2003 were presented in the 2005 assessment (Sinclair and Starr 2005).

The original design of this survey assigned fishing locations by 10 fm depth intervals within a 10 nm grid of Hecate Strait. The survey was post-stratified for the purpose of calculating an abundance index for Pacific Cod (Sinclair 1999). The post stratification used 10 fm depth intervals for the entire survey area, thereby treating each depth interval as a single stratum.

The Hecate Strait Assemblage survey was designed as a systematic fixed-station survey. Despite attempts to apply post-sampling stratification, this approach had high survey variance (Sinclair et al. 2007). In 2004 the Hecate Strait Assemblage survey was discontinued in favour of the Hecate Strait Synoptic survey (described below).

A.1.2 HECATE STRAIT SYNOPTIC SURVEY

The Hecate Strait synoptic groundfish bottom trawl survey is part of a coordinated set of long-term surveys that together cover the continental shelf and upper slope of most of the BC coast (Figure A.2. The Hecate Strait synoptic survey has been conducted during May-June, in odd years since 2005. All the synoptic surveys follow a random depth stratified design. The survey area is divided into 2 km by 2 km blocks and each block is assigned to one of four depth strata based on the average bottom depth in the block. The four depth strata for the Hecate Strait survey are 10–70m, 70–130m, 130–220m, and 220–500m. Each year blocks are randomly selected within each depth strata. For this survey and the other synoptic surveys discussed below, the relative allocation of blocks amongst depth strata was determined by modeling the expected catches of groundfish and determining the target number of tows per stratum that would provide sufficiently precise catch rate data for as many species as possible.

A.1.3 QUEEN CHARLOTTE SOUND SYNOPTIC SURVEY

The Queen Charlotte Sound (QCS) synoptic groundfish bottom trawl survey has been conducted in July–August in 2003, 2004, and in odd years since 2005 (Figure A.3. The four depth strata for the QCS survey are 50–125m, 125–200m, 200–330m, and 330–500 m. Each year blocks are randomly selected within each depth strata. In addition, for the purposes of allocating blocks, the QCS survey is divided into northern and southern spatial strata.

A.1.4 WEST COAST VANCOUVER ISLAND SYNOPTIC SURVEY

The West Coast Vancouver Island synoptic bottom trawl survey was first conducted in 2004 and is conducted in alternating (even-numbered) years on a chartered commercial trawler (Figure A.4). The survey area is off the west coast of Vancouver Island from approximately $49\,^{\circ}\,12'$

to 50 ° 36′ North latitude and approximately 124 ° 48′ to 128 ° 30′ West longitude. The southern boundary is contiguous with the Canada/U.S. boundary. The survey has a single aerial stratum in Pacific Fishery Management Area regions 3C and 3D separated into four depth strata: 50–125m; 125–200m; 200–330m; and 330–500m. Approximately 150 to 180 4 km^2 blocks are selected randomly among the four depth strata when conducting each survey.

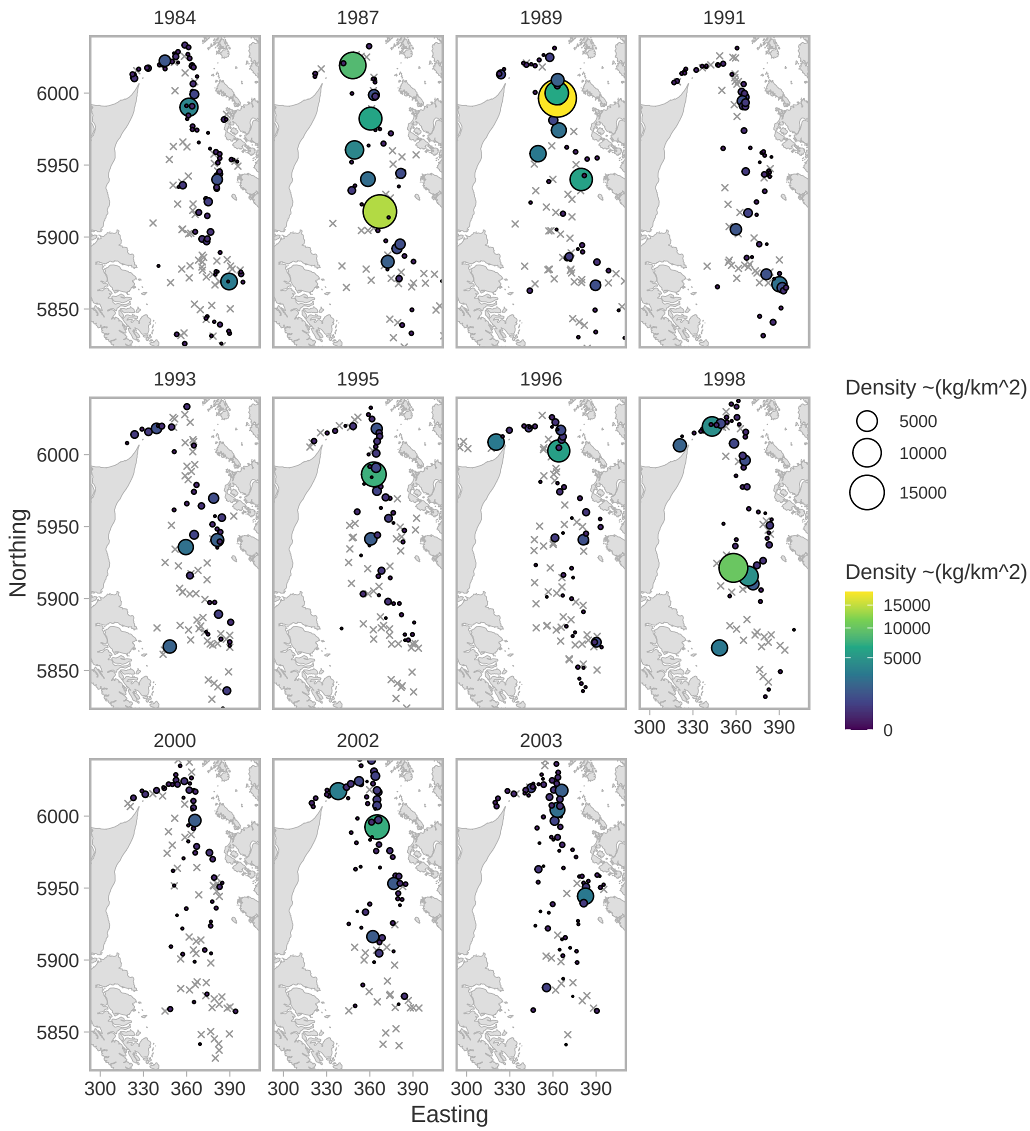

Figure A.1. Individual survey tows for the Hecate Strait multi-species groundfish bottom trawl survey. Light gray crosses indicate survey sets that did not catch Pacific Cod. Circles have their area and color proportional to the density of Pacific Cod for that survey set. Eastings and Northings are for UTM zone 9.

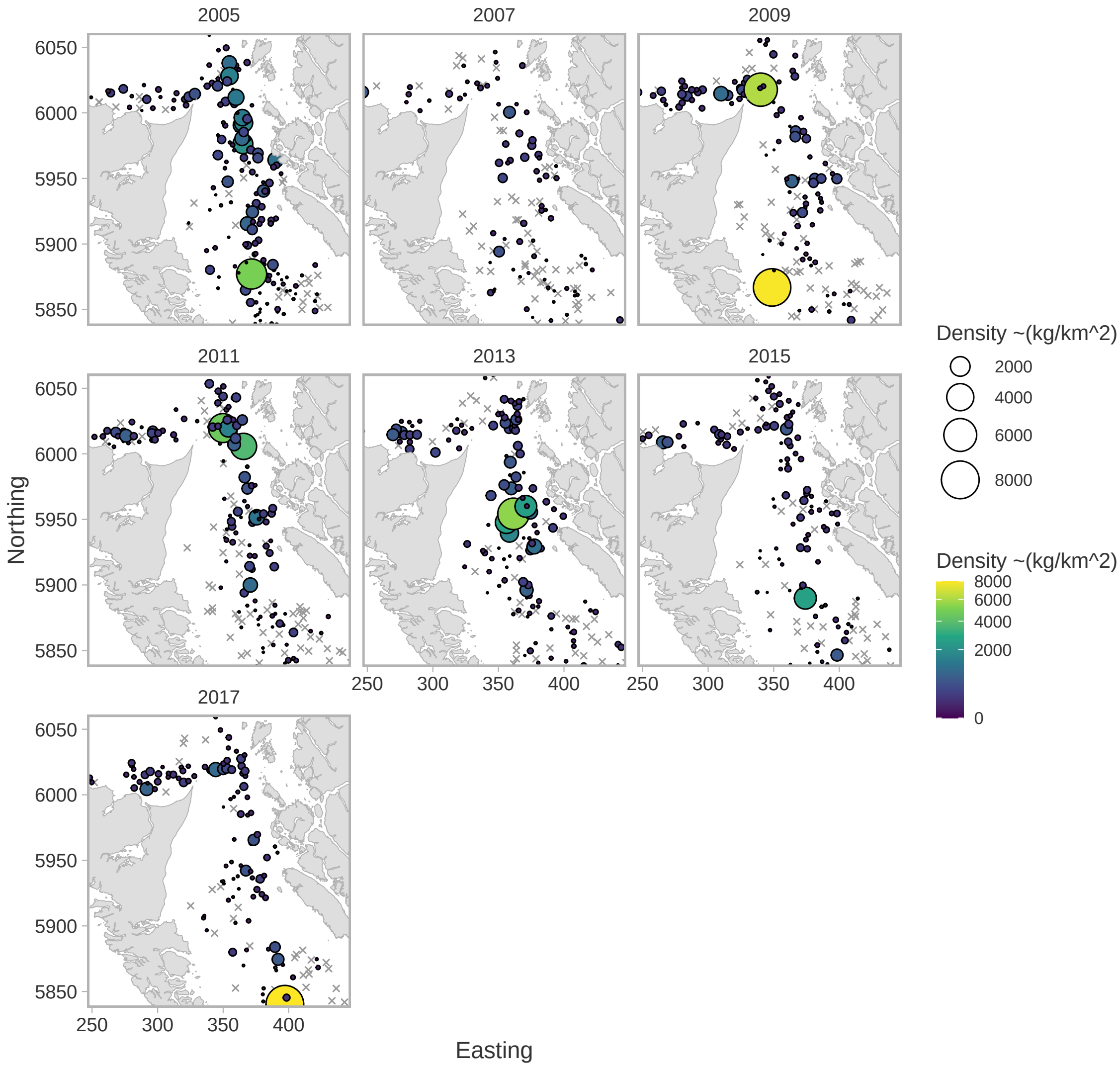

Figure A.2. Individual survey tows for the Hecate Strait (SYN HS) synoptic groundfish bottom trawl survey. Light gray crosses indicate survey sets that did not catch Pacific Cod. Circles have their area and color proportional to the density of Pacific Cod for that survey set. Eastings and Northings are for UTM zone 9.

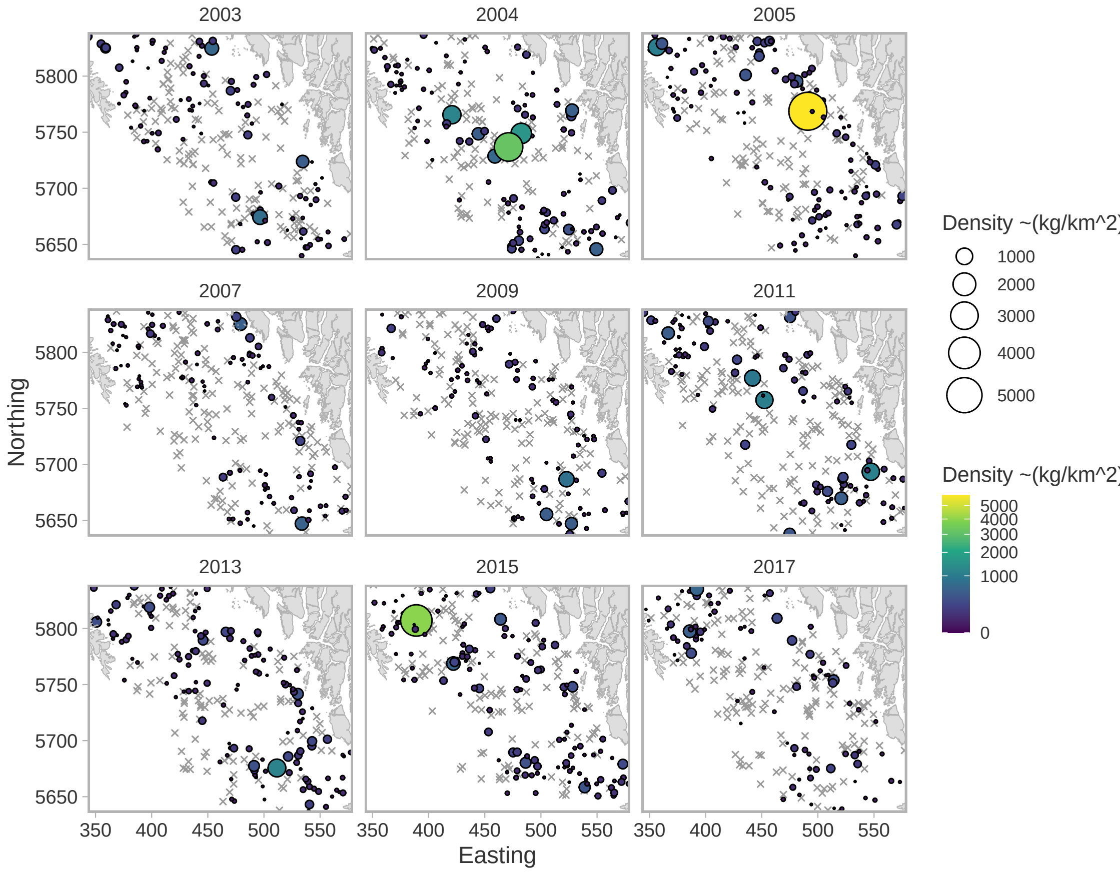

Figure A.3. Individual survey tows for the Queen Charlotte Sound (SYN QCS) synoptic groundfish bottom trawl survey. Light gray crosses indicate survey sets that did not catch Pacific Cod. Circles have their area and color proportional to the density of Pacific Cod for that survey set. Eastings and Northings are for UTM zone 9.

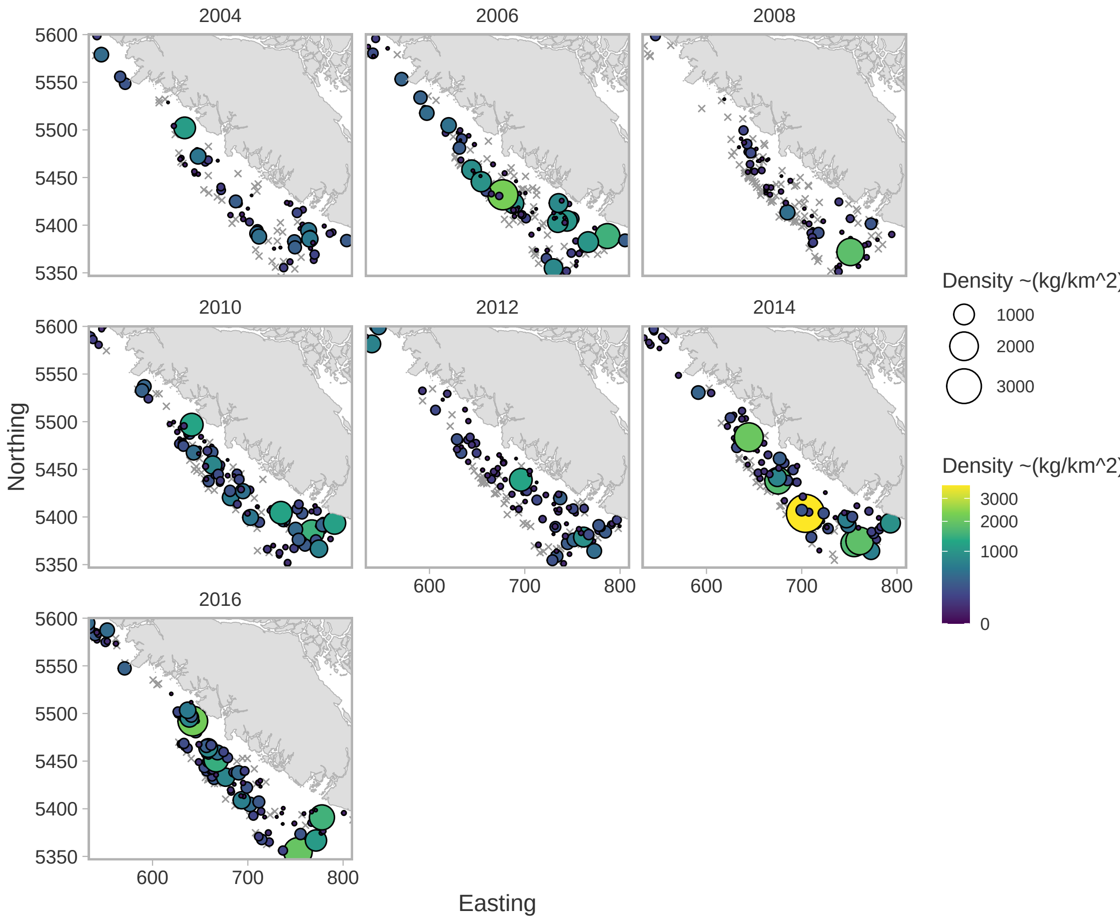

Figure A.4. Individual survey tows for the West Coast Vancouver Island (SYN WCVI) synoptic groundfish bottom trawl survey. Light gray crosses indicate survey sets that did not catch Pacific Cod. Circles have their area and color proportional to the density of Pacific Cod for that survey set. Eastings and Northings are for UTM zone 9.

A.1.5 SWEPT AREA ANALYSIS

For all Canadian surveys, a swept area estimate of biomass in any year y was obtained by summing the product of the CPUE and the area surveyed across the surveyed strata i:

$$B_y = \sum_{i=1}^{k} C_{y_i} A_i = \sum_{i=1}^{k} B_{y_i} \tag{A.1}$$

where C_{y_i} = mean CPUE density (kg/km^2) for Pacific Cod in stratum i, A_i = area of stratum i (km^2), B_{y_i} = biomass of Pacific Cod in stratum i for year y, and k = number of strata.

CPUE (C_{y_i}) for Pacific Cod in stratum i for year y was calculated as a density in kg/km^2 by

$$C_{y_i} = \frac{1}{n_{y_i}} \sum_{j=1}^{n_{y_i}} \frac{W_{y_i,j}}{D_{y_i,j} w_{y_i,j}} \tag{A.2}$$

where $W_{y_i,j}$ = catch weight (kg) for Pacific Cod in stratum i for year y and tow j, $D_{y_i,j}$ = distance travelled (km) by tow j in stratum i for year y, $w_{y_i,j}$ = net opening (km) by tow j in stratum i for year y, and n_{y_i} = number of tows in stratum i.

The variance of the survey biomass estimate V_y for Pacific Cod in year y was calculated in kg^2 as follows:

$$V_y = \sum_{i=1}^{k} \frac{\sigma^2_{y_i} A_i^2}{n_{y_i}} = \sum_{i=1}^{k} V_{y_i} \tag{A.3}$$

where $\sigma^2_{y_i}$ is the variance of the CPUE in kg^2/km^4 for year y in stratum i, V_{y_i} is the variance of Pacific Cod in stratum i for year y, and where $\sigma^2_{y_i}$ was obtained from bootstrapped samples (see below).

The CV for Pacific Cod for each year y was calculated as follows:

$$(CV)_y = \frac{{V_y}^{1/2}}{B_y} \tag{A.4}$$

where $(CV)_y$ is the CV for year y.

One thousand bootstrap replicates with replacement were constructed from the survey data to estimate bias corrected 95% confidence intervals for each survey year (Efron 1982). The resulting values are shown in Table A.1 and Figure A.5.

Table A.1. Pacific Cod survey data for Canadian trawl surveys. Relative biomass and associated lower and upper confidence intervals (CI) are shown in metric tons (without accounting for survey catchability). Positive sets refers to the number of trawl sets that caught Pacific Cod.

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

Survey abbrev.	Year	Biomass	CV	Lower CI	Upper CI	Sets	Positive sets
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	1948.0	0.24	1147.1	3016.2	198	161
SYN HS	2007	582.4	0.21	355.9	833.5	134	74
SYN HS	2009	2469.5	0.46	792.3	4972.0	156	103
SYN HS	2011	1872.0	0.26	1079.6	2984.8	185	125
SYN HS	2013	2328.3	0.23	1407.2	3477.4	175	132
SYN HS	2015	957.4	0.20	630.5	1389.8	148	107
SYN HS	2017	1555.3	0.35	771.3	2832.9	138	107
SYN QCS	2003	813.3	0.17	556.5	1101.0	233	101
SYN QCS	2004	1636.5	0.26	926.7	2553.9	230	118
SYN QCS	2005	1517.7	0.36	783.3	2885.5	224	125
SYN QCS	2007	437.9	0.25	258.4	681.2	255	105
SYN QCS	2009	569.6	0.24	333.4	871.8	233	95
SYN QCS	2011	1026.6	0.21	653.6	1537.9	251	98
SYN QCS	2013	936.1	0.16	668.1	1247.8	240	134
SYN QCS	2015	1131.3	0.30	650.5	1902.9	238	124
SYN QCS	2017	526.0	0.17	358.9	705.2	240	90
SYN WCHG	2006	52.0	0.23	30.9	77.1	110	36
SYN WCHG	2007	33.8	0.42	10.8	65.3	111	23
SYN WCHG	2008	12.7	0.26	6.5	19.5	118	20
SYN WCHG	2010	22.0	0.49	7.7	47.5	129	27
SYN WCHG	2012	40.8	0.32	18.9	69.6	130	34
SYN WCHG	2016	33.1	0.16	23.1	44.0	112	42
SYN WCVI	2004	1144.9	0.22	700.9	1676.8	89	54
SYN WCVI	2006	1166.9	0.24	655.8	1795.8	164	88
SYN WCVI	2008	518.5	0.39	238.8	980.0	159	65
SYN WCVI	2010	1596.0	0.17	1138.9	2165.9	136	100
SYN WCVI	2012	931.8	0.18	643.5	1294.7	151	94
SYN WCVI	2014	2172.2	0.21	1375.0	3170.4	146	110
SYN WCVI	2016	2047.4	0.19	1347.0	2911.2	140	99

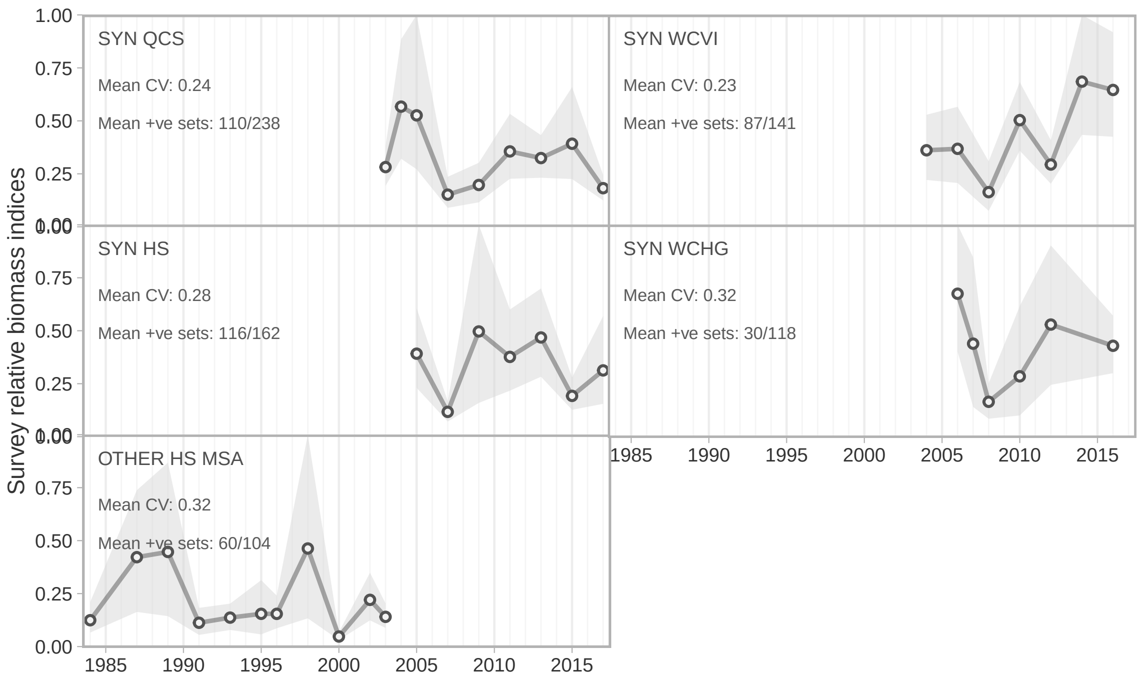

Figure A.5. Pacific Cod survey data for Canadian trawl surveys. Shown is relative biomass and associated lower and upper confidence intervals. Positive sets refers to the number of trawl sets that caught Pacific Cod.

A.2 NMFS TRIENNIAL SURVEY (IN CANADIAN WATERS)

A relative abundance index was developed for Area 3CD from data from the National Marine Fisheries Service (NMFS) Triennial survey operated off the lower half of Vancouver Island.

A.2.1 DATA SELECTION

Tow-by-tow data from the US National Marine Fisheries Service (NMFS) triennial survey covering the Vancouver INPFC (International North Pacific Fisheries Commission) region were provided by Mark Wilkins (NMFS, pers. comm.) for the seven years that the survey worked in BC waters (Table A.2, Figure A.6)). These tows were assigned to strata by the NMFS, although the size and definition of these strata have changed over the life of the survey. The NMFS survey database also identified in which country the tow was located. This information was plotted and checked against the accepted Canada/USA marine boundary: all tows appeared to be appropriately located with respect to country, based on the tow start position Figure A.6)). The NMFS designations were accepted for tows located near the marine border.

All usable tows had an associated median net width (with 1–99% quantiles) of 13.4 (11.3-15.7) m and median distance travelled of 2.8 (1.4–3.5) km, allowing for the calculation of the area swept by each tow. Biomass indices and the associated analytical CVs for Pacific Cod were calculated for the total Vancouver INPFC region and for each of the Canadian- and US-Vancouver sub-regions, using appropriate area estimates for each stratum and year. Strata that were not surveyed consistently in all seven years of the survey were dropped from the analysis, allowing the remaining data to provide a comparable set of data for each year.

Table A.2. Number of tows by stratum and by survey year for the NFMS triennial survey. Strata denoted with an asterisk have been excluded from the analysis due to incomplete coverage across the seven survey years or were from locations outside the Vancouver INPFC area.

Stratum No.	1980	1980	1983	1983	1989	1989	1992	1992	1995	1995	1998	1998	2001	2001
	CDN	US	CDN	US	CDN	US	CDN	US	CDN	US	CDN	US	CDN	US
10	-	15	-	7	-	-	-	-	-	-	-	-	-	-
11	38	-	-	34	-	-	-	-	-	-	-	-	-	-
12	-	-	32	-	-	-	-	-	-	-	-	-	-	-
17N	-	-	-	-	-	8	-	9	-	8	-	8	-	8
17S*	-	-	-	-	-	27	-	27	-	24	-	26	-	25
18N*	-	-	-	-	1	-	1	-	-	-	-	-	-	-
18S	-	-	-	-	-	31	-	20	-	12	-	20	-	14
19N	-	-	-	-	56	-	53	-	55	-	48	-	33	-
19S	-	-	-	-	-	4	-	6	-	3	-	3	-	3
27N	-	-	-	-	-	2	-	1	-	2	-	2	-	2
27S*	-	-	-	-	-	4	-	2	-	3	-	4	-	5
28N*	-	-	-	-	1	-	1	-	2	-	1	-	-	-
28S	-	-	-	-	-	6	-	9	-	7	-	6	-	7
29N	-	-	-	-	7	-	6	-	7	-	6	-	3	-
29S	-	-	-	-	-	3	-	2	-	3	-	3	-	3
30	-	4	-	2	-	-	-	-	-	-	-	-	-	-
31	7	-	-	11	-	-	-	-	-	-	-	-	-	-
32	-	-	5	-	-	-	-	-	-	-	-	-	-	-
37N*	-	-	-	-	-	-	-	-	-	1	-	1	-	1
37S*	-	-	-	-	-	-	-	-	-	2	-	1	-	1
38N*	-	-	-	-	-	-	-	-	1	-	-	-	-	-
38S*	-	-	-	-	-	-	-	-	-	2	-	-	-	3
39*	-	-	-	-	-	-	-	-	6	-	4	-	2	-
50	-	4	-	1	-	-	-	-	-	-	-	-	-	-
51	3	-	-	10	-	-	-	-	-	-	-	-	-	-
52	-	-	2	-	-	-	-	-	-	-	-	-	-	-
Total	48	23	39	65	65	85	61	76	71	67	59	74	38	72

The stratum definitions used in the 1980 and 1983 surveys were different than those used in subsequent surveys, particularly in Canadian waters. Consequently, these indices were not used in the 3CD stock assessment. The tow density was much higher in US waters although the overall number of tows was approximately the same for each country. This occurs because the size of the total area fished in the INPFC Vancouver area was about twice as large in Canadian waters than in US waters. Note that the northern extension of the survey has varied from year to year (Figure A.6), but this difference has been compensated for by using a constant survey area for all years and assuming that catch rates in the unsampled areas were the same as in the sampled area.

A reviewer from NOAA for Yellowtail Rockfish in 2014 noted that a number of the early Triennial survey tows had been deemed “water hauls” (catching no fish or invertebrates) and should be discarded. The tows used to estimate relative Pacific Cod biomass exclude these water haul tows.

A.2.2 TRIENNIAL SURVEY METHODS

When calculating the variance for this survey, it was assumed that the variance and CPUE within any stratum were equal, even for strata that were split by the Canada/USA border. The total biomass within a stratum that straddled the border was split between the two countries by the ratio of the relative area within each country:

$$B_{y_{i,c}} = B_{y_i} \frac{A_{y_{i,c}}}{A_{y_i}} \tag{A.5}$$

where $A_{y_{i,c}} =$ area (km^2) within country *c* in year *y* and stratum *i* and *B* represents biomass.

The variance *V* for that part of stratum *i* within country *c* was calculated as being in proportion to the ratio of the square of the area within each country *c* relative to the total area of stratum *i*. This assumption resulted in the CVs within each country stratum being the same as the CV in the entire stratum:

$$V_{y_{i,c}} = V_{y_i} \frac{A^2_{y_{i,c}}}{A^2_{y_i}}. \tag{A.6}$$

The partial variance for country *c* was used in instead of the total variance in the stratum when calculating the variance for the total biomass in Canadian or American waters.

The biomass estimates and the associated standard errors were adjusted to a constant area covered using the ratios of area surveyed. This was required to adjust the Canadian biomass estimates for 1980 and 1983 to account for the smaller area surveyed in those years compared to the succeeding surveys. he 1980 and 1983 biomass estimates from Canadian waters were consequently multiplied by the ratio 1.24 (= 9166 km^2 / 7399 km^2) to make them equivalent to the coverage of the surveys from 1989 onwards.

Biomass estimates were bootstrapped for 1000 random draws with replacement to obtain bias-corrected (Efron 1982) 95% confidence intervals for each year and for three area categories (total Vancouver region, Canadian-Vancouver only and US-Vancouver only) based on the distribution of biomass estimates and using the above equations.

Catch and effort data for strata i in year y yield catch per unit effort (CPUE) valuesU_{yi}. Given a set of data $\{C_{yij}, E_{yij}\}$ for tows$j = 1, \ldots, n_{yi}$,

$$U_{yi} = \frac{1}{n_{yi}} \sum_{j=1}^{n_{yi}} \frac{C_{yij}}{E_{yij}}, \tag{A.7}$$

where C_{yij} = catch (kg) in tow j, stratum i, year y; E_{yij} = effort (h) in tow j, stratum i, year y; and n_{yi} = number of tows in stratum i, year y.

CPUE values U_{yi} convert to CPUE densities δ_{yi} (kg/km2) using:

$$\delta_{yi} = \frac{1}{vw} U_{yi}, \tag{A.8}$$

where v = average vessel speed (km/h) and w = average net width (km).

Alternatively, if vessel information exists for every tow, CPUE density can be expressed

$$\delta_{yi} = \frac{1}{n_{yi}} \sum_{j=1}^{n_{yi}} \frac{C_{yij}}{D_{yij} w_{yij}}, \tag{A.9}$$

where C_{yij} = catch weight (kg) for tow j, stratum i, year y; D_{yij} = distance travelled (km) for tow$j$, stratum$i$, year$y$; w_{yij} = net opening (km) for tow$j$, stratum$i$, year$y$; and n_{yi} = number of tows in stratum$i$, year$y$.

The annual biomass estimate is then the sum of the product of CPUE densities and bottom areas across m strata:

$$B_y = \sum_{i=1}^{m} \delta_{yi} A_i = \sum_{i=1}^{m} B_{yi}, \tag{A.10}$$

where δ_{yi} = mean CPUE density (kg/km2) for stratum i, year y; A_i = area (km2) of stratum$i$; B_{yi} = biomass (kg) for stratum$i$, year$y$; and m = number of strata.

The variance of the survey biomass estimate V_y (kg^2) follows:

$$V_y = \sum_{i=1}^{m} \frac{\sigma_{yi}^2 A_i^2}{n_{yi}} = \sum_{i=1}^{m} V_{yi}, \tag{A.11}$$

where σ_{yi}^2 = variance of CPUE density (kg^2/km^4) for stratum i, year y and V_{yi} = variance of the biomass estimate (kg^2) for stratum$i$, year y.

The coefficient of variation (CV) of the annual biomass estimate for year y is

$$CV_y = \frac{\sqrt{V_y}}{B_y}. \tag{A.12}$$

A.2.3 TRIENNIAL SURVEY RESULTS

Relative biomass estimates and confidence intervals are shown in Table A.3 and Figure A.8. Pacific Cod are characterized with most catches taken along the shelf edge and in the deep gully entering Juan de Fuca Strait (e.g., Figure A.6). A more consistent biomass estimate was obtained by excluding deep strata that were not covered in the earlier surveys. Figure A.7 shows that this species was mainly found between 57 and 256 m (1 and 99% quantiles of bottom depth), with infrequent observations at depths up to 326 m which means that the deeper strata (>367 m) are not needed to monitor Pacific Cod. Note that the deep strata which were not used in the biomass estimation are included in Figure A.7.

Table A.3. Biomass estimates and confidence intervals for the Triennial NMFS survey relevant to Canadian waters.

Year	Biomass	Mean	Lower	Upper	CV	Analytical CV
1989	5142	5022	2751	8726	0.30	0.30
1992	2023	2011	1091	3119	0.26	0.26
1995	1662	1685	620	4410	0.53	0.53
1998	631	623	369	975	0.24	0.26
2001	836	838	356	1464	0.33	0.36

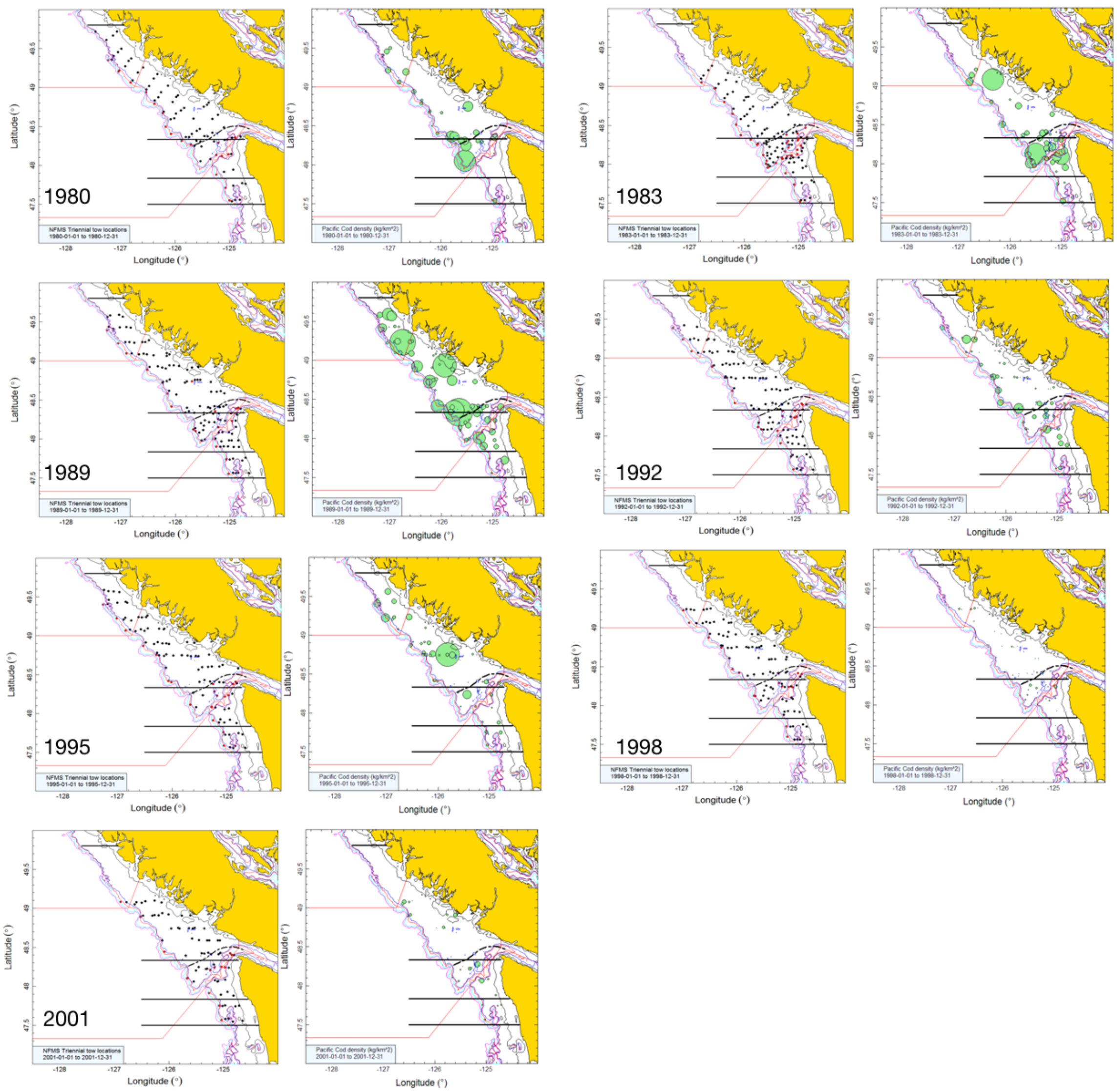

Figure A.6. (Left panels): plot of tow locations in the Vancouver INPFC region for the NMFS triennial survey in US and Canadian waters. Tow locations are colour-coded by depth range: black=55–183m; red=184-366m; grey=367-500m. Dashed line shows approximate position of the Canada/USA marine boundary. Horizontal lines are the stratum boundaries: 47 30, 47 50, 48 20 and 49 50. Tows south of the 47 30 line were not included in the analysis. (Right panels): circle sizes in the density plot are scaled across all years (1980, 1983, 1989, 1992, 1995, 1998, and 2001), with the largest circle = 7,229 kg/km2 in 1989. The red solid lines indicate the boundaries between PMFC areas 3B, 3C and 3D.

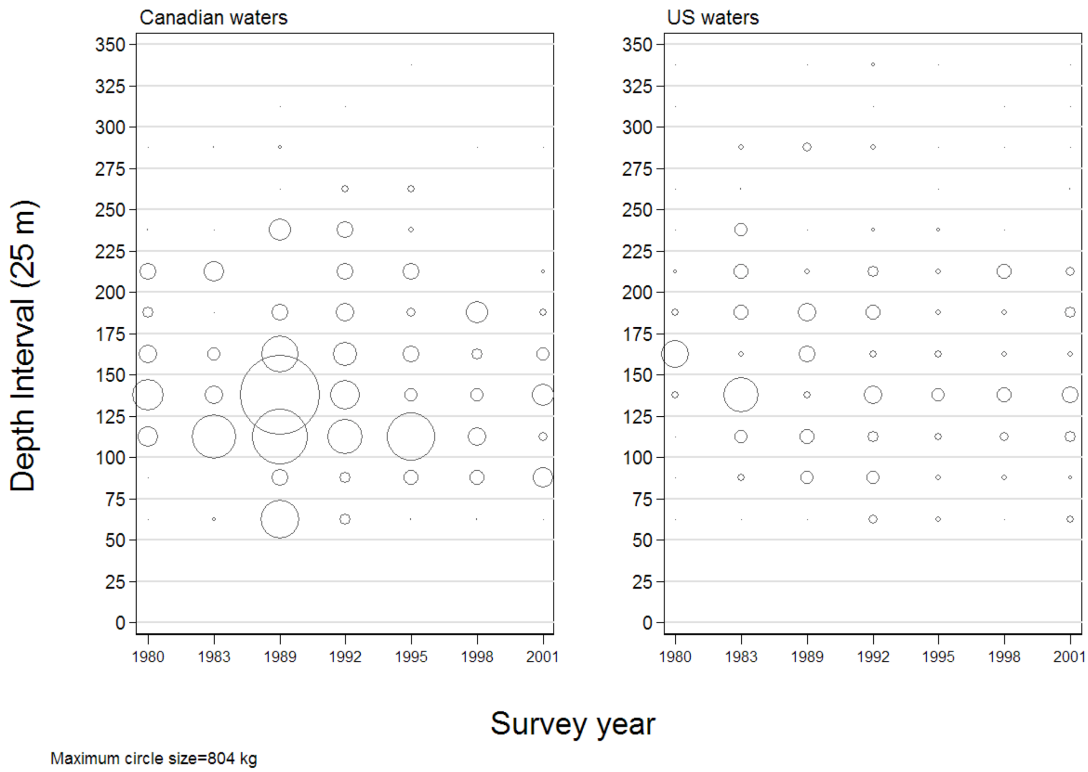

Figure A.7. Distribution of Pacific Cod catch weights for each survey year summarised into 25 m depth intervals for all tows (Table B.2) in Canadian and US waters of the Vancouver INPFC area. Catches are plotted at the mid-point of the interval. Note that the deep strata introduced in 1995 (see Table B.2) have been included in this plot but were not used in the biomass estimation.

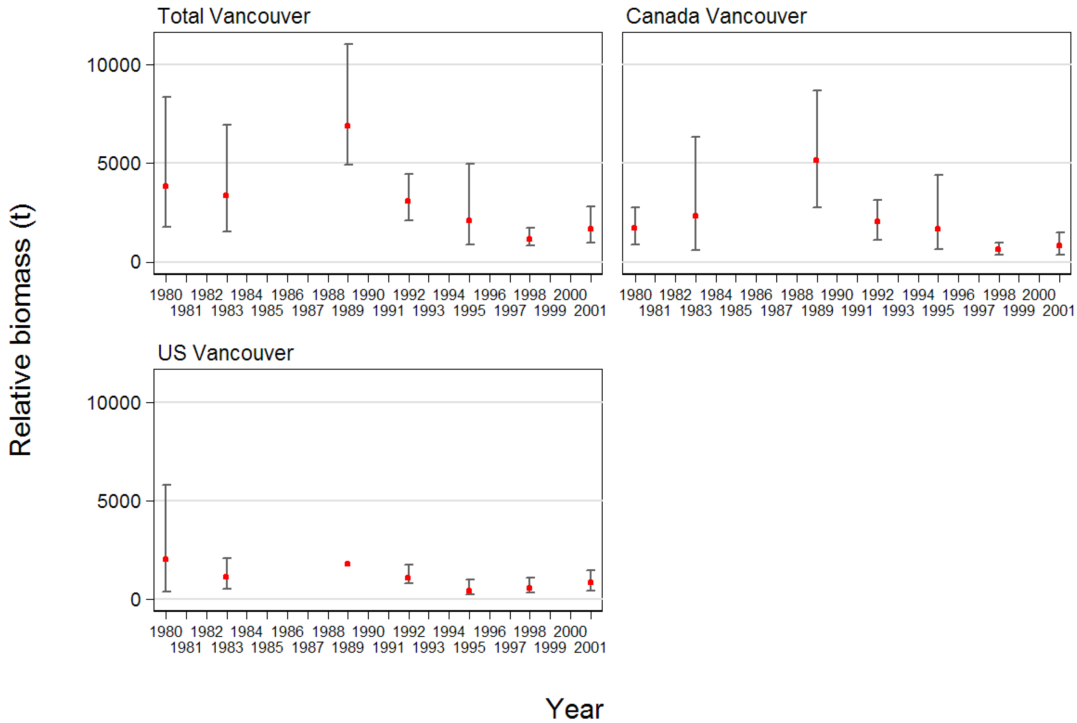

Figure A.8. Biomass estimates for three series of Pacific Cod in the INPFC Vancouver region (total region, Canadian waters only, US waters only) with 95% error bars estimated from 1000 bootstraps.

APPENDIX B. COMMERCIAL CPUE STANDARDIZATION

We sought to generate an index of Pacific Cod abundance from commercial trawl catch per unit effort data that was standardized for depth, fishing locality (defined spatial regions; Figures B.1, B.2), month, vessel, and latitude, when available. Before fitting a standardization model, we had to filter and manipulate the available catch and effort data to generate a dataset appropriate for model fitting. In the following sections we describe those decisions for the 'historical' (1956–1995) and 'modern' data (1996–2017). We then describe our index standardization model, explore the contribution of the various standardization components, and identify the effect of including or ignoring space-time interactions.

B.1 DEFINING THE 1956–1995 FLEET

Commercial groundfish bottom trawl data prior to 1991 was recorded via dockside interviews and aggregated to fishing locality and trip combinations. Data from 1991 to 1995 was recorded via logbooks at the fishing-event (trawl) level. We therefore aggregated the 1991–1995 data to the locality-trip level (hereafter referred to as 'trips' in this appendix) to match the resolution of the earlier data. When aggregating this 1991–1995 data, we removed any trawl events that were longer than five hours, since these are likely to be data entry errors. During these time periods, the variables depth, date, and locality are available as model covariates.

B.2 DEFINING THE 1996–2017 FLEET

Commercial groundfish bottom trawl data from 1996 to present have been recorded to the fishing-event level in the presence of on-board observers or video monitoring. We have treated this modern dataset separately from the historical dataset to (1) take advantage of the higher data resolution, (2) include information on latitude and vessel ID in our standardization model, and (3) to avoid assuming a constant catchability and relationship between CPUE and the standardization covariates across major regulatory changes.

Since we have data on individual vessels for this modern fleet, and in keeping with previous analyses for Pacific groundfish stocks, we defined a 'fleet' for the modern dataset that includes only vessels that qualify by passing some criteria of regularly catching Pacific Cod. We follow the approach used in a number of recent BC groundfish stock assessments by requiring vessels to have caught the species in at least 100 tows across all years of interest, and to have passed a threshold of five trips (trips that recorded some of the species) for at least five years — all from 1996 to 2017.

B.3 DEFINING THE STANDARDIZATION MODEL PREDICTORS

For depth and latitude, we binned the values into a sequence of bands to allow for nonlinear relationships between these predictors and CPUE (e.g. Maunder and Punt 2004). For depth, we binned trawl depth into bands 25m wide. For latitude, we used bands that were 0.1 degrees wide. To ensure sufficient data to estimate a coefficient for each factor level, we limited the range of depth bins to those that fell within the 0.1% to 99.9% cumulative probability of positive observations and then removed any factor levels (across all predictors) that contained fewer than 0.1% of the positive observations.

Predictors that are treated as factors in a statistical model need a reference or base level — a level from which the other coefficients for that variable estimate a difference. The base level then becomes the predictor value that is used in the prediction for the standardized index. We chose the most frequent factor level as the base level — a common choice for these types of models (Maunder and Punt 2004). For example, we set the base month as the most common month observed in the dataset filtered for only tows where the species was caught. This choice of base level only affects the intercept or relative magnitude of our index because of the form of our model (discussed below). This relative magnitude should not affect the outcomes of the stock assessment model because we estimated separate catchabilities for each commercial CPUE index.

B.4 A TWEEDIE GLMM INDEX STANDARDIZATION MODEL

Fisheries CPUE data contains both zeros and positive continuous values. A variety of approaches have been used in the fishery literature to model such data. One approach has been to fit a delta-GLM (generalized linear model) — a model that fits the zero vs. non-zero values with a logistic regression (a binomial GLM and a logit link) and the positive values with a linear regression fit to log-transformed data or a Gamma GLM with a log link (e.g. Maunder and Punt 2004, Thorson and Ward 2013). The probability of a non-zero CPUE from the first component can then be multiplied by the expected CPUE from the second component to derive an unconditional estimate of CPUE. However, this approach suffers from a number of issues:

1. The delta-GLM approach adds complexity by needing to fit and report on two models.
2. In the typical delta-GLM approach, the two models are fit with separate links and so the coefficients cannot be combined.
3. The delta-GLM approach assumes independence among the two components (e.g. Thorson 2017).
4. The delta-GLM approach has been shown to be insufficiently robust to variable sampling intensity (e.g. in time or space) (Lecomte et al. 2013).
5. Perhaps most importantly for our purpose, a delta-GLM in which the two models use different links renders a final index in which the index trend is dependent on the specific reference levels that the predictors are set to (e.g. Maunder and Punt 2004).

The Tweedie distribution (Jorgensen 1987) solves the above problems (e.g. Candy 2004, Shono 2008, Foster and Bravington 2013, Lecomte et al. 2013, Thorson 2017) but has not seen widespread use presumably mostly because of the computational expense of calculating the Tweedie probability density function. Recently, the Tweedie density function has been introduced to the software TMB (Kristensen et al. 2016) and can be fit relatively quickly to large datasets and for models with many fixed and random effect parameters either with custom written TMB models or via the glmmTMB R package (Brooks et al. 2017).

In addition to a mean parameter, the Tweedie distribution has two other parameters: a power parameter p and a dispersion parameter ϕ. If $1 > p > 2$ then the Tweedie distribution represents a compound distribution between the Poisson ($p = 1$) and the Gamma distribution ($p = 2$) (Figure B.3). In fact, the Tweedie is alternatively referred to as the compound-Poisson-Gamma distribution in this bounded case. We note, however, that the compound-Poisson-Gamma distribution is often used to refer to a re-parameterization in which the Poisson and Gamma components are fit so that they are not assumed to have the same predictive coefficients as they are in the

Tweedie distribution (Foster and Bravington 2013, Lecomte et al. 2013).

We fit the Tweedie GLMM (generalized linear mixed effect model) as

$$y_i \sim \mathrm{Tweedie}(\mu_i, p, \phi), \quad 1 < p < 2, \tag{B.1}$$

$$\mu_i = \exp\left(\boldsymbol{X}_i \boldsymbol{\beta} + \alpha^{\mathrm{locality}}_{j[i]} + \alpha^{\mathrm{locality-year}}_{k[i]} + \alpha^{\mathrm{vessel}}_{l[i]}\right), \tag{B.2}$$

$$\alpha^{\mathrm{locality}}_{j} \sim \mathrm{Normal}(0, \sigma^2_{\alpha\ \mathrm{locality}}), \tag{B.3}$$

$$\alpha^{\mathrm{locality-year}}_{k} \sim \mathrm{Normal}(0, \sigma^2_{\alpha\ \mathrm{locality-year}}), \tag{B.4}$$

$$\alpha^{\mathrm{vessel}}_{l} \sim \mathrm{Normal}(0, \sigma^2_{\alpha\ \mathrm{vessel}}), \tag{B.5}$$

where i represents a single trip (historical data) or tow (modern data), y_i represents the catch (kg) per unit effort (hours trawled), $\boldsymbol{X_i}$ represents a vector of fixed-effect predictors (historical: depth bins, months; modern: depth bins, months, latitude bins), $\boldsymbol{\beta}$ represents a vector of coefficients, and μ_i represents the expected CPUE in a trip or tow. The random effect intercepts (α symbols) are allowed to vary from the overall intercept by locality j ($\alpha^{\mathrm{locality}}_{j}$), locality-year k ($\alpha^{\mathrm{locality-year}}_{k}$), and vessel l ($\alpha^{\mathrm{vessel}}_{l}$) (for the modern dataset only) and are constrained by normal distributions with respective standard deviations denoted by σ parameters.

We can then calculate the standardized estimate of CPUE for year t, μ_t, as

$$\mu_t = \exp\left(\boldsymbol{X}_t \boldsymbol{\beta}\right) \tag{B.6}$$

where $\boldsymbol{X_t}$ represents a vector of predictors set to the reference (r) levels with the year set to the year of interest. Because each of the α random intercepts is set to zero, the index is predicted for an average locality, locality-year, and vessel (for modern data). We estimated the fixed effects with maximum marginal likelihood while integrating over the random effects with the statistical software TMB via the R package glmmTMB. We used standard errors (SE) as calculated by TMB on $\log(\mu_t)$ via the delta method. We then calculated the 95% Wald confidence intervals as $\exp(\mu_t \pm 1.96\mathrm{SE}_t)$.

For comparison, we calculated an unstandardized timeseries using a similar procedure but without any of the covariates other than a factor predictor for each year. This is similar to calculating the geometric mean of CPUE each year but with an assumed Tweedie observation model instead of a lognormal observation model that does not allow for zeros.

B.5 COMMERCIAL CPUE STANDARDIZATION RESULTS

The raw Pacific Cod catch and total fleet effort show variable trends through time in both the historical and modern datasets (Figure B.4). The majority of positive fishing events for Pacific Cod occurred at depths ranging from approximately 50m to 200m (Figure B.5). We can see an increase in the total number of trip-locality combinations since 1991, some changes to the localities typically fished, and an introduction of trips with deeper average fishing depths towards the end of the 1956–1995 period (Figure B.6, B.7). For the modern datasets, we see some changes to the distribution of fished depths, latitudes, and months through time, along with changes to the vessels participating in the 'fleet' and the localities fished (Figure B.8, B.9).

The Tweedie GLMM index standardization models fit the data relatively well (Figure B.10). The Tweedie p parameters tended to be around 1.6, indicating a distribution roughly midway between the Poisson and Gamma distributions and the ϕ parameters indicated relatively dispersed observations (Table B.1). There was considerably more variability across the locality and locality-year random effects than the vessel random effects (Table B.1).

For the 1956–1995 time period, depth and locality had a moderate effect on the standardized CPUE index for 3CD, but the standardized and unstandardized series differed little in 5ABCD (Figure B.11). Accounting for either depth or locality reduced the 3CD CPUE in the 1970s and increased the CPUE from the mid 1980s to 1995. Accounting for depth also reduced a spike in CPUE in 3CD in the mid 1960s. For the 1996–2017 time period, depth and latitude had the largest effect on the standardized index, and again had a larger effect in 3CD than 5ABCD (Figure B.12). Accounting for depth or latitude somewhat decreased the CPUE index for two to three years before and after 2010 and this effect carried through to the standardization model with all covariates.

Accounting for locality-year interactions had little effect on the shape of the standardized indices with the exception of a slight change in shape 2014–2015 for the modern dataset in 5ABCD (Figure B.13). The main effect of including the locality-year random effect interactions was to increase the width of the confidence intervals in all areas and time periods. We can examine the contribution of all the fixed and random effect parameters via coefficient plots (historical: Figures B.14, B.15, B.16; modern: Figures B.17, B.18, B.19).

B.6 SPACE-TIME (LOCALITY-YEAR) INTERACTIONS

To test the effect of including or not including space-time interactions when such interactions are or are not present, we performed a simulation test. While a full simulation test with many stochastic iterations and a range of parameter values is beyond the scope of this appendix, we think this simple simulation remains instructive. We parameterized our simulation to approximately match the parameters estimated from observed data. Our simulation included 20 years of data; 12 localities with their effects ($\alpha_j^{\mathrm{locality}}$) in log space drawn from a normal distribution with a standard deviation of 0.3 and mean 0; optional year-locality random effects ($\alpha_j^{\mathrm{locality-year}}$) drawn from a distribution with a standard deviation of 0.5 and mean of 0; 10 observations per year per locality; a true known CPUE index that, in log space, followed an auto-regressive process with correlation of 0.3 at lag 1, standard deviation of 1 and a mean of 2; and Tweedie parameters of $p = 1.6$ and $\phi = 5$. We generated versions of this dataset with and without the locality-year interactions and then fit standardization models to those datasets that either allowed for or ignored locality-year interactions.

For the real data, including locality-year random effects allowed for each locality to have a trend that deviates slightly from the overall trend (Figure B.20). Omitting these locality-by-year random effects, on the other hand, assumed that the CPUE trend is identical in shape and only deviated in magnitude across localities (Figure B.21). Ignoring these space-time interactions can result in confidence intervals that are substantially too narrow if the trends are not in fact identical across space (Figure B.22). Furthermore, allowing for the interactions has no qualitative effect on model performance or coverage if the interactions are not present (Figure B.22).

Fitting a proper geostatistical spatiotemporal standardization model would be an alternative to these locality-year random effects (e.g. Thorson et al. 2015, Monnahan and Stewart 2018). For this assessment, we chose to model spatial variation through the DFO localities to maintain consistency with previous assessments in this region. However, in the future we may explore a spatiotemporal standardization model.

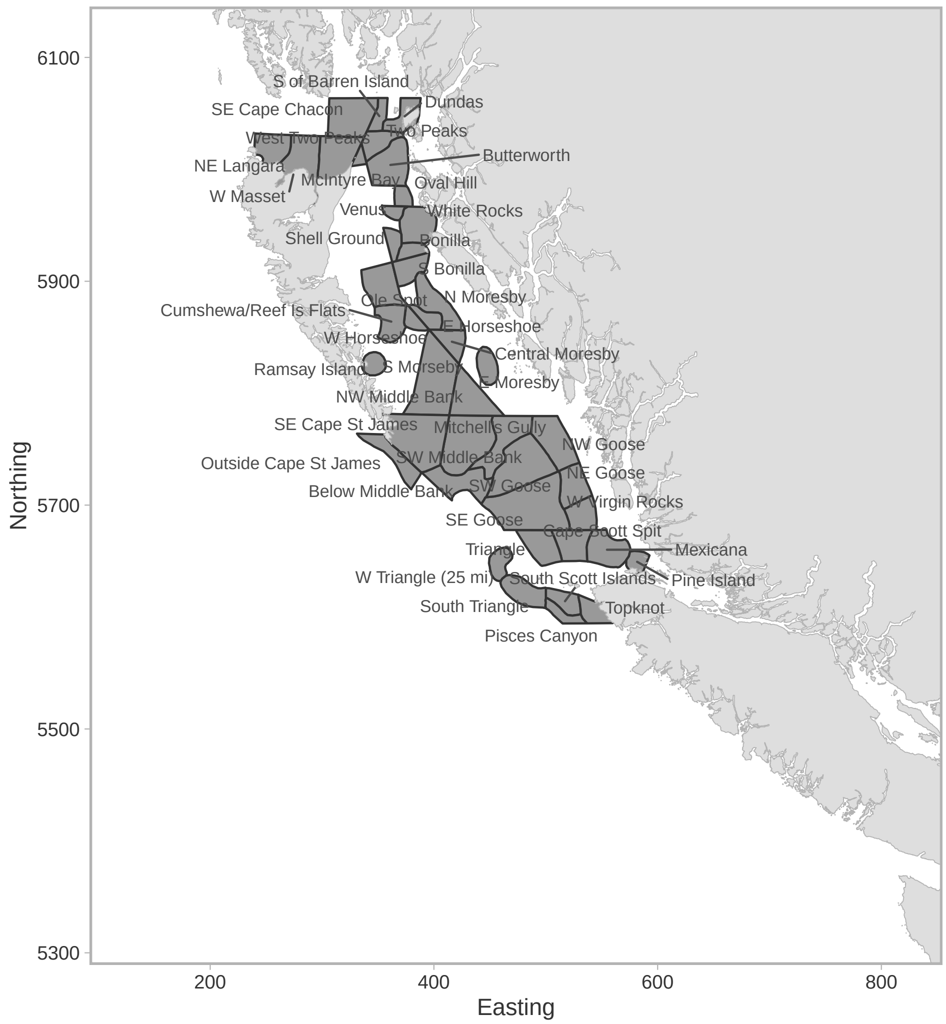

Figure B.1. DFO localities used in the 5ABCD modern CPUE standardization model.

Table B.1. Random effect standard deviation (SD) and Tweedie observation model power (p) and dispersion (ϕ) parameter estimates.

Model	Parameter	Estimate
Historical 3CD	locality SD	0.83
Historical 3CD	year-locality SD	0.83
Historical 3CD	p	1.58
Historical 3CD	ϕ	17.88
Historical 5ABCD	locality SD	0.82
Historical 5ABCD	year-locality SD	0.79
Historical 5ABCD	p	1.61
Historical 5ABCD	ϕ	16.22
Modern 3CD	locality SD	0.44
Modern 3CD	vessel SD	0.21
Modern 3CD	year-locality SD	0.67
Modern 3CD	p	1.60

Model	Parameter	Estimate
Modern 3CD	ϕ	11.29
Modern 5ABCD	locality SD	1.06
Modern 5ABCD	vessel SD	0.25
Modern 5ABCD	year-locality SD	0.77
Modern 5ABCD	p	1.65
Modern 5ABCD	ϕ	10.54

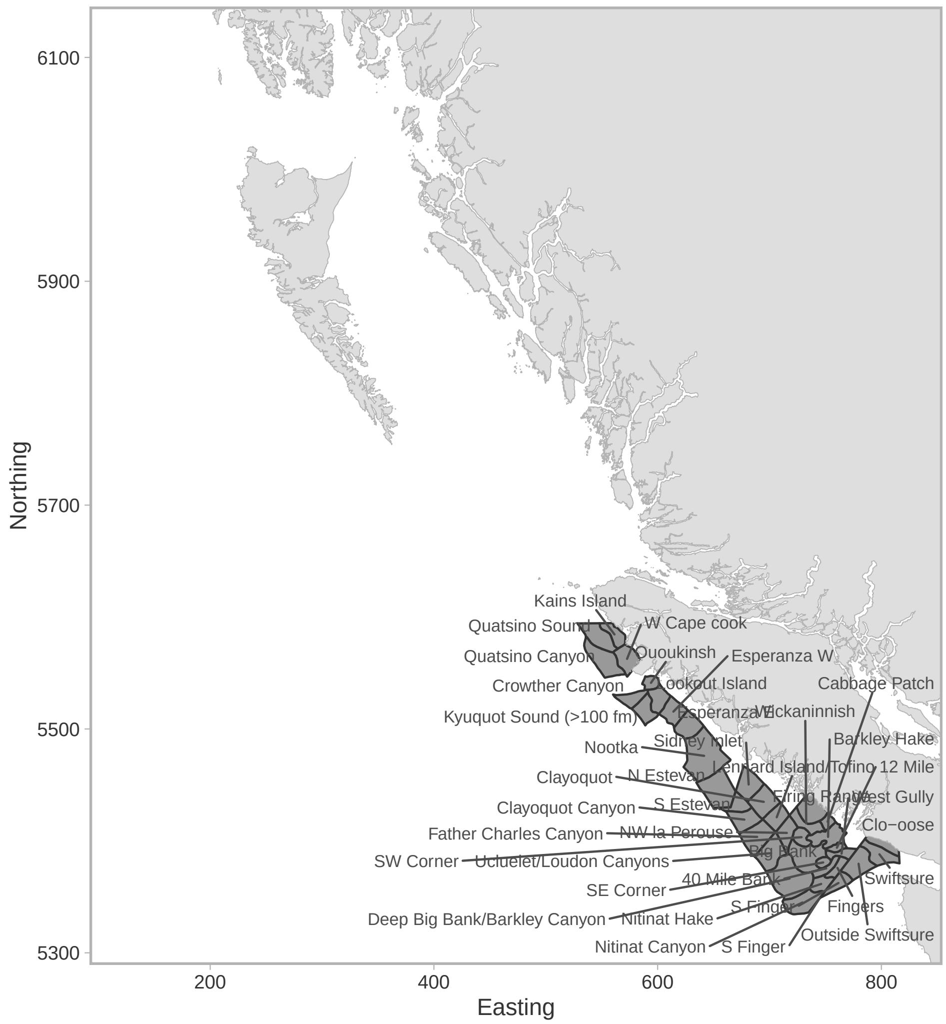

Figure B.2. DFO localities used in the 3CD modern CPUE standardization model.

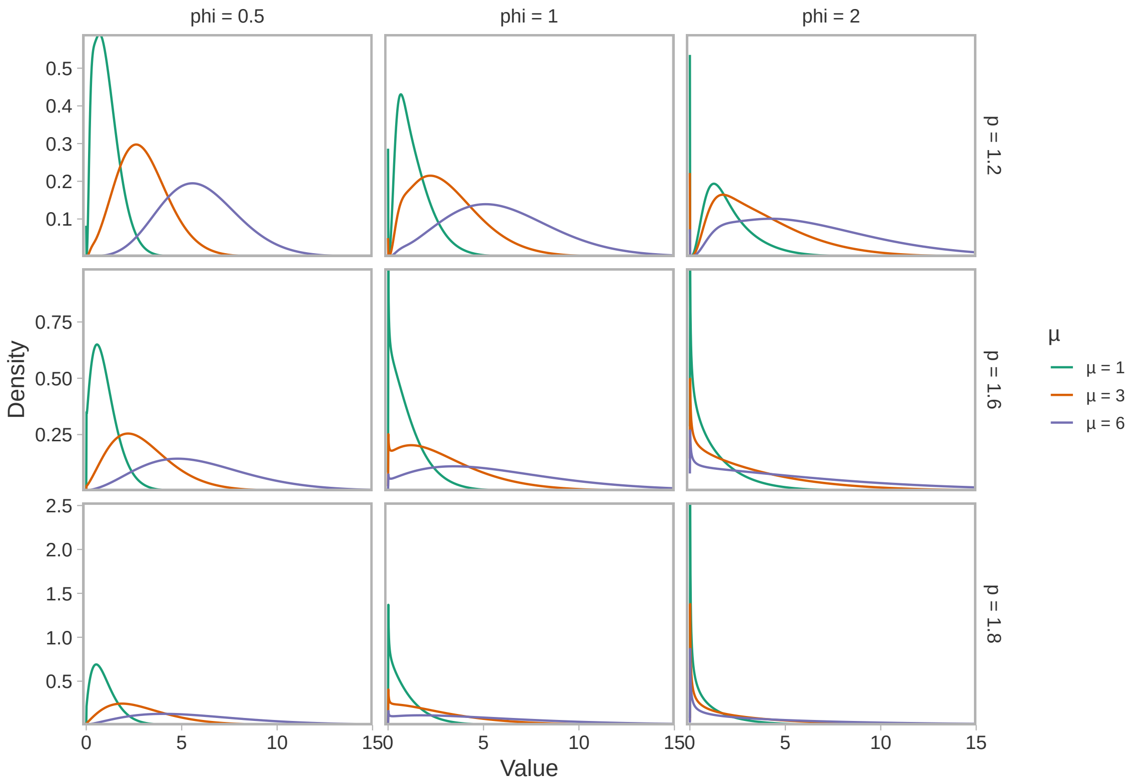

Figure B.3. Example density functions for the Tweedie distribution. The symbol ϕ (written as phi in this figure) represents the dispersion parameter, p represents the power parameter, and μ represents the mean. Note that the spike in density that is seen towards the left of the panels is at a value of 0 on the x axis.

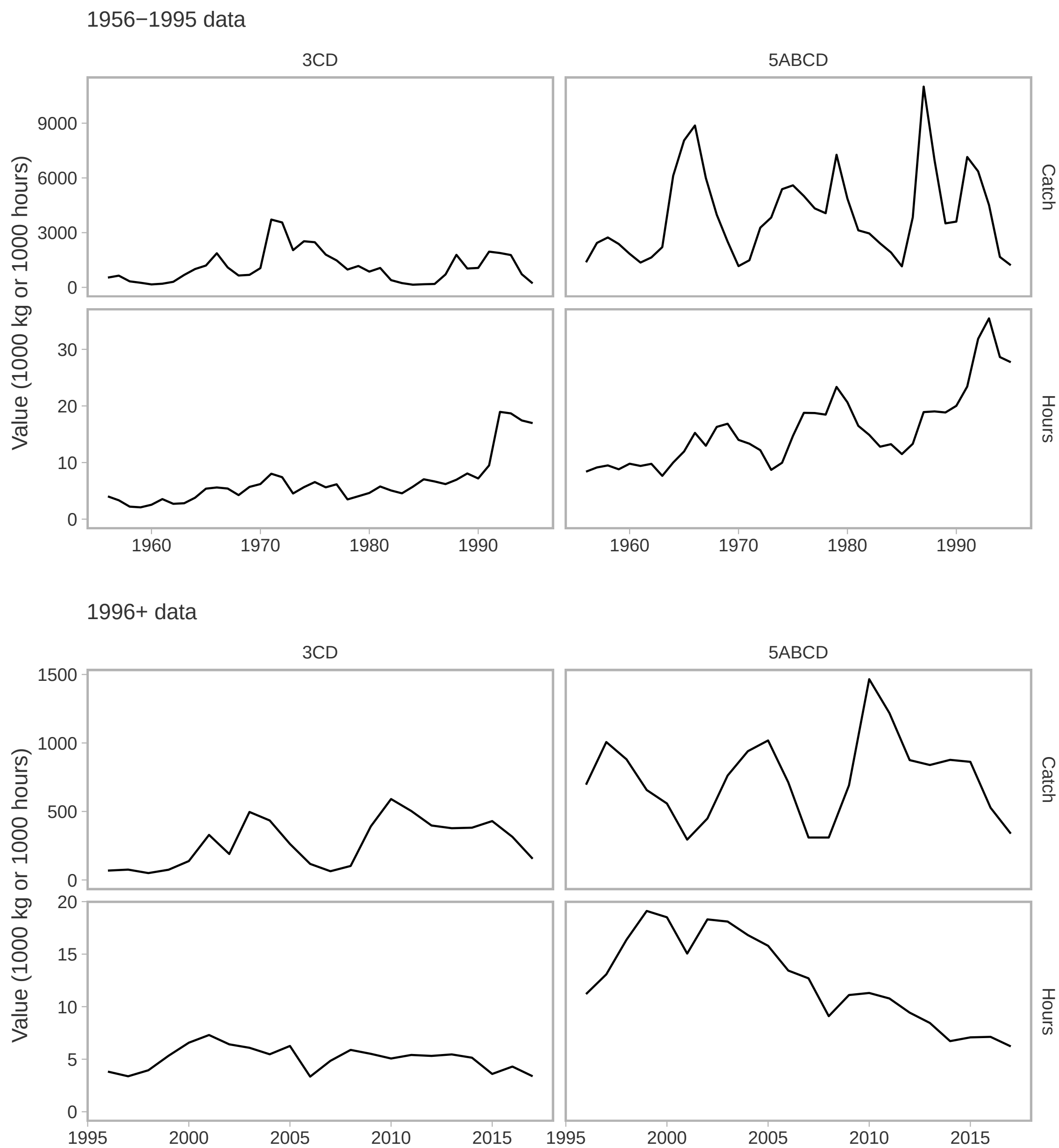

Figure B.4. Raw time series of Pacific Cod catch and total hours trawled (regardless of species caught). Data prior to 1996 is shown separately from data after 1996.

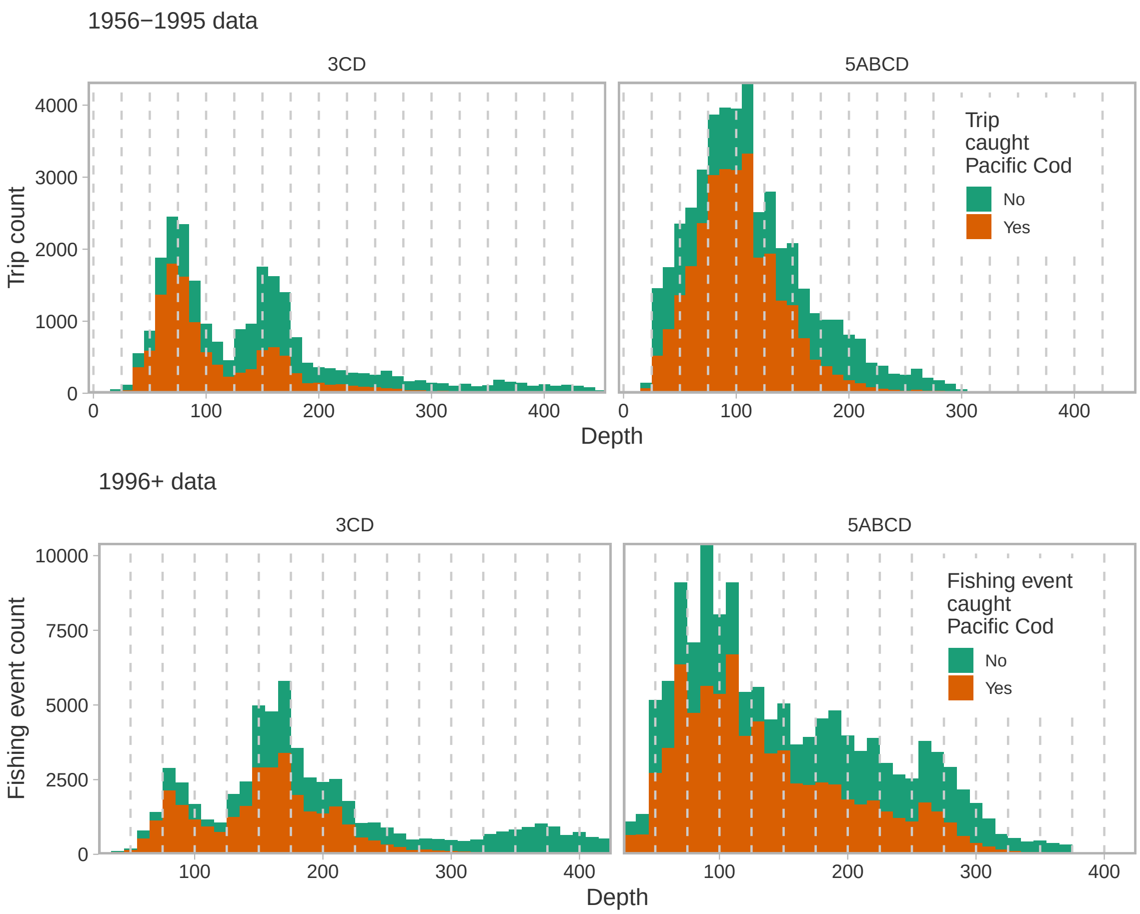

Figure B.5. The depth distribution for fishing trips (top row) and fishing trawl events (bottom row) that caught Pacific Cod or did not catch Pacific Cod.

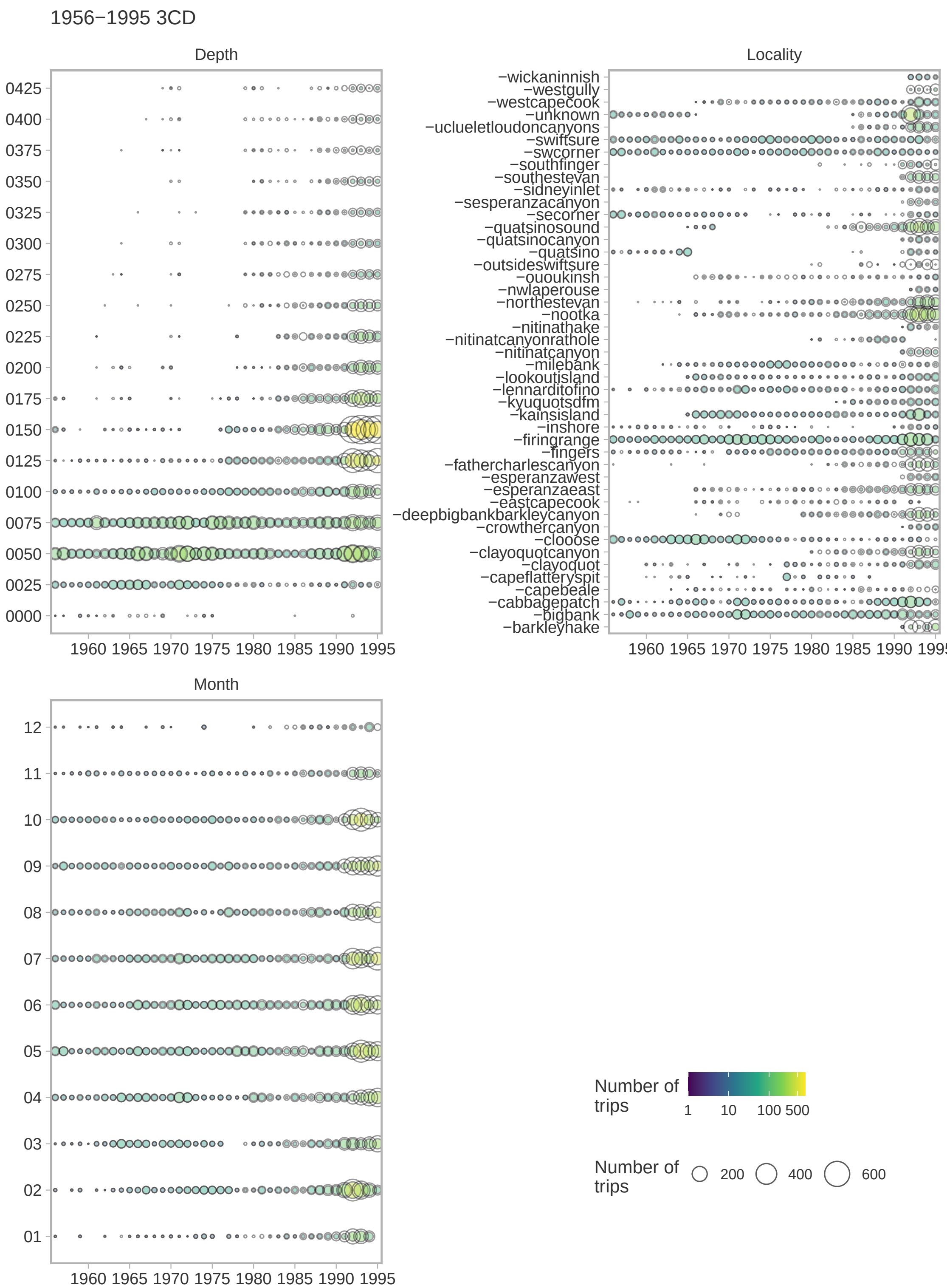

Figure B.6. Distribution of predictors in CPUE standardization models for 1956–1995 3CD dataset. Area of outermost circles represents the number of trip-locality combinations for that predictor value and year combination. Area and shading of innermost circles represents the number of trip-locality combinations for that predictor value and year combination that caught Pacific Cod.

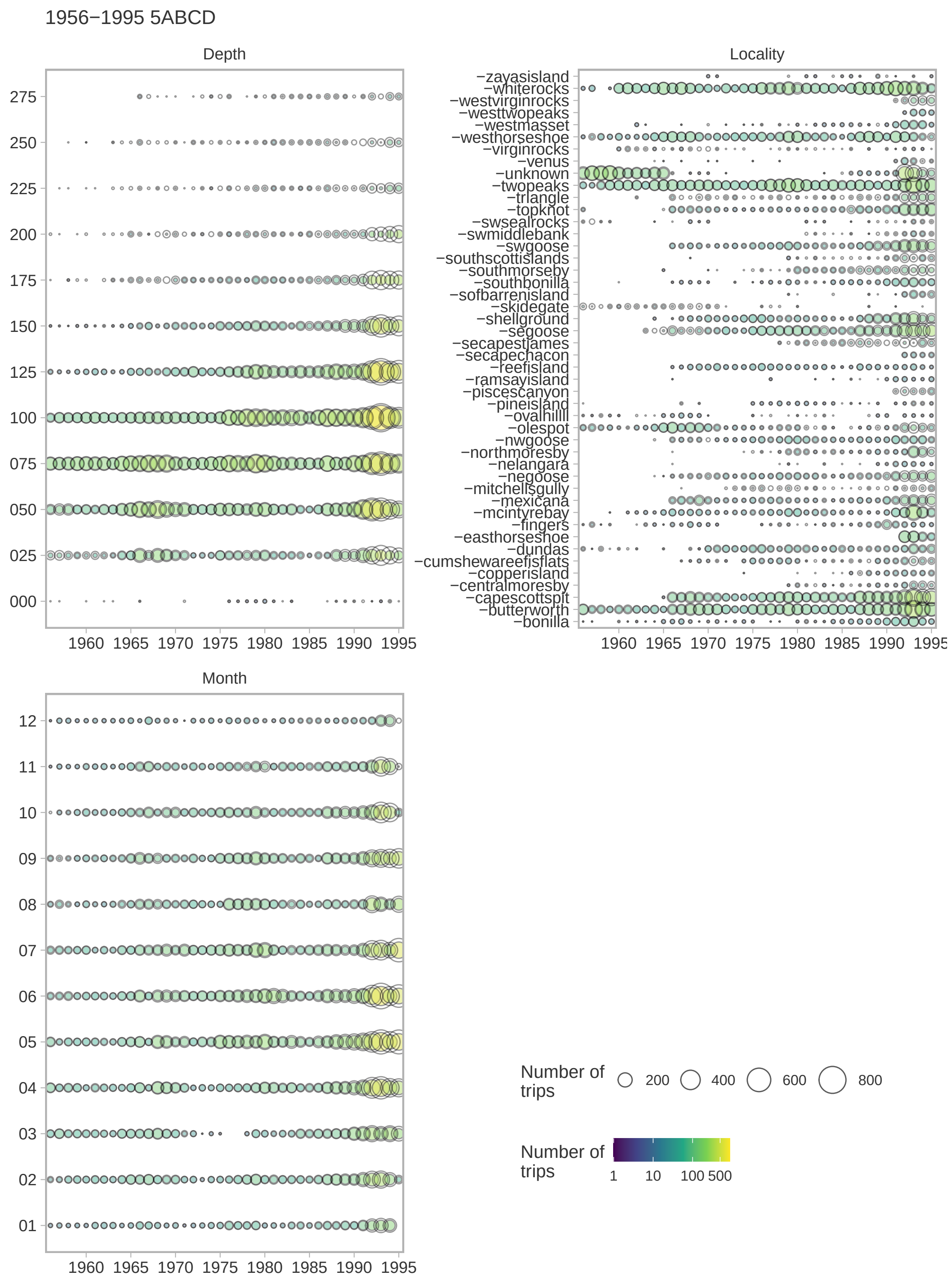

Figure B.7. Same as Figure B.6 but for 5ABCD.

Figure B.8. Same as Figure B.6 but for 1996–2017 3CD.

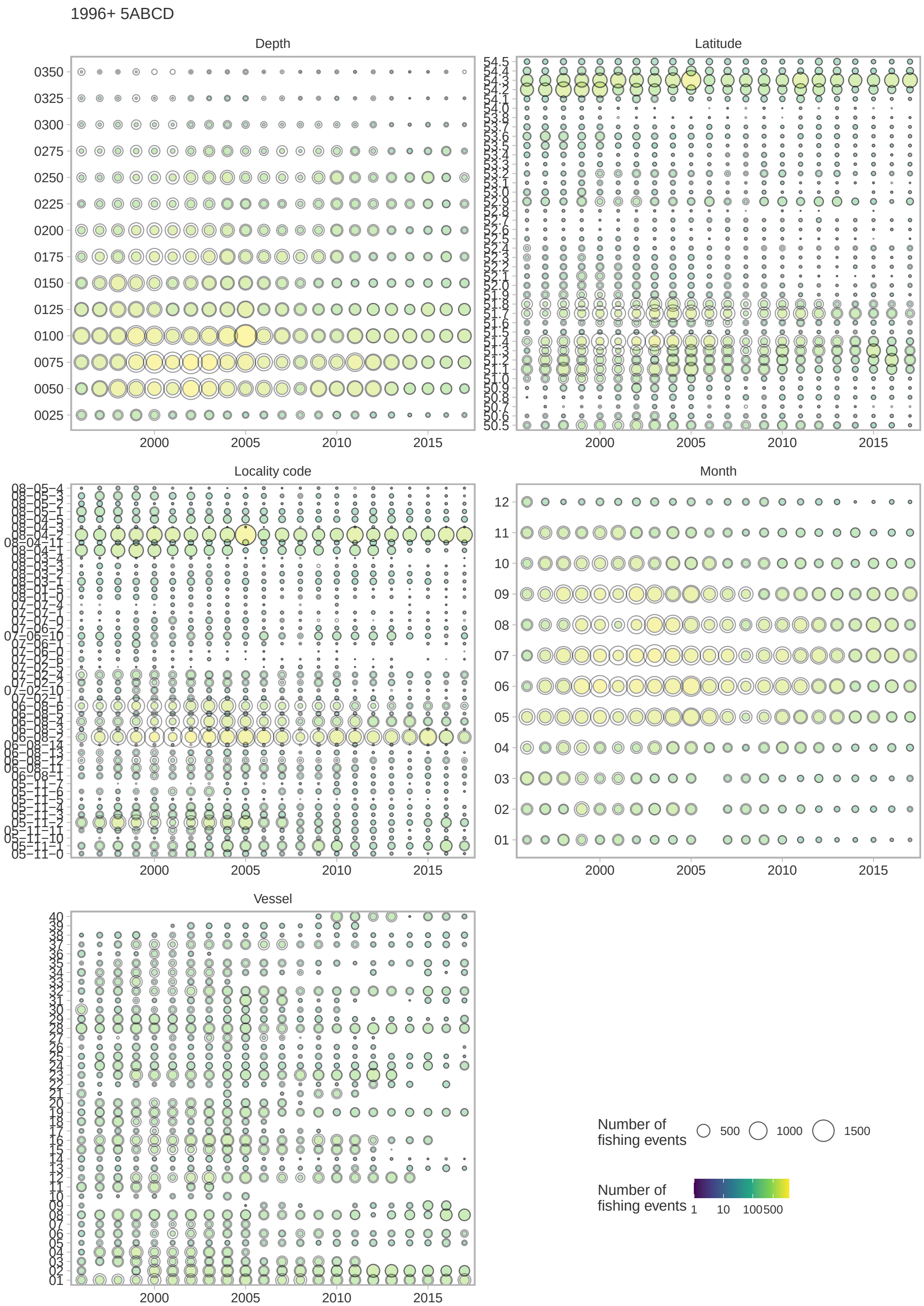

Figure B.9. Same as Figure B.6 but for 1996–2017 5ABCD.

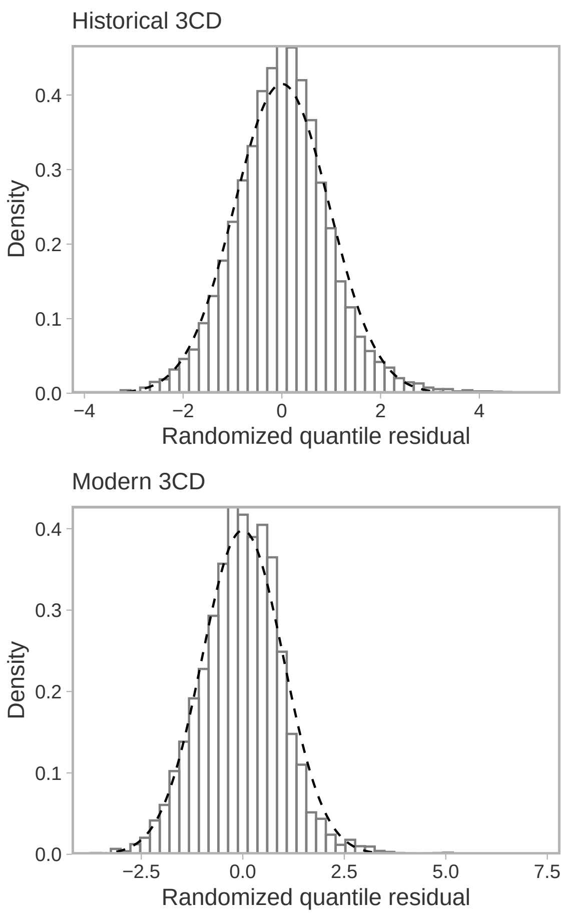

Figure B.10. Histograms of randomized quantile residuals (Dunn and Smyth 1996) for the CPUE GLMM standardization models. The histograms illustrate the actual density distribution of 10,000 randomly selected randomized quantile residuals. The dashed lines show the probability density for a normal distribution with the same standard deviation.

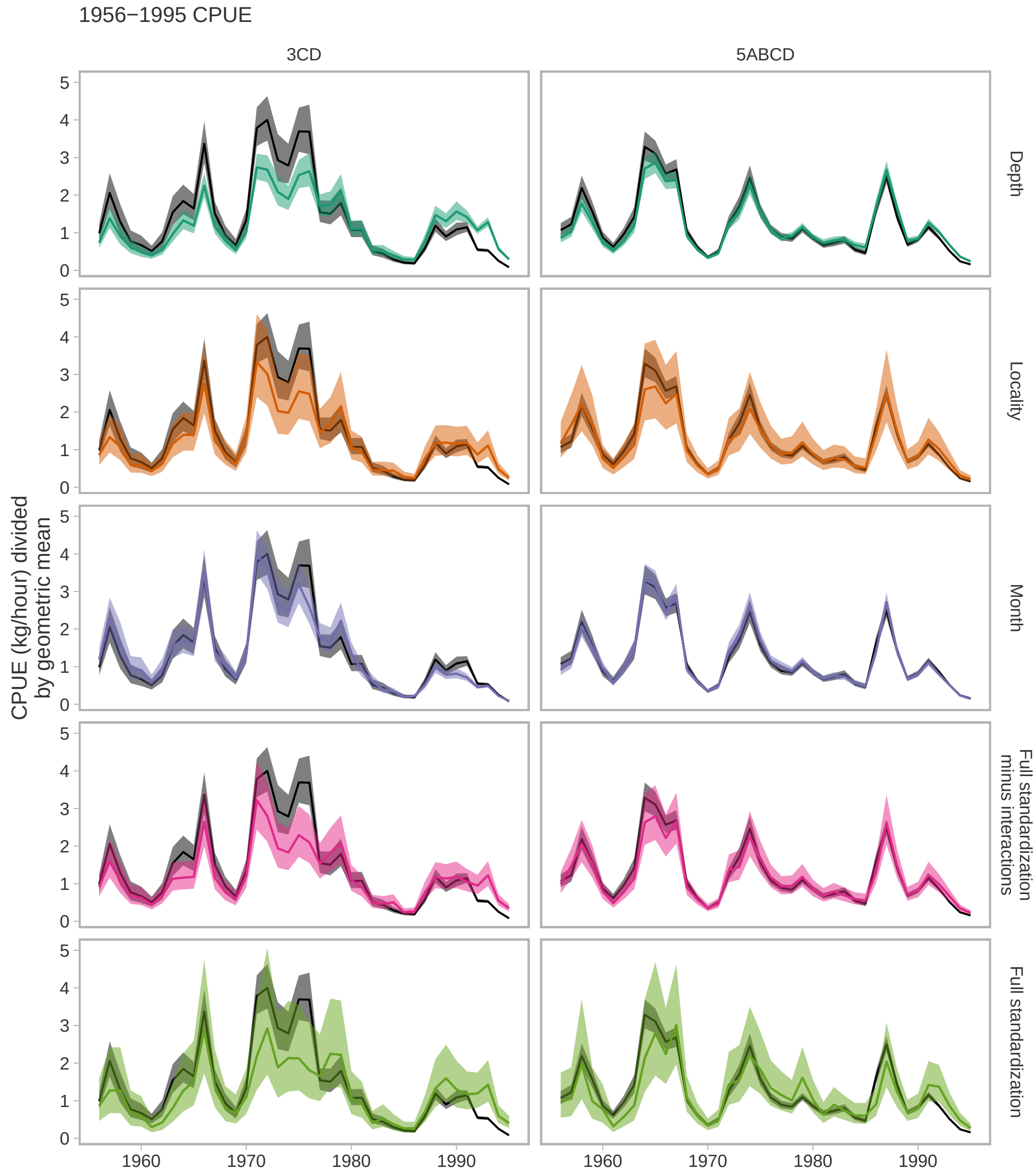

Figure B.11. Commercial trawl CPUE standardization models. Throughout, the black line and shaded region indicate a CPUE index with only a year predictor. The coloured line and shaded ribbons indicate indices that have been standardized by one or more predictors. The first three rows illustrate standardization models that include a single predictor listed on the right. The second last row illustrates a standardization model that includes all the predictors in one model. The last row illustrates 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.

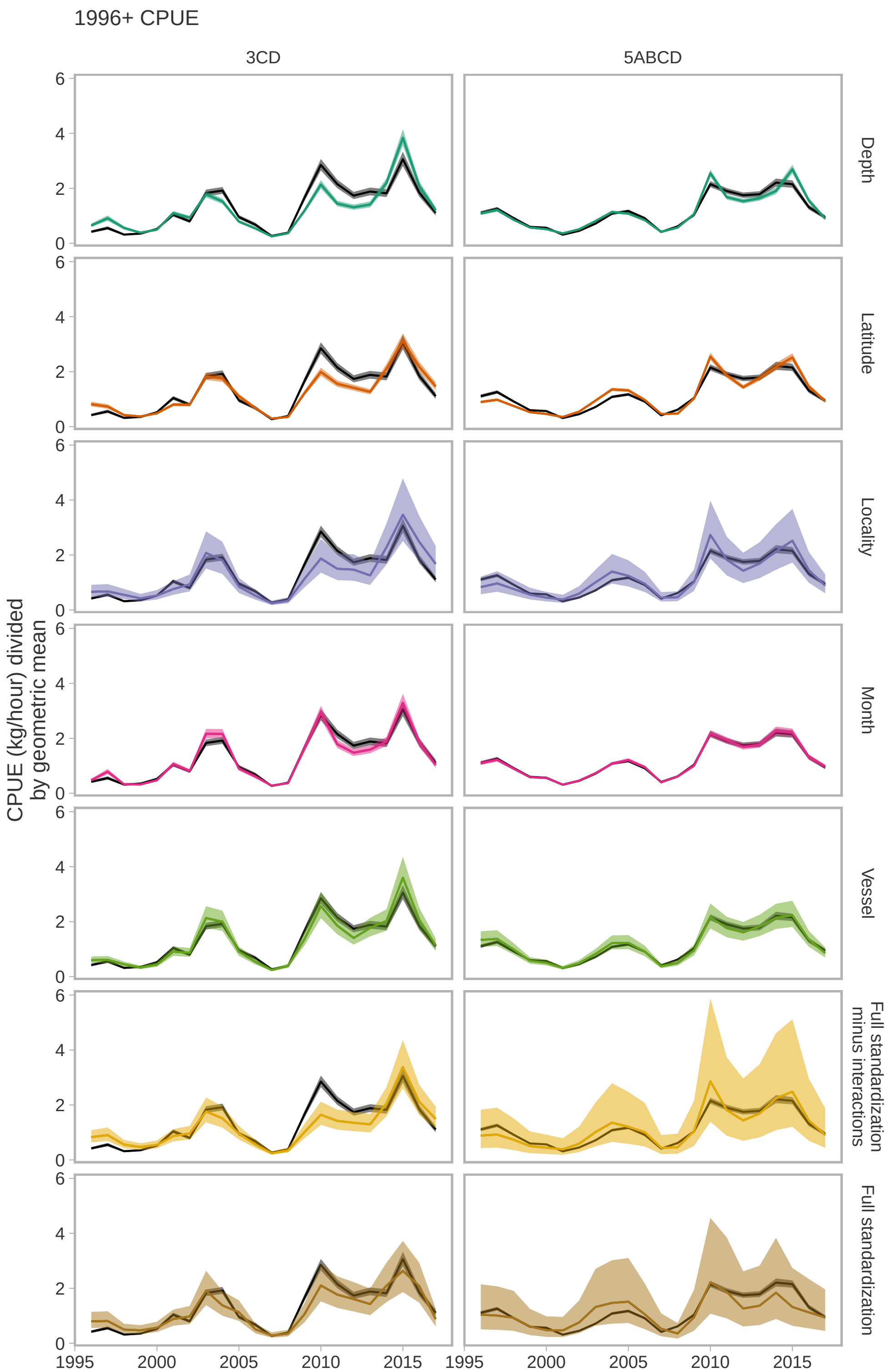

Figure B.12. Same as Figure B.11 but for the 1996 to 2017 data. Locality, vessel, and locality-year interactions are fit as random effects and all other variables are fit as fixed effects.

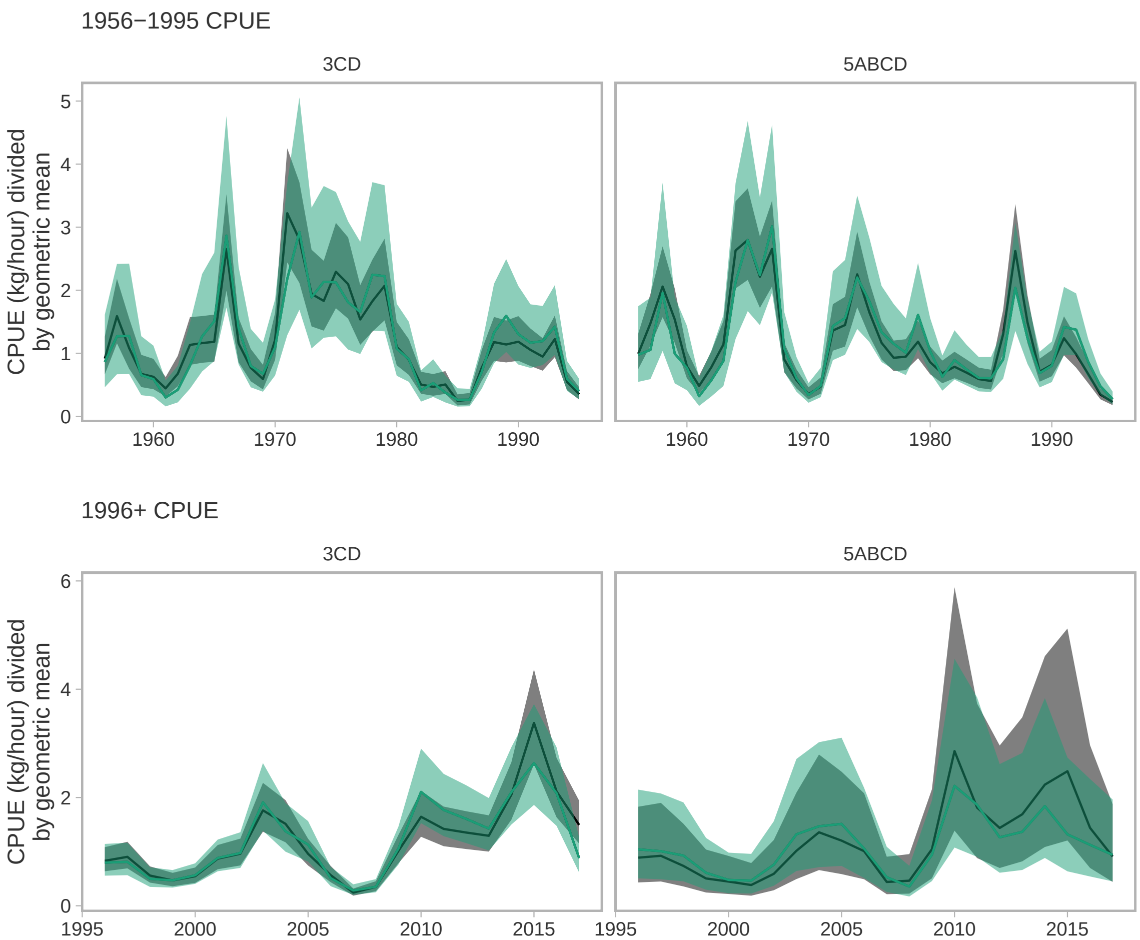

Figure B.13. A comparison of CPUE timeseries standardized with a model that does not include locality-year (space-time) random effects (black/grey) and a model that does include the locality-year random effects (coloured).

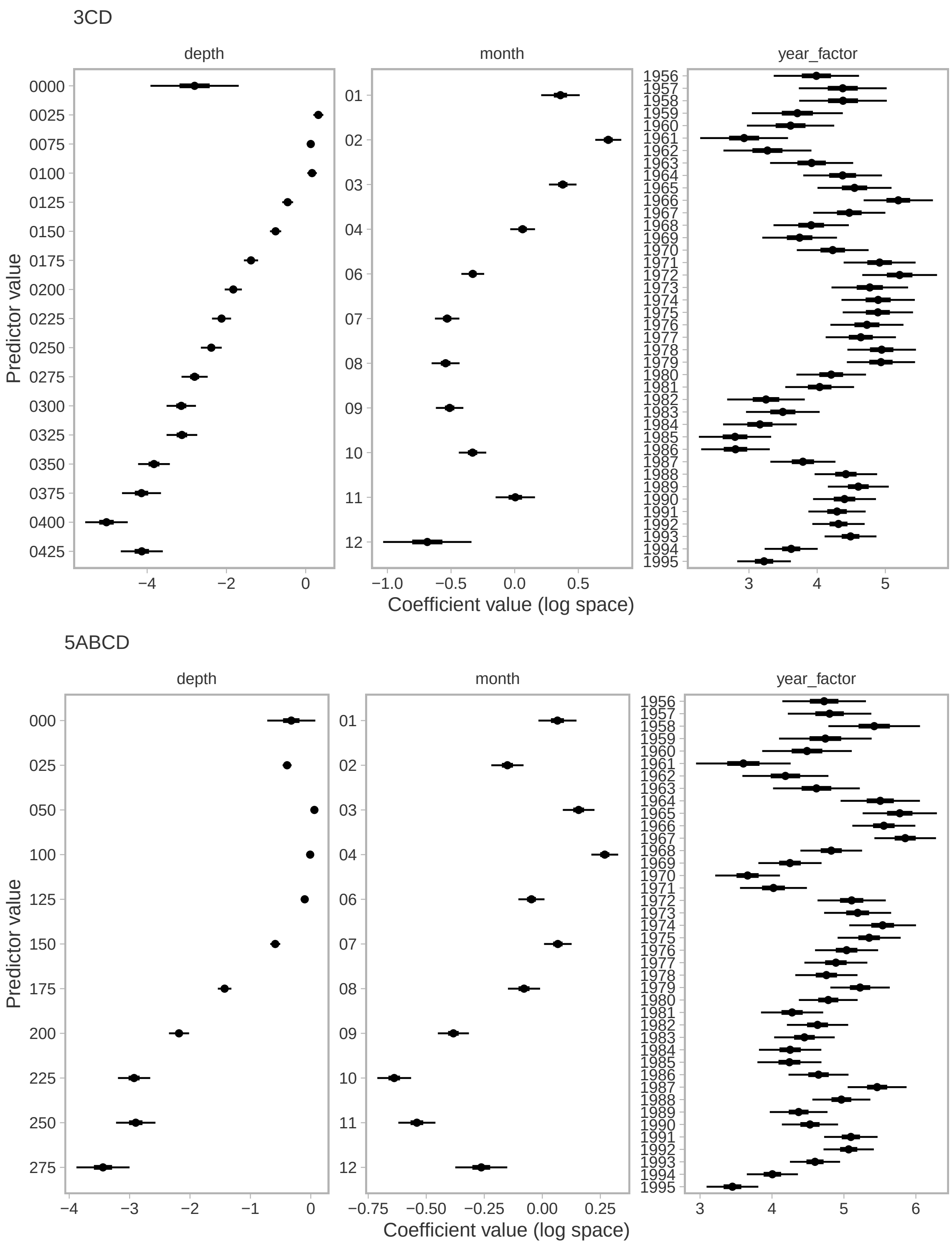

Figure B.14. Fixed effect coefficients for historical commercial CPUE standardization model. Dots and thick and thin line segments represent means and 50% and 95% Wald confidence intervals.

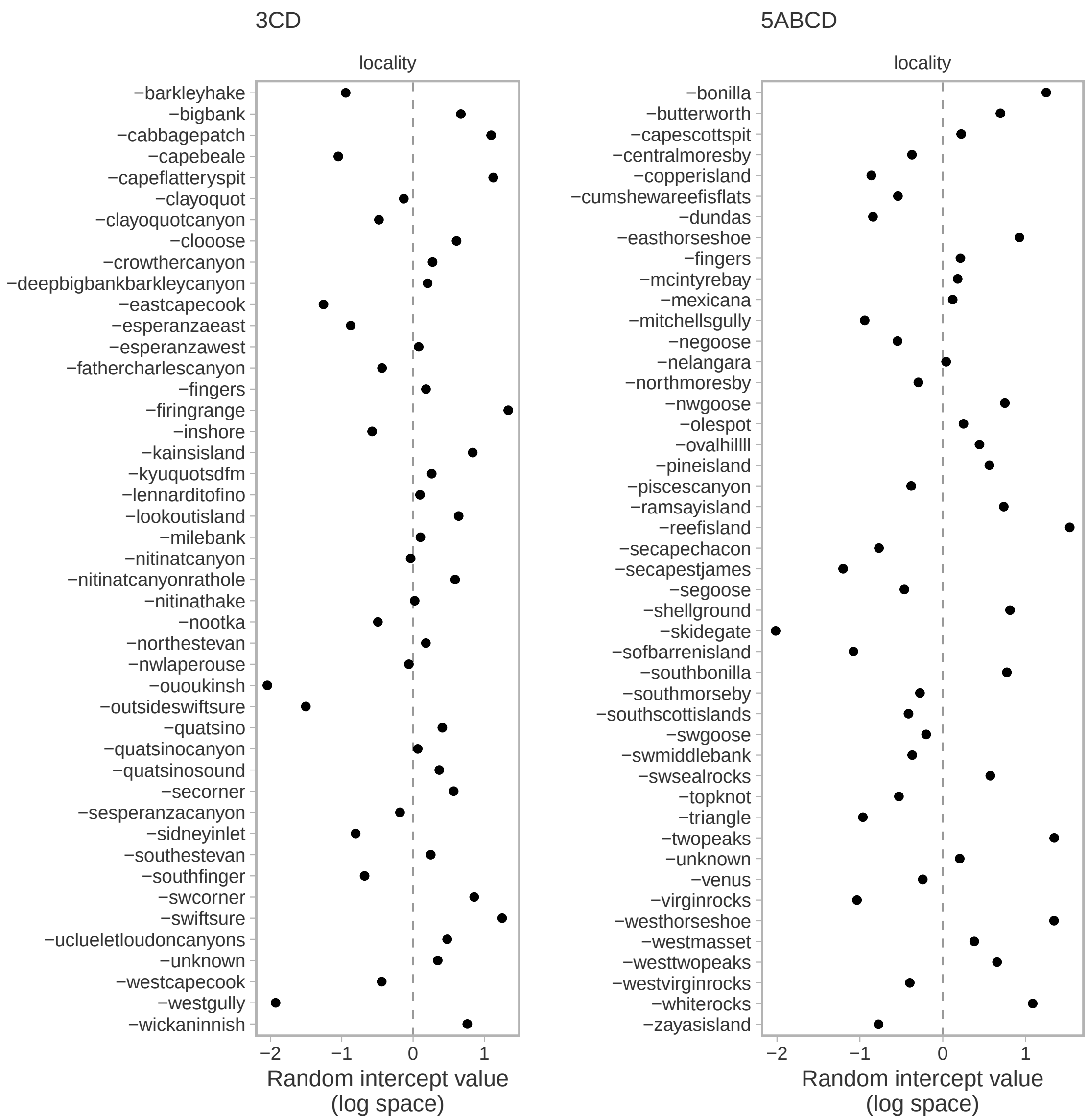

Figure B.15. Locality random effects for the historical commercial CPUE standardization model.

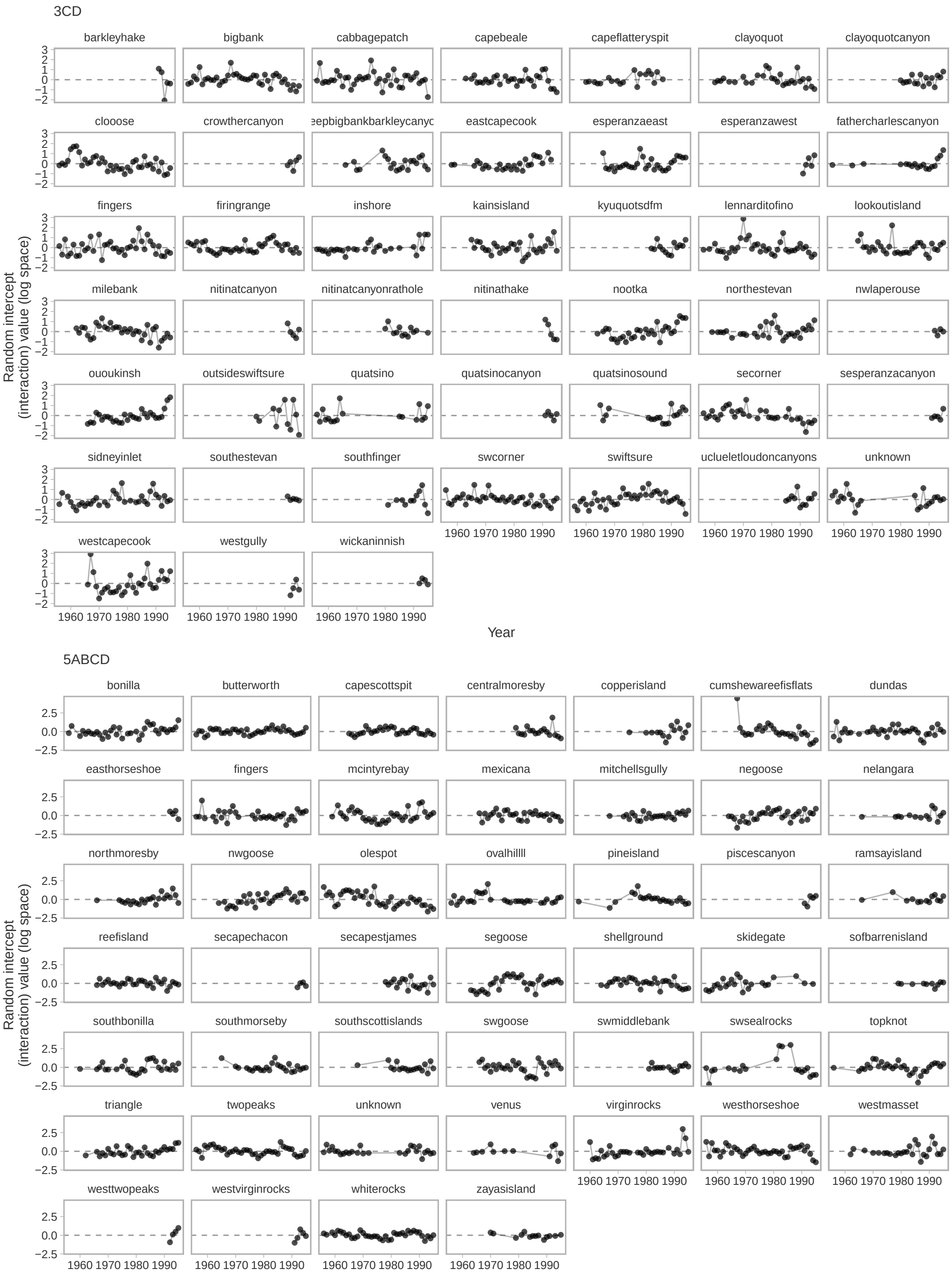

Figure B.16. Locality-by-year (space-time) random effects for the historical commercial CPUE standardization model.

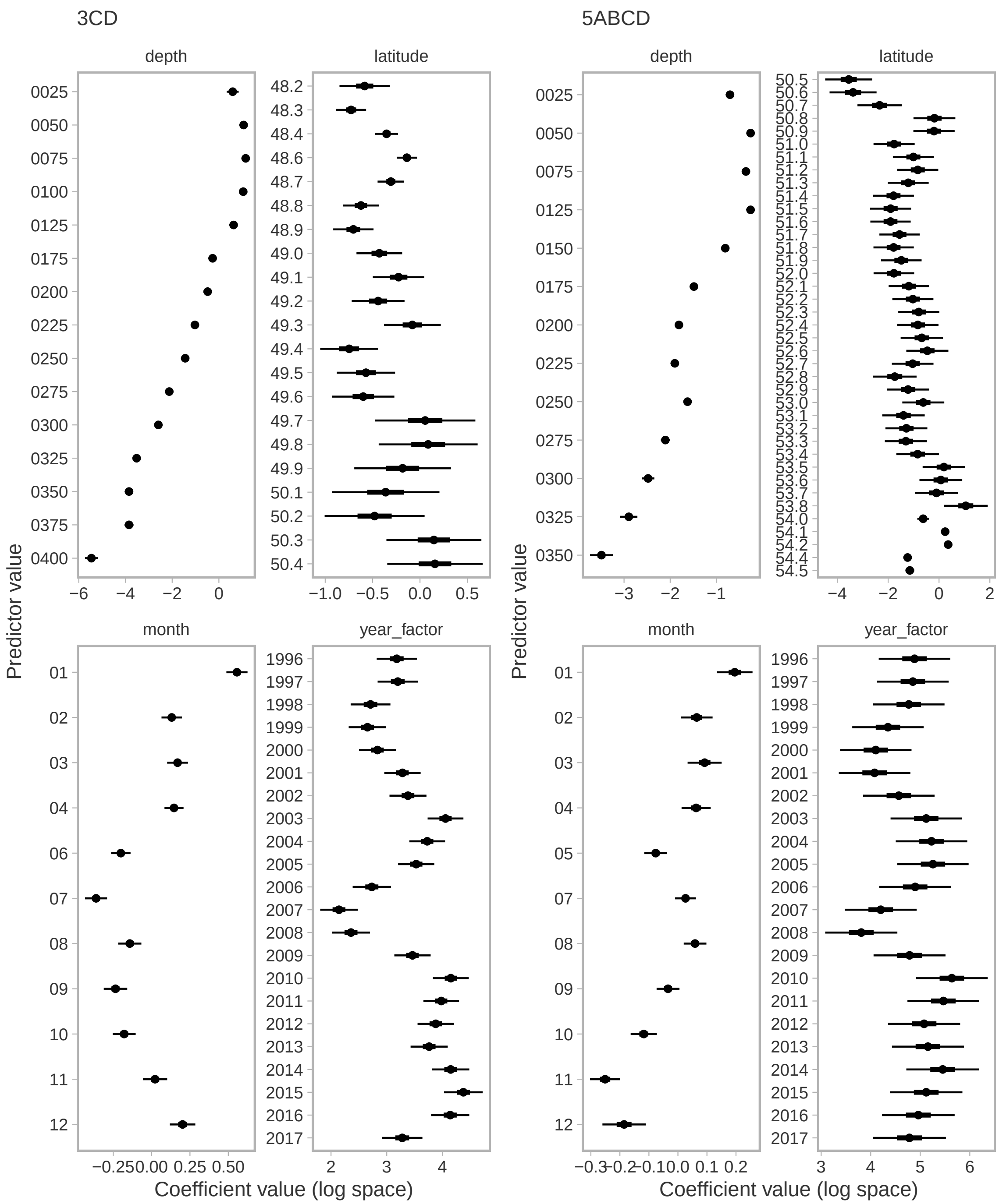

Figure B.17. Fixed effect coefficients for modern commercial CPUE standardization model. Dots and thick and thin line segments represent means and 50% and 95% Wald confidence intervals.

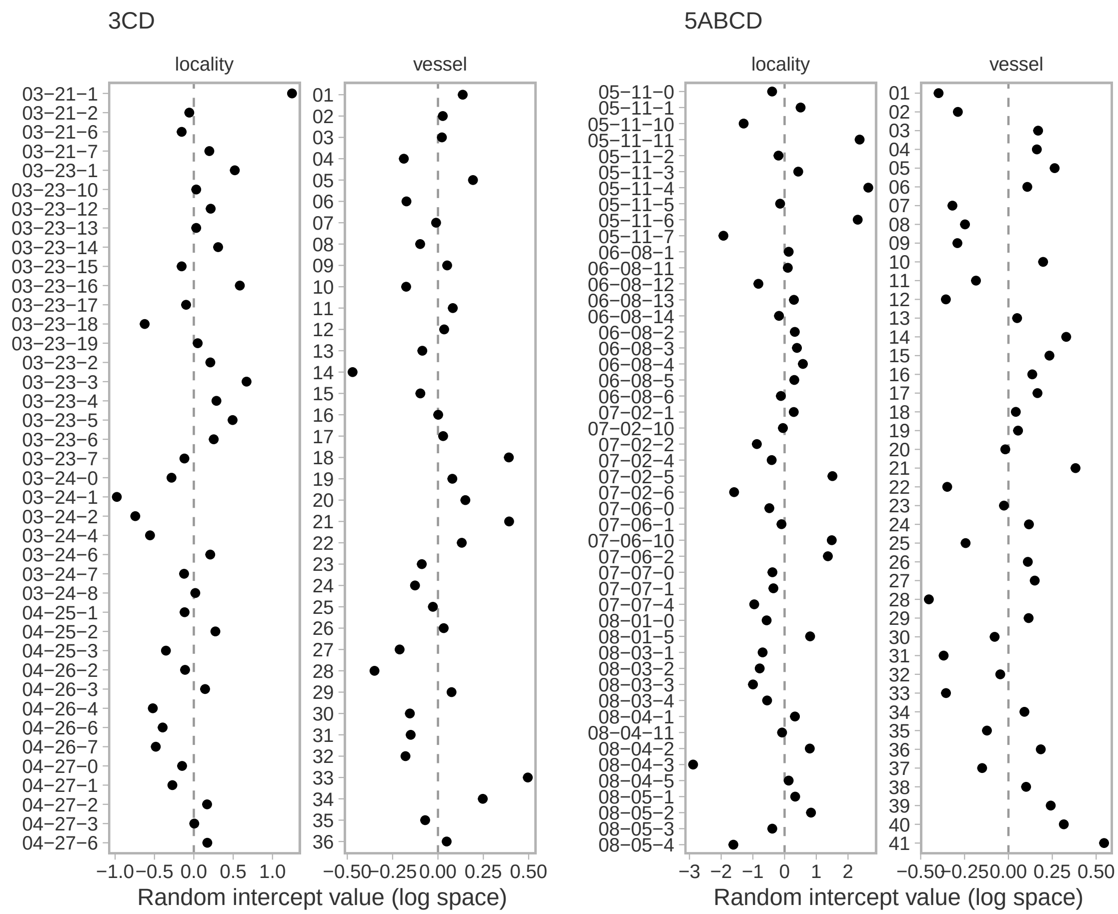

Figure B.18. Locality and vessel random effects for the modern commercial CPUE standardization model.

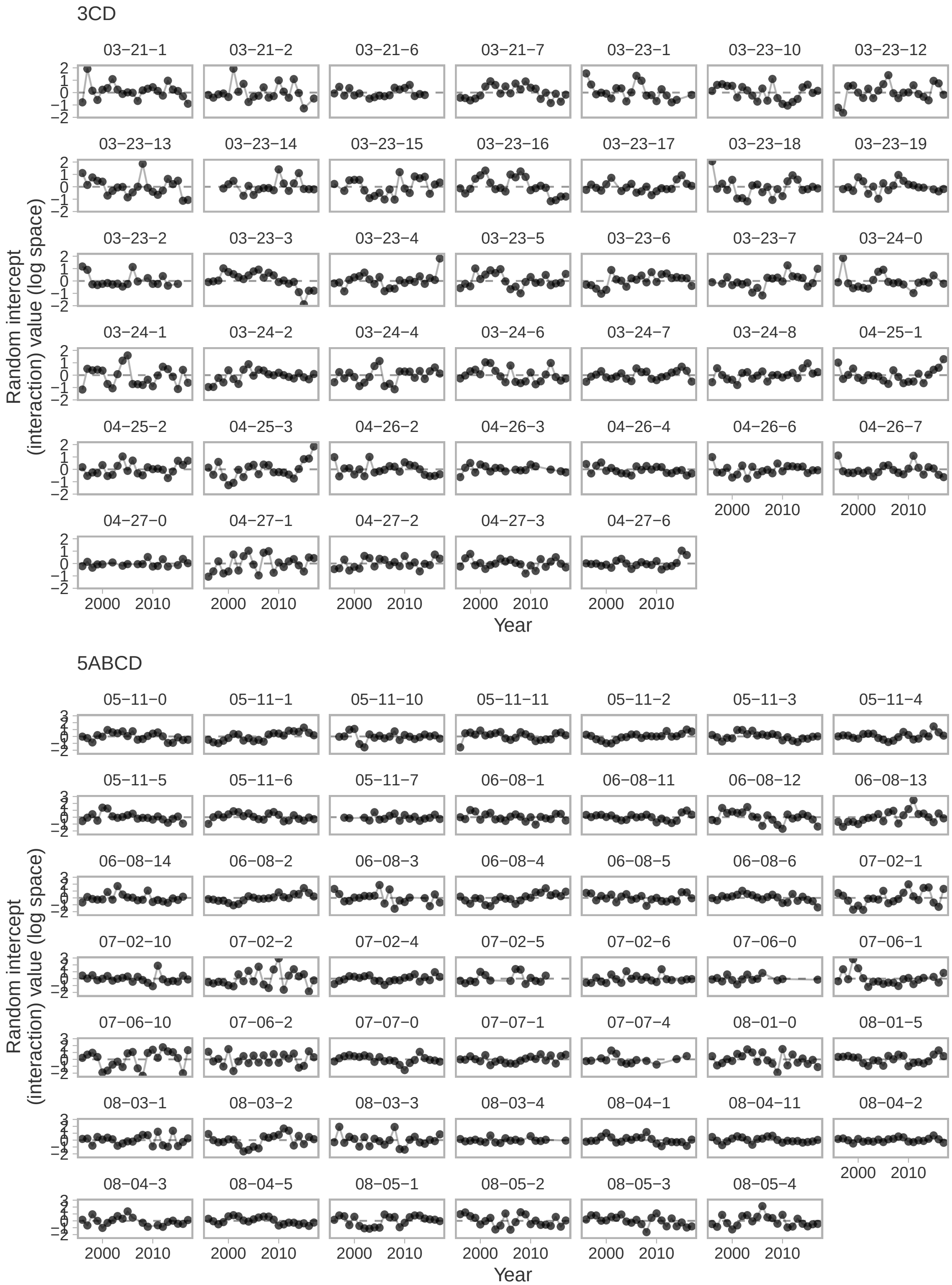

Figure B.19. Locality-by-year (space-time) random effects for the modern commercial CPUE standardization model.

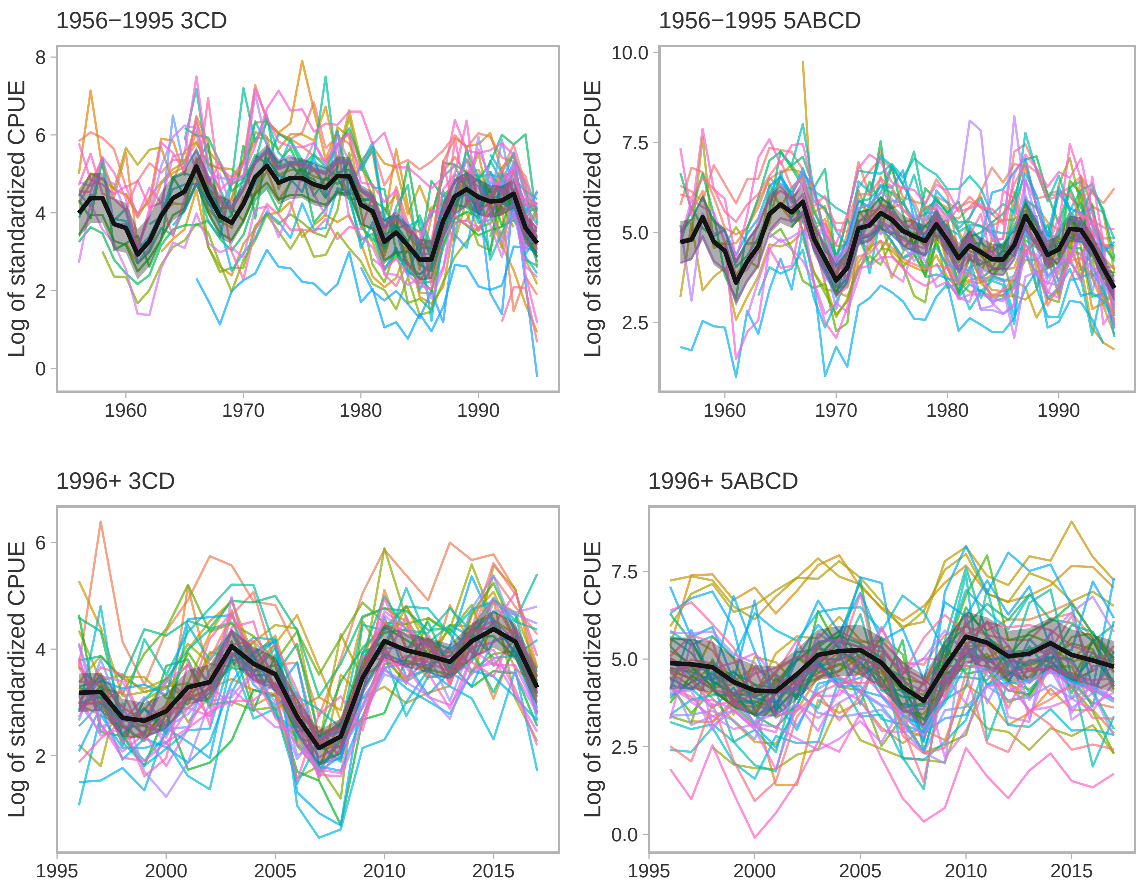

Figure B.20. Locality-specific CPUE index trends for a standardization model that allows for locality-year (space-time) interactions. The coloured lines indicate the locality-specific estimates with all other predictors set to their base levels. The black line and shaded ribbon indicate the overall average annual CPUE.

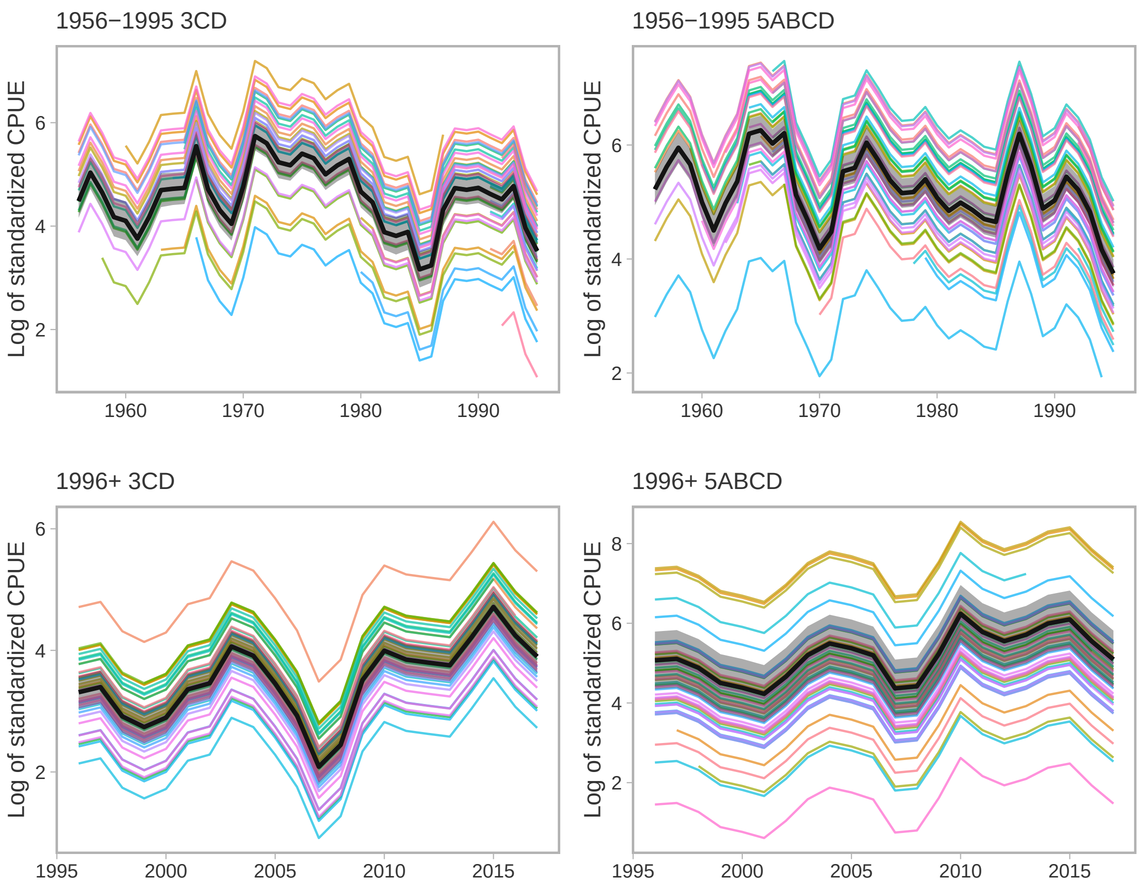

Figure B.21. Locality-specific CPUE index trends for a standardization model that does not allow for locality-year (space-time) interactions. The coloured lines indicate the locality-specific estimates with all other predictors set to their base levels. The black line and shaded ribbon indicate the overall average annual CPUE.

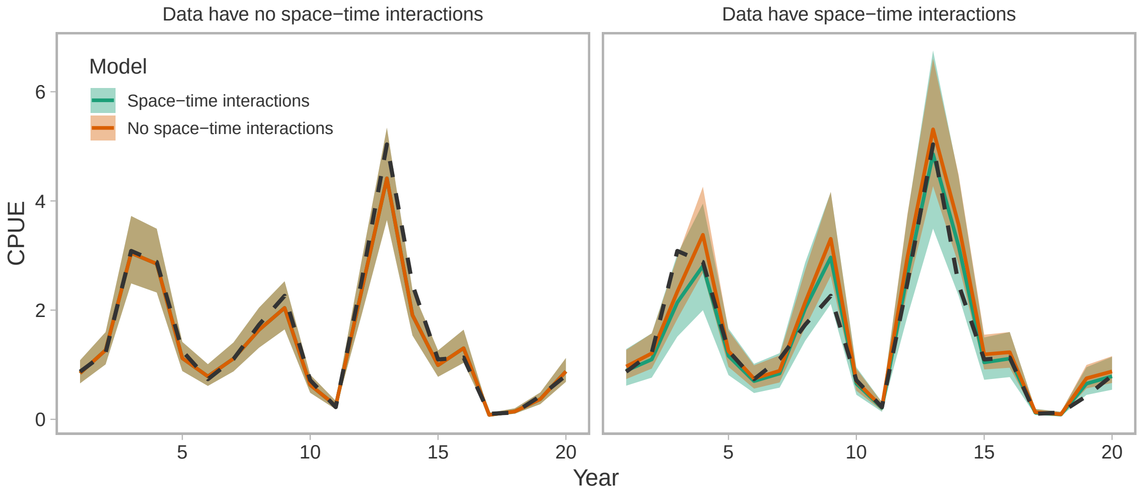

Figure B.22. An example simulation illustrating the effect of modelling or not modelling space-time interactions as random effects in a CPUE index standardization model. Left panel shows a scenario where the data were generated with the same trend for all localities in space. Right panel shows a scenario where the data were generated with space-time interactions. The green and orange lines and shaded regions represent estimated CPUE indices from models that allow for space-time interactions or do not allow for space-time interactions along with 95% confidence intervals. The dashed black line indicates the true mean CPUE for each year. All model and data combinations have correct 95% coverage except for the no-space-time-interactions model fitted to data that does have space-time interactions, which has 55% coverage. Note that the confidence intervals in the left panel are completely overlapping.

APPENDIX C. ANALYSIS OF BIOLOGICAL DATA

In this appendix we analyse length, maturity, and available ageing data to update growth and maturity parameters. We also plot age-frequency data derived from an age-length key to visualise the probable age composition in survey and commercial catch data.

C.1 SYNOPTIC SURVEY DATA

We extracted length, weight and maturity data from the Hecate Strait, Queen Charlotte Sound, and West Coast Vancouver Island synoptic surveys from the GFBio database using the following criteria:

1. `SPECIES_CODE` = 222: Pacific Cod.
2. `TRIP_SUB_TYPE_CODE` = 2 or 3: research trips.
3. `SAMPLE_TYPE_CODE` = 1, 2, 6, 7, or 8: include only samples that are of type 'random' or 'total'.
4. `SPECIES_CATEGORY_CODE` = NULL, 1, 3, 5, 6, or 7: to eliminate samples sorted on unknown criteria.
5. `SAMPLE_SOURCE_CODE` = NULL, 1, 2: to extract sorted and unsorted samples but remove stomach content samples.

A summary of number of fish measured by year, survey and sex is provided in Table C.1. Survey length-frequencies are shown in Figure C.1. A summary of number of fish weighed by year, survey and sex is provided in Table C.2. A summary of number of maturity records by year and survey is provided in Table C.3.

Table C.1. Number (N) of length measurements taken in the Hecate Strait (SYN HS), Queen Charlotte Sound (SYN QCS) and West Coast Vancouver Island (SYN WCVI) synoptic surveys

Survey	Year	N male	N female	N unsexed	Max male (cm)	Max female (cm)	Max unsexed (cm)
SYN HS	2005	324	314	2635	82.1	84.2	93.0
SYN HS	2007	622	613	0	80.7	88.6	NA
SYN HS	2009	568	615	13	77.0	81.0	34.0
SYN HS	2011	687	708	0	82.5	86.0	NA
SYN HS	2013	671	682	402	83.0	83.0	84.0
SYN HS	2015	375	401	127	74.5	88.5	12.0
SYN HS	2017	424	397	0	75.5	84.0	NA
SYN QCS	2003	702	687	0	81.8	83.8	NA
SYN QCS	2004	533	542	0	66.0	82.0	NA
SYN QCS	2005	2	1	1188	55.3	61.6	87.4
SYN QCS	2007	439	359	0	79.9	80.7	NA
SYN QCS	2009	292	323	0	66.0	86.0	NA
SYN QCS	2011	427	478	0	75.5	87.5	NA
SYN QCS	2013	476	564	0	74.0	79.5	NA
SYN QCS	2015	459	503	0	70.5	87.5	NA
SYN QCS	2017	255	312	0	73.5	81.5	NA
SYN WCVI	2004	352	374	0	75.2	83.0	NA
SYN WCVI	2006	663	748	0	71.1	79.3	NA
SYN WCVI	2008	346	380	0	66.5	75.0	NA
SYN WCVI	2010	671	658	0	70.0	76.0	NA
SYN WCVI	2012	489	489	0	77.0	78.5	NA
SYN WCVI	2014	547	648	0	82.5	80.0	NA
SYN WCVI	2016	438	532	0	74.5	82.5	NA

Table C.2. Number (N) of weight measurements taken in the Hecate Strait (SYN HS), Queen Charlotte Sound (SYN QCS) and West Coast Vancouver Island (SYN WCVI) synoptic surveys.

Survey	Year	N male	N female	N unsexed
SYN HS	2005	315	310	2633
SYN HS	2007	622	613	0
SYN HS	2009	536	590	11
SYN HS	2011	515	523	0
SYN HS	2013	455	457	0
SYN HS	2015	319	341	0
SYN HS	2017	366	350	0
SYN QCS	2003	427	406	0
SYN QCS	2004	346	358	0
SYN QCS	2005	2	1	1179
SYN QCS	2007	439	359	0
SYN QCS	2009	263	281	0
SYN QCS	2011	427	478	0
SYN QCS	2013	476	565	0
SYN QCS	2015	458	503	0
SYN QCS	2017	255	311	0
SYN WCVI	2004	352	374	0
SYN WCVI	2006	662	747	0
SYN WCVI	2008	301	306	0
SYN WCVI	2010	565	536	0
SYN WCVI	2012	402	402	0
SYN WCVI	2014	424	475	0
SYN WCVI	2016	369	469	0

Table C.3. Number (N) of maturities recorded in the Hecate Strait (SYN HS), Queen Charlotte Sound (SYN QCS) and West Coast Vancouver Island (SYN WCVI) synoptic surveys.

Survey	Year	N male	N female
SYN HS	2005	19	17
SYN HS	2007	622	613
SYN HS	2009	470	533
SYN HS	2011	514	521
SYN HS	2013	455	455
SYN HS	2015	319	341
SYN HS	2017	309	293
SYN QCS	2003	427	406
SYN QCS	2004	348	359
SYN QCS	2005	2	1
SYN QCS	2007	440	361
SYN QCS	2009	204	218
SYN QCS	2011	330	332
SYN QCS	2013	287	329
SYN QCS	2015	370	408
SYN QCS	2017	189	242
SYN WCVI	2004	353	377
SYN WCVI	2006	663	747
SYN WCVI	2008	298	302
SYN WCVI	2010	407	363
SYN WCVI	2012	344	346
SYN WCVI	2014	424	475
SYN WCVI	2016	368	469

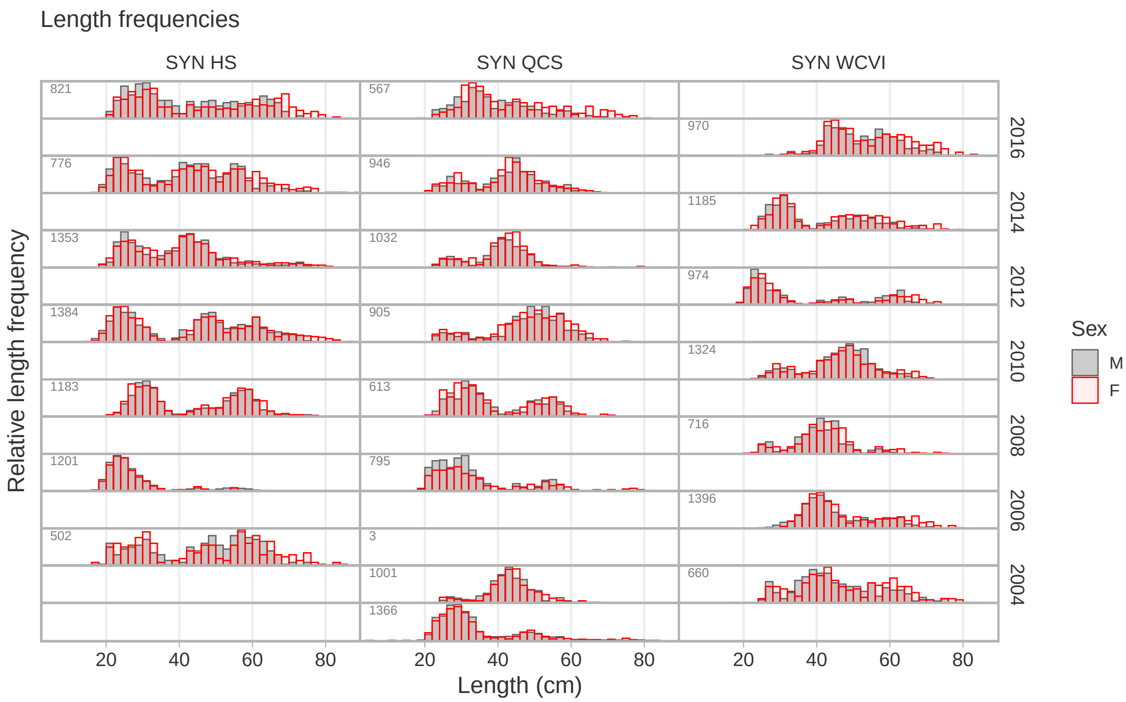

Figure C.1. Length-frequencies of Pacific Cod taken in the Hecate Strait (SYN HS), Queen Charlotte Sound (SYN QCS) and West Coast Vancouver Island (SYN WCVI) synoptic surveys. Note that for clarity only male and female specimens are plotted.

C.2 COMMERCIAL FISHERY DATA

We extracted length and weight data from commercial bottom trawl vessels from the GFBio database using the following criteria:

1. SPECIES_CODE = 222: Pacific Cod.
2. TRIP_SUB_TYPE_CODE = 1 or 4: 1 = non-observed domestic; 4 = observed domestic.
3. GEAR_CODE = 1: Bottom trawl.
4. SAMPLE_TYPE_CODE = 1, 2, 6, 7, or 8: include only samples that are of type 'random' or 'total'.
5. SPECIES_CATEGORY_CODE = NULL, 1, 3, 5, 6, or 7: to eliminate samples sorted on unknown criteria.
6. SAMPLE_SOURCE_CODE = NULL, 1, 2, 3: to extract sorted and unsorted samples but remove stomach content samples.
7. SAMPLE_ID not in 173726, 173740, 191471, 184243, 184159, 215903, or 223726: these samples were coded as Pacific Cod but have size composition inconsistent with the species. These samples were therefore excluded from further analysis.
8. Fishing year: April 1 to March 31 based on trip_start_date.
9. Quarter: months 4–6 = 1, months 7–9 = 2, months 10–12 = 3, months 1–3 = 4.

Summaries of number of fish measured by year, survey and sex are provided in Tables C.4 and C.5. Commercial length-frequencies are shown in Figure C.2.

Table C.4. Number (N) of length measurements taken in the commercial trawl fishery in Area 5ABCD.

Area	Year	N male	N female	N unsexed
5ABCD	1962	97	110	374
5ABCD	1972	0	0	523
5ABCD	1973	44	35	1325
5ABCD	1977	39	44	0
5ABCD	1978	102	107	0
5ABCD	1979	27	37	0
5ABCD	1980	265	230	0
5ABCD	1981	239	326	4880
5ABCD	1982	118	123	5193
5ABCD	1983	0	0	1839
5ABCD	1987	283	324	382
5ABCD	1990	355	395	0
5ABCD	1991	754	755	1672
5ABCD	1993	0	6	3
5ABCD	1996	53	62	0
5ABCD	1997	46	49	484
5ABCD	1998	33	40	2724
5ABCD	1999	0	0	2293
5ABCD	2000	0	0	187
5ABCD	2001	23	24	1359
5ABCD	2002	0	0	4682
5ABCD	2003	24	40	6349
5ABCD	2004	0	0	13407
5ABCD	2005	0	0	11719
5ABCD	2006	0	0	8183
5ABCD	2007	0	0	3617
5ABCD	2008	0	0	1501
5ABCD	2009	0	0	2851
5ABCD	2010	360	436	7220
5ABCD	2011	65	79	4255
5ABCD	2012	1	4	3793
5ABCD	2013	0	0	4723
5ABCD	2014	0	0	3416
5ABCD	2015	0	0	2907
5ABCD	2016	0	0	380
5ABCD	2017	27	29	0

Table C.5. Number (N) of length measurements taken in the commercial trawl fishery in Area 3CD.

Area	Year	N male	N female	N unsexed
3CD	1973	0	0	628
3CD	1974	0	0	698
3CD	1982	0	0	6798
3CD	1988	1503	1381	0
3CD	1996	76	98	0
3CD	1999	0	0	271
3CD	2000	0	0	281
3CD	2001	0	0	2688
3CD	2002	28	21	1689
3CD	2003	0	0	2235
3CD	2004	0	0	5627
3CD	2005	0	0	5555
3CD	2006	0	0	1099
3CD	2007	0	0	557
3CD	2008	0	0	715
3CD	2009	0	0	1866
3CD	2010	0	0	2198
3CD	2011	54	85	2900
3CD	2012	0	0	2065
3CD	2013	0	0	1679
3CD	2014	0	0	1291
3CD	2015	0	0	1233
3CD	2016	0	0	311

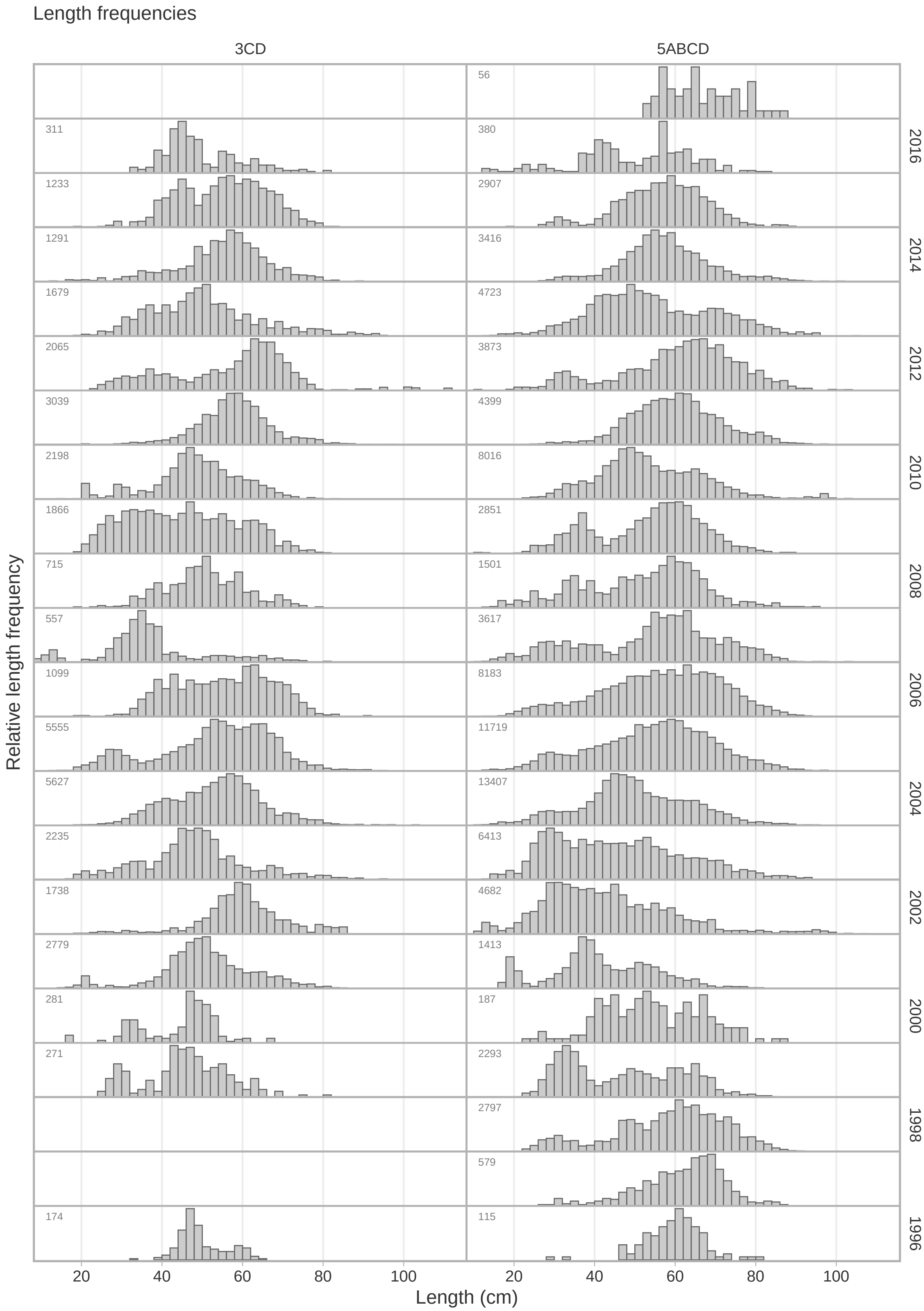

Figure C.2. Length-frequencies of Pacific Cod taken in the commercial trawl fishery. For clarity only lengths since 1996 are shown.

C.3 AGE SAMPLES

Pacific Cod are difficult to age due to inconsistency in annual marks, especially in the first few years of life (Beamish 1981, Johnston and Anderl 2012, Kastelle et al. 2017). A recent microchemistry-based validation study of Alaskan Pacific Cod otoliths revealed that visual aging of otoliths resulted in a high probability of over-ageing fish of ages 3–4 y. This was due to difficulty of readers distinguishing growth checks (translucent zones) from annuli (Kastelle et al. 2017). Due to large difficulties in interpreting growth patterns on otoliths from BC Pacific Cod, they are here aged using dorsal finray sections, although this method is unvalidated (Beamish 1981). Ageing finray sections is resource intensive, since fins must be dried, sectioned and mounted in resin before reading. Therefore, production ageing of Pacific Cod has not been routinely done for BC populations.

A request was made in 2012 to age Pacific Cod from dorsal fin rays collected in recent Hecate Strait, Queen Charlotte Sound and West Coast Vancouver Island synoptic surveys. A total of 2847 fin rays were aged, covering the years 2007, 2009, 2011 for SYN HS; 2011 for SYN QCS and 2006, 2008 and 2010 for SYN WCVI. A summary of number of fish aged by year, survey and sex is provided in Table C.6. Proportions at each age are shown in Figure C.3. Due to the difficulties with interpreting annuli for Pacific Cod, a subset of fin rays were read by a second reader. There were 162 such secondary reads for Area 5CD and 57 for Area 3CD. Results showed that precision reads sometimes differed from the primary read by one or more years, particularly for older fish (Figure C.4).

Given the small ranges of years with aged fish, these data are insufficient to support an age-structured stock assessment model. However, they can be used to estimate growth and maturity parameters, and may be useful for visualizing probable age compositions in the commercial catch data.

Table C.6. Numbers (N) of otoliths aged in the Hecate Strait (SYN HS), Queen Charlotte Sound (SYN QCS) and West Coast Vancouver Island (SYN WCVI) synoptic surveys.

Survey	Year	N male	N female
SYN HS	2007	143	143
SYN HS	2009	191	194
SYN HS	2011	292	286
SYN QCS	2011	179	175
SYN WCVI	2006	273	305
SYN WCVI	2008	157	156
SYN WCVI	2010	209	184

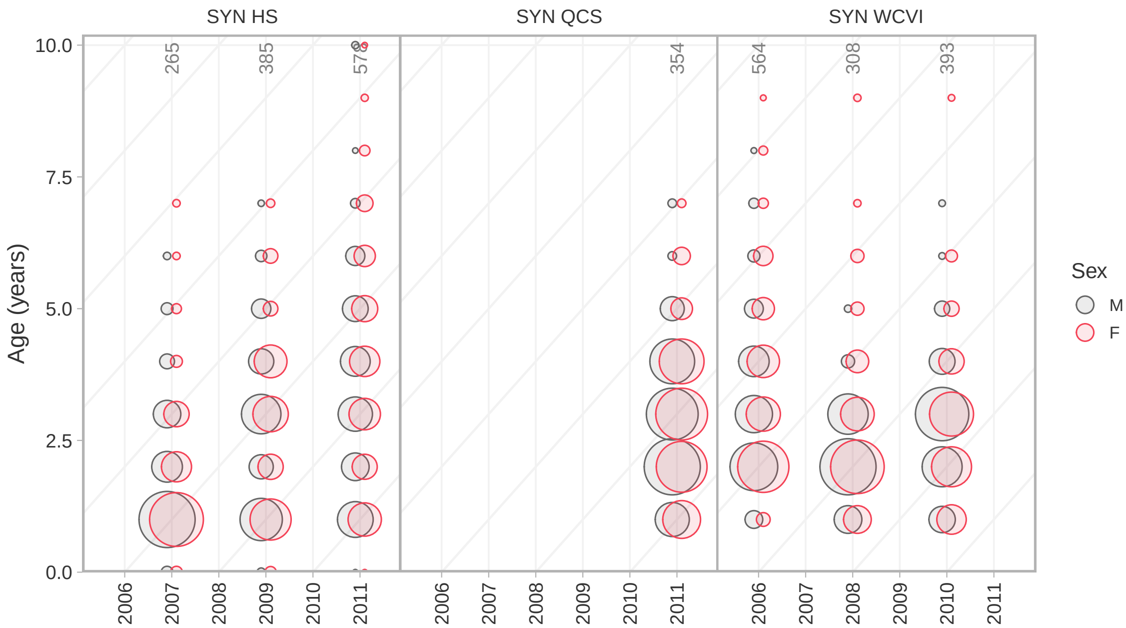

Figure C.3. Proportions at age of fish aged in the Hecate Strait (SYN HS), Queen Charlotte Sound (SYN QCS) and West Coast Vancouver Island (SYN WCVI) synoptic surveys. Grey circles = males. Red circles = females.

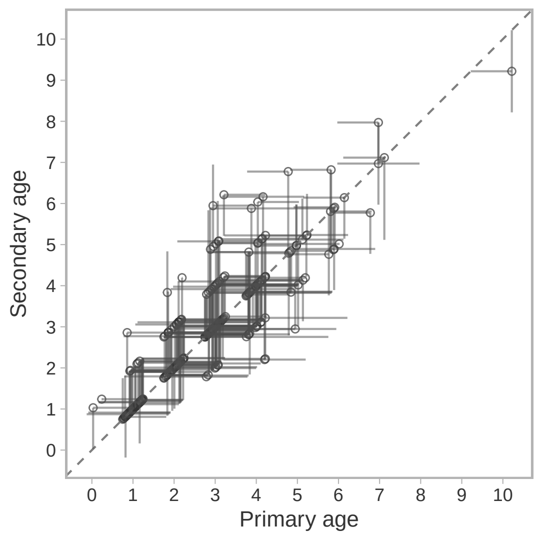

Figure C.4. Ageing precision for Pacific Cod. Each dot and cross-hatch represents an individual fish that has been aged twice. The x-axis represents the age and confidence interval recorded by the primary reader. The y-axis represents the age and confidence interval recorded by the second reader. The dashed diagonal line represents a perfect one-to-one agreement between the two age readings. A small amount of random jitter has been added to both axes to improve readability.

C.4 GROWTH PARAMETERS

Growth parameters were estimated by fitting the von Bertalanffy growth function to age and length data:

$$L_s = L_{\infty,s}\left(1 - e^{-k_s(a_s - a_{0s})}\right) \tag{C.1}$$

where $L_{\infty,s}$, k_s and a_{0s} are the parameters of the equation specific to sex, and L_s and a_s are paired length (L) and age (a) observations from synoptic surveys (Tables C.1 and C.6). We allowed for lognormal observation error.

The model was fit for combined sex data to: (a) all paired age-length samples; (b) Hecate Strait/Queen Charlotte Sound age-length samples; and (c) West Coast Vancouver Island age-length samples (Figures C.5 and C.6; Table C.7). Hecate Strait and Queen Charlotte Sound samples were combined because there was only one year of age observations (2011) for Queen Charlotte Sound (Table C.6). We sampled from the joint posterior distributions of each model with Stan (Carpenter et al. 2017, Stan Development Team 2018) using four chains and 2000 iterations per chain, discarding the first half of each as warmup. We placed uniform priors bounded at zero on k, L_∞, and σ (lognormal observation standard deviation), and a uniform prior on a_0.

Table C.7. von Bertalanffy growth coefficients for Pacific Cod in the Hecate Strait (SYN HS), Queen Charlotte Sound (SYN QCS) and West Coast Vancouver Island (SYN WCVI) synoptic surveys. The Area 5ABCD model used the parameters shown for SYN HS, SYN QCS. The Area 3CD model used the parameters shown for SYN WCVI.

Surveys	Term	Estimate	Conf.low	Conf.high
SYN HS, SYN QCS, SYN WCVI	k	0.21	0.19	0.23
SYN HS, SYN QCS, SYN WCVI	L_∞	90.64	86.43	95.55
SYN HS, SYN QCS, SYN WCVI	a_0	-0.77	-0.84	-0.70
SYN HS, SYN QCS	k	0.19	0.17	0.22
SYN HS, SYN QCS	L_∞	95.71	89.61	103.58
SYN HS, SYN QCS	a_0	-0.81	-0.91	-0.73
SYN WCVI	k	0.25	0.21	0.29
SYN WCVI	L_∞	82.80	77.60	89.89
SYN WCVI	a_0	-0.67	-0.85	-0.53

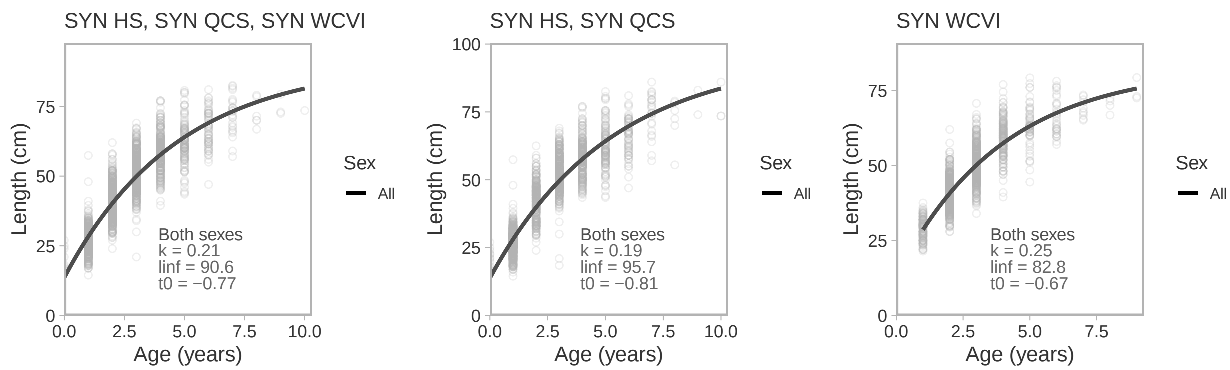

Figure C.5. Length-age model fits. The length-age growth curve is a von Bertalanffy model. Text on the panels shows the parameter estimates and light dots represent data for individual fish.

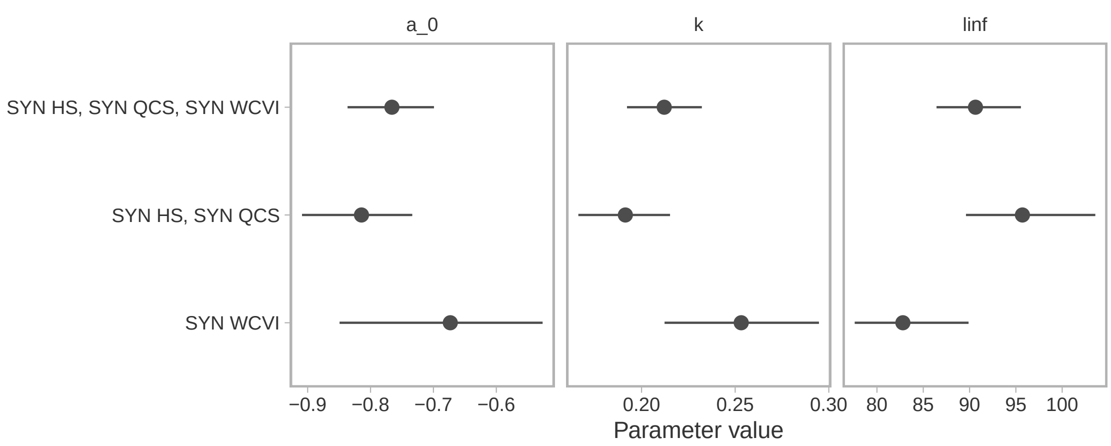

Figure C.6. Coefficient estimates from the von Bertalanffy model.

Estimates of the von Bertalanffy growth rate k were higher in the WCVI survey (k = 0.25 y^{-1}) compared to estimates of k from the HS-QCS surveys combined (k = 0.19 y^{-1}), and all surveys combined (k = 0.21 y^{-1}) (Table C.7). The 2013 stock assessments for Hecate Strait and Queen Charlotte Sound (Forrest et al. 2015) used the same growth parameters that had been used in the 2004 assessment for Hecate Strait (L_∞ = 89.48 cm; k = 0.307 y^{-1} and a_0 = -0.116 y (Sinclair and Starr 2005)). These values had been reported by Westrheim (1996) for the WCVI stock, based on analyses of length-frequency data (Foucher and Fournier 1982). Westrheim (1996) had actually reported a lower growth rate for the Hecate Strait stock, i.e., k = 0.203 y^{-1}.

The current results for Hecate Strait (Table C.7), are consistent with the parameters reported by Westrheim (1996). This suggests that the growth rate use in the delay difference models in Forrest et al. (2015) and Sinclair and Starr (2005) may have been too high for the Hecate Strait stock. The current Reference Case models therefore use the growth parameters reported in Table C.7, i.e., “SYN HS, SYN QCS” for Area 5ABCD; and “SYN WCVI” for Area 3CD.

Length-weight parameters (Equation C.2) were estimated using paired length and weight data from the synoptic surveys.

$$W_s = \alpha_s {L_s}^{\beta_s} \tag{C.2}$$

where α_s and β_s are the parameters of the equation specific to sex, and L_s and W_s are paired length (L) and weight (W) observations from synoptic surveys (Tables C.1 and C.2). As for the growth parameters, Equation C.2 was evaluated using data from all surveys combined; the HS-QCS surveys combined; and the WCVI survey (Figures C.7 and C.8, Table C.8). The models were fit as robust linear regressions: $\ln(W_s) = \ln(a) + b \cdot \ln(L_s)$ with an M estimator (Venables and Ripley 2002). Robust linear models were chosen over linear models with normally distributed error to downweight the influence of a small number of outlying specimens.

Table C.8. Length-weight coefficients for Pacific Cod in the Hecate Strait (SYN HS), Queen Charlotte Sound (SYN QCS) and West Coast Vancouver Island (SYN WCVI) synoptic surveys.

Surveys	Sex	Term	Estimate	Conf.low	Conf.high
SYN HS, SYN QCS, SYN WCVI	Male and Female	$ln(\alpha_s)$	-11.90	-11.91	-11.89
SYN HS, SYN QCS, SYN WCVI	Male and Female	β_s	3.11	3.11	3.12
SYN HS, SYN QCS	Male and Female	$ln(\alpha_s)$	-11.91	-11.92	-11.90
SYN HS, SYN QCS	Male and Female	β_s	3.11	3.11	3.12
SYN WCVI	Male and Female	$ln(\alpha_s)$	-11.78	-11.80	-11.76
SYN WCVI	Male and Female	β_s	3.08	3.08	3.09

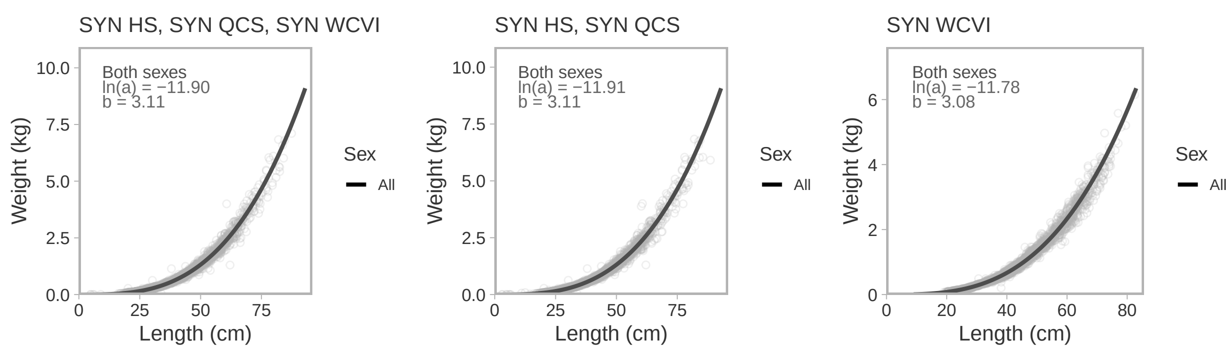

Figure C.7. Length-weight model fits. Text on the panels shows the parameter estimates and light dots represent data for individual fish.

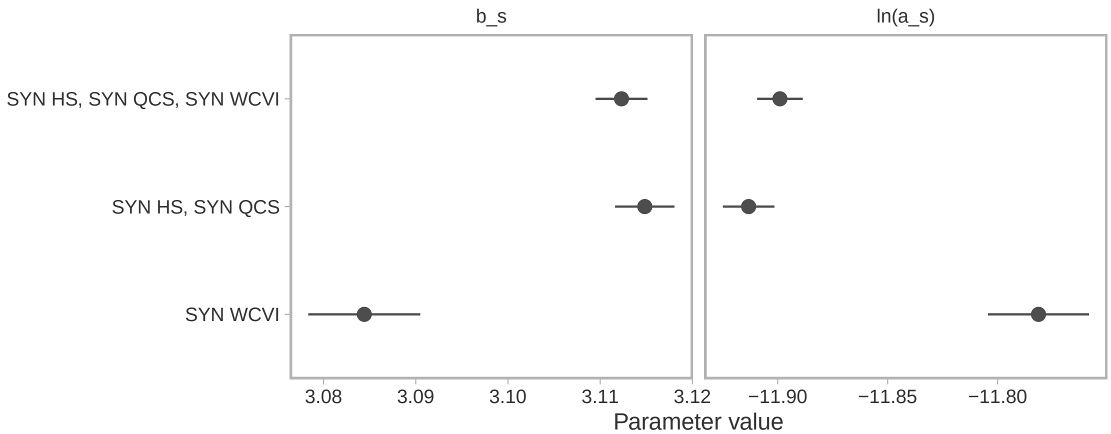

Figure C.8. Coefficients from the length-weight model fits.

C.5 MATURITY PARAMETERS

Maturity for Pacific Cod is assessed by visual inspection of the gonads, where maturity is assigned a code according to Gadid maturity stage.Fish are assessed as being in one of six states: 1.immature; 2.maturing; 3.mature (resting); 4.mature; 5.mature (spent); and 6.mature (ripe). For the purposes of fitting to a logistic curve, maturity was assigned a binary code, where fish with gonad maturity code 3 or higher were defined as mature (maturity assigned 1), and fish with gonad code 1 or 2 were defined as immature (maturity assigned 0).

We fit maturity ogives as logistic regressions of maturity (mature vs. not mature) against length or age:

$$y_i \sim \mathrm{Binomial}(\pi_i) \quad \text{(C.3)}$$

$$\mathrm{logit}\,(\pi_i) = \beta_0 + \beta_1 x_i + \beta_2 F_i + \beta_3 x_i F_i \quad \text{(C.4)}$$

where y_i represents a 1 if fish i is considered mature and a 0 if fish i is considered immature. The β parameters represent estimated coefficients, x_i represents the age of fish i, and F_i represents a binary predictor that is 1 if the fish is female and 0 if the fish is male. The variable π_i represents the expected probability of fish i being mature. We can then calculate of the age at 50% maturity as: $-(\log(1/0.5-1)+\beta_0)/\beta_1$ or $-(\log(1)+\beta_0)/\beta_1$ for males and $-(\log(1)+\beta_0+\beta_2)/(\beta_1+\beta_3)$ for females.

Estimated parameters are provided in Tables C.10 and C.9, and Figure C.10. Estimated maturity ogives are shown in Figure C.9.

Results suggest that age 3 y may be a more appropriate assumption for knife-edged maturity than age 2 y.

Table C.9. Coefficients from the logistic regression maturity ogives.

Survey	Term	Estimate	Conf.low	Conf.high
SYN HS, SYN QCS	Intercept male: β_0	-3.83	-4.35	-3.31
SYN HS, SYN QCS, SYN WCVI	Intercept male: β_0	-4.68	-5.16	-4.20
SYN WCVI	Intercept male: β_0	-6.58	-7.61	-5.56
SYN HS, SYN QCS	Intercept female: $\beta_0 + \beta_2$	-3.47	-3.97	-2.98
SYN HS, SYN QCS, SYN WCVI	Intercept female: $\beta_0 + \beta_2$	-4.47	-4.93	-4.01
SYN WCVI	Intercept female: $\beta_0 + \beta_2$	-6.93	-7.95	-5.90
SYN HS, SYN QCS	Slope male: β_1	1.47	1.27	1.66
SYN HS, SYN QCS, SYN WCVI	Slope male: β_1	1.58	1.41	1.75
SYN WCVI	Slope male: β_1	2.04	1.70	2.39
SYN HS, SYN QCS	Slope female: $\beta_1 + \beta_3$	1.47	1.27	1.66
SYN HS, SYN QCS, SYN WCVI	Slope female: $\beta_1 + \beta_3$	1.58	1.41	1.74
SYN WCVI	Slope female: $\beta_1 + \beta_3$	2.15	1.81	2.49

Table C.10. Estimates of age at 50% maturity from the logistic regression maturity ogives.

Survey	Sex	Estimated age-at-50% maturity
SYN HS, SYN QCS, SYN WCVI	Female	2.8
SYN HS, SYN QCS, SYN WCVI	Male	3.0
SYN HS, SYN QCS	Female	2.4
SYN HS, SYN QCS	Male	2.6
SYN WCVI	Female	3.2
SYN WCVI	Male	3.2

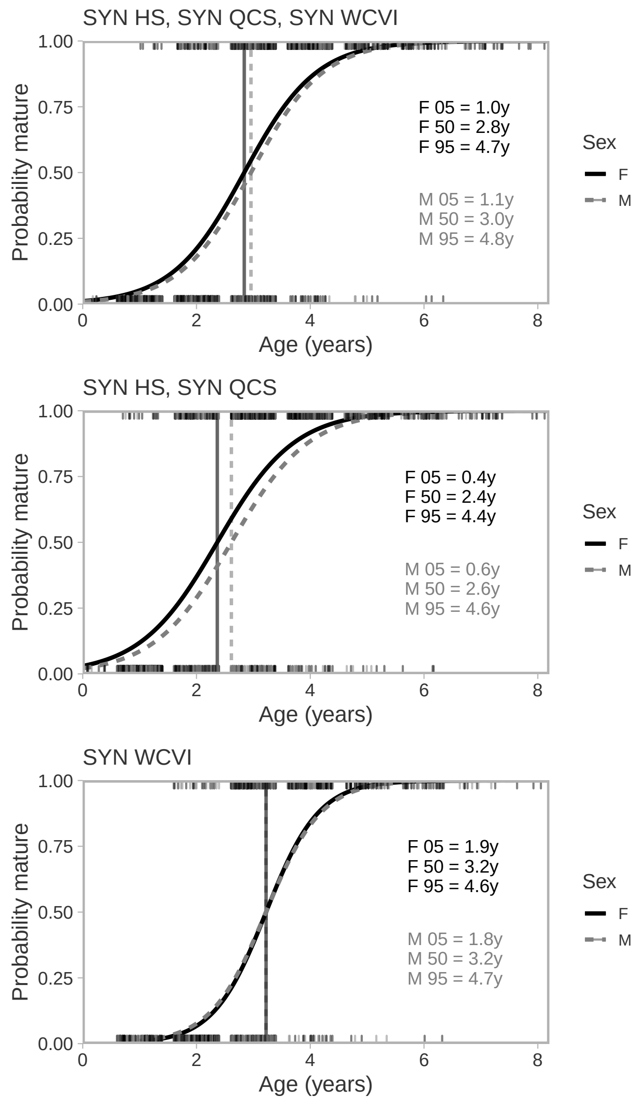

Figure C.9. Age-at-maturity ogives. Maturity ogives are fit as logistic regressions to individual fish specimens, which are categorized as mature vs. not mature. The solid black lines represent fits to the female fish and the dashed gray lines represent fits to the male fish. The vertical lines indicate the estimated age or at length at 50% maturity. Text on the panels indicates the estimated age and length at 5, 50 and 95% maturity for females (F) and males (M). Short rug lines along the top and bottom of each panel represent up to 1500 randomly chosen individual fish with a small amount of random jittering to help differentiate individual fish.

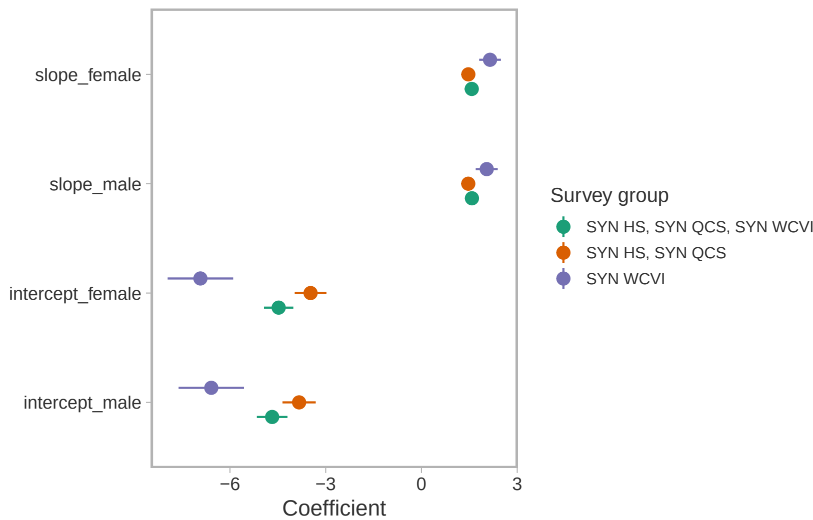

Figure C.10. Rearranged coefficients from the logistic regression maturity ogives (e.g. intercept female = $\beta_0 + \beta_2$*). Parameters are in logit or log odds space. The intercept refers to the log odds of maturity for a theoretical fish of age zero.*

C.6 AVERAGE ANNUAL MEAN WEIGHT IN COMMERCIAL CATCH

The calculation of annual mean weight was done in the following steps. The same steps were used in both Areas 3CD and 5ABCD. The same length-weight relationship was use for all quarters, but differ by area. The values of the length-weight parameters used are for Area 3CD: $\alpha = 7.65616e - 06$ and $\beta = 3.08$; for Area 5ABCD: $\alpha = 6.79e - 06$ and $\beta = 3.11$.

Step 1. Convert individual length (l_i) in each Sample ID (j) to weight (w_i):

$$W_i = a^q {L_i}^{b^q} \tag{C.5}$$

where a^q and b^q are constant length-weight parameters.

Step 2. From the selected data set, calculate the mean weight (W_j) for each Sample ID (j):

$$W_j = \frac{\sum\limits_{i=1}^{N_j} w_{i,j}}{N_j} \tag{C.6}$$

where N_j is the number of weights w_{ij} in Sample ID (j).

Step 3. The mean weight (W_s) for each sequential quarter was then calculated, weighted by the sample weight of Pacific Cod (S_j) in each SampleID (j). If the sample weight was recorded as data, it is used. Otherwise, the sum of the calculated weights from the sample is used:

$$W_s = \frac{\sum\limits_{i=1}^{K_s} W_{j,s} S_{j,s}}{\sum\limits_{j=1}^{K_s} S_{j,s}} \tag{C.7}$$

where K_j is the number of SampleIDs (j) in sequential quarter (s), where sequential quarter is a unique identifier for each quarter in the time series.

Step 4. The mean weight (W_f) for a fishing year was calculated by averaging the quarterly mean weight weighted by the commercial catch of Pacific Cod (C_s) during sequential quarter (s):

$$W_f = \frac{\sum\limits_{s=1}^{4} W_s C_s}{\sum\limits_{s=1}^{4} C_s} \tag{C.8}$$

APPENDIX D. DELAY-DIFFERENCE MODEL

The last assessment for Pacific Cod for Areas 5AB and 5CD used a delay-difference model (Forrest et al. 2015). A delay-difference model is essentially a collapsed age-structured model, subject to certain assumptions age-structured models. The delay-difference structure tracks the effects of recruitment, survival and growth on biomass, without requiring a fully age-structured framework. Difference equations, which allow for a time-delay between spawning and recruitment, are used to build the population model in discrete annual time-steps, in which the surviving biomass for next year is predicted from the surviving biomass from last year, afte adjusting for growth and adding recruitment. An advantage of delay-difference models over simpler production models is that they do not assume constant recruitment over time.

The key assumptions of the delay-difference model are:

- Growth in mean body weight Wa follows the linear relationship described by the Ford-Walford equation, $W_a = \alpha_g + \rho W_{a-1}$, where W_a is derived from the von Bertalanffy growth parameters;
- Knife edge selectivity, where all fish aged k and older are equally vulnerable to the fishing gear, and knife-edged maturity at age k; and
- Constant mortality M at age.

The delay-difference model collapses all the equations needed to fully describe the population's age structure into equations for the total numbers (N_t) and biomass (B_t) at time t:

$$B_t = S_{t-1}(\alpha_g N_{t-1} + \rho_g B_{t-1}) + w_k R_t \tag{D.1}$$

and

$$N_t = S_{t-1} N_{t-1} + R_t \tag{D.2}$$

where S is survival, given by

$$S_t = e^{-(M+F_t)} \tag{D.3}$$

where M is natural mortality rate; F is the estimated instantaneous fishing mortality rate; α_g and ρ_g are the intercept and slope of the Ford-Walford equation, for all ages > k, where k is the age at which fish are assumed to become fully vulnerable to fishing; w_k is the weight at k; and R_t is the assumed stock-recruit function, here constrained to conform to a Beverton-Holt function with a and b the constants of this equation (Eq. D.21). For both 5ABCD and 3CD stocks, it is assumed that recruitment to the fishery, survey and spawning stock occurs at age 2 y (i.e., k = 2 *y*), as assumed by Sinclair et al. (2001), Sinclair and Starr (2005) and Forrest et al. (2015).

A list of model parameters is given in Table D.1. Equilibrium and dynamic equations are given in Sections D.7 and D.8. Variance parameters and components of the objective function are given in are given in Section D.8. Leading estimated parameters are shown in bold type in Table D.1. Fixed parameter values and prior probability distributions are given in the description of the Reference Case models (Section 5).

To avoid the assumption that the stocks were at equilibrium in 1956, Forrest et al. (2015) used the same approach as an age-structured model for initializing numbers in the first year. The same approach was used here (Eq. D.15).

From 1956-2017, bias-corrected annual recruitments were estimated as the product of an estimated average unfished recruitment (R_0, estimated in log space) and bias-corrected annual log recruitment deviations (ω_t), which were weakly constrained to a normal distribution with $\omega_t \sim \mathcal{N}(0, 2^2)$. $\ln(R_0)$ and an estimated vector of eight years of log deviates (age 3–age 10; ω_{t_init}), was used to fill the first year of the numbers-at-age matrix, with natural mortality used to calculate survival Eq. D.15. The number of fish in the first year was then calculated as the sum of numbers at age in the first year Eq. D.16. For the years 1957-2013, annual numbers of fish (N_t) were calculated using (Eq. D.16). Biomass in the first year was calculated as the sum over ages of the product of numbers-at-age and the weight-at-age (Eq. D.17), with the latter derived from the von Bertlanffy growth parameters (Table D.1). Delay-difference equations were used to calculate annual biomass (B_t) for the years 1957-2014 (Eq. D.17), with recruitment given by Eq. D.21. Log recruitment anomalies in the 2018 projection year were drawn from a normal distribution, $\omega_t \sim \mathcal{N}(0, \sigma_R^2)$.

D.1 CONDITIONING THE MODEL

Models were fit to observed catch data, observed mean weight data and fishery-independent and -dependent indices of abundance.

D.2 OBJECTIVE FUNCTION COMPONENTS

The objective function in the delay-difference model contained five major components:

- the negative log-likelihood for the relative abundance data;
- the negative log-likelihood for the catch data;
- the negative log-likelihood for the mean weight data;
- the prior distributions for model parameters;
- two penalty functions that: (1) constrain the estimates of annual recruitment to conform to a Beverton-Holt stock-recruit function (Eq. D.21); and (2) weakly constrain the log recruitment deviations to a normal distribution ($\sim \mathcal{N}(0, 2)$).

Tests showed the model was insensitive to changes in the penalty function parameters, indicating that the other likelihood components and prior probability distributions were the most important contributors to the objective function.

D.3 INDICES OF ABUNDANCE

The fishery-independent and -dependent abundance indices (Appendices A and B) were treated as relative abundance indices, assumed to be directly proportional to the biomass with lognormal errors. The survey scaling (catchability) parameter q_j for each survey j was treated as an uncertain parameter, with the conditional maximum posterior density (MPD) estimate of q_j used in the objective function (Eq. D.29, where the parameter j_z represents the maximum likelihood estimate of $\ln(j_q)$, conditional on other model parameters, with n_j the number of observations in index j (Walters and Ludwig 1994) (Eqs. D.26–D.28).

D.4 CATCH DATA

The model was conditioned on total catch, with annual log fishing mortality rates for the bottom trawl fishery estimated directly. Estimated fishing mortality rates (F_t) were then used to predict catch using the Baranov catch equation (Eq. D.26). Log residuals (Eq. D.30) were assumed to be normally distributed with fixed standard deviation σ_C (Eq. D.31).

D.4.1 MEAN WEIGHT

Predicted annual mean weight ($\hat{\bar{W}}_t$) was calculated using Eq. D.20. Log residuals (Eq. D.32) were assumed to be normally distributed with fixed standard deviation σ_W (Eq. D.33).

D.5 RECRUITMENT

Bias-corrected annual recruitment (Eq. D.21) was estimated as the product of estimated mean unfished recruitment (R_0) and estimated annual deviations (ω_t), with both parameters estimated in log space. Predicted recruits ($\hat{R}_t$) were assumed to come from Beverton-Holt stock-recruit function. Log recruitment residuals (Eq. D.34) were assumed to be normally distributed with standard deviation σ_R (Eq. D.35).

Sinclair and Starr (2005) included an environmental correlate into the stock-recruit relationship, linking recruitment anomalies to Prince Rupert Sea Level anomalies (after Sinclair and Crawford (2005)). Sinclair and Starr (2005) reported that the effect of including the environmental correlate made very little difference to estimates of biomass. Unpublished analyses by the authors of the current assessment suggested that model estimates of biomass and recruitment were most strongly influenced by catch and commercial annual mean weight data; and that incorporating a parameter relating the stock-recruit function to an updated time series of air pressure adjusted Prince Rupert sea level data (Forrest et al. (2015), their Figure 55) simply resulted in a shift in estimated recruitment anomalies, resulting in almost identical estimates of biomass and recruits. For this reason, the current assessment does not incorporate the Prince Rupert sea level data for Area 5ABCD.

D.6 VARIANCE COMPONENTS AND WEIGHTING OF INDEX DATA

Variance components of the delay-difference model implemented within the iScam modelling framework (Martell et al. 2011) were partitioned using an errors in variables approach. The key variance parameter is the inverse of the total variance ϑ^{-2} (i.e., total precision). This parameter can be fixed or estimated, and was fixed here. The total variance is partitioned into observation and process error components by the model parameter ρ, which represents the proportion of the total variance that is due to observation error (Punt and Butterworth 1993, Deriso et al. 2007).

The equation for the observation error component of the total variance (σ_O) is given in Eq. D.22, while the process error term, σ_R is given in Eq. D.22. The process error term (σ_R) enters the objective function in the log likelihood function for the recruitment residuals (Eq. D.35). In cases when the index of abundance data are informative about absolute abundance (e.g.,an acoustic survey), one or both of these parameters, ϑ^{-2} and ρ, may be estimable. In practice, however, one or both of these parameters usually must be fixed.

The overall observation error term σ_O influences the fit to all indices of abundance through its contribution to $\sigma_{j,t}$, the standard deviation of log observation residuals for each index j in survey year t in the log-likelihood function (Eq. D.29). For a theoretical assessment with only one index of abundance with equally weighted observations, $\sigma_{j,t}$ would be equal to σ_O for all observations. Commonly, however, there are multiple surveys available. Within a given survey, annual coefficients of variation ($CV_{j,t}$) for each observation may also differ from year to year, due to annual sampling differences (e.g., sample size, spatial effects, etc.). It is therefore desirable to weight each observation according to its $CV_{j,t}$,where a low $CV_{j,t}$ for a given observation gives it a higher weight (and lower standard deviation in the objective function). This is implemented multiplicatively using Eqs. D.24 and D.25, where the $c_{j,t}$ term allows each observation to be weighted relative to the total observation error σ_O. In this case, $c_{j,t}$ is simply obtained from the inverse of $CV_{j,t}$ (Eq. D.25). For consistency with the use of an overall observation error term applied to all indices of abundance, the vector of $c_{j,t}$ terms was normalized across all surveys by dividing by the mean value of $c_{j,t}$. This had the effect weighting each survey observation consistently across all three datasets.

For the fishery-independent survey indices, annual coefficients of variation ($CV_{j,t}$) were derived from bootstrapping the swept area estimates (Appendix A). For the commercial CPUE indices, annual coefficients of variation were derived from the GLMMs used to produce the indices (Appendix B).

A number of authors have noted that there is little consensus on the best approach to managing the relative weighting of multiple survey indices, and that there is always a degree of subjectivity in the choice of weighting strategy (e.g., Francis (2011), McAllister et al. (2001)). In particular, there is no objective means of deciding how well a model should fit to commercial CPUE data, given that there is no independent means of knowing the degree to which commercial CPUE data are proportional to the underlying biomass. Commercial fisheries do not sample populations randomly; catchability and selectivity are unlikely to be constant through time; and spatial effects can impact the underlying relationship between CPUE and abundance (Hilborn and Walters 1992). Surveys are assumed to be proportional to abundance by virtue of survey design, however this assumption too can be vulnerable to various effects.

Francis (2011) reviewed some approaches to weighting abundance indices in fisheries stock assessment and advised against subjective down-weighting of commercial CPUE data. He described a two-stage approach to weighting some or all of the datasets with the intention of making data weights more consistent with model output, i.e., satisfying a statistical fit criterion. He proposed a survey-specific weighting term, set so that the standard deviation of normalized Pearson residuals (SDNR) for each index of abundance dataset is equal to about 1.0 (Francis 2011).

In the current assessment, adopting an iterative re-weighting approach similar to that reported in Francis (2011) would necessitate introducing a third, survey-specific weighting term to the calculation of $\sigma_{j,t}$. That is, $\sigma_{j,t}$ would be composed of σ_O, $c_{j,t}$, and a survey-specific weighting term w_j that would bring SDNR close to 1.0 Francis (2011). Given that both σ_O and the commercial CPUE $CV_{j,t}$ terms were already fixed at subjectively-determined values, and that $c_{j,t}$ was already normalized across surveys, it seemed an unwarranted addition to introduce another fixed weighting term. Francis (2011) stated that the overall goal is a stock assessment that fits all indices of abundance well, and that the SDNR provides a means of judging whether that is the case. However, expert judgment can also be employed (McAllister et al. 2001). We present sensitivity analyses to the values of fixed variance parameters (Section 7) and suggest that an understanding of the impact of fixed variance assumptions on management advice for Pacific Cod can be obtained without an iterative re-weighting step.

Table D.1. List of parameters for the delay-difference model.Estimated (or fixed) leading parameters are highlighted in bold type.

Parameter	Description	Value 5ABCD	Value 3CD
Indices			
t	Time (years)	1956–2018	1956–2018
j	Gear (fishery or index of abundance)		
a	Age (years) used for initializing numbers in first year	2–10 y	2–10 y
A	Maximum age (years) used for initializing numbers in first year	10 y	10 y
Fixed input parameters			
k	Age at knife-edge recruitment	2 y	2 y
L_∞	Theoretical maximum length	95.51 cm	82.59 cm
K_{VB}	von Bertalannfy growth rate	0.19	0.26
a_{LW}	Scaling parameter of the length/weight relationship	6.72e-06	7.66e-06
b_{LW}	Exponent of the length/weight relationship	3.11	3.08
t_0	Theoretical age at 0 cm	-0.81	-0.67
α_g	Intercept of the Ford-Walford plot, for all ages > k	0.8181	0.7973
ρ_g	Slope of the Ford-Walford plot, for all ages > k	0.9366	0.8838
W_k	Weight at age of recruitment k	0.6214	0.7284
Annual input data			
C_t	Catch (metric tonnes)		
W_t	Mean weight of individuals in the population		
$I_{j,t}$	Index of abundance j (Survey or commercail trawl CPUE)		
$CV_{j,t}$	Annual coefficients of variation in index of abundance observations		
Time-invariant parameters			
R_0	**Equilibrium unfished age-0 recruits** [a]		
h	**Steepness of the stock-recruit relationship**		
M	**Natural mortality** [a]		

Parameter	Description	Value 5ABCD	Value 3CD
R_{AVG}	**Average annual recruitment** [a]		
R_{AVG_init}	**Average annual recuitment for initializing the model** [a]		
CR	Recruitment compensation ratio		
a	Slope of the stock-recruit function at the origin		
b	Scaling parameter of the stock-recruit function		
N_0	Equilibrium unfished numbers		
B_0	Equilibrium unfished biomass		
S_0	Equilibrium unfished survival rate		
$\bar{W}_0$	Equilibrium unfished mean weight		
c_j	Additional process error in index of abundance observations for gear j		
Time-varying parameters			
ω_t	Log-recruitment deviations[a]		
F_t	Fishing mortality in the trawl fishery		
S_t	Annual survival rate		
N_t	Numbers		
R_t	Recruits		
B_t	Biomass		
$\bar{W}_t$	Predicted mean weight		
Likelihood components			
σ_R	Standard deviation in log-recruitment residuals		
σ_O	Overall standard deviation in observation residuals		
$\sigma_{i,j}$	Annual standard deviation in observation residuals for each survey		
σ_C	Standard deviation in catch		
σ_W	Standard deviation in mean weight		
ϑ^{-2}	**Inverse of the total variance (total precision)**		

Parameter	Description	Value 5ABCD	Value 3CD
ρ	**Proportion of total variance due to observation error**		
τ	**Variance in age composition residuals** ^{b}		
q_j	**Constant of proportionality in indices of (catchability)** ^{a,b}		
$d^2_{j,t}$	Residual log difference for j indices of abundance		
$d^2_{C_t}$	Residual log difference for catch data		
$d^2_{W_t}$	Residual log difference for mean weight data		

[a] Estimated in log space

[b] Conditional MPD estimates

D.7 SUMMARY OF EQUILIBRIUM EQUATIONS FOR THE DELAY-DIFFERENCE MODEL

Equilibrium equations for calculation of stock-recruit parameters

Equilibrium unfished survival:

$$S_0 = e^{-M} \tag{D.4}$$

Equilibrium unfished mean weight:

$$\bar{w}_0 = \frac{S_0 \alpha_g + w_k (1 - S_0)}{1 - \rho_g S_0} \tag{D.5}$$

Equilibrium unfished numbers:

$$N_0 = \frac{R_0}{(1 - S_0)} \tag{D.6}$$

Equilibrium unfished biomass:

$$B_0 = N_0 \bar{w}_0 \tag{D.7}$$

Recruitment compensation ratio (Beverton-Holt):

$$\mathrm{CR} = \frac{4h}{1 - h} \tag{D.8}$$

Parameters of the stock-recruit relationship (Beverton-Holt):

$$b = \frac{\mathrm{CR} - 1}{B_0} \tag{D.9}$$

Equilibrium equations for fishery reference points

Equilibrium survival rate at fixed long-term fishing mortality F_e:

$$S_e = e^{-(M + F_e)} \tag{D.10}$$

Equilibrium long-term mean weight at F_e:

$$\bar{w}_e = \frac{S_e \alpha_g + w_k (1 - S_e)}{1 - \rho_g S_e} \tag{D.11}$$

Equilibrium long-term biomass at F_e:

$$B_e = -\frac{\left(-\bar{\mathrm{W}}_e + \mathrm{S}_e \alpha_g + \mathrm{S}_e \rho_g \bar{\mathrm{W}}_e + W_k a \bar{\mathrm{W}}_e\right)}{b\left(-\bar{\mathrm{W}}_e + \mathrm{S}_e \alpha_g + \mathrm{S}_e \rho_g \bar{\mathrm{W}}_e\right)} \tag{D.12}$$

Equilibrium long-term yield at F_e:

$$Y_e = B_e \frac{F_e}{(F_e + M)} \left(1 - e^{-(F_e + M)}\right) \tag{D.13}$$

D.8 TIME-DYNAMIC EQUATIONS AND LIKELIHOOD COMPONENTS FOR THE DELAY-DIFFERENCE MODEL

Time-dynamic equations

Survival rate:

$$S_t = e^{-(M+F_t)} \tag{D.14}$$

Initial numbers at age calculations:

$$\left\{ \begin{array}{ll} N_{2,1} = R_0 e^{\omega_1} & a = 2 \\ N_{a,1} = \left(R_0 e^{\omega Init_a}\right) e^{-M(a-2)} & 2 < a < A \\ N_{A,1} = \frac{\left(R_0 e^{\omega Init_A}\right) e^{-M(A-2)}}{(1-e^{-M})} & a = A \end{array} \right\} \tag{D.15}$$

Numbers:

$$\left\{ \begin{array}{ll} N_t = \sum\limits_{i=2}^{A} N_{a,1} & t = 1956 \\ N_t = S_{t-1} N_{t-1} + R_t & t > 1956 \end{array} \right\} \tag{D.16}$$

Biomass:

$$\left\{ \begin{array}{l} B_t = \sum\limits_{a=2}^{A} N_{a,t} w_{a,t} \quad t = 1956 \\ B_t = S_{t-1} \left(\alpha_g N_{t-1} + \rho_g B_{t-1}\right) + W_k R_t \quad t > 1956 \end{array} \right\} \tag{D.17}$$

Recruits:

$$R_t = R_0 e^{\omega_t - \frac{\sigma_R^2}{2}} \tag{D.18}$$

Predicted variables used in objective function

Predicted catch:

$$\hat{C}_t = B_t \frac{F_t}{(F_t + M)} \left(1 - e^{-(F_t+M)}\right) \tag{D.19}$$

Predicted mean weight:

$$\hat{\hat{W}}_t = \frac{B_t}{N_t} \tag{D.20}$$

Predicted recruits:

$$\hat{R}_{\mathrm{t}} = \frac{a B_{\mathrm{t-k+1}}}{1 + b B_{\mathrm{t-k+1}}} \tag{D.21}$$

D.9 CALCULATION OF VARIANCE PARAMETERS, RESIDUALS AND LIKELIHOODS

Variance parameters

Base standard deviation in index of abundance residuals:

$$\sigma_O = \sqrt{\frac{\rho}{\vartheta^{-2}}} \tag{D.22}$$

Standard deviation in ln recruitment residuals:

$$\sigma_R = \sqrt{\frac{(1-\rho)}{\vartheta^{-2}}} \tag{D.23}$$

Standard deviation in index of abundance observations:

$$\sigma_{j,t} = \frac{\sigma_O}{c_{j,t}} \tag{D.24}$$

Weighting term for index observations:

$$c_{j,t} = \frac{1}{\mathrm{CV}_{j,t}} \tag{D.25}$$

Indices of abundance

Residuals:

$$z_{j,t} = \ln\left(I_{j,t}\right) - \ln\left(\hat{B}_t\right) \tag{D.26}$$

$$\bar{z}_j = \frac{\sum_t^{n_j} z_{j,t}}{n_j} \tag{D.27}$$

$$d_{j,t} = z_{j,t} - \bar{z}_j \tag{D.28}$$

Ln likelihood:

$$L_{j,t} = \ln\left(\sigma_{j,t}^2\right) + \frac{d_{j,t}^2}{2\sigma_{j,t}^2} \tag{D.29}$$

Catch

Residuals:

$$d_{C t} = \ln\left(C_t\right) - \ln\left(\hat{C}_t\right) \tag{D.30}$$

Ln likelihood:

$$L_t = \ln\left({\sigma_C}^2\right) + \frac{{d_C}_t^2}{2{\sigma_C}^2} \tag{D.31}$$

Mean weight

Residuals:

$$d_{W t} = \ln\left(\bar{W}_t\right) - \ln\left(\hat{\bar{W}}_t\right) \tag{D.32}$$

Ln likelihood:

$$L_t = \ln\left({\sigma_W}^2\right) + \frac{{d_W}_t^2}{2{\sigma_W}^2} \tag{D.33}$$

Recruitment

Residuals:

$$d_{R t} = \ln\left(R_t\right) - \ln\left(\hat{R}_t\right) \tag{D.34}$$

Ln likelihood:

$$L_t = \ln\left({\sigma_R}^2\right) + \frac{{d_R}_t^2}{2{\sigma_R}^2} \tag{D.35}$$

COMPUTATIONAL ENVIRONMENT

This version of the document was generated on 2020-09-29 13:57:06 with R version 4.0.2 (2020-06-22) (R Core Team 2018) and R package versions:

	Package	Version	Date	Source
bookdown	bookdown	0.20	2020-06-23	CRAN (R 4.0.0)
broom	broom	0.5.6	2020-04-20	CRAN (R 4.0.0)
cowplot	cowplot	1.0.0	2019-07-11	CRAN (R 4.0.0)
csasdown	csasdown	0.0.8	2020-09-28	Github (pbs-assess/csasdown@05a6f3c)
dplyr	dplyr	1.0.0	2020-05-29	CRAN (R 4.0.0)
gfplot	gfplot	0.1.4	2020-09-25	Github (pbs-assess/gfplot@85dec42)
ggplot2	ggplot2	3.3.2	2020-06-19	CRAN (R 4.0.2)
kableExtra	kableExtra	1.2.1	2020-08-27	CRAN (R 4.0.2)
knitr	knitr	1.29	2020-06-23	CRAN (R 4.0.0)
purrr	purrr	0.3.4	2020-04-17	CRAN (R 4.0.0)
rmarkdown	rmarkdown	2.3	2020-06-18	CRAN (R 4.0.2)
rstan	rstan	2.19.3	2020-02-11	CRAN (R 4.0.0)
scales	scales	1.1.1	2020-05-11	CRAN (R 4.0.2)
TMB	TMB	1.7.16	2020-01-15	CRAN (R 4.0.0)
xtable	xtable	1.8-4	2019-04-21	CRAN (R 4.0.0)

In particular, most of the data extraction and many of the plots were made with the gfplot package version 0.1.1. The document was compiled with R package csasdown version 0.0.1. The specific versions used to generate this report can be installed with:

```
devtools::install_github("pbs-assess/gfplot", ref = "f55710d")
devtools::install_github("pbs-assess/csasdown", ref = "baf78d8")
```