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Widow Rockfish (*Sebastes entomelas*) stock assessment for British Columbia in 2019

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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

Widow Rockfish (*Sebastes entomelas*, WWR) is ubiquitous along the British Columbia (BC) coast (at ~100-500 m depth) and occurs in high densities along the west coast of Vancouver Island (WCVI) and off the shelf edge between the top of Vancouver Island and south of Cape St. James. Shoals of WWR have been studied near Triangle Island using acoustic surveys. This species exhibits diel migration from near bottom during the day to midwater at night, feeding on shrimps, euphausiids, salps, and fish. Night time aggregations make WWR very susceptible to capture by commercial midwater trawl nets.

This species supports the fourth largest rockfish fishery in BC with an annual coastwide 'total allowable catch' (TAC) in 2017 of 2,358 t (98% allocated to the trawl fishery) and an average annual catch by all fisheries combined of 2001 t from 2014-2018. This stock assessment evaluates a BC coastwide population harvested by multiple fisheries aggregated into a single modelled fishery. Analyses of biology and distribution did not support separate regional stocks for WWR. A single coastwide stock was assumed for the last WWR stock assessment in 1998.

We use an annual catch-at-age model tuned to fishery-independent trawl survey series, a bottom trawl catch per unit effort (CPUE) series, annual estimates of commercial catch since 1940, and age composition data from survey series (five years of data from four surveys) and the commercial fishery (30 years of data). The model starts from an assumed equilibrium state in 1940, and the survey data cover the period 1967 to 2018 (although not all years are represented). Nine base runs using a two-sex model were implemented in a Bayesian framework (using the Markov Chain Monte Carlo procedure) under a scenario that fixed natural mortality (M) to three levels (0.07, 0.08, 0.09) and set the accumulator age (A) to three values (40, 45, 50 y) while estimating steepness of the stock-recruit function (h), catchability (q) for surveys and CPUE, and selectivity (μ) for surveys and the commercial trawl fleet. These nine runs were combined into a composite base case which explored the major axes of uncertainty in this stock assessment. Twelve sensitivity analyses were performed to test the effect of alternative model assumptions.

The composite base case suggests that low exploitation in the early years, including that by foreign fleets, coupled with several strong recruitment events (in 1961 and 1990) have sustained the population to the present. Exploitation rates were high during a period of heavy fishing by the domestic fleet extending from the mid-1980s to the mid-1990s, causing the stock size to diminish. Exploitation rates dropped with the implementation of 100% observer coverage in 1996 and the introduction of catch limits coupled with individual vessel quotas (IVQs) in 1997.

The spawning biomass (mature females only) at the beginning of 2019 is estimated to be 0.37 (0.26, 0.54) of unfished biomass (median and 5th and 95th quantiles of the Bayesian posterior distribution). This biomass is estimated to be 1.51 (0.92, 2.61) of the spawning biomass at maximum sustainable yield, B_{MSY}.

Advice to managers is presented as decision tables that provide probabilities of exceeding limit and upper stock reference points for five-year projections across a range of constant catches. The DFO provisional 'Precautionary Approach compliant' reference points were used, which specify a 'limit reference point' (LRP) of $0.4B_{\text{MSY}}$ and an 'upper stock reference point' (USR) of $0.8B_{\text{MSY}}$. The estimated spawning biomass at the beginning of 2019 has a probability of 1 of being above the LRP, and a probability of 0.98 of being above the USR. Five-year projections using a constant catch of 2000 t/y indicate that, in 2024, the spawning biomass has probabilities of 0.99 of remaining above the LRP, and 0.91 of remaining above the USR. Catches greater than 2250 t/y will cause u_{2024} to exceed the u_{MSY} reference point with a probability of greater than 0.5.

1. INTRODUCTION

Widow Rockfish (*Sebastes entomelas*, abbreviated as WWR) is ubiquitous along the British Columbia (BC) coast (at ~100-500 m depth) and occurs in high densities along the west coast of Vancouver Island (WCVI) and off the shelf edge between the top of Vancouver Island and south of Cape St. James. Shoals of WWR have been studied near Triangle Island using acoustic surveys in Jan-Feb 1998 (Stanley et al. 1999, 2000). This species exhibits diel migration from near bottom during the day to midwater at night, feeding on shrimps, euphausiids, salps, and fish (Adams 1982, Stanley et al. 1999), probably during dawn (while descending) and dusk (while ascending). Night time aggregations make WWR very susceptible to capture by commercial midwater trawl nets. Although sampling using bottom trawl gear would be theoretically better on dispersed populations (e.g., WWR during the day), Wilkins (1987) found that WWR was poorly represented in fishery-independent surveys. This appears to be the case in the BC synoptic surveys as well.

Adult WWR appear greyish black, brown, brass, or orange in colour and are often referred to by fishers as ‘brownies’. A distinctive black membrane lining the abdominal cavity (*entomelas* is Latin for ‘within’ and ‘black’), coupled with a delicate snout lends itself to the name ‘widow’, especially when occasional specimens are dispersed in catches of other species of red rockfish (Love at al. 2002). In BC, WWR is commonly caught with Yellowtail Rockfish (*S. flavidus*) (Brian Mose, Canadian Groundfish Research and Conservation Society, pers. comm.).

According to a literature summary by Love at al. (2002), spawning females produce ~10^5-10^6 eggs/year and release larvae from January to April in BC. Juveniles remain in the pelagic zone for 5 months, feeding on copepods and krill, before reaching 4.0-7.5 cm and settling out of the plankton into nearshore habitats such as kelp beds and rocky reefs. This species may move into deeper water as they age, though evidence for ontogenetic migration thus far has only suggested a northward movement of cohorts along the continental US west coast (Hicks and Wetzel 2015). As mentioned above, adult WWR feed mostly on crustaceans, gelatinous zooplankton, and small fish, and in turn, are preyed upon by Chinook Salmon (*Oncorhynchus tshawytscha*) and Northern Fur Seal (*Callorhinus ursinus*) (Love et al. 2002).

The maximum reported age for WWR is 60 years (Munk 2001), which comes from a BC female specimen (length = 51 cm) caught in June 1996 off the WCVI in an area known as ‘Nootka’. Estimates of natural mortality rate for WWR based on estimators of Hoenig (1983), Then et al. (2015), and Hamel (2015), using the maximum age 60 y, are M = 0.077, 0.115, and 0.090, respectively (Appendix D). At age 50 y (0.999 quantile), the estimates of M are 0.092, 0.136, and 0.108 for the three estimators. All estimators using maximum age solely are based on exponential decay, which does not allow uncertainty from other factors.

Widow Rockfish supports the fourth largest rockfish fishery in BC (based on the 2017 management harvest plan) with an annual coastwide ‘total allowable catch’ (TAC) in 2017 of 2,358 t (98% allocated to the trawl fishery plus minor amounts to the hook and line fisheries and research surveys) and an average annual catch by all fisheries combined of 2001 t from 2014-2018. Based on consensus among members of the WWR technical working group, this assessment covers one BC coastwide (CST) population harvested by one fishery comprising combined bottom and midwater trawl tows. Analyses of biology and distribution did not support separate regional stocks for WWR. A single coastwide stock was assumed for the last WWR stock assessment (Stanley 1999).

A modified version of the Coleraine statistical catch-at-age software (Hilborn et al. 2003) called Awatea (Appendix E) was used to model the WWR CST population. The assessment model includes:

- sex-specific parameters;
- abundance indices by year (y):
  three synoptic surveys – WCVI=west coast Vancouver Island (8y), QCS=Queen Charlotte Sound (9y), WCHG=west coast Haida Gwaii (8y);
  two historical surveys – GIG=Goose Island Gully (8y), Triennial=US WCVI triennial (7y);
  one bottom trawl CPUE series (23y);
- proportions-at-age data (also called age frequencies or 'AF') by year (y): five sets – commercial trawl catch (30y), WCVI synoptic (1y), QCS synoptic (2y), WCHG synoptic (1y), and GIG historical (1y);
- three values (40, 45 and 50) of maximum modelled age, with older ages accumulated into the final age class;
- estimated selectivities for the commercial fishery and for four of the five sets of survey indices.

The input data were reweighted once based on the recommendations of Francis (2011) to balance abundance and composition data (Appendix E).

In the absence of science advice, there is uncertainty about the risks posed to the BC WWR stock by the current annual catch. There is also a desire to evaluate all groundfish stocks, if possible, within the context of the DFO Precautionary Approach (DFO 2009).

1.1. ASSESSMENT BOUNDARIES

This assessment includes Pacific Marine Fisheries Commission (PMFC) major areas (3CD and 5ABCDE) along the BC coast (Figure 1). Area-specific stock differences (growth, size, and composition taken by gear type) were not discernible; therefore, the BC coastal population was treated as one stock (Appendix D). The PMFC areas are similar but not identical to the management areas used by the Groundfish Management Unit (GMU), which uses combinations of DFO Pacific Fishery Management Areas. We have not used GMU management areas because catch reporting from these areas has only been available since 1996. However, PMFC areas are sufficiently similar to the GMU areas such that managers can prorate any catch policy using TAC ratios outlined in Appendix A.

1.2. RANGE AND DISTRIBUTION

Widow Rockfish occurs along the Pacific rim of North America, ranging from the western Gulf of Alaska southward through BC down to northern Baja California (Love et al. 2002). In BC, grid hotspots (≥ the 0.95 quantile) of catch per unit effort (CPUE) from combined midwater and bottom trawl tows, summed over 23 years (1996-2018), occur WNW off Vancouver Island, along the central WCVI, and in discrete locations off WCHG (Figure 2). Another feature of this figure is the almost-continuous distribution of catches along the BC coast. These mainly come from the bycatch of WWR in the coastwide groundfish bottom trawl fishery.

Appendix G provides maps of hotspots by fishing locality, where the top three mean CPUE hotspots occur in North Frederick-Langara, South Triangle, and Minor 34 Offshore (Fig. G.6). Hotspots of total catch (Fig. G.7) are more geographically concentrated than those for catch rates – 12.8 kt in South Triangle, 4.2 kt in Esperanza East, and 3.3 kt in Deep Big Bank/Barkley Canyon over 23 years.

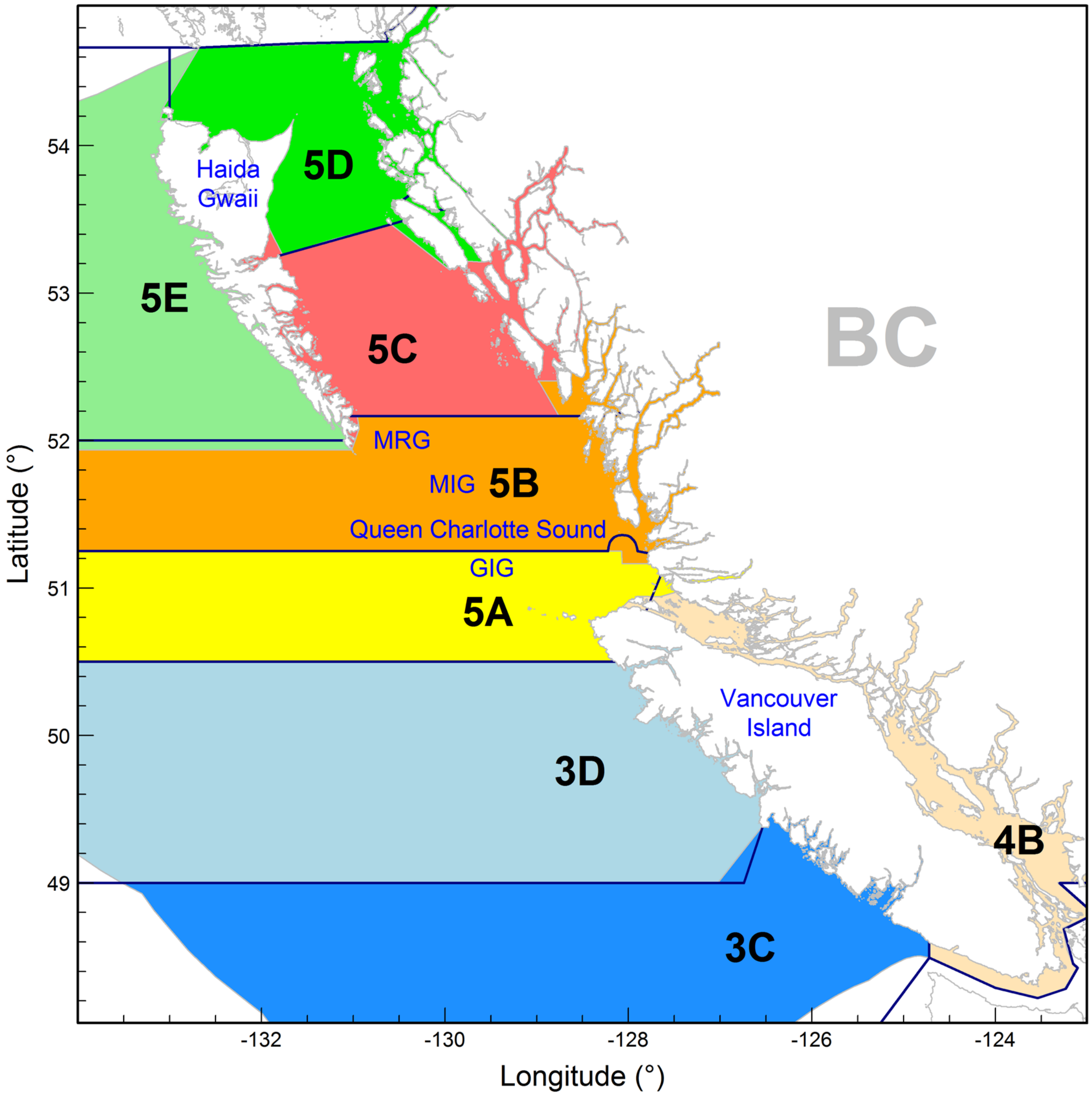

Figure 1. Pacific Marine Fisheries Commission (PMFC) major areas (outlined in dark blue) compared with Groundfish Management Unit areas for Widow Rockfish (shaded). For reference, the map indicates Moresby Gully (MRG), Mitchell's Gully (MIG), and Goose Island Gully (GIG). This assessment covers one coastwide stock: PMFC 3CD + 5ABCDE.

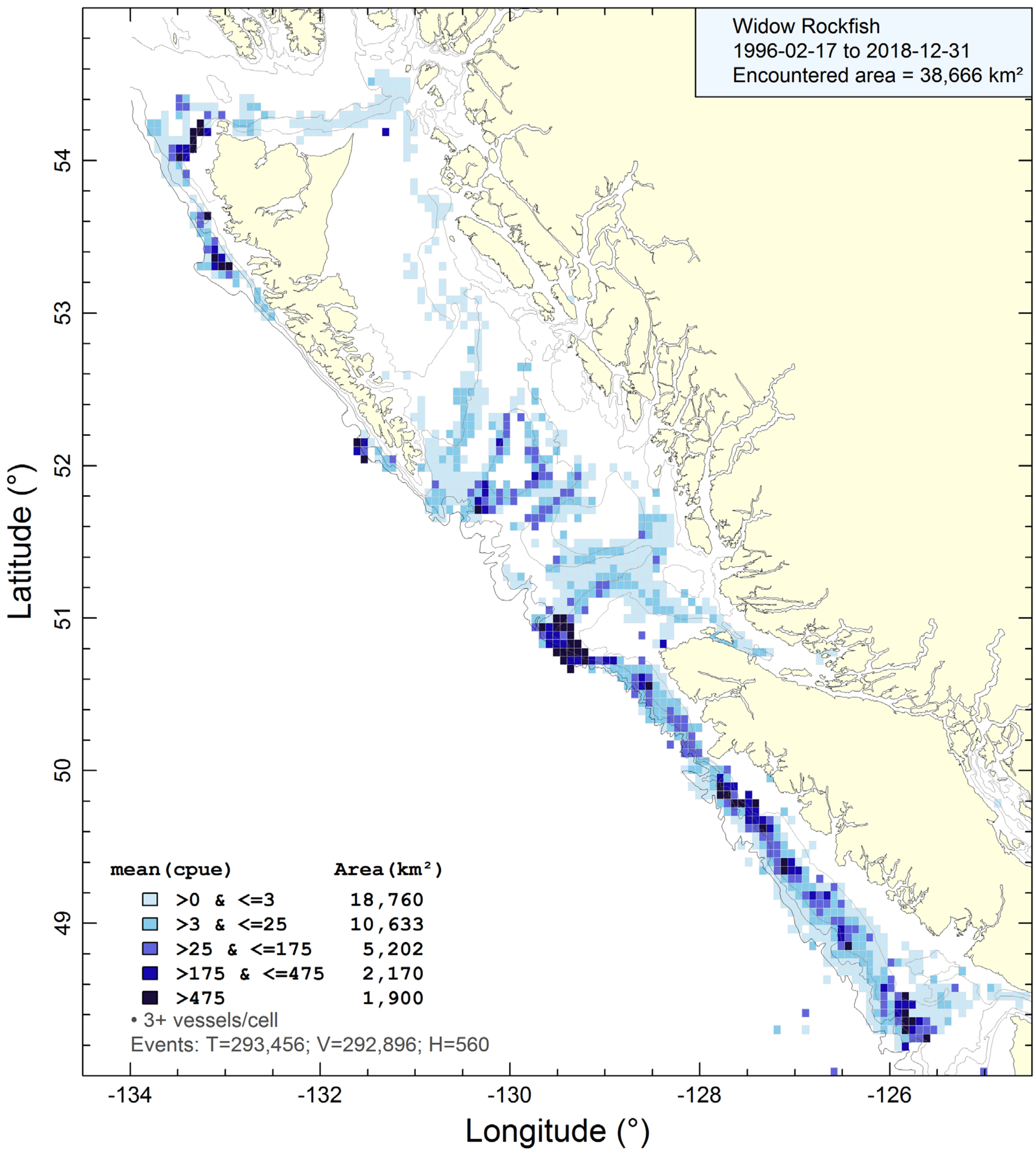

Figure 2. Aerial distribution of WWR mean trawl (bottom + midwater) catch per unit effort (kg/hour) from 1996 to 2018 in grid cells 0.075° longitude by 0.055° latitude (roughly 32 km² each). Isobaths show the 100, 200, 500, and 1000 m depth contours. Note that cells with <3 fishing vessels are not displayed.

2. CATCH DATA

The methods used to prepare a catch history for this WWR assessment, along with the full catch history, are presented in detail in Appendix A. Information about species caught concurrently with WWR commercial catches is presented in Appendix G. The average annual catch over the most recent five years (2014-18) was 2001 metric tonnes (t) coastwide.

3. FISHERIES MANAGEMENT

Appendix A summarises all management actions taken for WWR in BC since 1993. The GMU sets total allowable catch (TAC) of WWR along the BC coast – 2316 t for the trawl fishery and 42 t for the ZN Outside hook and line (H&L) fishery in 2019.

To the south, along the west coast of the continental USA, Hicks and Wetzel (2015) provided an extensive age-structured stock assessment for WWR. Domestic catches of this species off the coasts of California, Oregon, and Washington jumped from 600 t in 1976 to a peak of 27,600 t in 1981 (Table 1 in Hicks and Wetzel 2015), once the industry realised that WWR formed dense aggregations at night (Gunderson 1984). In 2001, WWR was declared overfished and catches reduced to less than 100 t from 2003-2012. The US west coast WWR resource has since recovered from what was thought to be critical levels in historic assessments.

4. SURVEY DESCRIPTIONS

Five sets of fishery independent survey indices have been used to track changes in the biomass of this population (Appendix B):

BC Coastwide:

1. **WCVI Synoptic** – a random-stratified synoptic (species comprehensive) trawl survey covering the west coast of Vancouver Island (WCVI). This survey has been repeated 7 times between 2004 to 2016 using the research vessel FV *Ricker* and in 2018 using a commercial vessel. The survey employs a consistent design, including the same net, and targets a wide range of finfish species.
2. **QCS Synoptic** – a random-stratified synoptic trawl survey covering all of Queen Charlotte Sound (QCS) and targeting a wide range of finfish species. This survey has been repeated 9 times between 2003 to 2017, using three different commercial vessels but with a consistent design, including the same net.
3. **WCHG Synoptic** – a random-stratified synoptic trawl survey covering the west coast (WC) of Graham Island in Haida Gwaii (HG) and the western part of Dixon Entrance. This survey has been repeated 7 times between 2006 to 2018 using three commercial vessels and a consistent design, including the same net and targeting a wide range of finfish species. The 2014 survey has been omitted from the series because less than ½ of the tows were completed. A WCHG survey operated in 1997 was added to this series (as was done for the WCHG Pacific Ocean Perch stock assessment, Edwards et al. 2014a). This survey used a similar design to the synoptic surveys, including the same net specifications and random selection of tow stations.
4. **GIG Historical** – an early composite series of 8 indices extending from 1967 to 1994 in Goose Island Gully (GIG). Most of these surveys were performed by the research vessel *G.B. Reed*, but two commercial vessels (*Eastward Ho* and *Ocean Selector*) were used in 1984 and 1994 respectively. Only tows located in Goose Island Gully (GIG) have been used to ensure continuity across all surveys.
5. **WCVI Triennial** – the United States National Marine Fisheries Service (NMFS) Triennial survey series covered the lower half of the west coast of Vancouver Island for seven years from 1980 to 2001.

The relative biomass survey indices were used as data in the models along with the associated relative error for each index value. No process error was added to the survey relative errors.

This was done because the relative errors were already uniformly high and adding process error would effectively remove the information value from these series.

5. COMMERCIAL CPUE

Commercial catch per unit effort (CPUE) data were used to generate indices of abundance used in the model fitting procedure. This series of indices, extending from 1996 to 2018, provided stability to the population model. Bottom trawl CPUE was selected because the BC trawl fishery, under an individual vessel quota trading system, appears to catch WWR largely as a bycatch when targeting a range of rockfish species. WWR is a mid-water species which appears to occur regularly at low levels in bottom trawl catches.

The CPUE abundance index series was standardised for changes to vessel configuration, catch timing (seasonality) and location of catch (e.g., latitude and depth) to remove potential biases in CPUE that may result from changes in fishing practices and other non-abundance effects. In these models, abundance was represented as a 'year effect' and the explanatory variables were selected sequentially by a GLM model, which accounted for variation in the available data. Other factors that might affect the behaviour of fishers, particularly economic factors, do not enter these models due to a lack of applicable data, thus resulting in indices that may not entirely reflect changes in the underlying stock abundance. Appendix C provides details on the CPUE analyses and Appendix G provides various sensitivities to the CPUE input, including replacement with a GLM fit using a Tweedie distribution.

6. BIOLOGICAL INFORMATION

6.1. BIOLOGICAL SAMPLES

Commercial catches of WWR by trawl (combined midwater and bottom) gear were sampled for age proportions in 1979 and then resumed annually from 1986. A few early research cruises sampled ages in 1979 and 1980 while most of the modern synoptic surveys have sampled some WWR. Only otoliths aged using the 'break and burn' (B&B) method have been included in age samples used in this assessment because the earlier surface ageing method was known to be biased, especially with increasing age. In practice, this means that no age data are available before 1978. During the 2018 Redstripe Rockfish review meeting, one participant mentioned that surface ageing is currently the preferred method for ageing very young rockfish (≤ 3y), which was later confirmed by the ageing lab. Commercial fishery age frequency (AF) data were summarised for each quarter, weighted by the WWR catch weight for the sampled trip. The total quarterly samples were scaled up to the entire year using the quarterly landed commercial catch weights of WWR. See Appendix D (Section D.3) for details.

Sampled AFs from bottom and midwater trawl were combined after comparing cumulative AFs for each gear type by sex and capture year (earlier years comprising mostly sorted samples, later years unsorted) and concluding that there were no consistent differences in the AFs between the two gear types for either sex (females: Figure D.8, males: Figure D.9). Consequently, the model was run assuming a joint selectivity for the two fishing methods by combining the AFs and the catch data into a single fishery. Age frequency data were available in at least one survey year from four of the five survey series used in the model. The only exception was for the WCVI Triennial survey, for which no biological data were available. The WCHG Synoptic survey had one year in 2006, the GIG Historical survey had one year in 1979, the QCS Synoptic survey had two years from 2004 and 2005, and the WCVI Synoptic survey had a single year in 2006. The survey AFs were sparse, poorly sampled and consequently associated with a lot of process error. The survey AFs were scaled to represent the total survey in a manner similar to that used for the commercial samples: within an area stratum, samples were weighted by the WWR catch density in the sampled tows; stratum samples were then weighted by the stratum areas (described in Appendix D).

6.2. GROWTH PARAMETERS

Growth parameters were estimated from WWR length and age data from biological samples collected from 1979 to 2018 (Appendix D). Survey otolith age data were sparse and potentially biased, given the midwater behaviour of this species; therefore, data from the commercial fishery and research surveys were combined for use in determining growth (Appendix D). This included the parameters for the allometric weight-length relationship and growth specified as a von Bertalanffy model. While females are larger on average than males, the difference is not as pronounced as in some other *Sebastes* species (L_∞: ♀=52.8 cm, ♂=49.0 cm).

6.3. MATURITY AND FECUNDITY

The proportions of females that mature at ages 1 through 40 were computed from biological samples. Stage of maturity was determined macroscopically, partitioning the samples into one of seven maturity stages (Stanley and Kronlund 2000). Fish assigned to stages 1 or 2 were considered immature while those assigned to stages 3-7 were considered mature. Data representing staged and aged females (using the B&B method) were pooled from commercial trips and the observed proportion mature at each age was calculated. All months were used in creating the maturity curve because these data provided cleaner fits than using a subset of months. A monotonic increasing maturity-at-age vector was constructed by fitting a half-Gaussian function (Equation D.3, equivalent to that in Equation E.7) to the observed maturity values (Appendix D). The ogive used in the model set proportions mature to zero for ages 1 to 4, then switched to the fitted monotonic function for ages 5 to 40, all forced to 1 (fully mature) after age 12. This was done because the fitted model overestimates the proportion mature at younger ages (Figure D.22). Females older than age 12 were assumed to be 100% mature and maturity was assumed to be constant over time. Fecundity was assumed to be proportional to the female body weight.

6.4. NATURAL MORTALITY

It was not possible to estimate WWR natural mortality (*M*) within the model because of the lack of contrast in the abundance indices and relatively uninformative MPD likelihood profiles for catch-at-age (commercial and survey) across a possible range for *M* (0.02-0.15). The tail of the age distribution was used to estimate the maximum age, rather than use a single isolated observation. The 1% quantile for the available age data was 43 years and there were only 17 observations where age>49 (=0.135% of the age distribution collected over a 40 year period). A maximum age=55 (Figure D.7) gives *M* estimates of 0.08 (Hoenig 1983), 0.13 (Then et al. 2015) and 0.10 (Hamel 2015). We decided to test a range of fixed *M* values from 0.07 to 0.10 in this model to create a composite stock assessment. Values of *M* = 0.07, 0.08, and 0.09 were selected because they lay within a plausible range for this value, with values > 0.10 ruled out because of very poor MCMC (Monte Carlo Markov Chain) behaviour. We did not evaluate values less than *M*=0.07, a value which seemed to be at the lower end of plausible *M* values, given the lack of fish at or above the age of 50 and with only one fish aged >60.

6.5. STEEPNESS

A Beverton-Holt (BH) stock-recruitment function was used to generate average recruitment estimates in each year, based on the biomass of female spawners (Equation E.10).

Recruitments were allowed to deviate from this average (Equations E.17 and E.24) in order to improve the fit of the model to the data. The BH function was parameterised using a 'steepness' parameter, *h,* which specified the proportion of the maximum recruitment that was available at 0.2 B_0, where B_0 is the unfished equilibrium spawning biomass (mature females). The parameter *h* was estimated, constrained by a prior developed for west coast rockfish by Forrest et al. (2010), after removing all information for QCS POP (Edwards et al. 2012b). This prior took the form of a beta distribution with equivalent of mean 0.674 and standard deviation 0.168.

7. AGE STRUCTURED MODEL

A two-sex, age-structured, stochastic model was used to reconstruct the population trajectory of WWR from 1940 to the beginning of 2019. Ages were tracked from 1 to A, where A $\in \{40, 45, 50\}$ and acts as an accumulator age category. The population was assumed to be in equilibrium with average recruitment and with no fishing at the beginning of the reconstruction. Selectivities by sex for the surveys (all but the WCVI Triennial) and the commercial fisheries were estimated using four parameters describing double half-Gaussian functions, although the right-hand limb was assumed to be fixed at the maximum selectivity to avoid the creation of a cryptic population. Dome-shaped selectivity was not explored. The model and its equations are described more fully in Appendix E.

The model was fit to the available data by minimising a function which summed the negative log-likelihoods arising from each data set, the deviations from mean recruitment and the penalties stemming from the Bayesian priors.

A composite base case for Widow Rockfish comprised nine model runs, and the MCMC samples from the nine were pooled for advice to managers. Important decisions made during the assessment of WWR included:

- fixed natural mortality *M* to three levels: 0.07, 0.08, and 0.09 using three accumulator ages *A*: 40, 45, and 50 y for a total of nine base case models:
    - Run01 – fix *M*=0.07, *A*=40; Run02 – fix *M*=0.07, *A*=45; Run03 – fix *M*=0.07, *A*=50;
    - Run04 – fix *M*=0.08, *A*=40; Run05 – fix *M*=0.08, *A*=45; Run06 – fix *M*=0.08, *A*=50;
    - Run07 – fix *M*=0.09, *A*=40; Run08 – fix *M*=0.09, *A*=45; Run09 – fix *M*=0.09, *A*=50;
- used five survey abundance index series (WCVI Synoptic, QCS Synoptic, WCHG Synoptic, GIG Historical, WCVI Triennial), the first four with AF data;
- used one commercial fishery abundance index series (bottom trawl CPUE index);
- assumed one fishery (commercial bottom + midwater trawl) with pooled catches and AF data;
- assumed two sexes (females, males);
- developed selectivity priors (μ_g, log $v_{g\mathrm{L}}$, Δ_g) for the surveys from MCMC estimates of selectivity for Yellowtail Rockfish (Starr et al. 2014[1]) but fixed the shift in the survey vulnerability of males ($\Delta_{g=1:5}$) to 0;

[1] Starr, P.J., Kronlund, A.R., Olsen, N. and Rutherford, K. 2014. Yellowtail Rockfish (*Sebastes flavidus*) stock assessment for the coast of British Columbia, Canada. CSAP Working Paper PAC_GF08_2014-15

- applied abundance reweighting: added CV process error to index CVs, c_p=0 for surveys and c_p=0.1859 for commercial CPUE series;
- applied composition reweighting: adjusted AF effective sample sizes using the mean-age method of Francis (2011);
- fixed standard deviation of recruitment residuals (σ_R) to 0.9;
- excluded the 1995 survey index from the GIG Historical series (design incompatible);
- excluded water hauls from the WCVI Triennial series;
- excluded the 1997 WCHG age frequency data (caused instability in the MCMC simulations).

All model runs were reweighted one time for (i) abundance, by adding process error cp $\in$ { 0, 0, 0, 0, 0, and 0.1859 } to the index CVs for the five surveys and the commercial trawl CPUE, respectively, and (ii) composition using the procedure of Francis (2011) for age frequencies.

Twelve sensitivity analyses were run (with full MCMC simulations) relative to the central run of the composite base case (Run05: M=0.08, A=45) to test the sensitivity of the outputs to alternative model assumptions:

- S01 (Run10) – decreased σ_R from 0.9 to 0.6;
- S02 (Run11) – increased σ_R from 0.9 to 1.2;
- S03 (Run12) – increased M from 0.08 to 0.10;
- S04 (Run13) – estimated M with 50% CV;
- S05 (Run14) – added simple ageing error matrix with 0.8 along the diagonal and 0.1 on either side of the diagonal;
- S06 (Run15) – added ageing error matrix based on observed spread between minimum and maximum ages specified by readers;
- S07 (Run16) – dropped the CPUE index series;
- S08 (Run17) – removed process error on the CPUE series;
- S09 (Run18) – dropped all survey age data and set survey selectivities to prior means;
- S10 (Run19) – halved commercial catch during years of foreign fleet activity (1965-1976) and during years of possible misreporting by the domestic fleet (1988-1995);
- S11 (Run20) – doubled commercial catch during years of foreign fleet activity (1965-1976) and during years of possible misreporting by the domestic fleet (1988-1995); and
- S12 (Run21) – used Tweedie CPUE with no added process error.

The MPD (mode of the posterior distribution) ‘best fit’ was used as the starting point for a Bayesian search across the joint posterior distributions of the parameters using the Monte Carlo Markov Chain (MCMC) procedure. All models (base and sensitivity runs) were judged to have converged after 12,000,000 iterations, sampling every 10,000th, to give 1,200 draws (1,000 samples after dropping the first 200 for burn in).

8. MODEL RESULTS

8.1. BASE CASE

8.1.1. Central Run

The model fits to the abundance indices were generally satisfactory (Figures F.1 and F.7), although there were some very large residuals, such as for WCVI in 2004 (Figure F.2). These surveys showed large interannual variations which exceeded the capacity for a population to change so rapidly. Such behaviour was expected from a bottom trawl survey capturing a mid-water species and these shifts were often associated with large Pearson residuals in spite of the high relative errors. Fits to the commercial age frequency data were good, with the Pearson residuals generally lying between –1 and +1 although there was a suggestion that there are more negative than positive residuals (Figure F.10). Model estimates of mean age matched the observed mean ages (Figure F.19) for the commercial series, for the most part, but the fits were poor for the survey data sets. The poor fits to the survey age data were unsurprising, given the mid-water behaviour of this species and the sporadic nature of the available age data. For this reason, we dropped the survey age data in a sensitivity run which showed that the model results were robust to these data.

Because this stock assessment indicated that the WWR spawning biomass never went to levels that would impair recruitment, the stock-recruitment relationship (Figure F.20) showed little contrast, with a few large recruitment events spread across the parent population. High, episodic recruitment occurred in 1961 and 1990. The latter recruitment peak was very well defined but there appeared to be blurring into adjacent years for the 1961 peak which was likely due to ageing error. Recruitment deviations fluctuated over time, but significant auto-correlation of these deviations occurred only at lag 1 (Figure F.21). The MPD estimate of age at full selectivity (Figure F.22) was similar among the surveys ($\mu_{1:5}$ = 12.7-15.1) and lower for the commercial fishery (μ_6 = 10.8), but the survey selectivities may have been poorly estimated due to the highly variable survey ageing data. The selectivity curves either overlaid or lay to the right of the maturity ogive, indicating that the fishery and the surveys were capturing mature fish (Figure F.22).

Spawning biomass (B_t) relative to unfished equilibrium biomass (B_0) showed rapid depletion from the late 1970s to the mid-1990s, with the MPD estimate of 2019 spawning biomass (B_{2019}) sitting at $0.37B_0$ (Figure F.23). Exploitation rates (u_t) exceeded 0.08 (the central run M) in 33 years, 23 of which occurred after the fishery became more controlled in 1996. The current exploitation rate (mean of last 5 years) was estimated to be 0.11 (bottom panel: Figure F.23).

MCMC traces showed acceptable convergence properties (no trend with increasing sample number) for the estimated parameters (Figure F.24), as did diagnostic analyses that split the posterior samples into three equal consecutive segments (Figure F.25) and checked for parameter autocorrelation out to 60 lags (Figure F.26). Some of the parameters (e.g., R_0, h, μ_2) moved from the initial MPD estimate to a median value that differed from the MPD (Figure F.27), indicating that the MCMC search found plausible fits to the data at levels other than those found by the 'best fit'.

The marginal posterior distributions of vulnerable biomass and catch (Figure F.28, top panel) showed that this stock was not greatly reduced by the early foreign fleet fishery (1965-76) but experienced a prolonged decline once the domestic fishery took over in 1977. The decline ended when catch limits, implemented through Individual Vessel Quotas (IVQ), were imposed in 1997. A mandatory system of onboard observers was also implemented at the same time. A major recruitment event in 1961 likely ameliorated the effects of the foreign fleet activity, and a second major recruitment in 1990 likely stabilised the population in conjunction with management controls (Figure F.28, middle panel). Further good recruitment years in 2006 and 2008 should sustain the population in coming years. The median spawning biomass relative to unfished equilibrium values reached a minimum of 0.33 in 2012 and currently sits at 0.37. The exploitation rate peaked at 0.16 in 1992 and is estimated to be 0.10 (0.06, 0.15) in 2018 (Figure F.28, bottom panel).

8.1.2. Composite Base Case

The composite base case comprised nine runs which explored major axes of uncertainty for this stock assessment:

- $M_{1,2}$ = 0:07 using $A \in \{40, 45, 50\}$,
- $M_{1,2}$ = 0:08 using $A \in \{40, 45, 50\}$,
- $M_{1,2}$ = 0:09 using $A \in \{40, 45, 50\}$.

While exploring across a range of values for M is self-evident, particularly when it was not possible to estimate this parameter, the decision to average across a range of values for A is not. This was done because early model fits indicated that there was sensitivity in some of the quantities of management importance, particularly current stock status, associated with the choice of the accumulator age (see Figure F.33). Initially we had selected A=40 because that was the value used for Redstripe Rockfish (RSR, *S. proriger*, Starr and Haigh in press) and the distribution of ages for these two *Sebastes* species is similar. However, once it was realised that there was sensitivity in the advice resulting from this choice, it was decided to make this parameter the second axis of the composite base case.

For each run, 1000 MCMC samples were generated then pooled to provide an average stock trajectory for population status and advice to managers. Estimating M was not possible given the uninformative nature of the data, with MPD estimates not shifting from the prior means. MCMC runs that estimated M exhibited unstable behaviour with no credible convergence.

The nine component runs outlined above converged with no serious pathologies in the MCMC diagnostics (similar diagnostic results to those outlined for the central run, see Appendix F. Figures F.29 to F.31 show diagnostics for the R_0 parameter in each of the nine component runs, and Figure F.32 shows the distribution of all the estimated parameters. In most cases, the component runs had parameter estimates with very similar distributions. The R_0 parameter varied with M and, to a lesser extent, with A. MCMC chains of this parameter showed increasing autocorrelation as M increased (Figure F.31). Setting M=0.10 caused a high degree of autocorrelation in this parameter and in all of the q parameters (see Section 8.1.3).

The composite base case, comprising nine pooled MCMC runs, was used to calculate a set of parameter estimates (Table 1) and derived quantities at equilibrium and associated with MSY (Table 2). The composite base case population trajectory from 1940 to 2019 and average projected biomass to 2024, assuming a constant catch policy of 2000 t/y, appears in Figure 3. A phase plot of the time-evolution of spawning biomass and exploitation rate in MSY space (Figure 4) suggests that the stock has been sustainably exploited in recent years, with a current position at B_{2019}/B_{MSY} = 1.51 (0.92-2.61) and u_{2018}/u_{MSY} = 0.66 (0.29-1.35).

Table 1. Quantiles of the MCMC posterior distributions for the main estimated model parameters for the composite base case WWR stock assessment. Except for R_0, subscripts refer to the data source, where 1= WCVI Synoptic survey, 2=QCS Synoptic survey, 3=WCHG Synoptic survey, 4= GIG Historical survey, 5=WCVI Triennial survey, and 6=commercial trawl fishery or CPUE index series. Selectivity parameters appear on the right side of the table

Value	5%	50%	95%	Value	5%	50%	95%
R_0	3,301	4,551	6,774	μ_1	10.4	12.8	15.9
h	0.567	0.788	0.945	μ_2	10.7	12.4	14.4
q_1	0.000857	0.00161	0.00296	μ_3	12.8	15.2	17.8
q_2	0.00274	0.00528	0.0110	μ_4	10.6	12.8	14.7
q_3	0.00257	0.00535	0.0108	μ_6	9.72	10.7	11.7
q_4	0.000469	0.000778	0.00129	Δ_6	-0.933	-0.355	0.209
q_5	0.00493	0.00829	0.0135	$\log v_{1L}$	2.53	3.37	4.15
q_6	3.45E-05	5.75E-05	8.46E-05	$\log v_{2L}$	1.32	2.22	3.00
				$\log v_{3L}$	2.15	2.97	3.76
				$\log v_{4L}$	1.16	2.00	2.91
				$\log v_{6L}$	1.63	2.18	2.60

Table 2. Quantiles of MCMC-derived quantities from the 9,000 samples of the MCMC posterior of the composite base case. Definitions: B_0 – unfished equilibrium spawning biomass (mature females), V_0 – unfished equilibrium vulnerable biomass (males and females), B_{2019} – spawning biomass at the start of 2019, V_{2019} – vulnerable biomass in the middle of 2018, u_{2018} – exploitation rate (ratio of total catch to vulnerable biomass) in the middle of 2018, u_{max} – maximum exploitation rate (calculated for each sample as the maximum exploitation rate from 1940-2018), B_{MSY} – equilibrium spawning biomass at MSY (maximum sustainable yield), u_{MSY} – equilibrium exploitation rate at MSY, V_{MSY} – equilibrium vulnerable biomass at MSY. All biomass values (including MSY) are in tonnes. The average catch over the last 5 years (2014-18) was 2001 t.

From model output

Value	5%	50%	95%
B_0	26,282	29,951	36,692
V_0	46,361	53,380	66,080
B_{2019}	7,179	11,017	18,660
V_{2019}	12,396	19,526	34,035
B_{2019} / B_0	0.257	0.369	0.537
V_{2019} / V_0	0.252	0.366	0.54
u_{2018}	0.0574	0.0975	0.149
$u_{\max}$	0.112	0.161	0.214

MSY-based quantities

Value	5%	50%	95%
MSY	1,460	1,909	2,685
B_{MSY}	4,815	7,373	11,307
$0.4B_{MSY}$	1,926	2,949	4,523
$0.8B_{MSY}$	3,852	5,898	9,045
B_{2019} / B_{MSY}	0.921	1.51	2.61
B_{MSY} / B_0	0.17	0.246	0.327
V_{MSY}	8,284	13,145	20,430
V_{MSY} / V_0	0.168	0.247	0.33
u_{MSY}	0.081	0.148	0.271
u_{2018} / u_{MSY}	0.289	0.658	1.35

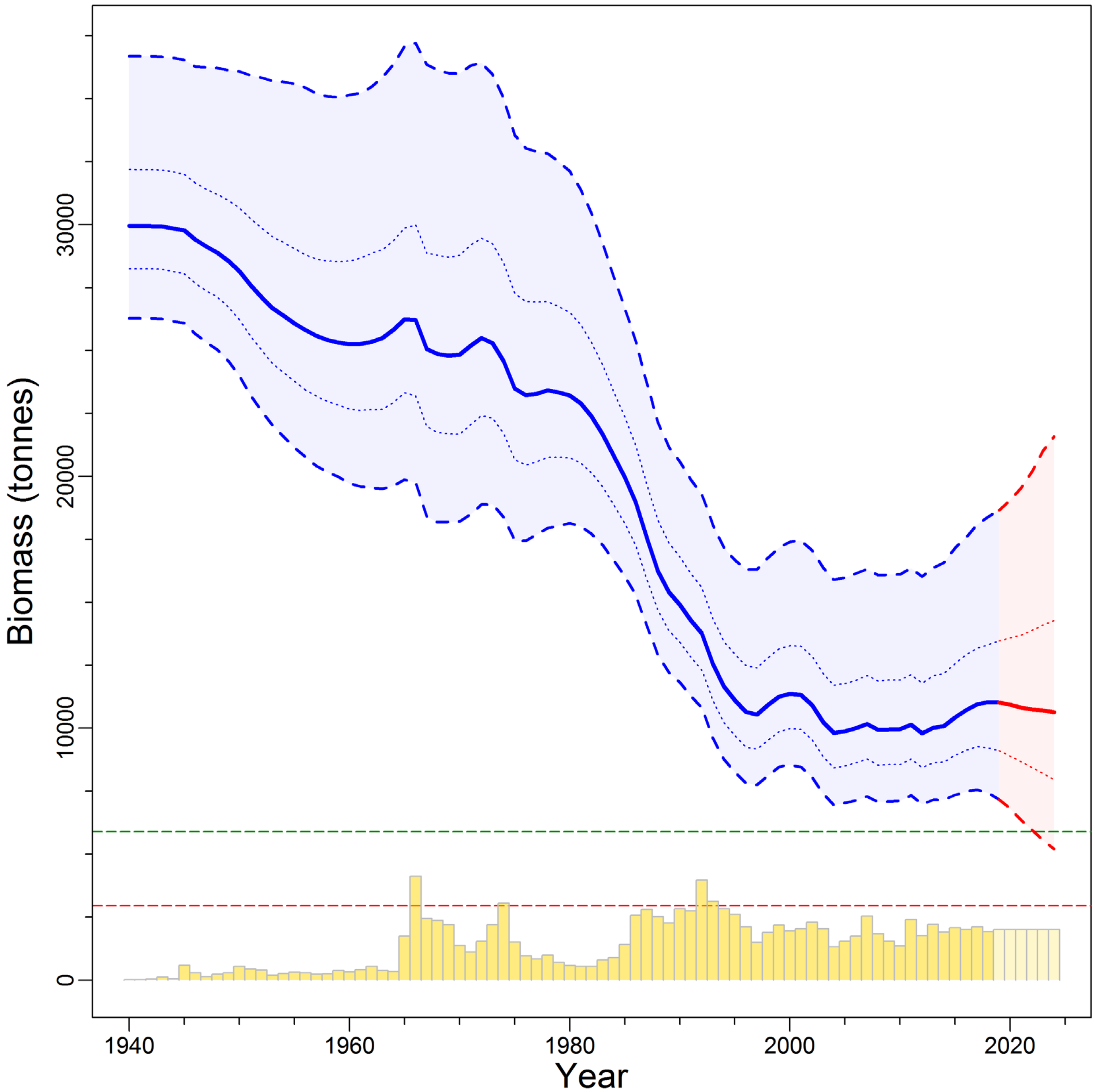

Figure 3. Estimates of spawning biomass B_t (tonnes) for the composite base case. The median biomass trajectory appears as a solid curve surrounded by a 90% credibility envelope (quantiles: 0.05-0.95) in light blue and delimited by dashed lines for years t=1940-2019; projected biomass appears in light red for years t=2019-2024. Also delimited is the 50% credibility interval (quantiles: 0.25-0.75) delimited by dotted lines. The horizontal dashed lines show the median LRP and USR. Catch and assumed catch policy (2000 t/y) are represented as bars along the bottom axis.

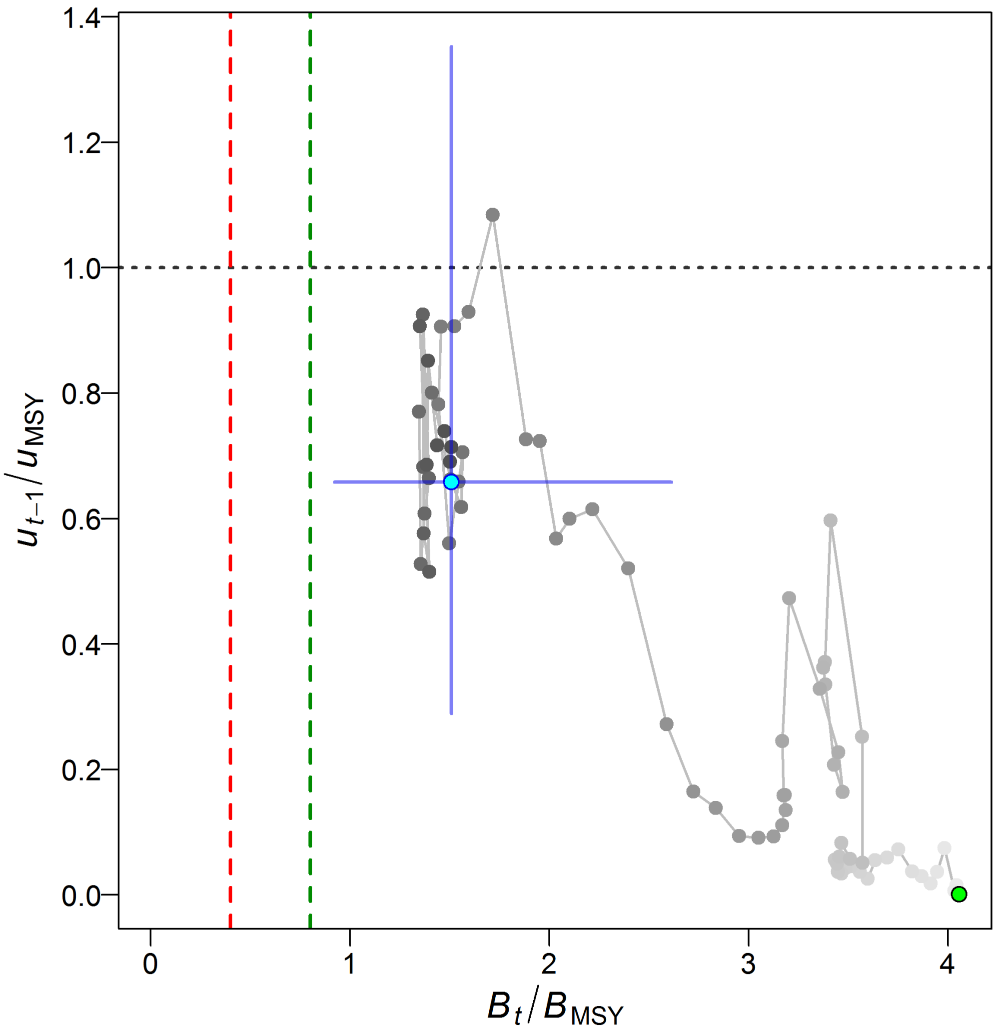

Figure 4. Phase plot through time of the medians of the ratios B_t/B_{MSY} (the spawning biomass at the start of year t relative to B_{MSY}) and u_{t-1}/u_{MSY} (the exploitation rate in the middle of year t-1 relative to u_{MSY}) for the composite base case. The filled green circle is the starting year (1941). Years then proceed from light grey through to dark grey with the final year (t=2019) as a filled cyan circle, and the blue lines represent the 0.05 and 0.95 quantiles of the posterior distributions for the final year. Red and green vertical dashed lines indicate the PA provisional LRP = $0.4B_{MSY}$ and USR = $0.8B_{MSY}$, and the horizontal grey dotted line indicates u_{MSY}.

8.1.3. Sensitivity Analyses

Twelve sensitivity analyses were run (with full MCMC simulations) relative to the central run of the composite base case (see Section 7 for details) to test the sensitivity of the outputs to alternative model assumptions. Each sensitivity run was reweighted once (as were the component base runs) before MCMC simulation. The differences among the sensitivity runs (including the central run) are summarised in tables of median parameter estimates (Table F.17) and median MSY-based quantities (Table F.18).

The trajectories of B_t medians relative to B_0 (Figure 5) indicate that estimating M (S04) and fixing M=0.10 (S03) resulted in the most optimistic scenarios, while the most pessimistic runs were generated when pre-1996 catches (foreign and pre-observer domestic) were doubled (S11) and when the commercial CPUE series was dropped (S07). All other sensitivities tended to reflect the central run closely, especially in the last 20 years of the reconstructed population trajectory. The overall conclusion is that, other than being sensitive to values of *M*, the model outcome is largely driven by the data because the only substantive changes in advice resulted when data series were omitted or changed. This set of selectivities also indicate that there is reasonable consistency among the different data sources (CPUE, survey biomass indices and ageing data) because stepwise omission of the data sets did not result in large shifts in model results.

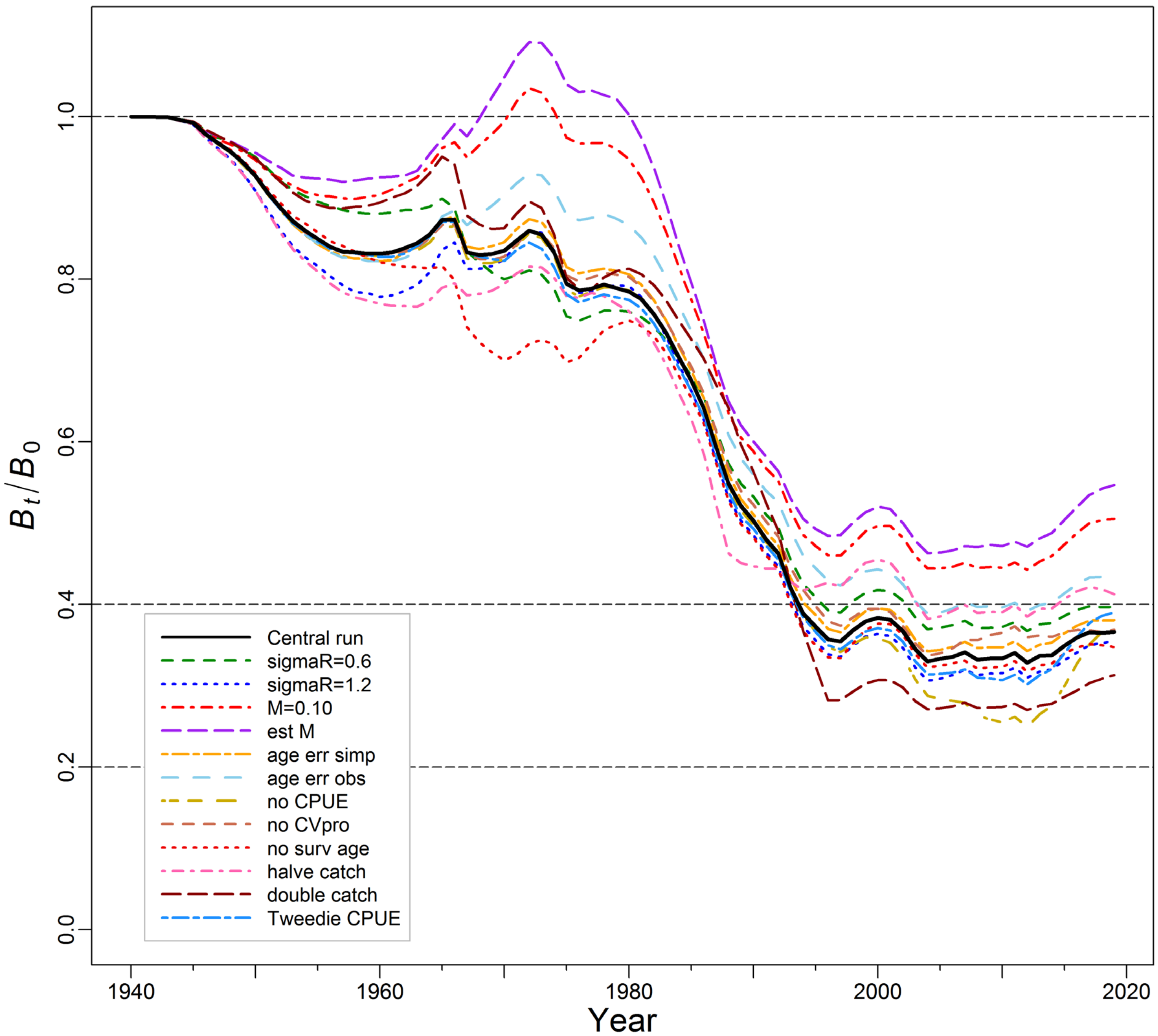

Figure 5. Model median trajectories of spawning biomass as a proportion of unfished equilibrium biomass (B_t/B_0) for the central run and 12 sensitivity runs (see legend lower left). Horizontal dashed lines show alternative reference points used by other jurisdictions: $0.2B_0$ (~DFO's USR), $0.4B_0$ (often a target level above B_{MSY}), and B_0 (equilibrium spawning biomass).

The diagnostic plots (Figures F.43-F.45) suggest that seven of the sensitivities exhibited good MCMC behaviour, three were marginal but probably acceptable, and two had poor diagnostic behaviour:

- Good – no trend in traces, split-chains align, no autocorrelation
    - S01 (σR=0.6)

- S05 (simple age error)
- S06 (reader-based age error)
- S07 (no commercial CPUE)
- S09 (no survey ages)
- S10 (halve pre-1996 commercial catch)
- S12 (Tweedie CPUE series)

- Marginal – trace trend temporarily interrupted, split-chains somewhat frayed, some autocorrelation
  - S02 (σR =1.2)
  - S03 (M=0.10)
  - S11 (double pre-1996 commercial catch)
- Poor – trace trend fluctuates substantially or shows a persistent increase/decrease, split-chains differ from each other, substantial autocorrelation
  - S04 (estimate M)
  - S08 (no process error on CPUE)

The run that estimated *M* using a prior with 50% CV (S04) appeared unstable and would likely never converge. Consequently, the reported results should be viewed with caution. The high-*M* run (S03) had one major short excursion, possibly indicating that the WWR data do not support higher values of natural mortality. Attempts at fitting the model data to values of *M* greater than 0.10 resulted in poor MCMC diagnostics and were excluded from consideration in the composite base case (these runs are not reported here). Increasing σ_R caused a deterioration in the MCMC diagnostics but did not appreciably affect the model results. Unsurprisingly, forcing the model to closely fit the CPUE indices also resulted in poor MCMC diagnostics but again did not appreciably affect the model results. Although doubling the pre-1996 catch caused a noticeable drop in the estimated stock status, such high levels of catch were unlikely to have occurred. This run was made solely to test the sensitivity of the stock assessment to this assumption.

9. ADVICE FOR MANAGERS

9.1. REFERENCE POINTS

The Sustainable Fisheries Framework (SFF, DFO 2009) established provisional reference points, which incorporate the 'precautionary approach' (PA), to guide management and assess harvest in relation to sustainability. These reference points are the limit reference point (LRP) of $0.4B_{\mathrm{MSY}}$ and the upper stock reference point (USR) of $0.8B_{\mathrm{MSY}}$, which have been adopted by previous rockfish assessments (Edwards et al. 2012 a,b, 2014 a,b; Starr et al. 2014, 2016; Haigh et al. 2018; Starr and Haigh 2021) and so are used here. Note that no modelling has been carried out to determine the suitability of these reference points for this stock, nor have acceptable levels of risk been specified.

The zone below $0.4B_{\mathrm{MSY}}$ is termed the 'critical zone' by the SFF, the zone lying between $0.4B_{\mathrm{MSY}}$ and $0.8B_{\mathrm{MSY}}$ is termed the 'cautious zone', and the region above the upper stock reference point ($0.8B_{\mathrm{MSY}}$) is termed the 'healthy zone'. Generally, stock status is evaluated as the probability of the spawning female biomass in year *t* being above the reference points, i.e., $P(B_t > 0.4B_{\mathrm{MSY}})$ and $P(B_t > 0.8B_{\mathrm{MSY}})$. The SFF also stipulates that, when in the healthy zone, the fishing mortality must be at or below that associated with MSY under equilibrium conditions (u_{MSY}). Furthermore, fishing mortality is to be proportionately ramped down when the stock is deemed to be in the cautious zone, and set equal to zero when in the critical zone.

The term ‘stock status’ should be interpreted as ‘perceived stock status at the time of the assessment in 2019’ because the value is calculated as the ratio of two estimated biomass values (B_{2019}/B_{MSY}) by a specific model using the data available in 2019. Further, the estimate of B_{MSY} depends on the model’s assessment of the stock’s productivity. Therefore, comparisons of stock status among various model scenarios can be misleading because the B_{MSY} space is not the same from one model to the next.

MSY-based reference points estimated within a stock assessment model can be highly sensitive to model assumptions about natural mortality and stock recruitment dynamics (Forrest et al. 2018). As a result, other jurisdictions use reference points that are expressed in terms of B_0 rather than B_{MSY} (e.g., N.Z. Min. Fish. 2011), because B_{MSY} is often poorly estimated as it depends on estimated parameters and a consistent fishery (although B_0 shares many of these same problems). Therefore, the reference points of $0.2B_0$ and $0.4B_0$ are also presented in Appendix F. These are default values used in New Zealand respectively as a ‘soft limit’, below which management action needs to be taken, and a ‘target’ biomass for low productivity stocks, a mean around which the biomass is expected to vary. The ‘soft limit’ is equivalent to the upper stock reference (USR, $0.8B_{\text{MSY}}$) in the provisional DFO Sustainable Fisheries Framework while a ‘target’ biomass is not specified by the provisional DFO SFF. Additionally, results are provided comparing projected biomass to B_{MSY} and to current spawning biomass B_{2019}, and comparing projected harvest rate to current harvest rate u_{2018} (Appendix F).

9.2. STOCK STATUS AND DECISION TABLES

Stock status plots for managers, which depict distributions of B_{2019}/B_{MSY} in zones delimited by 0.4 B_{MSY} (LRP) and 0.8 B_{MSY} (USR), show that the WWR composite base case lies in the healthy zone, as do all the component runs (Figure 6). More precisely, the composite base case has a probability of 0 of being in the critical zone, a 0.016 probability of being in the cautious zone, and a 0.984 probability of being in the healthy zone.

Stock status plots for sensitivity runs based on the central run of the WWR composite base case (Figure 7) show that most of these sensitivity runs lie in the healthy zone, with only the double pre-1996 commercial catch run (S11) dipping into the cautious zone. None of the sensitivities presented here indicate concern for the status of the WWR stock relative to the SFF reference points.

Decision tables for the WWR composite base case provide advice to managers as probabilities that projected biomass B_t (t = 2020, ..., 2024) will exceed biomass-based reference points (or that projected exploitation rate u_t will fall below harvest-based reference points) under constant-catch policies. Table 3 presents probabilities that projected B_t using the composite base case will exceed the LRP and the USR and will be less than the harvest rate at MSY. Alternative decision tables for the composite base case can be found in Appendix F.

Assuming that the average catch of 2000 t was taken each year for the next 5 years, Table 3 indicates that a manager could be 99% certain that B_{2024} lies above the LRP of $0.4B_{\text{MSY}}$, 91% certain that B_{2024} lies above the USR of $0.8B_{\text{MSY}}$, and 70% certain that u_{2024} lies below u_{MSY} for the composite base case. Generally, it is up to managers to choose the preferred catch levels and the preferred risk levels. For example, it may be desirable to be 95% certain that B_{2024} exceeds an LRP whereas exceeding a USR might only require a 50% probability. Assuming this risk profile, a catch policy of 2750 t/y would satisfy the LRP constraint and 3750 t/y would satisfy the USR constraint. Assuming that u_{MSY} is a target exploitation rate, a catch policy of 2250 t/y would mean that the harvest rate in 2024 would be less than u_{MSY} with a probability of at least 50%.

We caution that, although uncertainty is built into the assessment and its projections by taking a Bayesian approach for parameter estimation and by constructing a composite base case that spans ranges of inestimable parameter values, these results depend heavily on the assumed model structure, the informative priors, and data assumptions (particularly the average recruitment assumptions) used for the projections. This latter problem lessens with the short-term (e.g., 5-year) projections for long-lived stocks such as WWR which recruit at older ages to the fishery, because most of the recruitments in the projections are based on recruitments estimated during the stock reconstruction phase of the assessment.

Table 3. Decision tables for the reference points $0.4B_{MSY}$, $0.8B_{MSY}$, and u_{MSY} for 1-5 year projections for a range of constant catch strategies (in tonnes) using the composite base case. Values are the probability (proportion of 9000 MCMC samples) of the female spawning biomass at the start of year t being greater than the B_{MSY} reference points, or the exploitation rate of vulnerable biomass in the middle of year t being less than the u_{MSY} reference point. For reference, the average catch over the last 5 years (2014-2018) was 2001 t.

	$P(B_t > 0.4B_{MSY})$						$P(B_t > 0.8B_{MSY})$						$P(u_t < u_{MSY})$					
Catch	2019	2020	2021	2022	2023	2024	2019	2020	2021	2022	2023	2024	2019	2020	2021	2022	2023	2024
0	1	1	1	1	1	1	0.98	0.99	1	1	1	1	1	1	1	1	1	1
250	1	1	1	1	1	1	0.98	0.99	0.99	1	1	1	1	1	1	1	1	1
500	1	1	1	1	1	1	0.98	0.99	0.99	0.99	1	1	1	1	1	1	1	1
750	1	1	1	1	1	1	0.98	0.99	0.99	0.99	0.99	0.99	1	1	1	1	1	1
1000	1	1	1	1	1	1	0.98	0.98	0.98	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
1250	1	1	1	1	1	1	0.98	0.98	0.98	0.98	0.98	0.98	0.97	0.97	0.97	0.97	0.96	0.96
1500	1	1	1	1	1	1	0.98	0.98	0.98	0.97	0.97	0.96	0.93	0.92	0.92	0.91	0.91	0.90
1750	1	1	1	1	1	1	0.98	0.98	0.97	0.96	0.95	0.94	0.86	0.85	0.84	0.83	0.82	0.81
2000	1	1	1	1	1	0.99	0.98	0.97	0.96	0.95	0.93	0.91	0.78	0.77	0.75	0.73	0.72	0.70
2250	1	1	1	1	0.99	0.99	0.98	0.97	0.95	0.93	0.90	0.87	0.70	0.67	0.65	0.63	0.61	0.59
2500	1	1	1	1	0.99	0.98	0.98	0.97	0.94	0.90	0.86	0.82	0.61	0.58	0.55	0.53	0.51	0.49
2750	1	1	1	0.99	0.98	0.97	0.98	0.96	0.93	0.87	0.82	0.77	0.54	0.50	0.47	0.44	0.42	0.40
3000	1	1	1	0.99	0.97	0.94	0.98	0.96	0.91	0.85	0.78	0.72	0.47	0.43	0.39	0.36	0.34	0.31
3250	1	1	1	0.99	0.96	0.91	0.98	0.95	0.89	0.81	0.73	0.66	0.40	0.36	0.33	0.30	0.27	0.25
3500	1	1	1	0.98	0.93	0.87	0.98	0.95	0.87	0.77	0.68	0.60	0.35	0.30	0.26	0.24	0.21	0.20
3750	1	1	0.99	0.97	0.90	0.82	0.98	0.94	0.85	0.74	0.63	0.55	0.30	0.25	0.21	0.19	0.17	0.15
4000	1	1	0.99	0.95	0.87	0.77	0.98	0.93	0.83	0.70	0.58	0.49	0.25	0.21	0.17	0.15	0.13	0.12

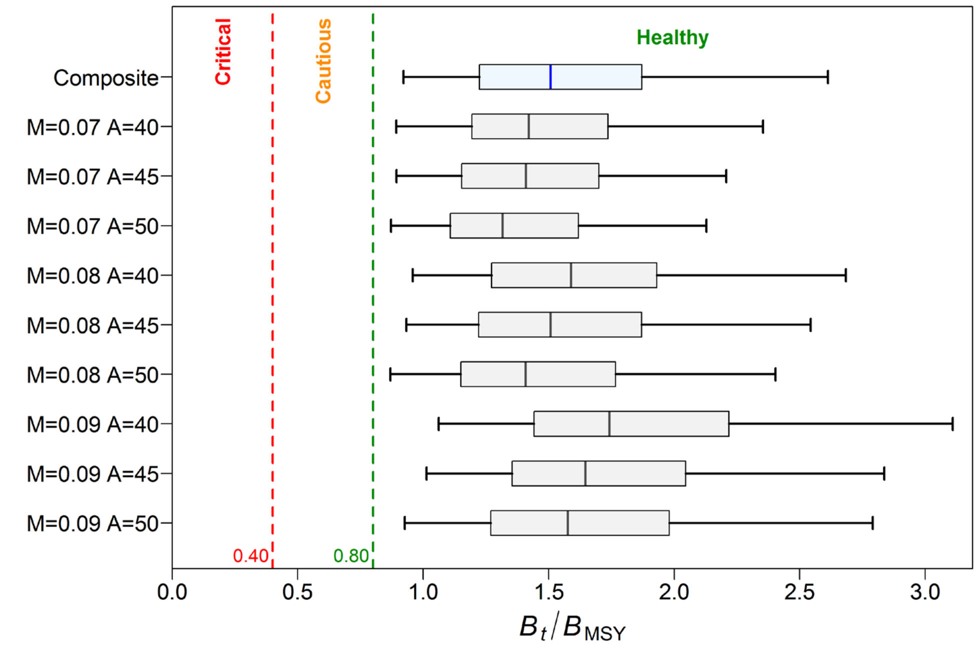

Figure 6. Status of the coastal WWR stock relative to the DFO PA provisional reference points of $0.4B_{MSY}$ and $0.8B_{MSY}$ for the t=2019 composite base case and the component base runs that are pooled to form the composite base case. Boxplots show the 0.05, 0.25, 0.5, 0.75 and 0.95 quantiles from the MCMC posterior.

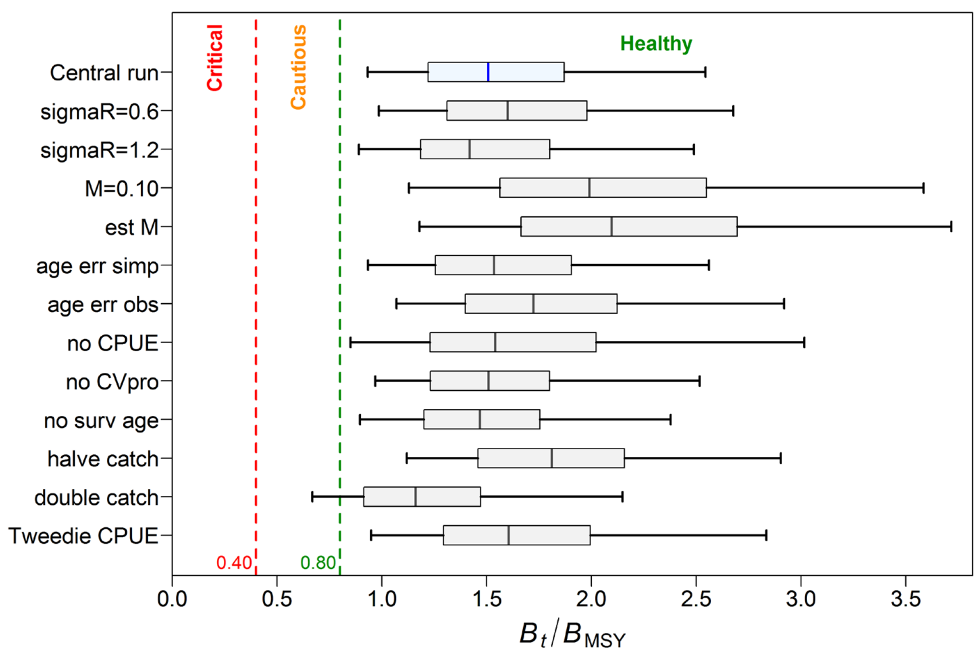

Figure 7. Stock status at beginning of 2019 of the WWR stock relative to the DFO PA provisional reference points of $0.4B_{MSY}$ and $0.8B_{MSY}$ for the central run of the composite base case and twelve sensitivity runs (see y-axis notation and sensitivity descriptions in the main text). Boxplots show the 0.05, 0.25, 0.5, 0.75 and 0.95 quantiles from the MCMC posterior. Appendix F contains the details of these sensitivity runs.

9.3. ASSESSMENT SCHEDULE

Advice was also requested concerning the appropriate time interval between future assessments and, for the interim years between assessments, potential values of indicators that could trigger a full assessment earlier than usual (as per DFO 2016). We suggest the next full stock assessment be scheduled after 2024, such that there will be three new indices from the QCS synoptic survey, two each from the WCHG and WCVI synoptic surveys, and five years of commercial fleet ageing and catch data. The estimated strong 2006 and 2008 year classes provide some confidence to the five year projections, making it unlikely that early intervention would be required. Intermediate progress before the next assessment year can be tracked using the commercial bottom trawl CPUE, given that this series shows the least inter-annual variation among the available biomass series. The relative errors associated with this species in the synoptic surveys are sufficiently large to exclude these series as reliable candidates for short term monitoring. Rapid intervention in the case of apparent stock decline is unlikely because there needs to be at least 6-12 months lead time to allow for the reading of new ageing structures necessary for any new assessment. However, advice for interim years is explicitly included in the decision tables and managers can select another line on the table if stock abundance appears to have declined and if greater certainty of staying above the reference point is desired.

10. GENERAL COMMENTS

As in all previous BC rockfish stock assessments, this assessment depicts a slow-growing, low productivity stock. Widow Rockfish is considered to be largely pelagic above high-relief substrata, forming shoals along the continental shelf at night. They exhibit diel vertical migration but the timing and direction of this migration can vary by latitude (Love et al. 2002). This behaviour means that bottom-trawl surveys are not ideal for assessing the abundance of this species, as indicated by the high relative errors associated with the survey indices (Appendix B). High relative errors, even without additional process error, give the model a lot of room to fit abundance trends to the observed survey indices and consequently are less informative to the model. This causes the stock assessment predictions to be more uncertain than from models for species with lower relative errors for the biomass surveys.

Foreign fleet effort in 1965-76 along the BC coast targeted POP, and WWR catch for these years was estimated as an assumed bycatch; therefore, the magnitude of the foreign fleet removals of WWR is uncertain. Despite this, depletion of WWR by this fleet does not appear to be strong in the population reconstruction, probably due to lower exploitation rates associated with a larger stock size (Figure 3).

Another source of uncertainty in the catch series was identified by previous stock assessment technical working groups, which suggested that domestic landings from 1988-1995 (pre-observer coverage) may have been misreported high to bypass quota restrictions on more desirable species like POP. Sensitivities on catch (halving in 1965-76 and 1988-95) did not have a major effect on the model's biomass trajectory or on the estimates of relative 2019 population stock size (Figure 5, Figure 7).

The biggest source of uncertainty for the assessment of the WWR stock is the inability of the model to estimate M, given the available data. Instead, this assessment attempted to bracket plausible values of natural mortality based on the observed frequency of older ages in the data. At values of M higher than 0.10, the model would not converge properly and the MCMC diagnostics for sensitivity run S03 were not ideal. However, alternative model runs which either estimated M or used M>0.09 improved perceived stock status relative to B_0, resulting in low sustainability concerns.

The use of commercial CPUE as an index of abundance is generally avoided in BC Rockfish stock assessments (primarily due to vessel master behaviour in response to regulations). However, we have successfully used CPUE based on the bycatch of the evaluated species in the BC bottom trawl fishery in two recent stock assessments (Redstripe Rockfish or RSR: Starr and Haigh, 2021; Shortspine Thornyhead or SST: Starr and Haigh 2017). The presumption was that these species are taken passively by the fishery in conjunction with a range of other finfish species. As long as the CPUE estimation model included the incidence of zero tows as well as the tows which captured the species, the resulting series would potentially track abundance. Because of the high level of observer coverage in the BC bottom trawl fishery, there is confidence that zero tows are being recorded reasonably accurately. Furthermore, for both of these recent stock assessments (RSR and SST) as well as for this WWR assessment, the CPUE series was consistent with the available survey data and the model estimates were relatively insensitive to the removal of the CPUE data. Note that the presence of the CPUE series in the model tends to stabilise the estimation procedure, particularly in the MCMC simulations. The TACs appear to be underused (see Appendix A), resulting in less pressure to obtain quota to cover catches and less consequent avoidance behaviour. Removing the CPUE index provided a signal that resulted in the lowest depletion levels (in about 2010), even though the 2019 stock status ended up at similar levels to that of the central run (Figure 5).

Reconstructed recruitment events come from signals in the age frequency data. As mentioned above, the central run had two large recruitment pulses centred on 1961 and 1990; however, some of the sensitivity runs promoted other years (e.g., 2006 and 2008 in S12) as high-productivity years in addition to those in the central run. Note that these years also had peaks (albeit relatively lower) in the central run and the composite base case. The episodic nature of WWR recruitment (6-8 above-average pulses from 1940 to 2019), although perhaps more frequent than seen in other assessed BC rockfish, is typical for *Sebastes* species.

Current stock status relative to the management reference levels appears to be firmly in the healthy zone for the WWR composite base case, a conclusion which holds as well for each component run of the composite base case (Figure 6) and for all of the sensitivity runs based on the central run (Figure 7). The composite base case MCMC medians of B_{2019}/B_{MSY} and u_{2018}/u_{MSY} are 1.51 and 0.66, respectively (Table 2). Five year projections indicate that the biomass will remain above the USR in 2024 at a 50% probability with catches up to 3750 t while the u_{MSY} reference point suggests that catches above 2250 t will exceed the u_{MSY} reference point at 50% probability (Table 3).

The decision tables provide guidance to the selection of short-term TAC recommendations and describe the range of possible future outcomes over the projection period at fixed levels of annual catch. The accuracy of the projections is predicated on the model being correct. Uncertainty in the parameters is explicitly addressed using a Bayesian approach but reflects only the specified model and weights assigned to the various data components. Projection accuracy also depends on some uncertain future recruitment values.

In addition to the uncertainties noted above in catch history accuracy, CPUE index confounding, and data paucity, there are other issues that lead to uncertainty in the results. There are no biomass indices before the mid-1960s and the surveys from that period did not use strong statistical designs. The available age composition data are relatively recent (1980 on). It is fortunate that the earliest available age data are able to provide information on year class strengths in the 1960s and 1970s, due to the long-lived nature of the species and the apparent high precision of the ageing methodology (Figure D.37).

On a positive note, results from three of the four synoptic groundfish surveys initiated in the previous decade will continue to provide some monitoring capability for WWR. Catches in the commercial groundfish fisheries are also well-monitored. These ongoing research initiatives give confidence that this stock is currently well-monitored, and management has demonstrated that corrective action can be taken when required.

11. FUTURE RESEARCH AND DATA REQUIREMENTS

The following issues should be considered when planning future stock assessments and management evaluations for Widow Rockfish:

1. Continue the suite of fishery-independent trawl surveys that have been established across the BC coast. This includes obtaining age and length composition samples, which will allow the estimation of survey-specific selectivity ogives.
2. Explore the use of acoustic surveys for use as an additional abundance index.
3. Increase the level of biological sampling of midwater trawl catch of WWR with the intent of including this fishery as a separate component in the next scheduled stock assessment.
4. Explore how single populations, such as WWR, are part of a complex system consisting of biological and economic components (Walker and Salt 2006). Such systems can have multiple stable states, which may have implications in our understanding of WWR population dynamics and resilience.
5. Explore the effects of climate change on WWR populations and identify how shifts in the ecosystem affect our perception of equilibrium conditions under different climate regimes.

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APPENDIX A. CATCH DATA

A.1. BRIEF HISTORY OF THE FISHERY

The early history of the British Columbia (BC) trawl fleet is discussed by Forrester and Smith (1972). A trawl fishery for slope rockfish has existed in BC since the 1940s. Aside from Canadian trawlers, foreign fleets targeted Pacific Ocean Perch (POP, *Sebastes alutus*) in BC waters for approximately two decades. These fleets were primarily from the USA (1959–1976), the USSR (1965–1968), and Japan (1966–1976). Consequently, the foreign vessels removed large amounts of rockfish biomass, including species other than POP, in Queen Charlotte Sound (QCS, Ketchen 1976, 1980b), off the west coast of Haida Gwaii (WCHG, Ketchen 1980a,b), and off the west coast of Vancouver Island (WCVI, Ketchen 1976, 1980a,b). Canadian effort escalated in 1985 but the catch of rockfish never reached the levels taken by the combined foreign vessels.

Prior to 1977, no quotas were in effect for any slope rockfish species. Since then, the groundfish management unit (GMU) at the Department of Fisheries and Oceans (DFO) imposed a combination of species/area quotas, area/time closures, and trip limits on the major species. Quotas were first introduced for Widow Rockfish (WWR, *Sebastes entomelas*) in 1993 for the BC coast (Table A.1, and see Table A.2 for additional management actions). In 1994-96, WWR was managed in aggregates with other rockfish species; however, this was abandoned in 1997 once the IVQ (individual vessel quota) system was implemented. Since that time, only a coastwide TAC (total allowable catch) has been set annually for this species. In 2006, the hook and line fishery was allocated 1.8% of the coastwide TAC. Management has kept the TAC values unchanged since 2001, likely due to the absence of stock assessment advice.

The WWR trawl fishery spans the BC coast with apparent high CPUE densities off various locations along the 200 m isobath (Figure A 1, left). The midwater fishery (Figure A 1, right) highlights the actively fished shelf region west and southwest of Triangle Island (129.082°W, 50.864°N) studied by Stanley et al. (1999, 2000).

In 2012, measures were introduced to reduce and manage the bycatch of corals and sponges by the BC groundfish bottom trawl fishery. These measures were developed jointly by industry and environmental non-governmental organisations (Wallace et al. 2015), and included: limiting the footprint of groundfish bottom trawl activities (Figure A.2), establishing a combined bycatch conservation limit for corals and sponges, and establishing an encounter protocol for individual trawl tows when the combined coral and sponge catch exceeded 20 kg. These measures have been incorporated into DFO's Pacific Region Groundfish Integrated Fisheries Management Plan (Feb 21, 2019, version 1.1).

Table A.1. Annual trawl Total Allowable Catches (TACs) in tonnes for WWR caught in BC waters: year can either be calendar year (1993-1996) or fishing year (1997 on); TACs for trawl and ZN delimited by '⁝' symbol. Aggregates A1 (1995-96), A2 (1994), and A6 (1997-2005) are defined in Table A.2; aggregate TACs for all fisheries combined appear in parentheses for A1 and A2. The hook and line fleet implemented an aggregate-based system from 1997 to 2005, and formalised a 0.982:0.018 trawl:ZN TAC split starting in 2006. (see Table A.2 for management actions indicated by note letter).

Year	Start	End	Coast	Notes
1993	1/1/2013	12/31/2013	2200	-
1994	1/15/1994	12/31/1994	A2(4000)	a,b
1995	1/1/1995	12/31/1995	A1(9716)	c
1996	2/6/1996	3/31/1997	A1(7734)	d,e
1997	4/1/1997	3/31/1998	2358⁝A6	f,g
1998	4/1/1998	3/31/1999	2157⁝A6	h
1999	4/1/1999	3/31/2000	2157⁝A6	-
2000	4/1/2000	3/31/2001	2358⁝A6	i
2001	4/1/2001	3/31/2002	2316⁝A6	-
2002	4/1/2002	3/31/2003	2316⁝A6	j
2003	4/1/2003	3/31/2004	2316⁝A6	-
2004	4/1/2004	3/31/2005	2316⁝A6	-
2005	4/1/2005	3/31/2006	2316⁝A6	-
2006	4/1/2006	3/31/2007	2316⁝42	k,l,m
2007	3/10/2007	3/31/2008	2316⁝42	-
2008	3/8/2008	2/20/2009	2316⁝42	-
2009	2/21/2009	2/20/2010	2316⁝42	-
2010	2/21/2010	2/20/2011	2316⁝42	-
2011	2/21/2011	2/20/2013	2316⁝42	-
2012	2/21/2011	2/20/2013	2316⁝42	n
2013	2/21/2013	2/20/2014	2316⁝42	o
2014	2/21/2014	2/20/2015	2316⁝42	-
2015	2/21/2015	2/20/2016	2316⁝42	p
2016	2/21/2016	2/20/2017	2316⁝42	-
2017	2/21/2017	2/20/2018	2316⁝42	-
2018	2/21/2018	2/20/2019	2316⁝42	-
2019	2/21/2019	2/20/2020	2316⁝42	-

Table A.2. Codes to notes on management actions and quota adjustments that appear in Table A.1. Abbreviations that appear under 'Management Actions': DMP = dockside monitoring program, GTAC =Groundfish Trawl Advisory Committee, H&L = hook and line, IVQ = individual vessel quota, TAC =Total Allowable Catch, IFMP = Integrated Fisheries Management Plan, DFO = Department of Fisheries & Oceans. ***Species abbreviations****: BKR = Black Rockfish, CAR = Canary Rockfish, CHR = China Rockfish, CPR = Copper Rockfish, LST = Longspine Thornyhead, ORF = other rockfish, POP = Pacific Ocean Perch, QBR = Quillback Rockfish, RER =Rougheye Rockfish, RSR = Redstripe Rockfish, SGR =Silvergray Rockfish, SKR = Shortraker Rockfish, SST = Shortspine Thornyhead, TIR = Tiger Rockfish, WWR = Widow Rockfish, YMR = Yellowmouth Rockfish, YTR =Yellowtail Rockfish. See Archived Integrated Fisheries Management Plans - Pacific Region for further details.*

	Year	Management Actions
a	1994	Started DMP for Trawl fleet.
b	1994	As a means of both reducing at-sea discarding and simplifying the harvesting regime, rockfish aggregation was implemented. Through consultation with GTAC, the following aggregates were identified: Agg 1= POP, YMR, RER, CAR, SGR, YTR; Agg 2= RSR, WWR; Agg 3= SKR, SST, LST; Agg 4= ORF.
c	1995	As a means of both reducing at-sea discarding and simplifying the harvesting regime, rockfish aggregation was implemented. Through consultation with GTAC, the following aggregates were identified: Agg 1= CAR, SGR, YTR, WWR, RER; Agg 2= POP, YMR, RSR; Agg 3= SKR, SST, LST; Agg 4= ORF.
d	1996	Rockfish aggregation will continue on a limited basis in 1996: Agg 1= YTR, WWR; Agg 2= CAR, SGR; Agg 3= POP, YMR; Agg 4= RER, SKR; Agg 5= RSR, SCR; Agg 6= ORF incl. SST, LST
e	1996	Started 100% onboard observer program for offshore Trawl fleet.
f	1997	Started IVQ system for Trawl *Total Allowable Catch* (TAC) species (April 1, 1997)
g	1997	All H&L rockfish, with the exception of YYR, shall be managed under the following rockfish aggregates: Agg 1= QBR, CPR; Agg 2= CHR, TIR; Agg 3= CAR, SGR; Agg 4= RER, SKR, SST, LST; Agg 5= POP, YMR, RSR; Agg 6= YTR, BKR, WWR; Agg 7= ORF excluding YYR.
h	1998	H&L Aggregate 4 – Option A: a quantity of Aggregates 2 to 5 and 7 combined not to exceed 100% of the total of Aggregate 1 per landing; an overage of Aggregate 1 and 6 up to a maximum of 10% per fishing period which shall be deducted from the vessel's succeeding fishing period limit. Option B: a quantity of Aggregates 2 to 7 combined not to exceed 100% of the Yelloweye rockfish per landing. Option C: 20,000 pounds of Aggregate 4 per fishing period; an overage for each of the Aggregates 3 to 5 and, Aggregates 6 and 7 combined, up to a maximum of 20% per fishing period which shall be deducted from the vessel's succeeding fishing period limit.
i	2000	Formal discussions between the hook and line rockfish (ZN), halibut and trawl sectors were initiated in 2000 to establish individual rockfish species allocations between the sectors to replace the 92/8 split. Allocation arrangements were agreed to for rockfish species that are not currently under TAC. The agreed to splits for these rockfish will be implemented in the future when or if TACs are set for those species.
j	2002	Closed areas to preserve four hexactinellid (glassy) sponge reefs.
k	2006	Introduced an *Integrated Fisheries Management Plan* (IFMP) for most groundfish fisheries.
l	2006	Started 100% at-sea electronic monitoring for H&L.
m	2006	Implemented mandatory retention of rockfish for H&L.
n	2012	Freeze the footprint of where groundfish bottom trawl activities can occur (all vessels under the authority of a valid Category "T" commercial groundfish trawl license selecting Option A as identified in the IFMP).
o	2013	To support groundfish research the Groundfish Trawl Industry agreed to the trawl TAC offsets to account for unavoidable mortality incurred during the 2013 DFO and Trawl industry agreed upon Groundfish Trawl Multi-species surveys.
p	2015	Research allocations for 2015-2019 to account for the mortalities associated with survey catches within TACs.

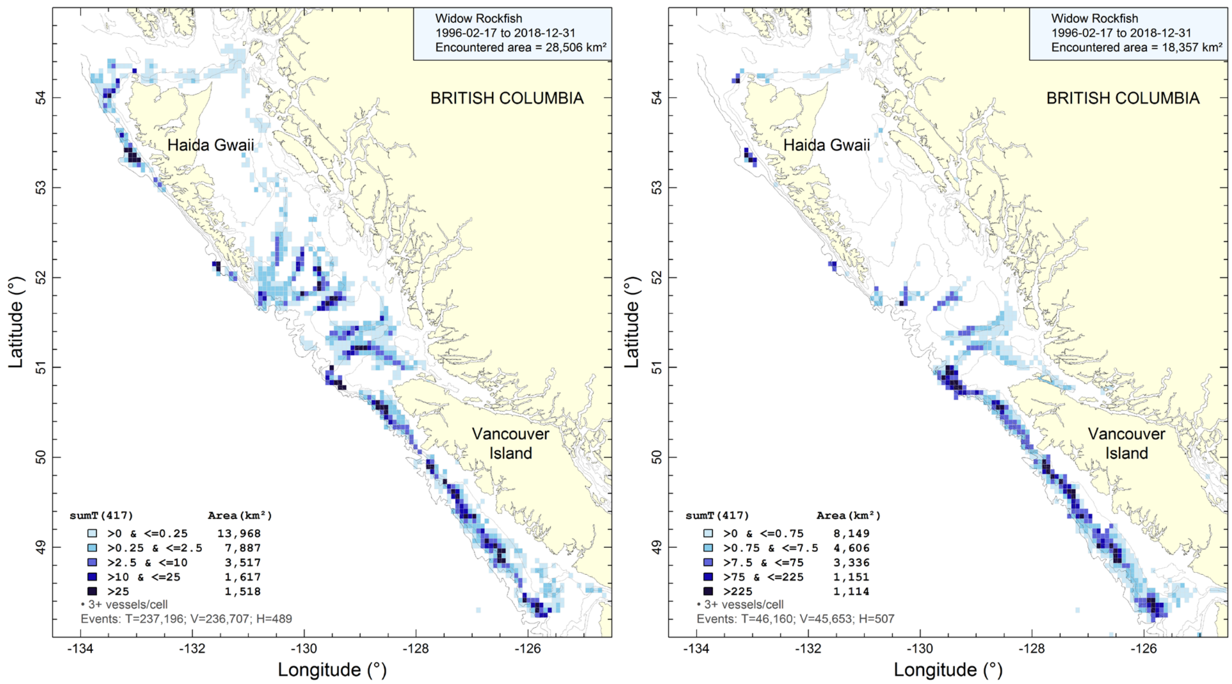

Figure A 1. Aerial distribution of accumulated WWR catch (tonnes) by bottom trawl (left) and midwater trawl (right) from 1996 to 2018 in grid cells 0.075° longitude by 0.055° latitude (roughly 32 km²). Isobaths show the 100, 200, 500, and 1200 m depth contours. Note that cells with <3 fishing vessels are not displayed.

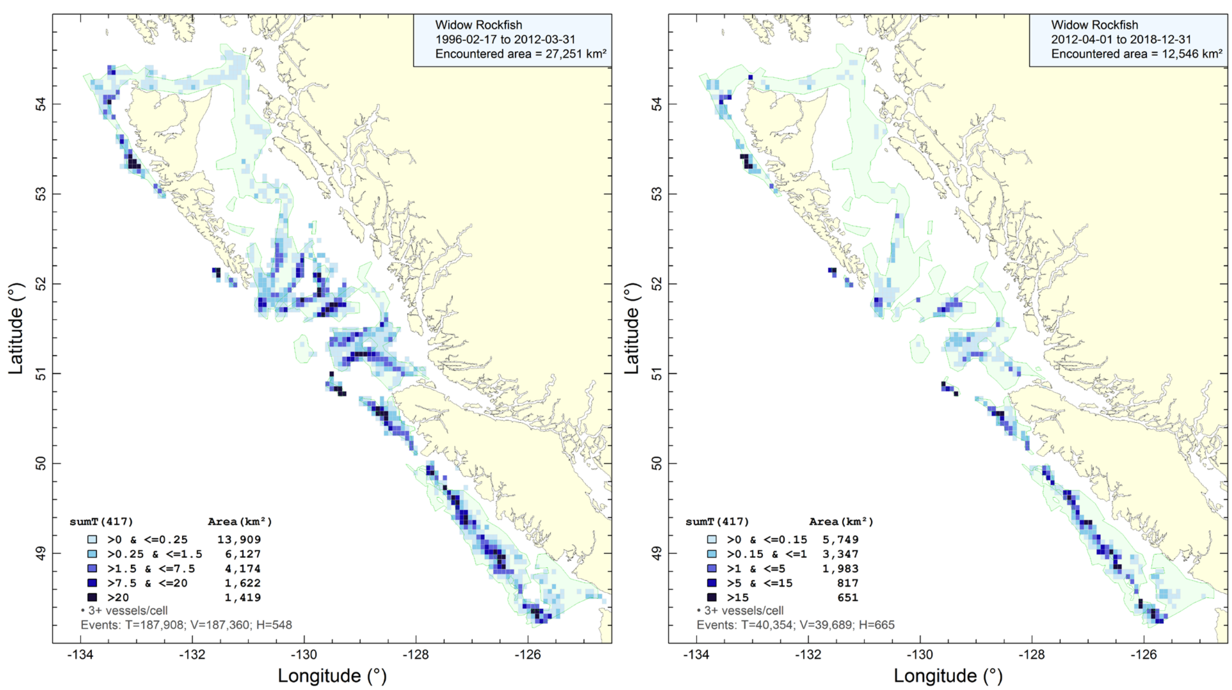

Figure A.2. Aerial distribution of accumulated WWR bottom trawl catch (tonnes) before (left) and after (right) the introduction of the trawl footprint in April 2012, limiting areas in which trawl vessels can operate. Note that cells with <3 fishing vessels are not displayed.

A.2. CATCH RECONSTRUCTION

This assessment reconstructs WWR catch back to 1918 but considers the start of the fishery to be 1940 (Figure A.3) when the fishery started to increase during World War II. From 1918 to 1939, removals were negligible compared to those that came after 1939. During the period 1950–1975, US vessels routinely caught more rockfish than did Canadian vessels. Additionally, from the mid-1960s to the mid-1970s, foreign fleets (Russian and Japanese) removed large amounts of rockfish, primarily POP. These large catches were first reported by various authors (Westrheim et al. 1972; Gunderson et al. 1977; Leaman and Stanley 1993); however, Ketchen (1980a,b) re-examined the foreign fleet catch, primarily because statistics from the USSR called all rockfish 'perches' while the Japanese used the term 'Pacific ocean perch' indiscriminately. In the catch reconstruction, all historical foreign catches (annual rockfish landings) were tracked separately from Canadian WWR landings, converted to WWR (Section A.2.2), and added to the latter during the reconstruction process.

A.2.1. Data Sources

Starting in 2015, all official Canadian catch tables from the databases below (except `PacHarv3`) have been merged into one table called "`GF_MERGED_CATCH`", which is available in DFO's `GFFOS` database. All groundfish DFO databases are now housed on the `DFBCV9TWVASP001` server. Widow Rockfish catch by fishery sector ultimately comes from the following seven DFO databases:

- `PacHarv3` sales slips (1982-1995) – hook and line only;
- `GFCatch` (1954-1995) – trawl and trap;
- `PacHarvHL` merged data table (1986-2006) – halibut, Dogfish+Lingcod, H&L rockfish;
- `PacHarvSable` fisherlogs (1995-2005) – Sablefish;
- `PacHarvest` observer trawl (1996-2007) – trawl;
- `GFFOS` groundfish subset from Fishery Operation System (2006-2018) – all fisheries and modern surveys; and
- `GFBioSQL` joint-venture hake and research survey catches (1947-2018) – multiple gear types.

However, all these data sources were superseded by `GFFOS` from 2007 on because this latter repository was designed to record all Canadian landings and discards from commercial fisheries and research activities.

Prior to the modern catch databases, historical landings of aggregate rockfish – either total rockfish (TRF) or rockfish other than POP (ORF) – are reported by eight different sources (see Haigh and Yamanaka 2011). The earliest historical source of rockfish landings comes from Canada Dominion Bureau of Statistics (1918-1950). The goal is to estimate the reconstructed rockfish (RRF) from ratios of RRF/ORF or RRF/TRF and then add estimated discards from RRF/TAR, where TAR is the target species landed.

A.2.2. Reconstruction Details

A brief synopsis of the catch reconstruction follows, with a reminder of the definition of terms:

Fisheries: there are 5 fisheries in the reconstruction (even though trawl dominates the WWR fishery):

- T = groundfish trawl (bottom + midwater),
- H = Halibut longline,
- S = Sablefish trap/longline.
- DL = Schedule II (mostly Lingcod and Dogfish longline),
- ZN = hook and line rockfish (called 'ZN' from 1986 on).

TRF: acronym for "total rockfish" (all species of *Sebastes* + *Sebastolobus*).

ORF: acronym for "other rockfish" (= TRF minus POP), landed catch aggregated by year, fishery, and PMFC (Pacific Marine Fisheries Commission) major area.

POP: Pacific Ocean Perch.

RRF: Reconstructed rockfish species – in this case, Widow Rockfish (WWR).

TAR: Target species landed catch.

L & D: L =landed catch, D =releases (formerly called "discards")

gamma: mean of annual ratios, $\sum_i \mathrm{RRF}_i^L \big/ \mathrm{ORF}_i^L$, grouped by major PMFC area and fishery using reference years i = 1997-2005. Note: major RRF species might use TRF in the denominator.

delta: mean of annual ratios, $\sum_i \mathrm{RRF}_i^D \big/ \mathrm{TAR}_i$, grouped by major PMFC area and fishery using reference years i = 1997-2006 for the trawl fishery and 2000-2004 for all other fisheries. Observer records were used to gather data on releases.

The assessment's population model uses calendar year, requiring catch estimates to be made by calendar year. For the trawl fishery, the reconstruction defaults to using "official" (reported) catch numbers from 1996 on; for the other fisheries, catches are minor but the default reported catches used are: H = 2000+, S/DL = 2007+, ZN = 1986+.

The reconstruction of Canadian WWR landings involves the estimation of landings for the years prior to the years of reported catch using `gamma` ratios (Table A.3). These ratios are also used to convert foreign landings of ORF to WWR. The ratios are calculated from a relatively modern period (1997-2005); therefore, an obvious caveat is that ratios derived from a modern fishery will likely not reflect catch ratios during the historical foreign fleet activity or regulatory regimes not using IVQs (individual vessel quotas).

After WWR landings have been estimated, non-retained catch (releases or discards) are added during default years identified by fishery: T = 1954:1995, H/S/DL/ZN: 1986:2005. The non-retained catch is estimated using the `delta` ratios of WWR discarded by a fishery to fishery-specific landed targets (TAR): T = WWR, H = Pacific Halibut, S = Sablefish, DL = Spiny Dogfish + Lingcod, ZN = WWR (Table A.3).

The current annual WWR catches by trawl fishery and those from the non-trawl fisheries appear in Table A.4 and Figure A.3. The combined fleet catches were used in the population models.

A.2.3. Changes to the Reconstruction Algorithm since 2011

In previous stock assessments for POP (Edwards et al. 2014a,b), the authors documented two departures from the catch reconstruction algorithm introduced by Haigh and Yamanaka (2011). The first dropped the use of trawl and trap data from the sales slip database `PacHarv3` because catches were sometimes reported by large statistical areas that cannot be clearly mapped to PMFC areas. In theory, `PacHarv3` should report the same catch as that in the `GFCatch` database (Rutherford 1999), but area inconsistencies cause catch inflation when certain large statistical areas cover multiple PMFC areas. Therefore, only the `GFCatch` database for the trawl and trap records from 1954 to 1995 were used, rather than trying to mesh `GFCatch` and `PacHarv3`. The point is somewhat moot as assessments by us since 2015 use the merged catch data table (Section A.2.1). Data for the H&L fisheries from `PacHarv3` are still used as these do not appear in other databases. The second departure was the inclusion of an additional data source for Japanese rockfish catch reported in Ketchen (1980a).

In 2014, the Yellowtail Rockfish assessment (Starr et al. 2014[1]) selected offshore areas that reflected the activity of the foreign fleets' impact on this species to calculate `gamma` (RRF/ORF) and `delta` ratios (RRF/TAR). This option was not used in the WWR reconstruction.

In the 2015 Yelloweye Rockfish assessment (Yamanaka et al. 2018), the concept of depth-stratified `gamma` and `delta` ratios was introduced; however, this functionality has not been used since. Also in the Yelloweye assessment, rockfish catch from seamounts was removed (implemented in the WWR reconstruction), as well as an option to exclude rockfish catch from the foreign fleet and the experimental Langara Spit POP fishery (neither were excluded from the WWR reconstruction).

In the 2018 Redstripe Rockfish assessment (Starr and Haigh, 2021), `gamma` and `delta` ratios from reference years (Section A.2.2) were calculated by taking the geometric mean across years instead of the previously used arithmetic mean. This reduces the influence of single anomalously large annual ratios. The geometric mean was used in the WWR reconstruction. Also new in 2018 was the ability to estimate RRF (using `gamma`) for landings later than 1996, should the user have reason to replace observed landings with estimated ones. For WWR, observed landings by fishery were used starting in 1996 (trawl), 2000 (halibut), 2007 (sablefish), 2007 (dogfish/lingcod), and 1986 (h&l rockfish); prior to these years, landings were estimated using `gamma`. The user can also specify years by fishery when discard ratios are to be applied; for WWR these years were 1954:1995 (trawl), 1986:2005 (halibut), 1986:2005 (sablefish), 1986:2005 (dogfish/lingcod), and 1986:2005 (h&l rockfish). As previously, years before the discard period assume no discarding, and years after the discard period assume that discards have been reported in the databases.

A substantial amount of WWR in GFBioSQL was reported as foreign catch (specifically 349 t in years 1982, 1987-1991, and 2000), which came from midwater gear off WCVI. New to this assessment, the algorithm assigns GFBio foreign catch to four of the five fisheries based on gear type – bottom and midwater trawl gear assigned to trawl, longline gear assigned to halibut, trap and line-trap mix gear assigned to sablefish, h&l gear assigned to h&l rockfish – assuming that the reconstruction uses foreign catch, which is optional. These foreign catches occurred well after the foreign fleet activity between 1965 and the implementation of an exclusive economic zone in 1977.

Table A.3. *Estimated 'gamma' (WWR/ORF) and 'delta' (discard) ratios for each fishery and PMFC area used in the catch reconstruction of Widow Rockfish.*

gamma (proportion WWR/ORF)

PMFC	Trawl	Halibut	Sablefish	Dogfish/ Lingcod	H&L Rockfish
3C	0.1197	0.0001	0	0.0217	0.0055
3D	0.1147	0.0001	0	0.0063	0.0007
5A	0.2679	0.0001	0	0.0004	0.0007
5B	0.0423	0.0001	0	0	0.0010
5C	0.0106	0.0001	0	0.0045	0.0008
5D	0.0023	0.0001	0	0.0085	0.0017
5E	0.1168	0.0001	0	0.0029	0.0004

delta (discard rate)

PMFC	Trawl	Halibut	Sablefish	Dogfish/ Lingcod	H&L Rockfish
3C	0.0031	0	0	0	0
3D	0.0031	0	0	0	0
5A	0.0011	0	0	0	0
5B	0.0031	0	0	0.0001	0
5C	0.0012	0	0	0	0
5D	0.0520	0.0001	0	0	0
5E	0.0057	0	0	0	0

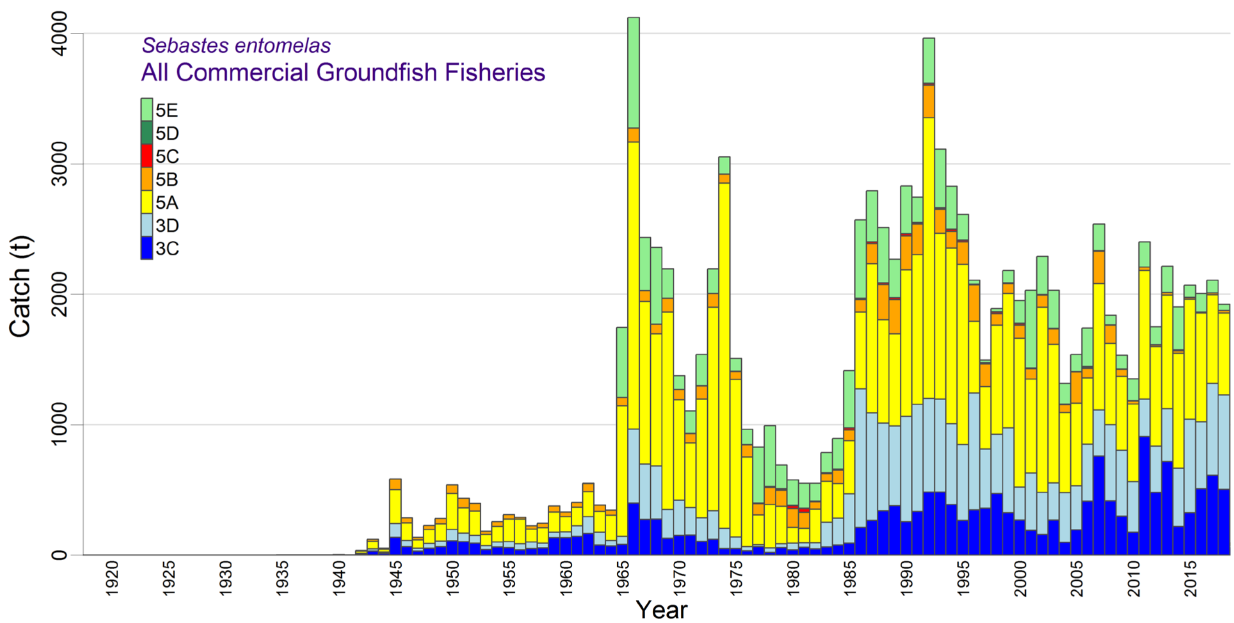

Figure A.3. Reconstructed total (landed + released) catch (t) for WWR from the trawl fishery in PMFC major areas 3C to 5E. Catches from other fisheries were negligible.

Table A.4. Reconstructed catches (in tonnes, landings + releases) of WWR in coastwide PMFC areas (3C to 5E combined) from each fishery and for coastwide BC.

Year	Trawl	Halibut	Sablefish	Dogfish +Lingcod	H&L Rockfish	BC Coast
1940	4	0	0	0.001	0.002	4
1941	2	0	0	0.004	0.010	2
1942	36	0	0	0.008	0.015	36
1943	121	0	0	0.023	0.041	121
1944	52	0	0	0.031	0.055	52
1945	583	0	0	0.028	0.061	583
1946	285	0	0	0.029	0.073	286
1947	137	0	0	0.007	0.014	137
1948	228	0	0	0.011	0.022	228
1949	279	0	0	0.015	0.030	279
1950	539	0	0	0.006	0.012	539
1951	435	0	0	0.027	0.065	435
1952	396	0	0	0.016	0.039	397
1953	181	0	0	0.018	0.043	181
1954	256	0	0	0.023	0.046	256
1955	310	0	0	0.022	0.030	311
1956	290	0	0	0.022	0.040	290
1957	226	0	0	0.043	0.093	226
1958	244	0	0	0.030	0.042	244
1959	375	0	0	0.034	0.056	375
1960	331	0	0	0.041	0.075	331
1961	405	0	0	0.048	0.078	405
1962	549	0	0	0.067	0.145	549
1963	383	0	0	0.048	0.127	383
1964	344	0	0	0.027	0.054	344
1965	1747	0	0	0.025	0.047	1747
1966	4121	0	0	0.027	0.047	4121
1967	2436	0	0	0.042	0.081	2436
1968	2358	0	0	0.030	0.053	2358
1969	2194	0	0	0.037	0.107	2194
1970	1374	0	0	0.061	0.213	1374
1971	1104	0	0	0.032	0.143	1104
1972	1539	0	0	0.084	0.231	1539
1973	2193	0	0	0.050	0.155	2193
1974	3052	0	0	0.086	0.302	3053
1975	1506	0	0	0.073	0.285	1507
1976	964	0	0	0.068	0.233	964
1977	827	0	0	0.080	0.305	827
1978	991	0.001	0	0.088	0.304	992
1979	689	0.001	0	0.141	0.456	690
1980	575	0.001	0	0.140	0.414	576
1981	551	0.001	0	0.110	0.343	551
1982	550	0.006	0	0.760	0.263	551
1983	785	0.006	0	0.817	0.265	786
1984	893	0.007	0	0.629	0.312	894
1985	1413	0.018	0	0.849	0.506	1414
1986	2567	0.062	0	2.672	0.013	2570
1987	2791	0.090	0	3.915	0.007	2795
1988	2509	0.076	0	3.229	0.020	2512
1989	2265	0.082	0	2.186	0.005	2268
1990	2827	0.081	0	1.843	1.020	2830

Year	Trawl	Halibut	Sablefish	Dogfish +Lingcod	H&L Rockfish	BC Coast
1991	2741	0.058	0	1.865	0.414	2743
1992	3962	0.057	0	1.367	0.271	3964
1993	3111	0.102	0	1.171	0.071	3112
1994	2826	0.080	0	1.197	0.164	2827
1995	2608	0.117	0	2.208	1.263	2611
1996	2104	0.064	0	0.120	2.600	2107
1997	1491	0.070	0	0.209	2.985	1494
1998	1886	0.079	0	0.169	2.426	1888
1999	2179	0.069	0	0.162	2.299	2182
2000	1952	0.091	0	0.222	0.536	1953
2001	2029	0.090	0	0.127	0.203	2030
2002	2289	0.128	0	0.156	0.448	2289
2003	2031	0.083	0	0.159	0.112	2032
2004	1316	0.072	0	0.146	0.167	1316
2005	1537	0.072	0	0.254	0.264	1538
2006	1742	0.063	0	0.257	0.290	1742
2007	2537	0.035	0.002	0.002	0.057	2537
2008	1838	0.011	0.006	0.005	0.039	1838
2009	1530	0.013	0.000	0.014	0.051	1530
2010	1350	0.047	0.000	0.009	0.429	1350
2011	2400	0.071	0.005	0.020	0.198	2400
2012	1752	0.044	0.001	0.005	0.042	1752
2013	2215	0.018	0.016	0.001	0.017	2215
2014	1902	0.027	0.008	0.014	0.009	1902
2015	2069	0.020	0.005	0.008	0.010	2069
2016	2005	0.052	0.027	0.011	0.050	2005
2017	2107	0.045	0.012	0.000	0.029	2107
2018	1923	0.029	0.011	0.008	0.023	1923

A.2.4. Scaling Catch Policy to GMU Area TACs

The area definitions used by DFO Groundfish Science (PMFC areas) differ somewhat from those used by the DFO Groundfish Management, which uses Pacific Fishery Management Areas (PFMA). The reasons for these discrepancies varies depending on the species, but it occurs to address different requirements by Science and Management. For Science, there is a need to reference historical catch using consistently reported areas in databases and catch records. The PMFC and GMU areas are similar but not identical (Figure 1).

As this assessment covers the coastwide (PMFC areas 3CD + 5ABCDE) stock of WWR, and GMU only issues a coastwide TAC, there is no need to scale the catch policies presented in the decision tables (Appendix F). Should managers wish to assign TACs to individual regions, Table A.5 offers some guidance on the distribution of catches over the last five years in each of the PMFC areas. For instance, 20% of the coastwide WWR catch occurred in PMFC area 3C, 30% occurred in 3D, and 39% occurred in 5A.

Table A.5. Catch of WWR in PMFC areas from the last 5 years of the combined fishery. Annual proportions of catch by area are shown in rows marked by year. Area-specific 5-year geometric means of annual proportions are shown in the final row.

Catch (t)

Year	3C	3D	5A	5B	5C	5D	5E	BC
2014	220	446	882	20	1	6	327	1902
2015	325	716	921	12	1	0.3	94	2069
2016	510	510	836	7	1	0.3	141	2005
2017	611	704	680	13	0.4	0.4	97	2107
2018	505	722	630	20	0.4	0.1	47	1923

Proportion

Year	3C	3D	5A	5B	5C	5D	5E	BC
2014	0.1155	0.2343	0.4637	0.0105	0.0006	0.0032	0.1722	1
2015	0.1572	0.3461	0.4452	0.0056	0.0004	0.0002	0.0454	1
2016	0.2544	0.2545	0.4168	0.0037	0.0003	0.0002	0.0702	1
2017	0.2900	0.3343	0.3228	0.0064	0.0002	0.0002	0.0461	1
2018	0.2624	0.3752	0.3275	0.0102	0.0002	0.0001	0.0244	1
GeoMean	0.2038	0.3038	0.3907	0.0067	0.0003	0.0002	0.0573	1

A.2.5. Caveats

The available catch data before 1996 (first year of onboard observer program) present difficulties for use in a stock assessment model without some form of interpretation, both in terms of misreporting (i.e., reporting catches of one species as another) or misidentifying species and the possible existence of at-sea discarding due to catches exceeding what was permitted for retention. Although there were reports that fishermen misreported the location of catches, this issue is not a large problem for assessment of a coastwide stock. Additionally, there was a significant foreign fishery for rockfish in BC waters, primarily by the United States, the Soviet Union and Japan. These countries tended to report their catches in aggregate form, usually lumping rockfish into a single category. These fisheries ceased after the declaration of the 200 nm exclusive economic zone by Canada in 1977.

The accuracy and precision of reconstructed catch series inherently reflect the problems associated with the development of a commercial fishery:

- trips offloading catch with no area information,
- unreported discarding,
- recording catch of one species as another to avoid quota violations,
- developing expertise in monitoring systems,
- shifting regulations,
- changing data storage technologies, etc.

Many of these problems have been solved through the introduction of onboard observer programs (started in 1996 for the offshore trawl fleet), dockside monitoring, and tradable individual vessel quotas (starting in 1997) that confer ownership of the resource to the fishing sector.

The catch reconstruction procedure does not rebuild catch by gear (e.g., bottom trawl vs. midwater trawl). While adding this dimension is possible, it would mean splitting catches back in time using ratios observed in the modern fishery which likely would not represent historical activity by gear type (see Section A.2.2 for similar caveats regarding the estimation of ratios to reconstruct the catch of one species from a total rockfish catch). In this assessment, we combined the catches of WWR by bottom and midwater trawl because the biological data (Appendix D) by gear type were inadequate to support two fleets in the population model and it was inconclusive whether there was a demonstrable difference in selectivity. Table A.6 and Figure A.4 show the reported coastwide catch (landings plus non-retained) by gear type.

Table A.6. Trawl catch (tonnes) by gear type for the coastwide BC WWR stock from years when fleet activity was monitored by onboard observers.

Year	Bottom Trawl	Midwater Trawl	Hook & Line
1996	140	1949	2.057
1997	202	1276	2.756
1998	178	1636	2.336
1999	231	1919	2.465
2000	298	1644	0.508
2001	426	1596	0.118
2002	537	1743	0.515
2003	364	1663	0.102
2004	216	1095	0.139
2005	188	1343	0.225
2006	273	1462	0.322
2007	330	2199	0.045
2008	187	1635	0.051
2009	286	1231	0.048
2010	186	1131	0.452
2011	236	2158	0.248
2012	182	1563	0.082
2013	246	1941	0.044
2014	234	1657	0.040
2015	203	1860	0.032
2016	223	1773	0.104
2017	107	1997	0.070
2018	189	1716	0.055

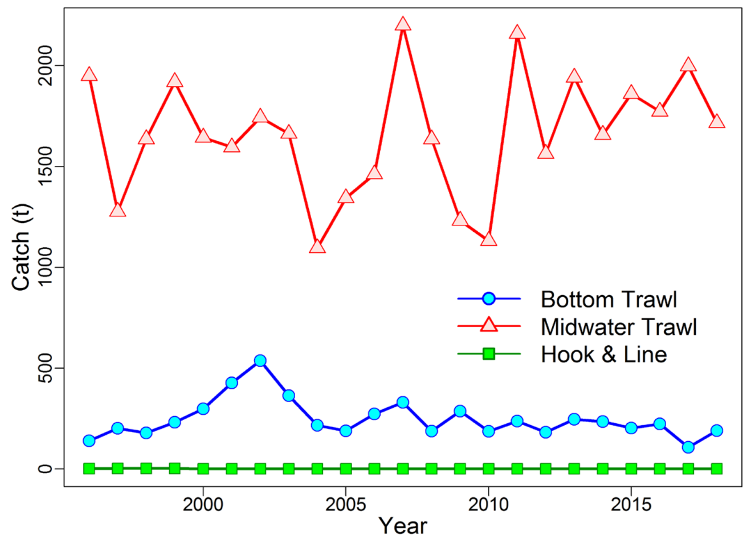

Figure A.4. Reported trawl catch (landings + released) of WWR by gear since the implementation of the onboard-observer program in 1996.

A.3. REFERENCES – CATCH

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APPENDIX B. TRAWL SURVEYS

B.1. INTRODUCTION

This appendix summarises the derivation of relative Widow Rockfish (WWR) abundance indices from the following bottom trawl surveys:

- a set of historical surveys operated in the Goose Island Gully of Queen Charlotte Sound (Section B.3);
- National Marine Fisheries Service (NMFS) Triennial survey operated off the lower half of Vancouver Island (Section B.4);
- Queen Charlotte Sound synoptic survey (Section B.5);
- West Coast Vancouver Island (WCVI) synoptic survey (Section B.6);
- West Coast Haida Gwaii (WCHG) synoptic survey (Section B.7).

Only surveys which were used in the WWR stock assessment are presented. The Hecate Strait multi-species survey, the Hecate Strait synoptic survey, the WCVI shrimp and Queen Charlotte Sound shrimp surveys have been omitted because the presence of WWR in these surveys has been either sporadic or the coverage, either spatial or by depth, has been incomplete, rendering these surveys poor candidates to provide abundance series for this species.

B.2. ANALYTICAL METHODS

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

Eq. B.1 $$U_{yi} = \frac{1}{n_{yi}} \sum_{j=1}^{n_{yi}} \frac{C_{yij}}{E_{yij}},$$

where C_{yij} = catch (kg) in tow j, stratum i, year y;

E_{yij} = effort (h) in tow j, stratum i, year y;

n_{yi} = number of tows in stratum i, year y.

CPUE values U_{yi} convert to CPUE densities δ_{yi} (kg/km^2) using:

Eq. B.2 $$\delta_{yi} = \frac{1}{vw} U_{yi},$$

where v = average vessel speed (km/h);

w = average net width (km).

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

Eq. B.3 $$\delta_{yi} = \frac{1}{n_{yi}} \sum_{j=1}^{n_{yi}} \frac{C_{yij}}{D_{yij} w_{yij}},$$

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;

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:

Eq. B.4 $$B_y = \sum_{i=1}^{m} \delta_{yi} A_i = \sum_{i=1}^{m} B_{yi} ,$$

where δ_{yi} = mean CPUE density (kg/km^2) for stratum i, year y;

A_i = area (km^2) of stratum i;

B_{yi} = biomass (kg) for stratum i, year y;

m = number of strata.

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

Eq. B.5 $$V_y = \sum_{i=1}^{m} \frac{\sigma_{yi}^2 A_i^2}{n_{yi}} = \sum_{i=1}^{m} V_{yi} ,$$

where σ_{yi}^2 = variance of CPUE density (kg^2/km^4) for stratum i, year y;

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

Eq. B.6 $$CV_y = \frac{\sqrt{V_y}}{B_y} .$$

B.3. EARLY SURVEYS IN QUEEN CHARLOTTE SOUND GOOSE ISLAND GULLY

B.3.1. Data Selection

Tow-by-tow data from a series of historical trawl surveys were available for 12 years spanning the period from 1965 to 1995. The first two surveys, in 1965 and 1966, were wide-ranging, with the 1965 survey extending from near San Francisco to halfway up the Alaskan Panhandle (Westrheim 1966a, 1967b). The 1966 survey was only slightly less ambitious, ranging from the southern US-Canada border in Juan de Fuca Strait into the Alaskan Panhandle (Westrheim 1966b, 1967b). It was apparent that the design of these two early surveys was exploratory and that these surveys would not be comparable to the subsequent Queen Charlotte Sound (QCS) surveys which were much narrower in terms of area covered and which had a much higher density of tows in the Goose Island Gully (GIG). This can be seen in the small number of tows used by the first two surveys in GIG (Table B.1). As a consequence, these surveys are not included in this series.

The 1967 ([left panel]: Figure B.1) and 1969 ([left panel]: Figure B.2) surveys (Westrheim 1967a, 1969; Westrheim et al. 1968) also performed tows on the west coast of Vancouver

Island, the west coast of Haida Gwaii and SE Alaska, but both of these surveys had a reasonable number of tows in the GIG grounds (Table B.1). The 1971 survey ([left panel]: Figure B.3) was entirely confined to GIG (Harling et al. 1971) while the 1973 ([left panel]: Figure B.4), 1976 ([left panel]: Figure B.5) and 1977 ([left panel]: Figure B.6) surveys covered both Goose Island and Mitchell Gullies in QCS (Harling et al. 1973; Westrheim et al. 1976; Harling and Davenport 1977).

A 1979 survey (Nagtegaal and Farlinger 1980) was conducted by a commercial fishing vessel (*Southward Ho*, Table B.1), with the distribution of tows being very different from the preceding and succeeding surveys (plot not provided; see Figure C5 in Edwards et al. 2012). As well, the distribution of tows by depth was also different from the other surveys (Table B.2). These observations imply a substantially different survey design and consequently this survey was not included in the time series.

The 1984 survey was conducted by two vessels: the *G.B. Reed* and the *Eastward Ho* (Nagtegaal et al. 1986). Part of the design of this survey was to compare the catch rates of the two vessels (one was a commercial fishing vessel and the other a government research vessel – Greg Workman, DFO, pers. comm.), thus they both followed similar design specifications, including the configuration of the net. Unfortunately, the tows were not distributed similarly in all areas, with the *G.B. Reed* fishing mainly in the shallower portions of the GIG, while the *Eastward Ho* fished more in the deeper and seaward parts of the GIG ([left panel]: Figure B.7) although the two vessels fished more contiguously in Mitchell Gully (immediately to the north). When the depth-stratified catch rates for POP (the main design species of the surveys) of the two vessels were compared within the GIG only (using a simple ANOVA), the *Eastward Ho* catch rates were significantly higher ($p=0.049$) than those observed for the *G.B. Reed*. However, the difference in catch rates was no longer significant when tows from Mitchell's Gully were added to the analysis ($p=0.12$). Given the lack of significance when the full suite of available tows were compared, along with the uneven spatial distribution of tows among vessels within the GIG (although the ANOVA was depth-stratified, it is possible that the depth categories were too coarse), the most parsimonious conclusion was that there was no detectable difference between the two vessels. Consequently, all the GIG tows from both vessels were pooled for this survey year.

The 1994 survey, also conducted by a commercial vessel (the *Ocean Selector*, Table B.2) ([left panel]: Figure B.8), was modified by the removal of 19 tows which were part of an acoustic experiment and therefore were not considered appropriate for biomass estimation (they were tows used to estimate species composition for ensonified schools). Although this survey was designed to emulate as closely as possible the previous *G.B. Reed* surveys in terms of tow location selection (same fixed tow locations, G. Workman, DFO, pers. comm.), the timing of this survey was about two to three months earlier than the previous surveys (starting in mid-June rather than August or September, Table B.3).

The 1995 survey, conducted by two commercial fishing vessels: the *Ocean Selector* and the *Frosti* (Table B.2), used a random stratified design with each vessel duplicating every tow (G. Workman, DFO, pers. comm.). This type of design was entirely different from the fixed station (based on Loran coordinates) used in the previous surveys. As well, the focus of this survey was on Pacific Ocean Perch (POP), with tows optimised to capture this species. Given the difference in design (random stations rather than fixed locations), this survey was not used in the stock assessment.

Given that the only area that was consistently monitored by these surveys was the GIG grounds, tows lying between 50.9°N & 51.6°N latitude from the seven acceptable survey years, covering the period 1967-1984, were considered for indexing the WWR population (Table B.1).

Table B.1. Number of tows in GIG and in other areas (Other) by survey year and vessel conducting the survey for the 12 historical (1965 to 1995) surveys. Survey years in grey were not used in the assessment

Survey	GB Reed		Southward Ho		Eastward Ho		Ocean Selector		Frosti	
Year	Other	GIG	Other	GIG	Other	GIG	Other	GIG	Other	GIG
1965	76	8	-	-	-	-	-	-	-	-
1966	49	15	-	-	-	-	-	-	-	-
1967	17	33	-	-	-	-	-	-	-	-
1969	3	32	-	-	-	-	-	-	-	-
1971	3	36	-	-	-	-	-	-	-	-
1973	13	33	-	-	-	-	-	-	-	-
1976	23	33	-	-	-	-	-	-	-	-
1977	15	47	-	-	-	-	-	-	-	-
1979	-	-	20	59	-	-	-	-	-	-
1984	19	42	-	-	15	27	-	-	-	-
1994	-	-	-	-	-	-	2	69	-	-
1995	-	-	-	-	-	-	2	55	1	57

Table B.2. Total number of tows by 20 fathom depth interval (in metres) in GIG and in other areas (Other) by survey year for the 12 historical (1965 to 1995) surveys. Survey years in grey were not used in the assessment. Some of the tows in the GIG portion of the table have usability codes other than 0,1,2, or 6.

Areas other than GIG

Survey	20 fathom depth interval (m)									Total
year	66-146	147-183	184-219	220-256	257-292	293-329	330-366	367-402	440-549	Tows
1965	3	15	26	17	6	6	1	1	1	76
1966	3	11	18	8	2	1	3	2	1	49
1967	1	-	6	1	2	1	1	4	-	16
1969	-	1	-	1	-	1	-	-	-	3
1971	-	-	-	-	-	-	-	-	-	-
1973	-	-	4	3	2	2	2	-	-	13
1976	-	-	4	4	4	4	4	-	-	20
1977	-	-	3	2	2	3	2	-	-	12
1979	11	2	1	5	1	-	-	-	-	20
1984	-	-	4	10	7	7	6	-	-	34
1994	-	-	-	-	-	-	-	-	-	-
1995	-	-	-	-	-	-	-	-	-	-

GIG

Survey	20 fathom depth interval (m)									Total
year	66-146	147-183	184-219	220-256	257-292	293-329	330-366	367-402	440-549	Tows
1965	-	2	4	1	1	-	-	-	-	8
1966	3	2	3	5	2	-	-	-	-	15
1967	1	6	11	6	10	-	-	-	-	34
1969	-	9	11	6	6	-	-	-	-	32
1971	-	5	15	9	10	-	-	-	-	39
1973	-	7	11	7	8	-	-	-	-	33
1976	-	7	15	8	6	-	-	-	-	36
1977	1	12	14	14	9	-	-	-	-	50
1979	23	12	18	6		-	-	-	-	59
1984	-	13	25	17	13	1	-	-	-	69
1994	-	15	18	20	18	-	-	-	-	71
1995	2	23	47	22	15	6	-	-	-	115

The original depth stratification of these surveys was in 20 fathom (36.1 m) intervals, ranging from 36 fathoms (66 m) to 300 fathoms (549 m). These depth strata were combined for analysis into three ranges which encompassed most rockfish: 120–183 m, 184–218 m and 219–300 m, for a total of 332 tows from the eight accepted survey years (Table B.3).

Table B.3. Number of tows by survey year and depth stratum available for the analysis of the historical GIG trawl survey series. Survey year in grey was not used in the WWR stock assessment.

	Depth stratum					
Survey Year	120-183 m (70–100 fm)	184-218 m (100–120 fm)	219-300 m (120–160 fm)	Total	Start Date	End Date
1967	7	11	15	33	07-Sep-67	03-Oct-67
1969	8	11	12	31	14-Sep-69	24-Sep-69
1971	4	15	17	36	14-Oct-71	28-Oct-71
1973	7	11	15	33	07-Sep-73	24-Sep-73
1976	7	13	13	33	09-Sep-76	26-Sep-76
1977	13	14	20	47	24-Aug-77	07-Sep-77
1984	13	23	33	69	05-Aug-84	08-Sep-84
1994	10	16	24	50	21-Jun-94	06-Jul-94
1995	22	45	45	112	11-Sep-95	22-Sep-95

Table B.4. Biomass estimates for Widow Rockfish from the historical Goose Island Gully trawl surveys for the years 1967 to 1994. Biomass estimates are based on three depth strata (Table B.3), assuming that the survey tows were randomly selected within these areas. Bootstrap bias corrected confidence intervals and CVs are based on 1000 random draws with replacement.

Survey Year	Biomass (t) (Eq. B.4)	Mean bootstrap biomass (t)	Lower bound biomass (t)	Upper bound biomass (t)	Bootstrap CV	Analytic CV (Eq. B.6)
1967	20.0	19.9	4.8	43.0	0.493	0.514
1969	8.1	8.0	1.3	18.7	0.546	0.551
1971	11.8	11.7	4.1	24.0	0.430	0.446
1973	11.5	11.6	4.0	24.3	0.464	0.462
1976	103.4	103.0	10.4	252.9	0.614	0.640
1977	81.0	82.7	19.4	219.6	0.597	0.587
1984	97.3	94.5	1.4	335.2	0.951	0.926
1994	45.9	45.1	0.0	158.7	0.926	0.946

A doorspread density (Eq. B.3) was calculated for each tow based on the catch of WWR, using a fixed doorspread value of 61.6 m (Yamanaka et al. 1996) for every tow and the recorded distance travelled. Unfortunately, the speed, effort and distance travelled fields were not well populated for these surveys. Therefore, missing values for these fields were filled in with the mean values for the survey year. This resulted in the majority of the tows having distances towed near 3 km, which was the expected result given the design specification of ½ hour tows at an approximate speed of 6 km/h (about 3.2 knots).

B.3.2. Results

Maps showing the locations where WWR were caught in the Goose Island Gully (GIG) indicate that this species is found intermittently in the outer parts of the GIG in some years, with occasional observations in the south-eastern branch of the gully (see Figure B.1 to Figure B.8). WWR was taken relatively infrequently in small amounts, with only 56 of the 332 valid tows capturing WWR with a median catch weight of 2.1 kg. The largest valid WWR tow in terms of catch weight was 98 kg in 1984. WWR were mainly taken at depths from 154 to 271 m (5% and 95% quantiles of the starting depth empirical distribution), with the minimum and maximum observed starting tow depths at 143 and 291 m respectively (Figure B.9).

Estimated biomass levels in the GIG for Widow Rockfish from the historical GIG trawl surveys were variable, with the maximum biomass recorded in 1976 (at 103 t) and the minimum biomass in 1969 (at 8 t) (Figure B.10; Table B.4). Survey relative errors were high to very high for this species, ranging from a low of 0.43 in 1971 to 0.95 in 1984 (Table B.4). The proportion of tows which caught WWR was low and variable between years, ranging between 4% and 28% of the tows (Figure B.11). Overall, 56 tows from a total 332 valid tows (17%) contained WWR.

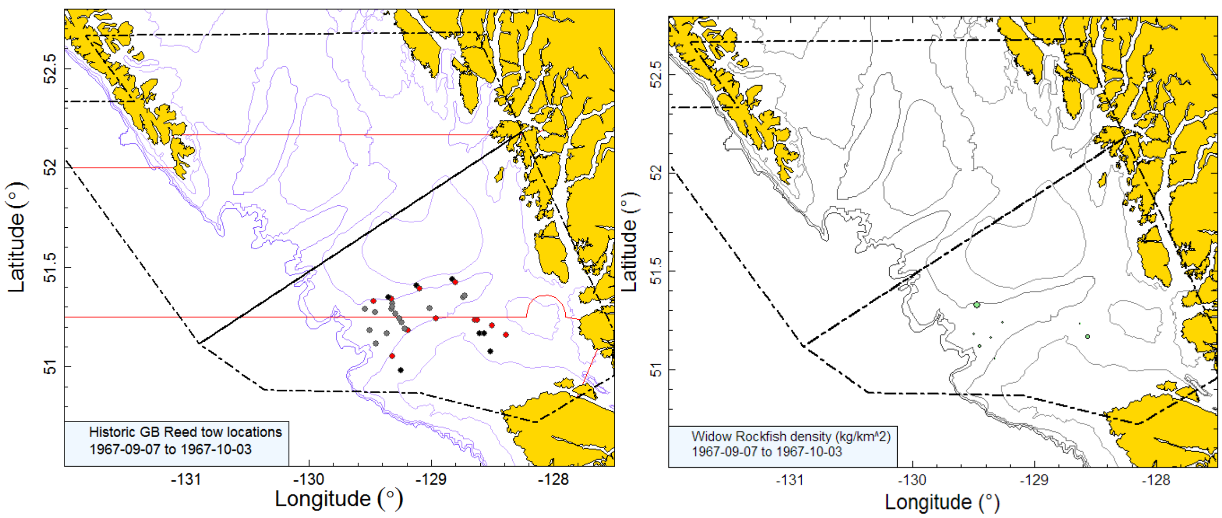

Figure B.1. Valid tow locations and density plots for the historic 1967 Goose Island Gully (GIG) survey. Tow locations are colour-coded by depth range: black=120–183m; red=184-218m; grey=219-300m. Circle sizes in the right-hand density plot scaled across all years (1967, 1969, 1971, 1973, 1976, 1977, 1984, and 1994), with the largest circle = 551 kg/km² in 1984. Black boundary lines show the extent of the modern Queen Charlotte Sound synoptic survey and the red solid lines indicate the boundaries between PMFC areas 5A, 5B and 5C.

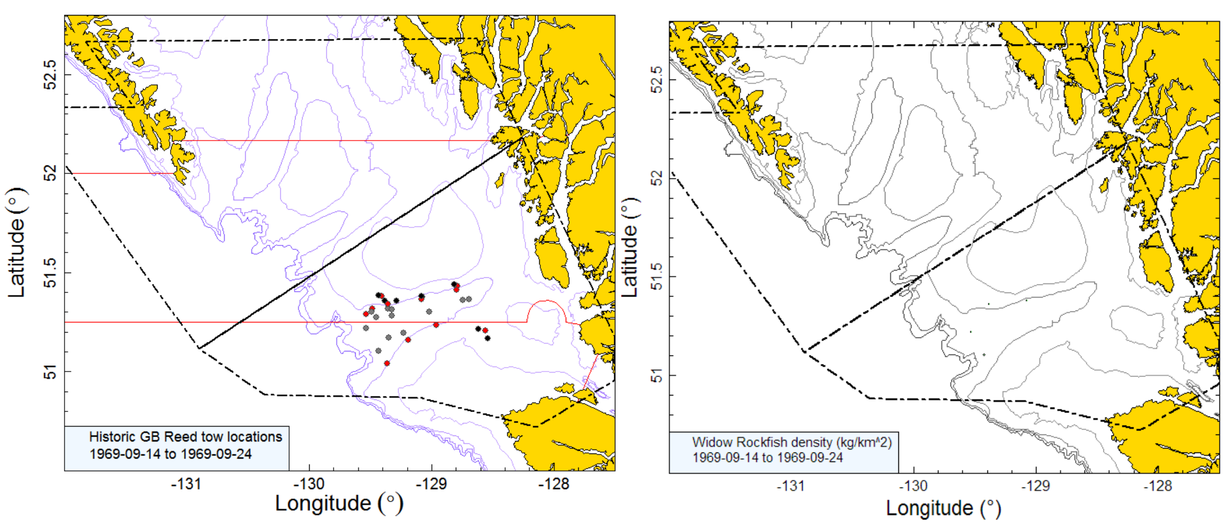

Figure B.2. Tow locations and density plots for the historic 1969 Goose Island Gully (GIG) survey (see Figure B.1 caption).

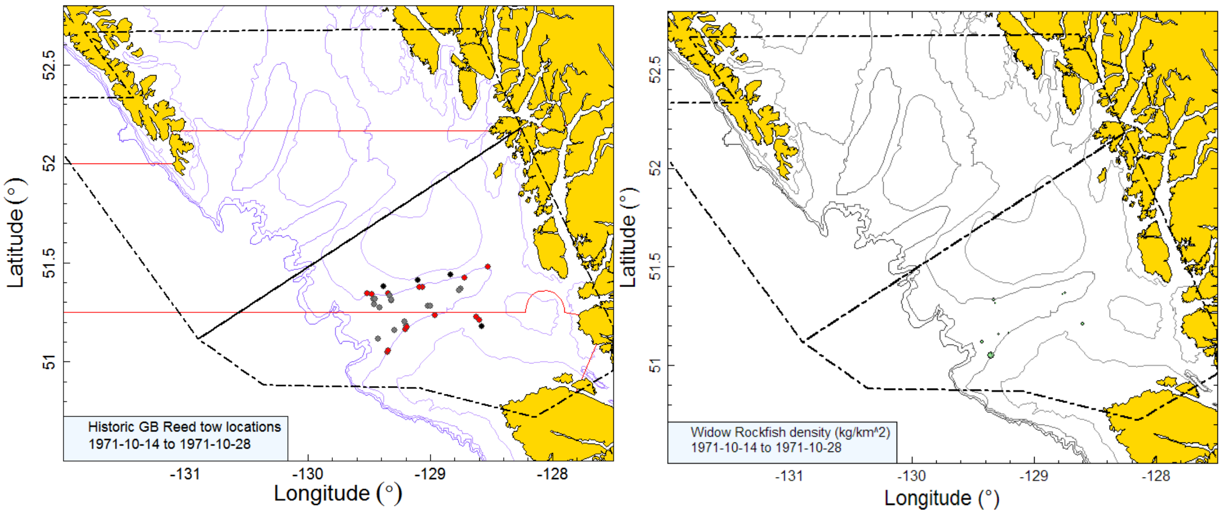

Figure B.3. Tow locations and density plots for the historic 1971 Goose Island Gully (GIG) survey (see Figure B.1 caption).

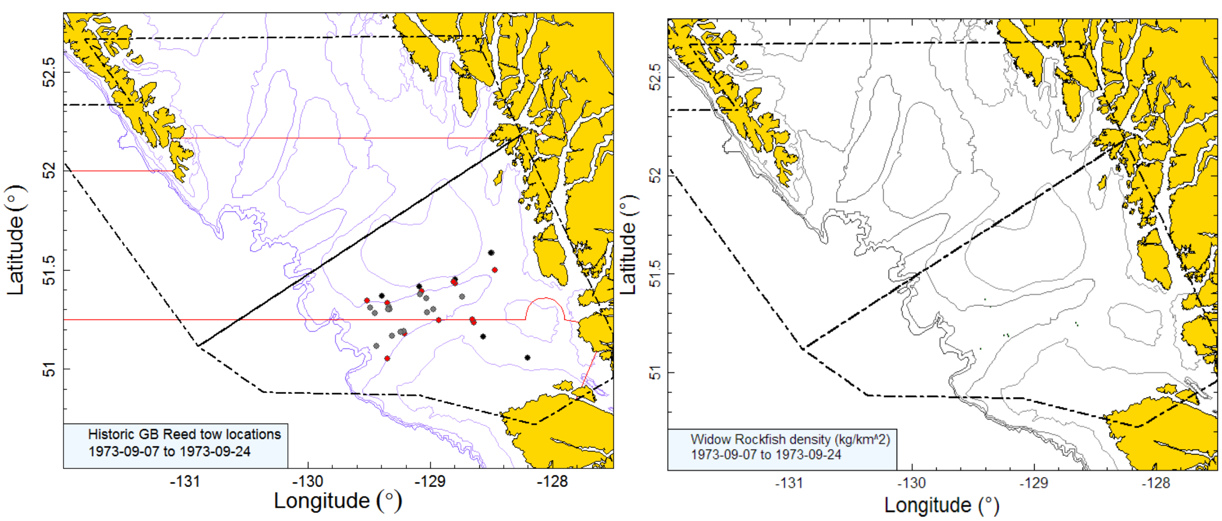

Figure B.4. Tow locations and density plots for the historic 1973 Goose Island Gully (GIG) survey (see Figure B.1 caption).

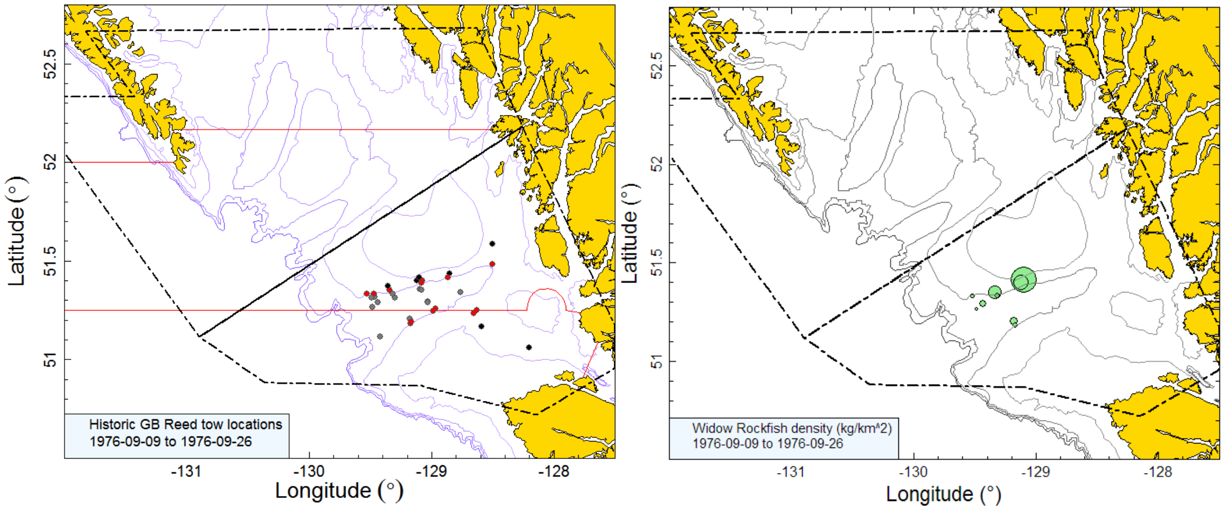

Figure B.5. Tow locations and density plots for the historic 1976 Goose Island Gully (GIG) survey (see Figure B.1 caption).

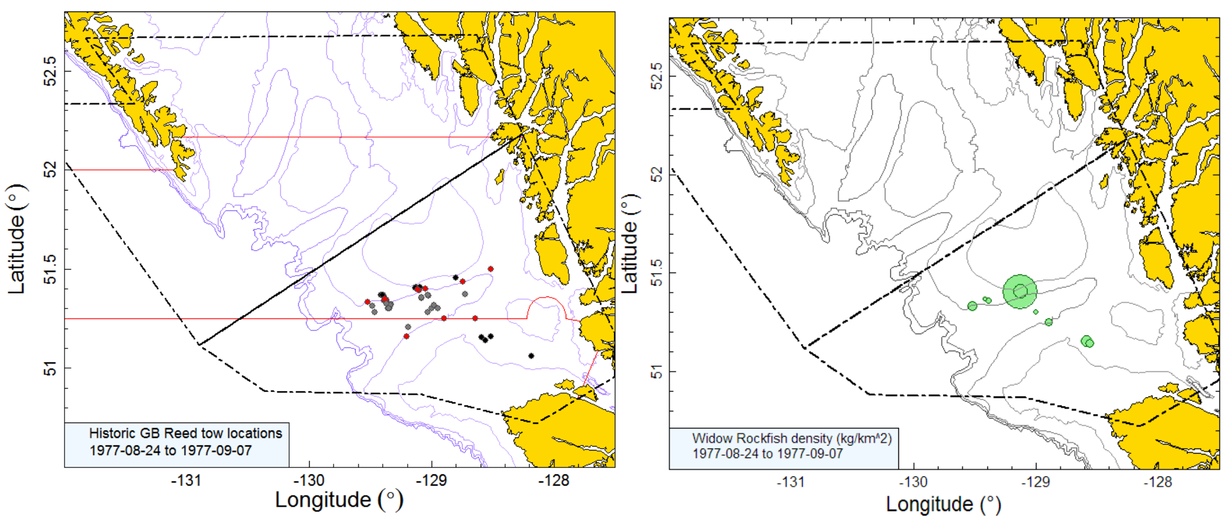

Figure B.6. Tow locations and density plots for the historic 1977 Goose Island Gully (GIG) survey (see Figure B.1 caption).

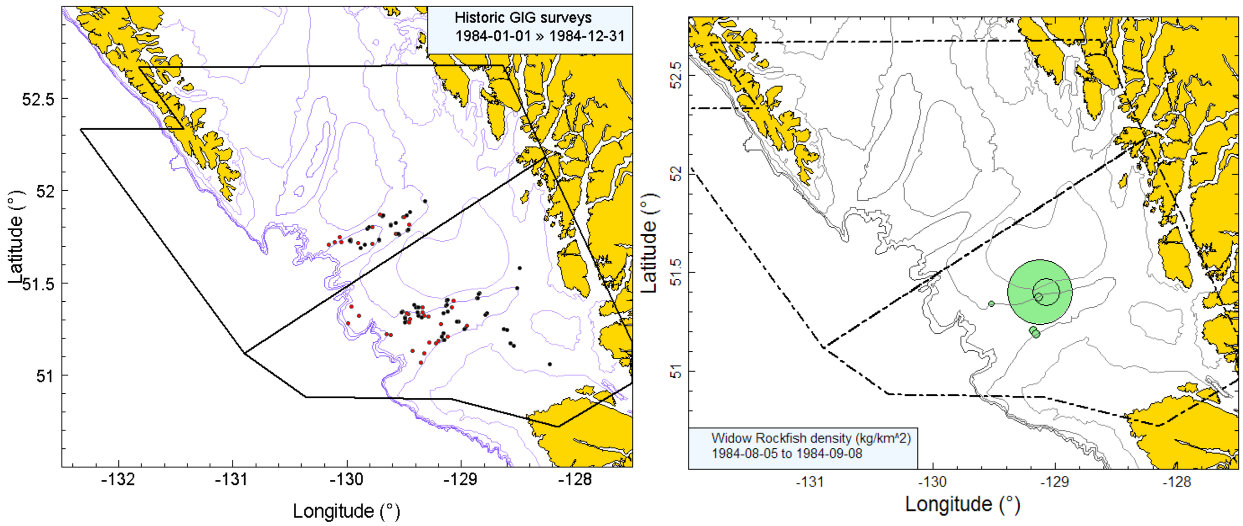

Figure B.7. [left panel]: Tow location colours indicate the vessel fishing rather than depth: black=G.B. Reed; red=Eastward Ho. Additional locations fished by vessel in Mitchell Gully are also shown; [right panel]: density plot for the historic 1984 Goose Island Gully (GIG) survey (see Figure B.1 caption).

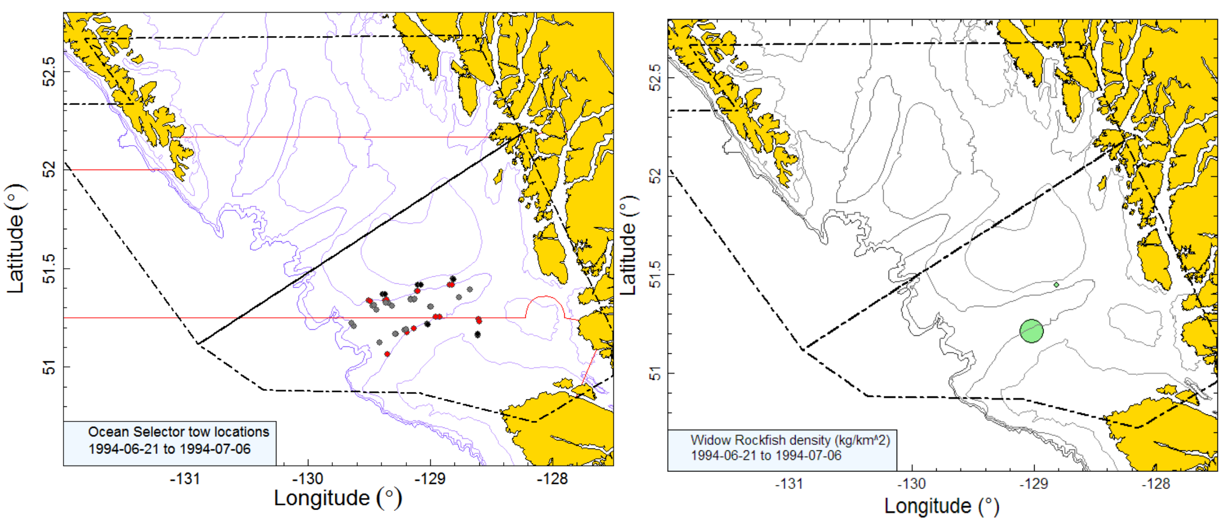

Figure B.8. Tow locations and density plots for the historic 1994 Goose Island Gully (GIG) survey (see Figure B.1 caption).

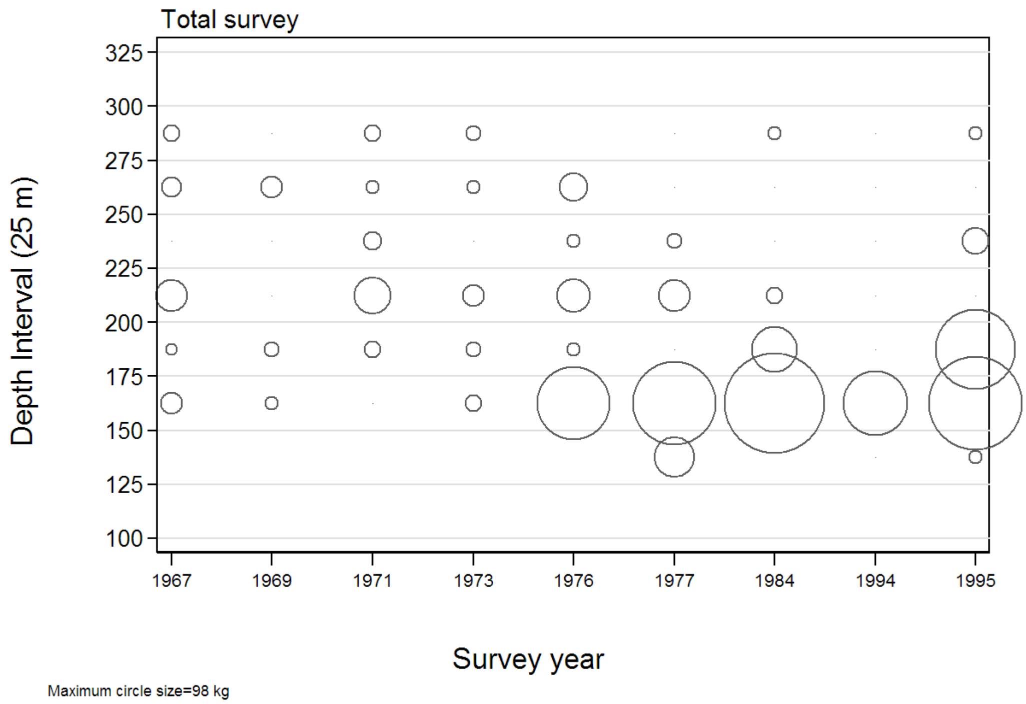

Figure B.9. Distribution of observed catch weights of Widow Rockfish (WWR) for the historic Goose Island Gully (GIG) surveys (Table B.3) by survey year and 25 m depth zone. Depth zones are indicated by the mid point of the depth interval and circles in the panel are scaled to the maximum value (98 kg) in the 150–175 m interval in 1984. The 1% and 99% quantiles for the WWR empirical start of tow depth distribution= 146 m and 282 m respectively.

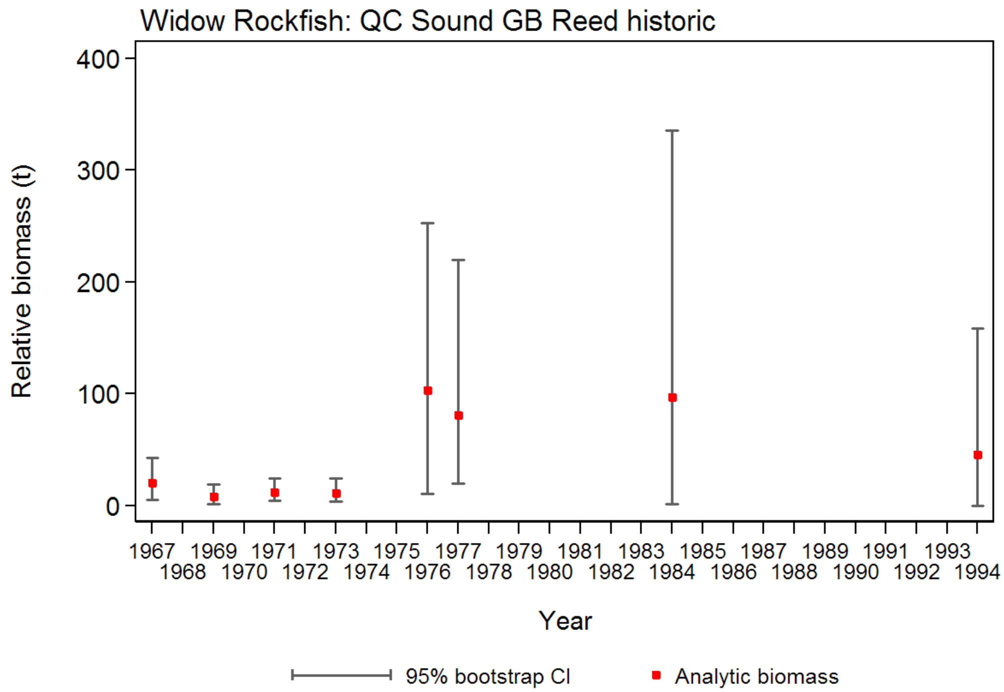

Figure B.10. Plot of biomass estimates for the WWR historic Goose Island Gully (GIG) surveys: 1967 to 1994 (values provided in Table B.4). Bias corrected 95% confidence intervals from 1000 bootstrap replicates are plotted.

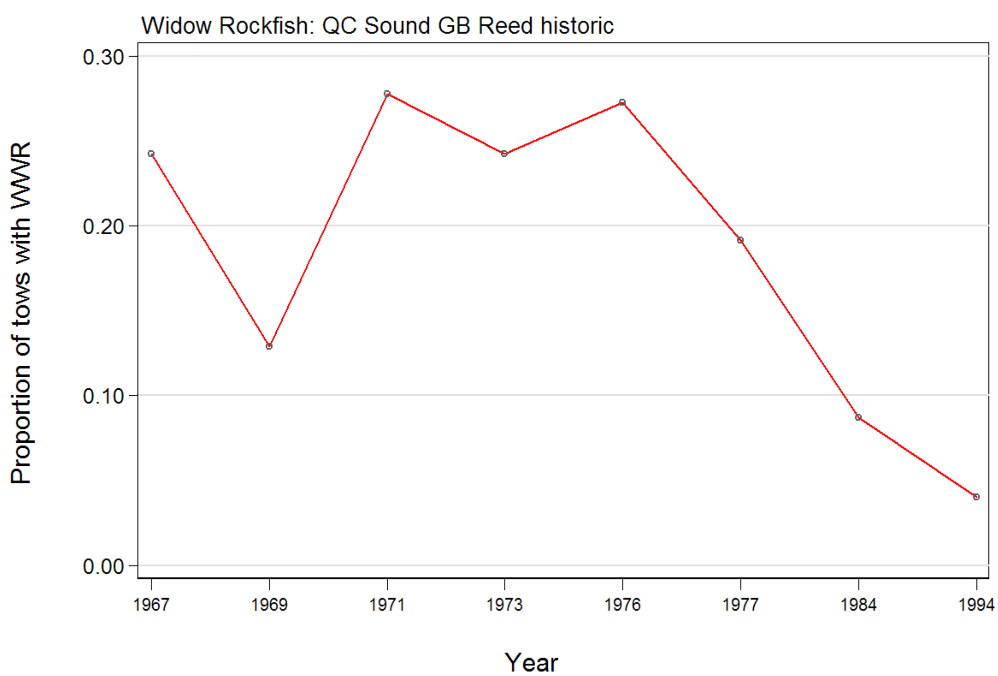

Figure B.11. Proportion of tows by year which contain WWR from the historic Goose Island Gully (GIG) surveys: 1967 to 1994.

B.4. NMFS TRIENNIAL TRAWL SURVEY

B.4.1. 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 operated in BC waters (Table B.5; 1980: Figure B.12; 1983: Figure B.13; 1989: Figure B.14; 1992: Figure B.15; 1995: Figure B.16; 1998: Figure B.17; 2001: Figure B.18). These tows were assigned to strata by the NMFS, but the size and definition of these strata have changed over the life of the survey (Table B.6). 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 B.12 to Figure B.18). The NMFS designations were accepted for tows located near the marine border.

Table B.5. Number of tows by stratum and by survey year for the NMFS triennial survey. Strata coloured grey have been excluded from the analysis due to incomplete coverage across the seven survey years or were from locations outside the Vancouver INPFC area (Table B.6).

Stratum	1980		1983		1989		1992		1995		1998		2001	
No.	CDN	US	CDN	US	CDN	US	CDN	US	CDN	US	CDN	US	CDN	US
10	-	17	-	7	-	-	-	-	-	-	-	-	-	-
11	48	-	-	39	-	-	-	-	-	-	-	-	-	-
12	-	-	38	-	-	-	-	-	-	-	-	-	-	-
17N	-	-	-	-	-	8	-	9	-	8	-	8	-	8
17S	-	-	-	-	-	27	-	27	-	25	-	26	-	25
18N	-	-	-	-	1	-	1	-	-	-	-	-	-	-
18S	-	-	-	-	-	32	-	23	-	12	-	20	-	14
19N	-	-	-	-	58	-	53	-	55	-	48	-	33	-
19S	-	-	-	-	-	4	-	6	-	3	-	3	-	3
27N	-	-	-	-	-	2	-	1	-	2	-	2	-	2
27S	-	-	-	-	-	5	-	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	-	5	-	1	-	-	-	-	-	-	-	-	-	-
51	4	-	-	10	-	-	-	-	-	-	-	-	-	-
52	-	-	4	-	-	-	-	-	-	-	-	-	-	-
Total	59	26	47	70	67	87	61	79	71	68	59	74	38	72

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 Widow Rockfish 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 (Table B.6). Strata that were not surveyed consistently in all seven years of the survey were dropped from the analysis (Table B.5; Table B.6), allowing the remaining data to provide a comparable set of data for each year (Table B.7).

The stratum definitions used in the 1980 and 1983 surveys were different than those used in subsequent surveys, particularly in Canadian waters (Table B.7). Therefore, the 1980 and 1983 indices were scaled up by the ratio (9166 km^2 / 7399 km^2 = 1.24) of the total stratum areas relative to the 1989 and later surveys so that the coverage from the first two surveys would be comparable to the surveys conducted from 1989 onwards. The tow density was much higher in US waters although the overall number of tows was approximately the same for each country (Table B.7). 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 (Table B.7). Note that the northern extension of the survey has varied from year to year (Figure B.12 to Figure B.18), 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.

Table B.6. Stratum definitions by year used in the NMFS triennial survey to separate the survey results by country and by INPFC area. Stratum definitions in grey are those strata which have been excluded from the final analysis due to incomplete coverage across the seven survey years or because the locations were outside the Vancouver INPFC area.

Year	Stratum No.	Area (km^2)	Start	End	Country	INPFC area	Depth range
1980	10	3537	47°30	US-Can Border	US	Vancouver	55-183 m
1980	11	6572	US-Can Border	49°15	CDN	Vancouver	55-183 m
1980	30	443	47°30	US-Can Border	US	Vancouver	184-219 m
1980	31	325	US-Can Border	49°15	CDN	Vancouver	184-219 m
1980	50	758	47°30	US-Can Border	US	Vancouver	220-366 m
1980	51	503	US-Can Border	49°15	CDN	Vancouver	220-366 m
1983	10	1307	47°30	47°55	US	Vancouver	55-183 m
1983	11	2230	47°55	US-Can Border	US	Vancouver	55-183 m
1983	12	6572	US-Can Border	49°15	CDN	Vancouver	55-183 m
1983	30	66	47°30	47°55	US	Vancouver	184-219 m
1983	31	377	47°55	US-Can Border	US	Vancouver	184-219 m
1983	32	325	US-Can Border	49°15	CDN	Vancouver	184-219 m
1983	50	127	47°30	47°55	US	Vancouver	220-366 m
1983	51	631	47°55	US-Can Border	US	Vancouver	220-366 m
1983	52	503	US-Can Border	49 °15	CDN	Vancouver	220-366 m
1989&after	17N	1033	47°30	47°50	US	Vancouver	55-183 m
1989&after	17S	3378	46°30	47°30	US	Columbia	55-183 m
1989&after	18N	159	47°50	48°20	CDN	Vancouver	55-183 m
1989&after	18S	2123	47°50	48°20	US	Vancouver	55-183 m
1989&after	19N	8224	48°20	49°40	CDN	Vancouver	55-183 m
1989&after	19S	363	48°20	49°40	US	Vancouver	55-183 m
1989&after	27N	125	47°30	47°50	US	Vancouver	184-366 m
1989&after	27S	412	46°30	47°30	US	Columbia	184-366 m
1989&after	28N	88	47°50	48°20	CDN	Vancouver	184-366 m
1989&after	28S	787	47°50	48°20	US	Vancouver	184-366 m
1989&after	29N	942	48°20	49°40	CDN	Vancouver	184-366 m
1989&after	29S	270	48°20	49°40	US	Vancouver	184-366 m
1995&after	37N	102	47°30	47°50	US	Vancouver	367-500 m
1995&after	37S	218	46°30	47°30	US	Columbia	367-500 m
1995&after	38N	66	47°50	48°20	CDN	Vancouver	367-500 m
1995&after	38S	175	47°50	48°20	US	Vancouver	367-500 m

A reviewer from NOAA for Yellowtail Rockfish in 2014 (DFO 2015) 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 Widow Rockfish biomass (summarised in Table B.7) exclude these water haul tows.

Table B.7. Number of usable tows performed and area surveyed in the INPFC Vancouver region separated by the international border between Canada and the United States. Strata 18N, 28N, 37, 38 and 39 (Table B.6) were dropped from this analysis as they were not consistently conducted over the survey period. All strata occurring in the Columbia INPFC region (17S and 27S; Table B.6) were also dropped. Thirty-three "water hauls" have been dropped from these totals.

Survey year	Number of tows			Area surveyed (km^2)		
	CDN waters	US waters	Total	CDN waters	US waters	Total
1980	48	23	71	7,399	4,738	12,137
1983	39	65	104	7,399	4,738	12,137
1989	63	54	117	9,166	4,699	13,865
1992	59	47	106	9,166	4,699	13,865
1995	62	35	97	9,166	4,699	13,865
1998	54	42	96	9,166	4,699	13,865
2001	36	37	73	9,166	4,699	13,865
Total	361	303	664	–	–	–

Table B.8. Water haul and usable tow distribution by survey year and national stratum. Only tows used in the biomass estimation (see Table B.7) are listed.

Year	Canadian waters			American waters			Total		
	Usable tows	Water hauls	Total	Usable tows	Water hauls	Total	Usable tows	Water hauls	Total
1980	48	11	59	23	3	26	71	14	85
1983	39	8	47	65	5	70	104	13	117
1989	63	2	65	54	1	55	117	3	120
1992	59	-	59	47	3	50	106	3	109
1995	62	-	62	35	-	35	97	-	97
1998	54	-	54	42	-	42	96	-	96
2001	36	-	36	37	-	37	73	-	73
Total	361	21	382	303	12	315	664	33	697

Twenty-one tows in Canadian waters and 12 tows in US waters were identified as water hauls, with all of the Canadian water hauls occurring in the first three surveys (Table B.8).

B.4.2. Methods

The data were analysed using the equations in Section B.1. 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 $\left(B_{y_i}\right)$ within a stratum that straddled the border was split between the two countries $\left(B_{y_{i_c}}\right)$ by the ratio of the relative area within each country:

Eq. B.7 $$B_{y_{i_c}} = B_{y_i} \frac{A_{y_{i_c}}}{A_{y_i}},$$

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

The variance $V_{y_{i_c}}$ 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:

Eq. B.8 $$V_{y_{i_c}} = V_{y_i} \frac{A^2_{y_{i_c}}}{A^2_{y_i}}.$$

The partial variance $V_{y_{i_c}}$ for country *c* was used in Eq. B.5 instead of the total variance in the stratum V_{y_i} when calculating the variance for the total biomass in Canadian or American waters. CVs were calculated as in Eq. B.6.

The biomass estimates Eq. B.4 and the associated standard errors were adjusted to a constant area covered using the ratios of area surveyed provided in Table B.7. 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. The 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.

B.4.3. Results

The occurrence of Widow Rockfish (WWR) in this survey is intermittent due to the midwater behaviour of this species, with less than 30 kg of this species caught in usable tows in 1980, 1995 and 2001. A total of 500 kg of this species was caught in usable tows occurring in Canadian waters over the 7 survey years. Catches are consequently sparse, occurring along the shelf edge and in the deep gully entering Juan de Fuca Strait (e.g., Figure B.12 and Figure B.13). A consistent biomass estimate was obtained by excluding deep strata that were not covered in the earlier surveys (Table B.6). Figure B.19 shows that this species was mainly found between 121 and 223 m (1 and 99% quantiles of [`bottom_depth`]), with infrequent observations at deeper depths which means that the deeper strata (>367 m) were not needed to monitor WWR. Note that the deep strata which were not used in the biomass estimation are included in Figure B.19.

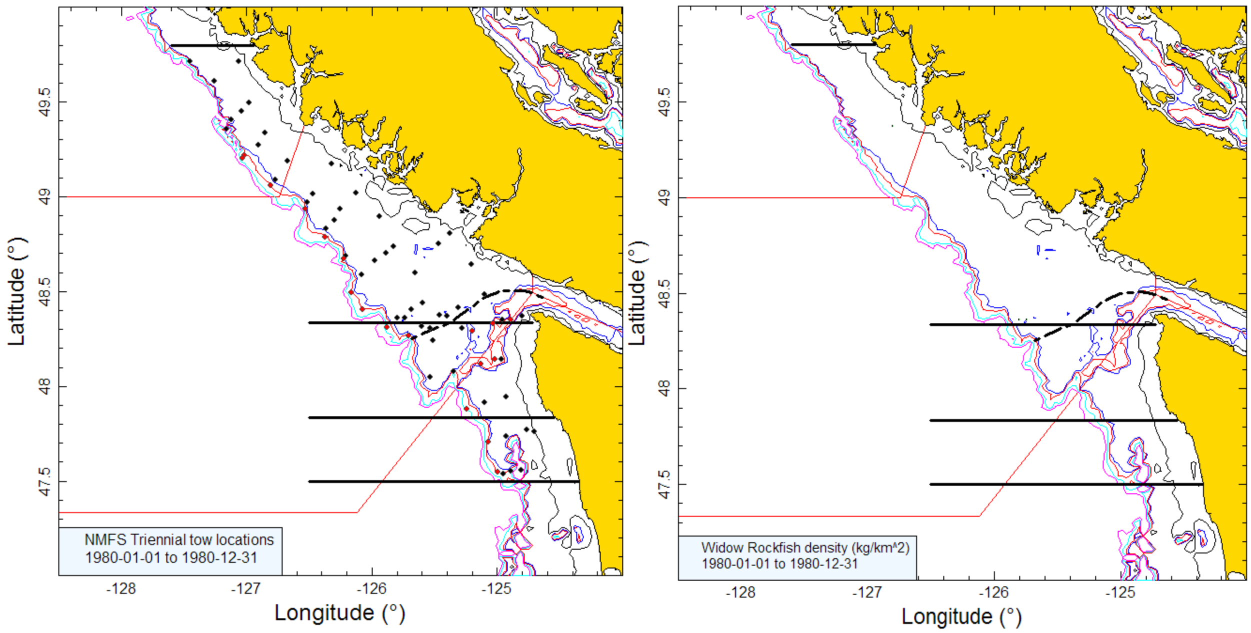

Figure B.12. [left panel]: plot of tow locations in the Vancouver INPFC region for the 1980 NMFS triennial survey in US and Canadian waters. Tow locations are colour-coded by depth range: black=55–183m; red=184-366m. Dashed line shows approximate position of the Canada/USA marine boundary. Horizontal 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. [left panel]:water hauls (Table B.8) have been excluded; [right panel]: circle sizes in the density plot are scaled across all years (1980, 1983, 1989, 1992, 1995, 1998, and 2001), with the largest circle = 52,357 kg/km² in 1989. The red solid lines indicate the boundaries between PMFC areas 3B, 3C and 3D.

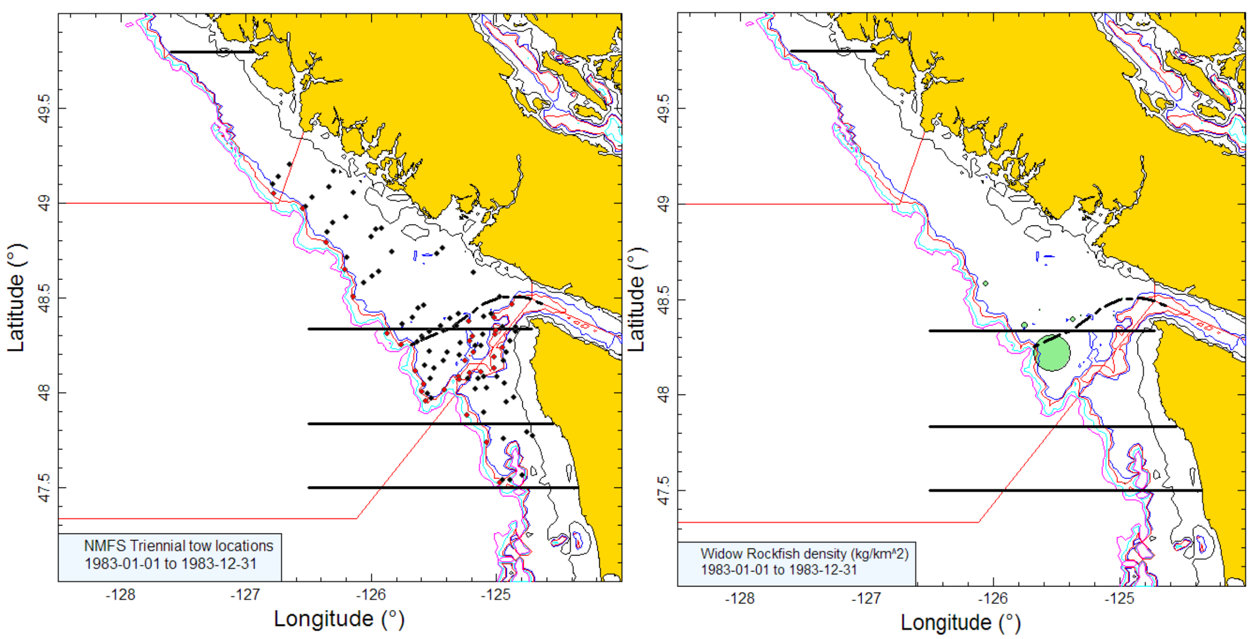

Figure B.13. Tow locations and density plots for the 1983 NMFS triennial survey in US and Canadian waters (see Figure B.12 caption).

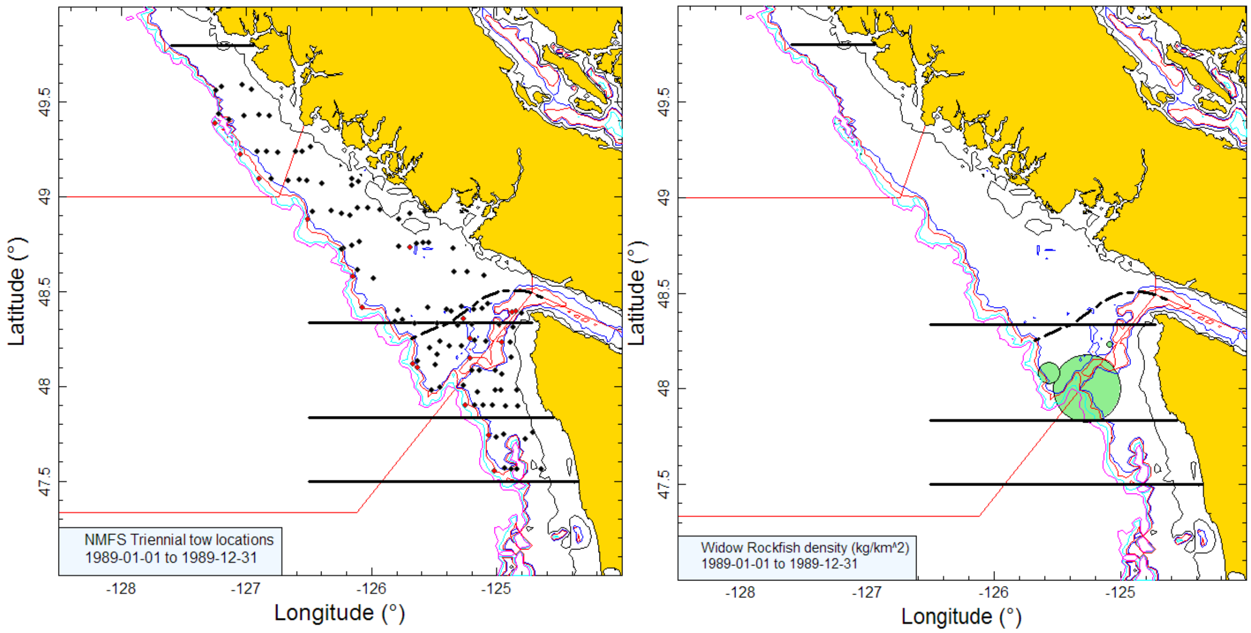

Figure B.14. Tow locations and density plots for the 1989 NMFS triennial survey in US and Canadian waters (see Figure B.12 caption).

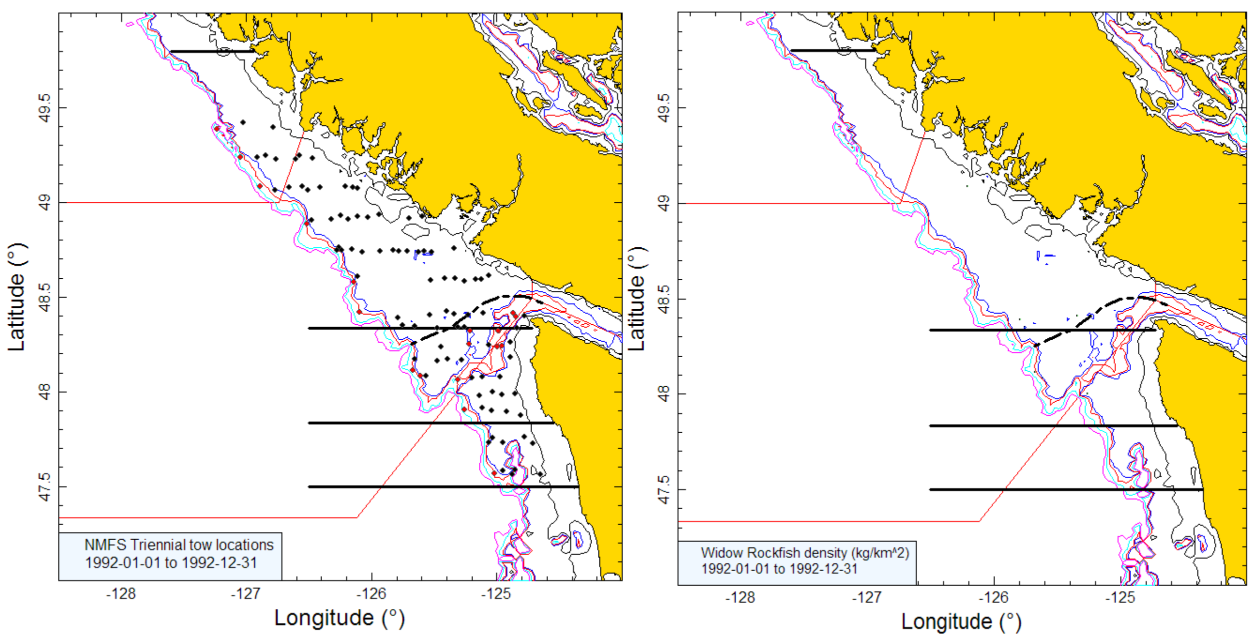

Figure B.15. Tow locations and density plots for the 1992 NMFS triennial survey in US and Canadian waters (see Figure B.12 caption).

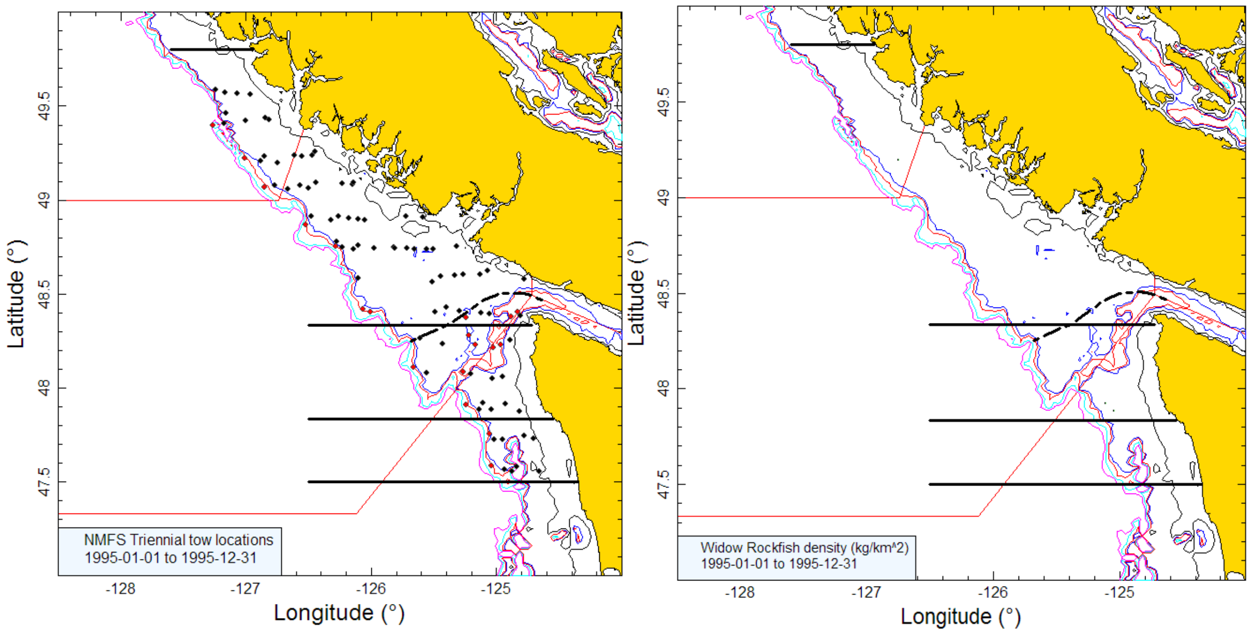

Figure B.16. Tow locations and density plots for the 1995 NMFS triennial survey in US and Canadian waters (see Figure B.12 caption).

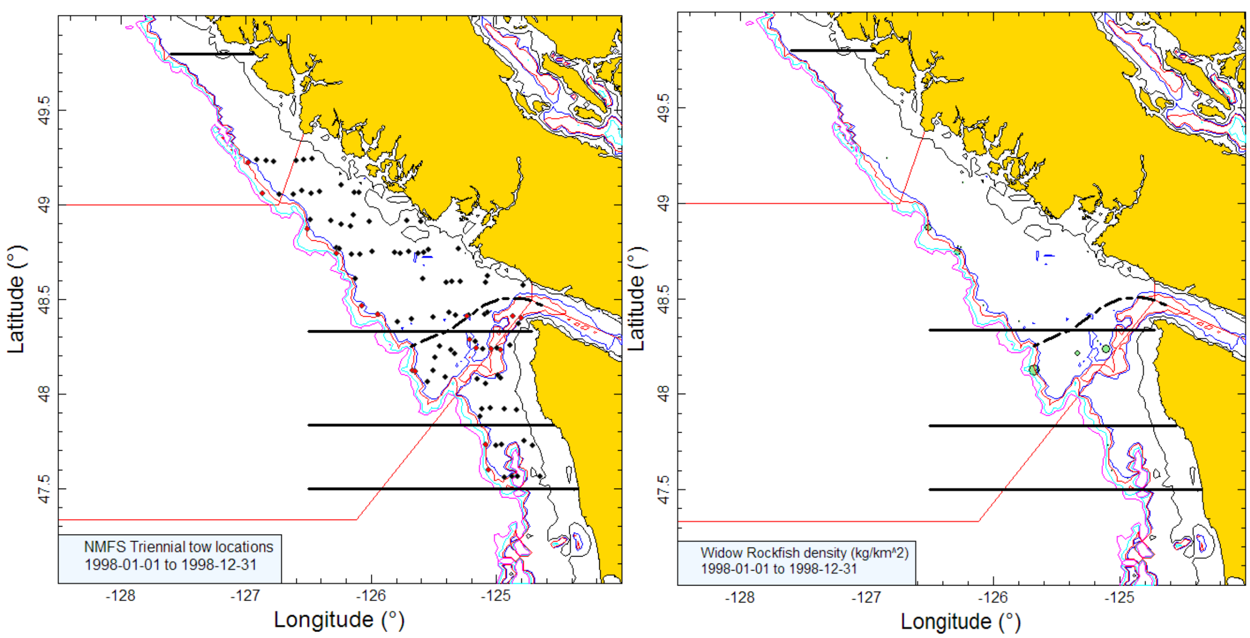

Figure B.17. Tow locations and density plots for the 1998 NMFS triennial survey in US and Canadian waters (see Figure B.12 caption).

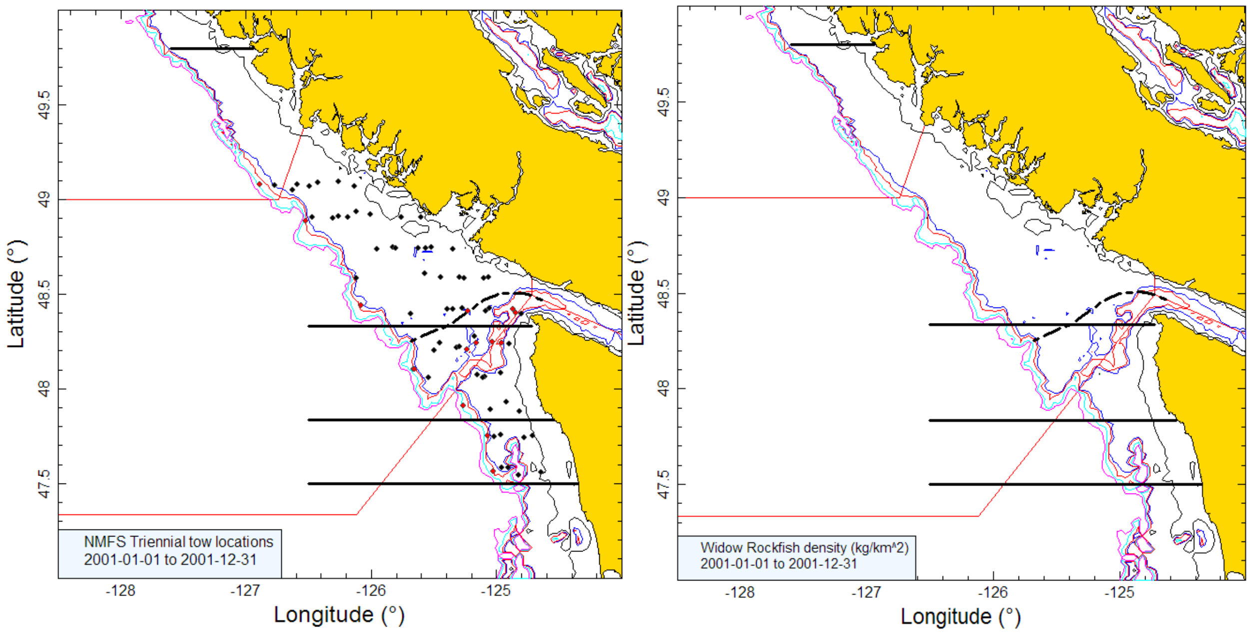

Figure B.18. Tow locations and density plots for the 2001 NMFS triennial survey in US and Canadian waters (see Figure B.12 caption).

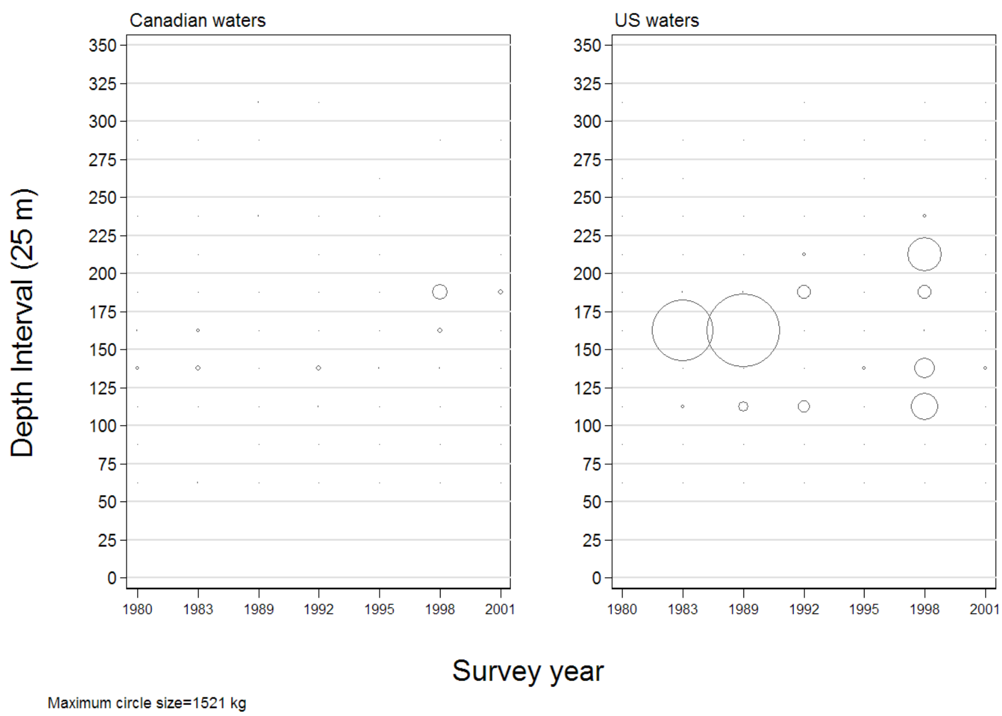

Figure B.19. Distribution of Widow Rockfish catch weights for each survey year summarised into 25 m depth intervals for all tows (Table B.6) in Canadian and US waters of the Vancouver INPFC area. Catches are plotted at the mid-point of the interval. Note that the deep strata introduced in 1995 (see Table B.6) have been included in this plot but were not used in the biomass estimation.

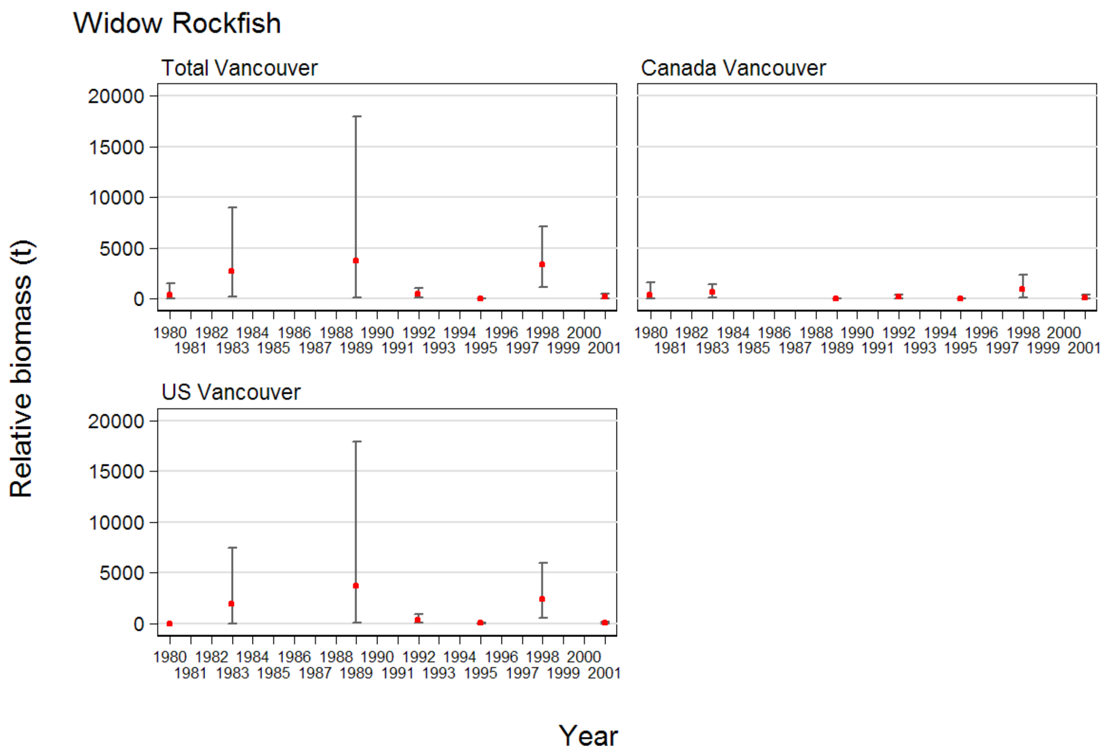

Figure B.20. Biomass estimates for three series of Widow Rockfish in the INPFC Vancouver region (total region, Canadian waters only, US waters only) with 95% error bars estimated from 1000 bootstraps.

Table B.9. Biomass estimates for Widow Rockfish in the Vancouver INPFC region (total region, Canadian waters only, and US waters only) with 95% confidence bounds based on the bootstrap distribution of biomass. Bootstrap estimates are based on 1000 random draws with replacement.

Estimate series	Year	Biomass (Eq. B.4)	Mean bootstrap biomass	Lower bound biomass	Upper bound biomass	CV bootstrap	CV Analytic (Eq. B.6)
Total Vancouver	1980	388	404	0	1,515	0.874	0.910
	1983	2,708	2,652	243	8,968	0.791	0.797
	1989	3,698	3,590	65.5	17,945	0.911	0.969
	1992	466	451	144	1,014	0.470	0.468
	1995	23.5	23.6	4.2	55.7	0.561	0.599
	1998	3,384	3,300	1,152	7,093	0.432	0.419
	2001	152	152	0	456	0.786	0.858
Canada Vancouver	1980	421	438	0	1,643	0.874	0.910
	1983	609	629	70.8	1,381	0.523	0.527
	1989	11.2	8.8	3.1	28.8	0.662	0.590
	1992	152	153	21.5	418	0.637	0.651
	1995	4.0	4.1	0	19.9	0.975	1.000
	1998	981	964	102	2,358	0.571	0.561
	2001	100	101	0	399	0.942	1.000
US Vancouver	1980	0	0	-	-	-	0.000
	1983	1,864	1,799	3	7,437	1.000	0.996
	1989	3,687	3,581	46.0	17,932	0.914	0.972
	1992	314	298	42.1	873	0.620	0.612
	1995	19.5	19.5	0	50.8	0.648	0.689
	1998	2,403	2,336	550	5,914	0.532	0.515
	2001	52.3	50.5	0	139	0.665	0.708

Widow Rockfish biomass estimates in both country strata were characterised by variable estimates that were very low in 1980, 1992, 1995 and 2001 and which show no pattern (Figure B.20; Table B.9). The US waters estimate for 1980 is zero and only 4 t were estimated for Canadian waters in 1995. There are also very low estimates in Canadian waters for 1989 and 1995. Relative error estimates are very high, with the lowest relative error occurring at 0.42 in 1998 for Total Vancouver and the greatest at 1.00 in 1995 and 2001 for the Canada Vancouver stratum (Table B.9). This is a mid-water species that is not well monitored with a bottom trawl survey. Note that the bootstrap estimates of relative error do not include any uncertainty with respect to the ratio expansion required to make the 1980 and 1983 survey estimates comparable to the 1989 and later surveys. Therefore, it is likely that the true uncertainty for this series is even greater than estimated.

Only 48 tows of the 664 valid tows captured WWR (7.2%), with half of the tows that captured WWR having less than 4.1 kg. The largest tow in US waters was 1520 kg in 1989; the largest tow in Canadian waters was 187 kg in 1998. The proportion of tows which contained Widow Rockfish was similar in US and Canadian waters, with the US proportions by year ranging from 0 to 19% (mean=6.8%) while the equivalent Canadian values were 2–17% with a mean value of 7.4% (Figure B.21). The incidence of WWR in Canadian waters for this survey is similar to the synoptic survey operating in the 2000s off the west coast of Vancouver Island, with the latter survey having a mean incidence of 11% (range: 2-18%) of the tows containing WWR.

The seven Triennial survey indices from the Canada Vancouver region spanning the period 1980 to 2001 were used as a series of abundance indices for use in the stock assessment model (described in Appendix F).

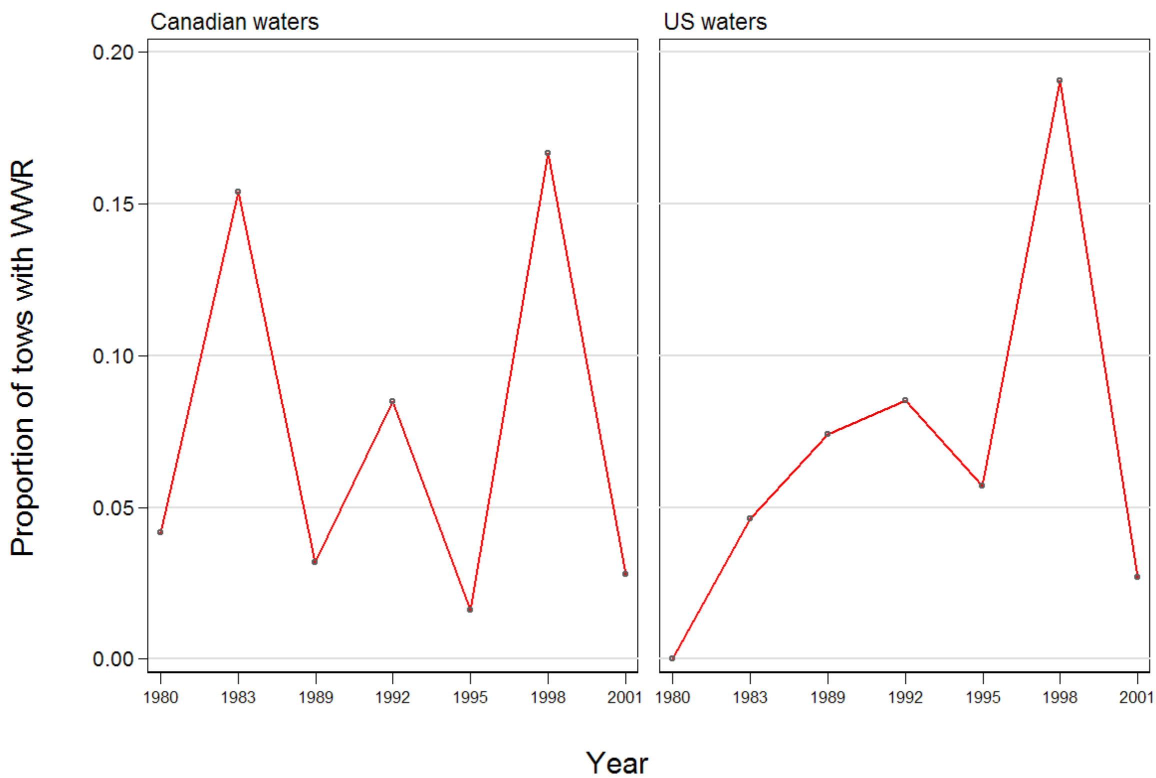

Figure B.21. Proportion of tows with Widow Rockfish by year for the Vancouver INPFC region (Canadian and US waters).

B.5. QUEEN CHARLOTTE SOUND SYNOPTIC TRAWL SURVEY

B.5.1. Data Selection

This survey has been conducted nine times over the period 2003 to 2017 in the Queen Charlotte Sound (QCS), which lies between the top of Vancouver Island and the southern portion of Moresby Island and extends into the lower part of Hecate Strait between Moresby Island and the mainland. The design divided the survey into two large areal strata which roughly correspond to the PMFC regions 5A and 5B while also incorporating part of 5C (all valid tow starting positions are shown by survey year in Figure B.22 to Figure B.29). Each of these two areal strata was divided into four depth strata: 50–125 m; 125–200 m; 200–330 m; and 330–500 m (Table B.10).

A doorspread density value (Eq. B.3) was generated for each tow based on the catch of Widow Rockfish (WWR) from the mean doorspread for the tow and the distance travelled. [`distance travelled`] is a database field which is calculated directly from the tow track. This field is used preferentially for the variable D_{yij} in Eq. B.3. A calculated value ([`vessel speed`] X [`tow duration`]) is used for this variable if [`distance travelled`] is missing, but there were only two instances of this occurring in the nine trawl surveys. Missing values for the [`doorspread`] field were filled in with the mean doorspread for the survey year (102 values over all years, Table B.11).

Table B.10. Number of usable tows for biomass estimation by year and depth stratum for the Queen Charlotte Sound synoptic survey over the period 2003 to 2017. Also shown is the area of each stratum for the 2017 survey and the vessel conducting the survey by survey year.

		South depth strata				**North depth strata**				**Total**
Year	**Vessel**	**50-125**	**125-200**	**200-330**	**330-500**	**50-125**	**125-200**	**200-330**	**330-500**	**tows[1]**
2003	*Viking Storm*	29	56	29	6	5	39	50	19	233
2004	*Viking Storm*	42	48	31	8	20	38	37	6	230
2005	*Viking Storm*	29	60	29	8	8	45	37	8	224
2007	*Viking Storm*	33	61	24	7	19	56	48	7	255
2009	*Viking Storm*	34	60	28	8	10	44	43	6	233
2011	*Nordic Pearl*	38	67	24	8	10	51	45	8	251
2013	*Nordic Pearl*	32	65	29	10	9	46	44	5	240
2015	*Frosti*	30	65	26	4	12	49	44	8	238
2017	*Nordic Pearl*	36	57	29	8	12	51	40	7	240
Area (km^2)[2]		5,028	5,344	2,668	532	1,760	3,960	3,708	1,236	24,236[2]

[1] GFBio usability codes=0,1,2,6 [2] Total area (km^2) for 2017 synoptic survey

Table B.11. Number of missing doorspread values by year for the Queen Charlotte Sound synoptic survey over the period 2003 to 2017 as well as showing the number of available doorspread observations and the mean doorspread value for the survey year.

Year	**Number tows with missing doorspread [1]**	**Number tows with doorspread observations [2]**	**Mean doorspread (m) used for tows with missing values [2]**
2003	13	236	72.1
2004	8	267	72.8
2005	1	258	74.5
2007	5	262	71.8
2009	2	248	71.3
2011	30	242	67.0
2013	42	226	69.5
2015	0	249	70.5
2017	1	265	64.7
Total	102	2,253	70.5

[1] valid biomass estimation tows only [2] includes tows not used for biomass estimation

Table B.12. Biomass estimates for Widow Rockfish from the Queen Charlotte Sound synoptic trawl survey for the survey years 2003 to 2017. Bootstrap bias corrected confidence intervals and CVs are based on 1000 random draws with replacement.

Survey Year	Biomass (t) (Eq. B.4)	Mean bootstrap biomass (t)	Lower bound biomass (t)	Upper bound biomass (t)	Bootstrap CV	Analytic CV (Eq. B.6)
2003	171.9	170.3	27.5	449.6	0.599	0.594
2004	359.1	362.8	27.4	923.5	0.602	0.601
2005	176.0	171.1	65.9	394.5	0.475	0.483
2007	35.6	34.1	11.7	79.8	0.497	0.490
2009	55.0	54.9	20.0	125.3	0.474	0.477
2011	11.4	11.5	2.4	26.5	0.519	0.516
2013	26.4	26.8	8.3	56.8	0.437	0.434
2015	150.6	151.5	45.0	385.0	0.587	0.580
2017	70.2	70.5	35.0	120.7	0.315	0.324

B.5.2. Results

WWR seems to be widely but sporadically distributed in QCS, with catches observed throughout the survey footprint (Figure B.22 to Figure B.30). WWR catches are generally low, with only one year (2004) catching about 500 kg with three years (2007, 2009 and 2011) catching less than 100 kg across all positive tows. WWR were mainly taken at depths from 69 to 282 m (5–95% quantiles for all positive weight observations), but there were sporadic observations up to depths near 350 m and down to 45 m (Figure B.31).

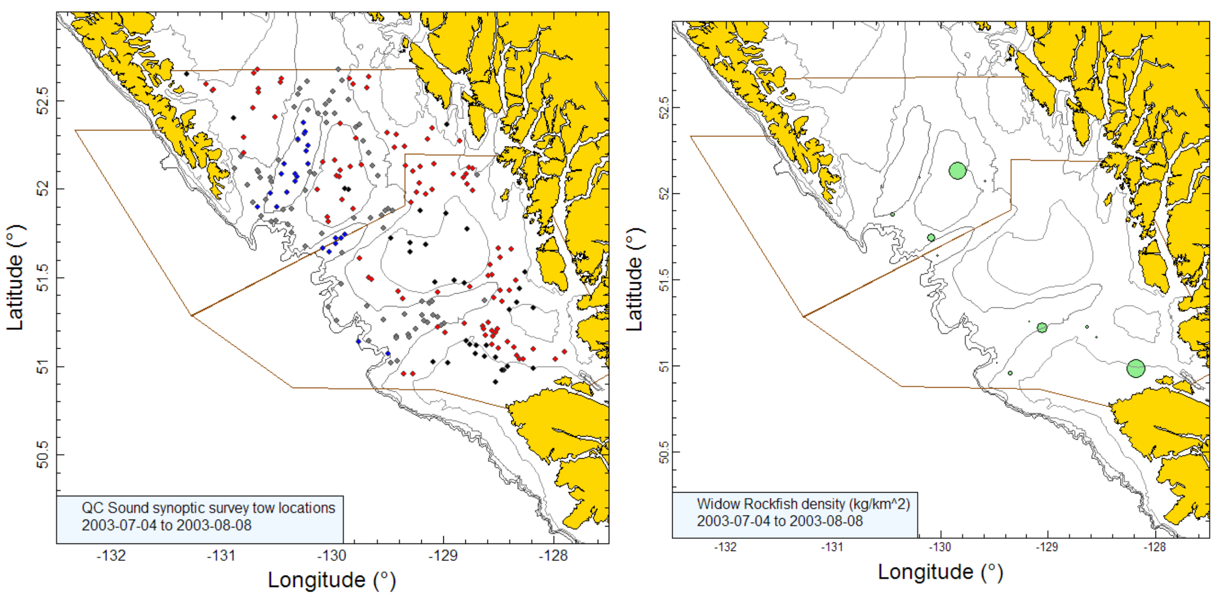

Figure B.22. Valid tow locations (50-125m stratum: black; 126-200m stratum: red; 201-330m stratum: grey; 331-500m stratum: blue) and density plots for the 2003 QC Sound synoptic survey. Circle sizes in the right-hand density plot scaled across all years (2003–2005, 2007, 2009, 2011, 2013, 2015, 2017), with the largest circle = 1,743 kg/km² in 2004. Boundaries delineate the North and South areal strata.

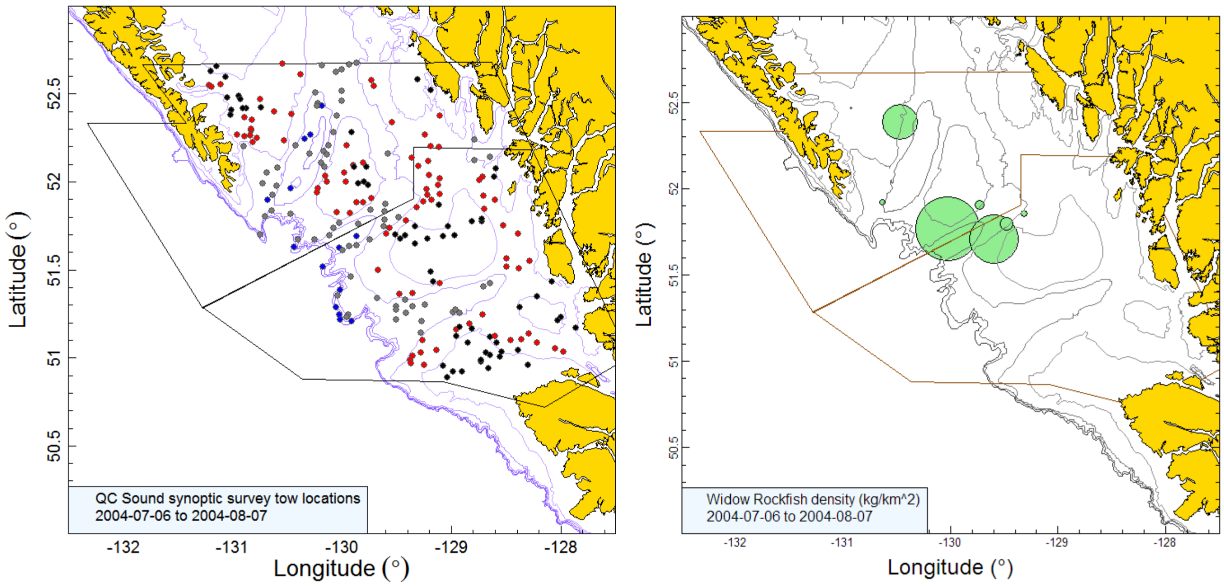

Figure B.23. Tow locations and density plots for the 2004 Queen Charlotte Sound synoptic survey (see Figure B.22 caption).

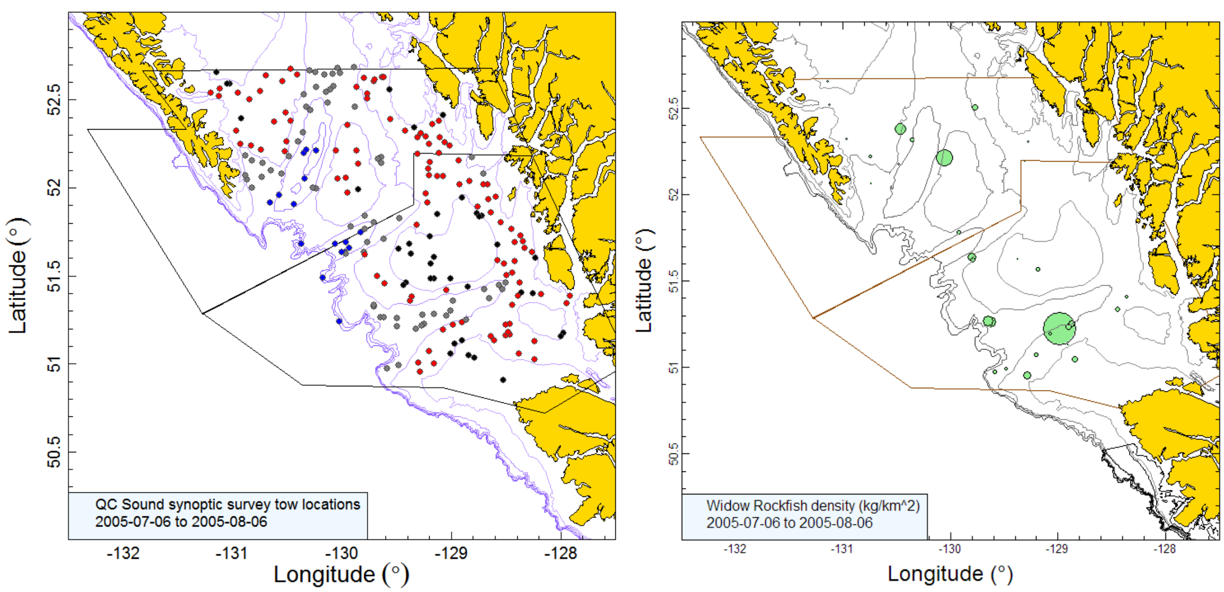

Figure B.24. Tow locations and density plots for the 2005 Queen Charlotte Sound synoptic survey (see Figure B.22 caption).

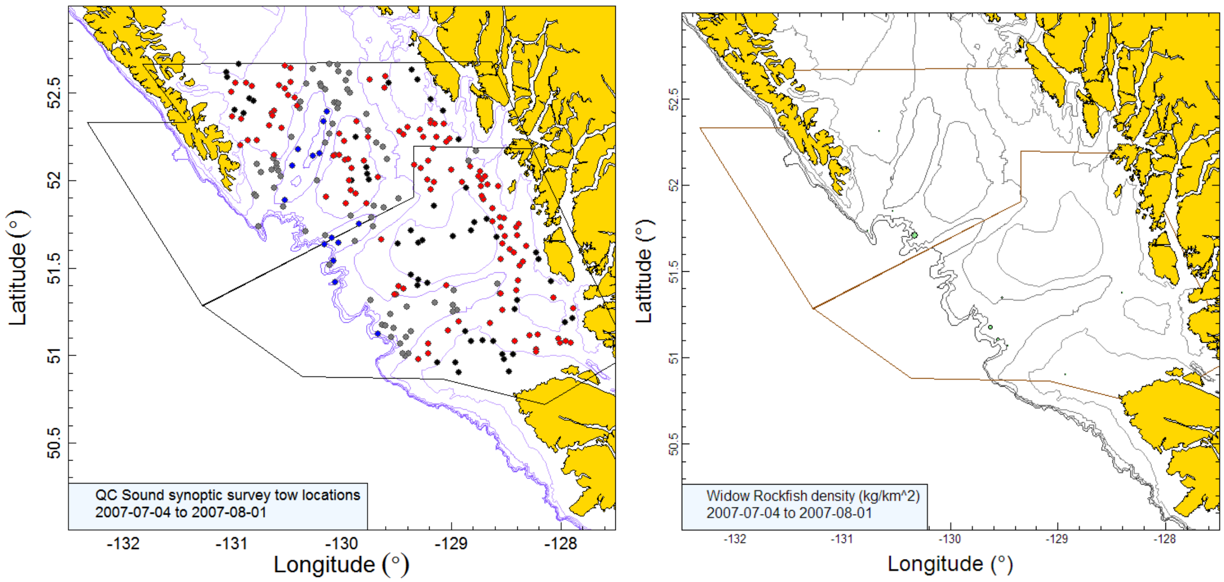

Figure B.25. Tow locations and density plots for the 2007 Queen Charlotte Sound synoptic survey (see Figure B.22 caption).

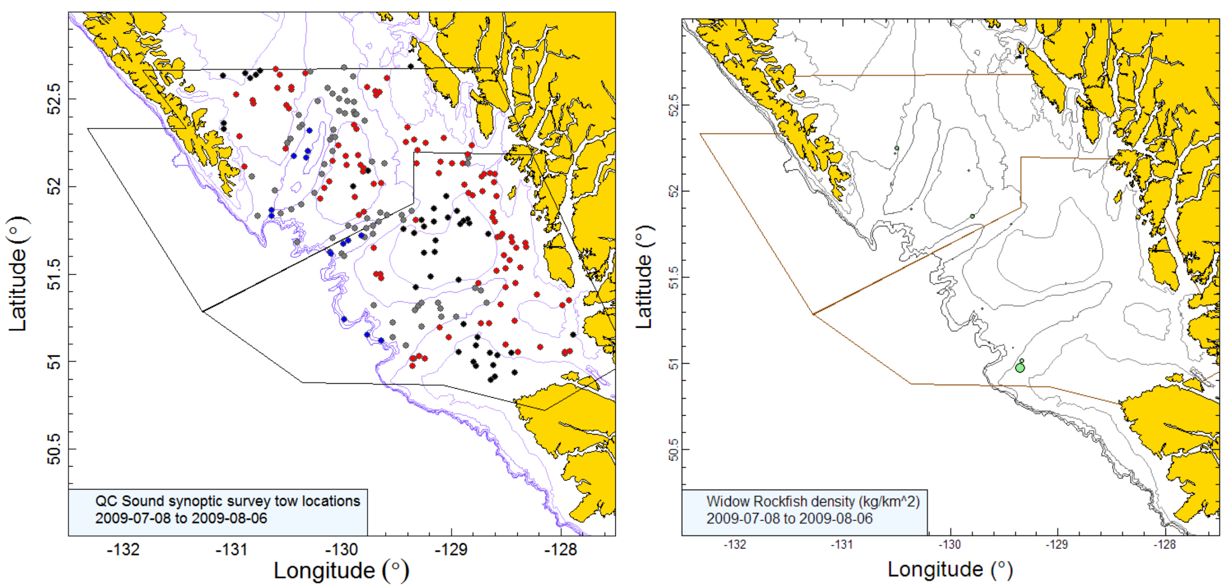

Figure B.26. Tow locations and density plots for the 2009 Queen Charlotte Sound synoptic survey (see Figure B.22 caption).

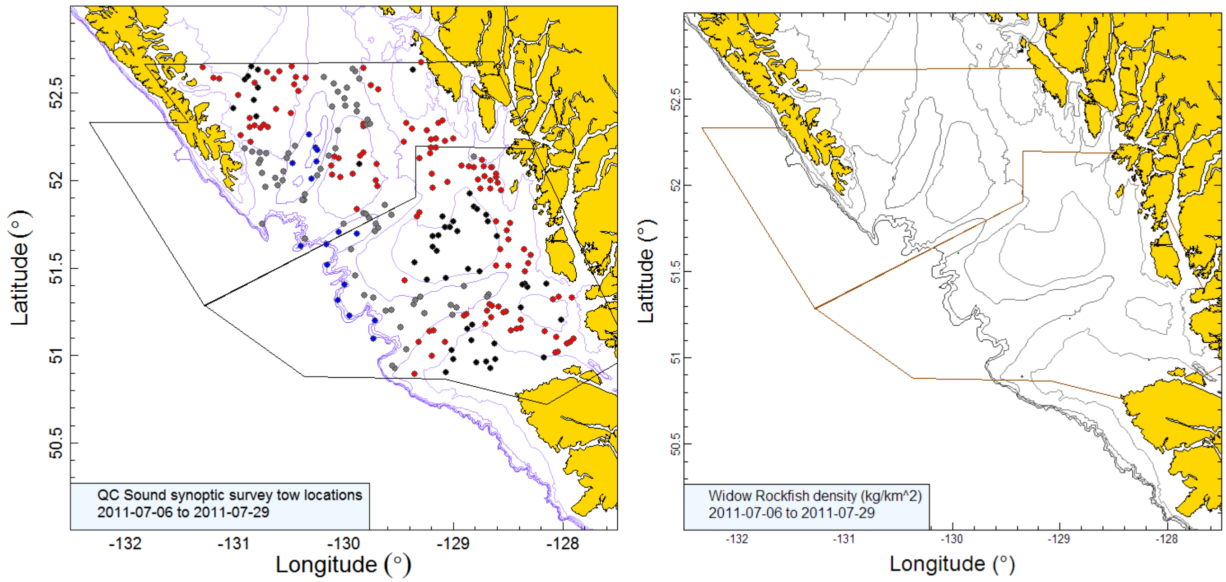

Figure B.27. Tow locations and density plots for the 2011 Queen Charlotte Sound synoptic survey (see Figure B.22 caption).

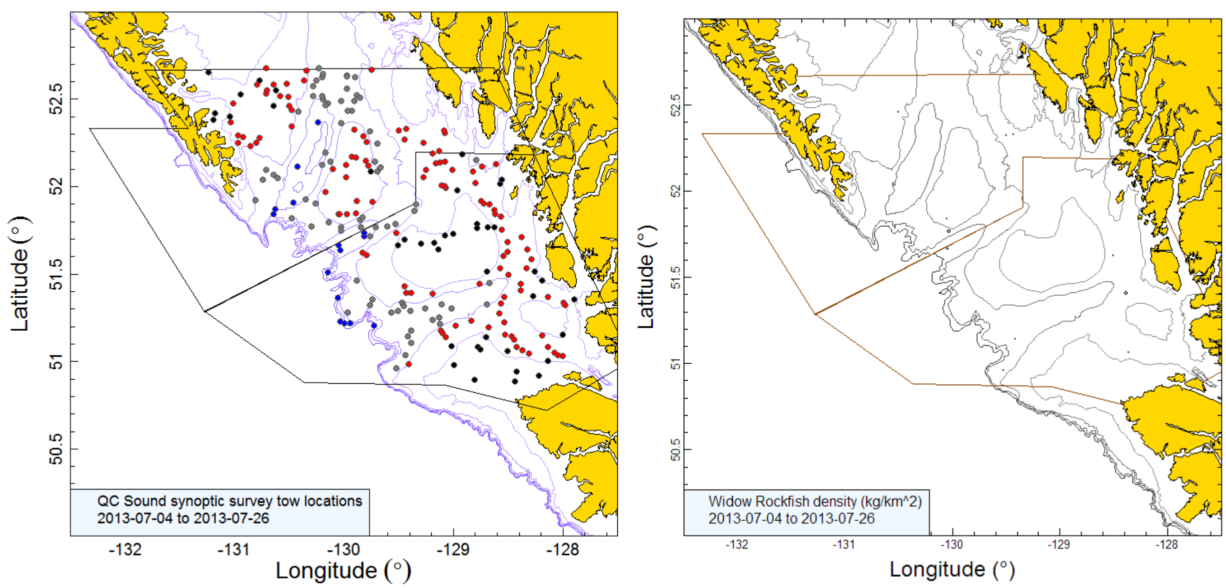

Figure B.28. Tow locations and density plots for the 2013 Queen Charlotte Sound synoptic survey (see Figure B.22 caption).

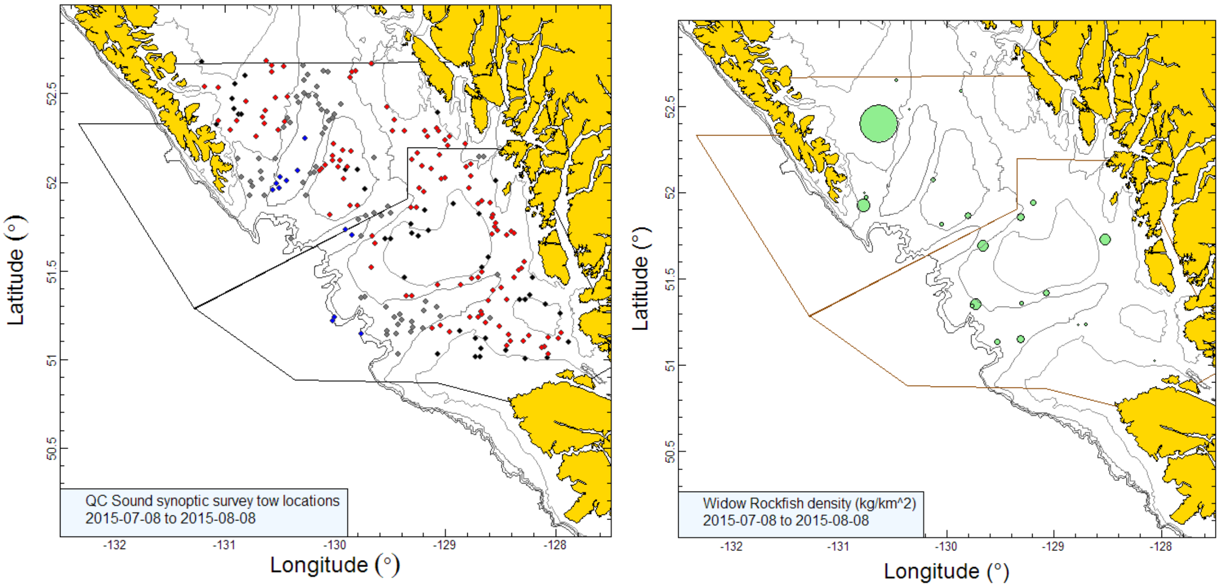

Figure B.29. Tow locations and density plots for the 2015 Queen Charlotte Sound synoptic survey (see Figure B.22 caption).

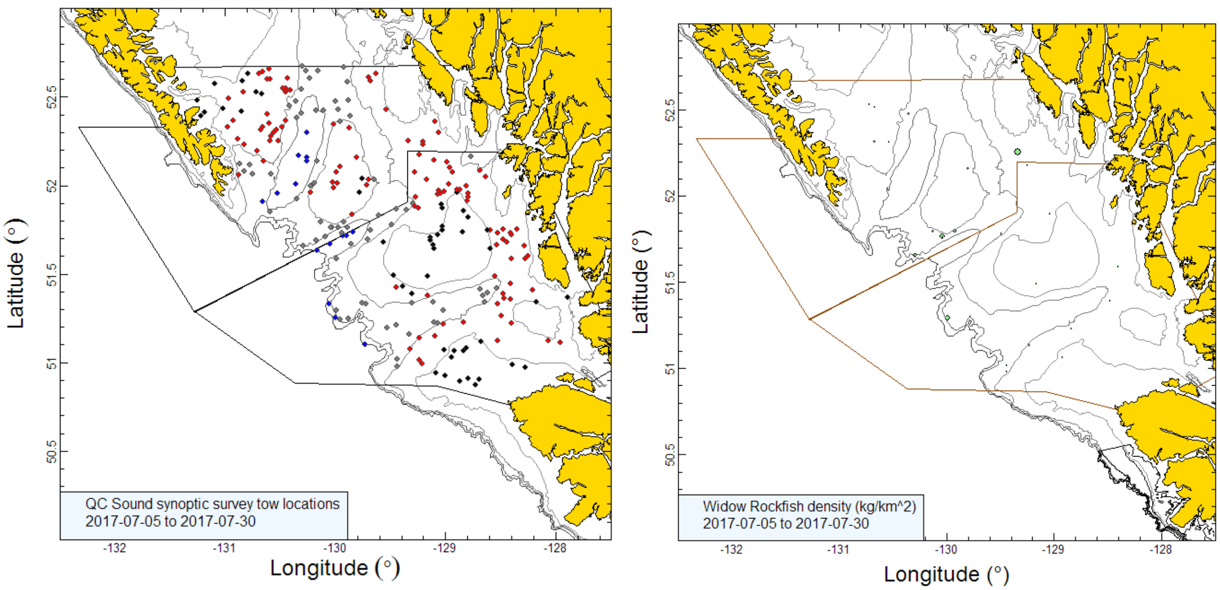

Figure B.30. Tow locations and density plots for the 2017 Queen Charlotte Sound synoptic survey (see Figure B.22 caption).

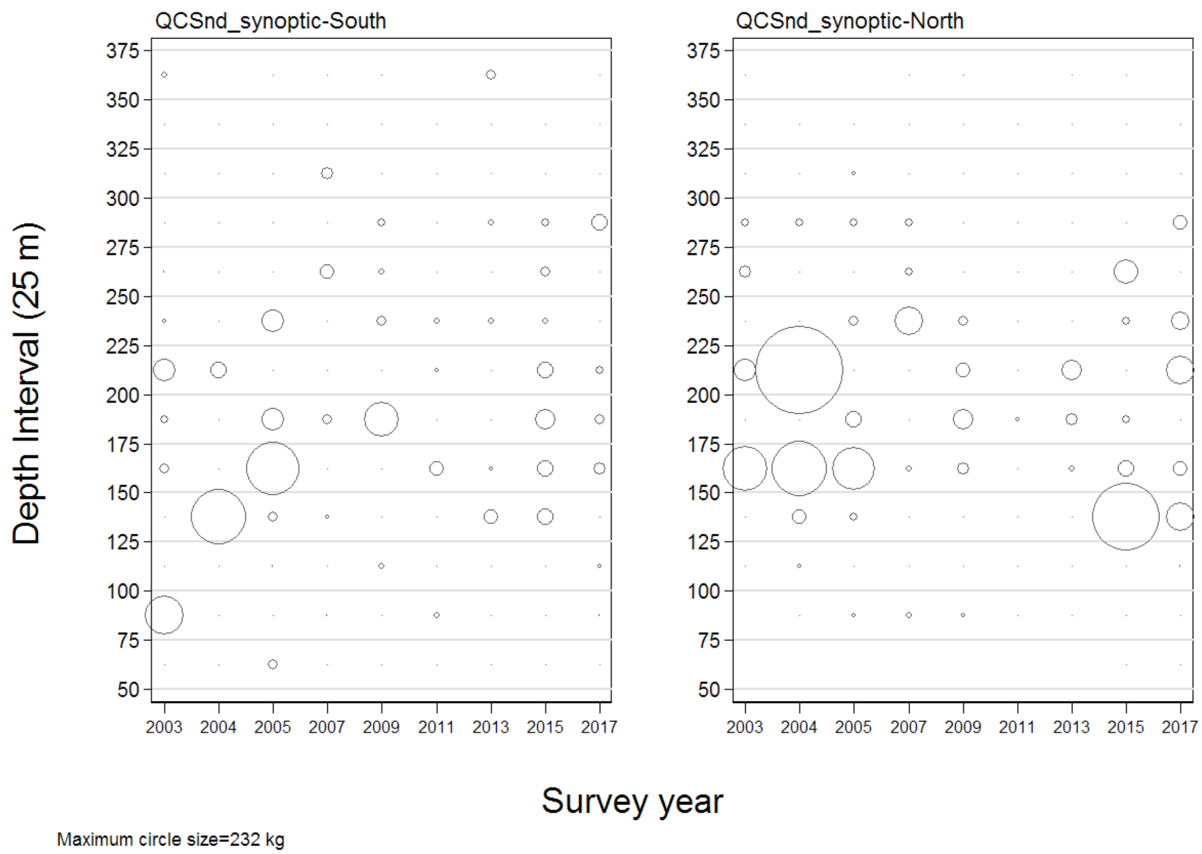

Figure B.31. Distribution of observed catch weights for tows used in biomass estimation for Widow Rockfish in the two main Queen Charlotte Sound synoptic survey areal strata (Table B.10) by survey year and 25 m depth zone. Catches are plotted at the mid-point of the interval and circles in the panel are scaled to the maximum value (232 kg) in the 200–225 m interval in the 2004 northern stratum. The 1% and 99% quantiles for the WWR empirical start of tow depth distribution= 80 m and 286 m respectively.

Estimated WWR doorspread biomass levels from this trawl survey have been variable and low over the nine survey years, varying between 11 t and 359 t (Table B.12; Figure B.32). Estimates below 100 t occurred in 2007–2013 and 2017. The estimated relative errors are high, lying between 32 and 60% (Table B.12). Between 2 and 15% of the South stratum tows and 1 to 12% of the North stratum tows captured some WWR (Figure B.33). Overall, 141 of the 2,144 valid survey tows (7%) contained WWR, with both the North and South strata having average proportion non-zero tows between 6–7%. The median catch weight for positive tows was 2.4 kg/tow across all nine surveys, and the maximum catch weight was 232 kg in the 2004 survey. The incidence of this species is low and sporadic because WWR are mainly found in mid-water while this survey uses bottom trawl gear.

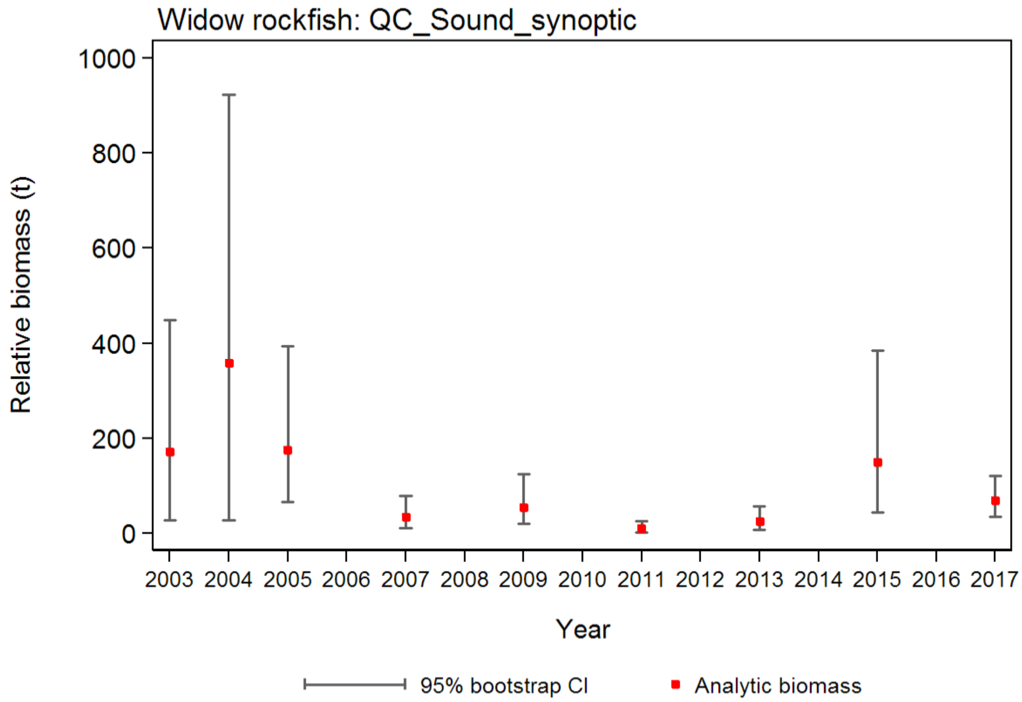

Figure B.32. Plot of biomass estimates for WWR (values provided in Table B.12) from the Queen Charlotte Sound synoptic survey over the period 2003 to 2017. Bias corrected 95% confidence intervals from 1000 bootstrap replicates are plotted.

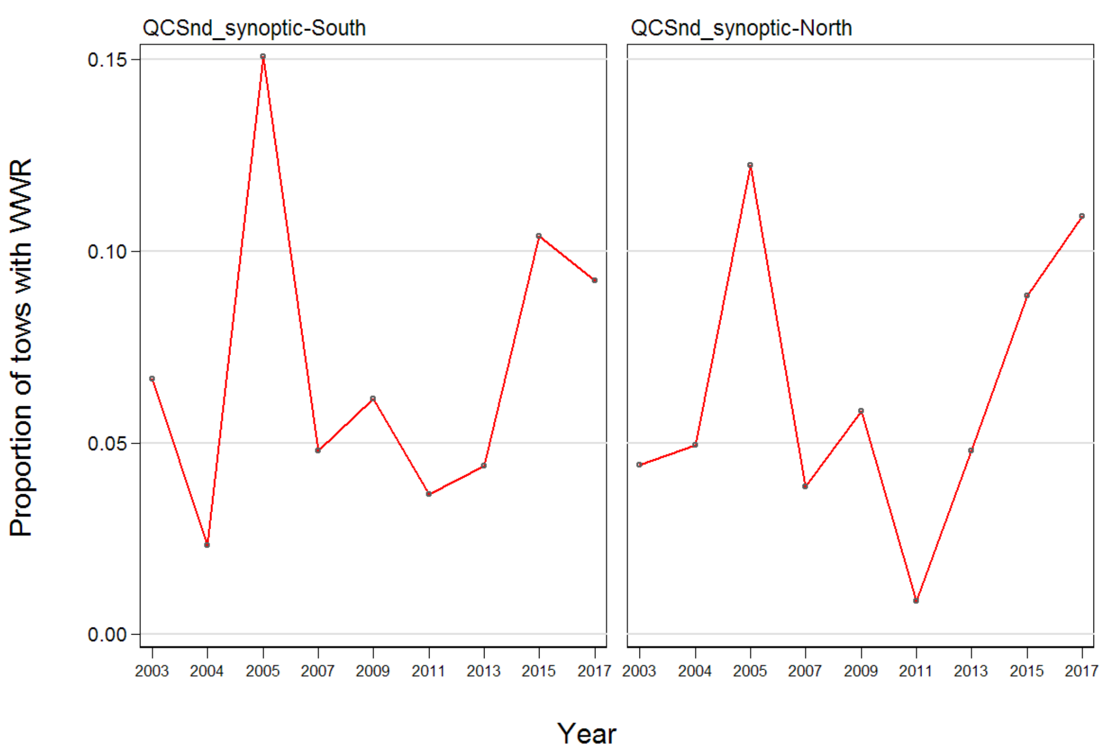

Figure B.33. Proportion of tows by stratum and year which contain WWR from the Queen Charlotte Sound synoptic survey over the period 2003 to 2017.

B.6. WEST COAST VANCOUVER ISLAND SYNOPTIC TRAWL SURVEY

B.6.1. Data Selection

This survey was conducted seven times in the period 2004 to 2016 off the west coast of Vancouver Island by RV *W.E. Ricker*. The eighth survey was conducted in 2018 by RV *Nordic Pearl* due to the decommissioning of the *W.E. Ricker*. The survey comprises a single areal stratum, separated into four depth strata: 50-125 m; 125-200 m; 200-330 m; and 330-500 m (Table B.13). Approximately 150 to 180 2-km^2 blocks are selected randomly among the four depth strata when conducting each survey (Olsen et. al. 2008).

A "doorspread density" value was generated for each tow based on the catch of Widow Rockfish, the mean doorspread for the tow and the distance travelled (Eq. B.3). The distance travelled was provided as a data field, determined directly from vessel track information collected during the tow. There were only two missing values in this field which were filled in by multiplying the vessel speed by the time that the net was towed. There were a large number of missing values for the doorspread field, which were filled in using the mean doorspread for the survey year or a default value of 64.6 m for the three years with no doorspread data (Table B.14). The default value is based on the mean of the observed doorspread from the net mensuration equipment, averaged across the years with doorspread estimates.

Table B.13. Stratum designations, number of usable and unusable tows, for each year of the west coast Vancouver Island synoptic survey. Also shown is the area of each stratum in 2018 and the start and end dates for each survey.

Survey year	Vessel	Stratum depth zone 50-125 m	125-200 m	200-330 m	330-500 m	Total Tows[1]	Unusable tows	Start date	End date
2004	*W.E. Ricker*	34	34	13	8	89	17	26-May-04	09-Jun-04
2006	*W.E. Ricker*	61	62	28	13	164	12	24-May-06	18-Jun-06
2008	*W.E. Ricker*	54	50	32	23	159	19	27-May-08	21-Jun-08
2010	*W.E. Ricker*	58	47	22	9	136	8	08-Jun-10	28-Jun-10
2012	*W.E. Ricker*	61	46	26	20	153	4	23-May-12	15-Jun-12
2014	*W.E. Ricker*	55	49	29	14	147	6	29-May-14	20-Jun-14
2016	*W.E. Ricker*	54	41	26	19	140	7	25-May-16	15-Jun-16
2018	*Nordic Pearl*	69	64	36	21	190	12	19-May-18	12-Jun-18
Area (km^2)		5,716	3,768	708	572	10,764[2]	–	–	–

[1] GFBio usability codes=0,1,2,6
[2] Total area (km^2) for 2018 synoptic survey

Table B.14. Number of tows with and without doorspread measurements by survey year for the WCVI synoptic survey. Mean doorspread values for those tows with measurements are provided.

Survey Year	Number tows: Without doorspread	With doorspread	Mean doorspread (m)
2004	89	0	–
2006	96	69	64.3
2008	58	107	64.5
2010	136	0	–
2012	153	0	–
2014	14	139	64.3
2016	0	147	65.5
2018	0	202	64.3
All surveys	546	664	64.6

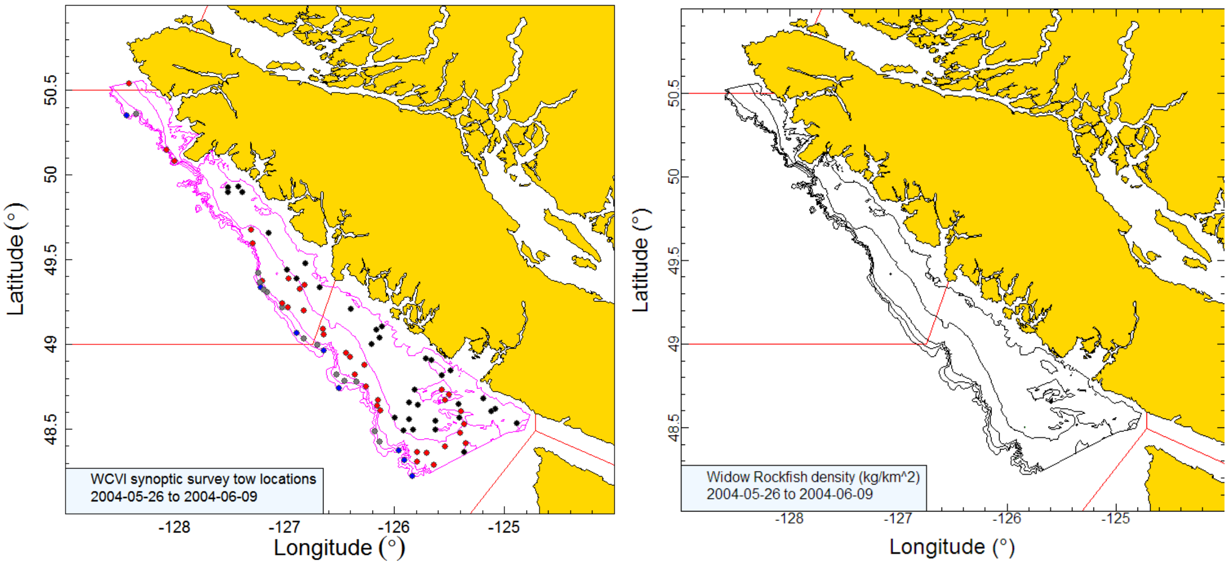

Figure B.34. Valid tow locations (50-125m stratum: black; 126-200m stratum: red; 201-330m stratum: grey; 331-500m stratum: blue) and density plots for the 2004 west coast Vancouver Island synoptic survey. Circle sizes in the right-hand density plot scaled across all years (2004, 2006, 2008, 2010, 2012, 2014, 2016, 2018), with the largest circle = 17,282 kg/km^2 in 2010. The red solid lines indicate the boundaries for PMFC areas 3C, 3D and 5A.

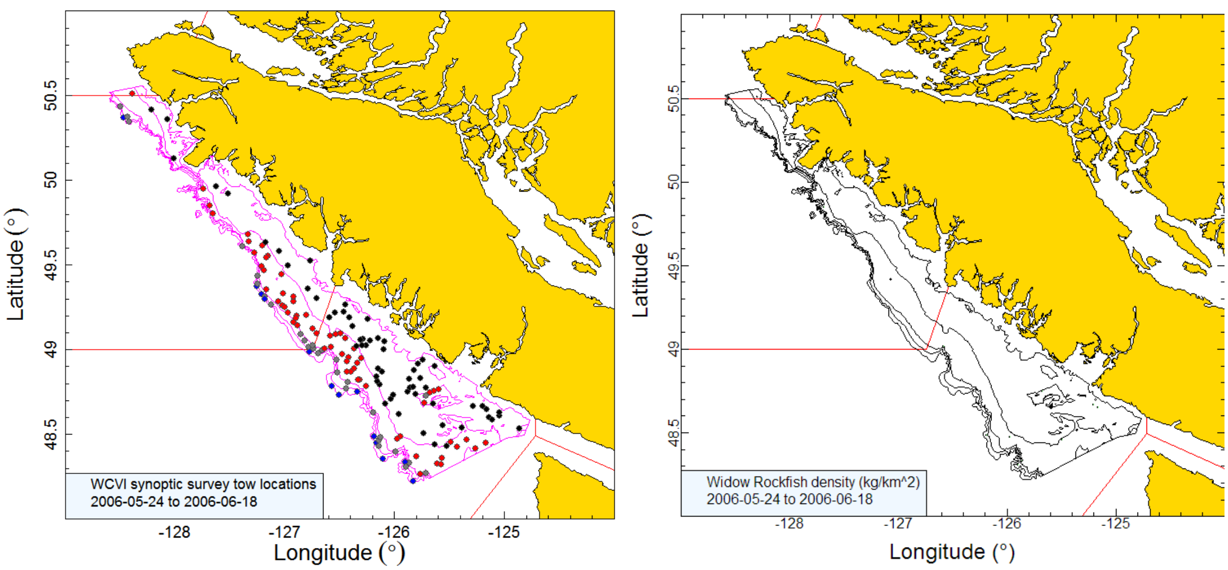

Figure B.35. Tow locations and density plots for the 2006 west coast Vancouver Island synoptic survey (see Figure B.34 caption).

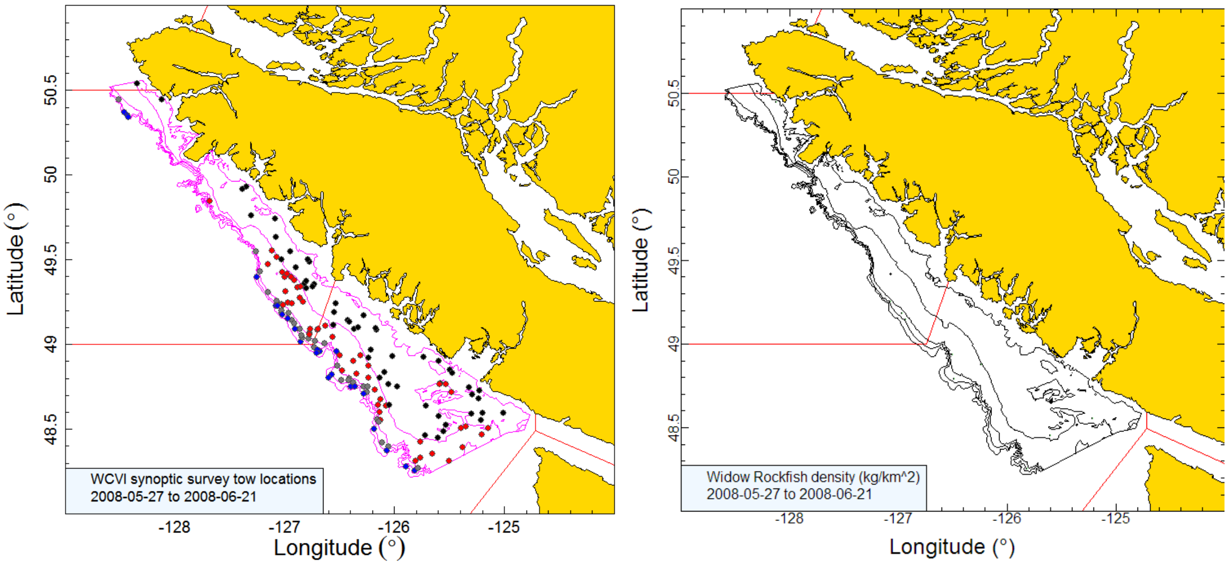

Figure B.36. Tow locations and density plots for the 2008 west coast Vancouver Island synoptic survey (see Figure B.34 caption).

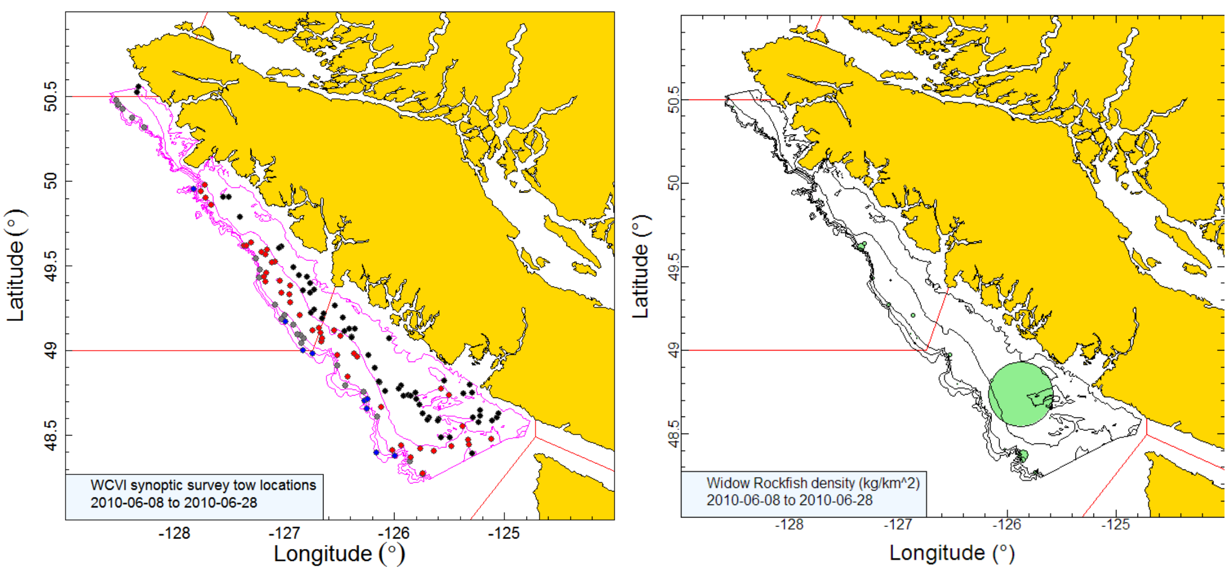

Figure B.37. Tow locations and density plots for the 2010 west coast Vancouver Island synoptic survey (see Figure B.34 caption).

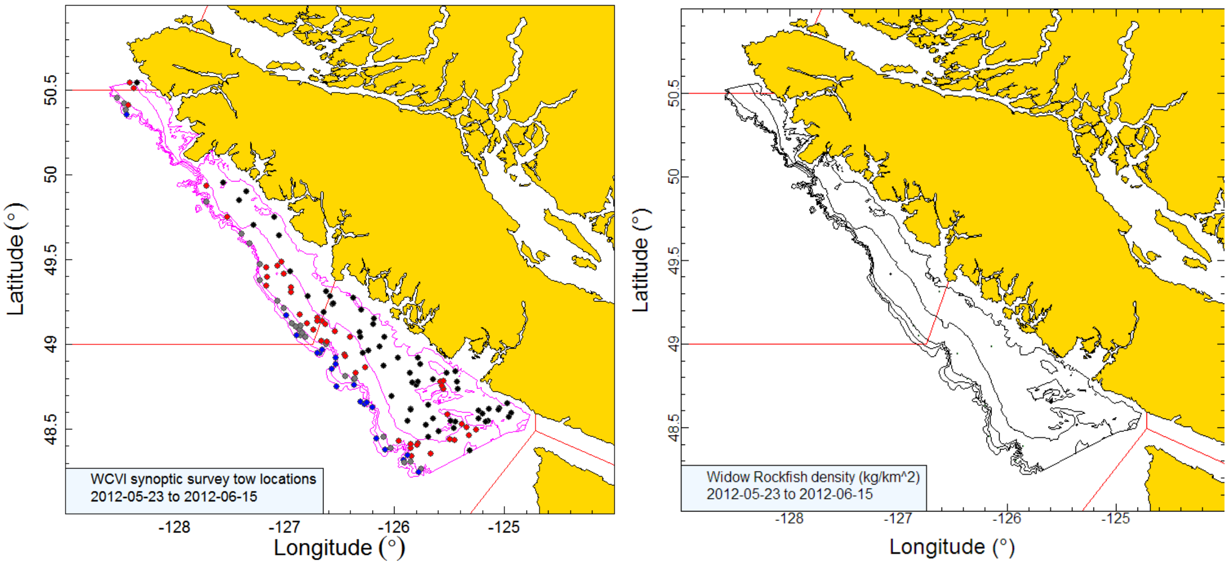

Figure B.38. Tow locations and density plots for the 2012 west coast Vancouver Island synoptic survey (see Figure B.34 caption).

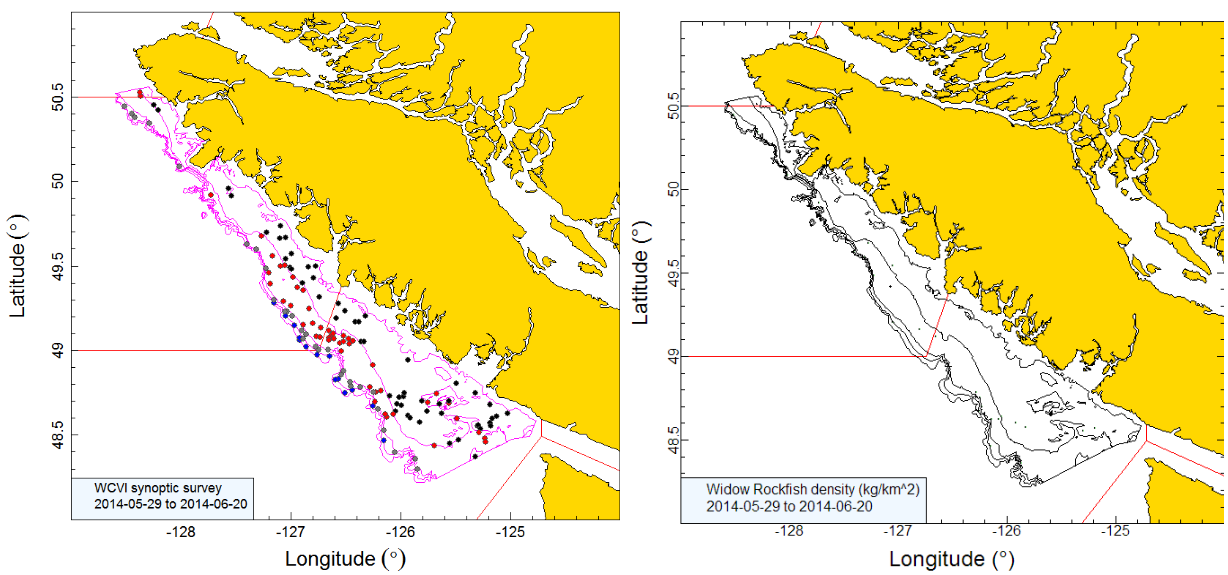

Figure B.39. Tow locations and density plots for the 2014 west coast Vancouver Island synoptic survey (see Figure B.34 caption).

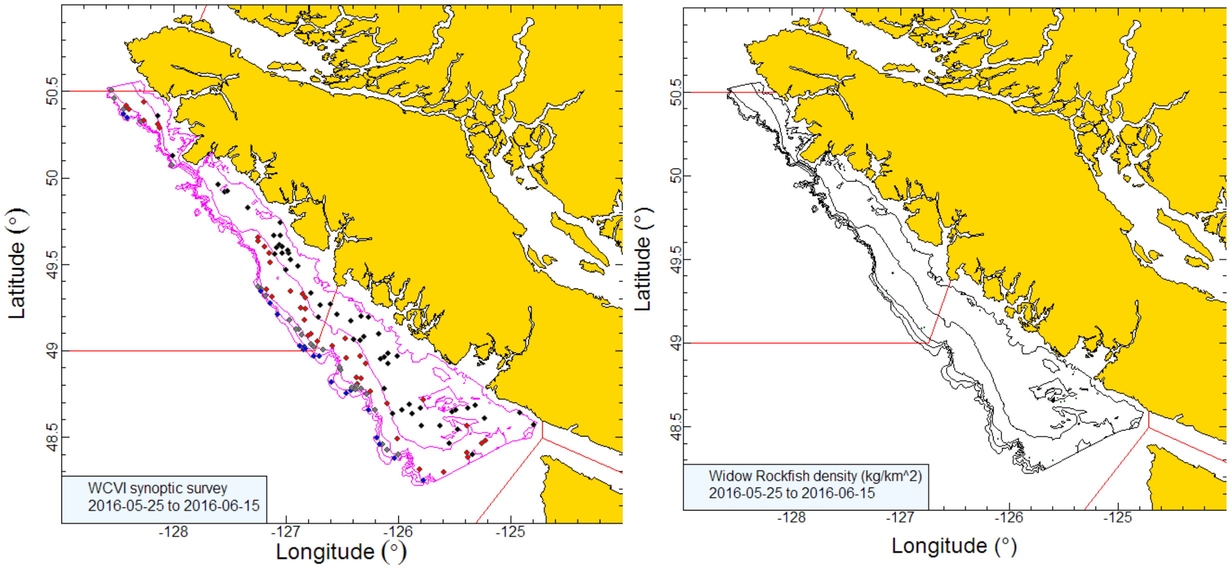

Figure B.40. Tow locations and density plots for the 2016 west coast Vancouver Island synoptic survey (see Figure B.34 caption).

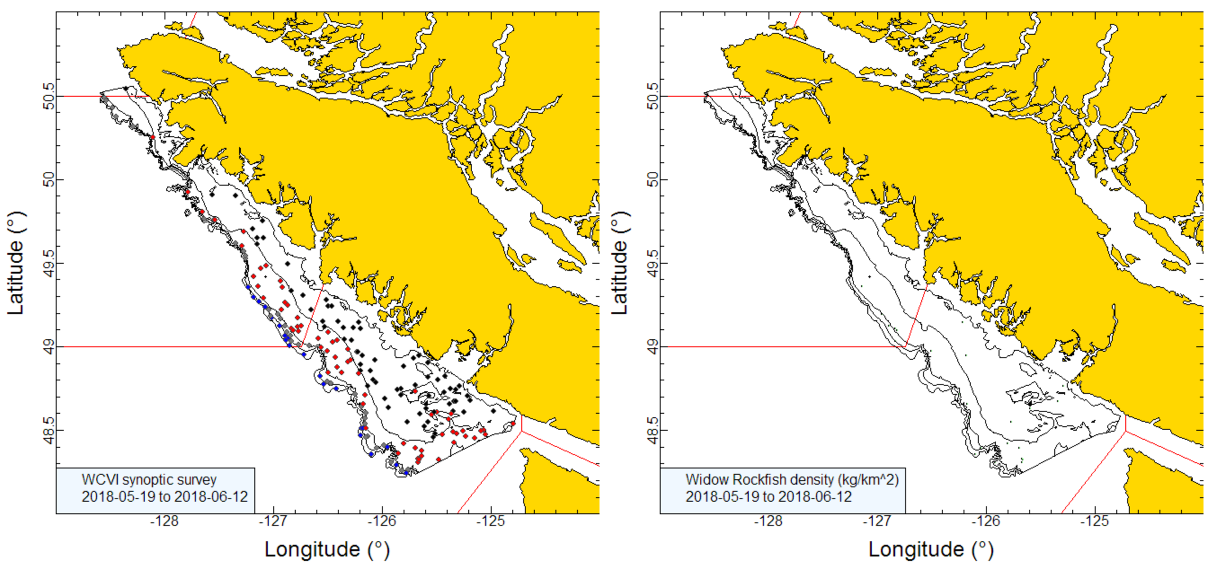

Figure B.41. Tow locations and density plots for the 2018 west coast Vancouver Island synoptic survey (see Figure B.34 caption).

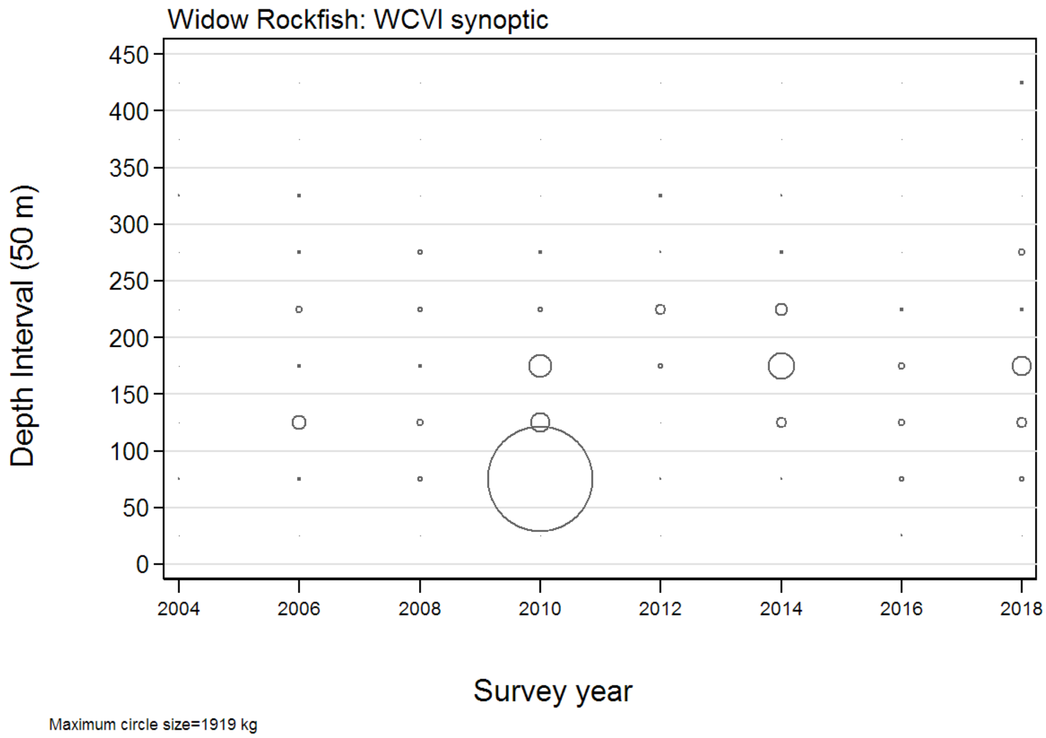

Figure B.42. Distribution of observed weights of Widow Rockfish by survey year and 50 m depth zone. Catches are plotted at the mid-point of the interval and circles in the panel are scaled to the maximum value (1919 kg) in the 50-100 m interval in 2010. The 1% and 99% quantiles for the WWR empirical start of tow depth distribution (for tows used in biomass estimation): 65 m and 254 m respectively. One very deep (988 m) tow of 2 kg WWR has been omitted from this plot.

B.6.2. Results

As seen in the NMFS Triennial survey (which covered the lower half of Vancouver Island, see Section B.4), WWR are caught rarely and sporadically by bottom trawl gear on the west coast of Vancouver Island (Figure B.34 to Figure B.39). There does not seem to be any region that predominates in the spatial distribution, with WWR taken only occasionally. Unfortunately, the output from the survey is dominated by a single tow that captured nearly 2,000 kg of WWR in 2010. The next largest catch is 83 kg and the median catch of WWR for positive tows over the eight survey years is less than 2 kg. The midwater schooling behaviour of this species results in occasional large catches as observed here.

Overall, WWR were mainly taken at depths from 67 to 320 m (5–95% quantiles for all positive tows) and there were only four observations at depths greater than 320 m, including one at 988 m (Figure B.42). Estimated biomass levels for Widow Rockfish from this trawl survey show a very large biomass of 1,800 t in 2010 associated with an enormous relative error of 0.91, but the biomass estimates for the other 7 survey years are all less than 100 t (Figure B.43; Table B.15), with no apparent trend over the survey period. Relative errors were high, ranging from 0.37 to 0.91 across the eight surveys (Figure B.43; Table B.15).

The proportion of tows capturing Widow Rockfish ranged between 2 and 18% for the eight surveys, with a mean value of 11% (Figure B.44). One hundred twenty-four of the 1175 usable tows from this survey contained WWR, with a median catch weight for positive tows of 1.8 kg/tow and maximum catch weight across all eight surveys of 1,919 kg (in 2010).

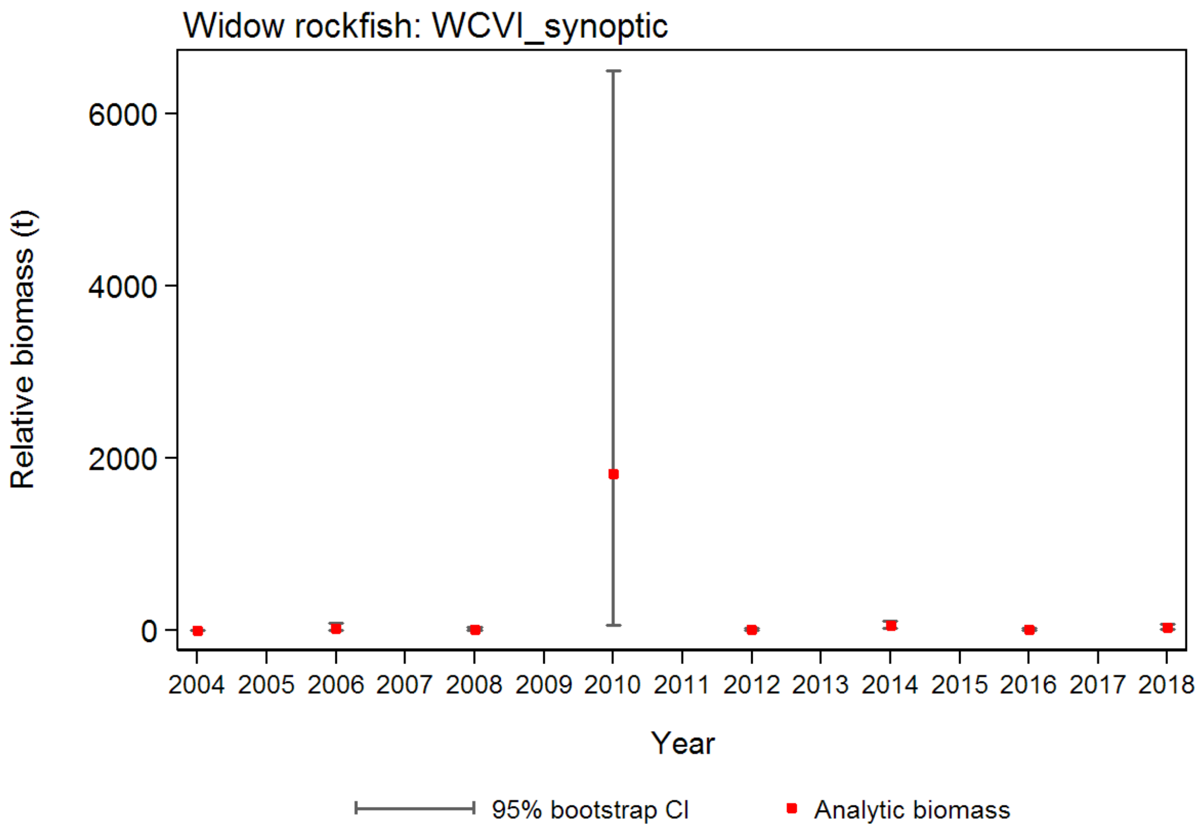

Figure B.43. Plot of biomass estimates for Widow Rockfish from the 2004 to 2018 west coast Vancouver Island synoptic trawl surveys (Table B.15). Bias-corrected 95% confidence intervals from 1000 bootstrap replicates are plotted.

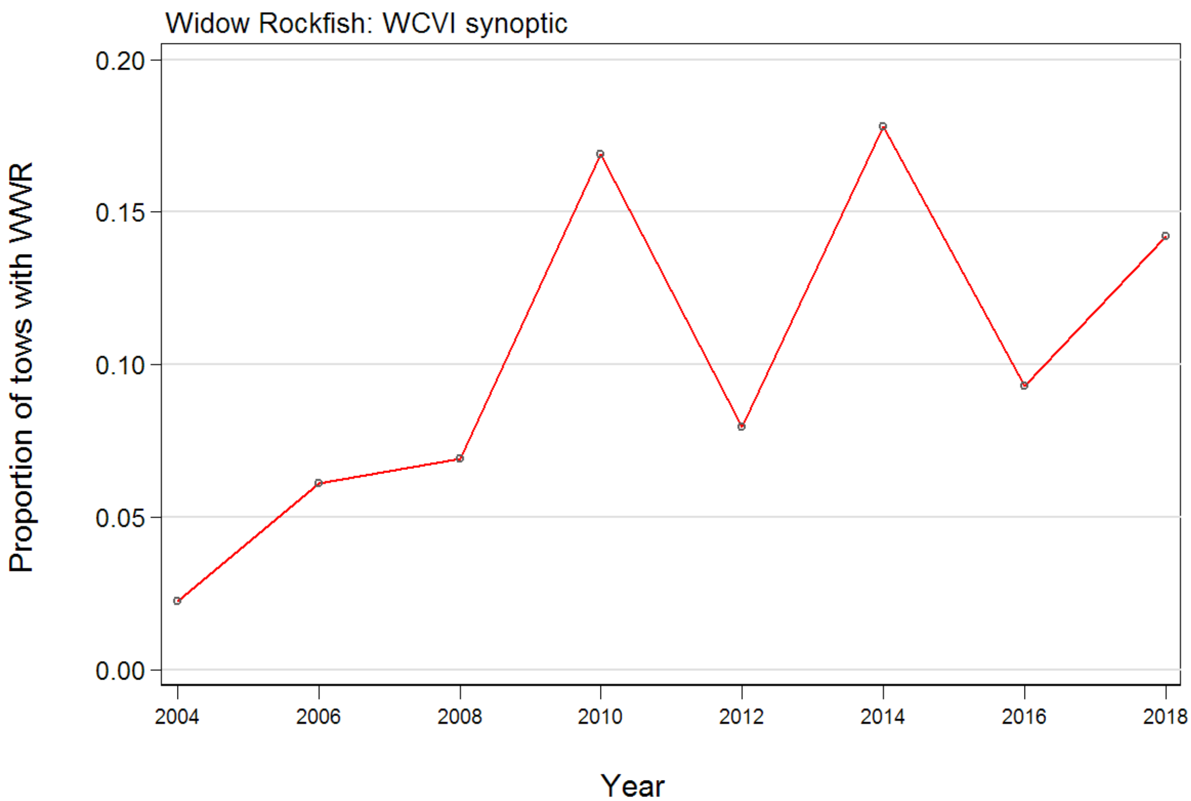

Figure B.44. Proportion of tows by stratum and year capturing Widow Rockfish in the WCVI synoptic trawl surveys, 2004–2018.

Table B.15. Biomass estimates for Widow Rockfish from the WCVI synoptic trawl survey for the survey years 2004 to 2018. Bootstrap bias-corrected confidence intervals and CVs are based on 1000 random draws with replacement.

Survey Year	Biomass (t) (Eq. B.4)	Mean bootstrap biomass (t)	Lower bound biomass (t)	Upper bound biomass (t)	Bootstrap CV	Analytic CV (Eq. B.6)
2004	1.0	1.0	0.0	2.9	0.714	0.707
2006	26.4	26.5	3.9	83.3	0.725	0.723
2008	14.8	14.7	3.5	36.8	0.559	0.551
2010	1,816.2	1,881.6	60.6	6,499.7	0.906	0.938
2012	9.9	9.9	2.4	23.4	0.552	0.554
2014	58.0	57.5	26.6	115.8	0.369	0.372
2016	16.6	16.8	6.5	31.4	0.372	0.363
2018	35.4	35.7	15.1	74.2	0.392	0.386

B.7. WEST COAST HAIDA GWAII SYNOPTIC TRAWL SURVEY

B.7.1. Data Selection

The west coast Haida Gwaii (WCHG) survey has been conducted eight times in the period 2006 to 2018 off the west coast of Haida Gwaii. This includes a survey conducted in 2014 which did not complete a sufficient number of tows for it to be considered completed and which is consequently omitted from Table B.16. An earlier survey, conducted in 1997, also using a random stratified design similar to the current synoptic survey design along with an Atlantic Western II box trawl net (Workman et al. 1998), has also been included in this time series. Both surveys comprise a single areal stratum extending from 53°N to the BC-Alaska border and east to 133°W (e.g., Olsen et al. 2008). The 1997 survey (depth stratification: 180-275 m, 275-365 m, 365-460 m, 460-625 m) and the 2006 survey (depth stratification: 150–200 m, 200–330 m, 330–500 m, 500–800 m, and 800–1300 m) have been re-stratified into the four depth strata used from 2007 onwards: 180–330 m; 330–500 m; 500–800 m; and 800–1300 m, based on the mean of the beginning and end depths of each tow (Table B.16). All tows S of 53°N from the two earliest surveys have been dropped from biomass estimation. Plots of the locations of all valid tows by year and stratum are presented in Figure B.45 (1997), Figure B.46 (2006), Figure B.47 (2007), Figure B.48 (2008), Figure B.49 (2010), Figure B.50 (2012), Figure B.51 (2016) and Figure B.52 (2018). Note that the depth stratum boundaries for this survey differ from those used for the Queen Charlotte Sound (Edwards et al., 2012) and west coast Vancouver Island (Edwards et al., 2014) synoptic surveys due to the considerable difference in the seabed topography of the area being surveyed. The deepest stratum (800–1300 m) has been omitted from this analysis because of lack of coverage in 2007.

Table B.16. Stratum designations, vessel name, number of usable and unusable tows, for each completed year of the west coast Haida Gwaii synoptic survey. Also shown are the dates of the first and last survey tow in each year.

		Depth stratum							
Survey year	**Vessel**	**180-330m**	**330-500m**	**500-800m**	**800-1300m**	**Total tows[1]**	**Unusable tows**	**Minimum date**	**Maximum date**
1997	*Ocean Selector*	39	57	6	0	90	5	07-Sep-97	21-Sep-97
2006	*Viking Storm*	55	26	16	13	97	13[2]	30-Aug-06	22-Sep-06
2007	*Nemesis*	68	34	9	0	111	5	14-Sep-07	12-Oct-07
2008	*Frosti*	71	31	8	8	110	9	28-Aug-08	18-Sep-08
2010	*Viking Storm*	82	29	12	6	123	2	28-Aug-10	16-Sep-10
2012	*Nordic Pearl*	75	29	10	16	114	11	27-Aug-12	16-Sep-12
2016	*Frosti*	69	28	5	10	101	8	28-Aug-16	24-Sep-16
2018	*Nordic Pearl*	67	31	10	11	108	11	05-Sep-18	20-Sep-18
Area (km^2)		1104	1024	956	2248	5332 [3]	–	–	–

[1] GFBio usability codes=0,1,2,6 and omitting the 800-1300 m stratum; [2] excludes 2 tows S of 53°N; [3] Total area in 2018 (km^2)

A doorspread density (Eq. B.3) was generated for each tow based on the catch of Widow Rockfish (WWR) from the mean doorspread for the tow and the distance travelled. [`distance travelled`] is a database field which is calculated directly from the tow track. This field is used preferentially for the variable D_{yij} in Eq. B.3. A calculated value ([`vessel speed`] X [`tow duration`]) is used for this variable if [`distance travelled`] is missing, but there were no instances of this occurring in the eight trawl surveys. Missing values for the [`doorspread`] field were filled in with the mean doorspread for the survey year (103 values over all years, Table B.17).

Table B.17. Number of valid tows with doorspread measurements, the mean doorspread values (in m) from these tows for each survey year and the number of valid tows without doorspread measurements.

Year	Tows with doorspread	Tows missing doorspread	Mean doorspread (m)
1997	107	0	61.6
2006	93	30	77.7
2007	113	3	68.5
2008	123	4	80.7
2010	129	2	79.1
2012	92	49	73.8
2016	105	15	74.1
2018	130	0	67.0
Total/Average	995	103	73.1[1]

[1] average 2006–2018: all observations

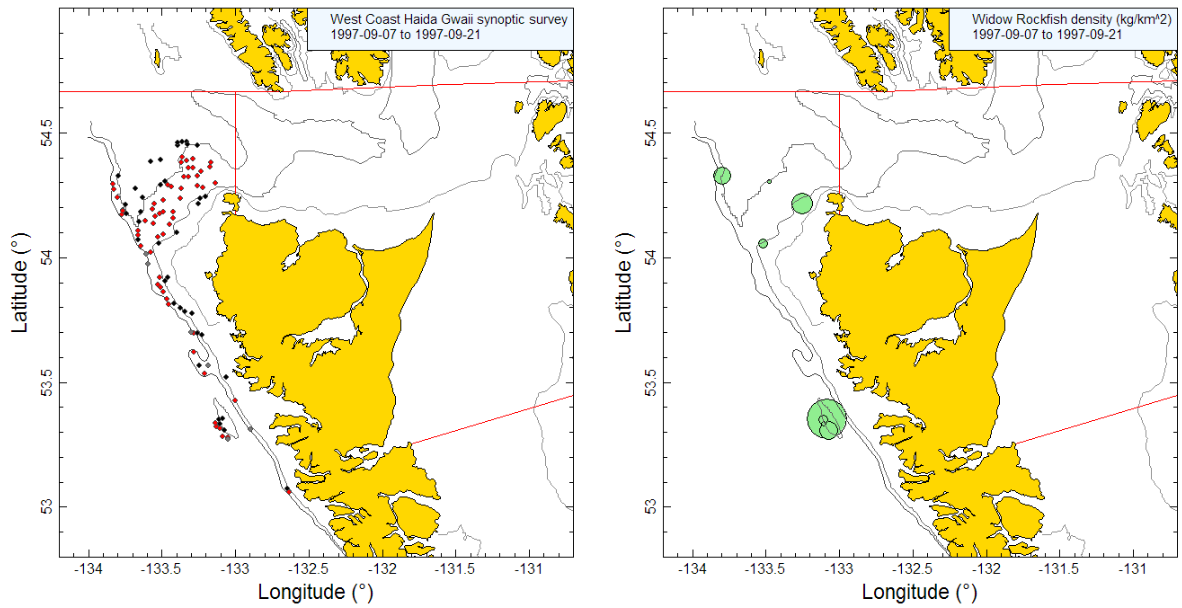

Figure B.45. Valid tow locations by stratum (180-330m: black; 330-500m: red; 500-800m: grey; 800-1300m: blue) and density plots for the 1997 Ocean Selector synoptic survey. Circle sizes in the right-hand density plot scaled across all years (1997, 2006–2018), with the largest circle =3098 kg/km² in 2012. The red lines show the Pacific Marine Fisheries Commission 5E and 5D major area boundaries.

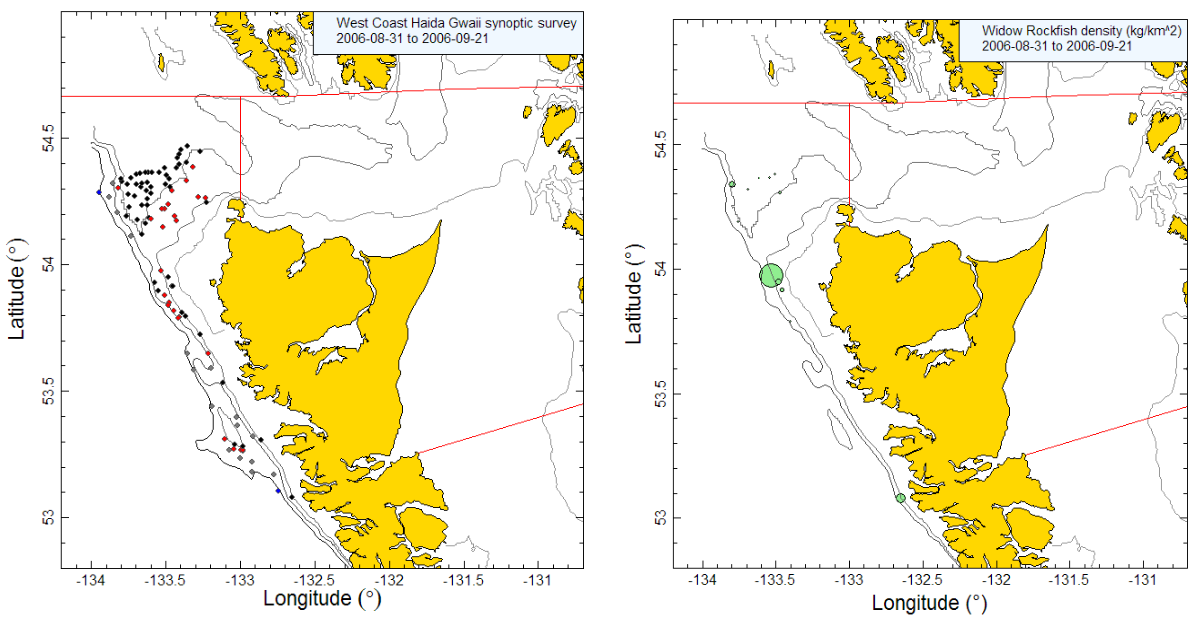

Figure B.46. Tow locations and density plots for the 2006 Viking Storm synoptic survey (see Figure B.45 caption).

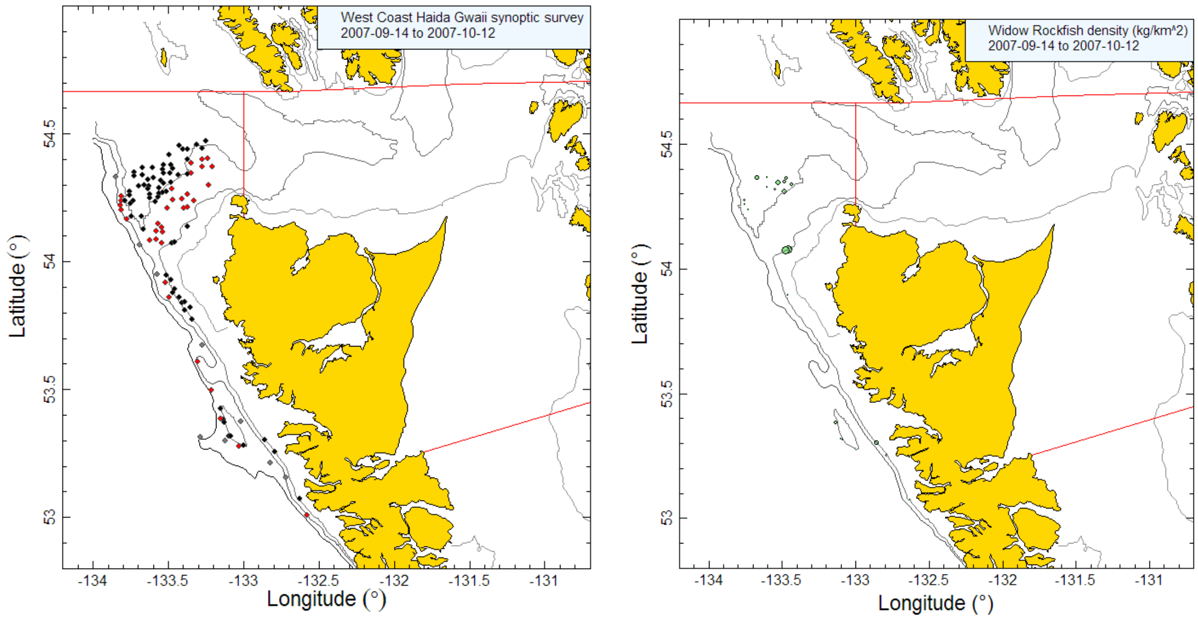

Figure B.47. Tow locations and density plots for the 2007 Nemesis synoptic survey (see Figure B.45 caption).

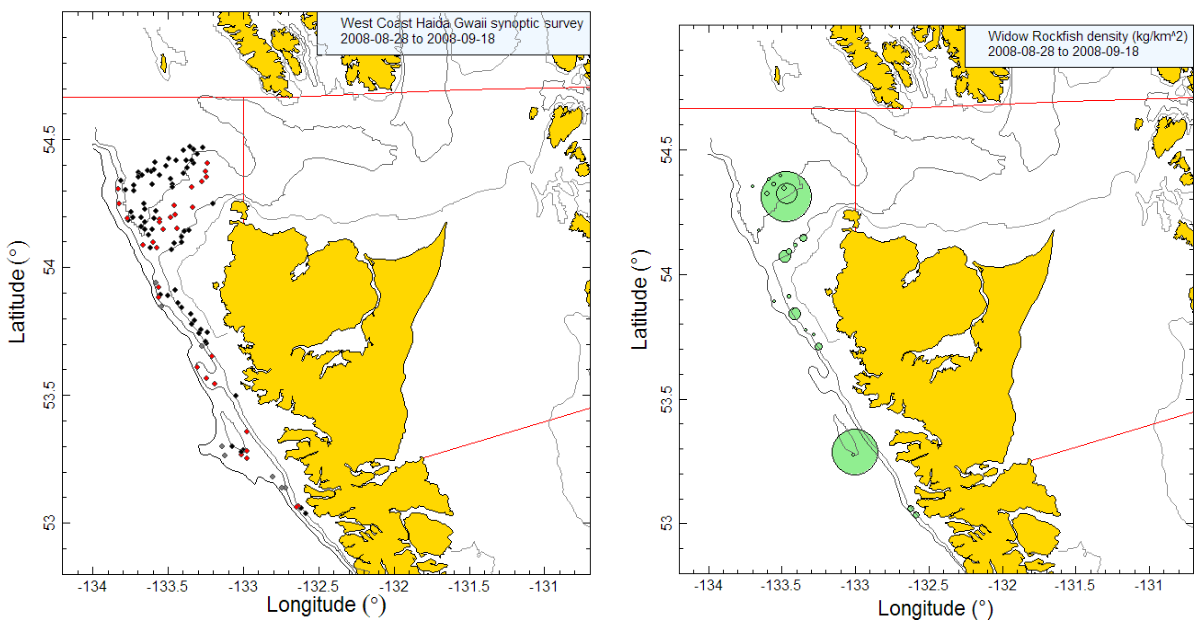

Figure B.48. Tow locations and density plots for the 2008 Frosti synoptic survey (see Figure B.45 caption).

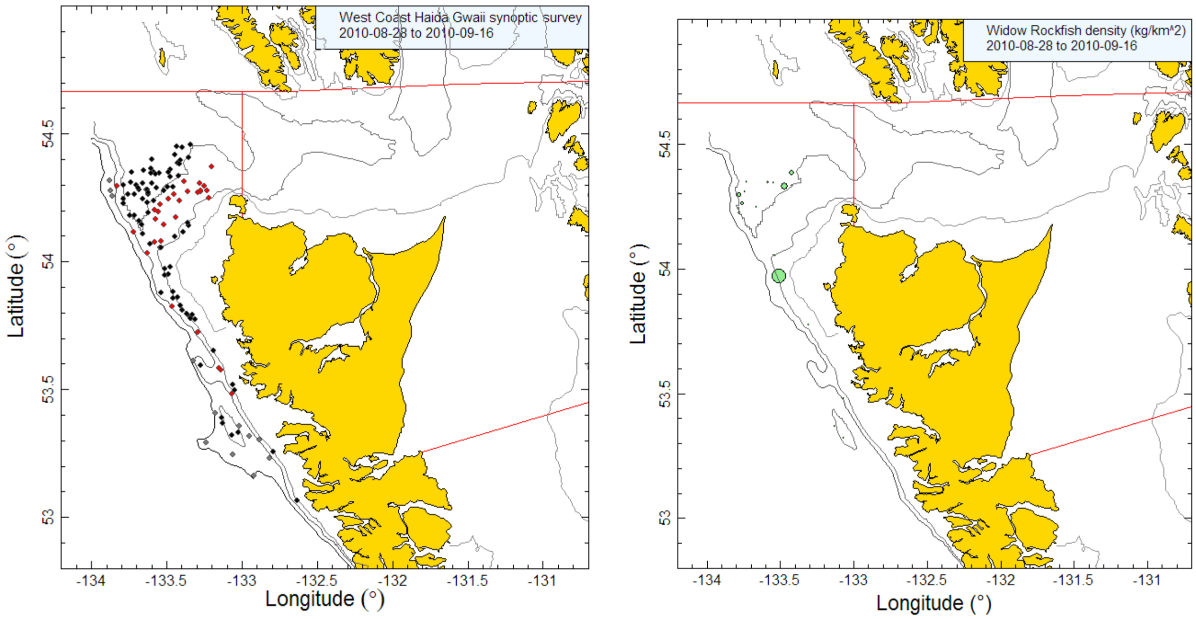

Figure B.49. Tow locations and density plots for the 2010 Viking Storm synoptic survey (see Figure B.45 caption).

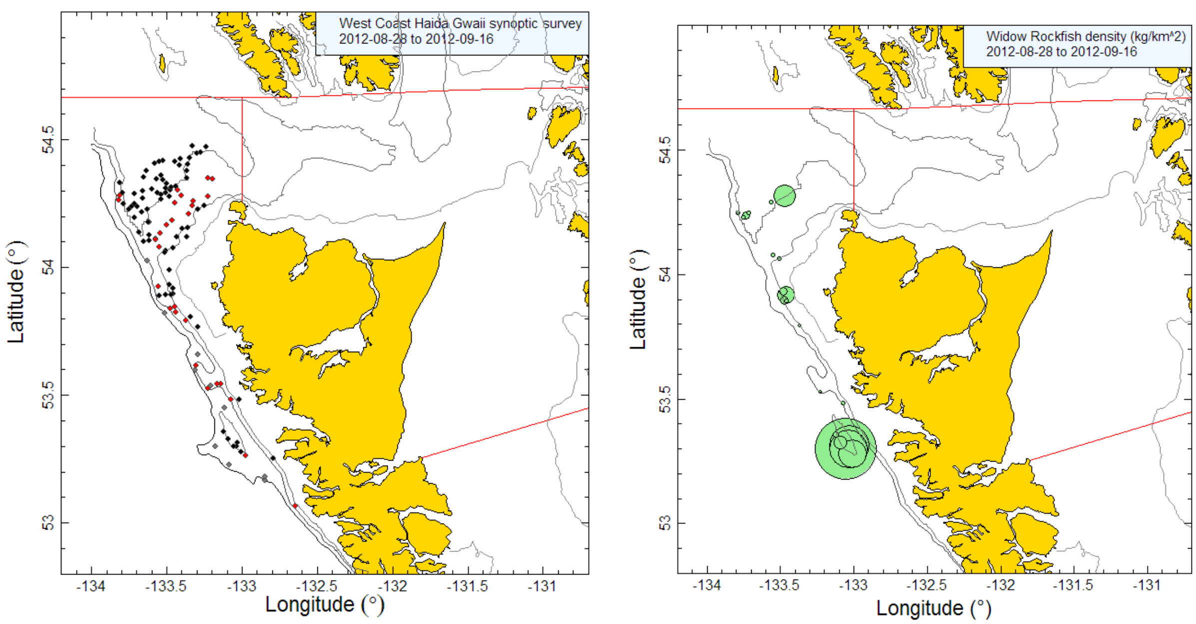

Figure B.50. Tow locations and density plots for the 2012 Nordic Pearl synoptic survey (see Figure B.45 caption).

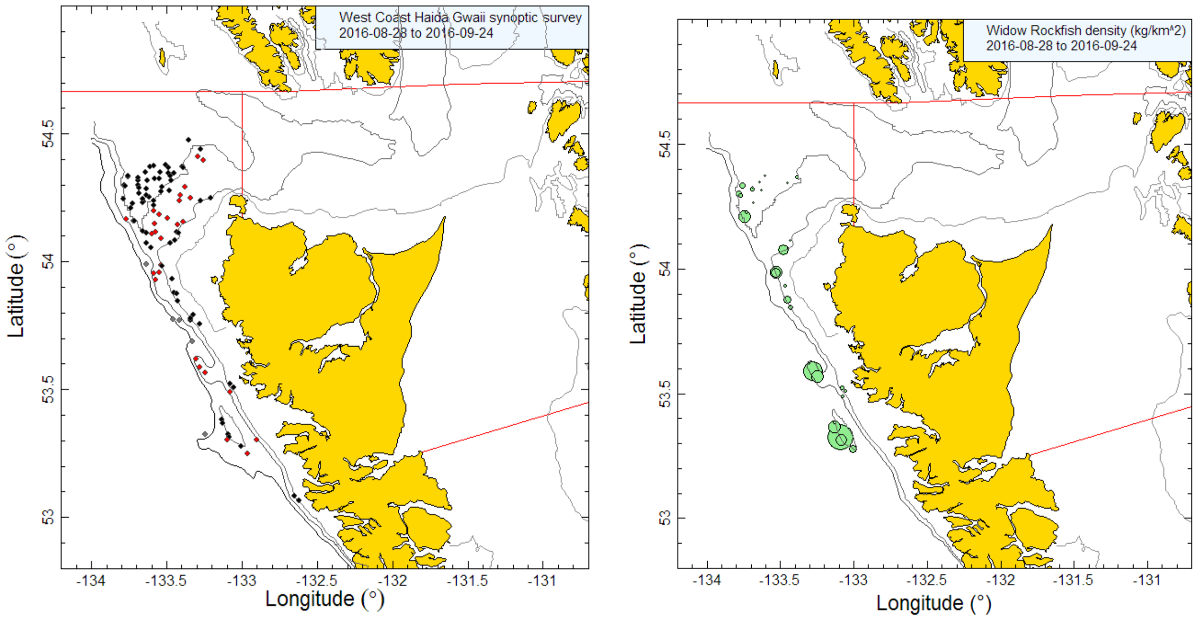

Figure B.51. Tow locations and density plots for the 2016 Frosti synoptic survey (see Figure B.45 caption).

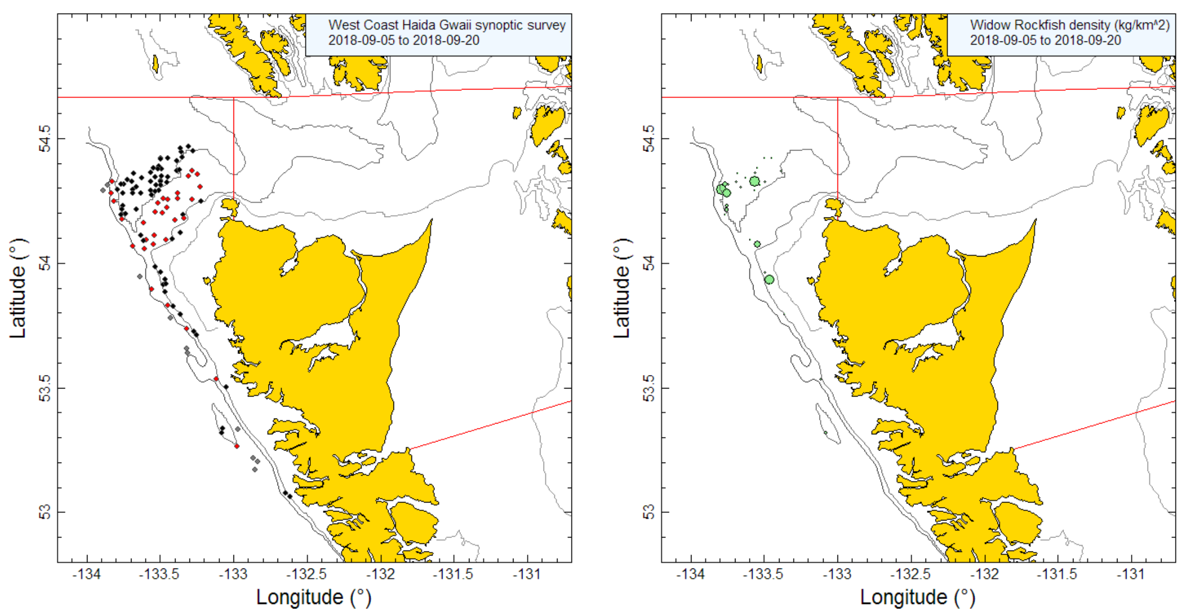

Figure B.52. Tow locations and density plots for the 2018 Nordic Pearl synoptic survey (see Figure B.45 caption).

B.7.2. Results

All eight usable surveys have taken Widow Rockfish in the western part of Dixon Entrance and off the west coast of Graham Island, down to about Rennell Sound (Figure B.45 to Figure B.52), although there are occasional observations of WWR right down to 53°N, the southernmost extent of this survey. Widow Rockfish were mainly taken at depths from 207 to 278 m (5 to 95% quantiles), with the majority of the observations lying between 221 and 254 m depth (25–75% quantiles, Figure B.53).

Table B.18. Biomass estimates for Widow Rockfish from the eight west coast Haida Gwaii synoptic surveys. Bootstrap bias-corrected confidence intervals and coefficients of variation (CVs) are based on 1000 random draws with replacement.

Survey Year	Biomass (t) (Eq. B.4)	Mean bootstrap biomass (t)	Lower bound biomass (t)	Upper bound biomass (t)	Bootstrap CV	Analytic CV (Eq. B.6)
1997	109.0	108.2	25.7	291.8	0.574	0.565
2006	35.4	34.6	5.9	93.4	0.658	0.688
2007	31.6	31.5	15.9	55.2	0.313	0.314
2008	90.2	91.0	15.1	228.8	0.562	0.561
2010	18.6	19.1	5.8	47.5	0.545	0.539
2012	107.2	106.3	28.2	231.1	0.481	0.477
2016	103.1	99.4	48.7	198.3	0.364	0.363
2018	50.5	50.9	21.1	88.5	0.331	0.334

Estimated biomass levels for WWR from these trawl surveys show no trend with very wide error bars (ranging from 19 t in 2010 to 109 t in 1997) (Figure B.54; Table B.18). The estimated relative errors (RE) for these surveys were slightly lower compared to other WWR surveys, ranging from 31 to 66%, but were still very large for use as indices of biomass (Table B.18).

The proportion of tows that captured Widow Rockfish ranged from 8 to 33% of tows over the eight survey years, with an overall mean of 19% (Figure B.55). The median WWR catch weight for positive tows was 4.1 kg/tow and the maximum catch weight across all eight surveys was 488 kg (in 2012).

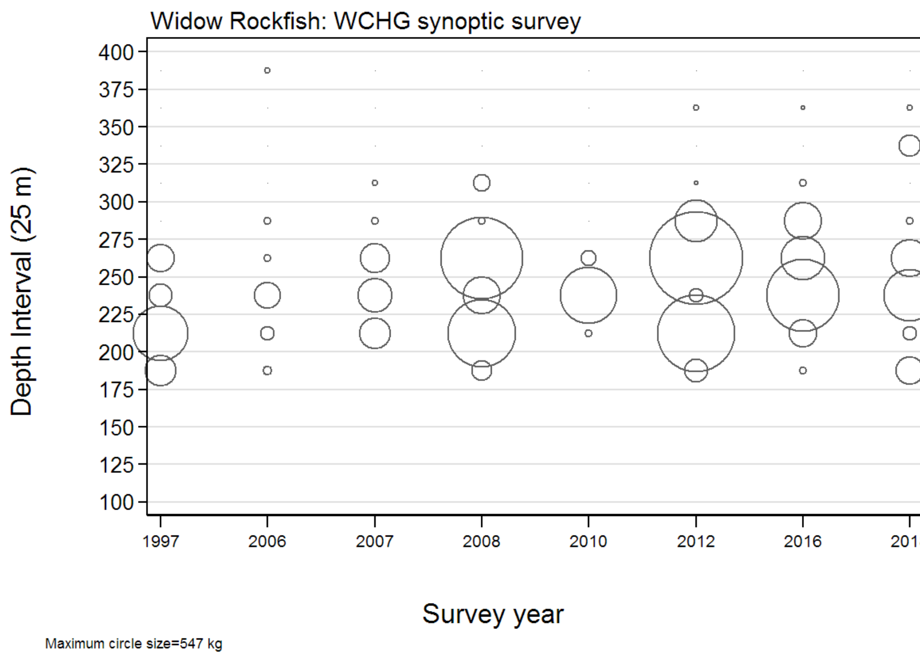

Figure B.53. Distribution of observed weights of Widow Rockfish by survey year and 25 m depth zone intervals. Catches are plotted at the mid-point of the interval and circles in the each panel are scaled to the maximum value (547 kg – 250-275 m interval in 2012). Minimum and maximum depths observed for WWR: 188 m and 376 m, respectively.

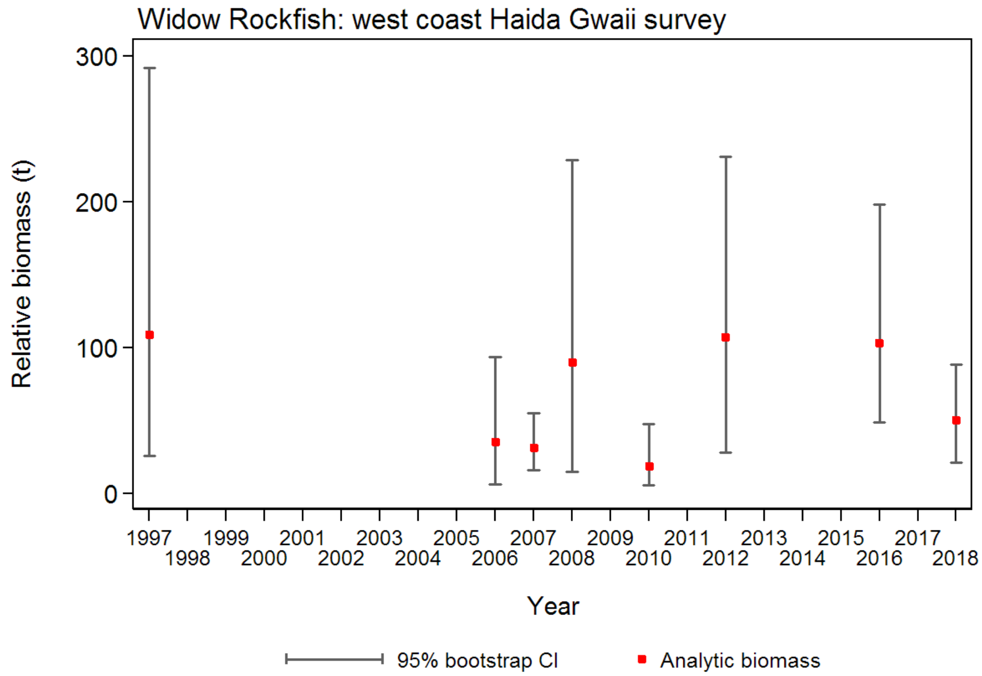

Figure B.54. Biomass estimates for Widow Rockfish from the 2006 to 2018 west coast Haida Gwaii synoptic surveys (Table B.18). Bias-corrected 95% confidence intervals from 1000 bootstrap replicates are plotted.

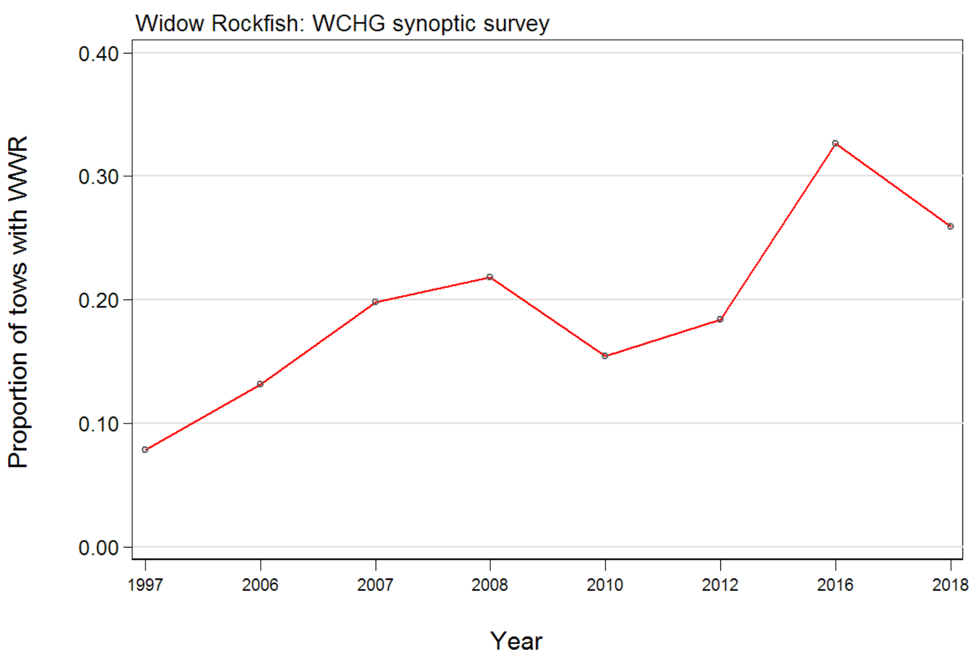

Figure B.55. Proportion of tows by year that contain Widow Rockfish for the eight west coast Haida Gwaii synoptic surveys.

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APPENDIX C. COMMERCIAL TRAWL CPUE

C.1. INTRODUCTION

Commercial catch and effort data have been used to generate indices of abundance in several ways. The simplest indices are derived from the arithmetic mean or geometric mean of catch divided by an appropriate measure of effort (Catch Per Unit Effort or CPUE) but such indices make no adjustments for changes in fishing practices or other non-abundance factors which may affect catch rates. Consequently, methods to standardise for changes to vessel configuration, the timing or location of catch and other possible effects have been developed to remove potential biases to CPUE that may result from such changes. In these models, abundance is represented as a “year effect” and the dependent variable is either an explicitly calculated CPUE represented as catch divided by effort, or an implicit CPUE represented as catch per tow or catch per record. In the latter case, additional effort terms can be offered as explanatory variables, allowing the model to select the effort term with the greatest explanatory power. It is always preferable to standardise for as many factors as possible when using CPUE as a proxy for abundance. Unfortunately, it is often not possible to adjust for factors that might affect the behaviour of fishers, particularly economic factors, resulting in indices that may not entirely reflect the underlying stock abundance.

C.2. METHODS

C.2.1. Arithmetic and Unstandardised CPUE

Arithmetic and unstandardised CPUE indices provide potential measures of relative abundance, but are generally considered unreliable because they fail to take into account changes in the fishery, including spatial and temporal changes as well as behavioural and gear changes. They are frequently calculated because they provide a measure of the overall effect of the standardisation procedure.

Arithmetic CPUE (Eq. C.1) in year y was calculated as the total catch for the year divided by the total effort in the year using Eq. C.1:

Eq. C.1
$$A_y = \sum_{i=1}^{n_y} C_{i,y} \Big/ \sum_{i=1}^{n_y} E_{i,y}$$

where $C_{i,y}$ is the `[catch]`, $E_{i,y}$ (`[tows]`) or $E_{i,y}$ (`[hours_fished]`) for record *i* in year *y*, and n_y is the number of records in year *y*.

Unstandardised (geometric) CPUE assumes a log-normal error distribution. An unstandardised index of CPUE (Eq. C.2) in year *y* was calculated as the geometric mean of the ratio of catch to effort for each *i* in year *y*, using Eq. C.2:

Eq. C.2
$$G_y = \exp\left[\frac{1}{n_y}\sum_{i=1}^{n_y}\ln\left(\frac{C_{i,y}}{E_{i,y}}\right)\right]$$

where $C_{i,y}$, $E_{i,y}$ and n_y are as defined for Eq. C.1

C.2.2. Standardised CPUE

These models are preferred over the unstandardised models described above because they can account for changes in fishing behaviour and other factors which may affect the estimated abundance trend, as long as the models are provided with adequate data. In the models described below, catch per record is used as the dependent variable and the associated effort is treated as an explanatory variable.

C.2.2.1. Lognormal Model

Standardised CPUE often assumes a lognormal error distribution, with explanatory variables to used represent changes in the fishery. A standardised CPUE index (Eq. C.3) is calculated from a generalised linear model (GLM) (Quinn and Deriso 1999) using a range of explanatory variables including `[year]`, `[month]`, `[depth]`, `[vessel]` and other available factors:

Eq. C.3 $$\ln\left(I_i\right) = B + Y_{y_i} + \alpha_{a_i} + \beta_{b_i} + \ldots + f\left(\chi_i\right) + f\left(\delta_i\right) + \ldots + \varepsilon_i$$

where I_i = C_i or catch;

B = the intercept;

Y_{y_i} = year coefficient for the year corresponding to record i;

α_{a_i} and β_{b_i} = coefficients for factorial variables a and b corresponding to record i;

$f\left(\chi_i\right)$ and $f\left(\delta_i\right)$ are polynomial functions (to the 3rd order) of the continuous variables χ_i and δ_i corresponding to record i;

ε_i = an error term.

The actual number of factorial and continuous explanatory variables in each model depends on the model selection criteria and the nature of the data. Because each record represents a single tow, $C_{i,y}$ has an implicit associated effort of one tow. Hours fished for the tow is represented on the right-hand side of the equation as a continuous (polynomial) variable.

Note that calculating standardised CPUE with Eq. C.3, while assuming a lognormal distribution and without additional explanatory variables, is equivalent to using Eq. C.2 as long as the same definition for $E_{i,y}$ is used.

Canonical coefficients and standard errors were calculated for each categorical variable (Francis 1999[2]). Standardised analyses typically set one of the coefficients to 1.0 without an error term and estimate the remaining coefficients and the associated error relative to the fixed coefficient. This is required because of parameter confounding. The Francis (1999[2]) procedure rescales all coefficients so that the geometric mean of the coefficients is equal to 1.0 and calculates a standard error for each coefficient, including the fixed coefficient.

Coefficient-distribution-influence (CDI) plots are visual tools to facilitate understanding of patterns which may exist in the combination of coefficient values, distributional changes, and annual influence (Bentley et al. 2012). CDI plots were used to illustrate each explanatory variable added to the model.

C.2.2.2. Binomial Logit Model

The procedure described by Eq. C.3 is necessarily confined to the positive catch observations in the data set because the logarithm of zero is undefined. Observations with zero catch were modelled by fitting a logit regression model based on a binomial distribution and using the

[2] Francis, R.I.C.C. 1999. The impact of correlations on standardised CPUE indices. N.Z. Fish. Ass. Res. Doc. 99/42 : 30 p. Unpublished report kept at NIWA Library, Wellington, N.-Z.

presence/absence of Widow Rockfish as the dependent variable (where 1 is substituted for $\ln(I_i)$ in Eq. C.3 if it is a successful catch record and 0 if it is not successful) and using the same data set. Explanatory factors are estimated in the model in the same manner as described in Eq. C.3. Such a model provides an alternative series of standardised coefficients of relative annual changes that is analogous to the series estimated from the lognormal regression.

C.2.2.3. Combined Model

A combined model (sometimes termed a “hurdle” model), integrating the two sets of relative annual changes estimated by the lognormal and binomial models, can be estimated using the delta distribution, which allows zero and positive observations (Fletcher et al. 2005). Such a model provides a single index of abundance which integrates the signals from the positive (lognormal) and binomial series.

This approach uses the following equation to calculate an index based on the two contributing indices, after standardising each series to a geometric mean=1.0:

Eq. C.4 $$^{C}Y_y = {^{L}Y_y}\,{^{B}Y_y}$$

where $^{C}Y_y$ = combined index for year y,

$^{L}Y_y$ = lognormal index for year y,

$^{B}Y_y$ = binomial index for year y

Francis (2001) suggests that a bootstrap procedure is the appropriate way to estimate the variability of the combined index. Therefore, confidence bounds for the combined model were estimated using a bootstrap procedure based on 250 replicates, drawn with replacement.

The index series plots below present normalised values, i.e., each series is divided by its geometric mean so that the series is centred on 1. This facilitates comparison among series.

C.3. PRELIMINARY INSPECTION OF THE DATA

The analyses reported in this Appendix are based on tow-by-tow total catch (landings + discards) data collected over the period 1996–2018 for which detailed positional data for every tow are available. Each tow will have an estimate of retained and discarded catch because of the presence of an observer on board the vessel. These data are held in the DFO PacHarvTrawl (PacHarvest) and GFFOS databases (Fisheries and Oceans Canada, Pacific Region, Groundfish Data Unit).

Tow-by-tow catch and effort data for Widow Rockfish (WWR) from the BC trawl fishery operating from Juan de Fuca Strait to the Dixon Entrance from 1996 to 2018 were selected using the following criteria:

- Tow start date between 1 January 1996 and 31 December 2018;
- Bottom trawl type (includes ‘unknown’ trawl gear);
- Fished in PMFC regions: 3C, 3D, 5A, 5B, 5C, 5D or 5E;
- Fishing success code <=1 (code 0= unknown; code 1= useable);
- Catch of at least one fish or invertebrate species (no water hauls or inanimate object tows);
- Valid depth field;

- Valid latitude and longitude co-ordinates;
- Valid estimate of time towed that was > 0 hours and <= 5 hours.

Each record represents a single tow, which results in equivalency between the number of records and number of tows. Catch per record can therefore be used to represent CPUE, because each record (tow) has an implicit effort component.

The catch and effort data for WWR were treated as a single area (3CD5ABCDE) representing all catch outside of the Strait of Georgia, upper Johnstone Strait and Juan de Fuca Strait, based on the declared distribution of trawl catches (see Appendix A). Only bottom trawl data were considered because WWR is a schooling midwater species which can be easily located and targeted, rendering the data uninformative for CPUE. On the other hand, bottom trawl rarely targets this species, which occurs as a background by-catch when targeting other groundfish species. Figure C.1 plots the distribution of depth for all successful WWR bottom trawl tows in the designated area. A depth range for this analysis was selected from this plot and is summarised in Table C.1.

Table C.1. Depth bins used in CPUE analyses of stock by gear.

Analysis	Trawl Gear	First year	Depth range (m)	Upper bound effort (h)	Minimum bin + records	N depth bins	N latitude bins	N locality bins
3CD5ABCDE	Bottom trawl	1996	75–400	5	150	13	42	34

Vessel qualification criteria for the bottom trawl fisheries were based on number of trips per year and number of years fishing to avoid including vessels which only occasionally captured Widow Rockfish. The vessel qualification criteria used in this analysis appear in Table C.2 and the distribution of tows by vessel and year is presented in Figure C.2. Once a vessel was selected, all data for the qualifying vessel were included, regardless of the number of trips in a year. Table C.2 shows the number of vessels used in this analysis and the fraction (87%) of the total catch represented in the core fleet. There was good vessel overlap across years (Figure C.2) in the fishery, where 18 of the 39 core vessels have participated in the fishery over the full 23 years of the analysis and a further 6 vessels were in the fishery for 20–22 years.

Table C.2. Vessel qualification criteria used in CPUE analyses of stock by gear.

		Vessel selection criteria			Data set characteristics				
Analysis	Trawl Gear	N years	N trips	Minimum positive Records	N vessels	% total catch[1]	catch (t)	Total records	Positive records
3CD5ABCDE	Bottom	7	7	100	39	87	4,718	160,100	25,748

[1] total catch calculated with all filters applied except for the vessel and depth restrictions

Table C.3 reports the explanatory variables offered to the model, based on the tow-by-tow information in each record, with the number of available categories varying as indicated in Table C.1 and Table C.2. Table C.4 summarises the core vessel data used in each analysis by calendar year, including the number of records, the total hours fished and the associated WWR catch. This table also tracks the proportion of tows which did not report WWR.

Table C.3. Explanatory variables offered to the CPUE model, based on the tow-by-tow information.

Variable	Data type
Year	23 categories (calendar years)
Hours fished	continuous: 3rd order polynomial
Month	12 categories
DFO locality	Fishing locality areas identified by Rutherford (1999) (includes a final aggregated category) (Table C.1)
Latitude	Latitude aggregated by 0.1° bands starting at 48°N (includes a final aggregated category) (Table C.1)
Vessel	See Table C.2 for number of categories by analysis (no final aggregated category) (Table C.2)
Depth	See Table C.1 for number of categories by analysis (no final aggregated category) (Table C.1)

Table C.4. Summary data for the Widow Rockfish bottom trawl fishery in 3CD5ABCDE by year for the core data set (after applying all data filters and selection of core vessels).

Year	Number vessels[1]	Number trips[1]	Number tows[1]	Number records[1]	Number records[2]	% zero records[2]	Total catch (t)[1]	Total hours[1]	CPUE (kg/h) (Eq. C.1)
1996	35	147	402	402	4,941	91.9	50.8	744	68.3
1997	37	277	917	917	6,755	86.4	123.9	1,802	68.8
1998	36	340	1,082	1,082	7,596	85.8	134.8	2,333	57.8
1999	36	381	1,120	1,120	8,436	86.7	189.9	2,316	82.0
2000	36	435	1,452	1,452	9,807	85.2	261.1	2,478	105.3
2001	36	422	1,354	1,354	8,820	84.6	308.6	2,289	134.8
2002	36	468	1,553	1,553	9,894	84.3	428.3	2,682	159.7
2003	36	492	1,528	1,528	9,412	83.8	285.3	2,574	110.8
2004	36	441	1,354	1,354	9,150	85.2	186.4	2,373	78.5
2005	36	468	1,455	1,455	9,957	85.4	173.8	2,784	62.4
2006	33	414	1,393	1,393	7,803	82.1	239.2	2,635	90.8
2007	32	350	1,252	1,252	6,879	81.8	266.7	2,357	113.1
2008	30	301	988	988	5,825	83.0	167.9	1,817	92.4
2009	30	321	1,184	1,184	6,348	81.3	250.2	2,077	120.5
2010	28	308	1,109	1,109	6,328	82.5	164.8	2,191	75.2
2011	30	299	1,094	1,094	6,379	82.8	224.2	2,090	107.3
2012	29	268	1,096	1,096	5,471	80.0	160.8	2,135	75.3
2013	28	255	930	930	5,857	84.1	218.4	1,778	122.8
2014	29	285	990	990	5,126	80.7	212.5	1,754	121.2
2015	26	253	886	886	5,336	83.4	179.4	1,600	112.1
2016	23	269	1,064	1,064	4,844	78.0	206.0	2,034	101.3
2017	24	244	797	797	4,855	83.6	103.3	1,428	72.3
2018	20	207	748	748	4,281	82.5	181.1	1,366	132.6

[1] calculated for tows with Widow Rockfish catch >0; [2] calculated for all tows

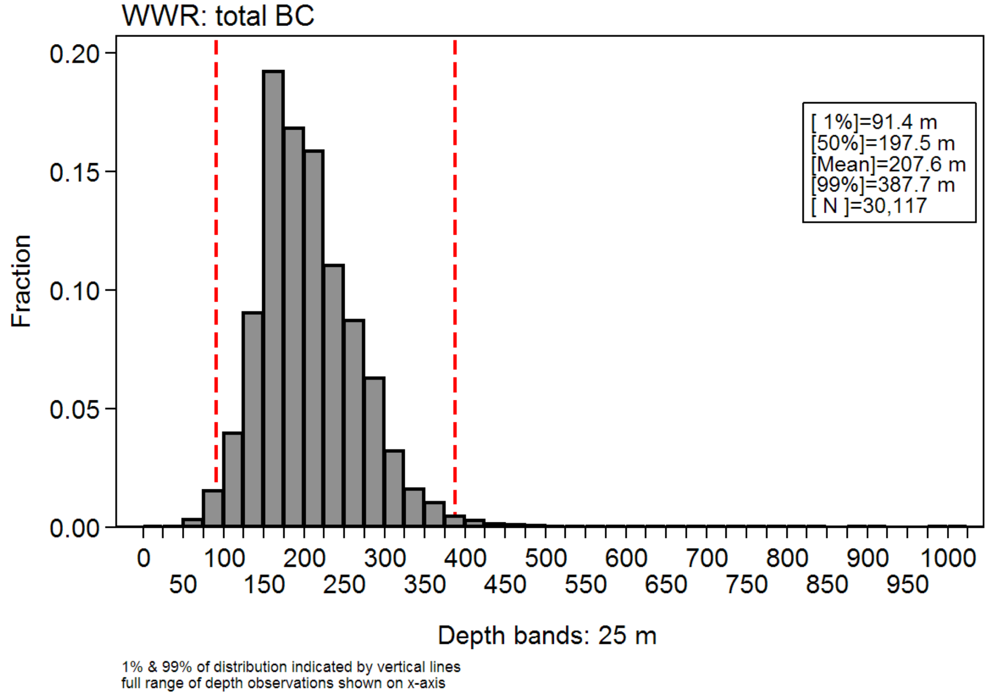


Figure C.1. Depth distribution of tows capturing WWR for the 3CD5ABCDE bottom trawl (BT) GLM analyses from 1996 to 2017 using 25m intervals (each bin is labelled with the upper bound of the interval). Vertical lines indicate the 1% and 99% percentiles.

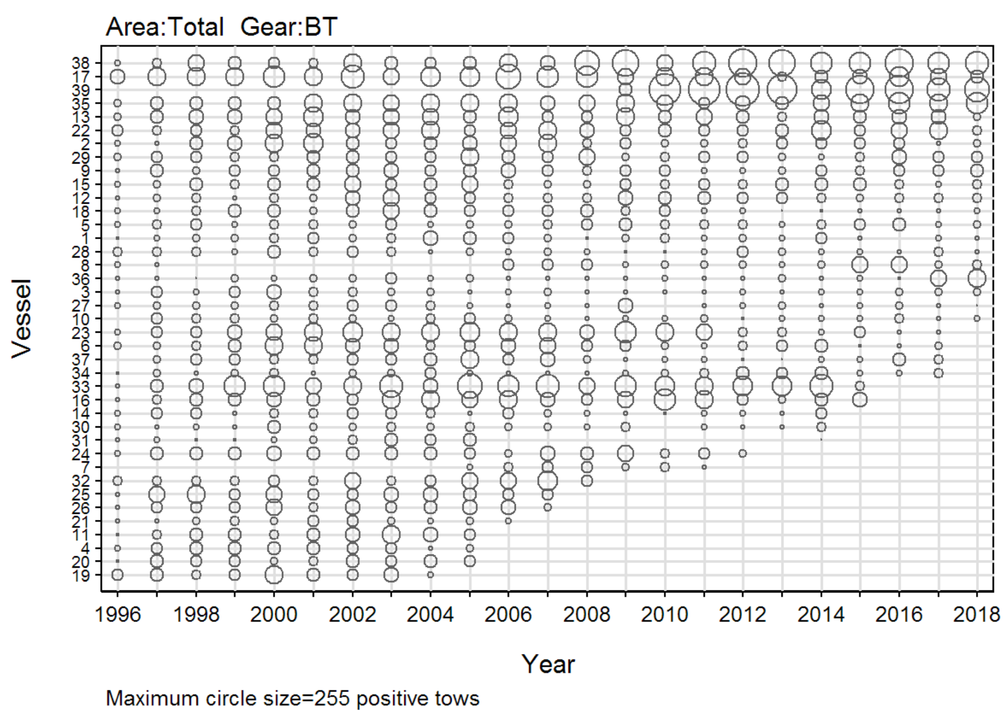


Figure C.2. Bubble plot showing vessel participation (number positive tows) by the core fleets in the 3CD5ABCDE BT GLM analyses. Vessels are coded in ascending order total effort by year.

C.4. RESULTS

C.4.1. PMFC Area 3CD5ABCDE

C.4.1.1. Bottom Trawl Fishery: Positive Lognormal Model

A standardised lognormal General Linear Model (GLM) analysis was performed on positive catch records from the bottom trawl tow-by-tow data set generated as described in Section C.3. Seven explanatory variables (described in Section C.3 above) were offered to the model and ln(catch) was used as the dependent variable, where catch is the total by weight of landed plus discarded Widow Rockfish in each record (tow) (Eq. C.3). The resulting CPUE index series is presented in Figure C.3.

The `[Year]` categorical variable was forced as the first variable in the model without regard to its effect on the model deviance. The remaining six variables were offered sequentially, with a stepwise acceptance of the remaining variables with the best AIC. This process was continued until the improvement in the model R^2 was less than 1% (Table C.5). This model selected four of the six remaining explanatory variables, including `[DFO locality]`, `[Depth_bands]`, `[Vessel]` and `[0.1° Latitude_bands]` in addition to `[Year]`. The final lognormal model accounted for 21% of the total model deviance (Table C.5), with the year variable explaining less than 1% of the model deviance.

Model residuals showed a good fit to the underlying lognormal distributional assumption, with only a small deviation at the upper tail of the distribution and none in the lower tail or in the body of the residual distribution (Figure C.4).

A stepwise plot showing the effect on the year indices as each explanatory variable was introduced into the model shows that the standardisation procedure made relatively small adjustments to the unstandardised series at the beginning of the series and in the period 2008 to 2013, resulting in a relatively smooth annual trend (Figure C.5).

*Table C.5. Order of acceptance of variables into the lognormal model of positive total mortalities (verified landings plus discards) of Widow Rockfish 3CD5ABCDE bottom trawl fishery with the amount of explained deviance (R^2) for each variable. Variables accepted into the model are identified in bold with an *. Year was forced as the first variable.*

Variable	1	2	3	4	5	6
Year*	**0.0091**	-	-	-	-	-
DFO locality*	0.1091	**0.1188**	-	-	-	-
Depth bands*	0.0422	0.0507	**0.1626**	-	-	-
Vessel*	0.0418	0.0511	0.1458	**0.1888**	-	-
0.1° Latitude bands*	0.0832	0.0910	0.1493	0.1882	**0.2124**	-
Month	0.0100	0.0191	0.1237	0.1693	0.1945	0.2175
Hours fished	0.0030	0.0120	0.1209	0.1655	0.1908	0.2142
Improvement in deviance	0	0.1097	0.0438	0.0262	0.0236	0.0051

CDI plots of the four explanatory variables introduced to the model in addition to `[Year]` show relatively minor standardisation effects in the series. Although `[DFO_locality]` (Figure C.6) and `[Depth_bands]` (Figure C.7) have the greatest explanatory power, neither variable caused much movement in the annual series (Figure C.5). The variable `[Vessel]` (Figure C.8) had more impact, with some raising of the initial years in the series and some minor shifts towards the end of the series. `[Latitude_bands]` (Figure C.9) did not have much impact on the overall annual indices.

The lognormal year indices show a declining trend at the beginning of the series, ending in the mid-2000s, and then followed by a flat or slightly increasing trend towards the end of the series (Figure C.3). This model has good diagnostics and shows only small changes from the unstandardised series.

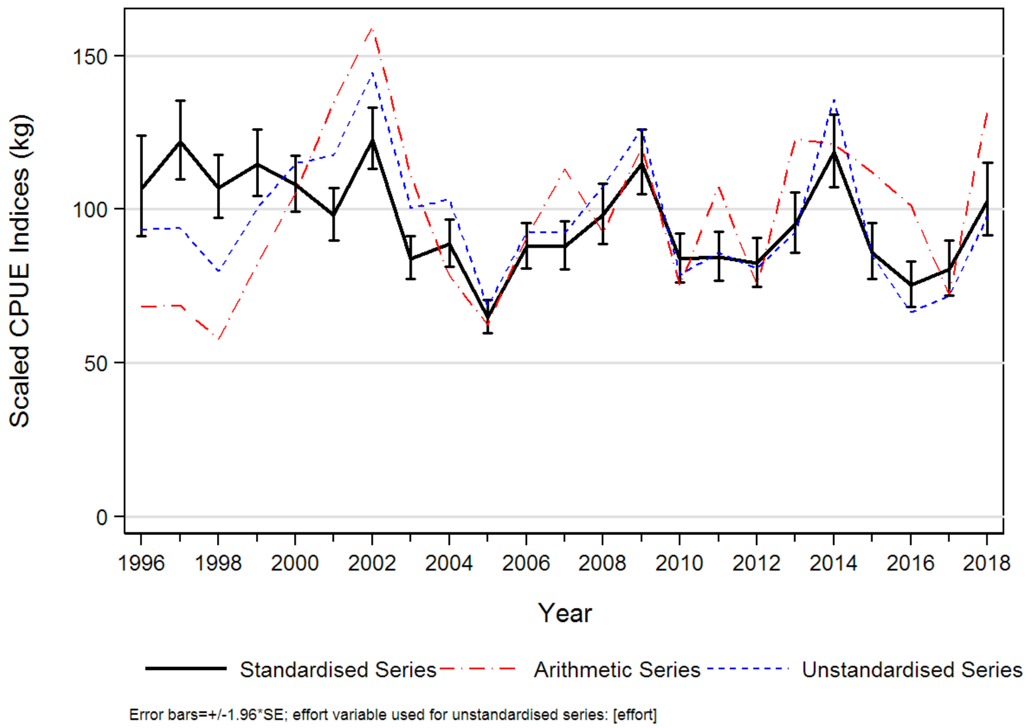


Figure C.3. Three CPUE series for Widow Rockfish from 1996 to 2018 in 3CD5ABCDE bottom trawl fishery. The solid line is the standardised CPUE series from the lognormal model (Eq. C.3). The arithmetic series (Eq. C.1) and the unstandardised series (Eq. C.2) are also presented. All three series have been scaled to same geometric mean.

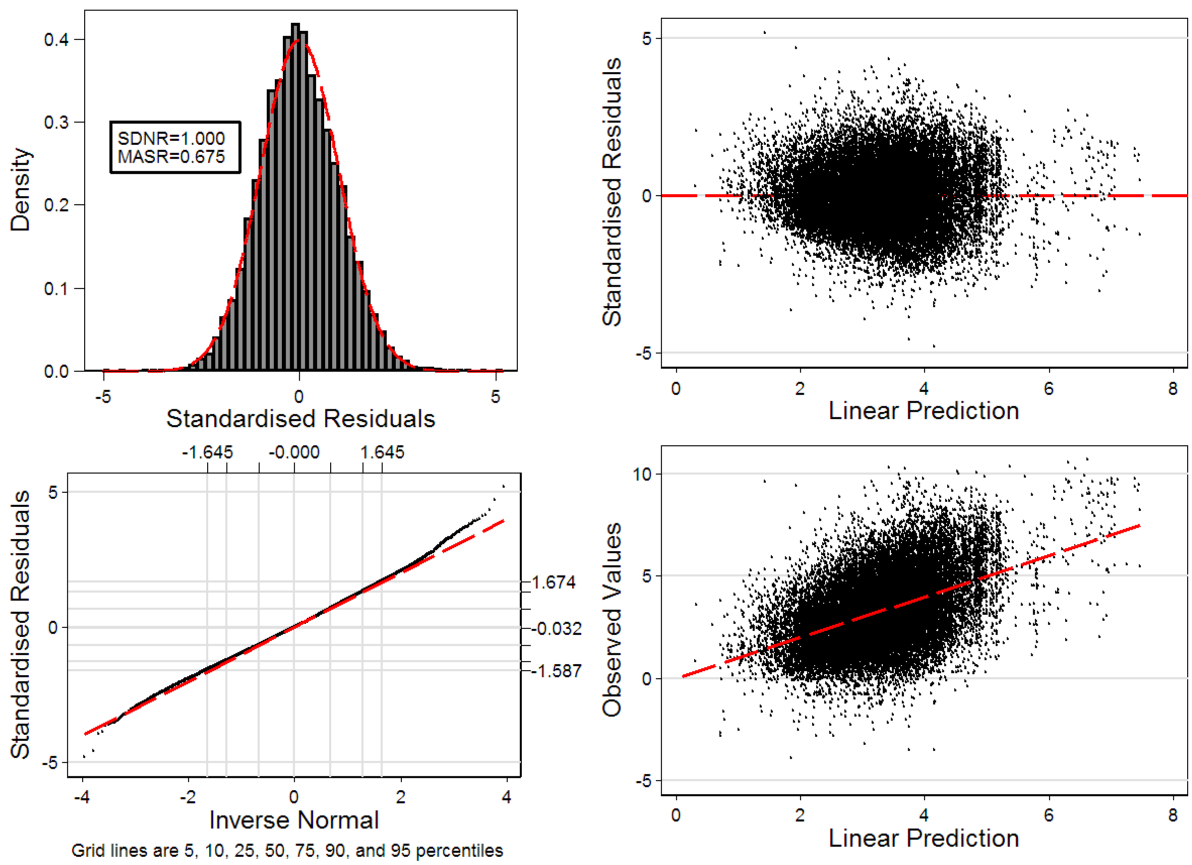


Figure C.4. Residual diagnostic plots for the GLM lognormal analysis for Widow Rockfish in 3CD5ABCDE bottom trawl fishery. Upper left: histogram of the standardised residuals with overlaid lognormal distribution (SDNR = standard deviation of normalised residuals. MASR = median of absolute standardised residuals). Lower left: Q-Q plot of the standardised residuals with the outside horizontal and vertical lines representing the 5th and 95th percentiles of the theoretical and observed distributions. Upper right: standardised residuals plotted against the predicted CPUE. Lower right: observed CPUE plotted against the predicted CPUE.

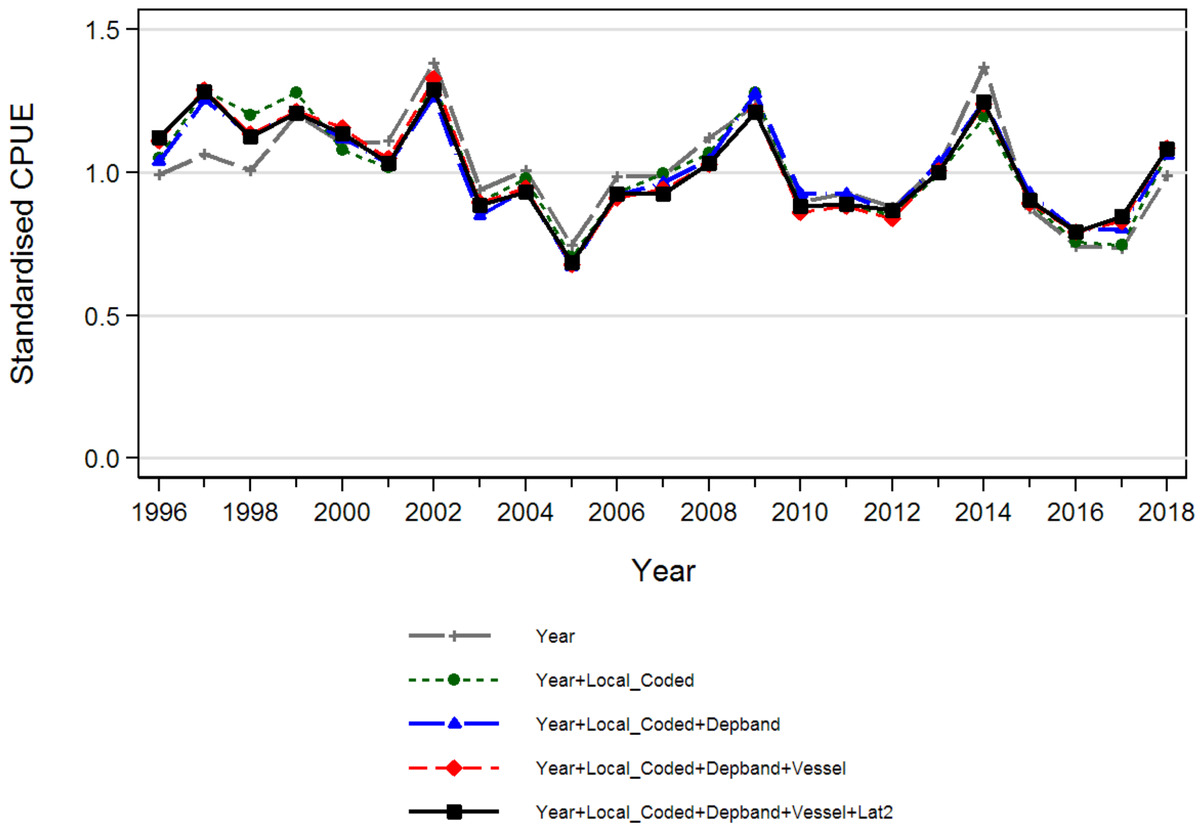


Figure C.5. Plot showing the year coefficients after adding each successive term of the standardised lognormal regression analysis for Widow Rockfish in the 3CD5ABCDE bottom trawl fishery. The final model is shown with a thick solid black line. Each line has been scaled so that the geometric mean equals 1.0.

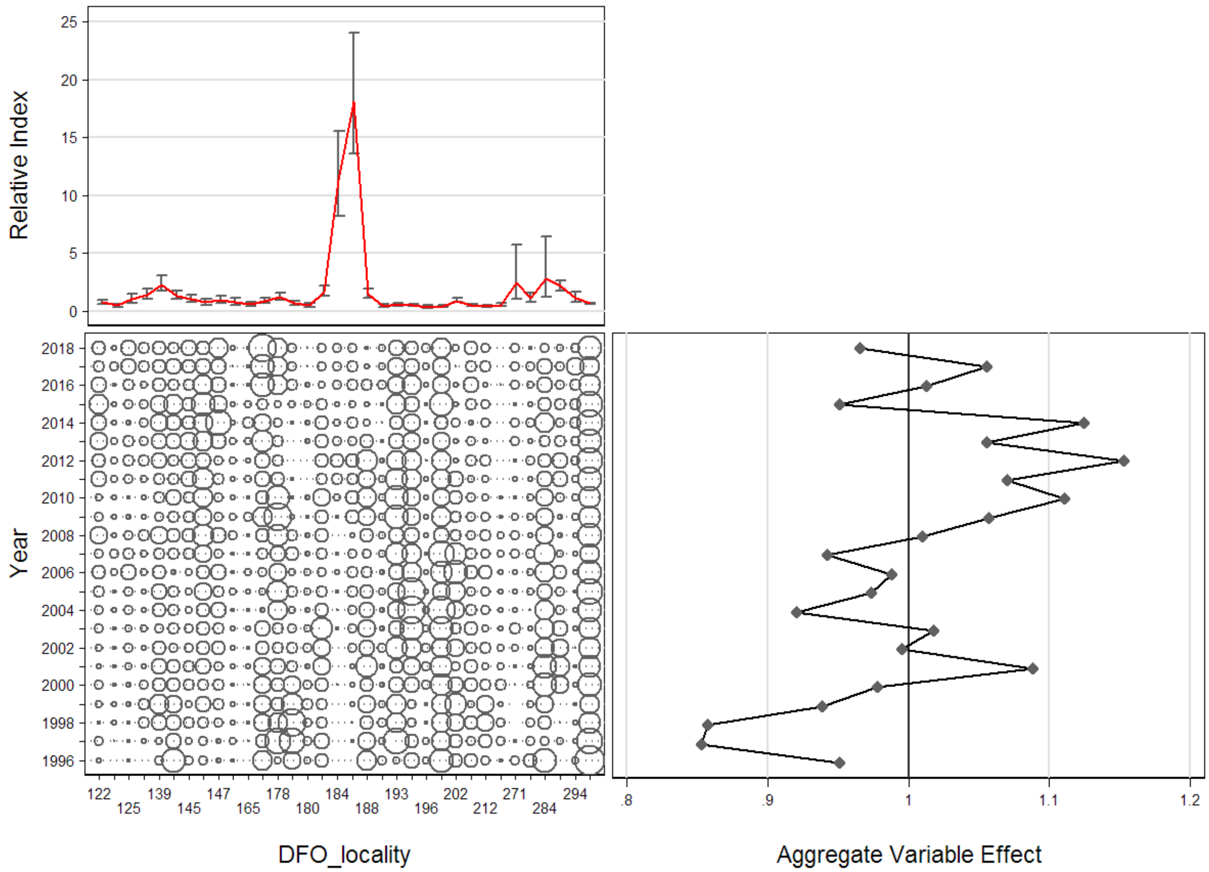


Figure C.6. CDI plot showing the effect of introducing the categorical variable [DFO locality] to the lognormal regression model for Widow Rockfish in the 3CD5ABCDE bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution by year of variable records (bottom left), and the cumulative effect of variable by year (bottom right).

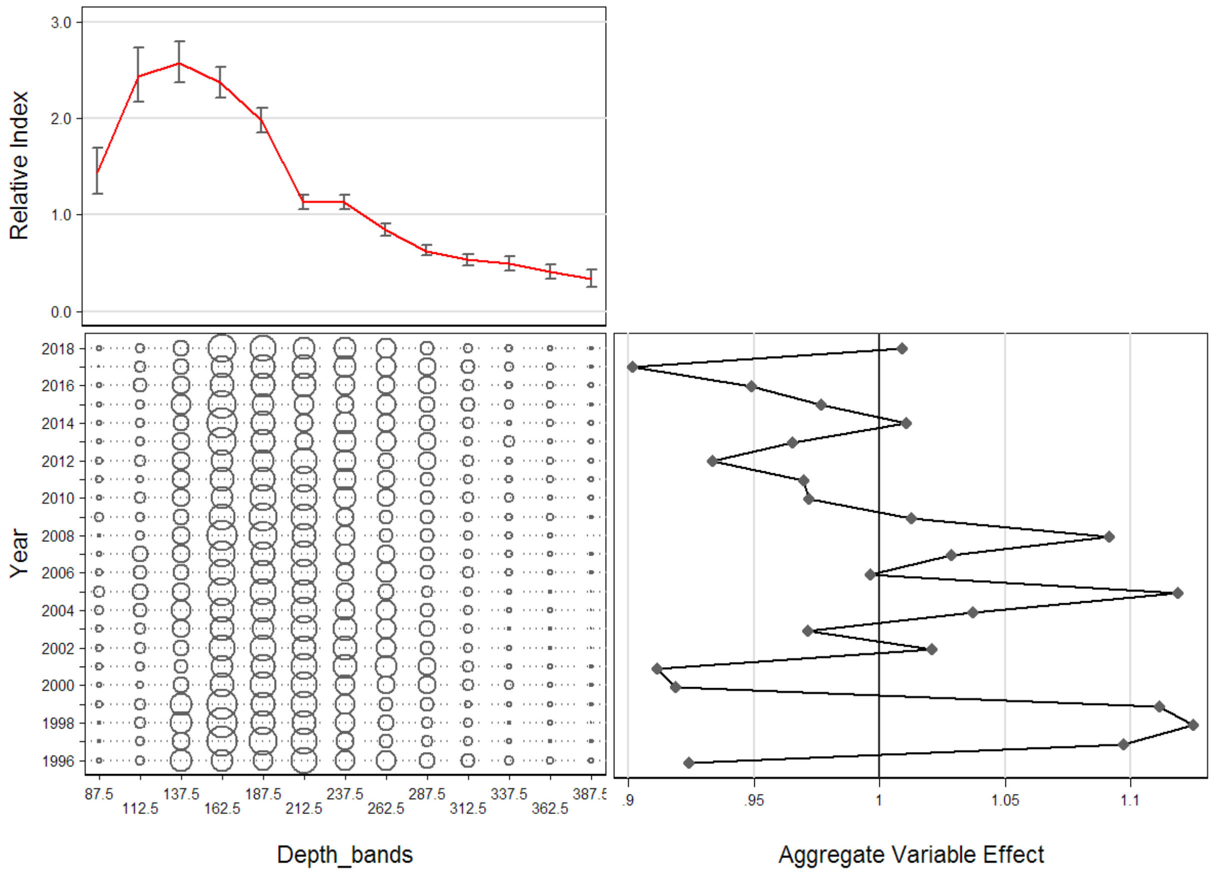


Figure C.7. CDI plot showing the effect of introducing the categorical variable [Depth bands] to the lognormal regression model for Widow Rockfish in the 3CD5ABCDE bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution by year of variable records (bottom left), and the cumulative effect of variable by year (bottom right). Locality codes are defined in Table C.6.

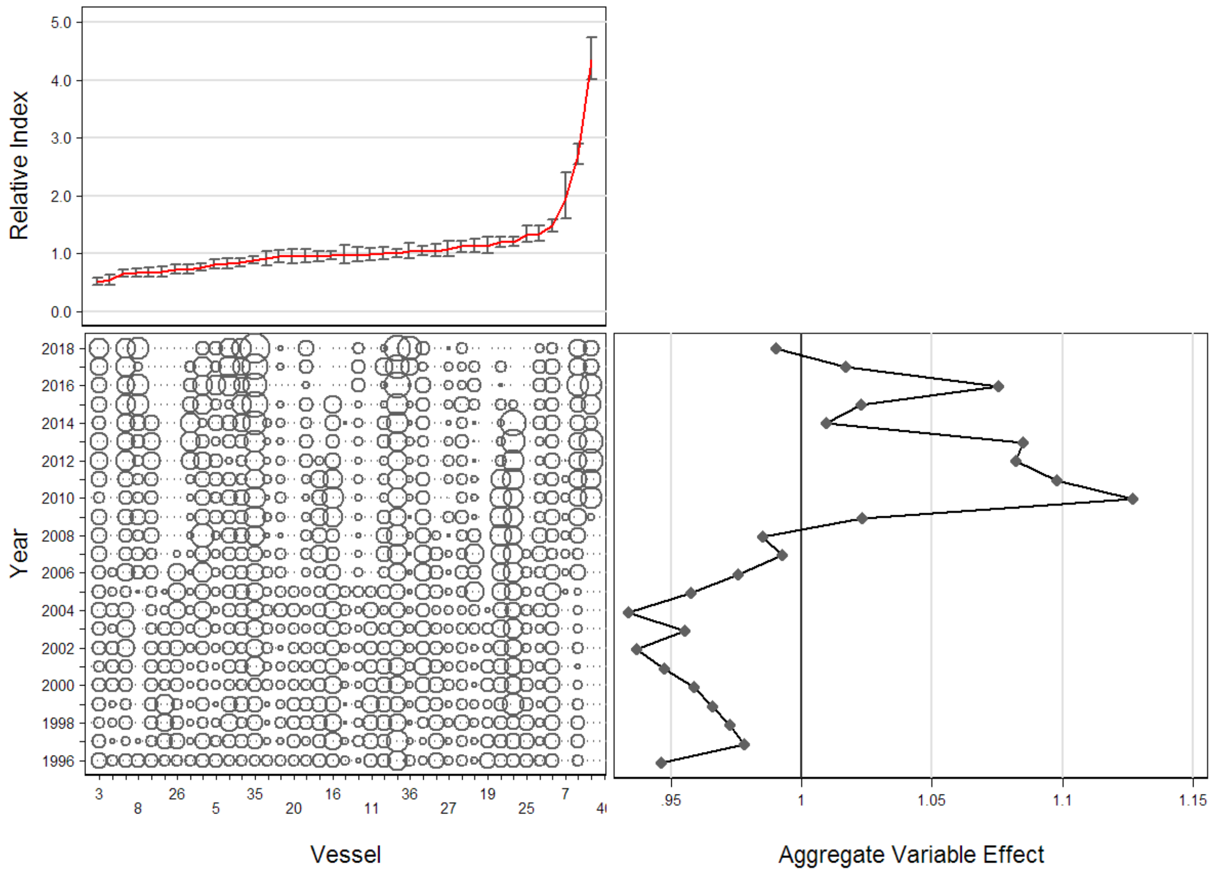


Figure C.8. CDI plot showing the effect of introducing the continuous variable [Vessel] to the lognormal regression model for Widow Rockfish in the 3CD5ABCDE bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution by year of variable records (bottom left), and the cumulative effect of variable by year (bottom right).

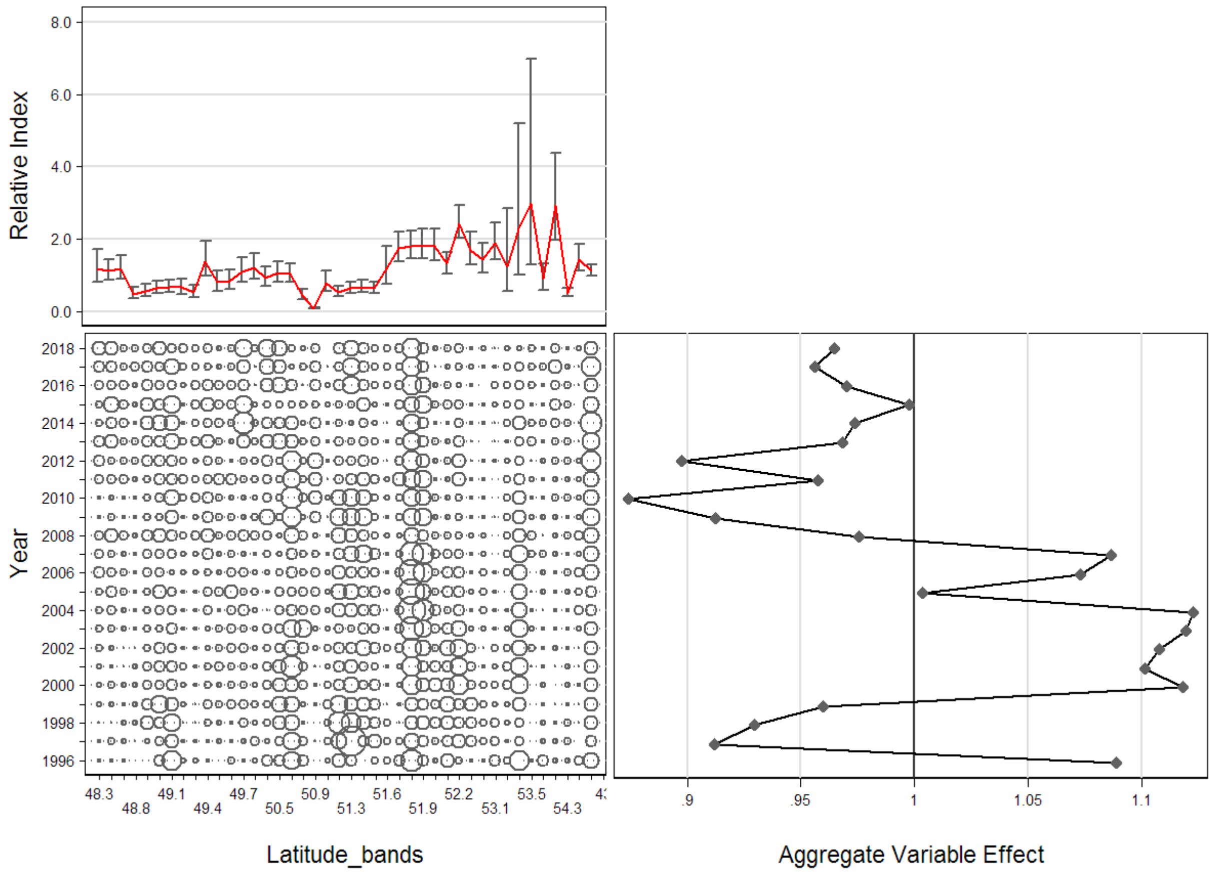


Figure C.9. CDI plot showing the effect of introducing the categorical variable [Latitude bands] to the lognormal regression model for Widow Rockfish in the 3CD5ABCDE bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution by year of variable records (bottom left), and the cumulative effect of variable by year (bottom right).

Table C.6. Definition of locality codes used in Figure C.6.

Code	PMFC Major	DFO Minor	Minor Name	Locality Name	Index Lognormal	Index Binomial
122	3	23	Big Bank	Deep Big Bank/Barkley Canyon	0.76	0.64
124	3	23	Big Bank	Ucluelet/Loudon Canyons	0.46	0.36
125	3	23	Big Bank	Nitinat Canyon	1.01	0.89
138	3	24	Clayoquot Sd.	Father Charles Canyon	1.39	0.57
139	3	24	Clayoquot Sd.	Clayoquot Canyon	2.29	0.98
140	3	24	Clayoquot Sd.	South Estevan	1.29	0.63
145	4	25	Estevan-Esperanza Inlet	North Estevan	1.05	0.62
146	4	25	Estevan-Esperanza Inlet	Nootka	0.73	0.54
147	4	25	Estevan-Esperanza Inlet	Esperanza East	0.96	0.77
157	4	26	Kyuquot Sd.	Crowther Canyon	0.76	0.83
165	4	27	Quatsino Sd.	West Cape Cook	0.55	0.58
166	4	27	Quatsino Sd.	Quatsino Sound	0.82	1.05
178	5	11	Cape Scott-Triangle	Triangle	1.22	0.74
179	5	11	Cape Scott-Triangle	Cape Scott Spit	0.66	0.43
180	5	11	Cape Scott-Triangle	Mexicana	0.46	0.29
183	5	11	Cape Scott-Triangle	South Scott Islands	1.66	1.83
184	5	11	Cape Scott-Triangle	W. Triangle (25 Mi.)	11.30	2.84
187	5	11	Cape Scott-Triangle	South Triangle	18.09	3.11

Code	PMFC Major	DFO Minor	Minor Name	Locality Name	Index Lognormal	Index Binomial
188	5	11	Cape Scott-Triangle	Pisces Canyon	1.49	2.43
192	6	8	Goose Island Bank	NE Goose	0.40	0.37
193	6	8	Goose Island Bank	SE Goose	0.56	0.38
195	6	8	Goose Island Bank	SW Goose	0.48	1.38
196	6	8	Goose Island Bank	Mitchell's Gully	0.36	0.85
197	6	8	Goose Island Bank	SE Cape St. James	0.40	1.09
202	6	8	Goose Island Bank	SW Middle Bank	0.88	1.59
203	6	8	Goose Island Bank	Outside Cape St. James	0.45	1.29
212	7	2	2B-East	South Morseby	0.44	0.60
218	7	2	2B-East	NW Middle Bank	0.49	0.74
271	9	31	2A West - Rennell Sound	Rennell Sound	2.41	9.71
272	9	31	2A West - Rennell Sound	Frederick Island	1.11	0.98
284	9	31	2A West - Rennell Sound	South Hogback	2.79	5.53
287	9	34	2B West - Anthony Island	Anthony Island	2.16	7.12
294	9	35	1 West - Langara	N Fred-Langara (Deep)	1.10	1.68

C.4.1.2. Bottom Trawl Fishery: Binomial Logit Model

The same variables used in the lognormal model were offered sequentially to this model, beginning with the year categorical variable, until the improvement in the model R^2 was less than 1% (Table C.7). A binary variable which equalled 1 for positive catch tows and 0 for zero catch tows was used as the dependent variable. The final binomial model accounted for 18% of the total model deviance, with the year variable explaining almost none of the model deviance.

The selected explanatory variables included `[DFO_locality]`, `[Depth_bands]` and `[Vessel]`, in addition to `[Year]`. This model shows little trend after an sharp increase in the first year (1996) of the series (which may be a reporting issue) (Figure C.10). A stepwise plot showing the effect of adding each successive explanatory variable indicates that there were only minor changes effected by the binomial standardisation, with the unstandardised “occurrence” function appearing very similar to the standardised binomial series (Figure C.11).

The effect of the standardisation is to flatten the series. The addition of the `[DFO_locality]` (Figure C.12) and `[Depth_bands]` (Figure C.13) variables lift the early half of the series and drop the latter half. The addition of the `[Vessel]` variable (Figure C.14) causes as much change in the `[Year]` coefficients as the combined effect of the `[DFO_locality]` and `[Depth_bands]` variables, even though this variable had the least explanatory power of the three.

*Table C.7. Order of acceptance of variables into the binomial model of presence/absence of verified landings plus discards of Widow Rockfish in 3CD5ABCDE bottom trawl fishery with the amount of explained deviance (R^2) for each variable. Variables accepted into the model are marked in bold with an *. Year was forced as the first variable.*

Variable	1	2	3	4	5
Year*	**0.005**	-	-	-	-
DFO locality*	0.107	**0.111**	-	-	-
Depth bands*	0.084	0.089	**0.158**	-	-
Vessel*	0.043	0.047	0.131	**0.178**	-
0.1° Latitude bands	0.083	0.089	0.130	0.169	0.187
Hours fished	0.003	0.008	0.112	0.159	0.178
Month	0.009	0.014	0.113	0.159	0.178
Improvement in deviance	0	0.106	0.047	0.020	0.010

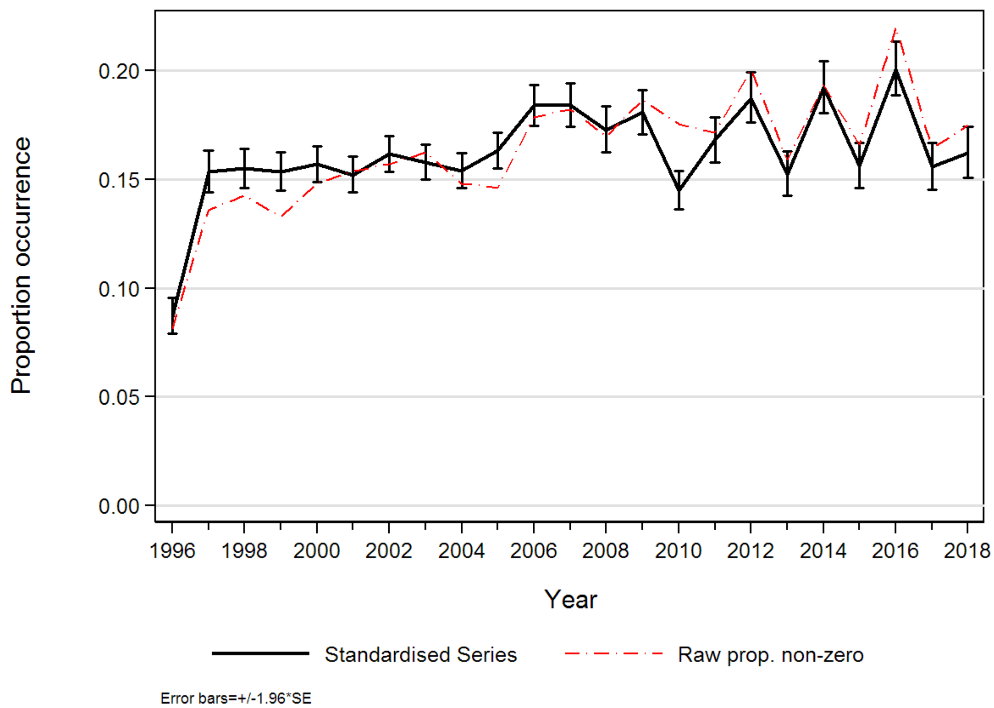


Figure C.10. Binomial index series for the 3CD5ABCDE bottom trawl fishery also showing the trend in proportion of zero tows from the same data set.

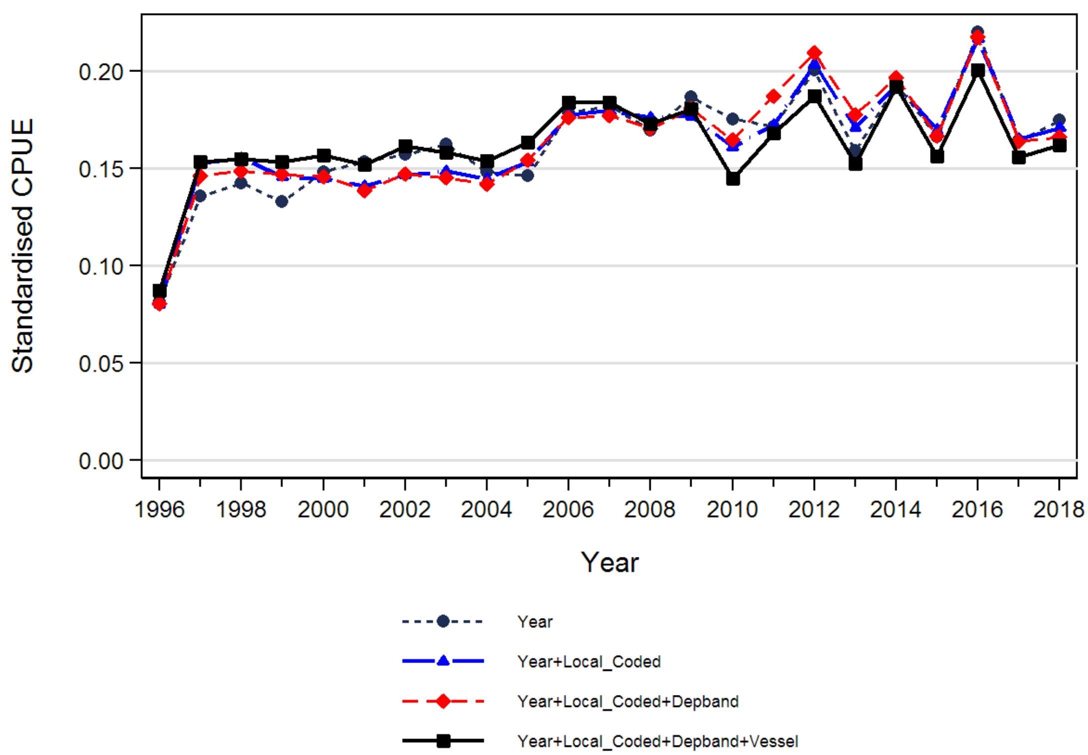


Figure C.11. Plot showing the year coefficients after adding each successive term of the standardised binomial regression analysis for Widow Rockfish in the 3CD5ABCDE bottom trawl fishery. The final model is shown with a thick solid black line. Each line has been scaled so that the geometric mean equals 1.0.

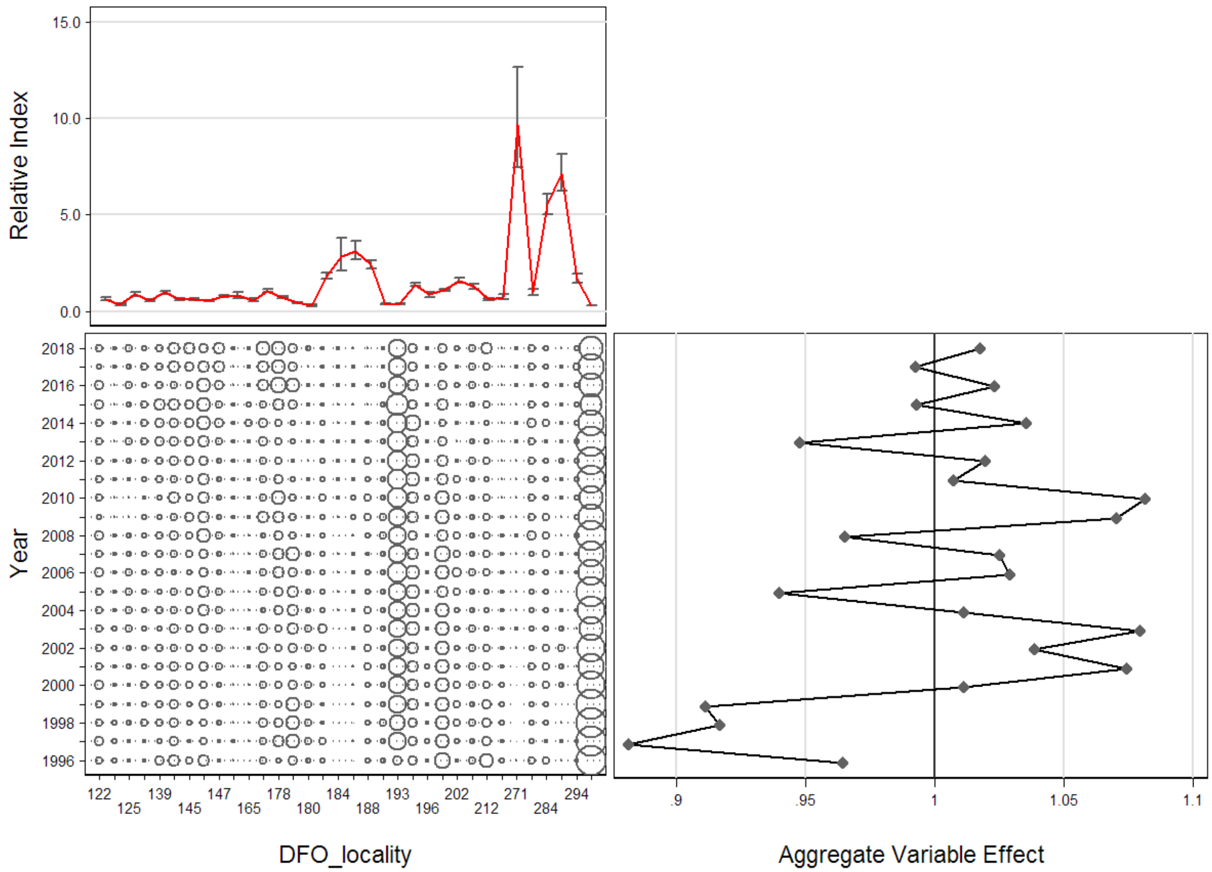


Figure C.12. CDI plot showing the effect of introducing the categorical variable [DFO locality] to the binomial regression model for Widow Rockfish in the 3CD5ABCDE bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution by year of variable records (bottom left), and the cumulative effect of variable by year (bottom right). Locality codes are defined in Table C.6.

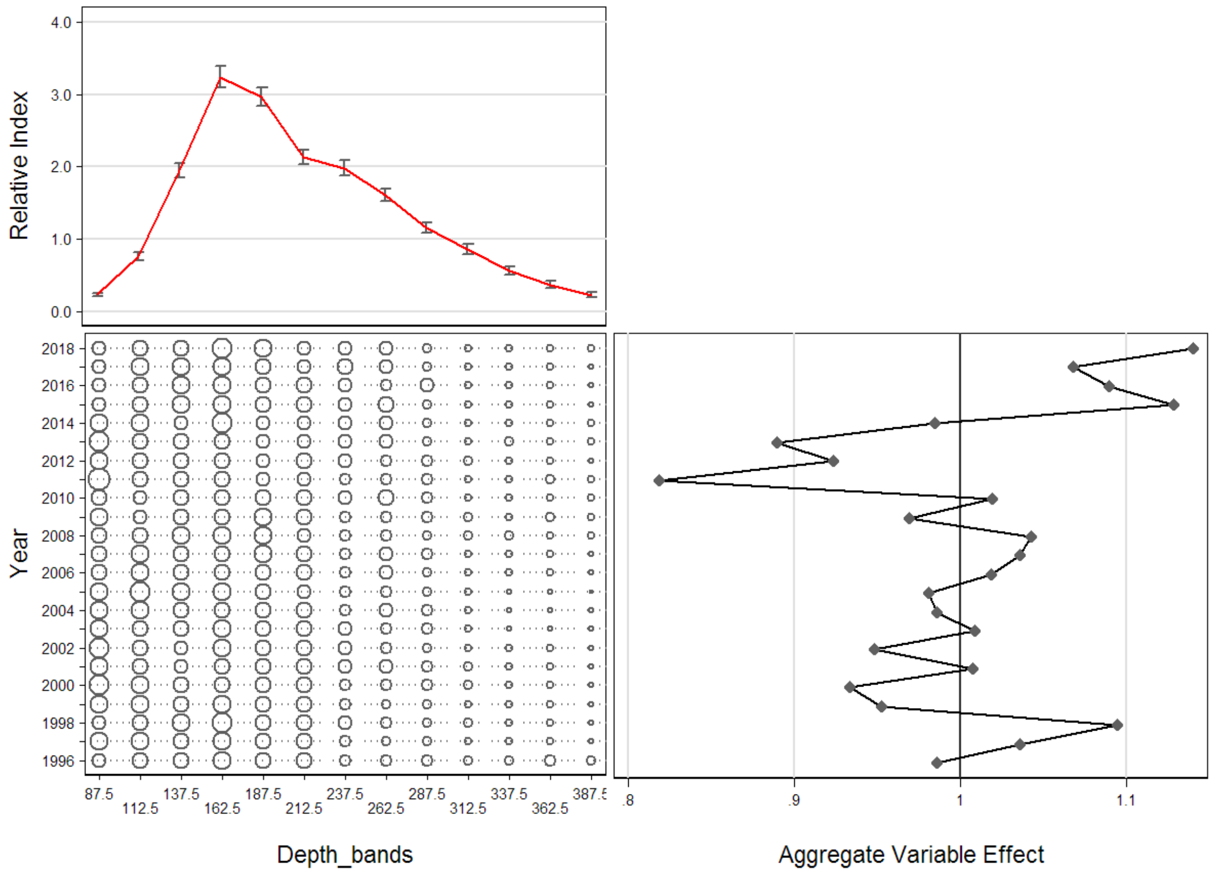


Figure C.13. CDI plot showing the effect of introducing the categorical variable [Depth bands] to the binomial regression model for Widow Rockfish in the 3CD5ABCDE bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution by year of variable records (bottom left), and the cumulative effect of variable by year (bottom right).

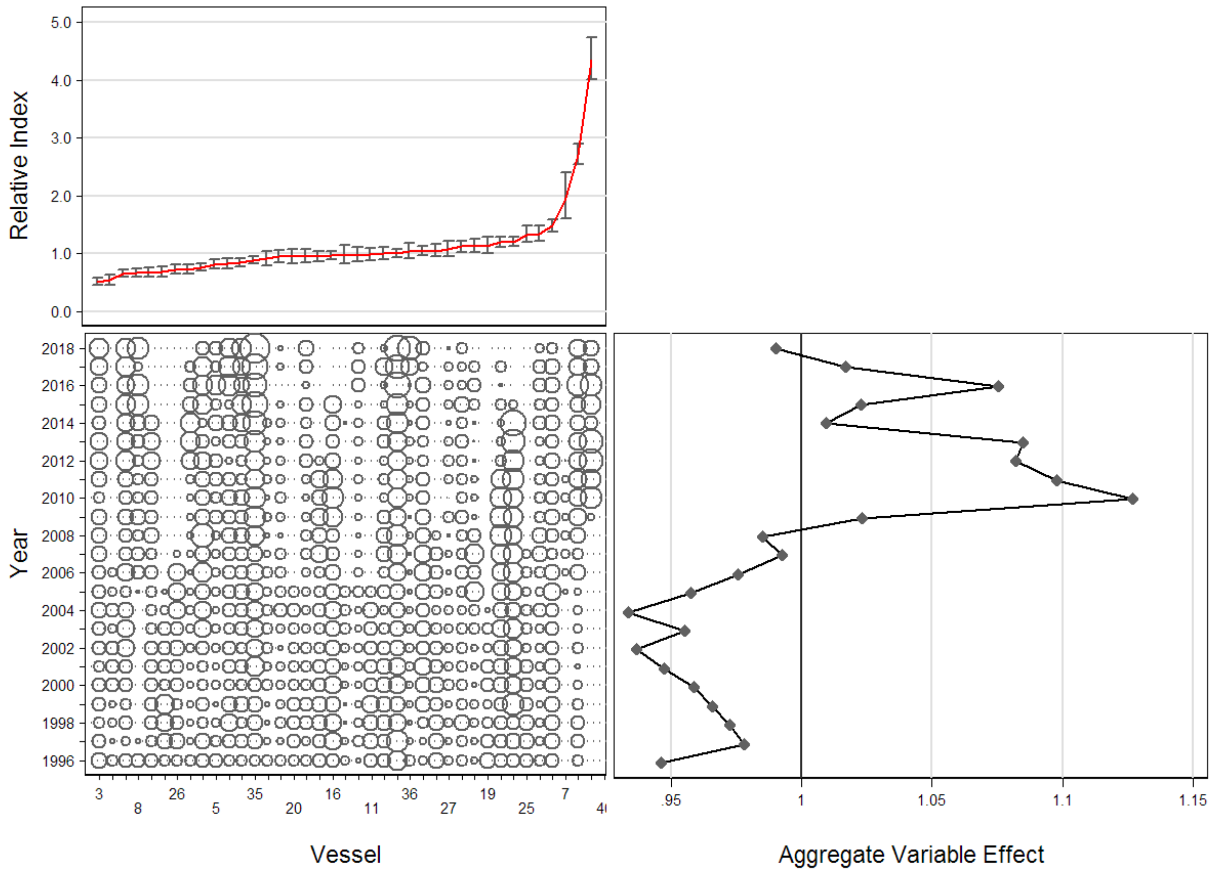


Figure C.14. CDI plot showing the effect of introducing the categorical variable [Vessel] to the binomial regression model for Widow Rockfish in the 3CD5ABCDE bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution of variable records by year (bottom left), and the cumulative effect of variable by year (bottom right).

C.4.1.3. Bottom Trawl Fishery: Combined Model

The combined model (Eq. C.4) closely resembles the lognormal indices throughout the series, with the exception of the strong increase in the first year, which comes from the logit series. (Figure C.15).

C.5. RELATIVE INDICES OF ABUNDANCE

Table C.8 summarises the relative indices of abundance derived from the WWR CPUE analysis. CPUE indices used in the age-structured stock assessment model appear as the delta-lognormal (combined) indices from the bottom trawl data (Figure C.15, Table C.8). The associated bootstrap standard errors (SE) were used as the initial CVs when fitting the stock assessment model.

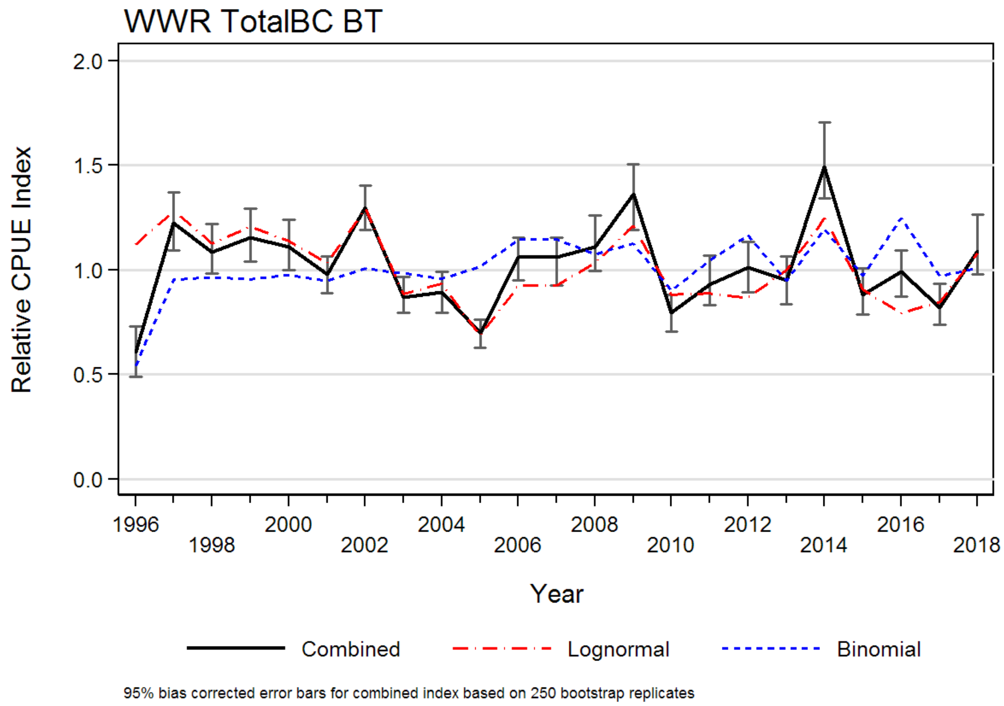


Figure C.15. Combined index series (Eq. C.4) for the 3CD5ABCDE bottom trawl fishery also showing the contributing lognormal and binomial index series. Confidence bounds based on 250 bootstrap replicates.

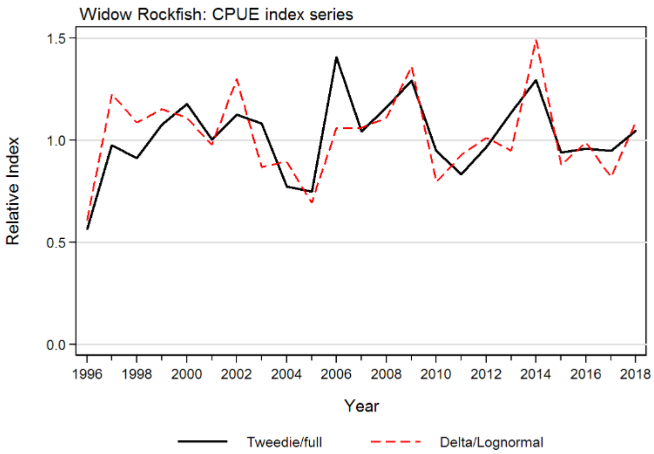
C.6. COMPARISON BETWEEN DELTA-LOGNORMAL AND TWEEDIE MODELS

The core vessel data set developed for this analysis was also analysed using a standardisation procedure using a model based on the Tweedie distribution (Anderson et al. 2020). The advantage of this distribution is that the Tweedie distribution accepts zero and positive observations within the same model, eliminating the two-step procedure described in Section C.2.2.3. In addition, the Tweedie standardisation procedure was conducted in a Bayesian framework, which may provide a more realistic estimate of the underlying uncertainty in the model.

However, the overall impact of this alternative standardisation procedure on the relative `[Year]` indices is small, with both models estimating very similar relative `[Year]` effects (Figure C.16). More importantly, the associated standard errors for the Tweedie model `[Year]` variable are much greater than the equivalent error bars from the delta-lognormal model. These estimates should reduce or eliminate the need to add process error to CPUE series.

Table C.8. Relative indices of annual CPUE from the arithmetic, unstandardised, lognormal models of non-zero bottom trawl catches of Widow Rockfish in 3CD5ABCDE. Also shown are the indices from the binomial model of presence/absence in this fishery and the combined delta-lognormal model (Eq. C.4). All indices are scaled so that their geometric means equal 1.0. Upper and lower 95% analytic confidence bounds and associated standard error (SE) are presented for the lognormal model, while bootstrapped upper and lower 95% confidence bounds and the associated SE are presented for the combined model.

Year	Arithmetic Index (Eq. C.1)	Geometric Index (Eq. C.2)	Lognormal (Eq. C.3)				Binomial Index (Eq. C.3)	Combined (Eq. C.4)			
			Index	Lower bound	Upper bound	SE		Index	Lower bound	Upper bound	SE
1996	0.719	0.983	1.121	0.890	1.209	0.0780	0.542	0.608	0.490	0.730	0.098
1997	0.724	0.989	1.283	1.069	1.318	0.0533	0.955	1.225	1.092	1.370	0.058
1998	0.608	0.841	1.126	0.946	1.147	0.0491	0.965	1.087	0.983	1.218	0.052
1999	0.863	1.055	1.207	1.016	1.227	0.0482	0.955	1.153	1.040	1.293	0.060
2000	1.109	1.209	1.137	0.967	1.143	0.0428	0.977	1.110	1.001	1.239	0.052
2001	1.419	1.238	1.033	0.876	1.041	0.0440	0.947	0.978	0.889	1.066	0.053
2002	1.681	1.521	1.292	1.103	1.295	0.0411	1.006	1.299	1.190	1.405	0.045
2003	1.166	1.055	0.884	0.754	0.888	0.0416	0.983	0.870	0.796	0.965	0.049
2004	0.827	1.087	0.934	0.793	0.941	0.0438	0.958	0.895	0.794	0.992	0.051
2005	0.657	0.720	0.684	0.582	0.688	0.0425	1.016	0.695	0.627	0.762	0.050
2006	0.955	0.973	0.926	0.787	0.932	0.0431	1.145	1.060	0.952	1.153	0.049
2007	1.191	0.973	0.926	0.784	0.936	0.0454	1.146	1.061	0.925	1.156	0.053
2008	0.972	1.131	1.032	0.865	1.054	0.0504	1.076	1.111	0.994	1.262	0.061
2009	1.268	1.329	1.211	1.022	1.227	0.0466	1.125	1.362	1.190	1.504	0.057
2010	0.791	0.828	0.883	0.743	0.898	0.0482	0.902	0.796	0.707	0.881	0.059
2011	1.129	0.905	0.888	0.747	0.903	0.0484	1.046	0.929	0.832	1.069	0.059
2012	0.793	0.850	0.868	0.730	0.883	0.0487	1.166	1.012	0.893	1.135	0.062
2013	1.293	0.976	1.001	0.835	1.026	0.0525	0.948	0.949	0.838	1.067	0.061
2014	1.275	1.428	1.247	1.044	1.275	0.0510	1.197	1.492	1.343	1.706	0.058
2015	1.180	0.893	0.905	0.753	0.930	0.0538	0.973	0.880	0.786	1.008	0.066
2016	1.066	0.700	0.793	0.666	0.808	0.0493	1.249	0.990	0.874	1.095	0.057
2017	0.761	0.757	0.846	0.701	0.875	0.0565	0.970	0.821	0.739	0.935	0.064
2018	1.396	1.032	1.081	0.891	1.122	0.0587	1.009	1.091	0.979	1.265	0.068



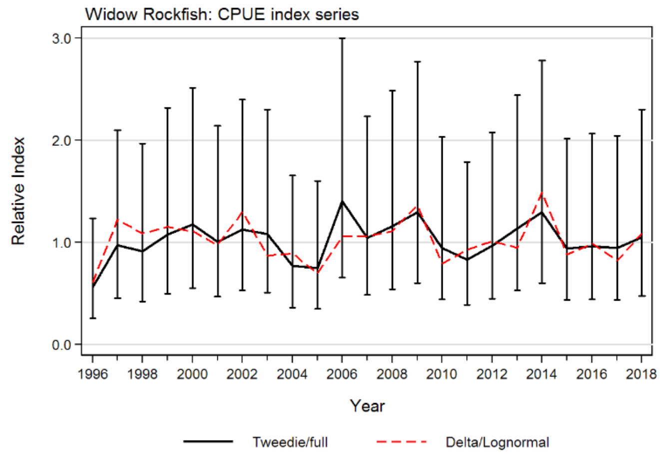


Figure C.16. Comparison of two standardised models using the 3CD5ABCDE bottom trawl fishery core vessel data set [left panel] median posterior estimates from the Tweedie model compared to the delta-lognormal based on the same data. [right panel] this is the same comparison shown in the left panel, except with added error bars (90% credibility intervals from the Bayesian Tweedie model posterior distribution).

C.7. REFERENCES – CPUE

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APPENDIX D. BIOLOGICAL DATA

This appendix describes analyses of Widow Rockfish (WWR) biological data from the British Columbia (BC) coast for the purposes of the derivation of the length-weight relationship, von Bertalanffy growth models, maturity schedule, and natural mortality for use in the WWR catch-at-age stock assessment model (see Sections D.1 and D.2). As well, these data were investigated for functional differences among areas as potential indicators of stock separation (Section D.3). All biological analyses are based on WWR data extracted from the Fisheries and Oceans Canada (DFO) Groundfish database `GFBioSQL` on 21 Mar 2019 (45,286 records). General data selection criteria for most analyses are summarized in Table D.1, although data selection can vary between analyses.

Table D.1. Data selection criteria for analyses of WWR biological data for allometric and growth analyses.

Field	Criterion	Notes
Trip type	`[trip_type] == c(2,3)` `[trip_type] == c(1,4,5)`	Definition of research observations. Definition of commercial observations
Sample type	`[sample_type] == c(1,2,6,7)`	Only random or total samples.

Ageing method	`[agemeth] == c(3, 17) or`
	`== 0 & [year]>=1980) or`
	`== 1 for ages 1:3`
		Break & burn|bake method, or unknown from 1980 onwards (assumed B&B); surface readings for young fish

Species category code	`[SPECIES_CATEGORY_CODE]==1 (or 3)`	1 = Unsorted samples 3 = Sorted (keeper) samples
Sex code	`[sex] == c(1,2)`	Clearly identified sex (1=male or 2=female).
Area code	`[stock]` select valid stock area (BC coast)	PMFC major area codes 3:9

Note that GFBioSQL data codes for `sex` (1=male, 2=female) are reversed in the catch-at-age model codes (1=female, 2=male).

D.1. LIFE HISTORY

D.1.1. Length-Weight

A log-linear relationship with additive errors was fit to females, males, and combined to all valid weight and length data pairs i, $\left\{W_{is}, L_{is}\right\}$:

$$\ln(W_{i\,s}) = \alpha_s + \beta_s \ln(L_{i\,s}) + \varepsilon_{i\,s}\,, \quad \varepsilon \sim N(0,\sigma^2) \tag{D.1}$$

where α_s and β_s are the intercept and slope parameters, respectively, for each sex s (2 for females, 1 for males).

Commercial and research survey samples, regardless of gear type, were used to derive length-weight parameters for consideration in the mode (Table D.2). Fits to data from Individual and grouped PMFC areas are reported, with only minor differences between areas evident. Only the coastwide fit (Figure D.1) was used in the model.

Table D.2. Length-weight parameter estimates, standard errors (SE) and number of observations (n) for Widow Rockfish (females, males and combined) for all commercial and survey samples, regardless of gear type from 1989 to 2018. W = specimen weight (kg), W_{pred} = predicted weight from fitted data set.

Area	Sex	*n*	ln(*a*)	SE ln(*a*)	*b*	SE *b*	mean W_i	SD W_i	min W_i	max W_i	mean W_{pred}
Coast	F	2,024	-11.323	0.0322	3.0545	0.0084	1.556	0.6170	0.012	3.244	1.506
	M	2,005	-11.603	0.0285	3.1281	0.0076	1.313	0.5488	0.018	2.908	1.247
	F+M	4,033	-11.490	0.0210	3.0981	0.0056	1.435	0.6001	0.010	4.670	1.377
3CD	F	445	-11.661	0.1145	3.1551	0.0301	1.491	0.5703	0.325	2.852	1.421
	M	376	-11.351	0.1391	3.0669	0.0372	1.181	0.3784	0.304	2.310	1.109
	F+M	822	-11.616	0.0880	3.1409	0.0233	1.350	0.5158	0.304	2.852	1.264
5ABC	F	891	-11.486	0.0370	3.0976	0.0099	1.407	0.6919	0.010	3.244	1.569
	M	949	-11.638	0.0331	3.1367	0.0090	1.189	0.6208	0.018	2.908	1.313
	F+M	1,840	-11.597	0.0247	3.1262	0.0066	1.294	0.6650	0.012	3.244	1.442
5DE	F	690	-10.774	0.0798	2.9062	0.0205	1.780	0.4725	0.192	2.833	1.732
	M	677	-11.317	0.0893	3.0519	0.0232	1.565	0.4173	0.202	2.660	1.513
	F+M	1,369	-11.022	0.0589	2.9724	0.0153	1.671	0.4617	0.176	2.833	1.626
3C	F	259	-11.826	0.1474	3.1995	0.0393	1.318	0.5584	0.325	2.852	1.242
	M	210	-11.811	0.1671	3.1939	0.0452	1.053	0.3730	0.304	2.310	0.988
	F+M	469	-11.838	0.1075	3.2020	0.0288	1.199	0.5014	0.304	2.852	1.112
3D	F	186	-11.300	0.2258	3.0609	0.0586	1.732	0.4953	0.544	2.848	1.644
	M	161	-10.763	0.3122	2.9090	0.0822	1.364	0.2983	0.610	2.110	1.266
	F+M	351	-11.472	0.1765	3.1014	0.0461	1.554	0.4634	0.468	2.848	1.455
5A	F	624	-11.919	0.0491	3.2079	0.0129	1.500	0.5767	0.012	3.244	1.360
	M	568	-11.833	0.0407	3.1818	0.0110	1.147	0.4639	0.018	2.276	1.066
	F+M	1,193	-11.880	0.0312	3.1961	0.0083	1.333	0.5548	0.012	3.244	1.219
5B	F	142	-11.037	0.0960	2.9849	0.0255	1.621	0.8602	0.010	4.670	2.093
	M	195	-11.450	0.0822	3.1013	0.0217	1.613	0.6459	0.060	2.908	1.817
	F+M	337	-11.221	0.0639	3.0378	0.0169	1.616	0.7426	0.010	4.670	1.950
5C	F	124	-11.569	0.0780	3.1378	0.0228	0.714	0.6643	0.014	2.766	1.132
	M	184	-11.409	0.0624	3.0790	0.0178	0.871	0.7655	0.044	2.637	1.186
	F+M	308	-11.451	0.0498	3.0960	0.0144	0.808	0.7294	0.014	2.766	1.165
5D	F	17	-8.862	0.7850	2.2940	0.2403	0.256	0.0346	0.192	0.304	0.770
	M	19	-10.196	1.2435	2.7005	0.3809	0.253	0.0317	0.202	0.328	0.935
	F+M	36	-9.353	0.6841	2.4430	0.2095	0.255	0.0327	0.192	0.328	0.824
5E	F	675	-10.149	0.1192	2.7465	0.0305	1.816	0.4144	0.470	2.833	1.772
	M	657	-11.020	0.1455	2.9750	0.0377	1.603	0.3574	0.590	2.660	1.539
	F+M	1,332	-10.431	0.0901	2.8206	0.0232	1.711	0.4015	0.470	2.833	1.660

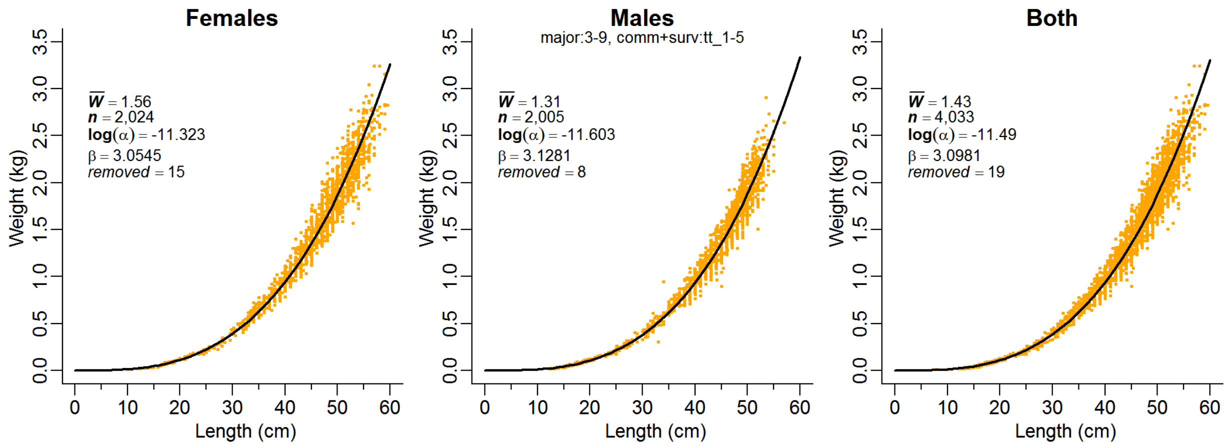

Figure D.1. Length-weight relationship for the coastwide stock of WWR – derived from commercial and research survey samples, regardless of gear type. Records with absolute value of standardised residuals >3 (starting with a preliminary fit) were dropped, removing 19 observations for the combined-sex fit.

D.1.2. von Bertalanffy Growth

Survey otolith age data were sparse and potentially biased, given the midwater behaviour of this species; therefore, data from the commercial fishery and research surveys were combined for use in determining growth. Paired observations i of length and age by sex, $\{L_{is}, a_{is}\}$, for $s = 2,1$ (females, males) were selected from 12,577 specimens, 90 with surface-read otoliths and 12,487 using the break and burn (B&B) method (MacLellan 1997). Table D.3 summarises the availability of WWR otoliths.

Table D.3. Number of WWR specimen otoliths aged by break-and-burn (B&B) and surface reading in GFBioSQL database (accessed 2019-03-21). Number of samples appear in parentheses and are not cumulative (i.e., otoliths by sex usually come from the same sample).

Trip Type	Activity	Age method	Female	Male	Unknown
Non-obs. domestic	commercial	B&B	1490 (79)	1609 (79)	---
Research	survey	B&B	18 (2)	9 (2)	---
		Surface	1 (1)	5 (1)	---
Charter	survey	B&B	292 (12)	311 (12)	---
		Surface	30 (2)	53 (2)	1 (1)
Observed domestic	commercial	B&B	4170 (220)	4412 (218)	79 (15)
Observed J-V	commercial	B&B	40 (2)	57 (2)	---

Growth was formulated as a von Bertalanffy model where lengths by sex, L_{is}, for fish $i = 1,\ldots,n_s$ are given by:

$$L_{is} = L_{\infty s}\left[1 - e^{-\kappa_s(a_{is}-t_{0s})}\right] + \varepsilon_{is}\,, \quad \varepsilon \sim N(0,\sigma^2) \qquad \text{(D.2)}$$

where for each sex s,

$L_{\infty s}$ = the average length at maximum age of an individual,

κ_s = growth rate coefficient, and

t_{0s} = age at which the average size is zero.

The negative log likelihood for each sex s, used for minimisation is:

$$\ell(L_\infty, \kappa, t_0, \sigma) = n\ln(\sigma) + \frac{\sum_i^n (L_i - \widehat{L_i})^2}{2\sigma^2}, \qquad i = 1, \dots, n.$$

Fits to growth (Table D.4, Figure D.2) show that WWR females are larger than WWR males. Area-specific parameter estimates differ little between areas. Only the sex-specific coastwide parameters (L_∞, K, t_0) in Table D.4 were used in the population model. Regional growth fits are reported for posterity.

Table D.4. Age-length parameter estimates for WWR (females, males, combined) from von Bertalanffy growth model fits for all commercial and survey samples, regardless of gear type, coastwide and regionally.

c	Sex	n	L_∞(cm)	K	t_0 (cm)	σ
Coast	F	5,949	52.8	0.1732	-0.8	2.52
	M	6,353	49.0	0.1965	-0.9	2.56
	F+M	12,327	50.8	0.1855	-0.8	2.81
3CD	F	2,125	53.3	0.1601	-1.3	2.52
	M	2,304	47.9	0.2078	-0.8	2.52
	F+M	4,457	43.5	0.9852	-4.8	5.42
5ABC	F	2,940	52.7	0.1767	-0.7	2.35
	M	3,240	49.4	0.1948	-0.8	2.42
	F+M	6,192	50.8	0.1882	-0.7	2.64
5DE	F	906	53.2	0.1256	-5.0	3.23
	M	828	49.2	0.1447	-5.0	3.25
	F+M	1,728	51.5	0.1315	-5.0	3.37
3C	F	655	54.2	0.1233	-3.1	2.46
	M	741	46.4	0.2177	-1.0	2.27
	F+M	1,396	49.0	0.1869	-1.2	2.60
3D	F	1,468	53.5	0.1620	-1.3	2.46
	M	1,563	48.1	0.2142	-0.5	2.58
	F+M	3,041	50.9	0.1824	-1.0	2.90
5A	F	2,400	52.1	0.1825	-0.7	2.28
	M	2,224	47.8	0.2236	-0.6	2.28
	F+M	4,636	50.5	0.1902	-0.7	2.58
5B	F	509	53.7	0.1800	-0.4	2.42
	M	911	49.8	0.2133	-0.3	2.35
	F+M	1,422	50.9	0.2112	-0.2	2.78
5C	F	30	54.1	0.1799	-0.4	1.75
	M	100	51.4	0.2417	1.6	2.08
	F+M	130	51.6	0.2636	2.0	2.09
5D	F	72	55.7	0.1265	-3.2	2.08
	M	62	50.4	0.1745	-2.4	1.94
	F+M	134	51.7	0.1816	-1.4	2.16
5E	F	833	52.9	0.1290	-5.0	3.28
	M	770	49.0	0.1464	-5.0	3.41
	F+M	1,597	51.4	0.1333	-5.0	3.49

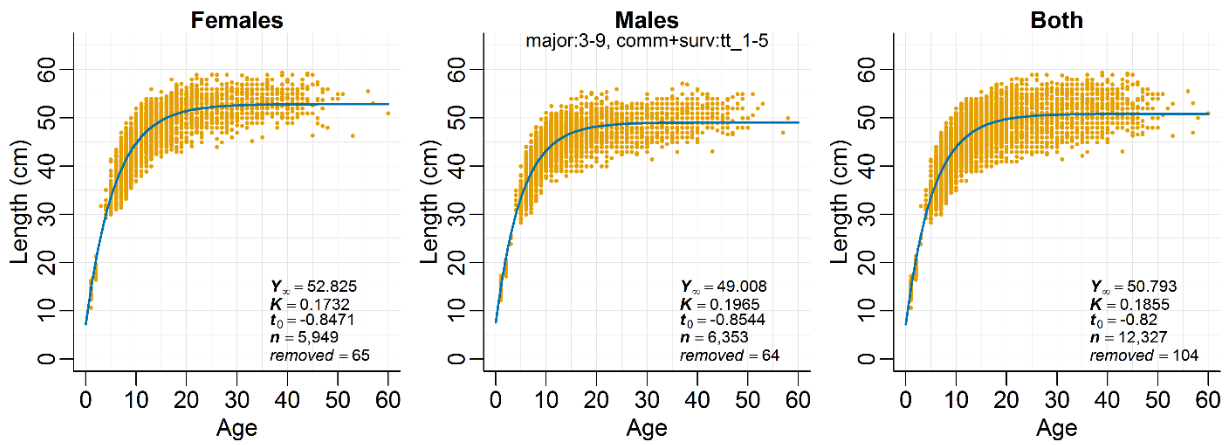

Figure D.2. Growth specified by age-length relationship: von Bertalanffy fits to WWR ages determined by break-and-burn otoliths and surface-read otoliths from ages 1 to 3. Records with absolute value of standardised residuals >3 (starting with a preliminary fit) were dropped.

D.1.3. Age Distribution

The median age of WWR appeared to be inconsistent across the PMFC areas, with older fish predominating in 5B and sometimes 5C and 5E (Figure D.3). Hicks and Wetzel (2015) noted a similar age distribution of cohorts (young in the south to older in the north) along the US continental Pacific coast. However, the scarcity of the BC survey samples might indicate that older fish were sampled by chance. This can be seen by comparing the survey 5E age distribution with that of the commercial fishery, which does not indicate that 5E fish are older than those in most other areas. The distribution in 5BC sampled from the commercial fishery does suggest that older fish live here, but this seems to be a sampling artefact in that 5B is over-represented by sorted samples (samples selected based on size or sex) that occurred earlier in the time series (Figure D.4, Table D.5). Additionally, the fishing industry catches resting (non-spawning) WWR in QC Sound shelf localities (primarily 5B) in the summer, which could skew the age distribution for this area during this time of year (see Section D.3.4).

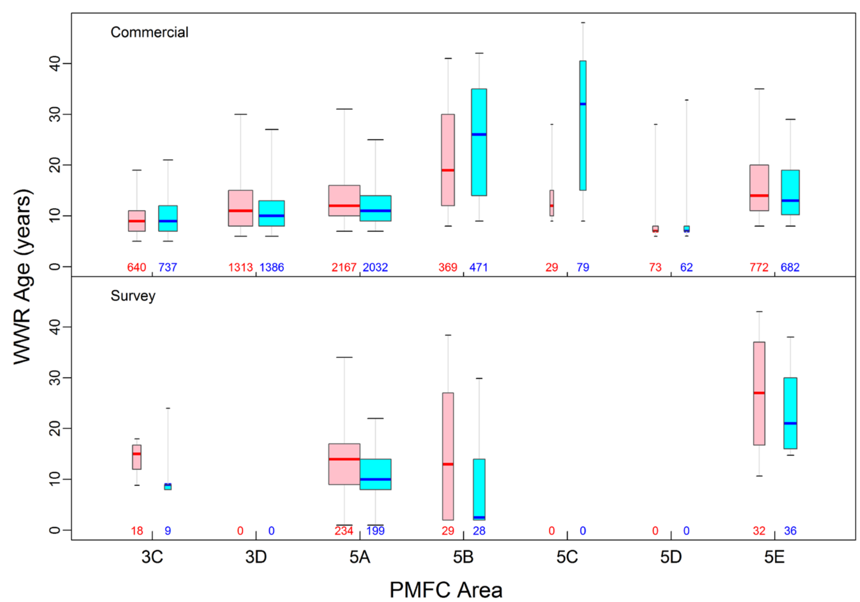

Figure D.3. Quantile plots of WWR age by sex and PMFC area for commercial trips (top) and surveys (bottom) from 1990 to 2018. Each quantile box includes all years with number of ages reported beneath.

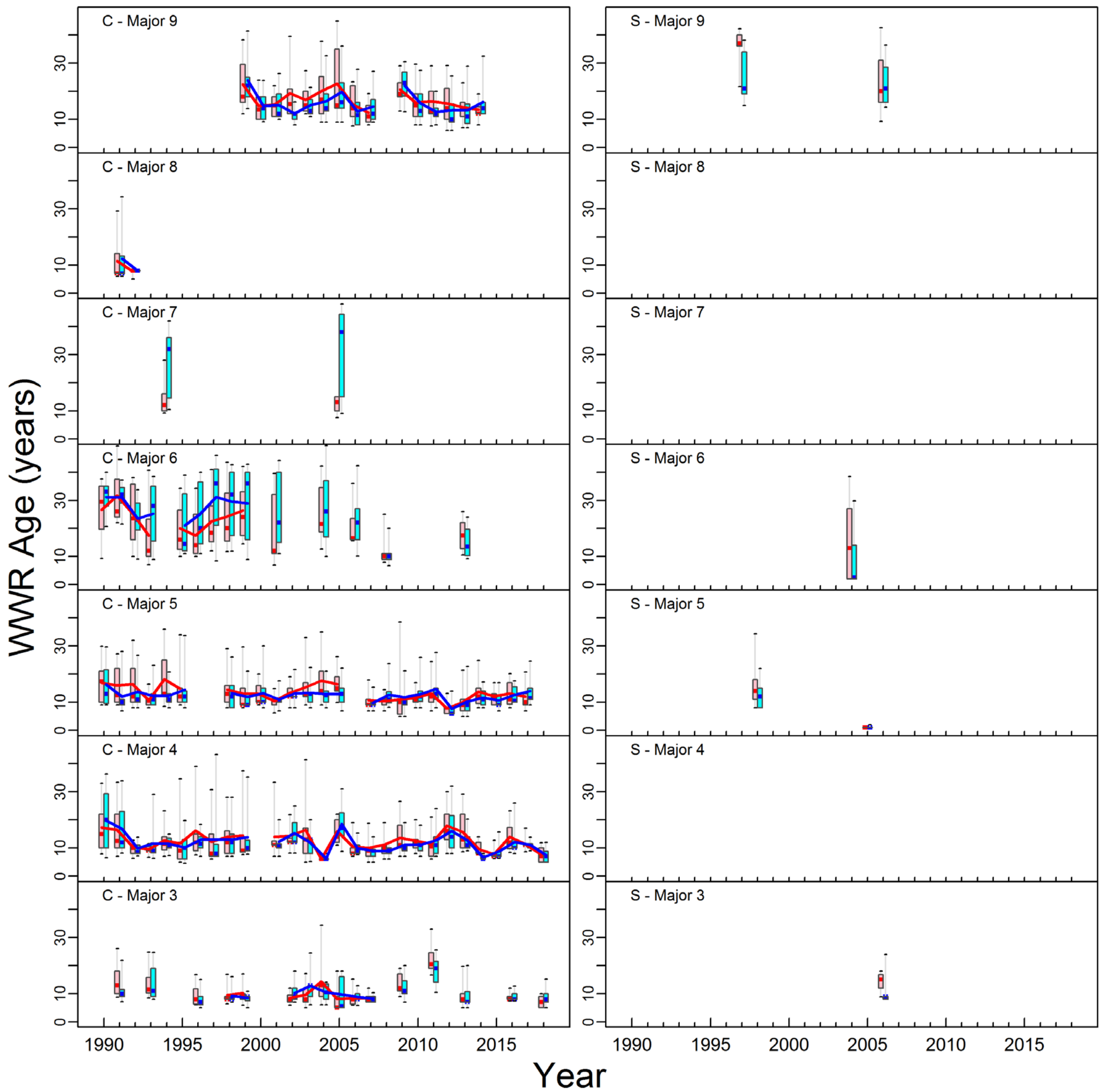

Figure D.4. Quantile plots of annual WWR age by sex and PMFC area for commercial trips (C) and surveys (S); PMFC major codes: 3=3C, 4=3D, 5=5A, 6=5B, 7=5C, 8=5D, 9=5E. The trends in mean age for females (red lines) and males (blue lines) are displayed when years are contiguous.

Table D.5. Mean age of WWR by PMFC area for three trawl gear types from 1990 to 2018; table entries show mean age for n fish (in parentheses) for unsorted and sorted samples (by size and/or sex).

Samp→	Unsorted			Sorted		
PMFC↓	Bottom	Midwater	Unknown	Bottom	Midwater	Unknown
3C	9.3 (n=99)	10.1 (n=638)	---	12.4 (n=29)	10.1 (n=590)	13.1 (n=53)
3D	14.2 (n=176)	11.1 (n=1229)	15 (n=62)	16.8 (n=140)	13.3 (n=919)	13 (n=185)
5A	10.2 (n=348)	13.5 (n=1732)	11.7 (n=93)	14.3 (n=341)	13.7 (n=1604)	15.1 (n=573)
5B	18.3 (n=126)	23.5 (n=76)	11.6 (n=96)	25.0 (n=82)	27.4 (n=304)	22.3 (n=217)
5C	---	---	---	29.2 (n=48)	21.6 (n=60)	---
5D	---	---	---	6.9 (n=48)	---	13.2 (n=87)
5E	17.8 (n=450)	13.4 (n=317)	13.7 (n=43)	16.6 (n=435)	17.6 (n=277)	---

D.1.4. Maturity

This analysis was based on all "staged" (examined for maturity status) females in the DFO GFBioSQL database. Maturity codes for WWR in the database (Table D.6) come from `MATURITY_CONVENTION_CODE = 1`, which describes 7 maturity conditions for Rockfish (1977+).

Table D.6. GFBio maturity codes for rockfish, including BC WWR.

Code	Female	Male
1	Immature - translucent, small	Immature - translucent, string-like
2	Maturing - small yellow eggs, translucent or opaque	Maturing - swelling, brown-white
3	Mature - large yellow eggs, opaque	-
4	Fertilized - large, orange-yellow eggs, translucent	Mature - large white, easily broken
5	Embryos or larvae - includes eyed eggs	Ripe - running sperm
6	Spent - large flaccid red ovaries; maybe a few larvae	Spent - flaccid, red
7	Resting - moderate size, firm, red-grey ovaries	Resting - ribbon-like, small brown

Bubble plots of frequency data (maturity vs. month) derived from various sources appear in Figure D.5. Ideally, lengths- and ages-at-maturity are calculated at times of peak development stages (males: insemination season, females: parturition season; Westrheim 1975). However, all months were used in creating the maturity curve because these data provided cleaner fits than using a subset of months.

For the maturity analysis, all stages 3 and higher were assumed to be mature, and a maturity ogive was fit to the filtered data using a double-normal model:

$$m_{as} = \begin{cases} e^{-(a-\nu_s)^2/\rho_{sL}}, & a \le \nu_s \\ 1, & a > \nu_s \end{cases} \qquad \text{(D.3)}$$

where, m_{as} = maturity at age a for sex s (combined),

ν_s = age of full maturity for sex s,

ρ_{sL} = variance for the left limb of the maturity curve for sex s.

To estimate a maturity ogive, the biological data were qualified as follows:

- `stocks – coastwide` `major=3:9` 45,217 records
- ageing method (see note below) `ameth = c(0,1,3,17)` 12,432 records
- `sample type – total catch/random` `stype = c(1,2,6,7)` 12,431 records
- species category (unsorted) `scat = 1` 12,431 records
- `sex – females only` `sex = 2` 6,014 records
- maturity codes for rockfish `mats = c(1:7)` 3,653 records
- `ogive age limits` `age = c(0,40)` `3,602 records`
- `trip type – commercial + survey` `ttype = c(1:10)` 3,602 records
- month – all months `month = c(1:12)` 3,602 records

Generally, rockfish biological analyses use ages from otoliths processed and read using the ‘break and burn’ procedure (`ameth=3`) or coded as ‘unknown’ (`ameth=0`) but processed in 1980 or later. There is also a method termed ‘break and bake’ (`ameth=17`); however, no WWR were processed using this technique. Finally rockfish otoliths aged 1-3 y are sometimes processed using surface readings (`ameth=1`) because the ageing lab finds this technique more reliable than B&B for very young fish; see Table D.3 for WWR otoliths processed.

The above qualification yielded 3,602 female specimens with maturity readings and valid ages. Mature specimens comprised those coded 3 to 7 for rockfish (Table D.6). The empirical proportion of mature females at each age was calculated (Table D.7). A double-normal function (Eq. D.3) was fit to the observed proportions mature at ages 1 to 40 to smooth the observations and determine an increasing monotonic function for use in the stock assessment model (Figure D.6). Additionally, a logistic function used by Vivian Haist (VH) for length models in New Zealand rock lobster assessments (Haist et al. 2009) was used to compare with the double normal model.

Following a procedure adopted by Stanley et al. (2009) for Canary Rockfish (*S. pinniger*), the proportions mature for young ages fitted by Eq. D.3 were not used because the fitted line may overestimate the proportion of mature females (Figure D.6). Therefore, the maturity ogive used in the stock assessment model (last column in Table D.7) set proportion mature to zero for ages 1 to 4, then switched to the fitted monotonic function for ages 5 to 40, all forced to 1 (fully mature) after age 12. This strategy follows previous assessments on BC rockfish where younger ages are not well sampled and those that are tend to be larger and more likely to be mature. The function of this ogive in the stock assessment model is to calculate the spawning biomass used in the Beverton-Holt stock recruitment function, and is treated as a constant known without error. The ages at 50% and full maturity are estimated from the double-normal fit at 8.2 y and 12.4 y, respectively.

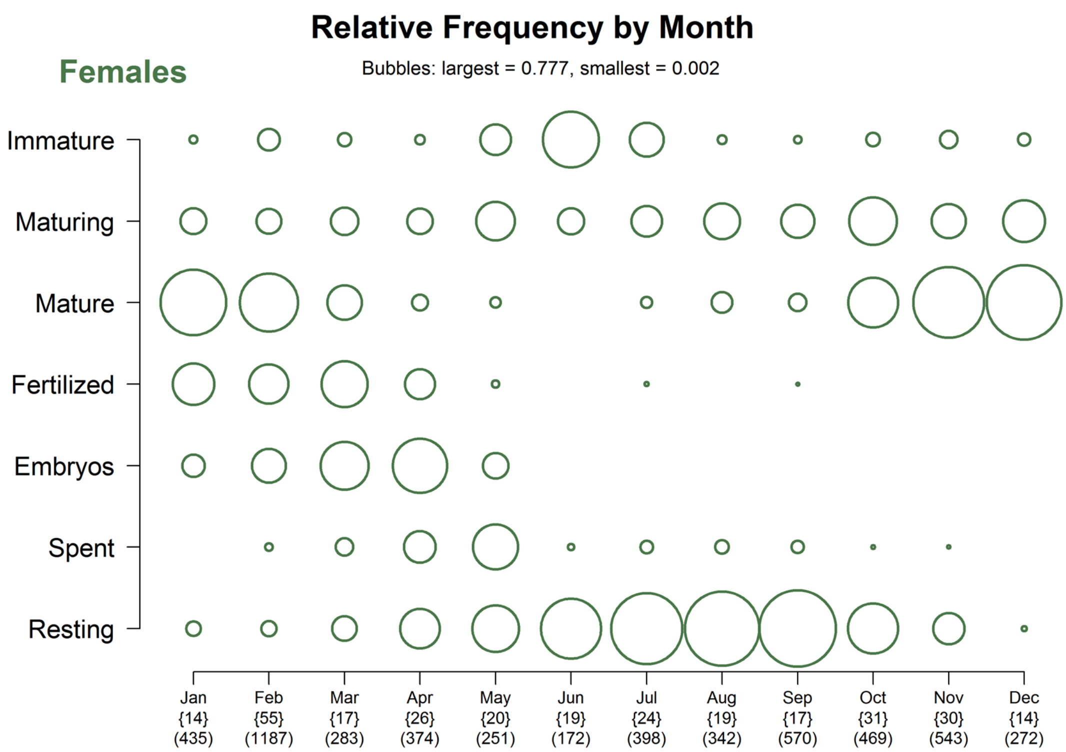

Figure D.5. Relative frequency of maturity codes by month for WWR females. Data include maturities from commercial and research specimens. Frequencies are calculated among each maturity category for every month.

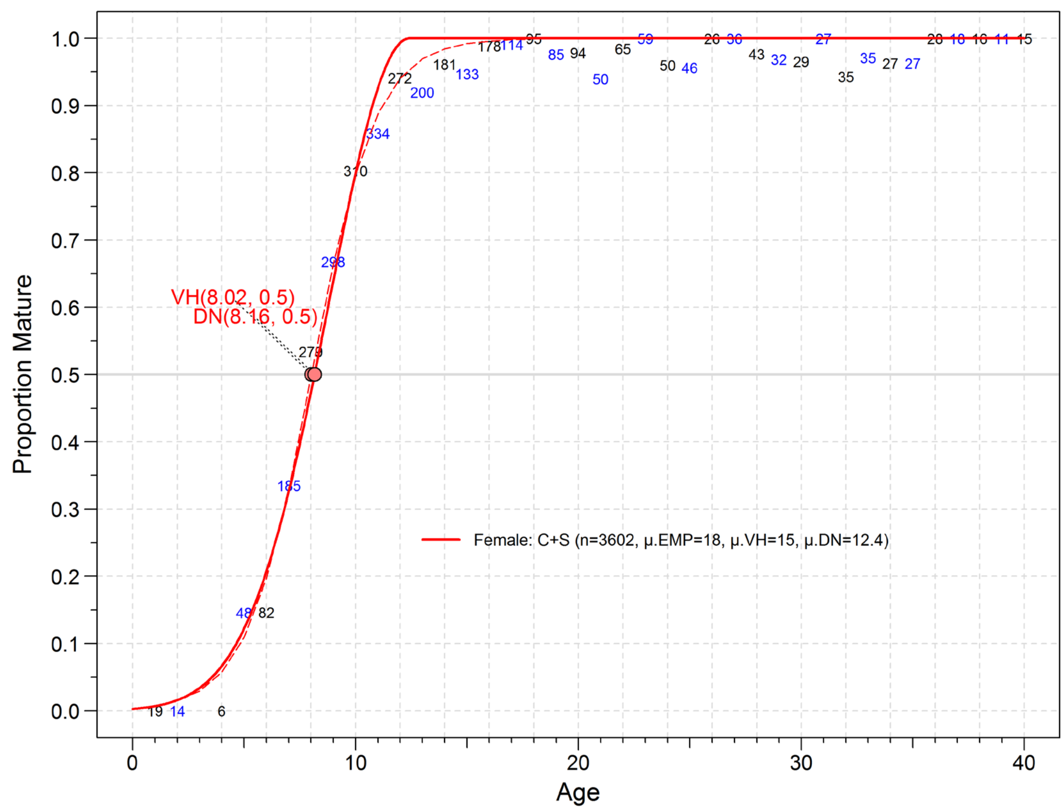

Figure D.6. Maturity ogives for WWR females. Solid line shows the double-normal (DN) curve fit; dashed line shows the logistic model fit (VH = Vivian Haist); numbers in alternating blue and black (for clarity only) denote number of female specimens used to calculate the input proportions-mature (EMP =empirical); crosses indicate values used in the model. Estimated ages at 50% maturity are indicated along the median line; ages at full maturity (µ.EMP, µ.VH, µ.DN) are displayed in the legend.

Table D.7. Proportion of WWR females mature by age (m_a, e.g., Eq.D.3) used in the catch-age model (final column). Maturity stages 1 and 2 were assumed to be immature fish and all other staged fish (stages 3 to 7) were assumed to be mature. EMP = empirical, BL = binomial logit, VH =logistic used by Vivian Haist, DN = double normal (Eq.D.3), Model = used in population model.

Age	# Fish	EMP m_a	BL m_a	VH m_a	DN m_a	Model m_a
1	19	0	0.062	0.0076	0.0069	0
2	14	0	0.0912	0.015	0.0159	0
3	0	-	0.1323	0.0296	0.0339	0
4	6	0	0.1881	0.0577	0.0669	0
5	48	0.1458	0.2604	0.1092	0.1224	0.1224
6	82	0.1463	0.3484	0.1971	0.2076	0.2076
7	185	0.3351	0.4482	0.3296	0.3261	0.3261
8	279	0.5341	0.5524	0.4961	0.4746	0.4746
9	298	0.6678	0.6522	0.6635	0.6401	0.6401
10	310	0.8032	0.7401	0.798	0.7998	0.7998
11	334	0.8593	0.8123	0.8878	0.926	0.926
12	272	0.9412	0.868	0.9406	0.9933	0.9933
13	200	0.9200	0.909	0.9694	1	1
14	181	0.9613	0.9382	0.9845	1	1
15	133	0.9474	0.9584	0.9922	1	1

Age	# Fish	EMP m_a	BL m_a	VH m_a	DN m_a	Model m_a
16	178	0.9888	0.9722	0.9961	1	1
17	114	0.9912	0.9815	0.998	1	1
18	95	1	0.9878	0.999	1	1
19	85	0.9765	0.9919	0.9995	1	1
20	94	0.9787	0.9947	0.9998	1	1
21	50	0.94	0.9965	0.9999	1	1
22	65	0.9846	0.9977	0.9999	1	1
23	59	1	0.9985	1	1	1
24	50	0.96	0.999	1	1	1
25	46	0.9565	0.9993	1	1	1
26	26	1	0.9996	1	1	1
27	36	1	0.9997	1	1	1
28	43	0.9767	0.9998	1	1	1
29	32	0.9688	0.9999	1	1	1
30	29	0.9655	0.9999	1	1	1
31	27	1	0.9999	1	1	1
32	35	0.9429	1	1	1	1
33	35	0.9714	1	1	1	1
34	27	0.963	1	1	1	1
35	27	0.963	1	1	1	1
36	28	1	1	1	1	1
37	18	1	1	1	1	1
38	16	1	1	1	1	1
39	11	1	1	1	1	1
40	15	1	1	1	1	1

D.1.5. Natural Mortality

Natural mortality (*M*) estimates for Widow Rockfish exhibit a large range in the literature. At the lower end, *M* is set to 0.05 for WWR in the assessment of 17 Tier 5 species in the Gulf of Alaska (Tribuzio et al. 2017). Along the west coast of the USA south of BC, Hicks and Wetzel (2015) use a lognormal prior, based on work by Owen Hamel using a maximum age of 54 y, with a median of 0.081 (-2.513 in log space) and a standard deviation in log space of 0.524. Despite the informed prior, the model-estimated *M* for females and males (with 0.125 and 0.875 quantiles) was 0.157 (0.145, 0.170) and 0.171 (0.158, 0.183), respectively. These estimates are much higher than those estimated using BC WWR data.

The main difference between the US model and the BC model is the use of fleets. Hicks and Wetzel (2015) specify five fleets: (i) shore-based bottom trawl, (ii) shore-based midwater trawl, (iii) various trawl operations that target Pacific Hake, (iv) a California net fishery, and (v) a hook and line (predominantly longline) fishery. The BC model uses only one fleet that comprises bottom and midwater trawls combined, based on results from a technical working group that found no clear evidence that the fleets should be separated (see Section D.3.2).

In the DFO database GFBioSQL, the maximum age is 60 years for one female specimen (51 cm in length) caught in PMFC area 3D, specifically in a fishing locality called “Nootka” (major=4, minor=25, locality=2), on Jun 27, 1996. The mean age for BC WWR is 14.7 y (n=12,491), the median age is 12 y, and the 0.025. 0.975, and 0.99 quantiles are 5, 38, and 43 y, respectively.

The Hoenig (1983) estimator describes an exponential decay LN(k) = $-Z\ t_L$, where Z = natural mortality, t_L = longevity of a stock, and k = proportion of animals that are still alive at t_L. Quinn and Deriso (1999) popularised the estimator by re-arranging Hoenig's equation and setting *k*=0.01 (as originally suggested by Hoenig):

$$M = -\ln(0.01) / t_{\max} \tag{D.4}$$

Then et al. (2015) revisited various natural mortality estimators and recommended the use of an updated Hoenig estimator based on nonlinear least squares:

$$M_{\text{est}} = 4.899 t_{\max}^{-0.916} \tag{D.5}$$

where t_{max} = maximum age.

During the review process for Redstripe Rockfish (DFO in prep[3]), one of the principal reviewers noted that Then et al. (2015) did not consistently apply a log transformation. In real space, one might expect substantial heteroscedasticity in both the observation and process errors associated with the relationship of M to t_{max}. Re-evaluating the data used in Then et al. (2015) by fitting the one-parameter t_{max} model using a log-log transformation (such that the slope is forced to be -1 in the transformed space, as in Hamel 2015), the point estimate for M becomes:

$$M_{\text{est}} = 5.4 / t_{\max} \tag{D.6}$$

In past assessment meetings, participants have been averse to adopting a maximum age that comes form a single, usually isolated individual, preferring instead to observe the tail distribution of ages (Figure D.7). For WWR, this suggests that age 55 y might be a more appropriate value for t_{max}, which means that M ranges from 0.08 (using Hoenig) to 0.10 (using Hamel, Table D.8). In this assessment, M is fixed to three values (0.07, 0.08, 0.09) for a variety of reasons discussed in the main document.

Table D.8. Estimates of WWR natural mortality using equations based on fish longevity. Three upper age values (t_{max}) are used to illustrated the variability in M base on maximum age.

Source	Equation	t_{max}= 50y	= 55y	= 60y
Hoenig (1983)	M = -LN(0.01)/tmax	0.092	0.084	0.077
Then et al. (2015)	M = 4.899(tmax^-0.916)	0.136	0.125	0.115
Hamel (2015)	M = 5.4/tmax	0.108	0.098	0.090

[3] DFO. in prep. Proceedings of the Pacific regional peer review on the Redstripe Rockfish (*Sebastes proriger*) stock assessment for British Columbia in 2018; June 13-14, 2018. DFO Can. Sci. Advis. Sec. Proceed. Ser.

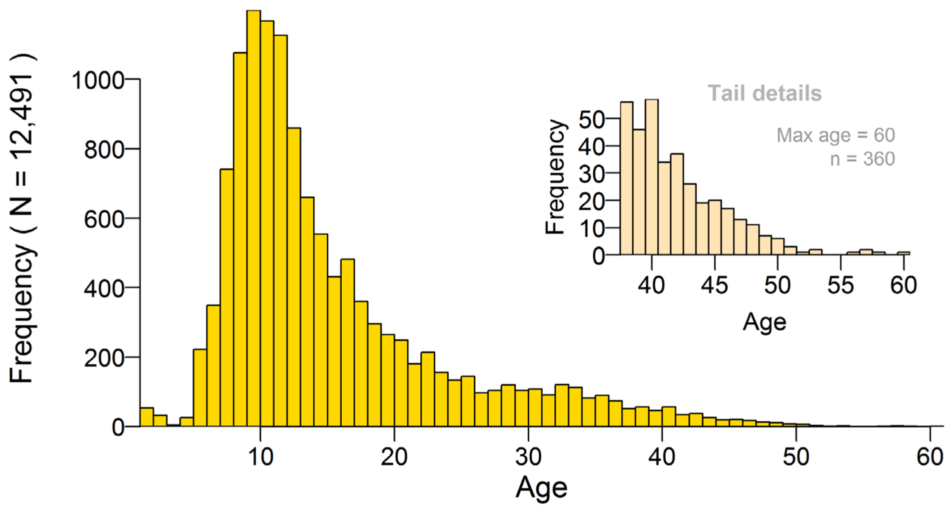

Figure D.7. Distribution of female + male ages; inset shows details for ages >=38 y old, which is the 0.975 quantile of the complete age data set.

D.2. WEIGHTED AGE PROPORTIONS

This section summarises a method for representing commercial and survey age structures in the stock assessment model for a given species (herein called 'target') through weighting observed age frequencies x_a or proportions x'_a by catch‖density in defined strata (*h*). (Throughout this section, the symbol '‖' is used to delimit parallel values for commercial and survey analyses, respectively, as the mechanics of the weighting procedure are similar for both. The symbol can be read 'or', e.g., catch or density.) For commercial samples, these strata comprise quarterly periods within a year, while for survey samples, the strata are defined by longitude, latitude, and depth boundaries unique to each survey series. A two-tiered weighting system is used as follows:

Within each stratum *h*, commercial age samples are identified by trip (usually one sample per trip) and the age frequencies per trip are weighted by the target catch weight (tonnes) of the tows that were sampled to yield one weighted age frequency per stratum (quarter). For each year, the quarterly age frequencies are then weighted by the quarterly fishery catch of the target. If a quarter has not been sampled, it does not get used in the weighting for the year. For example, if samples of the target were missing in Oct-Dec 2018, only the first three quarters of target catch would be used to prorate three quarterly age frequencies in 2018.

Annual survey ages are weighted similarly. Each sampled tow in a survey stratum is weighted by the tow's target catch density (t/km^2) to yield one weighted age frequency per stratum. As above, not all survey strata will have age samples and so weighted age frequencies by sampled stratum are weighted by the appropriate stratum area (km^2). For example, if only shallow strata are sampled for age, the deep strata areas are not used to prorate the shallow-strata age frequencies. As for commercial ages, the two-tiered weighting scheme yields one age frequency per survey year.

Ideally, sampling effort would be proportional to the amount of the target caught, but this is not usually the case. Personnel can control the sampling effort on surveys more than that aboard commercial vessels, but the relative catch among strata over the course of a year or survey cannot be known with certainty until the events have occurred. Therefore, the stratified weighting scheme outlined above and detailed below attempts to adjust for unequal sampling effort among strata.

For simplicity, the weighting of age frequencies x_a is used for illustration, unless otherwise specified. The weighting occurs at two levels: h (quarters for commercial ages, strata for survey ages) and i (years if commercial, stratum areas if survey). Notation is summarised in Table D.9.

Table D.9. Equations for weighting age frequencies or proportions; (c) = commercial, (s) = survey.

Indices

Symbol	Description
a	age class (1 to A, where A is an accumulator age-class)
d	(c) trip ID as sample unit (usually one sample per trip) (s) sample ID as sample unit (usually one sample per survey tow)
h	(c) calendar year quarter (1 to 4), 91.5 days each (s) survey stratum (area-depth combination)
i	(c) calendar year (1977 to present) (s) single survey ID in survey series (e.g., 2003 QCS Synoptic)

Data

Symbol	Description
x_{adhi}	observations-at-age a for sample unit d in quarter‖stratum h of year‖survey i
x'_{adhi}	proportion-at-age a for sample unit d in quarter‖stratum h of year‖survey i
C_{dhi}	(c) commercial catch (tonnes) of the target for sample unit d in quarter h of year i (s) density (t/km^2) of the target for sample unit d in stratum h of survey i
C'_{dhi}	C_{dhi} as a proportion of total catch‖density $C_{hi} = \sum_d C_{dhi}$
y_{ahi}	weighted age frequencies at age a in quarter‖stratum h of year‖survey i
K_{hi}	(c) total commercial catch (t) of the target in quarter h of year i (s) stratum area (km^2) of stratum h in survey i
K'_{hi}	K_{hi} as a proportion of total catch‖area $K_i = \sum_h K_{hi}$
p_{ai}	weighted frequencies at age a in year‖survey i
p'_{ai}	weighted proportions at age a in year‖survey i

For each quarter‖stratum h, sample unit frequencies x_{ad} are weighted by sample unit catch‖density of the target species. (For commercial ages, trip is used as the sample unit, though at times one trip may contain multiple samples. In these instances, multiple samples from a single trip will be merged into a single sample unit.) Within any quarter‖stratum h and year‖survey i there is a set of sample catches‖densities C_{dhi} that can be transformed into a set of proportions:

$$C'_{dhi} = C_{dhi} \Big/ \sum_d C_{dhi} \ . \tag{D.7}$$

The proportion C'_{dhi} is used to weight the age frequencies x_{adhi} summed over d, which yields weighted age frequencies by quarter‖stratum for each year‖survey:

$$y_{ahi} = \sum_{d} \left(C'_{dhi} x_{adhi} \right). \quad \text{(D.8)}$$

This transformation reduces the frequencies x from the originals, and so y_{ahi} is rescaled (multiplied) by the factor

$$\sum\nolimits_a x_{ahi} \Big/ \sum\nolimits_a y_{ahi} \quad \text{(D.9)}$$

to retain the original number of observations. (For proportions x' this is not needed.) Although this step is performed, it is strictly not necessary because at the end of the two-step weighting, the weighted frequencies are transformed to represent proportions-at-age.

At the second level of stratification by year‖survey i, the annual proportion of quarterly catch (t) for commercial ages or the survey proportion of stratum areas (km^2) for survey ages is calculated

$$K'_{hi} = K_{hi} \Big/ \sum\nolimits_h K_{hi} \quad \text{(D.10)}$$

to weight y_{ahi} and derive weighted age frequencies by year‖survey:

$$p_{ai} = \sum_{h} \left(K'_{hi} y_{ahi} \right). \quad \text{(D.11)}$$

Again, if this transformation is applied to frequencies (as opposed to proportions), it reduces them from the original, and so p_{ai} is rescaled (multiplied) by the factor

$$\sum\nolimits_a y_{ai} \Big/ \sum\nolimits_a p_{ai} \quad \text{(D.12)}$$

to retain the original number of observations.

Finally, the weighted frequencies are transformed to represent proportions-at-age:

$$p'_{ai} = p_{ai} \Big/ \sum\nolimits_a p_{ai} \,. \quad \text{(D.13)}$$

If initially we had used proportions x'_{adhi} instead of frequencies x_{adhi}, the final transformation would not be necessary; however, its application does not affect the outcome.

The choice of data input (frequencies x vs. proportions x') can sometimes matter: the numeric outcome can be very different, especially if the input samples comprise few observations. Theoretically, weighting frequencies emphasises our belief in individual observations at specific ages while weighting proportions emphasises our belief in sampled age distributions. Neither method yields inherently better results; however, if the original sampling methodology favoured sampling few fish from many tows rather than sampling many fish from few tows, then weighting frequencies probably makes more sense than weighting proportions. In this assessment, age frequencies x are weighted.

D.2.1. Commercial Ages

Sampled age frequencies from bottom and midwater trawl were combined after comparing cumulative age frequencies for each gear type by sex and capture year. It was concluded that there were no consistent differences in the age frequencies between the two gear types for either sex (females: Figure D.8, males: Figure D.9), leading to the conclusion that a model would estimate similar selectivities for each capture method. Furthermore, there were insufficient AF samples for bottom trawl to reliably separate the two gear types into independent fisheries (Table D.10). Consequently, the model was run assuming a joint selectivity for the two fishing methods by combining the AFs and the catch data into a single fishery.

The 2018 stock assessment of Redstripe Rockfish (Starr and Haigh, 2021) did not separate sorted (by size or sex) and unsorted samples when introducing proportions-at-age into the model. This practice was also followed for the WWR stock assessment after exploratory runs using only sorted and only unsorted samples were examined. Because sorted samples tend to occur in earlier years (1989-2009 for WWR) while unsorted samples occur in later years (1996-2018 for WWR), dropping the sorted samples loses information about early recruitment strength. In the case of WWR, an MPD model fit using sorted samples identified a large 1990 recruitment spike whereas an MPD model fit using unsorted samples estimated a large 1961 recruitment spike. The central run MPD fit estimated both years to be equally important, probably because composition information was more complete. Generally, using unsorted samples is best left to analyses of mean weight over time (e.g., Section D.3.1), which is often used in delay-difference models.

Table D.10. Number of WWR age samples from commercial trips by gear type (BT= bottom trawl, MW=midwater trawl).

Year	BT	MW	Year	BT	MW	Year	BT	MW	Year	BT	MW
1980	-	-	1990	3	9	2000	5	12	2010	1	9
1981	-	-	1991	5	5	2001	4	11	2011	3	6
1982	-	-	1992	-	2	2002	2	4	2012	4	4
1983	-	-	1993	-	-	2003	2	14	2013	5	6
1984	-	-	1994	-	4	2004	7	10	2014	1	2
1985	-	-	1995	1	9	2005	2	10	2015	-	3
1986	-	1	1996	-	7	2006	2	3	2016	-	2
1987	-	-	1997	-	4	2007	1	7	2017	-	2
1988	-	1	1998	2	22	2008	-	3	2018	1	2
1989	3	6	1999	2	7	2009	4	10	2019	-	-

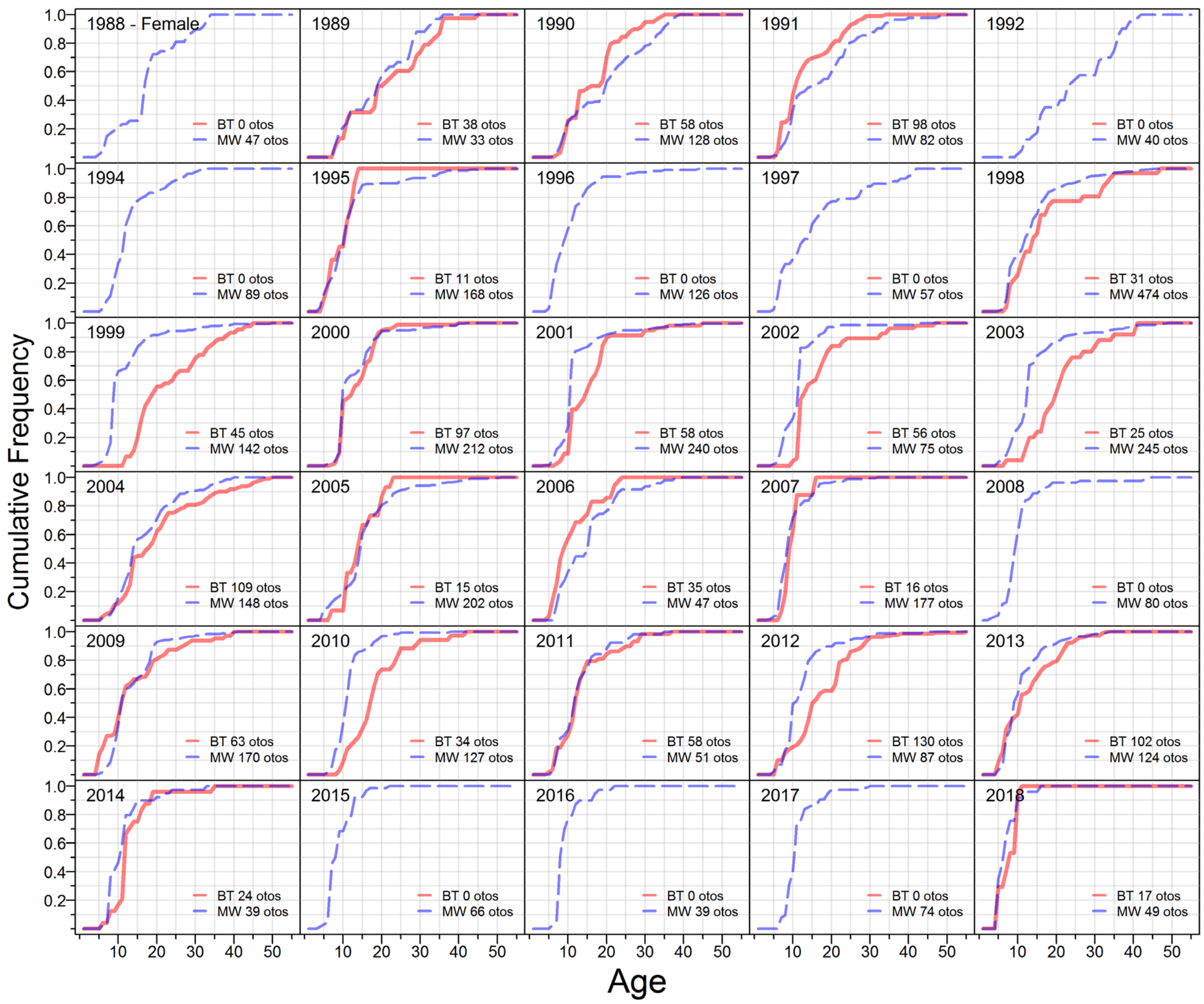

Figure D.8. Plots comparing the cumulative bottom trawl (red) and midwater trawl (blue) age frequencies by year for female WWR coastwide.

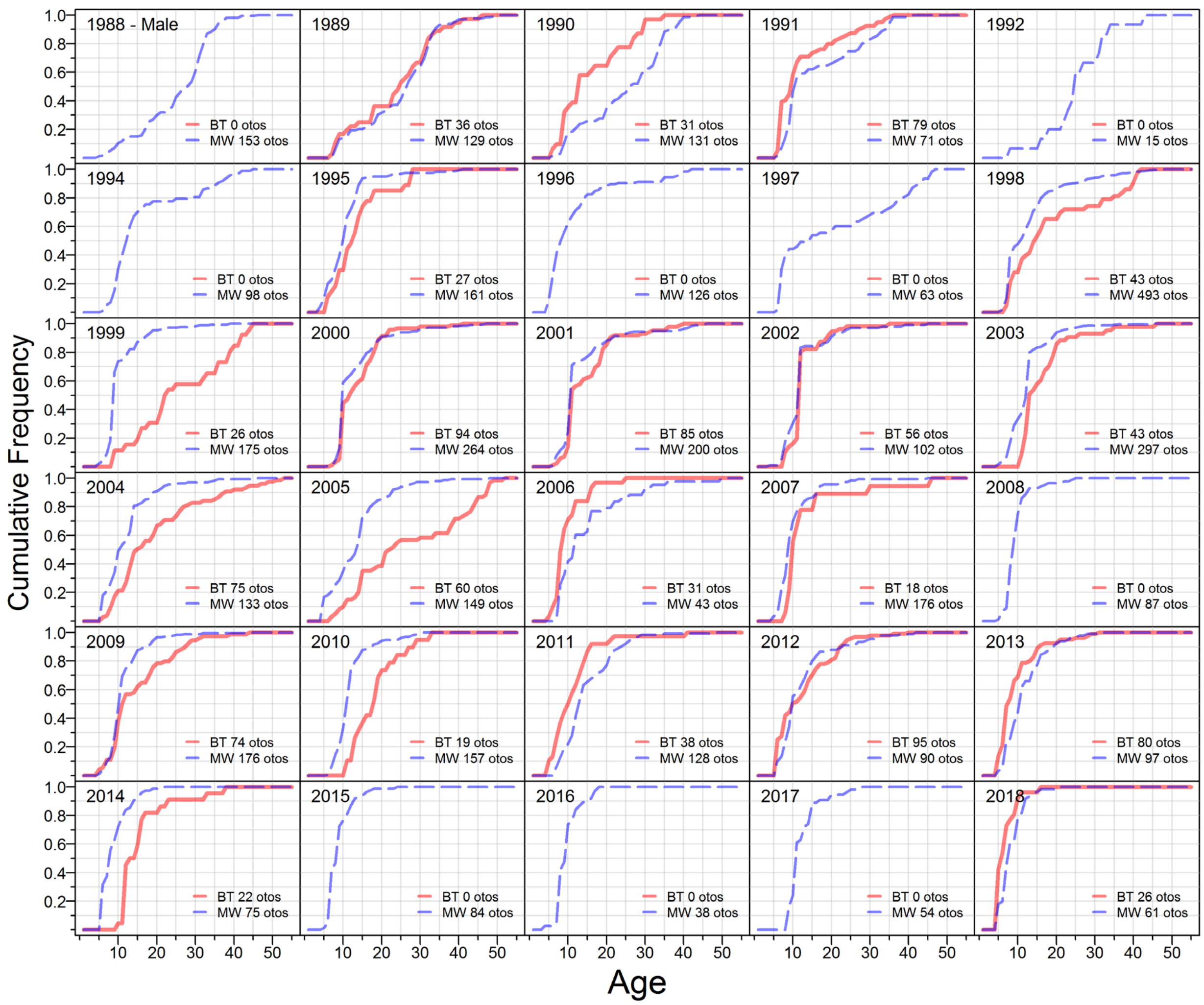

Figure D.9. Plots comparing the cumulative bottom trawl (red) and midwater trawl (blue) age frequencies by year for male WWR coastwide.

Table D.11. Commercial trip quarterly data from trawls used to weight WWR proportions-at-age: number of sampled trips, WWR catch (t) by sampled trip and by all trips.

Year	# Trips				Sampled trip catch (t)				All trip catch (t)			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1986	1	-	-	-	27.2	-	-	-	286	32	41	491
1988	-	1	-	-	-	167.8	-	-	342	1265	152	316
1989	2	8	2	-	8.6	156.3	18.6	-	143	900	444	207
1990	7	4	2	1	249	161	103.2	40.8	942	1076	653	1806
1991	6	-	2	5	163.7	-	56.7	158.8	695	423	559	1785
1992	4	5	1	2	119.3	191.4	15.9	206.4	704	1478	317	1337
1993	3	1	1	3	46	6.8	13.6	40.4	327	355	375	919
1994	4	-	-	4	68	-	-	93	964	130	61	960
1995	2	-	2	8	5.4	-	10.2	194.6	211	135	653	1420
1996	-	1	2	3	-	7.3	7.9	78.7	439	215	718	685
1997	-	-	3	1	-	-	24.5	18	345	353	156	633
1998	10	2	4	8	123.8	38.6	16	79.7	646	207	332	637
1999	3	1	4	2	32.4	4.2	21.5	51.3	710	119	514	814
2000	7	2	2	3	52.8	53.1	17.4	76.2	582	389	227	736
2001	6	4	2	2	76.1	34.6	20.6	19.7	645	393	439	552
2002	4	1	1	-	62.1	2.5	34	-	942	541	309	496
2003	5	3	2	6	25.6	12.8	9.9	116.5	500	426	300	805
2004	3	7	1	6	20.1	54.9	3.6	35.8	491	328	117	377
2005	-	7	1	3	-	88	5	53.3	719	233	199	374
2006	1	2	-	2	12.6	12.2	-	5.7	608	198	240	691
2007	2	2	-	4	28.5	30	-	47.9	1076	451	337	644
2008	2	-	-	3	4.4	-	-	13.7	733	318	322	434
2009	2	2	1	5	0.3	9.3	36.3	49.2	317	360	333	506
2010	3	1	-	2	38.6	12.1	-	55.6	359	218	216	500
2011	2	3	1	4	25.1	23.8	4.9	41	277	809	796	486
2012	2	1	-	4	14.1	3.5	-	60.6	198	574	398	539
2013	3	4	1	2	57.7	7.2	5.3	4.9	486	541	600	518
2014	1	1	-	1	0.4	0.2	-	7.3	383	295	718	476
2015	3	-	-	1	36.2	-	-	32.6	450	416	561	620
2016	1	1	1	-	11.3	1.5	0.1	-	510	463	492	499
2017	1	-	1	-	10.5	-	7.7	-	565	508	486	521
2018	2	1	-	-	6.7	0.4	-	-	687	325	440	285

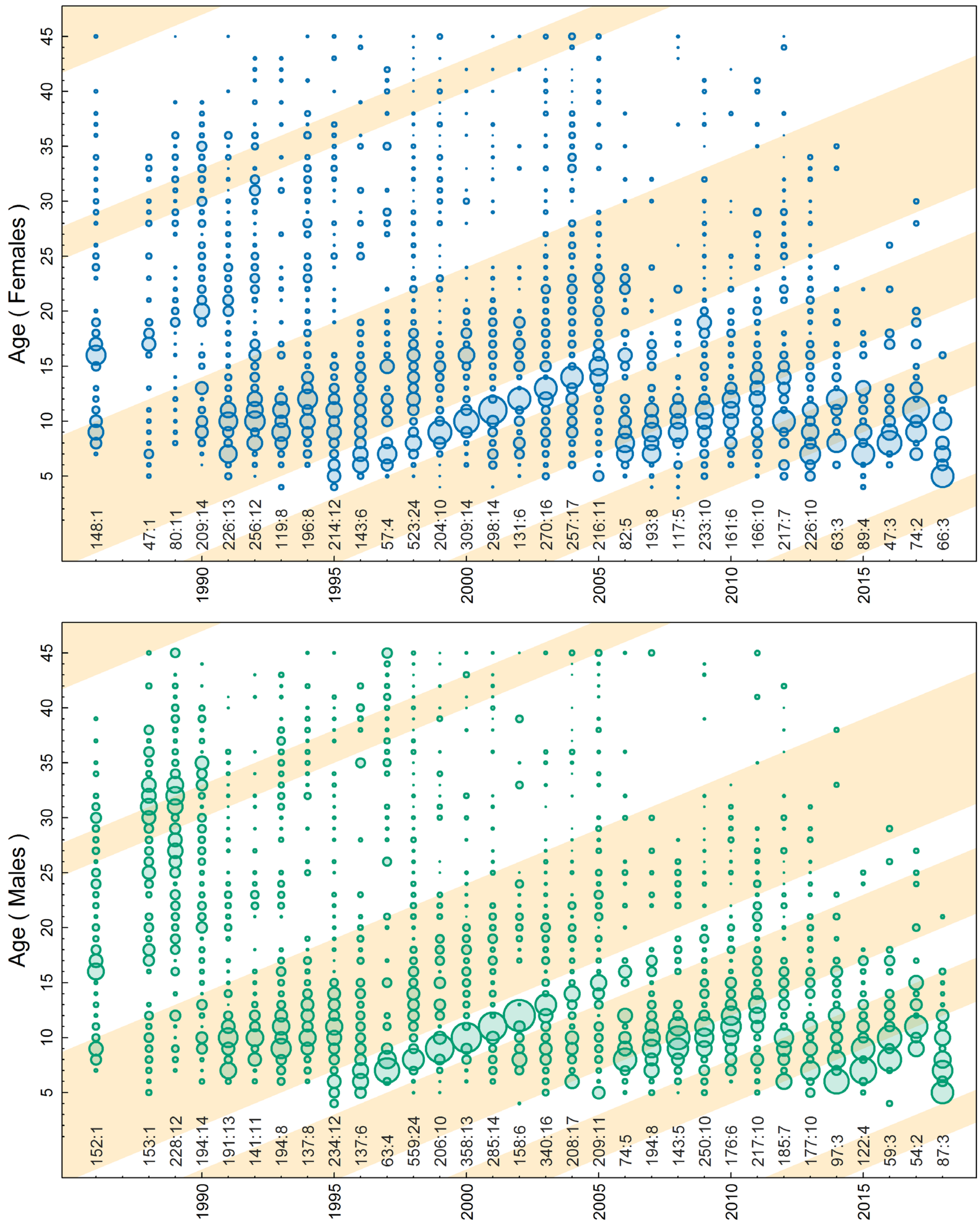

Figure D.10. Proportions-at-age for coastwide WWR caught by commercial trawl gear calculated as age frequencies weighted by trip catch within quarters and commercial catch within years. Diagonal shaded bands indicate cohorts that were born when the mean Pacific Decadal Oscillation was positive. Numbers displayed along the bottom axis indicate number of fish aged and number of samples (colon delimited) by year.

D.2.2. Research/Survey Ages

Age data for WWR from the surveys were very sparse, with only one sample per year per survey (Table D.13). Two surveys offer only one year of age proportion data (Figure D.11): west coast Vancouver Island (WCVI) synoptic (SSID 4) and Goose Island Gully (GIG) historical (SSID 21). The remaining two surveys only have two annual age proportions (Figure D.12): Queen Charlotte Sound (QCS) synoptic (SSID 1), west coast Haida Gwaii (WCHG) synoptic (SSID 16). The latter includes a single survey point from a preliminary survey off WCHG in 1997 (SSID 8). The survey proportions-at-age data show no cohort signal or coherence (Figure D.13).

Table D.12. Survey stratum ID and stratum area (km²) in which WWR otolith samples were collected and used in the assessment.

Survey	Stratum (h) and its area (km²)	
WCVI synoptic	66 (3768 km²)	68 (572 km²)
QCS synoptic	18 (5028 km²)	19 (5344 km²)
WCHG|WCQCI	114 (1244 km²)	126 (1266 km²)
GIG historical	161 (1826 km²)	-

Table D.13. Annual survey age data for WWR by stratum (h), where s = number of sampled tows and d = WWR density (kt/km²).

Year - Survey	Stratum (h), no. samples, mean density (kt/km²)	
2006 - WCVI	h=66, s=1, d=0.310	h=68, s=1, d=0.031
2004 - QCS	h=18, s=1, d=0.075	h=19, s=1, d=1.023
2005 - QCS	h=18, s=1, d=0.032	-
1997 - WCHG	h=114, s=1, d=0.564	-
2006 - WCHG	-	h=126, s=1, d=1.461
1979 - GIG	h=161, s=1, d=5.253	-

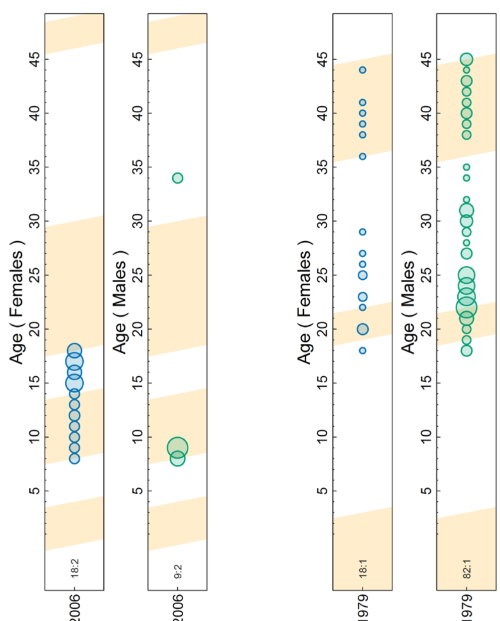

Figure D.11. WCVI Synoptic (left) and GIG Historical (right) surveys: coastwide WWR proportions-at-age based on age frequencies weighted by mean fish density within strata and by total stratum area within survey (Table D.12, Table D.13). See Figure D.10 for details on diagonal shaded bands and displayed numbers.

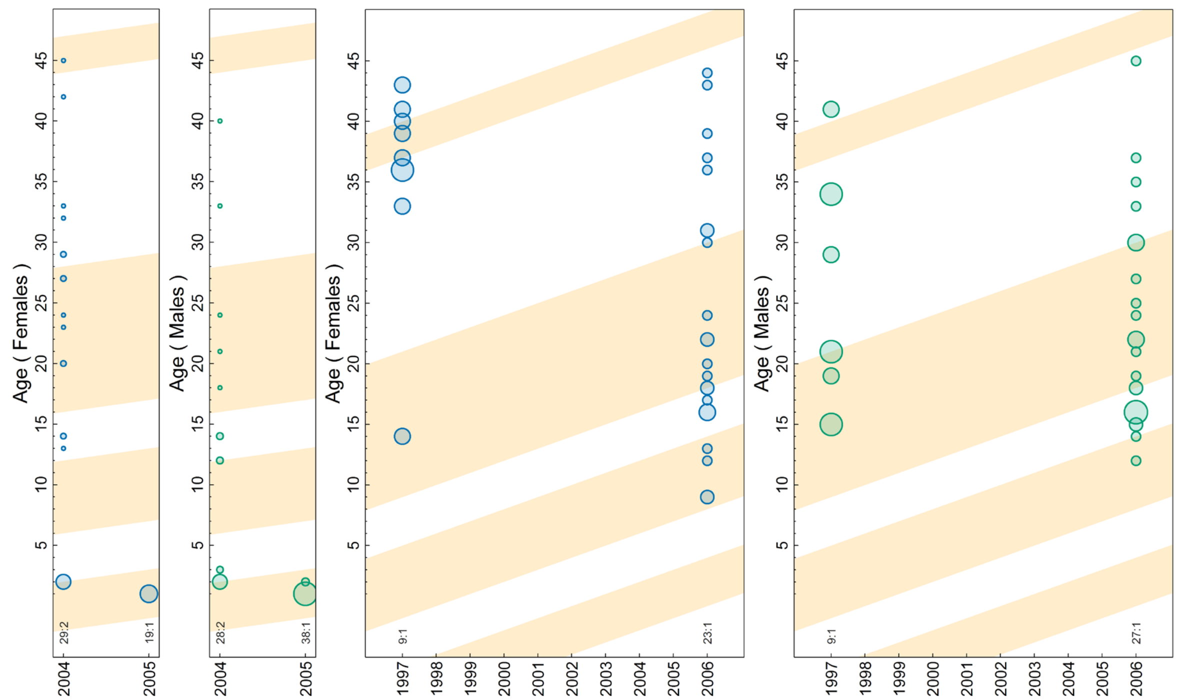

Figure D.12. QCS Synoptic survey (left) and 1997 West Coast QCI Rockfish survey plus 2006 WCHG Synoptic survey (right): coastwide WWR proportions-at-age based on age frequencies weighted by mean fish density within strata and by total stratum area within survey (Table D.12, Table D.13). See Figure D.10 for details on displayed numbers.

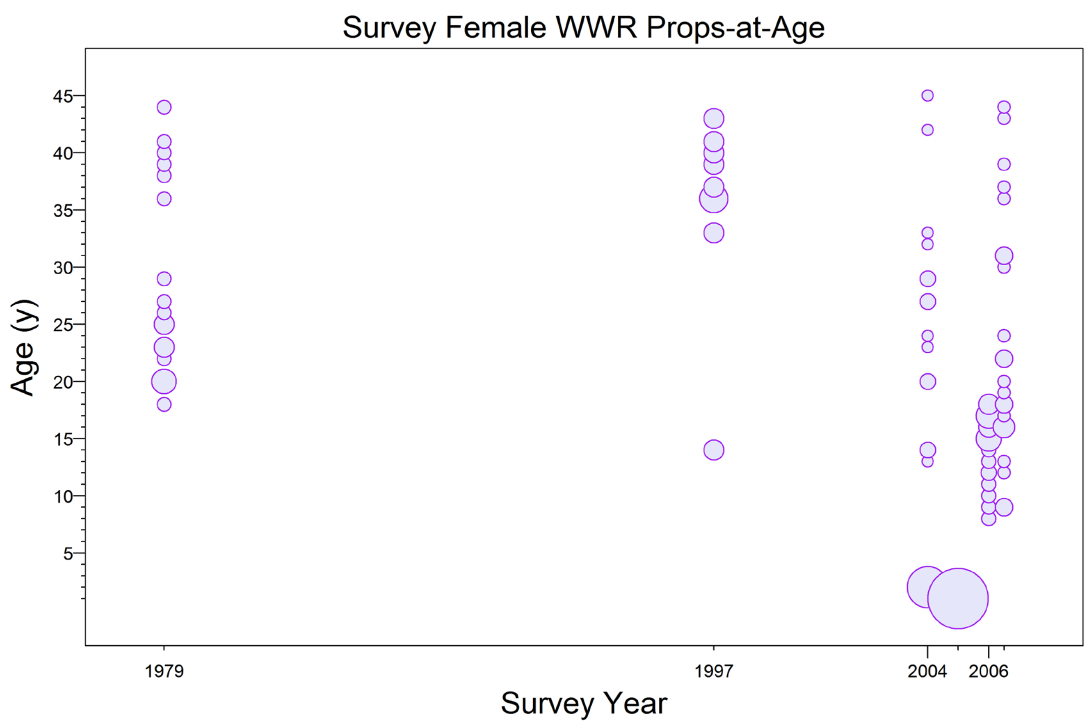

Figure D.13. Female WWR proportions-at-age for all surveys combined: 1979=GIG, 1997=WCQCI, 2004=QCI, 2005=QCI, 2006L=WCVI, 2006R=WCHG

D.2.3. Ageing Error

Ageing error routinely arises as an issue in stock assessments. The population model for WWR does not specify an ageing error matrix; however, Figure D.14 suggests that WWR ages are well-specified by the primary readers and can be reproduced consistently by secondary readers when performing spot-check analyses.

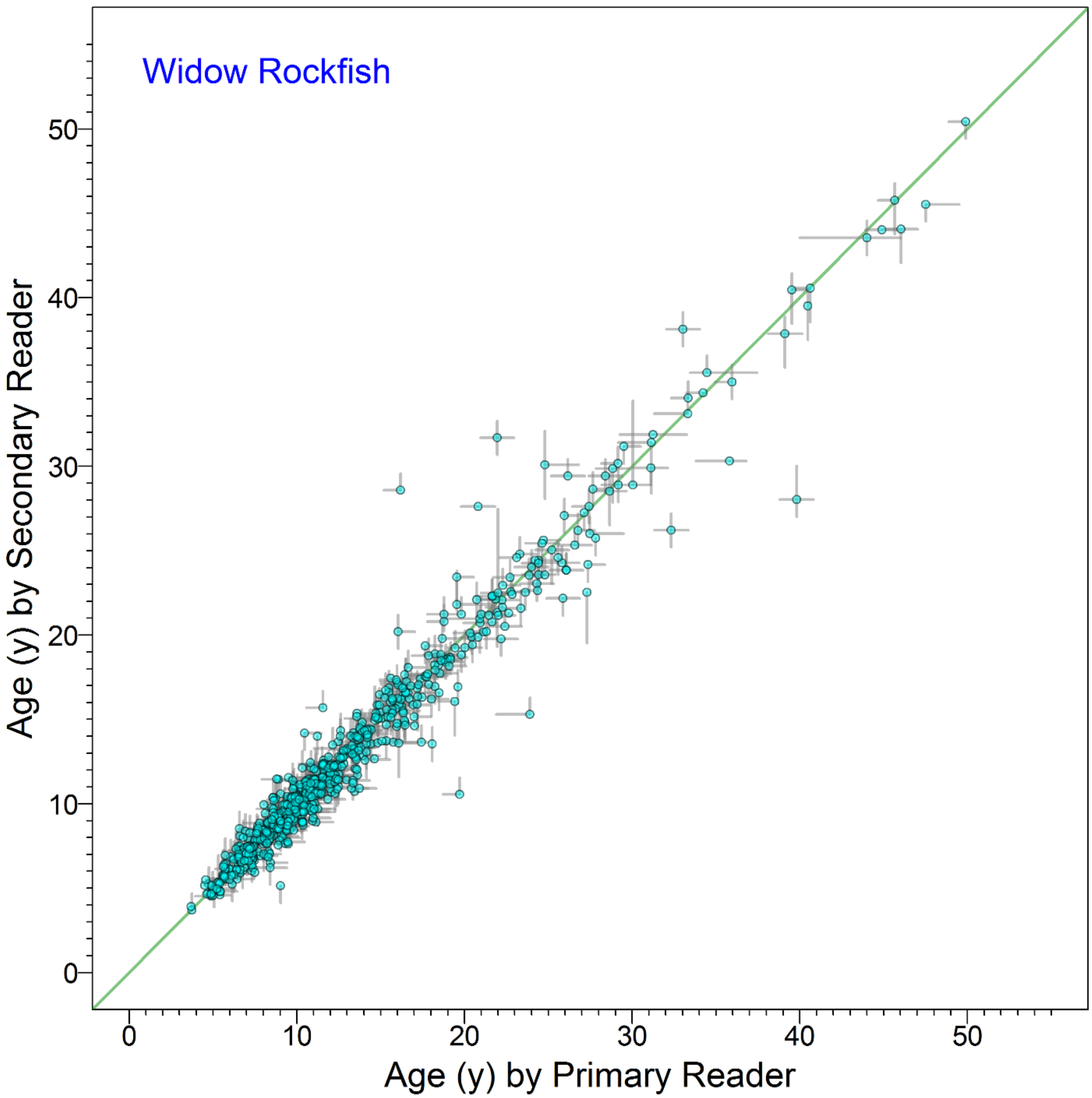

Figure D.14. Ageing error of WWR specified as the range between minimum and maximum age (grey bars) determined by primary and secondary readers for each accepted age (points). The data are jittered using a random uniform distribution between -0.5 and 0.5 y.

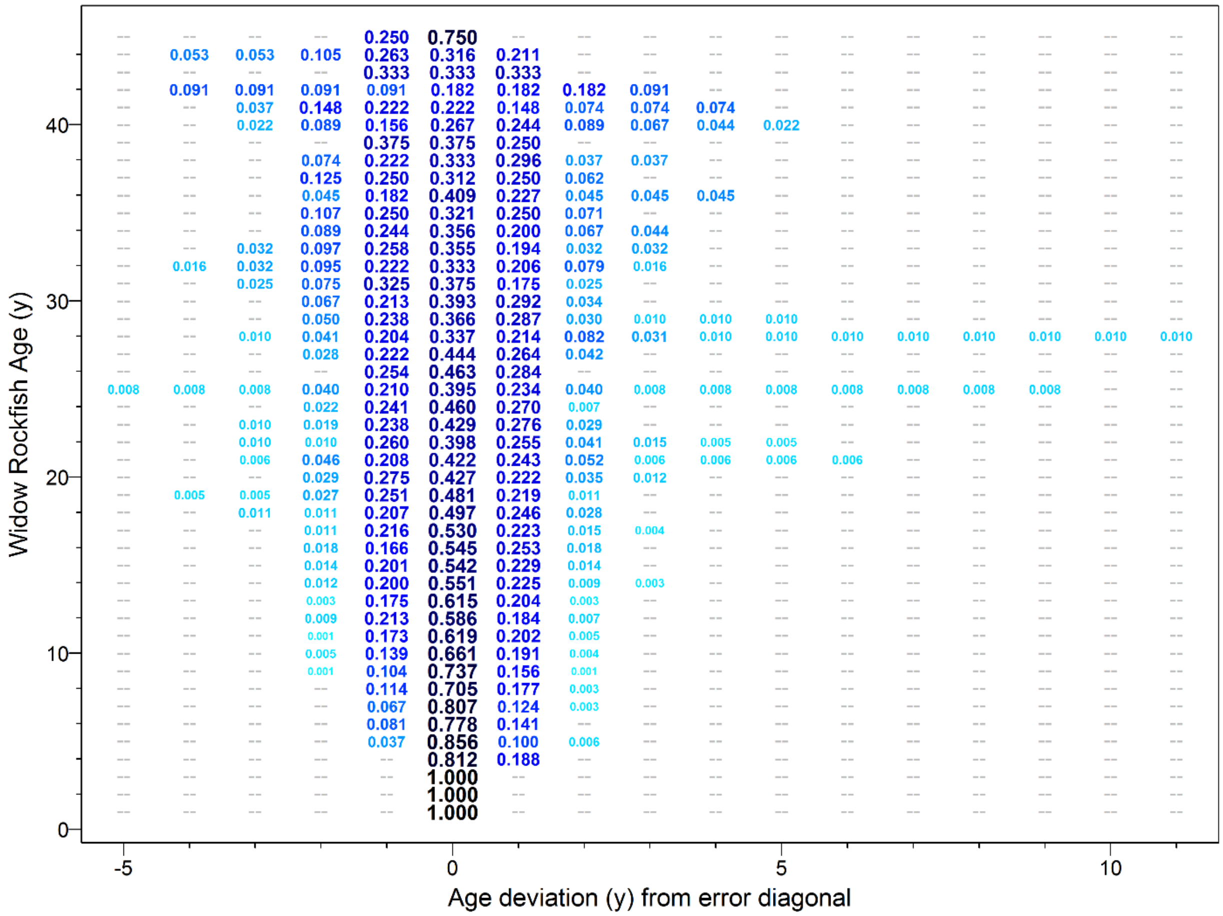

Figure D.15. Ageing error matrix calculated as cumulative probability assuming uniform distributions between minimum and maximum ages by all readers in Figure D.14

D.3. STOCK STRUCTURE ANALYSES

This stock assessment treats the BC population of WWR as a single coastwide stock. The rationale for this decision was based on analyses that showed no consistent differences when comparing data from three trial regional stock definitions:

- BCN – BC North comprising west coast Haida Gwaii (WCHG or 5E)
- BCC – BC Central comprising Queen Charlotte Sound (QCS or 5AB) plus Hecate Strait and Dixon Entrance (HS+DE or 5CD)
- BCS – BC South comprising west coast Vancouver Island (WCVI or 3CD)

Previous stock assessments of Redstripe Rockfish (RSR, Starr and Haigh 2021) and Walleye Pollock (Starr and Haigh 2021) each identified two stocks (one off WCHG, one further south). This separation may have been caused by the North Pacific Current bifurcation (Pickard and Emery 1982, Freeland 2006, Cummins and Freeland 2006, Batten and Freeland 2007) whereby free-swimming larvae from the two regions are kept apart. It was these observations which guided the above trial regional hypotheses.

D.3.1. Mean Weight in Commercial Fishery

Large differences in mean weight by region helped inform stock delineation decisions for Walleye Pollock (Starr and Haigh 2021). Consequently, WWR mean weights were checked for persistent regional differences. Data used to estimate the mean weight by year were selected following the relevant guidelines in Table D.1. The initial WWR biological data contained 45,286 records which were filtered as follows:

• positive definite lengths	`len > 0`	45,084 records
• all available years	`year = 1996:2018`	31,081 records
• BC offshore	`major = 3:9`	31,021 records
• comm. trips incl. JV Hake	`ttype = c(1,4,5)`	25,357 records
• random samples/total catch	`stype = c(1,2,6,7)`	25,356 records
• trawl: bottom, midwater, unknown	`gear = c(1,6,8)`	25,356 records
• species category (unsorted)	`scat = 1`	12,774 records

This process resulted in 12,774 WWR biological records from coastwide unsorted samples. Weights were calculated from the measured lengths using the length-weight parameters specific for each regional stock hypothesis (Table D.2). The allometric parameters used were sex-specific (females, males); lengths for fish with unknown or undetermined sex were converted using the parameters for combined sex.

Equations for the additive lognormal standardised regression model can be found in Appendix D of the RSR stock assessment (Starr and Haigh 2021). The factors offered to the GLM were calendar year, sex, gear type, season, major PMFC area, and fishing depth. The standardised and normalised mean weight trends by region resembled the coastwide trend and did not show any systematic regional differences (Figure D.16)

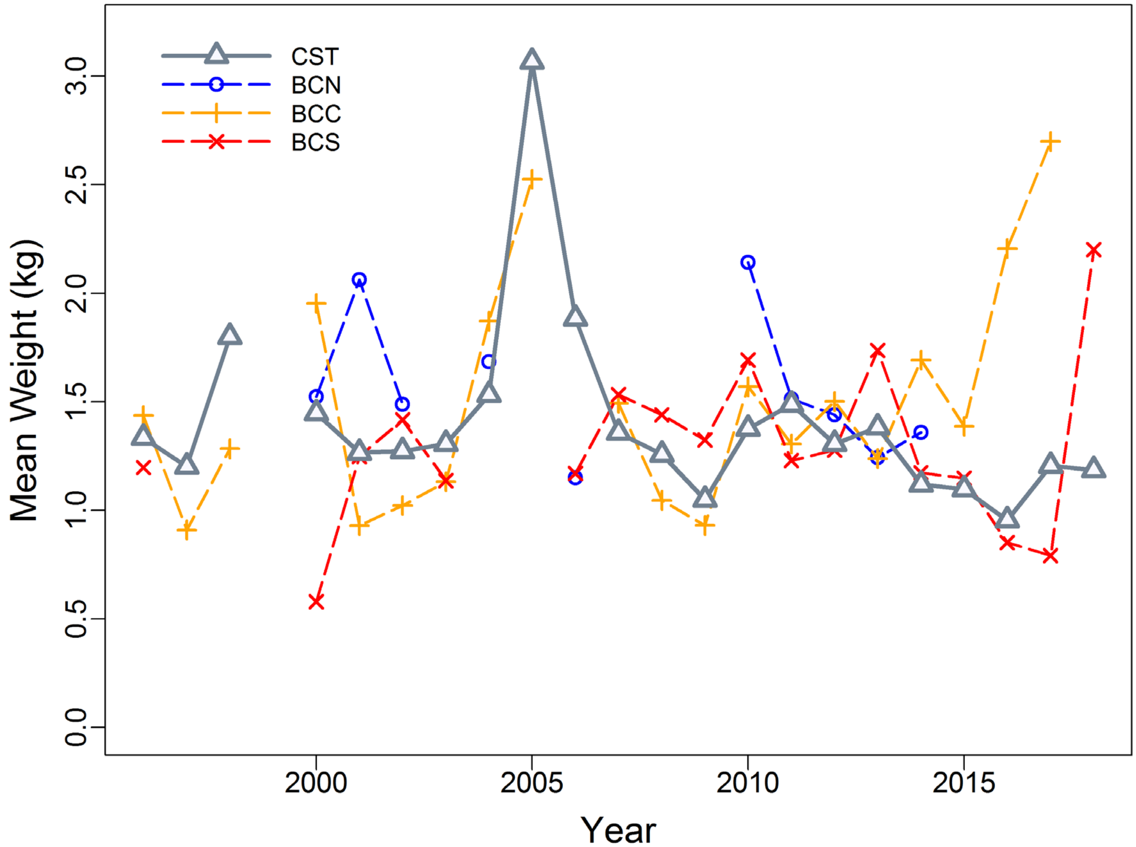

Figure D.16. Comparison of WWR mean weight series, after GLM-adjustment for various factors and normalisation, of the coastwide series (CST) with those of three subareas: 5E (BCN), 5ABCD (BCC), and 3CD (BCS).

D.3.2. Fish Length Distributions

Simple comparisons of commercial length distributions across regions from the two trawl fisheries (bottom and midwater) show no evidence that length frequency distributions are markedly different between capture methods within each area (Figure D.17). This suggests that it is likely reasonable to combine data from bottom and midwater trawl gear.

When the two capture methods are combined across regions to increase the power of the comparison (Figure D.18), there is still no strong evidence of regional differences:

- BCN lengths are often slightly larger than those in the other areas;
- length distributions largely overlap among areas;
- comparisons are not consistent across years and sex.

These observations are similar to the equivalent observations from the above weight comparisons and do not support splitting WWR into component stocks.

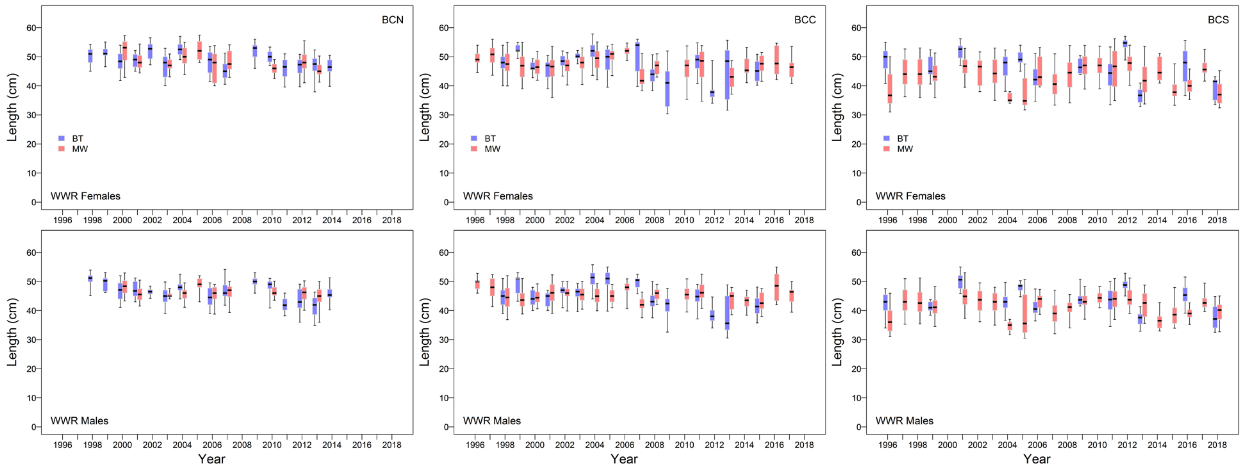

Figure D.17. Comparison of annual distributions of WWR length by sex between gear types (BT = bottom trawl, MW = midwater trawl) in each of the three coastal regions: BCN (left), BCC (middle), BCS (right). Boxplot quantiles: 0.05, 0.25, 0.5, 0.75, 0.95.

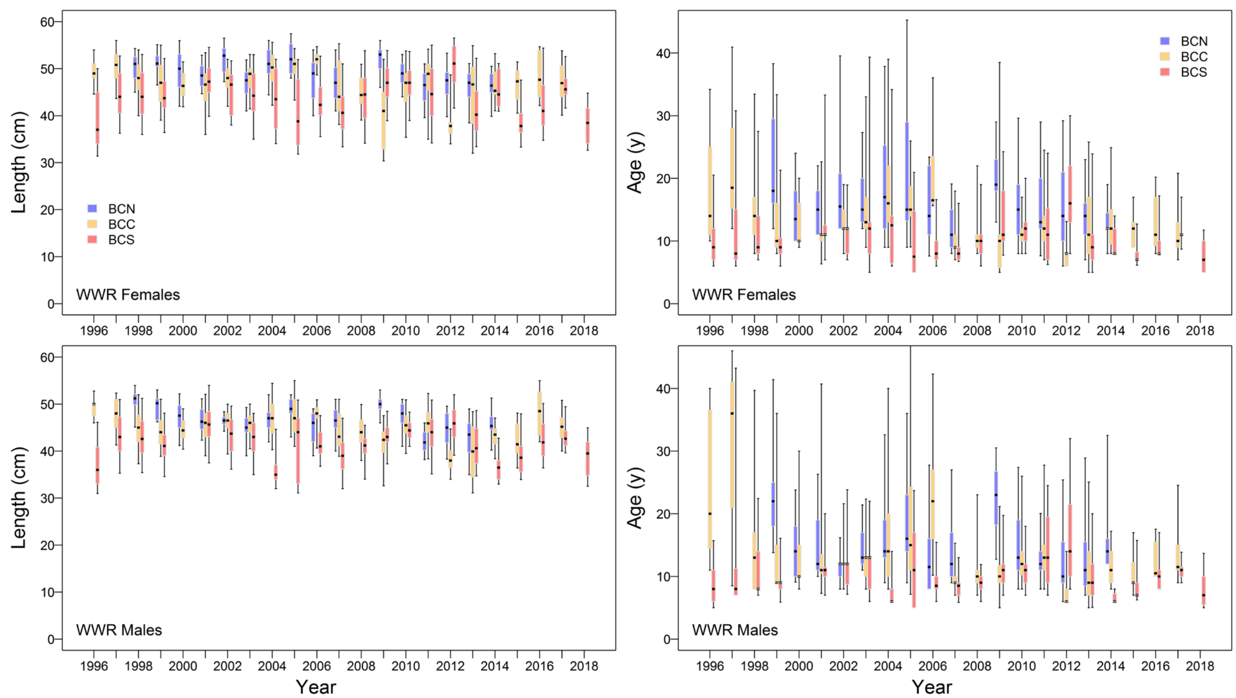

Figure D.18. Comparison of annual distributions of WWR length (left) and age (right) by sex among three coastal regions: BCN, BCC, and BCS. Boxplot quantiles: 0.05, 0.25, 0.5, 0.75, 0.95.

The distribution of lengths from the three primary synoptic surveys for WWR (Figure D.19) – west coast Haida Gwaii (WCHG) in BCN, Queen Charlottes Sound (QCS) in BCC, and west coast Vancouver Island (WCVI) in BCS – show that:

- WCHG survey has ‘mostly’ larger length observations (true for both sexes, some indication that 5E WWR are older than in the other surveys);
- QC Sound survey captures of WWR are too infrequent to reach conclusions.
- WCVI survey captures of WWR are also highly variable and probably not useful.

The survey age observations are practically useless, given the small number of observations and the infrequent encounter of this species in the bottom trawl surveys (Figure D.19, right column).

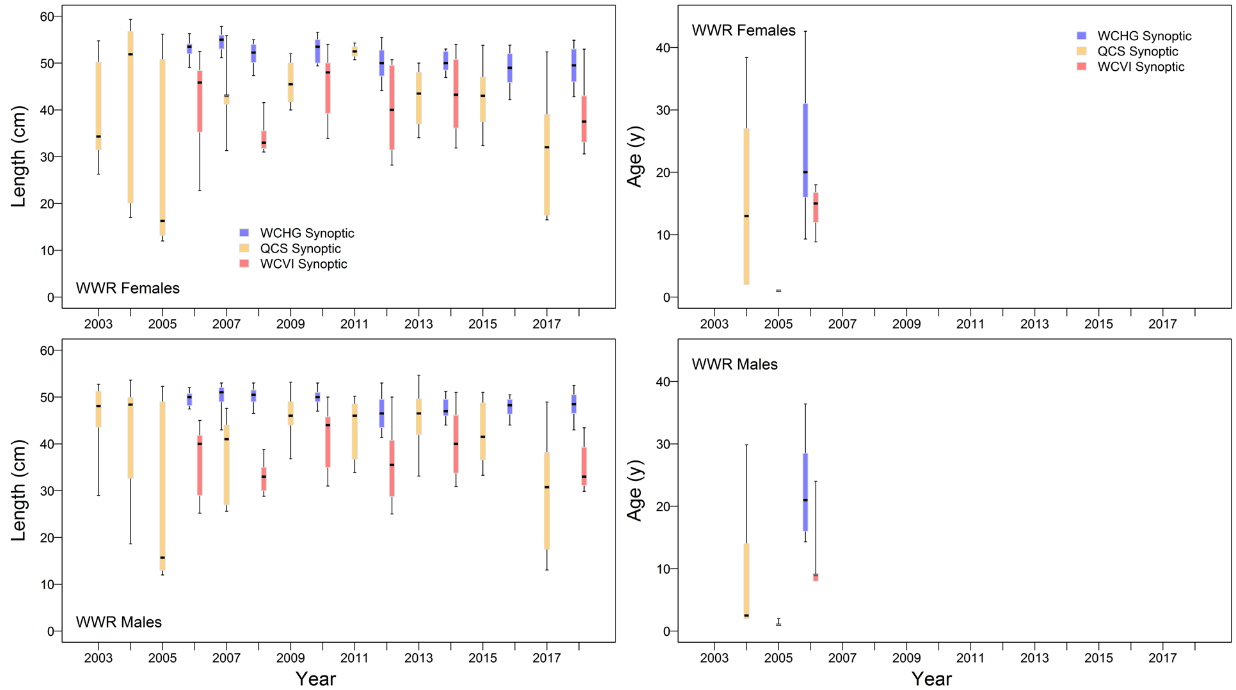

Figure D.19. Comparison of annual distributions of WWR length (left) and age (right) among three synoptic surveys – WCHG in BCN; QCS in BCC, and WCVI in BCS. Boxplot quantiles: 0.05, 0.25, 0.5, 0.75, 0.95.

D.3.3. Comparison of Growth Models

The survey data alone were too sparse for meaningful growth model analyses. Using commercial data, von Bertalanffy growth models were estimated using a Bayesian model (`rstan` package: Stan Development Team 2018). The growth models using the MPD parameter estimates show that the there are few differences in model fits among the trial regions by sex but show a consistent difference between the sexes across the three regions (Figure D.20). MCMC quantile distributions of the regional estimated parameters reflect the sex difference in the asymptotic length (L_∞) and the growth parameter (κ) but show considerable distributional overlap by region (Figure D.21). This lack of power to distinguish between regions is exacerbated by the difficulty to fit the BCN data (reflected in a broad range of t_0 estimates). There is a suggestion that L_∞ for females might be decreasing going northward along the BC coast (Figure D.21, upper left panel) but this doesn't seem to be a basis for a regional separation given that males are not varying similarly. MPD fits to the combined commercial and survey data using R's non-linear minimisation function `nlm` (R Core Team 2019) show the same patterns as those in Figure D.20 – differences by sex but not by region (Figure D.22).

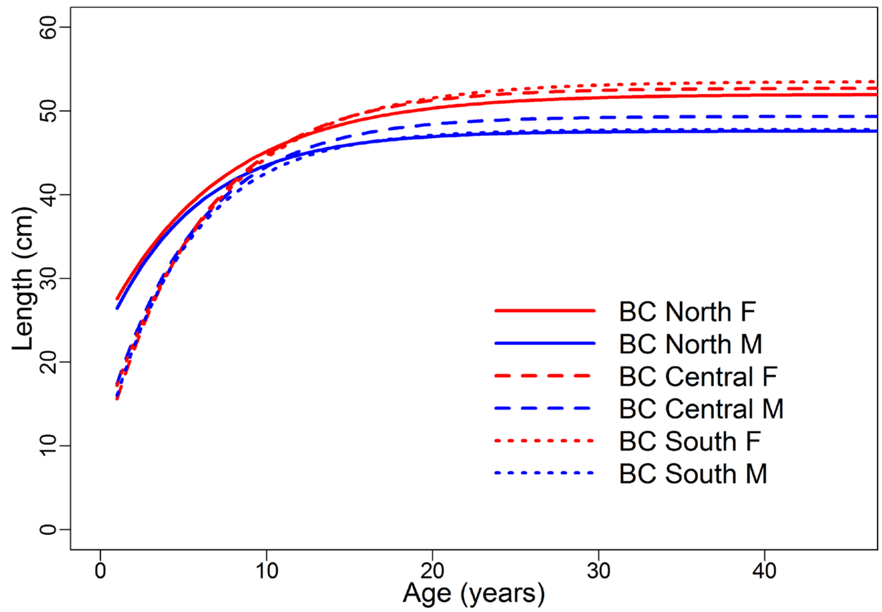

Figure D.20. von Bertalanffy fits using MPD parameter estimates from the rstan model fit to commercial fishery WWR length-age data by region. Line colour indicates sex (red=female, blue=male); line type indicates region (solid=BCN, dashed=BCC, dotted=BCS).

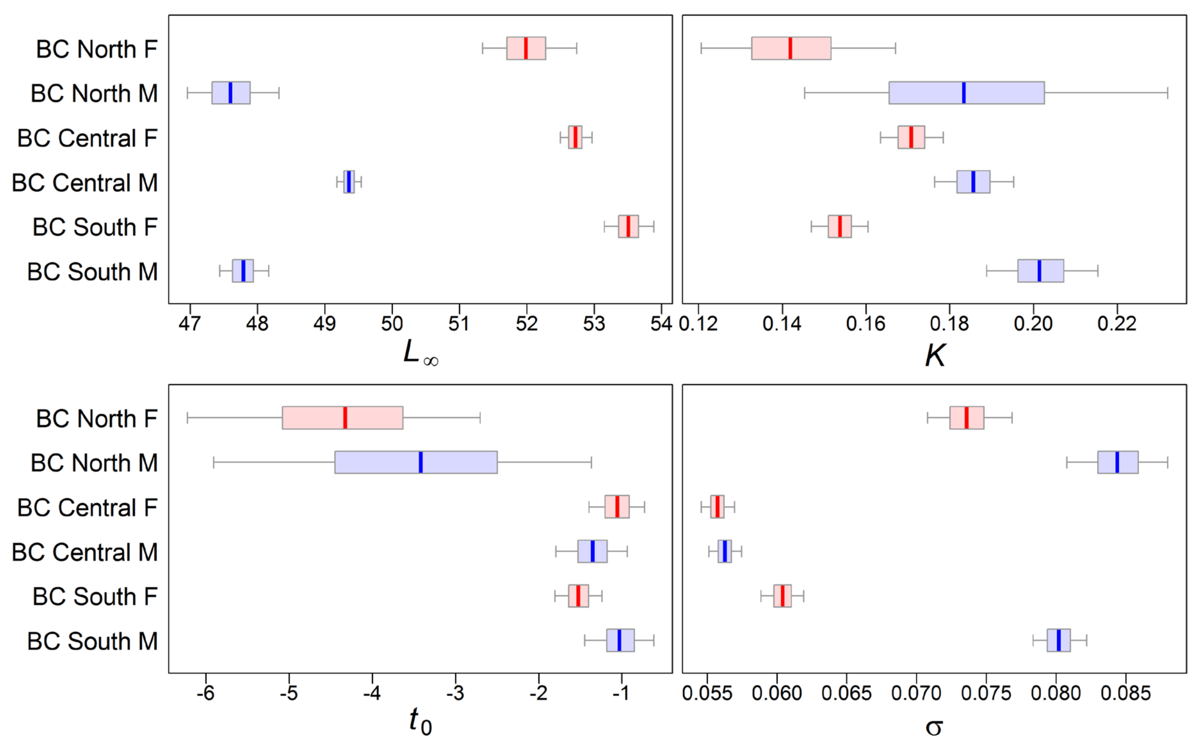

Figure D.21. MCMC samples (4 chains, 1000 each) for von Bertalanffy parameters using commercial fishery WWR length-age data by region. Boxplots (red=females, blue=males) show 0.05, 0.25, 0.5, 0.75, & 0.95 quantiles.

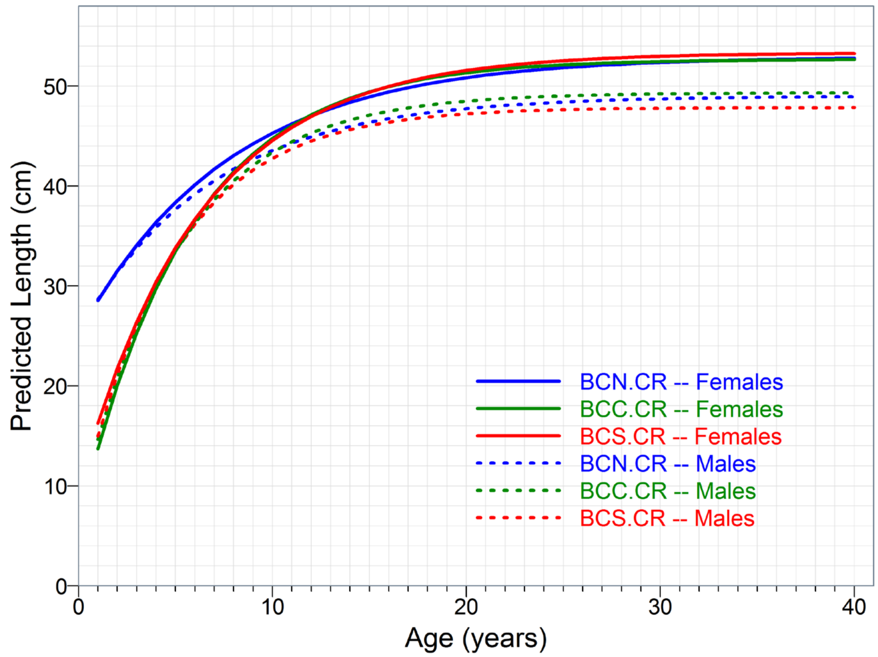

Figure D.22. Comparison of von Bertalanffy fits to WWR by sex and region using combined commercial and survey data.

D.3.4. Shelf vs Slope

Bottom trawl indices from a delta-lognormal model (these are undocumented analyses but the methodology is presented in Section C.2.2) for three outer-coast series (3CB, 5AB, 5E) exhibited different CPUE trends (Figure D.23, top row):

- 3CD: no overall trend, but with a strong nadir in 2005;
- 5AB: highly variable but flat trend to about 2010, then steady decline;
- 5E: variable, but generally flat trend to 2011, followed by variable increasing trend, and nadirs in 1998 and 2004.

However, the difference in CPUE trends between 3CD and 5E were not great (Figure D.23, bottom row). This suggested that the entire 'edge' could be combined into a single analysis, comprising combined areas 3CD, 5A edge, and 5E, with the remainder of the areas combined for an 'inside' analysis. Industry participants at the first technical working group suggested that the apparent CPUE patterns in the fishery could be explained by:

- a summer fishery on the 'shelf' (mostly inside QC Sound) on non-spawning fish, and
- a winter fishery on the 'slope' on spawning fish.

It is well-known among the fishing fleet that WWR migrate out from the shelf in summer to the slope in winter to spawn.

To test this hypothesis, 5AB data were separated into 'shelf' and 'slope' localities (Table D.14), and maturity data were analysed for 'shelf' WWR (in areas 5CD + 5AB_shelf) and 'slope' WWR (in areas 3CD + 5E + 5AB_slope). Data from bottom and midwater trawls were combined and summarised over the period 1996-2017 (Figure D.24), where column proportions sum to 1 (i.e., by month). The shelf maturity is either 'resting' or 'mature' in the summer/fall months, providing evidence of non-spawning; the slope maturity is ‘mature’, ‘spawning’ or ‘spent’ in winter months, providing evidence of spawning.

Figure D.25 is similar to the preceding plot except that the monthly maturity proportions are weighted by the cumulative monthly commercial catch in each area. The shelf catch occurs in late summer and autumn, and largely comprises resting specimens (no spawning). The slope catch occurs in late fall and winter, during spawning. The maturity analysis corroborates the industry explanation of the observed differences in fish sizes and CPUE trends. For this reason, WWR most likely forms a single BC-wide stock, consistent with the stock assumption reported by Stanley (1999).

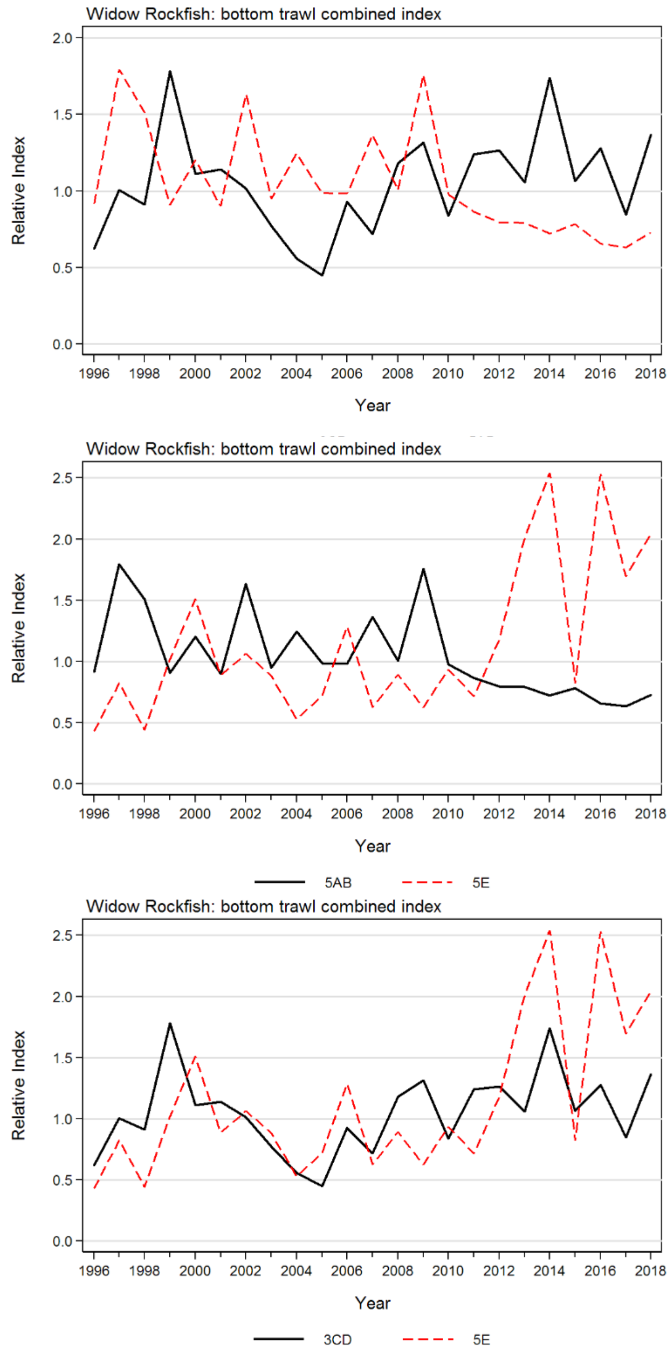

Figure D.23. Comparisons of WWR trawl delta-lognormal model trends from bottom trawl CPUE data. Top: 3CD vs. 5AB; middle: 5AB vs. 5E; bottom: 3CD vs. 5E. These analyses are undocumented but are the product of Equation C.4 in Section C.2.2.

Table D.14. Catch (t) of WWR by bottom trawl (BT) and midwater trawl (MW) by locality within PMFC major areas 5A and 5B. Highlighted localities are identified as either 'shelf' (yellow) or 'slope (blue).

PMFC	Major	Minor	Locality	Name	Class	BT (t)	MW (t)
5A	5	9	0	Missing	-	0	4
5A	5	9	1	Virgin Rocks	-	0	0
5A	5	9	2	Smith Sound	-	0	0
5A	5	11	0	Unknown	-	113	1228
5A	5	11	1	Triangle	Shelf	172	58
5A	5	11	2	Cape Scott Spit	Shelf	72	22
5A	5	11	3	Mexicana	Shelf	23	15
5A	5	11	4	Topknot	Slope	7	28
5A	5	11	5	Pine Island	Slope	0	0
5A	5	11	6	South Scott Islands	Slope	145	774
5A	5	11	7	W Triangle (25mi)	Slope	100	730
5A	5	11	10	South Triangle	Slope	846	12314
5A	5	11	11	Pisces Canyon	Slope	201	1117
5A	5	11	12	South Tide Marks	Slope	0	0
5B	6	8	0	Unknown	-	0	2
5B	6	8	1	NE Goose	Shelf	23	16
5B	6	8	2	SE Goose	Shelf	93	133
5B	6	8	3	NW Goose	Shelf	0	0
5B	6	8	4	SW Goose	Shelf	216	301
5B	6	8	5	Mitchell's Gully	Shelf	25	11
5B	6	8	6	SE Cape St. James	Shelf	64	12
5B	6	8	7	Hakai Pass	Shelf	0	0
5B	6	8	8	Fitzhugh Sound	Shelf	0	0
5B	6	8	10	Outside Goose & Mitchell's	Shelf	0	1
5B	6	8	11	SW Middle Bank	Shelf	254	190
5B	6	8	12	Outside Cape St. James	Slope	22	15
5B	6	8	13	W Virgin Rocks	Slope	8	6
5B	6	8	14	Below Middle Bank	Shelf	54	449
5B	6	8	15	Outside Middle Bank	Slope	0	0

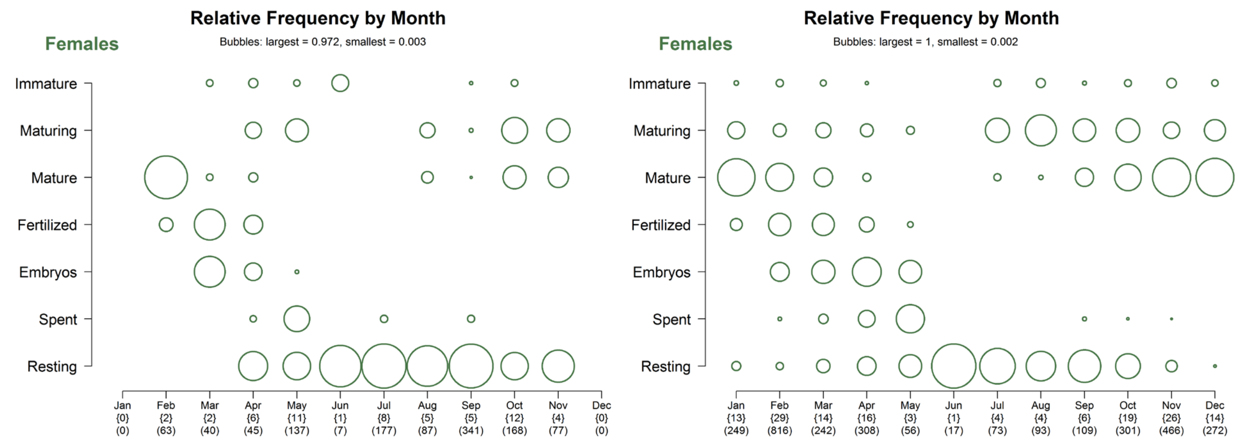

Figure D.24. Relative frequency of maturity codes by month for WWR females caught by the commercial fishery on the BC 'shelf' (left) and BC 'slope' (right). Frequencies are calculated among each maturity category for every month.

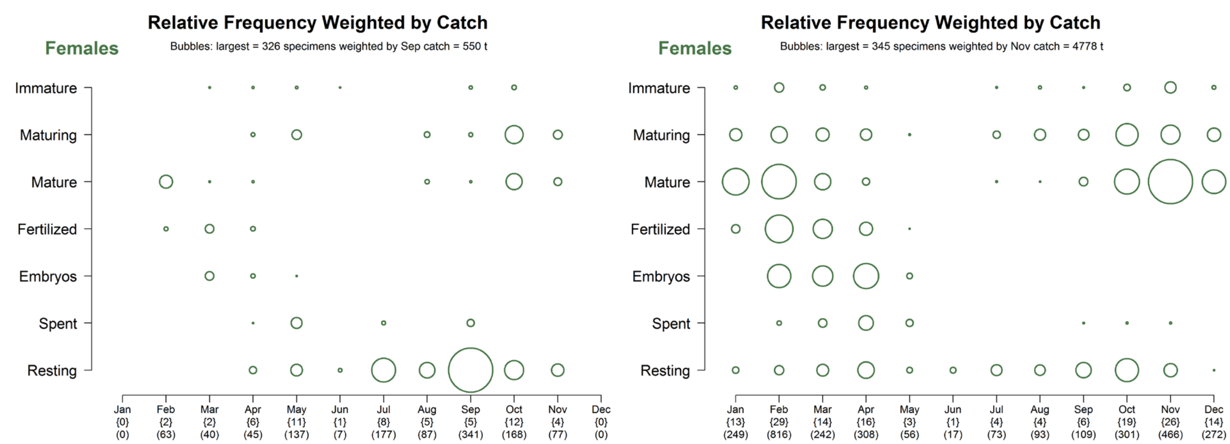

Figure D.25. Relative frequency of maturity codes weighted by commercial catch of WWR females caught by the commercial fishery on the BC 'shelf' (left) and BC 'slope' (right). Frequencies are relative to largest cumulative monthly catch from 1996-2017.

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APPENDIX E. MODEL EQUATIONS

E.1. INTRODUCTION

We used a sex-specific, age-structured model called 'Awatea' in a Bayesian framework. The model can simultaneously estimate the steepness of the stock-recruitment function and separate mortalities for the sexes. This approach follows that used in BC stock assessments since 2010:

- 2018 – Redstripe Rockfish in PMFC areas 5DE and 3CD5ABC (Starr and Haigh 2021),
- 2017 – Pacific Ocean Perch (POP) in Queen Charlotte Sound (Haigh et al. 2018*a*),
- 2014 – Yellowtail Rockfish for the coast of BC (DFO 2015),
- 2013 – Silvergray Rockfish along the Pacific coast of Canada (Starr et al. 2016),
- 2013 – Rock Sole in BC (Holt et al. 2016),
- 2012 – POP off the west coast of Vancouver Island (Edwards et al. 2014*b*),
- 2012 – POP off the west coast of Haida Gwaii (Edwards et al. 2014*a*),
- 2011 – Yellowmouth Rockfish along the Pacific coast of Canada (Edwards et al. 2012*a*),
- 2010 – POP in Queen Charlotte Sound (Edwards et al. 2012*b*).

The model structure is the same as that used previously, and, as for all the assessments above except 5ABC POP in 2010, we used the weighting scheme of Francis (2011) described below.

The Awatea model is a modified version of the Coleraine statistical catch-at-age software (Hilborn et al. 2003), and was originally created in 2006 and maintained by Allan Hicks (then at Univ. Washington, now at IPHC). There have been no changes to the code since 2012. Awatea is a platform for implementing the AD (Automatic Differentiation) Model Builder software (ADMB Project 2009), which provides (a) maximum posterior density estimates using a function minimiser and automatic differentiation, and (b) an approximation of the posterior distribution of the parameters using the Markov Chain Monte Carlo (MCMC) method, specifically using the Hastings-Metropolis algorithm (Gelman et al. 2004).

Running of Awatea is streamlined using custom code written in R (Haigh et al. 2018*b*), rather than through the original Excel implementation. Figures and tables of output were automatically produced through R (R Core Team 2017) using code adapted from the R packages `scape` (Magnusson 2009) and `plotMCMC` (Magnusson and Stewart 2020). We used the R software `Sweave` (Leisch 2002) to automatically collate, via LaTeX, the large amount of figures and tables into a single pdf file for each model run.

Below we describe details of the age-structured model, the Bayesian procedure, the reweighting scheme, the prior distributions, and the methods for calculating reference points and performing projections.

E.2. MODEL ASSUMPTIONS

The assumptions of the model are:

1. The assessed population of Widow Rockfish (BC) was treated as a single stock in combined PMFC areas 3CD+5ABCDE.
2. Annual catches were taken by a single fishery, known without error, and occurred in the middle of each year.

3. A time-invariant Beverton-Holt stock-recruitment relationship was assumed, with log-normal error structure.
4. Selectivity was different between surveys but the same between sexes, and remained invariant over time. Selectivity parameters were estimated when ageing data were available.
5. Natural mortality M was fixed at 0.07, 0.08, and 0.09 for females and males, and held invariant over time.
6. Growth parameters were fixed and assumed to be invariant over time.
7. Maturity-at-age parameters for females were fixed and assumed to be invariant over time. Male maturity did not need to be considered, because it was assumed that there were always sufficient mature males.The mature male population is not tracked by this model, with spawning biomass expressed as mature females only.
8. Recruitment at age 1 was 50% females and 50% males.
9. Fish ages determined by surface ageing methods (before 1978) were too biased to use (Beamish 1979); however, this methodology was deemed suitable for very young rockfish (ages 1-3). Ages determined using the otolith break-and-burn methodology (MacLellan 1997) were aged without error.
10. Commercial samples of catch-at-age in a given year were assumed to be representative of the fishery if there were $\geq$2 samples in that year.
11. Relative abundance indices were assumed to be proportional to the vulnerable biomass at the mid point of the year, after half of the catch and half of the natural mortality had been accounted for.
12. The age composition samples were assumed to come from the middle of the year after half of the catch and half of the natural mortality had been accounted for.

E.3. MODEL NOTATION AND EQUATIONS

The notation for the model is given in Table E.1, the model equations in Tables E.2 and E.3, and description of prior distributions for estimated parameters in Table E.4. The model description is divided into the deterministic components, stochastic components and Bayesian priors. Full details of notation and equations are given after the tables.

The main structure is that the deterministic components in Table E.2 can iteratively calculate numbers of fish in each age class (and of each sex) through time. The only requirements are the commercial catch data, weight-at-age and maturity data, and known fixed values for all parameters.

Given we do not have known fixed values for all parameters, we need to estimate many of them, and add stochasticity to recruitment. This is accomplished by the stochastic components given in Table E.3.

Incorporation of the prior distributions for estimated parameters gives the full Bayesian implementation, the goal of which is to minimise the objective function $f(\Theta)$ given by (E.23). This function is derived from the deterministic, stochastic and prior components of the model.

Table E.1. *Notation for the Awatea catch-at-age model (continued overleaf).*

Symbol	Description and units
	Indices (all subscripts)
a	age class, where $a = 1, 2, 3, ...A$, and $A \in \{40, 45, 50\}$ is the accumulator age class
t	model year, where $t = 1, 2, 3, ...T$, corresponds to actual years: 1940, ..., 2019, and $t = 0$ represents unfished equilibrium conditions
g	index for series (abundance|composition) data: 1 – WCVI Synoptic trawl survey series 2 – QCS Synoptic trawl survey series 3 – WCHG Synoptic trawl survey series 4 – GIG Historical trawl survey series 5 – WCVI Triennial trawl survey series 6 – commercial CPUE (bottom trawl)
s	sex, $1 =$ females, $2 =$ males
	Index ranges
A	accumulator age-class, $A \in \{40, 45, 50\}$
T	number of model years, $T = 80$
$\mathbf{T}_g$	sets of model years for survey abundance indices from series g, listed here for clarity as actual years (subtract 1939 to give model year t): $\mathbf{T}_1$ = {2004, 2006, 2008, 2010, 2012, 2014, 2016, 2018} $\mathbf{T}_2$ = {2003:2005, 2007, 2009, 2011, 2013, 2015, 2017} $\mathbf{T}_3$ = {1997, 2006:2008, 2010, 2012, 2014, 2016, 2018} $\mathbf{T}_4$ = {1967, 1969, 1971, 1973, 1976:1977, 1984, 1994} $\mathbf{T}_5$ = {1980, 1983, 1989, 1992, 1995, 1998, 2001} $\mathbf{T}_6$ = {1996, ..., 2018}
$\mathbf{U}_g$	sets of model years with proportion-at-age data for series g: $\mathbf{U}_1$ = {2006} $\mathbf{U}_2$ = {2004:2005} $\mathbf{U}_3$ = {2006} $\mathbf{U}_4$ = {1979} $\mathbf{U}_6$ = {1989, ..., 2018}
	Data and fixed parameters
p_{atgs}	observed weighted proportion of fish from series g in each year $t \in \mathbf{U}_g$ that are age-class a and sex s; so $\Sigma_{a=1}^{A}\Sigma_{s=1}^{2} p_{atgs} = 1$ for each $t \in \mathbf{U}_g$, $g = 1, ..., 6$
n_{tg}	effective sample size that yields corresponding p_{atgs}
C_t	observed catch biomass (tonnes) in year $t = 1, 2, ..., T-1$
w_{as}	average weight (kg) of individual of age-class a of sex s from fixed parameters
m_a	proportion of age-class a females that are mature, fixed from data
I_{tg}	biomass estimates (tonnes) from surveys $g = 1, ..., 5$, for year $t \in \mathbf{T}_g$, tonnes
κ_{tg}	standard deviation of I_{tg}
σ_R	standard deviation parameter for recruitment process error, $\sigma_R = 0.9$

Symbol	Description and units
	Estimated parameters
$\boldsymbol{\Theta}$	set of estimated parameters
R_0	virgin recruitment of age-1 fish (numbers of fish, 1000s)
M_s	natural mortality rate for sex $s = 1, 2$ (M fixed for the WWR assessment)
h	steepness parameter for Beverton-Holt recruitment
q_g	catchability for survey series $g = 1, ..., 5$
μ_g	age of full selectivity for females for series $g = 1, ..., 6$
Δ_g	shift in vulnerability for males for series $g = 1, ..., 6$
v_{gL}	variance parameter for left limb of selectivity curve for series $g = 1, ..., 6$
s_{ags}	selectivity for age-class a, series $g = 1, ..., 6$, and sex s, calculated from the parameters μ_g, Δ_g and v_{gL}
α, β	alternative formulation of recruitment: $\alpha = (1-h)B_0/(4hR_0)$ and $\beta = (5h-1)/4hR_0$
$\widehat{x}$	estimated value of observed data x
	Derived states
N_{ats}	number of age-class a fish (1000s) of sex s at the start of year t
u_{ats}	proportion of age-class a and sex s fish in year t that are caught
u_t	exploitation ratio of total catch to vulnerable biomass in the middle of the year t
B_t	spawning biomass (tonnes mature females) at the start of year $t = 1, 2, 3, ..., T$
B_0	virgin spawning biomass (tonnes mature females) at the start of year 0
R_t	recruitment of age-1 fish (numbers of fish, 1000s) in year $t = 1, 2, ..., T-1$
V_t	vulnerable biomass (tonnes males + females) in the middle of year $t = 1, 2, 3, ..., T$
	Deviations and likelihood components
ϵ_t	Recruitment deviations arising from process error
$\log L_1(\boldsymbol{\Theta}\|\{\epsilon_t\})$	log-likelihood component related to recruitment residuals
$\log L_2(\boldsymbol{\Theta}\|\{\widehat{p}_{atgs}\})$	log-likelihood component related to estimated proportions-at-age
$\log L_3(\boldsymbol{\Theta}\|\{\widehat{I}_{tg}\})$	log-likelihood component related to estimated survey biomass indices
$\log L(\boldsymbol{\Theta})$	total log-likelihood
	Prior distributions and objective function
$\pi_j(\boldsymbol{\Theta})$	Prior distribution for parameter j
$\pi(\boldsymbol{\Theta})$	Joint prior distribution for all estimated parameters
$f(\boldsymbol{\Theta})$	Objective function to be minimised

Table E.2. Deterministic components. Using the catch, weight-at-age and maturity data, with fixed values for all parameters, the initial conditions are calculated from (E.4)-(E.6), and then state dynamics are iteratively calculated through time using the main equations (E.1)-(E.3), selectivity functions (E.7) and (E.8), and the derived states (E.9)-(E.13). Estimated observations for survey biomass indices and proportions-at-age can then be calculated using (E.14) and (E.15). In Table E.3, the estimated observations of these are compared to data.

Deterministic components

State dynamics ($2 \le t \le T,\ s = 1, 2$)

$$N_{1ts} = 0.5 R_t \tag{E.1}$$

$$N_{ats} = e^{-M_s}(1 - u_{a-1,t-1,s}) N_{a-1,t-1,s}\,; \quad 2 \le a \le A-1 \tag{E.2}$$

$$N_{Ats} = e^{-M_s}(1 - u_{A-1,t-1,s}) N_{A-1,t-1,s} + e^{-M_s}(1 - u_{A,t-1,s}) N_{A,t-1,s} \tag{E.3}$$

Initial conditions ($t = 1$)

$$N_{a1s} = 0.5 R_0 e^{-M_s(a-1)}\,; \quad 1 \le a \le A-1,\ s = 1, 2 \tag{E.4}$$

$$N_{A1s} = 0.5 R_0 \frac{e^{-M_s(A-1)}}{1 - e^{-M_s}}\,; \quad s = 1, 2 \tag{E.5}$$

$$B_0 = B_1 = \sum_{a=1}^{A} w_{a1} m_a N_{a11} \tag{E.6}$$

Selectivities ($g = 1, ..., 6$)

$$s_{ag1} = \begin{cases} e^{-(a-\mu_g)^2/v_{gL}}, & a \le \mu_g \\ 1, & a > \mu_g \end{cases} \tag{E.7}$$

$$s_{ag2} = \begin{cases} e^{-(a-\mu_g-\Delta_g)^2/v_{gL}}, & a \le \mu_g + \Delta_g \\ 1, & a > \mu_g + \Delta_g \end{cases} \tag{E.8}$$

Derived states ($1 \le t \le T - 1$)

$$B_t = \sum_{a=1}^{A} w_{a1} m_a N_{at1} \tag{E.9}$$

$$R_t = \frac{4hR_0 B_{t-1}}{(1-h)B_0 + (5h-1)B_{t-1}} \quad \left(\equiv \frac{B_{t-1}}{\alpha + \beta B_{t-1}} \right) \tag{E.10}$$

$$V_t = \sum_{s=1}^{2} \sum_{a=1}^{A} e^{-M_s/2}\, w_{as}\, s_{a6s}\, N_{ats} \tag{E.11}$$

$$u_t = \frac{C_t}{V_t} \tag{E.12}$$

$$u_{ats} = s_{a6s}\, u_t\,; \quad 1 \le a \le A,\ s = 1, 2 \tag{E.13}$$

Estimated observations

$$\widehat{I}_{tg} = q_g \sum_{s=1}^{2} \sum_{a=1}^{A} e^{-M_s/2}(1 - u_{ats}/2) w_{as} s_{ags} N_{ats}\,; \quad t \in \mathbf{T}_g,\ g = 1, ..., 6 \tag{E.14}$$

$$\widehat{p}_{atgs} = \frac{e^{-M_s/2}(1 - u_{ats}/2) s_{ags} N_{ats}}{\sum_{s=1}^{2} \sum_{a=1}^{A} e^{-M_s/2}(1 - u_{ats}/2) s_{ags} N_{ats}}\,; \ {\scriptstyle 1 \le a \le A,\ t \in \mathbf{U}_g,\ g=1,...6,\ s=1,2} \tag{E.15}$$

Table E.3. Stochastic components. Calculation of likelihood function $L(\mathbf{\Theta})$ for stochastic components of the model in Table E.2, and resulting objective function $f(\mathbf{\Theta})$ to be minimised.

Stochastic components

Estimated parameters

$$\mathbf{\Theta} = \{R_0; M_{1,2}; h; q_{1,\ldots,6}; \mu_{1,\ldots,6}; \Delta_{1,\ldots,6}; v_{1,\ldots 6L}\} \tag{E.16}$$

Recruitment deviations

$$\epsilon_t = \log R_t - \log B_{t-1} + \log(\alpha + \beta B_{t-1}) + \sigma_R^2/2\,; \;\; 1 \le t \le T-1 \tag{E.17}$$

Log-likelihood functions

$$\log L_1(\mathbf{\Theta}|\{\epsilon_t\}) = -\frac{T}{2}\log 2\pi - T\log\sigma_R - \frac{1}{2\sigma_R^2}\sum_{t=1}^{T-1}\epsilon_t^2 \tag{E.18}$$

$$\begin{aligned}\log L_2(\mathbf{\Theta}|\{\widehat{p}_{atgs}\}) = &-\frac{1}{2}\sum_{g=1}^{6}\sum_{a=1}^{A}\sum_{t\in\mathbf{U}_g}\sum_{s=1}^{2}\log\left[p_{atgs}(1-p_{atgs}) + \frac{1}{10A}\right]\\ &+\sum_{g=1}^{6}\sum_{a=1}^{A}\sum_{t\in\mathbf{U}_g}\sum_{s=1}^{2}\log\left[\exp\left\{\frac{-(p_{atgs}-\widehat{p}_{atgs})^2\, n_{tg}}{2\left(p_{atgs}(1-p_{atgs})+\frac{1}{10A}\right)}\right\}+\frac{1}{100}\right]\end{aligned} \tag{E.19}$$

$$\log L_3(\mathbf{\Theta}|\{\widehat{I}_{tg}\}) = \sum_{g=1}^{6}\sum_{t\in\mathbf{T}_g}\left[-\frac{1}{2}\log 2\pi - \log\kappa_{tg} - \frac{(\log I_{tg} - \log\widehat{I}_{tg})^2}{2\kappa_{tg}^2}\right] \tag{E.20}$$

$$\log L(\mathbf{\Theta}) = \sum_{i=1}^{3}\log L_i(\mathbf{\Theta}|\cdot) \tag{E.21}$$

Joint prior distribution and objective function

$$\log(\pi(\mathbf{\Theta})) = \sum_j \log(\pi_j(\mathbf{\Theta})) \tag{E.22}$$

$$f(\mathbf{\Theta}) = -\log L(\mathbf{\Theta}) - \log(\pi(\mathbf{\Theta})) \tag{E.23}$$

Table E.4. *Details for estimation of parameters, including prior distributions with corresponding means and standard deviations, bounds between which parameters are constrained, and initial values to start the minimisation procedure for the MPD (mode of the posterior density) calculations. For uniform prior distributions, the bounds completely parameterise the prior. The resulting non-uniform prior probability density functions are the $\pi_j(\boldsymbol{\Theta})$ functions that contribute to the joint prior distribution in (E.22).*

Parameter	Phase	Prior distribution	Mean, SD	Bounds	Initial value
R_0	1	uniform	—	[1, 10e6]	10e3
M_1, M_2	-	fixed	—	—	{0.07,0.08,0.09}
A	-	fixed	—	—	{40,45,50}
h	5	beta	4.574, 2.212	[0.2, 0.999]	0.674
$\log \epsilon_t$	2	normal	0, 0.9	[-15, 15]	0
$\log q_{1,...,5}$	1	uniform	0, 0.6	[-12, 5]	-5
$\log q_6$	1	uniform	0, 0.1	[-15, 15]	-1.609
$\mu_{1,3}$	3	normal	13.802, 1.988	[5, 40]	13.802
$\mu_{2,4}$	3	normal	11.733, 1.177	[5, 40]	11.733
μ_5	-	fixed	—	—	13.802
μ_6	3	uniform	11.088, 0.325	[5, 40]	11.088
$\log v_{1,3}$	4	normal	3.288, 0.567	[-15, 15]	3.288
$\log v_{2,4}$	4	normal	2.148, 0.535	[-15, 15]	2.148
$\log v_5$	-	fixed	—	—	3.288
$\log v_6$	4	uniform	2.082, 0.147	[-15, 15]	2.082
$\Delta_{1,...,5}$	-	fixed	—	—	0
Δ_6	4	uniform	0.081, 0.171	[-8, 10]	0.081

E.4. DESCRIPTION OF DETERMINISTIC COMPONENTS

Notation (Table E.1) and set up of the deterministic components (Table E.2) are now described.

E.4.1. Age classes

Index (subscript) a represents age classes, going from 1 to the accumulator age class A of 40, 45, and 50. Age class $a = 5$, for example, represents fish aged 4-5 years (which is the usual, though not universal, convention, Caswell 2001), and so an age-class 1 fish was born the previous year. The variable N_{ats} is the number of age-class a fish of sex s at the *start* of year t, so the model is run to year T which corresponds to 2019.

E.4.2. Years

Index t represents model years, going from 1 to $T = 80$, and $t = 0$ represents unfished equilibrium conditions. The actual year corresponding to $t = 1$ is 1940, and so model year $T = 80$ corresponds to 2019. The interpretation of year depends on the model's derived state or data input:

- beginning of year: N_{ats}, B_t, R_t
- middle of year: C_t, V_t, u_t, I_{tg}, p_{atgs}

E.4.3. Survey data

Data from 5 series were used, as described in detail in Appendix B. Along the coast, g = 1 denotes the West Coast Vancouver Island (WCVI) Synoptic series, g = 2 denotes the Queen Charlotte Sound (QCS) Synoptic series, g = 3 denotes the West Coast Haida Gwaii (WCHG) Synoptic series, g = 4 denotes the Goose Island Gully (GIG) Historical series, g = 5 denotes the West Coast Vancouver Island (WCVI) Triennial series. The years for which data were available for each survey are given in Table E.1; $\mathbf{T}_g$ corresponds to years for the survey biomass estimates I_{tg} (and corresponding standard deviations κ_{tg}), and $\mathbf{U}_g$ corresponds to years for proportion-at-age data p_{atgs} (with effective sample sizes n_{tg}). Note that sample size refers to the number of samples, where each sample comprises multiple specimens, typically $\sim$30-350 fish.

E.4.4. Commercial data

As described in Appendix A, the commercial catch was reconstructed back to 1918. Given the negligible catches in the early years, the model was started in 1940, and catches prior to 1940 were not considered. The time series for catches is denoted C_t. The set $\mathbf{U}_6$ (Table E.1) gives the years of available ageing data from the commercial fishery. The proportions-at-age values are given by p_{atgs} with effective sample size n_{tg}, where $g = 6$ (to correspond to the commercial data). These proportions are the weighted proportions calculated using the stratified weighting scheme described in Appendix D, that adjusts for unequal sampling effort across temporal and spatial strata.

E.4.5. Sex

A two-sex model was used, with subscript $s = 1$ for females and $s = 2$ for males (note that these subscripts are the reverse of the codes used in the GFBioSQL database). Ageing data were partitioned by sex, as were the weights-at-age inputs. Selectivities and natural mortality were estimated by sex.

E.4.6. Weights-at-age

The weights-at-age w_{as} were assumed fixed over time and were based on sex-specific allometric (length-weight) and growth (age-length) model parameters derived from the biological data; see Appendix D for details.

E.4.7. Maturity of females

The proportion of age-class a females that are mature is m_a, and was assumed fix over time; see Appendix D for details.

E.4.8. State dynamics

The crux of the model is the set of dynamical equations (E.1)-(E.3) for the estimated number N_{ats} of age-class a fish of sex s at the start of year t. Equation (E.1) states that half of new recruits are males and half are females. Equation (E.2) calculates the numbers of fish in each age class (and of each sex) that survive to the following year, where u_{ats} represents the proportion caught by the commercial fishery, and e^{-M_s} accounts for natural mortality. Equation (E.3) is for the accumulator age class A, whereby survivors from this class remain in this class the following year.

Natural mortality M_s was estimated separately for males and females. It enters the equations in the form e^{-M_s} as the proportion of unfished individuals that survive the year.

E.4.9. Initial conditions

An unfished equilibrium situation at the beginning of the reconstruction was assumed because there was no evidence of significant removals prior to 1940. The initial conditions (E.4) and (E.5) were obtained by setting $R_t = R_0$ (virgin recruitment), $N_{ats} = N_{a1s}$ (equilibrium condition) and $u_{ats} = 0$ (no fishing) into (E.1)-(E.3). The virgin spawning biomass B_0 was then obtained from (E.9).

E.4.10. Selectivities

Separate selectivities were modelled for the commercial fishery and for each survey series (except WCVI Triennial). In this assessment (2019 Widow Rockfish), priors, including initial values for the selectivities were constructed from the means and standard deviations of the Yellowtail Rockfish (YTR) commercial fishery and survey selectivity posteriors. These priors were selected because YTR is a similar sized mid-water species frequently taken in conjunction with WWR (DFO 2015). Specifically, YTR estimates from:

- WCVI Synoptic survey were used for WWR's WCVI Synoptic, WCHG Synoptic, and WCVI Triennial surveys,
- QCS Synoptic survey were used for WWR's QCS Synoptic and GIG Historical survey, and
- YTR commercial fishery were used for WWR's commercial fishery.

A half-Gaussian formulation was used, as given in (E.7) and (E.8), to give selectivities s_{ags}. (Note that the subscript $\cdot_s$ always represents the index for sex, whereas $s_{\dots}$ always represents selectivity). This permits an increase in selectivity up to the age of full selection (μ_g for females). Given there was no evidence to suggest a dome-shaped function, it was assumed that fish older than μ_g remain fully selected. The rate of ascent of the left limb is controlled by the parameter v_{gL} for females. For males, the same function is used except that the age of full selection is shifted by an amount Δ_g, see (E.8). In this assessment, the male selectivity shift parameter Δ_g was fixed to 0 for all surveys because exploratory runs that estimated this parameter suggested that the data were insufficient to distinguish male selectivity from female selectivity μ_g. As well, the estimated male shift parameters in the YTR stock assessment were all very close to zero (=0.2).

E.4.11. Derived states

The spawning biomass (biomass of mature females, in tonnes) B_t at the start of year t is calculated in (E.9) by multiplying the numbers of females N_{at1} by the proportion that are mature (m_a), and converting to biomass by multiplying by the weights-at-age w_{a1}.

Equation (E.13) calculates, for year t, the proportion u_{ats} of age-class a and sex s fish that are caught. This requires the commercial selectivities s_{a6s} and the ratio u_t, which equation (E.12) shows is the ratio of total catch (assumed taken all at once mid-year) to vulnerable biomass in the middle of the year, V_t, given by equation (E.11). Therefore, (E.12) calculates the proportion of the vulnerable biomass that is caught, and (E.13) partitions this out by sex and age.

E.4.12. Stock-recruitment function

A Beverton-Holt recruitment function is used, parameterised in terms of steepness, h, which is the proportion of the long-term unfished recruitment obtained when the stock abundance is reduced to 20% of the virgin level (Mace and Doonan 1988; Michielsens and McAllister 2004). This was done so that a prior for h could be taken from Forrest et al. (2010). The formulation shown in (E.10) comes from substituting $\alpha = (1-h)B_0/(4hR_0)$ and $\beta = (5h-1)/4hR_0$ into the Beverton-Holt equation $R_t = B_{t-1}/(\alpha + \beta B_{t-1})$, where α and β are from the standard formulation given in the Coleraine manual (Hilborn et al. 2003; see also Michielsens and McAllister 2004), R_0 is the virgin recruitment, R_t is the recruitment in year t, B_t is the spawning biomass at the start of year t, and B_0 is the virgin spawning biomass.

E.4.13. Estimates of observed data

The model estimates of the survey biomass indices I_{tg} are denoted $\widehat{I}_{tg}$ and are calculated in (E.14). The estimated numbers N_{ats} are multiplied by the natural mortality term $e^{-M_s/2}$ (that accounts for half of the annual natural mortality), the term $1 - u_{ats}/2$ (that accounts for half of the commercial catch), weights-at-age w_{as} (to convert to biomass), and selectivity s_{ags}. The sum (over ages and sexes) is then multiplied by the catchability parameter q_g to give the model biomass estimate $\widehat{I}_{tg}$. A coefficient of 0.001 in (E.14) is not needed to convert kg into tonnes, because N_{ats} is in 1000s of fish (true also for (E.6) and (E.9)).

The estimated proportions-at-age $\widehat{p}_{atgs}$ are calculated in (E.15). For a particular year and gear type, the product $e^{-M_s/2}(1 - u_{ats}/2)s_{ags}N_{ats}$ gives the relative expected numbers of fish caught for each combination of age and sex. Division by $\sum_{s=1}^{2}\sum_{a=1}^{A} e^{-M_s/2}(1 - u_{ats}/2)s_{ags}N_{ats}$ converts these to estimated proportions for each age-sex combination, such that $\sum_{s=1}^{2}\sum_{a=1}^{A} \widehat{p}_{atgs} = 1$.

E.5. DESCRIPTION OF STOCHASTIC COMPONENTS

E.5.1. Parameters

The set **Θ** gives the parameters that are estimated. The estimation procedure is described in the Bayesian Computations section below.

E.5.2. Recruitment deviations

For recruitment, a log-normal process error is assumed, such that the stochastic version of the deterministic stock-recruitment function (E.10) is

$$R_t = \frac{B_{t-1}}{\alpha + \beta B_{t-1}} e^{\epsilon_t - \sigma_R^2/2} \tag{E.24}$$

where $\epsilon_t \sim$ Normal$(0, \sigma_R^2)$, and the bias-correction term $-\sigma_R^2/2$ term in (E.24) ensures that the mean of the recruitment deviations equals 0. This then gives the recruitment deviation equation (E.17) and log-likelihood function (E.18). In this assessment, the value of σ_R was fixed at 0.9 based on trials with $\sigma_R \in \{0.6, 0.9, 1.2\}$. Previous assessments have used σ_R = 0.6 following an assessment of Silvergray Rockfish (Starr et al. 2016) in which the authors stated that the value was typical for marine ‘redfish’ (Mertz and Myers 1996). An Awatea model of Rock Sole used σ_R = 0.6 (Holt et al. 2016), citing that it was a commonly used default for finfish assessments

(Beddington and Cooke 1983). In other rockfish assessments, authors have adopted σ_R = 0.9 based on an empirical model fit consistent with the age composition data for 5ABC POP (Edwards et al. 2012*b*). A study by Thorson et al. (2014) examined 154 fish populations and estimated σ_R = 0.74 (SD=0.35) across seven taxonomic orders; the marginal value for Scorpaeniformes was σ_R=0.78 (SD=0.32) but was only based on 7 stocks.

E.5.3. Log-likelihood functions

The log-likelihood function (E.19) arises from comparing the estimated proportions-at-age with the data. It is the Coleraine (Hilborn et al. 2003) modification of the Fournier et al. (1990, 1998) robust likelihood equation. The Coleraine formulation replaces the expected proportions $\widehat{p}_{atgs}$ from the Fournier et al. (1990, 1998) formulation with the observed proportions p_{atgs}, except in the $(p_{atgs} - \widehat{p}_{atgs})^2$ term (Bull et al. 2005).

The $1/(10A)$ term in (E.19) reduces the weight of proportions that are close to or equal zero. The $1/100$ term reduces the weight of large residuals $(p_{atgs} - \widehat{p}_{atgs})$. The net effect (Stanley et al. 2009) is that residuals larger than three standard deviations from the fitted proportion are treated roughly as $3(p_{atgs}(1 - p_{atgs}))^{1/2}$.

Lognormal error is assumed for the survey indices, resulting in the log-likelihood equation (E.20). The total log-likelihood $\log L(\boldsymbol{\Theta})$ is then the sum of the likelihood components – see (E.21).

E.6. BAYESIAN COMPUTATIONS

Estimation of parameters compares the estimated (model-based) observations of survey biomass indices and proportions-at-age with the data, and minimises the recruitment deviations. This is done by minimising the objective function $f(\boldsymbol{\Theta})$, which equation (E.23) shows is the negative of the sum of the total log-likelihood function and the logarithm of the joint prior distribution, given by (E.22).

The procedure for the Bayesian computations is as follows:

1. minimise the objective function $f(\boldsymbol{\Theta})$ to give estimates of the mode of the posterior density (MPD) for each parameter:
   - this is done in phases,
   - a reweighting procedure is performed;
2. generate samples from the joint posterior distributions of the parameters using Monte Carlo Markov Chain (MCMC) procedure, starting the chains from the MPD estimates.

E.6.1. Phases

The MPD estimates were obtained by minimising the objective function $f(\boldsymbol{\Theta})$, from the stochastic (non-Bayesian version) of the model. The resulting estimates were then used to initiate the chains for the MCMC procedure for the full Bayesian model.

Simultaneously estimating all the estimable parameters for complex nonlinear models is ill advised, and so ADMB allows some of the estimable parameters to be kept fixed during the initial part of the optimisation process ADMB Project (2009). Some parameters are estimated in phase 1, then some further ones in phase 2, and so on. The order used here was:

phase 1: virgin recruitment R_0 and survey catchabilities $q_{1,...,5}$;
phase 2: recruitment deviations ϵ_t (held at 0 in phase 1);
phase 3: age of full selectivity for females $\mu_{1,...,6}$;
phase 4: natural mortality $M_{1,2}$ and selectivity parameters Δ_g, v_{gL} for $g = 1, ..., 6$;
phase 5: steepness h.

E.6.2. Reweighting

Given that sample sizes are not comparable between different types of data, a procedure that adjusts the relative weights between data sources (abundance vs. composition) is required. The QCS POP assessment (Edwards et al. 2012*b*) used an iterative reweighting scheme based on adjusting the standard deviation of normal (Pearson) residuals (SDNRs) of data sets until these standard deviations were approximately 1 (which is the predicted standard deviation of a normal distribution with μ=0). This procedure did not perform well for the Yellowmouth Rockfish assessment (Edwards et al. 2012*a*), leading to spurious cohorts; therefore, the Yellowmouth assessment used the reweighting scheme proposed by Francis (2011). Rockfish stock assessments using the Awatea model since 2011, including this one, have adopted the Francis (2011) reweighting approach – adding series-specific process error to abundance index CVs on the first reweight, and iteratively reweighting age frequency (composition data) sample size by mean age on the first and subsequent reweights (see below). For the Widow Rockfish data set, subsequent reweighting of the composition data made little difference, and so only one reweight using mean age was performed for all presented model runs.

For abundance data such as survey indices, Francis (2011) recommends reweighting observed coefficients of variation, c_0, by first adding process error c_p ∼= 0.2 to give a reweighted coefficient of variation

$$c_1 = \sqrt{c_0^2 + c_\mathrm{p}^2}\,. \tag{E.25}$$

For each model run, the abundance index CVs were adjusted on the first reweight only using the process error c_p = 0, 0, 0, 0, 0, and 0.1859 along the Coast (g=1,...6). This last value was the CV of the residuals to the CPUE indices after a smoothing function was passed through the CPUE series, giving an approximation of the eventual fit to the indices (see Section E.6.2.1.).

Francis (2011) maintains that correlation effects are usually strong in age-composition data. Each age-composition data set has a sample size n_{tg} ($g = 1, ..., 6$, $t \in \mathbf{U}_g$), which is typically in the range 3-20, each sample comprising ∼30-350 specimen ages. Equation (T3.4) of Francis (2011) is used to iteratively reweight the sample size as

$$n_{tg}^{(r)} = W_g^{(r)} n_{tg}^{(r-1)} \tag{E.26}$$

where $r = 1, 2, 3$ represents the reweighting iteration, $n_{tg}^{(r)}$ is the effective sample size for reweighting r, $W_g^{(r)}$ is the weight applied to obtain reweighting r, and $n_{tg}^{(0)} = n_{tg}$. So a single weight $W_g^{(r)}$ is calculated for each series $g = 1, ..., 6$ for reweighting r.

The Francis (2011) weight $W_g^{(r)}$ given to each data set takes into account deviations from the mean age for each year, rather than using deviations from each proportion-at-age value (e.g., Edwards et al. 2012*b*). The weight is given by equation (TA1.8) of Francis (2011):

$$W_g^{(r)} = \left\{ \text{Var}_t \left[\frac{\overline{O}_{tg} - \overline{E}_{tg}}{\sqrt{\theta_{tg}/n_{tg}^{(r-1)}}} \right] \right\}^{-1} \tag{E.27}$$

where the observed mean age, the expected mean age and the variance of the expected age distribution are, respectively,

$$\overline{O}_{tg} = \sum_{a=1}^{A} \sum_{s=1}^{2} a p_{atgs} \tag{E.28}$$

$$\overline{E}_{tg} = \sum_{a=1}^{A} \sum_{s=1}^{2} a \widehat{p}_{atgs} \tag{E.29}$$

$$\theta_{tg} = \sum_{a=1}^{A} \sum_{s=1}^{2} a^2 \widehat{p}_{atgs} - \overline{E}_{tg}^2 \tag{E.30}$$

and Var_t is the usual finite-sample variance function applied over the index t.

The reweighting of abundance CVs (once) and age frequencies over r reweights affects the model fit to the abundance index series $\widehat{I}_{tg}$ after each reweight. These predicted indices at reweight r are used to calculate normalised residuals for each survey index:

$$\delta_{tg}^{(r)} = \frac{\log I_{tg}^{(r-1)} - \log \widehat{I}_{tg}^{(r)} + 0.5 \log(1 + c_{tg}^2)^2}{\sqrt{\log(1 + c_{tg}^2)}}, \tag{E.31}$$

where $I_{tg}^{(r-1)}$ = the observed survey indices from the previous reweight r, and the standard deviation of normalised residuals (SDNR) for each survey g is simply:

$$\sigma_{\delta_g}^{(r)} = \sqrt{\frac{\sum_t (\delta_{tg}^{(r)} - \overline{\delta}_{tg}^{(r)})^2}{\eta_g - 1}} \tag{E.32}$$

where η_g = number of indices (years t) for index series g.

The reweighted dataset chosen for MCMC analysis is typically the one where the sum of the absolute deviation from unity of the SDNRs for the 6 abundance index series was the lowest (E.33); however, the first reweight was chosen for all model runs in this assessment, including the sensitivity runs.

$$r' = \min_{r \in 1:3} \sum_{g=1}^{6} |1 - \sigma_{\delta_g}^{(r)}|. \tag{E.33}$$

E.6.2.1. Process error for commercial CPUE

A procedure was developed for estimating process error c_p to add to the commercial CPUE using a spline-smoother analysis. Francis (2011) (citing Clark and Hare 2006) recommends using a smoothing function to determine the appropriate level of process error to add to CPUE data, with

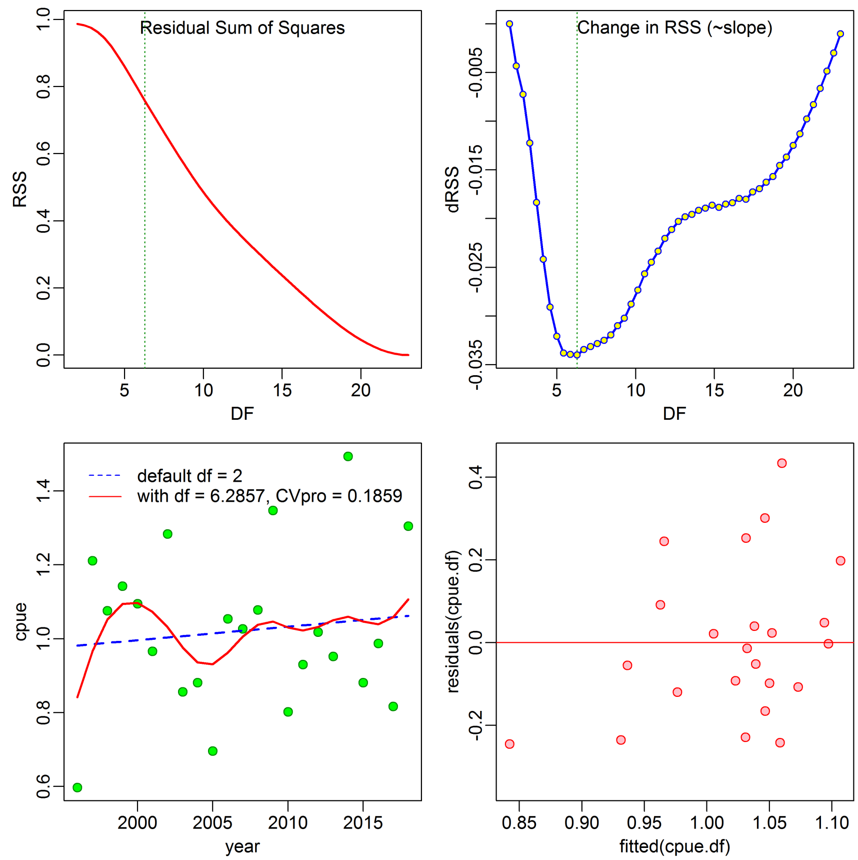

Figure E.1. Estimating process error to add to commercial CPUE data: top left – residual sum of squares (RSS) from spline-smoother at various degrees of freedom; top right – slope of RSS (∼ first derivative), vertical dotted line at DF where slope is at a minimum; bottom left – CPUE index data with spline fits at DF=2 (dashed blue curve) and DF=6.2587 (solid red curve); bottom right – standardised residual fit.

the goal of finding a balance between rigorously fitting the indices while not removing the majority of the signal in the data. An arbitrary sequence of length 50, comprising degrees of freedom (DF, ν_i), where $i = 2, ..., N$ and N = number of CPUE values U_t from $t = 1996, ..., 2018$, was used to fit the CPUE data with a spline smoother. At $i = N$, the spline curve fit the data perfectly and the residual sum of squares (RSS, ρ_N) was 0. Using spline fits across a range of trial DF ν_i, values of RSS ρ_i formed a logistic-type curve with an inflection point at $i = k$ (Figure E.1). The difference between point estimates of ρ_i (proxy for the slope δ_i) yielded a concave curve with a minimum δ_i, which occurred close to the inflection point k. At the inflection point k, ν_k=6.2857 that corresponded to ρ_k=0.7578, which was converted to a c_p of 0.1859 using:

$$c_\mathrm{p} = \sqrt{\frac{\rho_k}{N-2}} \, \left[\frac{1}{N} \sum_{t=1996}^{2018} U_t \right]^{-1} . \tag{E.34}$$

E.6.3. Prior distributions

Descriptions of the prior distributions for the estimated parameters (without including recruitment deviations) are given in Table E.4. The resulting probability density functions give the $\pi_j(\Theta)$, whose logarithms are then summed in (E.22) to give the joint prior distribution $\pi(\mathbf{\Theta})$. Since uniform priors are, by definition, constant across their bounded range (and zero outside), their contributions to the objective function can be ignored. Thus, in the calculation (E.22) of the joint prior distribution $\pi(\mathbf{\Theta})$, only those priors that are not uniform need to be considered in the summation.

A uniform prior over a large range was used for R_0. Initially, normal priors for female and male natural mortality, M_1 and M_2 respectively, were explored using various natural mortality estimators (Hoenig 1983; Then et al. 2015; Hamel 2015) at observed ages $A_{\max} \in \{50, 55, 60\}$y (Appendix D). Estimated M from these trials showed that the priors were not updated by the data; therefore, this assessment chose three fixed values of M (0.07, 0.08, 0.09) and three accumulator age-classes A (40, 45, 55) to generate a model average from nine runs.

For steepness, h, the same prior was used as for the QCS POP assessment (Edwards et al. 2012*b*) – a beta distribution with values fitted to the posterior distribution for rockfish calculated by Forrest et al. (2010). The mean of the beta distribution (Cooper and Weekes 1983) in terms of its two shape parameters (a=4.574 and b=2.212 in this assessment) is equal to $a/(a+b)$ = 0.674, and the standard deviation is $\mathrm{sqrt}(ab/[(a+b+1)(a+b)^2])$ = 0.168.

Uniform priors on a logarithmic scale were used for the catchability parameters q_g.

Selectivity is discussed more fully in Section E.4.10. Selectivity priors (means and standard deviations) were based on Yellowtail Rockfish MCMC samples of commercial fishery and survey selectivity (DFO 2015). The male selectivity shift parameter Δ_g was fixed to 0 for all surveys because exploratory runs that estimated this parameter suggested that the data were insufficient to distinguish male selectivity from female selectivity μ_g.

E.6.4. MCMC properties

The MCMC procedure started the search from the MPD values and performed 12 million iterations, sampling every 10,000$^{\mathrm{th}}$ for 1200 samples, 1000 of which were used after removing the first 200 for a burn-in period.

E.7. REFERENCES POINTS, PROJECTIONS AND ADVICE TO MANAGERS

Advice to managers is given with respect to a suite of reference points. The first set is based on MSY (maximum sustainable yield) and includes the provisional reference points of the DFO Precautionary Approach (DFO 2006), namely 0.4B_{MSY} and 0.8B_{MSY} (and we also provide B_{MSY} and u_{MSY}, which denote the estimated equilibrium spawning biomass and harvest rate at MSY, respectively). A second set of reference points, the current spawning biomass B_{2019} and harvest rate u_{2018}, is used to show the probability of increasing from the current female spawning biomass or decreasing from the current harvest rate. A third set of reference points, 0.2B_0 and 0.4B_0, is based on the estimated unfished equilibrium spawning biomass B_0. See main text for further discussion.

To estimate B_{MSY}, the model was projected forward across a range (0 to 0.401 incremented by 0.001) of constant harvest rates (u_t), for a maximum of 15,000 years until equilibrium was reached (with a tolerance of 0.01 t). The MSY is the largest of the equilibrium yields, and the associated exploitation rate is then u_{MSY} and the associated spawning biomass is B_{MSY}. This calculation was done for each of the 1000 MCMC samples, resulting in marginal posterior distributions for MSY, u_{MSY} and B_{MSY}.

The probability $\mathrm{P}(B_{2019} > 0.4B_{\mathrm{MSY}})$ is then calculated as the proportion of the 1000 MCMC samples for which $B_{2019} > 0.4B_{\mathrm{MSY}}$ (and similarly for the other biomass-based reference points). For harvest rates, the probability $\mathrm{P}(u_{2018} < u_{\mathrm{MSY}})$ is calculated so that both B- and u-based stock status indicators (and projections when $t = 2019, ..., 2024$) state the probability of being in a 'good' place.

Projections were made for 5 years starting with the biomass and age structure calculated for the start of 2019. A range of constant catch strategies were used, from 0 to 4000 t at 250 t increments (the average catch from 2014 to 2018 was 2001 t along the BC Coast). For each strategy, projections were performed for each of the 1000 MCMC samples (resulting in posterior distributions of future spawning biomass). Recruitments were randomly calculated using (E.24) (i.e. based on lognormal recruitment deviations from the estimated stock-recruitment curve), using randomly generated values of $\epsilon_t \sim$ Normal$(0, \sigma_R^2)$. For each of the 1000 MCMC samples a time series of $\{\epsilon_t\}$ was generated. For each MCMC sample, the same time series of $\{\epsilon_t\}$ was used for each catch strategy (so that, for a given MCMC sample, all catch strategies experience the same recruitment stochasticity).

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APPENDIX F. MODEL RESULTS

F.1. INTRODUCTION

This Appendix describes results for one coastwide stock of Widow Rockfish (WWR) using:

- mode of the posterior distribution (MPD) calculations to compare model estimates to observations,
- Markov chain Monte Carlo (MCMC) simulations to derive posterior distributions for the estimated parameters,
- MCMC diagnostics, and
- a range of sensitivity model runs.

The final advice draws from the MCMC results from all runs, but the proposed base case provides the primary guidance. Estimates of major quantities and advice to management (decision tables) are presented here and in the main text.

F.2. BC COAST STOCK

F.2.1. Base Case

The base case for Widow Rockfish was selected from combined model runs 1-9. Important decisions made during the assessment of WWR included:

- fixed natural mortality M to three levels: 0.07, 0.08, and 0.09;
- used three maximum ages as plus classes A: 40, 45, and 50 y;
- used five abundance index series (WCVI Synoptic, QCS Synoptic, WCHG Synoptic, GIG Historical, WCVI Triennial), the first four with age frequency (AF) data;
- used one commercial fishery abundance index series (bottom trawl CPUE index);
- assumed one fishery (commercial bottom + midwater trawl) with pooled catches and AF data;
- assumed two sexes (females, males);
- developed selectivity priors (μ_g, ν_{gL}, Δ_g) for the surveys from MCMC estimates of selelctivity for Yellowtail Rockfish (DFO 2015) but fixed the shift in the survey vulnerability of males ($\Delta_{g=1:5}$) to 0;
- applied abundance reweighting: added CV process error to index CVs, c_p=0 for surveys and c_p=0.1859 for commercial CPUE series;
- applied composition reweighting: adjusted AF effective sample sizes using the mean-age method of Francis (2011);
- fixed standard deviation of recruitment residuals (σ_R) to 0.9;
- excluded the 1995 survey index from the GIG Historical series (design incompatible);
- excluded water hauls from the WCVI Triennial series;
- excluded the 1997 WCHG age frequency data (caused instability in the MCMC simulations).

Combinations of three fixed M values and three fixed A values produced nine model runs, which were pooled as a base case for advice to managers. The central run of the composite base case (Run05: M=0.08, A=45) was used as an example case and served as the comparative run for 12 sensitivity runs.

All model runs were reweighted one time for (i) abundance, by adding process error $c_\mathrm{p} \in$ { 0, 0, 0, 0, 0, and 0.1859 } to the index CVs for the WCVI Synoptic, QCS Synoptic, WCHG Synoptic, GIG Historical, WCVI Triennial, and commercial trawl CPUE, respectively, and (ii) composition using the procedure of Francis (2011) for age frequencies.

F.2.1.1. Central Run MPD

The procedure followed in this assessment was to first determine the best MPD fit to the data by minimising the negative log likelihood. Because the WWR composite base case involved 9 models, only the central run (M=0.08, A=45) is used as an example (Tables F.1 and F.2). The MPDs became the starting points for the MCMC simulations. The following plot descriptions apply to the central run.

- Figure F.1 – survey index fits across all survey years;
- Figures F.2-F.6 – inidividual survey fits and residuals;
- Figure F.7 – bottom trawl CPUE fit and its residuals;
- Figures F.8-F.10 model fits to the female and male age frequency data for the commercial trawl fishery and combined-sex residuals;
- Figure F.11-F.12 – model fits and residuals to the age data for the West Coast Vancouver Island (WCVI) synoptic survey;
- Figure F.13-F.14 – model fits and residuals to the age data for the Queen Charlotte Sound (QCS) synoptic survey;
- Figure F.15-F.16 – model fits and residuals to the age data for the West Coast Haida Gwaii (WCHG) synoptic survey;
- Figure F.17-F.18 – model fits and residuals to the age data for the Goose Island Gully (GIG) historical survey;
- Figure F.19 – model estimates of mean age compared to the observed mean ages;
- Figure F.20 – the stock-recruitment relationship and recruitment time series;
- Figure F.21 – the recruitment deviations and auto-correlation of these deviations;
- Figure F.22 – fits for the gear selectivities, together with the ogive for female maturity;
- Figure F.23 – the relative spawning biomass (B_t/B_0) together with the exploitation over time.

Model fits to the abundance indices were satisfactory (Figures F.1 and F.7), although the high CVs allowed much room for the fits to follow variations in trajectory. Fits to age frequency data were generally satisfactory, although older ages were sometimes under-estimated (e.g., Figure F.17). Model estimates of mean age matched the observed mean ages (Figure F.19) for the commercial series, for the most part, but the fits were poor for the survey data sets. The poor fits to the survey age data are not surprising, given the mid-water behaviour of this species and the sporadic nature of the the available age data. Additionally, the synoptic design of the surveys adopts sampling procedures not optimised for any single species. The Francis (2011) weighting method (TA1.8) is designed to reduce the weight of the composition data relative to the abundance data because composition tends to be overweighted in these models if a multinomial effective sample size is applied. This overweighting occurs because the age (or length) proportions sum to 1.0, which means that adjacent observations are not independent, as assumed by the multinomial distribution, leading to a high level of correlation among observations.

Because this stock assessment indicated that the WWR spawning biomass never went to levels that would impair recruitment, the stock-recruitment relationship (Figure F.20) showed little contrast, with a few large recruitment events spread across the parent population. High, episodic recruitment occurred in 1961 and 1990. The latter recruitment peak was very well defined but there appeared to be blurring into adjacent years for the 1961 peak which was likely due to ageing error. Recruit deviations fluctuated over time, but significant auto-correlation of these deviations occurred only at lag 1 (Figure F.21). The MPD estimate of age at full selectivity (Figure F.22) was similar among the surveys ($\mu_{1:5}$ = 12.7-15.1) and lower for the commercial fishery (μ_6 = 10.8), but the survey selectivities may have been poorly estimated due to the highly variable survey ageing data. The selectivity curves either overlaid or lay to the right of the maturity ogive, indicating that the fishery and the surveys were capturing mature fish (Figure F.22).

The standard deviation (also called root mean-squared-error or RMSE) of recruitment process error ϵ_t (Table E.1), calculated over the period where the age frequency data allow for the estimation of recruitment deviations (1957-2010), was 0.58. This value is less than the assumed standard deviation (σ_R=0.9), and similar RMSE values were obtained for all runs made using this assumption. Sensitivity runs (see Section F.2.2) that altered the σ_R assumption resulted in RMSE values that were consistently lower than the associated recruitment process error deviation assumption: S01 (σ_R=0.6) = 0.46; S02 (σ_R=1.2) = 0.65. These results imply good consistency among the commercial age frequency data across 30 years (1989-2018), with similar fits obtained regardless of the recruitment process error deviation assumption.

Spawning biomass (B_t) relative to unfished equilibrium biomass (B_0) showed rapid depletion from the late 1970s to the mid 1990s, with the MPD estimate of 2019 spawning biomass (B_{2019}) sitting at 0.37B_0 (Figure F.23). Exploitation rates (u_t) exceeded 0.08 (the central run M) in 33 years, 23 of which occurred after the fishery became more controlled in 1996. The current exploitation rate (mean of last 5 years) was estimated to be 0.11 (bottom panel: Figure F.23).

F.2.1.1.1. MPD tables for central run

Table F.1. CR.05.01: Priors and MPD estimates for estimated parameters. Prior information – distributions: 0 = uniform, 1 = normal, 2 = lognormal, 5 = beta

Phase	Range	Type	(Mean,SD)	Initial	MPD
R_0 **(recruitment in virgin condition)**					
1	(1,10000000)	0	(0,0)	10000	4169.91
M_s **(natural mortality by sex** s**, where** $s = 1\ [\text{female}], 2\ [\text{male}]$**)**					
-4	(0.01,0.2)	1	(0.08,0.02)	0.08	0.08
-4	(0.01,0.2)	1	(0.08,0.02)	0.08	0.08
h **(steepness of spawner-recruit curve)**					
5	(0.2,0.999)	5	(4.574,2.212)	0.674	0.822045
ϵ_t **(recruitment deviations)**					
2	(-15,15)	1	(0,0.9)	0	Fig F.21
ω **(initial recruitment)**					
-1	(0,2)	0	(1,0.1)	1	1

Table F.2. CR.05.01: Priors and MPD estimates for index g (survey and commercial).

Index g	Phase	Range	Type	(Mean,SD)	Initial	MPD	exp (MPD)
CPUE catchability mode ($\log q_g$ where $g = 6, ...6$)							
6	1	(-15,15)	0	(0,0.1)	-1.60944	-9.6726	0.000062986
Survey catchability mode ($\log q_g$, where $g = 1, ..., 5$)							
1	1	(-12,5)	0	(0,0.6)	-5	-6.3592	0.0017308
2	1	(-12,5)	0	(0,0.6)	-5	-5.2368	0.0053174
3	1	(-12,5)	0	(0,0.6)	-5	-5.118	0.0059879
4	1	(-12,5)	0	(0,0.6)	-5	-6.9816	0.00092877
5	1	(-12,5)	0	(0,0.6)	-5	-4.7415	0.0087255
Commercial selectivity (μ_g, where $g = 6$)							
6	3	(5,40)	0	(11.0879,0.324665)	11.0879	10.828	
Survey selectivity (μ_g, where $g = 1, ..., 5$)							
1	3	(5,40)	1	(13.8018,1.98806)	13.8018	12.676	
2	3	(5,40)	1	(11.7325,1.17733)	11.7325	11.985	
3	3	(5,40)	1	(13.8018,1.98806)	13.8018	15.089	
4	3	(5,40)	1	(11.7325,1.17733)	11.7325	13.05	
5	-3	(5,40)	1	(13.8018,1.98806)	13.8018	13.802	
Variance (left) of commercial selectivity curve ($\log v_{gL}$, where $g = 6$)							
6	4	(-15,15)	0	(2.08185,0.147271)	2.08185	2.2105	
Variance (left) of survey selectivity curve ($\log v_{gL}$, where $g = 1, ..., 5$)							
1	4	(-15,15)	1	(3.28815,0.567089)	3.28815	3.3624	
2	4	(-15,15)	1	(2.14758,0.535061)	2.14758	2.4654	
3	4	(-15,15)	1	(3.28815,0.567089)	3.28815	2.9504	
4	4	(-15,15)	1	(2.14758,0.535061)	2.14758	1.9074	
5	-4	(-15,15)	1	(3.28815,0.567089)	3.28815	3.2882	
Shift in commercial selectivity for males (Δ_g, where $g = 6$)							
6	4	(-8,10)	0	(0.080832,0.171381)	0.080832	-0.36646	
Shift in survey selectivity for males (Δ_g, where $g = 1, ..., 5$)							
1	-4	(-8,10)	1	(0.219259,0.06438)	0	0	
2	-4	(-8,10)	1	(0.223938,0.065273)	0	0	
3	-4	(-8,10)	1	(0.219259,0.06438)	0	0	
4	-4	(-8,10)	1	(0.223938,0.065273)	0	0	
5	-4	(-8,10)	1	(0.219259,0.06438)	0	0	

Table F.3. CR.05.01: Negative log-likelihoods and objective function from the MPD results for the two models. Parameters and likelihood symbols are defined in Appendix F. For indices ($\hat{I}_{tg}$) and proportions-at-age ($\hat{p}_{atgs}$), subscripts $g = 1...5$ refer to the trawl surveys and subscript $g = 6+$ refers to the commercial fishery.

Description	Negative log likelihood	Value
Survey 1	$\log \mathsf{L}_3 \left(\boldsymbol{\Theta} \middle\| \left\{\hat{I}_{t1}\right\}\right)$	28.32
Survey 2	$\log \mathsf{L}_3 \left(\boldsymbol{\Theta} \middle\| \left\{\hat{I}_{t2}\right\}\right)$	13.02
Survey 3	$\log \mathsf{L}_3 \left(\boldsymbol{\Theta} \middle\| \left\{\hat{I}_{t3}\right\}\right)$	1.74
Survey 4	$\log \mathsf{L}_3 \left(\boldsymbol{\Theta} \middle\| \left\{\hat{I}_{t4}\right\}\right)$	9.83
Survey 5	$\log \mathsf{L}_3 \left(\boldsymbol{\Theta} \middle\| \left\{\hat{I}_{t5}\right\}\right)$	24.61
CPUE 1	$\log \mathsf{L}_3 \left(\boldsymbol{\Theta} \middle\| \left\{\hat{I}_{t1}\right\}\right)$	-25.72
CAs 1	$\log \mathsf{L}_2 \left(\boldsymbol{\Theta} \middle\| \left\{\hat{p}_{at1s}\right\}\right)$	-246.34
CAs 2	$\log \mathsf{L}_2 \left(\boldsymbol{\Theta} \middle\| \left\{\hat{p}_{at2s}\right\}\right)$	-500.43
CAs 3	$\log \mathsf{L}_2 \left(\boldsymbol{\Theta} \middle\| \left\{\hat{p}_{at3s}\right\}\right)$	-232.02
CAs 4	$\log \mathsf{L}_2 \left(\boldsymbol{\Theta} \middle\| \left\{\hat{p}_{at4s}\right\}\right)$	-227.83
CAc 1	$\log \mathsf{L}_2 \left(\boldsymbol{\Theta} \middle\| \left\{\hat{p}_{at6s}\right\}\right)$	-6886.37
Prior	$\log \mathsf{L}_1 \left(\boldsymbol{\Theta} \middle\| \left\{\epsilon_t\right\}\right) - \log\left(\pi(\boldsymbol{\Theta})\right)$	16.48
	Objective function $f(\boldsymbol{\Theta})$	-8024.72

F.2.1.1.2. MPD figures for central run

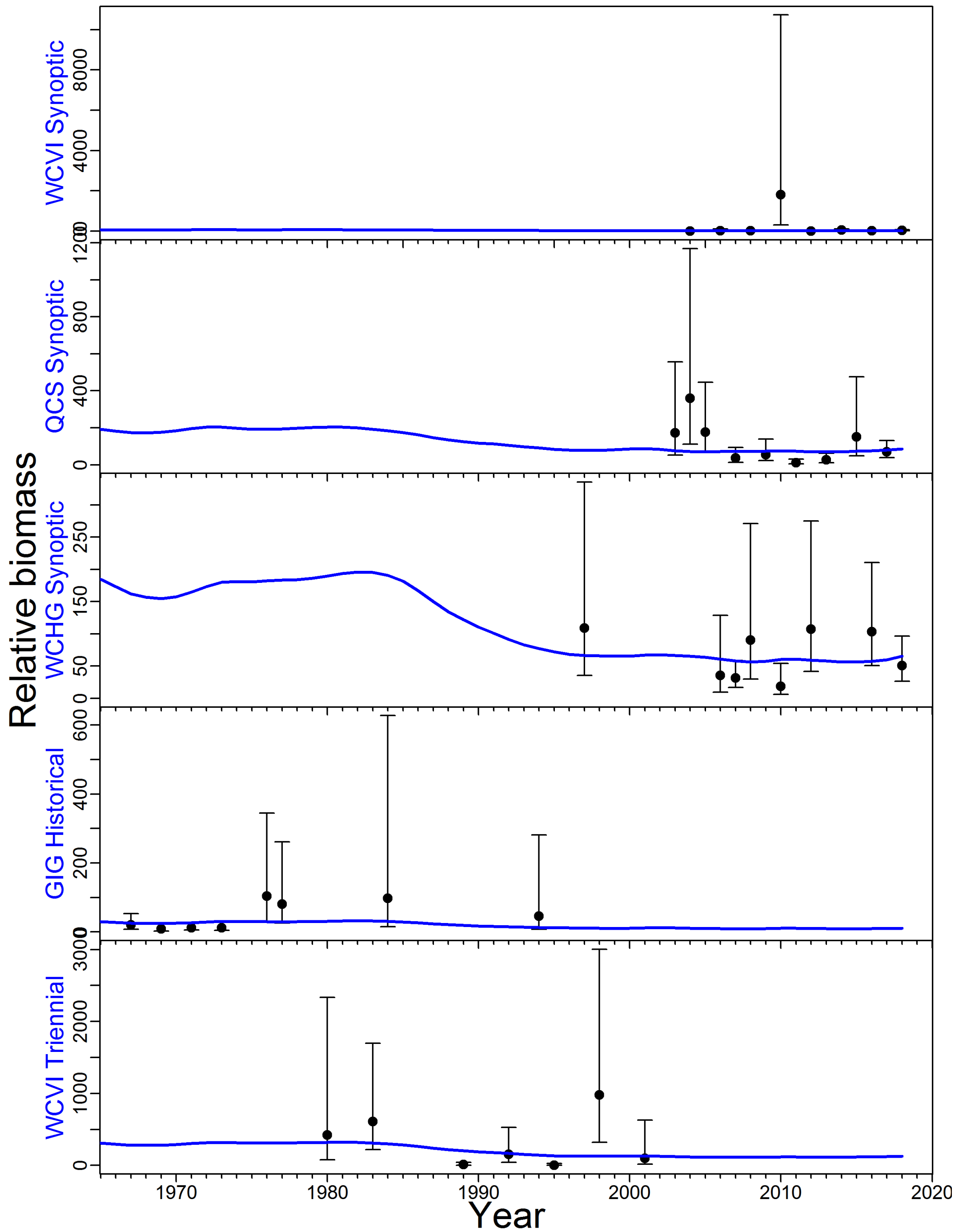


Figure F.1. CR.05.01: Survey index values (points) with 95% confidence intervals (bars) and MPD model fits (curves) for the fishery-independent survey series.

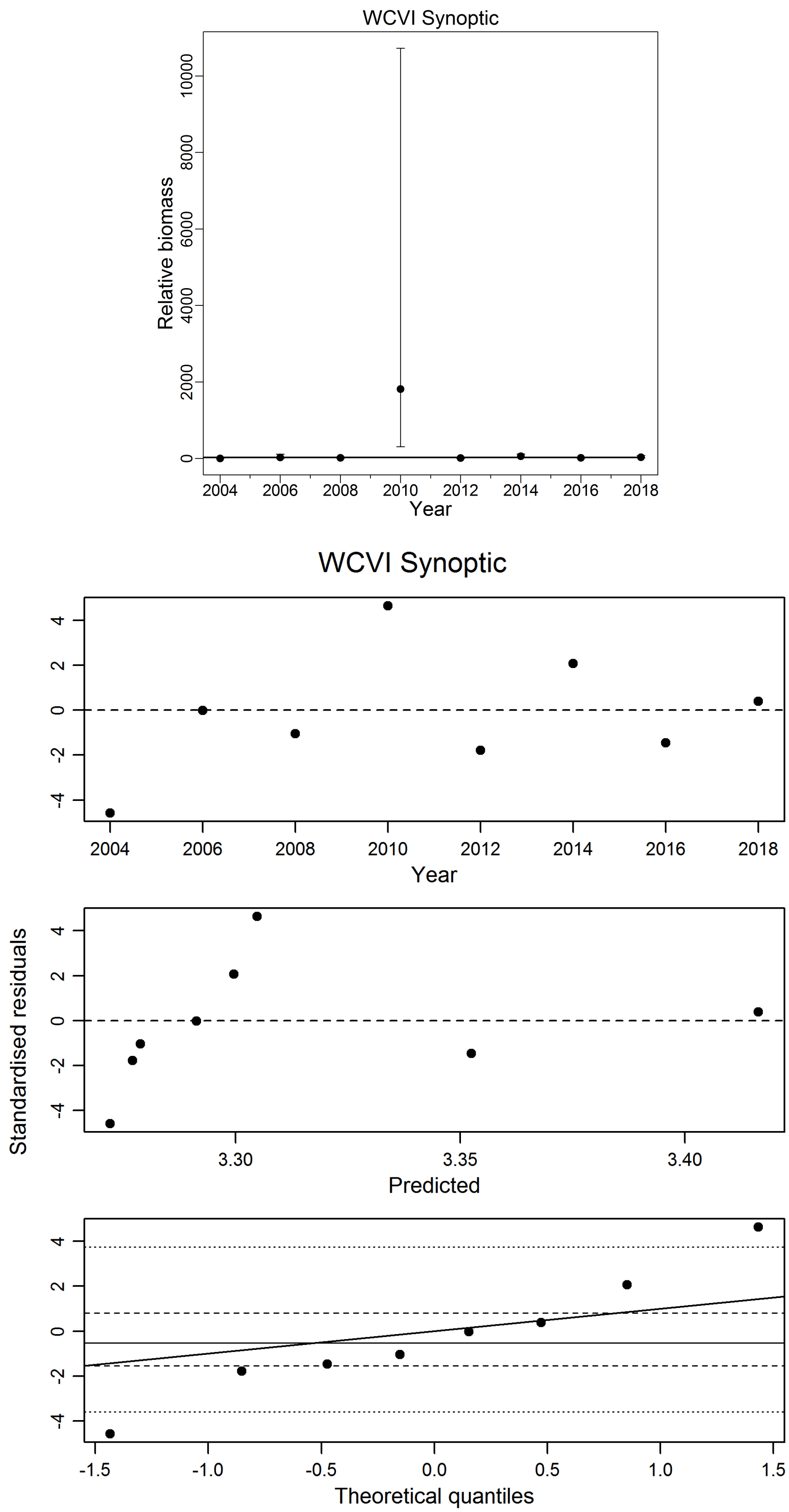


Figure F.2. CR.05.01: Fit (top) and residuals of fits (bottom) of model to WCVI Synoptic survey series (MPD values). Vertical axes are standardised residuals. The three plots show, respectively, residuals by year of index, residuals relative to predicted index, and normal quantile-quantile plot for residuals (horizontal lines give 5, 25, 50, 75 and 95 percentiles).

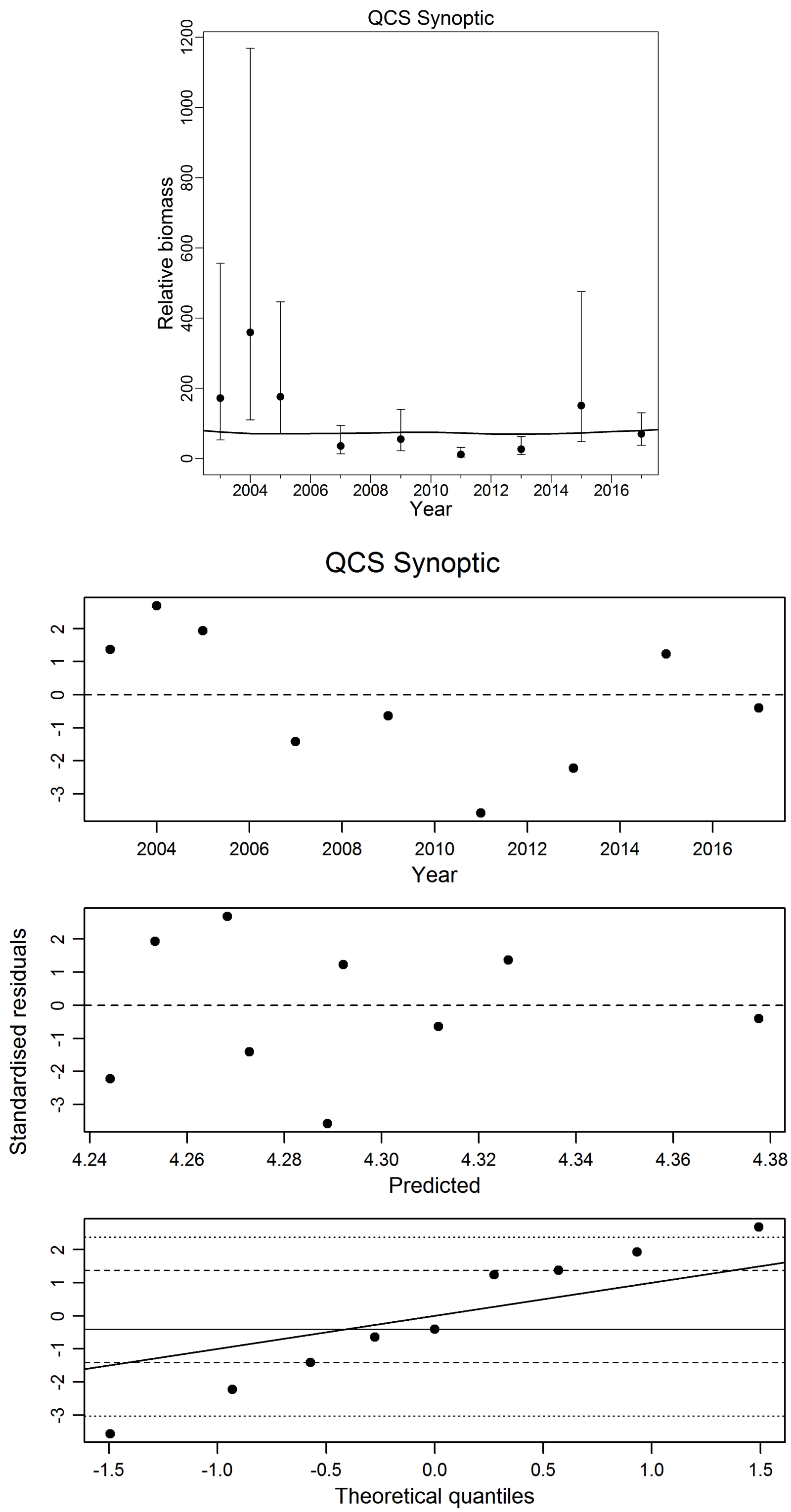


Figure F.3. CR.05.01: Fit (top) and residuals of fits (bottom) of model to QCS Synoptic survey series (MPD values). Vertical axes are standardised residuals. The three plots show, respectively, residuals by year of index, residuals relative to predicted index, and normal quantile-quantile plot for residuals (horizontal lines give 5, 25, 50, 75 and 95 percentiles).

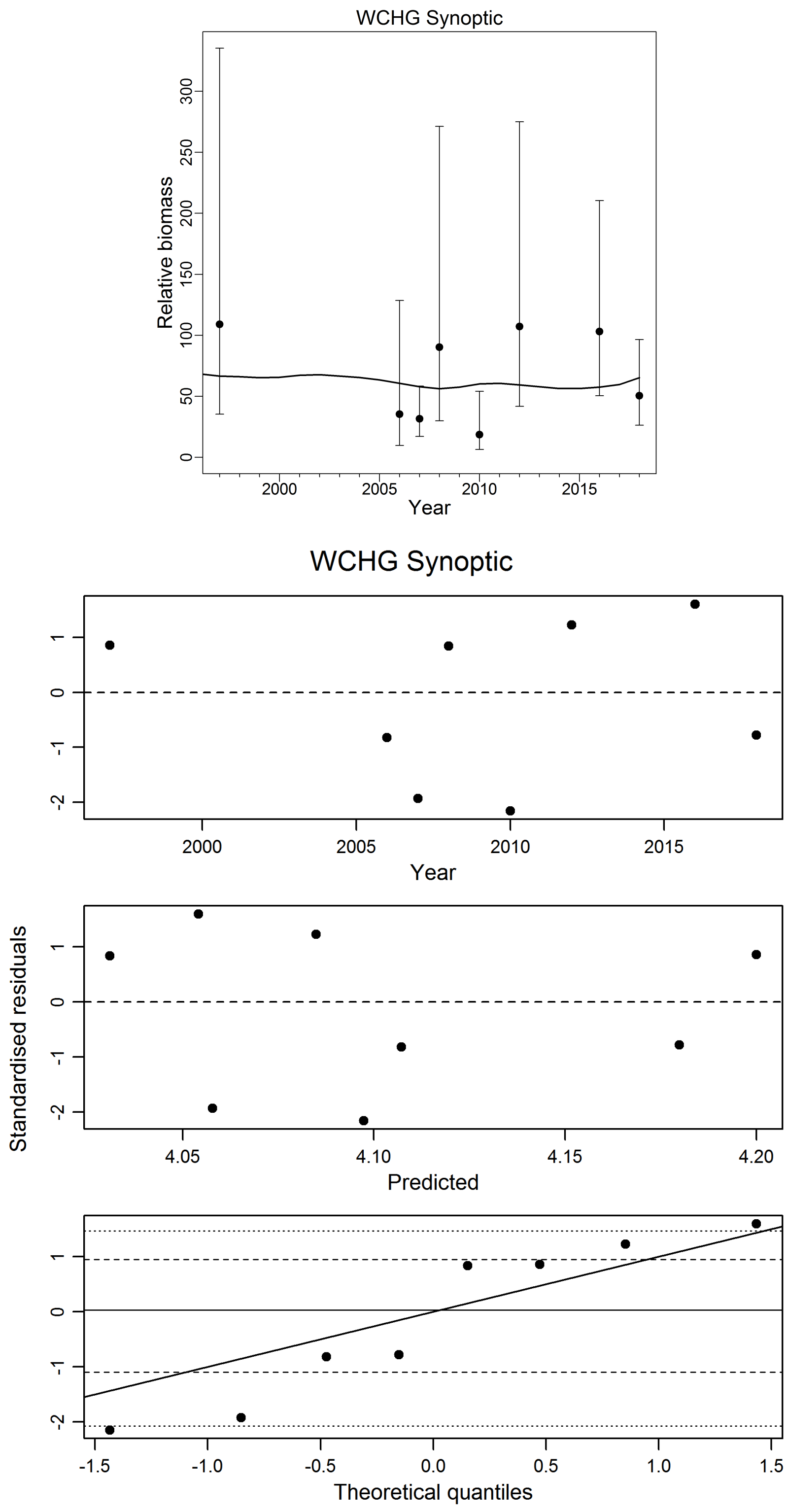


Figure F.4. CR.05.01: Fit (top) and residuals of fits (bottom) of model to WCHG Synoptic survey series (MPD values). Vertical axes are standardised residuals. The three plots show, respectively, residuals by year of index, residuals relative to predicted index, and normal quantile-quantile plot for residuals (horizontal lines give 5, 25, 50, 75 and 95 percentiles).

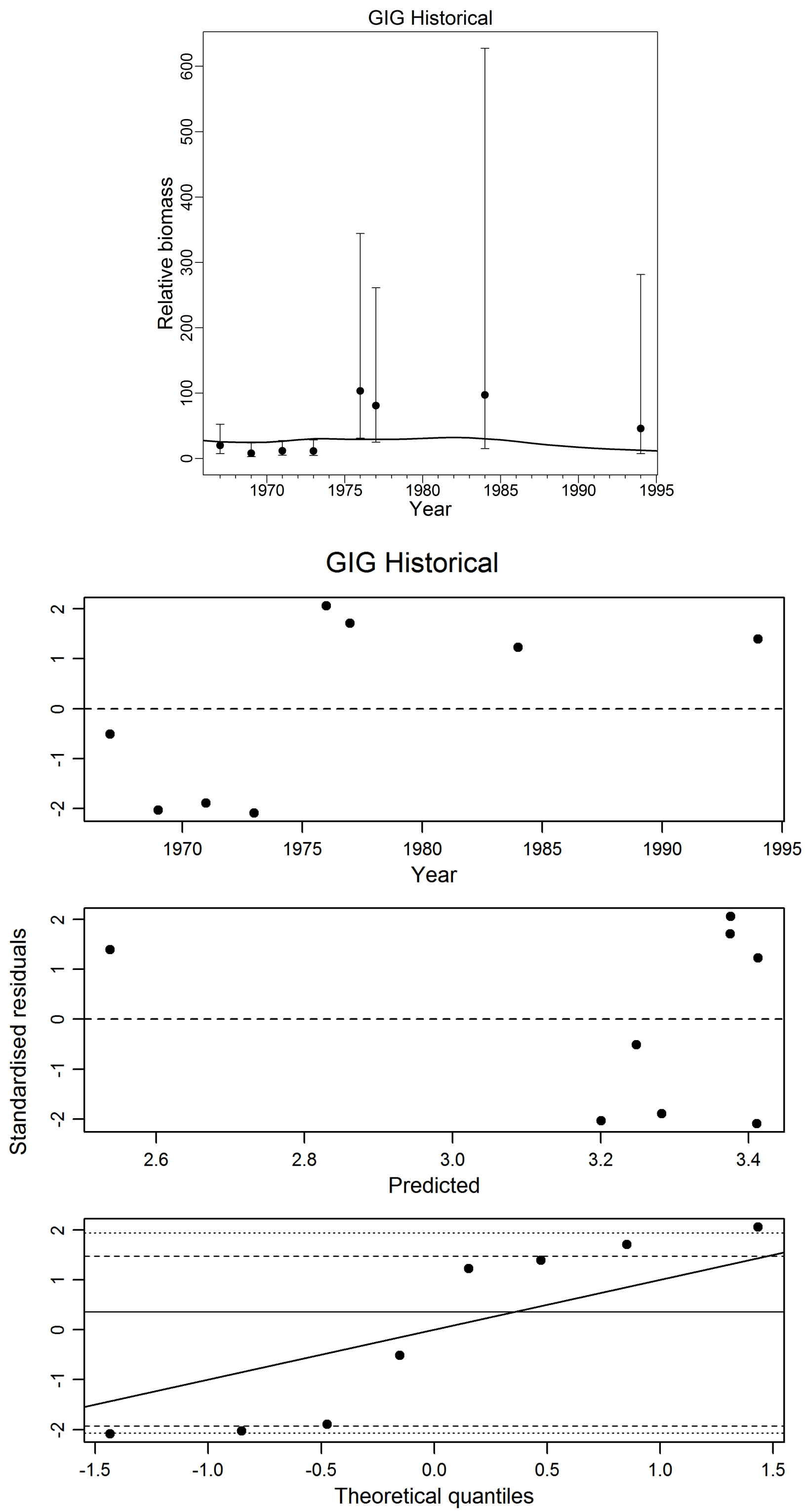


Figure F.5. CR.05.01: Fit (top) and residuals of fits (bottom) of model to GIG Historical survey series (MPD values). Vertical axes are standardised residuals. The three plots show, respectively, residuals by year of index, residuals relative to predicted index, and normal quantile-quantile plot for residuals (horizontal lines give 5, 25, 50, 75 and 95 percentiles).

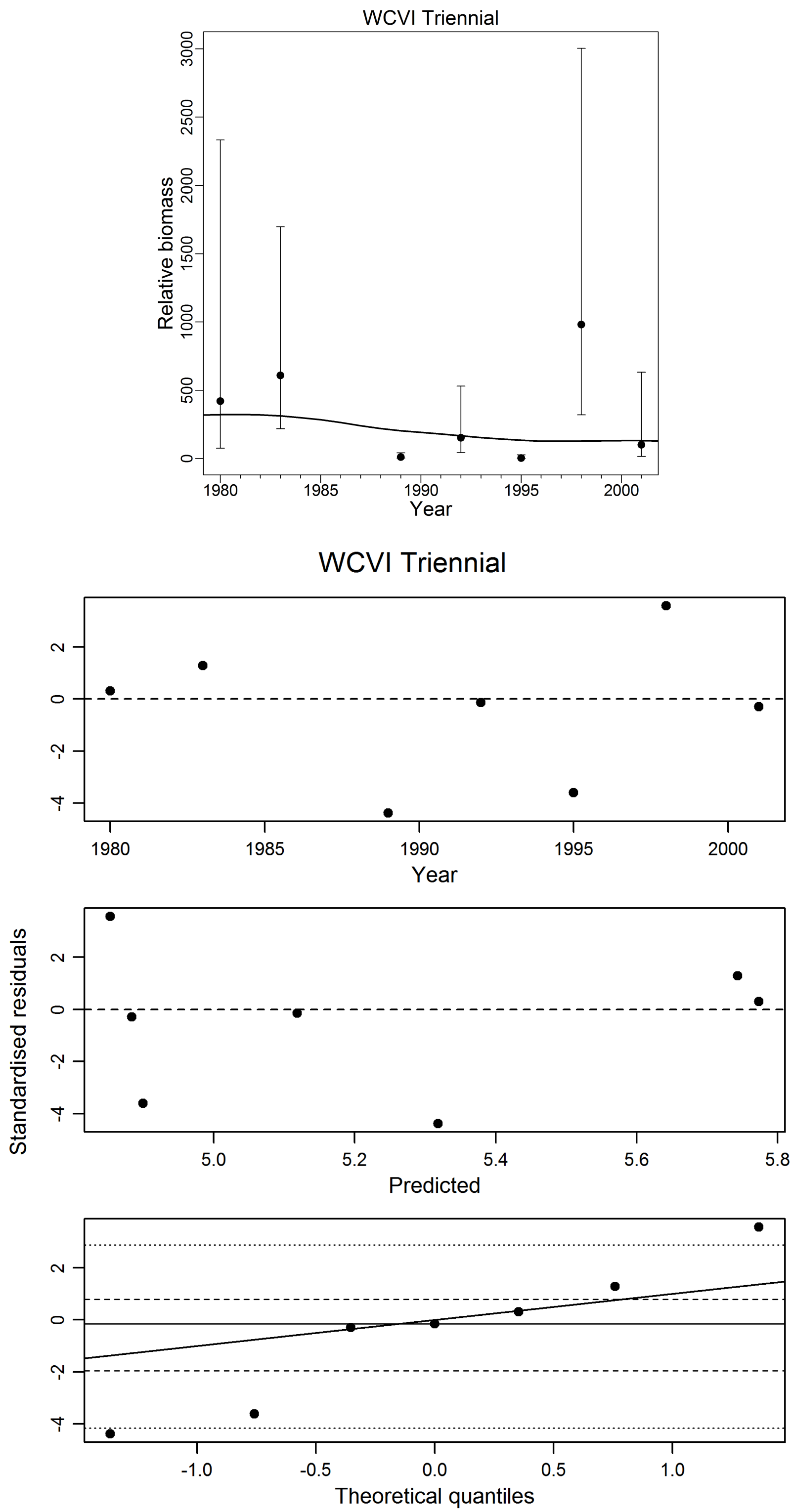


Figure F.6. CR.05.01: Fit (top) and residuals of fits (bottom) of model to WCVI Triennial survey series (MPD values). Vertical axes are standardised residuals. The three plots show, respectively, residuals by year of index, residuals relative to predicted index, and normal quantile-quantile plot for residuals (horizontal lines give 5, 25, 50, 75 and 95 percentiles).

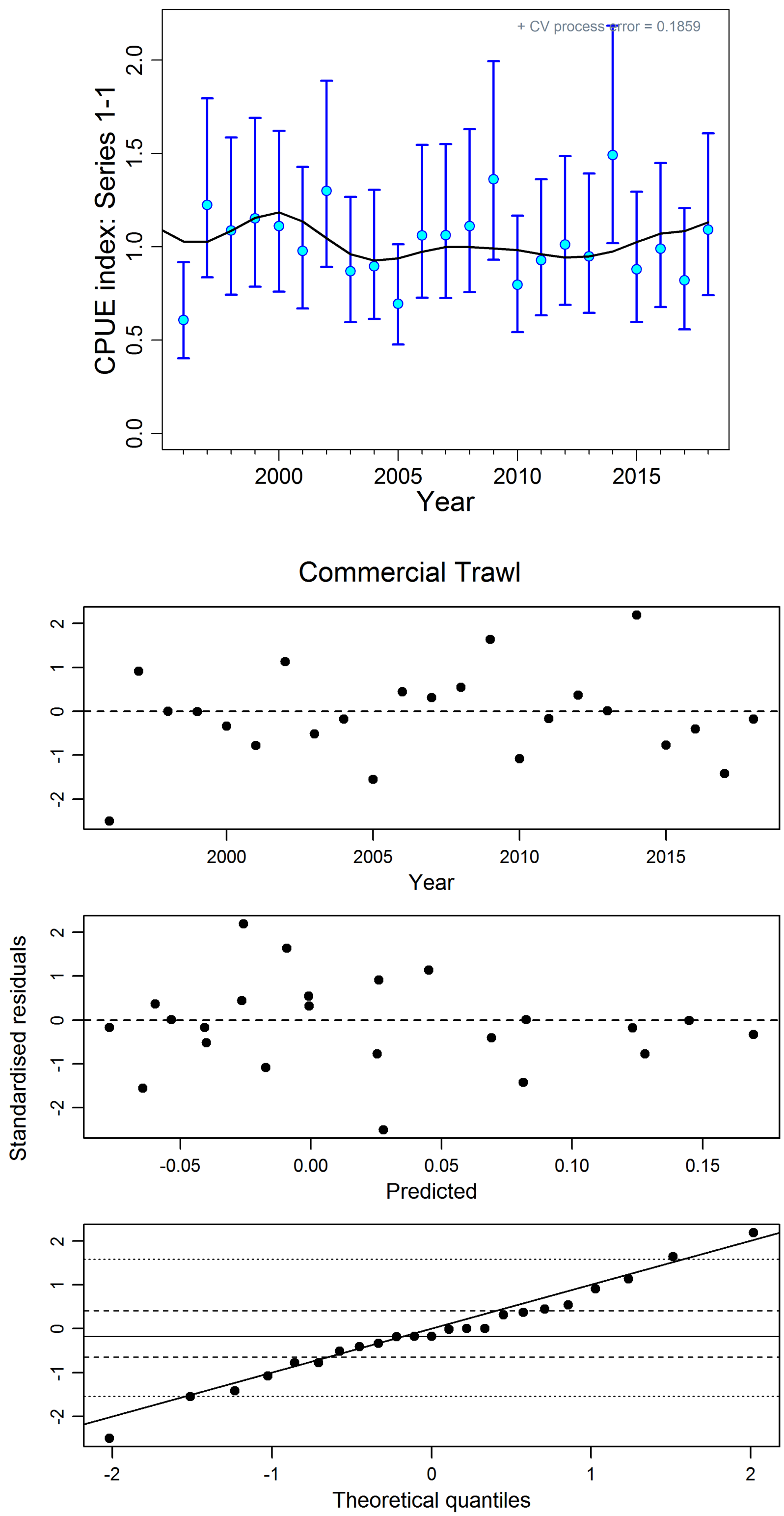


Figure F.7. CR.05.01: Fit (top) and residuals of fits (bottom) of model to CPUE index series (MPD values). Vertical axes are standardised residuals. The three plots show, respectively, residuals by year of index, residuals relative to predicted index, and normal quantile-quantile plot for residuals (horizontal lines give 5, 25, 50, 75 and 95 percentiles).

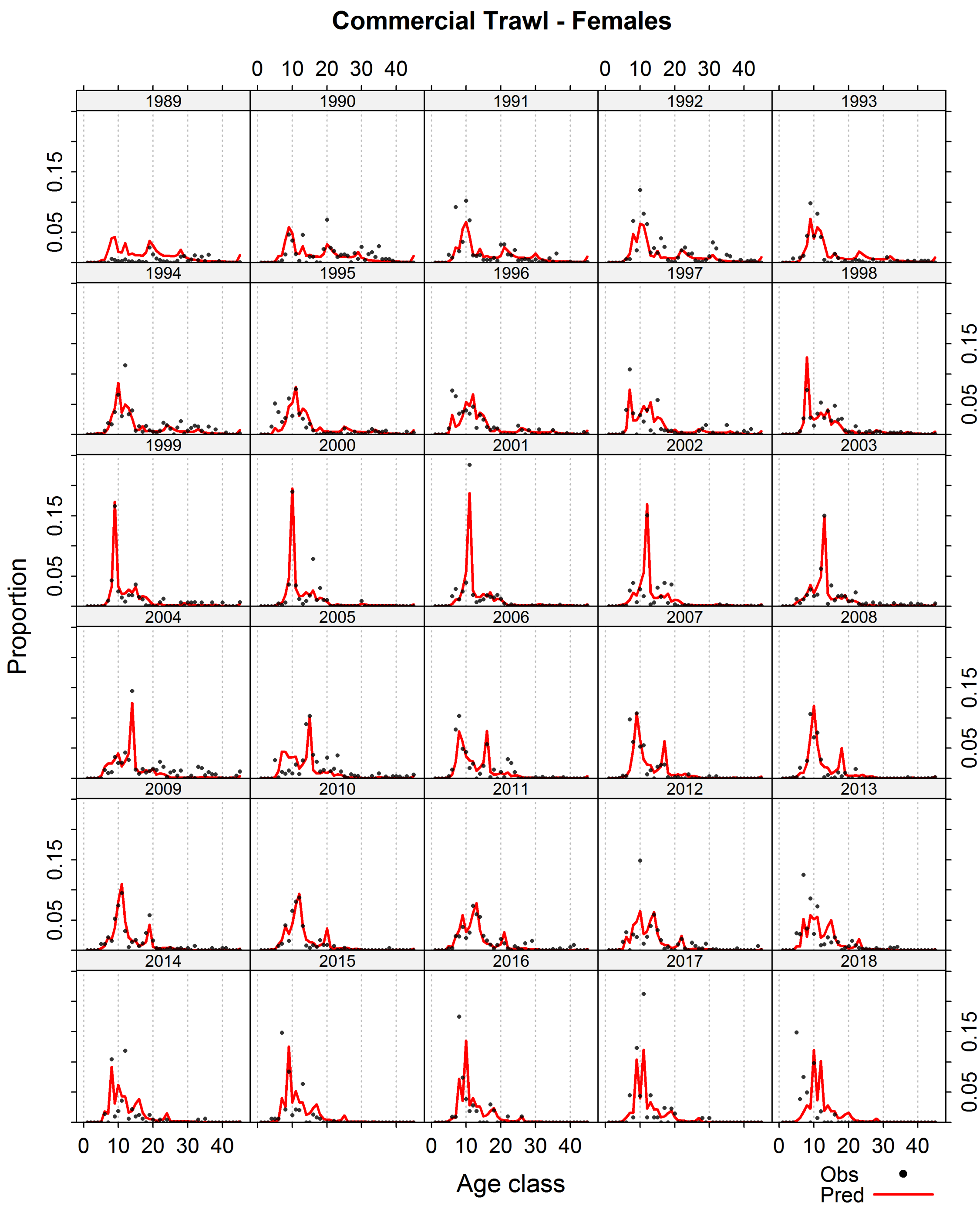


Figure F.8. CR.05.01: Observed and predicted commercial (commercial trawl) proportions-at-age for females. Note that years are not necessarily consecutive.

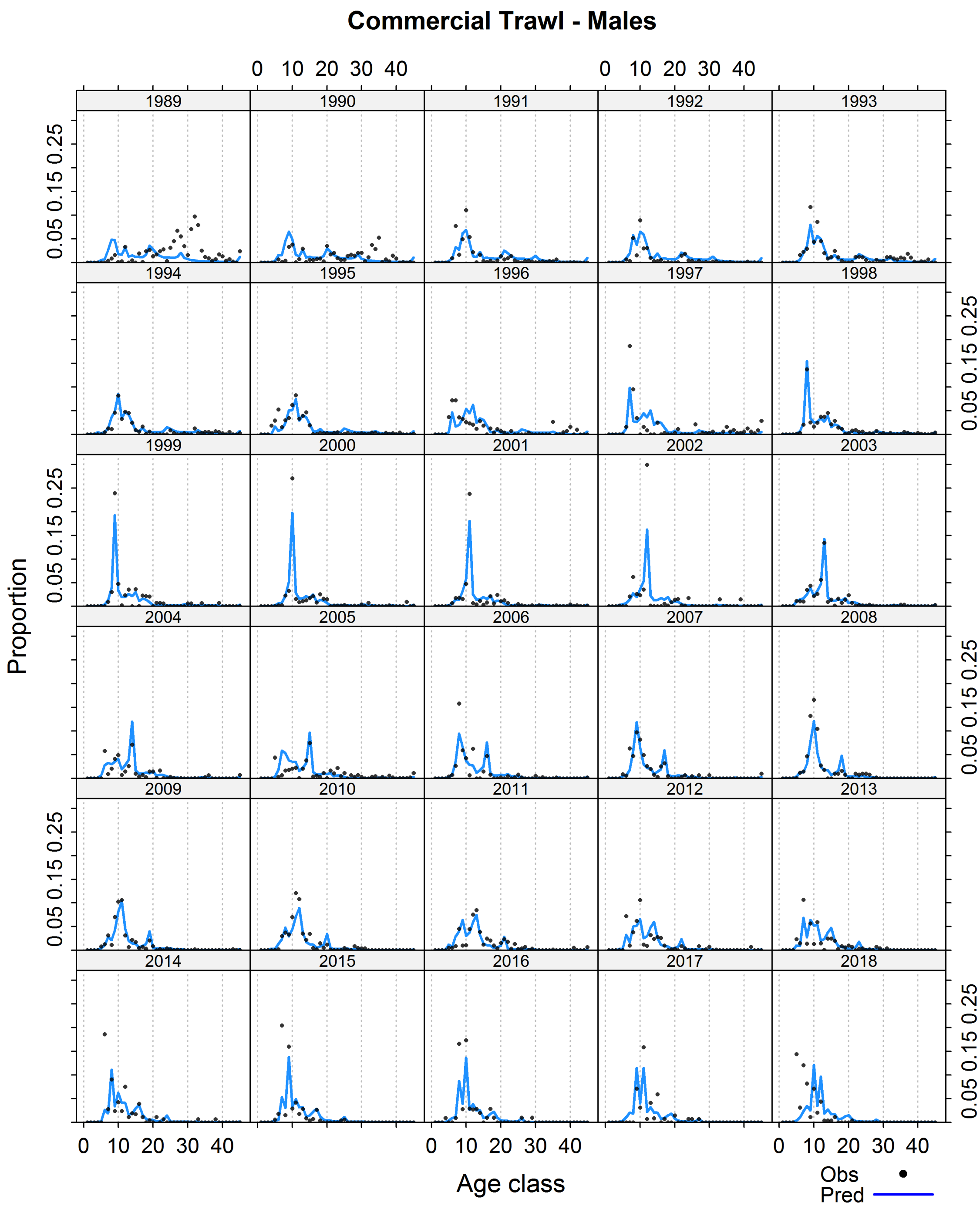


Figure F.9. CR.05.01: Observed and predicted commercial (commercial trawl) proportions-at-age for males. Note that years are not necessarily consecutive.

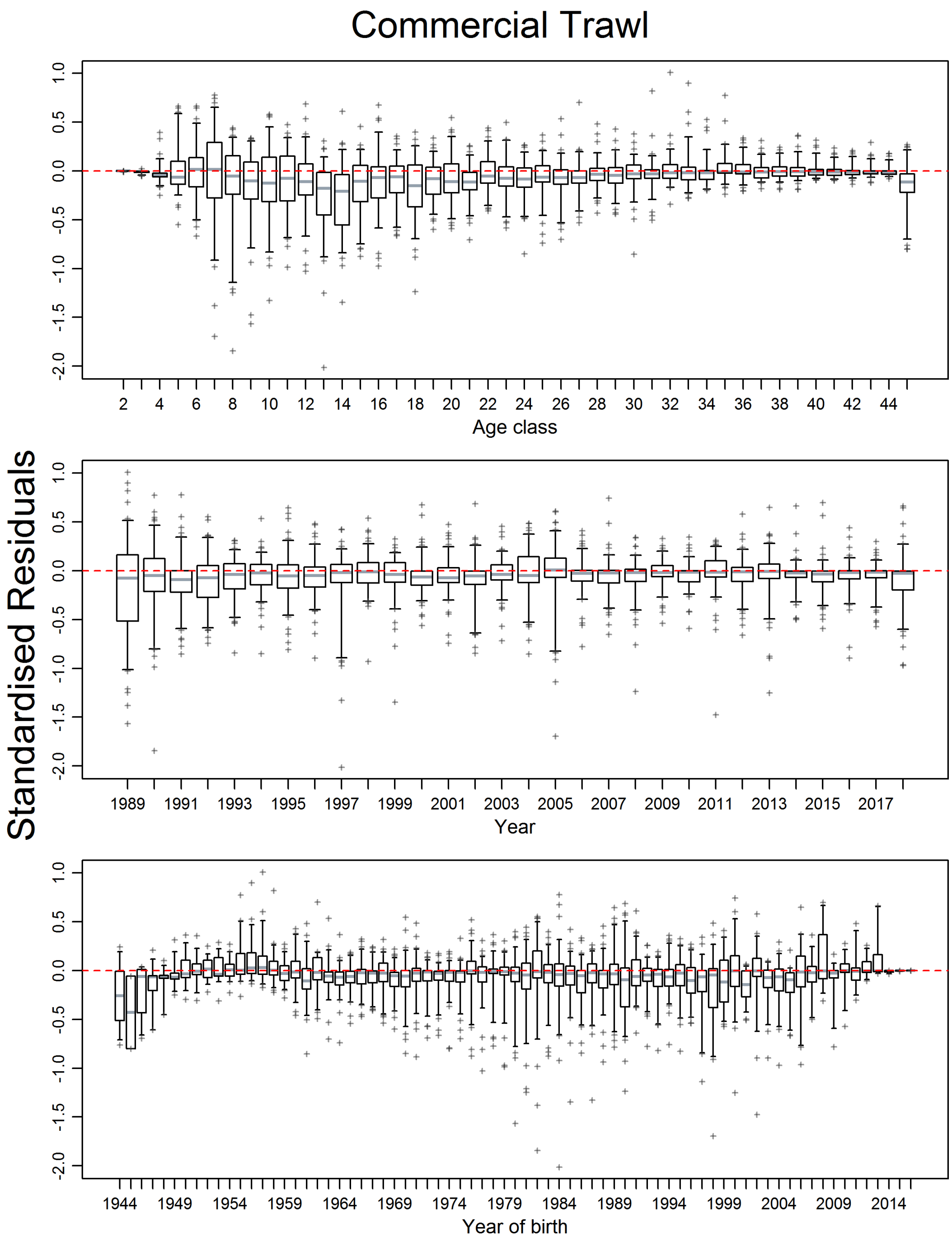
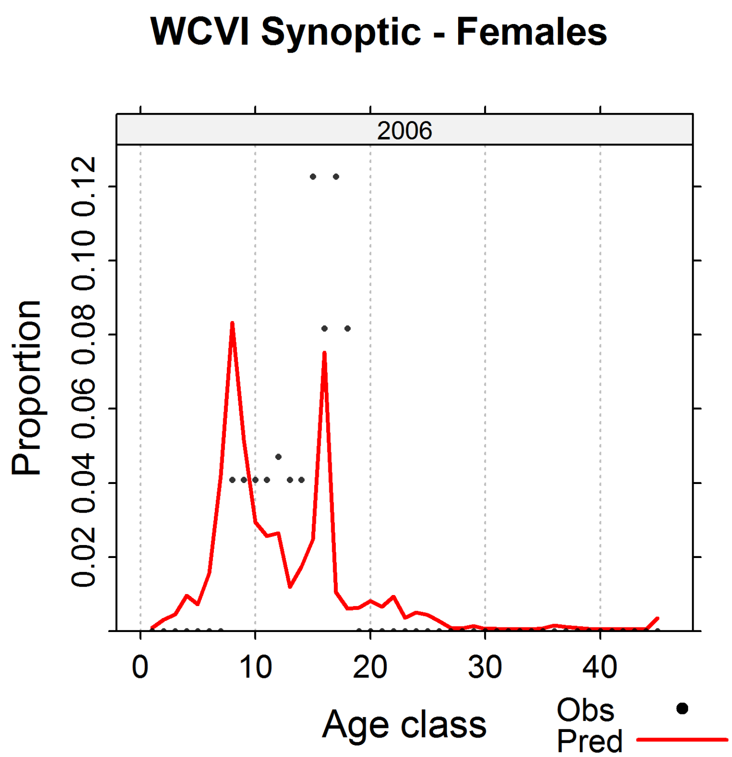


Figure F.10. CR.05.01: Residuals (2640 in total) of model fits to commercial proportions-at-age data (MPD values) for Commercial Trawl events. Vertical axes are standardised residuals. Boxplots show, respectively, residuals by age class, by year of data, and by year of birth (following a cohort through time). Boxes give quantile ranges (0.25-0.75) with horizontal lines at medians, vertical whiskers extend to the the 0.05 and 0.95 quantiles, and outliers appear as plus signs.



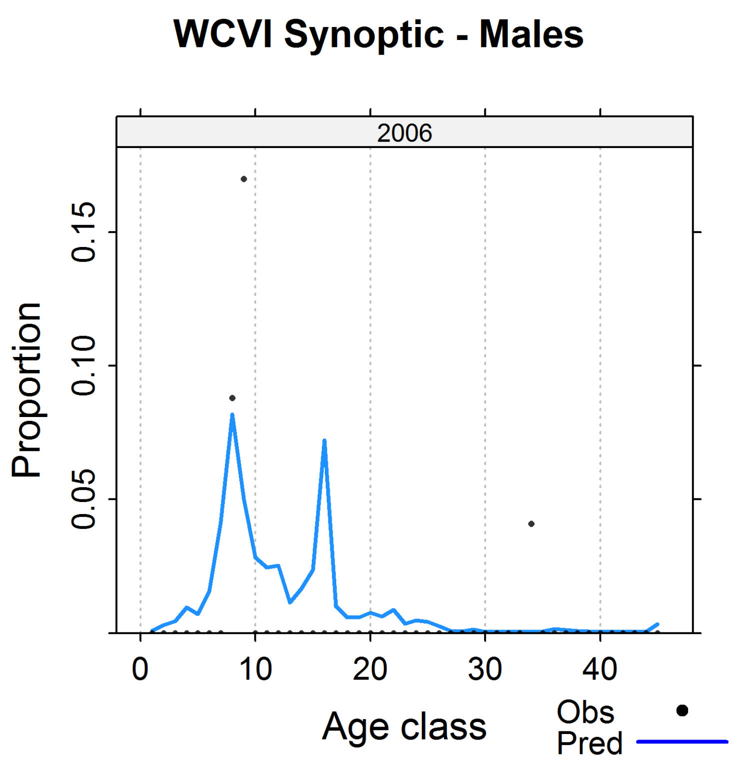


Figure F.11. CR.05.01: Observed and predicted proportions-at-age for WCVI Synoptic survey.

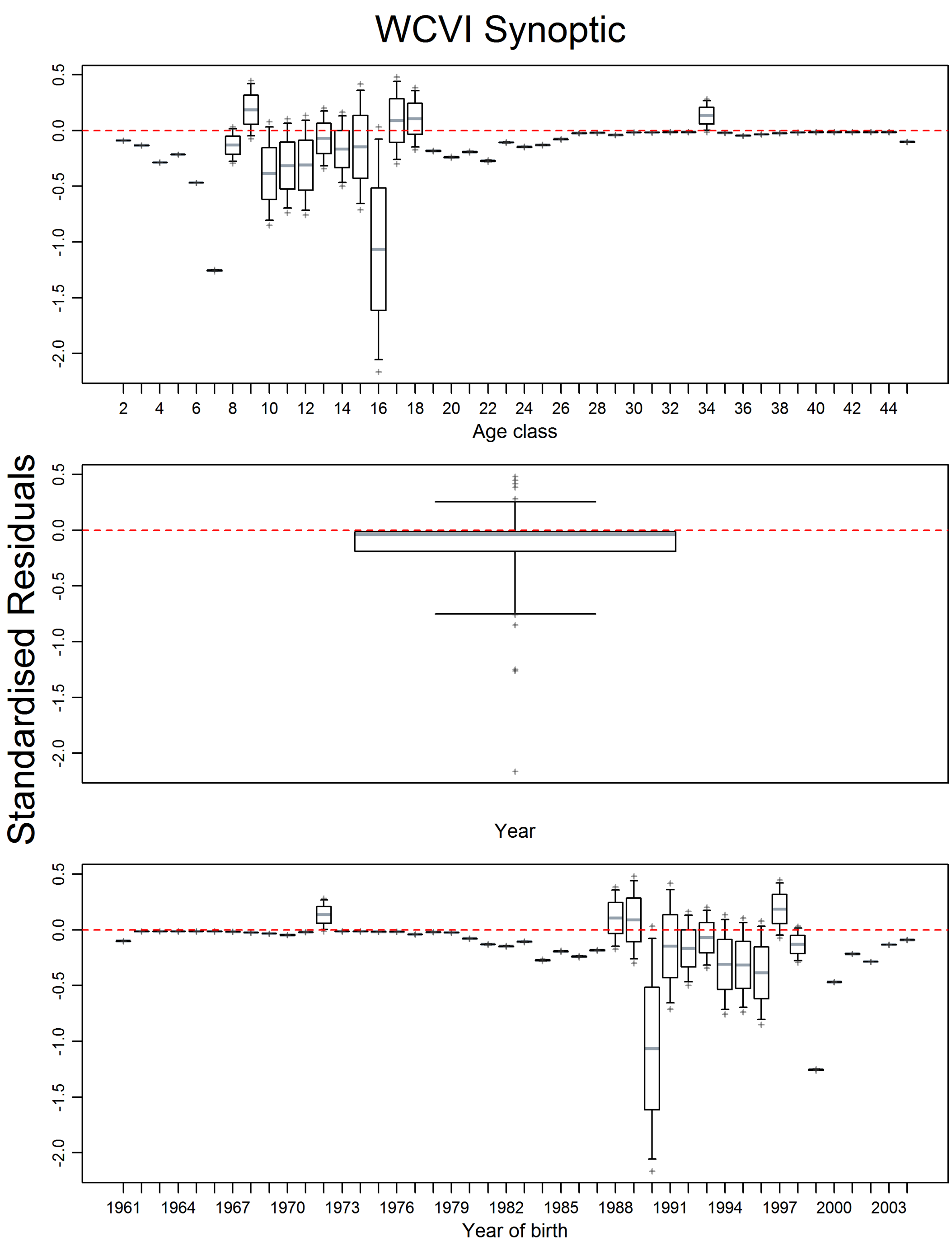
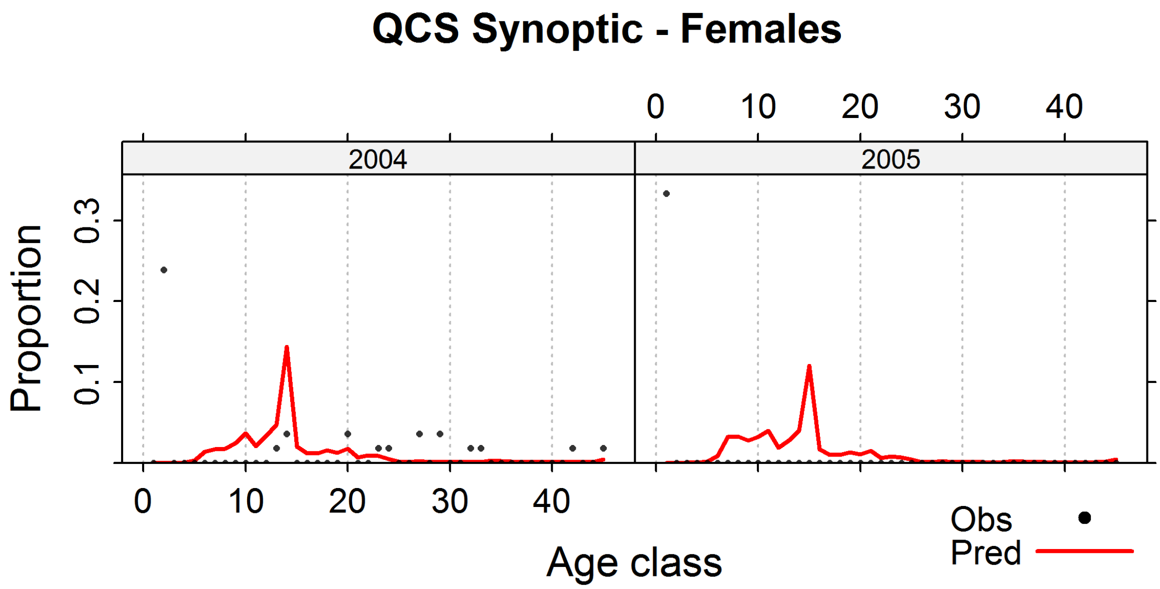


Figure F.12. CR.05.01: Residuals of model fits to proportions-at-age data (MPD values) from the WCVI Synoptic survey series. Details as for Figure F.10, for a total of 88 residuals.



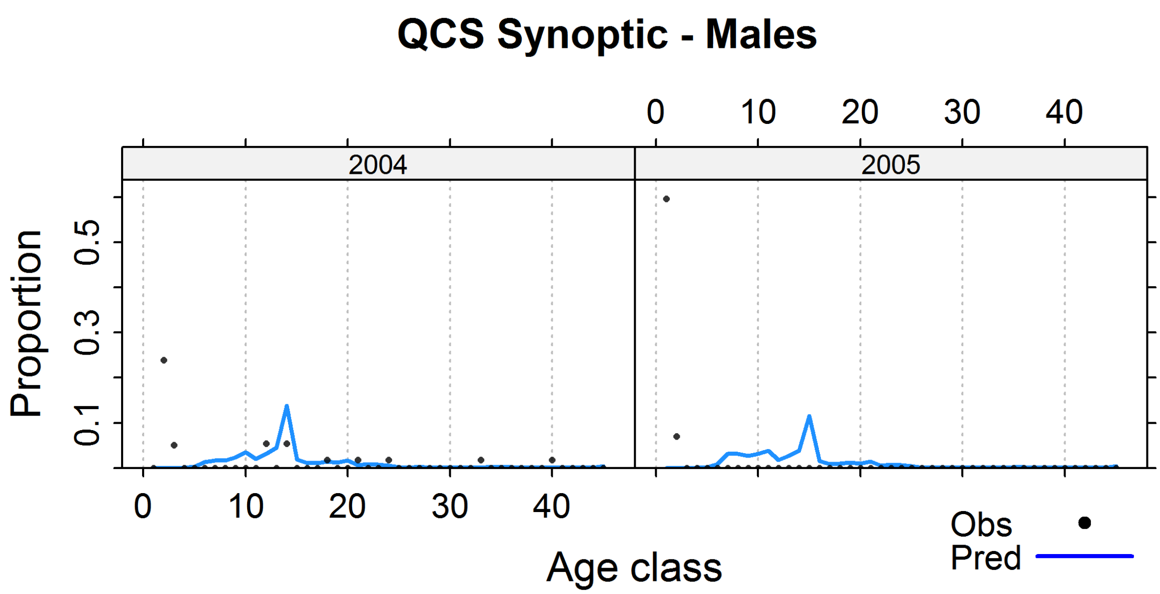


Figure F.13. CR.05.01: Observed and predicted proportions-at-age for QCS Synoptic survey.

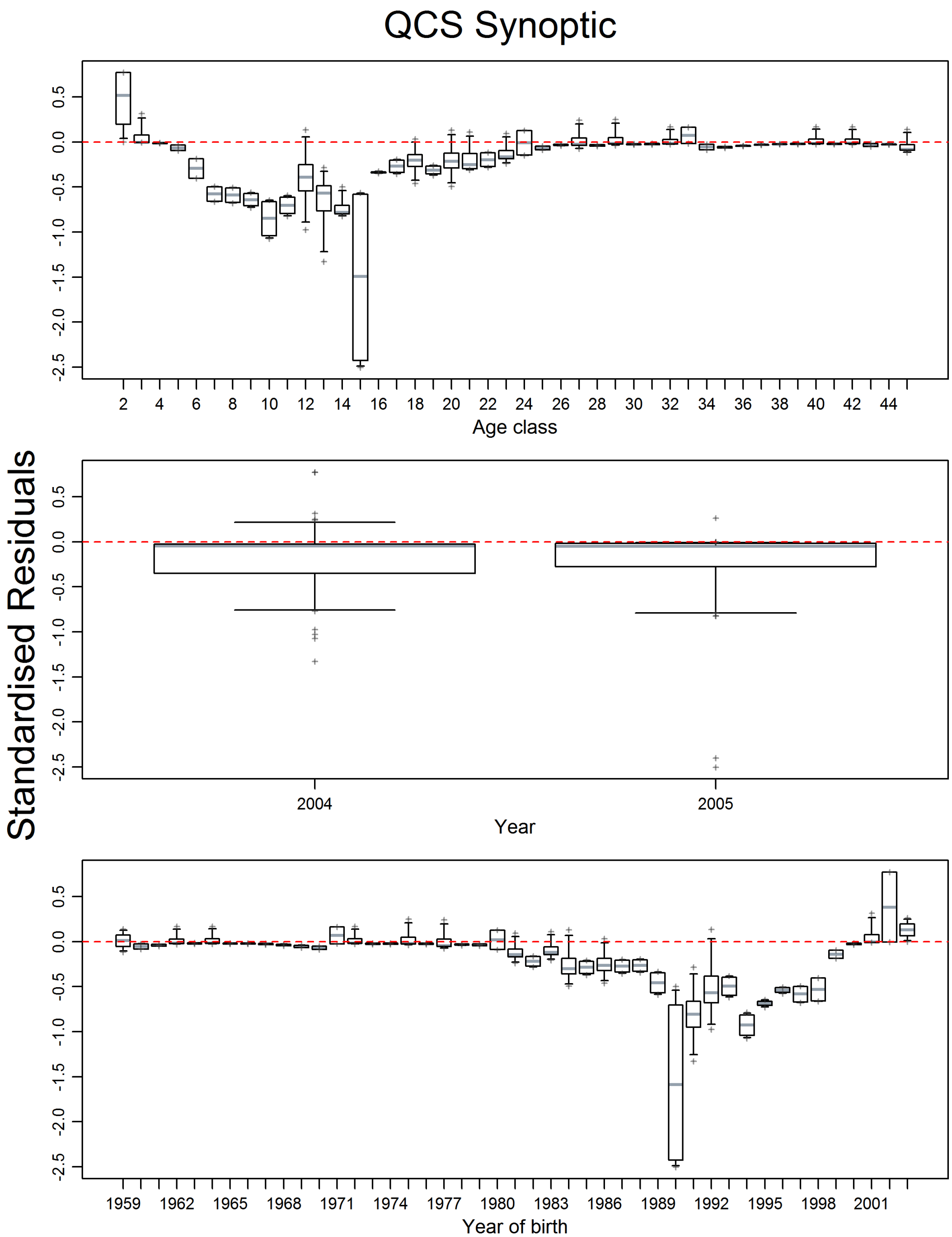


Figure F.14. CR.05.01: Residuals of model fits to proportions-at-age data (MPD values) from the QCS Synoptic survey series. Details as for Figure F.10, for a total of 176 residuals.

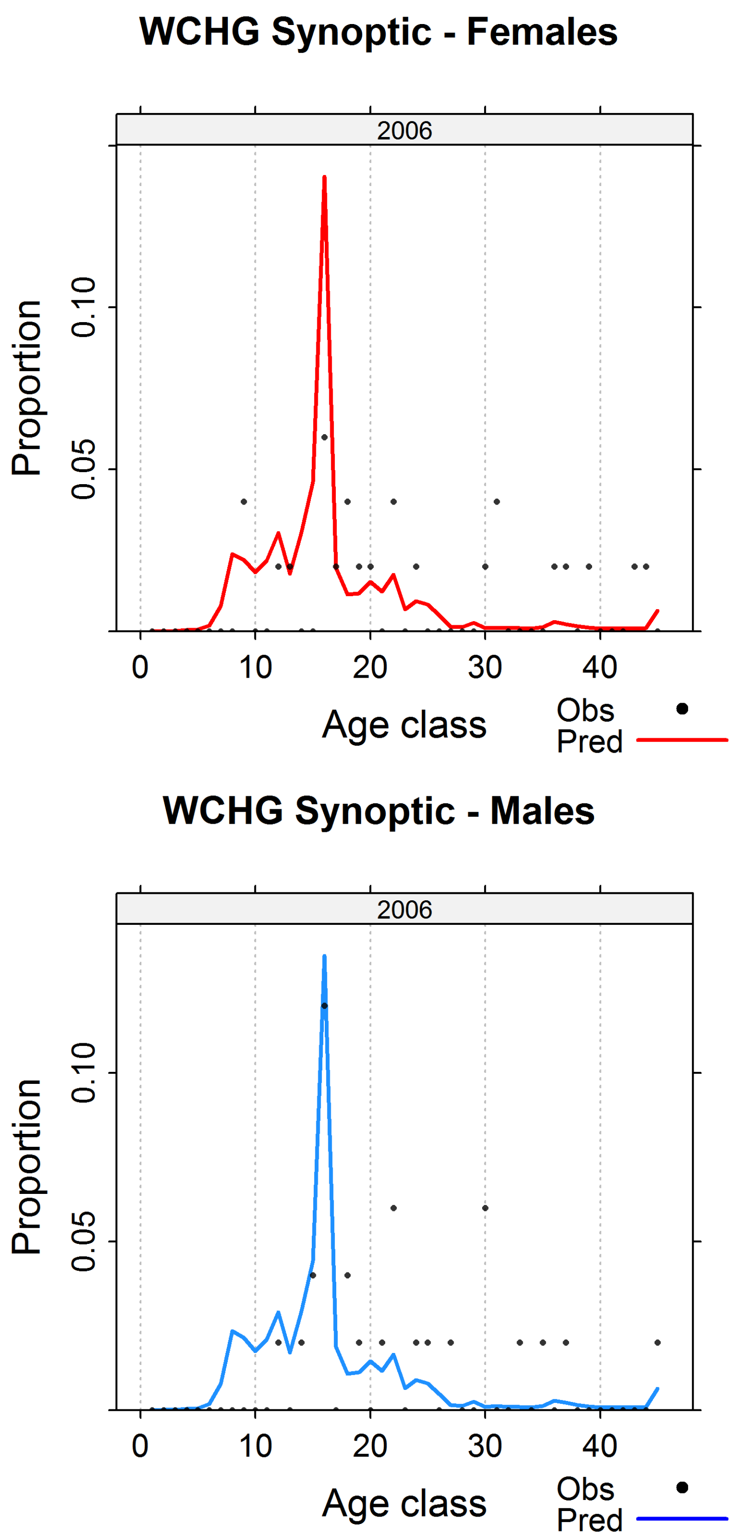


Figure F.15. CR.05.01: Observed and predicted proportions-at-age for WCHG Synoptic survey.

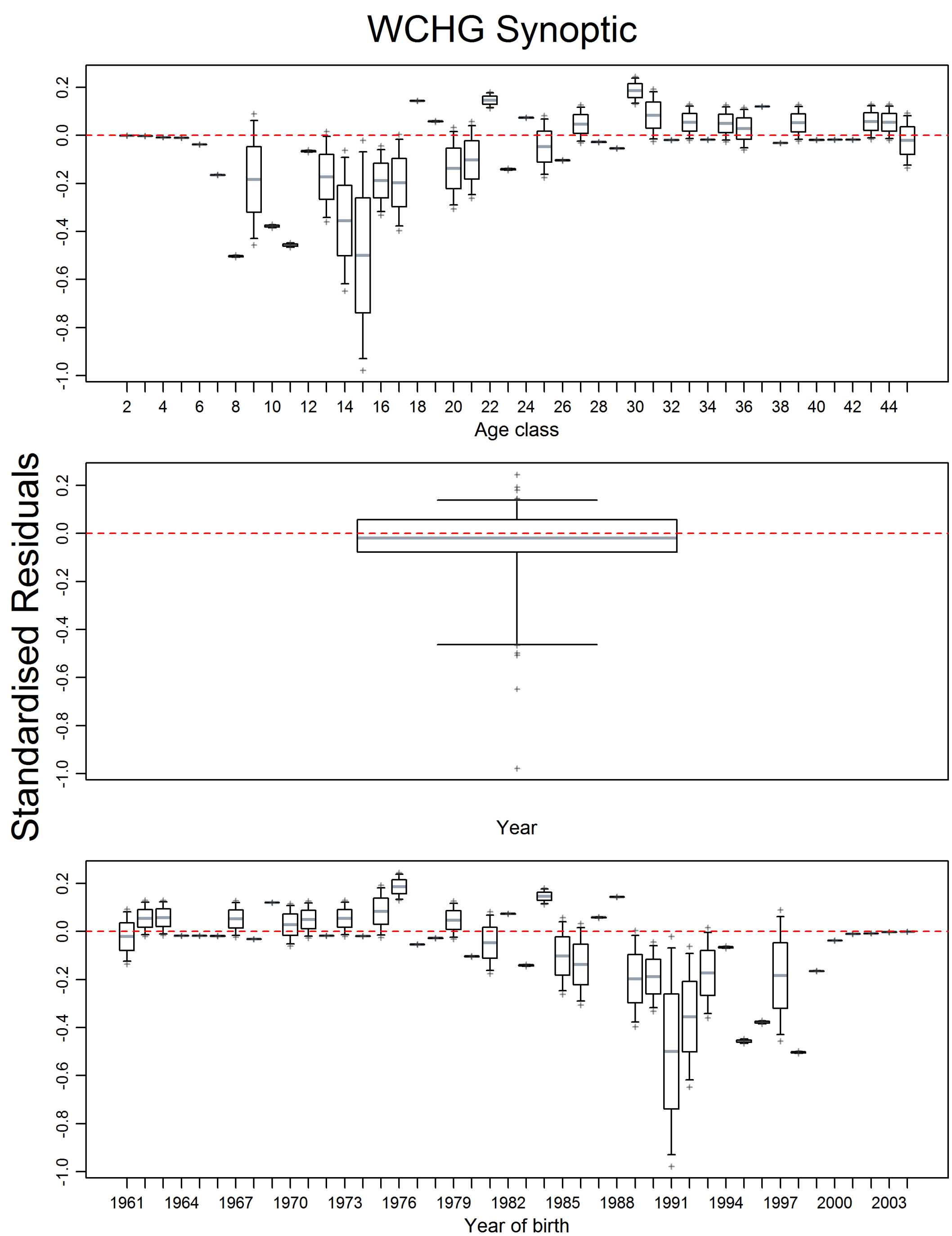


Figure F.16. CR.05.01: Residuals of model fits to proportions-at-age data (MPD values) from the WCHG Synoptic survey series. Details as for Figure F.10, for a total of 88 residuals.

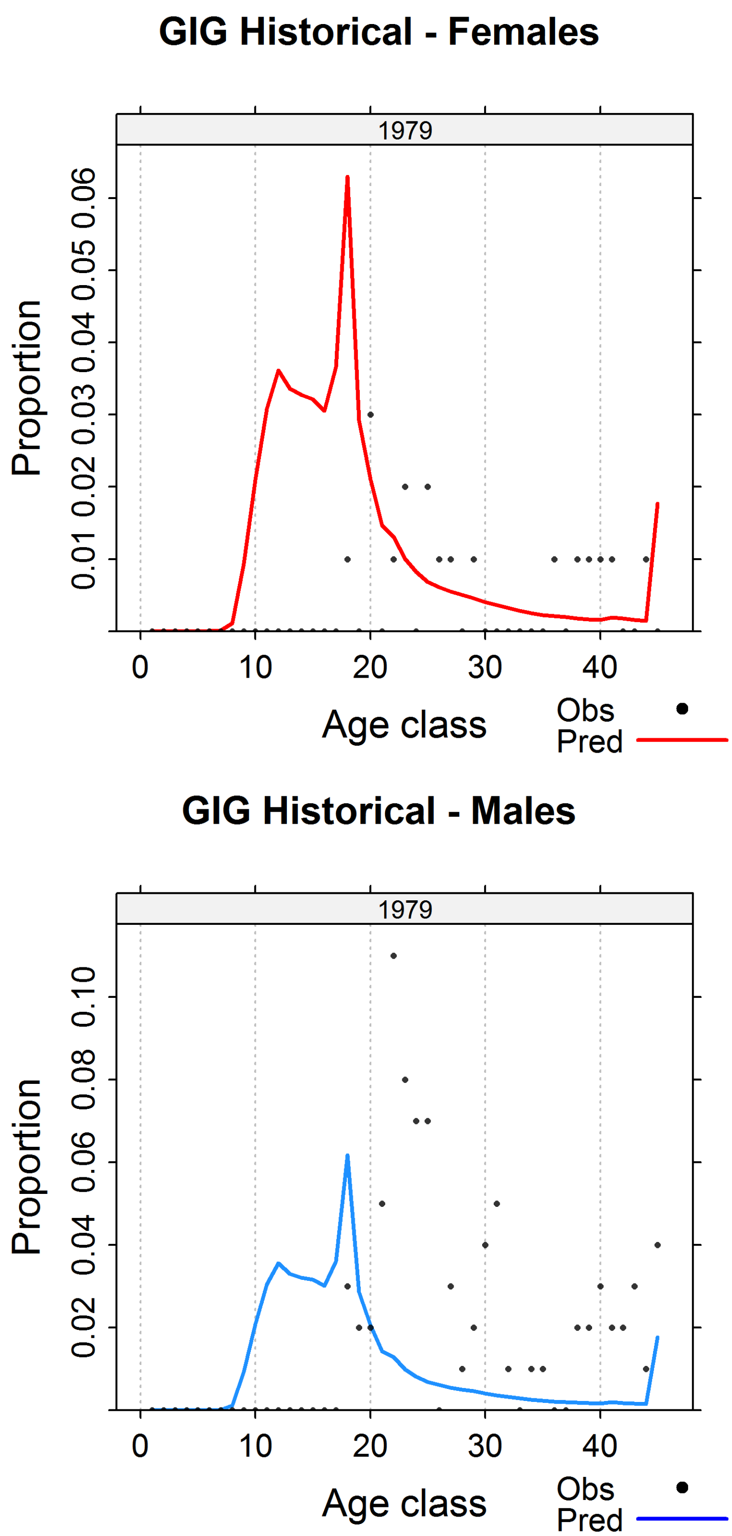


Figure F.17. CR.05.01: Observed and predicted proportions-at-age for GIG Historical survey.

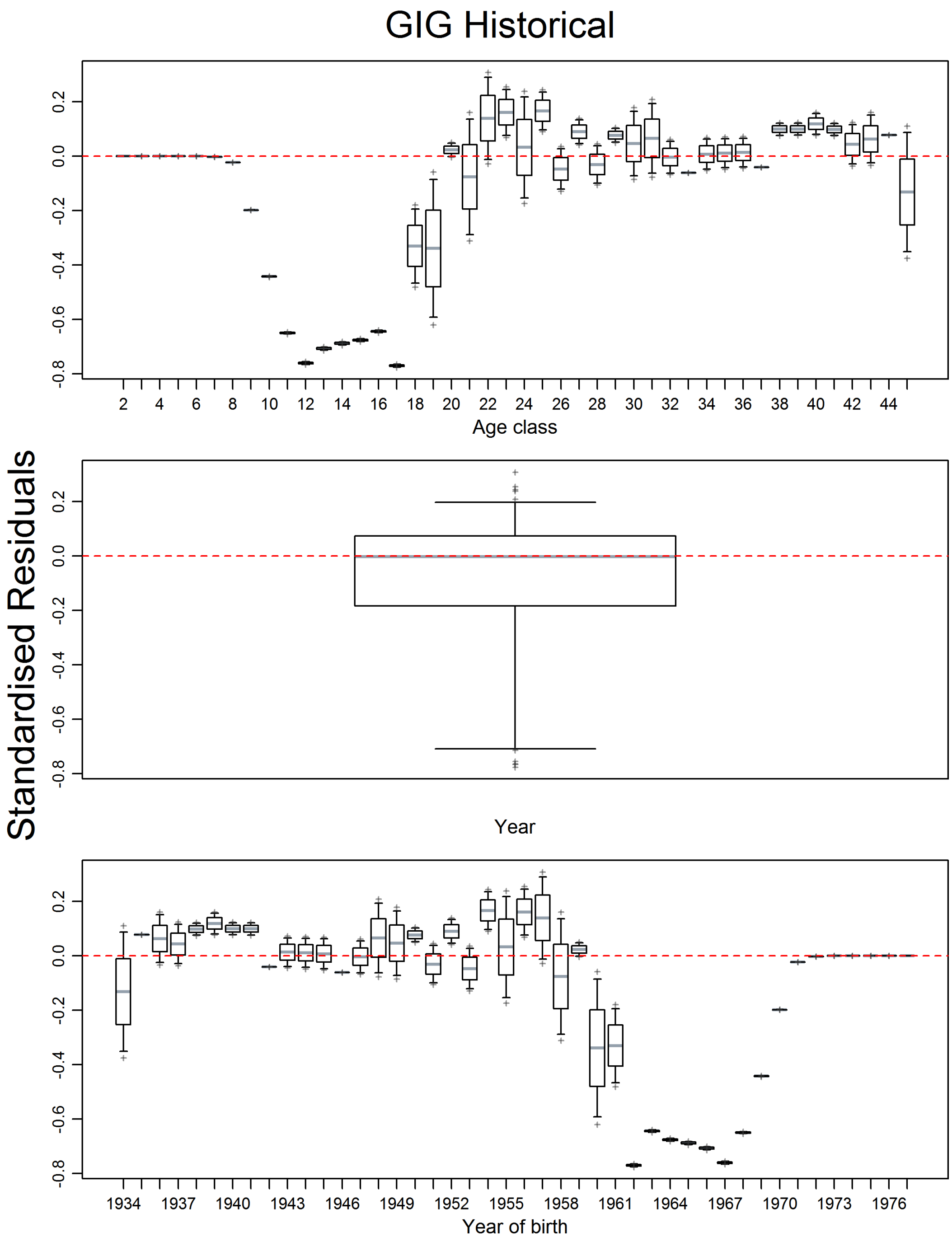


Figure F.18. CR.05.01: Residuals of model fits to proportions-at-age data (MPD values) from the GIG Historical survey series. Details as for Figure F.10, for a total of 88 residuals.

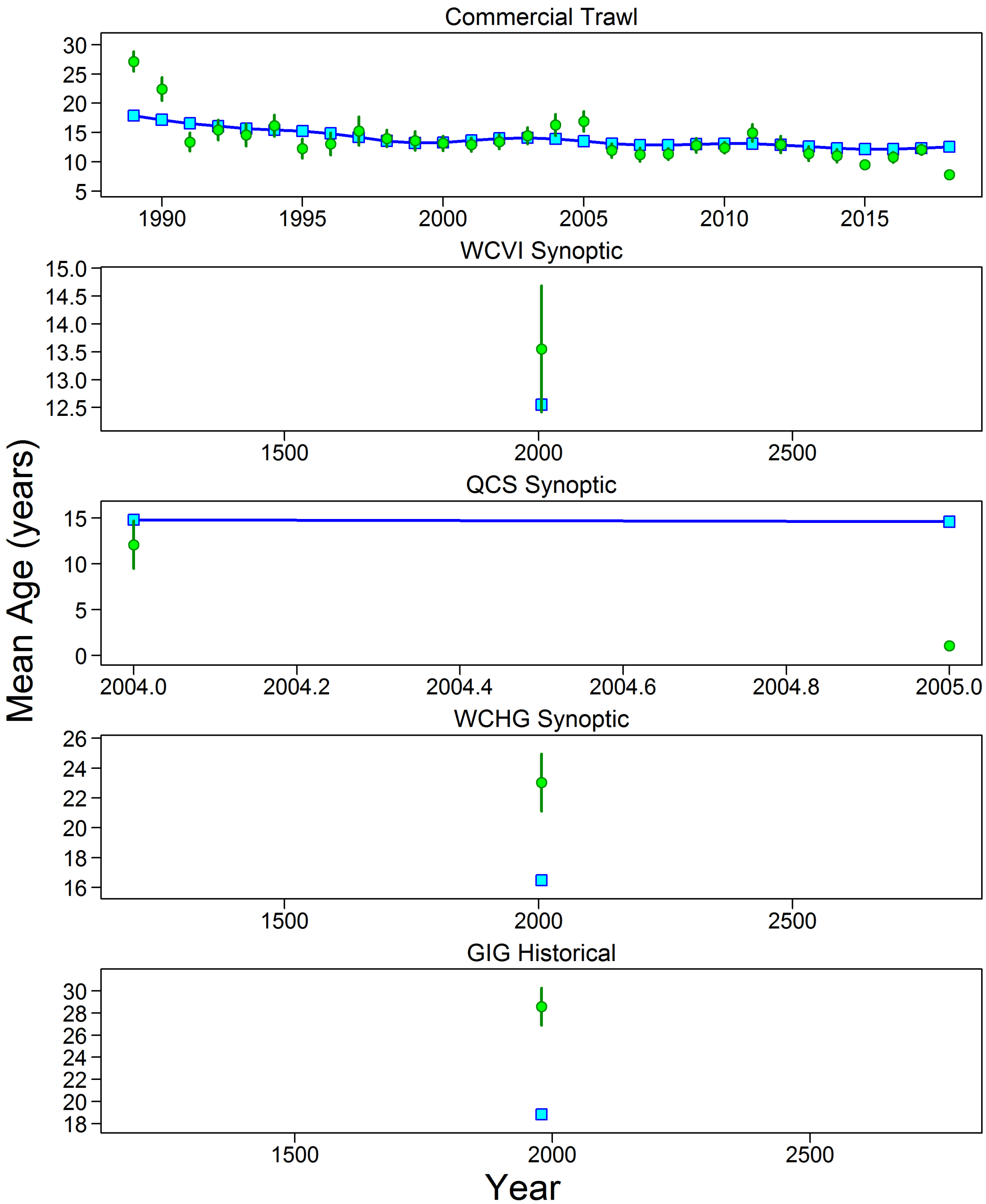


Figure F.19. CR.05.01: Mean ages each year for the data (solid circles) with 95% confidence intervals and model estimates (joined open squares) for the commercial and survey age data.

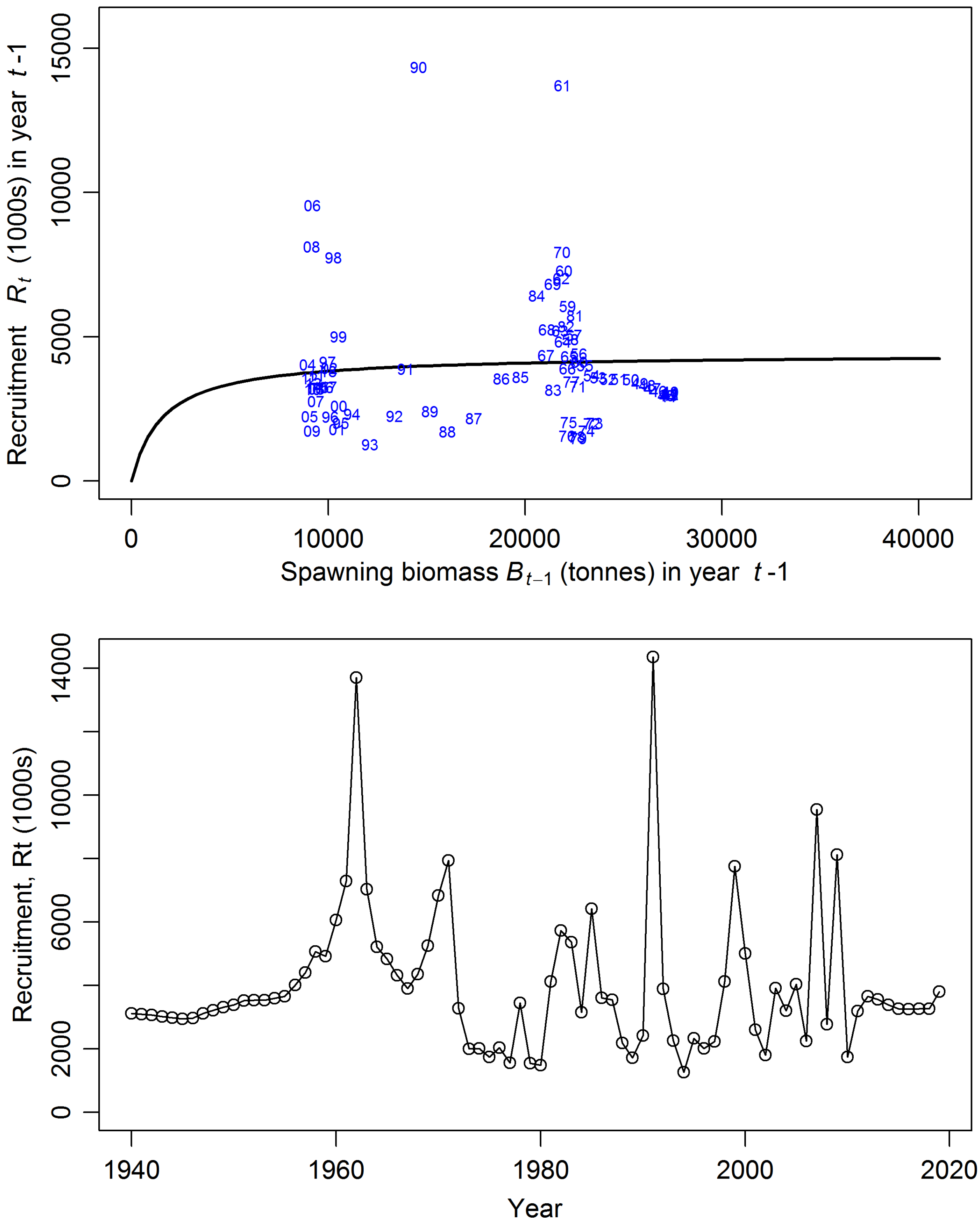


Figure F.20. CR.05.01: Top: deterministic stock-recruit relationship (black curve) and observed values (labelled by year of spawning) using MPD values. Bottom: recruitment (MPD values of age-1 individuals in year t) over time, in 1,000s of age-1 individuals, with a mean of 4,009.4.

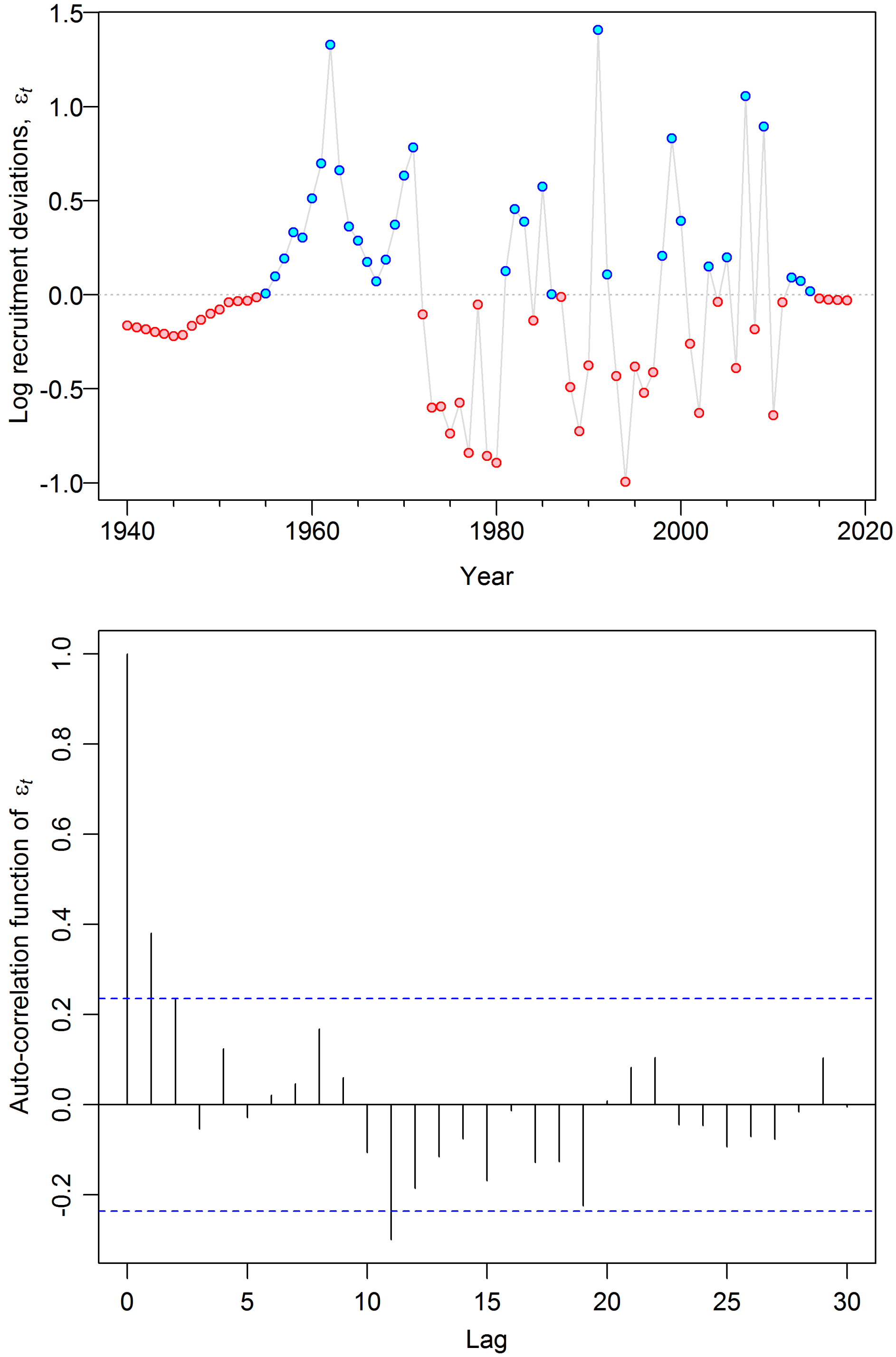


Figure F.21. CR.05.01: Top: log of the annual recruitment deviations, ϵ_t, where bias-corrected multiplicative deviation is $e^{\epsilon_t - \sigma_R^2/2}$ where $\epsilon_t \sim$ Normal$(0, \sigma_R^2)$. Bottom: auto-correlation function of the logged recruitment deviations (ϵ_t), for years 1942-2010. The start of this range is calculated as the first year of commercial age data (1979) minus the accumulator age class (A =45) plus the age for which commercial selectivity for females is 0.5 (namely 8); if the result is earlier than the model start year (1940), then the model start year is used. The end of the range is the final year that recruitments are calculated (2018) minus the age for which commercial selectivity for females is 0.5 (namely 8).

Widow Rockfish Selectivity

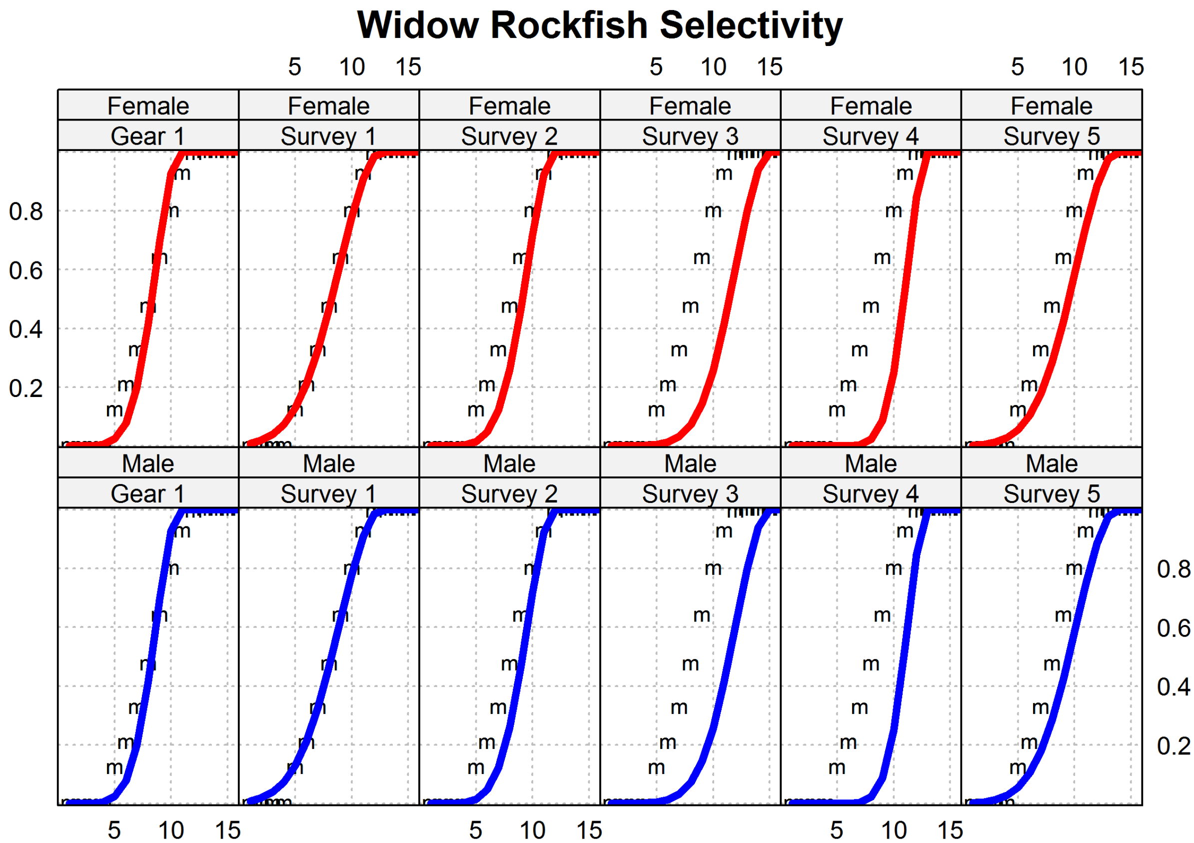


Figure F.22. CR.05.01: Selectivities for commercial catch (Gear 1: Commercial Trawl) and surveys (all MPD values), with maturity ogive for females indicated by 'm'.

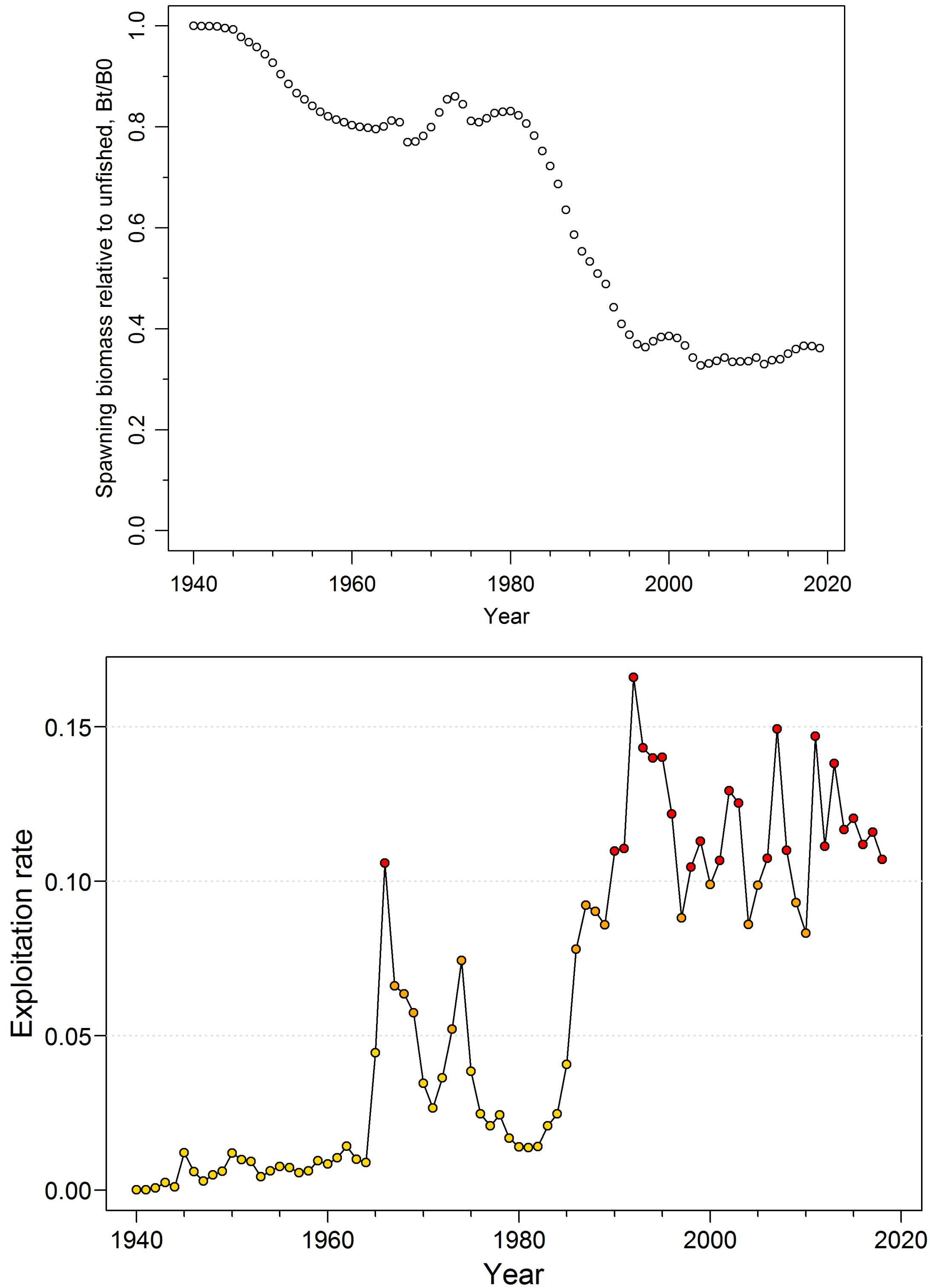


Figure F.23. CR.05.01: Top: spawning biomass (mature females) relative to unfished level, B_t/B_0, Bottom: exploitation rate (MPD) over time

F.2.1.2. Central Run MCMC

The MCMC procedure performed 12 million iterations, sampling every 10,000$^{\mathrm{th}}$ to give 1200 MCMC samples. The first 200 samples were discarded and 1000 samples were used for the MCMC analysis. The quantiles (0.05, 0.50, 0.95) for estimated parameters and derived quantities for the central run appear in Tables F.4 and F.5. The current year median estimate of B_{2019} is 10,662 t and the median estimate of B_{2019}/B_0 is 0.366.

The MCMC plots show:

- Figure F.24 – traces for 1000 samples of the primary estimated parameters;
- Figure F.25 – split-chain diagnostic plots for the primary estimated parameters;
- Figure F.26 – auto-correlation diagnostic plots for the primary estimated parameters;
- Figure F.27 – marginal posterior densities for the primary parameters compared to their respective prior density functions;
- Figure F.28 – top: estimated vulnerable biomass and catch over time, middle: marginal posterior distribution of recruitment over time, bottom:marginal posterior distribution of exploitation rate over time.

MCMC traces showed acceptable convergence properties (no trend with increasing sample number) for the estimated parameters (Figure F.24), as did diagnostic analyses that split the posterior samples into three equal consecutive segments (Figure F.25) and checked for parameter autocorrelation out to 60 lags (Figure F.26). Some of the parameters (e.g., R_0, h, μ_2) moved from the initial MPD estimate to a median value that differed from the MPD (Figure F.24), indicating that the MCMC search found plausible fits to the data at levels other than those found by the 'best fit'. The marginal posterior distribution for h – median = 0.79 (0.59, 0.95) – shifted higher from the informed prior mean of 0.674 (Figure F.27).

The marginal posterior distributions of vulnerable biomass and catch (Figure F.28, top panel) showed that this stock was not greatly reduced by the early foreign fleet fishery (1965-76) but experienced a prolonged decline once the domestic fishery took over in 1977. The decline ended when catch limits, implemented through Individual Vessel Quotas (IVQ), were imposed in 1997. A mandatory system of onboard observers was also implemented at the same time. A major recruitment event in 1961 likely ameliorated the affects of the foreign fleet activity, and a second major recruitment in 1990 likely stabilised the population in conjunction with management controls (Figure F.28, middle panel). Further good recruitment years in 2006 and 2008 should sustain the population in coming years. The median spawning biomass relative to unfished equilibrium values reached a minimum of 0.33 in 2012 and currently sits at 0.37. The exploitation rate peaked at 0.16 in 1992 and is estimated to be 0.1 in 2018 (Figure F.28, bottom panel).

F.2.1.2.1. MCMC tables for central run

Table F.4. CR.05.01: The 0.05, 0.5, and 0.95 quantiles for model parameters derived via MCMC estimation (defined in Appendix E).

	5%	50%	95%
R_0	3,969	4,471	5,147
h	0.5908	0.7913	0.9450
q_1	0.0009785	0.001672	0.002799
q_2	0.003162	0.005629	0.01074
q_3	0.002965	0.005563	0.01047
q_4	0.0005143	0.0008014	0.001314
q_5	0.005309	0.008502	0.01318
q_6	0.00004017	0.00005923	0.00008135
μ_1	10.37	12.82	15.95
μ_2	10.80	12.54	14.58
μ_3	12.90	15.21	17.74
μ_4	10.59	12.75	14.65
μ_6	9.809	10.75	11.72
Δ_6	-0.9102	-0.3627	0.1927
$\log v_{1L}$	2.537	3.365	4.148
$\log v_{2L}$	1.297	2.190	2.973
$\log v_{3L}$	2.181	2.951	3.708
$\log v_{4L}$	1.166	1.978	2.927
$\log v_{6L}$	1.654	2.197	2.586

Table F.5. CR.05.01: The 0.05, 0.5, and 0.95 quantiles of MCMC-derived quantities from the 1000 samples of the MCMC posterior. Definitions are: B_0 – unfished equilibrium spawning biomass (mature females), V_0 – unfished equilibrium vulnerable biomass (males and females), B_{2019} – spawning biomass at the start of 2019, V_{2019} – vulnerable biomass in the middle of 2019, u_{2018} – exploitation rate (ratio of total catch to vulnerable biomass) in the middle of 2018, $u_{\max}$ – maximum exploitation rate (calculated for each sample as the maximum exploitation rate from 1940-2018), B_{MSY} – equilibrium spawning biomass at MSY (maximum sustainable yield), u_{MSY} – equilibrium exploitation rate at MSY, V_{MSY} – equilibrium vulnerable biomass at MSY. All biomass values (and MSY) are in tonnes. For reference, the average catch over the last 5 years (2014-2018) is 2001 t.

Value	Percentile		
	5%	50%	95%
	From model output		
B_0	26,042	29,337	33,776
V_0	45,854	52,235	60,552
B_{2019}	7,562	10,662	16,385
V_{2019}	12,868	18,896	29,586
B_{2019}/B_0	0.27	0.366	0.499
V_{2019}/V_0	0.264	0.36	0.504
u_{2018}	0.066	0.1	0.143
$u_{\max}$	0.125	0.164	0.207
	MSY-based quantities		
MSY	1,499	1,918	2,405
B_{MSY}	4,687	7,223	10,081
$0.4B_{\mathrm{MSY}}$	1,875	2,889	4,032
$0.8B_{\mathrm{MSY}}$	3,750	5,778	8,064
$B_{2019}/B_{\mathrm{MSY}}$	0.932	1.508	2.543
B_{MSY}/B_0	0.169	0.245	0.32
V_{MSY}	8,074	12,899	18,413
V_{MSY}/V_0	0.164	0.246	0.321
u_{MSY}	0.085	0.151	0.28
$u_{2018}/u_{\mathrm{MSY}}$	0.325	0.66	1.285

F.2.1.2.2. MCMC figures for central run

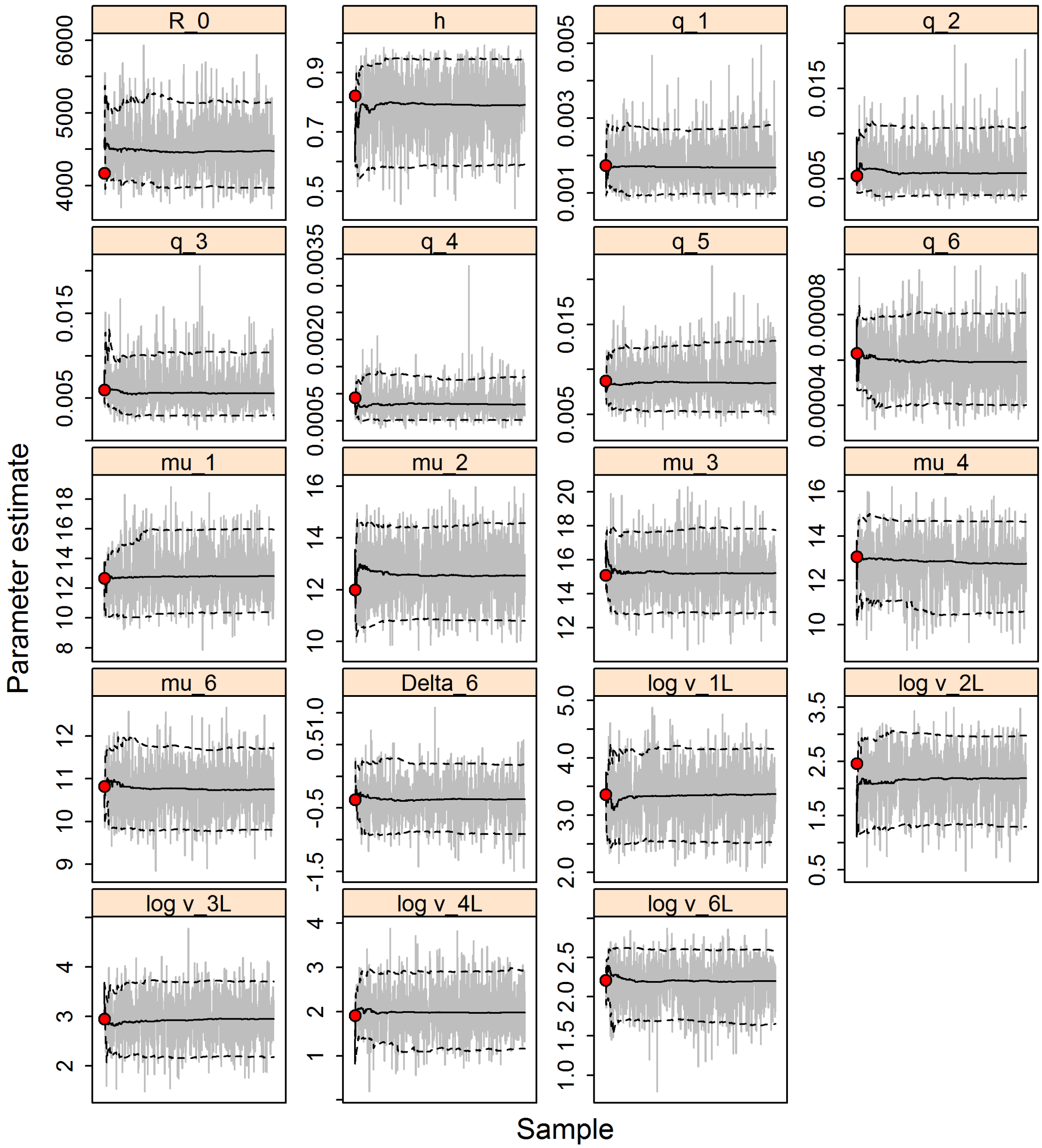


Figure F.24. CR.05.01: MCMC traces for the estimated parameters. Grey lines show the 1000 samples for each parameter, solid lines show the cumulative median (up to that sample), and dashed lines show the cumulative 0.05 and 0.95 quantiles. Red circles are the MPD estimates. For parameters other than M (if estimated), subscripts ≤ 5 correspond to fishery-independent surveys, and subscripts ≥ 6 denote the commercial fishery. Parameter notation is described in Appendix E.

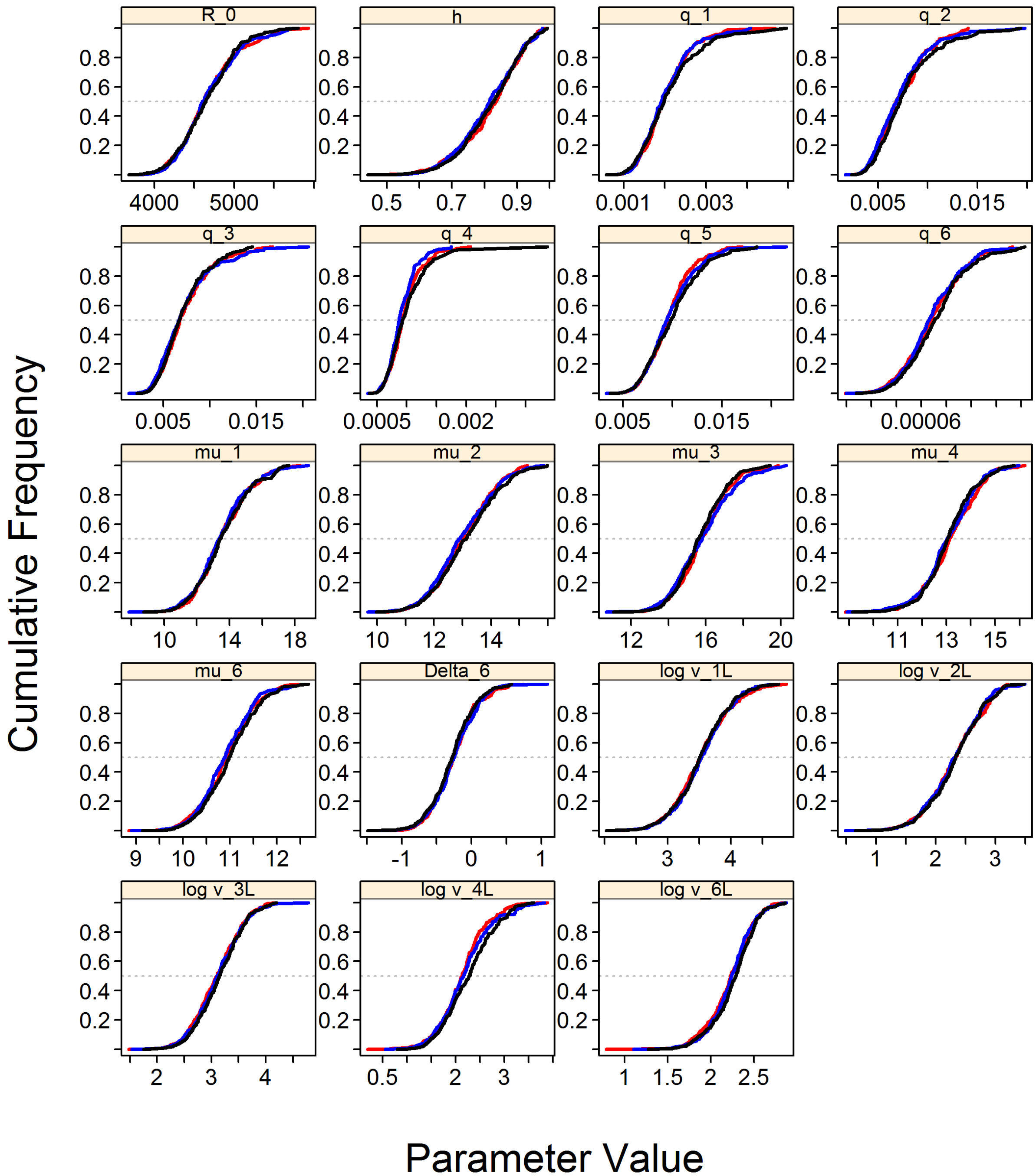


Figure F.25. CR.05.01: Diagnostic plot obtained by dividing the MCMC chain of 1000 MCMC samples into three segments, and overplotting the cumulative distributions of the first segment (red), second segment (blue) and final segment (black).

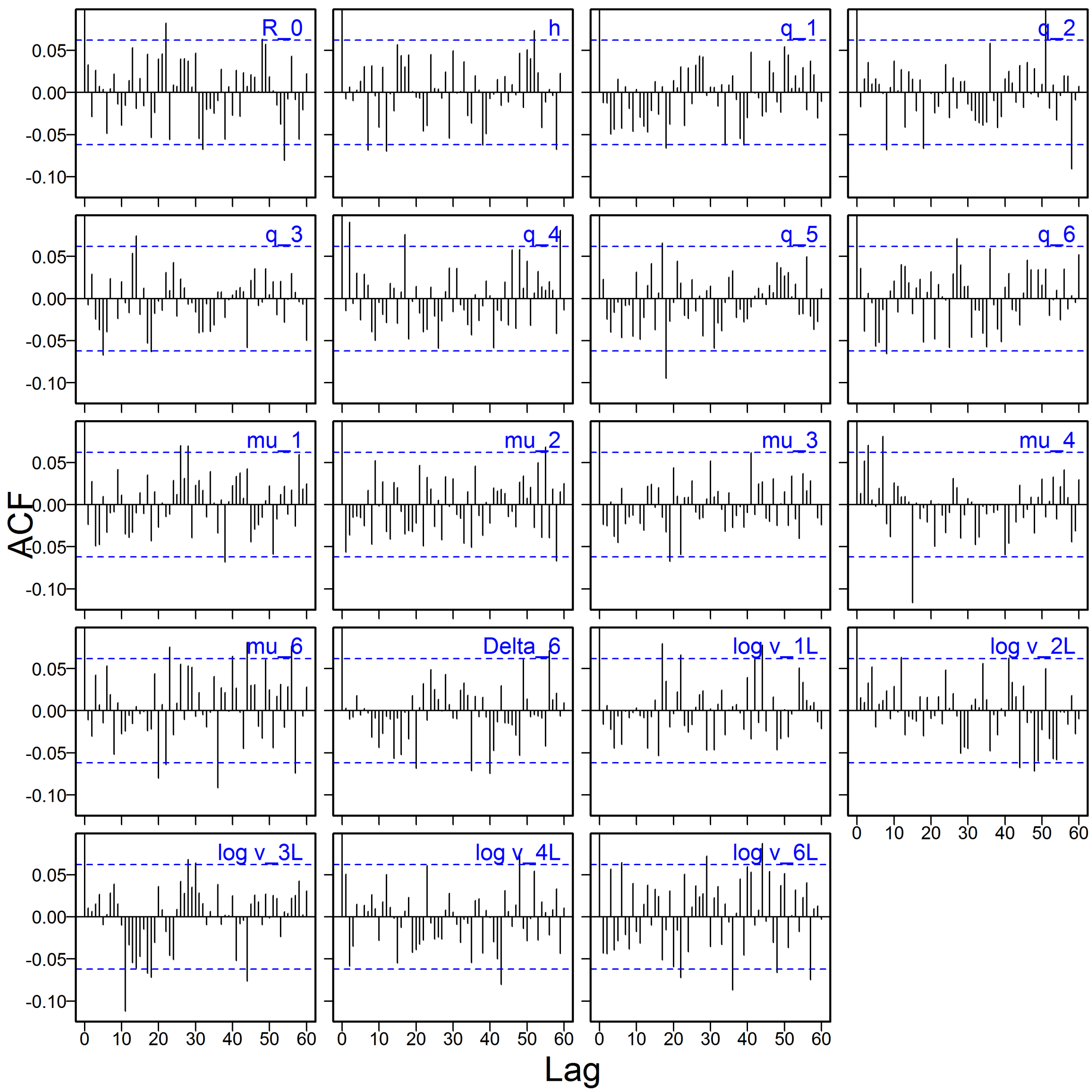


Figure F.26. CR.05.01: Autocorrelation plots for the estimated parameters from the MCMC output. Horizontal dashed blue lines delimit the 95% confidence interval for each parameter's set of lagged correlations.

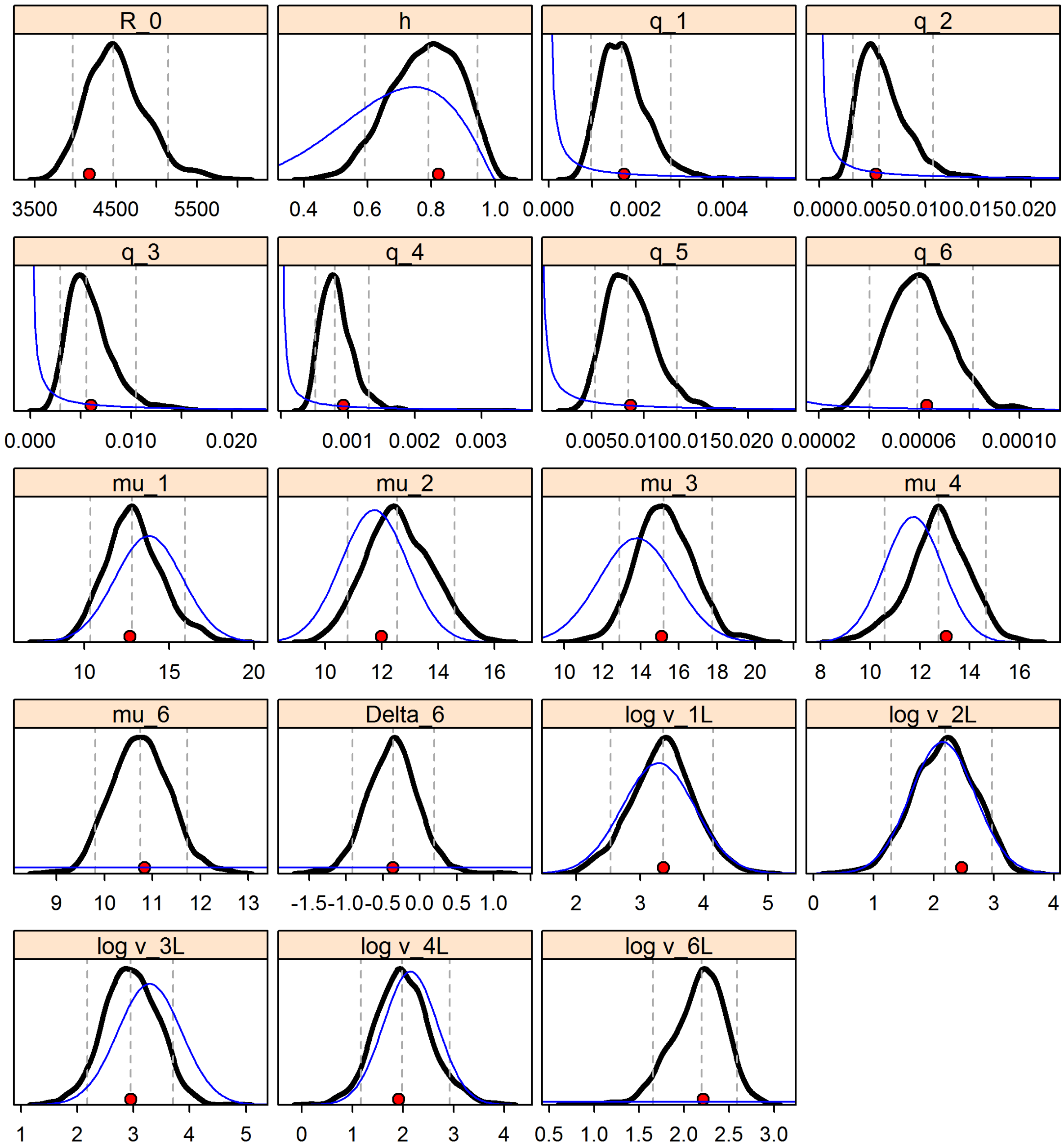


Figure F.27. CR.05.01: Marginal posterior densities (thick black curves) and prior density functions (thin blue curves) for the estimated parameters. Vertical lines represent the 0.05, 0.5, and 0.95 quantiles, and red filled circles are the MPD estimates. For R_0 the prior is a uniform distribution on the range [1, 1e7]. The priors for q_g are uniform on a log-scale, and so the probability density function is $1/(x(b-a))$ on a linear scale (where a and b are the bounds on the log scale).

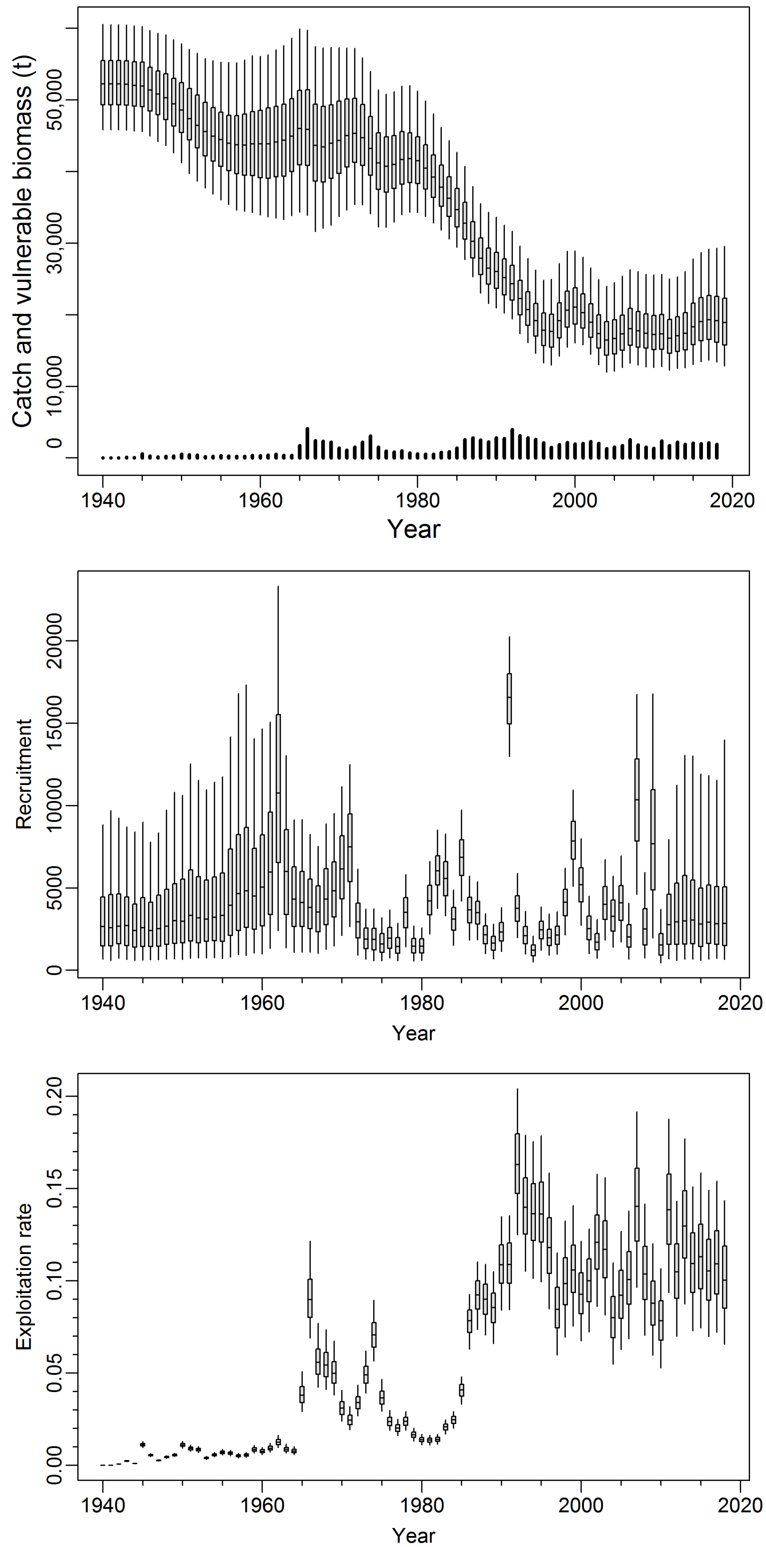


Figure F.28. CR.05.01: Top: estimated vulnerable biomass (boxplots) and commercial catch (vertical bars), in tonnes, over time. Middle: marginal posterior distribution of recruitment in 1,000s of age-1 fish plotted over time. Bottom: marginal posterior distribution of exploitation rate plotted over time. Boxplots show the 0.05, 0.25, 0.5, 0.75, and 0.95 quantiles from the MCMC results.

F.2.1.3. Composite Base Case

The composite base case comprised nine runs which explored major axes of uncertainty for this stock assessment:

- **B1** (Run01) – fixed $M_{1,2} = 0.07$ and set $A = 40$;
- **B2** (Run02) – fixed $M_{1,2} = 0.07$ and set $A = 45$;
- **B3** (Run03) – fixed $M_{1,2} = 0.07$ and set $A = 50$;
- **B4** (Run04) – fixed $M_{1,2} = 0.08$ and set $A = 40$;
- **B5** (Run05) – fixed $M_{1,2} = 0.08$ and set $A = 45$;
- **B6** (Run06) – fixed $M_{1,2} = 0.08$ and set $A = 50$;
- **B7** (Run07) – fixed $M_{1,2} = 0.09$ and set $A = 40$;
- **B8** (Run08) – fixed $M_{1,2} = 0.09$ and set $A = 45$;
- **B9** (Run09) – fixed $M_{1,2} = 0.09$ and set $A = 50$.

While exploring across a range of values for M is self-evident, particularly when it was not possible to estimate this parameter, the decision to average across a range of values for A is not. This was done because early model fits indicated that there was sensitivity in some of the quantities of management importance, particularly current stock status, associated with the choice of the accumulator age (Figure F.33). Initially we had selected A=40 because that was the value used for RSR (Starr and Haigh 2021) and the distribution of ages for these two *Sebastes* species is similar. However, once it was realised that there was sensitivity in the advice resulting from this choice, it was decided to make this parameter the second axis of the composite base case.

For each run, 1000 MCMC samples were pooled to provide an average stock trajectory for population status and advice to managers. Estimating M was not possible given the uninformative nature of the data, with MPD estimates not shifting from the prior means. MCMC runs that estimated M exhibited unstable behaviour with no credible convergence.

Composite base case median parameter estimates appear in Table F.6, and derived quantities at equilibrium and associated with MSY appear in Table F.7. The differences among the component base runs are summarised by various figures:

- Figure F.29 – MCMC traces of R_0 for the nine base-case runs;
- Figure F.30 – three chain segments of R_0 MCMC chains;
- Figure F.31 – autocorrelation plots for R_0 MCMC output;
- Figure F.32 – quantile plots of parameter estimates from 9 component runs;
- Figure F.33 – quantile plots of selected derived quantities from 9 component runs.

Various model trajectories and final stock status for the composite base case appear in the figures:

- Figure F.34 – estimates of spawning biomass B_t (tonnes) from pooled model posteriors;
- Figure F.35 – estimates of vulnerable biomass V_t (tonnes), recruitment R_t (1000s age-1 fish), and exploitation rate u_t from pooled model posteriors;
- Figure F.36 – phase plot through time of median B_t/B_{MSY} and u_{t-1}/u_{MSY};

- Figure F.37 – WWR stock status at beginning of 2019.

The nine runs outlined above converged with no serious pathologies in the MCMC diagnostics (similar diagnostic results to those outlined in Figures F.24–F.26 for the central run). Figures F.29 to F.31 show diagnostics for the R_0 parameter in each of the nine base runs. Figure F.32 shows the distribution of all the estimated parameters for the nine base-case runs. In most cases, the individual-case runs had parameter estimates with very similar distributions. The R_0 parameter varied with M and, to a lesser extent, with A. MCMC chains of this parameter showed increasing autocorrelation as M increased (Figure F.31). Setting M=0.10 caused a high degree of autocorrelation in this parameter and in all of the q parameters. Estimating M with a CV=50% caused a high degree of instability in the model as M simply bounced from 0.08 to 0.14. These model sensitivities are presented, along with others, in Section F.2.2.

The composite base case population trajectory from 1940 to 2019 and average projected biomass to 2024, assuming a constant catch policy of 2000 t/y, appears in Figure F.34. A phase plot of the time-evolution of spawning biomass and exploitation rate in MSY space (Figure F.36) suggests that the stock has been fished sustainably in recent years, with a current position at B_{2019}/B_{MSY} = 1.51 (0.92, 2.61) and u_{2018}/u_{MSY} = 0.66 (0.29, 1.35). Stock status plots for managers, which depict distributions of B_{2019}/B_{MSY} in zones delimited by 0.4B_{MSY} (LRP) and 0.8B_{MSY} (USR), show that the WWR stock lies in the healthy zone (Figure F.37). More precisely, the stock has a probability of 0 of being in the critical zone, a 0.016 probability of being in the cautious zone, and a 0.984 probability of being in the healthy zone.

Decision tables for the composite base case provide advice to managers as probabilities that projected biomass B_t ($t = 2019, ..., 2024$) will exceed biomass-based reference points (or that projected exploitation rate u_t will fall below harvest-based reference points) under constant-catch policies. Specifically:

- Table F.9 – probability of B_t exceeding the LRP $\equiv$ P$(B_t > 0.4B_{\text{MSY}})$
- Table F.10 – probability of B_t exceeding the USR $\equiv$ P$(B_t > 0.8B_{\text{MSY}})$
- Table F.11 – probability of B_t exceeding biomass at MSY $\equiv$ P$(B_t > B_{\text{MSY}})$
- Table F.12 – probability of u_t falling below harvest rate at MSY $\equiv$ P$(u_t < u_{\text{MSY}})$
- Table F.13 – probability of B_t exceeding current-year biomass $\equiv$ P$(B_t > B_{2019})$
- Table F.14 – probability of u_t falling below current-year harvest rate $\equiv$ P$(u_t < u_{2018})$
- Table F.15 – probability of B_t exceeding a non-DFO 'soft limit' $\equiv$ P$(B_t > 0.2B_0)$
- Table F.16 – probability of B_t exceeding a non-DFO 'target' biomass $\equiv$ P$(B_t > 0.4B_0)$

MSY-based reference points estimated within a stock assessment model can be highly sensitive to model assumptions about natural mortality and stock recruitment dynamics (Forrest et al. 2018). As a result, other jurisdictions use reference points that are expressed in terms of B_0 rather than B_{MSY} (e.g., N.Z. Min. Fish. 2011), because B_{MSY} is often poorly estimated as it depends on estimated parameters and a consistent fishery (although B_0 shares many of these same problems). Therefore, the reference points of 0.2B_0 and 0.4B_0 are also presented here. These are default values used in New Zealand respectively as a 'soft limit', below which management action needs to be taken, and a 'target' biomass for low productivity stocks, a mean around which the biomass is expected to vary. The 'soft limit' is equivalent to the upper stock reference (USR, 0.8B_{MSY}) in the provisional DFO Sustainable Fisheries Framework while a 'target' biomass is not specified by the provisional DFO SFF. Additionally, results are provided comparing projected biomass to B_{MSY} and to current spawning biomass B_{2019}, and comparing projected harvest rate to current harvest rate u_{2018}.

Table F.6. The 0.05, 0.5, and 0.95 quantiles for pooled model parameters (defined in Appendix E) from MCMC estimation of 9 base model runs.

	5%	50%	95%
R_0	3,301	4,551	6,774
h	0.567	0.788	0.945
q_1	0.000857	0.00161	0.00296
q_2	0.00274	0.00528	0.0110
q_3	0.00257	0.00535	0.0108
q_4	0.000469	0.000778	0.00129
q_5	0.00493	0.00829	0.0135
q_6	0.0000345	0.0000575	0.0000846
μ_1	10.4	12.8	15.9
μ_2	10.7	12.4	14.4
μ_3	12.8	15.2	17.8
μ_4	10.6	12.8	14.7
μ_6	9.72	10.7	11.7
Δ_6	-0.933	-0.355	0.209
$\log v_{1L}$	2.53	3.37	4.15
$\log v_{2L}$	1.32	2.22	3.00
$\log v_{3L}$	2.15	2.97	3.76
$\log v_{4L}$	1.16	2.00	2.91
$\log v_{6L}$	1.63	2.18	2.60

Table F.7. The 0.05, 0.5, and 0.95 quantiles of MCMC-derived quantities from 9000 samples pooled from 9 MCMC posteriors. Definitions are: B_0 – unfished equilibrium spawning biomass (mature females), V_0 – unfished equilibrium vulnerable biomass (males and females), B_{2019} – spawning biomass at the start of 2019, V_{2019} – vulnerable biomass in the middle of 2019, u_{2018} – exploitation rate (ratio of total catch to vulnerable biomass) in the middle of 2018, $u_{\max}$ – maximum exploitation rate (calculated for each sample as the maximum exploitation rate from 1940-2018)B_{MSY} – equilibrium spawning biomass at MSY (maximum sustainable yield), u_{MSY} – equilibrium exploitation rate at MSY, V_{MSY} – equilibrium vulnerable biomass at MSY. All biomass values (and MSY) are in tonnes. For reference, the average catch over the last 5 years (2014-2018) was 2001 t.

	5%	50%	95%
B_0	26,282	29,951	36,692
V_0	46,361	53,380	66,080
B_{2019}	7,179	11,017	18,660
V_{2019}	12,396	19,526	34,035
B_{2019}/B_0	0.257	0.369	0.537
V_{2019}/V_0	0.252	0.366	0.540
u_{2018}	0.0574	0.0975	0.149
$u_{\max}$	0.112	0.161	0.214
MSY	1,460	1,909	2,685
B_{MSY}	4,815	7,373	11,307
$0.4B_{2019}$	1,926	2,949	4,523
$0.8B_{2019}$	3,852	5,898	9,045
$B_{2019}/B_{\mathrm{MSY}}$	0.921	1.51	2.61
B_{MSY}/B_0	0.170	0.246	0.327
V_{MSY}	8,284	13,145	20,430
V_{MSY}/V_0	0.168	0.247	0.330
u_{MSY}	0.0810	0.148	0.271
$u_{2018}/u_{\mathrm{MSY}}$	0.289	0.658	1.35

Table F.8. Quantiles (0.05, 0.5, 0.95) of annual exploitation rate u_t (harvest rate = catch divided by vulnerable biomass) from 1940 to current model year 2018 and projected to 2024 assuming a constant catch of 2000 t. Prob = P($u_t < u_{\mathrm{MSY}}$).

Year	5%	50%	95%	Prob	Year	5%	50%	95%	Prob
1940	<0.01	<0.01	<0.01	1	1983	0.02	0.02	0.03	1
1941	<0.01	<0.01	<0.01	1	1984	0.02	0.02	0.03	1
1942	<0.01	<0.01	<0.01	1	1985	0.03	0.04	0.05	>0.99
1943	<0.01	<0.01	<0.01	1	1986	0.06	0.08	0.10	0.96
1944	<0.01	<0.01	<0.01	1	1987	0.07	0.09	0.11	0.90
1945	0.01	0.01	0.01	1	1988	0.06	0.09	0.11	0.91
1946	<0.01	0.01	0.01	1	1989	0.06	0.08	0.11	0.93
1947	<0.01	<0.01	<0.01	1	1990	0.08	0.11	0.14	0.80
1948	<0.01	<0.01	0.01	1	1991	0.08	0.11	0.14	0.80
1949	<0.01	0.01	0.01	1	1992	0.11	0.16	0.21	0.42
1950	0.01	0.01	0.01	1	1993	0.09	0.14	0.18	0.57
1951	0.01	0.01	0.01	1	1994	0.09	0.13	0.18	0.60
1952	0.01	0.01	0.01	1	1995	0.09	0.13	0.19	0.59
1953	<0.01	<0.01	<0.01	1	1996	0.07	0.12	0.16	0.72
1954	<0.01	0.01	0.01	1	1997	0.05	0.08	0.12	0.93
1955	<0.01	0.01	0.01	1	1998	0.06	0.10	0.14	0.85
1956	<0.01	0.01	0.01	1	1999	0.07	0.10	0.15	0.81
1957	<0.01	<0.01	0.01	1	2000	0.06	0.09	0.13	0.89
1958	<0.01	0.01	0.01	1	2001	0.06	0.10	0.13	0.85
1959	0.01	0.01	0.01	1	2002	0.07	0.12	0.16	0.71
1960	0.01	0.01	0.01	1	2003	0.07	0.11	0.16	0.73
1961	0.01	0.01	0.01	1	2004	0.05	0.08	0.11	0.94
1962	0.01	0.01	0.02	1	2005	0.05	0.09	0.13	0.89
1963	0.01	0.01	0.01	1	2006	0.06	0.10	0.14	0.84
1964	0.01	0.01	0.01	1	2007	0.08	0.14	0.20	0.57
1965	0.03	0.04	0.05	>0.99	2008	0.06	0.10	0.15	0.82
1966	0.06	0.09	0.12	0.91	2009	0.05	0.09	0.12	0.91
1967	0.04	0.05	0.08	>0.99	2010	0.05	0.08	0.11	0.95
1968	0.04	0.05	0.07	>0.99	2011	0.08	0.13	0.19	0.58
1969	0.03	0.05	0.07	>0.99	2012	0.06	0.10	0.15	0.81
1970	0.02	0.03	0.04	1	2013	0.08	0.13	0.18	0.64
1971	0.02	0.02	0.03	1	2014	0.06	0.11	0.16	0.78
1972	0.02	0.03	0.05	>0.99	2015	0.06	0.11	0.16	0.75
1973	0.03	0.05	0.07	>0.99	2016	0.06	0.10	0.15	0.80
1974	0.05	0.07	0.09	0.97	2017	0.06	0.11	0.16	0.78
1975	0.03	0.04	0.05	>0.99	2018	0.06	0.10	0.15	0.82
1976	0.02	0.02	0.03	1	2019	0.06	0.10	0.16	0.78
1977	0.01	0.02	0.03	1	2020	0.06	0.10	0.17	0.77
1978	0.02	0.02	0.03	1	2021	0.06	0.10	0.18	0.75
1979	0.01	0.02	0.02	1	2022	0.05	0.10	0.20	0.73
1980	0.01	0.01	0.02	1	2023	0.05	0.10	0.21	0.72
1981	0.01	0.01	0.02	1	2024	0.05	0.11	0.23	0.70
1982	0.01	0.01	0.02	1	—	—	—	—	—

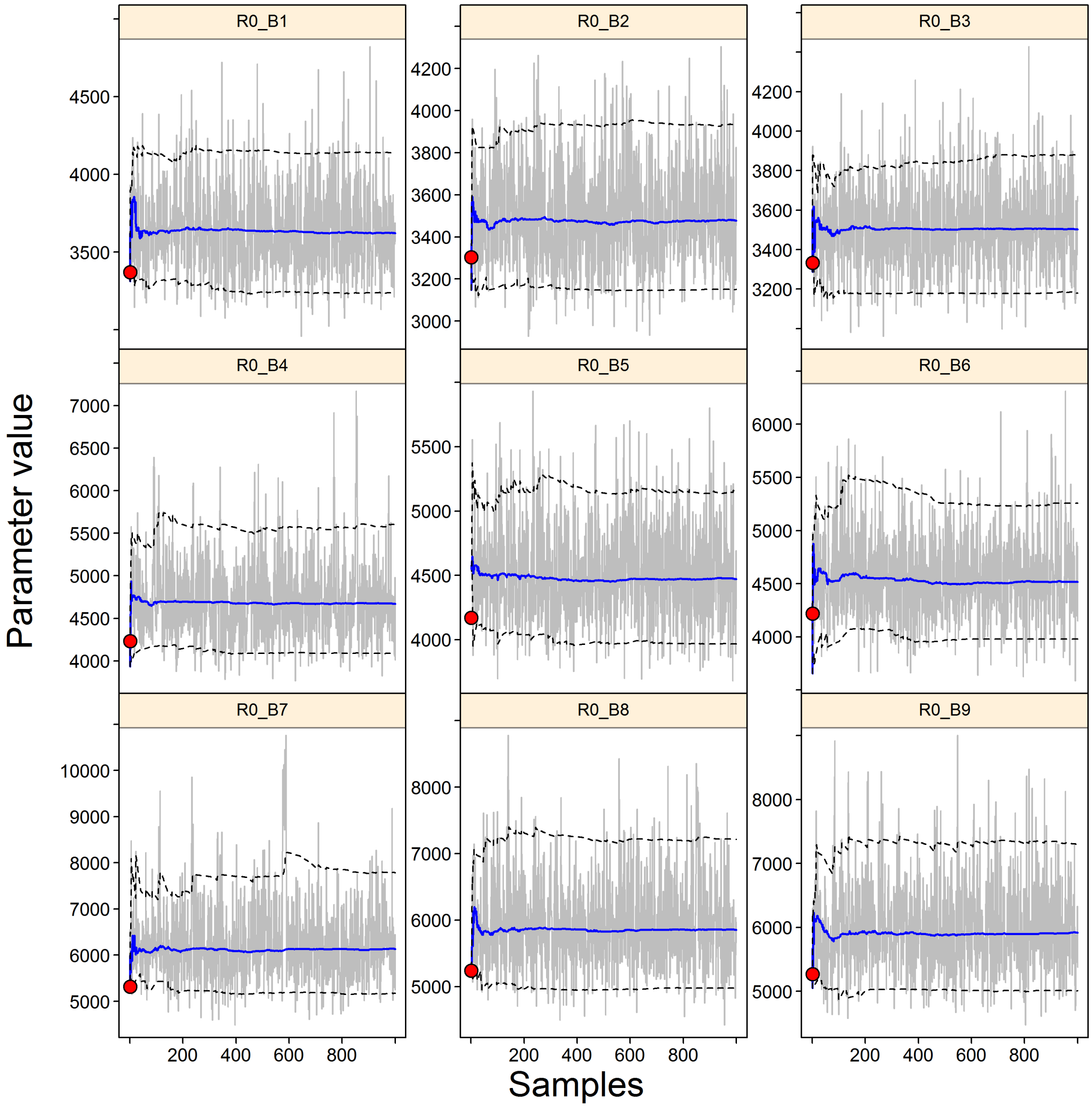


Figure F.29. Composite base: MCMC traces of R_0 for the nine base-case runs. Grey lines show the 1000 samples for the R_0 parameter, solid lines show the cumulative median (up to that sample), and dashed lines show the cumulative 0.05 and 0.95 quantiles. Red circles are the MPD estimates.

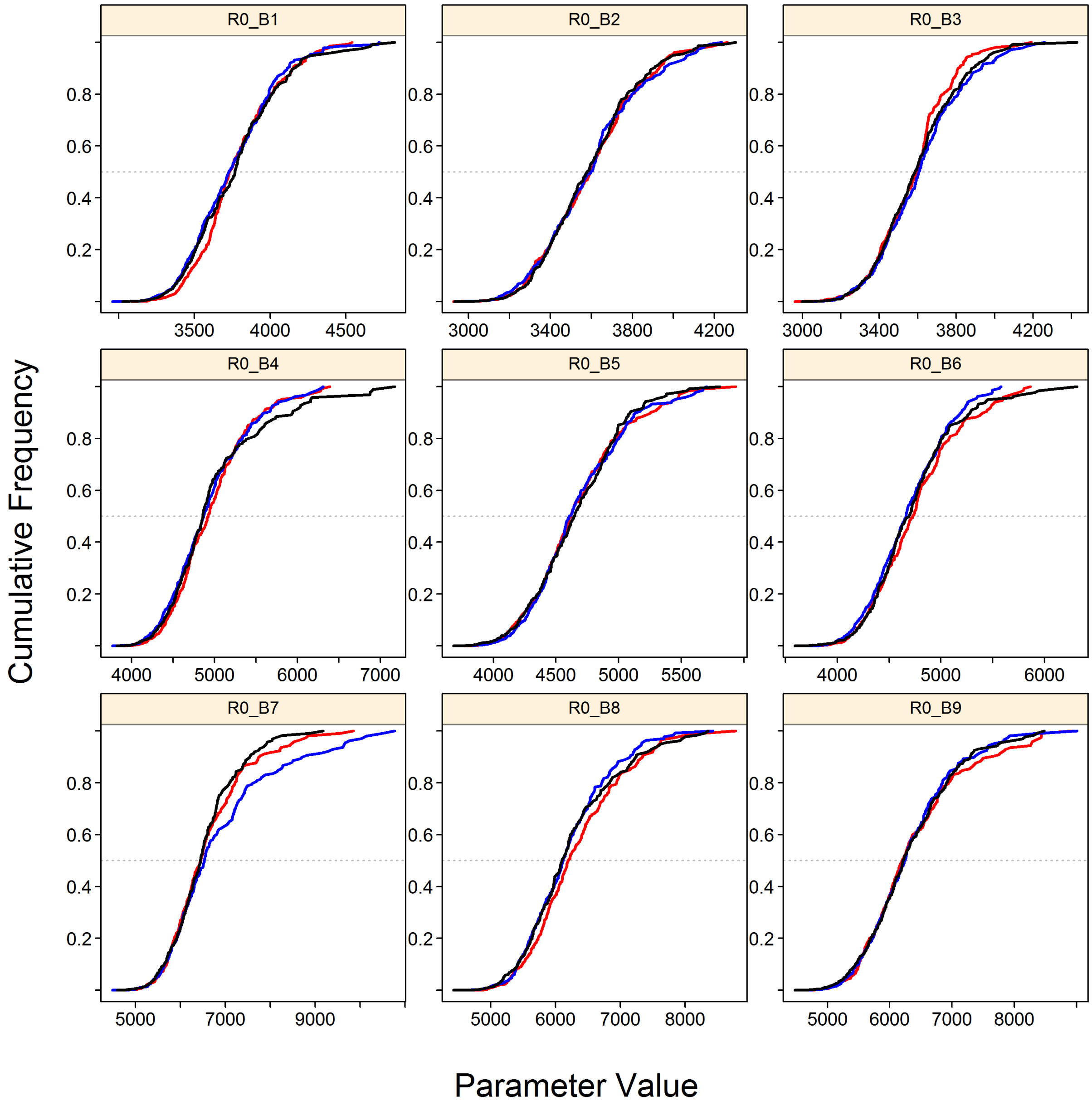


Figure F.30. Composite base: diagnostic plots obtained by dividing the R_0 MCMC chains of 1000 MCMC samples into three segments, and overplotting the cumulative distributions of the first segment (red), second segment (blue) and final segment (black).

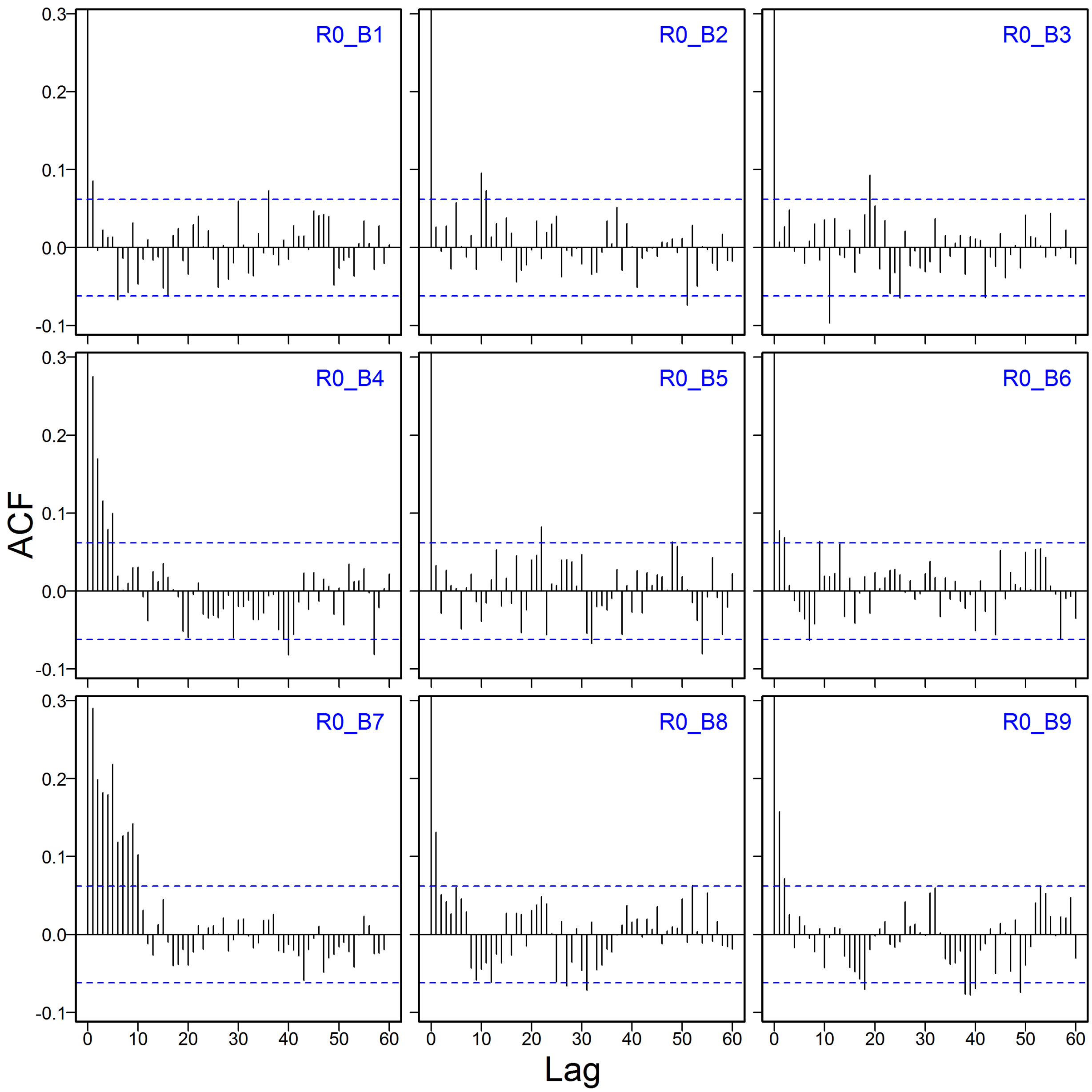


Figure F.31. Composite base: autocorrelation plots for the base-case R_0 parameters from the MCMC output. Horizontal dashed blue lines delimit the 95% confidence interval for each parameter's set of lagged correlations.

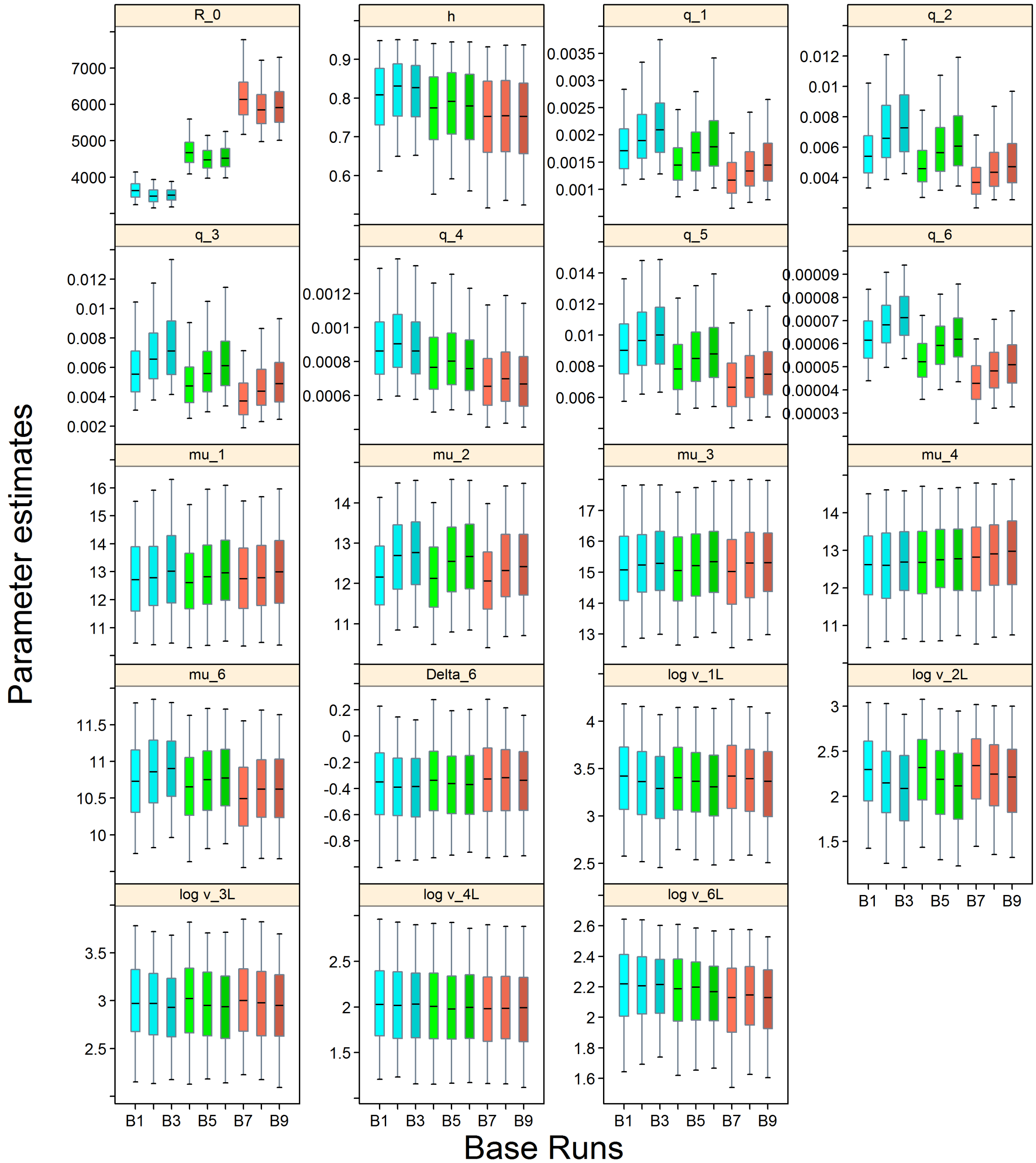


Figure F.32. Composite base: quantile plots of the parameter estimates from nine component runs of the base case, where blue boxes denote M=0.07, green boxes denote M=0.08, red boxes denote M=0.09, and groups by colour denote $A \in$40, 45, 50 years. The boxplots delimit the 0.05, 0.25, 0.5, 0.75, and 0.95 quantiles; outliers are included.

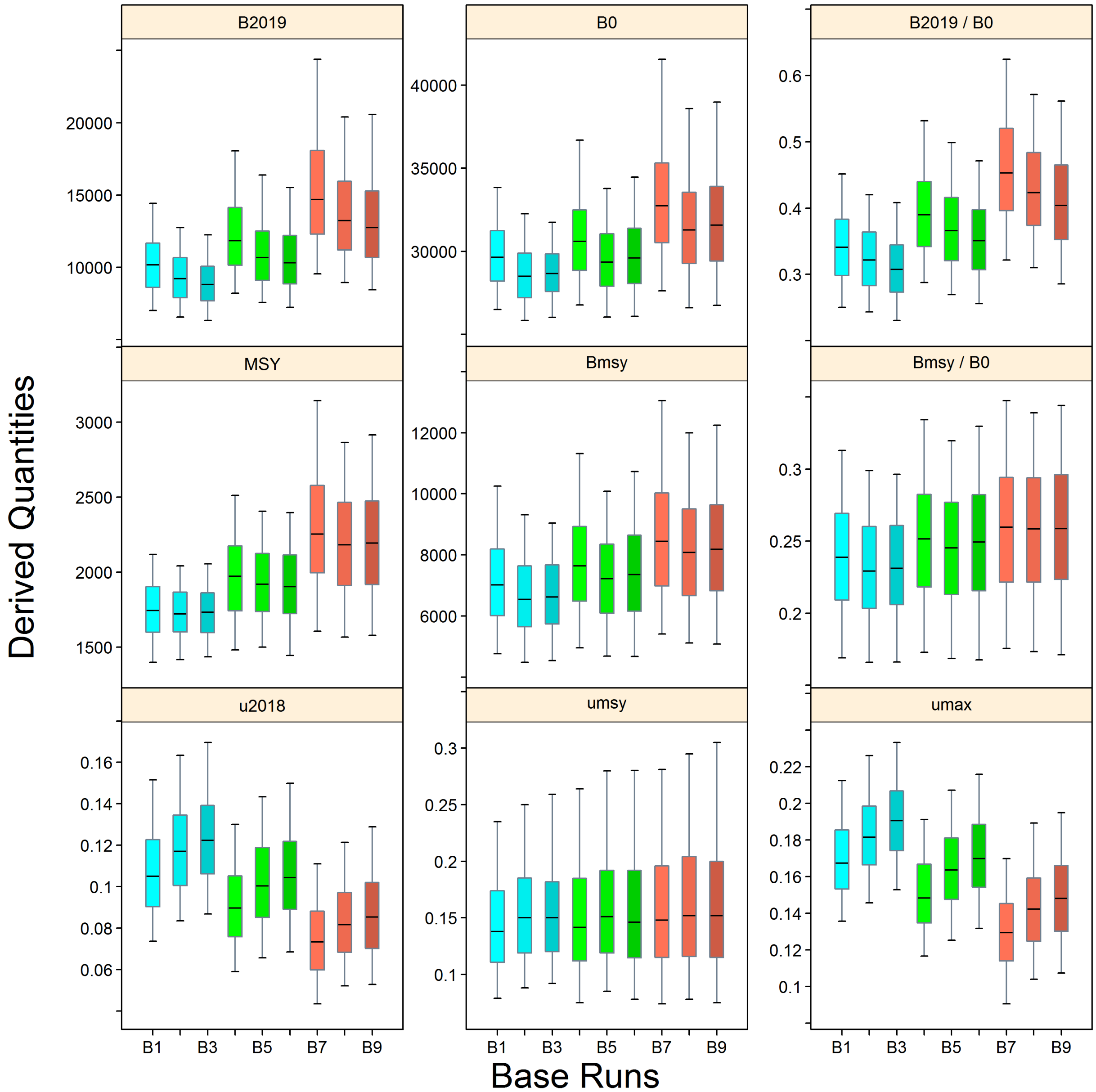


Figure F.33. Composite base: quantile plots of selected derived quantities (B_{2019}, B_0, B_{2019}/B_0, MSY, B_{MSY}, B_{MSY}/B_0, u_{2018}, u_{MSY}, u_{max}) from nine component runs of the base case, where blue boxes denote M=0.07, green boxes denote M=0.08, red boxes denote M=0.09, and groups by colour denote A ∈40, 45, 50 years. The boxplots delimit the 0.05, 0.25, 0.5, 0.75, and 0.95 quantiles; outliers are excluded.

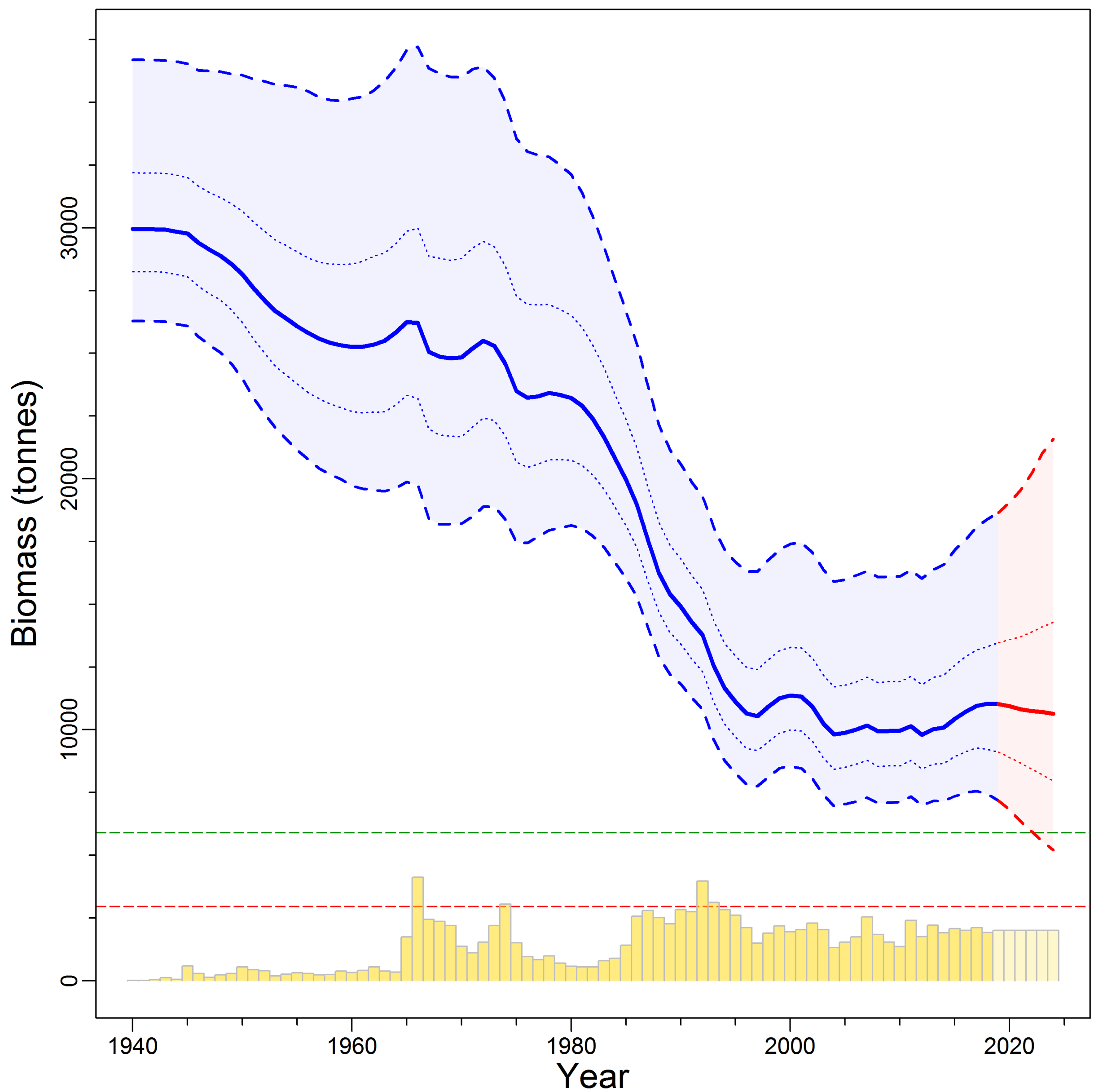


Figure F.34. Composite base: estimates of spawning biomass B_t (tonnes) from pooled model posteriors. The median biomass trajectory appears as a solid curve surrounded by a 90% credibility envelope (quantiles: 0.05-0.95) in light blue and delimited by dashed lines for years t=1940:2019; projected biomass appears in light red for years t=2020:2024. Also delimited is the 50% credibility interval (quantiles: 0.25-0.75) delimited by dotted lines. The horizontal dashed lines show the median LRP and USR. Catch and assumed catch policy (2000 t/y) are represented as bars along the bottom axis.

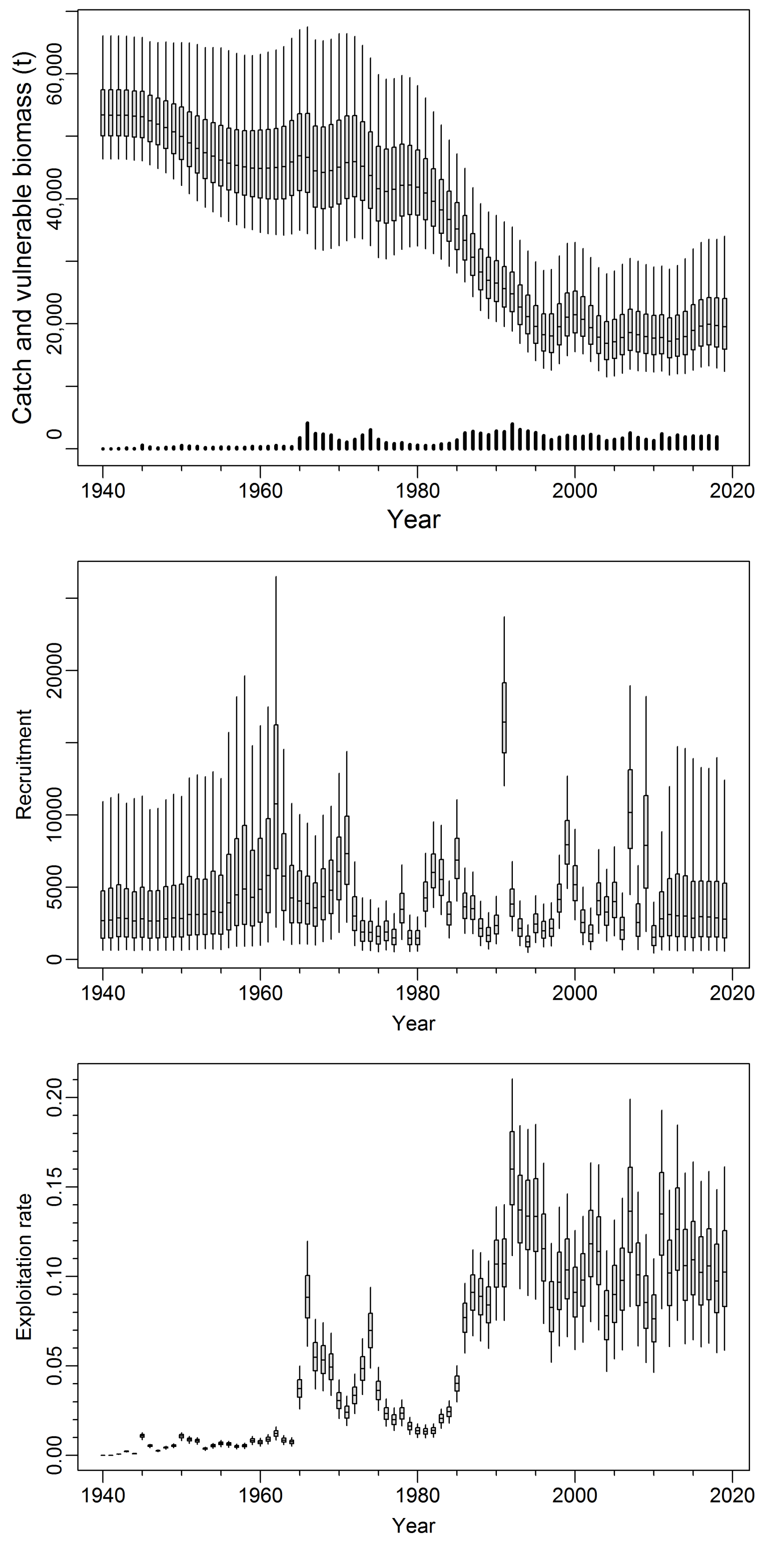


Figure F.35. Composite base: Top: estimated vulnerable biomass trajectory (boxplots) and commercial catch history (vertical bars), in tonnes. Middle: marginal posterior distribution of recruitment trajectory in 1,000s of age-1 fish. Bottom: marginal posterior distribution of exploitation rate trajectory. Boxplots show the 0.05, 0.25, 0.5, 0.75, and 0.95 quantiles from the MCMC results.

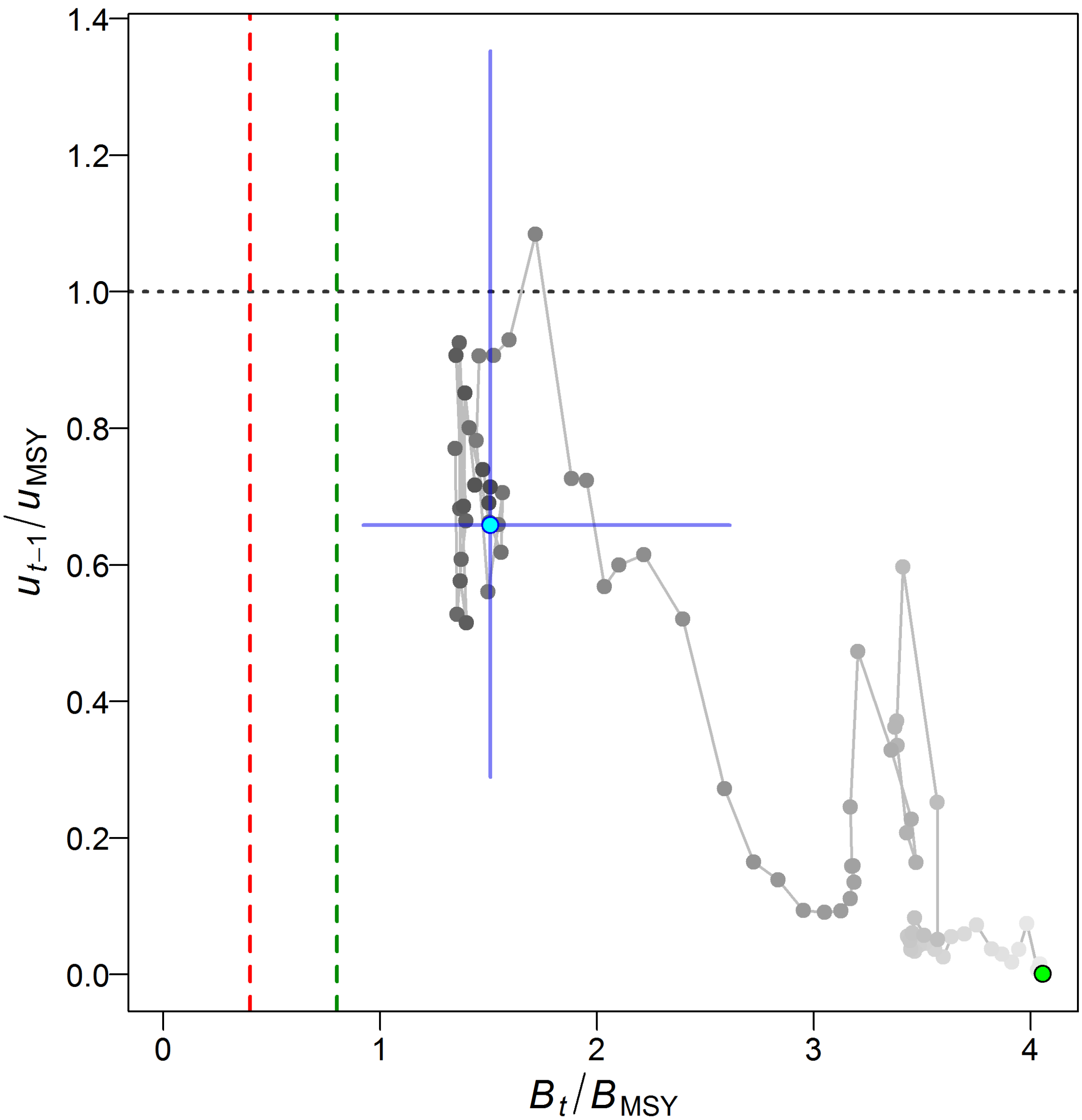


Figure F.36. Composite base: phase plot through time of the medians of the ratios B_t/B_{MSY} (the spawning biomass in year t relative to B_{MSY}) and u_{t-1}/u_{MSY} (the exploitation rate in year $t-1$ relative to u_{MSY}). The filled green circle is the starting year (1941). Years then proceed from light grey through to dark grey with the final year (2019) as a filled cyan circle, and the blue lines represent the 0.05 and 0.95 quantiles of the posterior distributions for the final year. Red and green vertical dashed lines indicate the Precautionary Approach provisional limit and upper stock reference points (0.4, 0.8 B_{MSY}), and the horizontal grey dotted line indicates u at MSY.

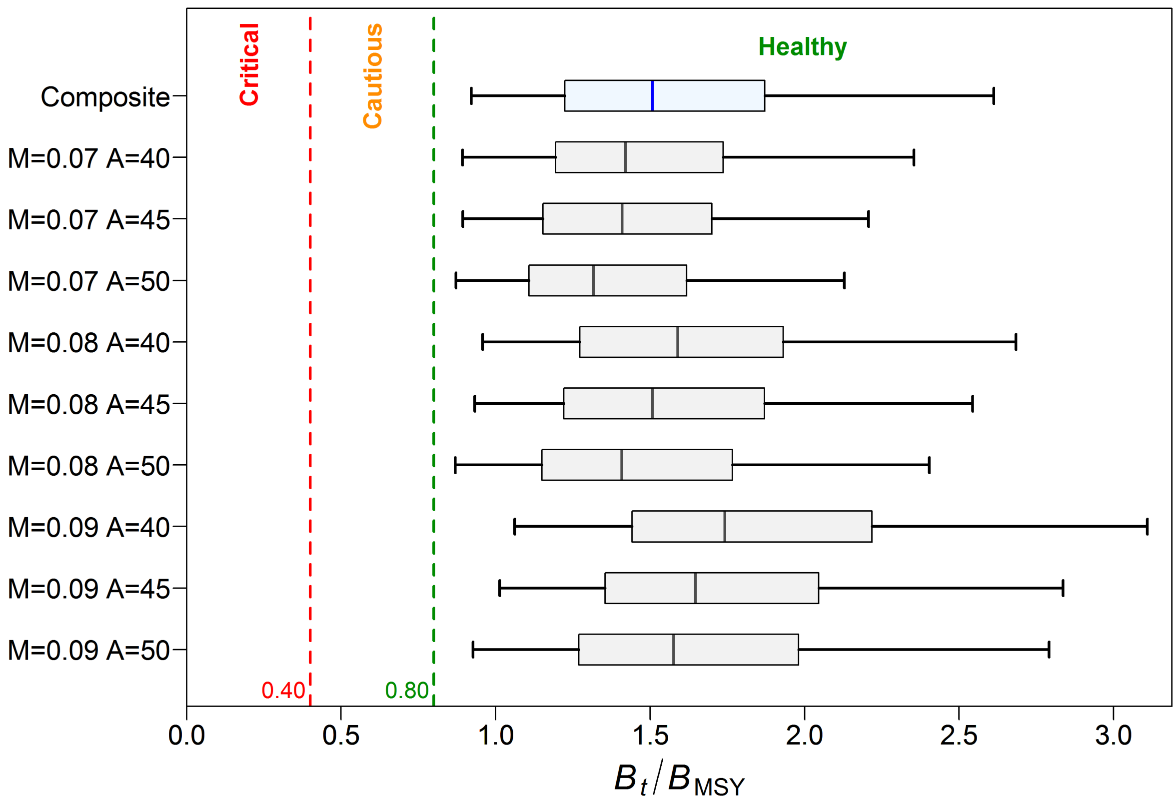


Figure F.37. Composite base: status at beginning of 2019 of the Widow Rockfish (BC) stock relative to the DFO PA provisional reference points of 0.4B_{MSY} and 0.8B_{MSY} for a base case comprising 9 model runs. The top quantile plot shows the composite distribution and below are the 9 contributing runs. Quantile plots show the 0.05, 0.25, 0.5, 0.75, and 0.95 quantiles from the MCMC posteriors.

Table F.9. Decision table concerning the limit reference point $0.4B_{\mathrm{MSY}}$ for 5-year projections for a range of constant catch strategies (in tonnes). Values are P$(B_t > 0.4B_{\mathrm{MSY}})$, i.e. the probability of the spawning biomass (mature females) at the start of year t being greater than the limit reference point. The probabilities are the proportion of the 9000 MCMC samples for which $B_t > 0.4B_{\mathrm{MSY}}$. For reference, the average catch over the last 5 years (2014-2018) was 2001 t.

	2019	2020	2021	2022	2023	2024
0	1.00	1.00	1.00	1.00	1.00	1.00
250	1.00	1.00	1.00	1.00	1.00	1.00
500	1.00	1.00	1.00	1.00	1.00	1.00
750	1.00	1.00	1.00	1.00	1.00	1.00
1000	1.00	1.00	1.00	1.00	1.00	1.00
1250	1.00	1.00	1.00	1.00	1.00	1.00
1500	1.00	1.00	1.00	1.00	1.00	1.00
1750	1.00	1.00	1.00	1.00	1.00	1.00
2000	1.00	1.00	1.00	1.00	1.00	0.99
2250	1.00	1.00	1.00	1.00	0.99	0.99
2500	1.00	1.00	1.00	1.00	0.99	0.98
2750	1.00	1.00	1.00	0.99	0.98	0.97
3000	1.00	1.00	1.00	0.99	0.97	0.94
3250	1.00	1.00	1.00	0.99	0.96	0.91
3500	1.00	1.00	1.00	0.98	0.93	0.87
3750	1.00	1.00	0.99	0.97	0.90	0.82
4000	1.00	1.00	0.99	0.95	0.87	0.77

Table F.10. Decision table concerning the upper stock reference point $0.8B_{\mathrm{MSY}}$ for 5-year projections, such that values are P$(B_t > 0.8B_{\mathrm{MSY}})$. For reference, the average catch over the last 5 years (2014-2018) was 2001 t.

	2019	2020	2021	2022	2023	2024
0	0.98	0.99	1.00	1.00	1.00	1.00
250	0.98	0.99	0.99	1.00	1.00	1.00
500	0.98	0.99	0.99	0.99	1.00	1.00
750	0.98	0.99	0.99	0.99	0.99	0.99
1000	0.98	0.98	0.98	0.99	0.99	0.99
1250	0.98	0.98	0.98	0.98	0.98	0.98
1500	0.98	0.98	0.98	0.97	0.97	0.96
1750	0.98	0.98	0.97	0.96	0.95	0.94
2000	0.98	0.97	0.96	0.95	0.93	0.91
2250	0.98	0.97	0.95	0.93	0.90	0.87
2500	0.98	0.97	0.94	0.90	0.86	0.82
2750	0.98	0.96	0.93	0.87	0.82	0.77
3000	0.98	0.96	0.91	0.85	0.78	0.72
3250	0.98	0.95	0.89	0.81	0.73	0.66
3500	0.98	0.95	0.87	0.77	0.68	0.60
3750	0.98	0.94	0.85	0.74	0.63	0.55
4000	0.98	0.93	0.83	0.70	0.58	0.49

Table F.11. Decision table concerning the reference point B_{MSY} for 5-year projections, such that values are P($B_t > B_{\mathrm{MSY}}$). For reference, the average catch over the last 5 years (2014-2018) was 2001 t.

	2019	2020	2021	2022	2023	2024
0	0.91	0.95	0.97	0.98	0.99	0.99
250	0.91	0.94	0.96	0.97	0.98	0.99
500	0.91	0.94	0.95	0.97	0.97	0.98
750	0.91	0.93	0.94	0.95	0.96	0.96
1000	0.91	0.93	0.93	0.94	0.94	0.95
1250	0.91	0.92	0.92	0.92	0.92	0.92
1500	0.91	0.91	0.90	0.90	0.89	0.89
1750	0.91	0.90	0.88	0.87	0.86	0.85
2000	0.91	0.89	0.87	0.84	0.82	0.80
2250	0.91	0.88	0.85	0.81	0.78	0.75
2500	0.91	0.87	0.82	0.77	0.73	0.69
2750	0.91	0.86	0.80	0.74	0.68	0.63
3000	0.91	0.85	0.77	0.70	0.64	0.58
3250	0.91	0.84	0.75	0.66	0.59	0.52
3500	0.91	0.83	0.72	0.62	0.54	0.47
3750	0.91	0.81	0.69	0.58	0.49	0.42
4000	0.91	0.80	0.66	0.54	0.44	0.37

Table F.12. Decision table for comparing the projected exploitation rate to that at MSY, such that values are P($u_t < u_{\mathrm{MSY}}$), i.e. the probability of the exploitation rate in the middle of year t being less than that at MSY. For reference, the average catch over the last 5 years (2014-2018) was 2001 t.

	2019	2020	2021	2022	2023	2024
0	1.00	1.00	1.00	1.00	1.00	1.00
250	1.00	1.00	1.00	1.00	1.00	1.00
500	1.00	1.00	1.00	1.00	1.00	1.00
750	1.00	1.00	1.00	1.00	1.00	1.00
1000	0.99	0.99	0.99	0.99	0.99	0.99
1250	0.97	0.97	0.97	0.97	0.96	0.96
1500	0.93	0.92	0.92	0.91	0.91	0.90
1750	0.86	0.85	0.84	0.83	0.82	0.81
2000	0.78	0.77	0.75	0.73	0.72	0.70
2250	0.70	0.67	0.65	0.63	0.61	0.59
2500	0.61	0.58	0.55	0.53	0.51	0.49
2750	0.54	0.50	0.47	0.44	0.42	0.40
3000	0.47	0.43	0.39	0.36	0.34	0.31
3250	0.40	0.36	0.33	0.30	0.27	0.25
3500	0.35	0.30	0.26	0.24	0.21	0.20
3750	0.30	0.25	0.21	0.19	0.17	0.15
4000	0.25	0.21	0.17	0.15	0.13	0.12

Table F.13. Decision table for comparing the projected biomass to the current biomass, given by probabilities P$(B_t > B_{2019})$. For reference, the average catch over the last 5 years (2014-2018) was 2001 t.

	2019	2020	2021	2022	2023	2024
0	0.00	1.00	1.00	1.00	1.00	1.00
250	0.00	0.99	0.99	0.99	0.99	0.99
500	0.00	0.98	0.97	0.97	0.97	0.97
750	0.00	0.94	0.92	0.91	0.91	0.92
1000	0.00	0.85	0.83	0.82	0.83	0.83
1250	0.00	0.73	0.71	0.72	0.72	0.72
1500	0.00	0.60	0.58	0.59	0.60	0.61
1750	0.00	0.47	0.47	0.48	0.49	0.49
2000	0.00	0.37	0.37	0.39	0.39	0.40
2250	0.00	0.28	0.29	0.31	0.31	0.32
2500	0.00	0.21	0.22	0.24	0.25	0.25
2750	0.00	0.16	0.17	0.19	0.20	0.20
3000	0.00	0.12	0.14	0.15	0.15	0.15
3250	0.00	0.10	0.11	0.12	0.12	0.12
3500	0.00	0.07	0.08	0.09	0.10	0.09
3750	0.00	0.05	0.06	0.07	0.08	0.08
4000	0.00	0.04	0.05	0.06	0.06	0.06

Table F.14. Decision table for comparing the projected exploitation rate to that in 2018, such that values are P$(u_t < u_{2018})$. For reference, the average catch over the last 5 years (2014-2018) was 2001 t.

	2019	2020	2021	2022	2023	2024
0	1.00	1.00	1.00	1.00	1.00	1.00
250	1.00	1.00	1.00	1.00	1.00	1.00
500	1.00	1.00	1.00	1.00	1.00	1.00
750	1.00	1.00	1.00	1.00	1.00	1.00
1000	1.00	1.00	1.00	1.00	1.00	1.00
1250	1.00	1.00	1.00	1.00	1.00	1.00
1500	1.00	1.00	0.99	0.96	0.92	0.90
1750	0.98	0.82	0.71	0.67	0.64	0.62
2000	0.11	0.22	0.28	0.32	0.33	0.35
2250	0.00	0.04	0.09	0.13	0.16	0.17
2500	0.00	0.01	0.03	0.05	0.07	0.08
2750	0.00	0.00	0.01	0.02	0.03	0.04
3000	0.00	0.00	0.00	0.01	0.02	0.02
3250	0.00	0.00	0.00	0.01	0.01	0.01
3500	0.00	0.00	0.00	0.00	0.00	0.01
3750	0.00	0.00	0.00	0.00	0.00	0.00
4000	0.00	0.00	0.00	0.00	0.00	0.00

Table F.15. *Decision table for the alternative limit reference point $0.2B_0$ (soft limit) for 5-year projections, such that values are P($B_t > 0.2B_0$). For reference, the average catch over the last 5 years (2014-2018) was 2001 t.*

	2019	2020	2021	2022	2023	2024
0	1.00	1.00	1.00	1.00	1.00	1.00
250	1.00	1.00	1.00	1.00	1.00	1.00
500	1.00	1.00	1.00	1.00	1.00	1.00
750	1.00	1.00	1.00	1.00	1.00	1.00
1000	1.00	1.00	1.00	1.00	1.00	1.00
1250	1.00	1.00	1.00	0.99	0.99	0.99
1500	1.00	1.00	0.99	0.99	0.98	0.98
1750	1.00	0.99	0.99	0.98	0.97	0.96
2000	1.00	0.99	0.98	0.97	0.95	0.93
2250	1.00	0.99	0.98	0.95	0.92	0.89
2500	1.00	0.99	0.97	0.93	0.89	0.84
2750	1.00	0.98	0.95	0.90	0.84	0.79
3000	1.00	0.98	0.94	0.87	0.79	0.72
3250	1.00	0.98	0.92	0.84	0.74	0.66
3500	1.00	0.97	0.90	0.79	0.69	0.60
3750	1.00	0.97	0.88	0.75	0.63	0.54
4000	1.00	0.96	0.85	0.71	0.58	0.48

Table F.16. *Decision table for the alternative limit reference point $0.4B_0$ (target biomass) for 5-year projections, such that values are P($B_t > 0.4B_0$). For reference, the average catch over the last 5 years (2014-2018) was 2001 t.*

	2019	2020	2021	2022	2023	2024
0	0.36	0.50	0.63	0.74	0.83	0.89
250	0.36	0.48	0.59	0.69	0.77	0.83
500	0.36	0.46	0.56	0.64	0.71	0.76
750	0.36	0.44	0.52	0.59	0.65	0.70
1000	0.36	0.42	0.48	0.54	0.59	0.63
1250	0.36	0.41	0.45	0.49	0.52	0.55
1500	0.36	0.39	0.42	0.44	0.47	0.49
1750	0.36	0.37	0.39	0.40	0.42	0.42
2000	0.36	0.36	0.36	0.36	0.37	0.37
2250	0.36	0.34	0.33	0.32	0.32	0.32
2500	0.36	0.33	0.31	0.29	0.28	0.28
2750	0.36	0.31	0.28	0.26	0.25	0.24
3000	0.36	0.30	0.26	0.23	0.22	0.20
3250	0.36	0.29	0.24	0.21	0.19	0.18
3500	0.36	0.27	0.22	0.18	0.17	0.15
3750	0.36	0.26	0.20	0.16	0.14	0.12
4000	0.36	0.25	0.18	0.15	0.12	0.10

F.2.2. Sensitivity Runs

Twelve sensitivity analyses were run (with full MCMC simulations) relative to the central run (Run05: M=0.08, A=45) to test the sensitivity of the outputs to alternative model assumptions:

- **S01** (Run10) – decreased σ_R from 0.9 to 0.6;
- **S02** (Run11) – increased σ_R from 0.9 to 1.2;
- **S03** (Run12) – increased M from 0.08 to 0.10;
- **S04** (Run13) – estimated M with 50% CV;
- **S05** (Run14) – added simple ageing error matrix with 0.8 along the diagonal and 0.1 on either side of the diagonal;
- **S06** (Run15) – added ageing error matrix based on observed spread between min and max ages specified by readers;
- **S07** (Run16) – dropped the CPUE index series;
- **S08** (Run17) – removed process error on CPUE series;
- **S09** (Run18) – dropped all survey age data and set survey selectivities to prior means;
- **S10** (Run19) – halved commercial catch during years of foreign fleet activity (1965-1976) and during years of possible misreporting by domestic fleet (1988-1995);
- **S11** (Run20) – doubled commercial catch during years of foreign fleet activity (1965-1976) and during years of possible misreporting by domestic fleet (1988-1995);
- **S12** (Run21) – used Tweedie CPUE with no added process error.

Each sensitivity was reweighted only once using the procedure of Francis (2011) for age frequencies. The abundance index CVs were adjusted on the first reweight only using the same process error adopted in the base case: c_p = 0, 0, 0, 0, 0, and 0.1859 (except S07, S08, S12) for the WCVI Synoptic, QCS Synoptic, WCHG Synoptic, GIG Historical, WCVI Triennial, and commercial trawl CPUE, respectively.

The differences among the sensitivity runs (including the central run) are summarised in tables of median parameter estimates (Table F.17) and median MSY-based quantities (Table F.18). Sensitivity plots appear in:

- Figure F.38 – trajectories of median B_t/B_0;
- Figure F.39 – trajectories of median recruitment R_t (one-year old fish);
- Figure F.40 – trajectories of median exploitation rate u_t;
- Figure F.41 – quantile plots of selected parameters for the sensitivity runs;
- Figure F.42 – quantile plots of selected derived quantities for the sensitivity runs;
- Figure F.43 – trace plots for chains of R_0 MCMC samples;
- Figure F.44 – diagnostic split-chain plots for R_0 MCMC samples;
- Figure F.45 – diagnostic autocorrelation plots for R_0 MCMC sample;
- Figure F.46 – stock status plots of B_{2019}/B_MSY.

The trajectories of B_t medians relative to B_0 (Figure F.38) indicate that estimating M (S04) and fixing M=0.10 (S03) resulted in the most optimistic scenarios, while the most pessimistic runs were generated when pre-1996 catches (foreign and pre-observer domestic) were doubled (S11) and when the commercial CPUE series was dropped (S07). All other sensitivities tended to reflect the central run closely, especially in the last 20 years of the reconstructed population trajectory. The overall conclusion is that the model outcome is largely driven by the data because the only substantive changes in advice resulted when data series were omitted or changed. This set of selectivities also indicates that there is reasonable consistency among the different data sources (CPUE, survey biomass indices and ageing data) because stepwise omission of the data sets did not result in large shifts in model results.

The diagnostic plots suggest that seven of the sensitivities exhibited good MCMC behaviour, three were marginal but probably acceptable, and two had poor diagnostic behaviour:

- Good – no trend in traces, split-chains align, no autocorrelation
  - S01 (σ_R=0.6)
  - S05 (simple age error)
  - S06 (reader-based age error)
  - S07 (no commercial CPUE)
  - S09 (no survey ages)
  - S10 (halve pre-1996 commercial catch)
  - S12 (Tweedie CPUE series)
- Marginal – trace trend temporarily interrupted, split-chains somewhat frayed, some autocorrelation
  - S02 (σ_R=1.2)
  - S03 (M=0.10)
  - S11 (double pre-1996 commercial catch)
- Poor – trace trend fluctuates substantially or shows a persistent increase/decrease, split-chains differ from each other, substantial autocorrelation
  - S04 (estimate M)
  - S08 (no process error on CPUE)

The run that estimated M using a prior with 50% CV (S04) appeared unstable and would likely never converge. Consequently, the reported results should be viewed with caution. The high-M run (S03) had one major short excursion, possibly indicating that the WWR data do not support higher values of natural mortality. Attempts at fitting the model data to values of $M > 0.10$ resulted in poor MCMC diagnostics and were excluded from consideration in the composite base case or a sensitivity run (these runs are not reported here). Increasing σ_R caused a deterioration in the MCMC diagnostics but did not appreciably affect the model results. Unsurprisingly, forcing the model to closely fit the CPUE indices also resulted in poor MCMC diagnostics but again did not appreciably affect the model results. Although doubling the pre-1996 catch caused a noticeable drop in the estimated stock status, such high levels of catch were unlikely to have occurred. This run was made solely to test the sensitivity of the stock assessment to this assumption.

The stock status ($B_{2019}/B_{\mathrm{MSY}}$) quantile plots (Figure F.46) show that most sensitivities lie in the healthy zone, with only the pre-1996 catch run dipping into the cautious zone.

Table F.17. Median values of MCMC samples for the primary estimated parameters, comparing the base case (runs 1-9, 9000 samples total) to sensitivity runs (10-21, 1000 samples each). C =Central, R = Run, S = Sensitivity. Numeric subscripts other than those for R_0 and M indicate the following gear types g: 1 = WCVI Synoptic, 2 = QCS Synoptic, 3 = WCHG Synoptic, 4 = GIG Historical, 5 = WCVI Triennial, and 6 = commercial trawl CPUE. Sensitivity runs: S01 = sigmaR=0.6, S02 = sigmaR=1.2, S03 = M=0.10, S04 = est M, S05 = age err simp, S06 = age err obs, S07 = no CPUE, S08 = no CVpro, S09 = no surv age, S10 = halve catch, S11 = double catch, S12 = Tweedie CPUE

	C(R05)	S01(R10)	S02(R11)	S03(R12)	S04(R13)	S05(R14)	S06(R15)	S07(R16)	S08(R17)	S09(R18)	S10(R19)	S11(R20)	S12(R21)
R_0	4,471	4,652	4,428	7,867	11,719	4,635	5,087	4,396	4,700	4,217	3,510	6,532	4,483
M_1	—	—	—	—	0.109	—	—	—	—	—	—	—	—
M_2	—	—	—	—	0.114	—	—	—	—	—	—	—	—
h	0.791	0.775	0.788	0.744	0.753	0.776	0.772	0.802	0.776	0.798	0.817	0.716	0.787
q_1	0.00167	0.00138	0.00179	0.000986	0.000858	0.00150	0.00119	0.00187	0.00162	0.00209	0.00184	0.00134	0.00165
q_2	0.00563	0.00434	0.00646	0.00319	0.00278	0.00484	0.00362	0.00722	0.00478	0.00555	0.00652	0.00428	0.00582
q_3	0.00556	0.00444	0.00615	0.00316	0.00276	0.00494	0.00363	0.00644	0.00497	0.00451	0.00629	0.00428	0.00572
q_4	0.000801	0.000745	0.000832	0.000584	0.000538	0.000768	0.000644	0.000831	0.000746	0.000882	0.00103	0.000549	0.000797
q_5	0.00850	0.00770	0.00888	0.00569	0.00495	0.00789	0.00640	0.00881	0.00769	0.00940	0.0105	0.00596	0.00848
q_6	0.0000592	0.0000500	0.0000641	0.0000364	0.0000309	0.0000546	0.0000420	—	0.0000496	0.0000649	0.0000647	0.0000484	0.000224
μ_1	12.8	12.8	12.8	12.8	12.9	12.8	12.8	12.6	13.2	—	12.8	12.7	12.8
μ_2	12.5	12.1	12.9	12.2	12.3	12.3	12.0	12.7	12.4	—	12.8	12.3	12.5
μ_3	15.2	15.1	15.2	15.0	15.1	15.1	14.9	14.9	15.3	—	15.3	15.0	15.1
μ_4	12.7	12.4	12.9	13.1	13.2	12.8	12.8	12.9	12.8	—	12.7	12.9	12.8
μ_6	10.8	10.5	10.9	10.4	10.6	10.5	10.1	10.9	8.01	10.9	10.8	10.6	10.9
Δ_6	-0.363	-0.379	-0.363	-0.307	-0.310	-0.358	-0.332	-0.389	-0.0286	-0.346	-0.331	-0.395	-0.371
$\log v_{1L}$	3.37	3.42	3.31	3.41	3.35	3.42	3.41	3.44	3.24	—	3.31	3.41	3.43
$\log v_{2L}$	2.19	2.34	2.08	2.30	2.23	2.28	2.43	2.16	2.25	—	2.15	2.29	2.22
$\log v_{3L}$	2.95	3.00	2.92	3.01	3.01	3.00	3.04	3.12	2.85	—	2.93	2.99	2.99
$\log v_{4L}$	1.98	2.07	1.95	1.91	1.91	1.98	1.95	2.04	1.96	—	2.00	1.95	2.00
$\log v_{6L}$	2.20	2.15	2.20	2.08	2.12	2.06	1.89	2.21	-0.600	2.22	2.16	2.17	2.21

Table F.18. Medians of MCMC-derived quantities from 9000 base-case samples and 1000 sensitivity samples of the MCMC posterior for each run. Definitions are: B_0 – unfished equilibrium spawning biomass (mature females), V_0 – unfished equilibrium vulnerable biomass (males and females), B_{2019} – spawning biomass at the start of 2019, V_{2019} – vulnerable biomass in the middle of 2019, u_{2018} – exploitation rate (ratio of total catch to vulnerable biomass) in the middle of 2018, $u_{\max}$ – maximum exploitation rate (calculated for each sample as the maximum exploitation rate from 1940 - 2018), B_{MSY} – equilibrium spawning biomass at MSY (maximum sustainable yield), u_{MSY} – equilibrium exploitation rate at MSY, V_{MSY} – equilibrium vulnerable biomass at MSY. All biomass values (and MSY) are in tonnes. Sensitivity runs: S01 = sigmaR=0.6, S02 = sigmaR=1.2, S03 = M=0.10, S04 = est M, S05 = age err simp, S06 = age err obs, S07 = no CPUE, S08 = no CVpro, S09 = no surv age, S10 = halve catch, S11 = double catch, S12 = Tweedie CPUE

	C(R05)	S01(R10)	S02(R11)	S03(R12)	S04(R13)	S05(R14)	S06(R15)	S07(R16)	S08(R17)	S09(R18)	S10(R19)	S11(R20)	S12(R21)
B_0	29,951	30,524	29,057	34,720	40,209	30,416	33,383	28,848	30,839	27,673	23,036	42,866	29,416
V_0	53,380	54,734	51,334	62,052	68,574	54,304	60,260	50,928	56,412	48,985	40,841	76,684	52,286
B_{2019}	11,017	12,090	10,342	17,476	22,185	11,607	14,430	10,595	11,339	9,674	9,409	13,362	11,522
V_{2019}	19,526	21,782	17,852	31,060	37,399	20,535	26,207	18,604	22,727	16,898	16,616	23,931	20,398
B_{2019}/B_0	0.369	0.397	0.355	0.505	0.547	0.381	0.432	0.372	0.369	0.347	0.413	0.313	0.390
V_{2019}/V_0	0.366	0.398	0.346	0.504	0.551	0.378	0.438	0.369	0.401	0.344	0.410	0.310	0.389
u_{2018}	0.0975	0.0877	0.106	0.0614	0.0512	0.0929	0.0735	0.103	0.0898	0.112	0.112	0.0811	0.0936
$u_{\max}$	0.161	0.146	0.174	0.115	0.101	0.153	0.124	0.195	0.136	0.184	0.156	0.215	0.171
MSY	1,909	1,943	1,892	2,669	3,128	1,944	2,092	1,926	1,951	1,832	1,562	2,517	1,924
B_{MSY}	7,373	7,650	7,074	9,242	10,128	7,618	8,348	6,880	7,597	6,659	5,396	11,679	7,207
$0.4B_{\text{MSY}}$	2,949	3,060	2,830	3,697	4,051	3,047	3,339	2,752	3,039	2,664	2,158	4,672	2,883
$0.8B_{\text{MSY}}$	5,898	6,120	5,659	7,394	8,102	6,095	6,679	5,504	6,077	5,327	4,317	9,343	5,766
B_{2019}/B_{MSY}	1.51	1.60	1.42	1.99	2.10	1.54	1.72	1.54	1.51	1.47	1.81	1.16	1.61
B_{MSY}/B_0	0.246	0.252	0.246	0.261	0.255	0.251	0.252	0.240	0.247	0.242	0.235	0.274	0.247
V_{MSY}	13,145	13,972	12,442	16,632	17,554	13,641	15,479	11,934	14,940	11,685	9,500	21,139	12,681
V_{MSY}/V_0	0.247	0.255	0.243	0.265	0.259	0.253	0.260	0.235	0.266	0.241	0.235	0.276	0.244
u_{MSY}	0.148	0.141	0.154	0.162	0.181	0.142	0.136	0.163	0.131	0.157	0.163	0.120	0.152
u_{2018}/u_{MSY}	0.658	0.622	0.708	0.362	0.293	0.640	0.547	0.642	0.688	0.706	0.661	0.671	0.621

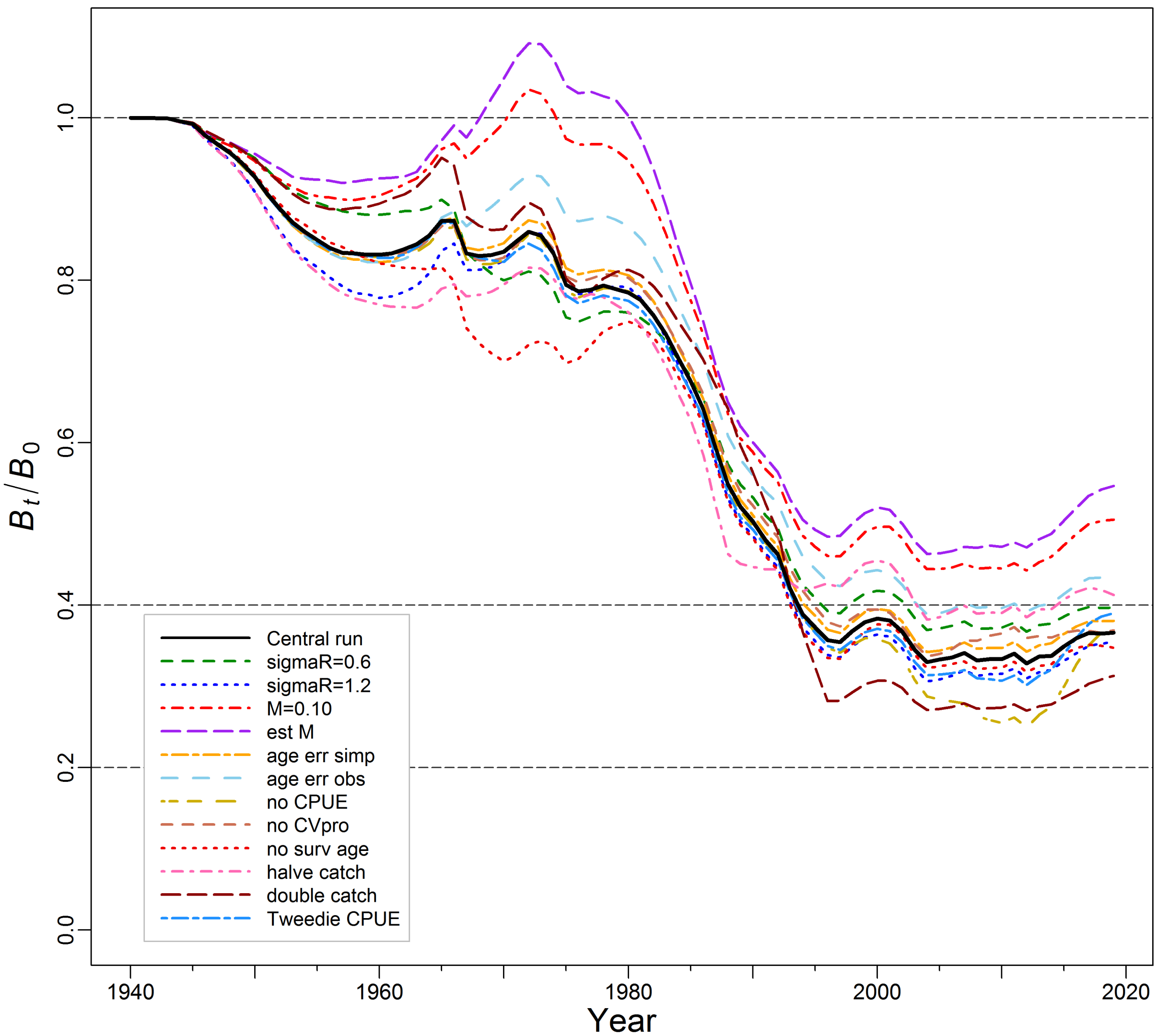


Figure F.38. Sensitivity: model median trajectories of spawning biomass as a proportion of unfished equilibrium biomass (B_t/B_0) for the central run of the composite base case and 12 sensitivity runs (see legend lower left). Horizontal dashed lines show alternative reference points used by other jurisdictions: 0.2B_0 (~DFO's USR), 0.4B_0 (often a target level above B_{MSY}), and B_0 (equilibrium spawning biomass).

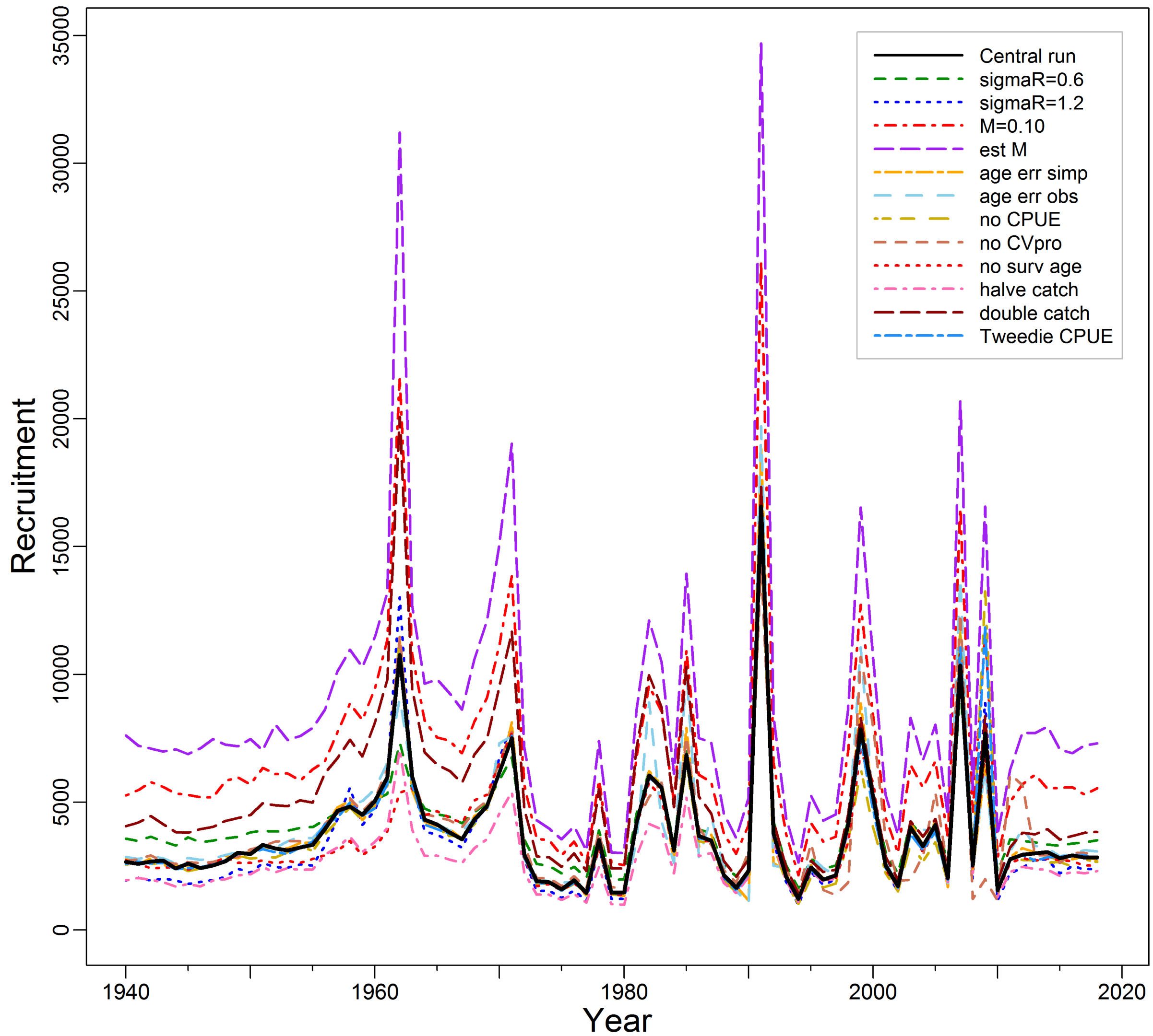


Figure F.39. Sensitivity: model median trajectories of recruitment of one-year old fish (R_t, 1000s) for the central run of the composite base case and 12 sensitivity runs (see legend upper right).

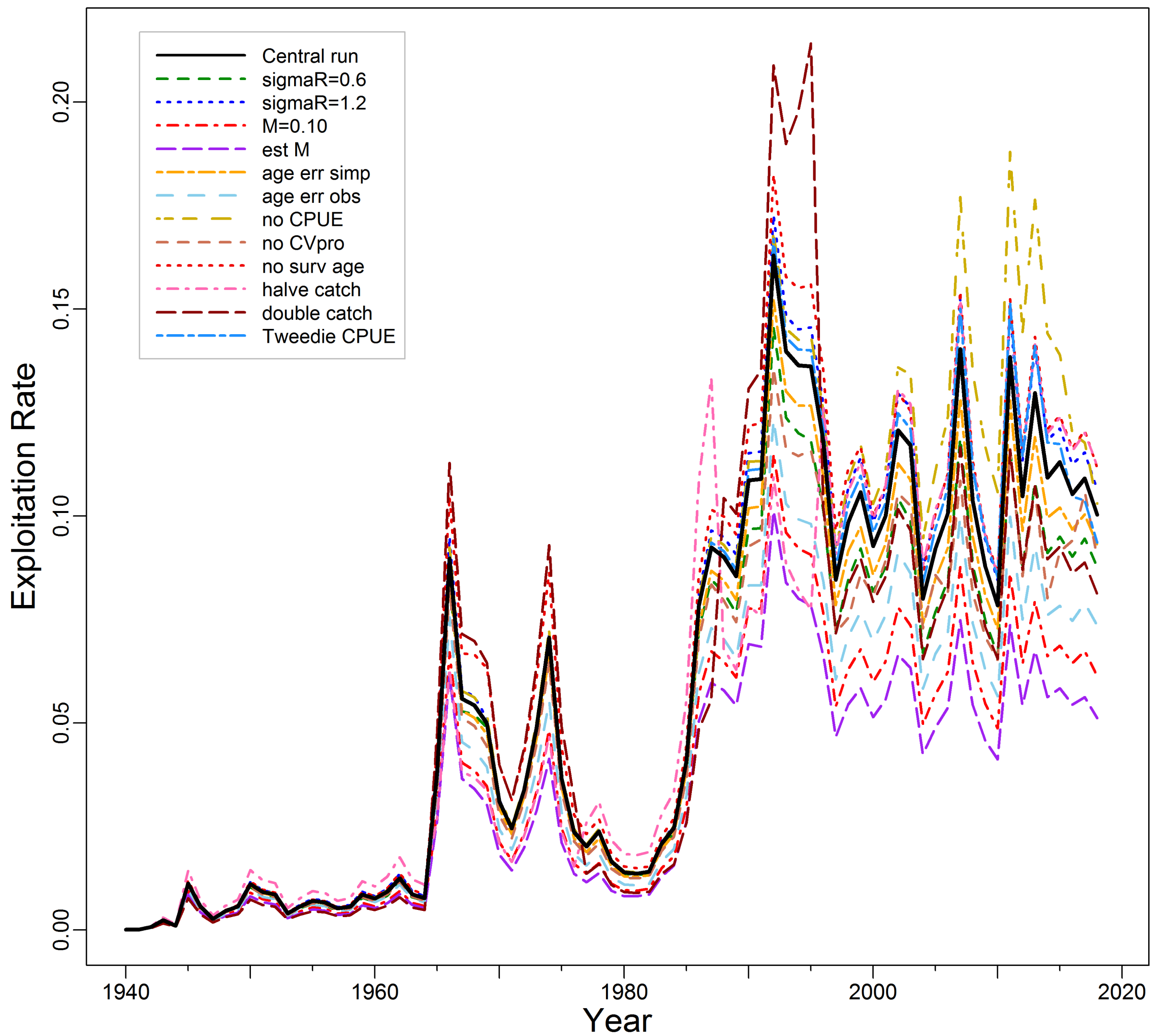


Figure F.40. Sensitivity: model median trajectories of exploitation rate of vulnerable biomass (u_t) for the central run of the composite base case and 12 sensitivity runs (see legend upper left).

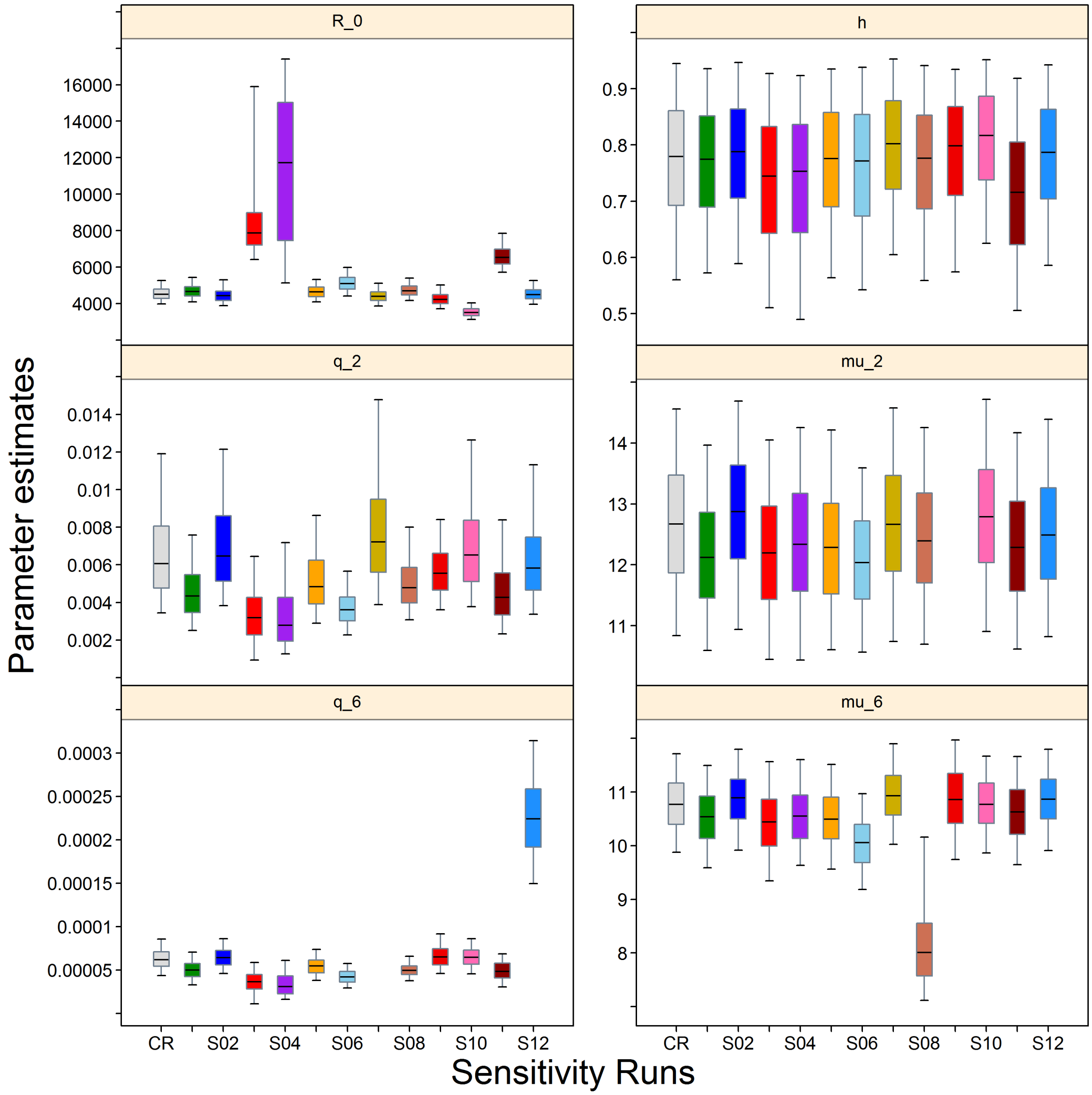


Figure F.41. Sensitivity: quantile plots of selected parameter estimates (R_0, h, q_g, μ_g) comparing the central run with 12 sensitivity runs. Subscripts: g=2 corresponds to the QCS synoptic survey, g=6 correspnds to the commercial trawl fishery. See text on sensitivity numbers. The boxplots delimit the 0.05, 0.25, 0.5, 0.75, and 0.95 quantiles; outliers are excluded.

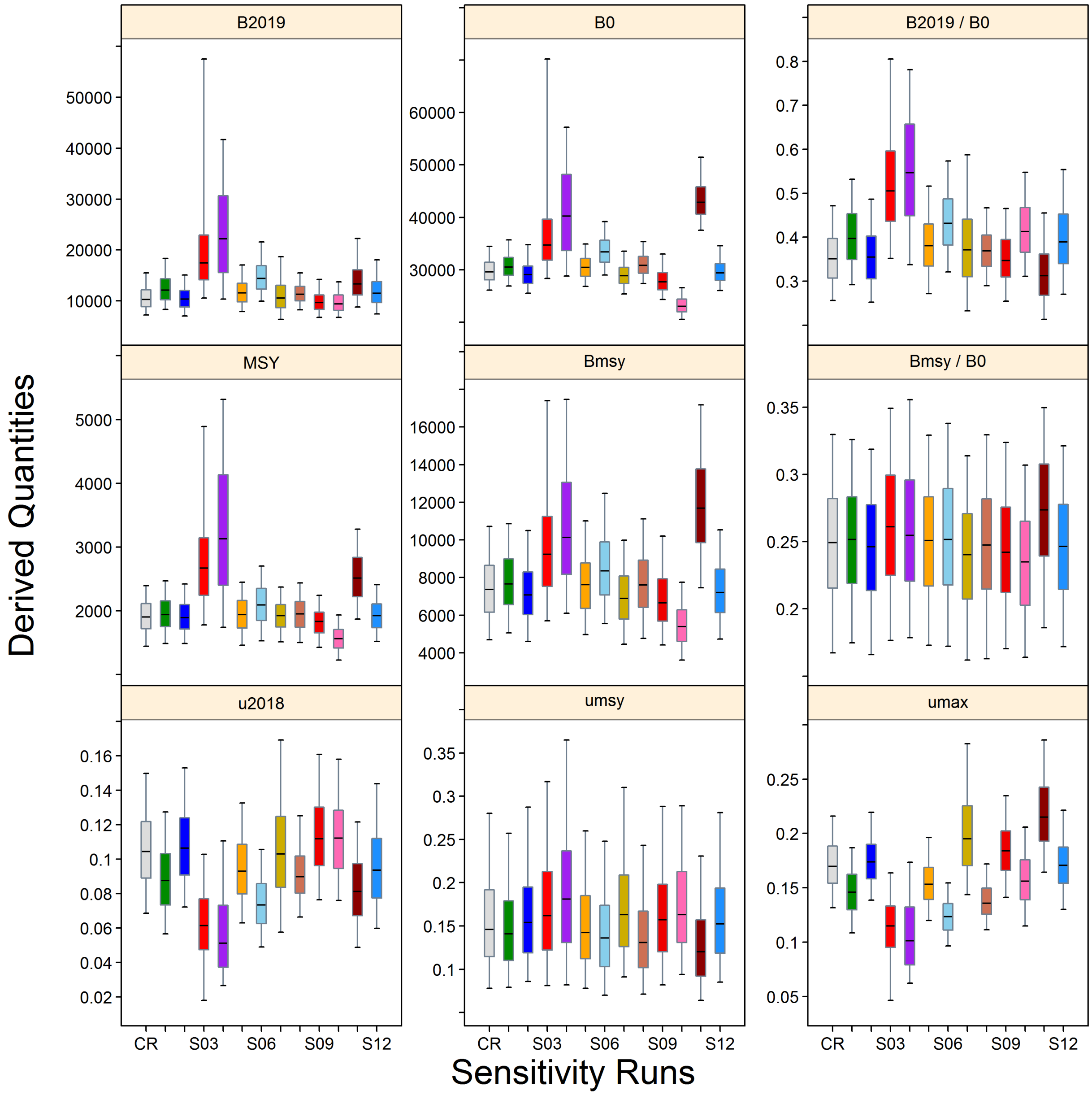


Figure F.42. Sensitivity: quantile plots of selected derived quantities (B_{2019}, B_0, B_{2019}/B_0, MSY, B_{MSY}, B_{MSY}/B_0, u_{2018}, u_{MSY}, $u_{\max}$) comparing the central run with 12 sensitivity runs. See text on sensitivity numbers. The boxplots delimit the 0.05, 0.25, 0.5, 0.75, and 0.95 quantiles; outliers are excluded.

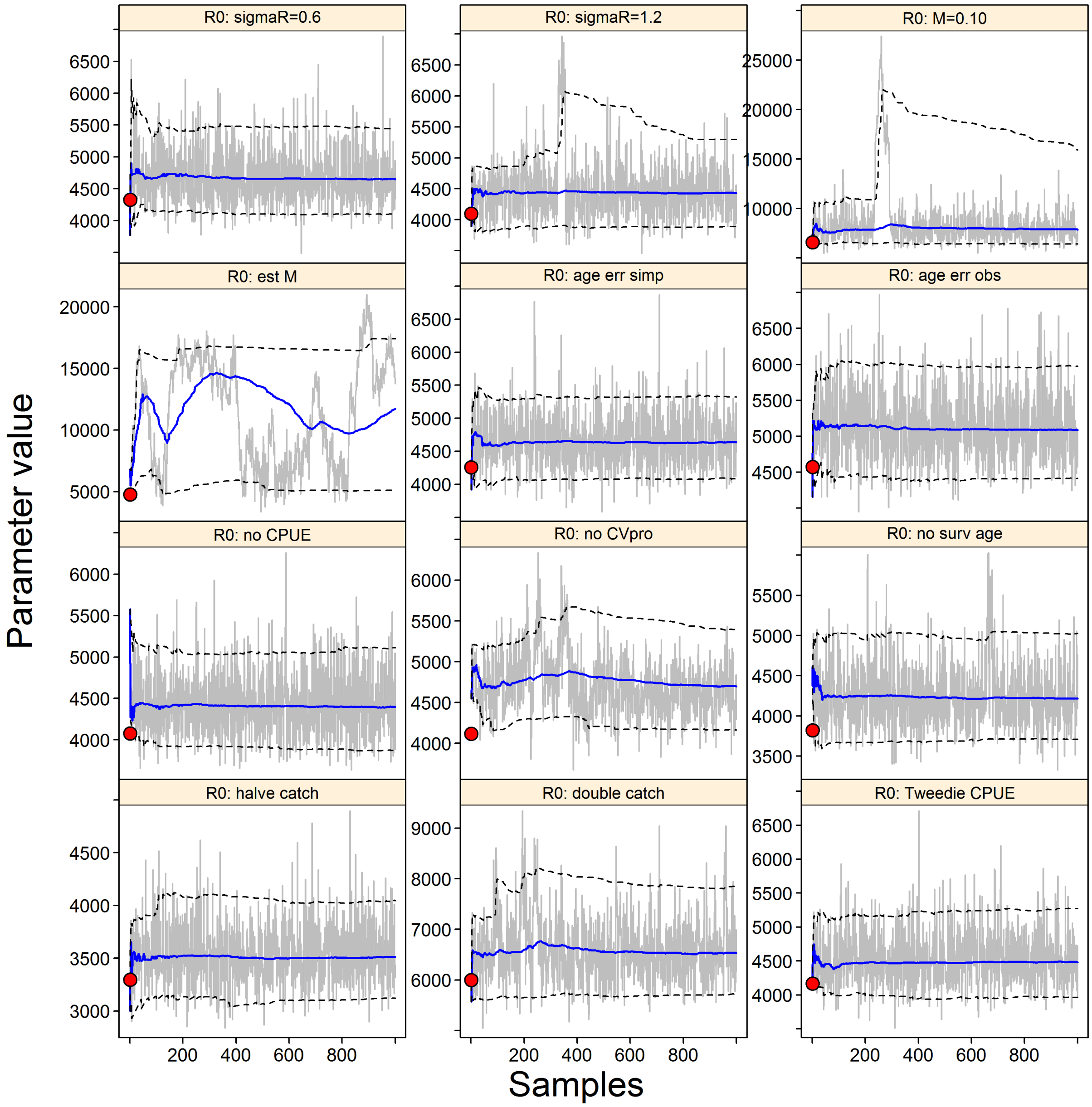


Figure F.43. Sensitivity R_0: MCMC traces for the estimated parameters. Grey lines show the 1000 samples for each parameter, solid blue lines show the cumulative median (up to that sample), and dashed lines show the cumulative 0.05 and 0.95 quantiles. Red circles are the MPD estimates.

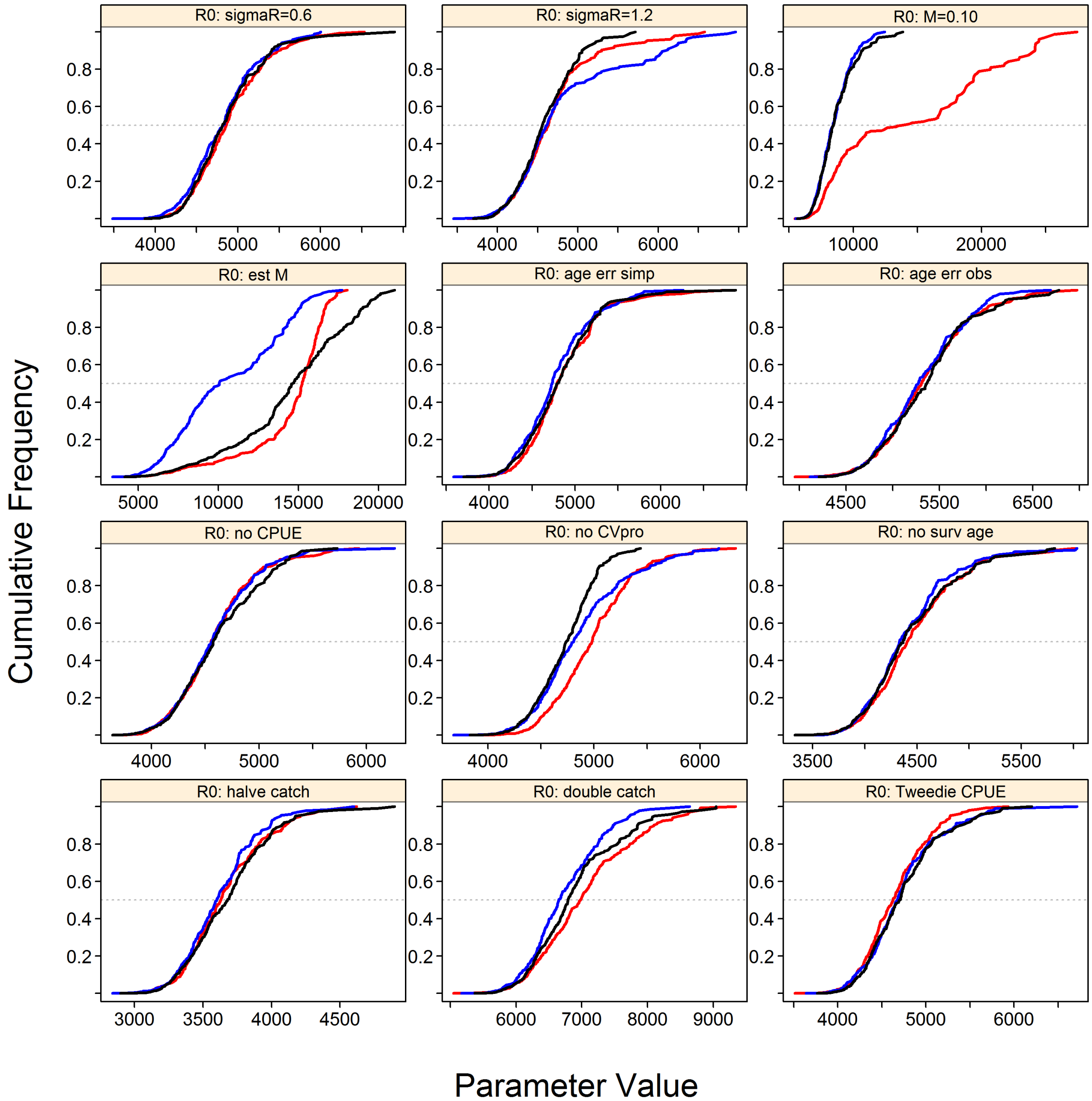


Figure F.44. Sensitivity R_0: diagnostic plot obtained by dividing the MCMC chain of 1000 MCMC samples into three segments, and overplotting the cumulative distributions of the first segment (red), second segment (blue) and final segment (black).

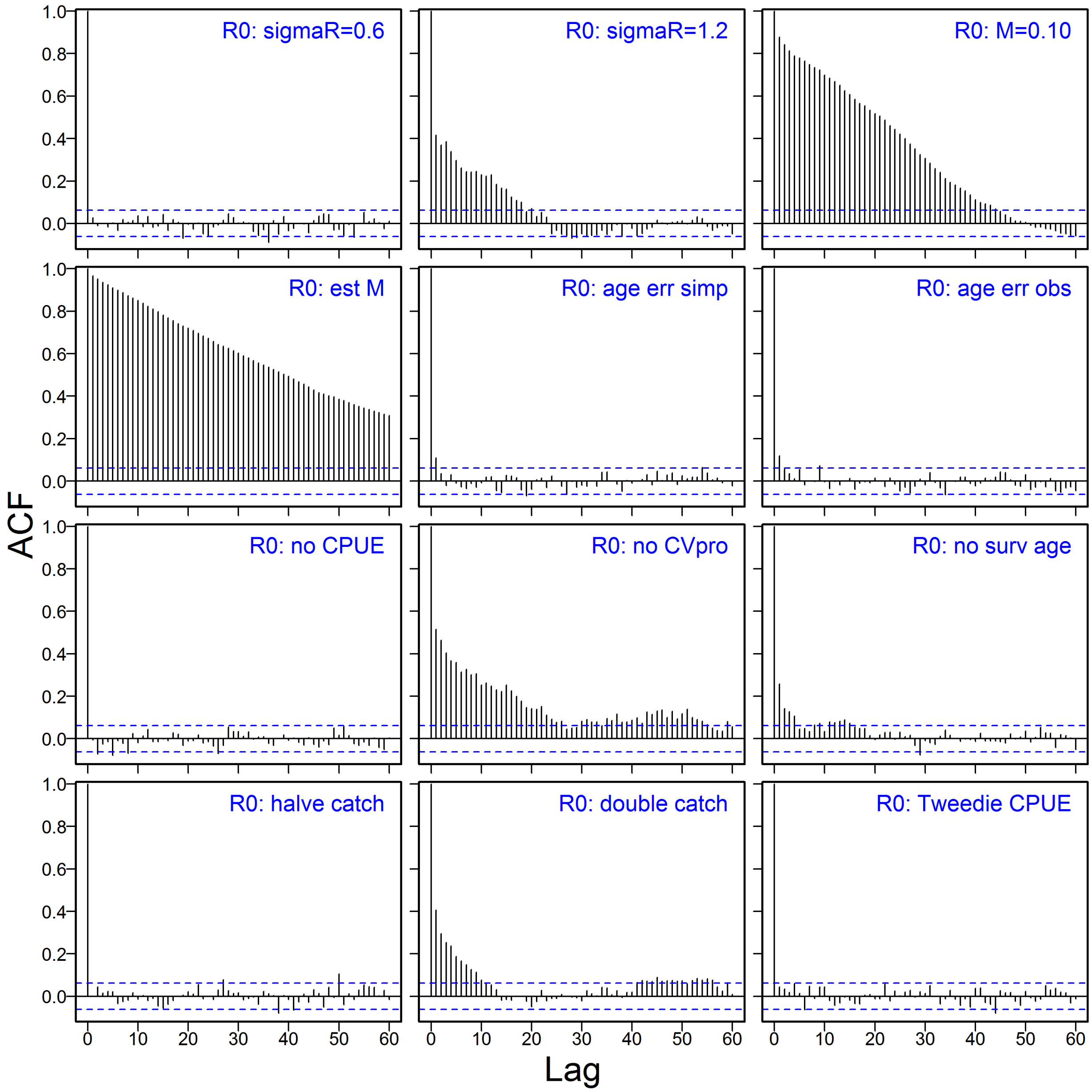


Figure F.45. Sensitivity R_0: autocorrelation plots for the estimated parameters from the MCMC output. Horizontal dashed blue lines delimit the 95% confidence interval for each parameter's set of lagged correlations.

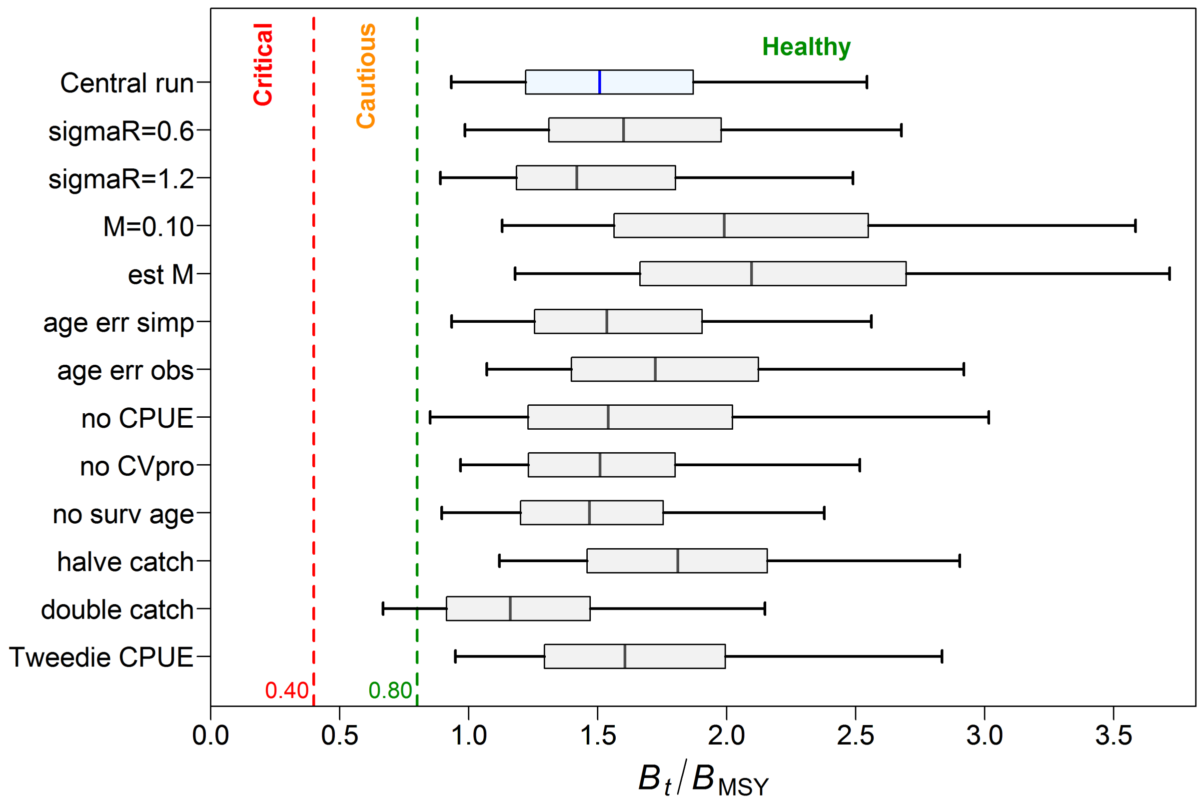


Figure F.46. Sensitivity: status at beginning of 2019 of the Widow Rockfish (BC) stock relative to the DFO PA provisional reference points of 0.4B_{MSY} and 0.8B_{MSY} for the central run of the composite base case (Run05) and 12 sensitivity runs: S1 = (Run10) remove the commercial CPUE index; S2 = (Run11) reduce the catch during periods of foreign fleet activity and during domestic fleet activity before observer coverage; S3 = (Run12) use only age frequencies from unsorted samples; S4 = (Run13) use a larger standard deviation for recruitment process error (σ_R=1.1). Boxplots show the 0.05, 0.25, 0.5, 0.75, and 0.95 quantiles from the MCMC posterior.

F.3. REFERENCES – MODEL RESULTS

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APPENDIX G. ECOSYSTEM INFORMATION

Preface: This appendix describes ecosystem information relevant to Widow Rockfish (WWR) along the British Columbia (BC) coast. This information is not used for the purposes of stock assessment but provides information that might be useful to other agencies.

G.1. SPATIAL DISTRIBUTION

Data for spatial analyses of WWR were extracted from the SQL DFO databases 'PacHarvest' and 'GFFOS' on Jan 14, 2019. Some of the analyses below are designed to facilitate the reporting of findings to COSEWIC (Committee on the Status of Endangered Wildlife in Canada), regardless of whether the assessed species is endangered or not.

Widow Rockfish is ubiquitous along the BC coast, and is known to form large midwater shoals along the shelf break (e.g. WSW of Triangle Island, Stanley et al. 1999, 2000). Broadly, its 'extent of occurrence' (EO) covers 118,185 km^2 (on water and excluding seamounts data) using historical fishing events (1982-2018) to determine a convex hull envelope (Figure G.1). Of the bottom trawl tows capturing WWR, 98% of the tows occur between 91 m and 384 m (Figure G.2). For midwater tows, this range widens (Figure G.3). Using the bottom-tow depth range as a proxy for suitable WWR benthic habitat, a refined estimate of EO is 58,940 km^2 in BC's Exclusive Economic Zone (Figure G.4). To estimate the 'area of occupancy' (AO), the catch of WWR was located within a grid comprising 4 km^2 cells (2km × 2km), and the cells occupied by WWR were summed to estimate an AO of 17,920 km^2 along the BC coast spanning 1996 to 2018 (Figure G.5). Figure G.6 and Figure G.7 provide alternative visualisations of relative abundance by fishing locality.

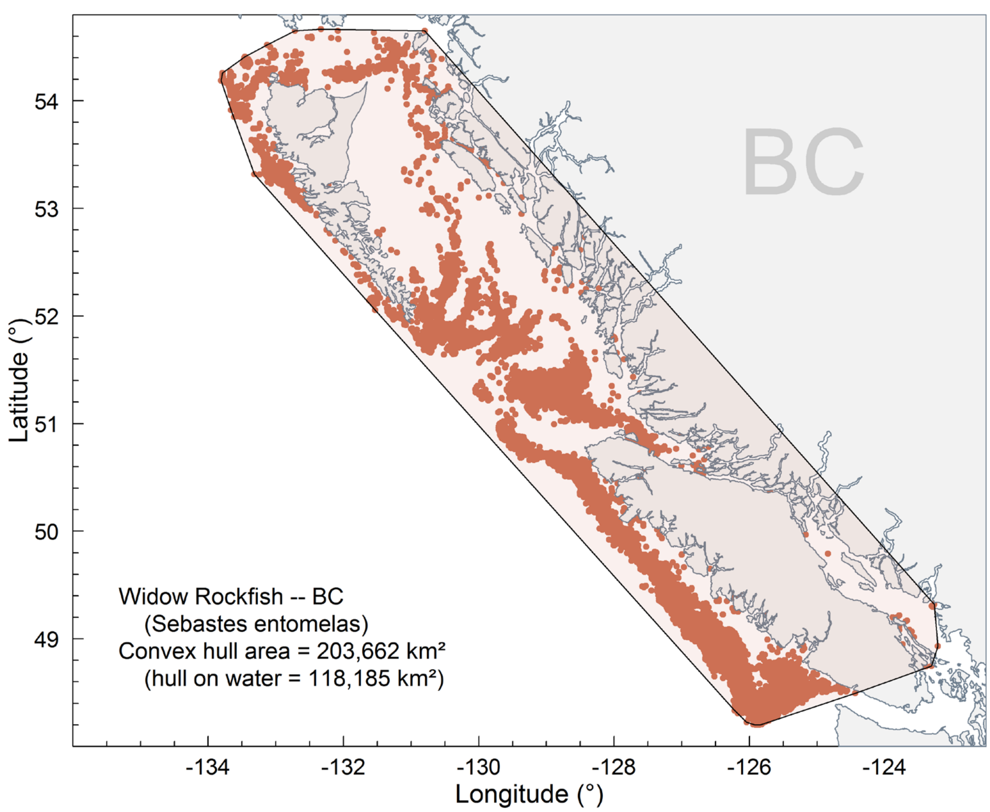

Figure G.1. Extent of Occurrence as a convex hull surrounding fishing events that caught WWR along the BC coast; the shading within the hull on water covers 118,185 km^2.

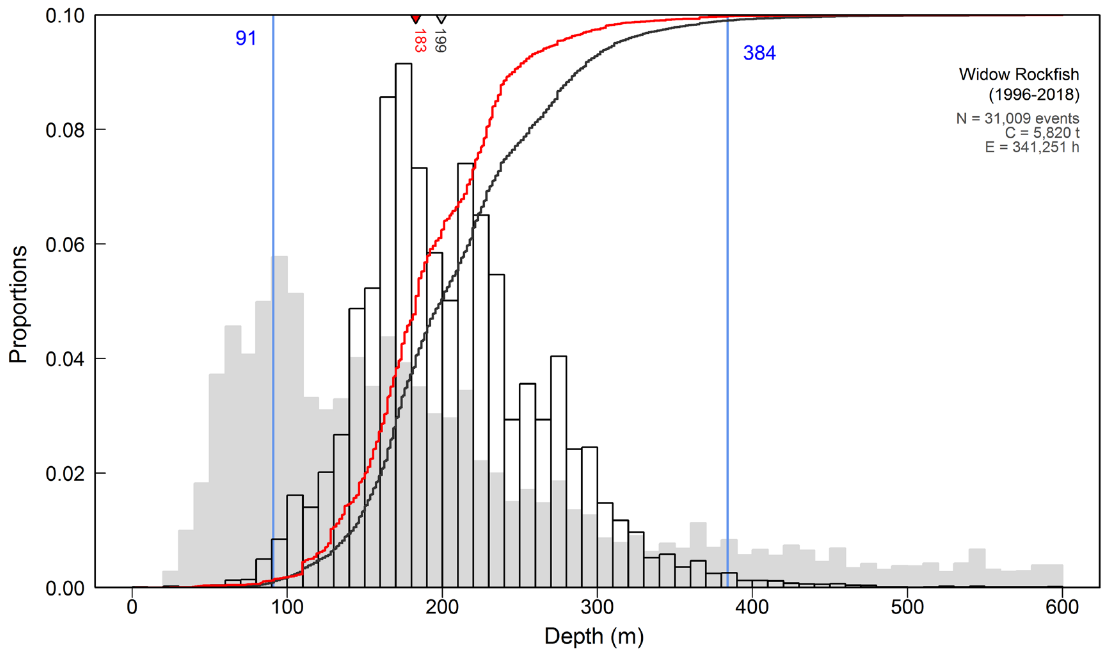

Figure G.2. BC Offshore – Depth frequency of bottom trawl tows (transparent histogram) that captured WWR from commercial logs (1996-2018 in PacHarvest and GFFOS) in areas outside the Strait of Georgia. The vertical solid lines denote the 1% and 99% percentiles. The black curve shows the cumulative frequency of tows that encounter WWR while the red curve shows the cumulative catch of WWR at depth (scaled from 0 to 1). The median depths of WWR encounters (inverted grey triangle) and of cumulative catch (inverted red triangle) are indicated along the upper axis. The shaded histogram in the background reports the relative trawl effort on all species offshore down to 600 m. Label summary: N= total number of WWR tows; C= total catch (t) of WWR, E= total effort (h) of all tows.

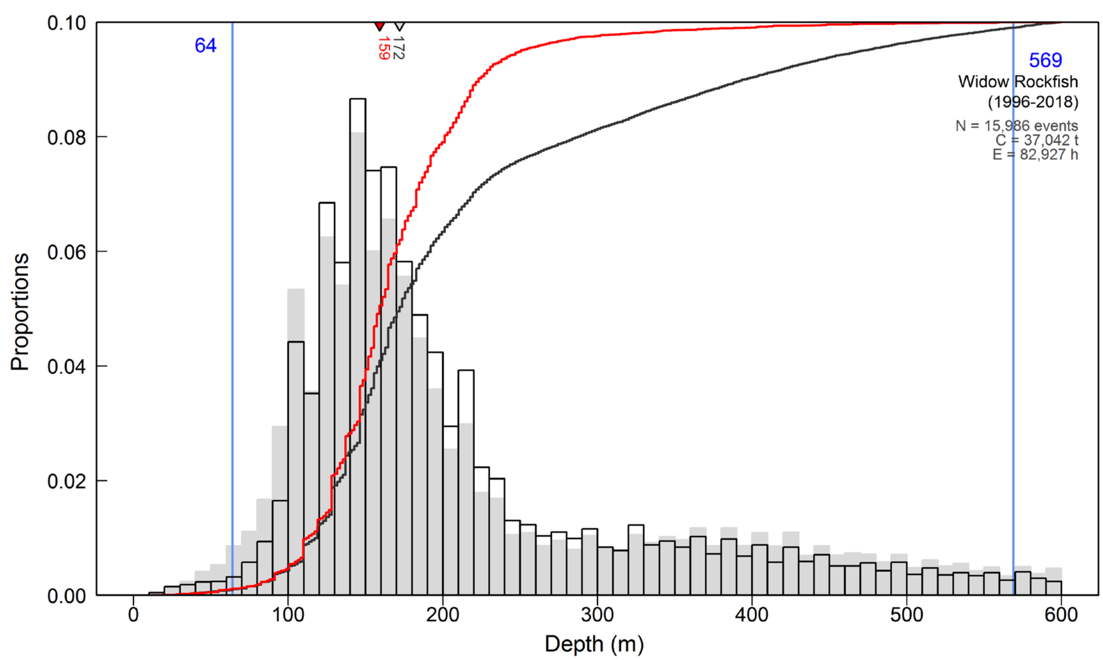

Figure G.3. BC Offshore – Depth frequency of midwater trawl tows (transparent histogram) limited to 600 m depth (proportion of WWR catch almost 100%). See caption in Figure G.2 for details.

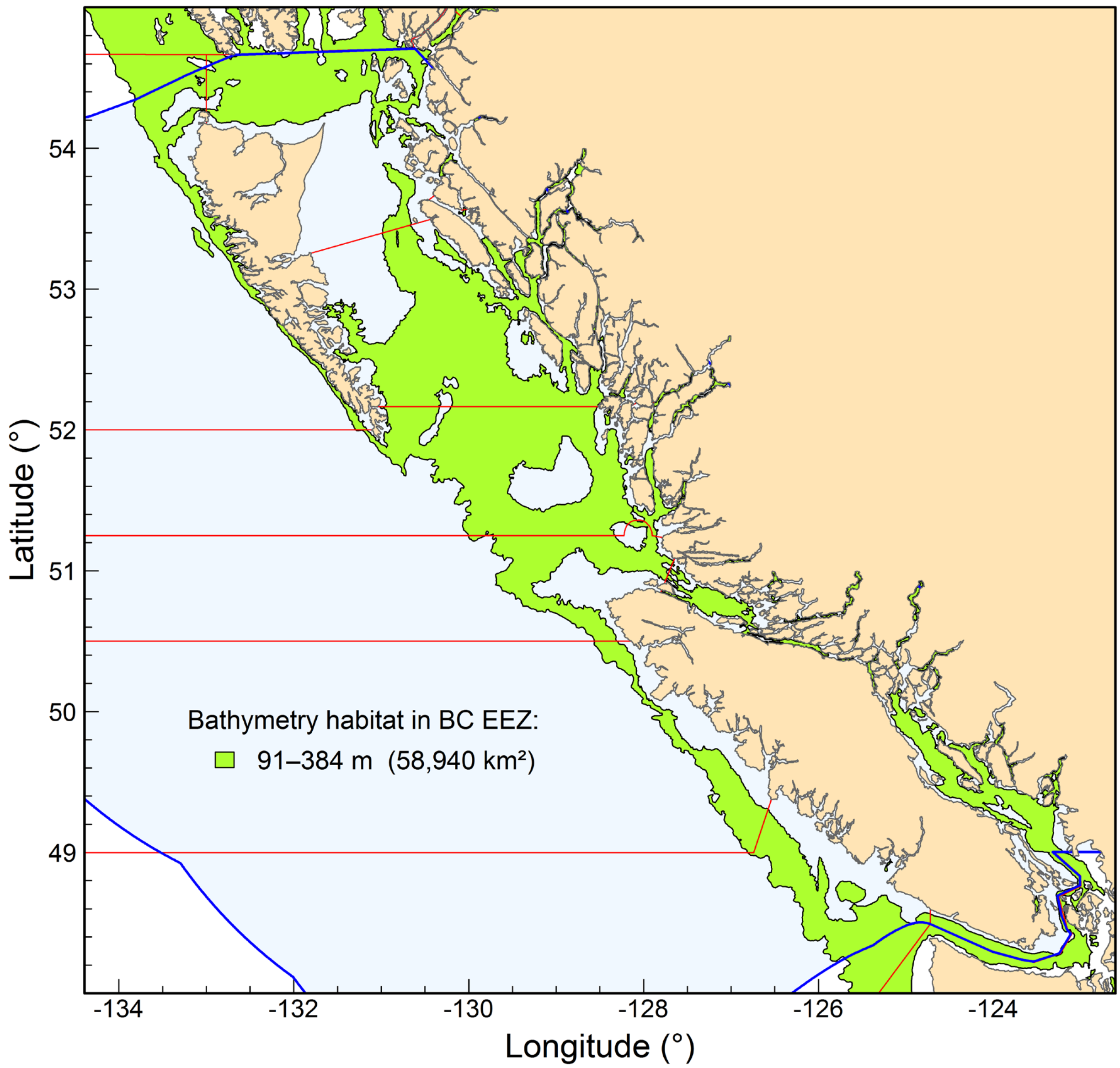

Figure G.4. Highlighted bathymetry (green) between 91 and 384 m serves as a proxy for benthic habitat for WWR along the BC coast. The green highlighted region within Canada's exclusive economic zone (EEZ, blue highlighted area) covers 58,940 km^2. The boundaries in red delimit PMFC areas.

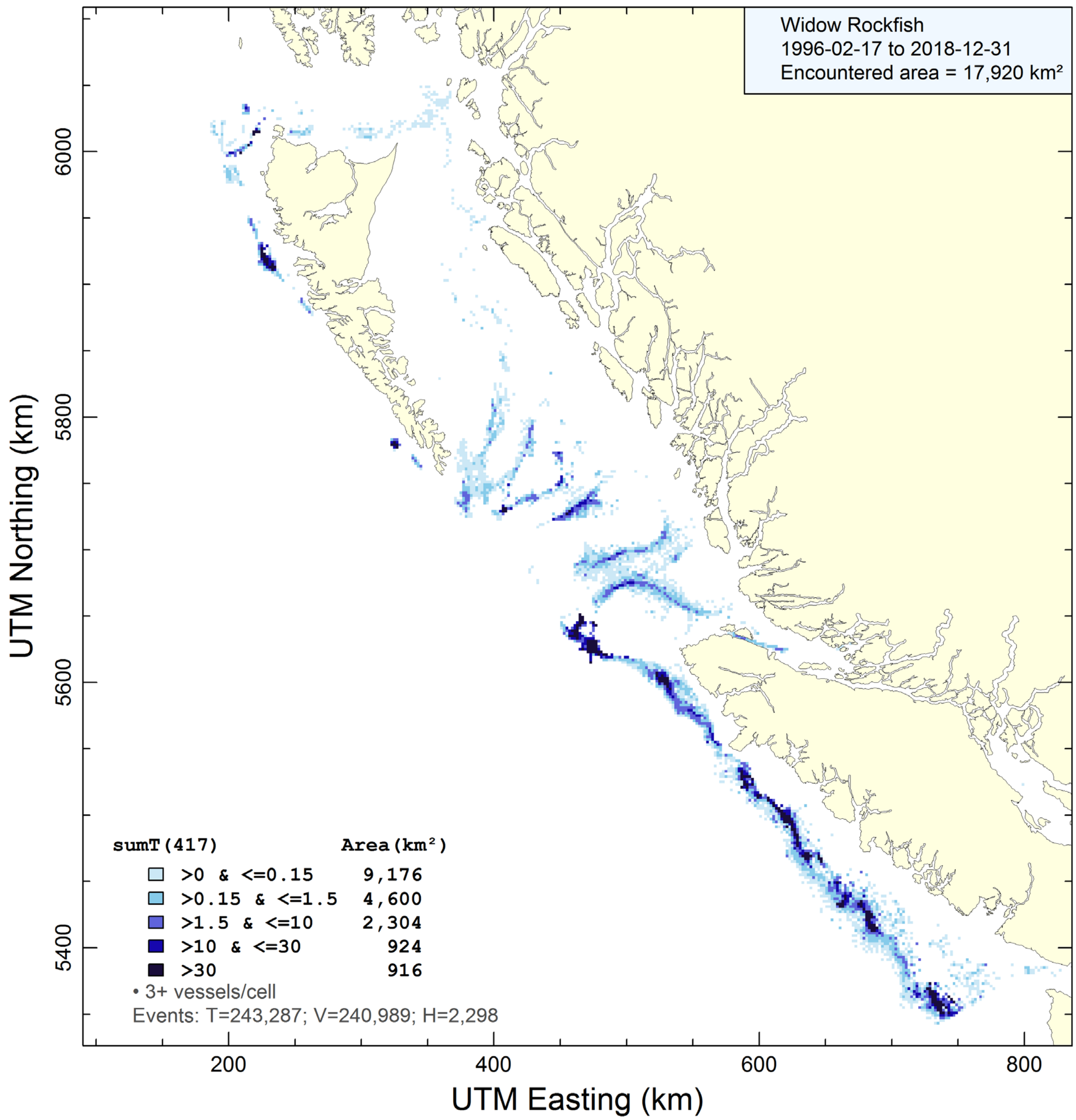

Figure G.5. Area of Occupancy (AO) determined by trawl capture of WWR in grid cells 2km × 2km. Cells with fewer than three fishing vessels are excluded. The estimated AO is 17,920 km² along the BC coast.

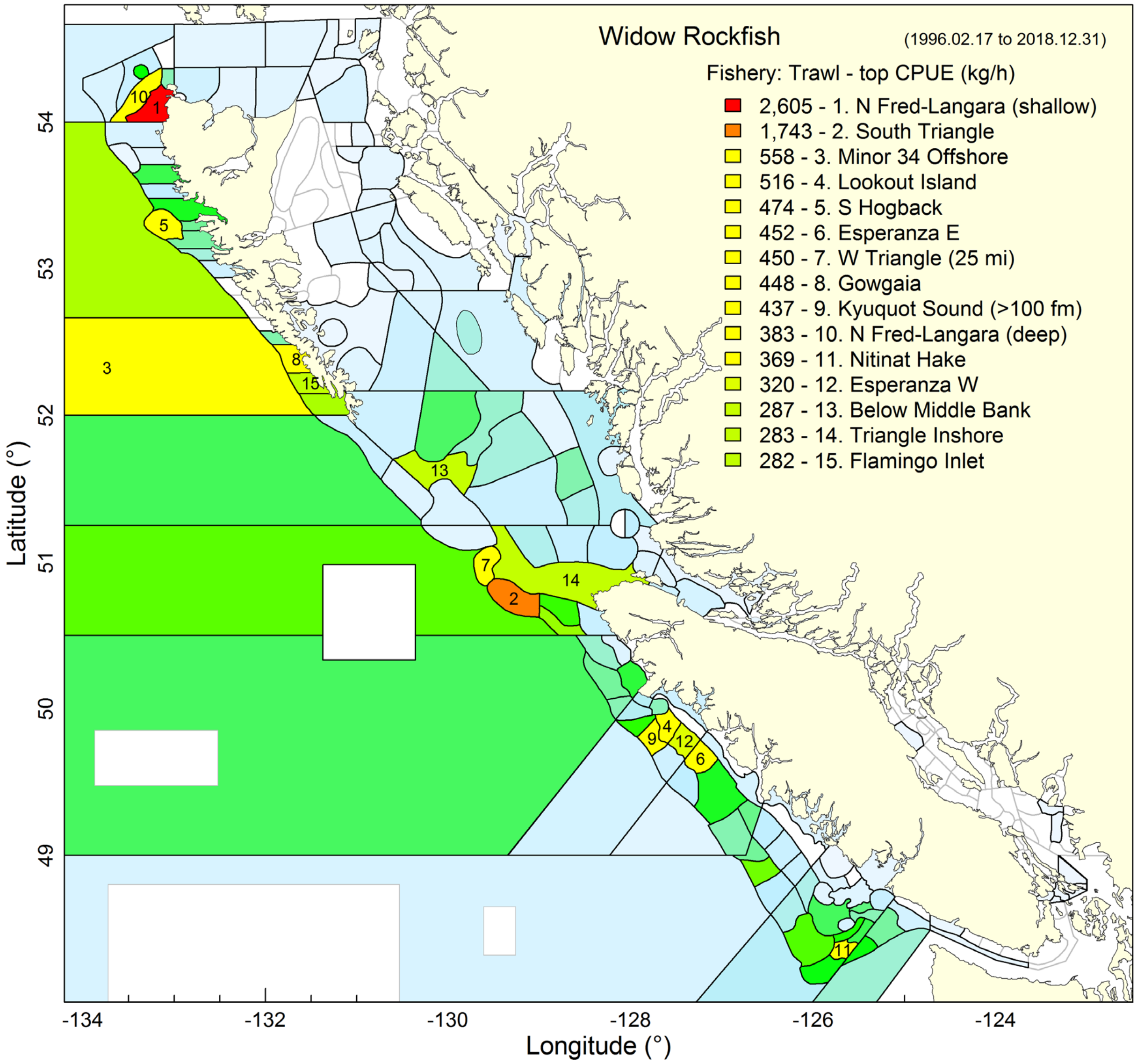

Figure G.6. Top 15 fishing localities by mean CPUE (kg/h) where WWR was caught by the trawl fleet. All shaded localities indicate areas where WWR was encountered from 1996 to 2018, ranging from relatively low numbers in cool blue, through the spectrum, to relatively high catch rates in red.

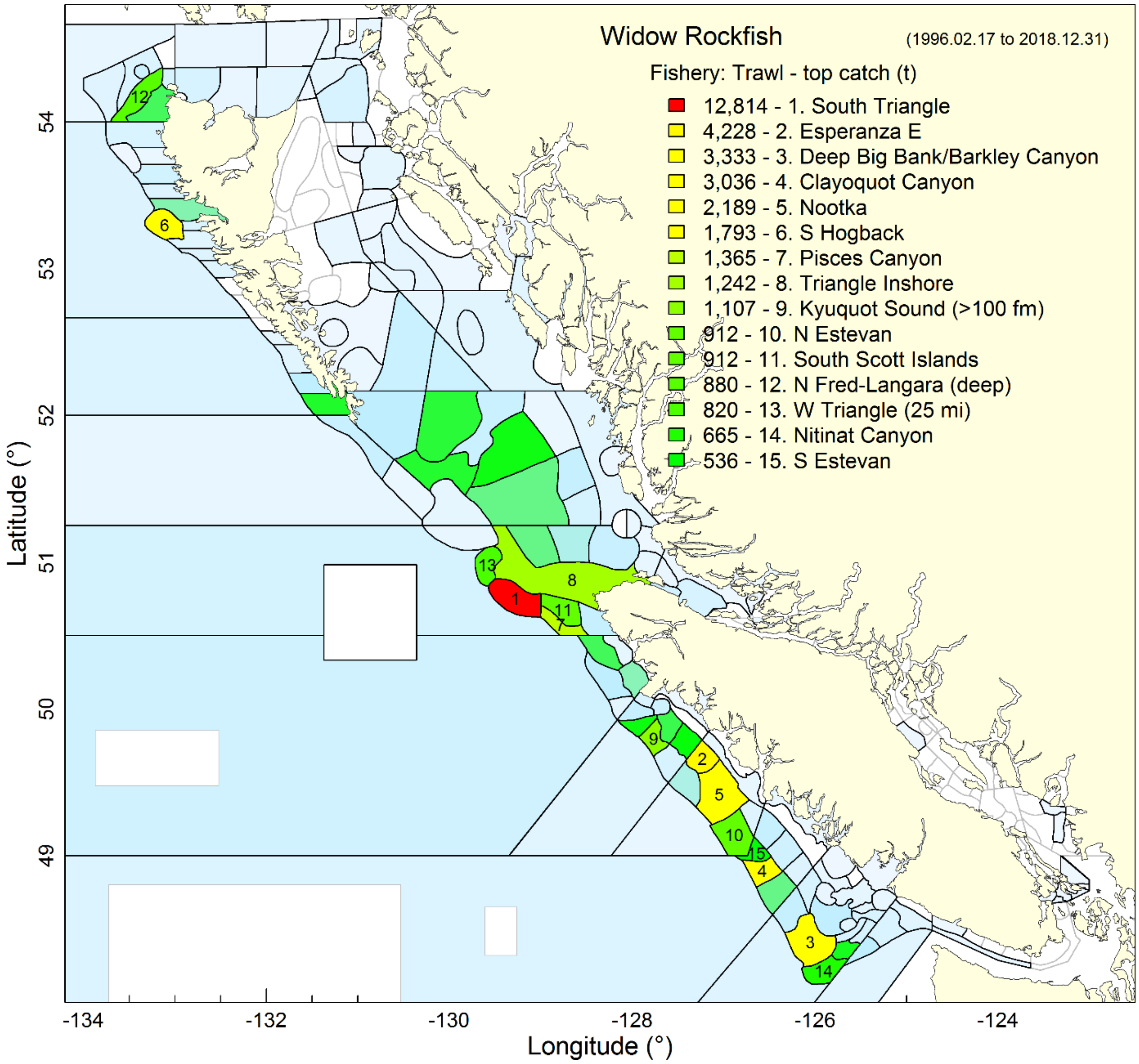

Figure G.7. Top 15 fishing localities by total catch (tonnes) where WWR was caught by the trawl fleet. All shaded localities indicate areas where WWR was encountered from 1996 to 2018, ranging from relatively low numbers in cool blue, through the spectrum, to relatively high catches in red.

G.2. CONCURRENT SPECIES

Species caught concurrently in coastwide bottom trawl tows that capture at least one WWR specimen are dominated by species other than WWR, which only accounts for 1% of total catch by weight (Table G.1, Figure G.8). The six predominant species comprise Arrowtooth Flounder (22%), Pacific Ocean Perch (19%), Yellowtail Rockfish (9%), Dover Sole (5%), Yellowmouth Rockfish (5%), and Silvergray Rockfish (5%). In midwater trawl tows capturing at least one WWR (Table G.2, Figure G.9), Pacific Hake predominates (83% by catch weight), followed by Yellowtail Rockfish (6%) and Widow Rockfish (5%). The latter two species are often caught together in specific regions along the BC coast – see the first two groups from a cluster analysis on commercial catch data in Figure G.10. For other species caught in mid-water tows, the spatial concurrence with WWR in three dimensions is not so strong (e.g. Walleye Pollock, Figure G.10).

Table G.1. BC Offshore – Top 25 species by catch weight (sum of landed + discarded from 1996 to 2018) that co-occur in WWR **bottom** trawl tows along the BC coast (Figure G.8). Rockfish species of interest to COSEWIC appear in red font, target species (occurs in every tow) appears in blue font.

Code	Species	Latin Name	Catch (t)	Catch (%)
602	Arrowtooth Flounder	*Atheresthes stomias*	123,269	21.65
396	Pacific Ocean Perch	*Sebastes alutus*	108,928	19.14
418	Yellowtail Rockfish	*Sebastes flavidus*	50,137	8.81
626	Dover Sole	*Microstomus pacificus*	30,821	5.41
440	Yellowmouth Rockfish	*Sebastes reedi*	29,877	5.25
405	Silvergray Rockfish	*Sebastes brevispinis*	29,183	5.13
467	Lingcod	*Ophiodon elongatus*	23,240	4.08
439	Redstripe Rockfish	*Sebastes proriger*	15,803	2.78
437	Canary Rockfish	*Sebastes pinniger*	15,445	2.71
044	Spiny Dogfish	*Squalus acanthias*	14,849	2.61
222	Pacific Cod	*Gadus macrocephalus*	13,895	2.44
610	Rex Sole	*Errex zachirus*	10,123	1.78
607	Petrale Sole	*Eopsetta jordani*	9,343	1.64
394	Rougheye Rockfish	*Sebastes aleutianus*	8,314	1.46
066	Spotted Ratfish	*Hydrolagus colliei*	8,125	1.43
628	English Sole	*Parophrys vetulus*	7,856	1.38
450	Sharpchin Rockfish	*Sebastes zacentrus*	7,380	1.30
056	Big Skate	*Raja binoculata*	6,937	1.22
614	Pacific Halibut	*Hippoglossus stenolepis*	6,578	1.16
455	Sablefish	*Anoplopoma fimbria*	5,657	0.99
417	Widow Rockfish	*Sebastes entomelas*	5,534	0.97
225	Pacific Hake	*Merluccius productus*	5,413	0.95
401	Redbanded Rockfish	*Sebastes babcocki*	4,729	0.83
228	Walleye Pollock	*Theragra chalcogramma*	4,200	0.74
059	Longnose Skate	*Raja rhina*	4,022	0.71

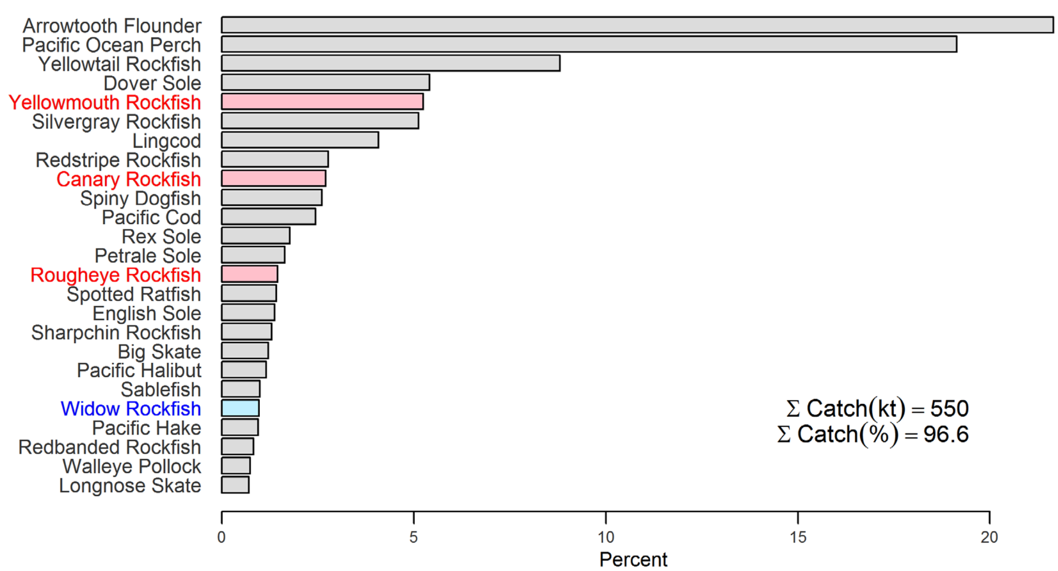

Figure G.8. BC Offshore – Distribution of WWR catch weights summed over the period February 1996 to January 2019 for important finfish species in ***bottom*** *trawl tows that caught at least one WWR coastwide. Tows were selected over a depth range between 91 and 384 m (the 1% and 99% quantile range, see Figure G.2). Relative concurrence is expressed as a percentage by species relative to the total catch weight summed over all finfish species in the specified period. Widow Rockfish is indicated in blue on the y-axis; other species of interest to COSEWIC are indicated in red.*

*Table G.2. BC Offshore – Top 25 species by catch weight (sum of landed + discarded from 1996 to 2017) that co-occur in WWR **midwater** trawl tows along the BC coast (Figure G.9). Rockfish species of interest to COSEWIC appear in red font, target species (occurs in every tow) appears in blue font.*

Code	Species	Latin Name	Catch (t)	Catch (%)
225	Pacific Hake	*Merluccius productus*	609,665	82.66
418	Yellowtail Rockfish	*Sebastes flavidus*	44,724	6.06
417	Widow Rockfish	*Sebastes entomelas*	36,810	4.99
228	Walleye Pollock	*Theragra chalcogramma*	17,721	2.40
439	Redstripe Rockfish	*Sebastes proriger*	5,905	0.80
440	Yellowmouth Rockfish	*Sebastes reedi*	5,338	0.72
396	Pacific Ocean Perch	*Sebastes alutus*	5,104	0.69
602	Arrowtooth Flounder	*Atheresthes stomias*	2,056	0.28
437	Canary Rockfish	*Sebastes pinniger*	1,921	0.26
044	Spiny Dogfish	*Squalus acanthias*	1,709	0.23
405	Silvergray Rockfish	*Sebastes brevispinis*	1,173	0.16
394	Rougheye Rockfish	*Sebastes aleutianus*	546	0.07
435	Bocaccio	*Sebastes paucispinis*	546	0.07
096	Pacific Herring	*Clupea pallasi*	515	0.07
467	Lingcod	*Ophiodon elongatus*	508	0.07
412	Splitnose Rockfish	*Sebastes diploproa*	434	0.06
626	Dover Sole	*Microstomus pacificus*	393	0.05
222	Pacific Cod	*Gadus macrocephalus*	242	0.03
056	Big Skate	*Raja binoculata*	241	0.03
92A	Squids	Teuthoidea	190	0.03
455	Sablefish	*Anoplopoma fimbria*	179	0.02
621	Rock Sole	*Lepidopsetta bilineatus*	175	0.02
628	English Sole	*Parophrys vetulus*	127	0.02
607	Petrale Sole	*Eopsetta jordani*	111	0.02
066	Spotted Ratfish	*Hydrolagus colliei*	95	0.01

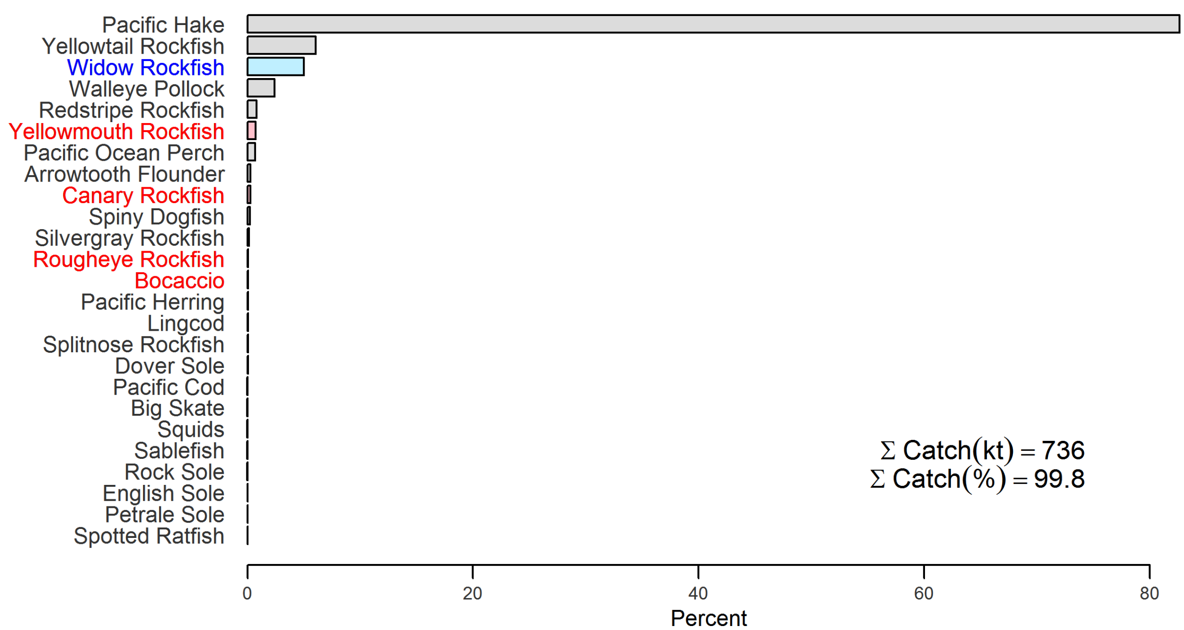

*Figure G.9. BC Offshore – Distribution of WWR catch weights for important finfish species in **midwater** trawl tows that caught at least one WWR coastwide. Tows were selected over a depth range between 64 and 569 m (the 1% and 99% quantile range, see Figure G.3). See caption in Figure G.8 for further details.*

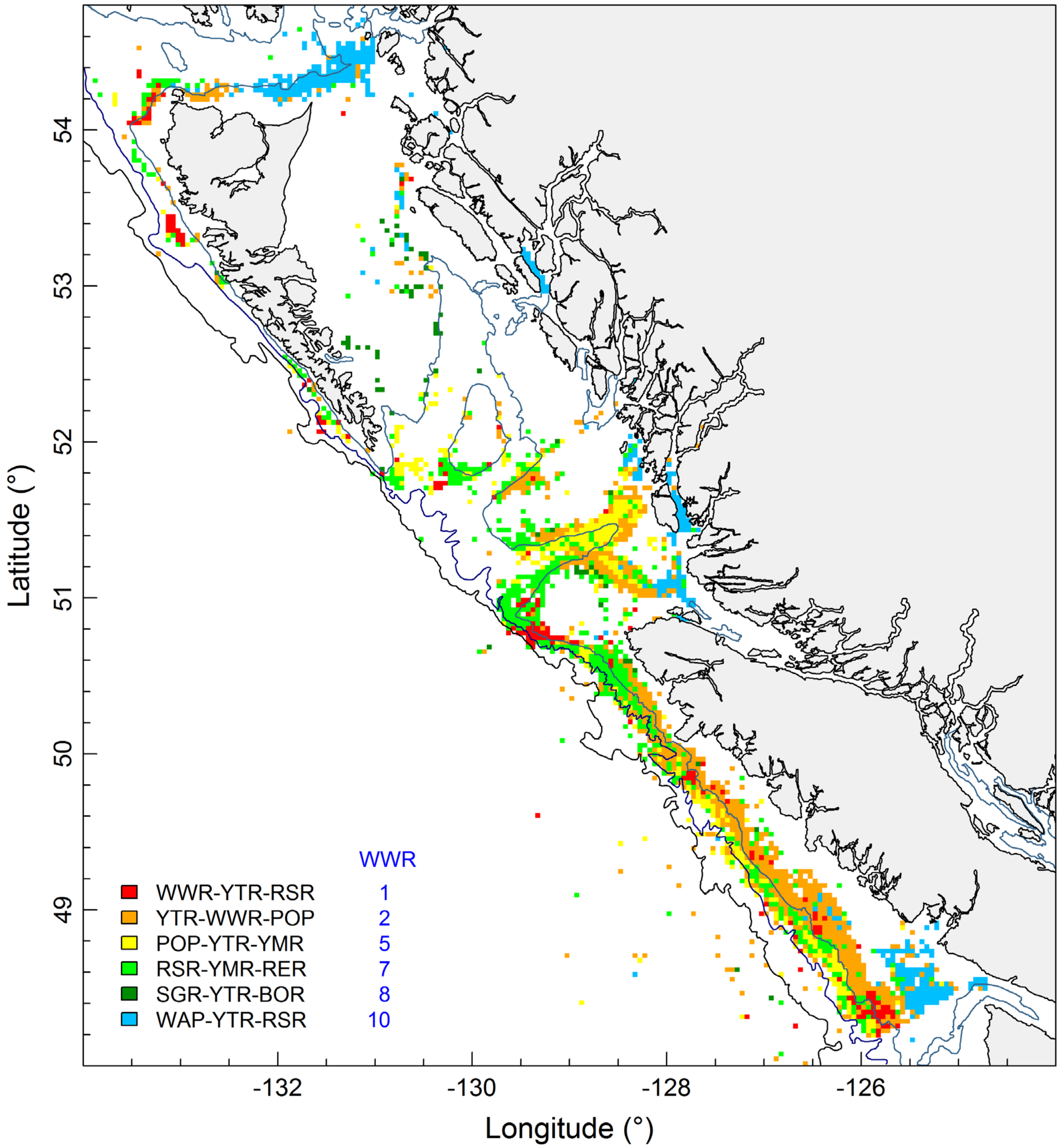

Figure G.10. Groups of fish (excluding Pacific Hake) in midwater trawl tows (1996-2918) identified by clara (clustering large applications) in R's package cluster (Maechler et al. 2018). Isobaths trace the 200, 1000, and 1800 m depth contours. The legend identifies six clusters represented by the top three species comprising the medoids; the clusters are ordered by the contribution of Widow Rockfish (WWR) to each medoid. Species codes: YTR =Yellowtail Rockfish, RSR = Redstripe Rockfish, POP =Pacific Ocean Perch, YMR = Yellowmouth Rockfish, RER =Rougheye Rockfish, SGR Silvergray Rockfish, BOR = Bocaccio, WAP =Walleye Pollock.

G.3. TROPHIC INTERACTIONS

The diet of Widow Rockfish includes copepods, planktonic amphipods, salps, krill, jellyfish, small fish, and crabs (Adams 1982, Love et al. 2002). Adams (1987) noted a seasonal shift in diet for WWR along northern California, perhaps due to onshore migration by WWR – shrimp in winter, salps in spring, euphausiids in summer, and juvenile hake in fall. He also noted that the primary prey species were vertical migrators, moving to the surface (upper 100 m) at night and back to deeper water (400 m) during the day.

A cursory look at the WWR specimens collected in Appendix D from GFBioSQL (accessed 2019-03-19) yields the frequency of prey items in stomach contents to be squids (95), euphausiids (40), Pacific Herring (28), lanternfish (9), ascidians and tunicates (4), and sand lances (2).

There are few reports of predators on *S. entomelas*. Love et al. (2002) mentions that young WWR are eaten by Chinook Salmon (*Oncorhynchus tshawytscha*) and Northern Fur Seals (*Callorhinus ursinus*).

G.4. ENVIRONMENTAL EFFECTS

Woodbury (1999) demonstrated a link between a strong El Niño year (1983) and reduced otolith growth in *S. entomelas* and *S. flavidus* off northern California. Reduced otolith growth was taken to be a conservative indicator of reduced body growth. The primary environmental proxy used in the study was correlated to ocean temperature, upwelling, and sea level anomaly. Poor environmental conditions in 1983 (high temperatures, low upwelling, high positive sea level anomaly) were postulated to reduce preferred food availability (lowering nutritional value), assuming that the fish did not migrate to areas where food was normally less nutritious.

G.5. ADVICE FOR MANAGERS

There is potential for environmental series to be incorporated into stock assessment models. However, a previous attempt to link recruitment estimates for 5ABC Pacific Ocean Perch with a number of environmental indicators (Haigh et al. 2018) proved inconclusive. Similarly, early analyses that used sea level indicators to predict Pacific Cod recruitment have since broken down (Forrest et al. in press). This type of oceanographic information falls outside our usual data sources in the stock assessment group, but collaboration with other DFO personnel or external colleagues may result in potentially useful hypotheses that could be incorporated into the stock assessment. For example, given that reduced WWR growth in northern California has been linked with the 1983 warm water event (Section G.3), it is possible that recent warm water events may similarly affect BC WWR. If available, time series for potential prey items (Section G.3) might provide similarly useable hypotheses.

G.6. REFERENCES – ECOSYSTEM

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