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Redstripe Rockfish (*Sebastes proriger*) stock assessment for British Columbia in 2018

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Foreword

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

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ABSTRACT

Redstripe Rockfish (*Sebastes proriger*, RSR) is a commercially important species of rockfish that inhabits the marine canyons along the coast of British Columbia (BC). The BC stock has supported a domestic trawl fishery for decades and was heavily fished by foreign fleets from the mid-1960s to mid-1970s. The status of RSR in BC is assessed as two stocks harvested in Pacific Marine Fisheries Commission (PMFC) major areas 5DE (BCN) and 3CD5ABC (BCS). The separation into two stocks was based on higher mean weights in the BCN population, a consistent observation that was confirmed across years, across research surveys and within the commercial fisheries. Additional checks comparing survey mean lengths by year and growth parameter estimates confirmed that BCN RSR are larger than BCS RSR, regardless of sex.

We use an annual catch-at-age model tuned to fishery-independent trawl survey series (two in BCN, four in BCS), bottom trawl CPUE series, annual estimates of commercial catch since 1940, and age composition data from survey series (BCN: 5 years of data from 2 surveys; BCS: 14 years from 3 surveys) and the commercial fishery (BCN: 12 years of data; BCS: 24 years). 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). The two-sex models were implemented in a Bayesian framework (using the Markov Chain Monte Carlo procedure) under a scenario that estimates both natural mortality (M) and steepness of the stock-recruit function (h). Sensitivity analyses were performed (four in BCN, five in BCS) to test the effect of alternative model assumptions.

The base model runs for BCN and BCS suggest that low exploitation in the early years, including that by foreign fleets, coupled with several strong recruitment events (in 1982 and 1996 for BCN and in 1974 and 2001 for BCS) have sustained the population to the present.

The spawning biomass (mature females only) at the beginning of 2018 for BCN and BCS is estimated to be 0.91 (0.69, 1.13) and 0.62 (0.47, 0.81) of unfished biomass (median and 5th and 95th quantiles of the Bayesian posterior distribution), respectively. For BCN and BCS, this biomass is estimated to be 3.16 (2.02, 4.00) and 2.43 (1.51, 3.77) of the spawning biomass at maximum sustainable yield, B_{MSY}, respectively.

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 2018 has a probability of 1 of being above the LRP, and a probability of 1 of being above the USR for both stocks. Five-year projections using a constant catch of 100 t/y in BCN and 700 t/y in BCS indicate that, in 2023, the spawning biomass has probabilities of 1 (BCN) and 1 (BCS) of remaining above the LRP, and 1 (BCN) and 1 (BCS) of remaining above the USR. The u_{MSY} reference point, however, suggests that catches in excess of 500 t in BCN and 1300 t in BCS will breach the Sustainable Fisheries Framework guidelines on fishing mortality, assuming that the manager wishes to be 95% certain that the harvest rate in 2023 will be less than u_{MSY}.

1. INTRODUCTION

Redstripe Rockfish (*Sebastes proriger*, RSR) is a long-lived, commercially important species of rockfish found along the Pacific rim of North America. Its commercial attractiveness stems from the bright red colour and long shelf life when properly processed. A distinguishing feature of RSR is strong lateral line that forms a clear distinctive stripe (Love et al. 2002). In British Columbia (BC), RSR is commonly caught with Pacific Ocean Perch (*S. alutus*) and Yellowmouth Rockfish (*S. reedi*).

The life history of RSR is thought to follow similar patterns to other *Sebastes* species, with the live release of larvae (reportedly April-July, Love et al. 2002) that spend periods ranging from three to twelve months as free-swimming pelagic larvae before settling to the bottom as juveniles. Redstripe Rockfish is considered to be partially benthic, forming groups near the bottom but not on the bottom. They prefer areas of high-relief and rugged terrain, and reportedly migrate vertically at night and disperse (Love at al, 2002).

The maximum age reported for RSR in marine waters off Alaska and BC is 55 years for a specimen from BC (Munk 2001); however, our database (`GFBioSQL`) reports one specimen older at age 61 y: male specimen (34.8 cm length) caught at a depth of 181 m in a fishing locality called “Cape Scott Spit” on Sep 7, 2001. The mean age of offshore RSR using the break-and-burn method is 15.6 y (n=12,496). The estimated natural mortality rate for RSR based on the revised Hoenig estimator (see Annexe , Section D.2.5) using the maximum age 61 y is 0.11. At age 50 y, the estimate of *M* is 0.136.

Redstripe Rockfish supports the sixth largest rockfish fishery (based on the 2017 management harvest plan) in BC with an annual coastwide TAC (total allowable catch) in 2017 of 1,564 t and an average annual catch of 842 t from 2013-2017. The trawl fishery accounts for 97% of the coastwide TAC, with the rest allocated to the hook and line fishery. Since 2006, the annual TACs have included catches from the groundfish research programs, primarily from the synoptic surveys. In this assessment, two stocks of RSR are identified that are delimited by Pacific Marine Fisheries Commission (PMFC) areas: 5DE in the north (called ‘BC North’ or ‘BCN’ for brevity) and 3CD5ABC in the south (‘BC South’ or ‘BCS’).

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

- sex-specific parameters;
- abundance indices:
  BCN – two synoptic surveys (HS=Hecate Strait, WCHG=west coast Haida Gwaii) and a bottom trawl CPUE series;
  BCS – two historical surveys (GIG=Goose Island Gully, WCVI=west coast Vancouver Island Triennial), two synoptic surveys (QCS=Queen Charlotte Sound, WCVI), and a bottom trawl CPUE series;
- proportions-at-age data (also called age frequencies or ‘AF’):
  BCN – three sets (commercial catch, HS synoptic, WCHG synoptic);
  BCS – four sets (commercial catch, GIG historical, QCS synoptic, WCVI synoptic);
- a maximum modelled age of 40 years with older ages accumulated into the final age class;
- independent selectivities for the commercial fishery and for each of the survey indices.

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

1.1. ASSESSMENT BOUNDARIES

This assessment includes Pacific Marine Fisheries Commission (PMFC) major areas (3CD and 5ABCDE) along the BC coast (Figure 1). We delineate two stocks based on consistent differences in mean weight and fitted growth parameters (Appendix D) – BC North (PMFC areas 5DE) and BC South (PMFC areas 3CD5ABC) observed in the commercial fisheries and the synoptic trawl surveys. 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 similar to the GMU areas and so managers can divide any catch policy using TAC ratios outlined in Appendix A.

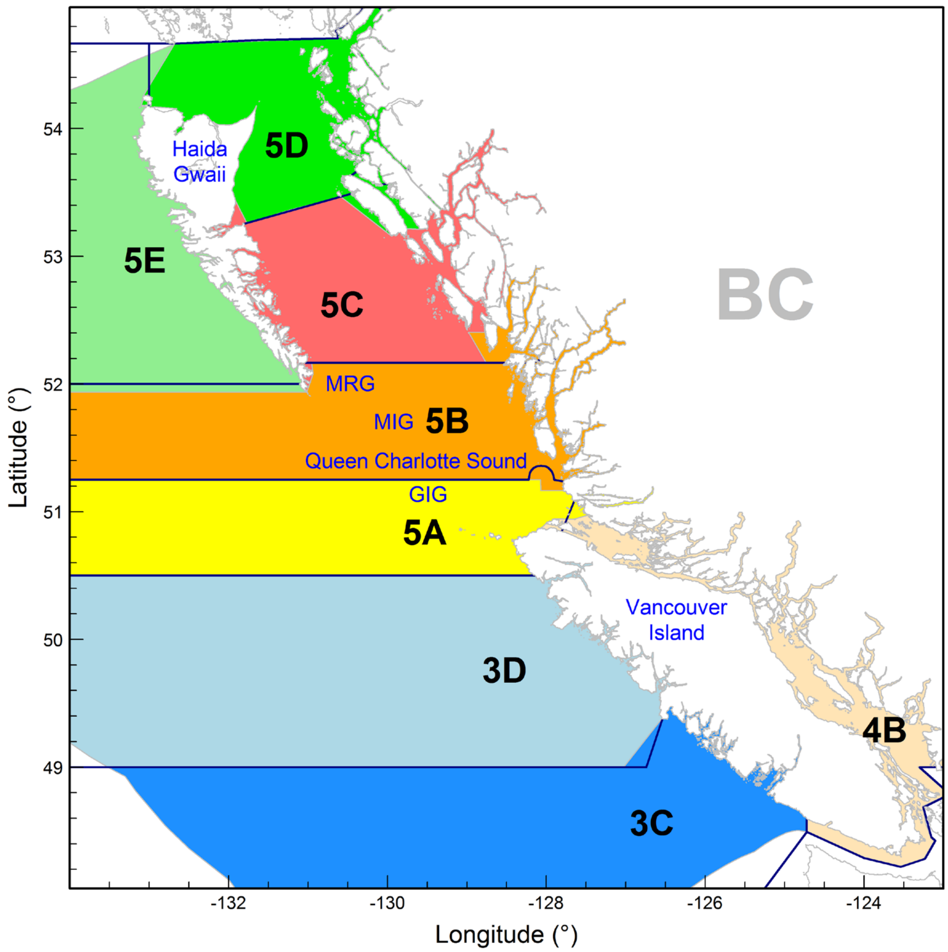

Figure 1. Pacific Marine Fisheries Commission (PMFC) major areas (outlined in dark blue) compared with Groundfish Management Unit areas for Redstripe Rockfish (shaded). For reference, the map indicates Moresby Gully ((MRG), Mitchell's Gully (MIG), and Goose Island Gully (GIG). This assessment covers two stocks: BC North (PMFC 5DE) and BC South (PMFC 3CD5ABC).

1.2. RANGE AND DISTRIBUTION

Redstripe Rockfish occurs along the Pacific rim of North America, ranging from the Aleutian Islands (Alaska) southward through BC down to central Baja California (Love et al. 2002). In BC, hotspots (≥ the 0.95 quantile) of catch per unit effort (CPUE) from bottom trawl tows summed over 22 years (1996-2017), occur off Rennell Sound (west of Graham Is., Haida

Gwaii), along the canyon walls of the three main gullies in Queen Charlotte Sound, NW off Vancouver Island, and SW off Barkley Sound, WCVI (Figure 2). Most of the commercial captures along the BC coast lie between depths 91 m and 380 m (Appendix G). Catches are continuous in BC from the lower part of Hecate Strait all the way to the BC border with Washington state. Another continuous stretch of RSR catches occurs along the west coast of Graham Island into the western part of Dixon Entrance (Figure 2). These stretches of continuous catches coincide with the separation of RSR into BCN and BCS stocks.

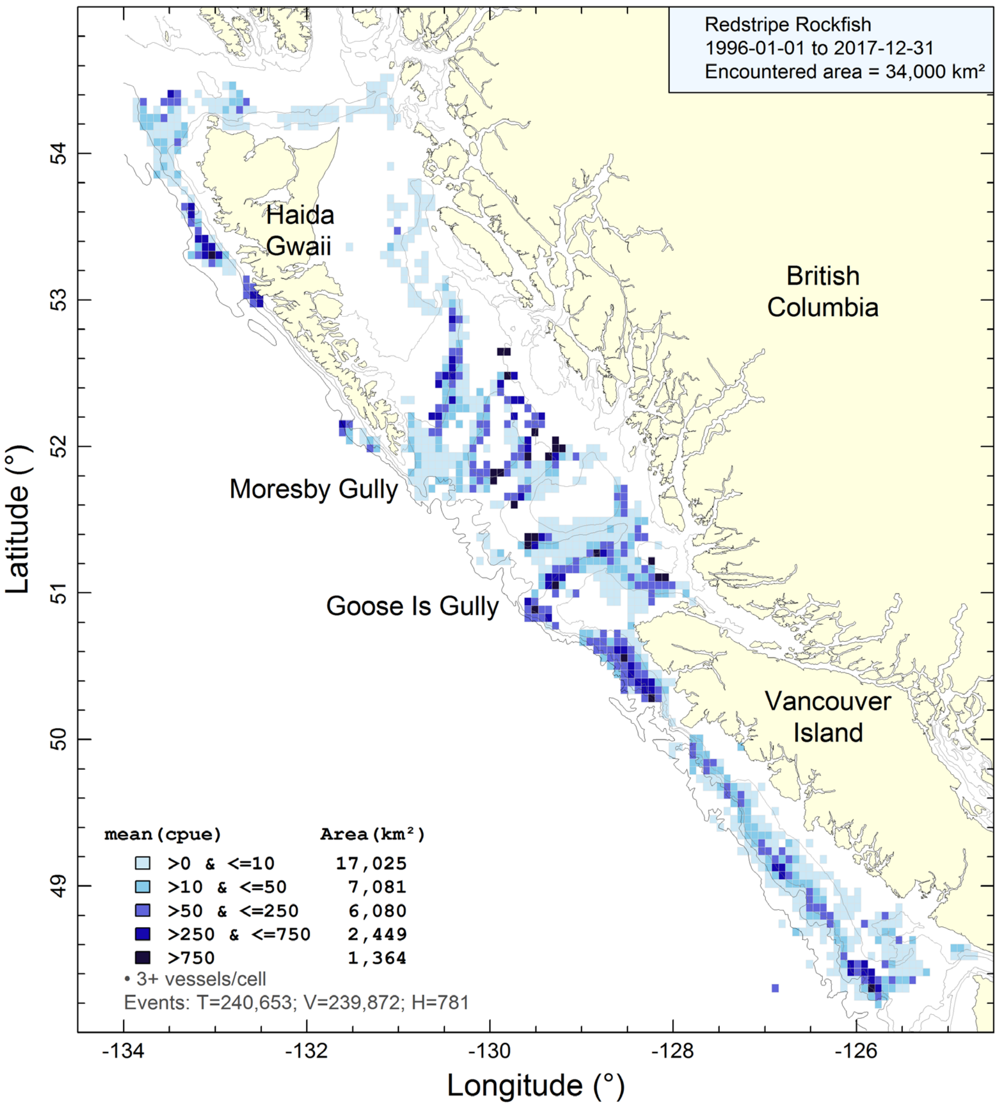

Figure 2. Aerial distribution of RSR mean bottom trawl catch per unit effort (kg/hour) from 1996 to 2017 in grid cells 0.075° longitude by 0.055° latitude (roughly 32 km²). Isobaths show the 100, 200, 500, and 1200 m depth contours. Note that cells with <3 fishing vessels are not displayed.

2. CATCH DATA

The methods used to prepare a catch history for this RSR assessment, along with the full catch history, are presented in detail in Appendix A. Information about species caught concurrently with RSR commercial catches are presented in Appendix G. The average annual catch over the most recent 5 years (2013-17) was 842 metric tonnes (t) coastwide, 109 t in PMFC 5DE, and 732 t in PMFC 3CD5ABC.

3. FISHERIES MANAGEMENT

Appendix A summarises all management actions taken for RSR in BC since 1993. The GMU sets TACs of RSR for regions approximating PMFC areas along the BC coast – 3C (TAC=178t), 3D5AB (TAC=794t), 5CD (TAC=339t), and 5E (TAC=253t).

4. SURVEY DESCRIPTIONS

Six sets of fishery independent survey indices, two in BC North and four in BC South, have been used to track changes in the biomass of this population (Appendix B):

BC North (BCN):

1. WCHG Synoptic – a random-stratified synoptic (species comprehensive) trawl survey covering the west coast (WC) of Graham Island in Haida Gwaii (HG) and western part of Dixon Entrance. This survey has been repeated 6 times between 2006 to 2016 using three vessels and a consistent design, including targeting a wide range of finfish species.
2. HS Synoptic – a random-stratified synoptic trawl survey covering all of Hecate Strait and extending into Dixon Entrance and across the top of Graham Island. This survey has been repeated 7 times between 2005 to 2017 using two vessels and a consistent design, including targeting a wide range of finfish species.

   The placement of this survey into the BCN stock grouping was queried during the review meeting, given that the BCN stock definition was confined to the WCHG (see Appendix D). This survey was placed with the BCN stock because it extends into the western end of Dixon Entrance, which is contiguous with PMFC 5E. However, RSR appear to be caught by this survey in the upper reaches of Moresby Gully (see Figures B.26 and B.27) rather than in the western Dixon Entrance, which aligns this survey with the BCS stock rather than the BCN stock. The scarcity of RSR information from this survey implies that there will be little impact to the stock assessment, regardless where these data are incorporated. It was agreed that future RSR stock assessments would group this survey with the BCS stock data.

BC South (BCS):

3. GIG Historical – an early 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.
4. 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 vessels but with a consistent design.
5. WCVI Synoptic – a random-stratified synoptic trawl survey covering the west coast of Vancouver Island (WCVI). This survey has been repeated 7 times between 2004 to 2016 using the same vessel and a consistent design, including targeting a wide range of finfish species.

6. 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, adjusted by adding process error to balance the relative weights of the surveys in the models.

5. COMMERCIAL CPUE

Commercial catch per unit effort (CPUE) data were used to generate indices of abundance used in the model fitting procedure for both the BCN and BCS stocks. This continuous series of indices, extending from 1996 to 2017, provided stability to the population model and improved the performance of the MCMC search procedure. Bottom trawl CPUE was selected because the BC trawl fishery, under an individual vessel quota trading system, appears to catch RSR largely as a bycatch when targeting more abundant and marketable rockfish.

The CPUE abundance index series for both stocks were standardised for changes to vessel configuration and the timing or location of catch (e.g., latitude and depth) to remove potential biases in CPUE that may result from changes in fishing practise and other non-abundance effects. In these models, abundance was represented as a “year effect” and the dependent variables were selected sequentially by a GLM model, which accounted for variation in the available data. Many 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.

6. BIOLOGICAL INFORMATION

6.1. BIOLOGICAL SAMPLES

Commercial catches of RSR by trawl (combined midwater and bottom) gear have been sampled for age proportions since the 1980s, while early research cruises sampled ages in 1967 and 1978 to 1980. However, 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 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 data were summarised for each quarter, weighted by the RSR catch weight for the sampled trip. The total quarterly samples were scaled up to the entire year using the quarterly landed commercial catch weights. See Appendix D (Section D.3) for details.

Age frequency (AF) data were available from all survey series except for the WCVI Triennial survey – the HS Synoptic only had one year of AF data in 2009, the WCHG Synoptic had 4 years from 2008-2016, the GIG Historical had one year in 1994, the QCS Synoptic had 8 years from 2003-2015, and the WCVI Synoptic had 5 years from 2008-2016. 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 RSR 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 RSR length and age data from biological samples collected primarily from 1994 to 2016 (Appendix D). Only data from research surveys were used to estimate biological parameters by sex for the model (Appendix E), specifically parameters for the allometric weight-length relationship and growth specified as a von Bertalanffy model. A pronounced difference in size exists between the sexes where females are larger on average than males (BCN L_∞: ♀=40.6 cm, ♂=33.9 cm; BCS L_∞: ♀=37.9 cm, ♂=31.1 cm).

6.3. MATURITY AND FECUNDITY

The proportions of females that mature at ages 1 through 25 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 between November and April and the observed proportion mature at each age was calculated. 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 10. This was done because the fitted model overestimates the proportion mature at younger ages (Figure D.22). Females older than age 10 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

Male and female natural mortalities were estimated as parameters of the model (see Appendix E), using an informed normal prior with a mean based on the calculation of Then et al. (2015, Equation D.4, Section D.2.5) using a maximum age of 61 y which estimates M = 0.11. An arbitrary CV of 10% was used to set a standard deviation = 0.011 (higher values led to some instability in the Bayesian model).

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 RSR from 1940 to the beginning of 2018. Ages were tracked from 1 to 40, with 40 being 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, two in BC North and three in BC South, 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. The model and its equations are described in Appendix E.

The model was fit to the available data (BCN: 2 sets of survey indices, 1 bottom trawl CPUE series, 12 annual proportions-at-age samples from the commercial fishery and 5 proportions-at-age samples from 2 surveys; BCS: 4 sets of survey indices, 1 bottom trawl CPUE series, 24 annual proportions-at-age samples from the commercial fishery and 14 proportions-at-age samples from 3 surveys) 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.

Initial model fits to the data using uniform selectivity priors gave unstable results (e.g. drifting MCMC traces, high autocorrelation). Unlike the data-rich stock 5ABC POP, the RSR data were insufficient to estimate a number of these parameters using uniform priors. Therefore, the means and standard deviations from the posterior distributions for the corresponding selectivity parameters from the appropriate 3CD, 5ABC and 5DE POP stock assessments (Haigh et al. 2019, Edwards et al. 2014a,b) were used to specify informed priors for RSR, assuming a normal distribution (e.g., for age at full selectivity, μ_g). The justification for this approach was twofold: RSR are of similar size to POP and are taken in conjunction with this species. The standard deviations for the commercial selectivity parameters based on the POP posterior distributions were much too tight (less than 5% CV) so a CV of 20% of the mean was used to specify the commercial selectivity priors. The use of informed priors greatly improved model performance by stabilising the MCMC procedure and was the key to arriving at a sensible outcome for this stock assessment.

Four sensitivity analyses (plus a fifth for BCS) were run (with full MCMC simulations) relative to the base case (Run16 for each stock) to test the sensitivity of the outputs to alternative model assumptions:

- S1 (Run19) – remove the commercial CPUE index series (BCN g=3, BCS g=5);
- S2 (Run20) – halve the catch during years of foreign fleet activity (1965-1976) and during years of possible misreporting by the domestic fleet before observer coverage (1988-1995);
- S3 (Run21) – use proportions-at-age from unsorted samples only;
- S4 (Run22) – increase sigmaR (σ_R) from 0.6 to 1.1;
- S5 (Run23) – (BCS only) remove the GIG Historical and WCVI Triennial surveys.

Four additional sensitivity analyses were run as diagnostics to the base case and S4:

- D1 (BCN:Run23, BCS:Run24) – same as base case but $M_{1,2}$ fixed at 0.11;
- D2 (BCN:Run24, BCS:Run25) – same as S4 but $M_{1,2}$ fixed at 0.11;
- D3 (BCN:Run26, BCS:Run27) – same as base case but prior on $M_{1,2}$ ~ N(0.136, 0.0136) [10%CV] assuming a maximum age of 50 y instead of 61 y;
- D4 (BCN:Run27, BCS:Run28) – same as base case but prior on $M_{1,2}$ ~ N(0.136, 0.0272) [20%CV].

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 24,000,000 iterations, sampling every 20,000th, to give 1,200 draws (1,000 samples after dropping the first 200 for burn in). Bayesian procedures were not applied to diagnostic runs D3 and D4, which were only evaluated at the MPD level.

8. MODEL RESULTS

8.1. BC NORTH

8.1.1. BCN Base Case

The base case model run had credible fits to the data, as demonstrated by visual examination of the MPD fits and the patterns of residuals (results in E.3). Fits to the survey indices were generally good (Figure F.1), as was the fit to the bottom trawl CPUE index series (Figure F.4). The fits to the commercial age composition data were good (Figure F.8), with only an occasional cohort showing a bad fit (females born in 1982, Fig. F.9; males born in 1995, Fig. F.10). The effectiveness of commercial sampling is usually a result of samples that generate adequate numbers of specimen otoliths (~200 per sex annually) and the flexibility of the fleet to target or avoid fish species. Fits to survey ages were not as good (e.g., Figure F.17) as those to the commercial age data, perhaps reflecting the multi-species nature of synoptic surveys and a sampling design that cannot target any single species for optimal biological sampling. Francis (2011) recommended using a diagnostic plot that compares the observed and predicted mean age by year to see if the model had captured that dynamic. Figure F.19 shows that the base case model fits the commercial annual mean ages very well while the predicted mean ages in the WCHG synoptic survey largely fall below the observed ones.

The MCMC results showed satisfactory convergence of the MCMC search process (E.3). Priors and marginal posteriors of the estimated parameters are presented in E.3, along with the values of the estimated parameters (Table F.4). For example, natural mortality was estimated as having a median (and 5-95% credible interval) of 0.106 (0.092-0.119) for females and 0.118 (0.105-0.131) for males. Steepness was estimated to be 0.725 (0.434-0.930). The remaining MCMC results are given in Table 1 and Table 2 as median and 90% credibility intervals. The median estimated ratio of spawning biomass at the start of 2018 to the equilibrium spawning biomass associated with MSY (B_{2018}/B_{MSY}) was 3.156 (2.015-3.999). The estimated median MSY was 497 (281-787) t. For reference, the average catch from 2013-2017 was 109 t. The median estimated ratio of the spawning biomass at the start of 2018 to the unfished level (B_{2018}/B_0) was 0.914 (0.692-1.129) for the base case.

Figure 3 shows the trajectory for the estimated vulnerable biomass, together with the reconstructed historical catches, and Figure 4 compares the medians of vulnerable and spawning (mature females only) biomass relative to their unfished values. Figure 3 demonstrates long periods of stable standing stock punctuated by periodic declines, e.g., after 1966 during the foreign fleet activity and in the 1990s during an emergent domestic trawl fleet. There are also periods of notable population increases generated by major recruitment events in 1982 and 1996 (Figure 5). The median spawning biomass relative to unfished equilibrium values (Figure 4) reached a minimum of 0.48 in 1999 and currently sits at 0.914. Median exploitation rates were higher than median female natural mortality (M_1=0.106) during the years 1966, 1968, 1977-1978, and 1985-1990; they peaked in 1986 at a median value of 0.176 (Figure 6).

Table 1. BC North – Quantiles of the MCMC posterior distributions for the main estimated model parameters for the base case 5DE RSR stock assessment. Except for R_0, M_1 and M_2, subscripts refer to the data source, where 1=HS Synoptic survey, 2=WCHG Synoptic survey, 3=commercial trawl fishery data or CPUE index series.

Value	5%	50%	95%
R_0	2,602	3,885	6,359
M_1	0.092	0.106	0.119
M_2	0.105	0.118	0.131
h	0.434	0.725	0.930
q_1	0.0081	0.0157	0.0329
q_2	0.0293	0.0578	0.1169
q_3	0.00012	0.000215	0.000357
μ_1	9.12	11.08	12.90
μ_2	10.56	11.43	12.62
μ_3	11.38	11.76	12.22
Δ_1	0.105	0.218	0.325
Δ_2	0.114	0.219	0.327
Δ_3	-0.196	0.069	0.339
$\log v_{1L}$	1.066	2.008	3.294
$\log v_{2L}$	1.272	1.883	2.445
$\log v_{3L}$	0.565	0.903	1.231

Table 2. BC North – Quantiles of MCMC-derived quantities from the 1,000 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_{2018} – spawning biomass at the start of 2018, V_{2018} – vulnerable biomass in the middle of 2018, u_{2017} – exploitation rate (ratio of total catch to vulnerable biomass) in the middle of 2017, u_{max} – maximum exploitation rate (calculated for each sample as the maximum exploitation rate from 1940-2017), 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 (2013-2017) is 109 t.

From model output

Value	5%	50%	95%
B_0	5,611	7,216	10,083
V_0	5,910	7,606	10,733
B_{2018}	4,193	6,500	11,079
V_{2018}	4,605	7,455	12,935
B_{2018} / B_0	0.692	0.914	1.129
V_{2018} / V_0	0.718	0.990	1.267
u_{2017}	0.009	0.016	0.027
$u_{\max}$	0.127	0.187	0.281

MSY-based quantities

Value	5%	50%	95%
MSY	281	497	787
B_{MSY}	1,488	2,135	3,411
0.4B_{MSY}	595	854	1,364
0.8B_{MSY}	1,190	1,708	2,728
B_{2018} / B_{MSY}	2.015	3.156	3.999
B_{MSY} / B_0	0.250	0.293	0.379
V_{MSY}	474	848	2,578
V_{MSY} / V_0	0.073	0.107	0.293
u_{MSY}	0.120	0.638	0.990
u_{2017} / u_{MSY}	0.011	0.025	0.154

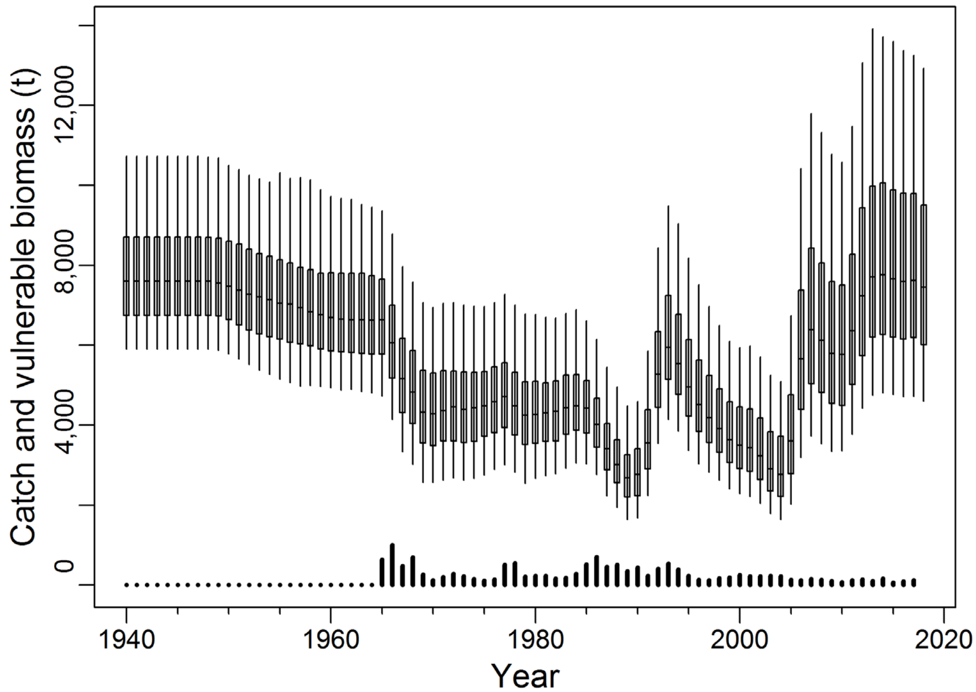

Figure 3. BC North – Vulnerable biomass (boxplots showing 5, 25, 50, 75 and 95 percentiles of the posteriors from the MCMC results) for the base case model run. Commercial catch (vertical bars along the x-axis) are presented on the same scale.

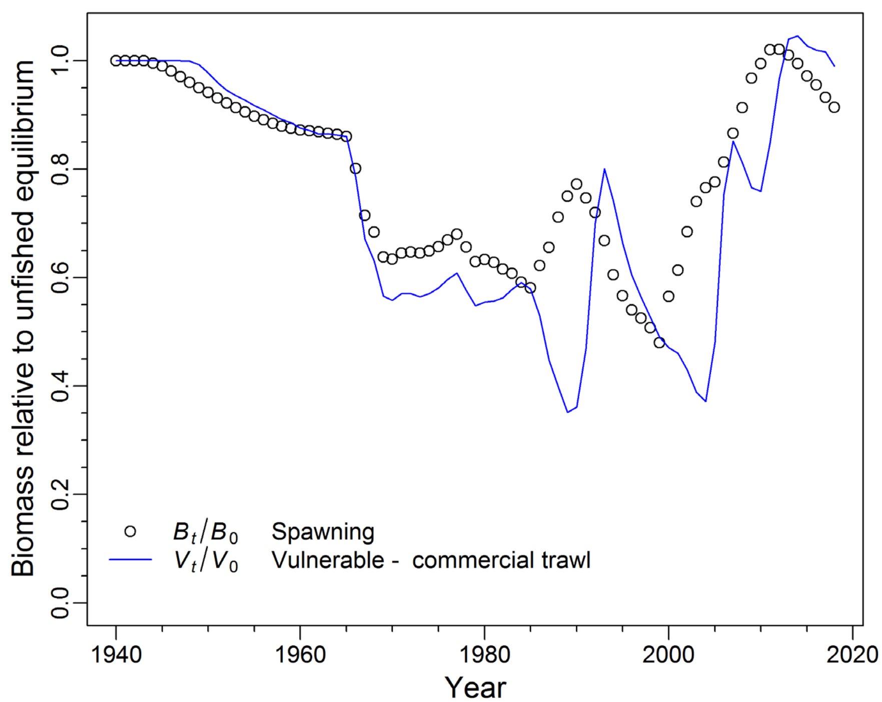

Figure 4. BC North – Trajectories of spawning and vulnerable biomass relative to virgin levels, B_t / B_0 and V_t / V_0 respectively, over time, shown as the medians of the MCMC posteriors for the base case model run.

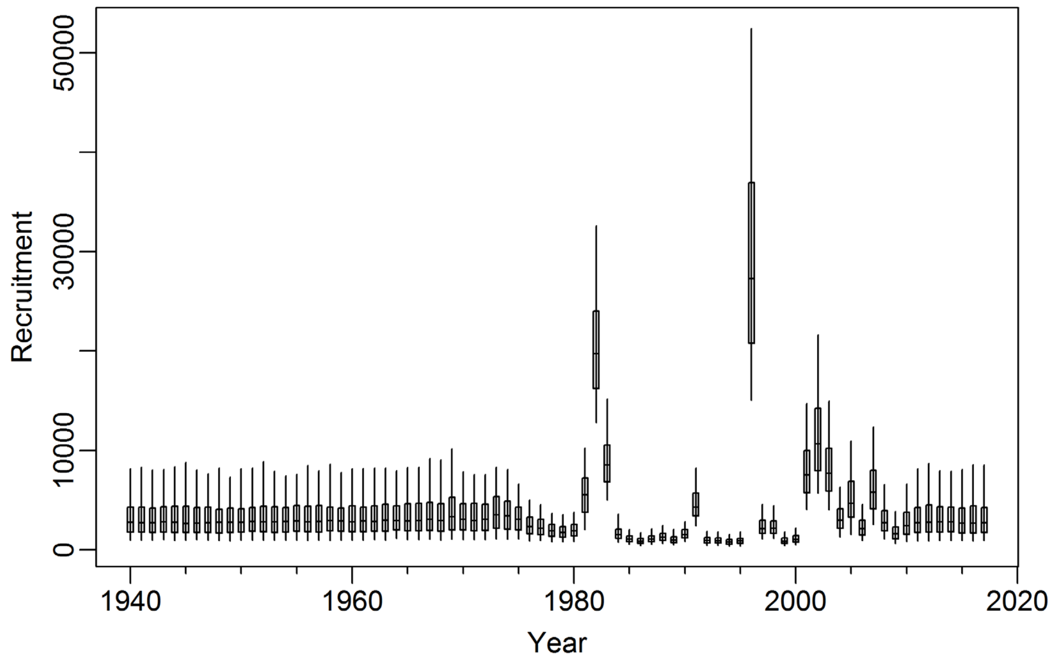

Figure 5. BC North – Marginal posterior distribution of recruitment in 1000s of age 1 fish plotted over time for the base case model run. The boxes give the 5, 25, 50, 75 and 95 percentiles from the MCMC results.

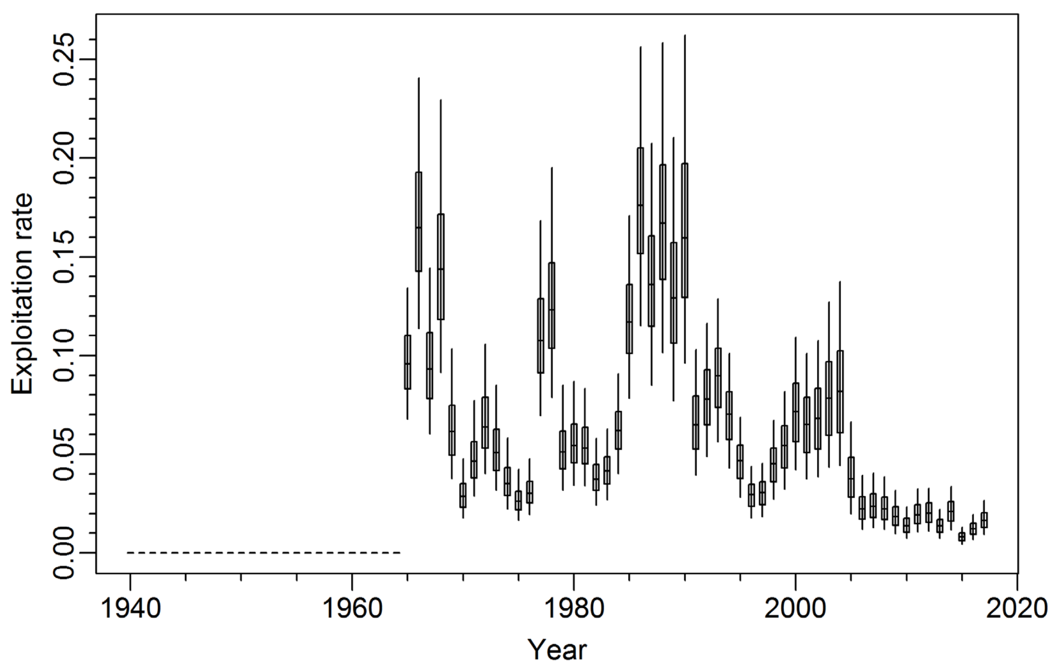

Figure 6. BC North – Marginal posterior densities of annual exploitation rate (Eq. E.12) by year for the base case model run. The boxes give the 5, 25, 50, 75 and 95 percentiles from the MCMC results.

8.1.2. BCN Sensitivity Analyses

Four sensitivity runs were identified (listed in Section 7 above) and evaluated with an MCMC search across the parameter space, with the differences among runs summarised in Section F.2.2 (E.3). Three of the four sensitivity runs estimated the 2018 population stock size (relative to the unfished equilibrium biomass) at a level that was similar to the base case. However, these runs showed different biomass trajectories and recruitment series compared to the base case run. The fourth sensitivity run [S4 (σ_R=1.1)] deviated even more from the base case, finding an alternative population trajectory scenario with good MCMC diagnostics. This run estimated a lower 2018 relative population stock size (median B_t/B_0=0.66 compared to >0.9 for the other runs; Figure 7) and estimated strong year classes in different years than either the base case or the other sensitivity runs. Run S4 also estimated higher exploitation rates, reaching a maximum of 0.49 in 1993. Natural mortality estimates for S4 diverged from those in the base case, with the female *M* 22% lower than the base case *M* and the male *M* 20% greater than the equivalent base case *M* (M_1 = 0.082 vs. 0.106, M_2 = 0.142 vs. 0.118, respectively; Table F.13). The capacity of the BCN models to find alternative plausible paths through the data is likely a function of the relatively small amount of data available for this model. This behaviour contrasts with the BCS model, which did not show equivalent divergence in model fits to the data when the same sensitivity assumptions were run (see Section 8.2.2).

The sensitivity that excluded the CPUE index series (S1) produced MCMC samples with unstable traces and vey high values of autocorrelation and should be considered unacceptable as an alternative to the base case.

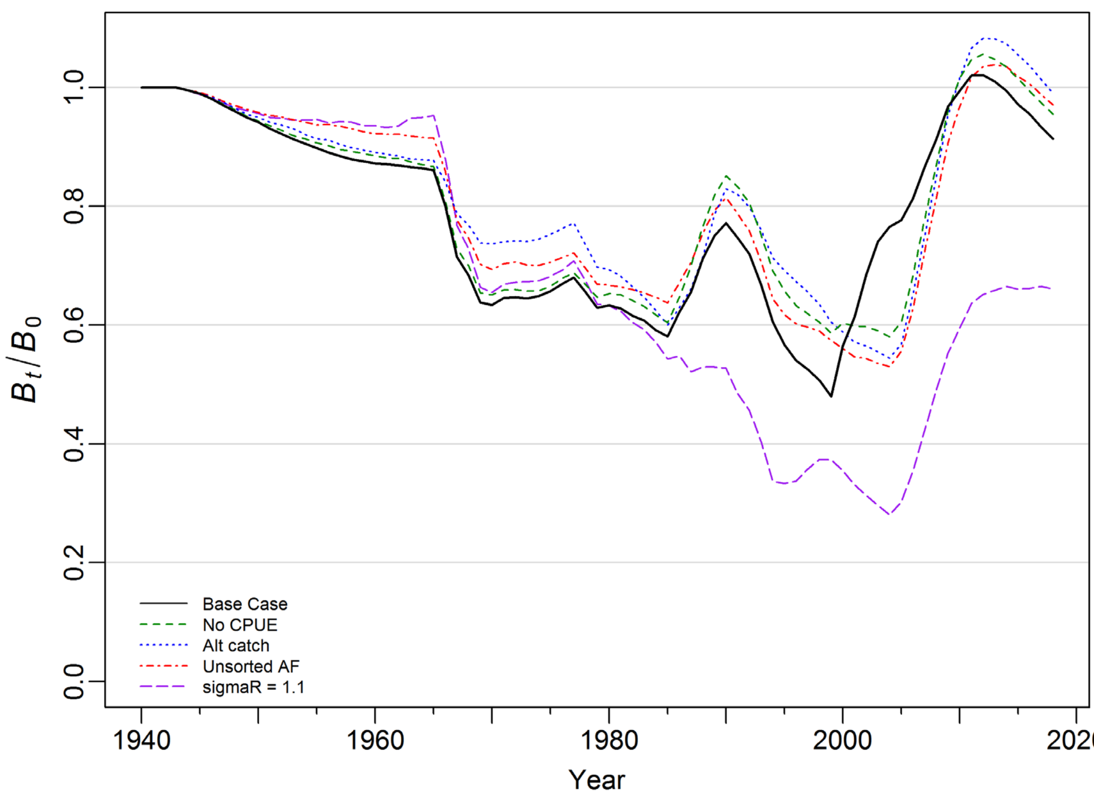

Figure 7. BC North – Model median trajectories of spawning biomass as a proportion of unfished equilibrium biomass (B_t/B_0) for the base case and four sensitivity runs (see legend lower left).

8.2. BC SOUTH

8.2.1. BCS Base Case

The base case model run had credible fits to the data, as demonstrated by visual examination of the MPD fits and the patterns of residuals (results in E.3). Fits to the survey indices were generally good, except for the final index point in the QCS Synoptic survey(Figure F.57). The fit to the bottom trawl CPUE index series (Figure F.62) was also good. The fits to the commercial age composition data were acceptable (Figure F.66), with some of the age classes centred on age 11 having trouble, especially for males. As seen in most other BC rockfish stock assessments, fits to survey ages were not as good (e.g., Figure F.74) as those to the commercial age data, perhaps reflecting the multi-species nature of these surveys and a sampling design that cannot target any single species for optimal biological sampling. Francis (2011) recommended using a diagnostic plot that compares the observed and predicted mean age by year to see if the model had captured that dynamic. Figure F.81 shows that the base case model had some lack of fit to the commercial annual mean ages at the beginning and end of the series and overestimated WCVI Synoptic survey mean age in the final two years, while the QCS Synoptic survey showed good coherence between observed and predicted mean ages by year.

The MCMC results showed satisfactory convergence of the MCMC search process (E.3). Priors and marginal posteriors of the estimated parameters are presented in E.3, along with the values of the estimated parameters (Table F.18). For example, natural mortality was estimated as having a median (and 5-95% credible interval) of 0.098 (0.086-0.111) for females and 0.130 (0.118-0.134) for males. Steepness was estimated to be 0.761 (0.507-0.933). The remaining MCMC results are given in Table 3 and Table 4 as median and 90% credibility intervals. The median estimated ratio of spawning biomass at the start of 2018 to the equilibrium spawning biomass associated with MSY (B_{2018}/B_{MSY}) was 2.429 (1.509-3.768). The estimated median MSY was 1467 (946-2481) t. For reference, the average catch from 2013-2017 was 732 t. The median estimated ratio of the spawning biomass at the start of 2018 to the unfished level (B_{2018}/B_0) was 0.622 (0.469-0.810) for the base case.

Figure 8 shows the trajectory for the estimated vulnerable biomass, together with the reconstructed historical catches, and Figure 9 compares the medians of vulnerable and spawning (mature females only) biomass relative to their unfished values. Figure 8 shows a steady decline in the population from 1940 to the mid 1970s, followed by a 10-year rise to levels above B_0 by 1985. Another steady decline, steeper this time due to higher catches than previously, continued for 20 years and reached a low point in 2006. A good recruitment event in 2000 (Figure 10) then occurred to produce a 5-year increase followed by a stable standing stock until the most recent year. The median female spawning biomass relative to unfished equilibrium values (Figure 9) reached a minimum of 0.386 in 2004 and currently sits at 0.622. Median exploitation rates were never higher than median female natural mortality (M_1=0.098); exploitation peaked in 2005 at a median value of 0.086 (Figure 11).

Table 3. BC South – Quantiles of the MCMC posterior distributions for the main estimated model parameters for the base case 5DE RSR stock assessment. Except for R_0, M_1 and M_2, subscripts refer to the data source, where 1=GIG Historical survey, 2=QCS Synoptic survey, 3=WCVI Synoptic survey, 4=WCVI Triennial survey, and 5=commercial trawl fishery data or CPUE index series.

Value	5%	50%	95%
R_0	9,980	14,312	24,249
M_1	0.086	0.098	0.111
M_2	0.118	0.130	0.144
h	0.507	0.761	0.933
q_1	0.0147	0.0288	0.0583
q_2	0.0867	0.1723	0.2888
q_3	0.0847	0.1656	0.2806
q_4	0.1206	0.2200	0.3681
q_5	0.000043	0.000074	0.000110
μ_1	11.62	17.73	25.43
μ_2	9.33	11.17	12.95
μ_3	13.04	15.36	17.98
μ_5	11.38	12.45	13.61
Δ_1	-2.647	0.519	3.787
Δ_2	0.108	0.212	0.327
Δ_3	-0.970	-0.133	0.694
Δ_5	-0.125	0.223	0.579
$\log v_{1L}$	2.636	4.118	5.160
$\log v_{2L}$	2.377	3.031	3.515
$\log v_{3L}$	3.186	3.660	4.075
$\log v_{5L}$	2.275	2.645	2.973

Table 4. BC South – Quantiles of MCMC-derived quantities from the 1,000 samples of the MCMC posterior. Definitions appear in caption for Table 2. For reference, the average catch over the last 5 years (2013-2017) is 732 t.

From model output

Value	5%	50%	95%
B_0	21,925	26,149	36,390
V_0	22,780	27,318	38,172
B_{2018}	10,700	16,235	28,967
V_{2018}	10,142	15,665	27,905
B_{2018} / B_0	0.469	0.622	0.810
V_{2018} / V_0	0.424	0.574	0.764
u_{2017}	0.027	0.049	0.075
u_{max}	0.056	0.089	0.125

MSY-based quantities

Value	5%	50%	95%
MSY	946	1467	2481
B_{MSY}	4,553	6,830	10,701
$0.4B_{MSY}$	1821	2732	4,280
$0.8B_{MSY}$	3,643	5,464	8,561
B_{2018} / B_{MSY}	1.509	2.429	3.768
B_{MSY} / B_0	0.190	0.256	0.344
V_{MSY}	2466	5043	9,080
V_{MSY} / V_0	0.088	0.183	0.302
u_{MSY}	0.115	0.300	0.800
u_{2017} / u_{MSY}	0.049	0.160	0.496

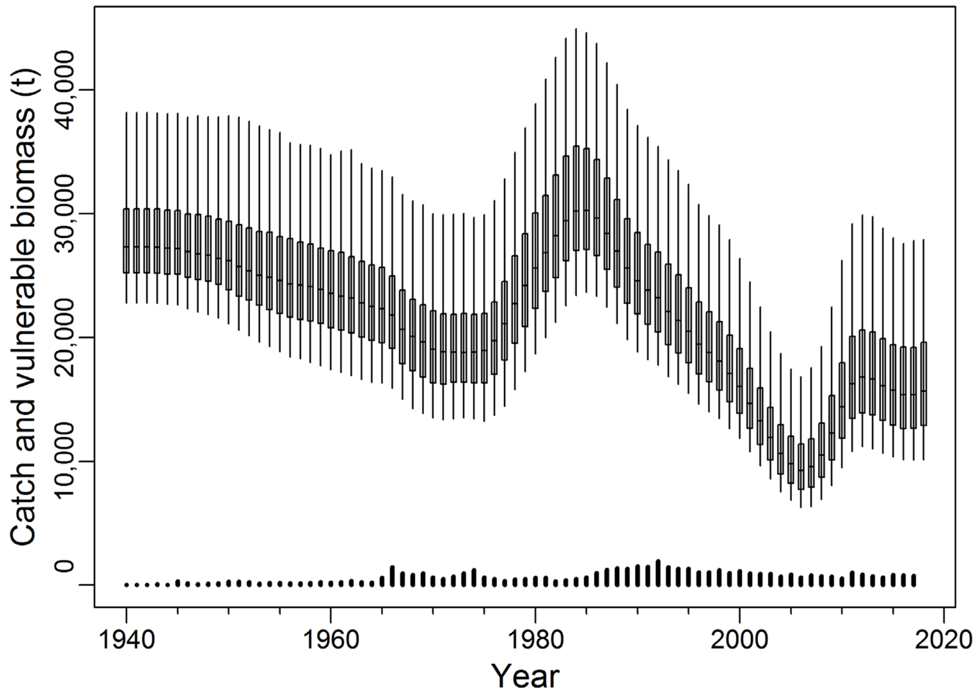

Figure 8. BC South – Vulnerable biomass (boxplots showing 5, 25, 50, 75 and 95 percentiles of the posteriors from the MCMC results) for the base case model run. Commercial catch (vertical bars along the x-axis) are presented on the same scale.

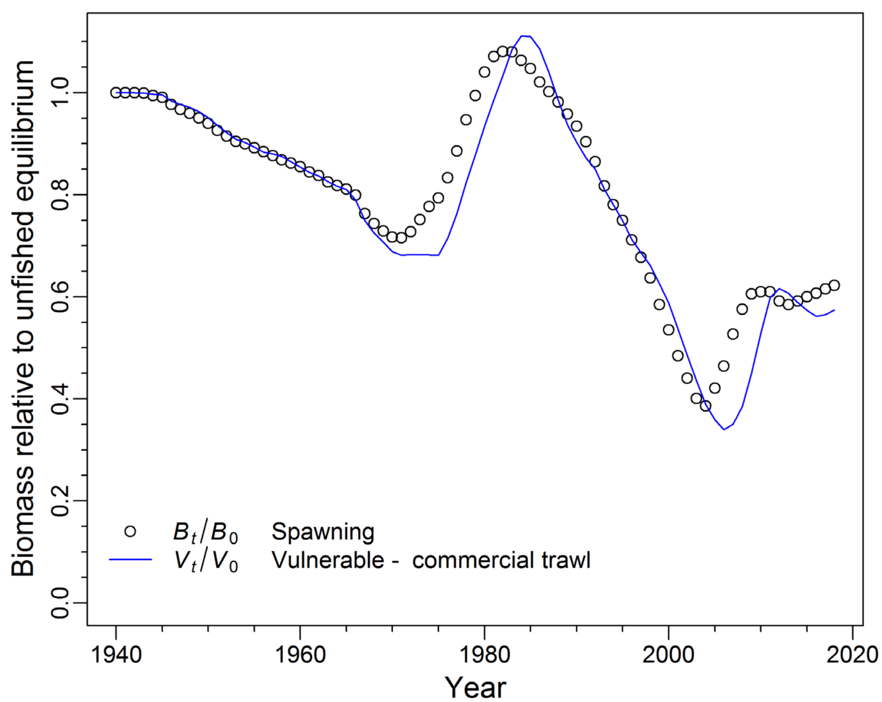

Figure 9. BC South – Trajectories of spawning and vulnerable biomass relative to virgin levels, B_t / B_0 and V_t / V_0 respectively, over time, shown as the medians of the MCMC posteriors for the base case model run.

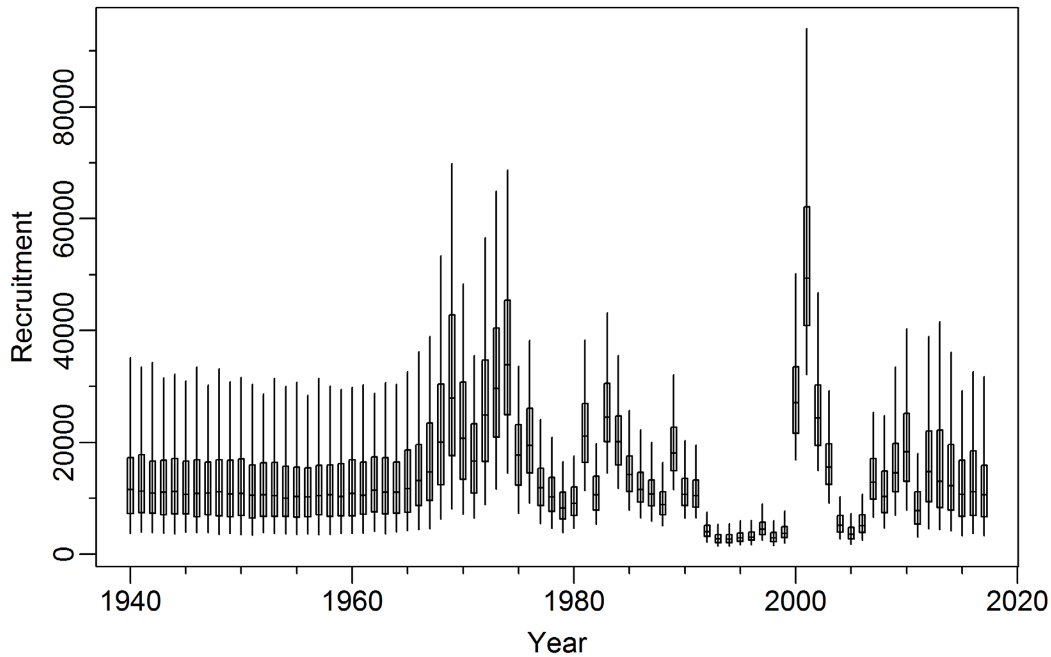

Figure 10. BC South – Marginal posterior distribution of recruitment in 1000s of age 1 fish plotted over time for the base case model run. The boxes give the 5, 25, 50, 75 and 95 percentiles from the MCMC results.

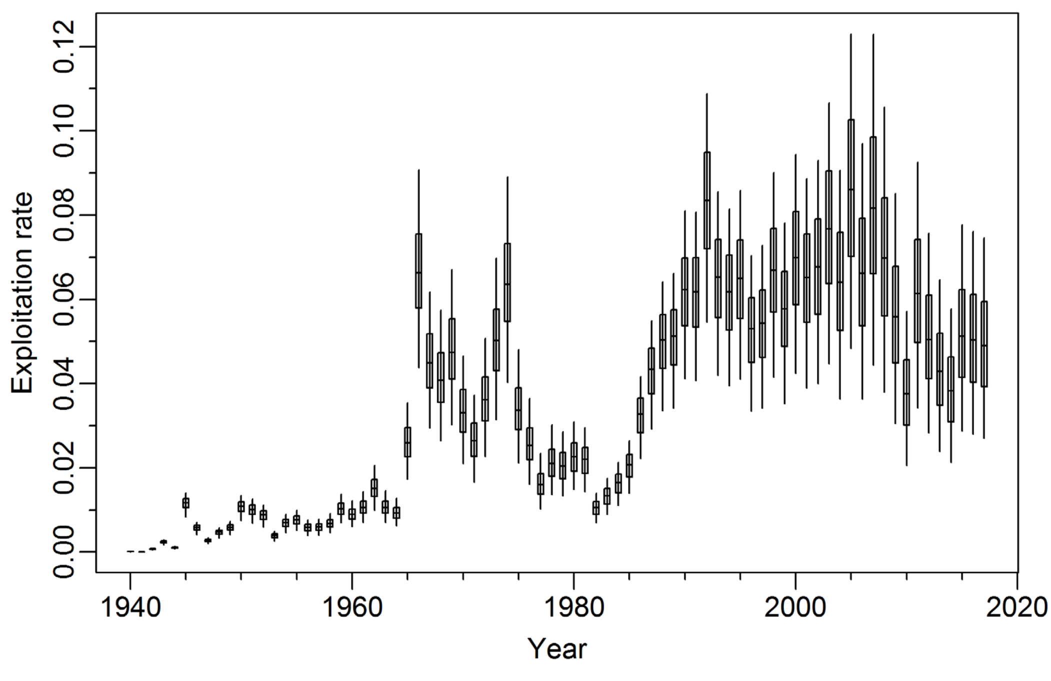

Figure 11. BC South – Marginal posterior densities of annual exploitation rate (see Eq. E.12) by year for the base case model run. The boxes give the 5, 25, 50, 75 and 95 percentiles from the MCMC results.

8.2.2. BCS Sensitivity Analyses

Five sensitivity runs were identified (listed in Section 7 above) and evaluated with an MCMC search across the parameter space, with the differences among runs summarised in

Section F.3.2 (E.3). Three of the five sensitivity runs estimated 2018 population stock sizes (relative to the unfished equilibrium biomass) at levels that were similar to the base case (Figure 12). The biomass trajectories for all of the sensitivity runs were similar to the base case, including estimating strong year classes in the same years as the base case, differing only in the relative strength of the estimates (Figure F.103). The most optimistic sensitivity (S1) in terms of relative 2018 population stock size excluded the CPUE time series, while the most pessimistic run (S3) excluded age frequencies from sorted samples. The S3 sensitivity run did not exhibit the strong recovery in the 1980s seen in the other runs which was likely due to the loss of the early age-composition data when sorted samples predominated. Unlike the model for the BC North stock, increasing the standard deviation of the recruitment process error (σ_R) had very little effect on model parameter estimates, including the recruitment deviations. This stability may have been due to the greater amount of data in BCS model compared to the BCN model, which demonstrated considerable divergence in model fits to the data under alternative model scenarios (see Section 8.1.2).

The sensitivity that excluded the early non-synoptic surveys (S5) produced MCMC samples with high values of autocorrelation and should be considered unacceptable as an alternative to the base case.

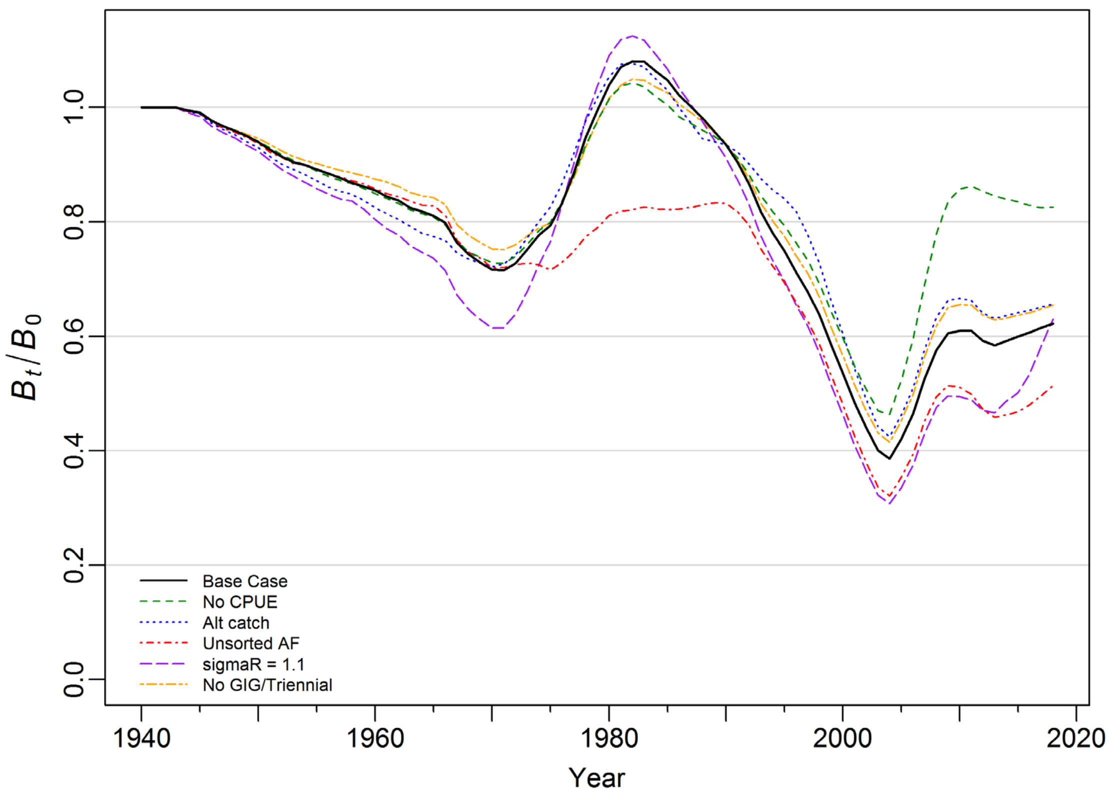

Figure 12. BC South – Model median trajectories of spawning biomass as a proportion of unfished equilibrium biomass (B_t/B_0) for the base case and four sensitivity runs (see legend lower left).

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 $0.4B_{\text{MSY}}$ and the upper stock reference point (USR) of $0.8B_{\text{MSY}}$, which have been adopted by previous rockfish assessments (Edwards et al. 2012 a,b; Edwards et al. 2014 a,b; Starr et al. 2014, 2016; Starr & Haigh 2017) 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 $0.4B_{\text{MSY}}$ is termed the "critical zone" by the SFF, the zone lying between $0.4B_{\text{MSY}}$ and $0.8B_{\text{MSY}}$ is termed the "cautious zone", and the region above the upper stock reference point ($0.8B_{\text{MSY}}$) 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., $P(B_t > 0.4B_{\text{MSY}})$ and $P(B_t > 0.8B_{\text{MSY}})$. The SSF 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 2018" because the value is calculated as the ratio of two estimated biomass values (B_{2018}/B_{MSY}) by a specific model using the data available in 2018. 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. Presenting multiple stock status results in one figure is used for convenience and represents our perception of how these models compare.

Other jurisdictions use 'proxy' reference points that are expressed in terms of B_0 rather than B_{MSY} (e.g. New Zealand Ministry of Fisheries 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 E.3. 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. We also give results comparing projected biomass to two more reference points: B_{MSY} and the current biomass, B_{2018} (E.3).

9.2. BASE CASE

Figure 13 shows that (based on medians), both RSR stocks (BC North and BC South) are estimated to have been in the healthy zone for the entire historical fishing period. For the northern stock, the spawning biomass is currently estimated to be above $0.4B_{\text{MSY}}$ with probability $P(B_{2018}>0.4B_{\text{MSY}}) = 1$ and above $0.8B_{\text{MSY}}$ with probability $P(B_{2018}>0.8B_{\text{MSY}}) = 0.999$. For the southern stock, the spawning biomass is currently estimated to be above $0.4B_{\text{MSY}}$ with a probability of 1 and above $0.8B_{\text{MSY}}$ with a probability of 1. Figure 14 shows the current stock status (B_{2018}/B_{MSY}) boxplots for the two RSR stocks, both of which are estimated to be in the healthy zone.

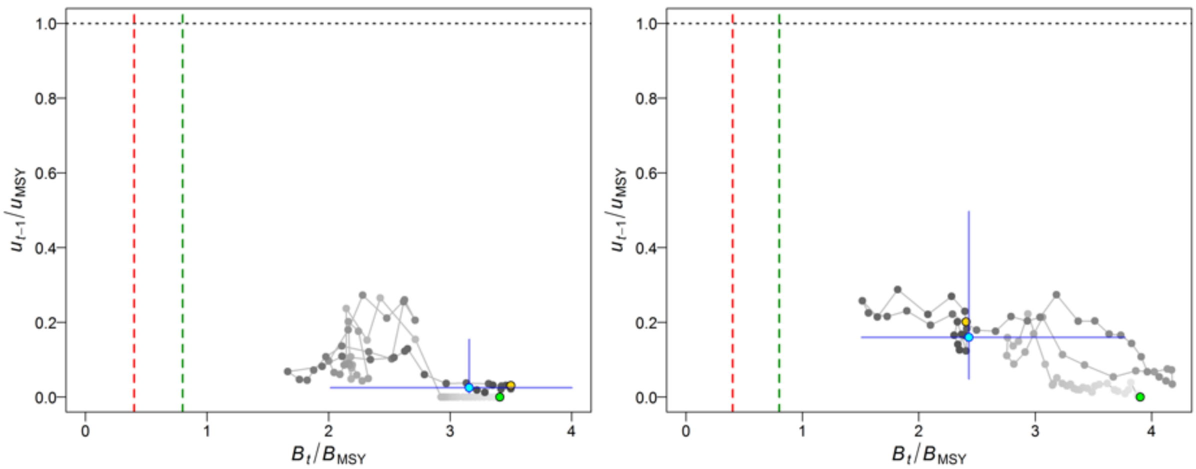

Figure 13. Phase plot (left: BC North, right: BC South) through time of the medians of the ratios B_t/B_{MSY} (the spawning biomass at the start of year t relative to B_{MSY}) and u_{t-1}/u_{MSY} (the exploitation rate in the middle of year t-1 relative to u_{MSY}). The filled green circle is the starting year (1941). Years then proceed from light grey through to dark grey with the final year (t=2018) as a filled cyan circle, and the blue lines represent the 5% and 95% quantiles of the posterior distributions for the final year. The filled gold circle indicates the status in 2010 (B_{2010}/B_{MSY}, u_{2009}/u_{MSY}), which coincides with the previous assessment of this stock. 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}.

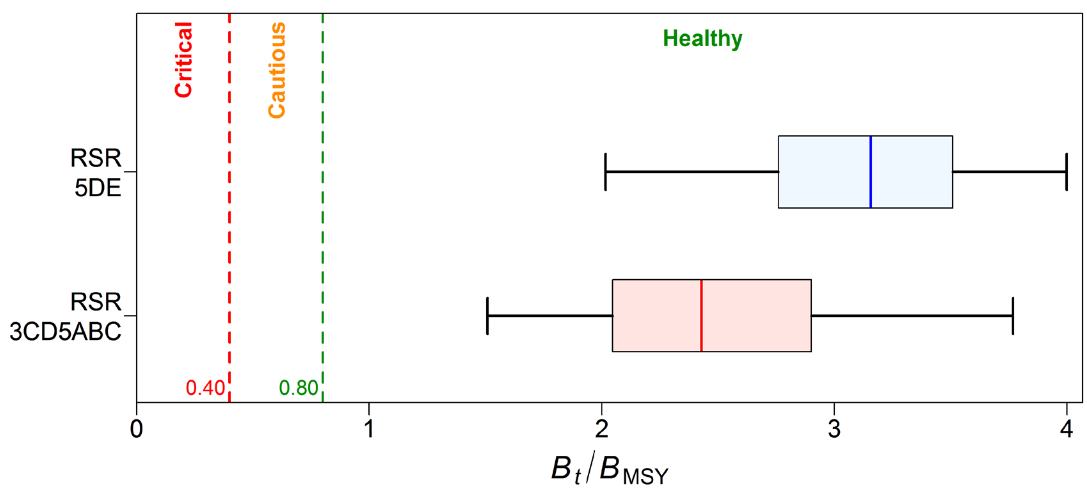

Figure 14. Status of RSR stocks 5DE (BC North) and 3CD5ABC (BC South) relative to the DFO PA provisional reference points of $0.4B_{MSY}$ and $0.8B_{MSY}$ for the t=2018 base case models. Boxplots show the 0.05, 0.25, 0.5, 0.75 and 0.95 quantiles from the MCMC posterior.

9.3. SENSITIVITY RUNS

The first four sensitivity scenarios are the same for each stock. Their effects vary by stock, primarily due to data availability: data are much sparser for the northern stock than they are for the southern one. Sensitivity comparisons appear in Table F.14 and Figure 15 for BC North and in Table F.27 and Figure 16 for BC South.

Figure 15 demonstrates that removing the commercial bottom trawl CPUE (S1) has very little effect on stock status in BCN. However, the MCMC diagnostics showed unstable sample traces and high autocorrelation, rendering this sensitivity unacceptable as a credible alternative to the base case for the northern stock. In BCS, removing CPUE does not cause instability in the MCMC samples, but it does improve stock status (Figure 16). This run is considered to be credible for the southern stock.

Reducing catch during years of peak foreign fleet activity and pre-observer domestic fleet activity (S2) has no great impact on the stock status estimates for either stock. The same is true when age frequencies from unsorted samples (S3) provide the only composition signal in BCN, primarily because the availability of earlier sorted samples is not great and, subsequently, their removal has little effect. In BCS, removing the early composition data (S3) reduces the stock status because the reconstruction of good recruitment in the 1970s has no supporting signal from the composition data which disappear when the sorted samples are dropped from the analysis.

In BCN, the sensitivity run (S4) that provides more freedom in choosing recruitment process error (by specifying *a priori* a larger standard deviation, σ_R) finds a different population trajectory from the ones found in the base case and the alternative trajectory found by the first three sensitivities (Figure 7). The primary driver behind this difference is the greater divergence in the sex-specific estimated M – with the female M 22% lower than the base case M and the male M 20% greater than the equivalent base case M (Table F.13). Despite good MCMC diagnostics and showing an even greater sex-specific divergence of M than seen in the southern stock, the data for the northern stock are likely too sparse to provide certainty on which trajectory is correct. The shift in the BCN population trajectory is due to the widening of the male and female M estimates, not to the increased estimate of σ_R. This conclusion comes from two additional diagnostic sensitivity runs (D1 and D2, reported in E.3) which fixed the male and female M to values of 0.11 while setting σ_R to values of 0.6 and 1.1. These two diagnostic runs have similar population trajectories and recruitment patterns as the BCN base case (Figure F.43). Increasing σ_R in the BCS made little difference because the underlying data used to estimate natural mortality allowed for more robust estimation of these parameters (Figure F.105), showing consistent estimates of M in each sensitivity run (Table F.27).

The review meeting participants requested two additional diagnostic sensitivities (D3 and D4) for each stock with priors $M \sim N(0.136, 0.0136)$ [10%CV] and $M \sim N(0.136, 0.0272)$ [20%CV]. The mean of these priors assumed M was based on a maximum age of 50 y instead of 61 y used in the base case. Given that these runs were made overnight at the review meeting, only the MPD results could be presented to the participants and consequently MCMC results are not reported. In BCN, the base case estimates of $M_{1,2}$ = (0.108, 0.118) increased to $M_{1,2}$ = (0.131, 0.142) and $M_{1,2}$ = (0.135, 0.144) for D3 and D4. These results indicate that there is insufficient information in the BCN data to move the estimate away from the prior mean for either sex with little sensitivity to increasing the CV on the prior mean. The spawning stock status in the final year relative to the unfished equilibrium (B_{2018}/B_0) increased by about 10% from 1.10 in the base case to 1.18 (D3) and 1.20 (D4).

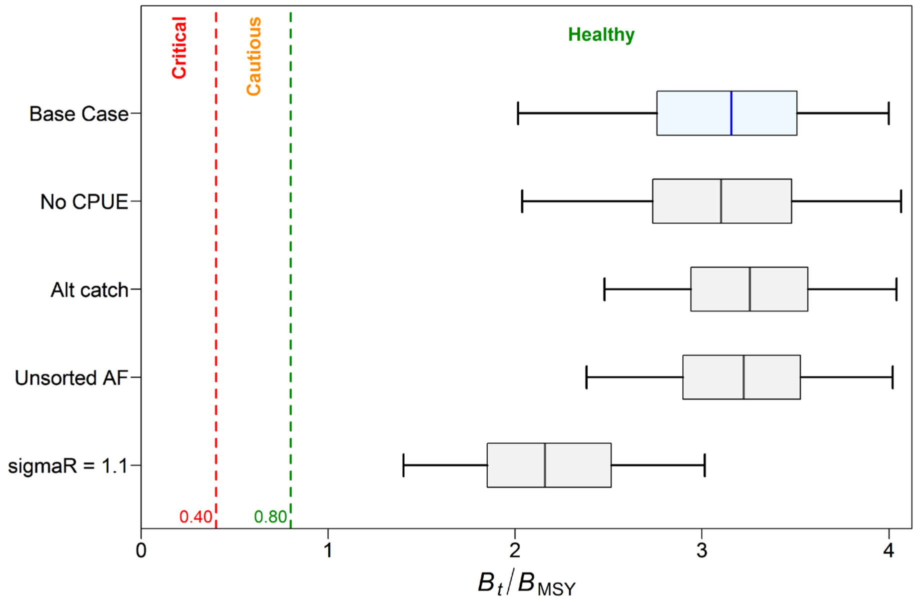

Figure 15. BC North – Stock status at beginning of 2018 of the 5DE RSR stock relative to the DFO PA provisional reference points of 0.4B_{MSY} and 0.8B_{MSY} for the base case stock assessment and four sensitivity runs (S1=drop commercial trawl CPUE; S2=halve the 1965-75 and 1988-1995 catches; S3=use age frequencies from unsorted samples only; S4=increase standard deviation of σ_R from 0.6 to 1.1). Boxplots show the 0.05, 0.25, 0.5, 0.75 and 0.95 quantiles from the MCMC posterior. E.3 contains the details of these sensitivity runs.

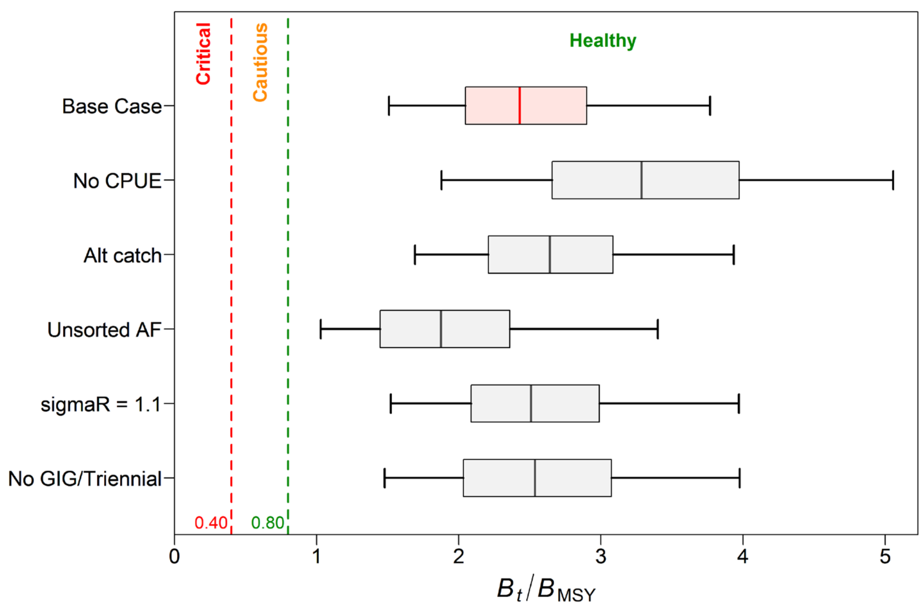

Figure 16. BC South – Stock status at beginning of 2018 of the 3CD5ABC RSR stock relative to the DFO PA provisional reference points of 0.4B_{MSY} and 0.8B_{MSY} for the base case stock assessment and five sensitivity runs (S1=drop commercial trawl CPUE; S2=halve the 1965-75 and 1988-1995 catches; S3=use age frequencies from unsorted samples only; S4=increase standard deviation of σ_R from 0.6 to 1.1; S5=remove GIG Historical and WCVI Triennial surveys). Boxplots show the 0.05, 0.25, 0.5, 0.75 and 0.95 quantiles from the MCMC posterior. E.3 contains the details of these sensitivity runs.

In BCS, the estimate of $M_{1,2}$ = (0.092, 0.126) in the base case increased to $M_{1,2}$ = (0.119, 0.151) and $M_{1,2}$ = (0.111, 0.147) for D3 and D4. Unlike for the BCN stock, the response by the BCS stock differed by sex with the two diagnostic runs estimating female M at a level lower than the prior mean while the male M estimates rose about 10% above the prior mean. These results are consistent with the MPD BCS base case results, where the M estimates by sex diverged in the same manner relative to the prior mean (see Table F.15). The shifts in spawning stock status in the final year relative to unfished equilibrium (B_{2018}/B_0) was greater for the BCS stock than for the BCN stock, with the MPD estimate of 0.61 in the base case increasing by more than 30% to 0.85 (D3) and 0.80 (D4). For both stocks, increasing the M prior mean resulted in higher levels of B_{2018} spawning stock biomass relative to B_0.

9.4. PROJECTION RESULTS AND DECISION TABLES

Five year projections (BCN: Figure 17; BCS: Figure 18) were made for the two base case model runs to evaluate the future behaviour of the population under different levels of constant catch, given the model assumptions and were applied without feedback controls. The projections, starting with the biomass at the beginning of 2018, were made over a range of constant catch strategies, including one that reflected recent mean catch, for each of the 1,000 MCMC samples in the posterior, generating a distribution of future biomass trends. Future recruitments were generated through the stock-recruitment function using recruitment deviations drawn randomly from a lognormal distribution with zero mean and a constant standard deviation of 0.6 (see Appendix E for a description of this procedure). At current average catches of 109 t in BCN and 732 t in BCS, the catch strategies of 100 t in Figure 17 and 700 t in Figure 18, respectively, show approximately how the projections would look if catch were to continue at these levels. The assumptions used for recruitment have only a small effect on the projections because the majority of the year classes in the five-year projection were estimated by the reconstruction procedure.

Decision tables are presented (in Appendix E, and in Table 5 and Table 6) with respect to the reference points outlined in Section 9.1. Each table expresses the probability that B_t (or u_t), where t = 2018...2023, will exceed the reference point in question under each constant catch strategy. 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_t exceeds an LRP whereas exceeding a USR might only require a 50% probability. Assuming this risk profile, all catch policies in Table 5 and Table 6 could be adopted to be 95% certain that the spawning biomass would remain above $0.4B_{\text{MSY}}$ at the start of 2023. Similarly, all catch policies in Table 5 and Table 6 could be adopted to be 50% certain that the spawning biomass is above $0.8B_{\text{MSY}}$ at the start of 2023. These tables also show that there is at least a 95% probability that harvest rates will be less than u_{MSY} in 2023 at annual catches of 500 t or less in BCN and 1300 t or less in BCS. The harvest reference removal rate guidance of the SFF is potentially the only reference point for the two RSR stocks that provides contrasting harvest advice for managers.

We caution that, although uncertainty is built into the assessment and its projections by taking a Bayesian approach for parameter estimation, 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 RSR 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 5. BC North – 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 base case model. Values are the probability (proportion of 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 (2013-2017) is 109 t.

	$P(B_t > 0.4B_{MSY})$						$P(B_t > 0.8B_{MSY})$						$P(u_t < u_{MSY})$					
Catch	2018	2019	2020	2021	2022	2023	2018	2019	2020	2021	2022	2023	2018	2019	2020	2021	2022	2023
0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
100	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
200	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
300	1	1	1	1	1	1	1	1	1	1	1	1	1	0.99	0.99	0.99	0.99	0.99
400	1	1	1	1	1	1	1	1	1	1	1	1	0.99	0.99	0.98	0.98	0.97	0.97
500	1	1	1	1	1	1	1	1	1	1	1	1	0.98	0.97	0.97	0.97	0.96	0.95
600	1	1	1	1	1	1	1	1	1	1	1	1	0.97	0.96	0.95	0.94	0.93	0.92
700	1	1	1	1	1	1	1	1	1	1	1	0.99	0.96	0.95	0.94	0.92	0.90	0.88
800	1	1	1	1	1	1	1	1	1	1	0.99	0.98	0.95	0.94	0.92	0.89	0.86	0.82
900	1	1	1	1	1	1	1	1	1	0.99	0.98	0.97	0.94	0.92	0.89	0.86	0.81	0.75
1000	1	1	1	1	1	1	1	1	1	0.99	0.98	0.95	0.93	0.90	0.87	0.82	0.76	0.68
1100	1	1	1	1	1	0.99	1	1	1	0.99	0.97	0.92	0.91	0.88	0.84	0.78	0.69	0.58
1200	1	1	1	1	1	0.99	1	1	0.99	0.98	0.95	0.88	0.90	0.86	0.82	0.72	0.61	0.49
1300	1	1	1	1	0.99	0.99	1	1	0.99	0.98	0.93	0.85	0.89	0.85	0.79	0.67	0.54	0.42
1400	1	1	1	1	0.99	0.99	1	1	0.99	0.97	0.90	0.81	0.88	0.83	0.73	0.62	0.47	0.35
1500	1	1	1	1	0.99	0.99	1	1	0.99	0.95	0.87	0.79	0.87	0.81	0.70	0.56	0.40	0.27
1600	1	1	1	1	0.99	0.99	1	1	0.99	0.94	0.84	0.76	0.85	0.79	0.66	0.51	0.35	0.22
1700	1	1	1	0.99	0.99	0.99	1	1	0.98	0.92	0.80	0.73	0.84	0.77	0.63	0.44	0.28	0.18
1800	1	1	1	0.99	0.99	0.99	1	1	0.98	0.89	0.78	0.72	0.83	0.74	0.59	0.39	0.23	0.13
1900	1	1	1	0.99	0.99	0.99	1	1	0.98	0.88	0.76	0.70	0.82	0.70	0.54	0.34	0.20	0.10
2000	1	1	1	0.99	0.99	0.99	1	1	0.97	0.84	0.74	0.68	0.80	0.68	0.51	0.29	0.16	0.08

Table 6. BC South – 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 base case model. See Table 5 caption for details. For reference, the average catch over the last 5 years (2013-2017) is 732 t.

	$P(B_t > 0.4B_{MSY})$						$P(B_t > 0.8B_{MSY})$						$P(u_t < u_{MSY})$					
Catch	2018	2019	2020	2021	2022	2023	2018	2019	2020	2021	2022	2023	2018	2019	2020	2021	2022	2023
0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
100	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
200	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
300	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
400	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
500	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
600	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
700	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
800	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
900	1	1	1	1	1	1	1	1	1	1	1	1	0.99	0.99	0.99	0.99	0.99	0.99
1000	1	1	1	1	1	1	1	1	1	1	1	1	0.99	0.99	0.99	0.99	0.99	0.98
1100	1	1	1	1	1	1	1	1	1	1	1	1	0.99	0.98	0.98	0.98	0.98	0.97
1200	1	1	1	1	1	1	1	1	1	1	1	1	0.98	0.98	0.97	0.97	0.97	0.97
1300	1	1	1	1	1	1	1	1	1	1	1	1	0.97	0.97	0.97	0.96	0.95	0.95
1400	1	1	1	1	1	1	1	1	1	1	1	1	0.96	0.96	0.95	0.95	0.94	0.93
1500	1	1	1	1	1	1	1	1	1	1	1	1	0.95	0.94	0.94	0.93	0.92	0.91
1600	1	1	1	1	1	1	1	1	1	1	1	0.99	0.94	0.93	0.92	0.91	0.90	0.89
1700	1	1	1	1	1	1	1	1	1	1	1	0.99	0.93	0.92	0.91	0.90	0.89	0.86
1800	1	1	1	1	1	1	1	1	1	1	1	0.99	0.92	0.90	0.89	0.88	0.86	0.84
1900	1	1	1	1	1	1	1	1	1	1	0.99	0.98	0.91	0.89	0.88	0.86	0.83	0.81
2000	1	1	1	1	1	1	1	1	1	1	0.99	0.98	0.90	0.88	0.86	0.83	0.81	0.78

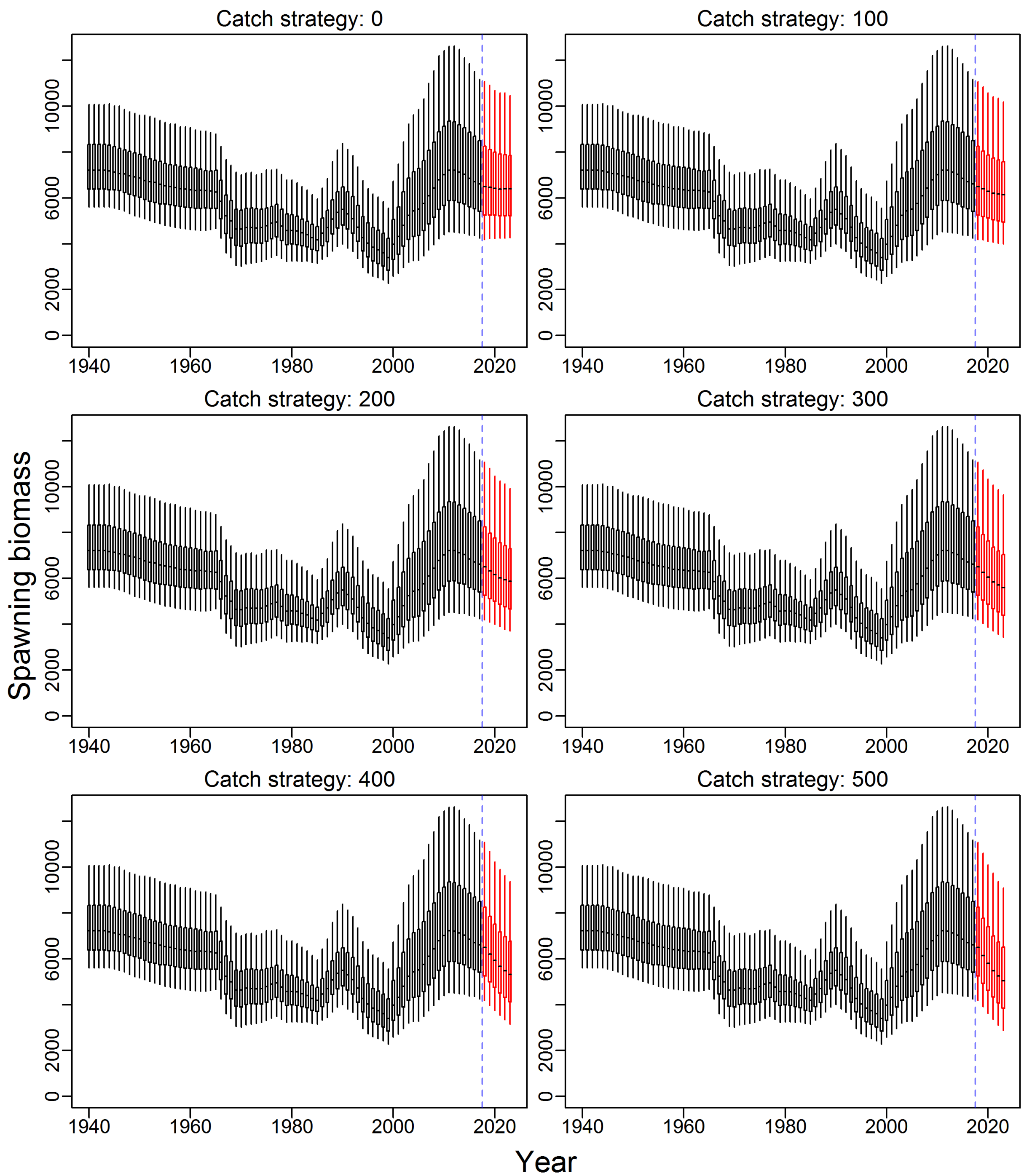

Figure 17. BC North – Projected biomass (t) under different constant catch strategies (t); boxplots show the 0.05, 0.25, 0.5, 0.75 and 0.95 quantiles from the MCMC results for the base-case model run. For each of the 1,000 samples from the MCMC posterior, the model was run forward in time (red, with medians in black) with a constant catch, and recruitment was simulated from the stock-recruitment function with lognormal error (see equation E.24). For reference, the average catch over the last 5 years (2013-2017) is 109 t.

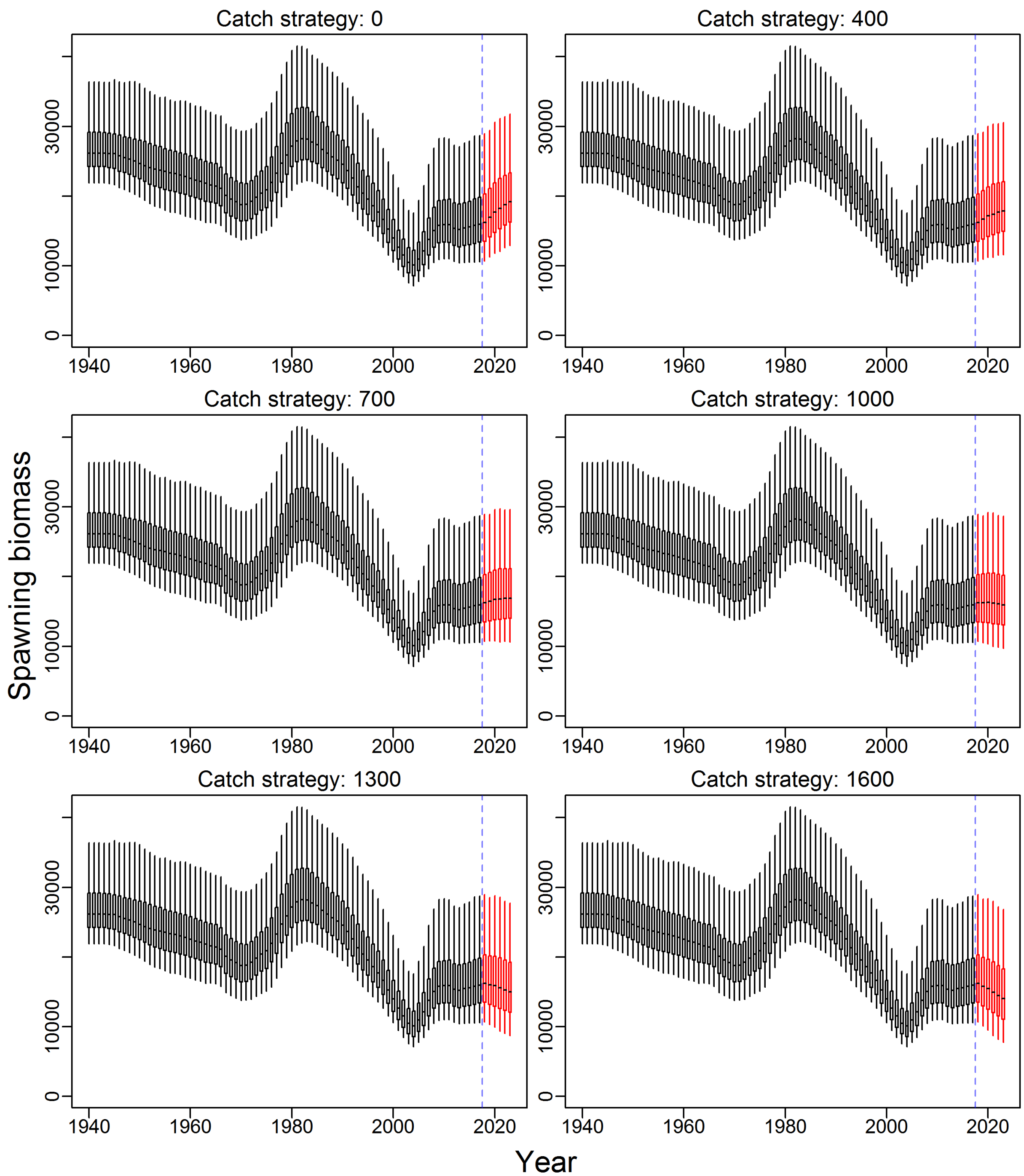

Figure 18. BC South – Projected biomass (t) under different constant catch strategies (t); boxplots show the 0.05, 0.25, 0.5, 0.75 and 0.95 quantiles from the MCMC results for the base-case model run. For each of the 1,000 samples from the MCMC posterior, the model was run forward in time (red, with medians in black) with a constant catch, and recruitment was simulated from the stock-recruitment function with lognormal error (see equation E.24). For reference, the average catch over the last 5 years (2013-2017) is 732 t.

9.5. 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 for 2023, such that there will be three new indices each from the four synoptic surveys and five years of commercial fleet ageing and catch data. Note that *advice* for the interim years is explicitly included in this assessment in the form of the decision tables.

10. GENERAL COMMENTS

As in all previous BC rockfish stock assessments, this assessment depicts a slow-growing, low productivity stock. Redstripe Rockfish is considered to be partially benthic, forming groups near the bottom but not on the bottom. They prefer areas of high-relief and rugged terrain, and reportedly migrate vertically at night and disperse (Love at 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 plus additional process error give the model a lot of room to fit abundance trends to the observed survey indices, and consequently, the results are more uncertain than fits to species with lower relative errors for the biomass surveys.

Foreign fleet effort in 1965-76 along the BC coast targeted POP, and RSR catch for these years was estimated as an assumed bycatch; therefore, the magnitude of the foreign fleet removals of RSR is uncertain. In BC North, the first big drop in the ratios of B_t/B_0 and V_t/V_0 reflects the transition from virtually no catch to substantial removals by the foreign fleet (1965-76), peaking at ~1000 t in 1966 (Figure 4). In BC South, depletion of RSR by this fleet does not appear to be strong, probably due to lower exploitation rates associated with a larger stock size (Figure 9).

Another source of uncertainty in the catch series was identified by the technical working group, 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 2018 population stock size (Figure 7, Figure 12).

The biggest source of uncertainty for the assessment of the BCN stock is the sparse amount of supporting data. While model fits were surprisingly good for most of the runs, the base case, three sensitivity runs (S1, S2, S3) and the S4 sensitivity run (with higher σ_R) each found different credible population trajectories with changed input assumptions. Specifically, increasing the standard deviation of the recruitment process error (σ_R) from 0.6 to 1.1 allowed the model to find an alternate set of sex-specific natural mortality estimates and estimated strong year classes in different years. The three sensitivity runs S1-S3 also estimated different strong recruitment years, but the estimates of M were closer to those of the base case. A similar change in σ_R to the BCS model did not change the model outcome substantially. There are no strong criteria for deciding which model is "best" for the BCN stock.

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, the RSR caught by bottom trawl gear was assumed to be entirely bycatch while vessel operators targeted some other species. Also the TACs appear to be well underutilised (see Appendix A), resulting in less pressure to obtain quota to cover catches. The CPUE index was essential for getting credible model fits to the BCN data. In BCS, removing CPUE caused instability for some of the estimated parameters; however, the model is credible and presents the most optimistic scenario with respect to current stock status (Figure 12).

Reconstructed recruitment events come from signals in the age frequency (AF) data. As mentioned above, the BCN base case had two large recruitment pulses centred on 1996 and 1982; however, the four sensitivity runs estimated the highest recruitment years to be 1982 and 2002, in descending order of magnitude. High recruitment pulses identified in the BCS runs (excluding the truncated AF run) were more consistent, with modes in 2001, 1974, and 1969, varying in magnitude only. The episodic nature of RSR recruitment (3-5 above-average pulses over 8 decades) is typical for *Sebastes* species. Also typical is the smearing of peaks due to ageing error.

Current stock status relative to the management target levels appears to be firmly in the healthy zone for both stocks, a conclusion which holds for each base case run and the associated sensitivity runs (Figure 13). The MCMC medians of $B_{2018}/B_{\mathrm{MSY}}$ and $u_{2017}/u_{\mathrm{MSY}}$ are 3.156 and 0.025 in BCN (Table 2) and 2.429 and 0.160 in BCS (Table 4). Projections to 5 years indicate that the B_{MSY} reference points provide no guidance other than to say that the biomass will remain healthy at catches up to 2000 t. The u_{MSY} reference point, however, suggests that catches in excess of 500 t in BCN and 1300 t in BCS will breach the SFF guidelines on fishing mortality, assuming that the manager wishes to be 95% certain that u_{2023} will be less than u_{MSY} (Table 5, Table 6).

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 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 the four synoptic groundfish surveys initiated in the previous decade will continue to provide monitoring capability for RSR. 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 is taken when required.

11. FUTURE RESEARCH AND DATA REQUIREMENTS

The following issues should be considered when planning future stock assessments and management evaluations for Redstripe 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. Develop informed priors specific to RSR for survey selectivity parameters. Using selectivity priors based on the POP posteriors was essential for placing meaningful bounds on survey

selectivity for this stock assessment; however, it is not known if these priors affected the scaling of biomass levels. Alternatively, the accumulation of additional age frequency data prior to the next stock assessment may allow the model(s) to proceed using uniform priors.

3. Conduct genetic sampling to clarify RSR stock structure along the BC coast.
4. Include the HS Synoptic survey when indexing the BCS stock, and exclude it from BCN, in the next formal RSR stock assessment in 2023. Data from 5D used in the CPUE analysis and the biological analyses should also be assigned to the BCS stock.
5. Ensure that the WCVI Triennial abundance index series discards water hauls from the analysis.
6. Explore the incorporation of ageing error into the next RSR stock assessment.
7. Increase the level of biological sampling of midwater trawl catch of RSR with the intent of including this fishery as a separate component in the next scheduled stock assessment.
8. Explore the potential to incorporate length data into the model for years with no age sampling.
9. Explore additional sensitivity runs on important model parameters, such as *M* and *h*.
10. Search for evidence that the BCN RSR stock may be the southern extent of an Alaskan population (transboundary).
11. Monitor available publications for published work on skip spawning, maturity, and fecundity, particularly from the Northwest Fisheries Science Center (Seattle WA).
12. Explore how single populations, such as RSR, 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 RSR population dynamics and resilience.
13. Explore the effects of climate change on RSR populations and identify how shifts in the ecosystem affect our perception of equilibrium conditions under different climate regimes.

12. ACKNOWLEDGEMENTS

Allan Hicks (IPHC) has previously supported the Awatea version of Coleraine stock assessment model used in this assessment. The staff in the Aging Lab at PBS were, as always, quick to process RSR otolith requests. Members of the RSR technical working group – Rob Tadey, Brian Mose, Greg Workman, Chris Grandin, and Bruce Turris – were very helpful during two meetings to review data inputs and model outputs. Written peer reviews and meeting participation by three reviewers – Kendra Holt (PBS, DFO), Cindy Tribuzio (AFSC, NOAA), and Vladlena Gertseva (NWFSC, NOAA) – provided helpful guidance and discussion during the regional peer review (RPR) meeting. Additional diagnostic plots by Sean Anderson facilitated the RPR discussion, and other RPR participants contributed generously to the process.

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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 never reached the levels of those 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 Redstripe Rockfish (RSR, *Sebastes proriger*) in 1993 for the BC coast (Table A.1 and Table A.2). In 1994-95, RSR was managed in aggregates with other rockfish species; however, this was abandoned in 1996 once the at-sea observer program became operational. Thereafter, the IVQ (individual vessel quota) system set up TACs (total allowable catches) in four stock areas: 3C, 3D5AB, 5CD, and 5E (see Figure A.1 for individual management areas). Meanwhile the hook and line fishery was allocated its own area-based TACs in 2006. Management has largely kept the TAC values unchanged since 2001, likely due to the absence of stock assessment advice.

The last official stock assessment for RSR was presented in 1999 (Schnute-etal:1999) as the final in a series of annual assessments of a multi-species slope rockfish complex from 1993 to 1999. These assessments did not evaluate stock status in relation to reference points. An attempt was made to assess RSR in 2011 as part of a simultaneous stock assessment of five rockfish species (Taylor et al 2011[1]); however, this document was not accepted for providing management advice by the regional peer review committee (DFO 2015).

The RSR trawl fishery spans the BC coast (Figure A.2) with apparent high CPUE densities off southern and northwestern Vancouver Island, along the canyon walls in Queen Charlotte Sound, and off Haida Gwaii's Rennell Sound.

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.3), 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, 2016, version 1.5).

Additional management actions appear in Table A.2.

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[1] Taylor, N., Stanley, R., Starr, P., Rutherford, K. and Haigh, R. 2011. A simultaneous stock assessment of five rockfishes in British Columbia waters: Splitnose Rockfish, Greenstriped Rockfish, Redstripe Rockfish, Harlequin Rockfish, Sharpchin Rockfish. Unpubl. manuscr.

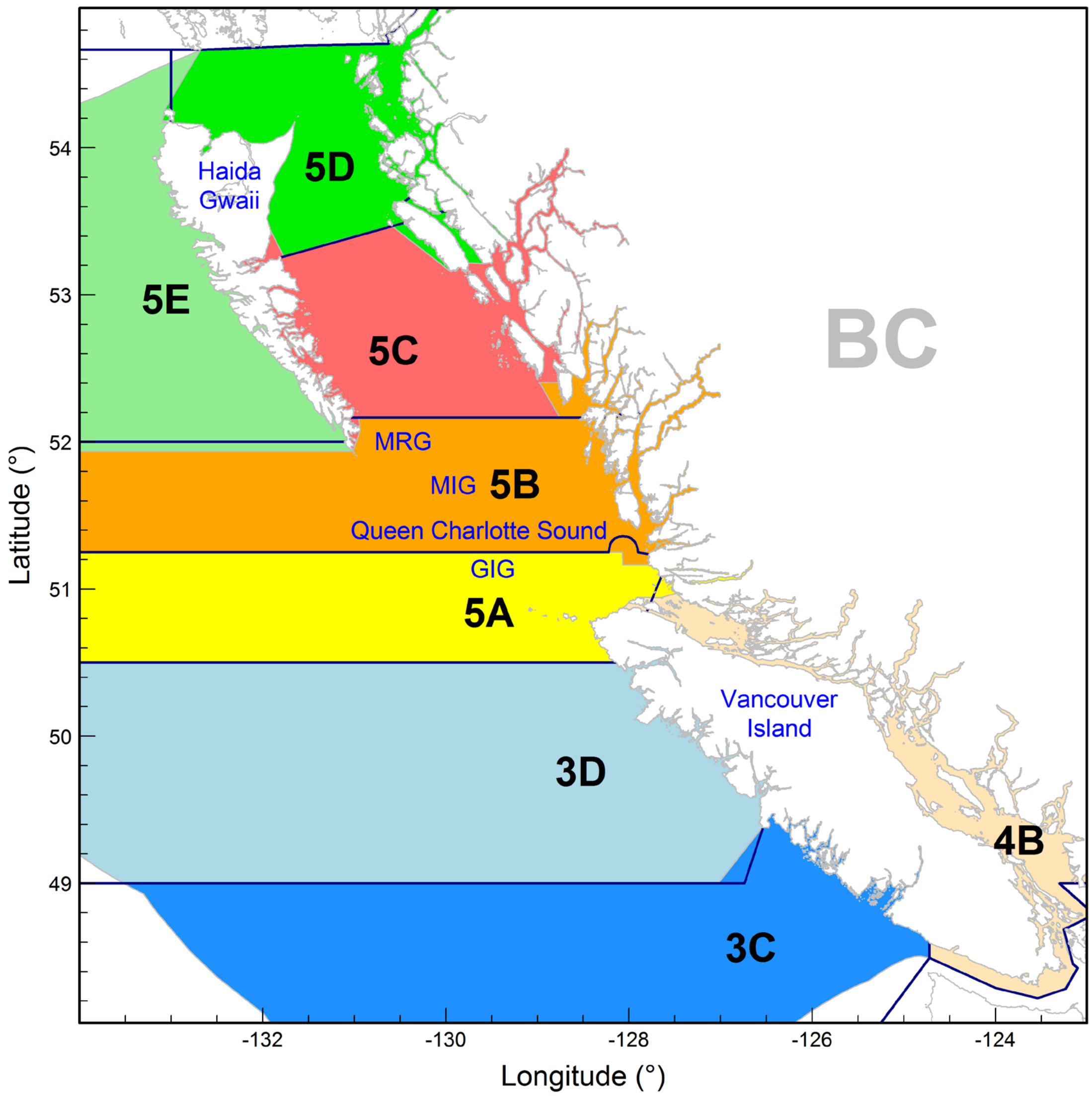

Figure A.1. Pacific Marine Fisheries Commission (PMFC) major areas (outlined in dark blue) compared with Groundfish Management Unit areas for RSR (shaded). For reference, the map indicates Goose Island Gully (GIG), Mitchell's Gully (MIG), and Moresby Gully (MRG). This assessment covers two stocks: BC North = 5DE and BC South 3CD5ABC.

Table A.1. Annual trawl Total Allowable Catches (TACs) in tonnes for RSR in groundfish management areas. Notes: year can either be calendar year (1993-1996) or fishing year (1997 on); TACs for trawl and ZN delimited by '⁝' symbol; A2 = all-fisheries aggregate 2 with aggregate TAC specified in parentheses; A5 = H&L aggregate 5 (see Table A.2 for aggregate details and management actions indicated by note letter).

Year	Start	End	3C	3D5AB	5CD	5E	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	-	-	-	-	A2(7320)	c,d
1996	2/6/1996	3/31/1997	-	-	-	-	2024	E
1997	4/1/1997	3/31/1998	150	1198	49	226	1623⁝A5	f,g
1998	4/1/1998	3/31/1999	178	794	339	253	1562⁝A5	-
1999	4/1/1999	3/31/2000	178	794	339	253	1562⁝A5	-

Year	Start	End	3C	3D5AB	5CD	5E	Coast	Notes
2000	4/1/2000	3/31/2001	178	794	339	253	1562⁝A5	-
2001	4/1/2001	3/31/2002	173	772	330	246	1521⁝A5	-
2002	4/1/2002	3/31/2003	173	772	330	246	1521⁝A5	h
2003	4/1/2003	3/31/2004	173	772	330	246	1521⁝A5	-
2004	4/1/2004	3/31/2005	173	772	330	246	1521⁝A5	-
2005	4/1/2005	3/31/2006	173	772	330	246	1521⁝A5	-
2006	4/1/2006	3/31/2007	173⁝5	772⁝22	330⁝9	246⁝7	1521⁝43	i,j
2007	3/10/2007	3/31/2008	173⁝5	772⁝22	330⁝9	246⁝7	1521⁝43	-
2008	3/8/2008	2/20/2009	173⁝5	772⁝22	330⁝9	246⁝7	1521⁝43	-
2009	2/21/2009	2/20/2010	173⁝5	772⁝22	330⁝9	246⁝7	1521⁝43	-
2010	2/21/2010	2/20/2011	173⁝5	772⁝22	330⁝9	246⁝7	1521⁝43	-
2011	2/21/2011	2/20/2013	173⁝5	772⁝22	330⁝9	246⁝7	1521⁝43	-
2012	2/21/2011	2/20/2013	173⁝5	772⁝22	330⁝9	246⁝7	1521⁝43	k
2013	2/21/2013	2/20/2014	173⁝5	772⁝22	330⁝9	246⁝7	1521⁝43	l
2014	2/21/2014	2/20/2015	173⁝5	772⁝22	330⁝9	246⁝7	1521⁝43	-
2015	2/21/2015	2/20/2016	173⁝5	772⁝22	330⁝9	246⁝7	1521⁝43	m
2016	2/21/2016	2/20/2017	173⁝5	772⁝22	330⁝9	246⁝7	1521⁝43	n
2017	2/21/2017	2/20/2018	173⁝5	772⁝22	330⁝9	246⁝7	1521⁝43	o

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: CAR = Canary Rockfish, POP = Pacific Ocean Perch, RER =Rougheye Rockfish, RSR = Redstripe Rockfish, SGR =Silvergray Rockfish, SKR = Shortraker Rockfish, SST = Shortspine Thornyhead, LST = Longspine Thornyhead, 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	Implemented catch limits (monthly) on rockfish aggregates for H&L.
d	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
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, 2007)
g	1997	All H&L rockfish, with the exception of Yelloweye Rockfish, shall be managed under the following rockfish aggregates: Agg 1 = Quillback & Copper Rockfish; Agg 2 = China & Tiger Rockfish; Agg 3 = Canary & Silvergray Rockfish; Agg 4 = Rougheye & Shortraker Rockfish and Shortspine & Longspine Thornyheads (Idiots); Agg 5 = Pacific Ocean Perch, Yellowmouth & Redstripe Rockfish; Agg 6 = Yellowtail, Black & Widow Rockfish; Agg 7 = all other rockfish species (*Sebastes* sp.) excluding Yelloweye Rockfish.
h	2002	Closed areas to preserve four hexactinellid (glassy) sponge reefs.
i	2006	Introduced an *Integrated Fisheries Management Plan* (IFMP) for most groundfish fisheries.
j	2006	Started 100% at-sea electronic monitoring for H&L.
k	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.
l	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: SST=1.7t; POP in 5AB=22.6t; POP in 5C=0.6t; WAP in 5CDE=2.2t, 5AB=1.2t; RSR=4.1t
m	2015	Research allocations for 2015 to account for the mortalities associated with survey catches within TACs: POP=17t; WAP=4.3t; RSR=5.1t.
n	2016	Research allocations for 2016 to account for the mortalities associated with survey catches within TACs: POP=57.1t; WAP=0.3t; RSR=11.4t.
o	2017	Research allocations for 2017 to account for the mortalities associated with survey catches within TACs: RSR=4.9t.

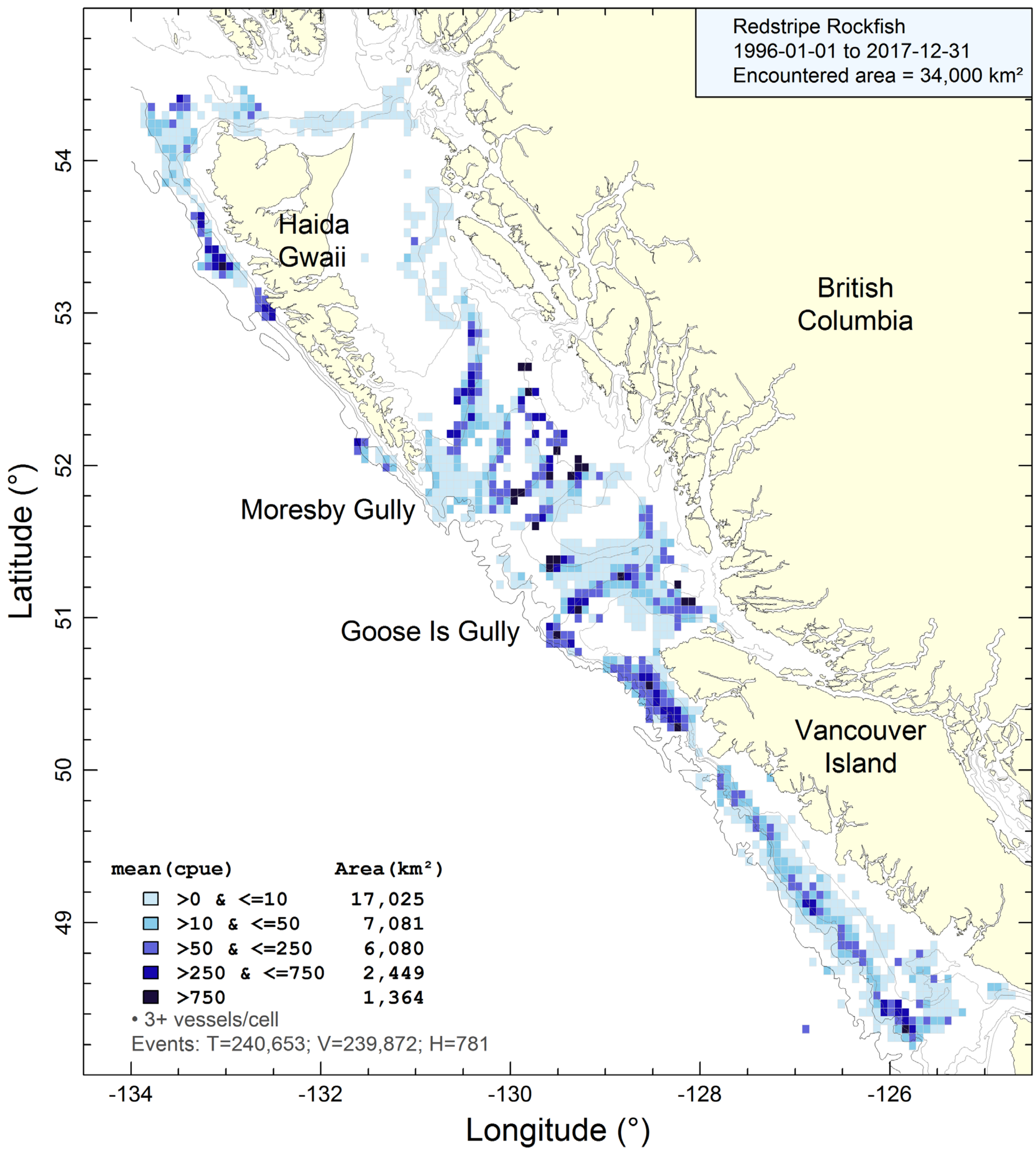

Figure A.2. Aerial distribution of Redstripe Rockfish mean trawl tow catch per unit effort (kg/hour) from 1996 to 2017 in grid cells 0.075° longitude by 0.055° latitude (roughly 32 km²). Isobaths show the 100, 200, 500, and 1200 m depth contours. Note that cells with <3 fishing vessels are not displayed.

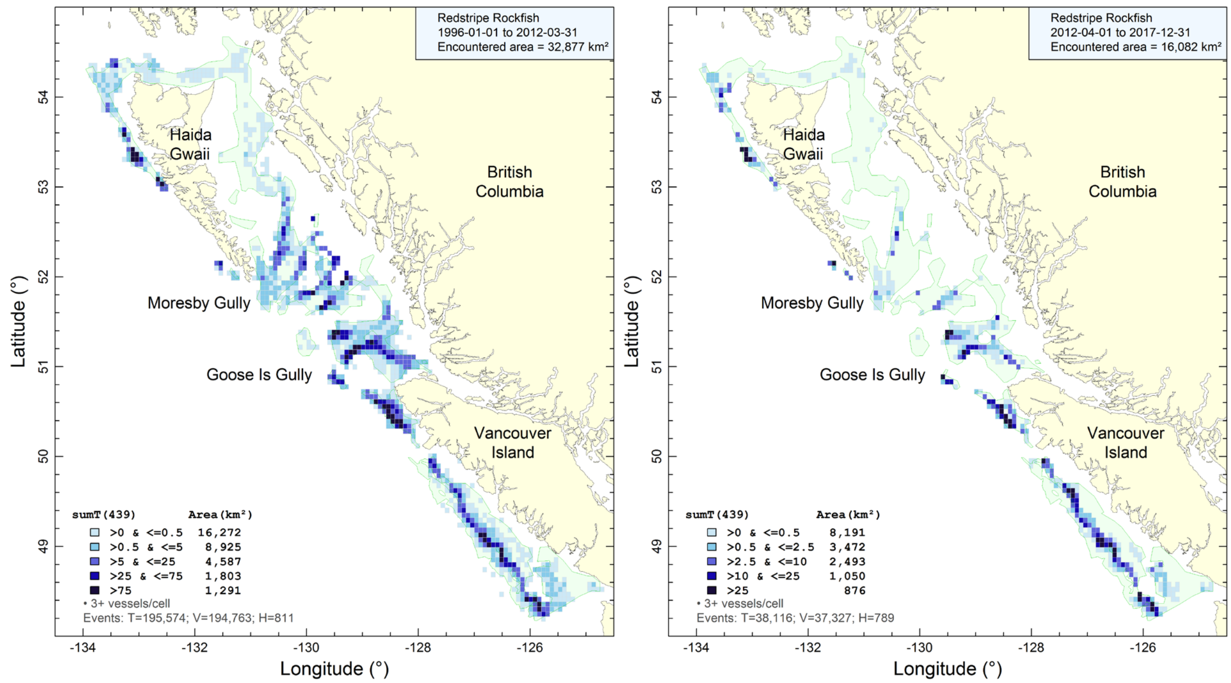

Figure A.3. Aerial distribution of accumulated Redstripe Rockfish bottom trawl catch (tonnes) before (left) and after (right) the introduction of the trawl footprint in April 2012, limiting areas in which trawl vessels can operate. Note that cells with <3 fishing vessels are not displayed.

A.2. CATCH RECONSTRUCTION

This assessment reconstructs RSR catch back to 1918 but considers the start of the fishery to be 1940 (Figure A.4) 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 RSR landings, converted to RSR (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 (formerly on the `SVBCPBSGFIIS` server). Redstripe 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 RSR 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, L =landed catch, D =releases (formerly called “discards”).

RRF: Reconstructed rockfish species – in this case, Redstripe Rockfish (RSR).

TAR: Target species landed catch.

`gamma`: mean of annual ratios, $\sum_i \mathrm{RRF}_i^L \big/ \mathrm{ORF}_i$, grouped by major PMFC area and fishery using reference years i = 1997-2005. Note: other 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 RSR 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 RSR. 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 RSR 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 RSR discarded by a fishery to fishery-specific landed targets (TAR): T = RSR, H = Pacific Halibut, S = Sablefish, DL = Spiny Dogfish + Lingcod, ZN = RSR (Table A.3).

The current annual RSR catches by trawl fishery and those from the non-trawl fisheries appear in Table A.4, Figure A.4, and Figure A.5. The combined fleet catches in two areas – BC North (5DE) and BC South (3CD5ABC) – were used in the population models (Table A.4, Figure A.6, and Figure A.7.

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[2]) 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 RSR 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 RSR 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 RSR reconstruction).

Newly introduced in this assessment, `gamma` and `delta` ratios from reference years (Section A.2.2) can be 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. Additionally, estimated RSR (using `gamma`) for landings later than 1996 can now be selected by fishery, should the user have reason to replace observed landings with estimated

[2] 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.

ones. The user can also now specify years by fishery when discard ratios are to be applied. 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.

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

gamma (proportion RSR/ORF)

PMFC	Trawl	Halibut	Sablefish	Dogfish/ Lingcod	H&L Rockfish
3C	0.0494	0	0	0.0006	0
3D	0.0309	0	0	0	0.0003
5A	0.0825	0	0	0	0.0004
5B	0.0807	0	0	0	0.0024
5C	0.0672	0	0	0	0.0008
5D	0.0020	0	0	0.0001	0.0022
5E	0.1365	0	0	0.0002	0

delta (discard rate)

PMFC	Trawl	Halibut	Sablefish	Dogfish/ Lingcod	H&L Rockfish
3C	0.3158	0	0	0	0
3D	0.2143	0	0	0	0
5A	0.1746	0	0	0	0
5B	0.2096	0	0	0	0
5C	0.2285	0	0	0	0
5D	0.1319	0	0	0	0
5E	0.0150	0	0	0	0

Table A.4. Reconstructed catches (in tonnes, landings + releases) of RSR in coastwide PMFC areas (3C to 5E combined) from each fishery; combined-fisheries totals for BC North (5DE), BC South (3CD5ABC), and BC are also given. Only those from BC North and BC South were used in the population model.

Year	Trawl	Halibut	Sablefish	Dogfish +Lingcod	H&L Rockfish	BC North	BC South	BC Coast
1940	2	0	0	0	0.002	0.003	2	2
1941	1	0	0	0	0.012	0.010	1	1
1942	20	0	0	0	0.012	0.018	20	20
1943	67	0	0	0.001	0.035	0.055	67	67
1944	29	0	0	0.001	0.048	0.046	29	29
1945	319	0	0	0.001	0.068	0.205	318	319
1946	158	0	0	0.001	0.096	0.156	158	158
1947	76	0	0	0	0.015	0.049	76	76
1948	127	0	0	0	0.024	0.083	127	127
1949	156	0	0	0	0.032	0.123	156	156
1950	284	0	0	0	0.013	0.237	284	284
1951	260	0	0	0.001	0.077	0.180	260	260
1952	225	0	0	0	0.054	0.173	224	225
1953	98	0	0	0.001	0.041	0.076	98	98
1954	173	0	0	0.001	0.044	0.121	173	173
1955	189	0	0	0.001	0.020	0.201	188	189
1956	141	0	0	0.001	0.019	0.049	141	141
1957	144	0	0	0.004	0.036	0.201	144	144
1958	164	0	0	0.001	0.017	0.095	164	164
1959	245	0	0	0.002	0.020	0.207	245	245

Year	Trawl	Halibut	Sablefish	Dogfish +Lingcod	H&L Rockfish	BC North	BC South	BC Coast
1960	211	0	0	0.002	0.040	0.287	211	211
1961	248	0	0	0.002	0.042	0.324	248	248
1962	349	0	0	0.005	0.052	0.475	349	350
1963	242	0	0	0.004	0.101	0.208	242	242
1964	209	0	0	0.002	0.035	0.259	209	209
1965	1215	0	0	0.001	0.026	636	579	1215
1966	2444	0	0	0.001	0.036	999	1446	2444
1967	1409	0	0	0.002	0.052	482	927	1409
1968	1513	0	0	0.002	0.031	694	819	1513
1969	1196	0	0	0.003	0.071	266	930	1196
1970	753	0	0	0.006	0.158	123	630	753
1971	701	0	0	0.004	0.115	203	498	701
1972	965	0	0	0.007	0.144	284	681	966
1973	1168	0	0	0.005	0.086	223	944	1168
1974	1351	0	0	0.012	0.123	156	1196	1351
1975	753	0	0	0.009	0.172	117	636	753
1976	639	0	0	0.009	0.138	138	501	639
1977	845	0	0	0.011	0.164	507	338	845
1978	1029	0	0	0.009	0.208	552	478	1030
1979	710	0	0	0.017	0.208	217	493	710
1980	810	0	0	0.015	0.209	232	578	810
1981	818	0	0	0.013	0.152	229	589	818
1982	459	0.003	0	0.019	0.086	162	297	459
1983	578	0.002	0	0.019	0.109	184	394	578
1984	776	0.003	0	0.015	0.164	277	499	776
1985	1143	0.008	0	0.020	0.355	518	626	1144
1986	1680	0.088	0.034	0.074	0.002	708	972	1681
1987	1697	0.107	0.030	0.113	0.065	464	1234	1698
1988	1860	0.103	0.037	0.110	0	504	1357	1860
1989	1657	0.090	0.038	0.078	0.106	346	1311	1658
1990	1959	0.077	0.03	0.115	11	442	1529	1970
1991	1694	0.060	0.034	0.080	8	231	1471	1702
1992	2348	0.064	0.037	0.057	0.501	412	1937	2348
1993	1974	0.096	0.041	0.037	1	533	1442	1975
1994	1708	0.087	0.040	0.040	2	389	1321	1710
1995	1558	0.105	0.039	0.076	3	231	1330	1562
1996	1162	0.078	0.034	0.033	0.677	133	1030	1163
1997	1147	0.096	0.041	0.025	1	128	1020	1148
1998	1386	0.104	0.045	0.028	0.419	177	1210	1387
1999	1182	0.098	0.046	0.038	0.663	197	986	1183
2000	1372	0.085	0.036	0.047	0.318	251	1121	1372
2001	1174	0.083	0.034	0.039	4	224	955	1179
2002	1117	0.189	0.028	0.033	0.317	220	897	1117
2003	1142	0.094	0.022	0.041	0.323	228	915	1143
2004	906	0.095	0.028	0.039	2	227	682	908
2005	978	0.111	0.047	0.038	0.823	135	844	979
2006	737	0.077	0.002	0.007	0.233	126	612	737
2007	931	0.009	0	0.012	0.121	151	780	931
2008	868	0.419	0.001	0.004	0.056	136	732	868
2009	792	0.014	0	0.017	0.072	106	686	792
2010	620	0.045	0.004	0.017	0.047	79	541	620
2011	1122	0.016	0.002	0.002	0.100	123	1000	1122
2012	992	0.045	0.001	0.012	0.089	145	847	992
2013	818	0.028	0	0.016	0.069	105	713	818

Year	Trawl	Halibut	Sablefish	Dogfish +Lingcod	H&L Rockfish	BC North	BC South	BC Coast
2014	778	0.020	0.001	0.002	0.077	162	616	778
2015	868	0.013	0	0.011	0.103	62	806	868
2016	865	0.029	0.001	0.002	0.173	92	773	865
2017	879	0.059	0.001	0	0.168	125	754	879

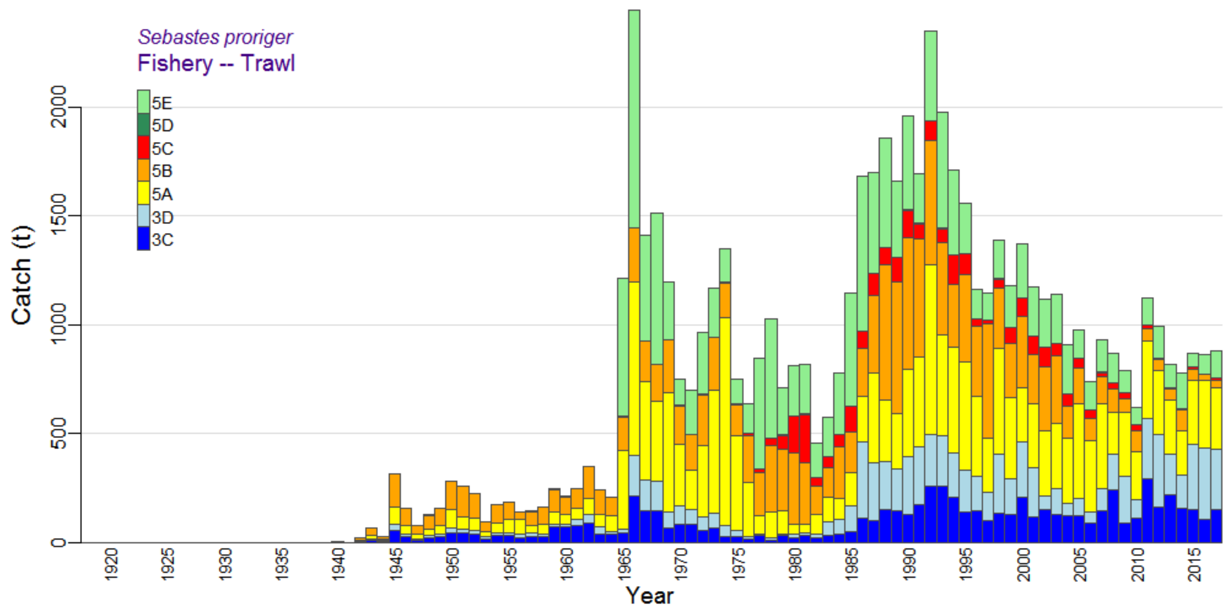

Figure A.4. Reconstructed total (landed + released) catch (t) for Redstripe Rockfish from the trawl fishery in PMFC major areas 3C to 5E. Catches from other fisheries were negligible.

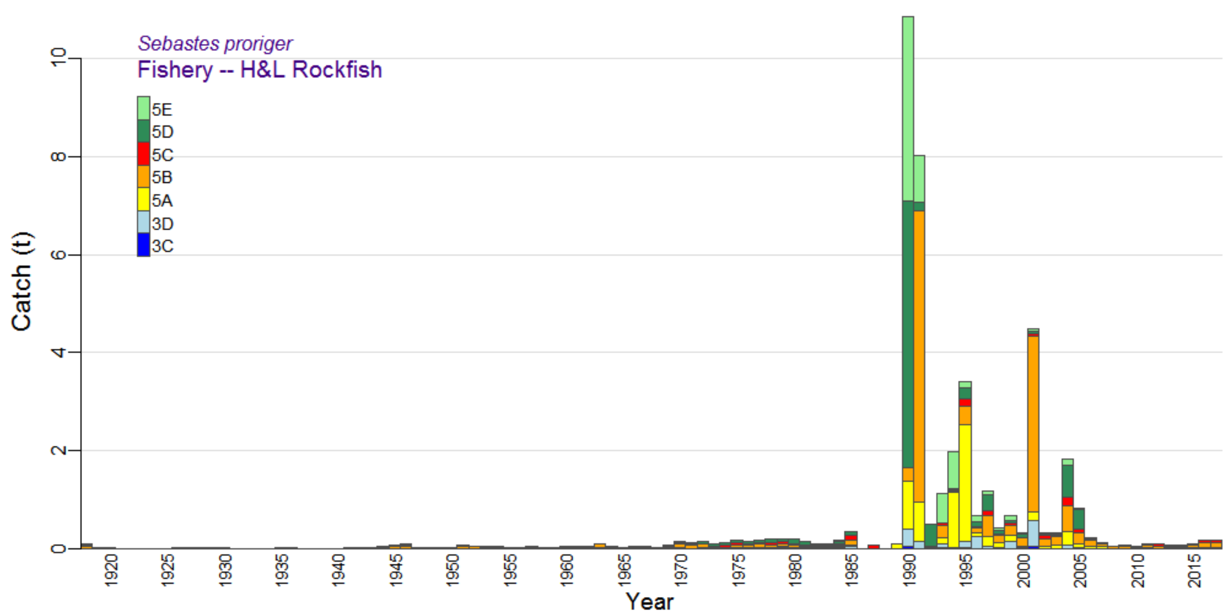

Figure A.5. Reconstructed total (landed + released) catch (t) for Redstripe Rockfish from the ZN hook and line fishery in PMFC major areas 3C to 5E.

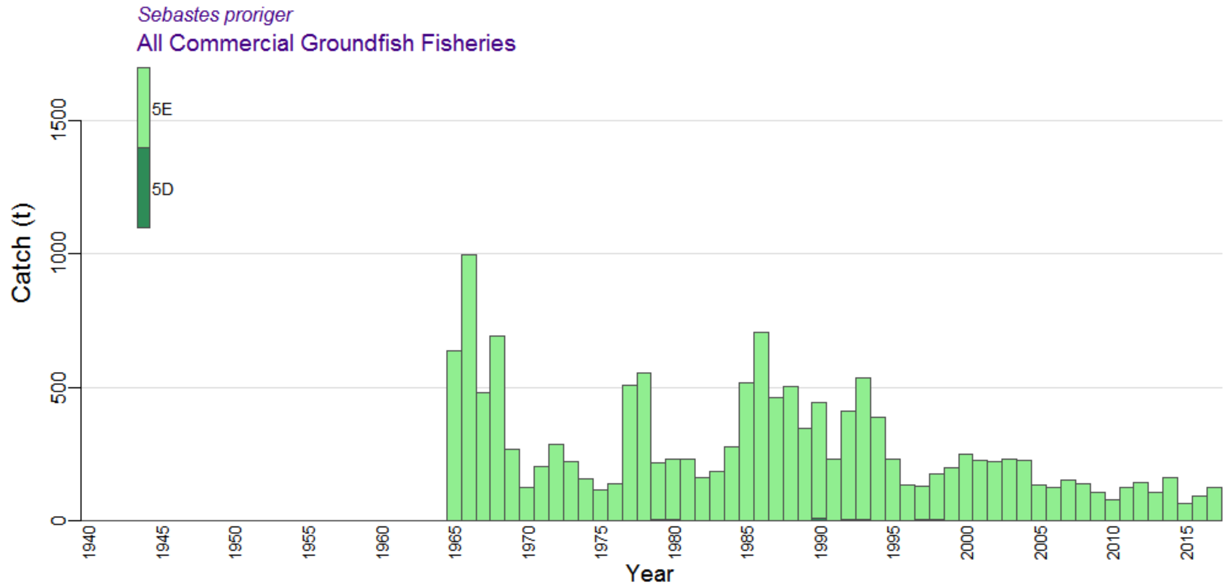

Figure A.6. BC North reconstructed total (landed + released) catch (t) for Redstripe Rockfish by all fisheries from 1940 to 2017.

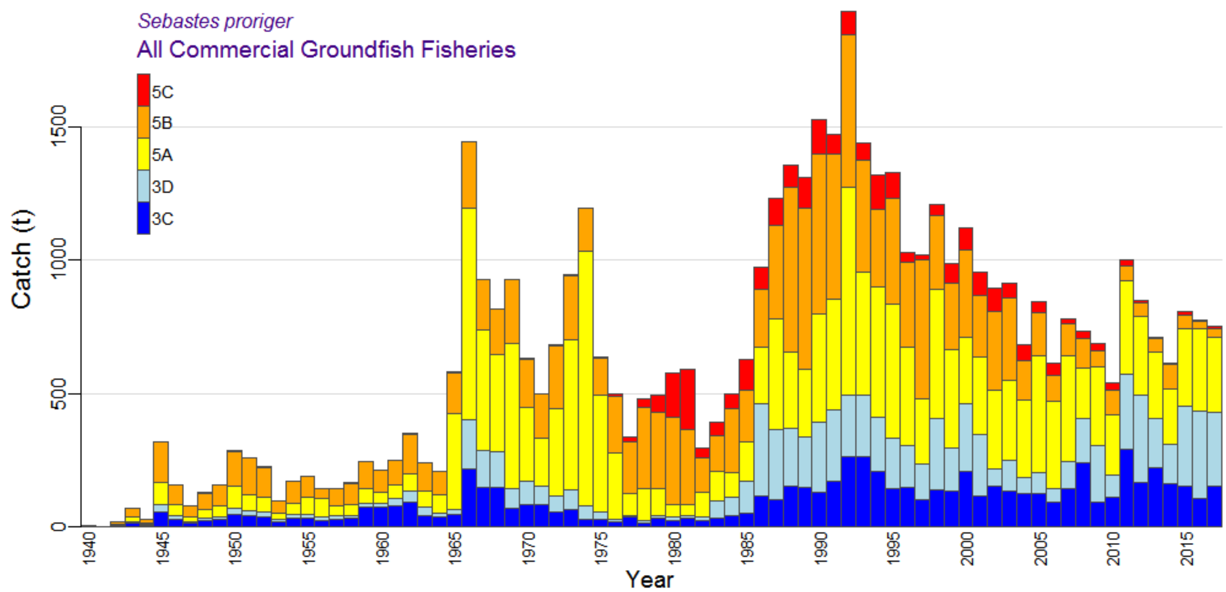

Figure A.7. BC South reconstructed total (landed + released) catch (t) for Redstripe Rockfish by all fisheries from 1940 to 2017.

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 A.1).

The GMU sets total allowable catches (TACs) of RSR for regions approximating PMFC areas along the BC coast – 3C (TAC=178t), 3D5AB (TAC=794t), 5CD (TAC=339t), and 5E (TAC=253t). This stock assessment offers decision tables based on constant catch policies for two stocks - BC North (5DE) and BC South (3CD5ABC). Ultimately, it is GMU's decision on how to update the existing TACs based on the decision tables.

Assuming that the TAC regions are maintained, the following algorithm provides one method on how catch policy by stock might be allocated to GMU regions. The first decision is how the TAC in 5CD should be split between 5C and 5D. Based on the last 5 years (2013-17), 5C catch accounts for an average 98.4% of the 5CD catch (Table A.5). This percentage is used to split the current 5CD TAC of 339 t to 334 t in 5C (part of BC South) and 5 t in 5D (part of BC North). The proportion of TAC is then re-calculated for the GMU areas {3C, 3D5AB, 5C} (column 'pTAC South' in Table A.6) and {5D, 5E} (column 'pTAC North' in Table A.6), and these ratios applied to chosen catch policies. For example, if the target catch policy for BC South is 1000 t then for GMU area 3C, the proportional 3C TAC ratio of 0.1363 would render a revised TAC of 136 t (0.1363*1000 t). Similarly, assuming a target catch policy for BC North of 500 t, the revised GMU 5E TAC would be 0.9789*500 t = 489 t. GMU area 3CD would use both catch policies: 0.2555*1000 t + 0.0211*500 t = 266 t.

Table A.5. Catch of RSR in 5C and 5D from the last 5 years of the combined fishery. The proportion of 5C catch to 5CD catch is reported for each year and the geometric mean of these rates is calculated.

Year	5C (t)	5D (t)	5CD (t)	5C/5CD
2013	5.859	0.112	5.971	0.9812
2014	7.306	0.088	7.394	0.9881
2015	10.755	0.177	10.932	0.9838
2016	2.428	0.052	2.480	0.9789
2017	10.750	0.136	10.887	0.9875
			Geometric mean	0.9839

*Table A.6. Example table of a TAC revision based on a Catch Policy of 1000 t in BC South and 500 t in BC North. The existing TAC for 5CD is split 98.4% to 5C and 1.6% to 5D. The proportion of TAC (pTAC) is re-calculated for South and North to determine revised TACs for the four GMU regions from the two catch policies. TAC revised for 5CD = 0.2555*1000 t + 0.0211*500 t = 266 t.*

GMU Area	TAC 2017	pTAC	TAC South	TAC North	pTAC South	pTAC North	RSR Stock	Catch Policy	TAC revised
3C	178	0.1138	178	-	0.1363	-	3CD5ABC	1000	136
3D5AB	794	0.5077	794	-	-0.6082	-	-	-	608
5CD	339	0.2168	334	5	0.2555	0.0211	5DE	500	266
5E	253	0.1618	-	253	-	0.9789	-	-	489
Sum	1564	1	1306	258	1	1		1500	1500

Another alternative might be to revise the existing combination of GMU areas to reflect the current stock areas used in this assessment.

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 limit 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 RSR 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.7 shows the reported trawl catch (landings plus non-retained) by gear type in each of the RSR stock areas from 1996 on.

Table A.7. Trawl catch (tonnes) by gear type (bottom trawl, midwater trawl) for the two RSR stocks from years when fleet activity was monitored by onboard observers. BCN=BC North, BCS=BC South.

Year	BCN Bottom	BCN Midwater	BCS Bottom	BCS Midwater
1996	127	0	519	498
1997	126	0	844	171
1998	173	1	878	328
1999	195	0	668	312
2000	248	3	958	161
2001	193	28	821	125
2002	205	13	654	238
2003	218	9	668	243
2004	216	8	466	211
2005	133	0	460	381
2006	118	5	441	166
2007	131	16	394	379
2008	132	0	487	238
2009	104	0	574	108
2010	73	4	415	121
2011	117	2	443	548
2012	142	0	590	250
2013	88	7	314	375
2014	153	6	411	200
2015	55	5	435	366
2016	87	0	427	334
2017	123	1	384	366

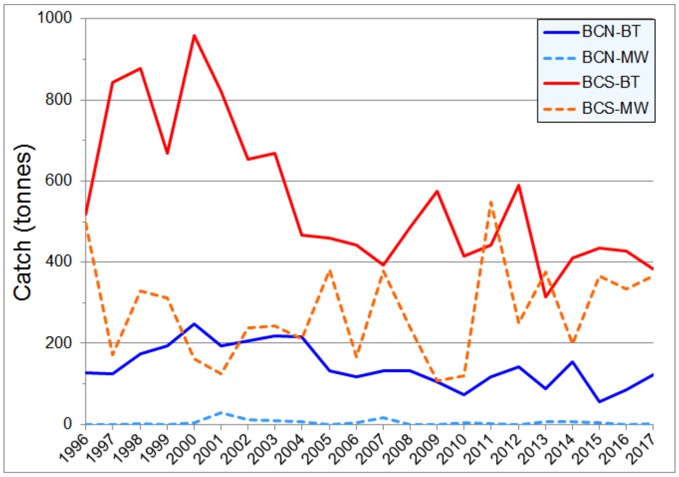

Figure A.8. Reported trawl catch (landings + released) of RSR since the implementation of the onboard-observer program in 1996. BCN=BC North, BCS = BC South, BT = bottom trawl, MW =midwater trawl.

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APPENDIX B. TRAWL SURVEYS

B.1. INTRODUCTION

This appendix summarises the derivation of relative Redstripe Rockfish (RSR) 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);
- Hecate Strait synoptic survey (Section B.4);
- Queen Charlotte Sound synoptic survey (Section B.6);
- West Coast Vancouver Island (WCVI) synoptic survey (Section B.7);
- West Coast Haida Gwaii (WCHG) synoptic survey (Section B.8).

Only surveys which were used in the RSR stock assessment are presented. The Hecate Strait multi-species survey, WCVI shrimp and Queen Charlotte Sound shrimp surveys have been omitted because the presence of RSR 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 reliable 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 that 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 from 1967 to 1984, were used to index the RSR 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 available by survey year and depth stratum for the analysis of the historical GIG trawl survey series. Survey year in grey was not used in the RSR stock assessment.

Survey Year	Depth stratum 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 Redstripe Rockfish from the historical Goose Island Gully trawl surveys for the years 1967 to 1995. 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	629	647	75	1,837	0.746	0.782
1969	445	433	137	1,063	0.515	0.526
1971	44	44	13	99	0.501	0.513
1973	786	798	49	1,977	0.645	0.644
1976	836	838	132	2,137	0.589	0.588
1977	435	434	176	793	0.349	0.351
1984	473	476	177	810	0.348	0.363
1994	1,110	1,103	90	3,036	0.664	0.662

A `doorspread` density (Eq. B.3) was calculated for each tow based on the catch of RSR, 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 RSR were caught in the Goose Island Gully (GIG) indicate that this species is found primarily in the outer parts of the GIG in most years, with observations in the southeastern branch of the gully in some years (see Figure B.1 to Figure B.8). RSR was taken relatively frequently in small amounts, with 140 of the 332 valid tows capturing RSR with a median catch weight of 6.1 kg. The largest valid RSR tow in terms of catch weight was 832 kg in 1994. RSR were mainly taken at depths from 150 to 207 m (5% and 95% quantiles of the starting depth empirical distribution), with the minimum and maximum observed starting tow depths at 143 and 287 m respectively (Figure B.9).

Estimated biomass levels in the GIG for Redstripe Rockfish from the historical GIG trawl surveys were variable, with the maximum biomass recorded in 1994 (at 1110 t) and the minimum biomass in 1971 (at 44 t) (Figure B.10; Table B.4). Survey relative errors are moderate to high for this species, ranging from a low of 0.35 in 1977 and 1984 to 0.78 in 1967 (Table B.4). The proportion of tows which caught RSR was variable between years, ranging between 20% and 71% of the tows (Figure B.11). Overall, 140 tows from a total 332 valid tows (42%) contained RSR.

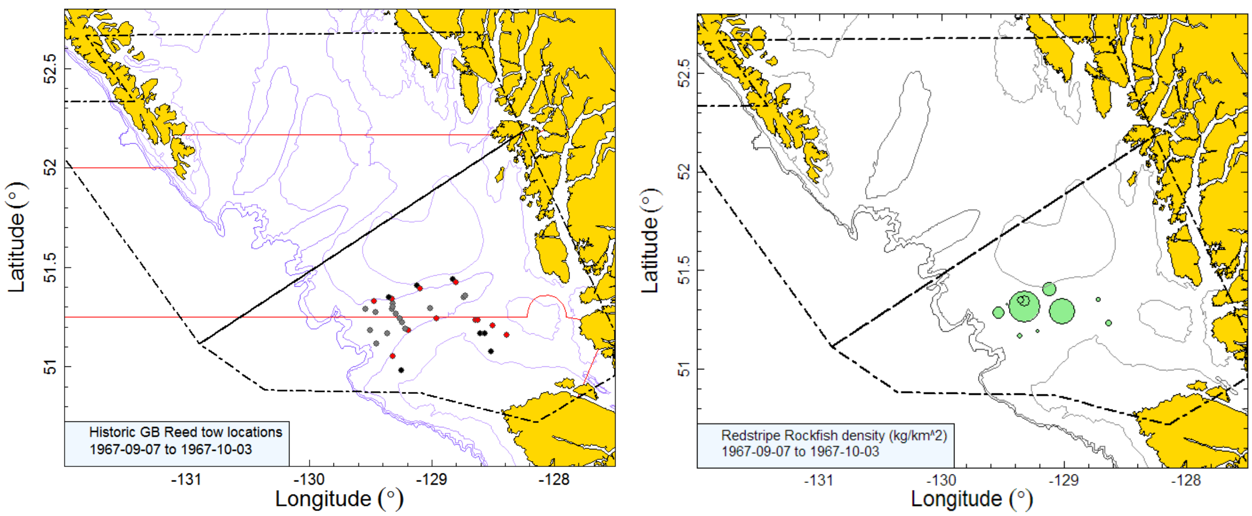


Figure B.1. Valid tow locations and density plots for the historic 1967 Goose Island Gully (GIG) survey. Tow locations are colour-coded by depth range: black=120–183m; red=184-218m; grey=219-300m. Circle sizes in the right-hand density plot scaled across all years (1967, 1969, 1971, 1973, 1976, 1977, 1984, and 1994), with the largest circle = 3,377 kg/km² in 1994. 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.

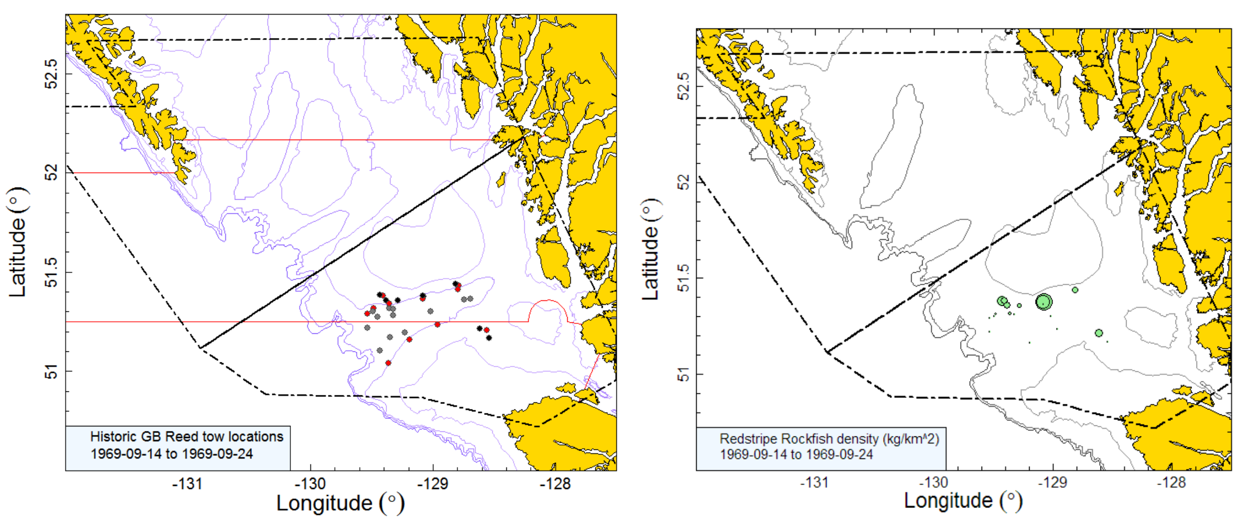


Figure B.2. Tow locations and density plots for the historic 1969 Goose Island Gully (GIG) survey (see Figure B.1 caption).

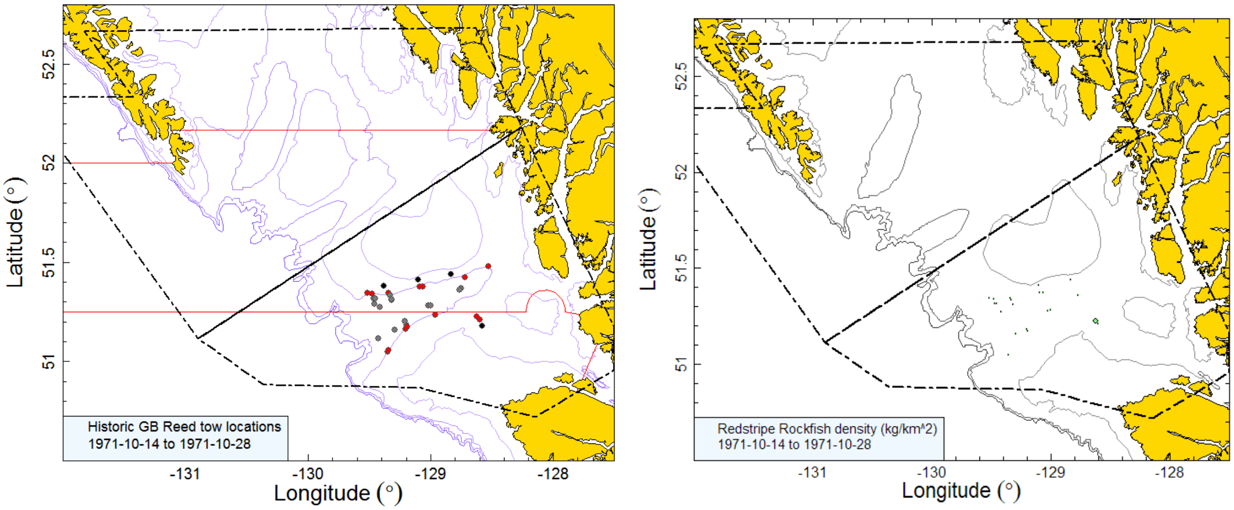


Figure B.3. Tow locations and density plots for the historic 1971 Goose Island Gully (GIG) survey (see Figure B.1 caption).

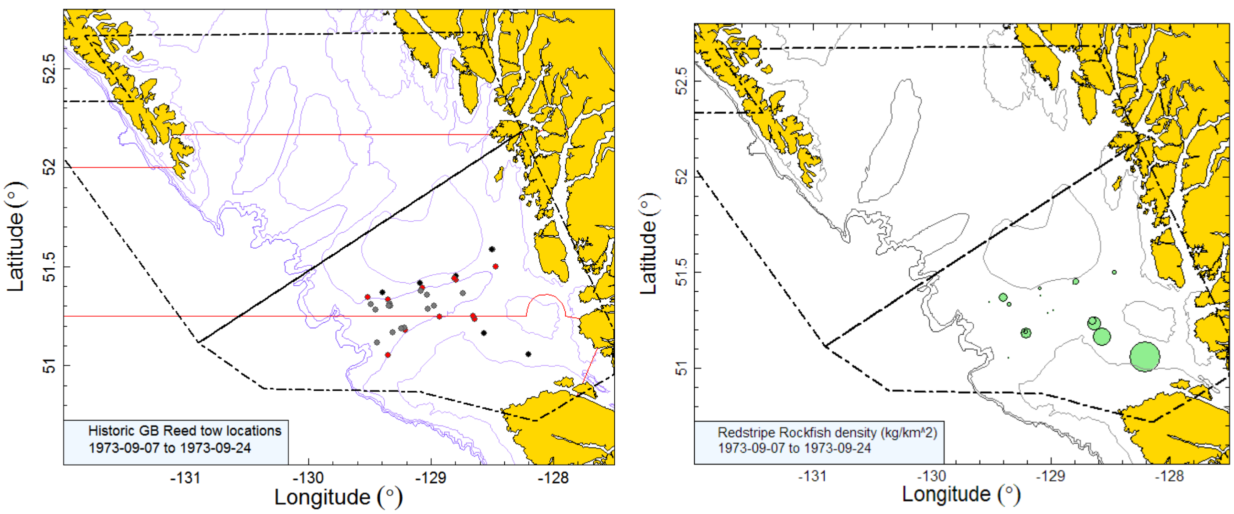


Figure B.4. Tow locations and density plots for the historic 1973 Goose Island Gully (GIG) survey (see Figure B.1 caption).

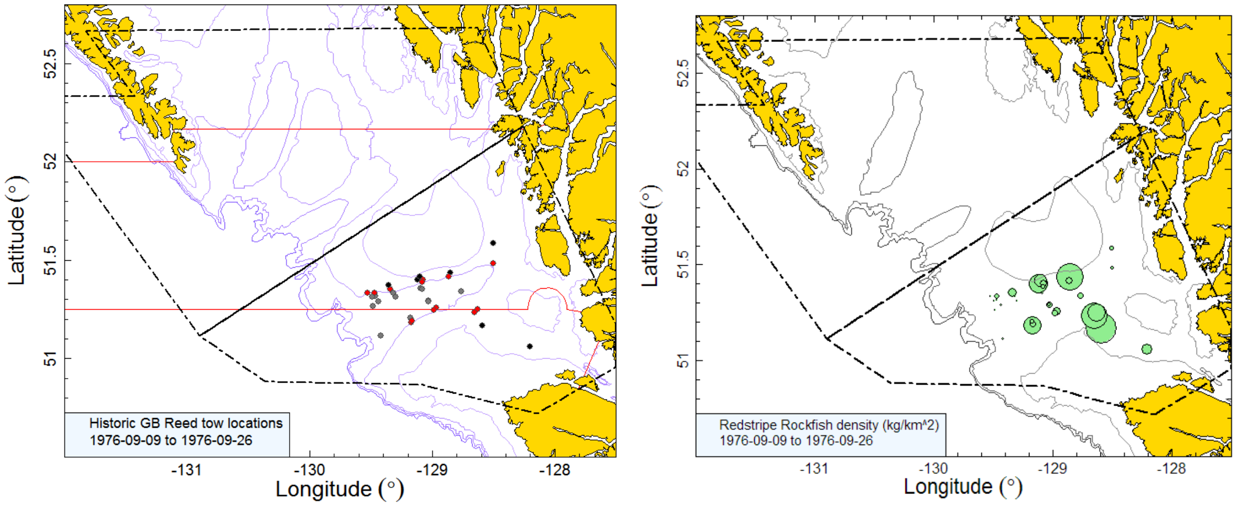


Figure B.5. Tow locations and density plots for the historic 1976 Goose Island Gully (GIG) survey (see Figure B.1 caption).

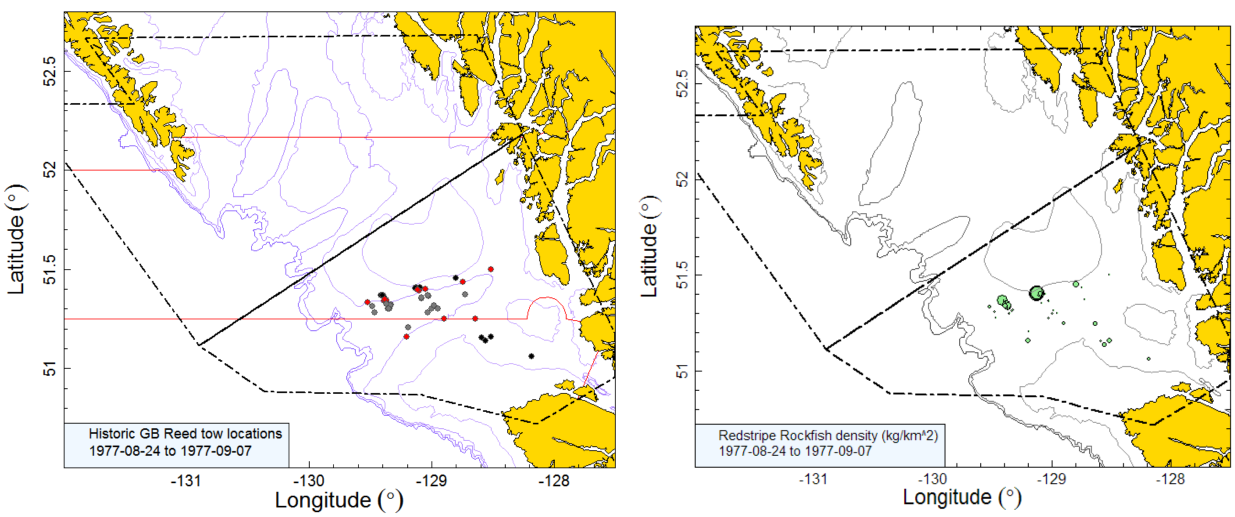


Figure B.6. Tow locations and density plots for the historic 1977 Goose Island Gully (GIG) survey (see Figure B.1 caption)

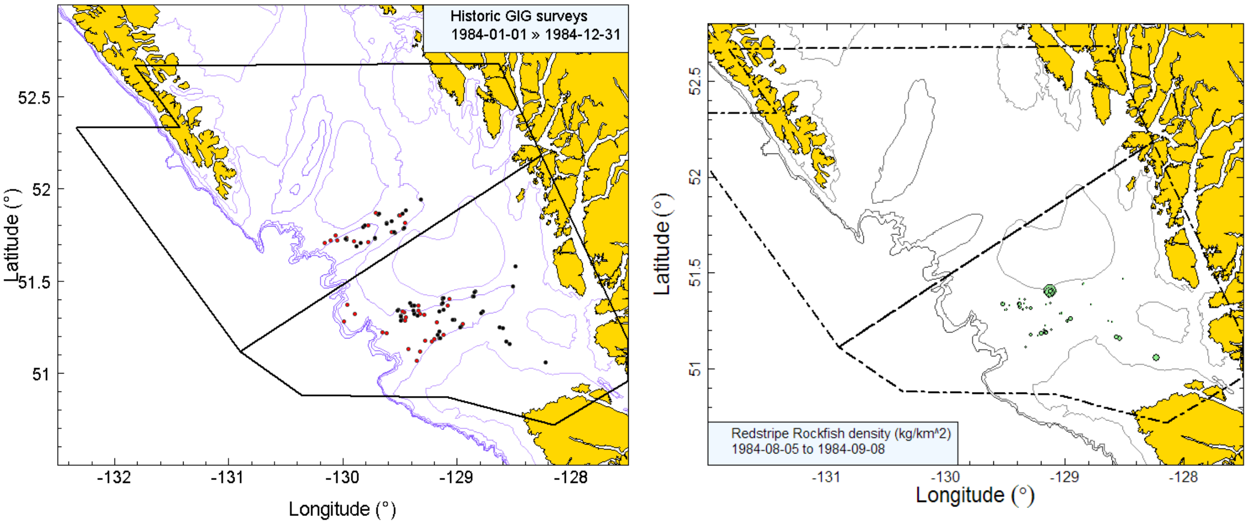


Figure B.7. [left panel]: Tow location colours indicate the vessel fishing rather than depth: black=G.B. Reed; red=Eastward Ho. Additional locations fished by vessel in Mitchell Gully are also shown; [right panel]: density plot for the historic 1984 Goose Island Gully (GIG) survey (see Figure B.1 caption).

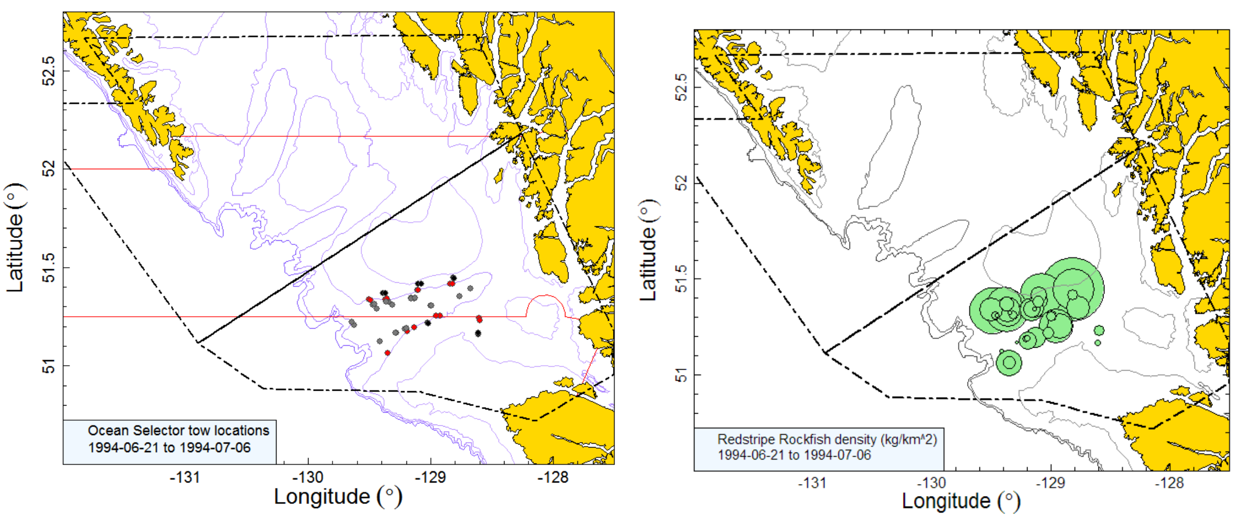


Figure B.8. Tow locations and density plots for the historic 1994 Goose Island Gully (GIG) survey (see Figure B.1 caption).

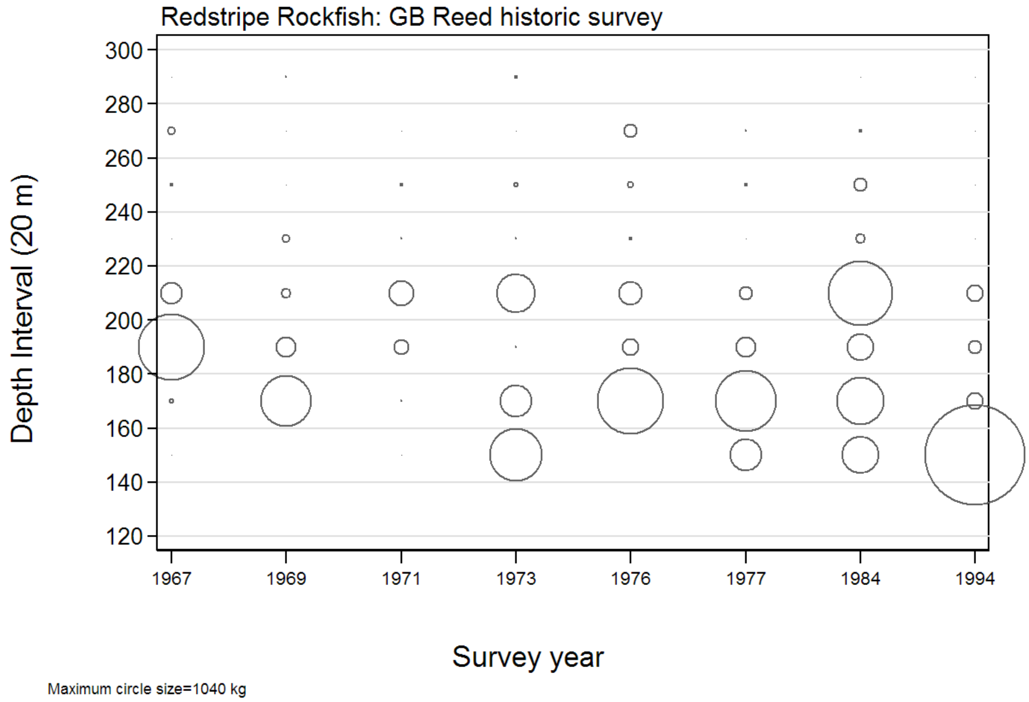


Figure B.9. Distribution of observed catch weights of Redstripe Rockfish (RSR) for the historic Goose Island Gully (GIG) surveys (Table B.3) by survey year and 25 m depth zone. Depth zones are indicated by the mid point of the depth interval and circles in the panel are scaled to the maximum value (1040 kg) in the 140–160 m interval in 1994. The 1% and 99% quantiles for the RSR empirical start of tow depth distribution= 148 m and 242 m respectively.

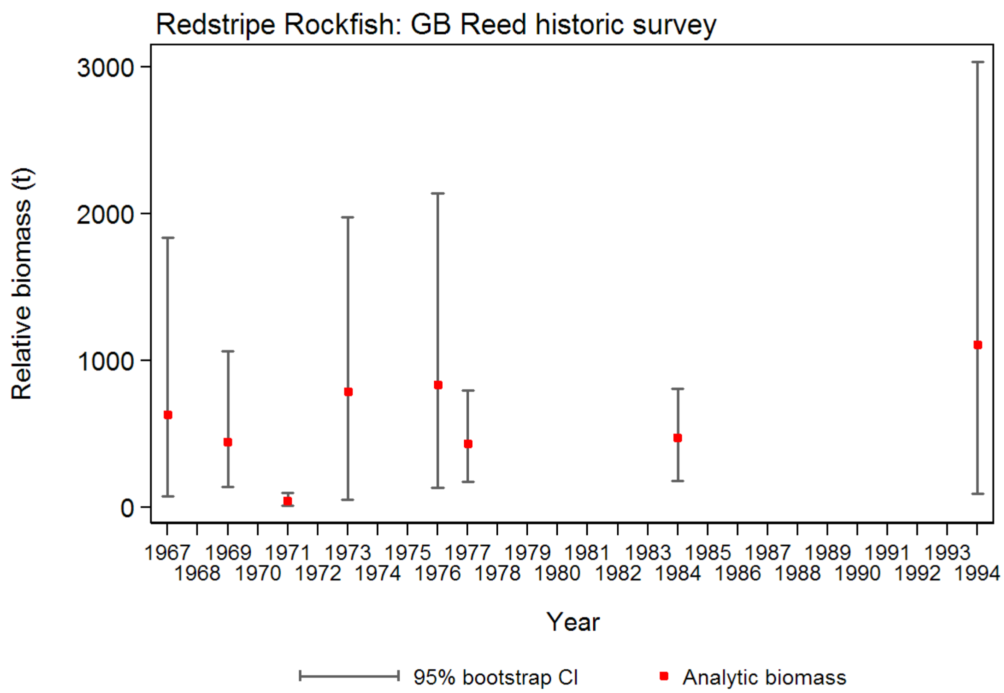


Figure B.10. Plot of biomass estimates for the RSR historic Goose Island Gully (GIG) surveys: 1967 to 1994 (values provided in Table B.4). Bias corrected 95% confidence intervals from 1000 bootstrap replicates are plotted.

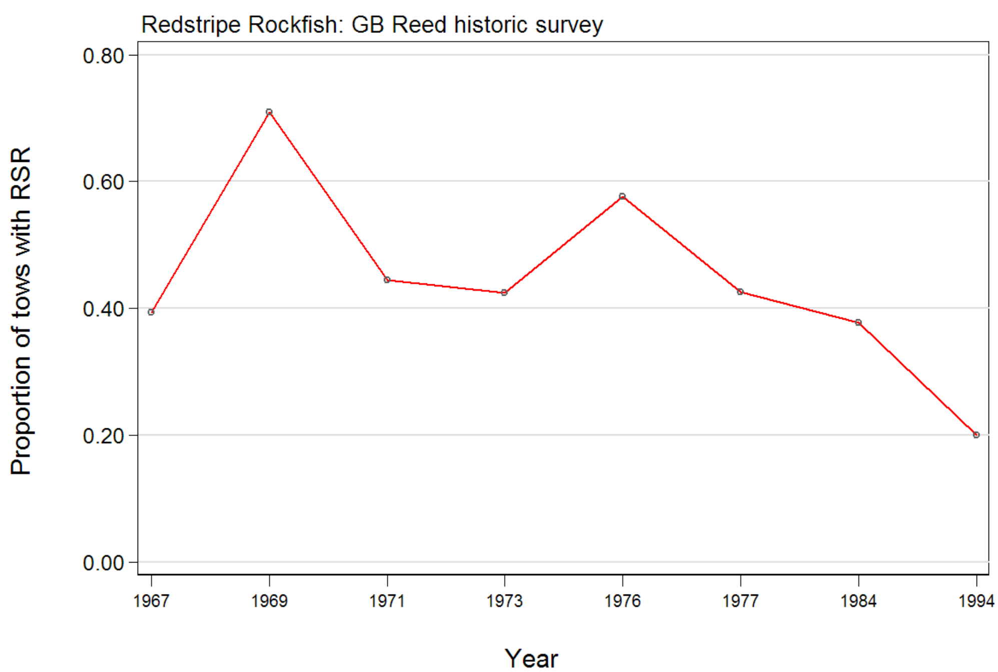


Figure B.11. Proportion of tows by year which contain RSR from the historic Goose Island Gully (GIG) surveys: 1967 to 1995.

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 worked 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.

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 Redstripe 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).

Table B.5. Number of tows by stratum and by survey year for the NFMS 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	-	-	-	-	-	-	-	-	-	-

Stratum No.	1980 CDN	1980 US	1983 CDN	1983 US	1989 CDN	1989 US	1992 CDN	1992 US	1995 CDN	1995 US	1998 CDN	1998 US	2001 CDN	2001 US
51	4	-	-	10	-	-	-	-	-	-	-	-	-	-
52	-	-	4	-	-	-	-	-	-	-	-	-	-	-
Total	59	26	47	70	67	87	61	79	71	68	59	74	38	72

The stratum definitions used in the 1980 and 1983 surveys were different than those used in subsequent surveys, particularly in Canadian waters (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

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.

	Number of tows			Area surveyed (km^2)		
Survey year	CDN waters	US waters	Total	CDN waters	US waters	Total
1980	59	26	85	7,399	4,738	12,137
1983	47	70	117	7,399	4,738	12,137
1989	65	55	120	9,166	4,699	13,865
1992	59	50	109	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	382	315	697	–	–	–

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

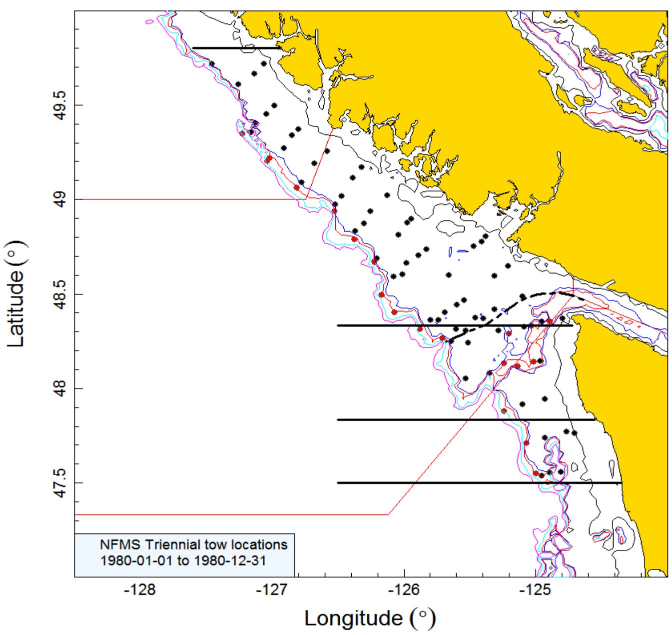
The partial variance $V_{y_{i_c}}$ for country *c* was used in Eq. B.5 instead of the total variance in the stratum V_{y_i} when calculating the variance for the total biomass in Canadian or American waters. CVs were calculated as in Eq. B.6.

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

Redstripe Rockfish (RSR) are characterised with most catches taken along the shelf edge and in the deep gully entering Juan de Fuca Strait (e.g., Figure B.12 and Figure B.13). A more 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 112 and 229 m (1 and 99% quantiles of [bottom_depth]), with infrequent observations at deeper depths which means that the deeper strata (>367 m) are not needed to monitor RSR. Note that the deep strata which were not used in the biomass estimation are included in Figure B.19.



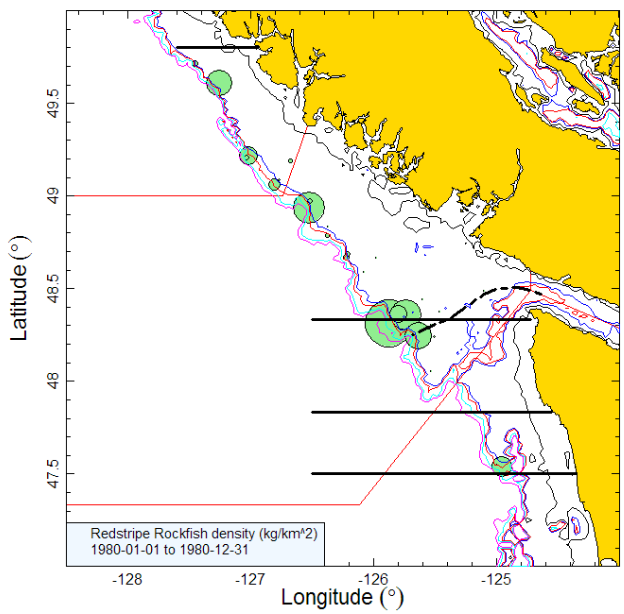


Figure B.12. [left panel]: plot of tow locations in the Vancouver INPFC region for the 1980 NMFS triennial survey in US and Canadian waters. Tow locations are colour-coded by depth range: black=55–183m; red=184-366m; grey=367-500m. Dashed line shows approximate position of the Canada/USA marine boundary. Horizontal lines are the stratum boundaries: 47°30', 47°50', 48°20' and 49°50'. Tows south of the 47°30' line were not included in the analysis. [right panel]: circle sizes in the density plot are scaled across all years (1980, 1983, 1989, 1992, 1995, 1998, and 2001), with the largest circle = 46,276 kg/km^2 in 1983. The red solid lines indicate the boundaries between PMFC areas 3B, 3C and 3D

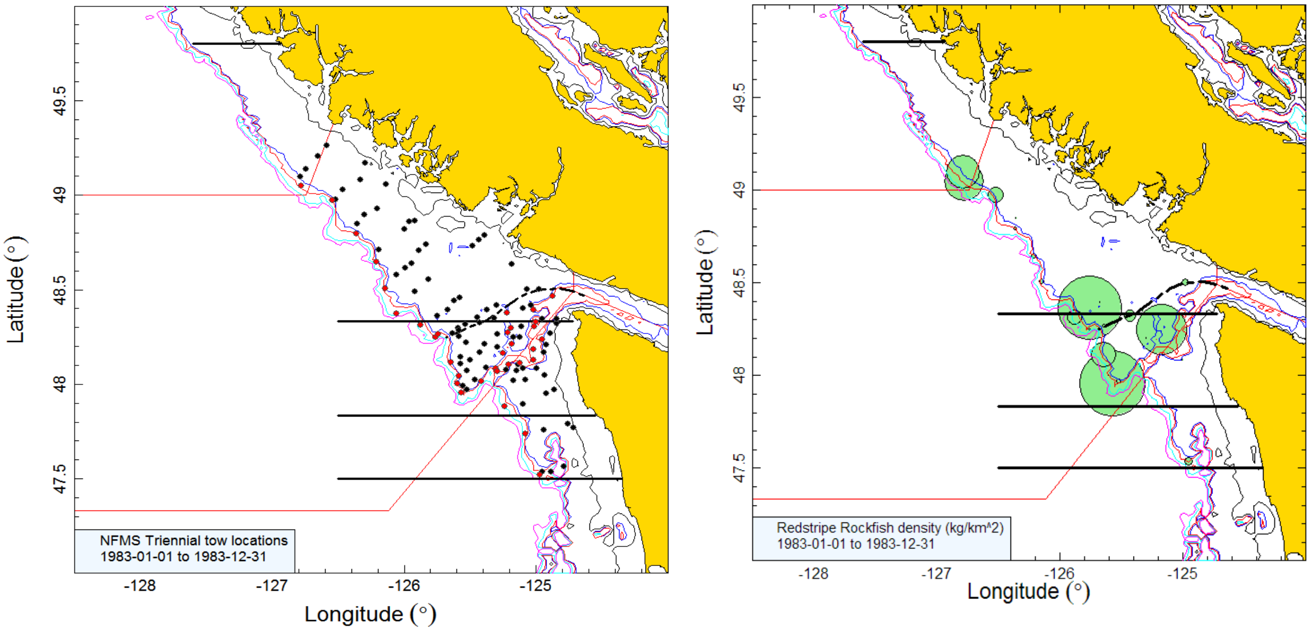


Figure B.13. Tow locations and density plots for the 1983 NMFS triennial survey in US and Canadian waters (see Figure B.12 caption).

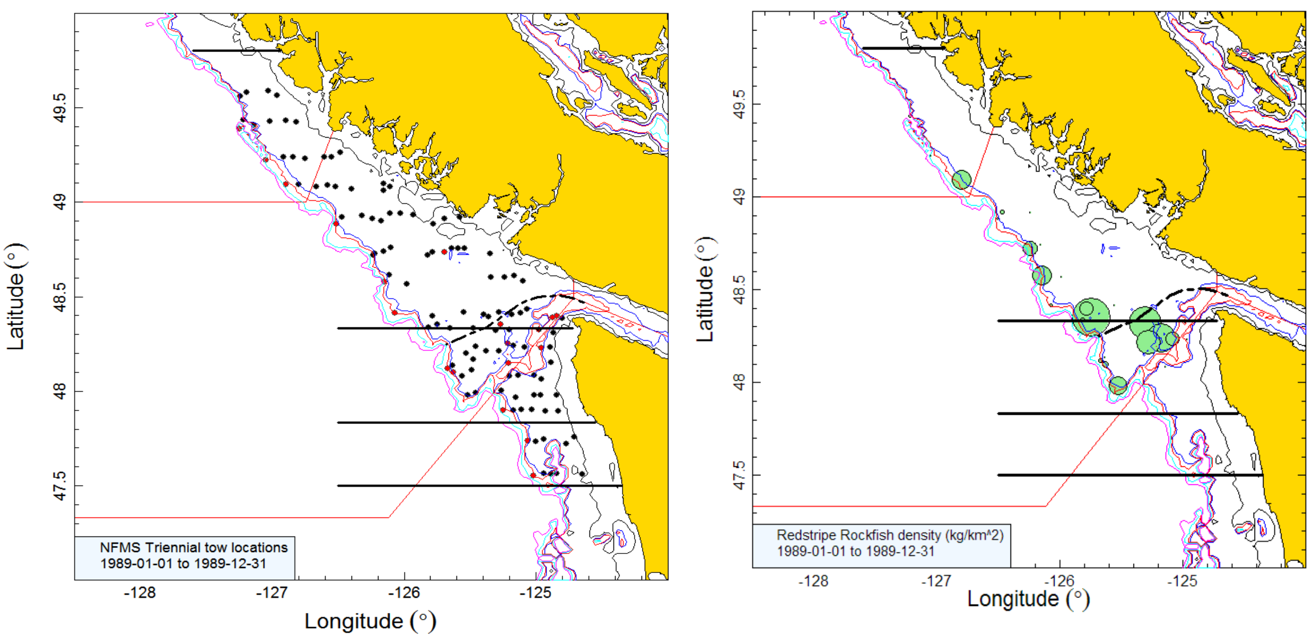


Figure B.14. Tow locations and density plots for the 1989 NMFS triennial survey in US and Canadian waters (see Figure B.12 caption).

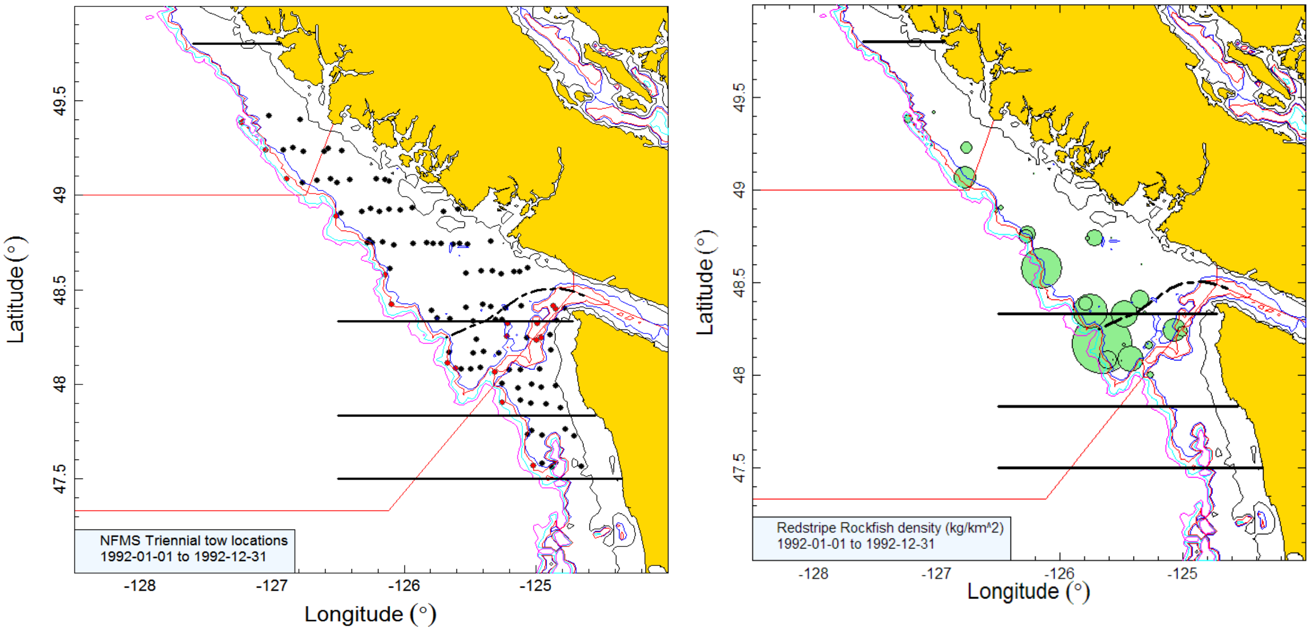


Figure B.15. Tow locations and density plots for the 1992 NMFS triennial survey in US and Canadian waters (see Figure B.12 caption).

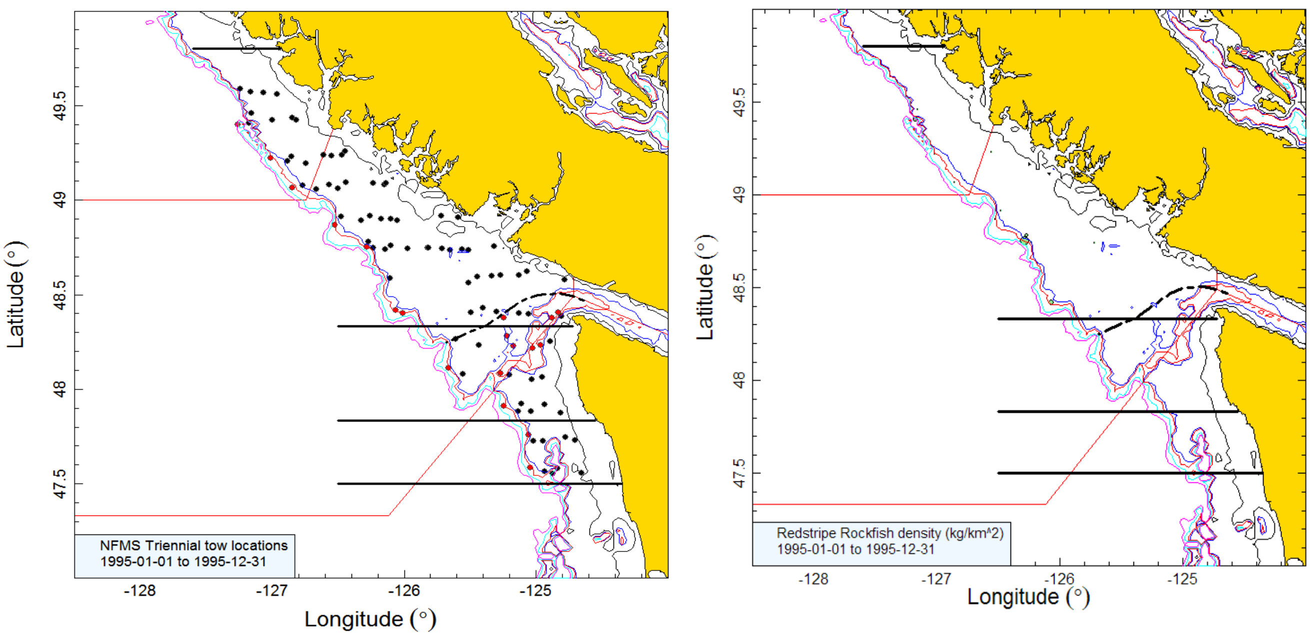


Figure B.16. Tow locations and density plots for the 1995 NMFS triennial survey in US and Canadian waters (see Figure B.12 caption).

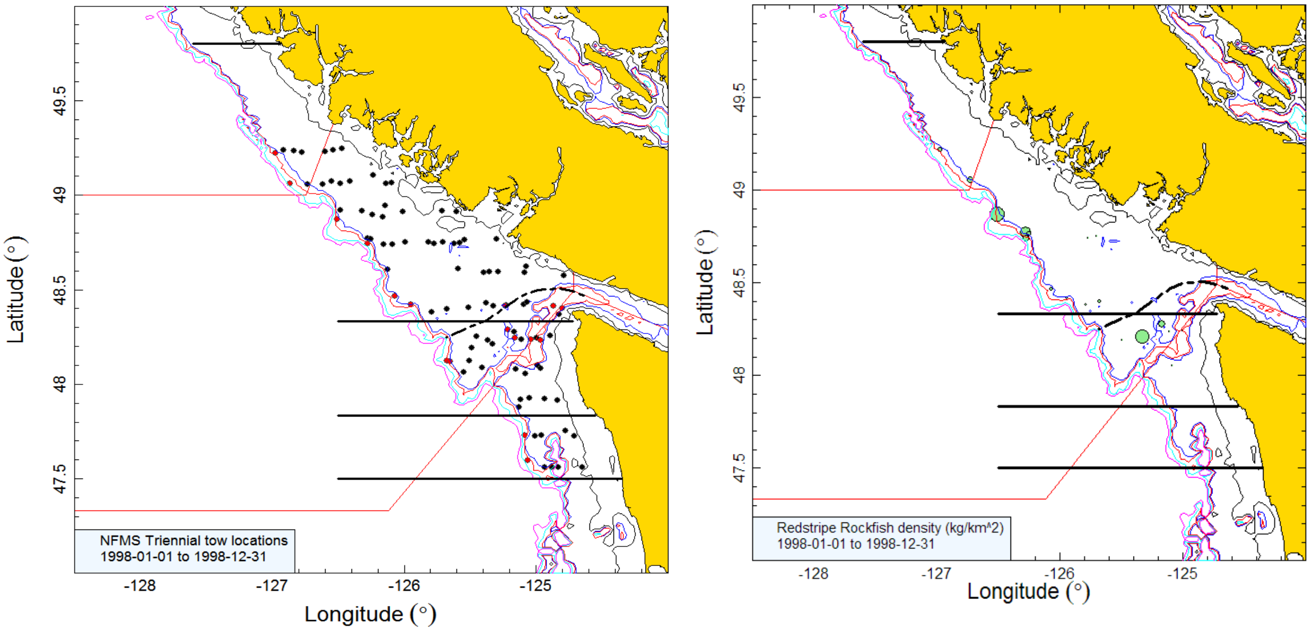


Figure B.17. Tow locations and density plots for the 1998 NMFS triennial survey in US and Canadian waters (see Figure B.12 caption).

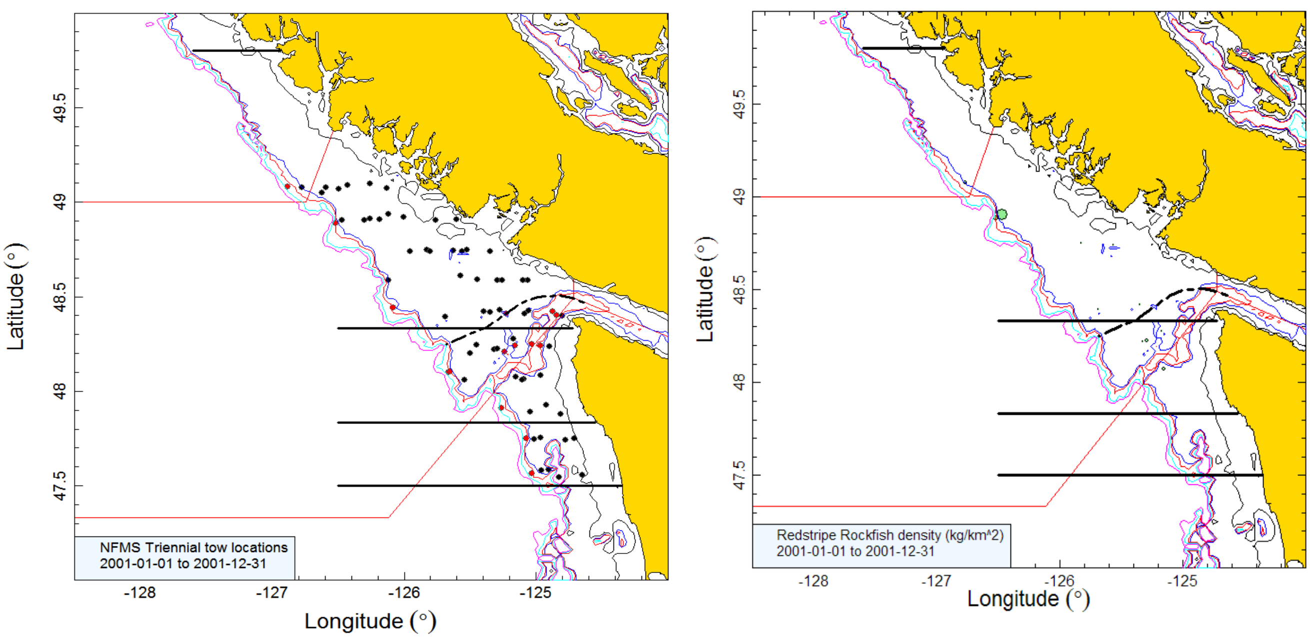


Figure B.18. Tow locations and density plots for the 2001 NMFS triennial survey in US and Canadian waters (see Figure B.12 caption).

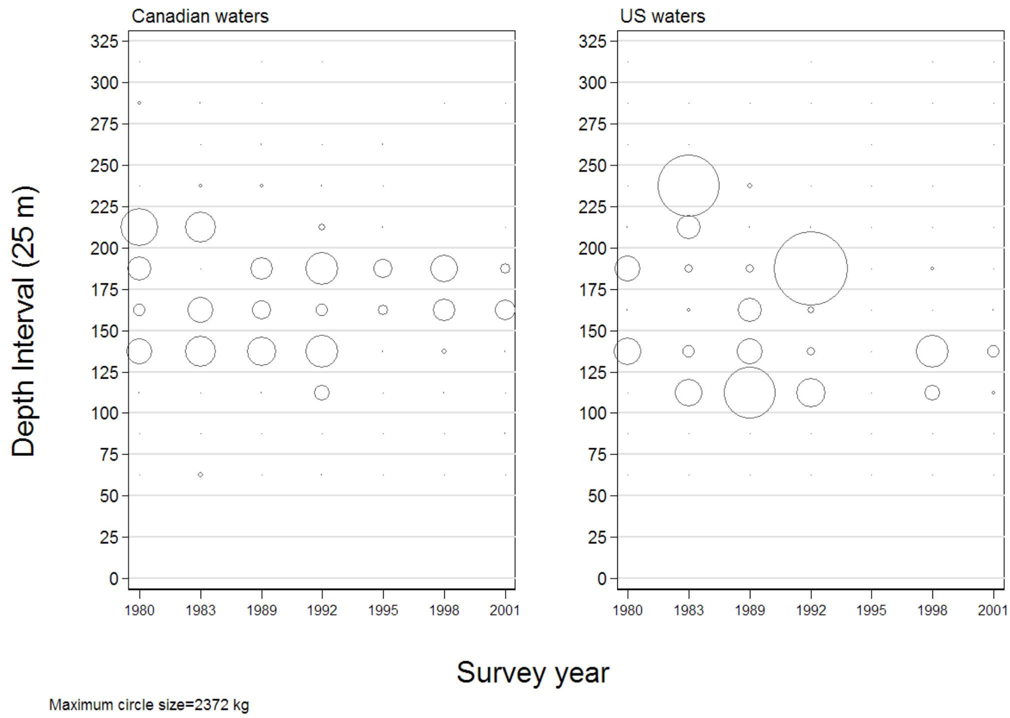


Figure B.19. Distribution of Redstripe Rockfish catch weights for each survey year summarised into 25 m depth intervals for all tows (Table B.6) in Canadian and US waters of the Vancouver INPFC area. Catches are plotted at the mid-point of the interval. Note that the deep strata introduced in 1995 (see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

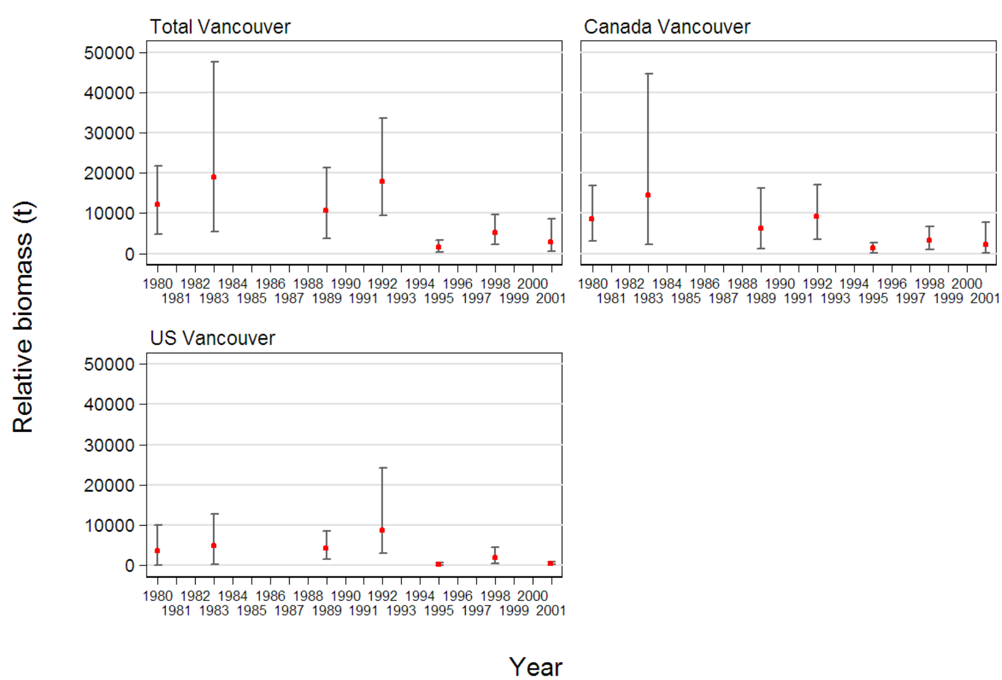


Figure B.20. Biomass estimates for three series of Redstripe Rockfish in the INPFC Vancouver region (total region, Canadian waters only, US waters only) with 95% error bars estimated from 1000 bootstraps.

Table B.8. Biomass estimates for Redstripe 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	12,193	12,326	4,764	21,725	0.351	0.362
	1983	18,993	18,774	5,471	47,569	0.514	0.517
	1989	10,700	10,750	3,793	21,392	0.413	0.409
	1992	17,890	15,979	9,488	33,580	0.358	0.331
	1995	1,554	1,574	247	3,333	0.519	0.551
	1998	5,096	4,955	2,181	9,690	0.382	0.400
	2001	2,803	2,859	463	8,538	0.694	0.705
Canada Vancouver	1980	8,632	8,642	3,005	16,873	0.397	0.410
	1983	14,402	14,057	2,184	44,519	0.679	0.681
	1989	6,341	6,503	1,203	16,302	0.591	0.601
	1992	9,153	9,180	3,437	17,039	0.379	0.376
	1995	1,292	1,319	226	2,717	0.509	0.531
	1998	3,245	3,237	994	6,761	0.452	0.471
	2001	2,309	2,375	201	7,820	0.796	0.813
US Vancouver	1980	3,705	3,813	38	10,079	0.677	0.700
	1983	5,001	5,087	287	12,753	0.638	0.666
	1989	4,358	4,248	1,620	8,458	0.404	0.407
	1992	8,736	6,799	3,004	24,138	0.595	0.503
	1995	262	255	11	665	0.678	0.684
	1998	1,851	1,718	481	4,462	0.552	0.560
	2001	494	483	199	923	0.389	0.412

Redstripe Rockfish biomass estimates in both country strata were characterised by four (1980 to 1992) early estimates that were generally higher than the final three estimates (1995 to 2001) (Figure B.20; Table B.8). The relative error estimates are high, with the lowest relative error occurring at 0.35 in 1980 for Total Vancouver and the greatest at 0.80 in 2001 for the Canada Vancouver stratum (Table B.8). The relative error estimates for the sub-divided national strata tend to be higher than for Total Vancouver in the same years. 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.

One hundred and sixty-two tows of the nearly 700 valid tows captured RSR (23%), with half of the tows that captured RSR having less than 11 kg. The largest tow was 1613 kg in 1983. The proportion of tows which contained Redstripe Rockfish was lower in US waters than in Canadian waters, with the US proportions by year ranging from 3 to 24% (mean=17%) while the equivalent Canadian values were 19–42% with a mean value of 27% (Figure B.21). The incidence of RSR 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 25% (range: 18-30%) of the tows containing RSR.

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).

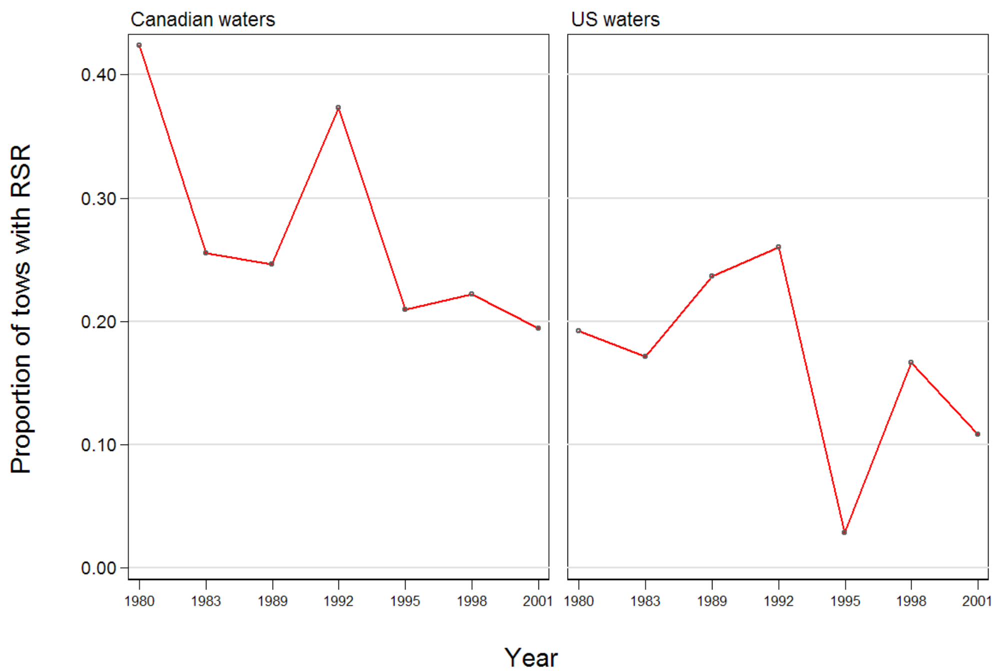


Figure B.21. Proportion of tows with Redstripe Rockfish by year for the Vancouver INPFC region (Canadian and US waters).

B.4.4. Water hauls

During the review process, a meeting participant asked if the NMFS Triennial survey tows designated as "water hauls" (catching no fish or invertebrates) had been discarded. The existence of these tows had been brought to the attention of DFO by a reviewer from NOAA for Yellowtail Rockfish in 2014 (DFO 2015); therefore, the data used in Table B.7 and Table B.8 were examined to see if these water hauls had been removed.

Table B.9. 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.

	Canadian waters			American waters			Total		
Year	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.9). These tows had not been removed during the biomass estimation procedure described in Sections B.4.2 and B.4.3. Table B.10 and Figure B.22 compare the 1980, 1983 and 1989 Canadian RSR biomass estimates before and after removing the 21 tows identified in Table B.9. Because these changes to the Triennial survey data have not been incorporated into the RSR BCS stock assessment, it is not known if these revised estimates will affect the estimates of stock status for the BCS stock or the predictions in the decision tables. However, it is unlikely that these changes will be consequential, given the high stock status estimated for the BCS stock and the capacity of these models to compensate for changes more than 30 years in the past.

Table B.10. Change in biomass estimates in Canadian waters when the 21 water haul tows (Table B.9) were removed from the biomass estimation.

Year	RSR biomass (t)	
	Stock Assessment	Water Hauls Removed
1980	8,632	10,050
1983	14,402	16,860
1989	6,341	6,530
1992	9,153	9,153
1995	1,292	1,292
1998	3,245	3,245
2001	2,309	2,309

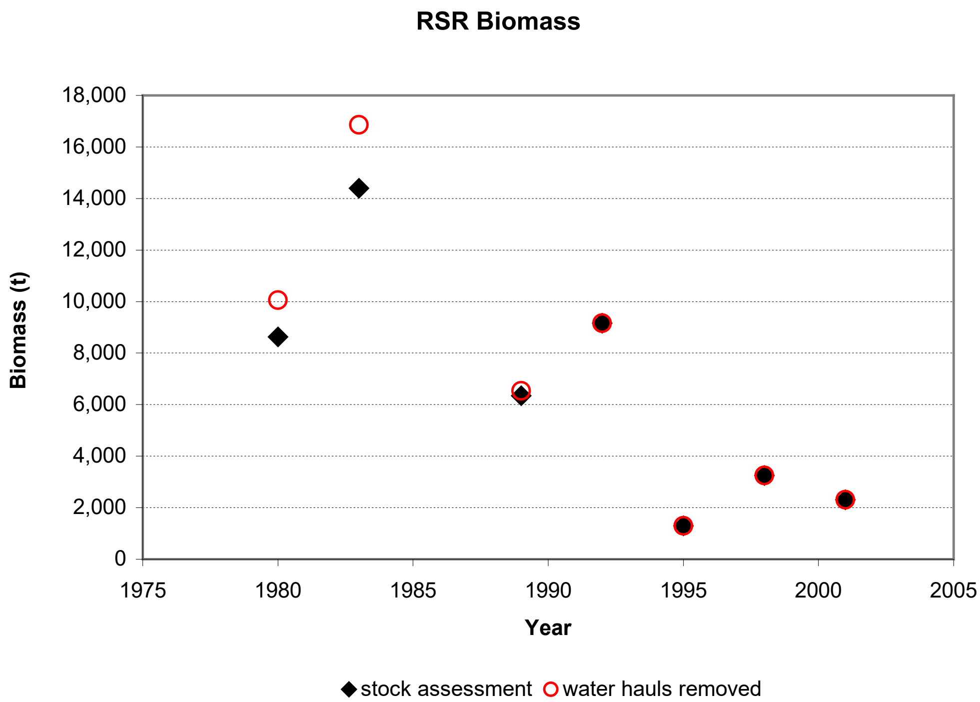


Figure B.22: Plot comparing the Canadian NMFS Triennial survey biomass estimates provided in Table B.10 with the biomass estimates used in the RSR stock assessment (Table B.8).

B.5. HECATE STRAIT SYNOPTIC SURVEY

B.5.1. Data selection

This survey has been conducted in seven alternating years over the period 2005 to 2017 in Hecate Strait (HS) between Moresby and Graham Islands and the mainland and in Dixon Entrance at the top of Graham Island (all valid tow starting positions by survey year are shown in Figure B.23 to Figure B.28). This survey treats the full spatial coverage as a single areal stratum divided into four depth strata: 10–70 m; 70–130 m; 130–220 m; and 220–500 m (Table B.11).

A doorspread density value (Eq. B.3) was generated for each tow based on the catch of Redstripe Rockfish (RSR) 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 seven trawl surveys. Missing values for the [doorspread] field were filled in with the mean doorspread for the survey year (217 values over all years: Table B.12).

Table B.11. Number of usable tows for biomass estimation by year and depth stratum for the Hecate Strait synoptic survey over the period 2005 to 2017. Also shown is the area of each depth stratum and the vessel conducting the survey by survey year.

		Depth stratum				Total
Year	**Vessel**	**10-70**	**70-130**	**130-220**	**220-500**	**tows[1]**
2005	Frosti	77	86	26	9	198
2007	W.E. Ricker	48	43	36	7	134
2009	W.E. Ricker	53	43	48	12	156
2011	W.E. Ricker	70	51	50	14	185
2013	W.E. Ricker	74	42	43	16	175
2015	W.E. Ricker	47	46	40	15	148
2017	Nordic Pearl	47	44	38	9	138
Area (km^2)		5,958	3,011	2,432	1,858	13,259[2]

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

Table B.12. Number of missing doorspread values by year for the Hecate Strait synoptic survey over the period 2005 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]
2005	7	217	64.4
2007	98	37	59.0
2009	93	70	54.0
2011	13	186	54.8
2013	6	169	51.7
2015	0	151	59.4
2017	2	150	64.2
Total	219	980	58.6

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

Table B.13. Biomass estimates for Redstripe Rockfish from the Hecate Strait synoptic trawl survey for the survey years 2005 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)
2005	102	101	21	274	0.591	0.588
2007	17	17	2	52	0.744	0.760
2009	23	24	3	64	0.633	0.602
2011	655	631	28	1,820	0.688	0.686
2013	401	407	50	1,080	0.616	0.596
2015	169	172	5	607	0.940	0.940
2017	49	48	14	118	0.539	0.541

B.5.2. Results

Catches of RSR from this survey are mainly taken in upper reaches of Moresby Gully, with only minor catches of this species in Dixon Entrance (Figure B.23 to Figure B.29). Furthermore, there seems to be little pattern in the observed spatial distribution of this species, with intermittent small catches and the occasional large tow. RSR are mainly taken at depths from 51 to 179 m (5–95% quantiles), but there are sporadic observations at depths above 200 m and below 50 m (Figure B.30).

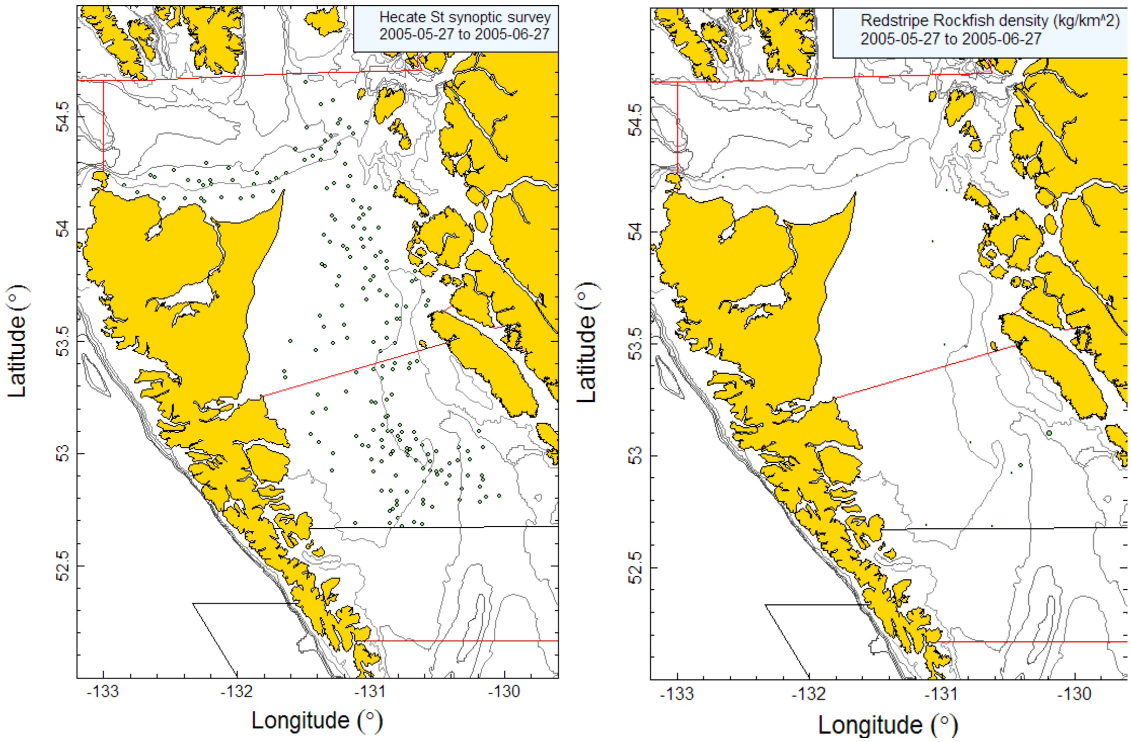


Figure B.23. Valid tow locations and density plots for the 2005 Hecate Strait synoptic survey. Circle sizes in the right-hand density plot scaled across all years (2005, 2007, 2009, 2011, 2013, 2015, 2017), with the largest circle = 6,821 kg/km² in 2011. Red lines indicate boundaries for PMFC major statistical areas 5C, 5D and 5E.

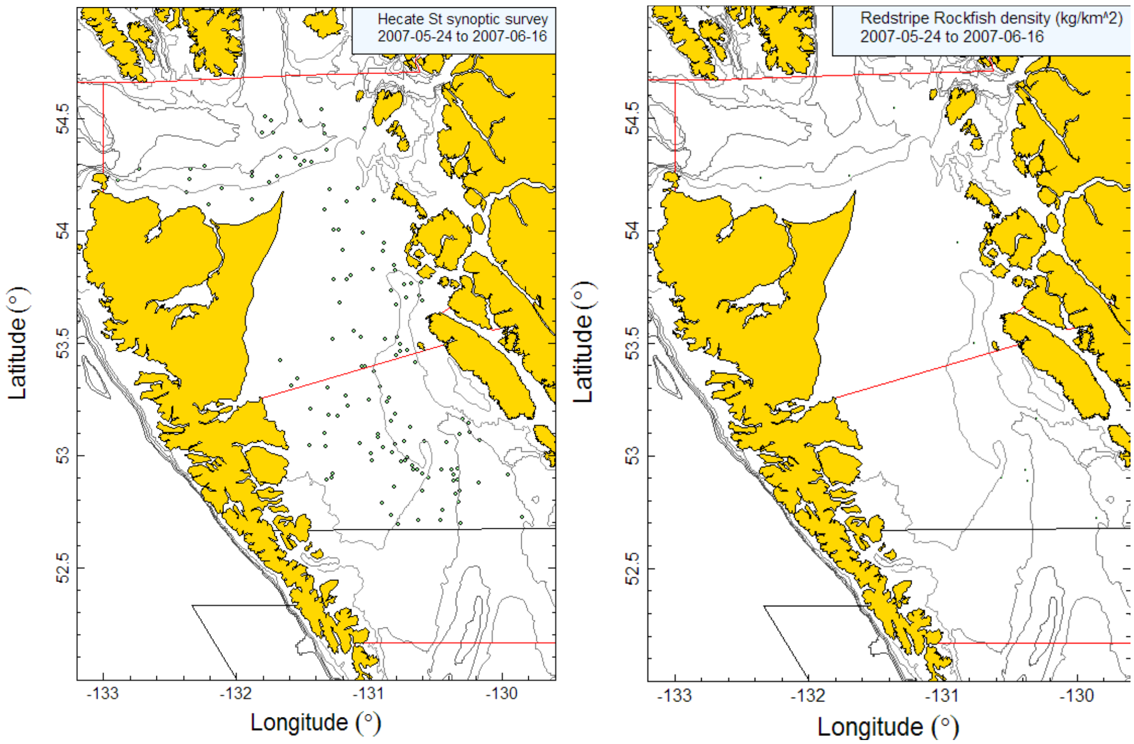


Figure B.24. Tow locations and density plots for the 2007 Hecate Strait synoptic survey (see Figure B.23 caption).

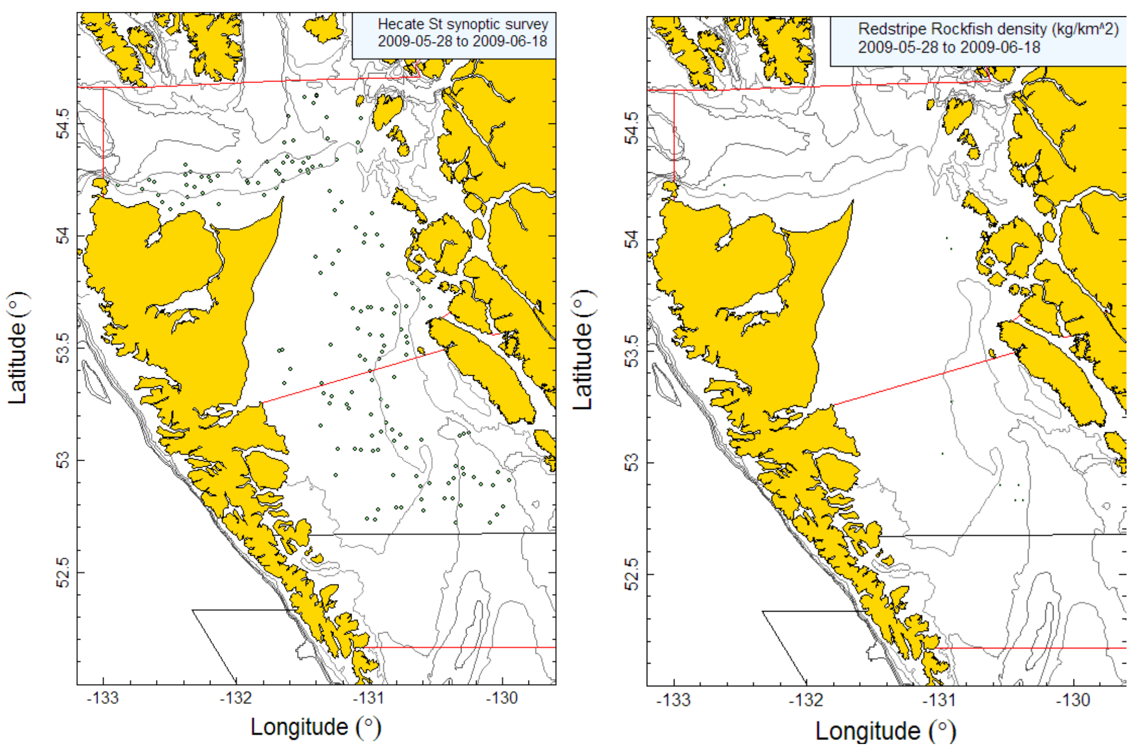


Figure B.25. Tow locations and density plots for the 2009 Hecate Strait synoptic survey (see Figure B.23 caption).

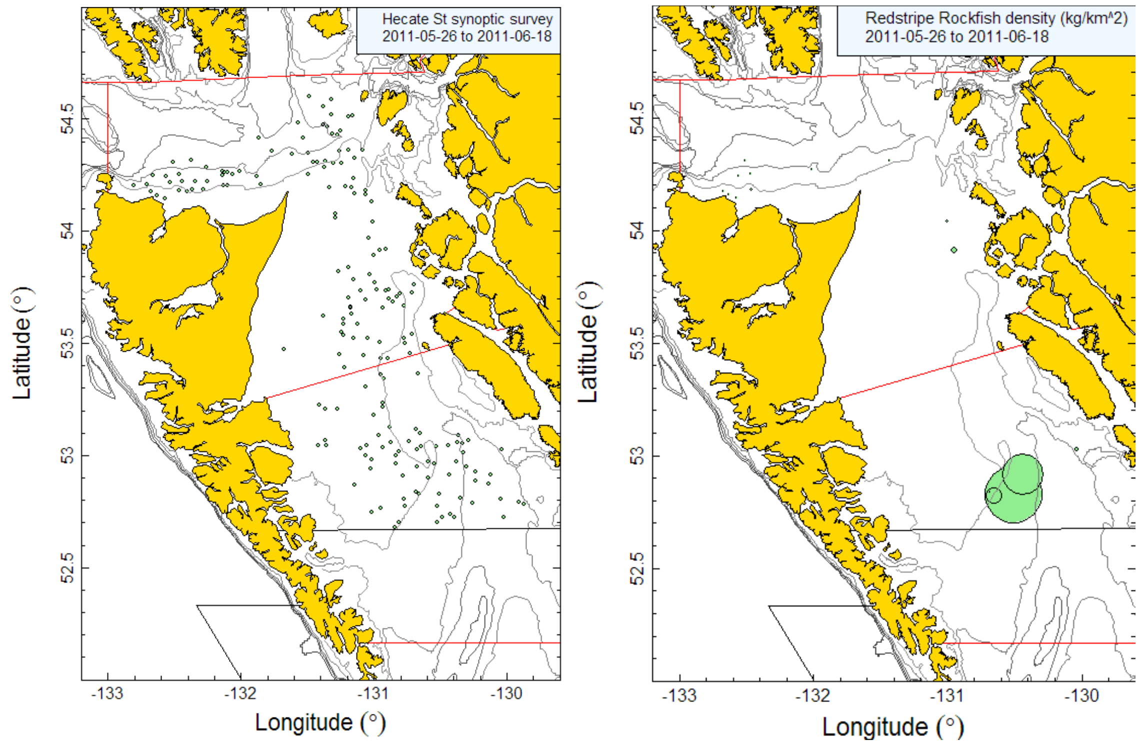


Figure B.26. Tow locations and density plots for the 2011 Hecate Strait synoptic survey (see Figure B.23 caption).

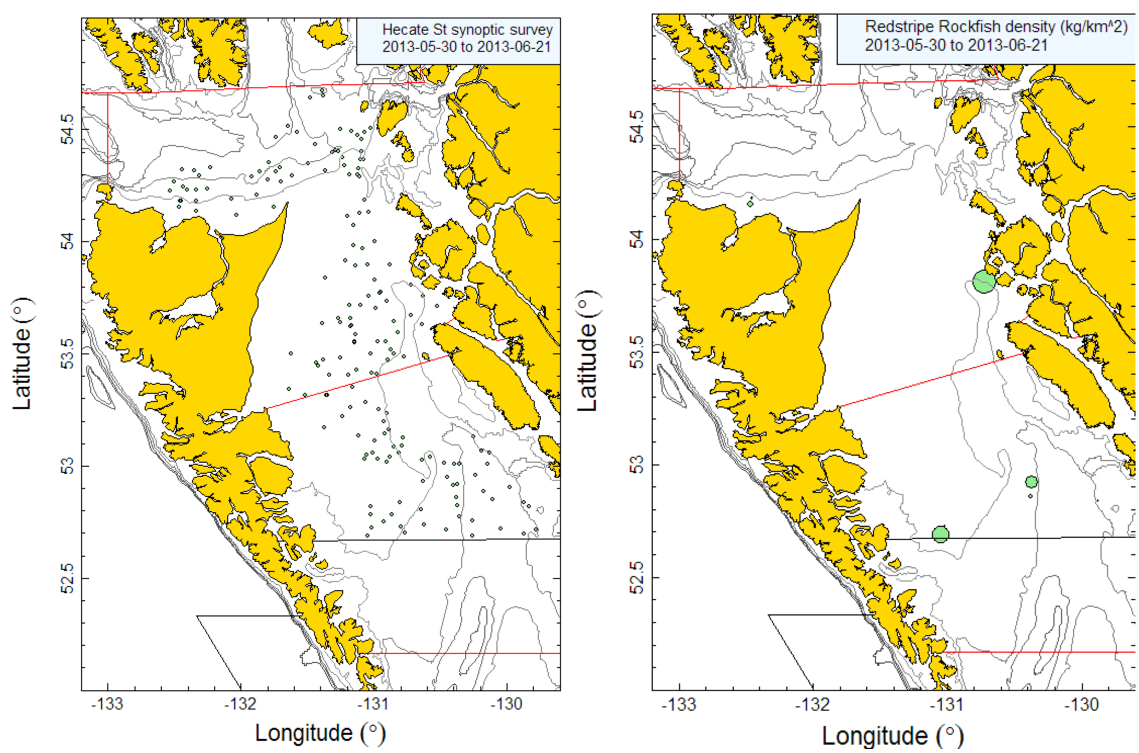


Figure B.27. Tow locations and density plots for the 2013 Hecate Strait synoptic survey (see Figure B.23 caption).

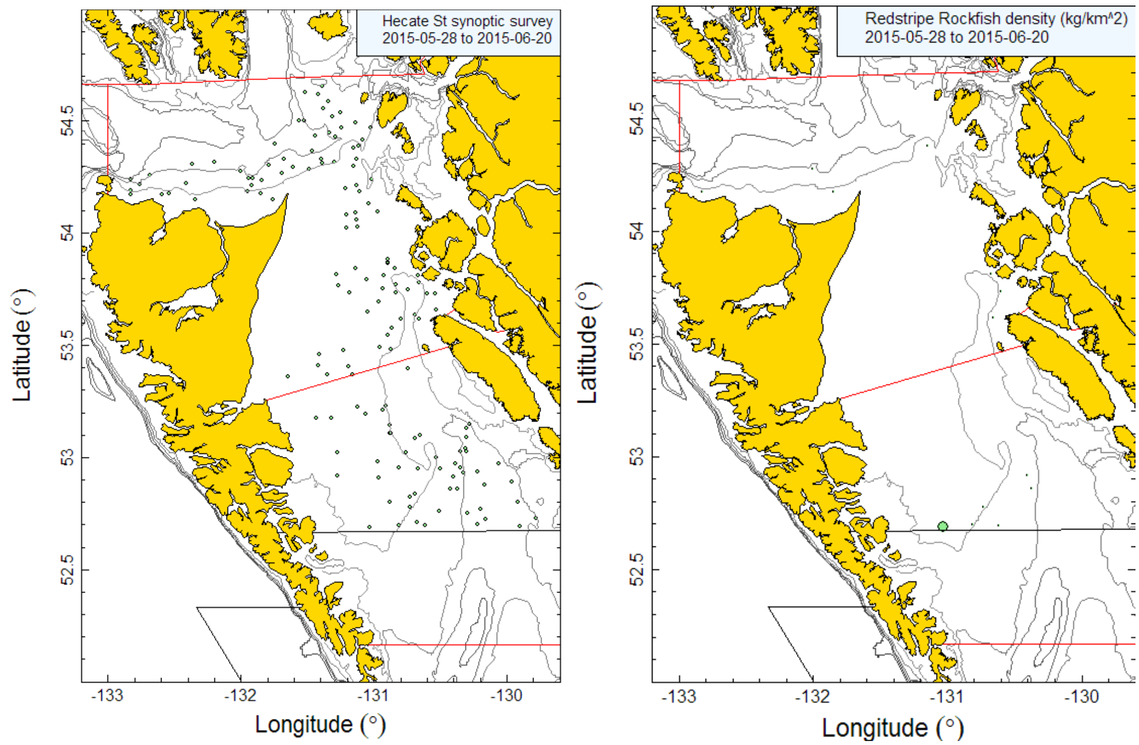


Figure B.28. Tow locations and density plots for the 2015 Hecate Strait synoptic survey (see Figure B.23 caption).

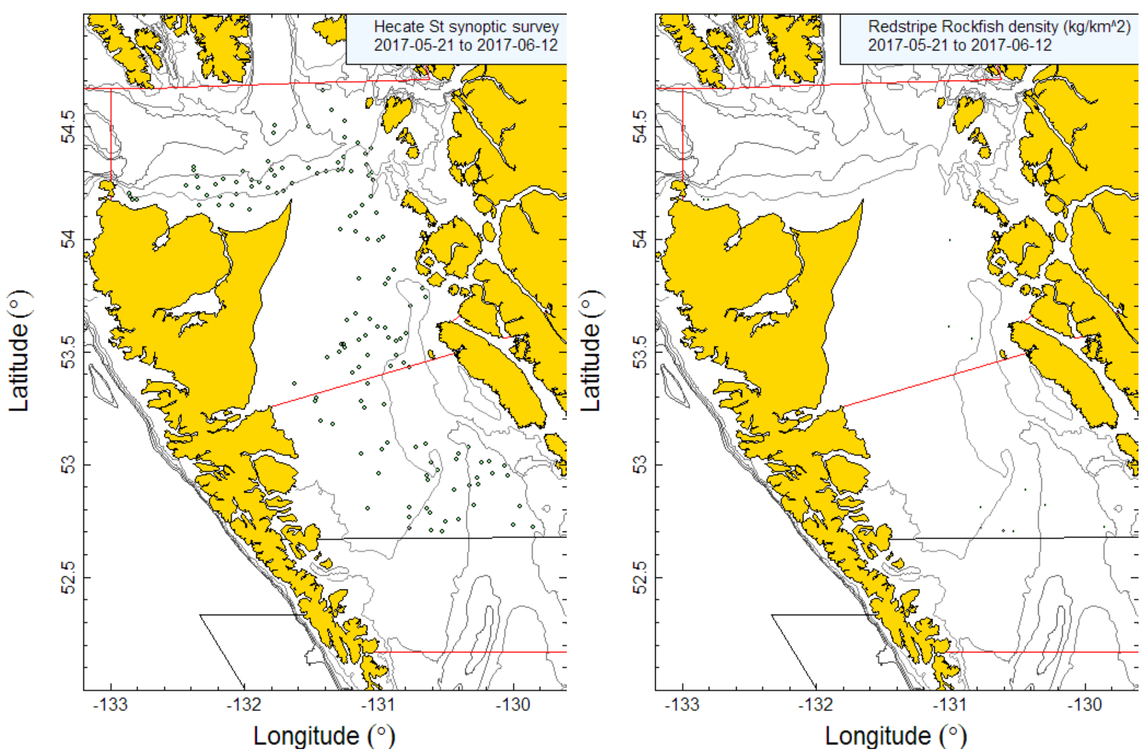


Figure B.29. Tow locations and density plots for the 2017 Hecate Strait synoptic survey (see Figure B.23 caption).

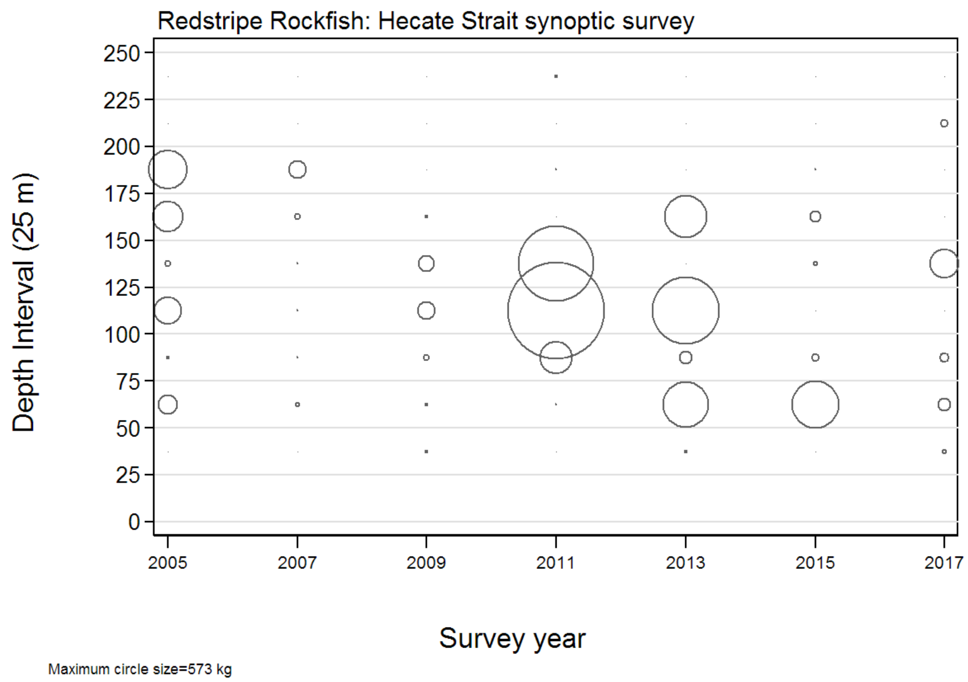


Figure B.30. Distribution of observed catch weights of Redstripe Rockfish for the Hecate Strait synoptic survey (Table B.11) by survey year and 25 m depth zone. Catches are plotted at the mid-point of the interval and circles in the panel are scaled to the maximum value (573 kg) in the 100-125 m interval in 2011. The 1% and 99% quantiles for the RSR empirical start of tow depth distribution= 51 m and 200 m respectively.

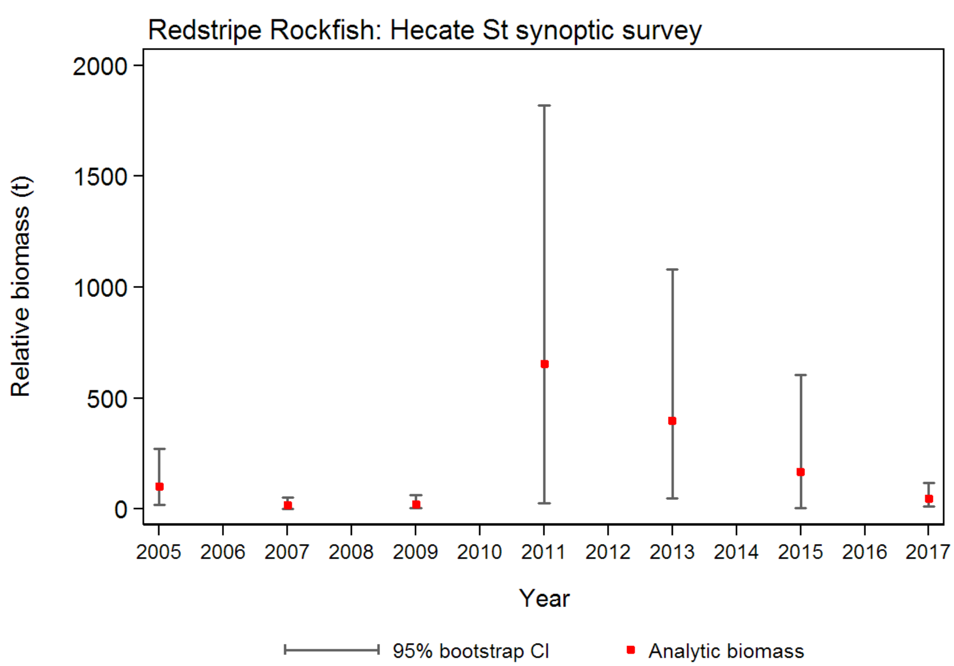


Figure B.31. Plot of biomass estimates for Redstripe Rockfish values provided in Table B.13 from the Hecate Strait synoptic survey over the period 2005 to 2017 . Bias corrected 95% confidence intervals from 1000 bootstrap replicates are plotted.

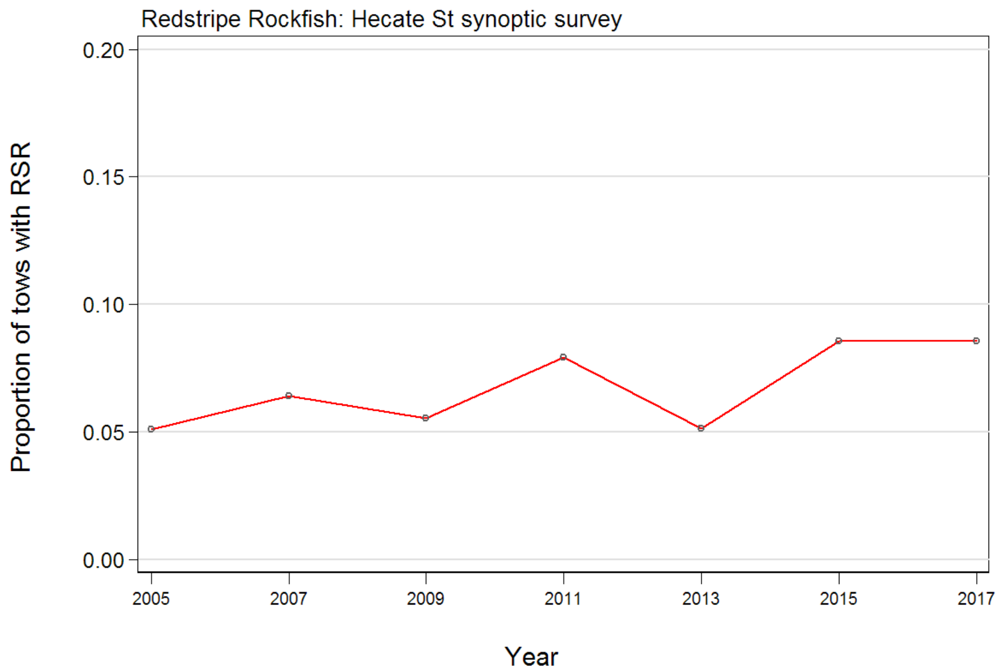


Figure B.32. Proportion of tows by year which contain Redstripe Rockfish from the Hecate Strait synoptic survey over the period 2005 to 2017.

Estimated RSR `doorspread` biomass indices from this trawl survey showed no overall trend over the period 2005 to 2017, with the highest estimates recorded in 2011 and 2013 and the lowest estimates in 2007 and 2009 (Table B.13; Figure B.31). The estimated relative errors were very high, ranging from 54 to 94%, rendering this survey almost useless for this species (Table B.13). The incidence of RSR in this survey is low, with less than 10% of the tows capturing this species in all years (survey average=7.2%) (Figure B.32). Overall, only 82 of the 1134 usable survey tows contained RSR with a low median catch weight for positive tows (1.5 kg/tow) and a maximum catch weight across all seven surveys of 573 kg (in 2011).

B.6. QUEEN CHARLOTTE SOUND SYNOPTIC TRAWL SURVEY

B.6.1. Data selection

This survey has been conducted in nine years over the period 2003 to 2017 in 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.33 to Figure B.40). Each of these two areas was divided into four depth strata: 50–125 m; 125–200 m; 200–330 m; and 330–500 m (Table B.14).

A `doorspread` density value (Eq. B.3) was generated for each tow based on the catch of Redstripe Rockfish (RSR) 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.15).

Table B.14. 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.15. 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

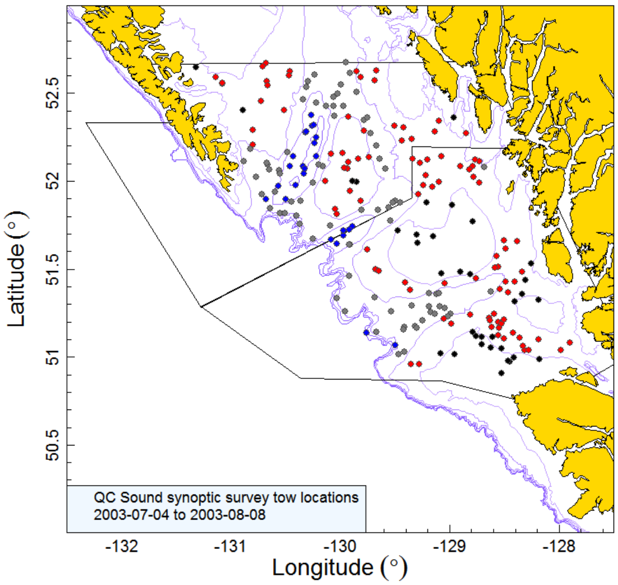
[1] valid biomass estimation tows only [2] includes tows not used for biomass estimation

Table B.16. Biomass estimates for Redstripe 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	2,485	2,501	715	6,533	0.569	0.573
2004	2,068	2,078	980	3,860	0.347	0.337
2005	1,616	1,620	969	2,712	0.270	0.258
2007	2,123	2,124	887	3,831	0.345	0.344
2009	1,719	1,715	985	2,775	0.264	0.272
2011	2,729	2,706	1,068	5,645	0.404	0.410
2013	2,918	2,956	1,329	5,520	0.362	0.364
2015	1,532	1,521	751	2,792	0.350	0.336
2017	1,074	1,078	618	1,754	0.263	0.271

B.6.2. Results

RSR seems to be widely distributed in QCS, with catches observed throughout the survey footprint, although the southern stratum, which mainly covers the GIG, seems to predominate over the northern stratum (Figure B.33 to Figure B.41). RSR catches appear to have been relatively low in both the 2015 (Figure B.40) and especially the 2017 (Figure B.41) surveys. RSR were mainly taken at depths from 118 to 210 m (5–95% quantiles), but there were sporadic observations up to depths near 350 m and down to about 40 m (Figure B.42).



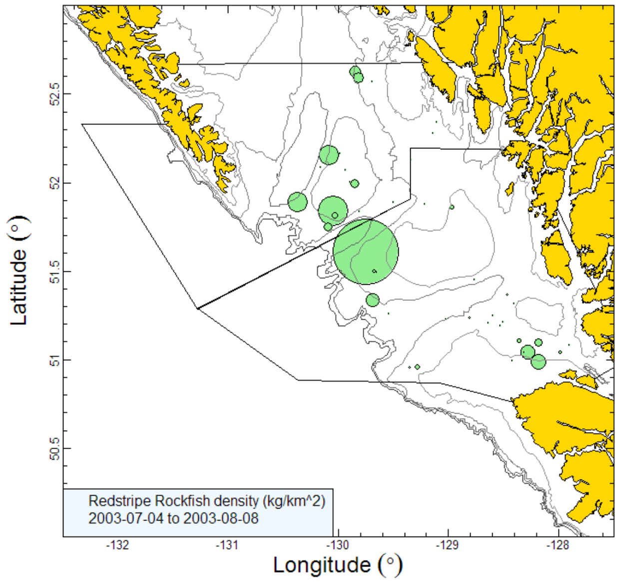
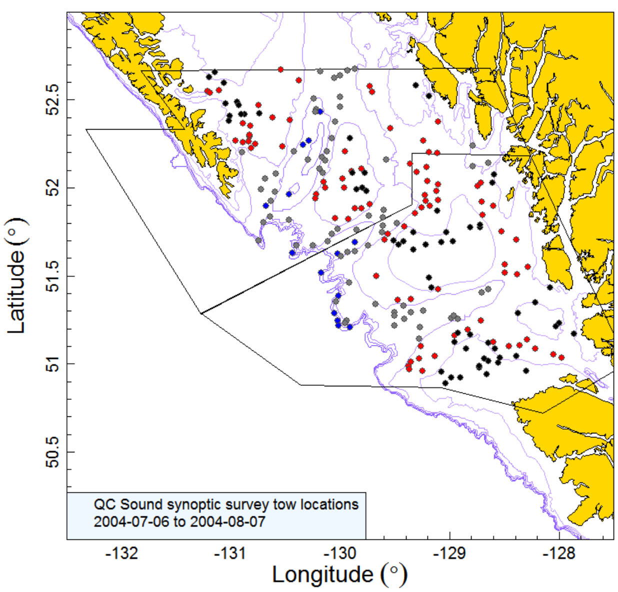


Figure B.33. Valid tow locations (50-125m stratum: black; 126-200m stratum: red; 201-330m stratum: grey; 331-500m stratum: blue) and density plots for the 2003 QC Sound synoptic survey. Circle sizes in the right-hand density plot scaled across all years (2003–2005, 2007, 2009, 2011, 2013, 2015, 2017), with the largest circle = 14,366 kg/km² in 2003. Boundaries delineate the North and South areal strata.



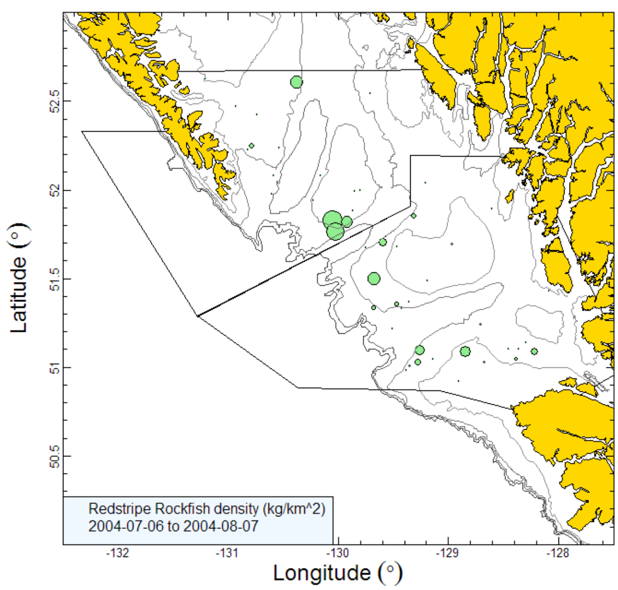


Figure B.34. Tow locations and density plots for the 2004 Queen Charlotte Sound synoptic survey (see Figure B.33 caption).

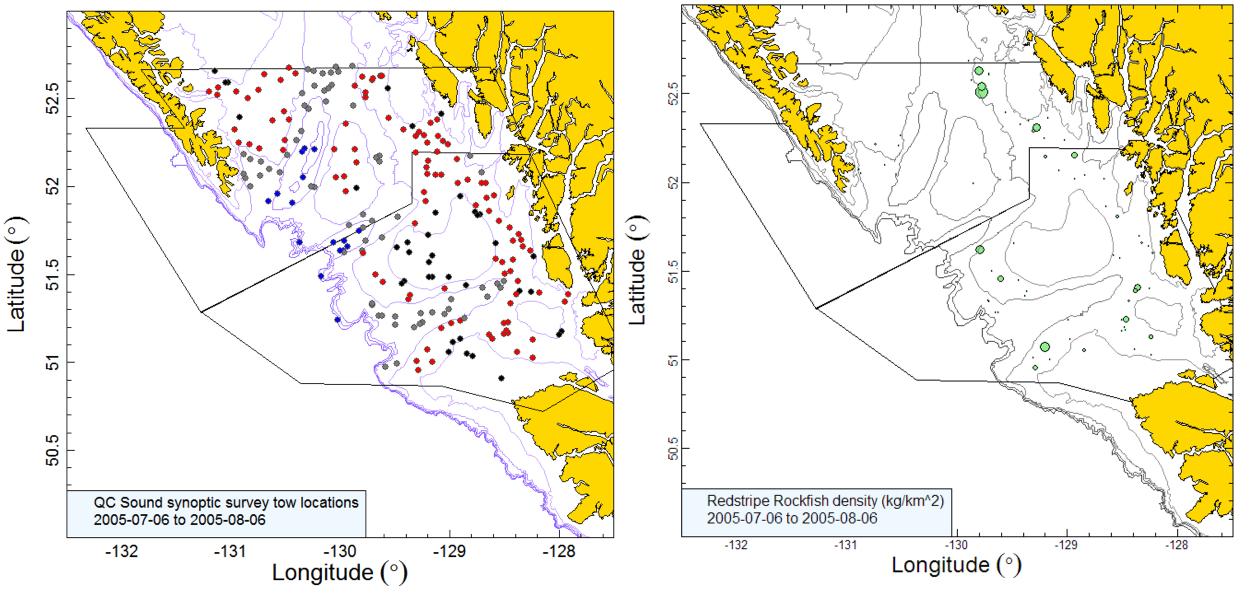


Figure B.35. Tow locations and density plots for the 2005 Queen Charlotte Sound synoptic survey (see Figure B.33 caption).

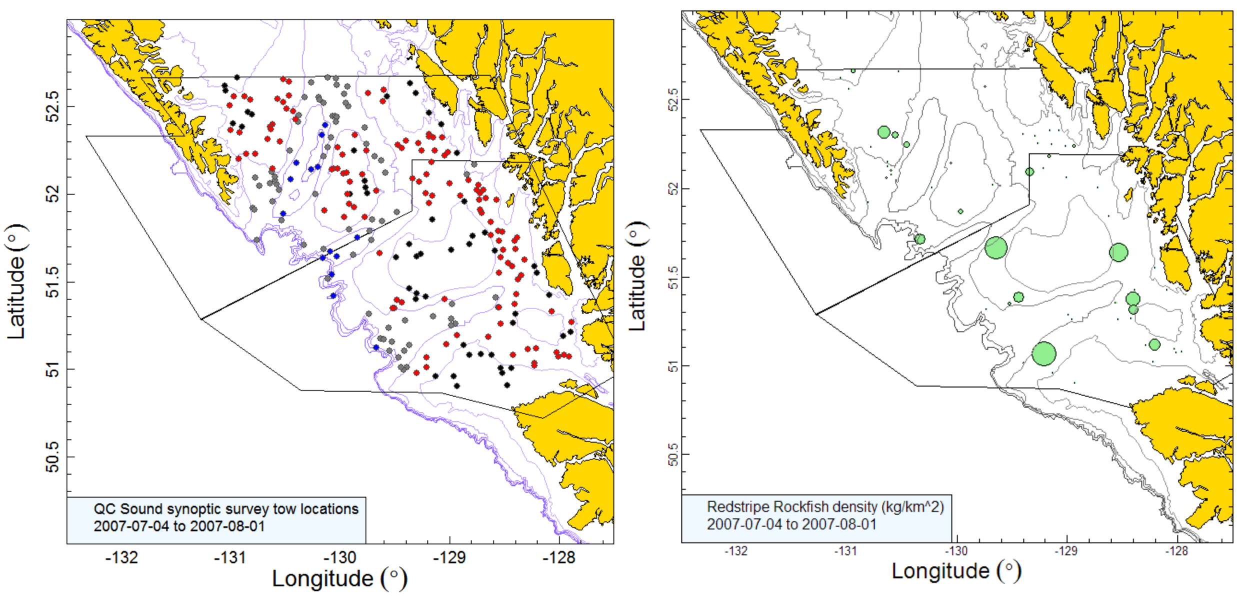


Figure B.36. Tow locations and density plots for the 2007 Queen Charlotte Sound synoptic survey (see Figure B.33 caption).

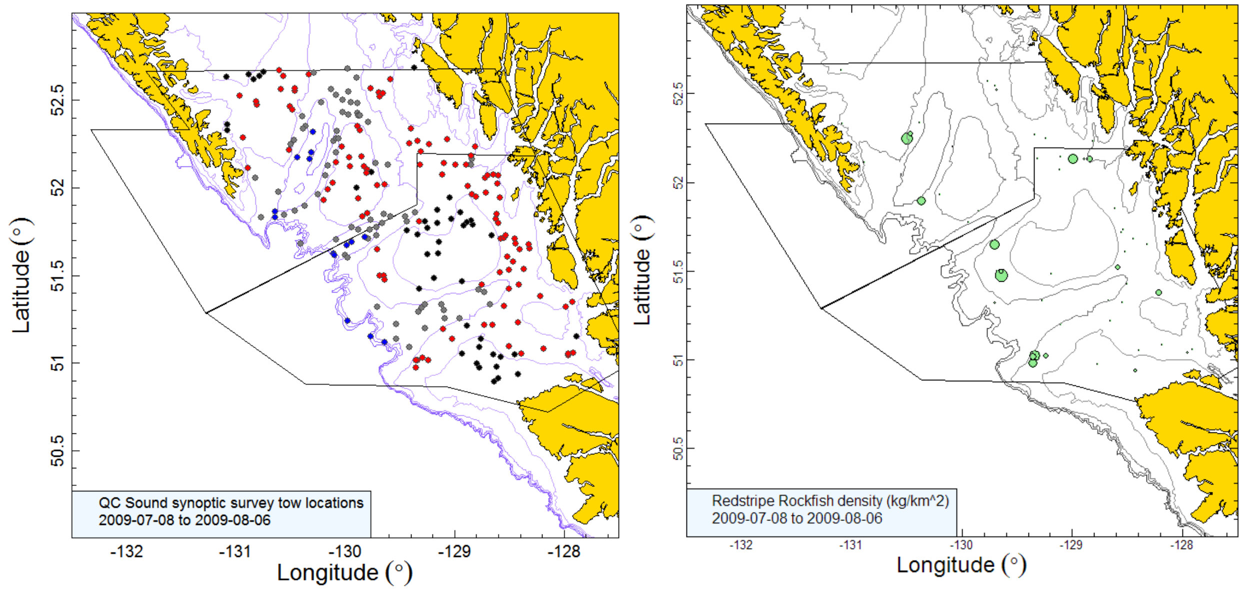


Figure B.37. Tow locations and density plots for the 2009 Queen Charlotte Sound synoptic survey (see Figure B.33 caption).

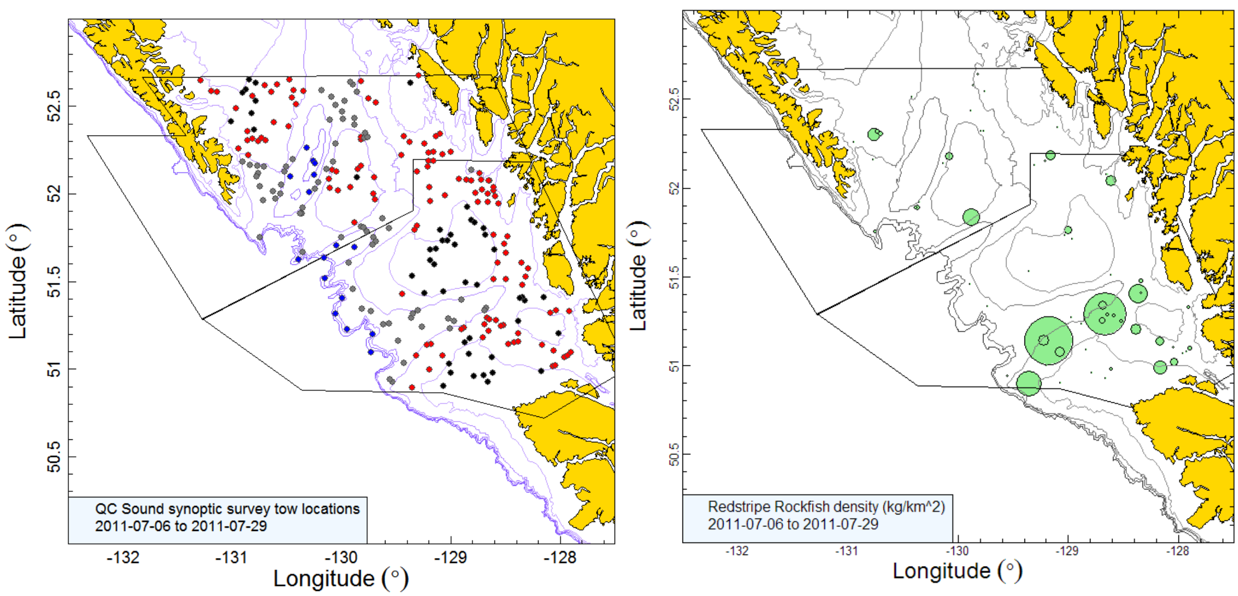


Figure B.38. Tow locations and density plots for the 2011 Queen Charlotte Sound synoptic survey (see Figure B.33 caption).

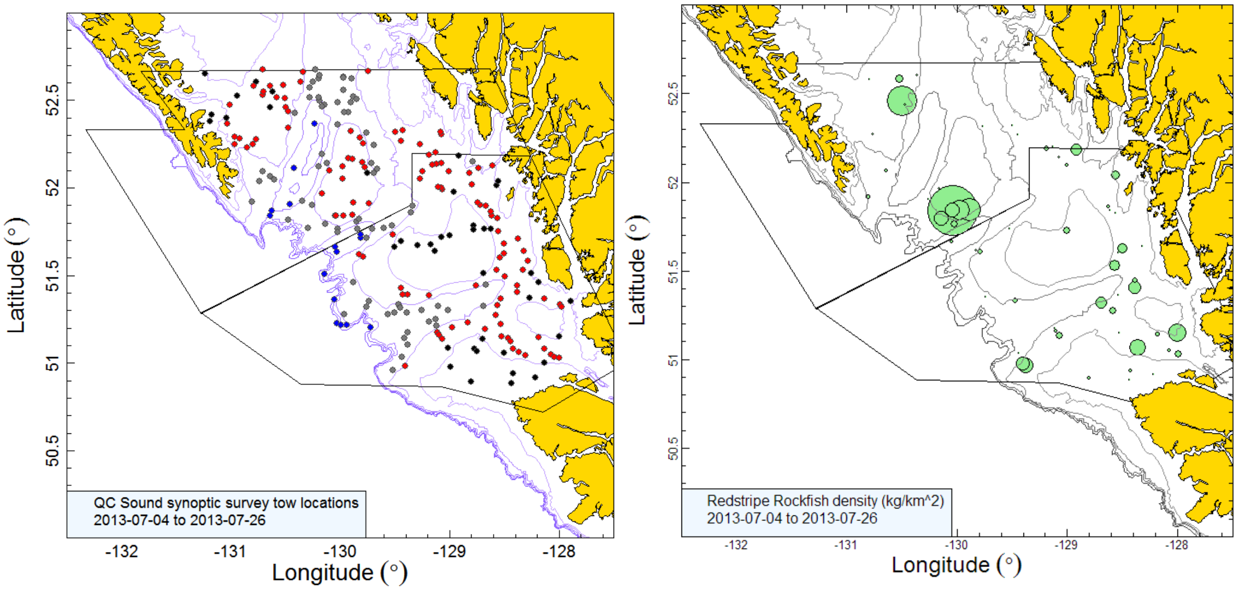


Figure B.39. Tow locations and density plots for the 2013 Queen Charlotte Sound synoptic survey (see Figure B.33 caption).

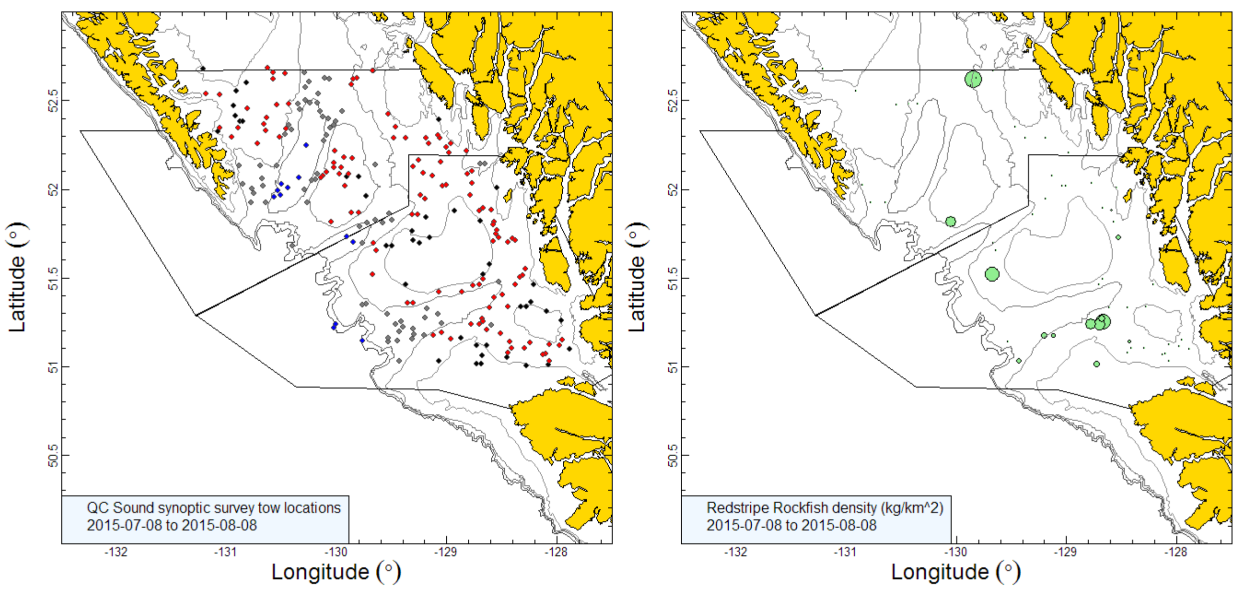


Figure B.40. Tow locations and density plots for the 2015 Queen Charlotte Sound synoptic survey (see Figure B.33 caption).

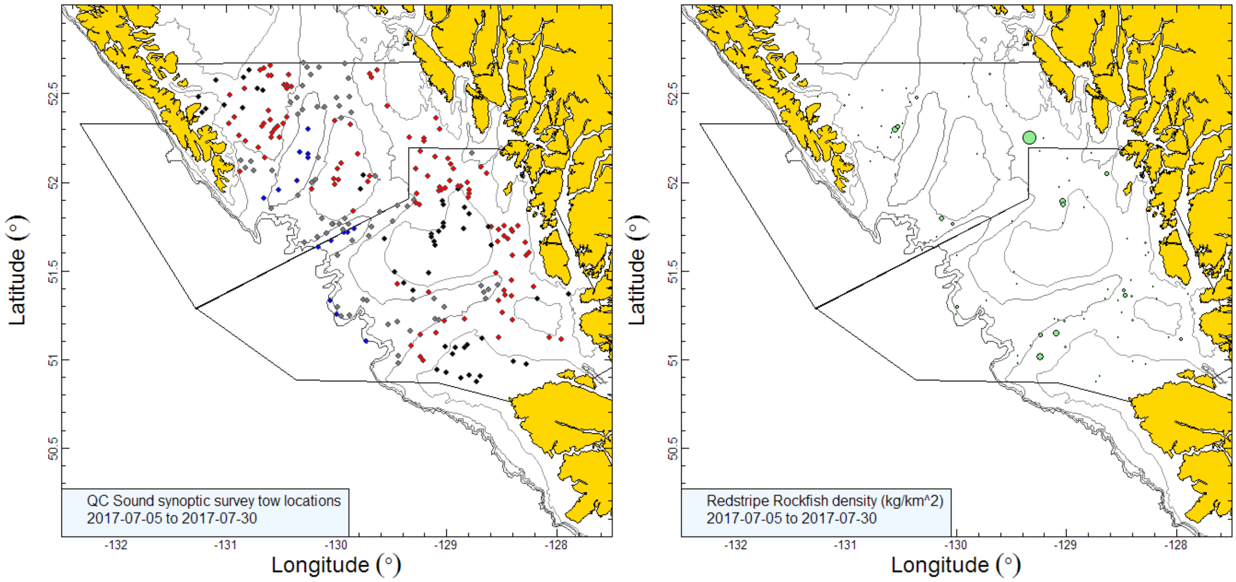


Figure B.41. Tow locations and density plots for the 2017 Queen Charlotte Sound synoptic survey (see Figure B.33 caption).

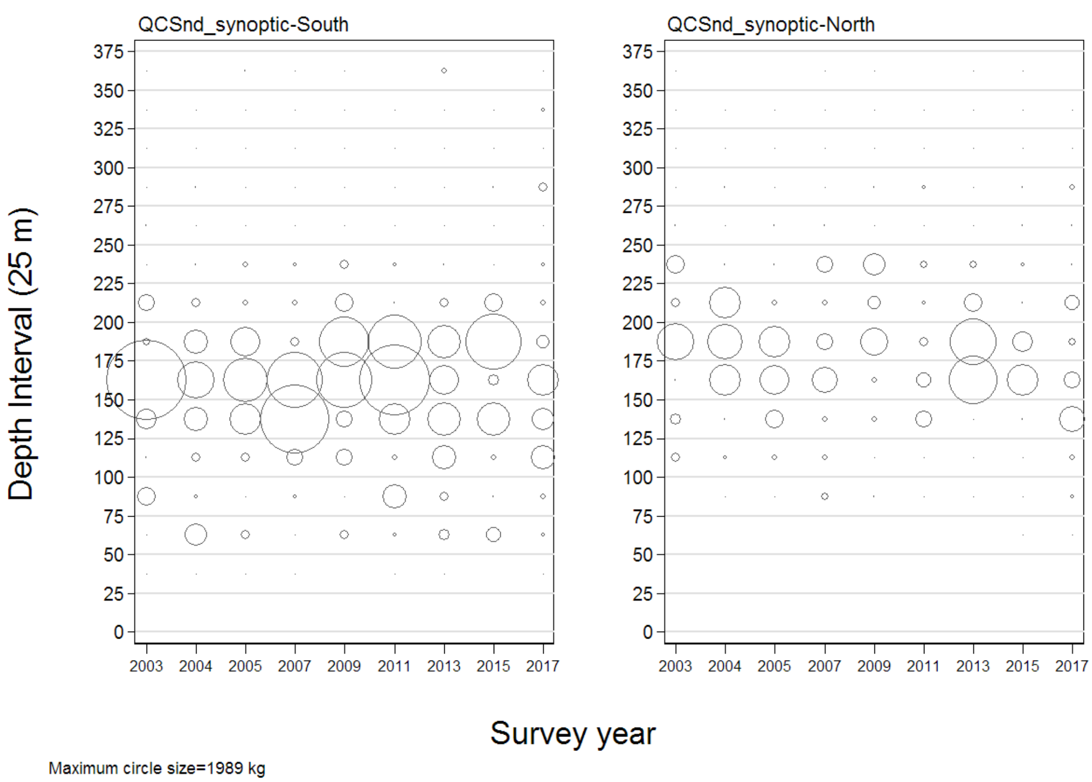


Figure B.42. Distribution of observed catch weights of Redstripe Rockfish for the two main Queen Charlotte Sound synoptic survey areal strata (Table B.14) by survey year and 25 m depth zone. Catches are plotted at the mid-point of the interval and circles in the panel are scaled to the maximum value (1989 kg) in the 150–175 m interval in the 2003 southern stratum. The 1% and 99% quantiles for the RSR empirical start of tow depth distribution= 68 m and 236 m respectively.

Estimated RSR `doorspread` biomass levels from this trawl survey have been relatively constant over the nine survey years, only varying between 1,070 and 2,900 t (Table B.16; Figure B.43). The most recent two survey years (2015 and 2017) are the two lowest in the series. The estimated relative errors are high, lying between 26 and 57% (Table B.16). Between 23 and 40% of the South stratum tows and 16 to 30% of the North stratum tows captured some RSR (Figure B.44). Overall, 549 of the 2144 valid survey tows (26%) contained RSR, with the North stratum having a 20% average proportion non-zero tows while the equivalent South stratum proportion was 30%. The median catch weight for positive tows was 4.0 kg/tow across all nine surveys, and the maximum catch weight was 1,932 kg in the 2003 survey.

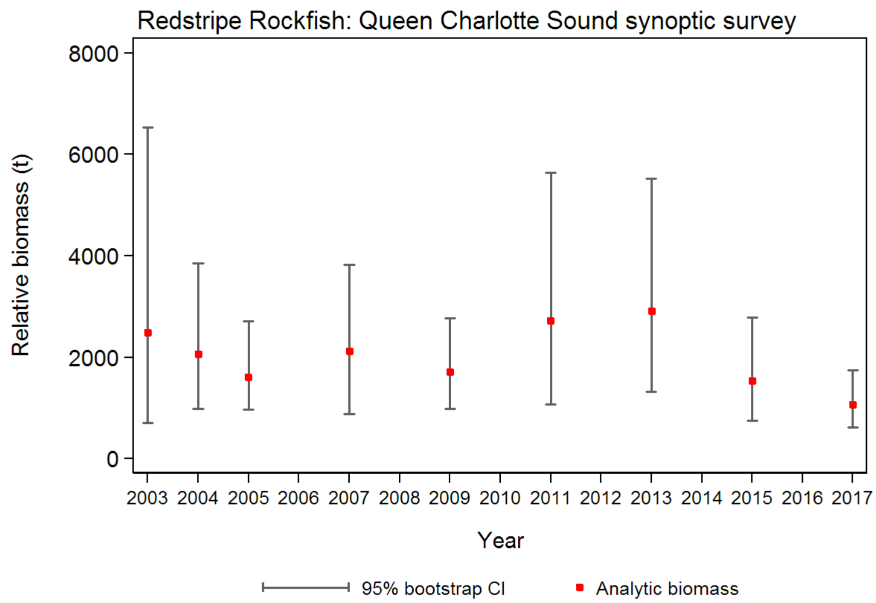


Figure B.43. Plot of biomass estimates for RSR (values provided in Table B.16) from the Queen Charlotte Sound synoptic survey over the period 2003 to 2017. Bias corrected 95% confidence intervals from 1000 bootstrap replicates are plotted.

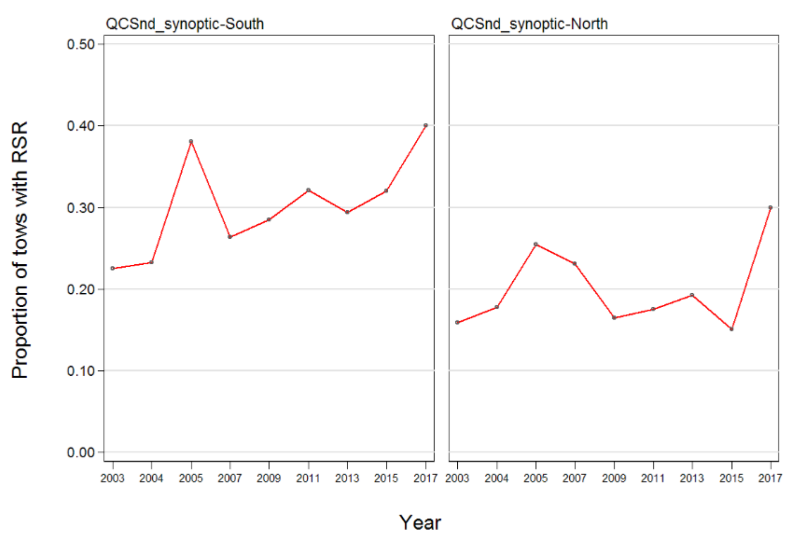


Figure B.44. Proportion of tows by stratum and year which contain RSR from the Queen Charlotte Sound synoptic survey over the period 2003 to 2017.

B.7. WEST COAST VANCOUVER ISLAND SYNOPTIC TRAWL SURVEY

B.7.1. Data selection

This survey has been conducted seven times in the period 2004 to 2016 off the west coast of Vancouver Island by RV *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.17). 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 Redstripe 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 64.7 m for the three years with no `doorspread` data (Table B.18). 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.17. 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 2016 and the start and end dates for each survey.

Survey year	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	34	34	13	8	89	17	26-May-04	09-Jun-04
2006	61	62	28	13	164	12	24-May-06	18-Jun-06
2008	54	50	32	23	159	19	27-May-08	21-Jun-08
2010	58	47	22	9	136	8	08-Jun-10	28-Jun-10
2012	61	46	26	20	153	4	23-May-12	15-Jun-12
2014	55	49	29	14	147	6	29-May-14	20-Jun-14
2016	54	41	26	19	140	7	25-May-16	15-Jun-16
Area (km^2)	5804	3796	708	608	10,916[2]	–	–	–

[1] GFBio usability codes=0,1,2,6

[2] Total area (km^2) for 2016 synoptic survey

Table B.18. 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.

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
All surveys	546	462	64.7

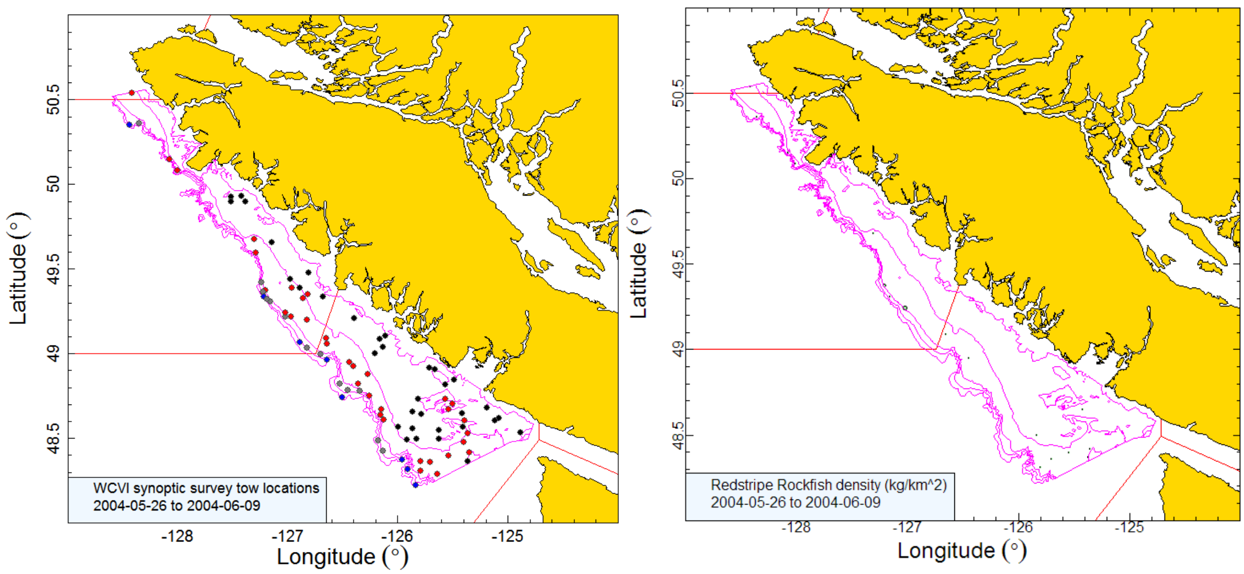


Figure B.45. Valid tow locations (50-125m stratum: black; 126-200m stratum: red; 201-330m stratum: grey; 331-500m stratum: blue) and density plots for the 2004 west coast Vancouver Island synoptic survey. Circle sizes in the right-hand density plot scaled across all years (2004, 2006, 2008, 2010, 2012, 2014, 2016), with the largest circle = 58,469 kg/km² in 2012. The red solid lines indicate the boundaries for PMFC areas 3C, 3D and 5A.

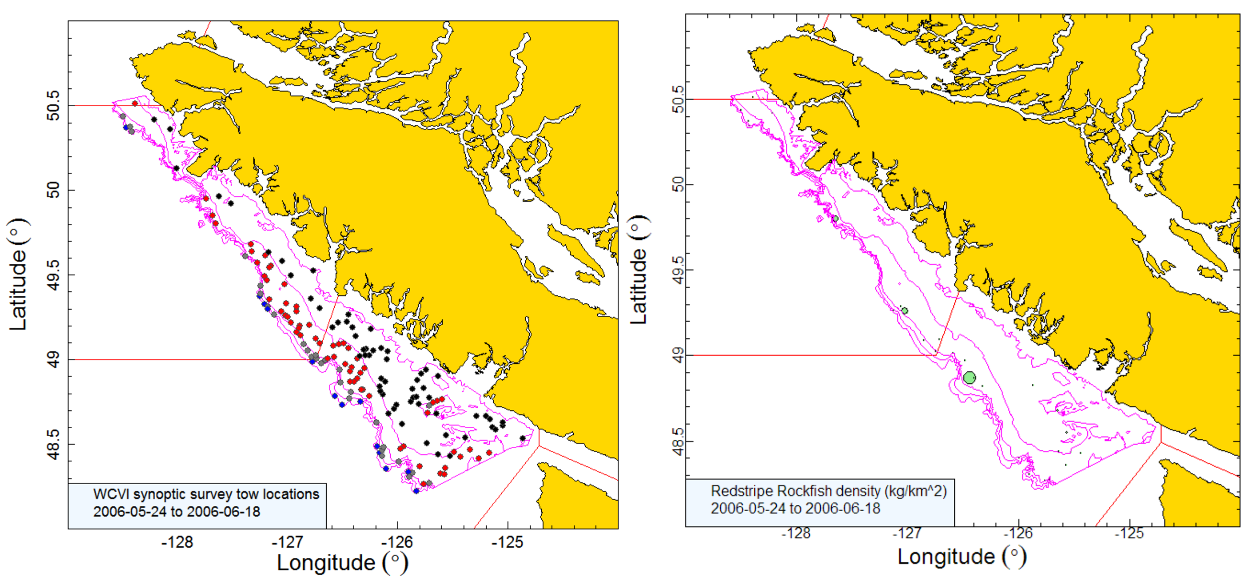


Figure B.46. Tow locations and density plots for the 2006 west coast Vancouver Island synoptic survey (see Figure B.45 caption).

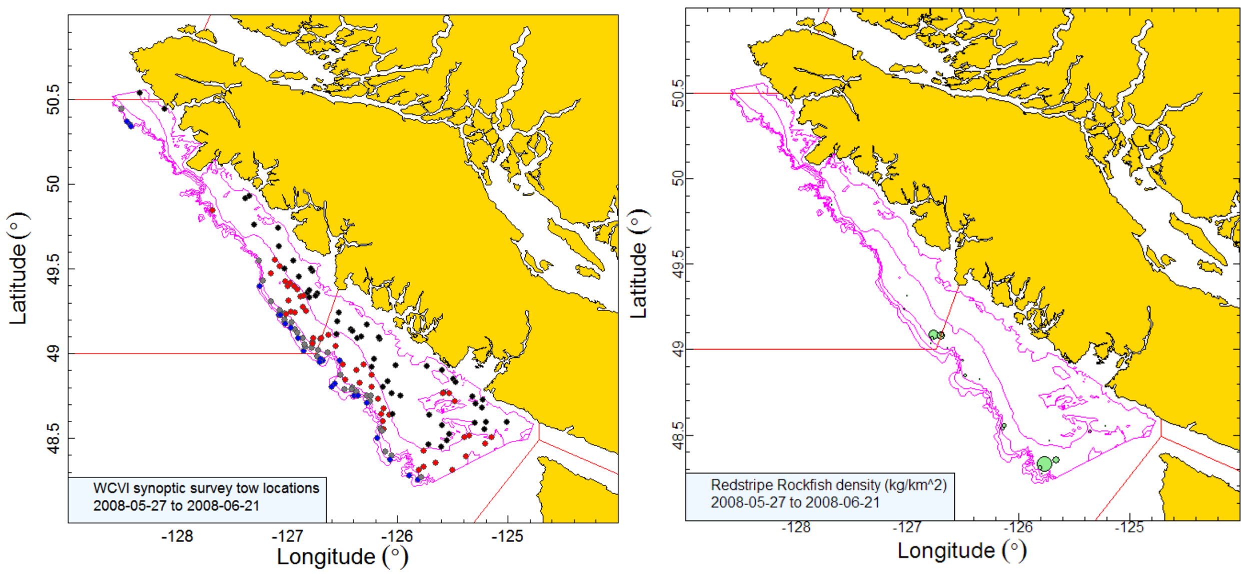


Figure B.47. Tow locations and density plots for the 2008 west coast Vancouver Island synoptic survey (see Figure B.45 caption).

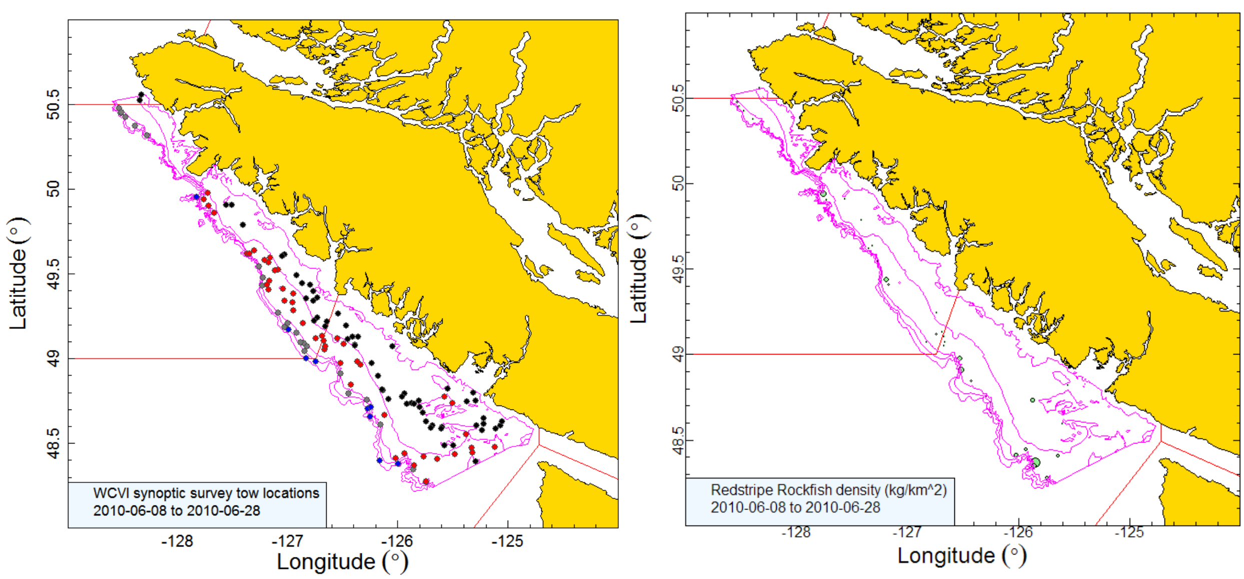


Figure B.48. Tow locations and density plots for the 2010 west coast Vancouver Island synoptic survey (see Figure B.45 caption).

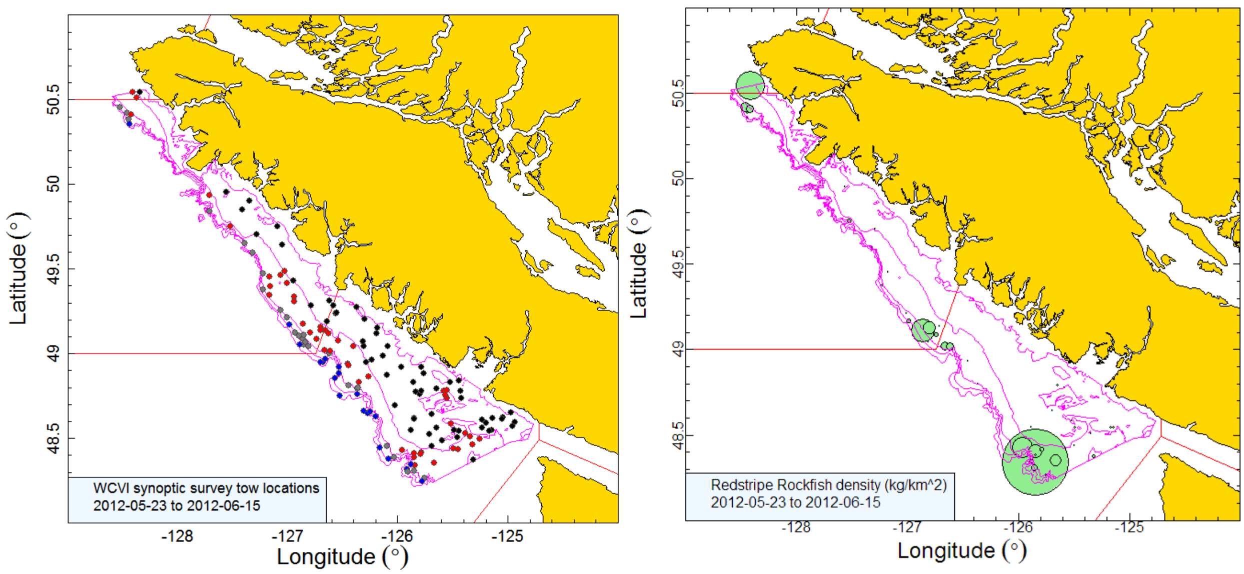


Figure B.49. Tow locations and density plots for the 2012 west coast Vancouver Island synoptic survey (see Figure B.45 caption).

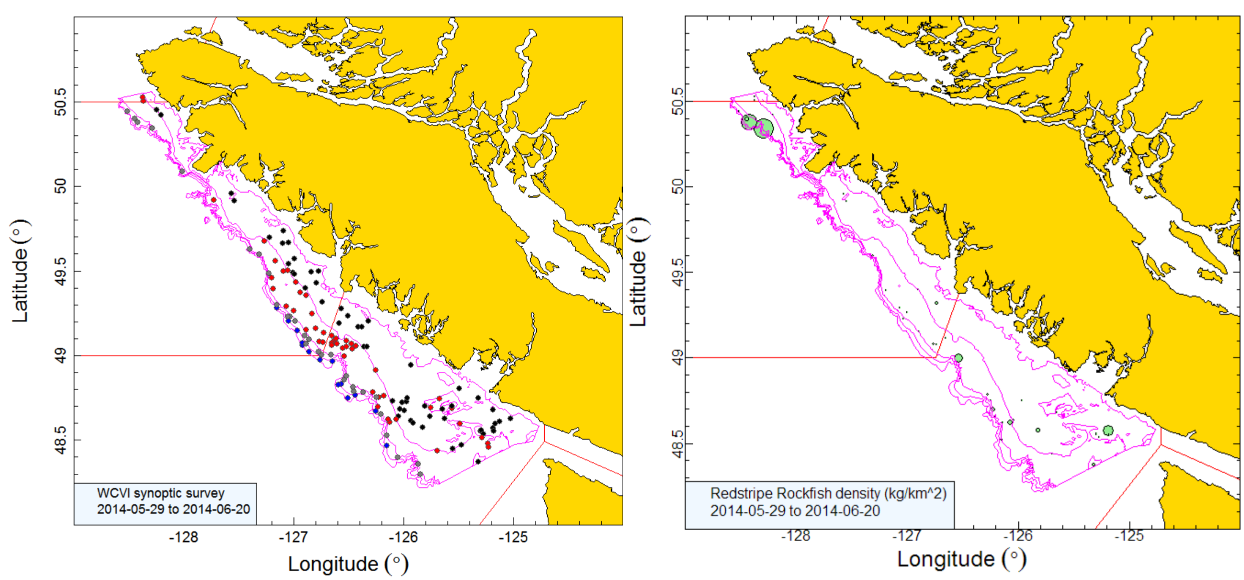


Figure B.50. Tow locations and density plots for the 2014 west coast Vancouver Island synoptic survey (see Figure B.45 caption).

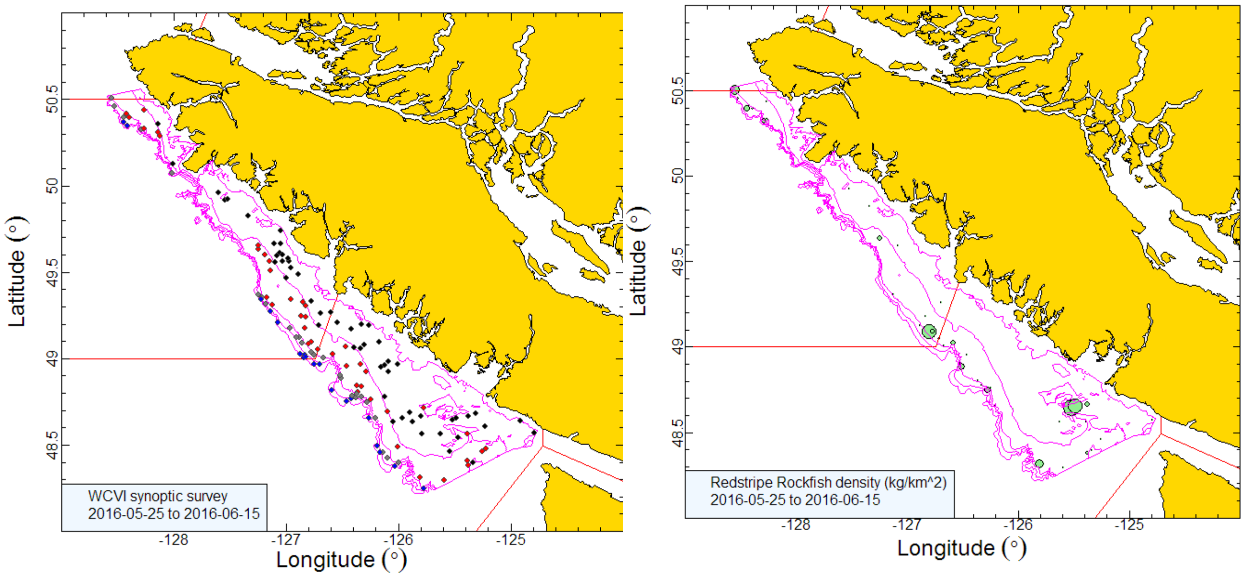


Figure B.51. Tow locations and density plots for the 2016 west coast Vancouver Island synoptic survey (see Figure B.45 caption).

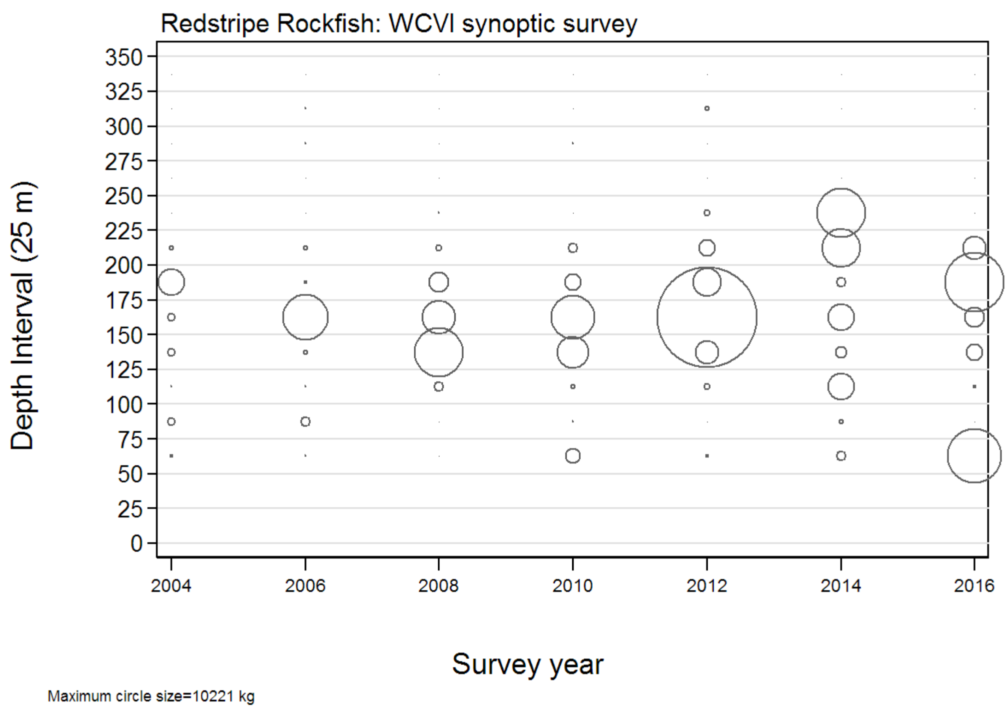


Figure B.52. Distribution of observed weights of Redstripe Rockfish by survey year and 25 m depth zone. Catches are plotted at the mid-point of the interval and circles in the panel are scaled to the maximum value (10221 kg) in the 150-175 m interval in 2012. The 1% and 99% quantiles for the RSR empirical start of tow depth distribution= 62 m and 234 m respectively.

B.7.2. Results

As seen in the NMFS Triennial survey (which covered the lower half of Vancouver Island, see Section B.4), RSR are taken all along the shelf edge from near the US border to the top of Vancouver Island (Figure B.45 to Figure B.50). There does not seem to be any region that predominates in the spatial distribution, with good but sporadic catches of RSR all up and down the west coast of Vancouver Island. Redstripe Rockfish were mainly taken at depths from 64 to 234 m (5–95% quantiles) and there were only four observations at depths greater than 300 m (Figure B.52). Estimated biomass levels for Redstripe Rockfish from this trawl survey show elevated biomass levels in 2012 and 2016, but there is no apparent trend over the survey period. Relative errors are high, ranging from 34 to 67% across the seven surveys (Figure B.53; Table B.19).

The proportion of tows capturing Redstripe Rockfish ranged between 18 and 30% for the seven surveys, with a mean value of 25% (Figure B.54). Two hundred forty-four of the 985 usable tows from this survey contain RSR, with a median catch weight for positive tows of 12.3 kg/tow and maximum catch weight across all seven surveys of 7,598 kg (in 2012).

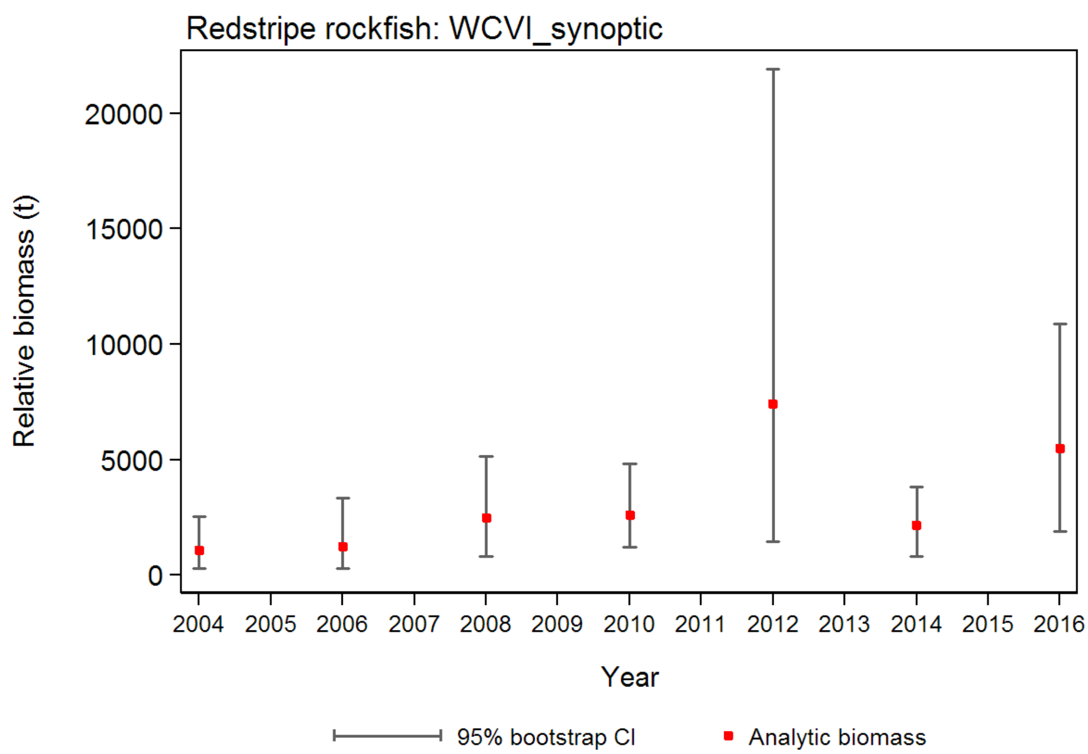


Figure B.53. Plot of biomass estimates for Redstripe Rockfish from the 2004 to 2016 west coast Vancouver Island synoptic trawl surveys (Table B.19). Bias-corrected 95% confidence intervals from 1000 bootstrap replicates are plotted.

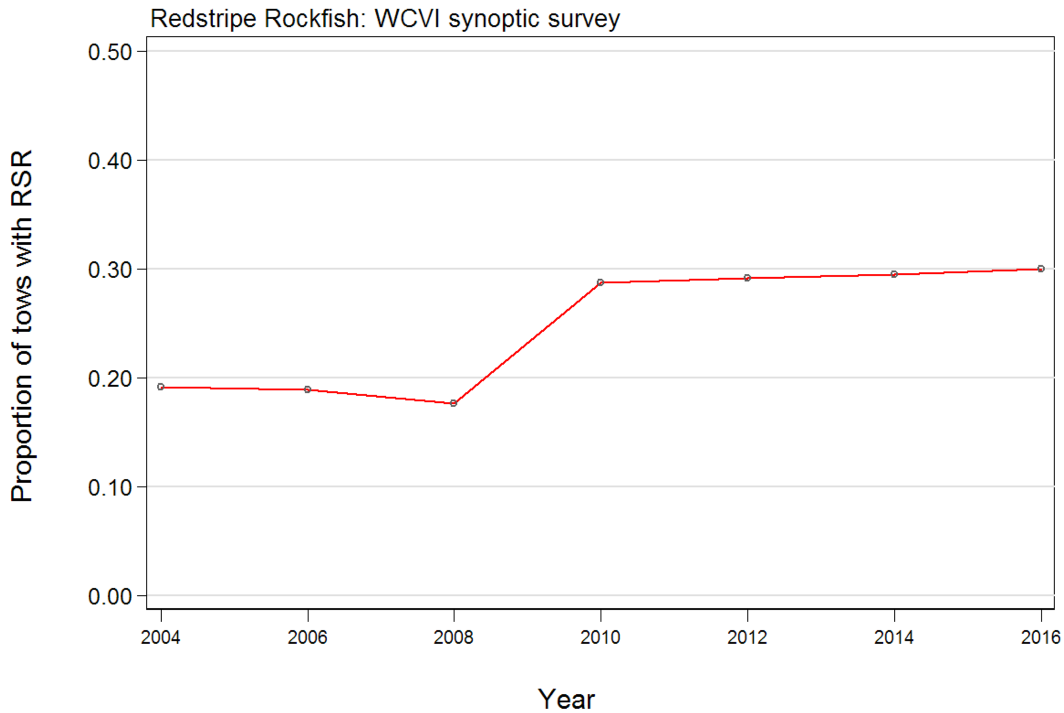


Figure B.54. Proportion of tows by stratum and year capturing Redstripe Rockfish in the WCVI synoptic trawl surveys, 2004–2016.

Table B.19. Biomass estimates for Redstripe Rockfish from the WCVI synoptic trawl survey for the survey years 2004 to 2016. 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	1,075	1,055	277	2,524	0.499	0.500
2006	1,261	1,232	283	3,349	0.607	0.591
2008	2,506	2,527	814	5,157	0.448	0.453
2010	2,607	2,636	1,227	4,841	0.343	0.336
2012	7,437	7,496	1,447	21,921	0.668	0.658
2014	2,174	2,240	836	3,832	0.345	0.357
2016	5,513	5,565	1,907	10,877	0.403	0.410

B.8. WEST COAST HAIDA GWAII SYNOPTIC TRAWL SURVEY

B.8.1. Data selection

The west coast Haida Gwaii (WCHG) survey has been conducted six times in the period 2006 to 2016 off the west coast of Haida Gwaii. A survey conducted in 2014 did not complete a sufficient number of tows for it to be considered completed. The survey comprises a single areal stratum extending from about 53°N to the BC-Alaska border and east to 133°W (e.g., Olsen et al. 2008). The 2006 survey used a different depth stratification scheme compared to the later synoptic surveys: 150–200 m, 200–330 m, 330–500 m, 500–800 m, and 800–1300 m (Workman et al. 2007). All tows from this survey were 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.20). Plots of the locations of all valid tows by year and stratum are presented in Figure B.55 (2006), Figure B.56 (2007), Figure B.57

(2008), Figure B.58 (2010), Figure B.59 (2012) and Figure B.60 (2016). 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) was omitted from this analysis because of lack of coverage in 2007.

Table B.20. Stratum designations, vessel name, number of usable and unusable tows, for each year of the west coast Haida Gwaii synoptic survey. Also shown are the area of each stratum and 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**
2006	Viking Storm	55	26	16	13	110 [2]	13	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	118	9	28-Aug-08	18-Sep-08
2010	Viking Storm	82	29	12	6	129	2	28-Aug-10	16-Sep-10
2012	Nordic Pearl	75	29	10	16	130	11	27-Aug-12	16-Sep-12
2016	Frosti	69	28	5	10	112	8	28-Aug-16	24-Sep-16
Area (km^2)		1104	1024	956	2248	5332 [3]	–	–	–

[1] GFBio usability codes=0,1,2,6; [2] excludes 2 tows S of 53°N; [3] Total area in 2016 (km^2)

Table B.21. 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)
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
Total/Average	655	103	75.8[1]

[1] average 2006–2016: all observations

A doorspread density (Eq. B.3) was generated for each tow based on the catch of Redstripe Rockfish (RSR) 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 six 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.21).

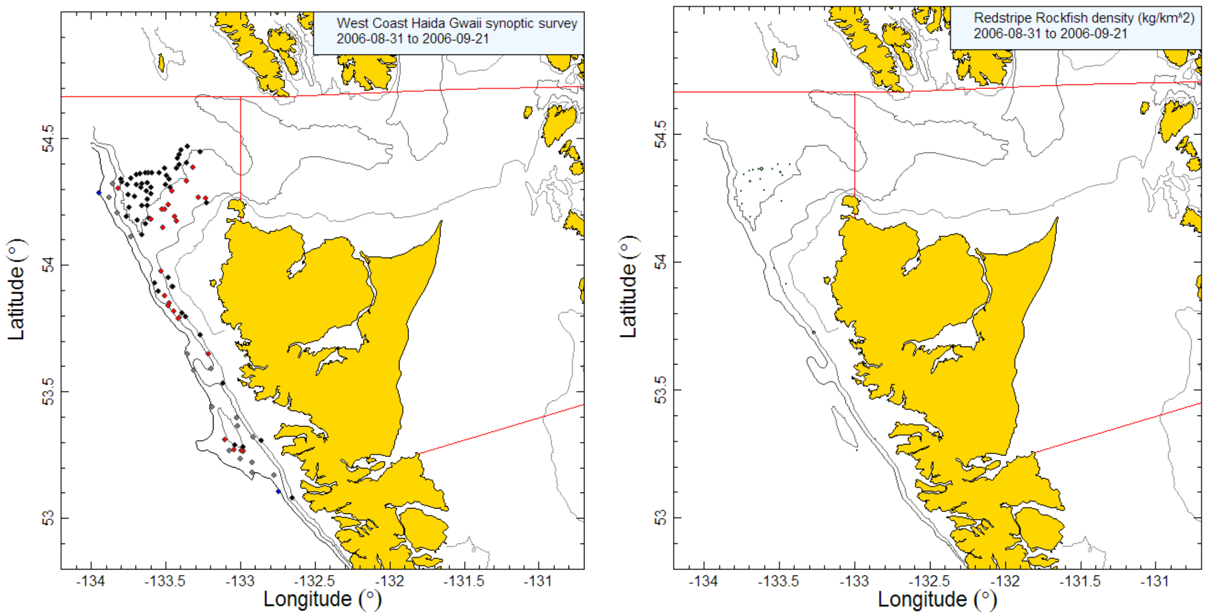


Figure B.55. Valid tow locations by stratum (180-330m: black; 330-500m: red; 500-800m: grey; 800-1300m: blue) and density plots for the 2006 Viking Storm synoptic survey. Circle sizes in the right-hand density plot scaled across all years (2006–2016), with the largest circle =2384 kg/km² in 2016. The red lines show the Pacific Marine Fisheries Commission 5E and 5D major area boundaries.

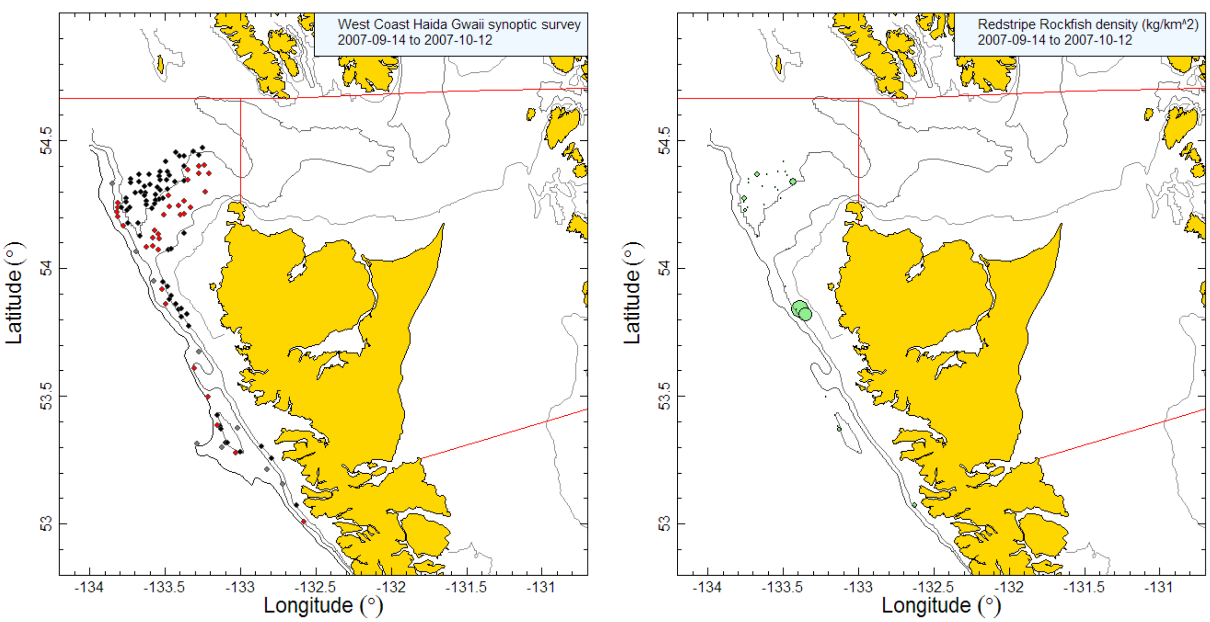


Figure B.56. Tow locations and density plots for the 2007 Nemesis synoptic survey (see Figure B.55 caption).

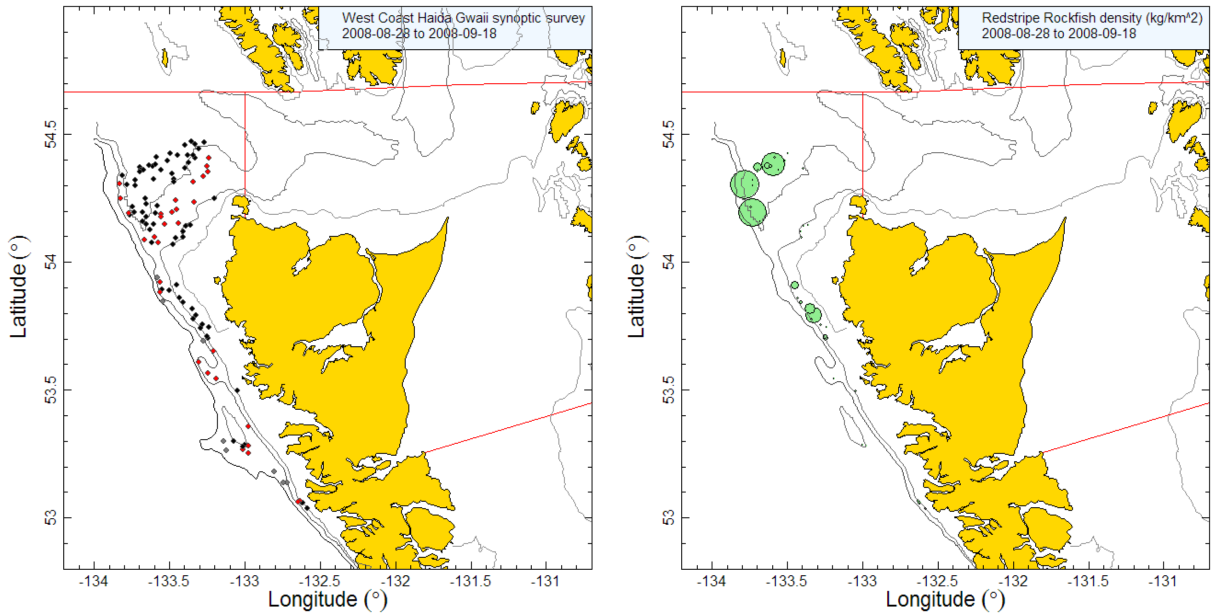


Figure B.57. Tow locations and density plots for the 2008 Frosti synoptic survey (see Figure B.55 caption).

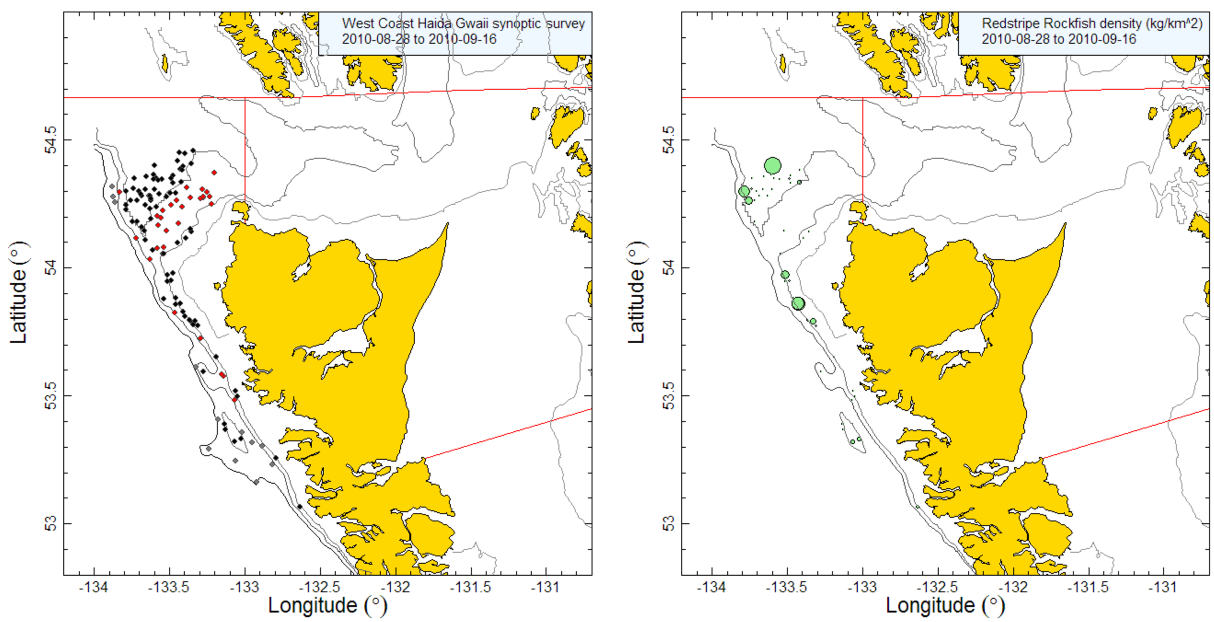


Figure B.58. Tow locations and density plots for the 2010 Viking Storm synoptic survey (see Figure B.55 caption).

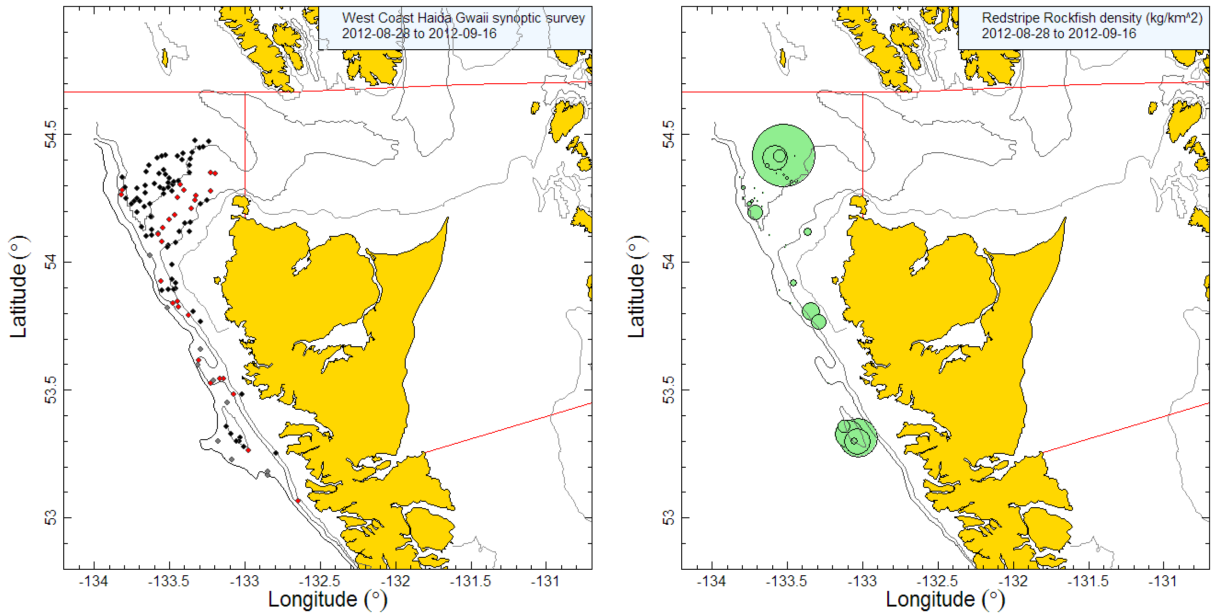


Figure B.59. Tow locations and density plots for the 2012 Viking Storm synoptic survey (see Figure B.55 caption).

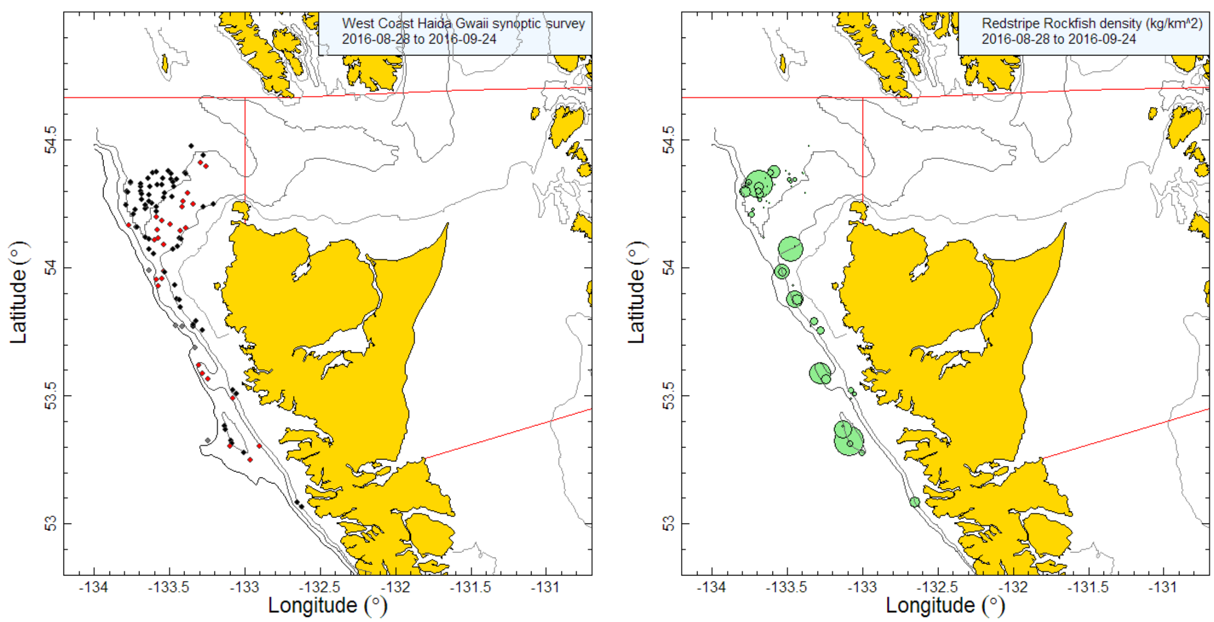


Figure B.60. Tow locations and density plots for the 2016 Frosti synoptic survey (see Figure B.55 caption).

B.8.2. Results

All six surveys have taken Redstripe Rockfish in the western part of Dixon Entrance and off the west coast of Graham Island, down to about Rennell Sound (Figure B.55 to Figure B.60), although there are occasional observations of RSR right down to 53°N, the southernmost extent of this survey. Redstripe Rockfish were mainly taken at depths from 202 to 258 m (5 to 95% quantiles), with the majority of the observations lying between 217 and 237 m depth (25–75% quantiles, Figure B.61).

Table B.22. Biomass estimates for Redstripe Rockfish from the six 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)
2006	100	100	43	182	0.356	0.358
2007	197	191	45	447	0.525	0.525
2008	501	498	141	1,041	0.435	0.434
2010	284	286	106	521	0.357	0.361
2012	669	677	199	1,461	0.471	0.478
2016	1,082	1,091	534	1,725	0.280	0.289

Estimated biomass levels for RSR from these trawl surveys may show a possible ascending trend (ranging from 100 t in 2006 to 1,082 t in 2016) (Figure B.62; Table B.22). The estimated relative errors (RE) for these surveys were slightly lower compared to other RSR surveys, ranging from 28 to 53%, but are still very large for use as indices of biomass (Table B.22).

The proportion of tows that captured Redstripe Rockfish ranged from 22 to 54% of tows over the six synoptic survey years, with an overall mean of 36% (Figure B.63). The median RSR catch weight for positive tows was 8.6 kg/tow and the maximum catch weight across all six surveys was 2,797 kg (in 2016).

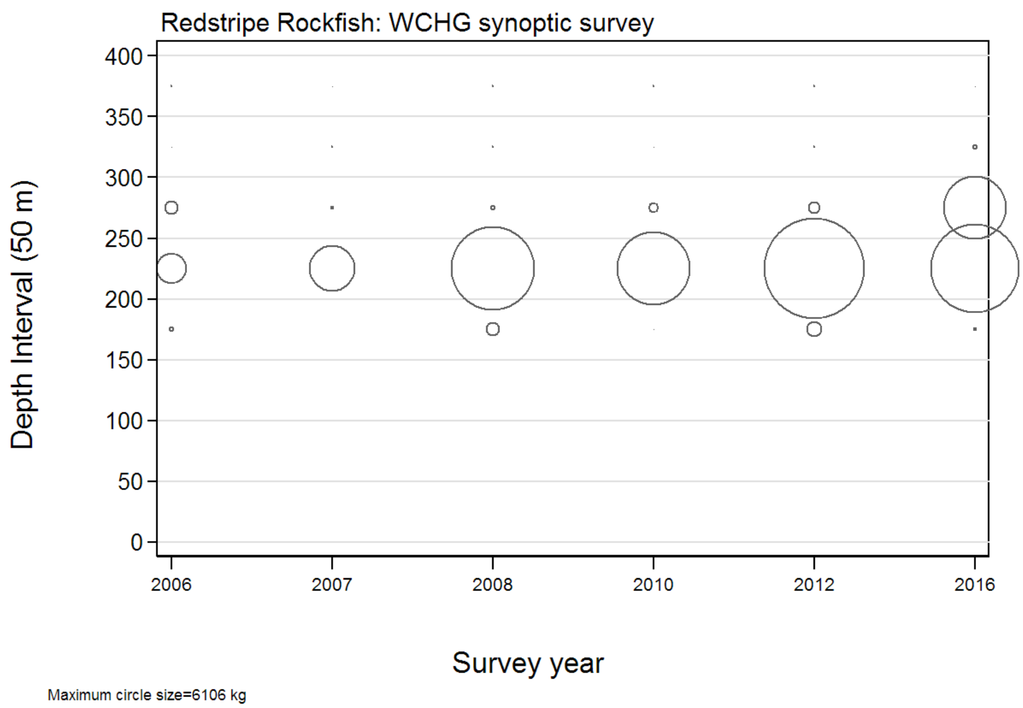


Figure B.61. Distribution of observed weights of Redstripe Rockfish by survey year and 50 m depth zone intervals. Catches are plotted at the mid-point of the interval and circles in the each panel are scaled to the maximum value (6106 kg – 200-250 m interval in 2012). Minimum and maximum depths observed for RSR: 157 m and 511 m, respectively. Three tows that captured RSR at depths greater than 400 m are not plotted. Depth is taken at the start position for each tow.

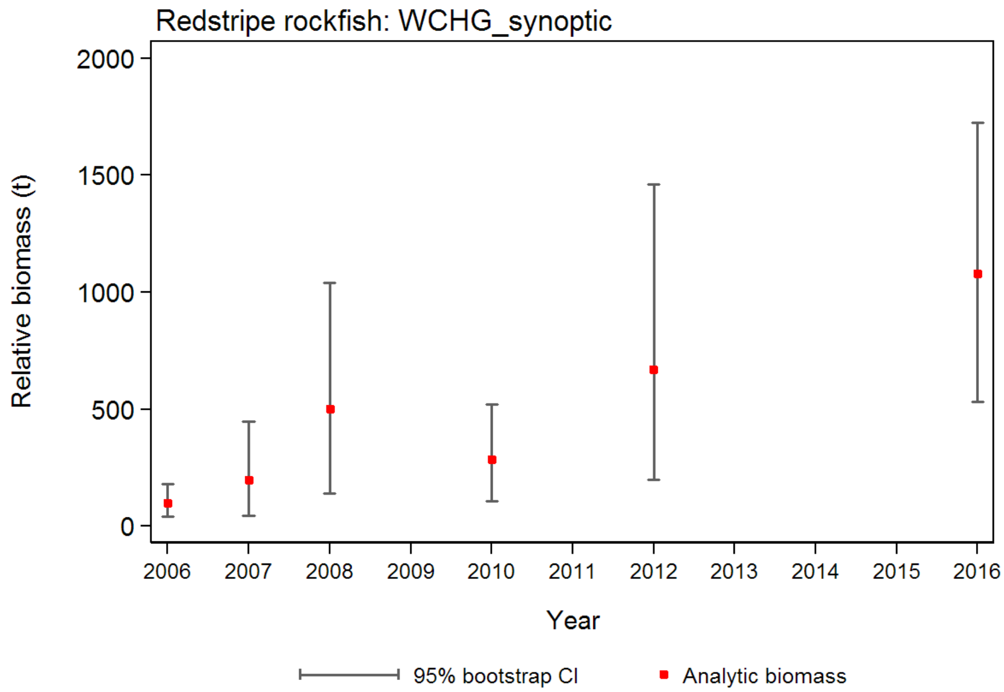


Figure B.62. Biomass estimates for Redstripe Rockfish from the 2006 to 2016 west coast Haida Gwaii synoptic surveys (Table B.22). Bias-corrected 95% confidence intervals from 1000 bootstrap replicates are plotted.

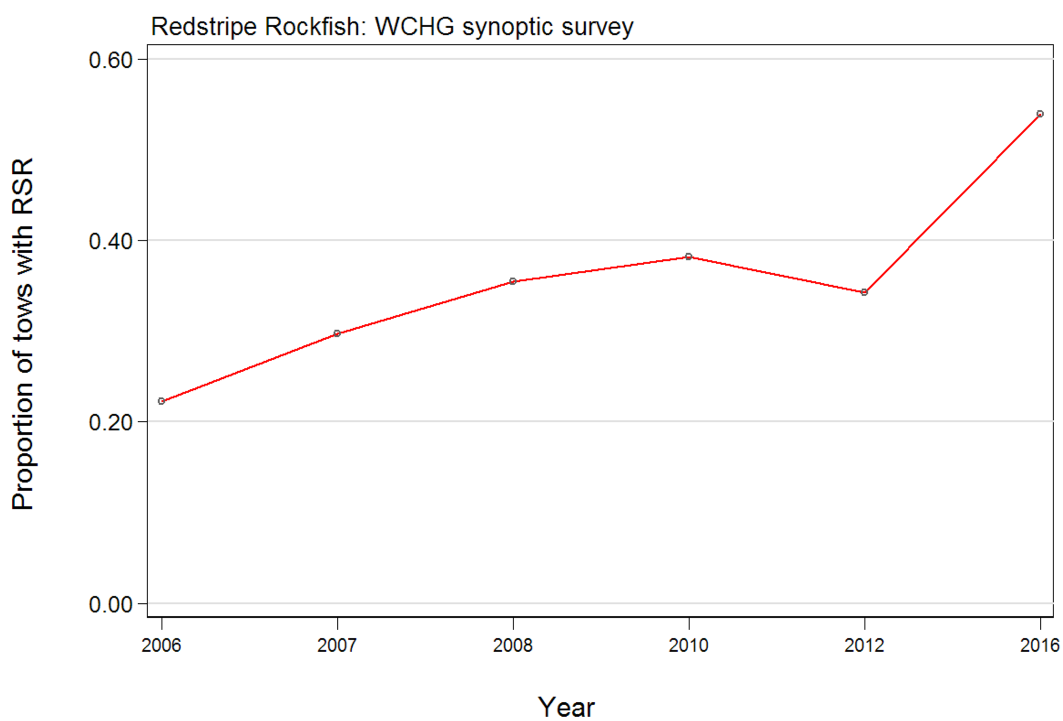


Figure B.63. Proportion of tows by year that contain Redstripe Rockfish for the six west coast Haida Gwaii synoptic surveys.

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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[3]). 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) 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.

[3] Francis, R.I.C.C. 1999. The impact of correlations on standardised CPUE indices. N.Z. Fish. Ass. Res. Doc. 99/42: 30 pp. (Unpublished report held in NIWA library, Wellington, NZ)

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 presence/absence of Redstripe 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, 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 500 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 is based on tow-by-tow total catch (landings + discards) data collected over the period 1996–2017 for which detailed positional data for every tow are available and there is an estimate of discarded catch for the tow 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 Redstripe Rockfish (RSR) from the BC trawl fishery operating from Juan de Fuca Strait to the Dixon Entrance from 1996 to 2017 were selected using the following criteria:

- Tow start date between 1 January 1996 and 31 December 2017;
- 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 <= 24 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 RSR were sub-divided into two areas (BC North and BC South) based on the localised distribution of trawl catches (see Appendix A). Only bottom trawl data were considered because previous experience had shown that the midwater trawl data were too sparse and tended to be clumped (only a few tows with high catch rates), rendering the data uninformative for CPUE. Figure C.1 plots the distribution of depth for all successful RSR bottom trawl tows for the two areas. A depth range for each analysis was selected from these plots and are 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
Area 5DE	Bottom	1996	100–450	6	50	14	14	16
Area 3CD5ABC	Bottom	1996	75–375	6	150	12	40	41

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 Redstripe Rockfish. The vessel qualification criteria used in each analysis appear in Table C.2 and the distribution of tows by vessel and fishery 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 each analysis and the fraction of the total catch represented in each core fleet. There was good vessel overlap across years (Figure C.2) in both fisheries, particularly in the BC South analysis where 20 of the 40 core vessels have participated in the fishery over the full 22 years of the analysis. The level of overlap is less in the BC North fishery with only five of the 16 vessels in the fishery for 22 years, as well as the number of vessels being much fewer; however, the degree of overlap across years seems satisfactory for estimating vessel effects.

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
Area 5DE	Bottom	3	3	60	16	93	2,727	22,132	4,384
Area 3CD5ABC	Bottom	5	5	200	40	91	10,771	132,134	33,109

[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 and Table C.5 summarise the core vessel data used in each analysis by calendar year, including the number of records, the total hours fished and the associated RSR catch.

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

Variable	**Data type**
Year	22 categories (calendar years)
Hours fished	continuous: 3rd order polynomial
Month	12 categories
DFO locality	Fishing locality areas identified by Rutherford (1995) (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 Redstripe Rockfish bottom trawl fishery in 5DE by year for the core data set (after applying all data filters and selection of core vessels).

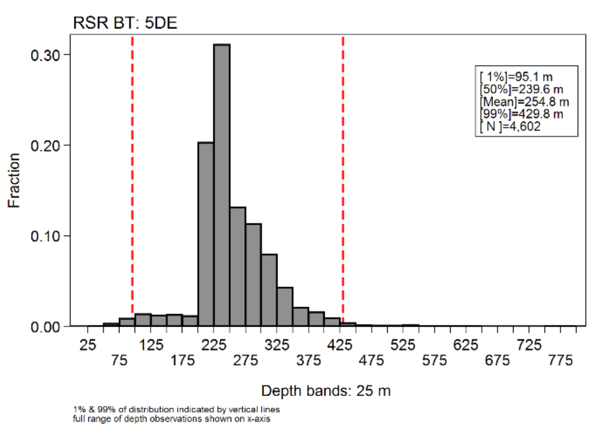
Year	Number vessels[1]	Number trips[1]	Number tows[1]	Number records[1]	Number records[2]	% zero records[2]	Total catch (t)[1]	Total hours[1]	CPUE (kg/h) (Eq. C.1)
1996	14	39	163	163	1,049	84.5	68.9	303	227.7
1997	11	36	99	99	969	89.8	60.5	171	354.8
1998	11	53	185	185	1,373	86.5	155.1	357	434.3
1999	11	45	177	177	1,027	82.8	164.1	326	503.5
2000	10	61	299	299	1,358	78.0	214.7	470	456.8
2001	10	58	255	255	1,232	79.3	149.8	364	411.2
2002	14	78	308	308	1,318	76.6	180.1	410	439.2
2003	14	81	310	310	1,195	74.1	186.6	442	422.4
2004	11	71	264	264	1,233	78.6	188.3	328	574.5
2005	10	56	204	204	1,384	85.3	99.5	284	350.7
2006	11	54	199	199	896	77.8	114.8	261	440.6
2007	10	50	195	195	837	76.7	116.5	288	405.0
2008	9	49	168	168	1,032	83.7	128.7	219	586.5
2009	10	44	164	164	961	82.9	101.9	219	465.5
2010	9	51	167	167	780	78.6	62.9	235	268.0
2011	9	50	170	170	887	80.8	111.3	233	477.4
2012	11	50	190	190	745	74.5	142.8	285	501.4
2013	10	63	168	168	934	82.0	76.7	276	278.0
2014	10	58	199	199	787	74.7	147.0	300	489.2
2015	9	44	143	143	655	78.2	53.4	222	240.5
2016	9	51	169	169	645	73.8	83.5	285	293.0
2017	9	62	188	188	835	77.5	119.5	307	388.9

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

Table C.5. Summary data for the Redstripe Rockfish bottom trawl fishery in Area 3CD5ABC 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	39	236	970	970	4,729	79.5	336.9	1,652	203.9
1997	39	343	1,518	1,518	5,601	72.9	567.2	2,742	206.9
1998	36	390	1,853	1,853	6,258	70.4	620.7	3,814	162.7
1999	37	451	1,826	1,826	7,226	74.7	569.7	3,720	153.2
2000	38	465	2,139	2,139	8,222	74.0	882.6	3,776	233.8
2001	37	447	1,923	1,923	7,399	74.0	753.8	3,231	233.3
2002	36	464	1,854	1,854	8,272	77.6	599.7	3,179	188.6
2003	36	474	1,869	1,869	8,335	77.6	628.7	3,150	199.6
2004	36	450	1,640	1,640	7,795	79.0	435.3	2,855	152.4
2005	34	469	1,839	1,839	8,059	77.2	430.7	3,443	125.1
2006	32	410	1,547	1,547	7,036	78.0	392.7	2,988	131.4
2007	32	343	1,505	1,505	5,918	74.6	349.5	2,811	124.3
2008	29	306	1,304	1,304	4,884	73.3	444.7	2,480	179.3
2009	30	331	1,378	1,378	5,893	76.6	533.1	2,441	218.4
2010	29	330	1,307	1,307	6,038	78.4	399.5	2,635	151.6
2011	29	312	1,388	1,388	5,541	75.0	429.5	2,753	156.0
2012	29	263	1,268	1,268	4,578	72.3	565.3	2,527	223.7
2013	24	244	1,082	1,082	4,526	76.1	305.7	2,084	146.7
2014	26	231	957	957	4,002	76.1	395.8	1,851	213.8
2015	23	265	1,251	1,251	4,493	72.2	388.7	2,439	159.4
2016	20	267	1,417	1,417	3,938	64.0	405.5	2,773	146.2
2017	20	249	1,274	1,274	3,391	62.4	335.9	2,455	136.8

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



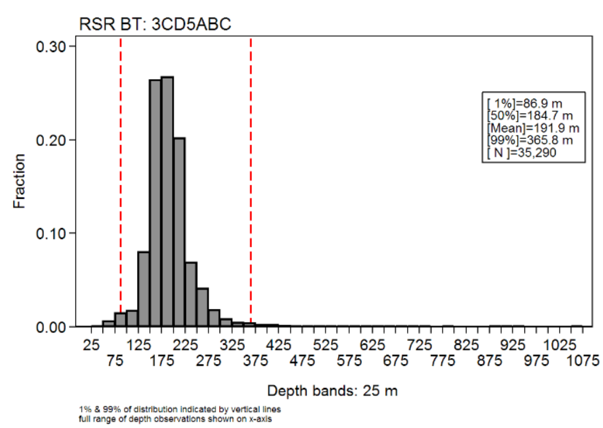


Figure C.1. Depth distribution of tows capturing RSR for the two bottom trawl (BT) GLM analyses from 1996 to 2017 using 25m intervals (each bin is labelled with the upper bound of the interval). Vertical lines indicate the 1% and 99% percentiles.

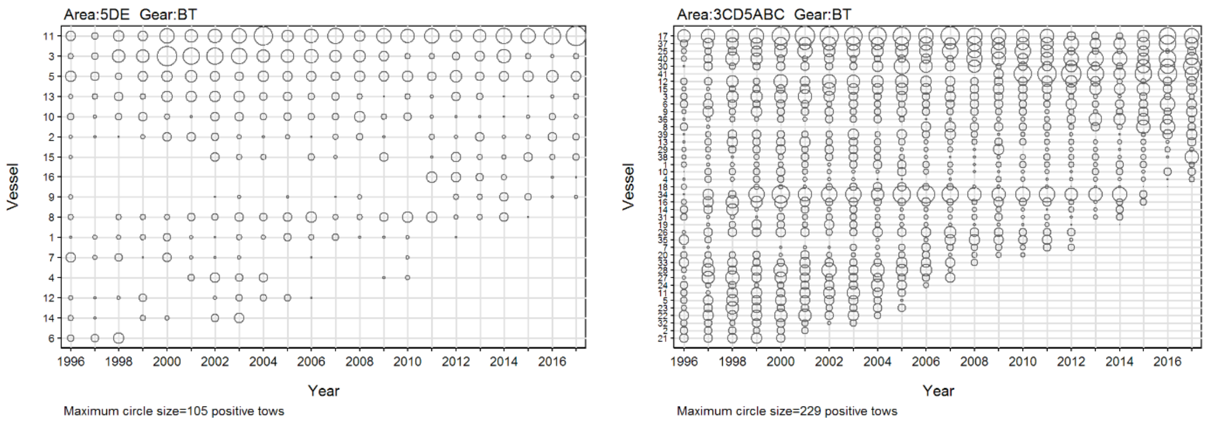


Figure C.2. Bubble plot showing vessel participation (number positive tows) by the core fleets in the two BT GLM analyses. Vessels are coded in ascending order total effort by year.

C.4. RESULTS

C.4.1. Areas 5DE (BC North)

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 Redstripe 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.6). This model selected five of the six of the remaining explanatory variables, including `[DFO locality]`, `[Depth_bands]`, `[Month]`, `[Vessel]` and `[0.1° Latitude_bands]` in addition to `[Year]`. The duration effort variable `[Hours_fished]` was not selected. The final lognormal model accounted for 50% of the total model deviance (Table C.6), with the year variable explaining 2% of the model deviance.

Model residuals show a reasonable fit with the underlying lognormal distributional assumption, with little deviation at the tails but some skewness near the mode 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 had considerable impact on the underlying annual indices, moving a flat or possibly gradually descending series to one that is clearly increasing (Figure C.5).

CDI plots of the five explanatory variables introduced to the model in addition to `[Year]` show a strong standardisation effect at the beginning of the series with the addition of `[DFO_locality]` variable, dropping the indices in the 2000s and raising the indices after 2012, in apparent response to shifts in preferred fishing locations (Figure C.6). There was also an effect with the addition of the [Depth_bands] variable, with the initial index strongly lifted by deep tows (Figure C.7). This effect is even stronger in the final years of the series, with a trend towards deeper tows. The addition of the variables [Vessel] (Figure C.8), [Month] (Figure C.9) and [Latitude_bands] (Figure C.10) all tend to lift the post-2012 indices by small, but cumulative amounts.

The final year indices show little trend up to 2015, but then a sharp increase in 2016 and 2017 (Figure C.3). This model has good diagnostics and the standardisation effects, while strong, are defensible given the apparent shifts in the data.

*Table C.6. Order of acceptance of variables into the lognormal model of positive total mortalities (verified landings plus discards) of Redstripe Rockfish 5DE 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	6	7
Year*	**0.0219**	-	-	-	-	-	-
DFO locality*	0.3143	**0.3283**	-	-	-	-	-
Depth bands*	0.3141	0.3230	**0.4353**	-	-	-	-
Vessel*	0.1020	0.1268	0.3619	**0.4655**	-	-	-
Month*	0.0425	0.0671	0.3456	0.4504	**0.4829**	-	-
0.1° Latitude bands*	0.2956	0.3092	0.3715	0.4515	0.4795	**0.4970**	-
Hours fished	0.0004	0.0222	0.3284	0.4371	0.4667	0.4845	0.4986
Improvement in deviance	0.0000	0.3064	0.1070	0.0302	0.0174	0.0141	0.0016

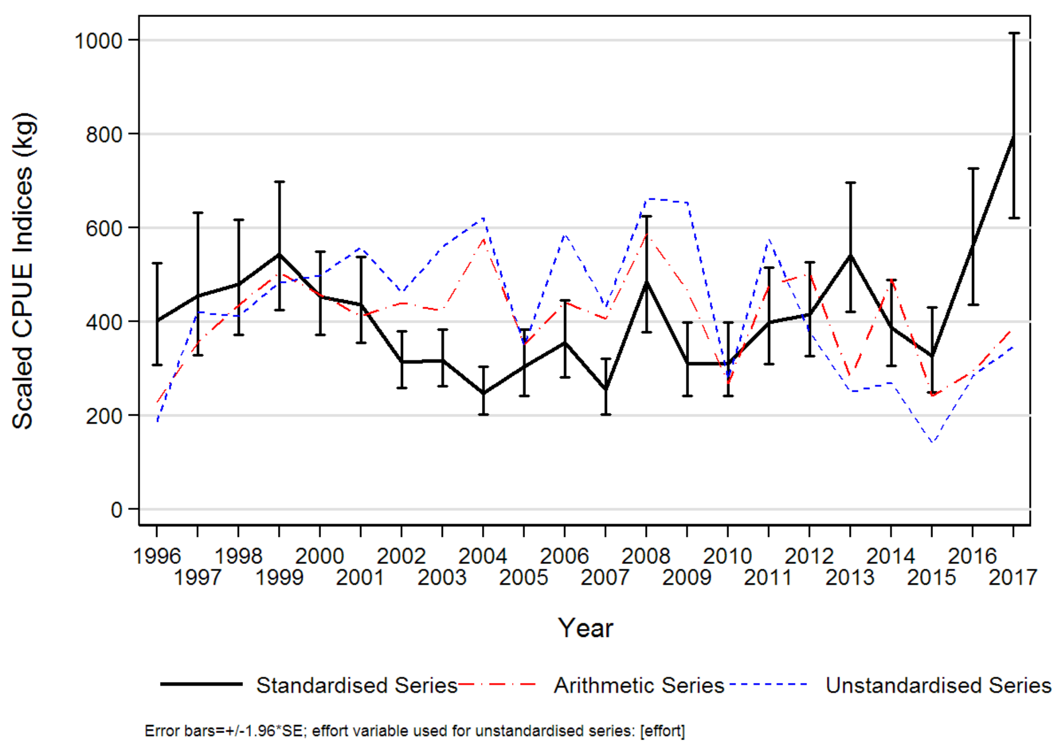


Figure C.3. Three positive catch CPUE series for Redstripe Rockfish from 1996 to 2017 in the 5DE bottom trawl fishery. The solid line is the standardised CPUE series from the lognormal model (Eq. C.3). The arithmetic series (Eq. C.1) and the unstandardised series (Eq. C.2) are also presented. All three series have been scaled to same geometric mean.

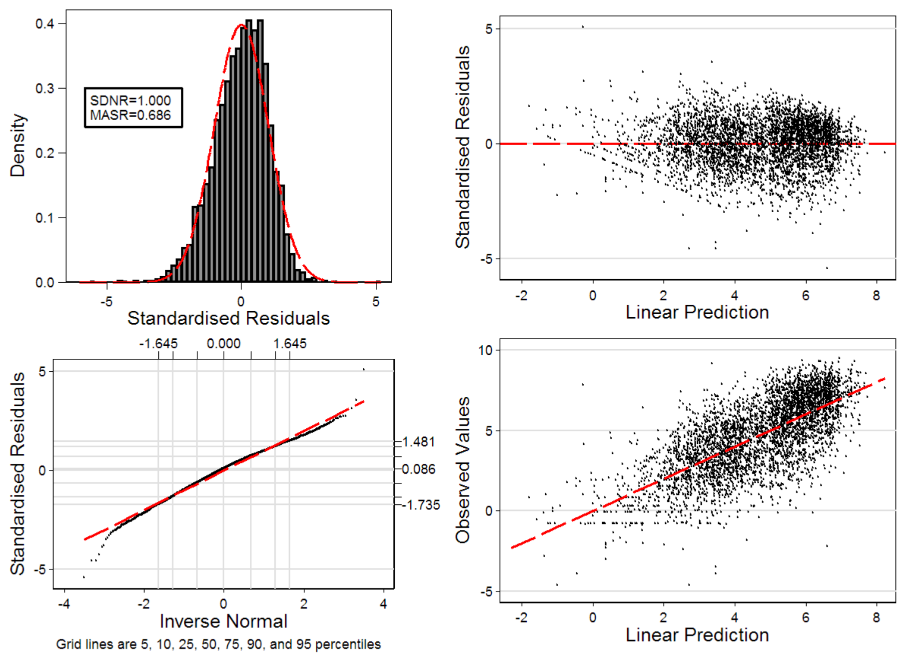


Figure C.4. Residual diagnostic plots for the GLM lognormal analysis for Redstripe Rockfish in 5DE bottom trawl fishery. Upper left: histogram of the standardised residuals with overlaid lognormal distribution (SDNR = standard deviation of normalised residuals. MASR = median of absolute standardised 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.

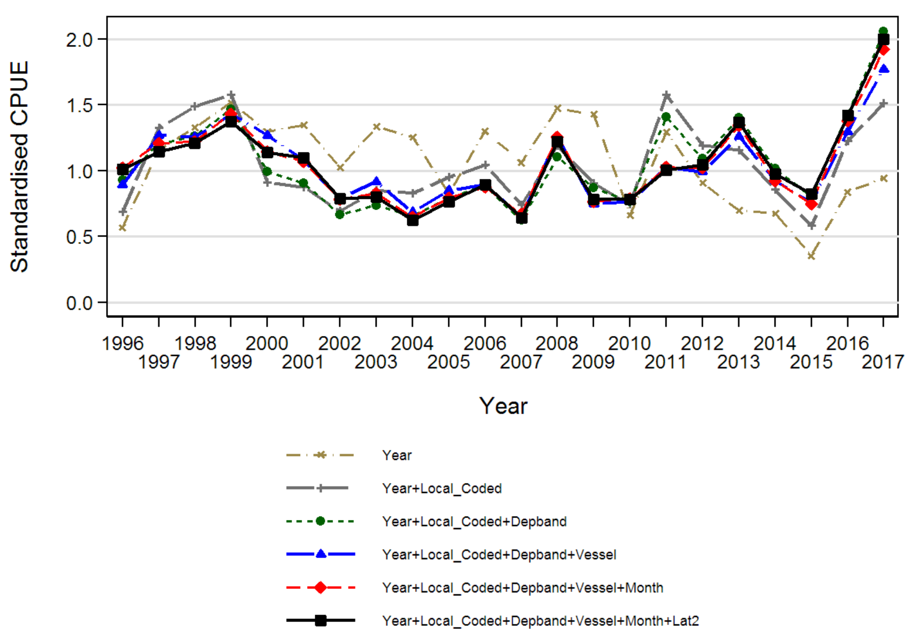


Figure C.5. Plot showing the year coefficients after adding each successive term of the standardised lognormal regression analysis for Redstripe Rockfish in the 5DE bottom trawl fishery. The final model is shown with a thick solid black line. Each line has been scaled so that the geometric mean equals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

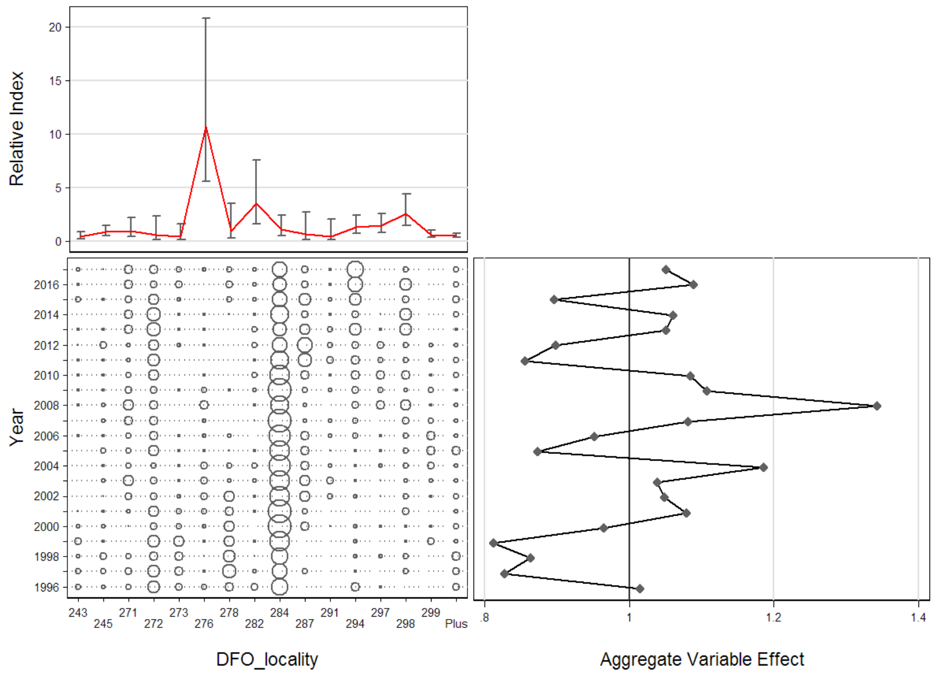


Figure C.6. CDI plot showing the effect of introducing the categorical variable [DFO locality] to the lognormal regression model for Redstripe Rockfish in the 5DE bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution by year of variable records (bottom left), and the cumulative effect of variable by year (bottom right). Locality codes are defined in Table C.7.

Table C.7. Definitions of locality codes used in Figure C.6.

Code	Major	Minor	Minor Name	Locality Name	Index
243	5D	3	1 East-Dixon Entrance	McIntyre Bay	0.434
245	5D	3	1 East-Dixon Entrance	NE Langara	0.843
271	5E	31	2A West - Rennell Sound	Rennell Sound	0.961
272	5E	31	2A West - Rennell Sound	Frederick Island	0.547
273	5E	31	2A West - Rennell Sound	Buck Point	0.406
276	5E	31	2A West - Rennell Sound	Fred Spot	10.742
278	5E	31	2A West - Rennell Sound	Englefield Bay	0.919
282	5E	31	2A West - Rennell Sound	Hippa Island	3.488
284	5E	31	2A West - Rennell Sound	South Hogback	1.075
287	5E	34	2B West - Anthony Island	Anthony Island	0.618
291	5E	34	2B West - Anthony Island	Flamingo Inlet	0.446
294	5E	35	1 West - Langara	N Fred-Langara (Deep)	1.317
297	5E	35	1 West - Langara	Langara Spit Inside/Compass Rock	1.437
298	5E	35	1 West - Langara	Langara Spit Outside/Whaleback	2.528
299	5E	35	1 West - Langara	Rockpile-Langara	0.579

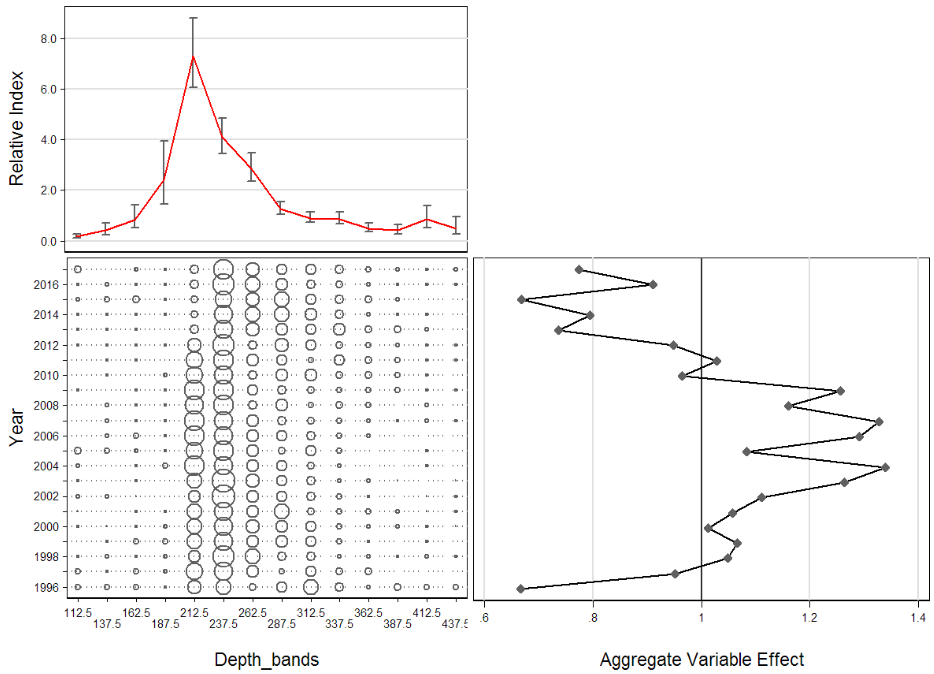


Figure C.7. CDI plot showing the effect of introducing the categorical variable [Depth_bands] to the lognormal regression model for Redstripe Rockfish in the 5DE bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution of variable records by year (bottom left), and the cumulative effect of variable by year (bottom right).

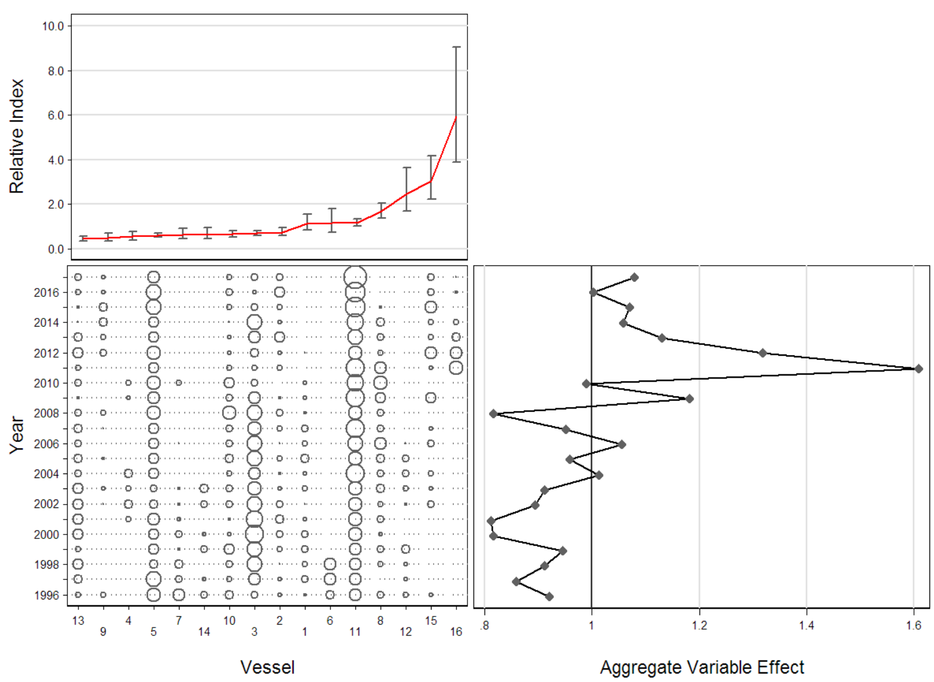


Figure C.8. CDI plot showing the effect of introducing the categorical variable [Vessel] to the lognormal regression model for Redstripe Rockfish in the 5DE bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution by year of variable records (bottom left), and the cumulative effect of variable by year (bottom right).

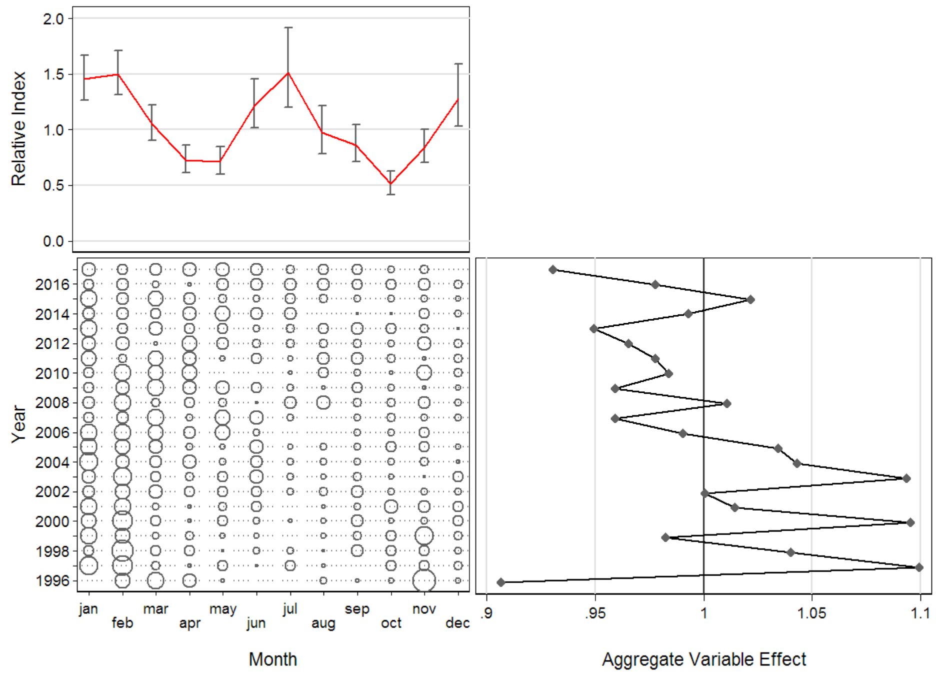


Figure C.9. CDI plot showing the effect of introducing the categorical variable [Month] to the lognormal regression model for Redstripe Rockfish in the 5DE bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution by year of variable records (bottom left), and the cumulative effect of variable by year (bottom right).

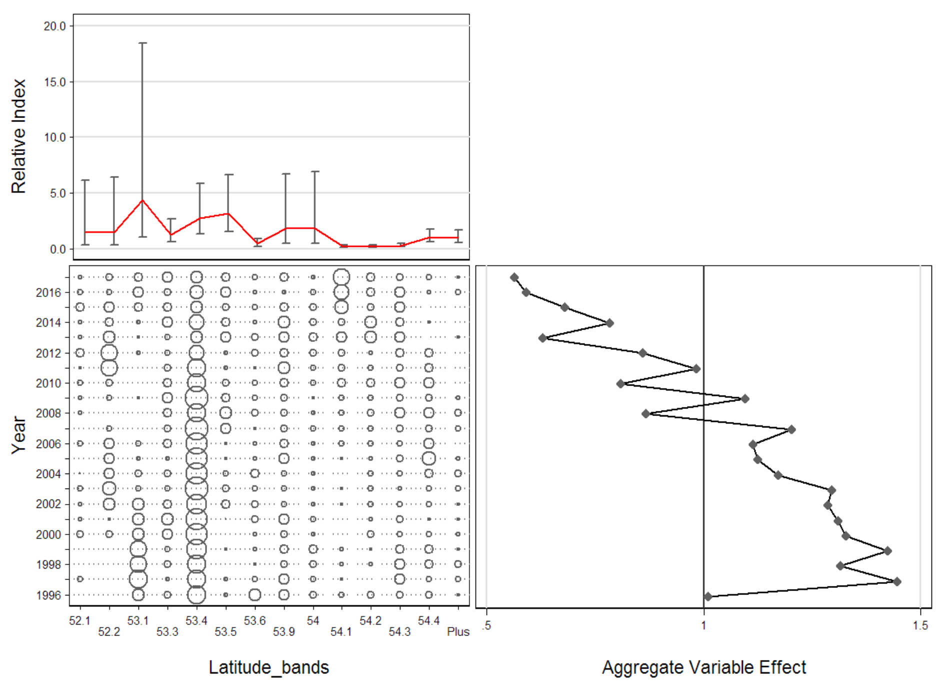


Figure C.10. CDI plot showing the effect of introducing the categorical variable [Latitude_bands] to the lognormal regression model for Redstripe Rockfish in the 5DE bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution by year of variable records (bottom left), and the cumulative effect of variable by year (bottom right).

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.8). 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 46% of the total model deviance, with the year variable explaining only 1% of the model deviance. The selected \explanatory variables included `[Depth_bands]`, `[0.1° Latitude_bands]` and `[Vessel]` in addition to `[Year]`. This model shows little trend up to 2009, after which it shows a steady increasing trend (Figure C.11). A stepwise plot showing the effect of adding each successive explanatory variable indicates that the main effect of the binomial standardisation was to raise the final two index values in a manner similar to the lognormal model (Figure C.12).

*Table C.8. Order of acceptance of variables into the binomial model of presence/absence of verified landings plus discards of Redstripe Rockfish in 5DE 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*	**0.0119**	-	-	-	-
Depth bands*	0.3768	**0.3854**	-	-	-
0.1° Latitude bands*	0.3107	0.3222	**0.4496**	-	-
Vessel*	0.0942	0.1081	0.4060	**0.4628**	-
DFO locality*	0.3461	0.3573	0.4487	0.4603	0.4725
Hours fished	0.0207	0.0305	0.3856	0.4503	0.4638
Month	0.0312	0.0453	0.3875	0.4536	0.4663
Improvement in deviance	0	0.3735	0.0642	0.0131	0.0098

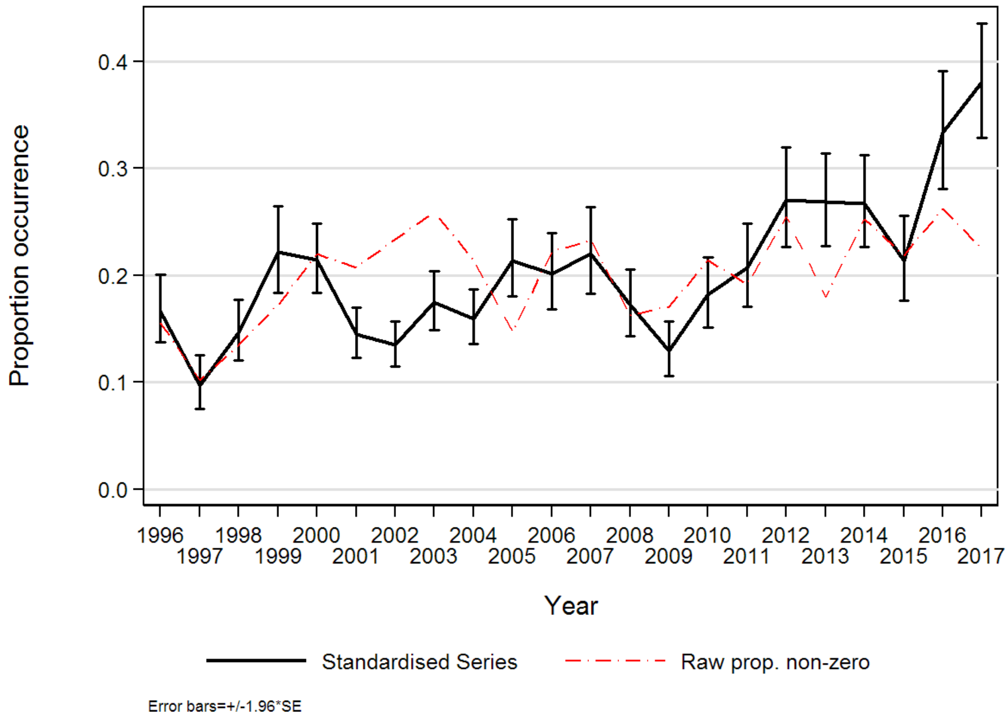


Figure C.11. Series plot for the 5DE bottom trawl fishery showing the trend in the unstandardised proportion of non-zero tows and the equivalent standardised series.

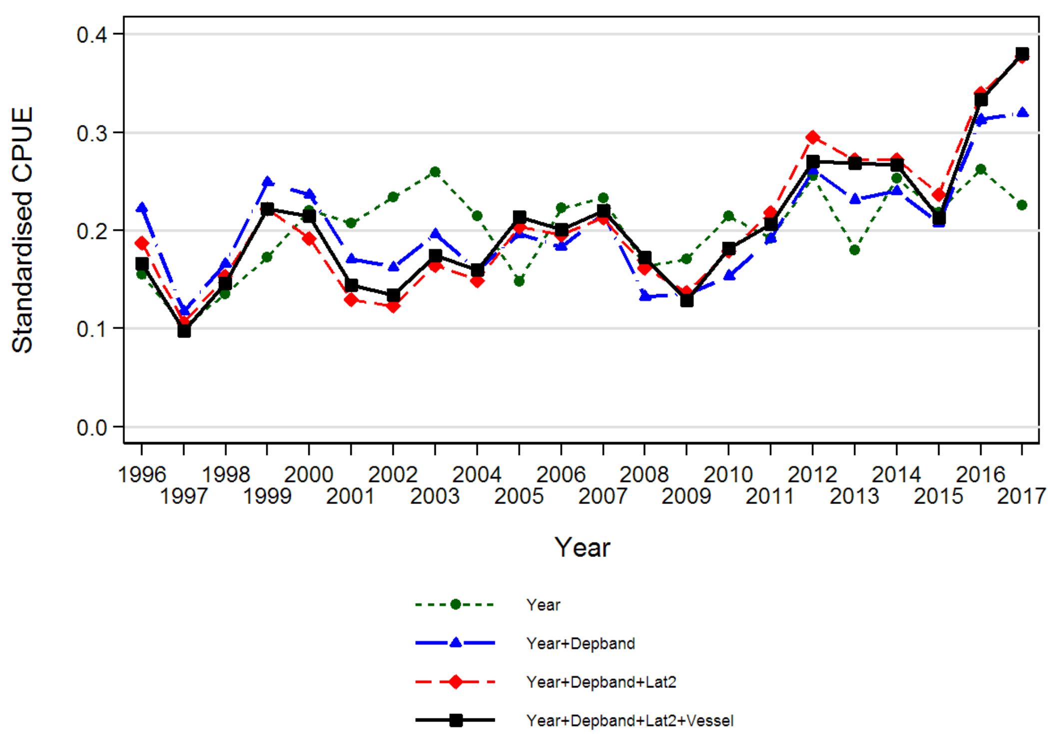


Figure C.12. Plot showing the year coefficients after adding each successive term of the standardised binomial regression analysis for Redstripe Rockfish in the 5DE bottom trawl fishery. The final model is shown with a thick solid black line. Each line has been scaled so that the geometric mean equals 1.0.

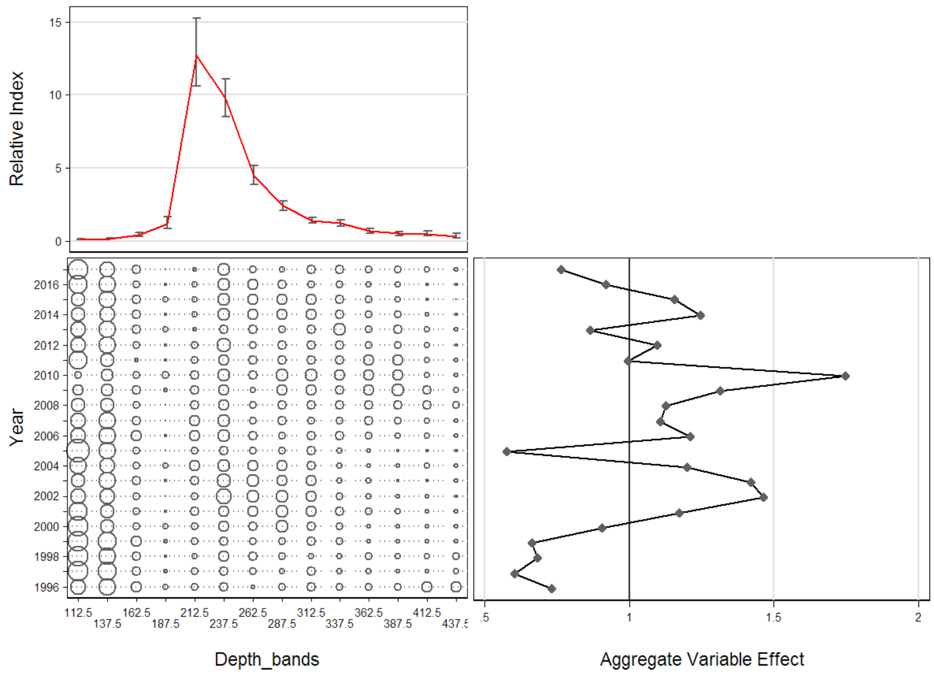


Figure C.13. CDI plot showing the effect of introducing the categorical variable [Depth_bands] to the binomial regression model for Redstripe Rockfish in the 5DE bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution by year of variable records (bottom left), and the cumulative effect of variable by year (bottom right).

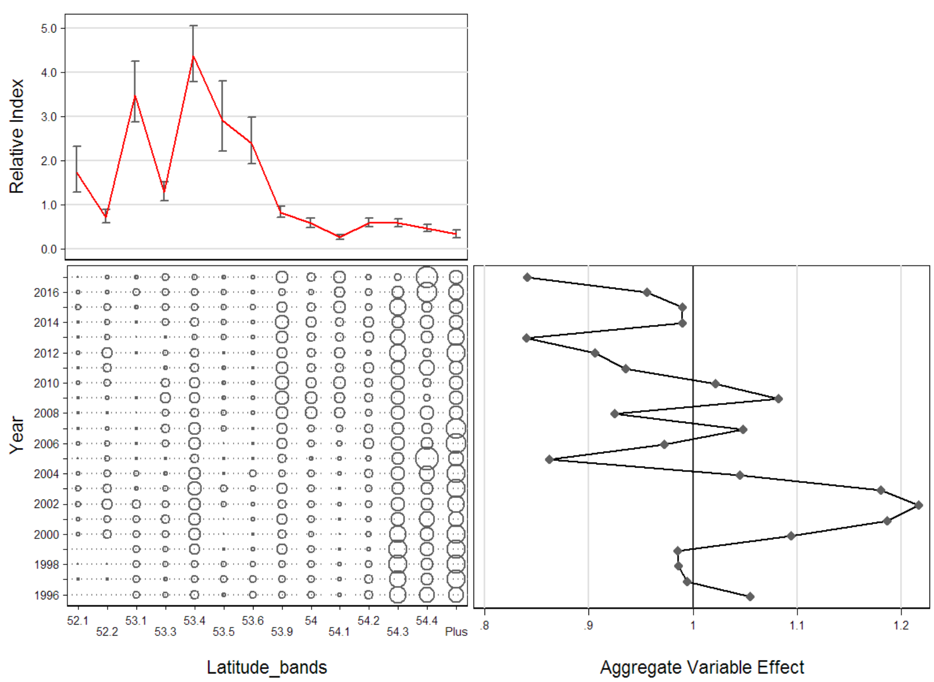


Figure C.14. CDI plot showing the effect of introducing the categorical variable [Latitude_bands] to the binomial regression model for Redstripe Rockfish in the 5DE bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution of variable records by year (bottom left), and the cumulative effect of variable by year (bottom right).

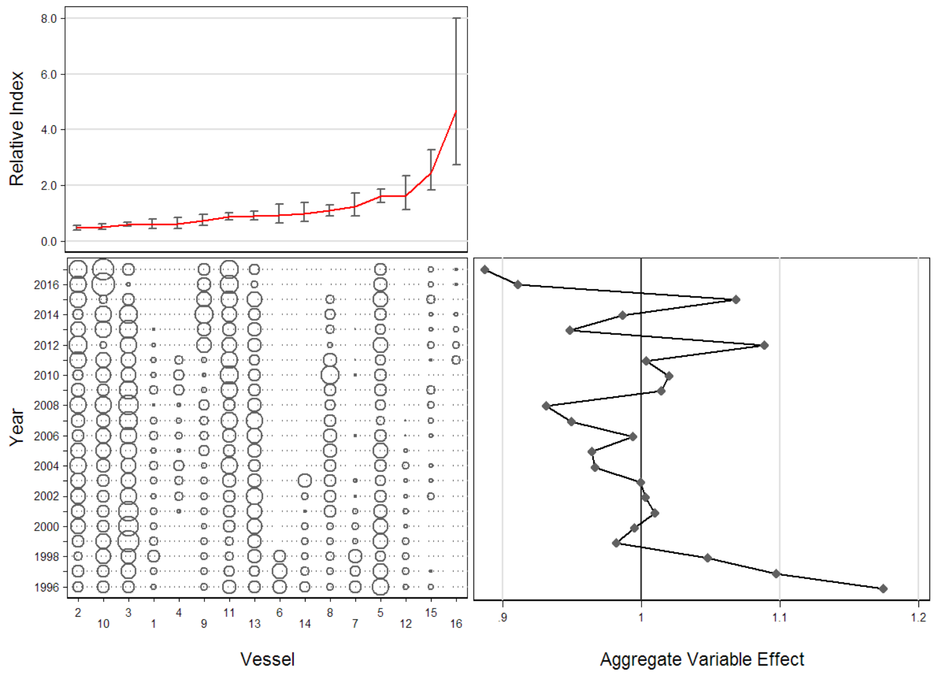


Figure C.15. CDI plot showing the effect of introducing the categorical variable [Vessel] to the binomial regression model for Redstripe Rockfish in the 5DE bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution by year of variable records (bottom left), and the cumulative effect of variable by year (bottom right).

The effect of the addition of the `[Depth_bands]` variable is considerable, with the explanatory variable adjusting for shifts over time in the distribution of tow depth (Figure C.13). The addition of the variable `[Latitude_bands]` (Figure C.14) appears to adjust for a southward movement of the fishery while there is very little impact from the addition of the `[Vessel]` variable (Figure C.15 and Figure C.12).

C.4.1.3. Bottom trawl fishery: combined model

The combined model (Eq. C.4) shows almost no trend up to and including 2015, as seen in both the lognormal and binomial series (Figure C.16). However, the multiplicative nature of Eq. C.4 results in an acceleration of the increase estimated by both models for 2016 and 2017, with the combined index showing a much stronger increase than either series.

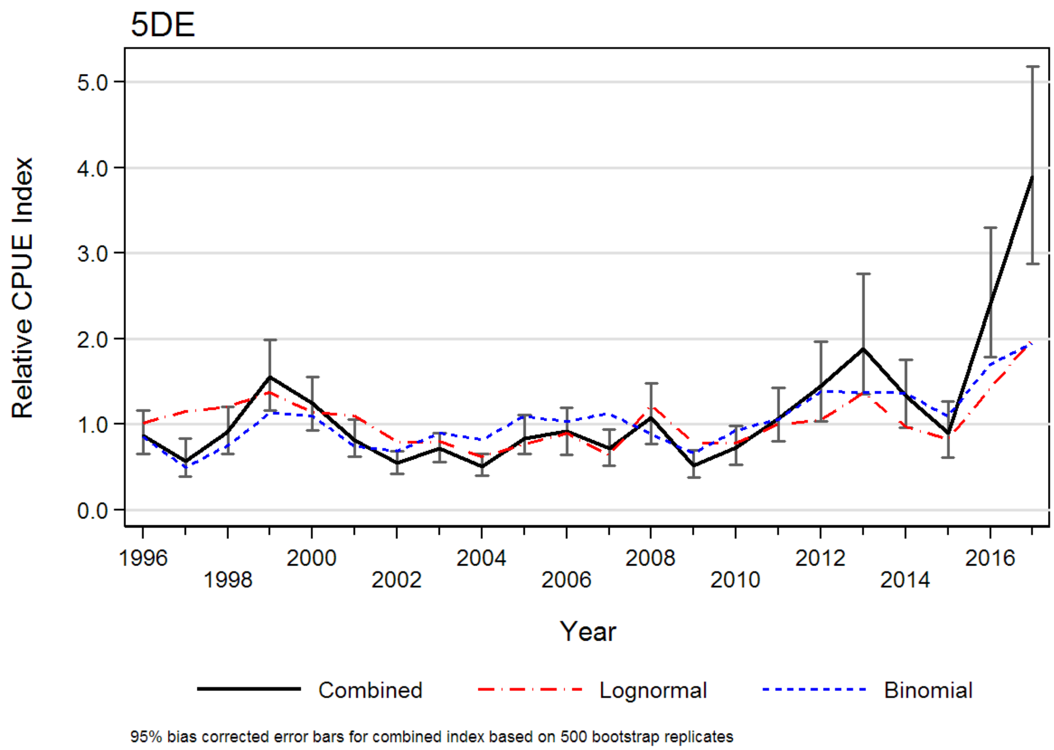


Figure C.16. Combined index series (Eq. C.4) for the 5DE bottom trawl fishery also showing the contributing lognormal and binomial index series. Confidence bounds based on 500 bootstrap replicates.

C.4.2. Areas 3CD5ABC (BC South)

C.4.2.1. 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 Redstripe Rockfish in each record (tow) (Eq. C.3). The resulting CPUE index series is presented in Figure C.17.

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.9). This model selected five of the six remaining explanatory variables, including `[Depth_bands]`, `[DFO locality]`, `[Vessel]`, `[0.1° Latitude_bands]` and `[Month]` in addition to `[Year]`. The final lognormal model accounted for 22% of the total model deviance (Table C.9), with the year variable explaining only 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.18).

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.19).

CDI plots of the five explanatory variables introduced to the model in addition to `[Year]` show relatively minor standardisation effects in the series. Although `[Depth_bands]` (Figure C.20) and `[DFO_locality]` (Figure C.21) have the greatest explanatory power, neither variable caused much movement in the annual series (Figure C.19). The variable `[Vessel]` (Figure C.22) had more impact, with some raising of the initial years in the series and some minor shifts towards the end of the series. Neither `[Latitude_bands]` (Figure C.22) or `[Month]` (Figure C.23) had much impact on the overall annual indices.

*Table C.9. Order of acceptance of variables into the lognormal model of positive total mortalities (verified landings plus discards) of Redstripe Rockfish Area 3CD5ABC 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	6	7
Year*	**0.0097**	-	-	-	-	-	-
Depth bands*	0.0845	**0.0915**	-	-	-	-	-
DFO locality*	0.0783	0.0872	**0.1498**	-	-	-	-
Vessel*	0.0446	0.0591	0.1358	**0.1848**	-	-	-
0.1° Latitude bands*	0.0564	0.0645	0.1438	0.1758	**0.2087**	-	-
Month*	0.0374	0.0476	0.1207	0.1696	0.2005	**0.2227**	-
Hours fished	0.0026	0.0120	0.0932	0.1503	0.1854	0.2091	0.2231
Improvement in deviance	0	0.0818	0.0584	0.0350	0.0239	0.0140	0.0005

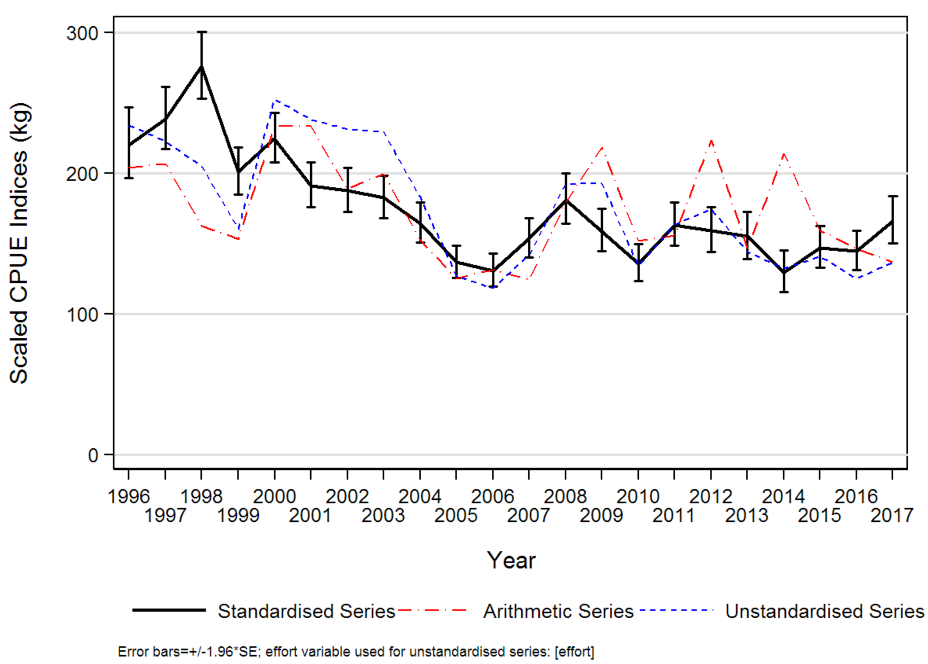


Figure C.17. Three CPUE series for Redstripe Rockfish from 1996 to 2017 in Area 3CD5ABC bottom trawl fishery. The solid line is the standardised CPUE series from the lognormal model (Eq. C.3). The arithmetic series (Eq. C.1) and the unstandardised series (Eq. C.2) are also presented. All three series have been scaled to same geometric mean.

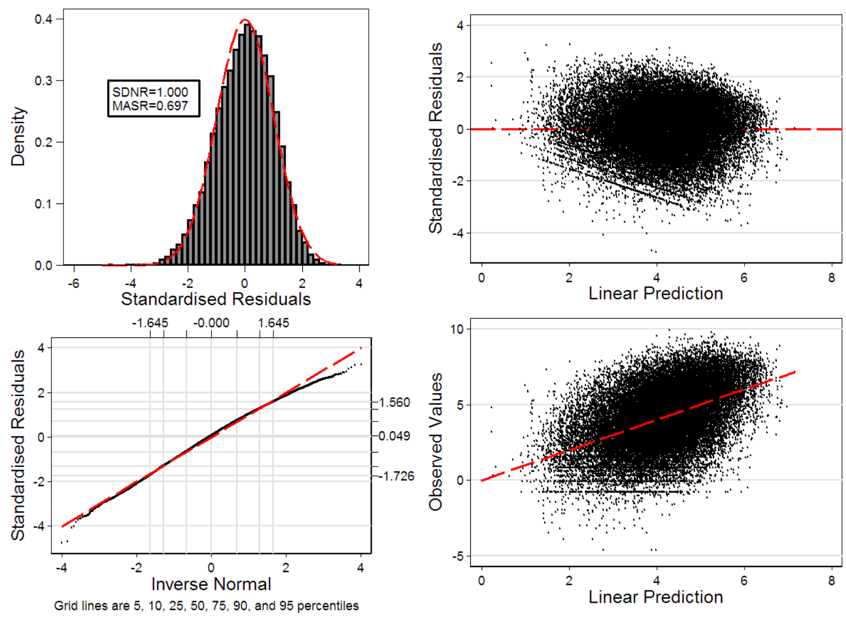


Figure C.18. Residual diagnostic plots for the GLM lognormal analysis for Redstripe Rockfish in Area 3CD5ABC bottom trawl fishery. Upper left: histogram of the standardised residuals with overlaid lognormal distribution (SDNR = standard deviation of normalised residuals. MASR = median of absolute standardised 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.

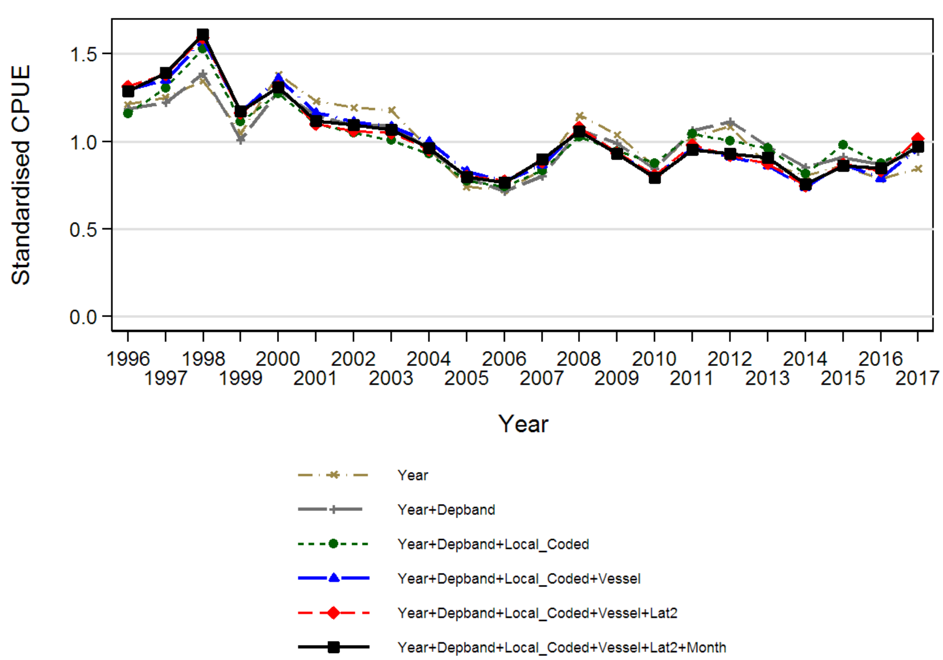


Figure C.19. Plot showing the year coefficients after adding each successive term of the standardised lognormal regression analysis for Redstripe Rockfish in the Area 3CD5ABC bottom trawl fishery. The final model is shown with a thick solid black line. Each line has been scaled so that the geometric mean equals 1.0.

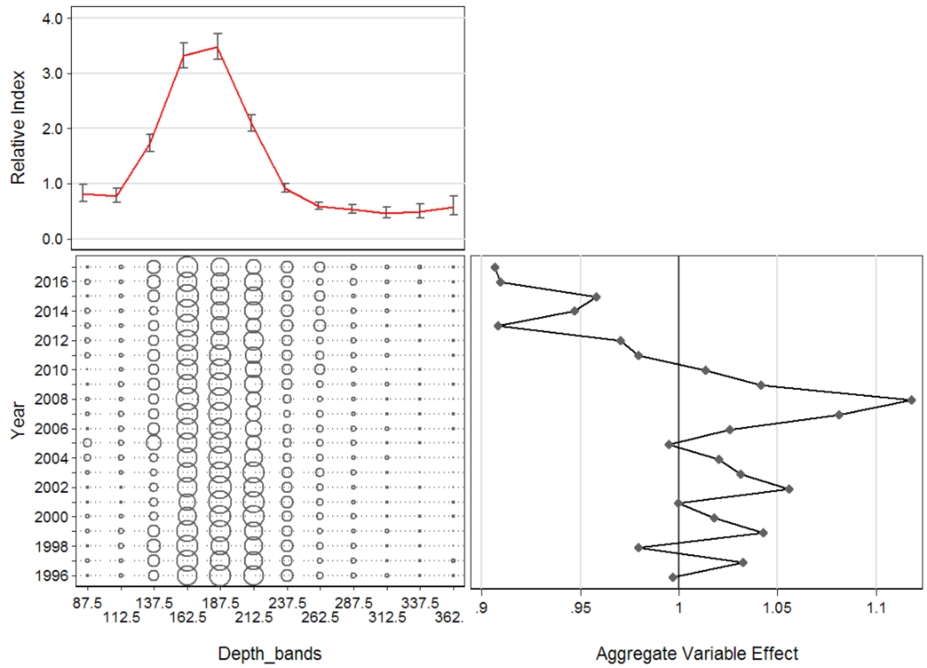


Figure C.20. CDI plot showing the effect of introducing the categorical variable [Depth_bands] to the lognormal regression model for Redstripe Rockfish in the Area 3CD5ABC bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution by year of variable records (bottom left), and the cumulative effect of variable by year (bottom right).

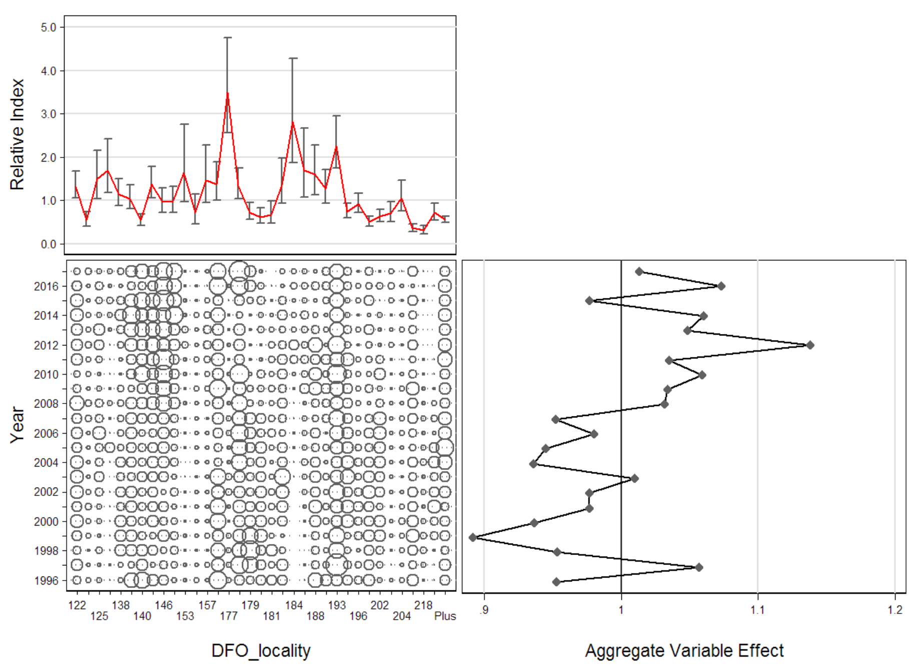


Figure C.21. CDI plot showing the effect of introducing the categorical variable [DFO locality] to the lognormal regression model for Redstripe Rockfish in the Area 3CD5ABC bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution by year of variable records (bottom left), and the cumulative effect of variable by year (bottom right). Locality codes are defined in Table C.10.

Table C.10. Definition of locality codes used in Figure C.21 and Figure C.28.

Code	Major	Minor	Minor Name	Locality Name	Index Lognormal	Index Binomial
122	3C	23	Big Bank	Deep Big Bank/Barkley Canyon	1.322	1.104
124	3C	23	Big Bank	Ucluelet/Loudon Canyons	0.537	0.822
125	3C	23	Big Bank	Nitinat Canyon	1.499	1.575
129	3C	23	Big Bank	Nitinat Hake	1.687	3.385
138	3C	24	Clayoquot Sd.	Father Charles Canyon	1.150	1.747
139	3C	24	Clayoquot Sd.	Clayoquot Canyon	1.042	1.348
140	3C	24	Clayoquot Sd.	South Estevan	0.534	0.742
145	3D	25	Estevan-Esperanza Inlet	North Estevan	1.369	1.158
146	3D	25	Estevan-Esperanza Inlet	Nootka	0.960	0.466
147	3D	25	Estevan-Esperanza Inlet	Esperanza East	0.978	0.608
153	3D	26	Kyuquot Sd.	Lookout Island	1.633	1.375
155	3D	26	Kyuquot Sd.	Kyuquot Sd (>100 fm)	0.720	0.662
157	3D	26	Kyuquot Sd.	Crowther Canyon	1.467	1.102
166	3D	27	Quatsino Sd.	Quatsino Sound	1.374	1.910
177	5A	11	Cape Scott-Triangle	Unknown	3.494	2.055
178	5A	11	Cape Scott-Triangle	Triangle	1.336	0.915
179	5A	11	Cape Scott-Triangle	Cape Scott Spit	0.726	0.418
180	5A	11	Cape Scott-Triangle	Mexicana	0.615	0.575
181	5A	11	Cape Scott-Triangle	Topknot	0.673	0.824
183	5A	11	Cape Scott-Triangle	South Scott Islands	1.354	2.348
184	5A	11	Cape Scott-Triangle	W. Triangle (25 mi)	2.831	8.997
187	5A	11	Cape Scott-Triangle	South Triangle	1.698	3.055
188	5A	11	Cape Scott-Triangle	Pisces Canyon	1.597	2.419
192	5B	8	Goose Island Bank	NE Goose	1.265	1.043
193	5B	8	Goose Island Bank	SE Goose	2.264	0.954
195	5B	8	Goose Island Bank	SW Goose	0.744	0.382
196	5B	8	Goose Island Bank	Mitchell's Gully	0.919	1.059
197	5B	8	Goose Island Bank	SE Cape St. James	0.498	0.559
202	5B	8	Goose Island Bank	SW Middle Bank	0.634	0.504
203	5B	8	Goose Island Bank	Outside Cape St. James	0.693	0.578
204	5B	8	Goose Island Bank	West Virgin Rocks	1.046	0.779
212	5C	2	2B-East	South Morseby	0.358	0.429
218	5C	2	2B-East	Nw Middle Bank	0.311	0.310
230	5C	7	6-Central Morseby-Milbanke Sd.	Unknown	0.713	1.147

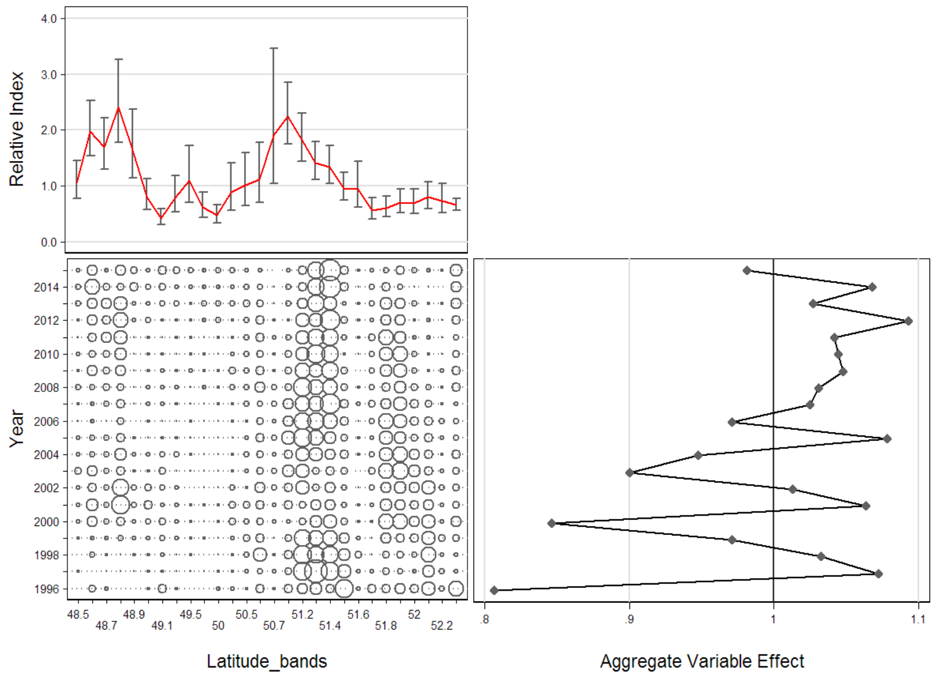


Figure C.22. CDI plot showing the effect of introducing the categorical variable [Latitude_bands] to the lognormal regression model for Redstripe Rockfish in the Area 3CD5ABC bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution by year of variable records (bottom left), and the cumulative effect of variable by year (bottom right).

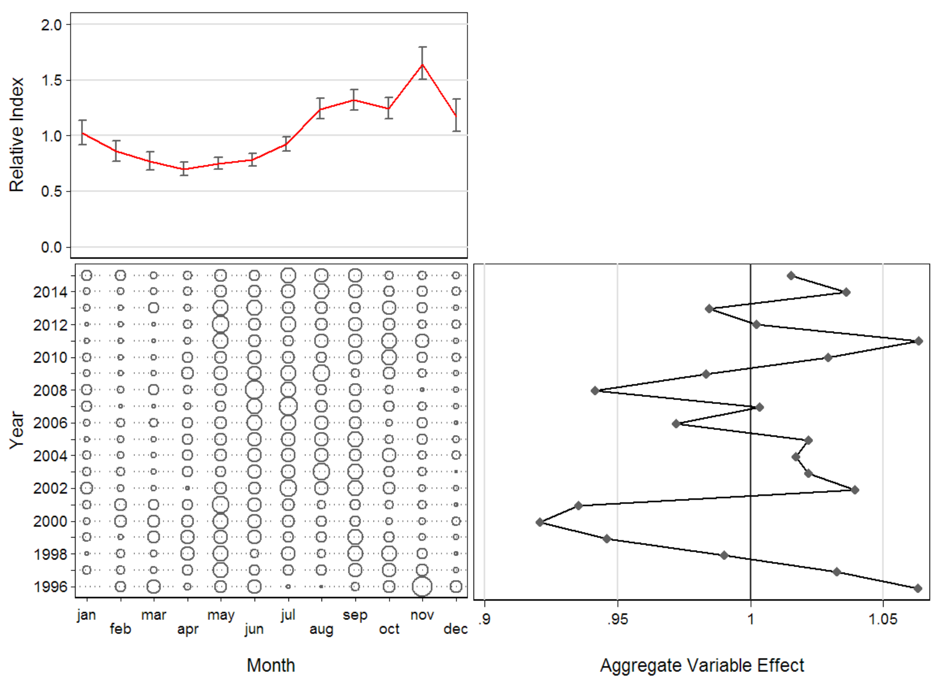


Figure C.23. CDI plot showing the effect of introducing the categorical variable [Month] to the lognormal regression model for Redstripe Rockfish in the Area 3CD5ABC bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution of variable records by year (bottom left), and the cumulative effect of variable by year (bottom right).

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.17). This model has good diagnostics and shows only small changes from the unstandardised series.

C.4.2.2. 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.11). 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 25% of the total model deviance, with the year variable explaining less than 1% of the model deviance.

*Table C.11. Order of acceptance of variables into the binomial model of presence/absence of verified landings plus discards of Redstripe Rockfish in Area 3CD5ABC 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*	**0.0062**	-	-	-	-
Depth bands*	0.1804	**0.1861**	-	-	-
0.1° Latitude bands*	0.0926	0.0977	**0.2320**	-	-
DFO locality*	0.0988	0.1044	0.2253	**0.2452**	-
Month	0.0417	0.0479	0.2038	0.2430	0.2544
Hours fished	0.0069	0.0134	0.1875	0.2325	0.2454
Vessel	0.0258	0.0304	0.2008	0.2432	0.2542
Improvement in deviance	0	0.1800	0.0459	0.0131	0.0092

The selected \explanatory variables included [Depth_bands], [0.1° Latitude_bands] and [DFO_locality] in addition to [Year] . This model shows little trend up to about 2009 or 2010, but is then followed by an increasing trend to 2017 (Figure C.24). 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.25).

The effect of the addition of the [Depth_bands] variable is considerable, with the explanatory variable making minor adjustments at the beginning and near 2011 to 2013 (Figure C.26). The addition of the variables [Latitude_bands] (Figure C.27) and [Vessel] (Figure C.28) appear to have had almost no impact on the standardised year variable..

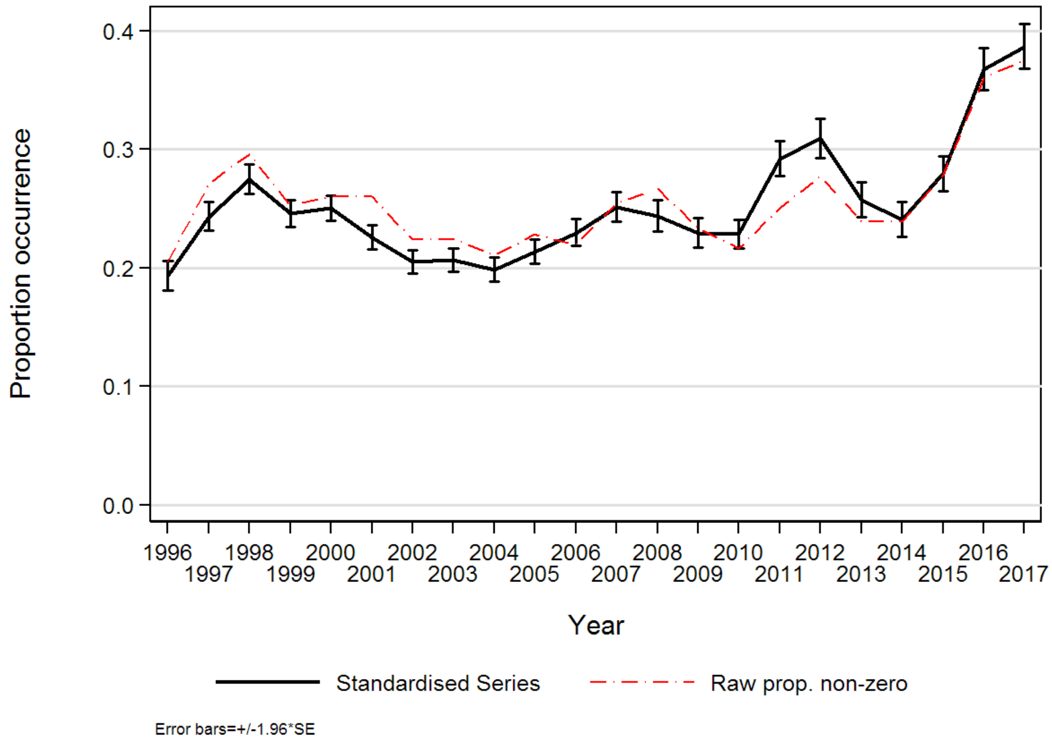


Figure C.24. Binomial index series for the 3CD5ABC bottom trawl fishery also showing the trend in proportion of zero tows from the same data set.

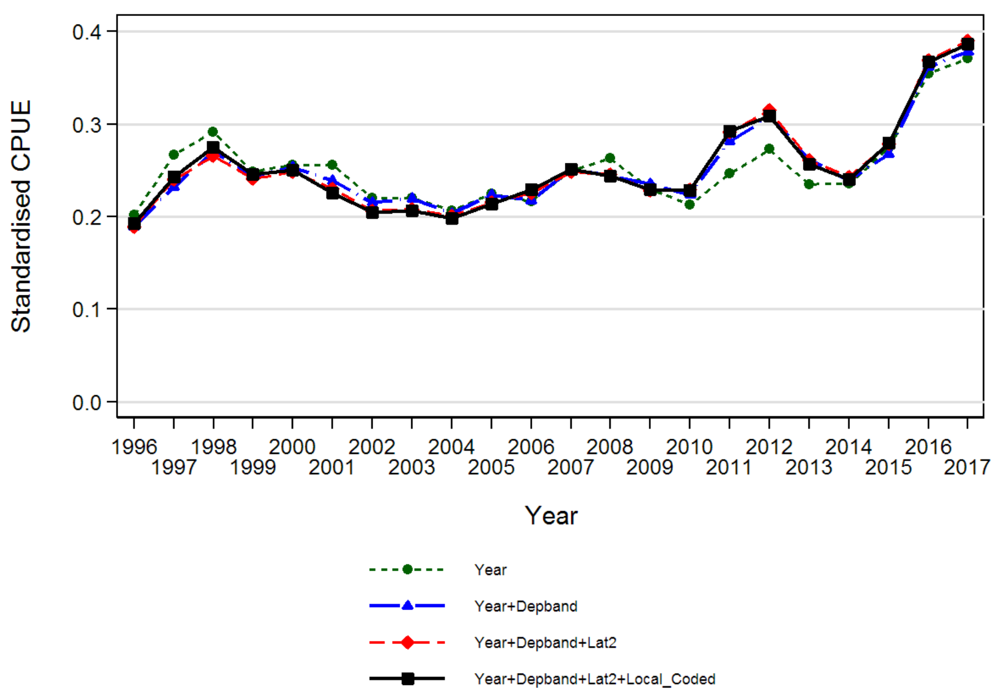


Figure C.25. Plot showing the year coefficients after adding each successive term of the standardised binomial regression analysis for Redstripe Rockfish in the 3CD5ABC bottom trawl fishery. The final model is shown with a thick solid black line. Each line has been scaled so that the geometric mean equals 1.0.

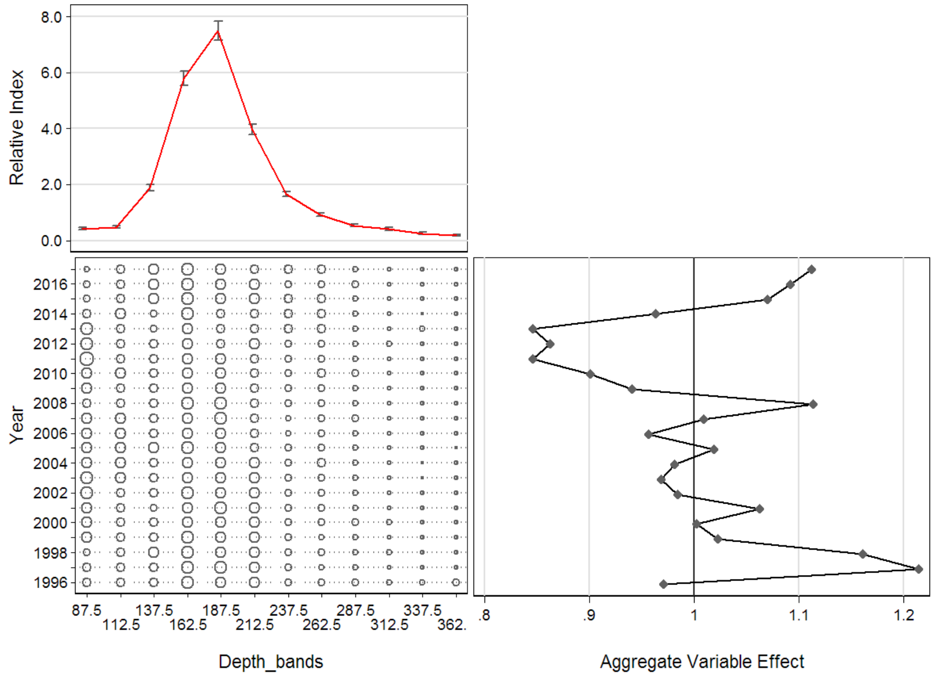


Figure C.26. CDI plot showing the effect of introducing the categorical variable [Depth_bands] to the binomial regression model for Redstripe Rockfish in the 5DE bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution by year of variable records (bottom left), and the cumulative effect of variable by year (bottom right).

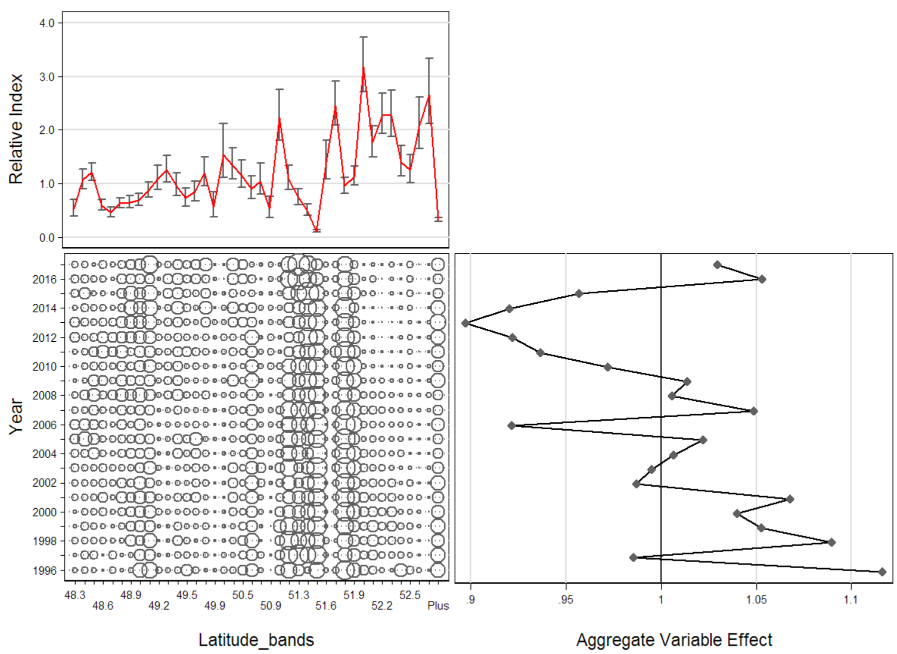


Figure C.27. CDI plot showing the effect of introducing the categorical variable [Latitude_bands] to the binomial regression model for Redstripe Rockfish in the 5DE bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution of variable records by year (bottom left), and the cumulative effect of variable by year (bottom right).

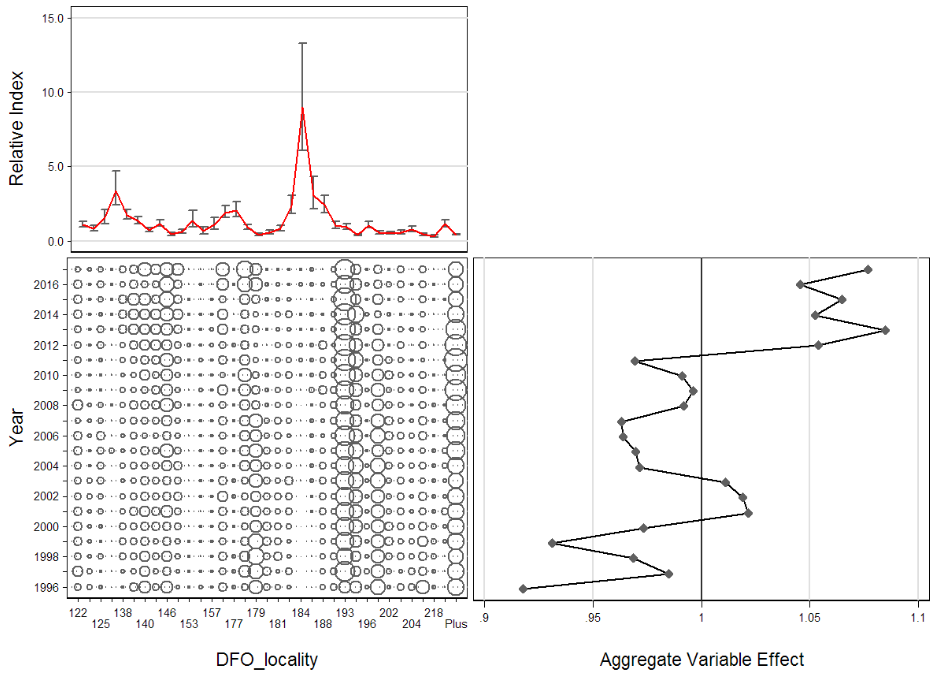


Figure C.28. CDI plot showing the effect of introducing the categorical variable [DFO_locality] to the binomial regression model for Redstripe Rockfish in the 5DE bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution by year of variable records (bottom left), and the cumulative effect of variable by year (bottom right). Locality codes are defined in Table C.10.

C.4.2.3. Bottom trawl fishery: combined model

The combined model (Eq. C.4) appears to be an amalgamation of the two series, with the combined model resembling the stronger lognormal indices at the beginning of the series which accepting the strong increase in the binomial index at the end of the series. (Figure C.29).

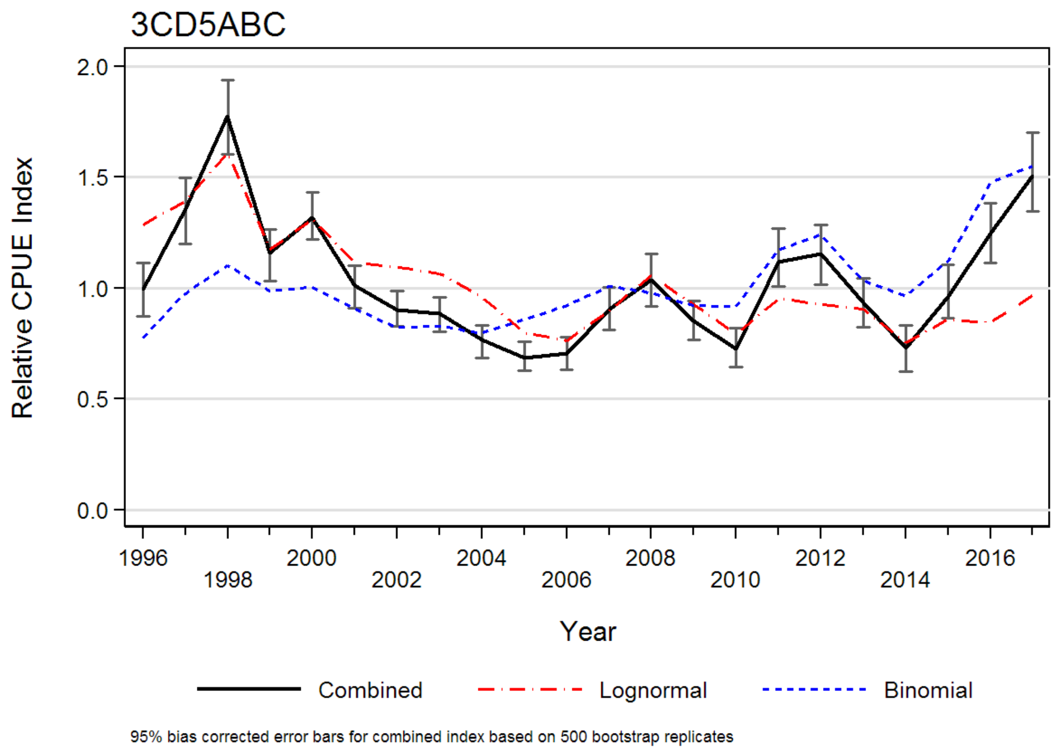


Figure C.29. Combined index series (Eq. C.4) for the Area 3CD5ABC bottom trawl fishery also showing the contributing lognormal and binomial index series. Confidence bounds based on 500 bootstrap replicates.

C.5. COMPARISONS WITHIN AND AMONG STOCKS

Neither the BC South nor the BC North combined bottom trawl CPUE show much trend up to 2014 or 2015 (Figure C.30), although they don't vary in unison by year. The BC North series shows a very strong increase in the final two years to 2017, while the BC South series only shows a modest increase in those two years.

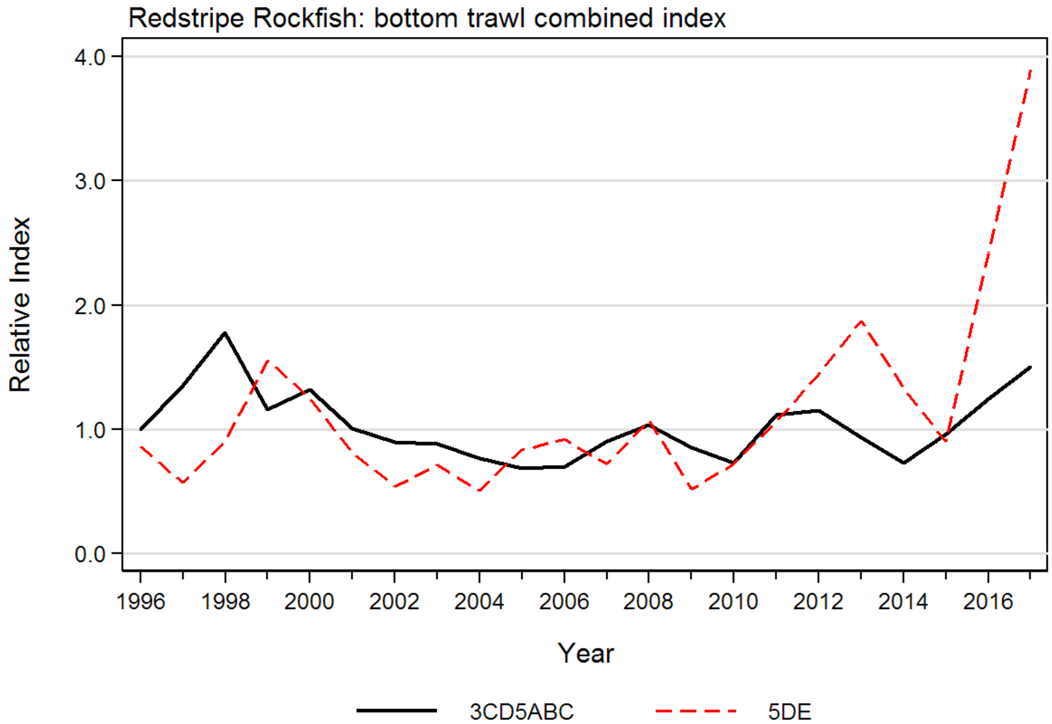


Figure C.30. Comparison of the combined (Eq. C.4) bottom trawl CPUE index series for the North and South RSR area definitions.

C.6. RELATIVE INDICES OF ABUNDANCE

Table C.12 and Table C.13 summarise the relative indices of abundance derived from the CPUE analyses for the two Redstripe Rockfish stocks. CPUE indices used in the age-structured stock assessment model appear as the `delta`-lognormal (combined) indices from the bottom trawl data (BC North: Table C.12, BC South: Table C.13). The associated bootstrap standard errors (SE) were used as the initial CVs when fitting the stock assessment model.

Table C.12. Relative indices of annual CPUE from the arithmetic, unstandardised, lognormal models of non-zero bottom trawl catches of Redstripe Rockfish in 5DE. 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	0.574	0.470	1.012	0.775	1.321	0.136	0.852	0.862	0.649	1.156	0.155
1997	0.895	1.058	1.148	0.827	1.593	0.167	0.498	0.571	0.391	0.831	0.205
1998	1.095	1.036	1.207	0.937	1.556	0.130	0.750	0.905	0.652	1.205	0.161
1999	1.270	1.217	1.370	1.068	1.758	0.127	1.134	1.554	1.157	1.983	0.139
2000	1.152	1.256	1.139	0.937	1.384	0.100	1.096	1.248	0.930	1.557	0.128
2001	1.037	1.404	1.100	0.894	1.353	0.106	0.740	0.814	0.624	1.059	0.128
2002	1.108	1.165	0.788	0.652	0.953	0.097	0.689	0.543	0.423	0.682	0.125
2003	1.066	1.408	0.798	0.658	0.967	0.098	0.894	0.713	0.558	0.892	0.122
2004	1.449	1.566	0.622	0.507	0.764	0.105	0.817	0.508	0.403	0.649	0.126
2005	0.885	0.880	0.766	0.608	0.964	0.117	1.094	0.838	0.654	1.109	0.140
2006	1.111	1.483	0.893	0.710	1.123	0.117	1.029	0.919	0.646	1.193	0.150
2007	1.022	1.087	0.640	0.507	0.806	0.118	1.127	0.721	0.520	0.942	0.153
2008	1.480	1.668	1.223	0.950	1.573	0.129	0.881	1.077	0.769	1.478	0.159
2009	1.174	1.647	0.782	0.609	1.005	0.128	0.660	0.516	0.379	0.694	0.154
2010	0.676	0.699	0.780	0.607	1.002	0.128	0.930	0.725	0.523	0.978	0.158
2011	1.204	1.449	1.005	0.778	1.298	0.131	1.058	1.063	0.799	1.422	0.152
2012	1.265	0.949	1.045	0.823	1.328	0.122	1.382	1.445	1.032	1.961	0.166
2013	0.701	0.627	1.365	1.062	1.756	0.128	1.374	1.875	1.347	2.759	0.181
2014	1.234	0.679	0.973	0.770	1.230	0.119	1.366	1.330	0.957	1.759	0.155
2015	0.607	0.351	0.824	0.627	1.083	0.139	1.091	0.899	0.612	1.262	0.188
2016	0.739	0.718	1.418	1.098	1.830	0.130	1.706	2.418	1.782	3.298	0.153
2017	0.981	0.875	2.000	1.565	2.557	0.125	1.946	3.892	2.874	5.182	0.156

Table C.13. Relative indices of annual CPUE from the arithmetic, unstandardised, lognormal models of non-zero bottom trawl catches of Redstripe Rockfish in Area 3CD5ABC. 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	1.190	1.366	1.286	1.146	1.442	0.0586	0.775	0.997	0.874	1.113	0.063
1997	1.207	1.301	1.392	1.269	1.526	0.0471	0.977	1.359	1.199	1.496	0.055
1998	0.950	1.196	1.610	1.479	1.753	0.0434	1.103	1.776	1.603	1.939	0.047
1999	0.894	0.937	1.173	1.078	1.276	0.0431	0.988	1.159	1.034	1.266	0.048
2000	1.364	1.474	1.312	1.213	1.419	0.0400	1.004	1.317	1.218	1.432	0.042
2001	1.362	1.390	1.116	1.027	1.212	0.0421	0.906	1.011	0.911	1.100	0.048
2002	1.101	1.351	1.094	1.007	1.189	0.0424	0.822	0.900	0.829	0.987	0.046
2003	1.165	1.339	1.067	0.982	1.159	0.0423	0.829	0.884	0.803	0.960	0.045
2004	0.890	1.068	0.960	0.879	1.048	0.0449	0.797	0.765	0.685	0.832	0.049
2005	0.730	0.742	0.798	0.733	0.868	0.0429	0.857	0.684	0.628	0.760	0.049
2006	0.767	0.690	0.763	0.698	0.835	0.0458	0.922	0.704	0.630	0.780	0.054
2007	0.726	0.829	0.897	0.819	0.983	0.0465	1.008	0.904	0.811	1.003	0.054
2008	1.046	1.122	1.058	0.960	1.166	0.0495	0.979	1.035	0.920	1.155	0.059
2009	1.275	1.125	0.927	0.843	1.020	0.0485	0.921	0.854	0.765	0.943	0.056
2010	0.885	0.782	0.793	0.719	0.874	0.0498	0.917	0.727	0.644	0.819	0.061
2011	0.910	0.954	0.952	0.866	1.047	0.0486	1.173	1.117	1.007	1.269	0.058
2012	1.306	1.019	0.929	0.840	1.026	0.0509	1.241	1.153	1.017	1.285	0.059
2013	0.856	0.842	0.905	0.812	1.008	0.0550	1.033	0.934	0.825	1.043	0.063
2014	1.248	0.773	0.756	0.674	0.847	0.0581	0.965	0.730	0.625	0.830	0.072
2015	0.930	0.823	0.859	0.776	0.950	0.0516	1.122	0.964	0.865	1.107	0.061
2016	0.854	0.730	0.845	0.767	0.930	0.0490	1.476	1.247	1.114	1.382	0.056
2017	0.798	0.798	0.969	0.876	1.071	0.0512	1.552	1.504	1.348	1.701	0.058

C.7. REFERENCES – CPUE

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Rutherford, K.L. 1999. A brief history of `GFCatch` (1954-1995), the groundfish catch and effort database at the Pacific Biological Station. Can. Data Rep. Fish. Aquat. Sci. 2299: v + 66 p

APPENDIX D. BIOLOGICAL DATA

This appendix describes the stock delineation of Redstripe Rockfish (RSR) along the British Columbia (BC) coast and the derivation of the length-weight relationship, von Bertalanffy growth relationship, maturity schedule, and natural mortality used in the RSR catch-at-age stock assessment model. All biological analyses are based on RSR data extracted from the Fisheries and Oceans Canada (DFO) Groundfish database `GFBioSQL` on Nov 27, 2017 (125,358 records). General data selection criteria for many analyses are summarized in Table D.1, though each analysis can vary the selection.

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

Field	Criterion	Notes
Trip type	`[trip_type] == c(2,3)`	Definition of research observations.
	`[trip_type] == c(1,4,5)`	Definition of commercial observations
Sample type	`[sample_type] == c(1,2,6,7)`	Only random or total samples.
Ageing method	`[agemeth]==3 | (==0 & [year]>=1980)`	Break & burn method, or unknown from 1980 onwards, assumed to be B&B.
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 areas	North (5DE): PMFC major area codes 8:9 South (5ABC3CD): PMFC major areas 5:7 (5ABC) + majors 3:4 (3CD)

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

D.1. STOCK DELINEATION

The BC population of RSR was treated as two stocks – BC North and BC South. The rationale for this decision was based on three analyses that showed consistent differences in (i) mean weights in the commercial fishery, (ii) fish length distributions in surveys, and (iii) growth parameters by survey. Differences in size between these two regions were previously noted for Walleye Pollock (Starr & Haigh, 2021).

The separation of these areas is supported by oceanographic conditions such as the winter outflow of warm freshwater from Hecate Strait, which wraps around Cape St. James and periodically forms Haida Eddies (Crawford 2002; Di Lorenzo et al., 2005). Additionally, the North Pacific Current (NPC) bifurcates to the northward Alaska Current (~60% by volume, Freeland 2006) and southward California Current at 50°N in summer and 45°N in winter (Pickard & Emery, 1982). Cummins and Freeland (2006) demonstrated a 5-y average (2002-2006) bifurcation at 46°N, -133°W; however, in 2002 the bifurcation occurred much further north at 53°N (Batten & Freeland 2007). The NPC bifurcation might also act as a physical separation mechanism for fish stocks on the BC coast.

D.1.1. Mean Weight in Commercial Fishery

Data used to estimate the mean weight by year were selected following the relevant guidelines in Table D.1. The initial RSR biological data contained 125,358 records which were filtered as follows:

- positive definite lengths `len > 0` 125,213 records
- all available years `year = 1967:2016` 125,213 records
- BC offshore `major = 3:9` 125,118 records
- comm. trips incl. JV Hake `ttype = c(1,4,5)` 61,776 records
- ransom samples/total catch `stype = c(1,2,6,7)` 60,870 records
- trawl tows: bottom + midwater `gear = c(1,6)` 60,214 records
- species category (unsorted) `scat = 1` 38,076 records

This process resulted in 38,076 RSR biological records from unsorted samples. Weights, missing or otherwise, were calculated from the measured lengths using the length-weight parameters in Table D.6. 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.

To remove some of the variance due to influential factors in the data, an additive lognormal model (Schnute et al. 2004) was used to adjust the annual index of fish weight:

$$w_m = \mu + \alpha_i + \beta_j + \delta_k + \gamma_l + \sigma\varepsilon_m \tag{D.1}$$

where, μ = the overall mean;

α_i = year effect (with missing years)

$i_{1,\ldots,N}$ = {1979, 1988, 1990:1994, 1996:2017}, where N = 29 years;

β_j = sex effect, where j = {1,2} for males and females, respectively;

δ_k = area effect, where k = {3:9} for PMFC areas 3C, 3D, 5A, 5B, 5C, 5D, 5E;

γ_l = gear effect, where l = {1,6} for bottom and midwater trawl, respectively;

m = index of fish specimen;

σ = standard deviation of the model; and

ε_m = independent residuals assumed to be standard normal N(0,1).

The fitted model was chosen using the R package `glmulti` (Calcagno & de Mazancourt 2010) and had a residual standard error of 0.1813 on 38,038 degrees of freedom (multiple R^2 = 0.2116, adjusted R^2 = 0.2109, Figure D.1).

The main purpose of the GLM fit was to adjust for trend in the annual indices of weight; however, the process rendered the scale of the indices relative. To transform the relative indices back to absolute, they were multiplied by the ratio of the geometric mean of the non-standardised annual indices (0.481 kg/fish) to the geometric mean of the standardised (and sometimes normalized) indices (1 kg/fish); see results in Table D.2.

$$\vec{W}_i = W_i \left[\left(\prod_{i_1}^{i_N} \overline{W}_i \right)^{1/N} \Big/ \left(\prod_{i_1}^{i_N} W_i \right)^{1/N} \right] \tag{D.2}$$

where, $i_{1,\ldots,N}$ = annual index (N=29 years),

$\overline{W}_i$ = unstandardized annual mean weights (kg/fish),

W_i = GLM-standardized annual mean weights (kg/fish), and

$\vec{W}_i$ = adjusted GLM-standardized annual mean weights (kg/fish).

The standardization removed effects due to sex (females are larger than males), coastal region using PMFC major areas, and gear types, specifically bottom vs. midwater trawl (Figure D.1). Additional effects were explored for the coast model but their effects on the annual index series were either minimal (e.g., season) or created large gaps due to missing data (e.g., depth).

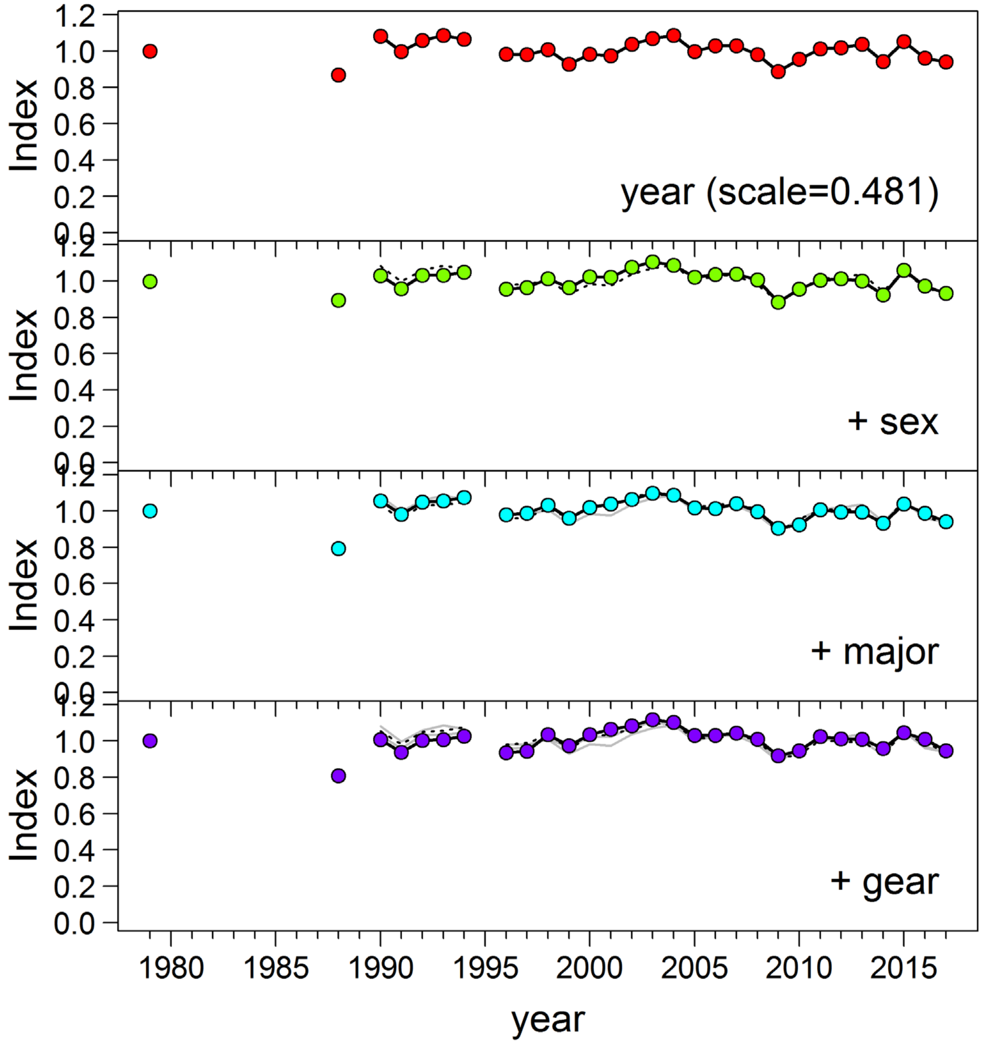


Figure D.1. Normalised mean weight (kg/fish) of RSR coastwide estimated from Eq. D.1 (original geometric mean = 0.481 kg/fish). Panels from top to bottom show how the annual indices change as residual variance from each factor is removed. Broken lines show the index series in the panel above (using the factor accepted just prior to that depicted in the current panel).

Table D.2. Annual mean weight (kg) of Redstripe Rockfish using unsorted samples from the BC coast: $\overline{W}_i$ = non-standardized (non-std), W_i = GLM-standardized (glm-std), $\overrightarrow{W}_i$ = adjusted GLM-standardized (adj glm-std); numbers of samples and fish used for annual mean calculations are also reported. Final row reports geometric mean weight of all years with data.

Year	# Samp	# Fish	Fish wt. (non-std)	Fish wt. (glm-std)	Fish wt. (adj glm-std)	Year	# Samp	# Fish	Fish wt. (non-std)	Fish wt. (glm-std)	Fish wt. (adj glm-std)
1979	2	316	0.346	1.000	0.481	2004	18	1,283	0.484	1.103	0.531
1988	1	98	0.564	0.808	0.389	2005	19	1,219	0.514	1.031	0.496
1990	1	191	0.483	1.007	0.484	2006	9	570	0.514	1.030	0.496
1991	2	253	0.542	0.936	0.451	2007	11	732	0.465	1.044	0.502
1992	5	245	0.568	1.003	0.483	2008	11	680	0.367	1.009	0.486
1993	4	214	0.550	1.008	0.485	2009	12	801	0.439	0.919	0.442
1994	17	907	0.468	1.025	0.493	2010	11	676	0.497	0.945	0.455
1996	3	185	0.465	0.935	0.450	2011	17	1,025	0.505	1.024	0.493
1997	6	321	0.493	0.943	0.454	2012	10	560	0.522	1.012	0.487
1998	50	6,629	0.411	1.034	0.498	2013	9	422	0.426	1.009	0.486
1999	35	4,250	0.468	0.973	0.468	2014	7	306	0.536	0.959	0.461
2000	41	5,575	0.459	1.035	0.498	2015	8	452	0.446	1.046	0.503
2001	55	5,804	0.522	1.064	0.512	2016	6	343	0.423	1.010	0.486
2002	25	2,176	0.553	1.084	0.522	2017	12	607	0.460	0.946	0.455
2003	21	1,236	0.569	1.117	0.537	-	-	-	-	-	-
							Σ = 428	Σ = 38,076	$\prod^{1/N}$ = 0.481	$\prod^{1/N}$ = 1.000	$\prod^{1/N}$ = 0.481

To explore regional variations in mean weight, the GLM procedure above (without the area effect) was applied to each PMFC area, using `glmulti` to choose among the effects: `year, sex, gear`, and `season`. The automated model selection chose `sex` as a significant factor in all areas (e.g., Figure D.1) and `season` in all areas but 3D (Figure D.2). Only in area 5A was `gear` selected as a significant effect (Figure D.3). Generally, all areas other than 5E had similar mean weights (kg/fish): 3C = 0.488, 3D = 0.478, 5A = 0.492, 5B = 0.406, 5C = 0.456, 5E = 0.578 (Table D.3).

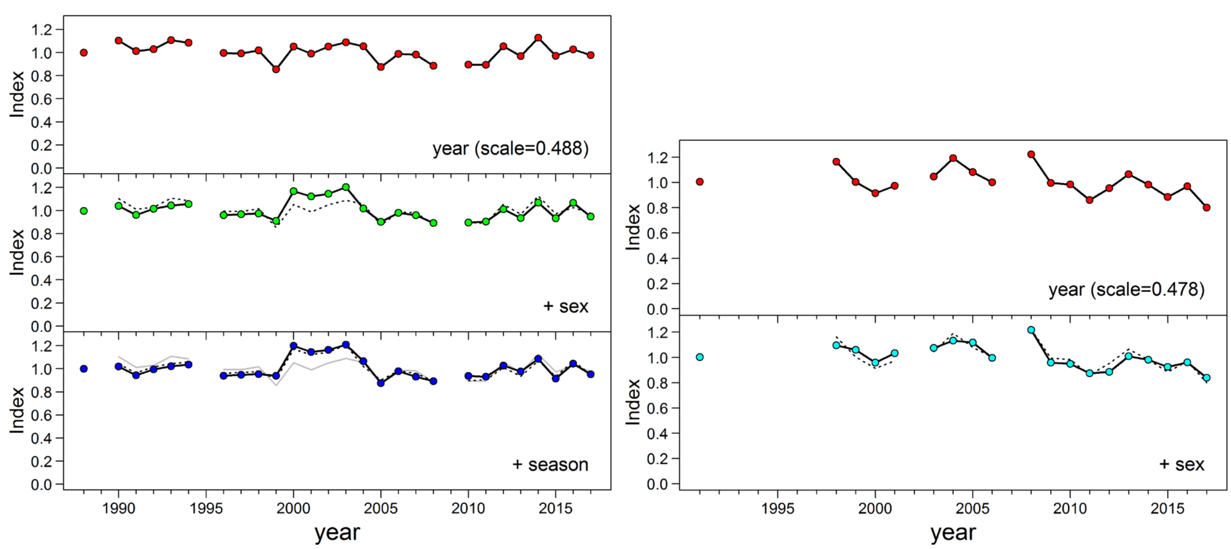


Figure D.2. Normalised mean weight (kg/fish) of RSR in 3C (left) and 3D (right) estimated from Eq. D.1; original geometric means (kg/fish): 3C=0.488, 3D=0.478. See Figure D.1 caption for plot details.

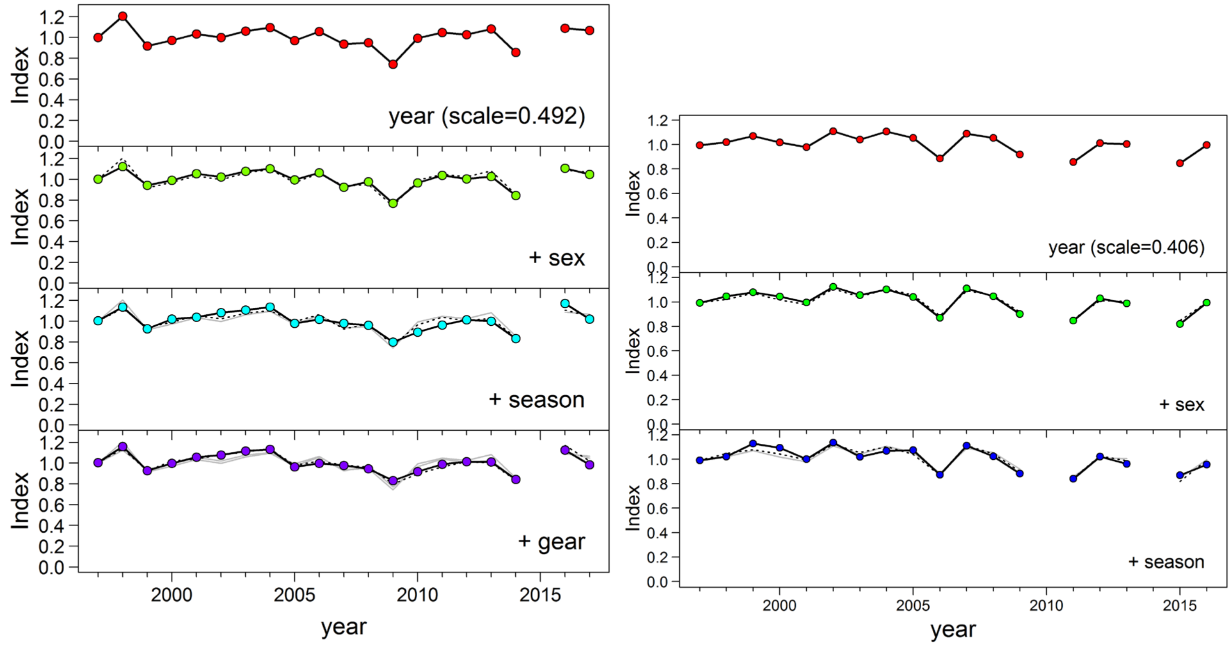


Figure D.3. Normalised mean weight (kg/fish) of RSR in 5A (left) and 5B (right) estimated from Eq. D.1; original geometric means (kg/fish): 5A=0.492, 5B=0.406. See Figure D.1 caption for plot details.

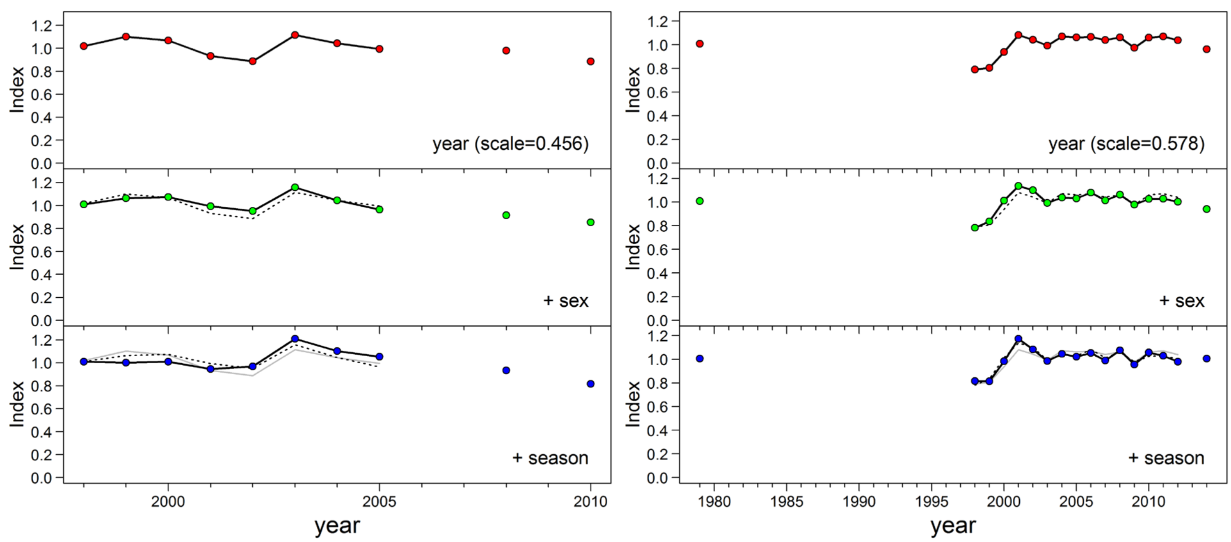


Figure D.4. Normalised mean weight (kg/fish) of RSR in 5C (left) and 5E (right) estimated from Eq. D.1; original geometric means (kg/fish): 5C=0.456, 5E=0.578. See Figure D.1 caption for plot details.

Table D.3. Annual, adjusted, GLM-standardised mean weight $\overrightarrow{W}_i$ (kg/fish) of RSR using unsorted samples from each PMFC area on the BC outer coast; final row shows geometric mean of annual mean weights. Values in parentheses and delimited by a colon are numbers of samples and specimens.

Year	3C	3D	5A	5B	5C	5E
1979	-	-	-	-	-	0.581 (2: 316)
1988	0.487 (1: 98)	-	-	-	-	-
1990	0.497 (1: 191)	-	-	-	-	-
1991	0.460 (1: 118)	0.479 (1: 135)	-	-	-	-
1992	0.485 (5: 245)	-	-	-	-	-
1993	0.498 (4: 214)	-	-	-	-	-
1994	0.505 (17: 907)	-	-	-	-	-
1996	0.458 (3: 185)	-	-	-	-	-
1997	0.462 (4: 107)	-	0.494 (1: 47)	0.402 (1: 167)	-	-
1998	0.465 (10:1467)	0.524 (10:1218)	0.571 (15:2248)	0.415 (9: 955)	0.461 (1: 59)	0.472 (5: 682)
1999	0.458 (7: 772)	0.507 (6: 714)	0.456 (14:1888)	0.458 (4: 409)	0.458 (1: 53)	0.470 (3: 414)
2000	0.585 (11:1706)	0.459 (9:1689)	0.492 (7: 820)	0.444 (8: 905)	0.461 (3: 326)	0.568 (3: 129)
2001	0.558 (4: 407)	0.495 (15:1388)	0.520 (8: 940)	0.406 (11:1101)	0.431 (5: 639)	0.677 (12:1329)
2002	0.568 (6: 624)	-	0.530 (7: 612)	0.461 (3: 251)	0.442 (3: 255)	0.626 (6: 434)
2003	0.589 (1: 68)	0.514 (5: 237)	0.549 (4: 267)	0.414 (7: 403)	0.552 (2: 115)	0.570 (2: 146)
2004	0.519 (2: 111)	0.542 (1: 46)	0.558 (5: 543)	0.433 (4: 230)	0.503 (3: 180)	0.604 (3: 173)
2005	0.427 (4: 251)	0.535 (1: 59)	0.474 (5: 290)	0.436 (3: 179)	0.480 (2: 104)	0.590 (4: 336)
2006	0.477 (2: 126)	0.477 (2: 99)	0.491 (2: 101)	0.354 (2: 198)	-	0.609 (1: 46)
2007	0.454 (3: 175)	-	0.481 (3: 271)	0.451 (3: 177)	-	0.571 (2: 109)
2008	0.435 (1: 30)	0.583 (3: 193)	0.466 (1: 59)	0.416 (3: 206)	0.426 (2: 167)	0.621 (1: 25)
2009	-	0.458 (1: 59)	0.409 (1: 50)	0.358 (5: 404)	-	0.552 (5: 288)
2010	0.457 (4: 252)	0.455 (1: 63)	0.452 (2: 128)	-	0.372 (2: 128)	0.611 (2: 105)
2011	0.454 (2: 119)	0.418 (3: 180)	0.487 (4: 246)	0.341 (4: 262)	-	0.594 (4: 218)
2012	0.501 (1: 61)	0.424 (3: 155)	0.499 (4: 233)	0.415 (1: 61)	-	0.565 (1: 50)
2013	0.476 (2: 105)	0.483 (3: 148)	0.498 (3: 110)	0.391 (1: 59)	-	-
2014	0.529 (2: 83)	0.470 (1: 60)	0.416 (2: 95)	-	-	0.581 (2: 68)
2015	0.447 (2: 127)	0.442 (4: 215)	-	0.353 (2: 110)	-	-
2016	0.510 (2: 110)	0.460 (1: 58)	0.554 (2: 110)	0.388 (1: 65)	-	-
2017	0.464 (7: 353)	0.402 (2: 103)	0.485 (3: 151)	-	-	-
Total	0.488 (109:9012)	0.478 (72:6819)	0.492 (93:9209)	0.406 (72:6142)	0.456 (24:2026)	0.578 (58:4868)

D.1.1.1. North vs. South

The same GLM standardisation D.1 and D.2 was applied to the North and South stocks of Redstripe Rockfish, using `glmulti` to choose among the effects: `year, sex, gear, season,` and `major` (which was not selected in either model). In BC North, the significant factors were `sex` and `season` (Figure D.5) with a geometric mean weight of 0.584 kg/fish (Table D.4). In BC South, the significant factors were `sex, gear`, and `season` (Figure D.6) with a geometric mean weight of 0.476 kg/fish (Table D.5). Figure D.7 illustrates the comparison between BC North and BC South.

Results from the mean weight analyses were not used in the assessment directly (as in a delay-difference model), but served to delineate RSR stocks along the BC coast in the absence of genetic information on this species.

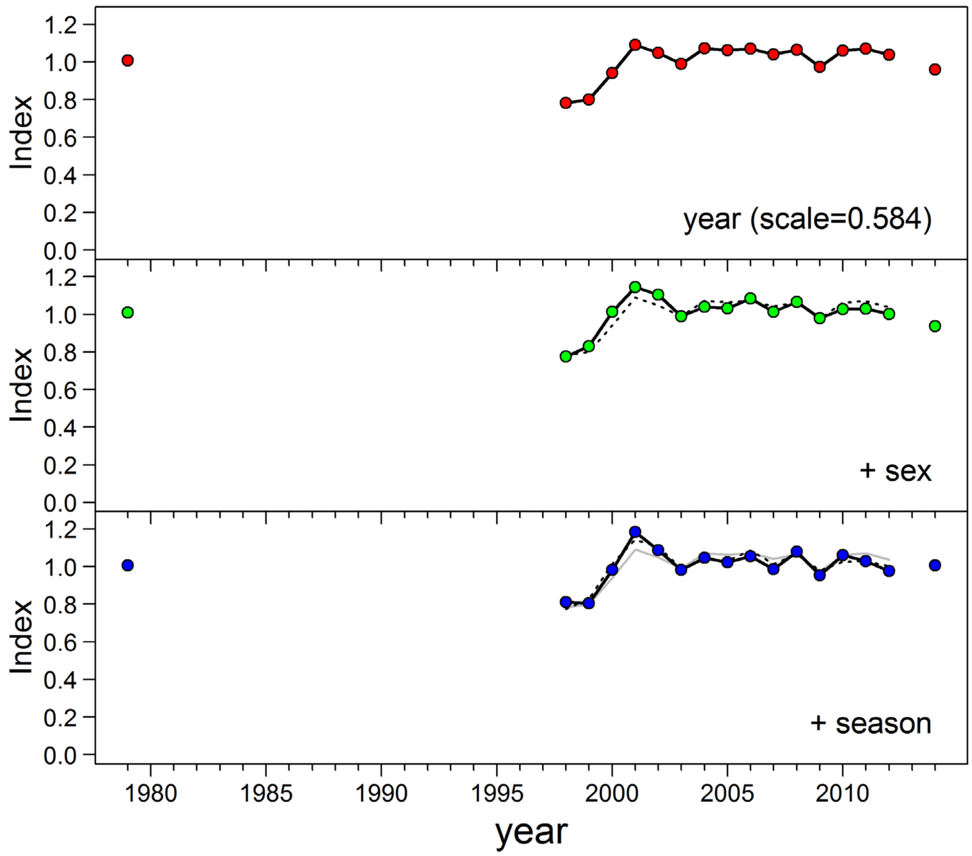


Figure D.5. Normalised mean weight (kg/fish) of RSR in BC North estimated from Eq. D.1; original geometric mean (kg/fish): 5DE=0.584. See Figure D.1 caption for plot details.

Table D.4. Annual mean weight (kg) of RSR using unsorted samples from the BC North stock: $\overline{W}_i$ = non-standardized (non-std), W_i = GLM-standardized (glm-std), $\vec{W}_i$ = adjusted GLM-standardized (adj glm-std); numbers of samples and fish used for annual mean calculations are also reported. Final row reports geometric mean weight of all years with data.

Year	# Samp	# Fish	Fish wt. (non-std)	Fish wt. (glm-std)	Fish wt. (adj glm-std)	Year	# Samp	# Fish	Fish wt. (non-std)	Fish wt. (glm-std)	Fish wt. (adj glm-std)
1979	2	316	0.341	1.006	0.587	2006	1	46	0.626	1.056	0.616
1998	5	682	0.362	0.811	0.474	2007	2	109	0.649	0.986	0.576
1999	3	414	0.525	0.804	0.470	2008	1	25	0.560	1.080	0.630
2000	3	129	0.673	0.983	0.574	2009	5	288	0.646	0.954	0.557
2001	12	1,329	0.633	1.183	0.691	2010	2	105	0.654	1.061	0.620
2002	6	434	0.576	1.086	0.634	2011	4	218	0.623	1.029	0.601
2003	2	146	0.655	0.982	0.573	2012	1	50	0.544	0.976	0.570
2004	3	173	0.647	1.047	0.612	2014	2	68	0.739	1.005	0.587
2005	4	336	0.655	1.022	0.597	-	-	-	-	-	-
							Σ = 58	Σ = 4,868	$\prod^{1/N}$ = 0.584	$\prod^{1/N}$ = 1.000	$\prod^{1/N}$ = 0.584

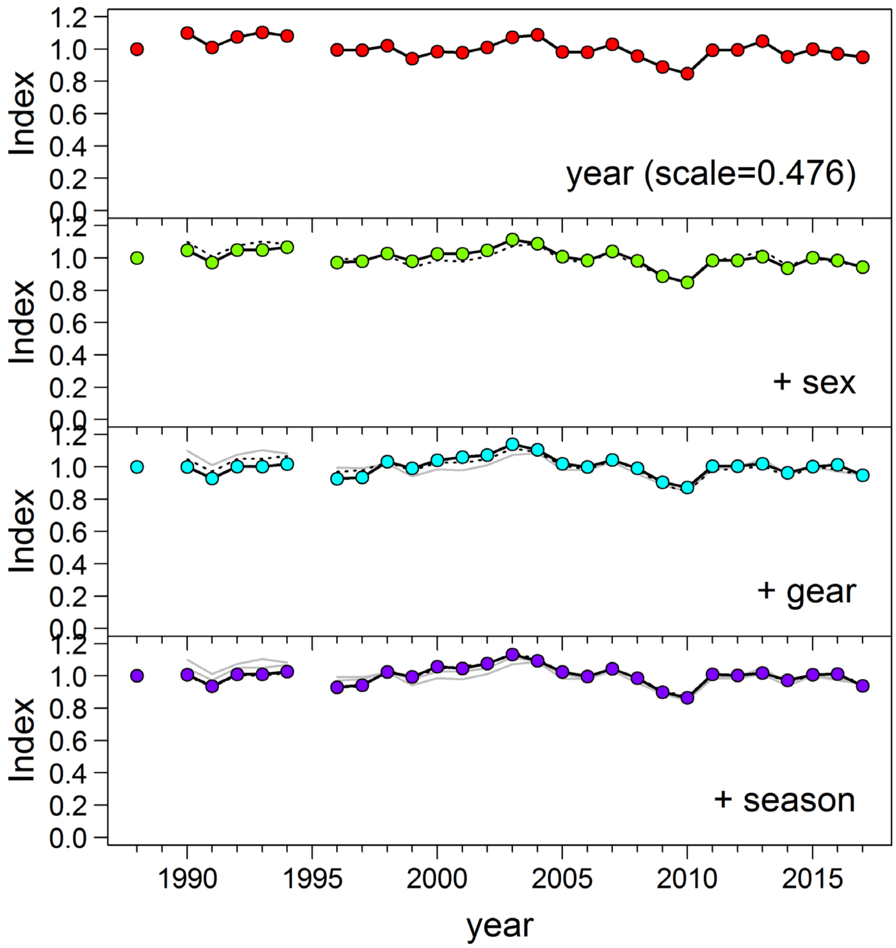


Figure D.6. Normalised mean weight (kg/fish) of RSR in BC South estimated from Eq. D.1; original geometric mean (kg/fish): 5DE=0.584. See Figure D.1 caption for plot details.

Table D.5. Annual mean weight (kg) of RSR using unsorted samples from the BC South stock: $\overline{W}_i$ = non-standardized (non-std), W_i = GLM-standardized (glm-std), $\overrightarrow{W}_i$ = adjusted GLM-standardized (adj glm-std); numbers of samples and fish used for annual mean calculations are also reported. Final row reports geometric mean weight of all years with data.

Year	# Samp	# Fish	Fish wt. (non-std)	Fish wt. (glm-std)	Fish wt. (adj glm-std)	Year	# Samp	# Fish	Fish wt. (non-std)	Fish wt. (glm-std)	Fish wt. (adj glm-std)
1988	1	98	0.575	1.001	0.476	2004	15	1,110	0.462	1.093	0.520
1990	1	191	0.491	1.007	0.479	2005	15	883	0.460	1.024	0.487
1991	2	253	0.552	0.935	0.445	2006	8	524	0.510	0.997	0.474
1992	5	245	0.578	1.009	0.480	2007	9	623	0.435	1.043	0.496
1993	4	214	0.559	1.008	0.480	2008	10	655	0.363	0.984	0.468
1994	17	907	0.475	1.025	0.488	2009	7	513	0.315	0.899	0.428
1996	3	185	0.472	0.930	0.442	2010	9	571	0.473	0.864	0.411
1997	6	321	0.500	0.941	0.448	2011	13	807	0.475	1.008	0.480
1998	45	5,947	0.420	1.024	0.487	2012	9	510	0.528	1.003	0.477
1999	32	3,836	0.465	0.995	0.473	2013	9	422	0.432	1.017	0.484
2000	38	5,446	0.458	1.058	0.503	2014	5	238	0.480	0.972	0.462
2001	43	4,475	0.491	1.046	0.498	2015	8	452	0.452	1.006	0.479
2002	19	1,742	0.550	1.076	0.512	2016	6	343	0.429	1.010	0.481
2003	19	1,090	0.563	1.132	0.539	2017	12	607	0.466	0.937	0.446
							Σ = 370	Σ = 33,208	$\prod^{1/N}$ = 0.476	$\prod^{1/N}$ = 1.000	$\prod^{1/N}$ = 0.476

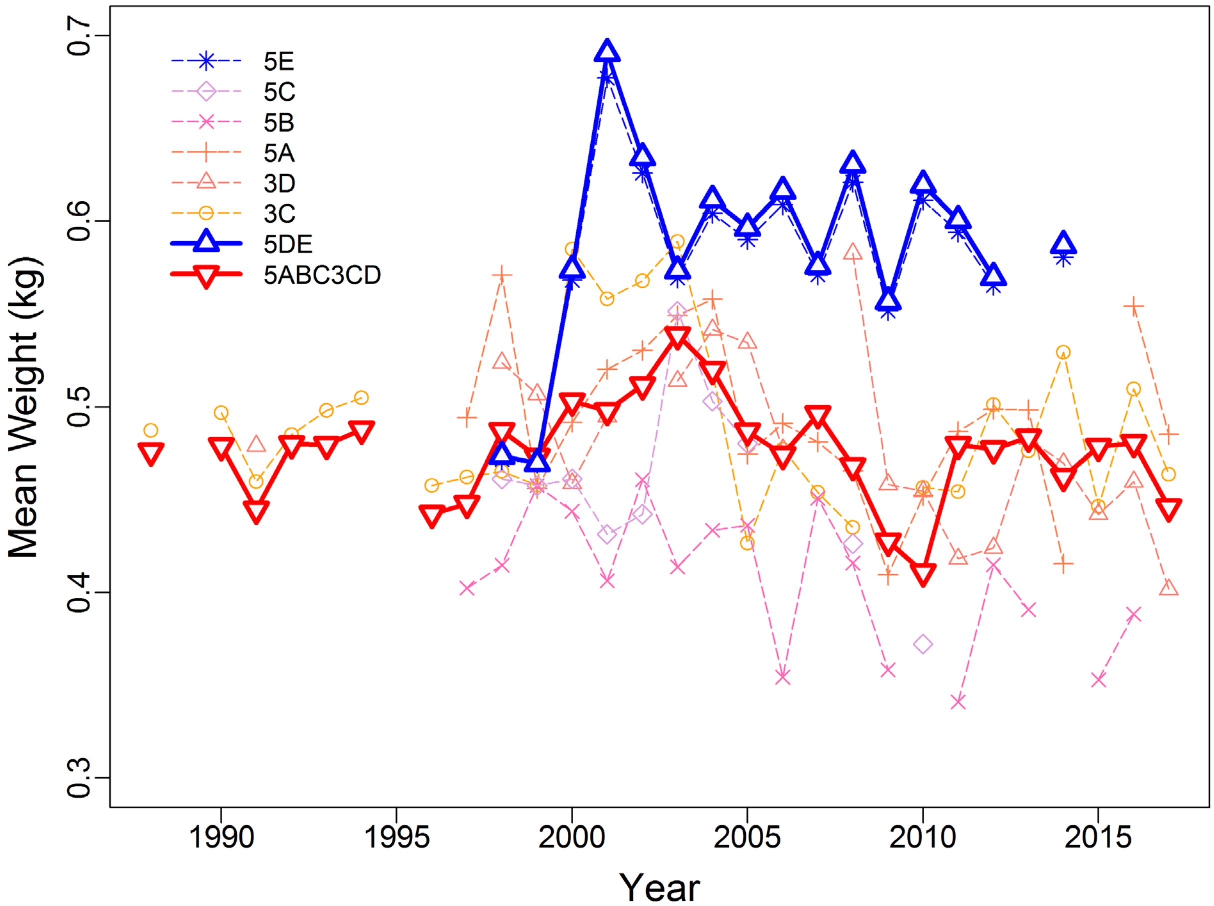


Figure D.7. Comparison of RSR mean weight series between BC North and BC South after GLM-adjustment for various factors (shown in Figure D.5 and Figure D.6). Individual adjusted GLM-standardised series for each PMFC area are included for comparison.

D.1.2. Fish Lengths in Surveys

The distribution of lengths from the three primary synoptic surveys for RSR – WCHG in the North and QCS and WCVI in the South – show that the quantile distributions for northern RSR lengths remain consistently above those for the South (Figure D.8, left). A similar comparison of age quantiles shows that ages are similar among all three surveys (Figure D.8, right).

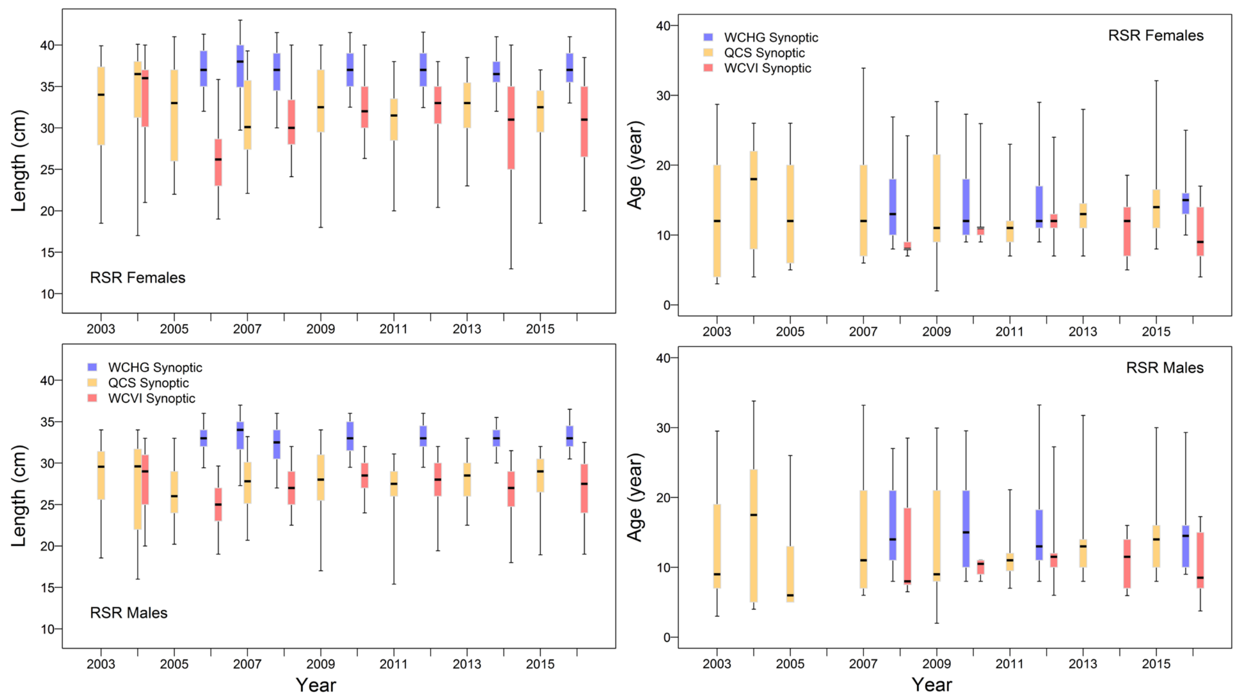


Figure D.8. Comparison of annual distributions of RSR length (left) and age(right) among three synoptic surveys – WCHG (west coast Haida Gwaii) in the North; QCS (Queen Charlotte Sound) and WCVI (west coast Vancouver Island) in the South. Boxplot quantiles: 0.05, 0.25, 0.5, 0.75, 0.95.

D.1.3. Growth Parameters by Survey

von Bertalanffy growth models fitted to age-length data from each of the three key RSR synoptic surveys estimate larger L_∞ parameters for the WCHG survey for each sex than for either of the two more southern surveys (Figure D.9, Figure D.10, Figure D.11). The other two von Bertalanffy growth parameters (*k* and *t0*) appear to be similar for all three surveys by sex. When these growth parameters were estimated in a Bayesian model using the same data (`rstan` package Stan Development Team. 2018), there was no overlap in the posterior distributions for the L_∞ parameter between the WCHG survey for either sex relative to the equivalent L_∞ posterior distributions from the two more southern surveys, while the posterior distributions by sex for the *k* and *t0* parameters show a greater degree of overlap (Figure D.12).

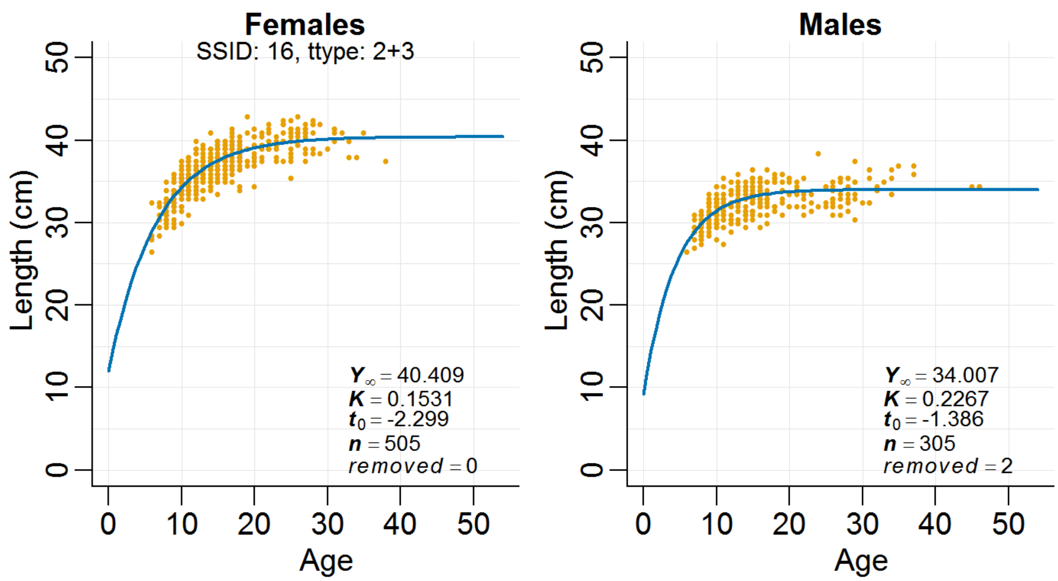


Figure D.9. WCHG synoptic: von Bertalanffy fits to RSR ages determined by break-and-burn otoliths.

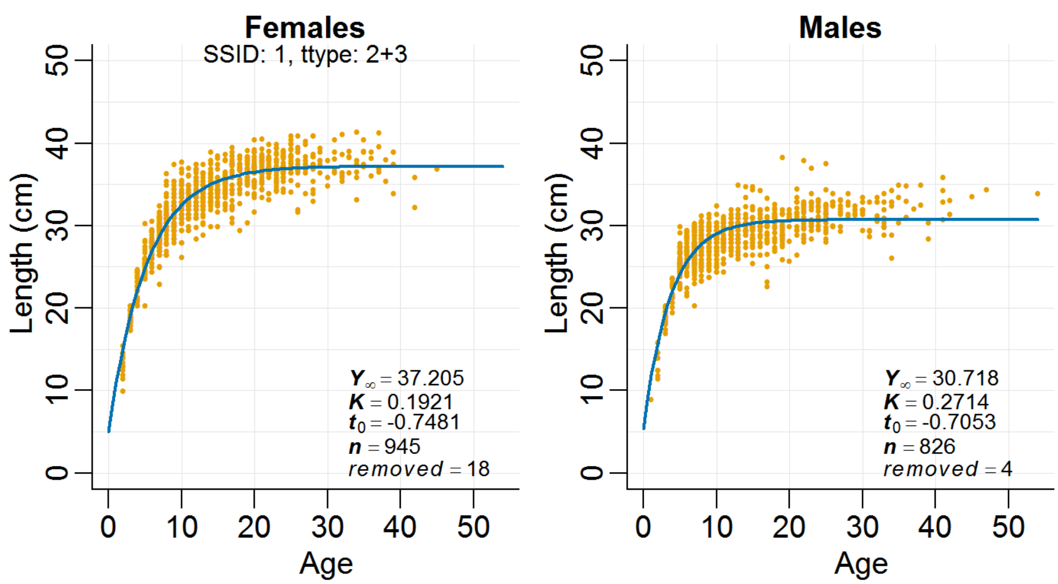


Figure D.10. QCS synoptic: von Bertalanffy fits to RSR ages determined by break-and-burn otoliths (surface otoliths included for ages 1-3).

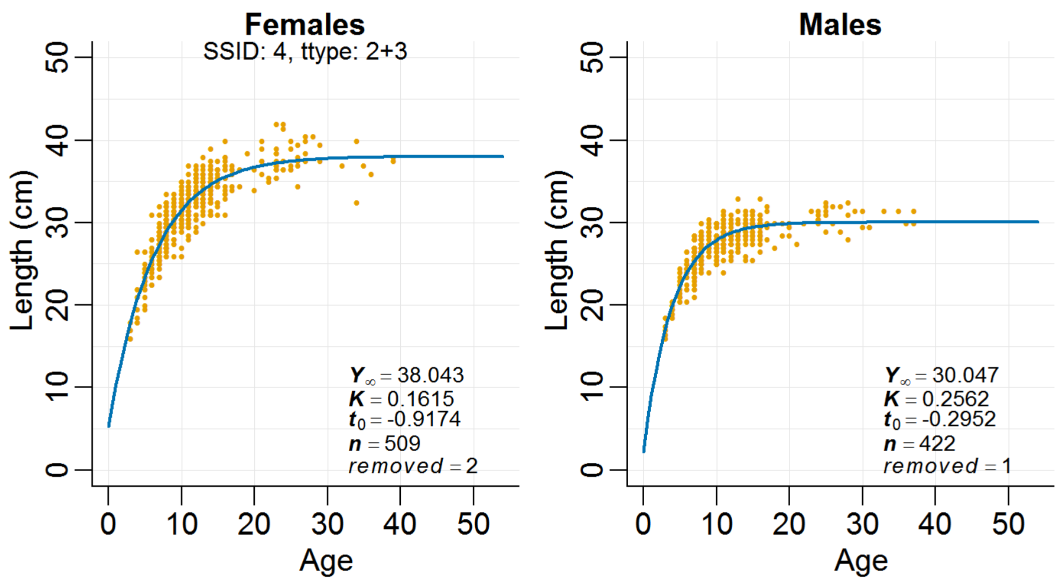


Figure D.11. WCVI synoptic: von Bertalanffy fits to RSR ages determined by break-and-burn otoliths.

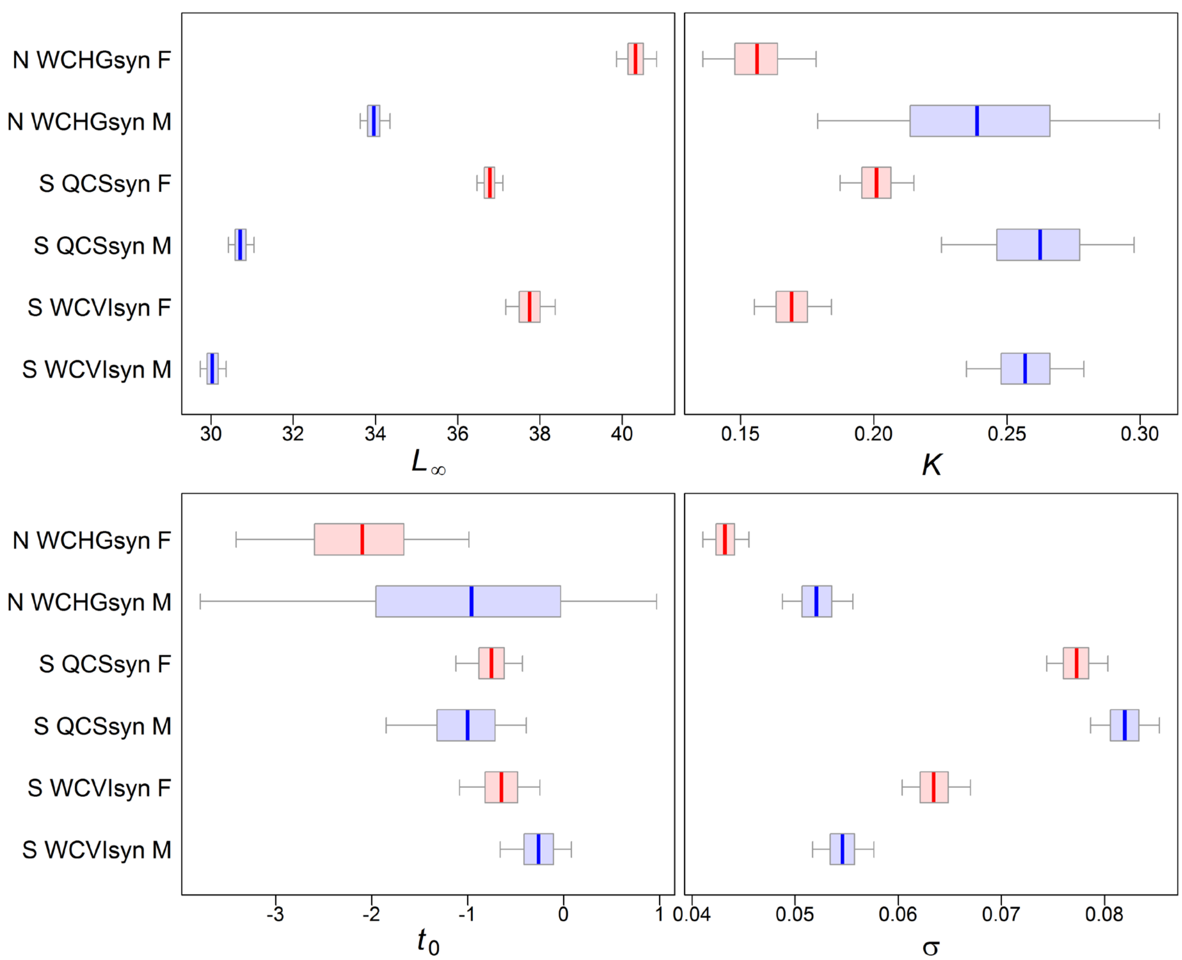


Figure D.12. MCMC samples (4 chains, 500 each) for von Bertalanffy parameters using RSR length-age data by survey series. Boxplots (red=females, blue=males) show 0.05, 0.25, 0.5, 0.75, & 0.95 quantiles.

D.2. LIFE HISTORY

D.2.1. 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, $\left\{W_{is}, L_{is}\right\}$:

$$\ln\left(W_{is}\right) = \alpha_s + \beta_s \ln\left(L_{is}\right) + \varepsilon_{is}, \quad \varepsilon \sim N(0,\sigma^2) \qquad \text{(D.1)}$$

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

Research samples from bottom trawl tows (Table D.6) were used to derive the length-weight parameters for the allometric relationship in the model. As there was a pronounced dimorphic difference between males and females, the sexes were treated separately in the two stock regions: North (Figure D.13, $\alpha_{2,1}$ = {1.3985E-05, 1.36344E-05}, $\beta_{2,1}$ = {2.9848, 2.9888}) and South (Figure D.14, $\alpha_{2,1}$ = {8.1572E-06, 9.6834E-06}, $\beta_{2,1}$ = {3.1501, 3.0925}).

Table D.6. Length-weight parameter estimates, standard errors (SE) and number of observations (n) for Redstripe Rockfish (females, males and combined) for all research/charter samples from bottom trawls operating in two stock areas from 1978 to 2017. W_{pred} = predicted weight (in kg) from the fitted data set.

Stock	*n*	ln(*a*)	SE ln(*a*)	*b*	SE *b*	mean W_i	SD W_i	min W_i	max W_i	mean W_{pred}
North -- 5DE (Research Survey)										
Females	1949	-11.178	0.0497	2.9848	0.0139	0.654	0.1752	0.021	1.343	0.638
Males	1522	-11.203	0.0437	2.9888	0.0126	0.446	0.1218	0.017	1.042	0.441
Both	3465	-11.246	0.0297	3.0026	0.0084	0.561	0.1844	0.017	1.219	0.548
South -- 5ABC+3CD (Research Survey)										
Females	4772	-11.717	0.0220	3.1501	0.0064	0.477	0.2311	0.007	1.786	0.514
Males	4425	-11.545	0.0212	3.0925	0.0064	0.283	0.1150	0.006	0.998	0.314
Both	9210	-11.700	0.0148	3.1426	0.0044	0.384	0.2086	0.006	1.786	0.417
PMFC 5E -- major area code 9 (Research/Survey)										
Females	1842	-10.855	0.0719	2.8943	0.0200	0.669	0.1524	0.150	1.219	0.650
Males	1385	-10.602	0.0932	2.8165	0.0267	0.471	0.0917	0.110	1.042	0.457
Both	3229	-11.012	0.0461	2.9362	0.0130	0.584	0.1630	0.110	1.219	0.564
PMFC 5D -- major area code 8 (Research/Survey)										
Females	119	-12.601	0.0763	3.4443	0.0229	0.448	0.3325	0.021	1.343	0.352
Males	138	-11.925	0.0717	3.2216	0.0229	0.193	0.1100	0.017	0.479	0.188
Both	258	-12.348	0.0549	3.3622	0.0170	0.313	0.2721	0.017	1.343	0.262
PMFC 5C -- major area code 7 (Research/Survey)										
Females	631	-11.797	0.0565	3.1664	0.0166	0.433	0.2226	0.028	1.036	0.513
Males	755	-11.370	0.0652	3.0343	0.0198	0.280	0.1179	0.032	0.874	0.293
Both	1394	-11.579	0.0461	3.0994	0.0138	0.349	0.1892	0.028	1.036	0.398
PMFC 5B -- major area code 6 (Research/Survey)										
Females	1545	-11.565	0.0462	3.0972	0.0133	0.516	0.2303	0.033	1.175	0.536
Males	1363	-11.522	0.0488	3.0809	0.0147	0.302	0.1126	0.021	0.754	0.327
Both	2909	-11.596	0.0304	3.1047	0.0089	0.416	0.2134	0.021	1.175	0.441
PMFC 5A -- major area code 5 (Research/Survey)										
Females	984	-11.778	0.0389	3.1684	0.0114	0.448	0.2264	0.010	1.081	0.564
Males	872	-11.796	0.0376	3.1681	0.0115	0.271	0.1086	0.006	0.760	0.333
Both	1856	-11.829	0.0264	3.1808	0.0079	0.365	0.2014	0.004	1.081	0.460

Stock	*n*	ln(*a*)	SE ln(*a*)	*b*	SE *b*	mean W_i	SD W_i	min W_i	max W_i	mean W_{pred}
PMFC 3D -- major area code 4 (Research/Survey)										
Females	468	-12.314	0.0791	3.3397	0.0229	0.519	0.2159	0.007	1.238	0.525
Males	391	-11.547	0.0616	3.1001	0.0186	0.303	0.0955	0.006	0.550	0.323
Both	858	-12.127	0.0504	3.2810	0.0148	0.421	0.2024	0.006	1.238	0.425
PMFC 3C -- major area code 3 (Research/Survey)										
Females	1144	-11.758	0.0384	3.1717	0.0113	0.457	0.2366	0.018	1.786	0.490
Males	1032	-11.514	0.0332	3.0908	0.0102	0.265	0.1224	0.010	0.998	0.307
Both	2177	-11.703	0.0247	3.1525	0.0074	0.366	0.2141	0.010	1.786	0.398

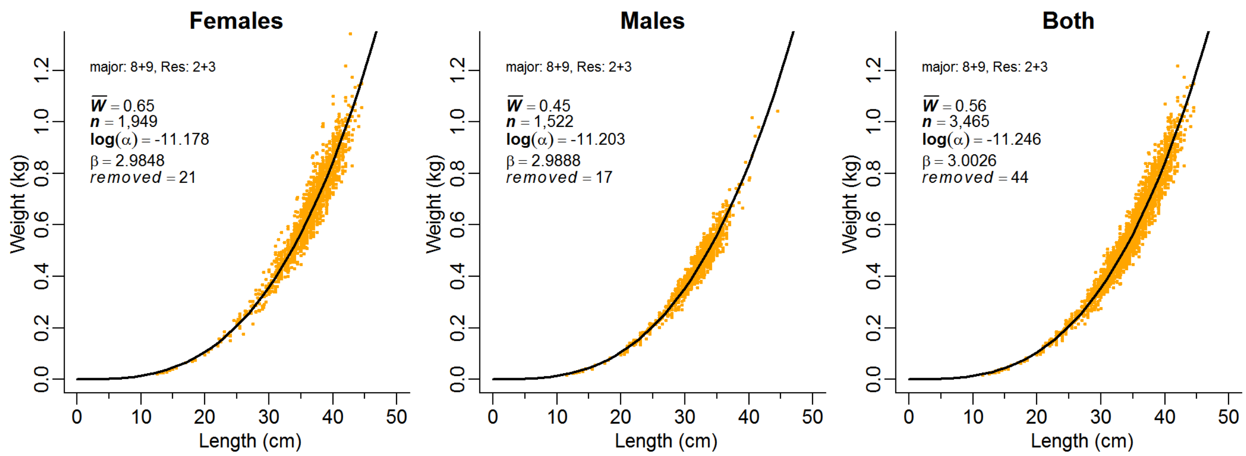


Figure D.13. Length-weight relationship for the BC North (5DE) stock of Redstripe Rockfish – derived from randomly selected research survey samples, regardless of gear type. Records with absolute value of standardised residuals >3 (starting with a preliminary fit) were dropped, removing 44 observations for the combined-sex fit.

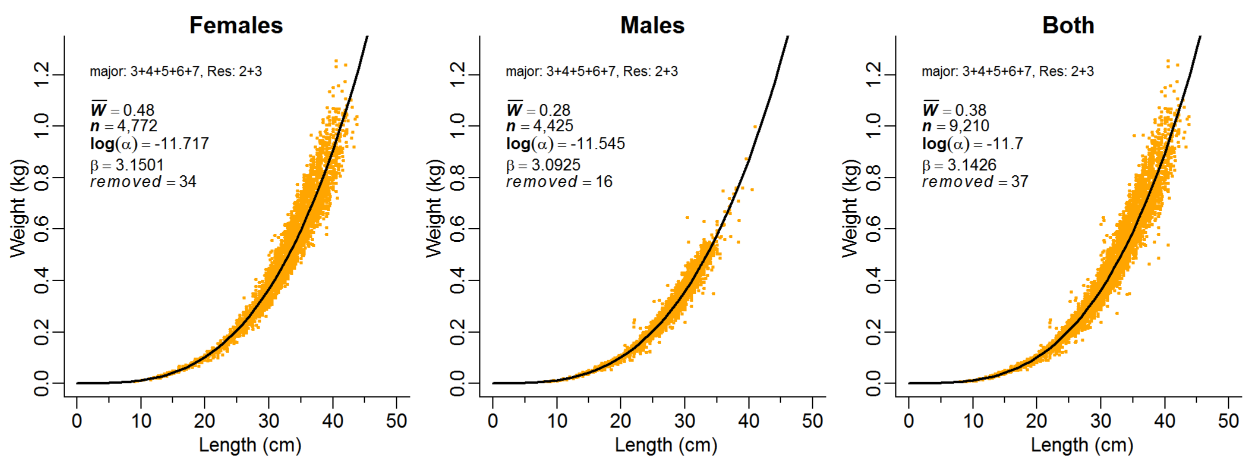


Figure D.14. Length-weight relationship for the BC South (5ABC3CD) stock of Redstripe Rockfish – derived from randomly selected research survey samples, regardless of gear type. Records with absolute value of standardised residuals >3 (starting with a preliminary fit) were dropped, removing 37 observations for the combined-sex fit.

D.2.2. von Bertalanffy Growth

Paired observations i of length and age by sex, $\{L_{is}, a_{is}\}$, for $s = 2,1$ (females, males) were available for 12,839 specimens: 343 by surface-read otoliths and 12,496 using the break and burn (B&B) method (MacLellan 1997). Table D.7 summarises the availability of B&B otoliths.

Table D.7. Redstripe Rockfish number of ages determined from broken-and-burnt otoliths in `GFBioSQL` database (accessed 2017-11-27). Number of samples appear in parentheses.

Trip Type	BC North			BC South		
	Females	Males	Unknown	Females	Males	Unknown
Commercial	674 (34)	622 (35)	0 (0)	4273 (161)	2152 (159)	92 (20)
Research	230 (14)	151 (14)	1 (1)	523 (39)	435 (38)	0 (0)
Survey	613 (25)	357 (25)	0 (0)	1320 (79)	1050 (78)	3 (3)

Growth was formulated as a von Bertalanffy model using research survey (`trip_type=2:3`) data where lengths by sex, L_{is}, for fish $i = 1,\ldots,n_s$ are given by:

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

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:

$$\ell\left(L_\infty, \kappa, t_0, \sigma\right) = n\ln\left(\sigma\right) + \frac{\sum_i^n \left(L_i - Li\right)^2}{2\sigma^2}, \quad i = 1,\ldots,n.$$

The ageing data, summarised in Table D.7, were qualified as follows before fitting the von Bertalanffy model:

- trip type = 2:3 (research, charter surveys),
- sample type = total catch or randomly selected,
- gear = bottom trawl tows,
- ageing method = break-and-burn otoliths.

Fits to growth (Table D.8, Figure D.15, Figure D.16) show that females are larger than males, and that RSR are bigger in BCN than BCS for both sexes (Figure D.17).

Table D.8. Parameter fits to a von Bertalanffy growth model for two stocks of RSR by sex.

Stock	***n***	L_∞ **(cm)**	κ	t_0 **(cm)**	σ
BC North – 5DE (Research Survey)					
Females	836	40.6	0.16304	-1.496	1.727
Males	505	33.9	0.22552	-1.575	1.640
Both	1348	37.4	0.22245	-0.027	2.811
BC South – 5ABC+3CD (Research Survey)					
Females	1805	37.9	0.16391	-1.459	1.950
Males	1468	31.1	0.19015	-2.805	1.809
Both	3293	35.1	0.16747	-2.118	2.963

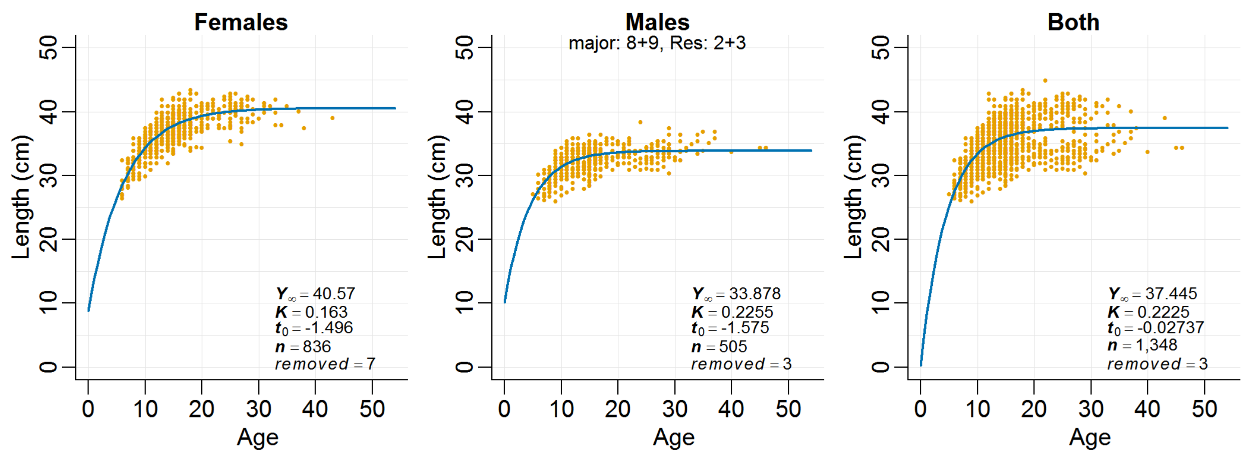


Figure D.15. BC North: von Bertalanffy fits to RSR ages determined by break-and-burn otoliths.

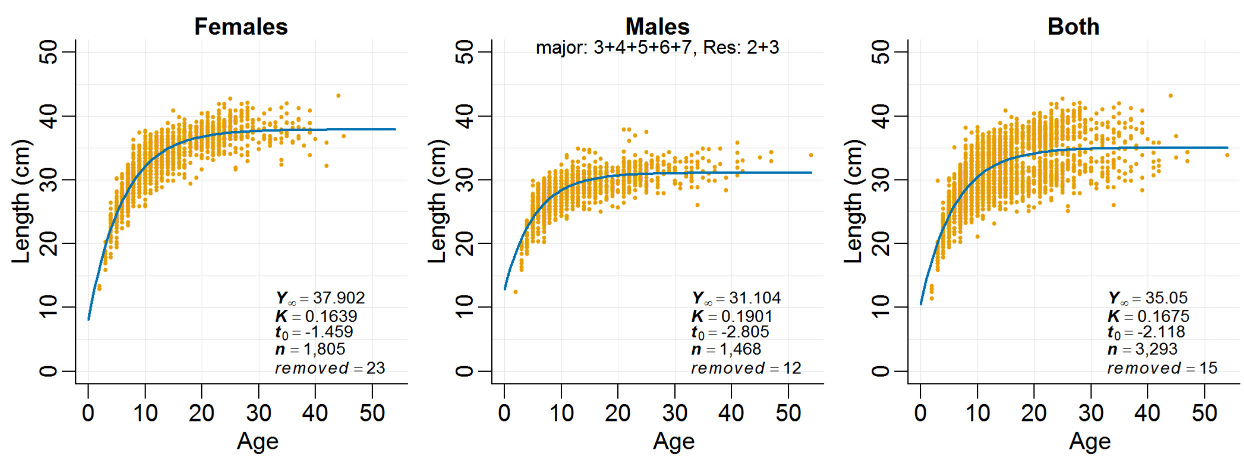


Figure D.16. BC South: von Bertalanffy fits to RSR ages determined by break-and-burn otoliths.

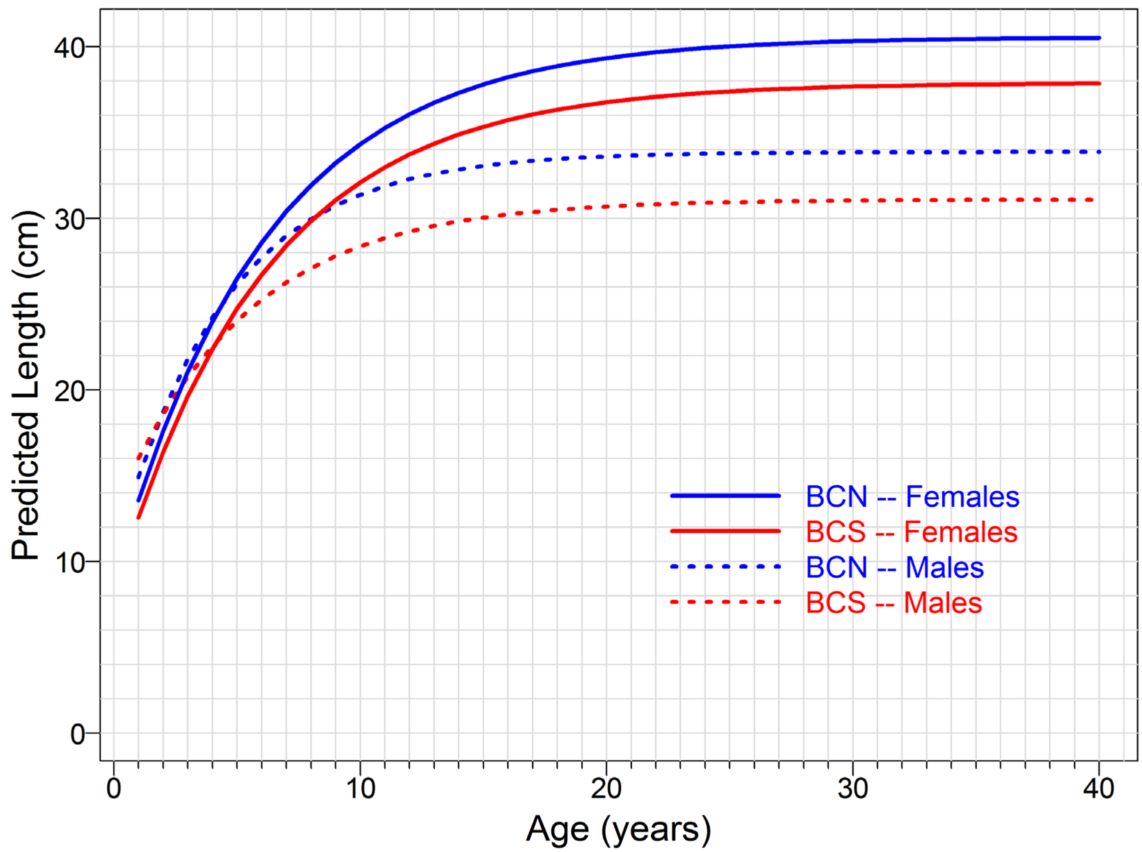


Figure D.17. Comparison of von Bertalanffy fits to RSR for females and males in BC North (BCN) and BC South (BCS).

D.2.3. Age Distribution

Aged females predominated in most of the PMFC (Pacific Marine Fisheries Commission) areas. Figure D.18 indicates some changes in mean age over time, with declines in some areas; however, the data are too sparse to suggest strong long-term trends. Figure D.19 shows that in the commercial fishery, median age increases slightly from south to north, but this trend is not reflected in the survey samples.

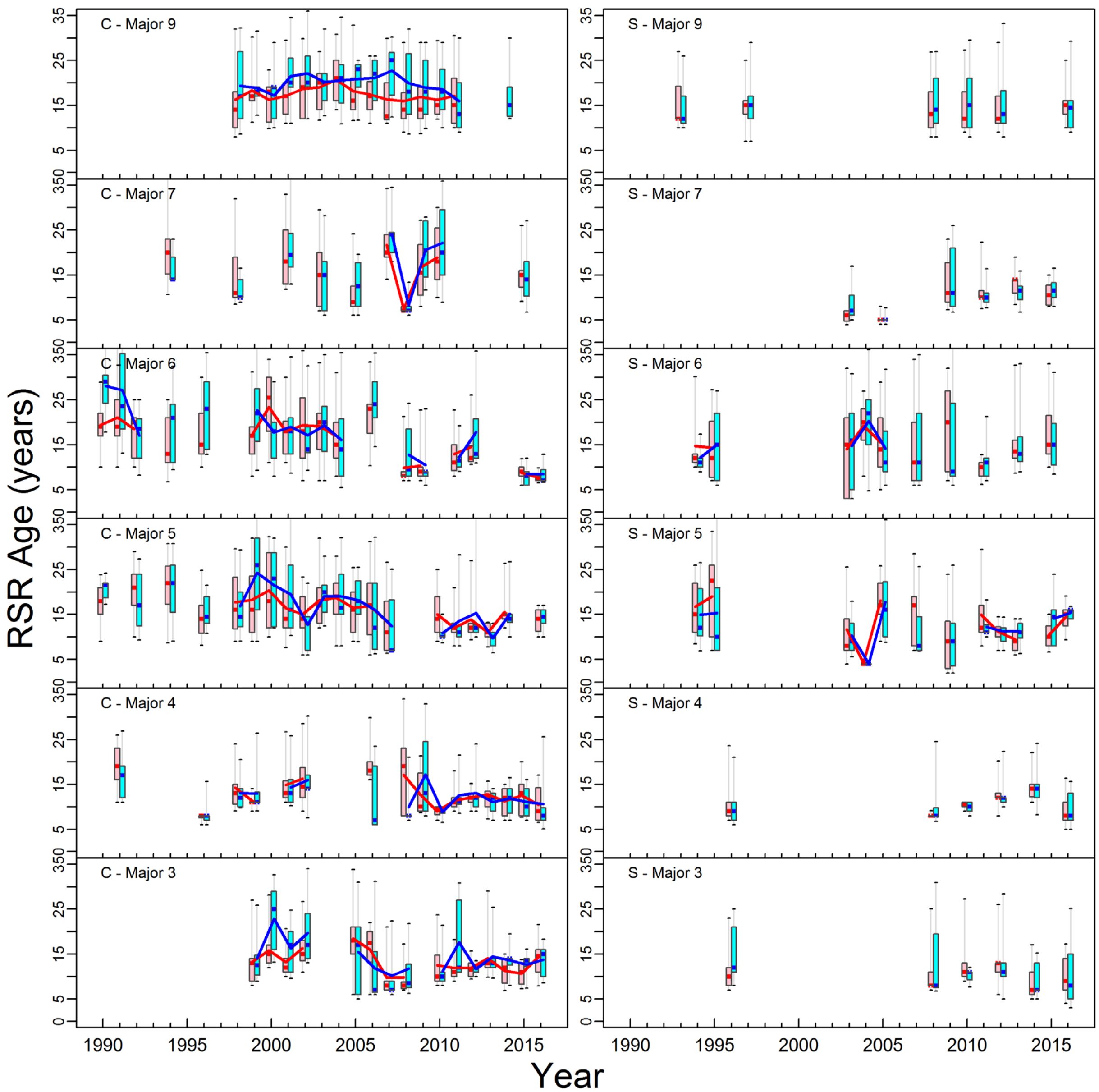


Figure D.18. Quantile plots of annual RSR age by sex and PMFC area for commercial trips (C) and surveys (S); PMFC major codes: 3=3C, 4=3D, 5=5A, 6=5B, 7=5C, 8=5D, 9=5E. The trends in mean age for females (red lines) and males (blue lines) are displayed when years are contiguous.

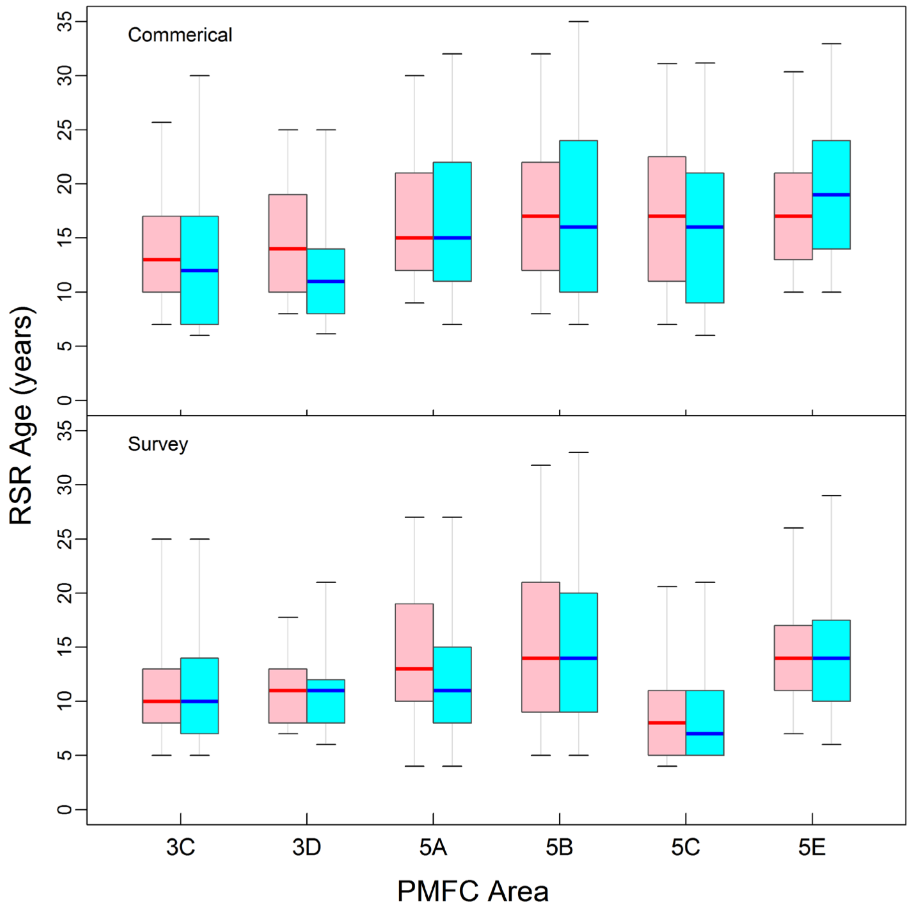


Figure D.19. Quantile plots of RSR age by sex and PMFC area for commercial trips (C) and surveys (S); each quantile plot includes all years.

D.2.4. Maturity

This analysis was based on all "staged" (examined for maturity status) females in the DFO `GFBioSQL` database. Maturity codes for RSR in the database (Table D.9) come from `MATURITY_CONVENTION_CODE = 1`, which describes 7 maturity conditions for Rockfish (1977+).

Table D.9. GFBio maturity codes for rockfish, including BC Offshore RSR.

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

Biological data for RSR maturity analyses were obtained from `GFBioSQL` on Nov 27, 2017.

Bubble plots of frequency data (maturity vs. month) derived from various sources appear in Figure D.20 (BC North) and Figure D.21 (BC South). The two regions appeared to have similar maturity maps and so the maturity ogive analysis combined the stocks. Ideally, lengths- and ages-at-maturity are calculated at times of peak development stages (males: insemination season, females: parturition season; Westrheim 1975). Therefore, only females sampled from November to April were used in creating the maturity curve because these months contained the majority of spawning (mature) females. As well, the proportion of immature fish started to rise in May concurrently with a rise in the proportion of spent fish, likely signalling the completion of spawning.

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:

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

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–BC North and BC South	major=8:9, major=3:7	125,358 records
• gear – bottom trawl tows	gear=1	96,673 records
• ageing method (see note below)	ameth = c(0,3)	11,001 records
• sample type – total catch/random	stype = c(1,2,6,7)	10,972 records
• species category (unsorted)	scat = 1	10,881 records
• sex – females only	sex = 2	6,628 records
• maturity codes for rockfish	mats = c(1:7)	4,964 records
• ogive age limits	age = c(0,25)	4,480 records
• trip type – commercial	ttype = c(1,4)	2,011 records
• month	month = c(11:12, 1:4)	1,123 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.

The above qualification yielded 1,123 female specimens with maturity readings and valid ages. Mature specimens comprised those coded 3 to 7 for rockfish (Table D.9). The empirical proportion of mature females at each age was calculated (Table D.10). A double-normal function (Eq. D.3) was fit to the observed proportions mature at ages 5 to 25 to smooth the observations and determine an increasing monotonic function for use in the stock assessment model (Figure D.22). 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.22). Therefore, the maturity ogive used in the stock assessment model (last column in Table D.10) was 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 10. This strategy follows previous assessments on BC rockfish where younger ages are not well sampled. The sole function of this ogive 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 at 5.9 y and 9.6 y, respectively.

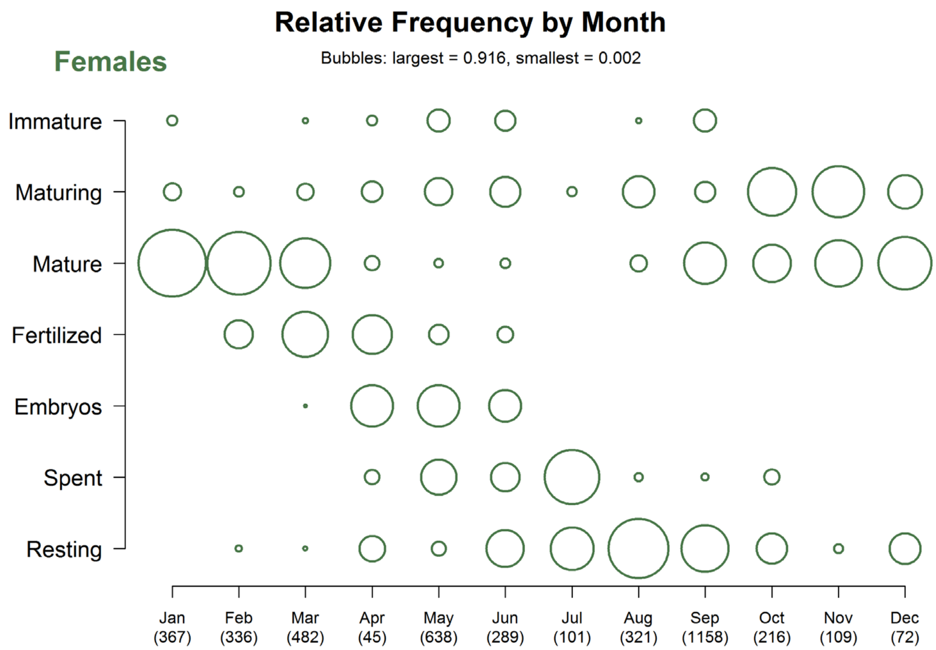


Figure D.20. BC North – Relative frequency of maturity codes by month for 5DE RSR females (data stored in DFO's `GFBioSQL` database). Data include maturities from commercial and research specimens. Frequencies are calculated among each maturity category for every month.

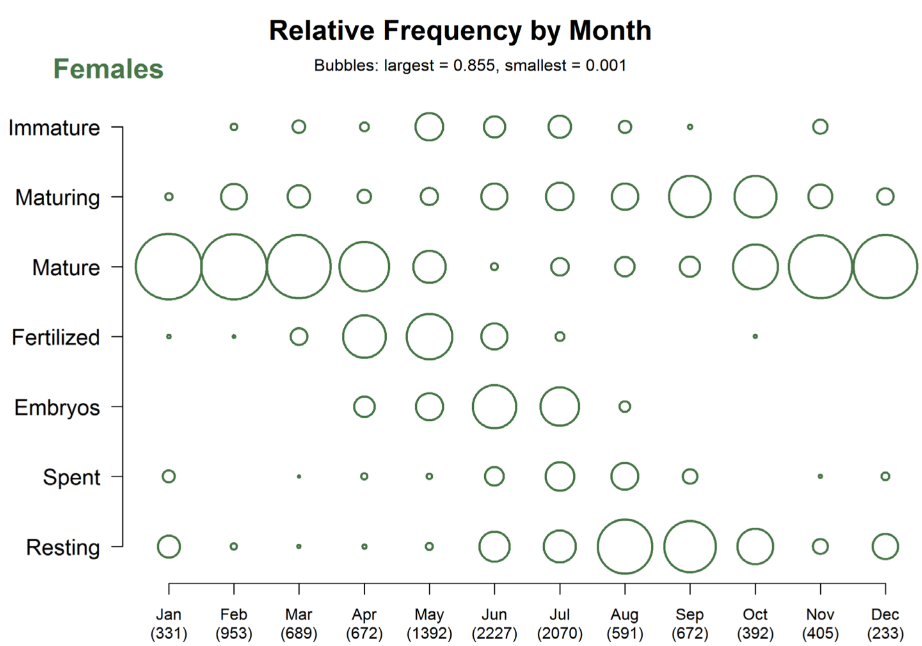


Figure D.21. BC South – Relative frequency of maturity codes by month for 5ABC3CD RSR females (data stored in DFO's `GFBioSQL` database). Data include maturities from commercial and research specimens. Frequencies are calculated among each maturity category for every month.

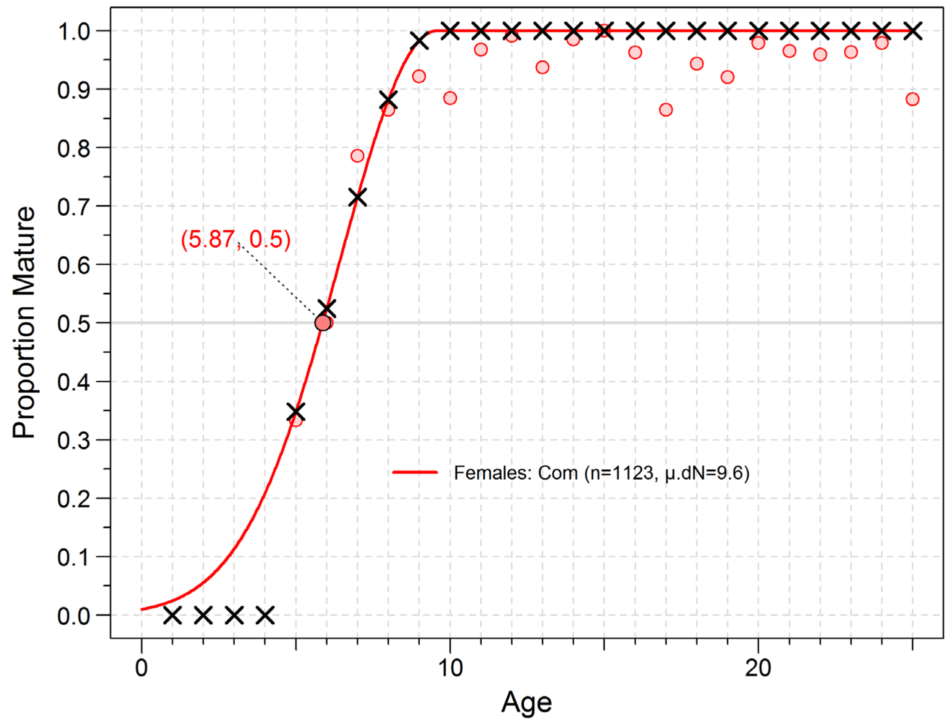


Figure D.22. Maturity ogives for BC Offshore RSR females (data stored in DFO's `GFBioSQL` database). Solid line shows the double-normal (dN) curve fit; circles denote input proportions-mature; crosses indicate values used in the model. Age at 50% maturity is indicated along the median line; age at full maturity (µ.dN) is displayed in the legend.

Table D.10. Proportion of 5ABC POP females mature by age 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.

Age	# Fish	Obs. m_a	Logit fit m_a	(D.3) fit m_a	Model m_a
1	0	0	0.88203	0.02466	0
2	0	0	0.88776	0.05559	0
3	0	0	0.89324	0.11332	0
4	0	0	0.89848	0.20889	0
5	3	0.33333	0.90349	0.34821	0.34821
6	4	0.5	0.90829	0.52490	0.52490
7	14	0.78571	0.91286	0.71552	0.71552
8	37	0.86486	0.91723	0.88203	0.88203
9	51	0.92157	0.92140	0.98323	0.98323
10	52	0.88462	0.92538	1	1
11	92	0.96739	0.92917	1	1
12	111	0.99099	0.93278	1	1
13	96	0.93750	0.93622	1	1
14	67	0.98507	0.93950	1	1
15	58	1	0.94261	1	1
16	54	0.96296	0.94558	1	1
17	59	0.86441	0.94840	1	1
18	71	0.94366	0.95108	1	1
19	63	0.92063	0.95363	1	1

Age	# Fish	Obs. m_a	Logit fit m_a	(D.3) fit m_a	Model m_a
20	48	0.97917	0.95606	1	1
21	57	0.96491	0.95836	1	1
22	49	0.95918	0.96055	1	1
23	55	0.96364	0.96262	1	1
24	48	0.97917	0.96459	1	1
25	34	0.88235	0.96646	1	1

D.2.5. Natural Mortality

A literature search found no information on natural mortality for this species.

In the DFO database `GFBioSQL`, the maximum age is 61 years for a male specimen (34.8 cm in length) caught at a depth of 181 m in PMFC area 5A, specifically in a fishing locality called "Cape Scott Spit" (major=5, minor=11, locality=2), on Sep 7, 2001. The mean age of RSR using the break-and-burn method is 15.6 y (*n*=12,496) and the 99% quantile is 37 y.

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

$$M_{\text{est}} = 4.899\, t_{\text{max}}^{-0.916} \tag{D.4}$$

where t_{max} = maximum age. For RSR with a maximum age of 61 y, the updated Hoenig estimator suggests that M = 0.113. This assessment estimates natural mortality (M_s) for each sex s, using a normal prior with μ=0.11 and σ=0.011.

During the review process for this stock assessment, one of the principal reviewers noted that Then et al. (2015) did not consistently apply a log transformation (see Proceedings Document for the meeting). 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 is:

$$M_{\text{est}} = 5.4 t_{\text{max}}^{-1} \tag{D.5}$$

Using this revision and t_{max} = 61 y, M = 0.089. However, the meeting participants noted that this maximum age observation came from a single, isolated individual and that a more appropriate maximum age for this distribution might be 50 y (Figure D.23), which would yield M = 0.108 using (D.5).

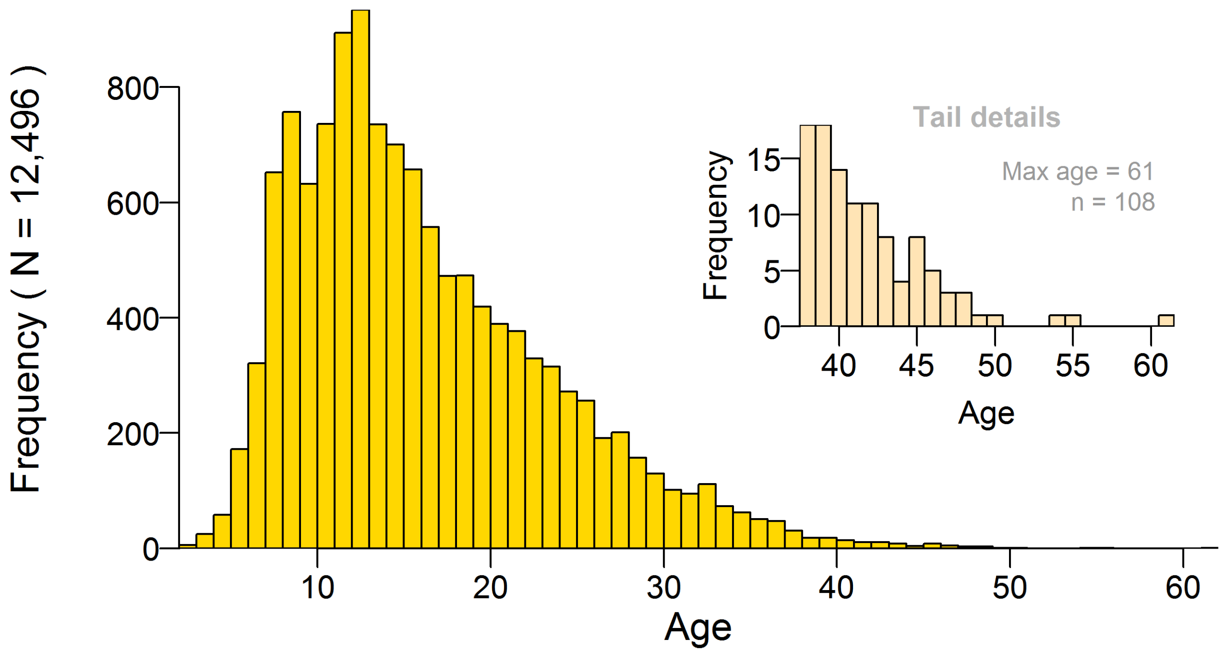


Figure D.23. Distribution of female + male ages; inset shows details for ages >37 y old, which is the 0.99 quantile of the complete age data set.

D.3. WEIGHTED AGE PROPORTIONS

This section summarizes a method for representing commercial and survey age structures for a given species (herein called 'target') through weighting observed age frequencies x_a or proportions x'_a by catch‖density in defined strata. (Throughout this section, we use the symbol '‖' 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, commercial ages are weighted by the catch weight (tonnes) of the target in tows that were sampled, and survey ages are weighted by the catch density (t/km^2) of the target in sampled tows.
- Quarterly commercial ages are weighted by the commercial catch weight of the target from all tows within each quarter; stratum survey ages are weighted by stratum areas (km^2) in the survey.

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 presented below attempts to adjust for unequal sampling effort among strata.

For simplicity, we illustrate the weighting of age frequencies x_a, 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.11.

Table D.11. 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 IDs as sample units
	(s) sample IDs as sample units
h	(c) calendar year quarter (1 to 4), 91.5 days each
	(s) stratum (area-depth combination)
i	(c) calendar year (1977 to present)
	(s) survey ID in survey series (e.g., 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 we weight sample unit frequencies x_{ad} by sample unit catch‖density of the assessment species. (For commercial ages, we use trip 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:

$$C'_{dhi} = \frac{C_{dhi}}{\sum_d C_{dhi}} \tag{D.6}$$

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:

$$y_{ahi} = \sum_d \left(C'_{dhi} x_{adhi} \right) \tag{D.7}$$

This transformation reduces the frequencies x from the originals, and so we rescale (multiply) y_{ahi} by the factor

$$\frac{\sum_a x_{ahi}}{\sum_a y_{ahi}} \tag{D.8}$$

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

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

$$K'_{hi} = \frac{K_{hi}}{\sum_h K_{hi}} \tag{D.9}$$

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

$$p_{ai} = \sum_h \left(K'_{hi} y_{ahi} \right) \tag{D.10}$$

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

$$\frac{\sum_a y_{ai}}{\sum_a p_{ai}} \tag{D.11}$$

to retain the original number of observations.

Finally, we standardise the weighted frequencies to represent proportions-at-age:

$$p'_{ai} = \frac{p_{ai}}{\sum_a p_{ai}} \tag{D.12}$$

If initially we had used proportions x'_{adhi} instead of frequencies x_{adhi}, the final standardisation 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, we weight age frequencies x.

D.3.1. Commercial Ages

Sampled age frequencies from midwater and bottom 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.24, males: Figure D.25), leading to the conclusion that a model would estimate similar selectivities for each capture method. Furthermore, there were insufficient AF data to reliably separate the two gear types into independent fisheries (Table D.12). 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 commercial age data for BC North (Figure D.26) and BC South (Figure D.27) RSR are barely sufficient but informative, especially in in the South with its clear cohort patterns. There is a strong 2000 year class (8 y-old fish in 2008) that dominates the female pattern in the South, with a hint of another strong year class in 2007. However, the number of specimens aged in the latest years is low, which can lead to spurious results. Note that all bubble plots for proportions-at-age are scaled to the largest proportion across sex and year, not within each year. The number of trips sampled per year (Table D.13) in BC North is unusually small and would not typically satisfy our criterion for using commercial age data (≥5 trips per year); however, this restriction was relaxed to exclude only years with one sample (2000, 2004, and 2014). In BC South, the restriction was relaxed to allow ≥3 trips per year, which meant that no years were excluded (Table D.14).

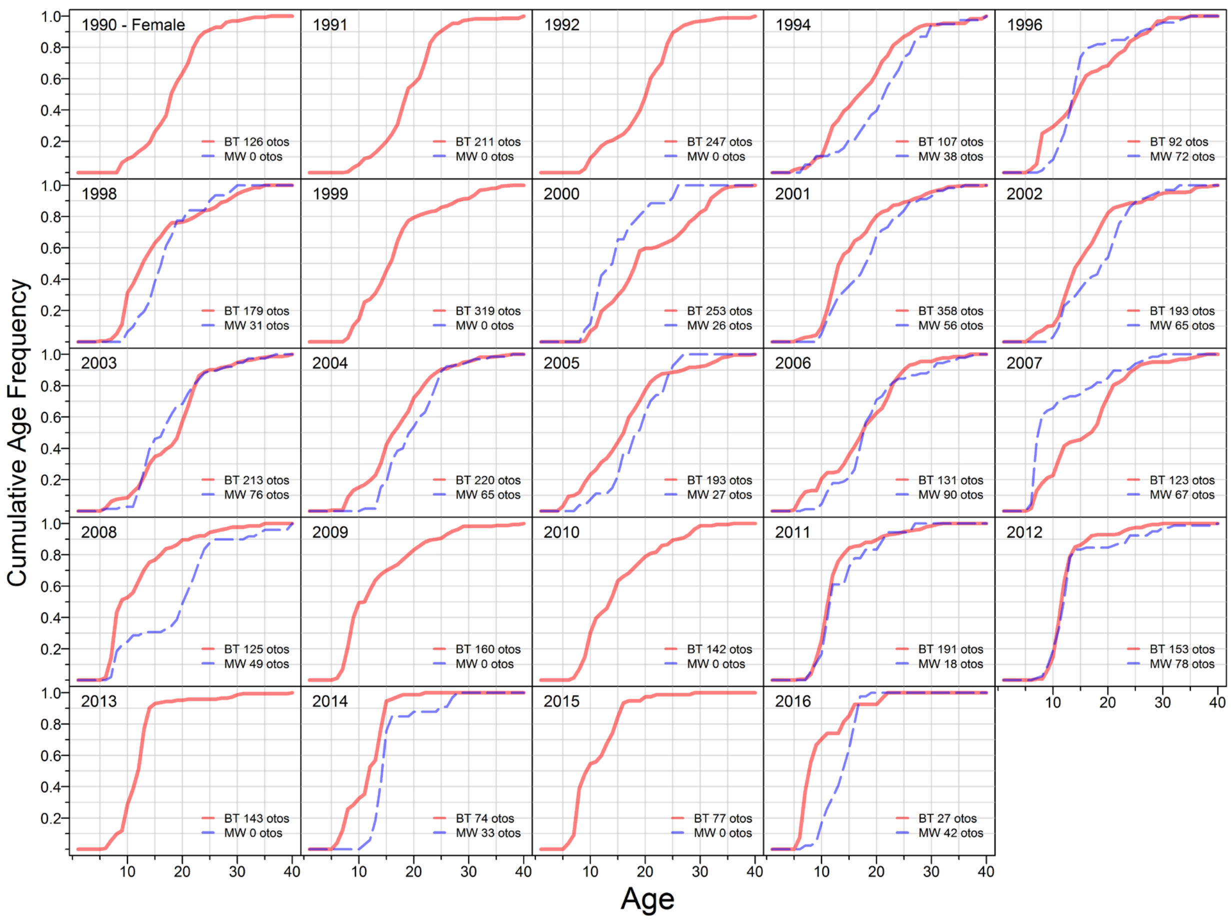


Figure D.24. Plots comparing the cumulative bottom trawl and midwater trawl age frequencies by year for female RSR (combined BCS and BCN).

Specimens used to calculate weighted proportions-at-age p'_{ai} are typically selected without regard to the SPECIES_CATEGORY code (`‘scat’` for brevity). In delay-difference models, `scat` is limited to codes that yield unsorted samples (e.g., `c(1,5:7)`, Table D.15) when calculating mean weights (Starr & Haigh 2017, also see Section D.1 herein). The issue was examined for RSR composition data (Figure D.28 to Figure D.33); however, limiting the samples to unsorted or keepers reduces the span of years for which data are available. Unsorted samples tend to occur late in the series while keepers (or sorted samples) occur early and then disappear (e.g., Figure D.31). The number of otoliths available for deriving annual proportions-at-age is already limited without subsetting on `scat`. The base model therefore uses the proportions-at-age regardless of `scat`, and offers a sensitivity run using p'_{ai} from unsorted samples.

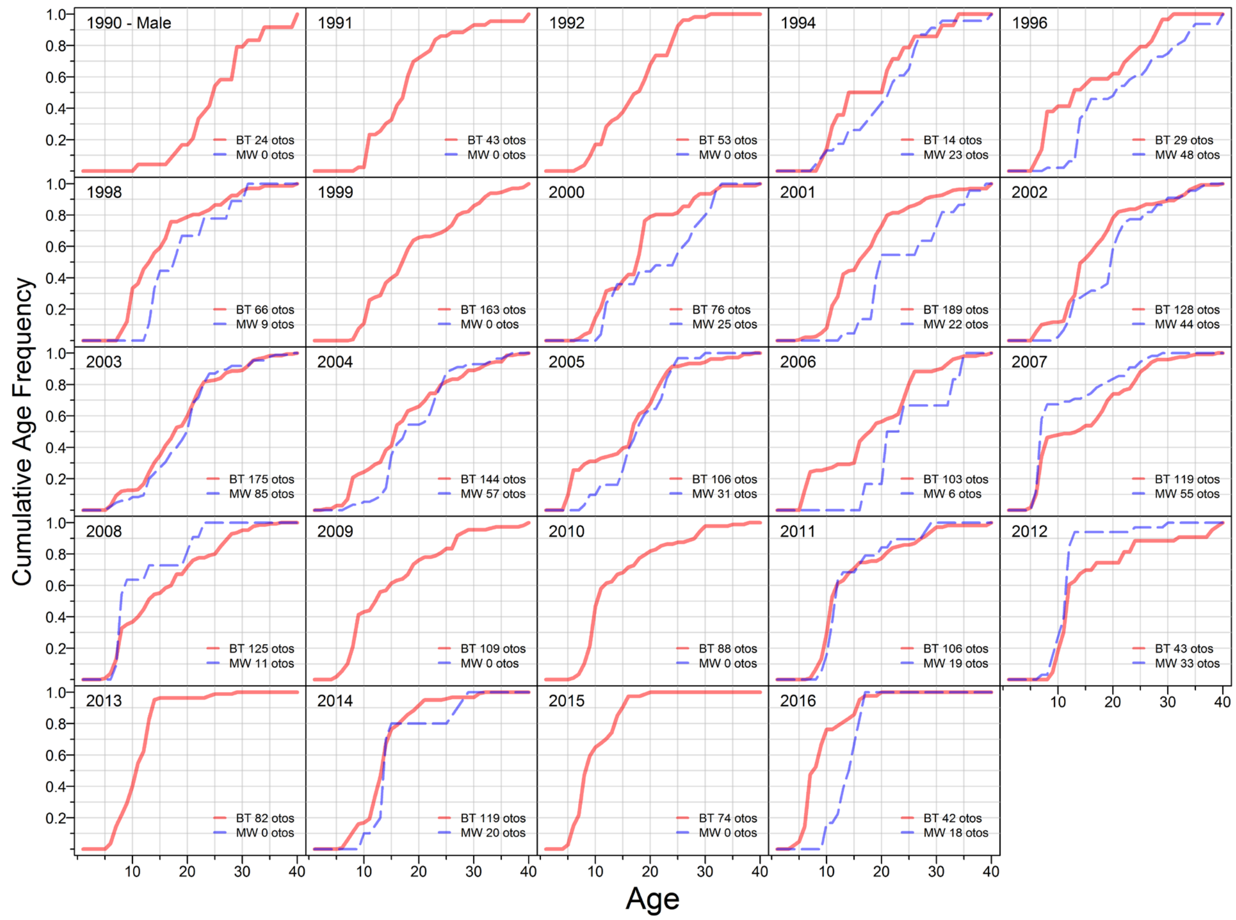


Figure D.25. Plots comparing the cumulative bottom trawl and midwater trawl age frequencies by year for male RSR (combined BCS and BCN).

Table D.12. Number of samples from commercial trips by stock and gear type.

Year	BC North Bottom Trawl	BC North Midwater trawl	BC South Bottom trawl	BC South Midwater trawl
1990	0	0	3	0
1991	0	0	5	0
1992	0	0	10	0
1994	0	0	2	1
1996	0	0	3	2
1998	2	0	4	1
1999	2	0	8	0
2000	1	0	5	1
2001	1	1	8	1
2002	1	1	4	1
2003	3	0	3	3
2004	0	1	6	2
2005	2	0	10	2
2006	3	0	7	2
2007	2	0	4	2
2008	5	0	5	1
2009	3	0	6	0
2010	2	0	6	0
2011	4	0	7	2
2012	0	0	7	2
2013	0	0	6	0
2014	1	0	3	1
2015	0	0	5	0
2016	0	0	3	2

Table D.13. BC North – Commercial trips (trawl): number of sampled trips and 5DE RSR catch (t) by sampled trip and all trips per quarter.

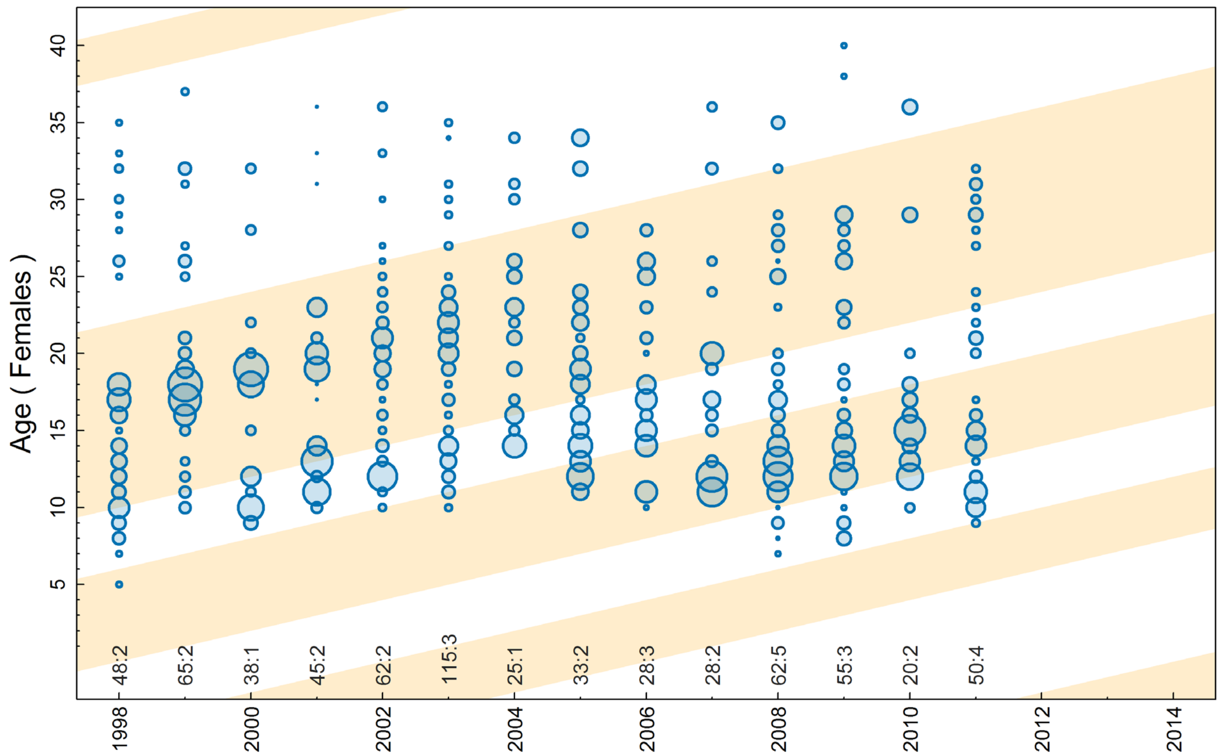
Year	**# Trips**				**Sampled trip catch (t)**				**All trip catch (t)**			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1998	1	0	0	1	15.9	0	0	3.7	89.8	15	39.8	25.6
1999	1	0	0	1	0	0	0	1.2	89.7	14.7	30.8	59.4
2000	0	1	0	0	0	8.6	0	0	165.6	20.6	20.6	41.7
2001	1	0	1	0	2.8	0	1.6	0	141.2	27.8	5.9	46.6
2002	1	0	1	0	6.2	0	6.9	0	121.4	32.7	45.7	16.9
2003	0	1	1	1	0	15.9	4.5	3	113.8	66.1	28.7	17.4
2004	1	0	0	0	16.4	0	0	0	128	52.6	34.8	8.6
2005	2	0	0	0	11.6	0	0	0	89.9	21.1	7.8	13.3
2006	3	0	0	0	23	0	0	0	80	40.6	0.5	2.5
2007	1	1	0	0	9.1	0.6	0	0	69.9	43.8	26.5	5.6
2008	3	0	1	1	18.5	0	0.7	1.8	63.8	22	36.8	9.3
2009	1	1	0	1	4.5	1.3	0	0	45.8	30.8	18.9	8.9
2010	1	1	0	0	3.2	2.3	0	0	38.6	15.1	5.3	15.8
2011	2	1	1	0	14.4	0.3	9.1	0	38.7	35.5	41.6	2.2
2014	0	0	1	0	0	0	0.2	0	23.8	63.5	62	9.4

Table D.14. BC South – Commercial trips (trawl): number of sampled trips and 5ABC3CD RSR catch (t) by sampled trip and all trips per quarter.

Year	# Trips				Sampled trip catch (t)				All trip catch (t)			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1990	1	1	0	1	5	2.2	0	7.7	285	1078	286	128
1991	4	1	0	0	34	54.5	0	0	466	469	335	137
1992	6	4	0	0	127.6	76.5	0	0	984	1027	388	346
1994	0	2	0	1	0	8.9	0	13.2	167	566	160	307
1996	2	1	1	1	25.6	11.4	10.4	14.8	356	227	144	252
1998	3	1	0	1	9.8	0.3	0	6.8	502	241	284	168
1999	3	3	1	1	1.6	6.9	0.5	2.7	359	259	178	181
2000	2	3	1	0	11.1	6.5	2.1	0	492	327	175	117
2001	2	2	3	2	14.4	1.4	6.9	11.9	376	273	204	95
2002	0	1	1	3	0	2	0.6	16.8	320	159	211	205
2003	1	0	3	2	0.7	0	5.9	5.4	245	287	252	129
2004	3	4	0	1	3.2	51.3	0	2.9	220	271	92	87
2005	4	5	2	1	7.3	13.2	0.3	0	342	344	93	60
2006	2	5	2	0	14.9	22.9	4.1	0	242	241	86	37
2007	3	1	1	1	72.2	0.3	1.4	0.2	344	275	89	58
2008	3	2	1	0	1.8	4.7	0.1	0	336	158	111	107
2009	3	2	1	0	8	2.9	0.7	0	391	195	69	26
2010	3	2	1	0	0.4	4.1	2.3	0	172	185	99	68
2011	4	5	0	1	13.4	16.6	0	15.3	252	321	188	198
2012	3	4	1	1	6	23.1	5.4	2.4	310	276	123	119
2013	3	1	1	1	3.9	0.1	0.9	2.7	175	166	244	87
2014	2	1	0	1	0.6	0.1	0	0.4	182	180	120	119
2015	5	1	1	0	4.2	0	0.9	0	303	224	172	87
2016	0	6	1	0	0	3.2	1.9	0	314	176	145	114

Table D.15. Species category code table from `GFBioSQL` (accessed 2018-03-07) amended with number of RSR otoliths available from the commercial fishery before qualification.

SPECIES_CATEGORY_CODE	SPECIES_CATEGORY_DESC	# otoliths comm. fishery
0	UNKNOWN	-
1	UNSORTED	4290
2	SORTED (UNK. CRITERION)	-
3	KEEPERS	3432
4	DISCARDED	91
5	REMAINS	-
6	LONGLINE - FISH HEAD ONLY	-
7	LONGLINE - WHOLE FISH AND FISH HEAD ONLY	-
8	LONGLINE/JIG - FISH LOST AT RAIL/LOST AT SURFACE	-



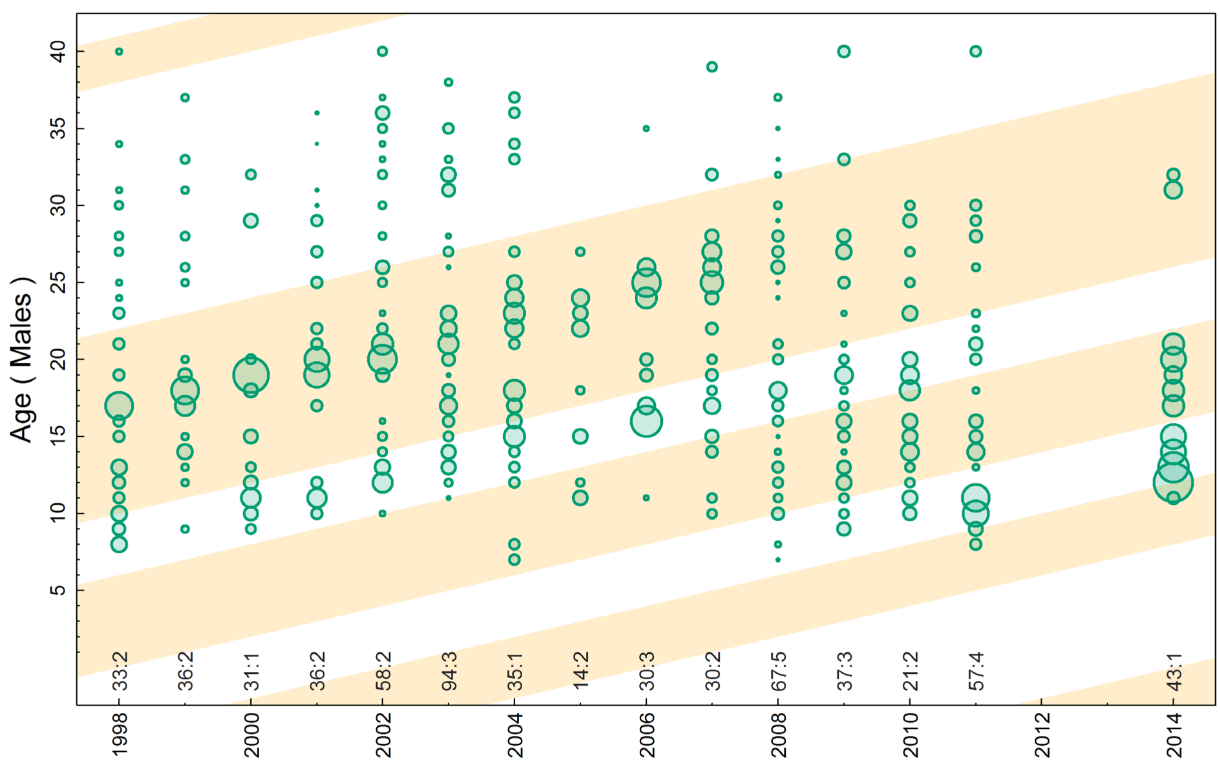


Figure D.26. BC North – Proportions-at-age for 5DE RSR caught by commercial trawl gear calculated as age frequencies weighted by trip catch within quarters and commercial catch within years. Diagonal shaded bands indicate cohorts that were born when the mean Pacific Decadal Oscillation was positive. Numbers displayed along the bottom axis indicate number of fish aged and number of samples (colon delimited) by year.

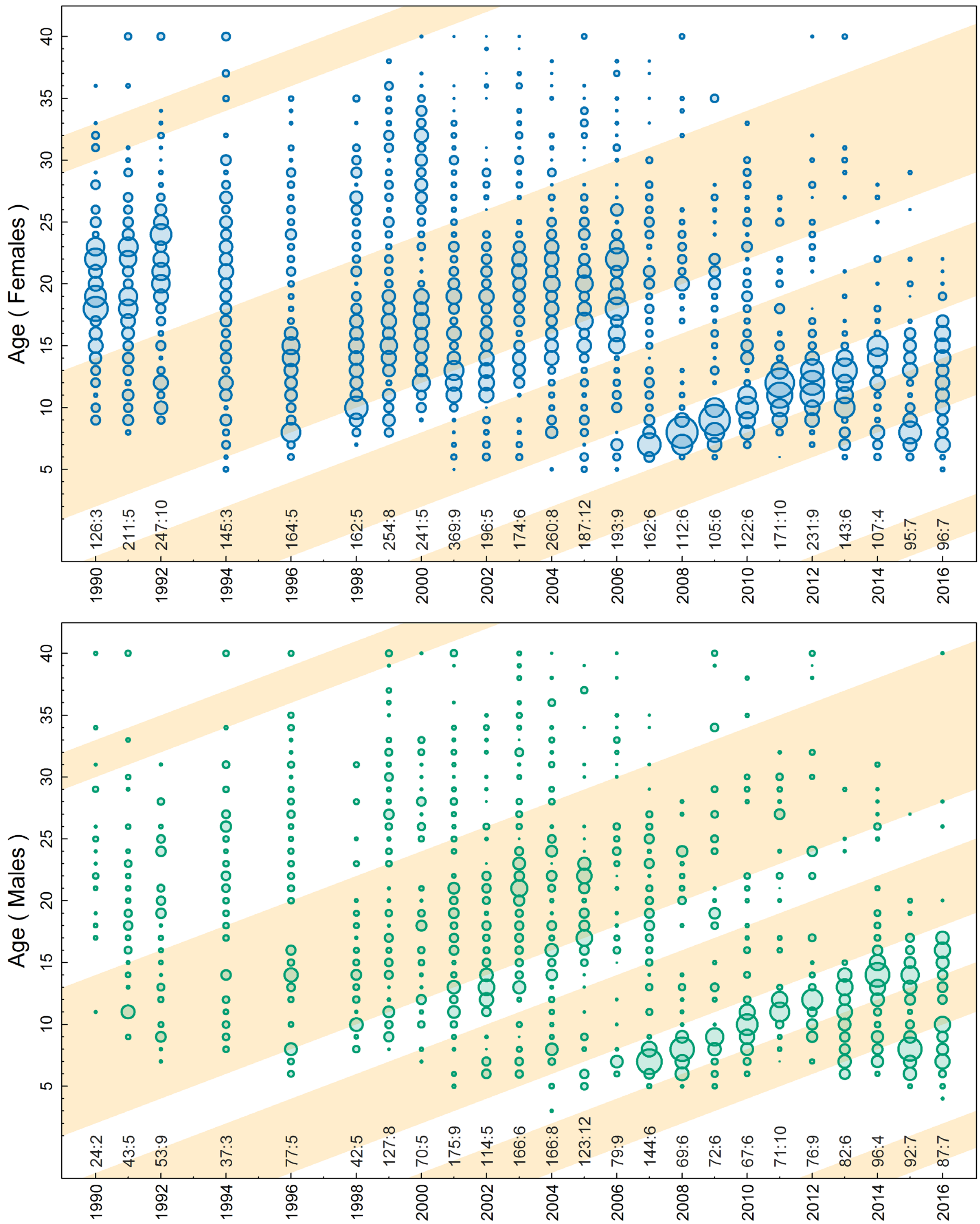


Figure D.27. BC South – Proportions-at-age for 5ABC3CD RSR caught by commercial trawl gear calculated as age frequencies weighted by trip catch within quarters and commercial catch within years. Diagonal shaded bands indicate cohorts that were born when the mean Pacific Decadal Oscillation was positive. Numbers displayed along the bottom axis indicate number of fish aged and number of samples (colon delimited) by year.

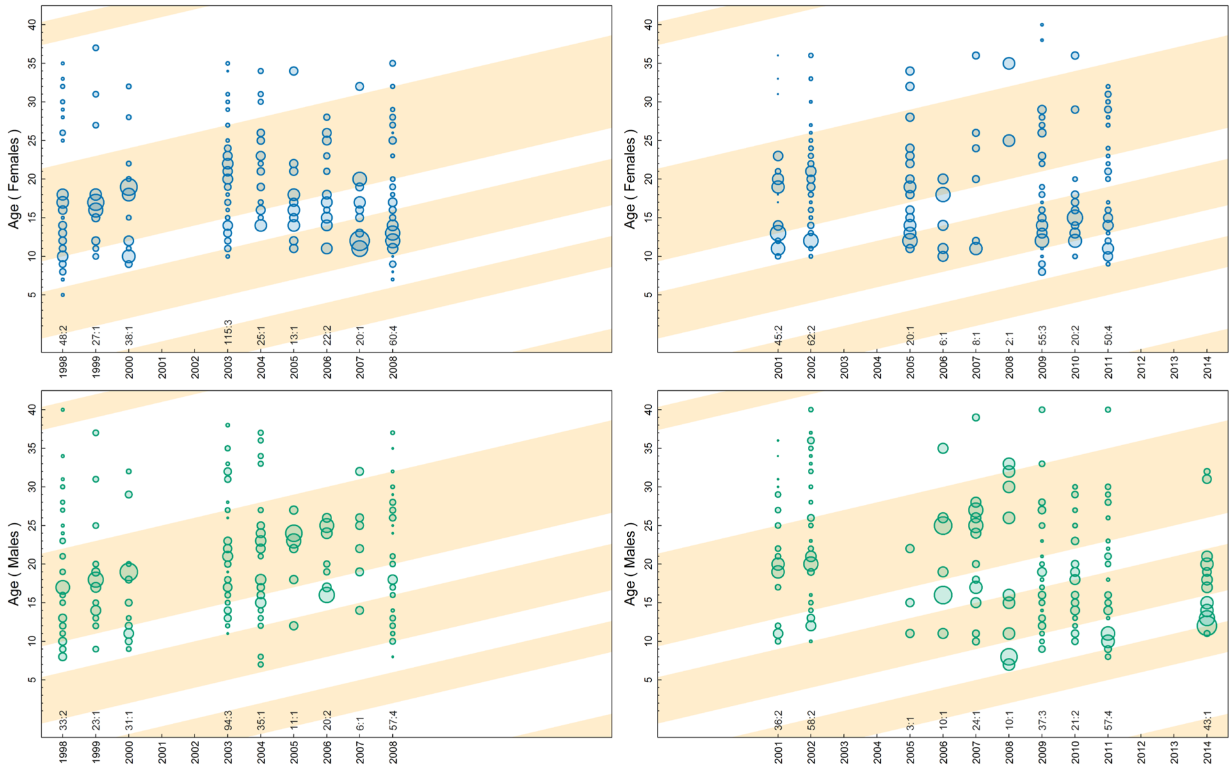


Figure D.28. BC North – Proportions-at-age for 5DE RSR caught by commercial trawl gear showing proportions-at-age from sorted samples or keepers (left) vs. unsorted samples (right). See Figure D.26 caption for further details.

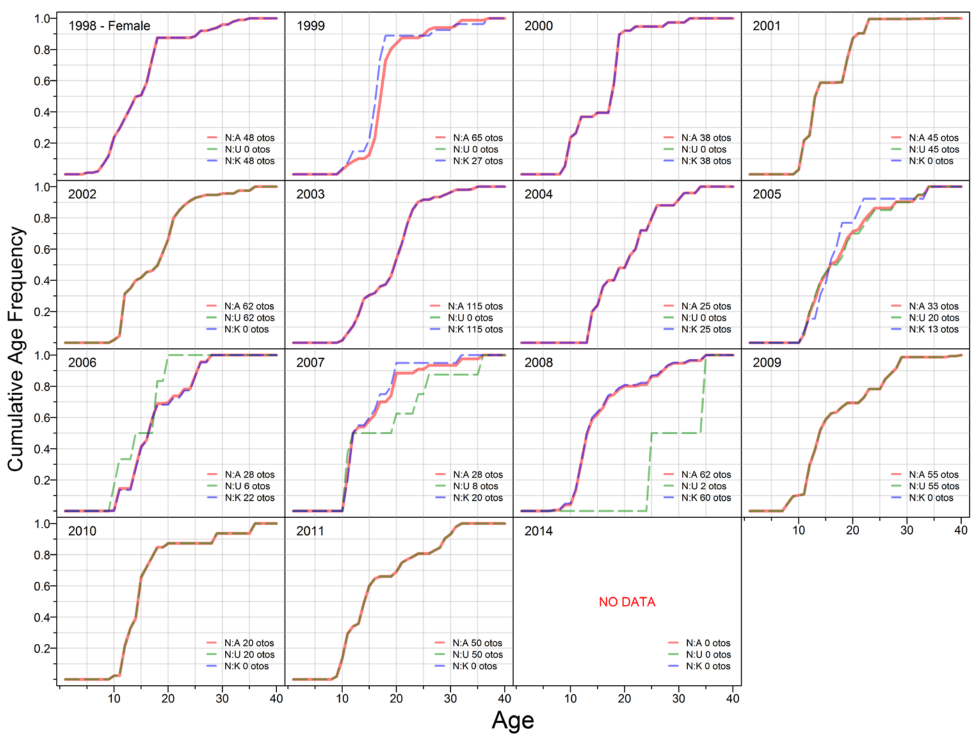


*Figure D.29. BC North – Cumulative commercial proportions-at-age for **female** RSR comparing results using all samples (N:A), unsorted (N:U), and keepers (N:K).*

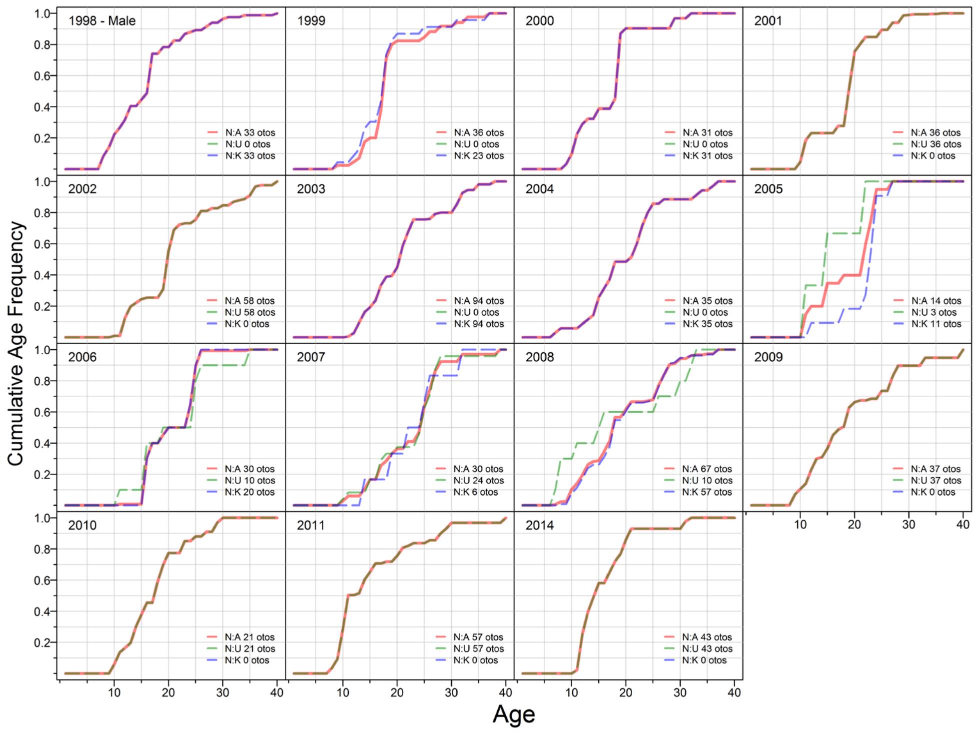


*Figure D.30. BC North – Cumulative commercial proportions-at-age for **male** RSR comparing results using all samples (N:A), unsorted (N:U), and keepers (N:K).*

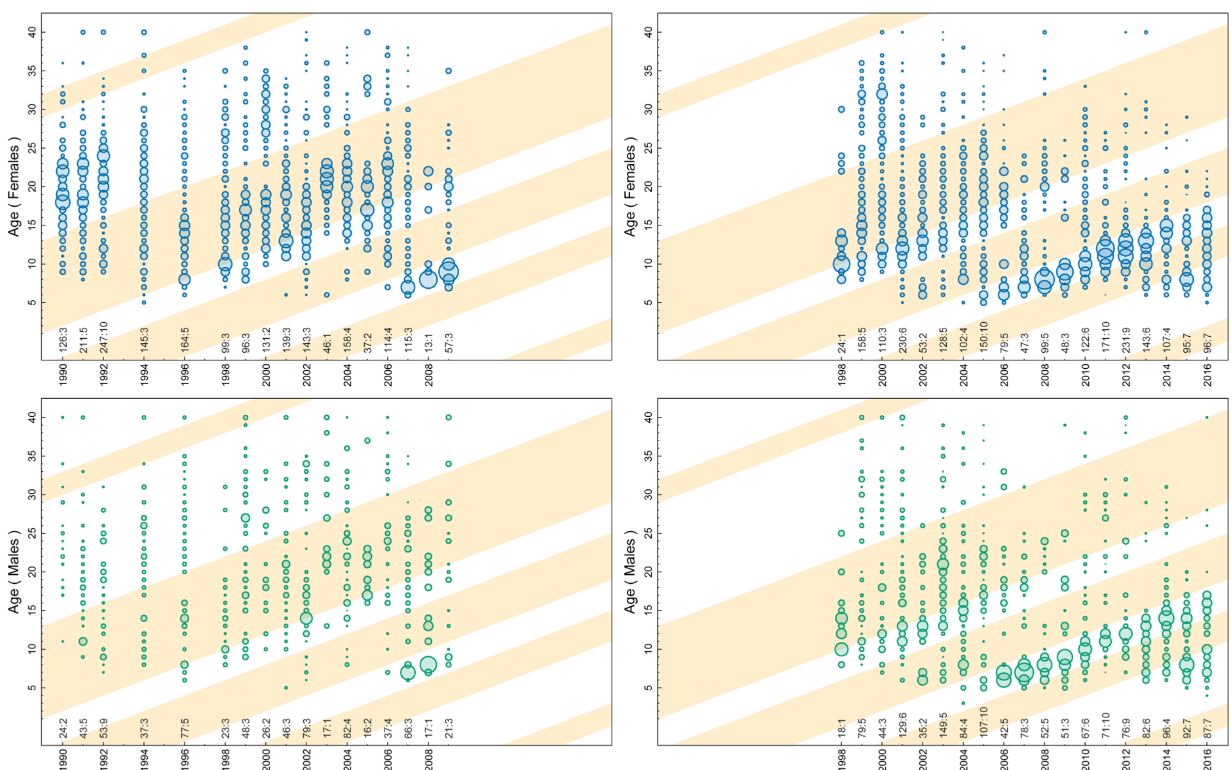


Figure D.31. BC South – Proportions-at-age for 5ABC3CD RSR caught by commercial trawl gear showing proportions-at-age from sorted samples or keepers (left) vs. unsorted samples (right). See Figure D.27 caption for further details.

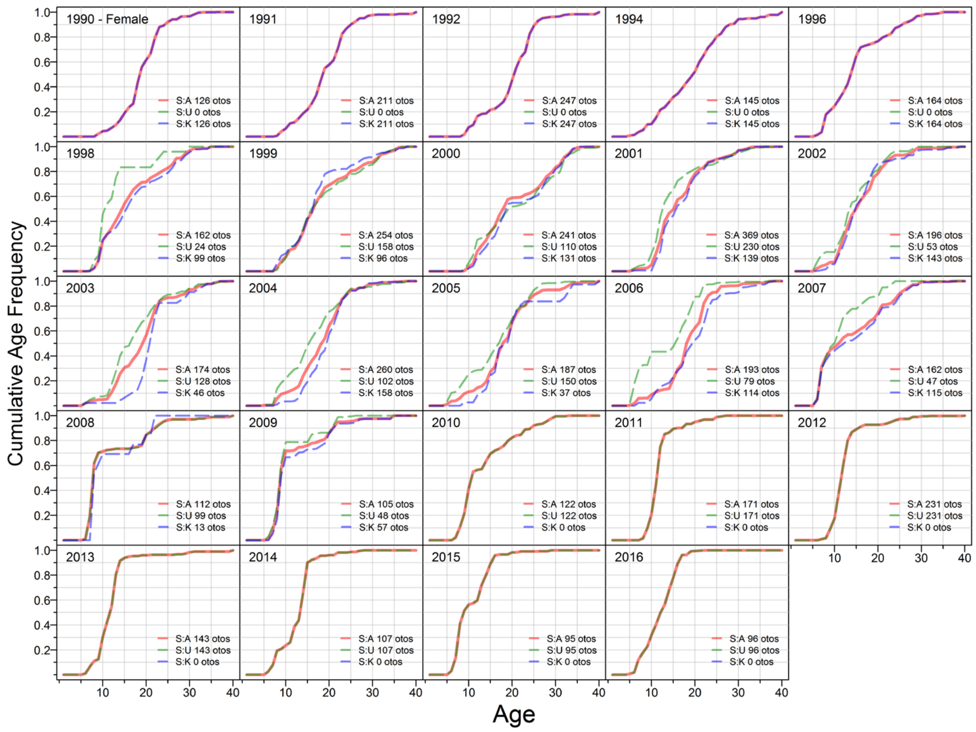


*Figure D.32. BC South – Cumulative commercial proportions-at-age for **female** RSR comparing results using all samples (N:A), unsorted (N:U), and keepers (N:K).*

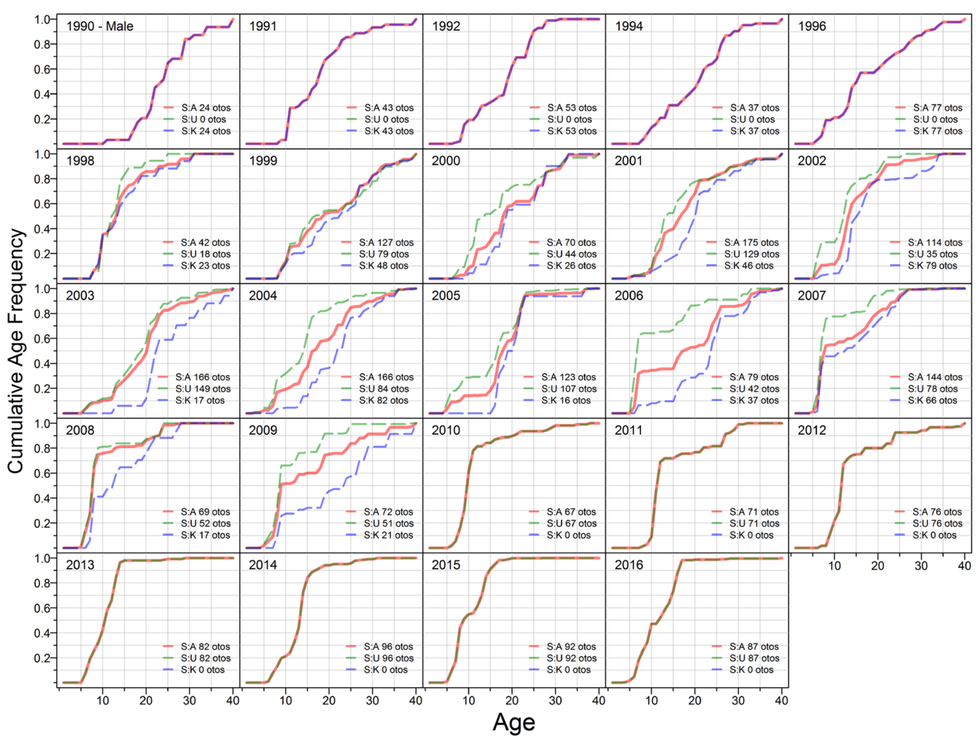


*Figure D.33. BC South – Cumulative commercial proportions-at-age for **male** RSR comparing results using all samples (N:A), unsorted (N:U), and keepers (N:K).*

D.3.2. Research/Survey Ages

In BC North, two survey series (SS) were used: Hecate Strait (HS) Synoptic (SSID 3) and West Coast Haida Gwaii (WCHG) Synoptic (SSID 16). Both surveys had ages although HS Synoptic had data for only one year (Table D.16, Table D.17). In the WCHG series, there is some evidence for the 2000 year cohort identified in the commercial data (Figure D.34).

In BC South, four survey series were used in the catch-age model, three of which had age data: Goose Island Gully (GIG) Rockfish (SSID 21), Queen Charlotte Sound (QCS) Synoptic (SSID 1), and West Coast Vancouver Island (WCVI) Synoptic (SSID 4). Only one of the years (1994) from the GIG Rockfish series was used in the model (Table D.18). The QCS Synoptic series (Table D.19) highlights clearly the dominant 2000 year class noticed in other series, as well as the remnants of a cohort from the early 1980s (Figure D.35). The WCVI series (Table D.20) also shows the strong 2000 cohort, along with a later 2007 year class; older ages are not well represented by this series (Figure D.36).

Table D.16. HS Synoptic survey: number of sampled tows (s) and RSR density (d) per stratum h (t/km^2). Stratum areas as of Jan 31, 2018 appear in parentheses.

Year↓	# samples, mean density (t/km²)
h→	73 (3052 km²)
2009	s=1, d=0.2

Table D.17. WCHG Synoptic survey: number of sampled tows (s) and RSR density (d) per stratum h (t/km^2). Stratum areas as of Jan 31, 2018 appear in parentheses.

Year↓	# samples, mean density (t/km²)	
h→	151 (1104 km²)	152 (1024 km²)
2008	s=5, d=17.9	s=0
2010	s=6, d=17.3	s=0
2012	s=6, d=40.4	s=0
2016	s=8, d=30.1	s=3, d=8.9

Table D.18. GIG Rockfish survey: number of sampled tows (s) and RSR density (d) per stratum h (t/km^2). Stratum areas as of Jan 31, 2018 appear in parentheses. Only 1994 age data used in catch-age model.

Year↓	# samples, mean density (t/km²)		
h→	185 (2122 km²)	185 (2122 km²)	187 (1746 km²)
1979	s=0	s=1, d=2.4	s=0
1994	s=4, d=23.5	s=1, d=0.1	s=1, d=0.3

Table D.19. QCS Synoptic survey: number of sampled tows (s) and RSR density (d) per stratum h (t/km^2). Stratum areas as of Jan 31, 2018 appear in parentheses.

Year↓	# samples, mean density (t/km²)					
h→	18 (5028 km²)	19 (5344 km²)	20 (2668 km²)	22 (1760 km²)	23 (3960 km²)	24 (3708 km²)
2003	s=2, d=1.2	s=1, d=14.4	s=1, d=0.7	s=0	s=2, d=3.5	s=0
2004	s=1, d=0.1	s=2, d=2.0	s=0	s=0	s=1, d=4.4	s=0
2005	s=1, d=0.9	s=2, d=2.5	s=0	s=0	s=2, d=2.7	s=0
2007	s=0	s=5, d=27.8	s=0	s=0	s=0	s=0
2009	s=1, d=0.2	s=8, d=12.0	s=1, d=0.8	s=1, d=18.3	s=0	s=2, d=3.8
2011	s=2, d=2.5	s=3, d=21.8	s=0	s=0	s=2, d=2.2	s=0
2013	s=1, d=1.5	s=1, d=1.1	s=0	s=0	s=5, d=20.0	s=1, d=1.0
2015	s=0	s=3, d=4.9	s=0	s=0	s=2, d=5.3	s=0

Table D.20. WCVI Synoptic survey: number of sampled tows (s) and RSR density (d) per stratum h (t/km²). Stratum areas as of Jan 31, 2018 appear in parentheses.

Year↓	# samples, mean density (t/km²)		
h→	65 (5796 km²)	66 (3792 km²)	67 (704 km²)
2008	s=0	s=3, d=9	s=1, d=1.4
2010	s=1, d=2.1	s=9, d=24	s=2, d=7
2012	s=0	s=5, d=79.9	s=2, d=8.8
2014	s=1, d=4.8	s=2, d=4.5	s=2, d=29.3
2016	s=3, d=27.2	s=4, d=19.3	s=4, d=12.3

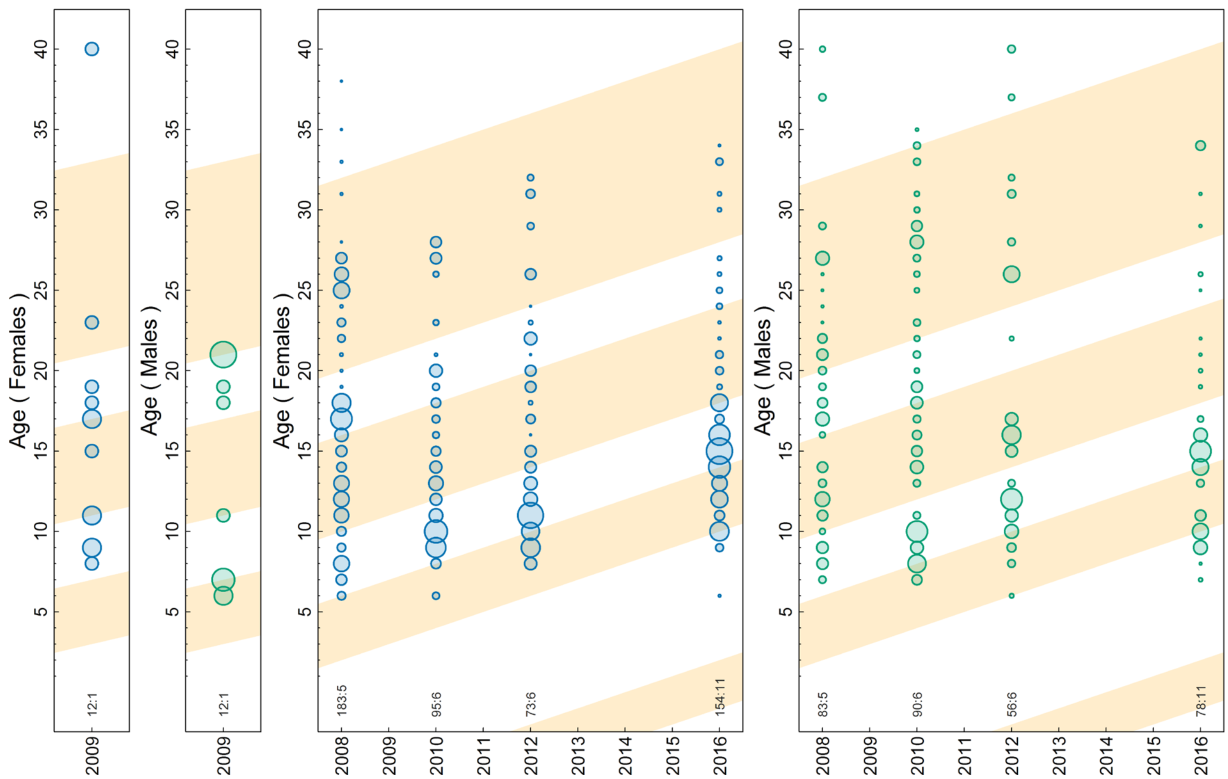


Figure D.34. HS Synoptic (left) and WCHG Synoptic (right) surveys: 5DE RSR proportions-at-age based on age frequencies weighted by mean fish density within strata and by total stratum area within survey. Only 1994 age data used in catch-age model. See Figure D.26 for details on diagonal shaded bands and displayed numbers.

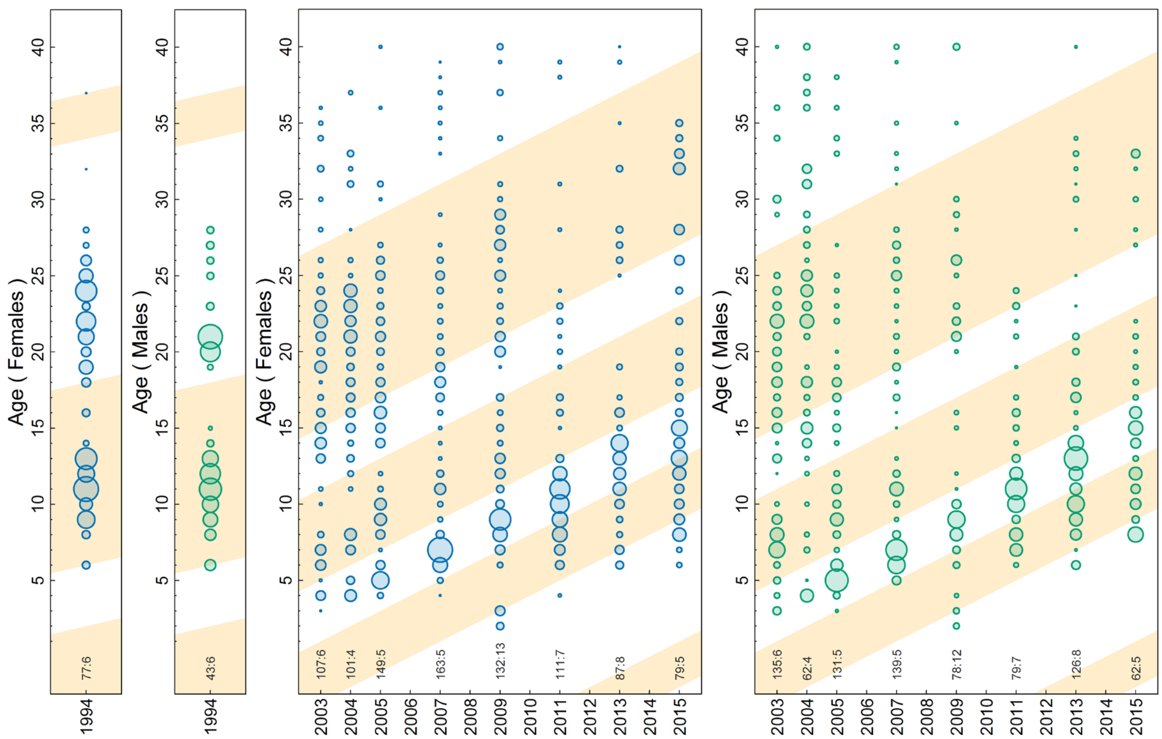


Figure D.35. Goose Island Gully Rockfish survey (left) and QCS Synoptic survey (right) – 5ABC RSR proportions-at-age based on age frequencies weighted by mean fish density within strata and by total stratum area within survey. See Figure D.26 for details on displayed numbers.

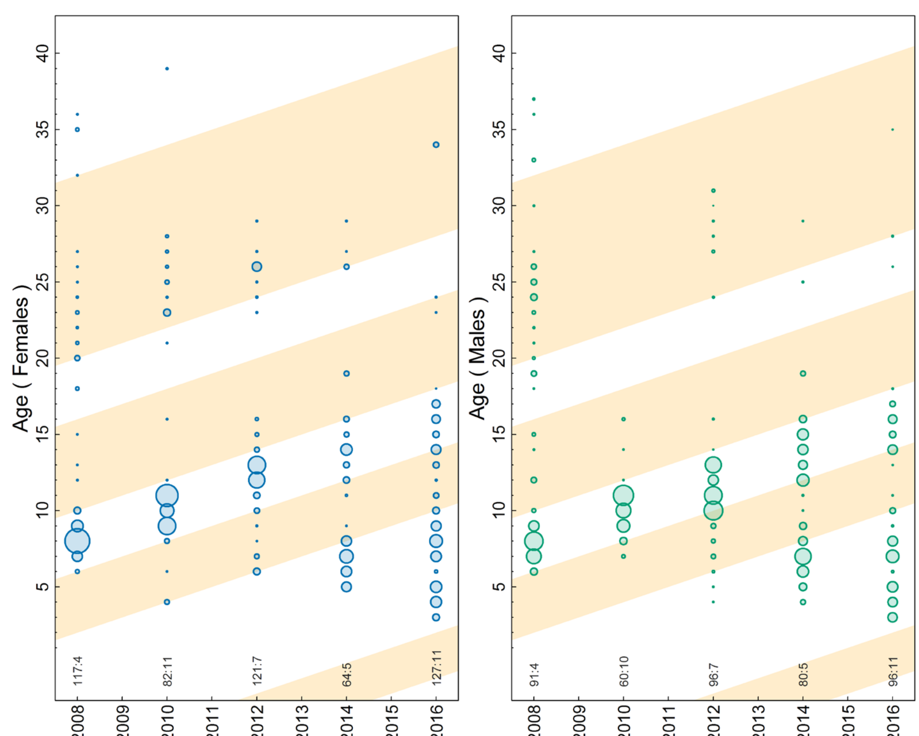


Figure D.36. WCVI Synoptic survey – 3CD RSR proportions-at-age based on age frequencies weighted by mean fish density within strata and by total stratum area within survey. See Figure D.26 for details on displayed numbers.

D.3.3. Ageing Error

Ageing error routinely arises as an issue in stock assessments. The population model for RSR does not specify an ageing error matrix; however, Figure D.37 suggests that RSR ages are well-specified by the primary readers and can be reproduced consistently by secondary readers when performing spot-check analyses.

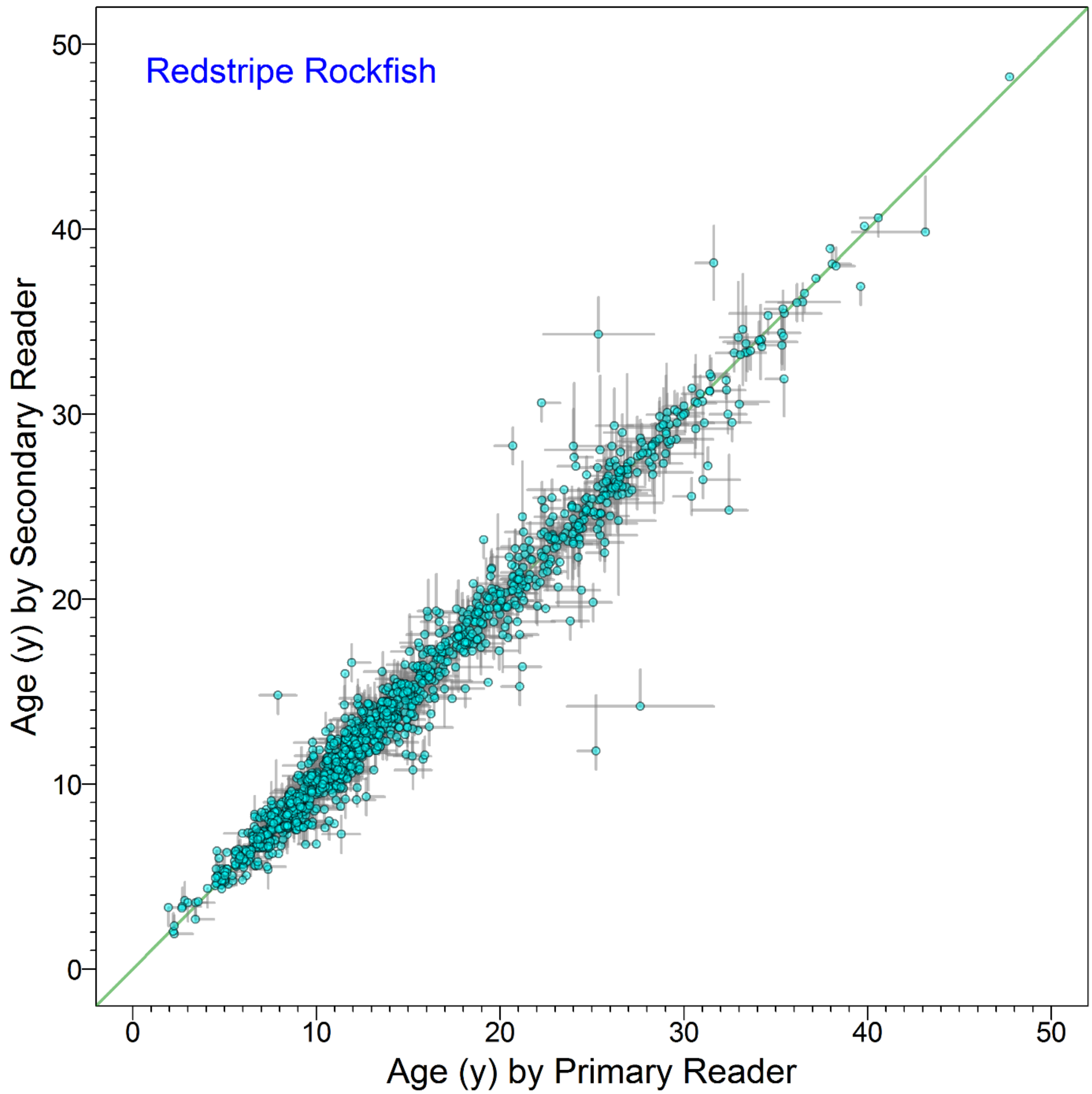


Figure D.37. Ageing error of RSR specified as the range between minimum and maximum age (grey bars) determined by primary and secondary readers for each accepted age (points). The data are jittered using a random uniform distribution between -0.5 and 0.5 y.

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APPENDIX E. MODEL EQUATIONS

E.1 INTRODUCTION

We used a sex-specific, age-structured model in a Bayesian framework. In particular, the model can simultaneously estimate the steepness of the stock-recruitment function and separate mortalities for males and females. This approach follows that used in recent stock assessments of Pacific Ocean Perch (POP) in Queen Charlotte Sound (Haigh et al. 2018; Edwards et al. 2012*b*) Silvergray Rockfish (Starr et al. 2016), POP off west coast Vancouver Island (Edwards et al. 2014*b*), POP off west coast Haida Gwaii (Edwards et al. 2014*a*), and Yellowmouth Rockfish along the Pacific coast of Canada (Edwards et al. 2012*a*).

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) desribed below.

Model implementation used a modified version of the Coleraine statistical catch-at-age software (Hilborn et al. 2003) called Awatea (Allan Hicks, NOAA, pers. comm.). 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 was streamlined using custom code written in R (Haigh and Edwards 2016), 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 `scapeMCMC` (Magnusson and Stewart 2007) (now called `plotMCMC`). 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 Redstripe Rockfish (N|S) was treated as 2 stocks in areas 5DE and 3CD5ABC.
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 sexes and surveys and invariant over time. Selectivity parameters were estimated when ageing data were available.
5. Natural mortality was estimated independently 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.
8. Recruitment at age 1 was 50% females and 50% males.
9. Fish ages determined using the surface ageing methods (before 1978) were too biased to use (Beamish 1979). 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$3 samples in that year (threshold reduced to 2 samples for 5DE).
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 $f(\mathbf{\Theta})$ 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 $A = 40$ is the accumulator age class
t	model year, where $t = 1, 2, 3, ...T$, corresponds to actual years: 1940, ..., 2018, and $t = 0$ represents unfished equilibrium conditions
g	index for series (abundance|composition) data: North: 1 – HS synoptic trawl survey series 2 – WCHG synoptic trawl survey series 3 – commercial CPUE (bottom trawl) South:

Symbol	Description and units
	1 – GIG historic trawl survey series 2 – WCVI synoptic trawl survey series 3 – QCS synoptic trawl survey series 4 – WCVI triennial trawl survey series 5 – commercial CPUE (bottom trawl)
s	sex, $1 =$ females, $2 =$ males
	Index ranges
A	accumulator age-class, $A = 40$
T	number of model years, $T = 79$
$\mathbf{T}_g$	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): North: $\mathbf{T}_1$ = {2005, 2007, 2009, 2011, 2013, 2015, 2017} $\mathbf{T}_2$ = {2006:2008, 2010, 2012, 2016} $\mathbf{T}_3$ = {1996, ..., 2017} South: $\mathbf{T}_1$ = {1967, 1969, 1971, 1973, 1976:1977, 1984, 1994} $\mathbf{T}_2$ = {2004, 2006, 2008, 2010, 2012, 2014, 2016} $\mathbf{T}_3$ = {2003:2005, 2007, 2009, 2011, 2013, 2015, 2017} $\mathbf{T}_4$ = {1980, 1983, 1989, 1992, 1995, 1998, 2001} $\mathbf{T}_5$ = {1996, ..., 2017}
$\mathbf{U}_g$	sets of model years with proportion-at-age data for series g: North: $\mathbf{U}_1$ = {2009} $\mathbf{U}_2$ = {2008, 2010, 2012, 2016} $\mathbf{U}_3$ = {1998:1999, 2001:2003, 2005:2011} South: $\mathbf{U}_1$ = {1994} $\mathbf{U}_2$ = {2008, 2010, 2012, 2014, 2016} $\mathbf{U}_3$ = {2003:2005, 2007, 2009, 2011, 2013, 2015} $\mathbf{U}_5$ = {1990:1992, 1994, 1996, 1998:2016}
	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 $t \in \mathbf{U}_g$, $g = 1, ..., \{3_{\mathrm{N}} \vee 5_{\mathrm{S}}\}$
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 $g = 1, ..., \{2_{\mathrm{N}} \vee 4_{\mathrm{S}}\}$, for year $t \in \mathbf{T}_g$, tonnes
κ_{tg}	standard deviation of I_{tg}
σ_R	standard deviation parameter for recruitment process error, $\sigma_R = 0.6$

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 $s = 1, 2$
h	steepness parameter for Beverton-Holt recruitment
q_g	catchability for survey series $g = 1, ..., \{2_{\mathrm{N}} \vee 4_{\mathrm{S}}\}$
μ_g	age of full selectivity for females for series $g = 1, ..., \{3_{\mathrm{N}} \vee 5_{\mathrm{S}}\}$
Δ_g	shift in vulnerability for males for series $g = 1, ..., \{3_{\mathrm{N}} \vee 5_{\mathrm{S}}\}$
v_{gL}	variance parameter for left limb of selectivity curve for series $g = 1, ..., \{3_{\mathrm{N}} \vee 5_{\mathrm{S}}\}$
s_{ags}	selectivity for age-class a, series $g = 1, ..., \{3_{\mathrm{N}} \vee 5_{\mathrm{S}}\}$, 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 ($2 \leq t \leq T,\ s = 1, 2$)

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

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

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

Initial conditions ($t = 1$)

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

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

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

Selectivities ($g = 1, ..., \{3_{\mathrm{N}} \vee 5_{\mathrm{S}}\}$)

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

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

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

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

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

$$V_t = \sum_{s=1}^{2} \sum_{a=1}^{A} e^{-M_s/2}\, w_{as}\, s_{a\{3_{\mathrm{N}} \vee 5_{\mathrm{S}}\}s}\, N_{ats} \tag{E.11}$$

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

$$u_{ats} = s_{a\{3_{\mathrm{N}} \vee 5_{\mathrm{S}}\}s}\, u_t\,; \quad 1 \leq a \leq A,\ s = 1, 2 \tag{E.13}$$

Estimated observations

$$\widehat{I}_{tg} = q_g \sum_{s=1}^{2} \sum_{a=1}^{A} e^{-M_s/2}(1 - u_{ats}/2) w_{as} s_{ags} N_{ats}\,; \quad t \in \mathbf{T}_g,\ g = 1, ..., \{3_{\mathrm{N}} \vee 5_{\mathrm{S}}\} \tag{E.14}$$

$$\widehat{p}_{atgs} = \frac{e^{-M_s/2}(1 - u_{ats}/2) s_{ags} N_{ats}}{\sum_{s=1}^{2} \sum_{a=1}^{A} e^{-M_s/2}(1 - u_{ats}/2) s_{ags} N_{ats}}\,; \; 1 \leq a \leq A,\ t \in \mathbf{U}_g,\ g = 1, ...\{3_{\mathrm{N}} \vee 5_{\mathrm{S}}\},\ s = 1,2 \tag{E.15}$$

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

Stochastic components

Estimated parameters

$$\boldsymbol{\Theta} = \left\{ R_0; M_{1,2}; h; q_{1,\ldots,\{3_\mathrm{N} \vee 5_\mathrm{S}\}}; \mu_{1,\ldots,\{3_\mathrm{N} \vee 5_\mathrm{S}\}}; \Delta_{1,\ldots,\{3_\mathrm{N} \vee 5_\mathrm{S}\}}; v_{1,\ldots\{3_\mathrm{N} \vee 5_\mathrm{S}\}L} \right. \qquad \text{(E.16)}$$

Recruitment deviations

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

Log-likelihood functions

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

$$\begin{aligned}\log L_2(\boldsymbol{\Theta}|\{\widehat{p}_{atgs}\}) = &-\frac{1}{2}\sum_{g=1}^{\{3_\mathrm{N} \vee 5_\mathrm{S}\}}\sum_{a=1}^{A}\sum_{t\in\mathbf{U}_g}\sum_{s=1}^{2}\log\left[p_{atgs}(1-p_{atgs}) + \frac{1}{10A}\right] \\ &+ \sum_{g=1}^{\{3_\mathrm{N} \vee 5_\mathrm{S}\}}\sum_{a=1}^{A}\sum_{t\in\mathbf{U}_g}\sum_{s=1}^{2}\log\left[\exp\left\{\frac{-(p_{atgs}-\widehat{p}_{atgs})^2\, n_{tg}}{2\left(p_{atgs}(1-p_{atgs}) + \frac{1}{10A}\right)}\right\} + \frac{1}{100}\right] \qquad \text{(E.19)}\end{aligned}$$

$$\log L_3(\boldsymbol{\Theta}|\{\widehat{I}_{tg}\}) = \sum_{g=1}^{\{3_\mathrm{N} \vee 5_\mathrm{S}\}}\sum_{t\in\mathbf{T}_g}\left[-\frac{1}{2}\log 2\pi - \log\kappa_{tg} - \frac{(\log I_{tg} - \log\widehat{I}_{tg})^2}{2\kappa_{tg}^2}\right] \qquad \text{(E.20)}$$

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

Joint prior distribution and objective function

$$\log(\pi(\boldsymbol{\Theta})) = \sum_j \log(\pi_j(\boldsymbol{\Theta})) \qquad \text{(E.22)}$$

$$f(\boldsymbol{\Theta}) = -\log L(\boldsymbol{\Theta}) - \log(\pi(\boldsymbol{\Theta})) \qquad \text{(E.23)}$$

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 $\pi_j(\mathbf{\Theta})$ 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	4	normal	0.11, 0.011	[0.02, 0.20]	0.11
h	5	beta	4.574, 2.212	[0.2, 0.999]	0.674
$\log \epsilon_t$	2	normal	0, 0.6	[-15, 15]	0
$\log q_{1,2_\mathrm{N}}$	1	uniform	—	[-5, 5]	-5
$\log q_{1,\ldots,4_\mathrm{S}}$	1	uniform	—	[-12, 5]	-5
$\log q_{\{3_\mathrm{N} \vee 5_\mathrm{S}\}}$	1	uniform	—	[-15, 15]	-1.609
$\mu_{1,2_\mathrm{N}}$	3	normal	11.024, 1.149	[5, 40]	11.024
μ_{3_N}	3	normal	10.634, 2.127	[5, 40]	10.634
μ_{1_S}	3	normal	18.232, 5.280	[5, 40]	18.232
μ_{2_S}	3	normal	15.639, 2.392	[5, 40]	15.639
μ_{3_S}	3	normal	15.995, 2.721	[5, 40]	15.995
μ_{4_S}	-	fixed	—	—	8.068
μ_{5_S}	3	normal	10.748, 2.150	[5, 40]	10.748
$\log v_{1,2_\mathrm{N}L}$	4	normal	2.070, 0.591	[-15, 15]	2.070
$\log v_{3_\mathrm{N}L}$	4	normal	1.364, 0.310	[-15, 15]	1.364
$\log v_{1_\mathrm{S}L}$	4	normal	4.501, 1.065	[-15, 15]	4.501
$\log v_{2_\mathrm{S}L}$	4	normal	3.420, 0.648	[-15, 15]	3.420
$\log v_{3_\mathrm{S}L}$	4	normal	3.714, 0.497	[-15, 15]	3.714
$\log v_{4_\mathrm{S}L}$	-	fixed	—	—	2.277
$\log v_{5_\mathrm{S}L}$	4	normal	1.578, 0.305	[-15, 15]	1.578
$\Delta_{1,2_\mathrm{N}}$	4	normal	0.213, 0.066	[-8, 10]	0.213
Δ_{3_N}	4	normal	0.027, 0.220	[-8, 10]	0.027
Δ_{1_S}	4	normal	1.387, 2.538	[-8, 10]	1.387
Δ_{2_S}	4	normal	0.221, 0.066	[-8, 10]	0.221
Δ_{3_S}	4	normal	-0.153, 0.769	[-8, 10]	-0.153
Δ_{4_S}	-	fixed	—	—	0
Δ_{5_S}	4	normal	0.009, 0.239	[-8, 10]	0.009

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. 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 2018.

E.4.2. Years

Index t represents model years, going from 1 to $T = 79$, and $t = 0$ represents unfished equilibrium conditions. The actual year corresponding to $t = 1$ is 1940, and so model year $T = 79$ corresponds to 2018.

E.4.3. Survey data

Data from $\{2_{\mathrm{N}} \vee 4_{\mathrm{S}}\}$ series were used, as described in detail in Appendix B. For Redstripe Rockfish (N|S), survey subscript g varies by stock. In the North, g = 1 denotes the Hecate Strait (HS) synoptic series, g = 2 denotes the West Coast Haida Gwaii (WCHG) synoptic series. In the South, g = 1 denotes the Goose Island Gully (GIG) historic series, g = 2 denotes the West Coast Vancouver Island (WCVI) synoptic series, g = 3 denotes the Queen Charlotte Sound (QCS) synoptic series, g = 4 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 $\mathbf{U}_{\{3_{\mathrm{N}} \vee 5_{\mathrm{S}}\}}$ (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 $g = \{3_{\mathrm{N}} \vee 5_{\mathrm{S}}\}$ (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 the biological data.

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) are 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 is then obtained from (E.9).

E.4.10. Selectivities

Separate selectivities were modelled for the commercial catch data and for each survey series. 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 $s_{...}$ 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).

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 $s_{a\{3_\mathrm{N} \vee 5_\mathrm{S}\}s}$ 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

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

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). The value of σ_R was fixed at 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). In past rockfish assessments, authors had 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*). 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). 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 $\log L(\mathbf{\Theta})$ 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 $f(\mathbf{\Theta})$, 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 $f(\mathbf{\Theta})$ 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 $f(\mathbf{\Theta})$, 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 $q_{1,...,\{2_\mathrm{N} \vee 4_\mathrm{S}\}}$;
phase 2: recruitment deviations ϵ_t (held at 0 in phase 1);
phase 3: age of full selectivity for females $\mu_{1,...,\{3_\mathrm{N} \vee 5_\mathrm{S}\}}$;
phase 4: natural mortality $M_{1,2}$ and selectivity parameters Δ_g, υ_{gL} for $g = 1, ..., \{3_\mathrm{N} \vee 5_\mathrm{S}\}$;
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 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). In this assessment, we adopt the Francis (2011) approach, adding series-specific process error to CVs on the first reweight and iteratively reweighting age frequency sample size by mean age (see below).

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 ajusted on the first reweight only using the process error c_p = 0.5, 0.5, and 0.34 in the North (g=1,...3) and 0.5, 0.3, 0.25, 0.5, and 0.2 in the South (g=1,...5).

Francis (2011) maintains that correlation effects are usually strong in age-composition data. Each age-composition data set has a sample size n_{tg} ($g = 1, ..., \{3_\mathrm{N} \vee 5_\mathrm{S}\}$, $t \in \mathbf{U}_g$), which is typically in the range 3-20, each sample comprising $\sim$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 $g = 1, ..., \{3_\mathrm{N} \vee 5_\mathrm{S}\}$ 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 porportion-at-age value (e.g., Edwards et al. 2012*b*). The weight is given by equation (TA1.8) of Francis (2011):

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

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 was the one where the sum of the absolute deviation from unity of the SDNRs for the $\{3_\mathrm{N} \vee 5_\mathrm{S}\}$ abundance index series was the lowest:

$$r' = \min_{r \in 1:3} \sum_{g=1}^{\{3_\mathrm{N} \vee 5_\mathrm{S}\}} |1 - \sigma_{\delta_g}^{(r)}|. \tag{E.33}$$

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 $\pi_j(\boldsymbol{\Theta})$, whose logarithms are then summed in (E.22) to give the joint prior distribution $\pi(\boldsymbol{\Theta})$. 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 $\pi(\boldsymbol{\Theta})$, 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. The normal priors for female and male natural mortality, M_1 and M_2 respectively, were based on the revised Hoenig natural mortality estimator of Then et al. (2015) using a maximum observed age of 61 y (Appendix D), with consideration to assessments of Redstripe Rockfish in Alaskan waters (M=0.1 as total mortality based on catch-curve anlysis, e.g., Tribuzio et al. 2017), and set to 0.11 with a tight CV of 10%.

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 was estimated for two surveys in BC North (HS synoptic and WCHG synoptic) and three surveys in BC South (GIG historic, QCS synoptic, and WCVI synoptic) with age composition data. Informative priors were developed for the three selectivity parameters for each of these surveys, $\mu_{1,\ldots,\{2_\mathrm{N} \vee 3_\mathrm{S}\}}$, $v_{1,\ldots,\{2_\mathrm{N} \vee 3_\mathrm{S}\}L}$, and $\Delta_{1,\ldots,\{2_\mathrm{N} \vee 3_\mathrm{S}\}}$, based on the posterior distributions for the same parameters from matching base-case POP assessments (Haigh et al. 2018; Edwards et al. 2014*b*,*a*). The parameter estimates from the WCHG synoptic survey were used for the HS synoptic survey because this survey was not used in the these POP assessments. Normal distributions were assumed for each selectivity prior, with the mean and standard deviation set to the mean and standard deviation of the same parameter from the corresponding area's POP posterior.

No age data were available for the WCVI triennial survey series (National Marine Fisheries Service), so the three selectivity parameters for this survey were fixed rather than estimated. The fixed values used for these selectivities were set to the priors estimated in Edwards et al. (2012*b*) using a half-Gaussian fit to Gulf of Alaska POP selectivity data that appeared in Hanselman et al. (2007).

For commercial fleet selectivity ($g = \{3_\mathrm{N} \vee 5_\mathrm{S}\}$), normal (informative) priors were used for the three selectivity parameters, with means set to the mean values of the posterior disributions for commerical selectivity from two POP stock assessments (WCHG in 2012 and QCS in 2017) mentioned above. The standard deviation for the prior $\mu_{\{3_\mathrm{N} \vee 5_\mathrm{S}\}}$ was set to 20% of the prior's mean; standard deviations for the priors $v_{\{3_\mathrm{N} \vee 5_\mathrm{S}\}L}$ and $\Delta_{\{3_\mathrm{N} \vee 5_\mathrm{S}\}}$ were set to the standard deviations from the equivalent parameter posteriors in the 2012 WCHG and 2017 QCS POP assessments.

E.6.4. MCMC properties

The MCMC procedure started the search from the MPD values and performed 24,000,000 iterations, sampling every 20,000$^{\mathrm{th}}$ 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). The second set of reference points, 0.2B_0 and 0.4B_0, are based on the estimated unfished equilibrium spawning biomass B_0. Finally, the current spawning biomass B_{2018} is used to show the probability of increasing or decreasing from the current standing stock. See main text for further discussion.

To estimate B_{MSY}, the model was projected forward across a range (0 to 0.995 incremented by 0.005) 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 1,000 MCMC samples, resulting in marginal posterior distributions for MSY, u_{MSY} and B_{MSY}.

The probability $\mathrm{P}(B_{2018} > 0.4B_{\mathrm{MSY}})$ is then calculated as the proportion of the 1,000 MCMC samples for which $B_{2018} > 0.4B_{\mathrm{MSY}}$ (and similarly for the other reference points).

Projections were made for 5 years starting with the biomass and age structure calculated for the start of 2018. A range of constant catch strategies were used, from 0 to 2,000 t at 100 t increments (the average catch from 2013 to 2017 was 109 t and 732 t in BC North and BC South). For each strategy, projections were performed for each of the 1,000 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 1,000 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).

E.8 REFERENCES – MODEL RESULTS

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APPENDIX F. MODEL RESULTS

F.1. INTRODUCTION

This Appendix describes results for two stocks of Redstripe Rockfish (RSR), BC North (BCN) and BC South (BCS), from mode of the posterior distribution (MPD) calculations to compare model estimates to observations, MCMC (Markov chain Monte Carlo) simulations to derive posterior distributions for the estimated parameters of the accepted base-case model, including MCMC diagnostics, and a range of sensitivity model runs. The final advice draws from the MCMC results from all runs, but the base cases for each stock provide the primary guidance. Estimates of major quantities and advice to management (decision tables) for the base case are presented here and in the main text.

In 2011, Redstripe Rockfish was part of a 'five-rockfish' multi-species stock assessment (Taylor et al. 2011) that was not accepted for providing management advice, but was recommended for publication, subject to revisions; however, the paper was neither revised nor published. This assessment departs from the 2011 Redstripe Rockfish assessment in two ways:

1. The BC RSR population was identified to comprise two stocks based on a persistent difference in mean weight and growth model parameters (see Appendix D). The two stocks occupy Pacific Marine Fisheries Commission (PMFC) areas 5DE in the north and 3CD5ABC in the south.
2. Each stock was assessed using a catch-age model called `Awatea` (variant of `Coleraine`, Hilborn et al. 2003) which reconstructed the RSR population rather than using the **M**ultistock **A**ge-structured **R**ockfish a**S**sessment (MARS) model designed to assess five rockfish simultaneously. The MARS model borrowed information from data-rich stocks to help assess data-poor ones. In this case, RSR was relatively data-rich compared to the others and did not require additional information.

Important decisions made during the assessment of RSR include:

1. Normal priors on M with fairly tight CVs (10%) were necessary for the stability of the model output.
2. Informed priors for survey and commercial selectivities (μ_g, Δ_g, ν_{gL} for survey gears g) were required to stabilise model output. Unlike the 2017 5ABC POP assessment, these data were not sufficiently informative to use uniform priors.
3. Commercial fishery and survey CVs were re-weighted three times, and the optimal reweight was chosen based on the sum of absolute deviations of the index SDNRs (standard deviations of the normalised residuals) from 1, where lower values of this metric were preferred.
4. The effective sample sizes of age frequency data (as proportions) were re-weighted using the mean age technique of Francis (2011).

F.2. BC NORTH (BCN) STOCK

F.2.1. BCN Base Case

The base case for Redstripe Rockfish was selected from model run 16, which featured:

- 3 abundance index series: HS Synoptic survey (g=1), WCHG Synoptic survey (g=2), and commercial trawl CPUE (g=3);

- two sexes: female (s=1) and male (s=2);
- proportions-at-age by sex for g = c(1,2,3) using all samples (unsorted + keepers);
- a normal prior for natural mortality M_s with CV = 10%;
- a normal prior for age of full selectivity for females (μ_g) with CV = 20%;
- bounds for shift in the vulnerability for males (Δ_g) and the variance parameter for the left limb of the selectivity curve ($\nu_g L$) = c(-8,10);
- abundance CVs reweighted once using cvpro = c(0.5, 0.5, 0.34) for the 2 surveys and the CPUE series, respectively;
- age frequency sample sizes iteratively reweighted using the Francis (2011) mean-ages method;
- a standard deviation parameter for recruitment process error (σ_R) set to 0.6.

The base-case run was reweighted three times using the procedure of Francis (2011) for age frequencies. The abundance index CVs were ajusted on the first reweight only using the process error: c_p = 0.5, 0.5, and 0.34 for the HS Synoptic survey, WCHG Synoptic survey, and commercial trawl CPUE, respectively. The reweighted dataset chosen for MCMC analysis was the one where the sum of the absolute deviation from unity of the three SDNRs for the three abundance index series was the lowest (Equation E.33).

F.2.1.1. BCN Mode of the Posterior Distribution (MPD)

The procedure followed in this assessment was to first determine the best MPD fit to the data by minimising the negative log likelihood (Tables F.1 and F.2). The MPDs became the starting points for the MCMC simulations. The following description applies to the base case.

The MPD plots show:

- survey index fits (Figure F.1) and their residuals (Figures F.2–F.3);
- the bottom trawl CPUE fit (Figure F.4) and its residuals (Figures F.5);
- fits to the age frequency data by sex for the commercial trawl fishery (Figures F.6–F.7) and their residuals (Figures F.8–F.10);
- fits to the age data by sex for the Hecate Strait (HS) synoptic survey (Figure F.11) and their residuals (Figures F.12–F.14);
- fits to the age data by sex for the West Coast Haida Gwaii (WCHG) synoptic survey (Figure F.15) and their residuals (Figures F.16–F.18);
- model estimates of mean age compared to the observed mean ages (Figure F.19);
- the stock-recruitment relationship and recruitment time series (Figure F.20);
- the recruitment deviations and auto-correlation of these deviations (Figure F.21);
- fits for the gear selectivities, together with the ogive for female maturity (Figure F.22);
- the relative spawning biomass (B_t/B_0) together with catch on the same time scale (Figure F.23); and
- the exploitation over time with catch presented again for reference (Figure F.24).

The model fits to the abundance indices are good (Figures F.1 and F.4). Fits to age frequency data are generally satisfactory, although older ages are sometimes under-estimated (e.g.,

Figure F.7). Model estimates of mean age match the observed mean ages (Figure F.19) for the commercial series but the fits tend to be poor for the survey data sets. This may in part be due to the synoptic design of the survey, with the 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.

The stock-recruitment relationship (Figure F.20) displays the variation that rockfish typically exhibit and the simplifying effect of fitting production using a deterministic function. High, episodic recruitment occurred in 1981-1982 and 2000-2002. Recuitment peaks may occur only in single years, with ageing error making it appear as though the events span multiple years. Recruit deviations fluctuate over time, but significant auto-correlation of these deviations occurs only at lag 1 (Figure F.21). The MPD estimate of age at full selectivity is similar for both the commercial fishery and the two surveys (Figure F.22). All selectivity curves occur to the right of the maturity ogive, which indicates that only mature fish are captured by trawling.

Spawning biomass (B_t) relative to unfished equilibrium biomass (B_0) shows minimal depletion with the MPD estimate of 2018 spawning biomass (B_{2018}) greater that B_0 (Figure F.23). Exploitation rates (u_t) exceeded 0.11 in 6 years, all before the fishery became more controlled in the mid-1990s. Current exploitation rates are estimated to be low (less than 0.025) (top panel: Figure F.24).

F.2.1.1.1. BCN MPD tables for base case

Table F.1. BC North: 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	(1,1e+07)	0	(0,0)	10000	4436.55
M_s **(natural mortality by sex** s**, where** $s = 1$ [female], 2 [male]**)**					
4	(0.02,0.2)	1	(0.11,0.011)	0.11	0.10777
4	(0.02,0.2)	1	(0.11,0.011)	0.11	0.118162
h **(steepness of spawner-recruit curve)**					
5	(0.2,0.999)	5	(4.574,2.212)	0.674	0.850697
ϵ_t **(recruitment deviations)**					
2	(-15,15)	1	(0,0.6)	0	Fig F.21
ω **(initial recruitment)**					
-1	(0,2)	0	(1,0.1)	1	1

Table F.2. BC North: 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 $g = 3, ...3$)							
3	1	(-15,15)	0	(0,0.1)	-1.60944	-8.5442	0.00019466
Survey catchability mode ($\log q_g$, where $g = 1, ..., 2$)							
1	1	(-5,5)	0	(0,0.6)	-5	-4.1838	0.01524
2	1	(-5,5)	0	(0,0.6)	-5	-2.8537	0.057632
Commercial selectivity (μ_g, where $g = 3$)							
3	3	(5,40)	1	(10.6337,2.12674)	10.6337	12.231	
Survey selectivity (μ_g, where $g = 1, ..., 2$)							
1	3	(5,40)	1	(11.0239,1.1495)	11.0239	11.26	
2	3	(5,40)	1	(11.0239,1.1495)	11.0239	11.128	
Variance (left) of commercial selectivity curve ($\log v_{gL}$, where $g = 3$)							
3	4	(-15,15)	1	(1.36441,0.310057)	1.36441	0.85029	
Variance (left) of survey selectivity curve ($\log v_{gL}$, where $g = 1, ..., 2$)							
1	4	(-15,15)	1	(2.0703,0.591216)	2.0703	1.8783	
2	4	(-15,15)	1	(2.0703,0.591216)	2.0703	1.7987	
Shift in commercial selectivity for males (Δ_g, where $g = 3$)							
3	4	(-8,10)	1	(0.027252,0.219754)	0.027252	0.12235	
Shift in survey selectivity for males (Δ_g, where $g = 1, ..., 2$)							
1	4	(-8,10)	1	(0.213218,0.065637)	0.213218	0.22167	
2	4	(-8,10)	1	(0.213218,0.065637)	0.213218	0.20001	

Table F.3. BC North: 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 $g = 1...2$ refer to the trawl surveys and subscript $g = 3+$ refers to the commercial fishery.

Description	Negative log likelihood	Value
Survey 1	$\log \mathsf{L}_3 \left(\boldsymbol{\Theta} \middle| \left\{\hat{I}_{t1}\right\}\right)$	6.09
Survey 2	$\log \mathsf{L}_3 \left(\boldsymbol{\Theta} \middle| \left\{\hat{I}_{t2}\right\}\right)$	-0.41
CPUE 1	$\log \mathsf{L}_3 \left(\boldsymbol{\Theta} \middle| \left\{\hat{I}_{t1}\right\}\right)$	-11.71
CAs 1	$\log \mathsf{L}_2 \left(\boldsymbol{\Theta} \middle| \left\{\hat{p}_{at1s}\right\}\right)$	-210.94
CAs 2	$\log \mathsf{L}_2 \left(\boldsymbol{\Theta} \middle| \left\{\hat{p}_{at2s}\right\}\right)$	-709.69
CAc 1	$\log \mathsf{L}_2 \left(\boldsymbol{\Theta} \middle| \left\{\hat{p}_{at3s}\right\}\right)$	-2183.33
Prior	$\log \mathsf{L}_1 \left(\boldsymbol{\Theta} \middle| \left\{\epsilon_t\right\}\right) - \log\left(\pi(\boldsymbol{\Theta})\right)$	46.19
	Objective function $f(\boldsymbol{\Theta})$	-3063.8

F.2.1.1.2. BCN MPD figures for base case

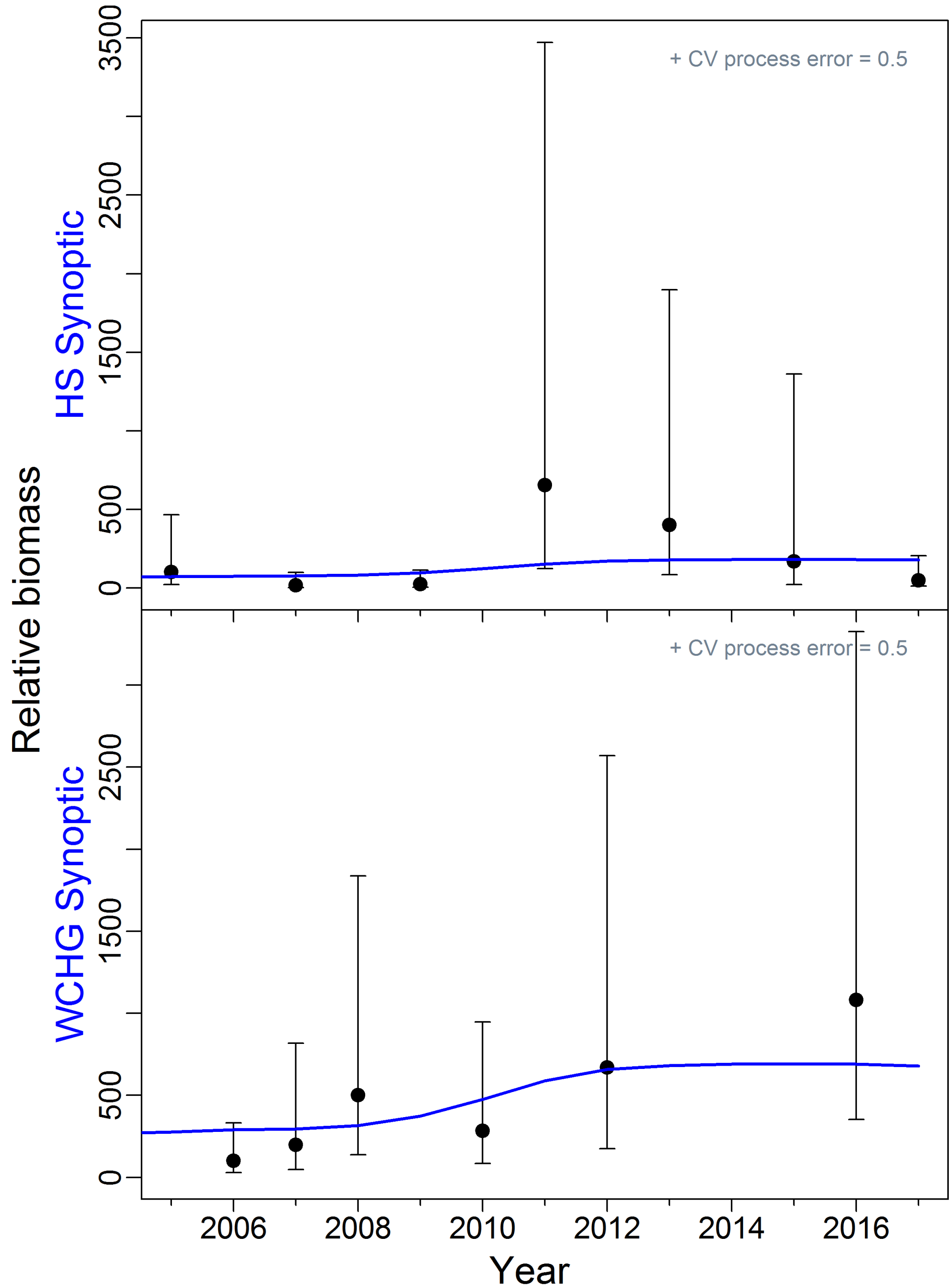


Figure F.1. BC North: Survey index values (points) with 95% confidence intervals (bars) and MPD model fits (curves) for the fishery-independent survey series.

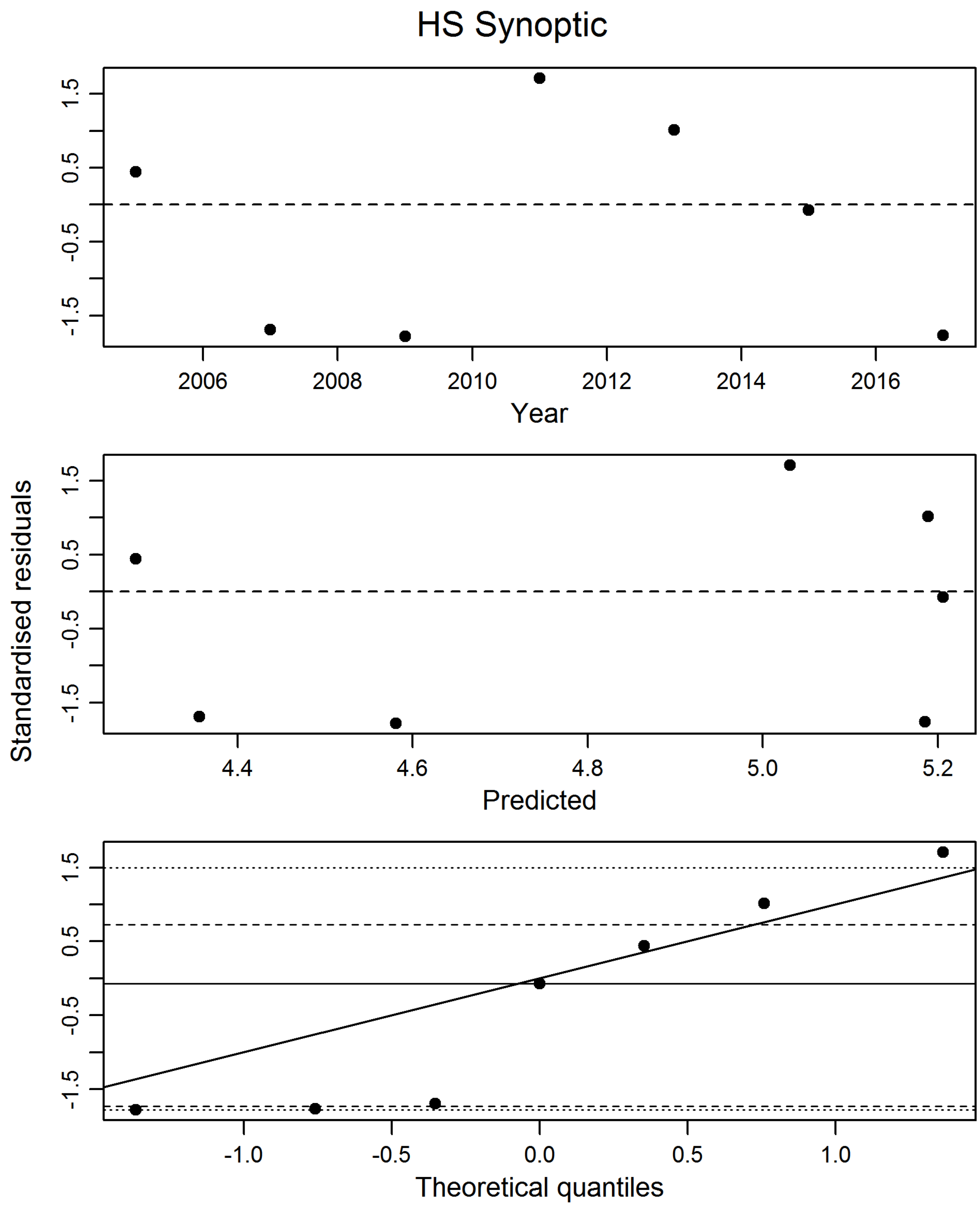


Figure F.2. BC North: Residuals of fits of model to HS Synoptic survey series (MPD values). Vertical axes are standardised residuals. The three plots show, respectively, residuals by year of index, residuals relative to predicted index, and normal quantile-quantile plot for residuals (horizontal lines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

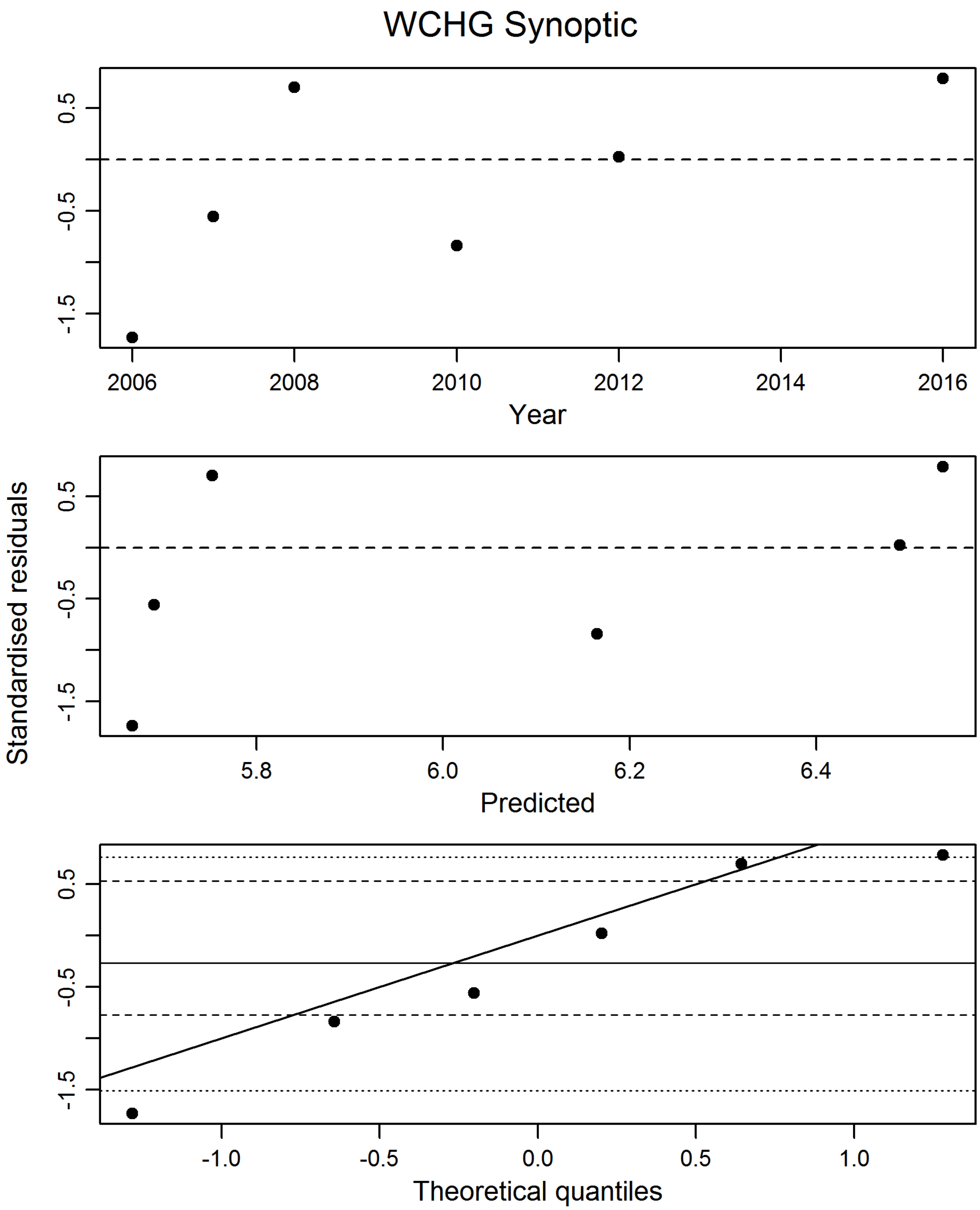


Figure F.3. BC North: Residuals of fits of model to WCHG Synoptic survey series (MPD values). Vertical axes are standardised residuals. The three plots show, respectively, residuals by year of index, residuals relative to predicted index, and normal quantile-quantile plot for residuals (horizontal lines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

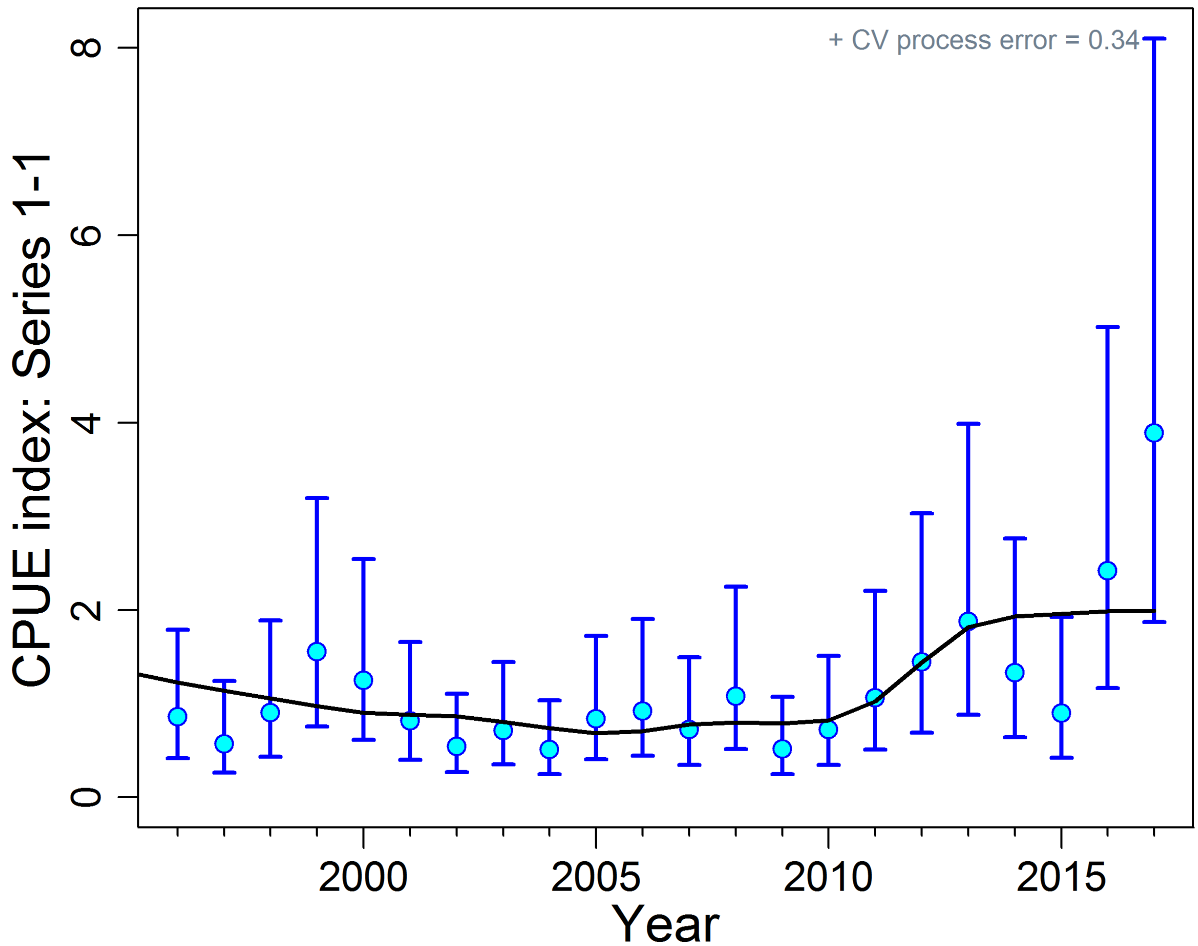


Figure F.4. BC North: CPUE index series, 90% error bars are based on lognormal assumption (double check error bars).

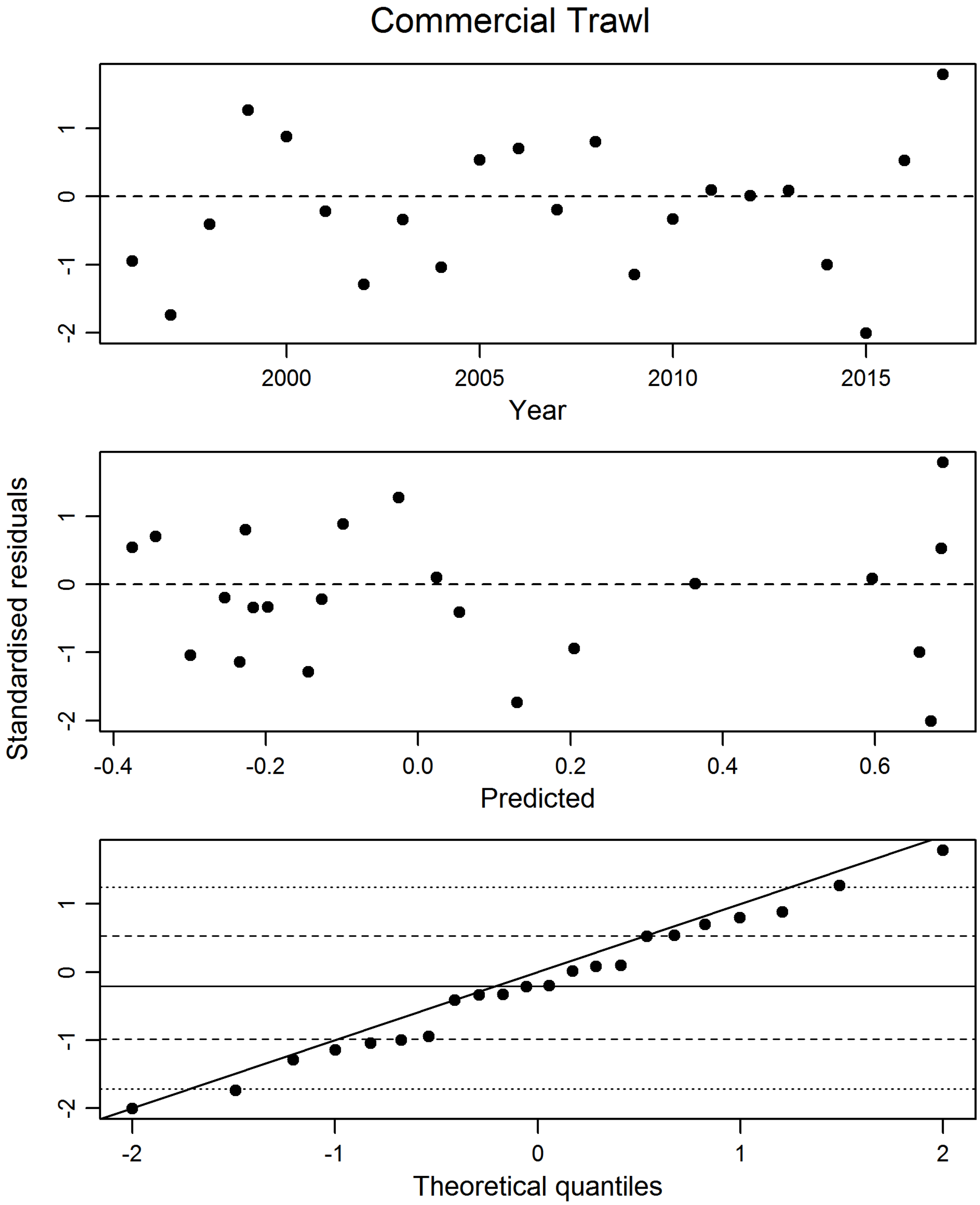


Figure F.5. BC North: Residuals of fits of model to bottom trawl CPUE series (MPD values). Vertical axes are standardised residuals. The three plots show, respectively, residuals by year of index, residuals relative to predicted index, and normal quantile-quantile plot for residuals (horizontal lines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

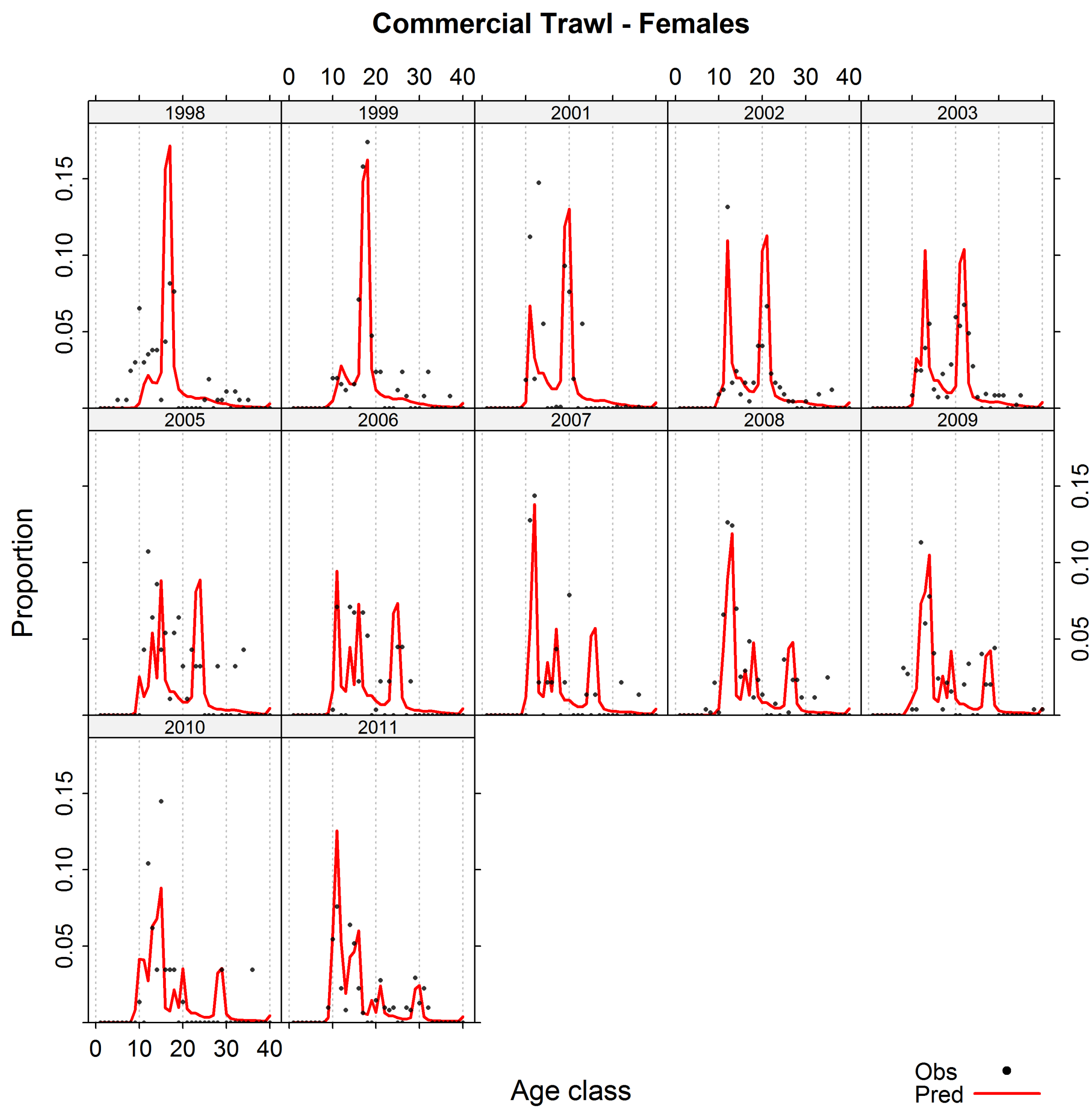


Figure F.6. BC North: Observed and predicted commercial trawl proportions-at-age for females. Note that years are not necessarily consecutive.

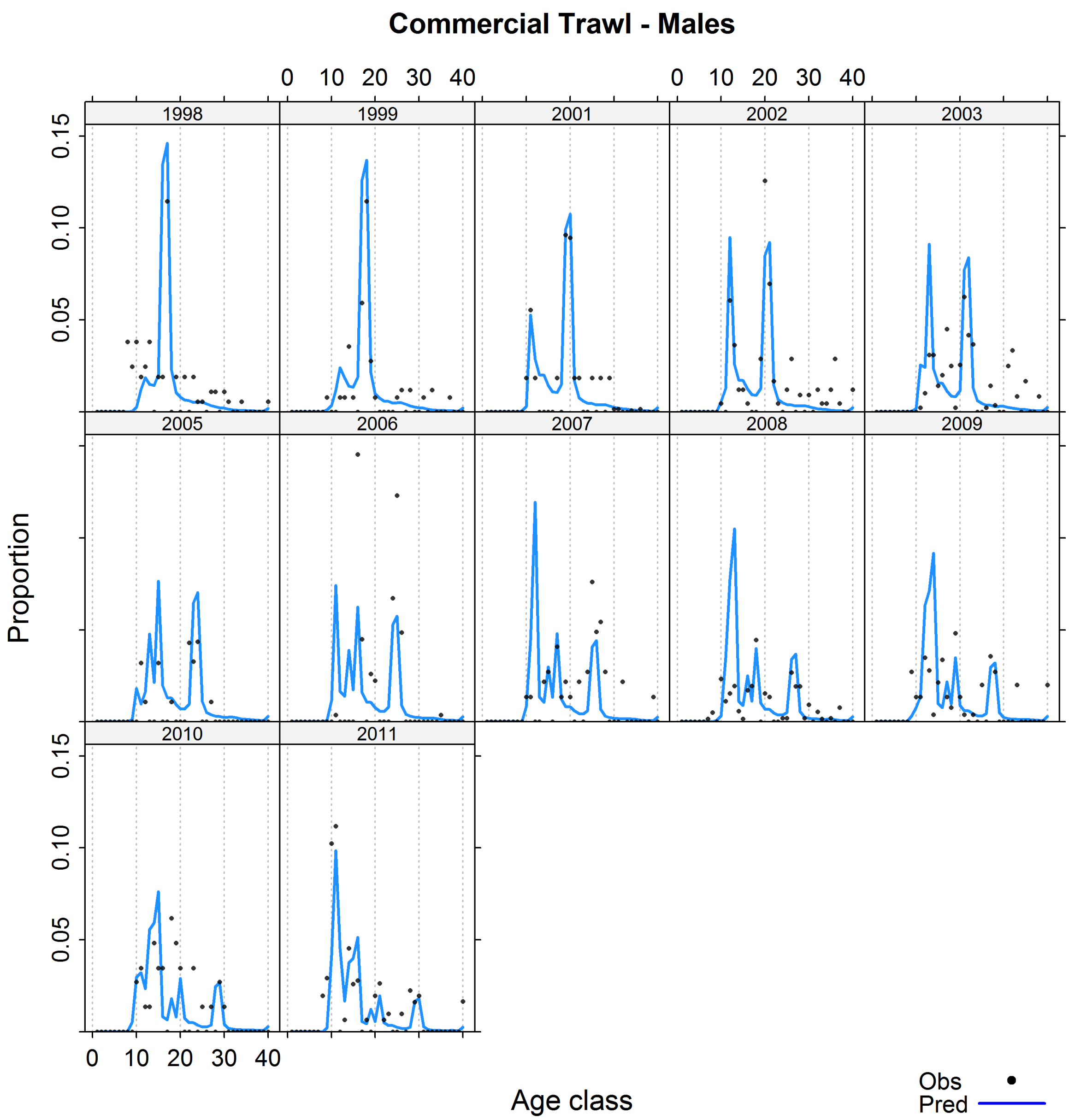


Figure F.7. BC North: Observed and predicted commercial trawl proportions-at-age for males. Note that years are not necessarily consecutive.

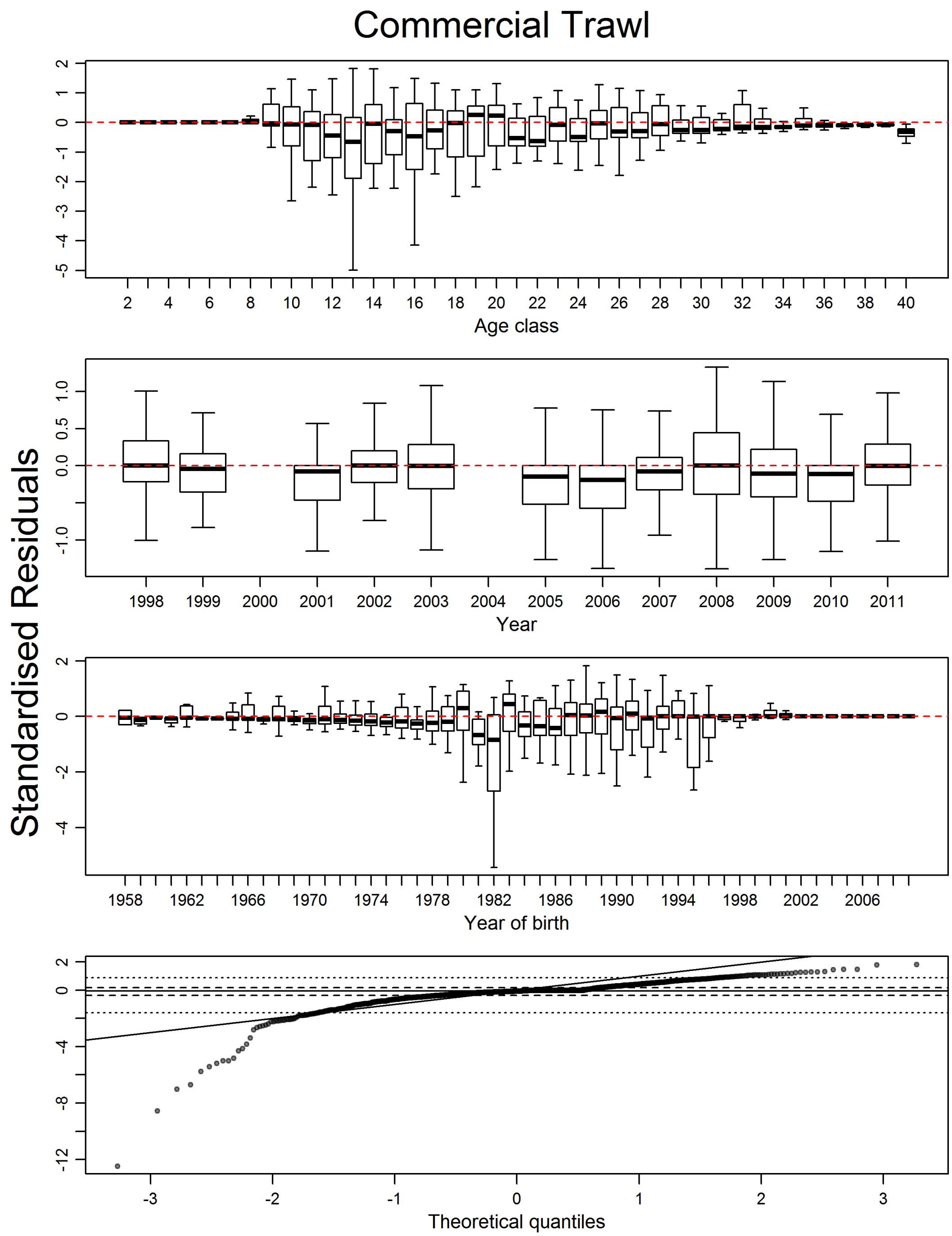


Figure F.8. BC North: Residual of fits of model to commercial proportions-at-age data (MPD values) for Commercial Trawl events. Vertical axes are standardised residuals. Boxplots show, respectively, residuals by age class, by year of data, and by year of birth (following a cohort through time). Boxes give interquartile ranges, with bold lines representing medians and whiskers extending to the most extreme data point that is $<$1.5 times the interquartile range from the box. Bottom panel is the normal quantile-quantile plot for residuals, with the 1:1 line, though residuals are not expected to be normally distributed because of the likelihood function used; horizontal lines give the 5, 25, 50, 75, and 95 percentiles (for a total of 936 residuals).

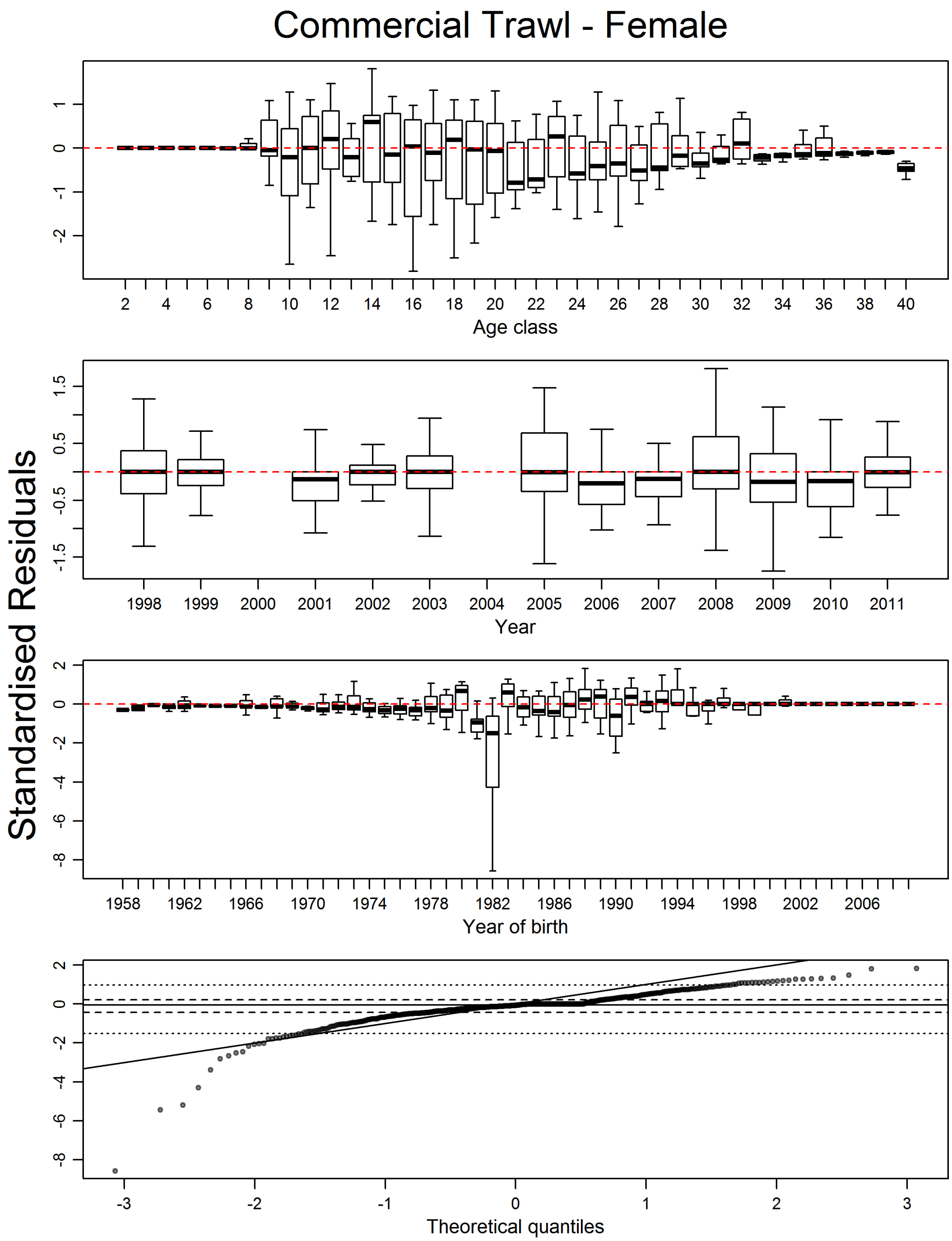


Figure F.9. BC North: Residual of fits of model to commercial proportions-at-age data (MPD values) for females (Commercial Trawl). Details as for Figure F.8, for a total of 468 residuals.

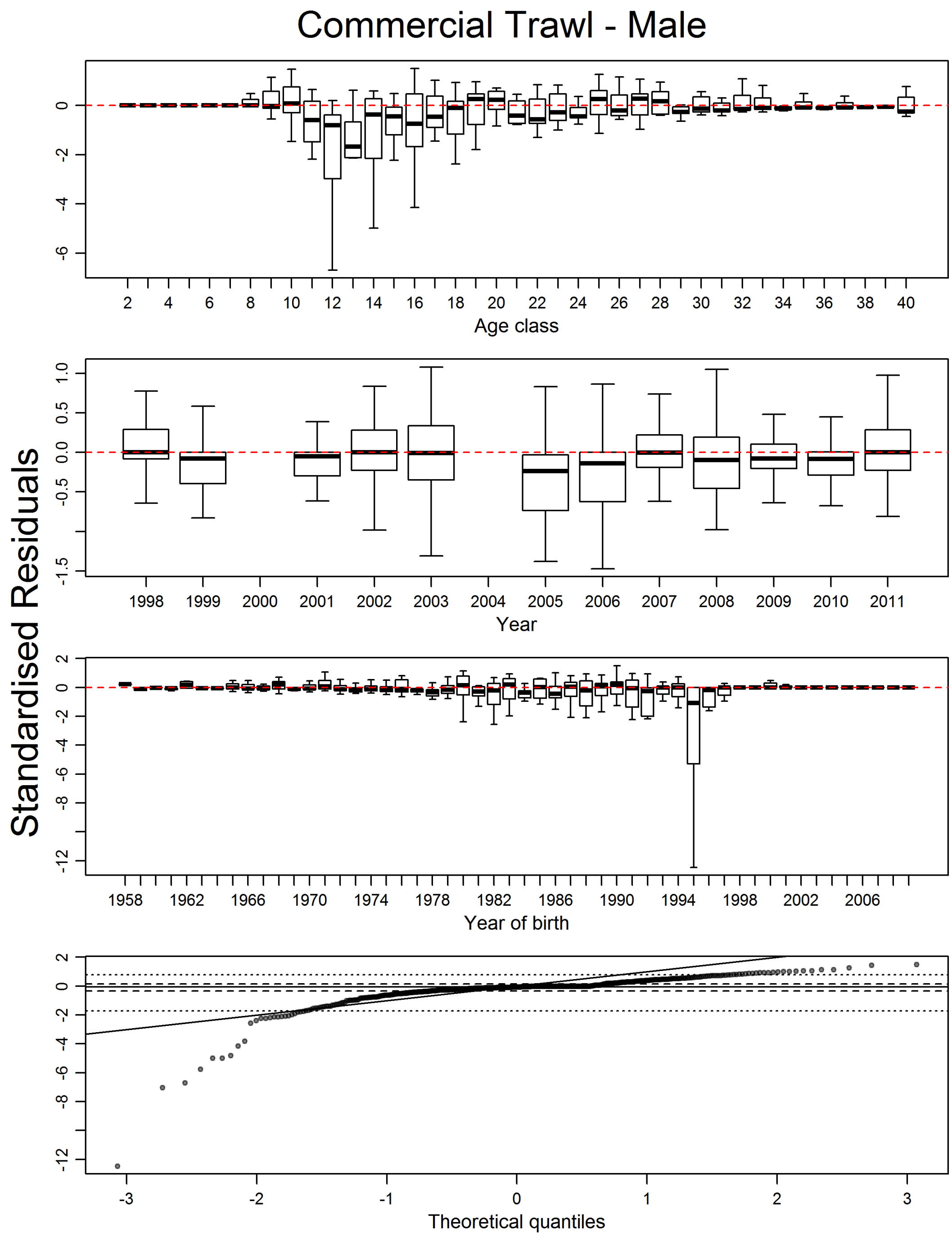


Figure F.10. BC North: Residual of fits of model to commercial proportions-at-age data (MPD values) for males (Commercial Trawl). Details as for Figure F.8, for a total of 468 residuals.

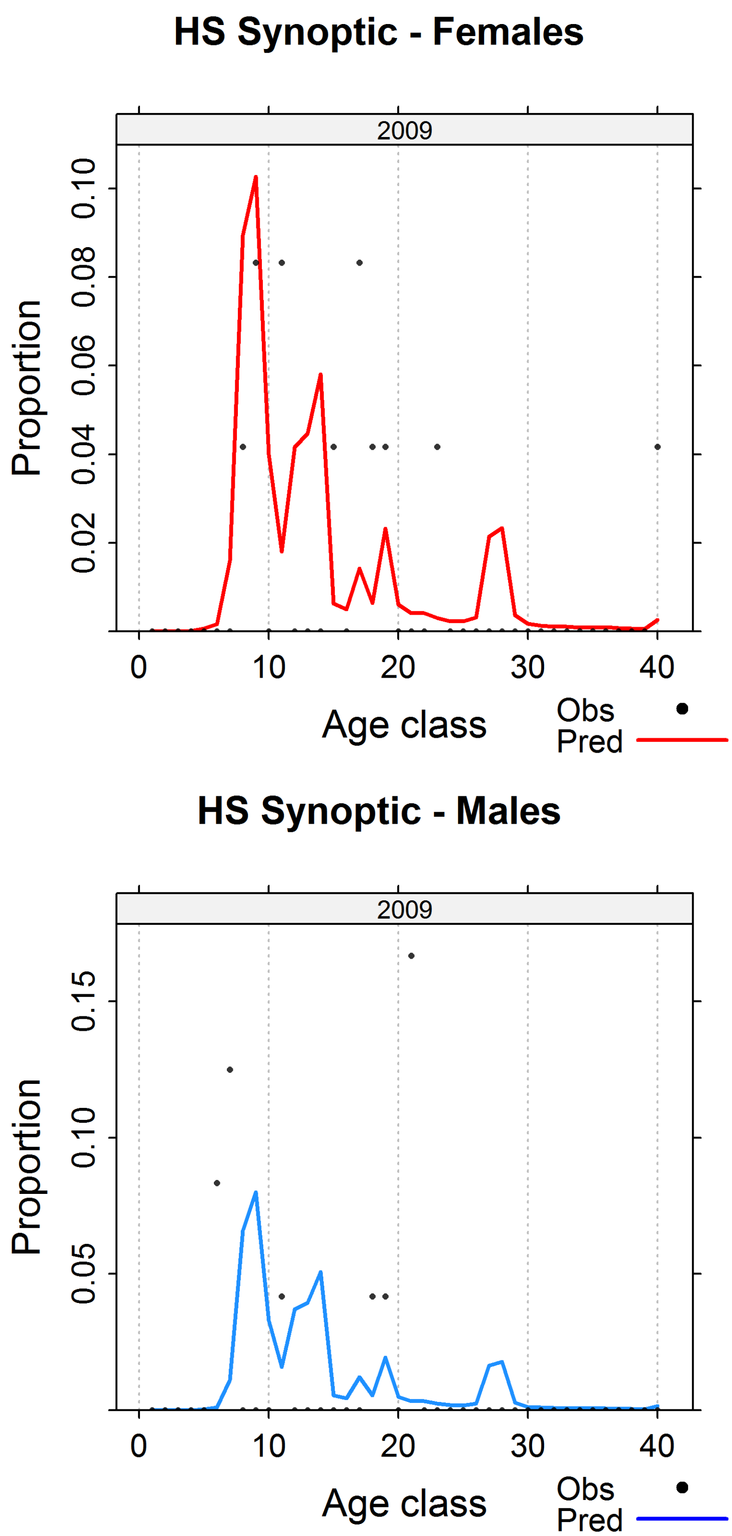


Figure F.11. BC North: Observed and predicted proportions-at-age for HS Synoptic survey.

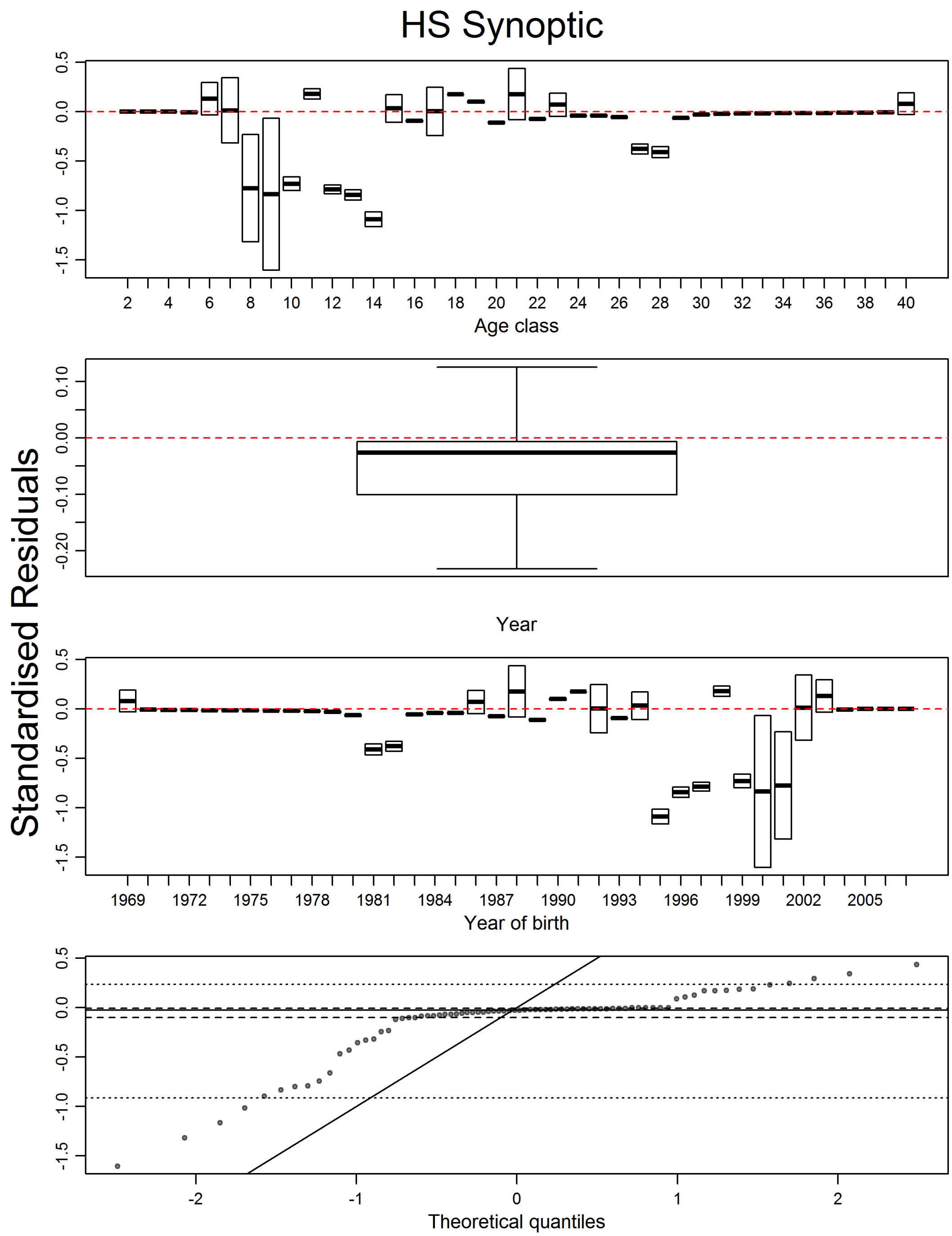


Figure F.12. BC North: Residuals of fits of model to proportions-at-age data (MPD values) from the HS Synoptic survey series. Details as for Figure F.8, for a total of 78 residuals.

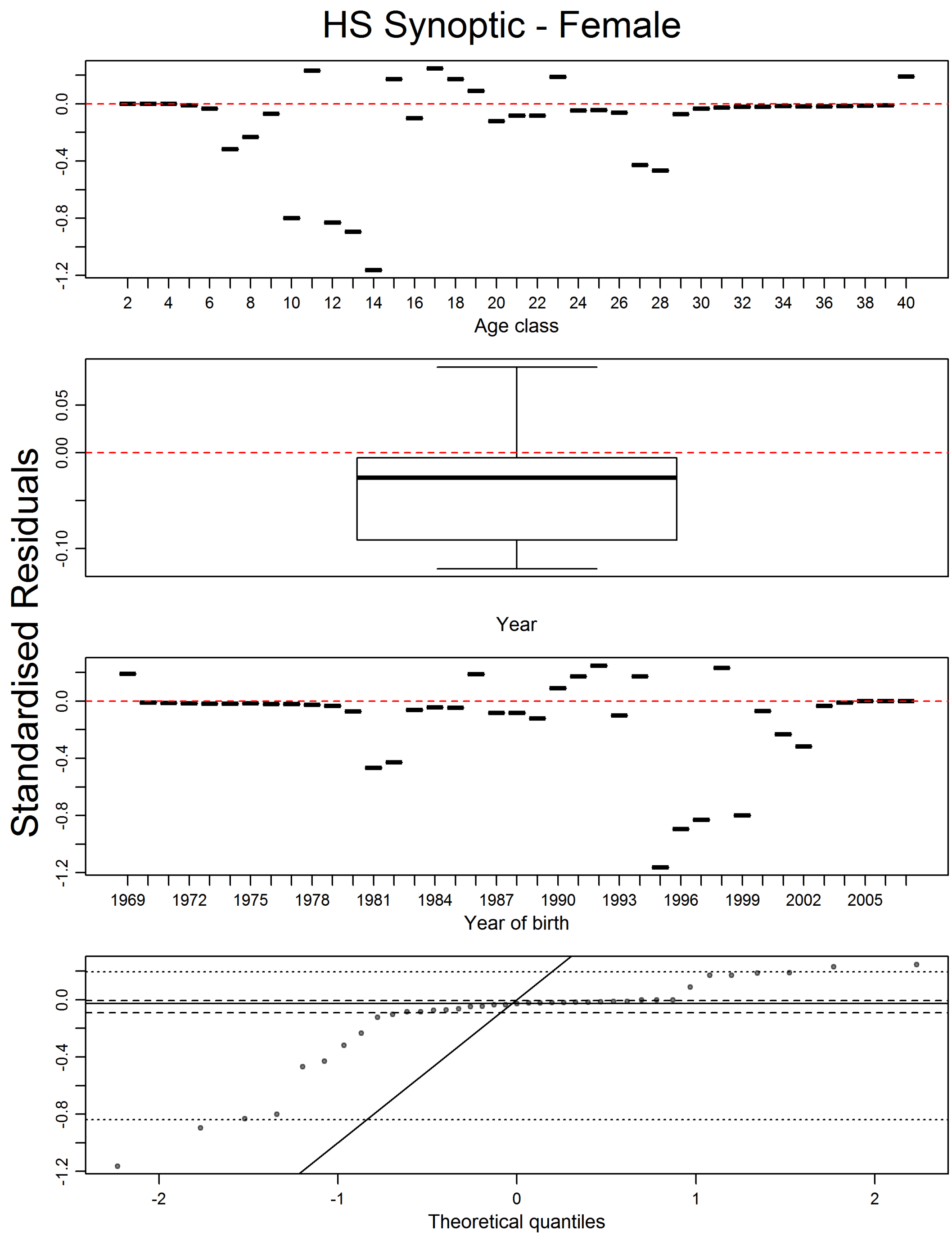


Figure F.13. BC North: Residuals of fits of model to proportions-at-age data (MPD values) for females from HS Synoptic survey series. Details as for Figure F.8, for a total of 39 residuals.

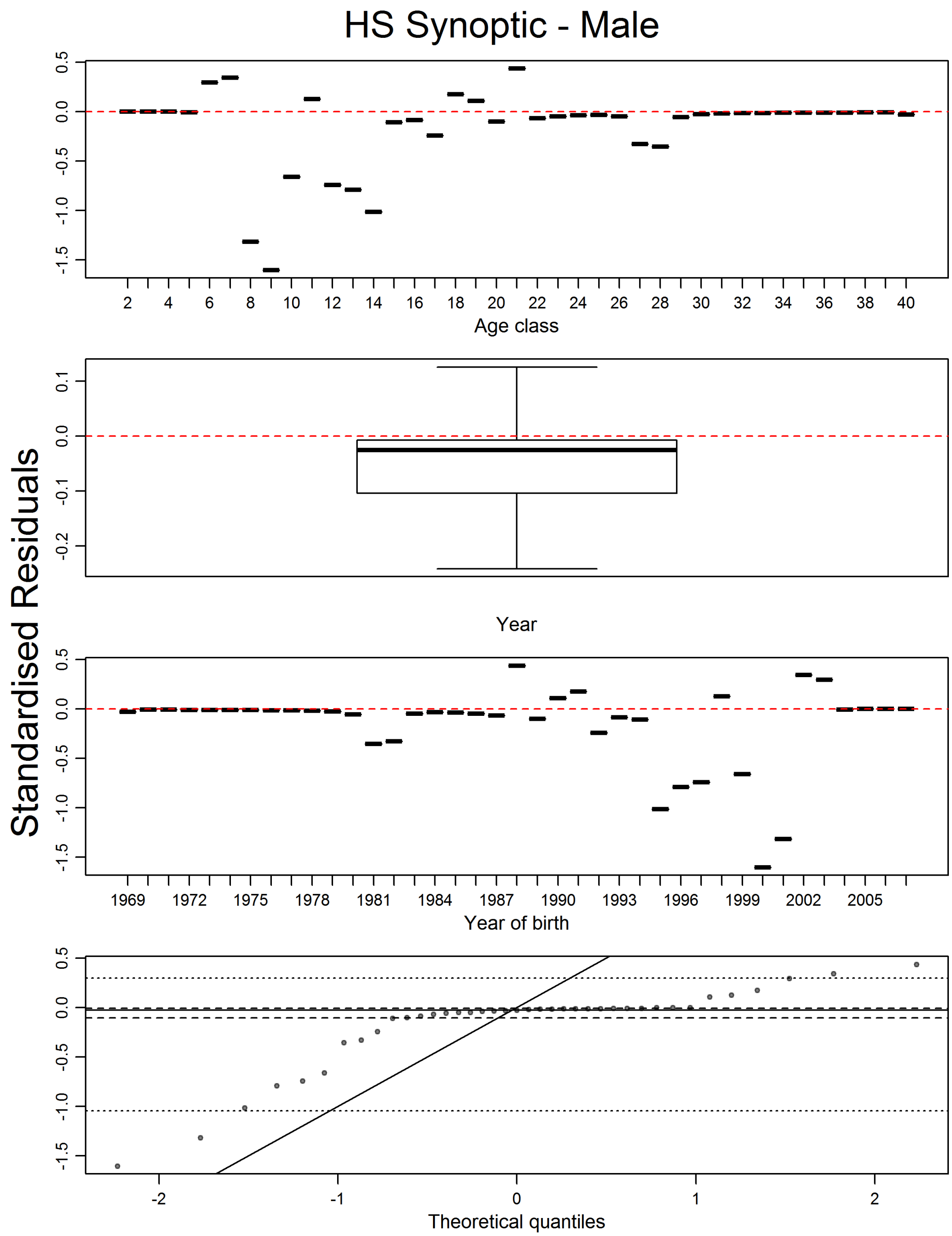
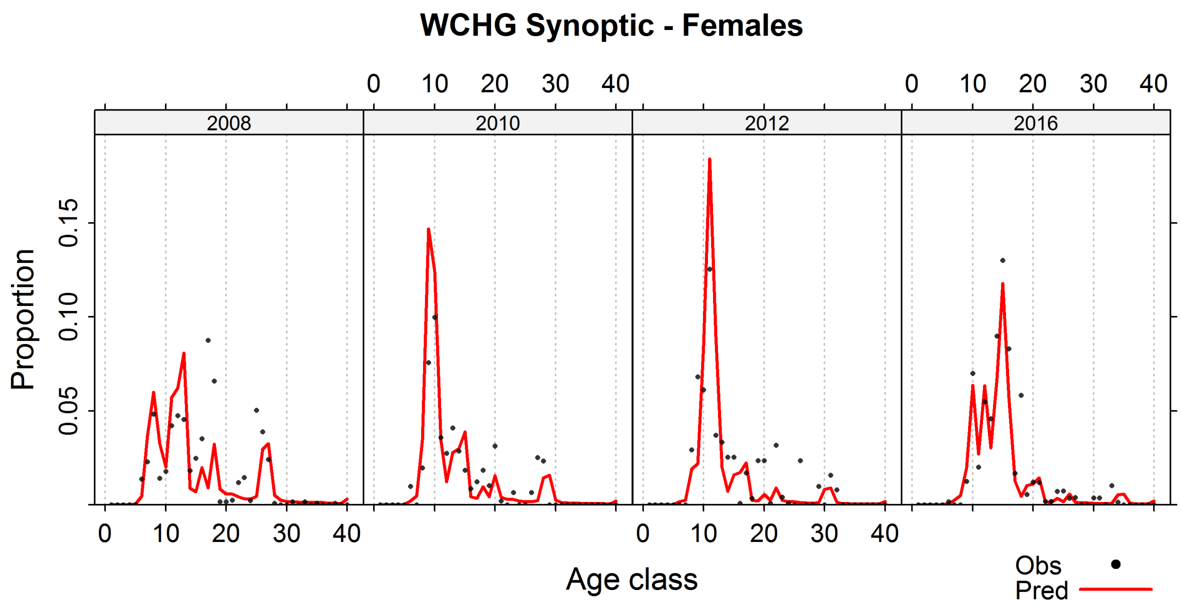


Figure F.14. BC North: Residuals of fits of model to proportions-at-age data (MPD values) for males from HS Synoptic survey series. Details as for Figure F.8, for a total of 39 residuals.



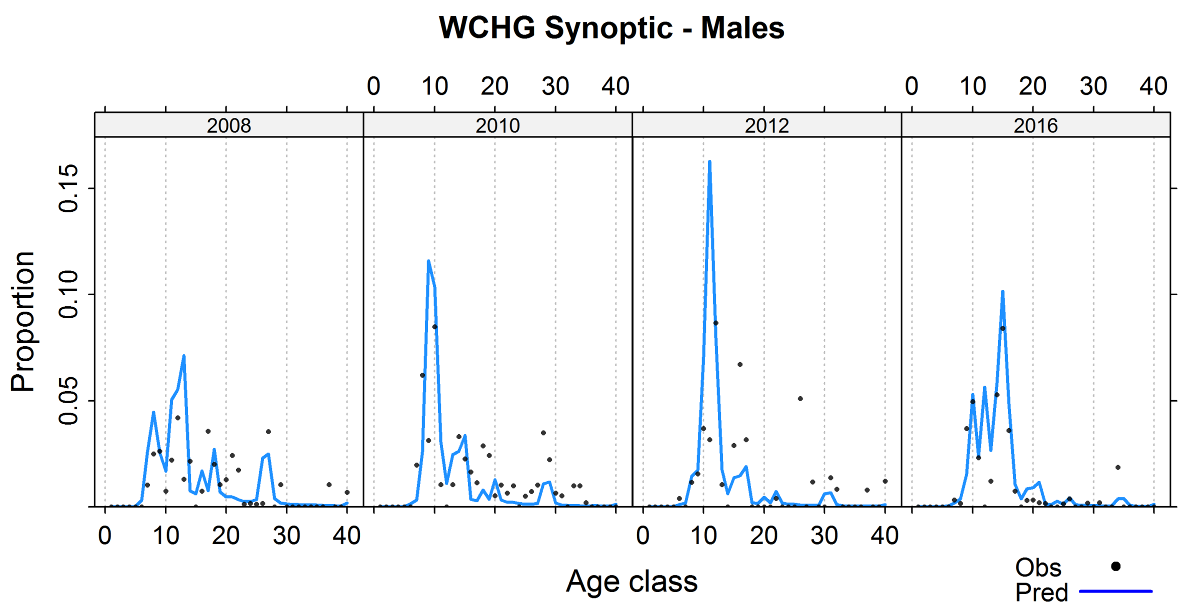


Figure F.15. BC North: Observed and predicted proportions-at-age for WCHG Synoptic survey.

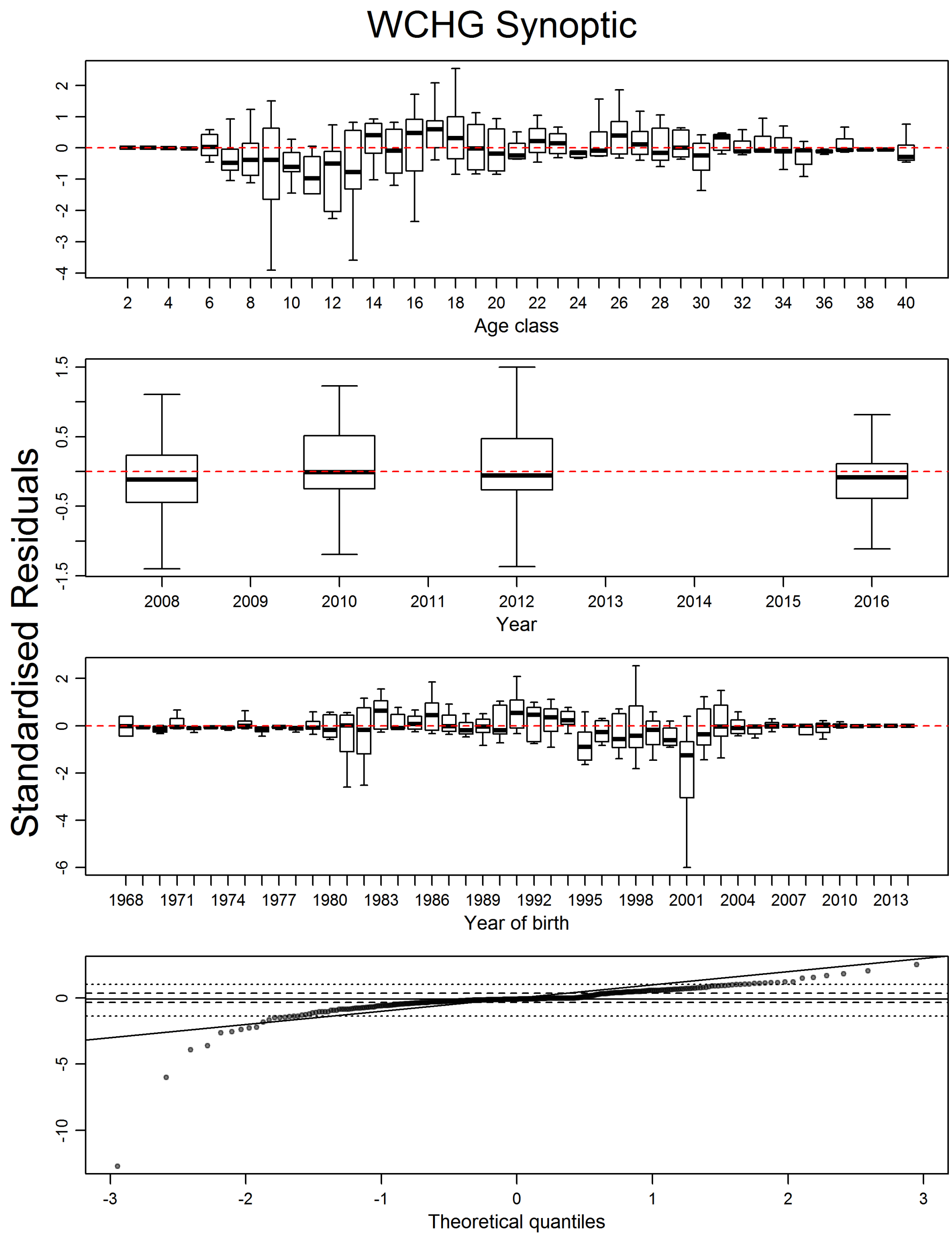


Figure F.16. BC North: Residuals of fits of model to proportions-at-age data (MPD values) from the WCHG Synoptic survey series. Details as for Figure F.8, for a total of 312 residuals.

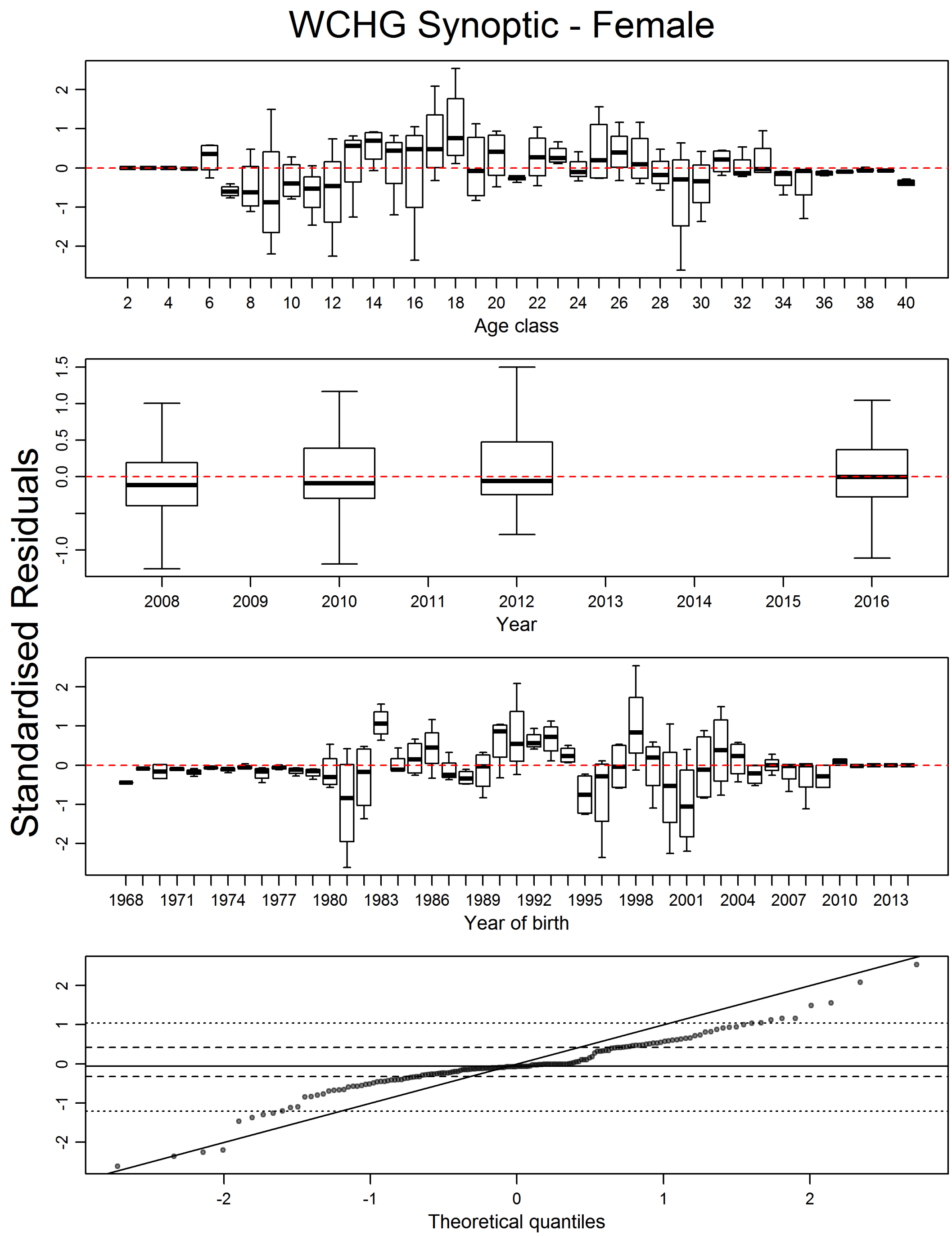


Figure F.17. BC North: Residuals of fits of model to proportions-at-age data (MPD values) for females from WCHG Synoptic survey series. Details as for Figure F.8, for a total of 156 residuals.

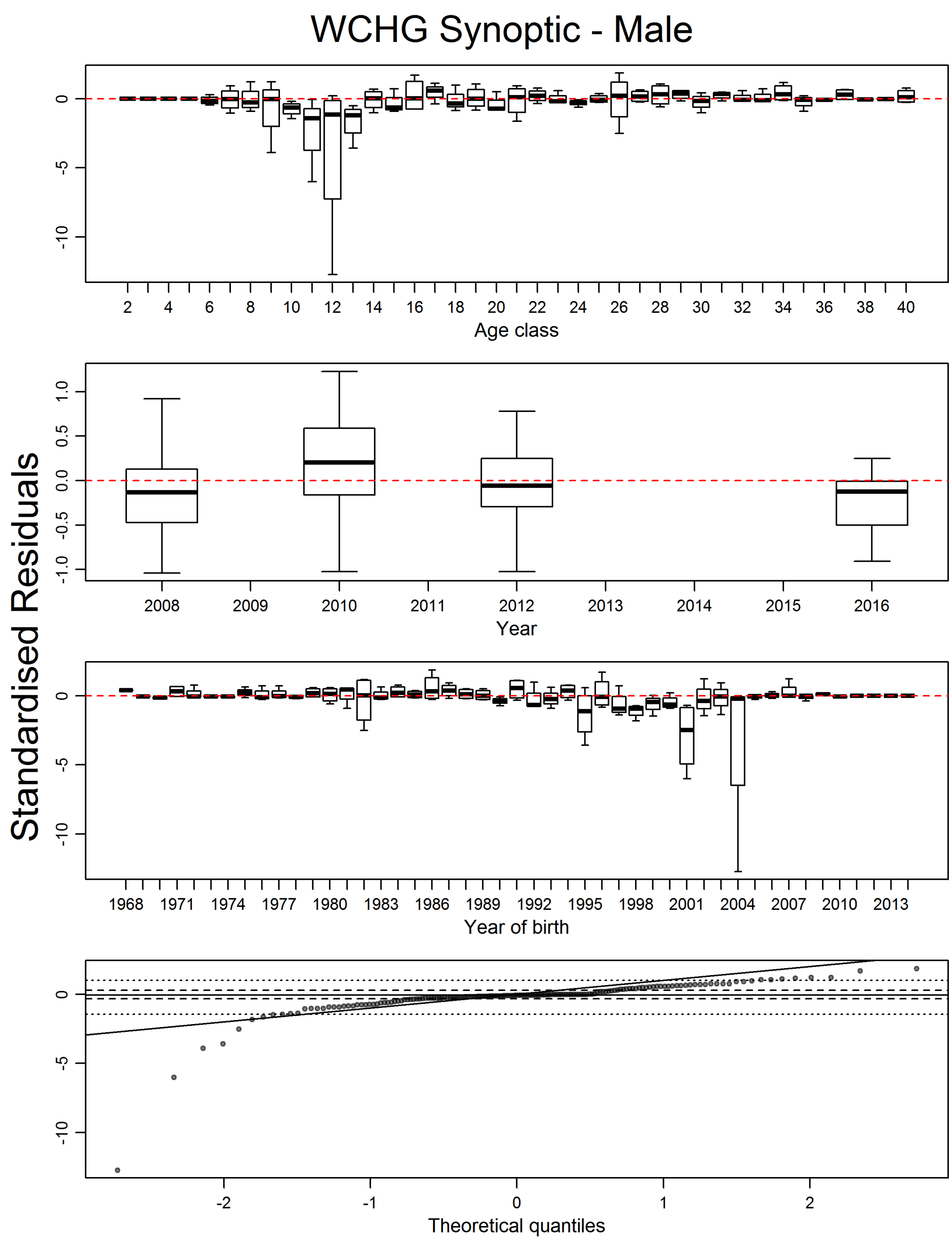


Figure F.18. BC North: Residuals of fits of model to proportions-at-age data (MPD values) for males from WCHG Synoptic survey series. Details as for Figure F.8, for a total of 156 residuals.

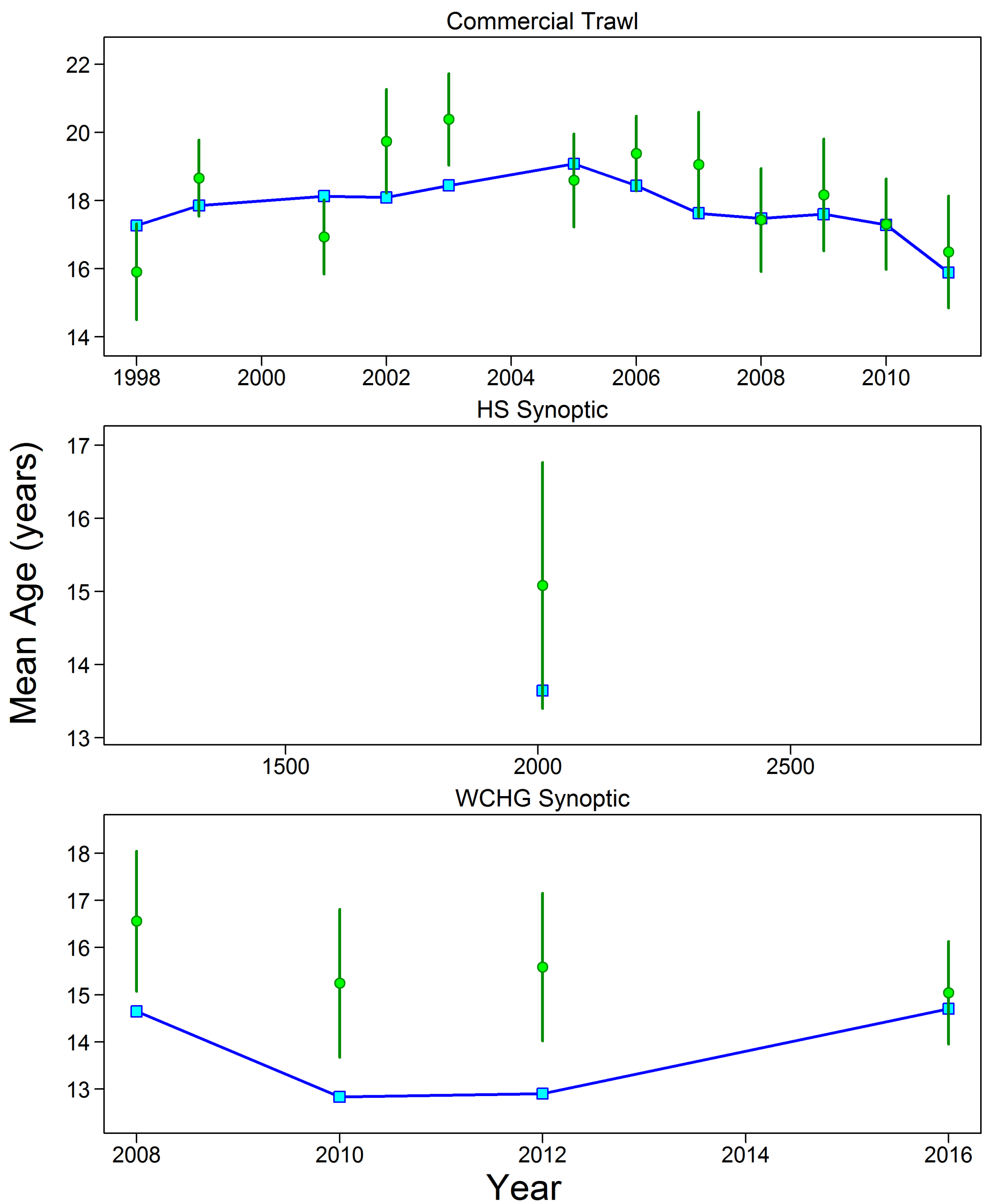


Figure F.19. BC North: Mean ages each year for the data (solid circles) with 95% confidence intervals and model estimates (joined open squares) for the commercial and survey age data.

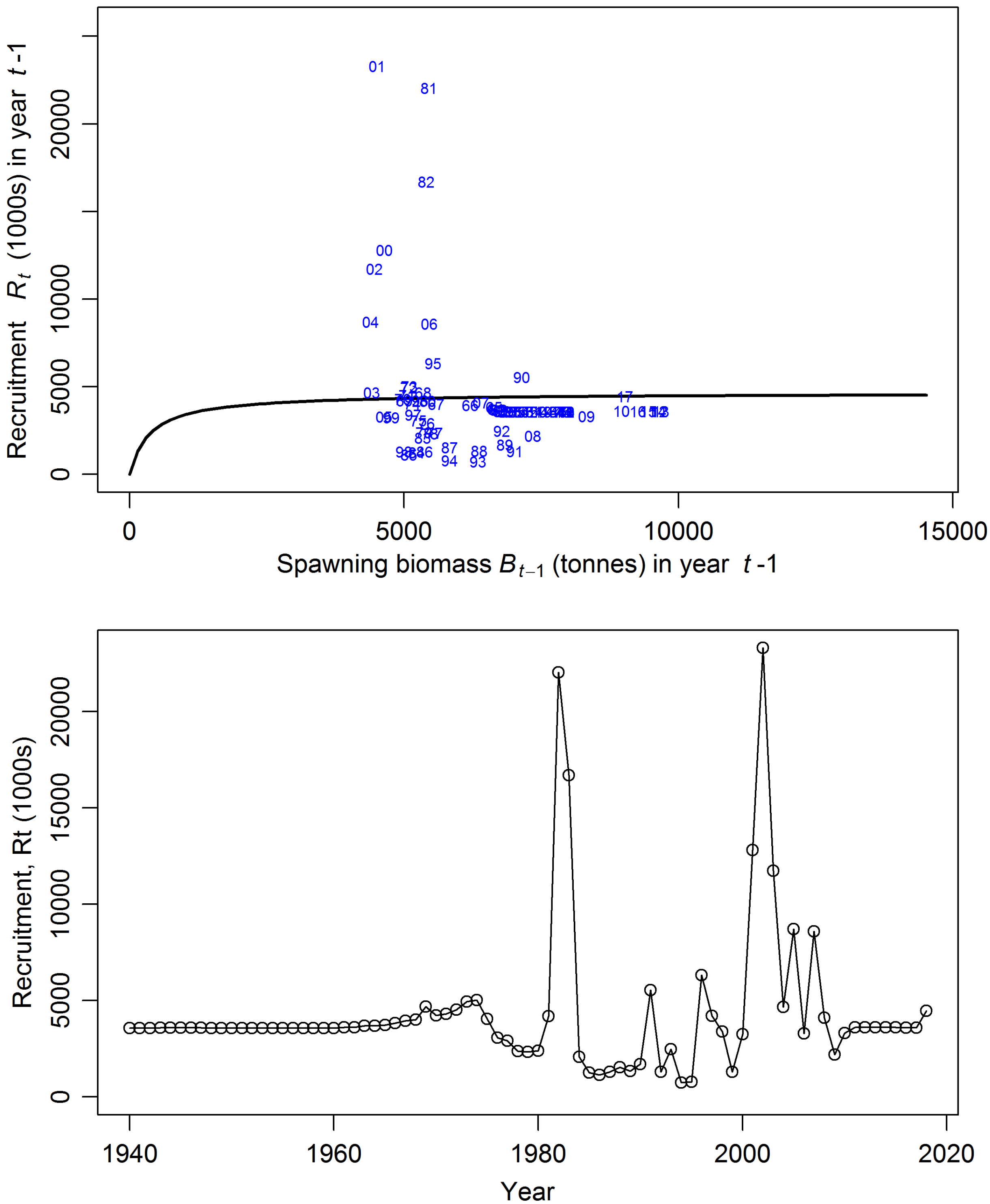
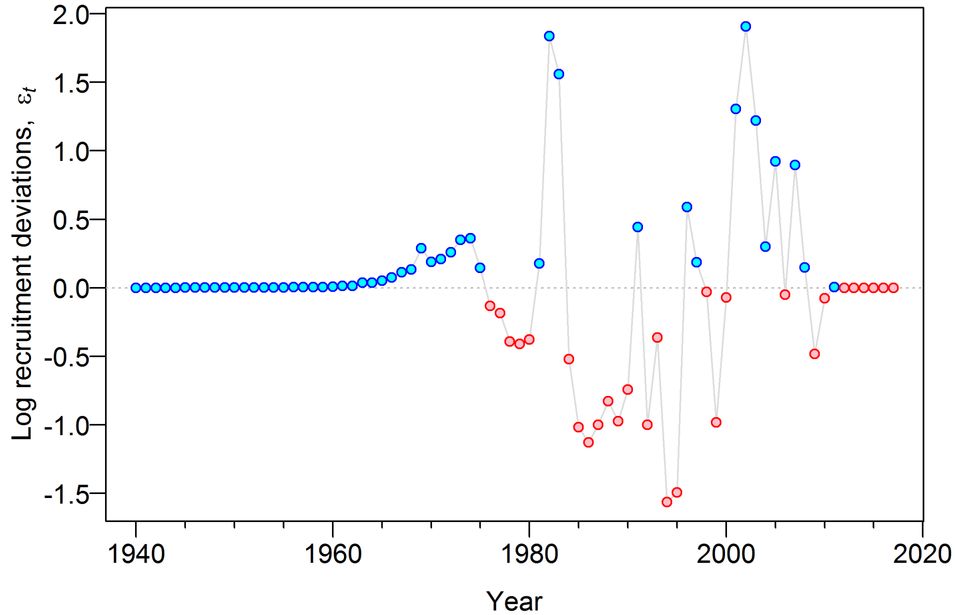


Figure F.20. BC North: Top: Deterministic stock-recruit relationship (black curve) and observed values (labelled by year of spawning) using MPD values. Bottom: Recruitment (MPD values of age-1 individuals in year t) over time, in 1,000s of age-1 individuals, with a mean of 4,369.4.



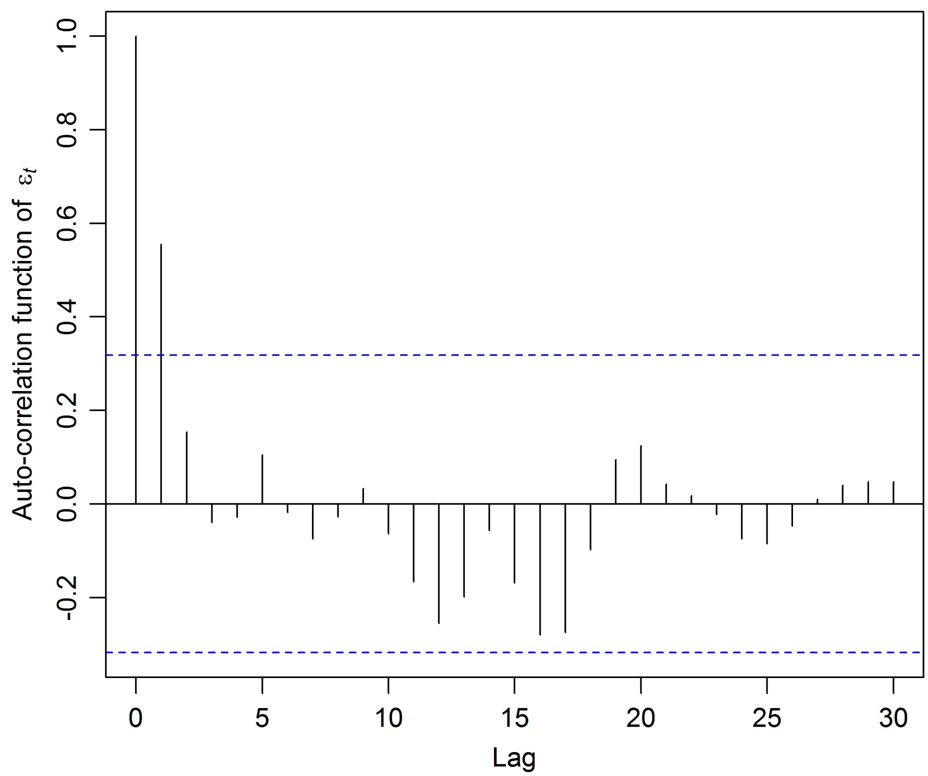


Figure F.21. BC North: Top: log of the annual recruitment deviations, ϵ_t, where bias-corrected multiplicative deviation is e$^{\epsilon_t - \sigma_R^2/2}$ where $\epsilon_t \sim$ Normal$(0, \sigma_R^2)$. Bottom: Auto-correlation function of the logged recruitment deviations (ϵ_t), for years 1969-2006. The start of this range is calculated as the first year of commercial age data (1998) minus the accumulator age class (A =40) plus the age for which commercial selectivity for females is 0.5 (namely 11); 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 (2017) minus the age for which commercial selectivity for females is 0.5 (namely 11).

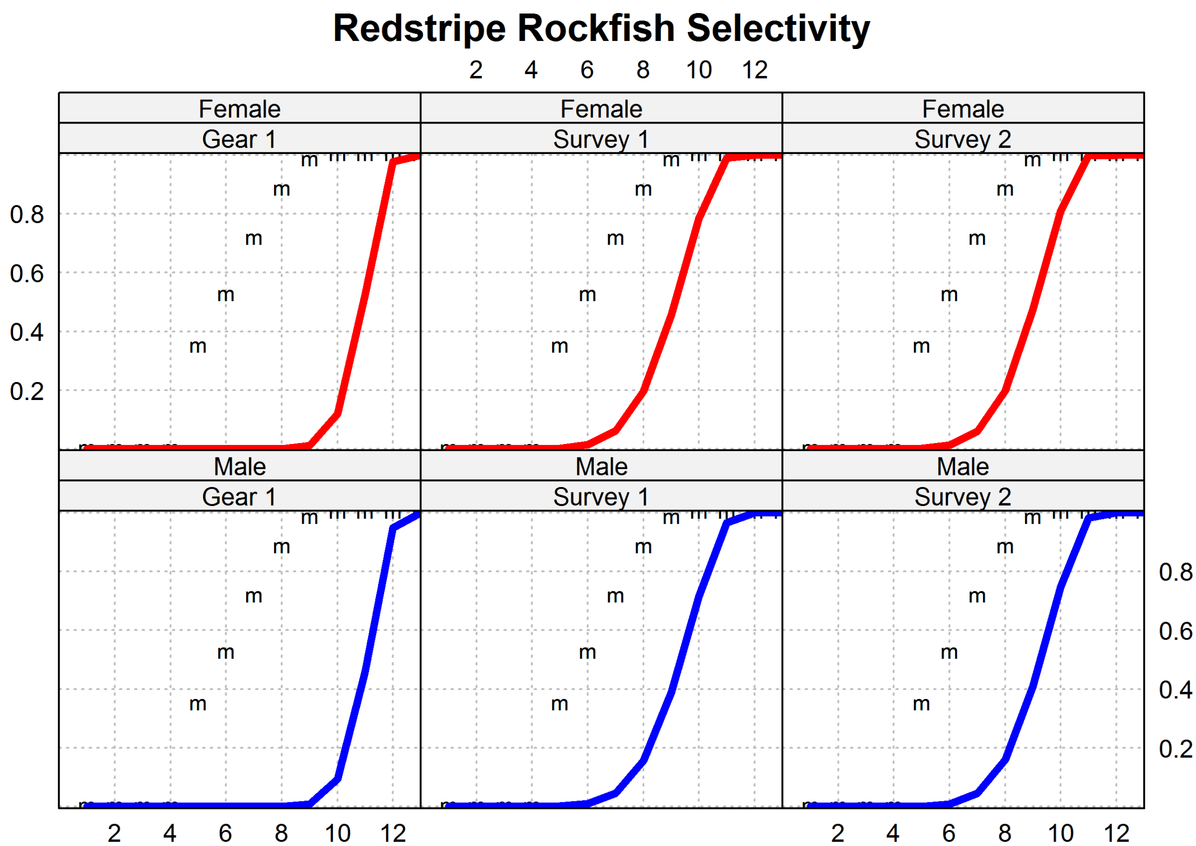


Figure F.22. BC North: Selectivities for commercial catch (Gear 1: Commercial Trawl) and surveys (all MPD values), with maturity ogive for females indicated by 'm'.

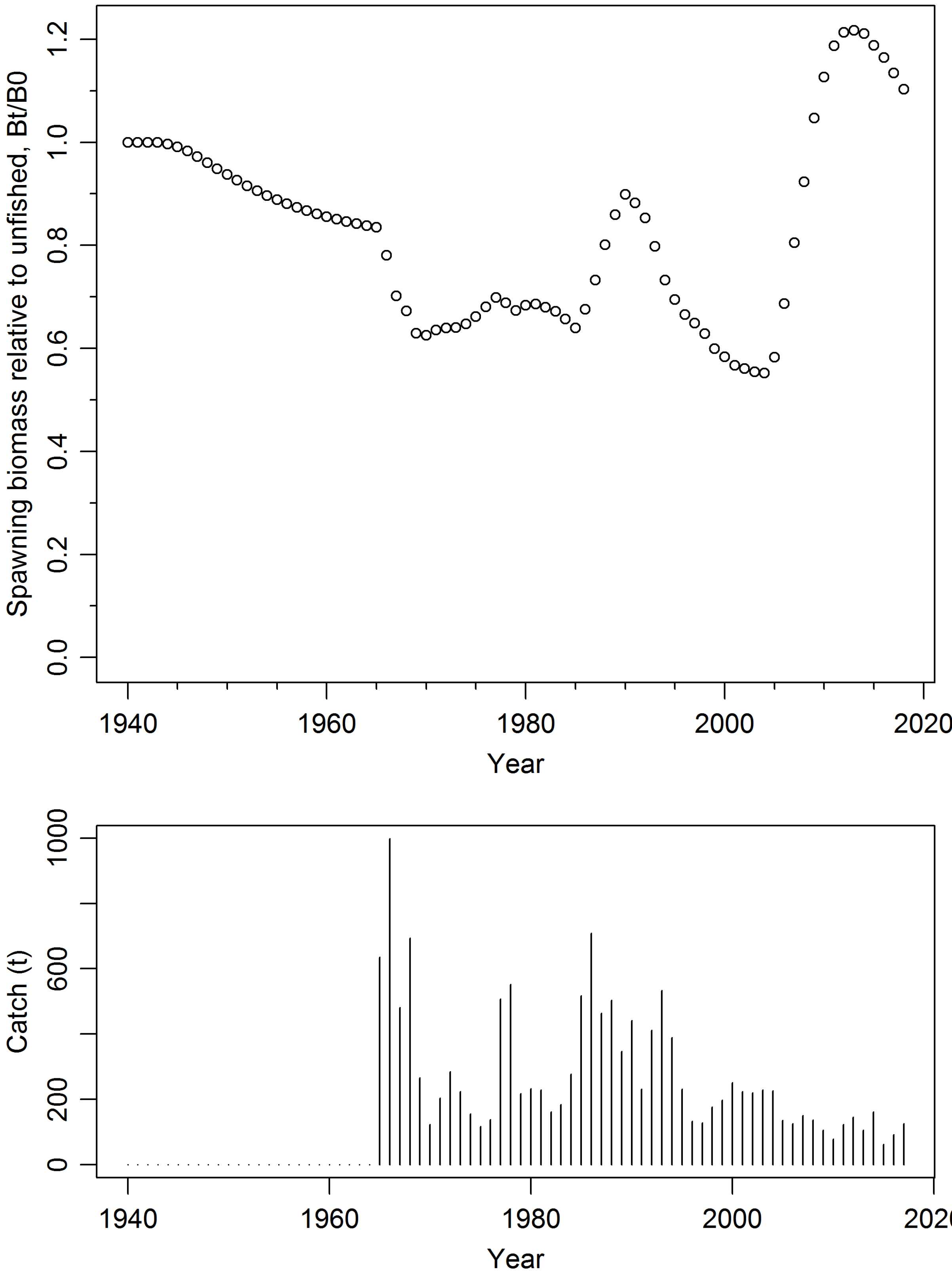
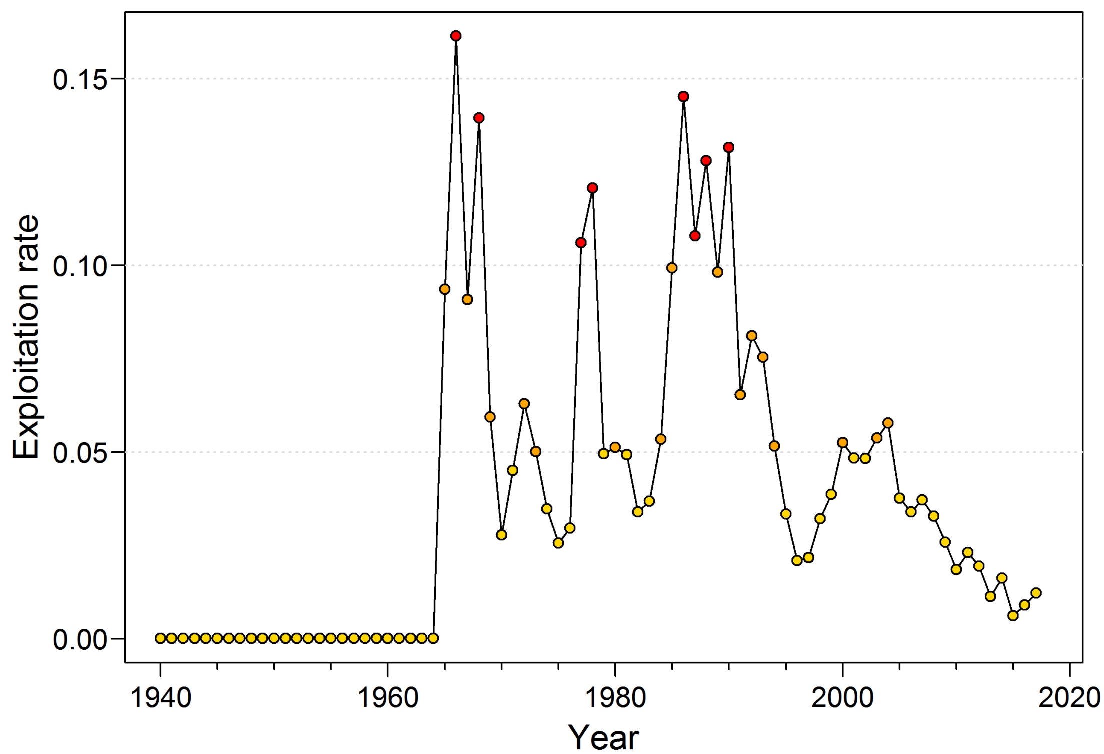


Figure F.23. BC North: Spawning biomass (mature females) relative to unfished level, B_t/B_0, and commercial catch, for the base case.



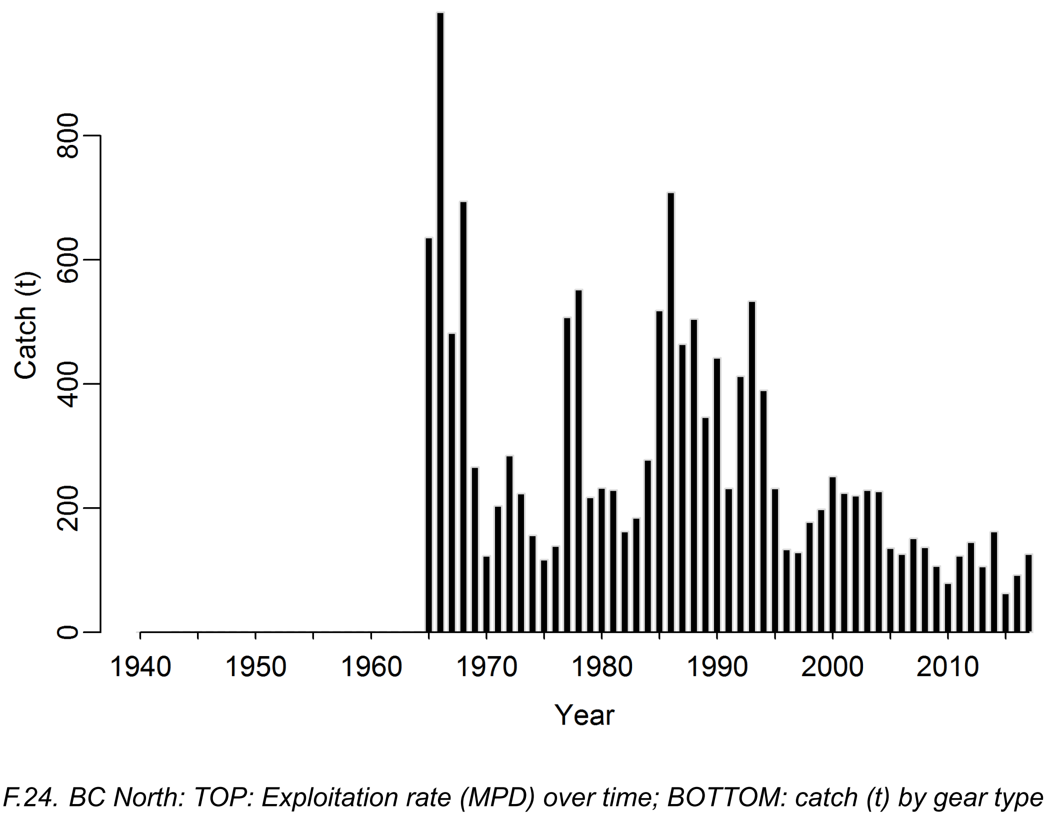


Figure F.24. BC North: TOP: Exploitation rate (MPD) over time; BOTTOM: catch (t) by gear type for the base case.

F.2.1.2. BCN Bayesian Markov chain Monte Carlo (MCMC)

Reweight 1 was chosen for the MCMC analysis based on Equation E.33. The MCMC procedure performed 24,000,000 iterations, sampling every 20,000$^{\mathrm{th}}$ to give 1,200 MCMC samples. The first 200 samples were discarded and 1,000 samples were used for the MCMC analysis. The quantiles (0.05, 0.50, 0.95) for estimated parameters and derived quantities appear in Tables F.4 and F.5. The current year median estimate of B_{2018} is 6,500 t and the median estimate of B_{2018}/B_0 is 0.914.

The MCMC plots show:

- traces for 1,000 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);
- pairs plots showing how each sampled parameter relates to the others (Figure F.28);
- pairs plots showing how MSY-derived paramters relate to the others (Figure F.29);
- traces for 1,000 samples of female spawning biomass at five-year intervals (Figure F.30);
- traces for 1,000 samples of recruitment estimates at five-year intervals (Figure F.31);
- marginal posterior densities for the primary parameters compared to their respective prior density functions (Figure F.32);
- marginal posterior densities for beginning year female spawning biomass at five-year intervals (Figure F.33);
- marginal posterior densities for recruitment at five-year intervals (Figure F.34);
- estimated vulnerable biomass and catch over time (Figure F.35);
- median ratios of spawning biomass and vulnerable biomass to their respective unfished equilibrium values (Figure F.36);
- marginal posterior distribution of recruitment over time (Figure F.37);
- marginal posterior distribution of exploitation rate over time (Figure F.38);
- phase plot through time of median ratios of B_t/B_{MSY} and $u_{t\text{-}1}/u_{\mathrm{MSY}}$ (Figure F.39).

MCMC traces show acceptable convergence properties (no trend with increasing sample number) for the estimated parameters (Figure F.25), as do diagnostic analyses that split the posterior samples into three equal consecutive segments (Figure F.26) and the check for parameter autocorrelation out to 60 lags (Figure F.27). Some of the parameters (e.g., h and μ_3) moved from the initial MPD estimate to a median value that differs from the MPD (Figure F.25), indicating that the MCMC search found plausible fits to the data at levels other than those found by the ‘best fit’. Pairs plots of the estimated parameters (Figure F.28) show no undesirable or unexpected correlations between parameters. In particular, steepness h and the natural mortality parameters (M_1,M_2) show little correlation, suggesting that sufficient data exist to estimate these parameters simultaneously. Trace plots of the derived quantities ‘female spawning biomass’ (Figure F.30) and recruitment (Figure F.31) also show good convergence properties.

The marginal posterior distribution for h is almost unchanged from the informed prior (Figure F.32), indicating that there is very little information in the model data to update this prior. Similarly, the posterior distribution for M_1 closely resembles the informed prior, except for a small shift to the left (lower M). In contrast, the M_2 posterior distribution has shifted to the right of the prior distribution, indicating that the male age composition data tend to favour a higher M. Corresponding summary statistics for the estimated parameters are given in Table F.4.

The marginal posterior distributions of vulnerable biomass and catch (Figure F.35) show long periods of stable standing stock punctuated by periodic declines, e.g., after 1966 during the foreign fleet activity and in the late 1980s and early 1990s as an emergent domestic trawl fleet increased its activity. There are also periods of notable population increases, associated with the major recruitment events of 1982 and 1996 (Figure F.37). The median spawning biomass relative to unfished equilibrium values (Figure F.36) reached a minimum of 0.48 in 1999 and currently sits at 0.914.

Median exploitation rates were higher than median female natural mortality (0.106) during the years 1966, 1968, 1977-1978, and 1985-1990, peaking in 1986 at a median value of 0.176 (Figure F.38). A phase plot of the time-evolution of spawning biomass and exploitation rate in MSY space (Figure F.39) suggests that the stock is underutilized, with a current position at $B_{2018}/B_{\mathrm{MSY}}$ = 3.156 (2.015-3.999) and $u_{2017}/u_{\mathrm{MSY}}$ = 0.025 (0.011-0.154).

F.2.1.2.1. BCN MCMC tables for base case

Table F.4. BC North: The 5$^{\mathrm{th}}$, 50$^{\mathrm{th}}$, and 95$^{\mathrm{th}}$ percentiles for model parameters derived via MCMC estimation (defined in Appendix E).

	5%	50%	95%
R_0	2,602	3,885	6,359
M_1	0.09191	0.1059	0.1193
M_2	0.1047	0.1182	0.1314
h	0.4344	0.7248	0.9298
q_1	0.008145	0.01571	0.03293
q_2	0.02926	0.05779	0.1169
q_3	0.0001197	0.0002154	0.0003570
μ_1	9.123	11.08	12.90
μ_2	10.56	11.43	12.62
μ_3	11.38	11.76	12.22
Δ_1	0.1047	0.2183	0.3252
Δ_2	0.1142	0.2187	0.3266
Δ_3	-0.1963	0.06942	0.3391
$\log v_{1L}$	1.066	2.008	3.294
$\log v_{2L}$	1.272	1.883	2.445
$\log v_{3L}$	0.5646	0.9030	1.231

Table F.5. BC North: The 5$^{\mathrm{th}}$, 50$^{\mathrm{th}}$ and 95$^{\mathrm{th}}$ percentiles of MCMC-derived quantities from the 1,000 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_{2018} – spawning biomass at the start of 2018, V_{2018} – vulnerable biomass in the middle of 2018, u_{2017} – exploitation rate (ratio of total catch to vulnerable biomass) in the middle of 2017, $u_{\max}$ – maximum exploitation rate (calculated for each sample as the maximum exploitation rate from 1940-2017), 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 (2013-2017) is 109 t.

Value	Percentile		
	5%	50%	95%
	From model output		
B_0	5,611	7,216	10,083
$V_{0,g=3}$	5,910	7,606	10,733
B_{2018}	4,193	6,500	11,079
$V_{2018,g=3}$	4,605	7,455	12,935
B_{2018}/B_0	0.692	0.914	1.129
$V_{2018,g=3}/V_{0,g=3}$	0.718	0.99	1.267
$u_{2017,g=3}$	0.009	0.016	0.027
$u_{\max}$	0.127	0.187	0.281
	MSY-based quantities		
MSY	281	497	787
B_{MSY}	1,488	2,135	3,411
$0.4B_{\mathrm{MSY}}$	595	854	1,364
$0.8B_{\mathrm{MSY}}$	1,190	1,708	2,728
$B_{2018}/B_{\mathrm{MSY}}$	2.015	3.156	3.999
B_{MSY}/B_0	0.25	0.293	0.379
V_{MSY}	474	848	2,578
$V_{\mathrm{MSY}}/V_{0,g=3}$	0.073	0.107	0.293
u_{MSY}	0.12	0.638	0.99
$u_{2017,g=3}/u_{\mathrm{MSY}}$	0.011	0.025	0.154

F.2.1.2.2. BCN MCMC figures for base case

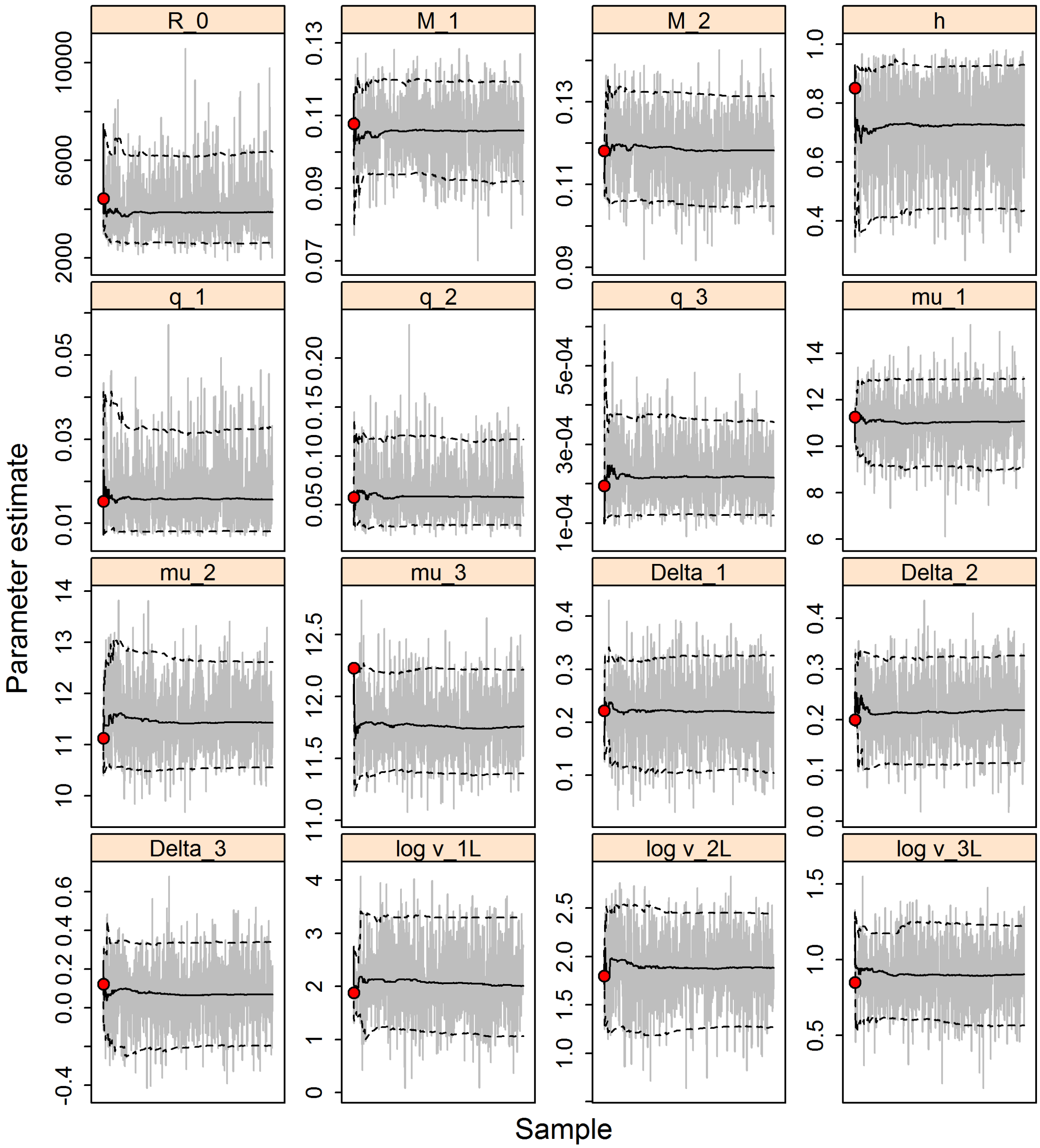


Figure F.25. BC North: MCMC traces for the estimated parameters. Grey lines show the 1,000 samples for each parameter, solid lines show the cumulative median (up to that sample), and dashed lines show the cumulative 0.05 and 0.95 quantiles. Red circles are the MPD estimates. For parameters other than M (if estimated), subscripts ≤ 2 correspond to fishery-independent surveys, and subscripts ≥ 3 denote the commercial fishery. Parameter notation is described in Appendix E.

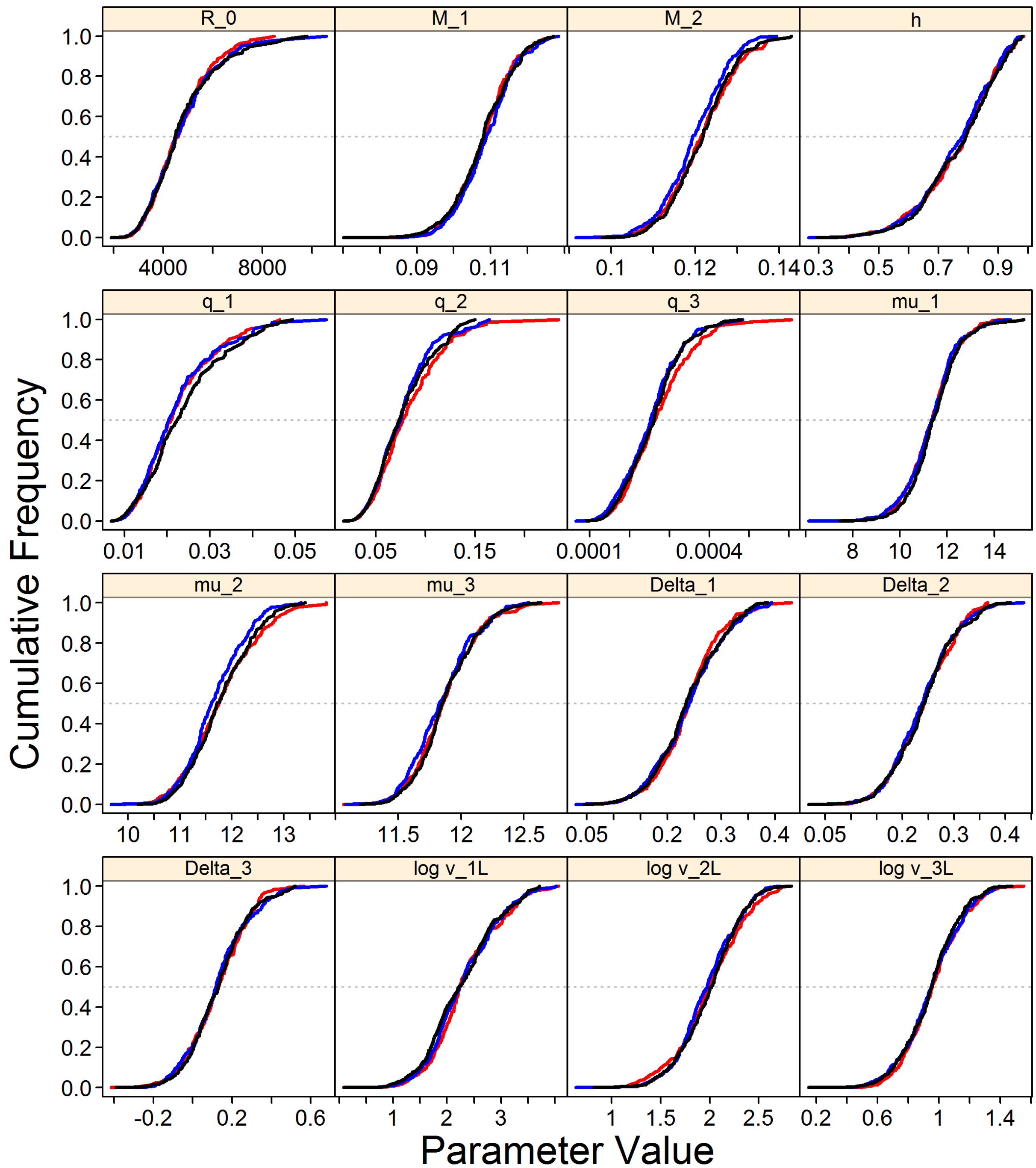


Figure F.26. BC North: Diagnostic plot obtained by dividing the MCMC chain of 1,000 MCMC samples into three segments, and overplotting the cumulative distributions of the first segment (red), second segment (blue) and final segment (black).

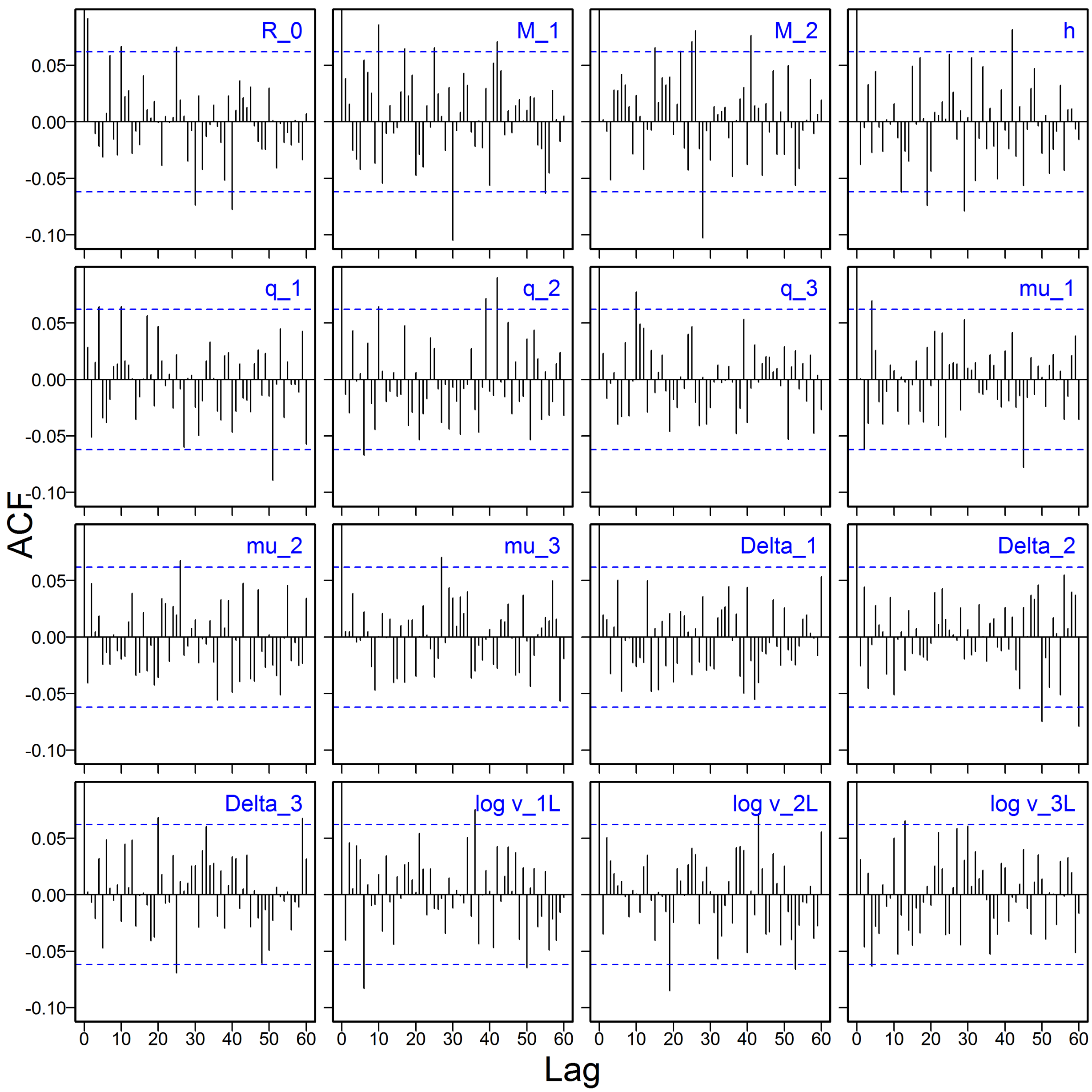


Figure F.27. BC North: Autocorrelation plots for the estimated parameters from the MCMC output. Horizontal dashed blue lines delimit the 95% confidence interval for each parameter's set of lagged correlations.

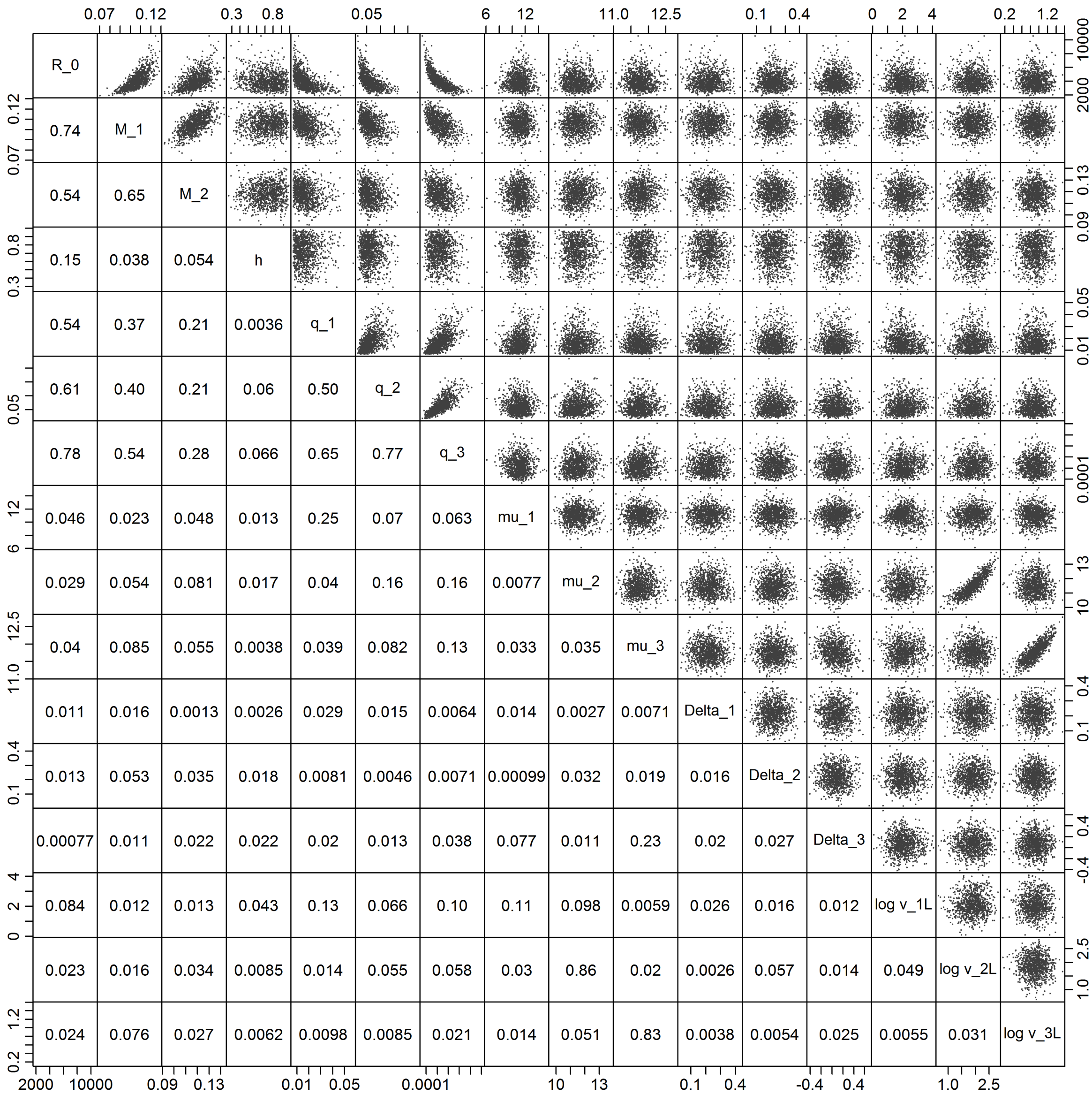


Figure F.28. BC North: Pairs plot of 1,000 MCMC samples for 16 parameters. Numbers in the lower panels are the absolute values of the correlation coefficients.

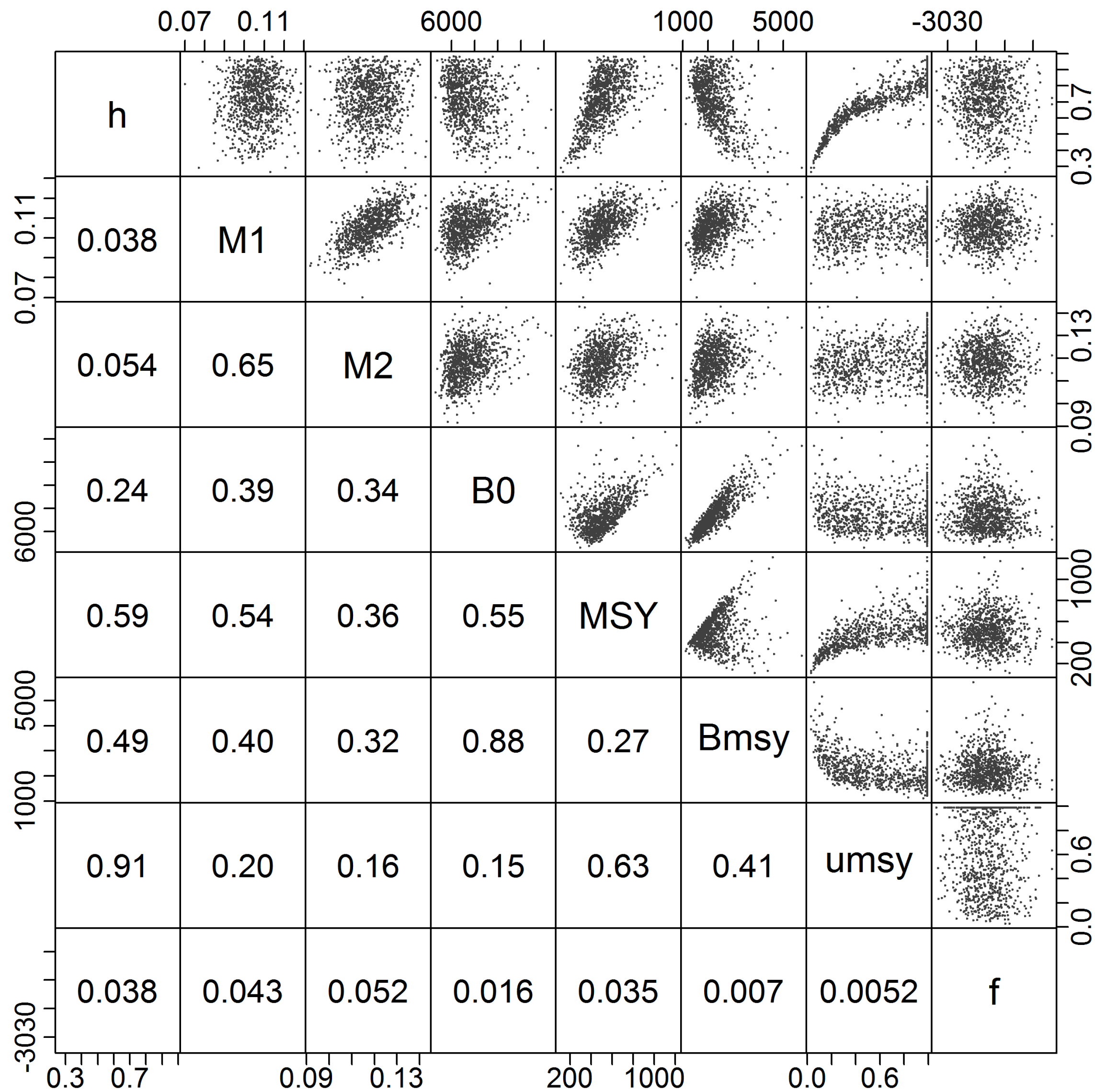


Figure F.29. BC North: Pairs plot of 1,000 MCMC samples comparing some parameters, key derived quantities, and function value (f). Numbers in the lower panels are the absolute values of the correlation coefficients.

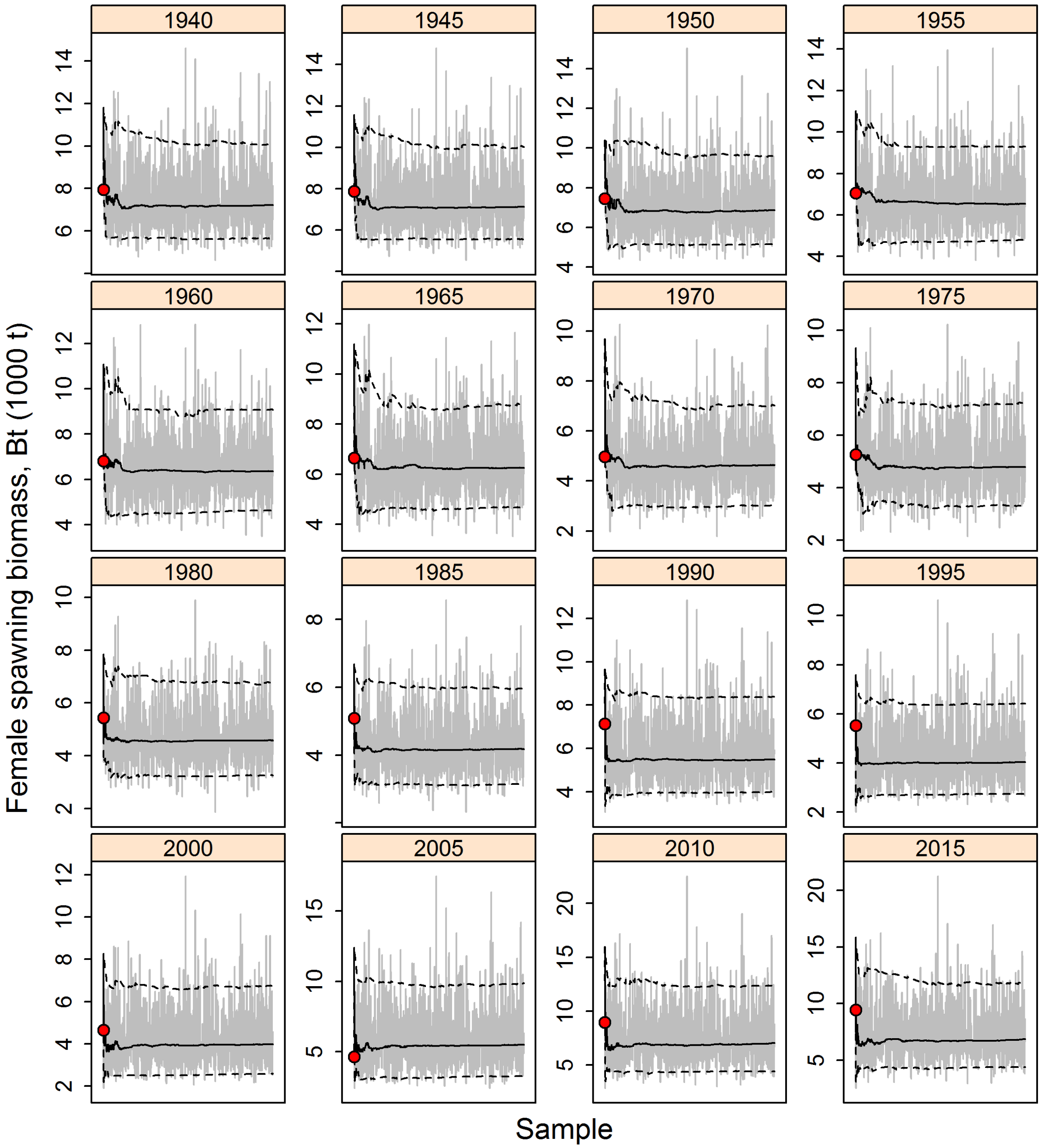


Figure F.30. BC North: MCMC traces for female spawning biomass estimates at five-year intervals. Note that vertical scales are different for each plot (to show convergence of the MCMC chain, rather than absolute differences in annual values). Grey lines show the 1,000 samples for each parameter, solid 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.

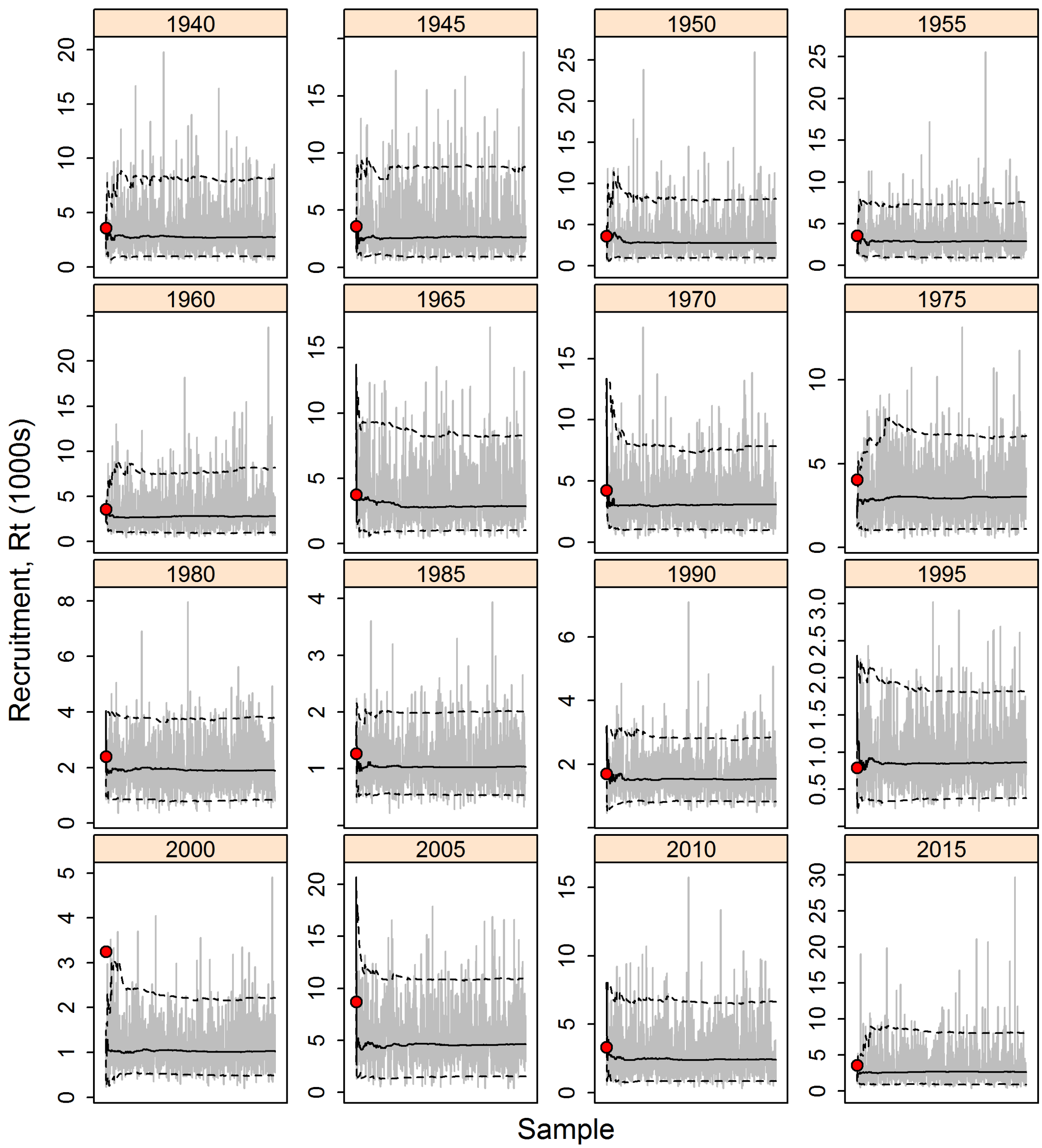


Figure F.31. BC North: MCMC traces for recruitment estimates at five-year intervals. Note that vertical scales are different for each plot (to show convergence of the MCMC chain, rather than absolute differences in annual recruitment). Grey lines show the 1,000 samples for each parameter, solid lines 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.

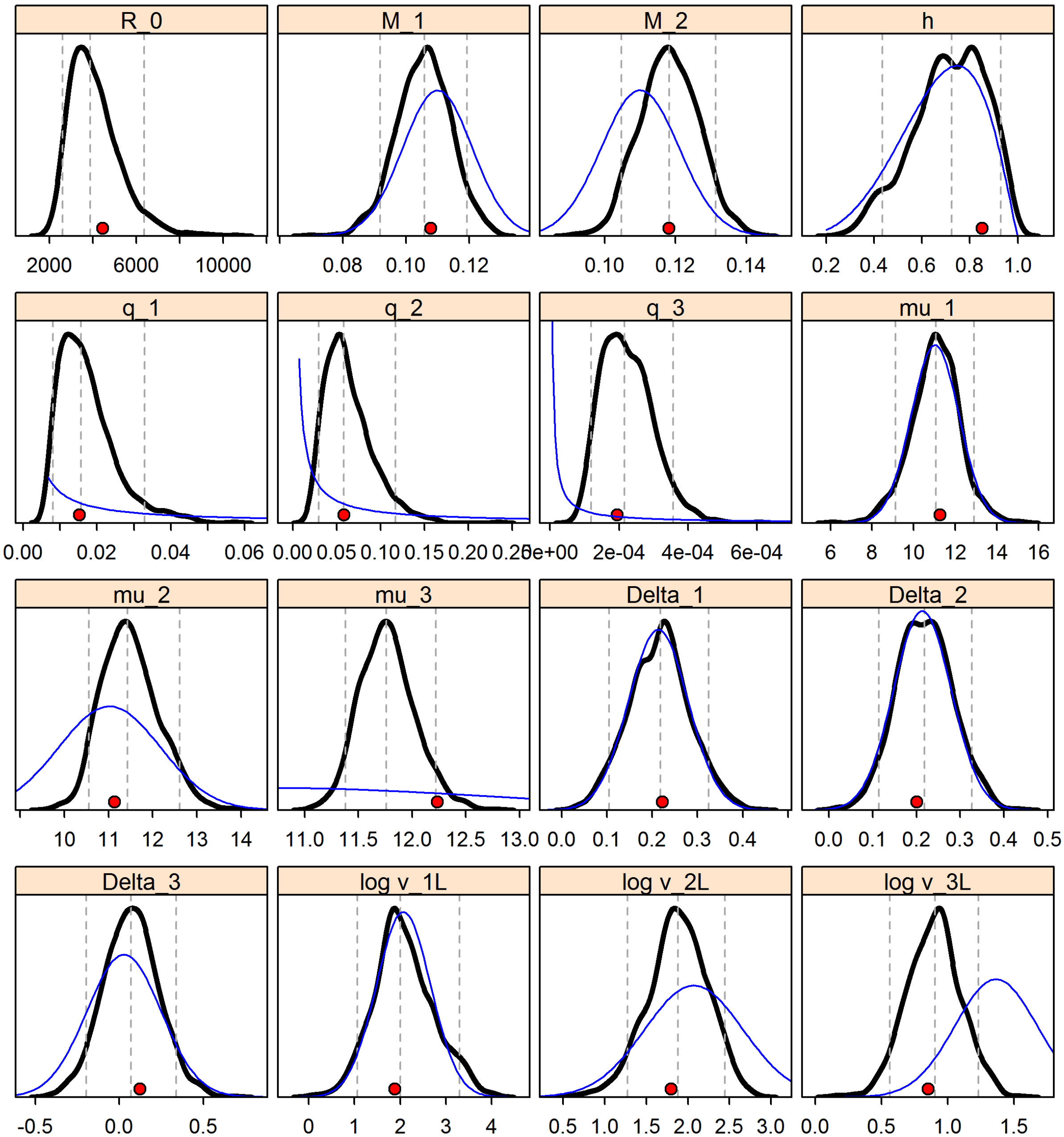


Figure F.32. BC North: Marginal posterior densities (thick black curves) and prior density functions (thin blue curves) for the estimated parameters. Vertical lines represent the 5, 50 and 95 percentiles, and red filled circles are the MPD estimates. For R_0 the prior is a uniform distribution on the range [1, 10000000]. 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).

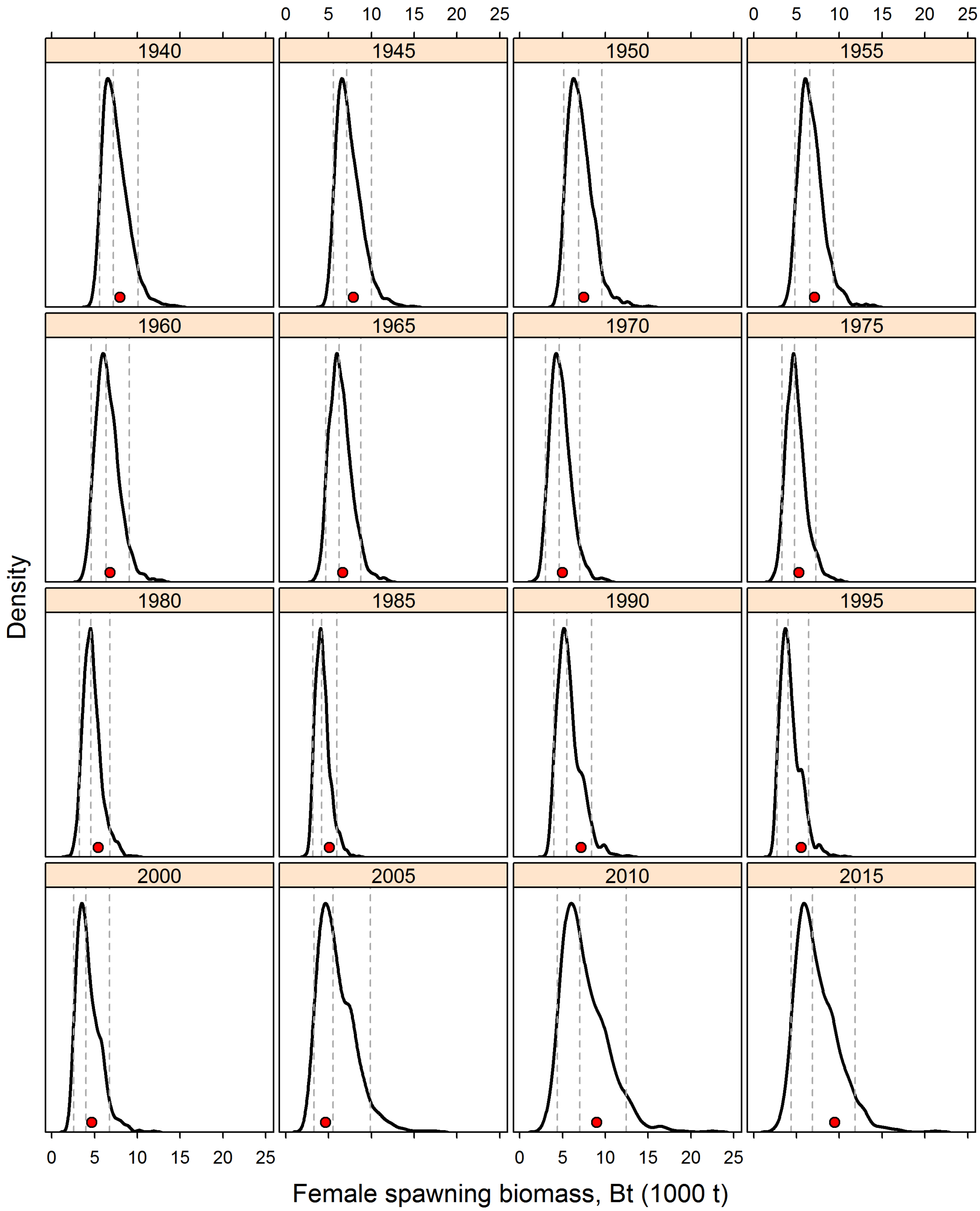


Figure F.33. BC North: Marginal posterior densities for beginning year female spawning biomass (1,000 tonnes) every 5 years starting in 1940 for the base case. Horizontal axes are all to same scale. Note that vertical axes are not to the same scale, but each is scaled to the peak of the density; with the area under each curve integrating to 1.0. Vertical lines are 5, 50 and 95 percentiles, and filled red circle indicates MPD value.

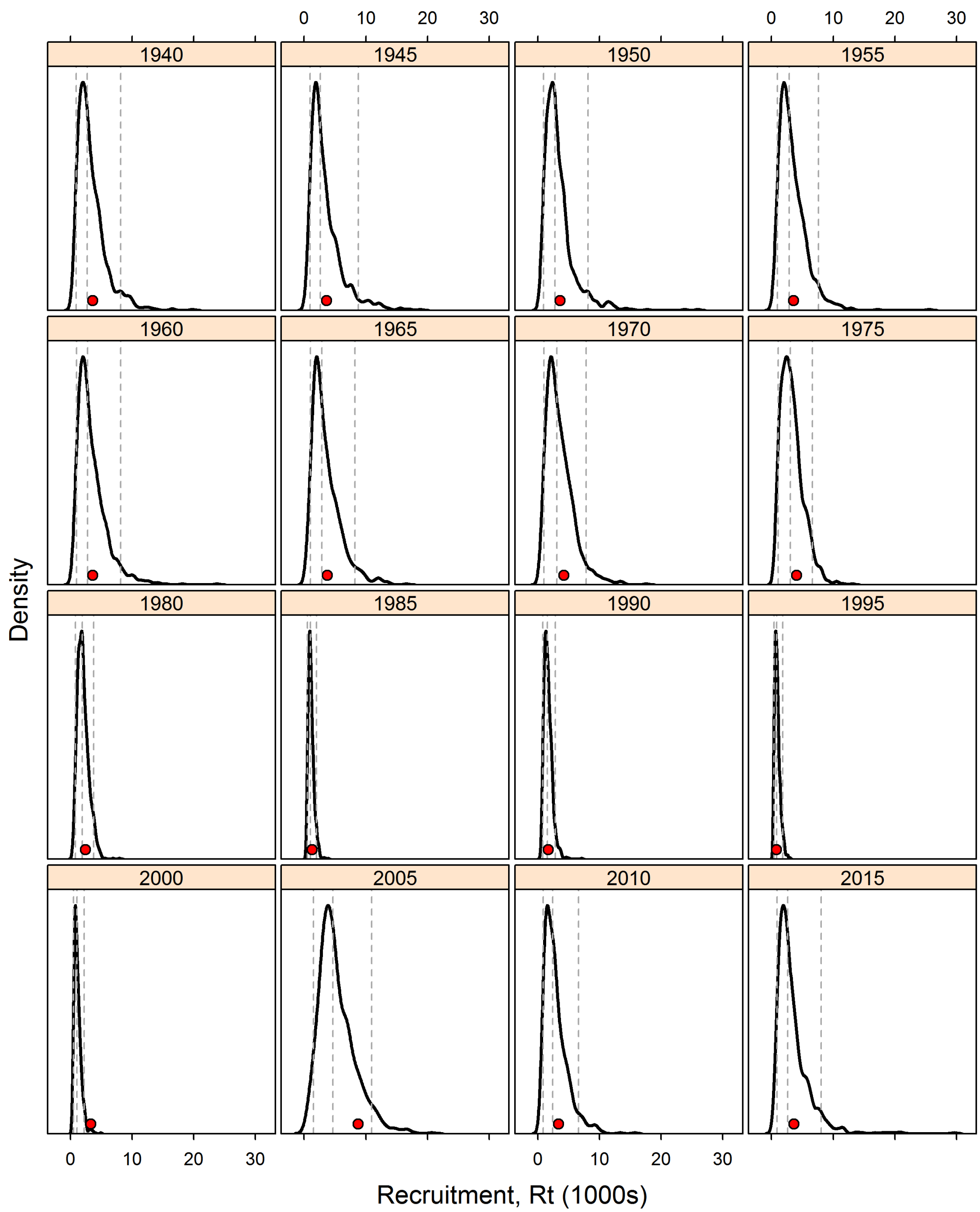


Figure F.34. BC North: Marginal posterior densities for recruitment every 5 years starting in 1940 for the base case. Horizontal axes are all to same scale, such that large recruitments in certain large years can be seen. Note that vertical axes are not to the same scale, but each is scaled to the peak of the density; areas under each curve will integrate to 1.0. Vertical lines are 5, 50 and 95 percentiles, and filled red circle indicates MPD value.

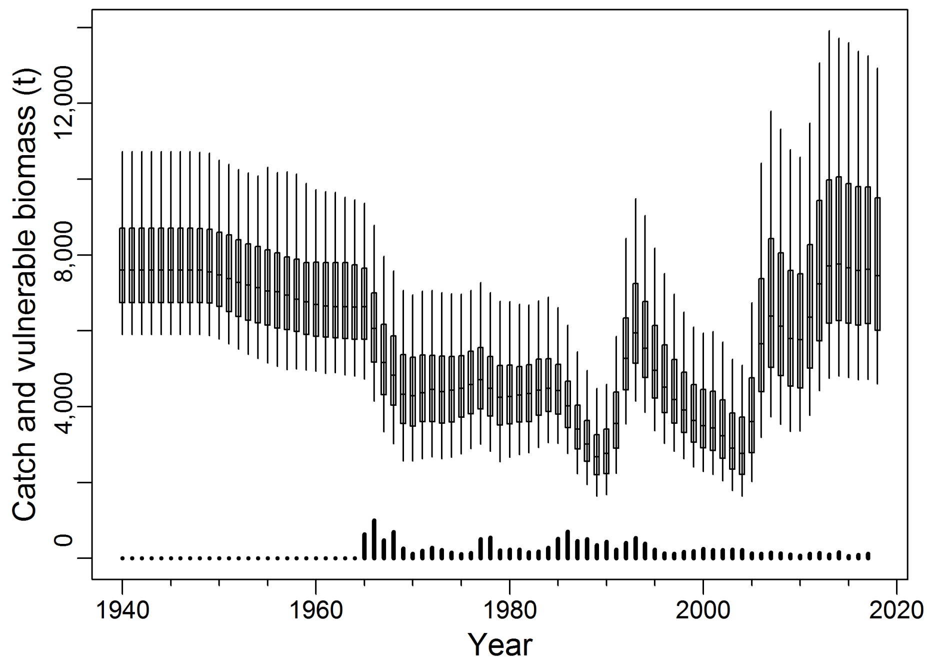


Figure F.35. BC North: Estimated vulnerable biomass (boxplots) and commercial catch (vertical bars), in tonnes, over time. Boxplots show the 5, 25, 50, 75 and 95 percentiles from the MCMC results. Catch is shown to compare its magnitude to the estimated vulnerable biomass.

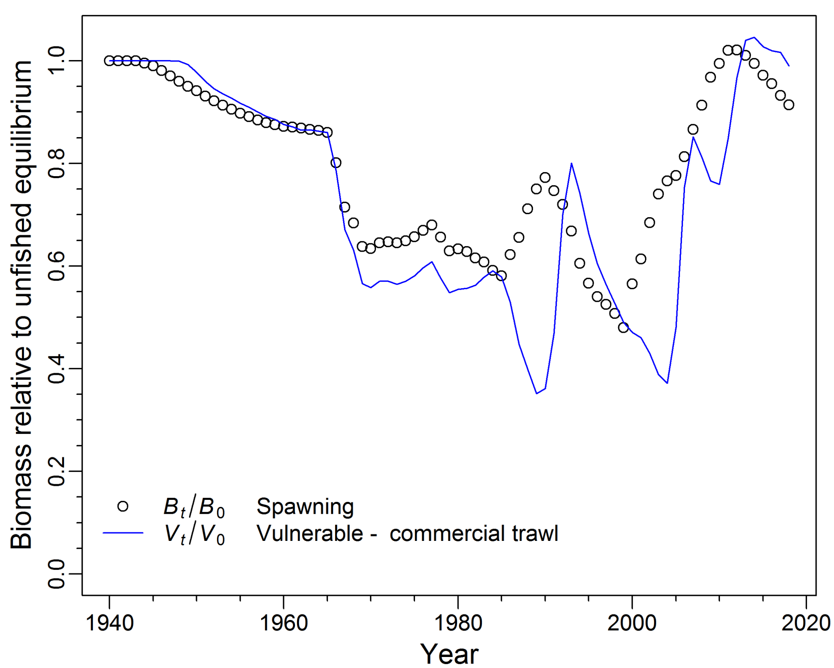


Figure F.36. BC North: Changes in B_t/B_0 and V_t/V_0 (spawning and vulnerable biomass relative to unfished equilibrium levels) over time, shown as the medians of the MCMC posteriors.

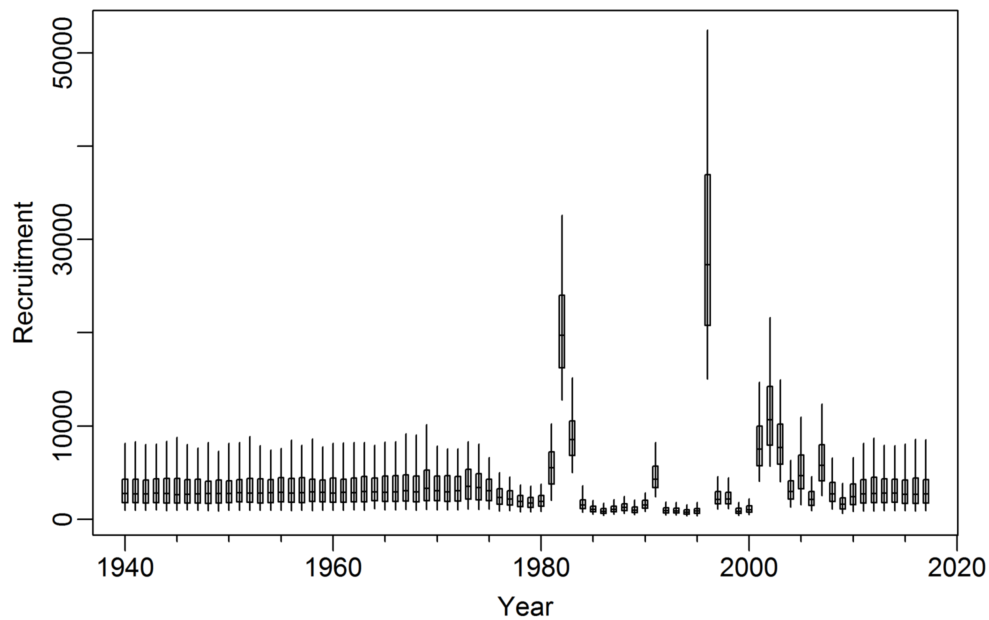


Figure F.37. BC North: Marginal posterior distribution of recruitment in 1,000s of age-1 fish plotted over time. Boxplots show the 5, 25, 50, 75 and 95 percentiles from the MCMC results. Note that the first year for which there are age data is 1998, and the plus-age class is 40, such that there are no direct data concerning age-1 fish before 1959. Also, the final few years have no direct age-data from which to estimate recruitment, because fish are not fully selected until age 11.8 by the commercial vessels or age 11.3 by surveys (mean of the MCMC median ages at full selectivity for commercial catch, μ_3, and survey $\mu_{1,2}$, respectively).

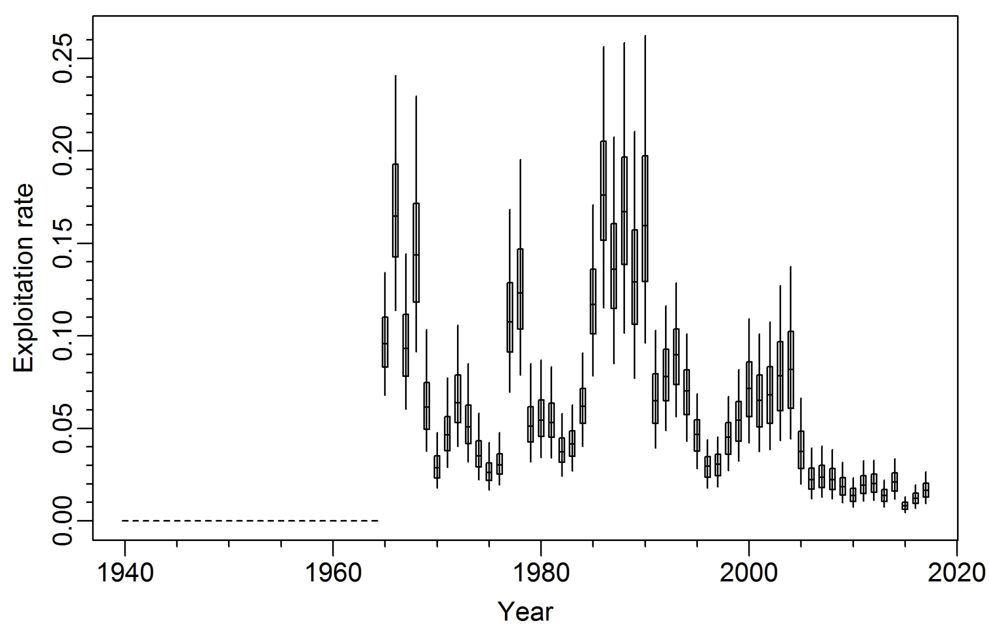


Figure F.38. BC North: Marginal posterior distribution of exploitation rate plotted over time. Boxplots show the 5, 25, 50, 75 and 95 percentiles from the MCMC results.

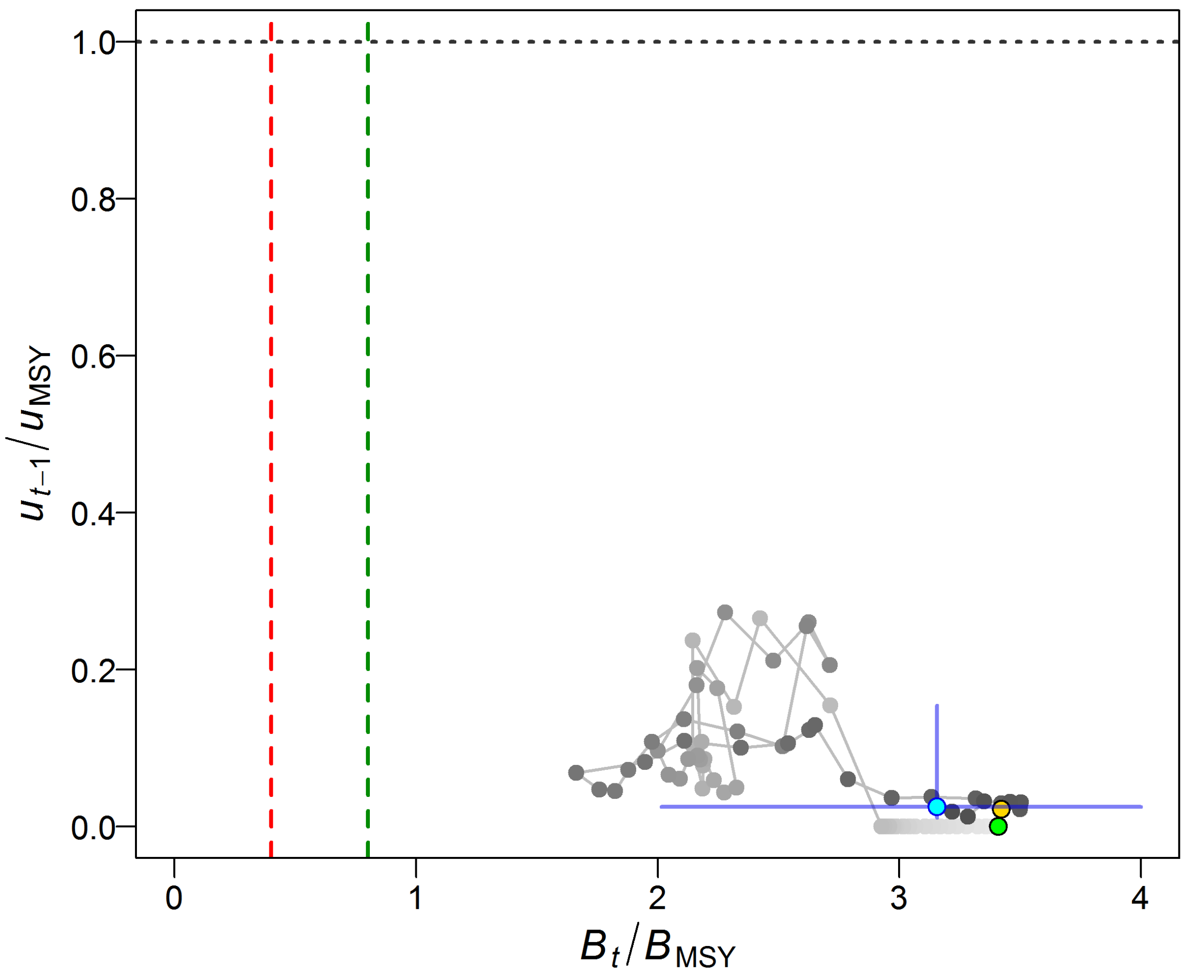


Figure F.39. BC North: Phase plot through time of the medians of the ratios B_t/B_{MSY} (the spawning biomass in year t relative to B_{MSY}) and u_{t-1}/u_{MSY} (the exploitation rate in year $t-1$ relative to u_{MSY}). The filled cyan circle is the starting year (1941). Years then proceed from light grey through to dark grey with the final year (2018) as a filled blue circle, and the blue lines represent the 10% and 90% percentiles of the posterior distributions for the final year. The filled gold circle indicates the status in 2010 ($B_{2010}/B_{\mathrm{MSY}}$, $u_{2009}/u_{\mathrm{MSY}}$), which coincides with the previous assessment in 2011. 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.

F.2.1.3. BCN Projection Results and Decision Tables

Projections were made to evaluate the future behaviour of the population under different levels of constant catch, given the model assumptions. The projections, starting with the biomass at the beginning of 2018, were made over a range of constant annual catch strategies (0-2,000 t) for each of the 1,000 MCMC samples in the posterior, generating future biomass trends by assuming random recruitment deviations. Future recruitments were generated through the stock-recruitment function using recruitment deviations drawn randomly from a lognormal distribution with zero mean and constant standard deviation (see Appendix E for full details). Projections were made for 5 years, which means that projected biomass levels will be based on recruitments estimated during the model reconstruction, rather than the stock recruitment function, given the $\sim$10 year lag before recruitment to the commercial fishery (Table F.4). Resulting projections of spawning biomass are shown for a range of selected catch strategies (Figure F.40).

The approach of obtaining future recruitments based on mean recruitment and assuming a fixed variability about that mean does not accurately simulate the occasional large recruitment events that characterise this stock and other long-lived rockfish species (Figure F.37). However, as indicated above, nearly all of the recruitments used in these projections are estimated during the stock reconstruction phase, due to the longevity of this species, the relatively late age at maturity (estimated at 9.6 y for females, Appendix D) and the short time frame over which the projections are made.

Decision tables give the probabilities of spawning biomass exceeding various reference points in specified years, calculated by counting the proportion of MCMC samples for which the biomass exceeded the given reference point. Results for the three B_{MSY}-based reference points are presented in Tables F.6-F.8. For example, the estimated probability that the stock is in the provisional healthy zone in 2018 under a constant catch strategy of 1,000 t is P$(B_{2018} > 0.8B_{\mathrm{MSY}}) = 1$ (row '1000' and column '2018' in Table F.7).

Table F.9 provides probabilities that projected spawning biomass B_t will exceed the current-year biomass B_{2018} at the various catch levels. The first column populated by zero values simply means that the current-year biomass will never be greater than itself. If the current mean catch (109 t) is maintained until 2023, the probability that spawning biomass B_{2023} will be greater than B_{2018} is 0.187 (Table F.9).

Table F.10 shows the probabilities of projected exploitation rate u_t exceeding that at MSY (u_{MSY}). Tables F.11 and F.12 offer additional decision tables using 0.2 and 0.4B_0 as reference points, sometimes preferred by other jurisdictions.

For the maximum sustainable yield (MSY) calculations, projections were run across a range of constant exploitation rates u_t between 0 and 0.99, with an increment value of 0.005, until an equilibrium yield was reached within a tolerance of 0.01 t (or until 15,000 years had been reached). This was done for each of the 1,000 samples and the exploitation rate resulting in the highest yield would represent MSY for that MCMC draw. The lower bound of u_t was reached for none of the MCMC samples, and the upper bound was reached by 281 samples. Of the 199,000 projection calculations, all converged by 15,000 years.

F.2.1.3.1. BCN projection tables for base case

Table F.6. BC North: Decision table concerning the limit reference point $0.4B_{\mathrm{MSY}}$ for 1-5 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 (to two decimal places) of the 1000 MCMC samples for which $B_t > 0.4B_{\mathrm{MSY}}$. For reference, the average catch over the last 5 years (2013-2017) is 109 t.

	2018	2019	2020	2021	2022	2023
0	1.000	1.000	1.000	1.000	1.000	1.000
100	1.000	1.000	1.000	1.000	1.000	1.000
200	1.000	1.000	1.000	1.000	1.000	1.000
300	1.000	1.000	1.000	1.000	1.000	1.000
400	1.000	1.000	1.000	1.000	1.000	0.999
500	1.000	1.000	1.000	1.000	0.999	0.999
600	1.000	1.000	1.000	0.999	0.999	0.999
700	1.000	1.000	1.000	0.999	0.999	0.997
800	1.000	1.000	1.000	0.999	0.998	0.997
900	1.000	1.000	0.999	0.999	0.997	0.997
1000	1.000	1.000	0.999	0.999	0.997	0.995
1100	1.000	1.000	0.999	0.997	0.997	0.993
1200	1.000	1.000	0.999	0.997	0.996	0.992
1300	1.000	1.000	0.999	0.997	0.993	0.989
1400	1.000	1.000	0.999	0.997	0.992	0.989
1500	1.000	1.000	0.999	0.997	0.992	0.988
1600	1.000	0.999	0.997	0.996	0.990	0.988
1700	1.000	0.999	0.997	0.994	0.990	0.988
1800	1.000	0.999	0.997	0.994	0.990	0.987
1900	1.000	0.999	0.997	0.992	0.988	0.986
2000	1.000	0.999	0.997	0.992	0.988	0.986

Table F.7. BC North: Decision table concerning the upper stock reference point $0.8B_{\mathrm{MSY}}$ for 1-5 year projections, such that values are P($B_t > 0.8B_{\mathrm{MSY}}$). For reference, the average catch over the last 5 years (2013-2017) is 109 t.

	2018	2019	2020	2021	2022	2023
0	0.999	0.999	0.999	0.999	0.999	0.999
100	0.999	0.999	0.999	0.999	0.999	0.999
200	0.999	0.999	0.999	0.999	0.999	0.999
300	0.999	0.999	0.999	0.999	0.998	0.997
400	0.999	0.999	0.999	0.999	0.997	0.996
500	0.999	0.999	0.999	0.997	0.996	0.996
600	0.999	0.999	0.999	0.996	0.996	0.995
700	0.999	0.999	0.997	0.996	0.995	0.989
800	0.999	0.999	0.997	0.995	0.991	0.979
900	0.999	0.999	0.997	0.994	0.984	0.971
1000	0.999	0.999	0.996	0.992	0.977	0.953
1100	0.999	0.999	0.995	0.985	0.969	0.922
1200	0.999	0.999	0.994	0.980	0.950	0.884
1300	0.999	0.997	0.994	0.977	0.925	0.851
1400	0.999	0.997	0.990	0.968	0.901	0.810
1500	0.999	0.997	0.989	0.954	0.866	0.788
1600	0.999	0.997	0.985	0.939	0.835	0.757
1700	0.999	0.997	0.981	0.921	0.803	0.733
1800	0.999	0.997	0.980	0.892	0.784	0.715
1900	0.999	0.997	0.975	0.875	0.761	0.698
2000	0.999	0.997	0.966	0.844	0.739	0.679

Table F.8. BC North: Decision table concerning the reference point B_{MSY} for 1-5 year projections, such that values are P($B_t > B_{\mathrm{MSY}}$). For reference, the average catch over the last 5 years (2013-2017) is 109 t.

	2018	2019	2020	2021	2022	2023
0	0.999	0.999	0.999	0.999	0.999	0.999
100	0.999	0.999	0.999	0.998	0.996	0.996
200	0.999	0.999	0.996	0.996	0.996	0.996
300	0.999	0.999	0.996	0.996	0.996	0.996
400	0.999	0.997	0.996	0.996	0.996	0.995
500	0.999	0.997	0.996	0.996	0.994	0.990
600	0.999	0.996	0.996	0.995	0.989	0.986
700	0.999	0.996	0.996	0.992	0.985	0.977
800	0.999	0.996	0.994	0.986	0.978	0.964
900	0.999	0.996	0.993	0.984	0.973	0.931
1000	0.999	0.996	0.991	0.978	0.950	0.898
1100	0.999	0.996	0.989	0.975	0.926	0.836
1200	0.999	0.996	0.984	0.966	0.896	0.779
1300	0.999	0.996	0.983	0.945	0.847	0.716
1400	0.999	0.995	0.980	0.926	0.795	0.664
1500	0.999	0.993	0.977	0.903	0.741	0.616
1600	0.999	0.993	0.974	0.869	0.701	0.561
1700	0.999	0.993	0.965	0.834	0.662	0.526
1800	0.999	0.993	0.955	0.795	0.616	0.486
1900	0.999	0.992	0.946	0.752	0.575	0.455
2000	0.999	0.989	0.930	0.716	0.532	0.427

Table F.9. BC North: Decision table for comparing the projected biomass to the current biomass, given by probabilities P($B_t > B_{2018}$). For reference, the average catch over the last 5 years (2013-2017) is 109 t.

	2018	2019	2020	2021	2022	2023
0	0.000	0.334	0.337	0.330	0.346	0.380
100	0.000	0.172	0.185	0.176	0.182	0.187
200	0.000	0.075	0.073	0.076	0.083	0.095
300	0.000	0.038	0.034	0.037	0.043	0.041
400	0.000	0.019	0.019	0.015	0.013	0.014
500	0.000	0.012	0.011	0.009	0.007	0.006
600	0.000	0.007	0.005	0.003	0.002	0.001
700	0.000	0.003	0.003	0.002	0.001	0.001
800	0.000	0.001	0.001	0.001	0.001	0.001
900	0.000	0.001	0.001	0.001	0.001	0.001
1000	0.000	0.001	0.001	0.001	0.001	0.000
1100	0.000	0.001	0.001	0.000	0.000	0.000
1200	0.000	0.001	0.000	0.000	0.000	0.000
1300	0.000	0.001	0.000	0.000	0.000	0.000
1400	0.000	0.000	0.000	0.000	0.000	0.000
1500	0.000	0.000	0.000	0.000	0.000	0.000
1600	0.000	0.000	0.000	0.000	0.000	0.000
1700	0.000	0.000	0.000	0.000	0.000	0.000
1800	0.000	0.000	0.000	0.000	0.000	0.000
1900	0.000	0.000	0.000	0.000	0.000	0.000
2000	0.000	0.000	0.000	0.000	0.000	0.000

Table F.10. BC North: 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 greater than that at MSY. For reference, the average catch over the last 5 years (2013-2017) is 109 t.

	2018	2019	2020	2021	2022	2023
0	0.000	0.000	0.000	0.000	0.000	0.000
100	0.001	0.001	0.001	0.001	0.001	0.001
200	0.004	0.004	0.004	0.004	0.004	0.004
300	0.005	0.006	0.009	0.009	0.011	0.014
400	0.013	0.014	0.016	0.020	0.027	0.028
500	0.016	0.026	0.029	0.034	0.044	0.052
600	0.028	0.037	0.048	0.058	0.067	0.083
700	0.039	0.053	0.063	0.078	0.103	0.125
800	0.050	0.065	0.085	0.114	0.141	0.176
900	0.063	0.082	0.114	0.141	0.186	0.248
1000	0.072	0.103	0.133	0.176	0.240	0.320
1100	0.088	0.119	0.156	0.217	0.308	0.420
1200	0.099	0.137	0.183	0.280	0.388	0.513
1300	0.111	0.152	0.214	0.327	0.457	0.582
1400	0.124	0.167	0.266	0.384	0.534	0.655
1500	0.135	0.189	0.299	0.444	0.596	0.729
1600	0.148	0.212	0.341	0.494	0.652	0.782
1700	0.158	0.232	0.369	0.556	0.719	0.824
1800	0.168	0.258	0.412	0.612	0.767	0.871
1900	0.182	0.301	0.458	0.656	0.799	0.900
2000	0.197	0.316	0.492	0.706	0.838	0.922

Table F.11. BC North: Decision table for alternative reference point $0.2B_0$ for 1-5 year projections, such that values are P($B_t > 0.2B_0$). For reference, the average catch over the last 5 years (2013-2017) is 109 t.

	2018	2019	2020	2021	2022	2023
0	1.000	1.000	1.000	1.000	1.000	1.000
100	1.000	1.000	1.000	1.000	1.000	1.000
200	1.000	1.000	1.000	1.000	1.000	1.000
300	1.000	1.000	1.000	1.000	1.000	0.999
400	1.000	1.000	1.000	1.000	0.999	0.999
500	1.000	1.000	1.000	0.999	0.999	0.999
600	1.000	1.000	1.000	0.999	0.999	0.997
700	1.000	1.000	0.999	0.999	0.998	0.997
800	1.000	1.000	0.999	0.999	0.997	0.995
900	1.000	1.000	0.999	0.999	0.996	0.985
1000	1.000	1.000	0.999	0.997	0.995	0.981
1100	1.000	0.999	0.999	0.997	0.984	0.970
1200	1.000	0.999	0.999	0.996	0.977	0.946
1300	1.000	0.999	0.999	0.993	0.972	0.928
1400	1.000	0.999	0.997	0.987	0.958	0.905
1500	1.000	0.999	0.997	0.981	0.931	0.892
1600	1.000	0.999	0.995	0.974	0.919	0.883
1700	1.000	0.999	0.995	0.964	0.902	0.873
1800	1.000	0.999	0.993	0.957	0.890	0.862
1900	1.000	0.999	0.990	0.931	0.878	0.858
2000	1.000	0.999	0.986	0.917	0.870	0.853

Table F.12. BC North: Decision table for alternative reference point $0.4B_0$ for 1-5 year projections, such that values are P($B_t > 0.4B_0$). For reference, the average catch over the last 5 years (2013-2017) is 109 t.

	2018	2019	2020	2021	2022	2023
0	0.999	0.999	0.999	0.999	0.999	0.999
100	0.999	0.999	0.999	0.999	0.999	0.997
200	0.999	0.999	0.999	0.997	0.997	0.997
300	0.999	0.999	0.998	0.997	0.997	0.997
400	0.999	0.998	0.997	0.997	0.996	0.992
500	0.999	0.998	0.997	0.996	0.992	0.981
600	0.999	0.998	0.997	0.992	0.981	0.966
700	0.999	0.997	0.995	0.988	0.966	0.939
800	0.999	0.997	0.994	0.977	0.949	0.874
900	0.999	0.997	0.990	0.965	0.912	0.814
1000	0.999	0.997	0.988	0.953	0.850	0.735
1100	0.999	0.996	0.980	0.927	0.800	0.653
1200	0.999	0.995	0.973	0.884	0.729	0.570
1300	0.999	0.994	0.964	0.846	0.663	0.499
1400	0.999	0.994	0.951	0.796	0.608	0.430
1500	0.999	0.994	0.943	0.749	0.529	0.369
1600	0.999	0.994	0.928	0.690	0.467	0.301
1700	0.999	0.992	0.899	0.648	0.420	0.264
1800	0.999	0.992	0.875	0.605	0.366	0.229
1900	0.999	0.988	0.845	0.549	0.314	0.173
2000	0.999	0.985	0.807	0.488	0.278	0.148

F.2.1.3.2. BCN projection figures for base case

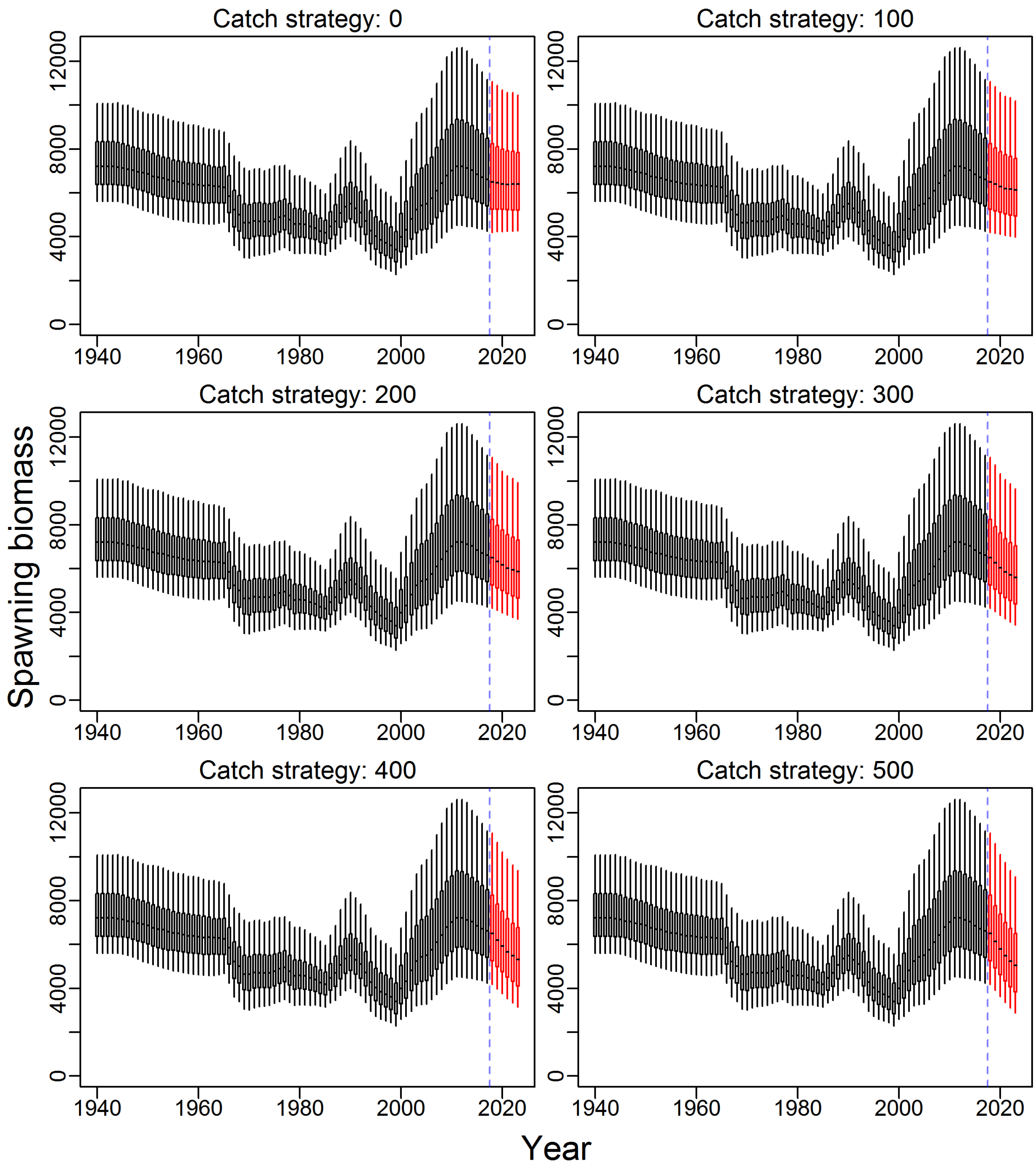


Figure F.40. BC North: Projected biomass (t) under different constant catch strategies (t); boxplots show the 2.5, 25, 50, 75 and 97.5 percentiles from the MCMC results. For each of the 1,000 samples from the MCMC posterior, the model was run forward in time (red, with medians in black) with a constant catch, and recruitment was simulated from the stock-recruitment function with lognormal error (see Appendix E). For reference, the average catch over the last 5 years (2013-2017) is 109 t.

F.2.2. BCN Sensitivity Runs

Four sensitivity analyses were run (with full MCMC simulations) relative to the base case (Run16) to test the sensitivity of the outputs to alternative model assumptions:

- **S1** (Run19) – remove the commercial CPUE index series (g=3);
- **S2** (Run20) – halve the catch during years of foreign fleet activity (1965-1976) and during years of possible misreporting by domestic fleet before observer coverage (1988-1995);
- **S3** (Run21) – use proportions-at-age from unsorted samples only;
- **S4** (Run22) – increase sigmaR (σ_R) from 0.6 to 1.1;

Four additional sensitivity analyses were run as diagnostics to the base case and S4:

- **D1** (Run23) – same as base case but fix $M_{1,2}$ to 0.11;
- **D2** (Run24) – same as S4 but fix $M_{1,2}$ to 0.11.
- **D3** (Run26) – same as base case but prior on $M_{1,2} \sim$ N(0.136, 0.0136) [10%CV] assuming a maximum age of 50 y instead of 61 y;
- **D4** (Run27) – same as base case but prior on $M_{1,2} \sim$ N(0.136, 0.0272) [20%CV].

Each sensitivity (including the diagnostic runs) was reweighted three times using the procedure of Francis (2011) for age frequencies. The abundance index CVs were ajusted on the first reweight only using the same process error adopted in the base case: c_p = 0.5, 0.5, and 0.34 for the HS Synoptic survey, WCHG Synoptic survey, and commercial trawl CPUE, respectively. The reweighted dataset chosen for MCMC analysis was based on Equation E.33 for each sensitivity.

The differences among the runs are summarised in Tables F.13 and F.14 and Figures F.41 to F.43. Diagnostic plots for the sensitivity MCMCs appear in Figures F.44 to F.52.

Run S1 explores the effect of removing the CPUE index series. The diagnostic plots (Figures F.44–F.46) indicate that taking out CPUE destabilizes the model. Natural mortality exhibits prolonged excursions to values outside the main sample space, with M_1 and M_2 diverging markedly to lower and higher values, respectively. Selectivity for the commercial trawl gear (μ_3) exhibits a continuous downward trend in the median, as do the survey catchability parameters ($q_{1,2}$). Autocorrelation is hopelessly high, even out to 60 lags for some parameters (FigureF.46).

Run S2 explores the effect of catch mis-specification during the period of peak foreign fleet activity and during the rise of the domestic fleet. It is not certain how much Redstripe Rockfish was removed by foreign fishing vessels as they were likely targeting POP. The catch reconstruction uses ratios of RSR to rockfish other than POP from data spanning 1997-2005, which likely do not represent the period 1965-1976. There are also anecdotes that desirable rockfish like POP were mistakenly or purposefully reported as RSR during the years 1988-1995, perhaps to bypass quota restrictions. The MCMC diagnostics of this run are excellent (Figures F.47–F.49). Reducing the catch has little impact on the estimated parameters (Table F.13) or on the reference points, other than to estimate a lower standing stock (Table F.14); however, this is the most optimistic scenario.

Run S3 explores the effect of using only unsorted samples to supply the composition signal to the model. Unsorted samples do not occur in the earlier years of age data, so the model loses this information from the reconstruction. However, despite this limitation, the MCMC diagnostics are good (Figures F.50–F.52), estimates of M are similar to those of the base case (Table F.13), and stock status $B_{2018}/B_{\mathrm{MSY}}$ remains healthy (Table F.14).

Run S4 explores the effect of a larger standard deviation for recruitment process error. This model run is interesting in that it has found a plausible population trajectory scenario that differs noticeably from the base case trajectory (Figure F.41) with good MCMC diagnostics (Figures F.53–F.55). However, the exploitation rate for this scenario reaches a maximum of 0.49 in 1993 (Figure F.41), which seems relatively high. Natural mortality estimates for S4 have diverged from the base case, with the female M 22% lower than the base case M and the male M 20% greater the equivalent base case M (M_1 = 0.082 vs. 0.106; M_2 = 0.142 vs. 0.118; Table F.13). The estimated current spawning stock biomass relative to unfished equilibrium (B_{2018}/B_0) is only 0.661 compared to the base run's value of 0.914, but still remains well above 50% of the unfished equilibrium biomass. The shift observed for this sensitivity run appears to be largely due to the estimates of M, which diverge considerably among the two sexes. This conclusion is based on two diagnostic sensitivity runs (D1 and D2) which fixed M to the mean of the prior (0.11) and re-estimated the model using both σ_R values (diagnostic MCMC runs), the population trajectory and recruitment patterns remain closely aligned to those of the base case (Figure F.43).

The stock status ($B_{2018}/B_{\mathrm{MSY}}$) of Redstripe Rockfish (5DE) is well within DFO's 'Healthy Zone' (Figure F.56) for the base case and each sensitivity run, with a probability of being above 0.8B_{MSY} of 0.999. The first three sensitivities do not show much change in the perceived stock status, although they do show somewhat different recruitment patterns and alternative biomass trajectories compared to the base case. Sensitivity 4 (sigmaR = 1.1) indicates a lower status than that for the base case and the other sensitivities; however, the probability of being above 0.8B_{MSY} is still 0.999.

The review meeting participants requested two additional runs (D3 and D4) for each stock. The mean of these priors assumed M was based on a maximum age of 50 y instead of 61 y used in the base case. Given that these runs were made overnight at the review meeting, only the MPD results could be presented to the participants and consequently MCMC results are not reported. In BC North, the base case estimates of $M_{1,2}$ = (0.108, 0.118) increased to $M_{1,2}$ = (0.131, 0.142) and $M_{1,2}$ = (0.135, 0.144) for D3 and D4. These results indicate that there is insufficient information in the BCN data to move the estimate away from the prior mean for either sex with little sensitivity to increasing the CV on the prior mean. The spawning stock status in the final year relative to the unfished equilibrium (B_{2018}/B_0) increased by about 10% from 1.10 in the base case to 1.18 (D3) and 1.20 (D4).

F.2.2.1. BCN tables for sensitivity runs

Table F.13. BC North: Median values of 1000 MCMC samples for the primary estimated parameters, comparing the Base Case (run 16) to sensitivity runs (19-24). R = Run, S = Sensitivity, D =Diagnostic sensitivity (M=0.11). Numeric subscripts other than those for R_0 and M indicate the following gear types g: 1 = HS Synoptic survey, 2 = WCHG Synoptic survey, and 3 = commercial trawl CPUE.

	Base(R16)	S1(R19)	S2(R20)	S3(R21)	S4(R22)	D1(R23)	D2(R24)
R_0	3,885	4,454	3,424	4,276	2,427	4,150	3,584
M_1	0.106	0.107	0.107	0.108	0.0817	—	—
M_2	0.118	0.123	0.119	0.120	0.142	—	—
h	0.725	0.762	0.782	0.792	0.751	0.723	0.735
q_1	0.0157	0.0153	0.0203	0.0175	0.0386	0.0140	0.0214
q_2	0.0578	0.0575	0.0808	0.0670	0.170	0.0516	0.0869
q_3	0.000215	—	0.000264	0.000221	0.000810	0.000185	0.000299
μ_1	11.1	11.2	11.2	11.2	11.3	11.2	11.2
μ_2	11.4	11.2	11.3	11.3	12.0	11.4	11.9
μ_3	11.8	12.3	12.2	12.2	15.5	11.7	11.8
Δ_1	0.218	0.218	0.225	0.220	0.223	0.218	0.215
Δ_2	0.219	0.212	0.212	0.217	0.210	0.220	0.226
Δ_3	0.0694	0.139	0.0713	-0.140	0.0758	0.0680	0.0383
$\log v_{1L}$	2.01	1.98	1.99	1.99	1.95	1.97	2.00
$\log v_{2L}$	1.88	1.85	1.86	1.91	2.07	1.90	1.99
$\log v_{3L}$	0.903	1.01	0.923	1.08	2.16	0.880	0.914

Table F.14. BC North: The 50$^{\mathrm{th}}$ percentiles of MCMC-derived quantities from the 1000 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_{2018} – spawning biomass at the start of 2018, V_{2018} – vulnerable biomass in the middle of 2018, u_{2017} – exploitation rate (ratio of total catch to vulnerable biomass) in the middle of 2017, $u_{\max}$ – maximum exploitation rate (calculated for each sample as the maximum exploitation rate from 1940 - 2017), 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.

	Base(R16)	S1(R19)	S2(R20)	S3(R21)	S4(R22)	D1(R23)	D2(R24)
B_0	7,216	8,442	6,245	7,642	6,916	7,177	6,197
V_0	7,606	8,194	6,279	7,901	5,307	8,129	6,977
B_{2018}	6,500	7,798	6,139	7,469	4,532	6,855	5,123
V_{2018}	7,455	8,438	6,921	8,342	3,415	8,430	6,063
B_{2018}/B_0	0.914	0.955	0.990	0.971	0.661	0.952	0.828
V_{2018}/V_0	0.990	1.04	1.10	1.06	0.653	1.03	0.881
u_{2017}	0.0164	0.0145	0.0179	0.0148	0.0366	0.0145	0.0206
$u_{\max}$	0.187	0.166	0.203	0.169	0.526	0.173	0.217
MSY	497	585	468	578	325	536	477
B_{MSY}	2,135	2,560	1,911	2,295	2,104	2,157	1,859
$0.4B_{\mathrm{MSY}}$	854	1,024	764	918	842	863	744
$0.8B_{\mathrm{MSY}}$	1,708	2,048	1,529	1,836	1,683	1,726	1,487
$B_{2018}/B_{\mathrm{MSY}}$	3.16	3.10	3.26	3.22	2.16	3.18	2.77
B_{MSY}/B_0	0.293	0.307	0.303	0.302	0.307	0.298	0.300
V_{MSY}	848	822	582	733	410	900	696
V_{MSY}/V_0	0.107	0.0913	0.0881	0.0875	0.0788	0.105	0.0923
u_{MSY}	0.638	0.922	0.985	0.990	0.940	0.665	0.780
$u_{2017}/u_{\mathrm{MSY}}$	0.0253	0.0186	0.0213	0.0180	0.0439	0.0236	0.0290

F.2.2.2. BCN figures for sensitivity runs

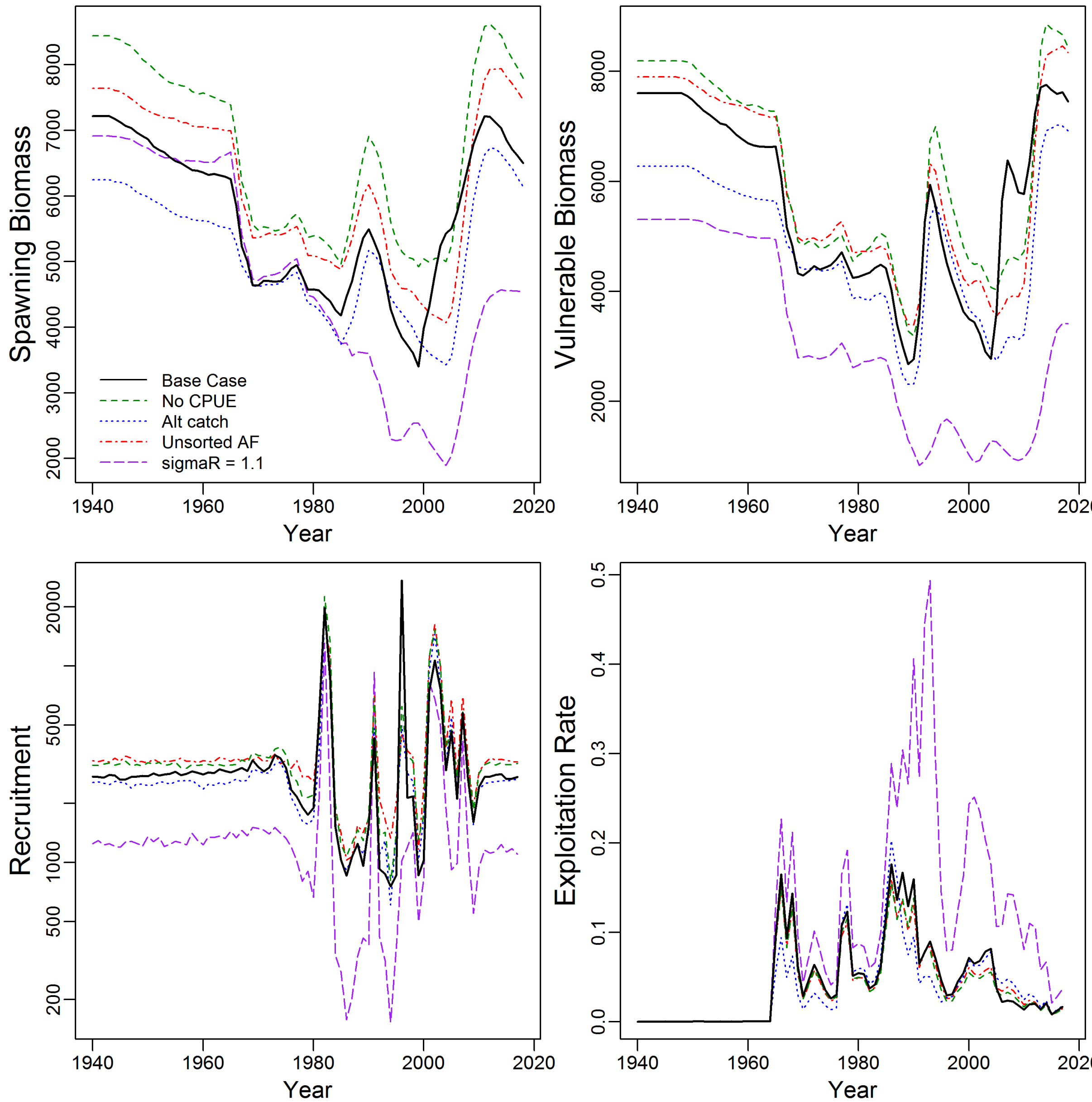


Figure F.41. BC North: model median trajectories of spawning biomass (t), vulnerable biomass (t), recruitment (1000s fish at age 1y), and exploitation rate for the base case and four sensitivity runs, indicated by a legend in the first panel.

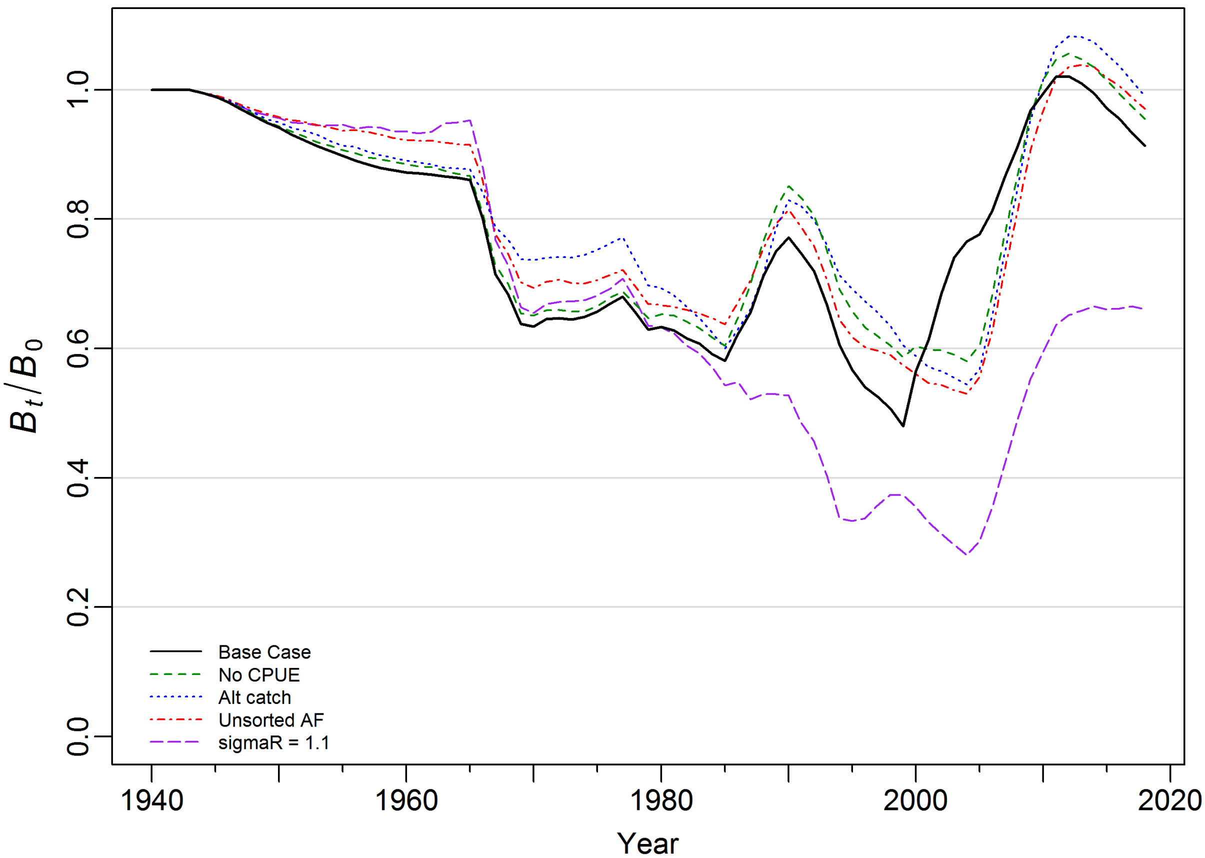


Figure F.42. BC North: model median trajectories of spawning biomass as a proportion of unfished equilibrium biomass (B_t/B_0) for the base case and 4 sensitivity runs, indicated by a legend in the first panel.

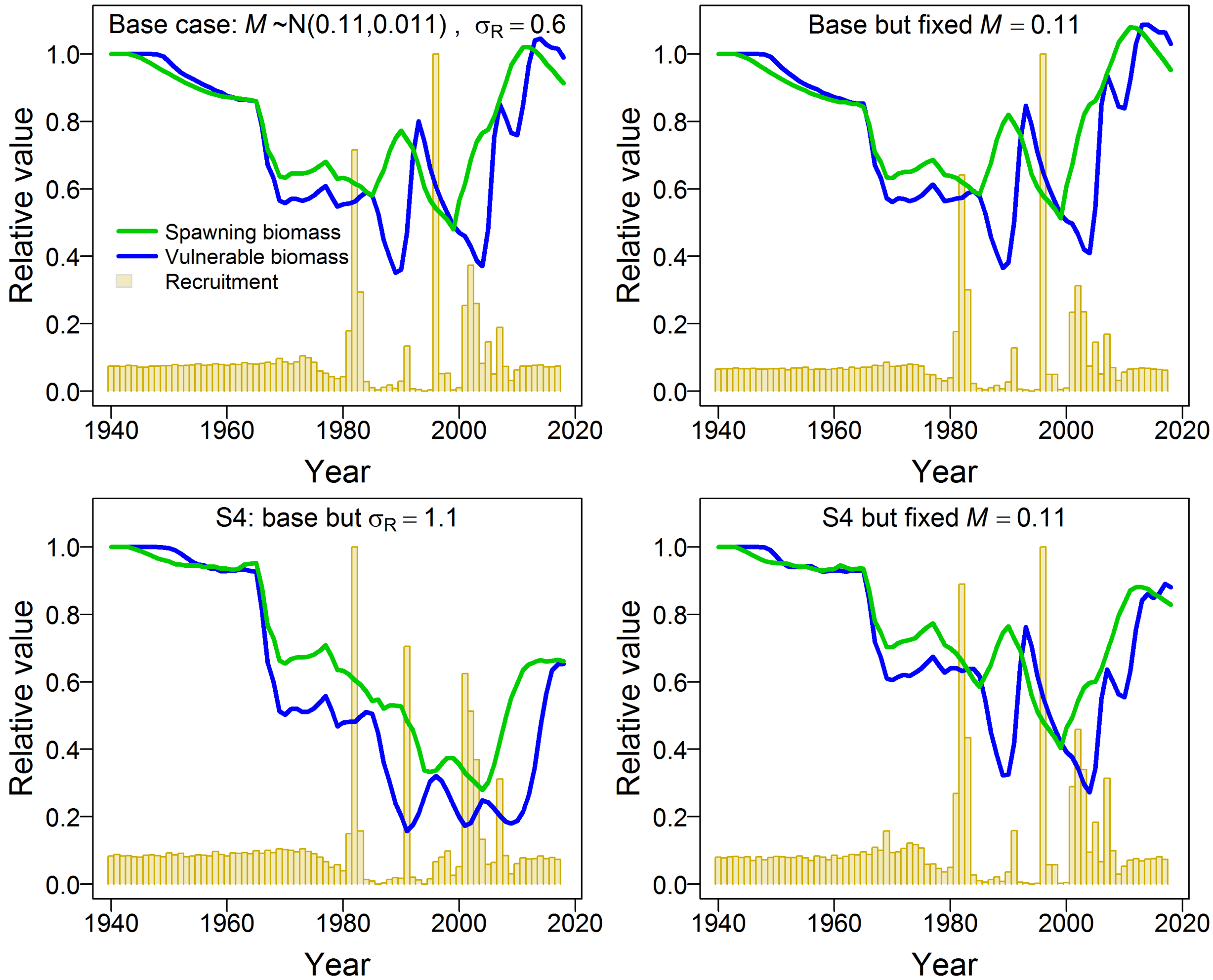


Figure F.43. BC North: model median trajectories of spawning and vulnerable biomass relative to unfished equilibrium values (B_{2018}/B_0 and V_{2018}/V_0) and standardised median annual recruitment (bars) for the base case and sensitivity 4 (σ_R=1.1) on the left and two corresponding runs (D1 and D2) with $M_{1,2}$ fixed at 0.11 on the right.

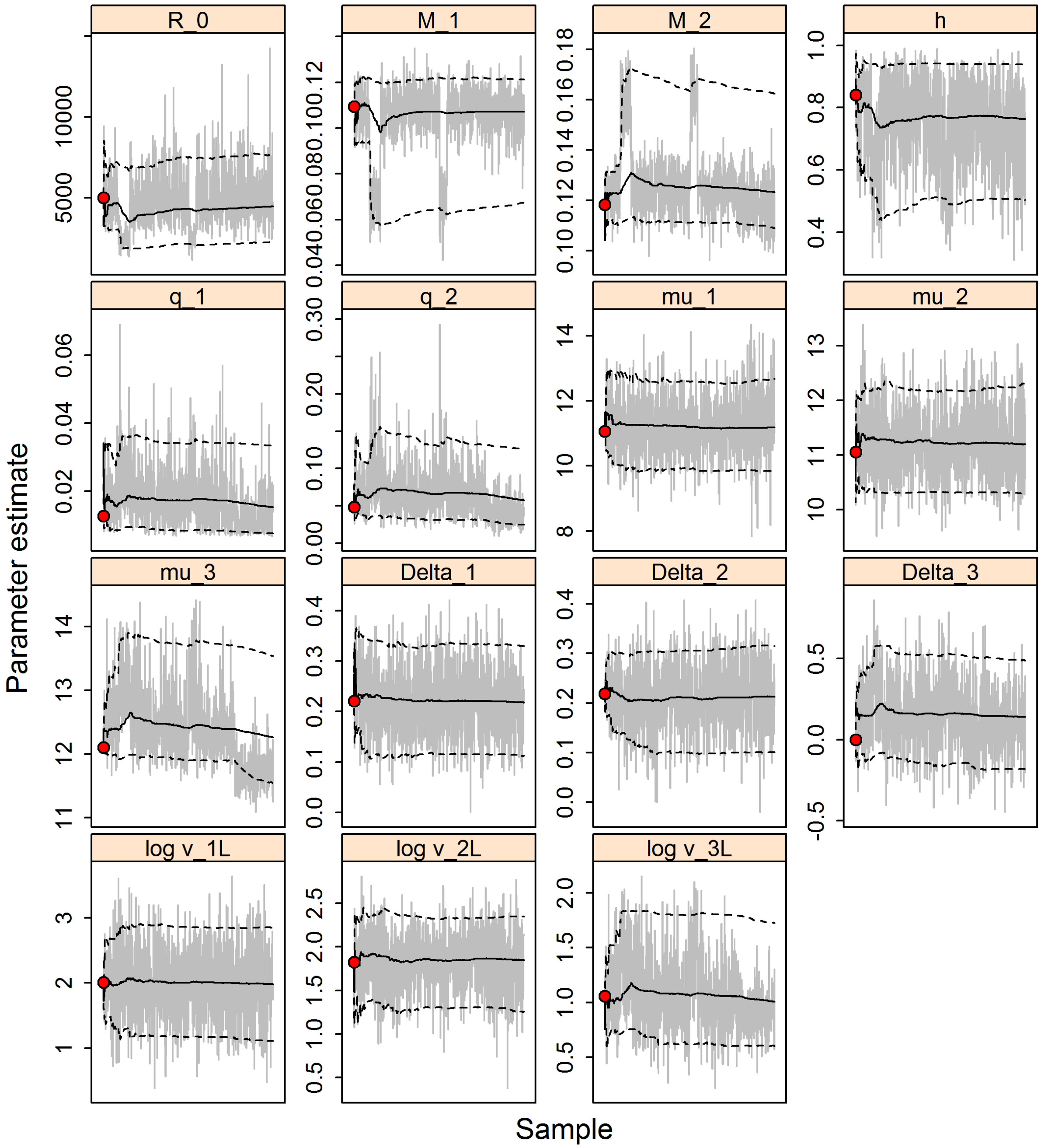


Figure F.44. BC North: Sensitivity 1: MCMC traces for the estimated parameters. Grey lines show the 1,000 samples for each parameter, solid lines show the cumulative median (up to that sample), and dashed lines show the cumulative 2.5 and 97.5 quantiles. Red circles are the MPD estimates. For parameters other than M (if estimated), subscripts ≤ 2 correspond to fishery-independent surveys, and subscripts ≥ 3 denote the commercial fishery. Parameter notation is described in Appendix E.

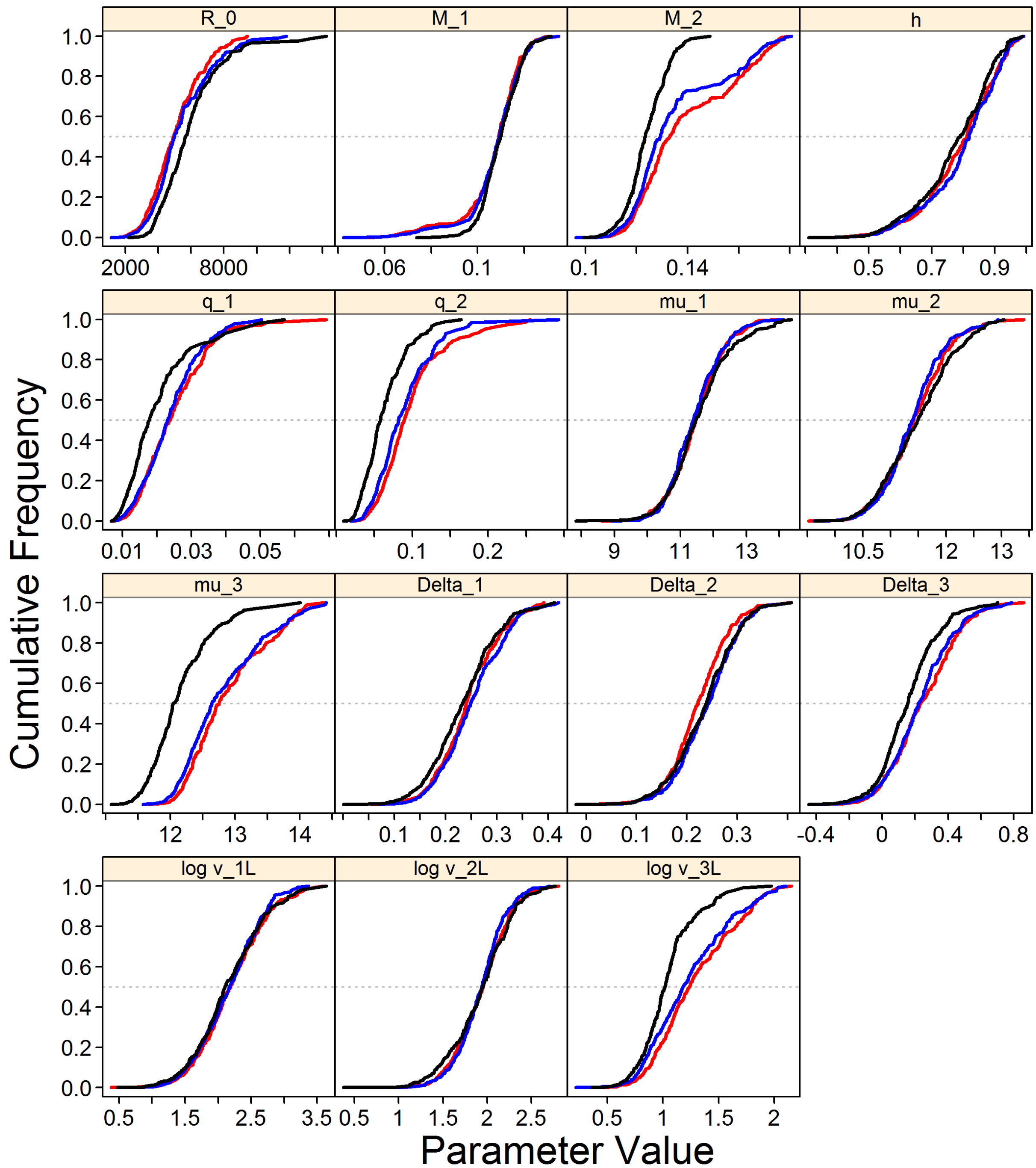


Figure F.45. BC North: Sensitivity 1: Diagnostic plot obtained by dividing the MCMC chain of 1,000 MCMC samples into three segments, and overplotting the cumulative distributions of the first segment (red), second segment (blue) and final segment (black).

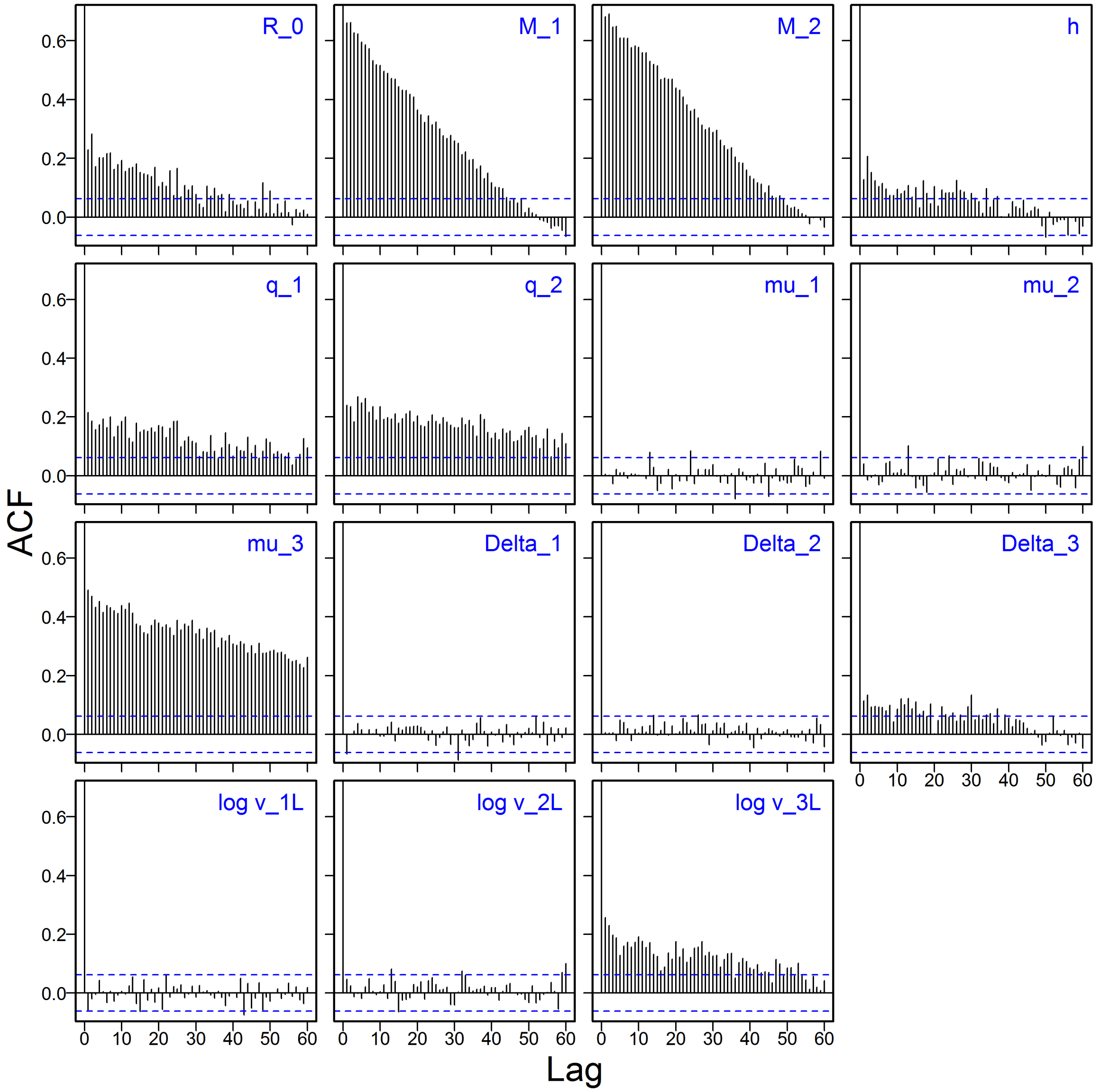


Figure F.46. BC North: Sensitivity 1: Autocorrelation plots for the estimated parameters from the MCMC output. Horizontal dashed blue lines delimit the 95% confidence interval for each parameter's set of lagged correlations.

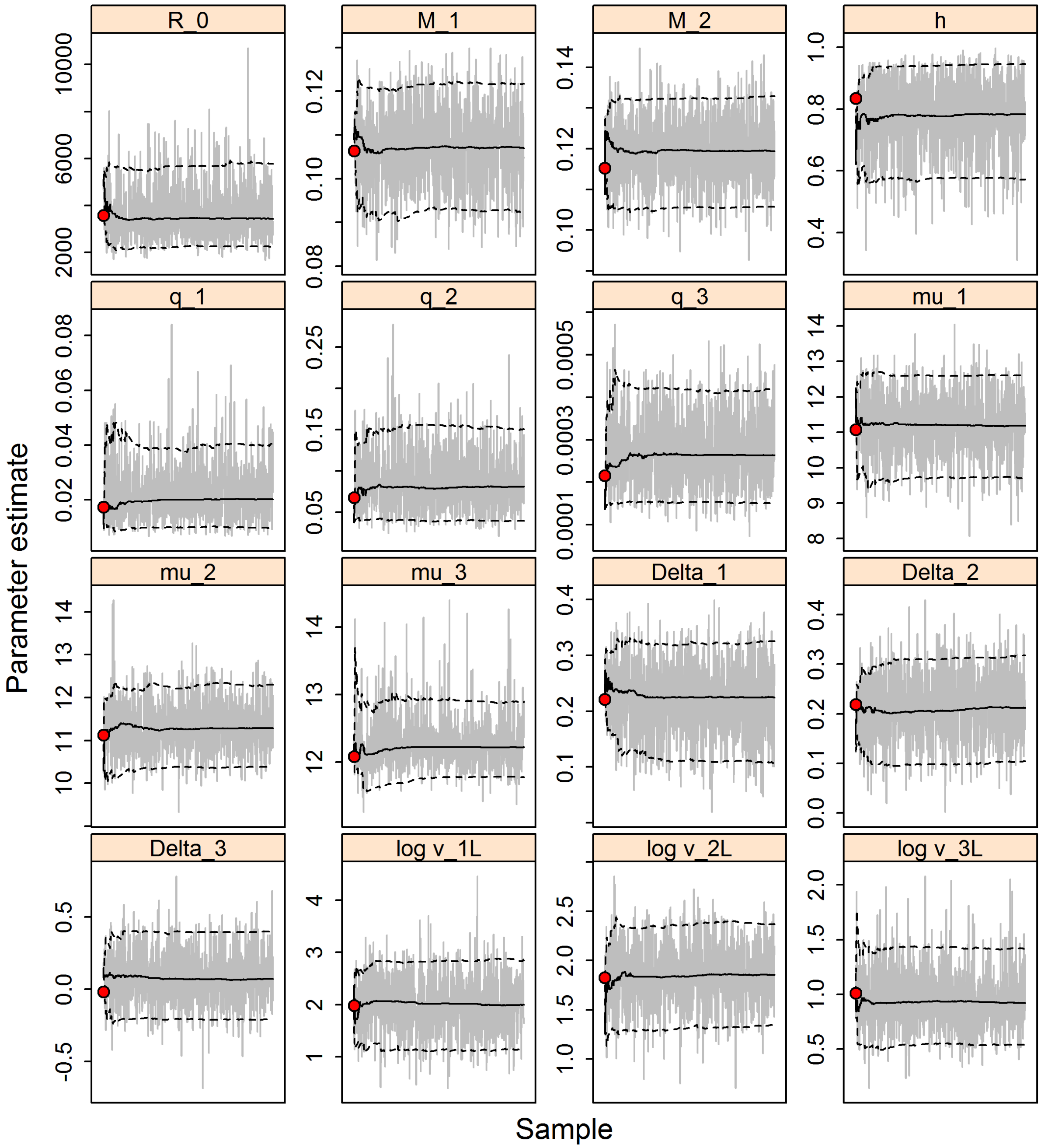


Figure F.47. BC North: Sensitivity 2: MCMC traces for the estimated parameters. Grey lines show the 1,000 samples for each parameter, solid lines show the cumulative median (up to that sample), and dashed lines show the cumulative 2.5 and 97.5 quantiles. Red circles are the MPD estimates. For parameters other than M (if estimated), subscripts ≤ 2 correspond to fishery-independent surveys, and subscripts ≥ 3 denote the commercial fishery. Parameter notation is described in Appendix E.

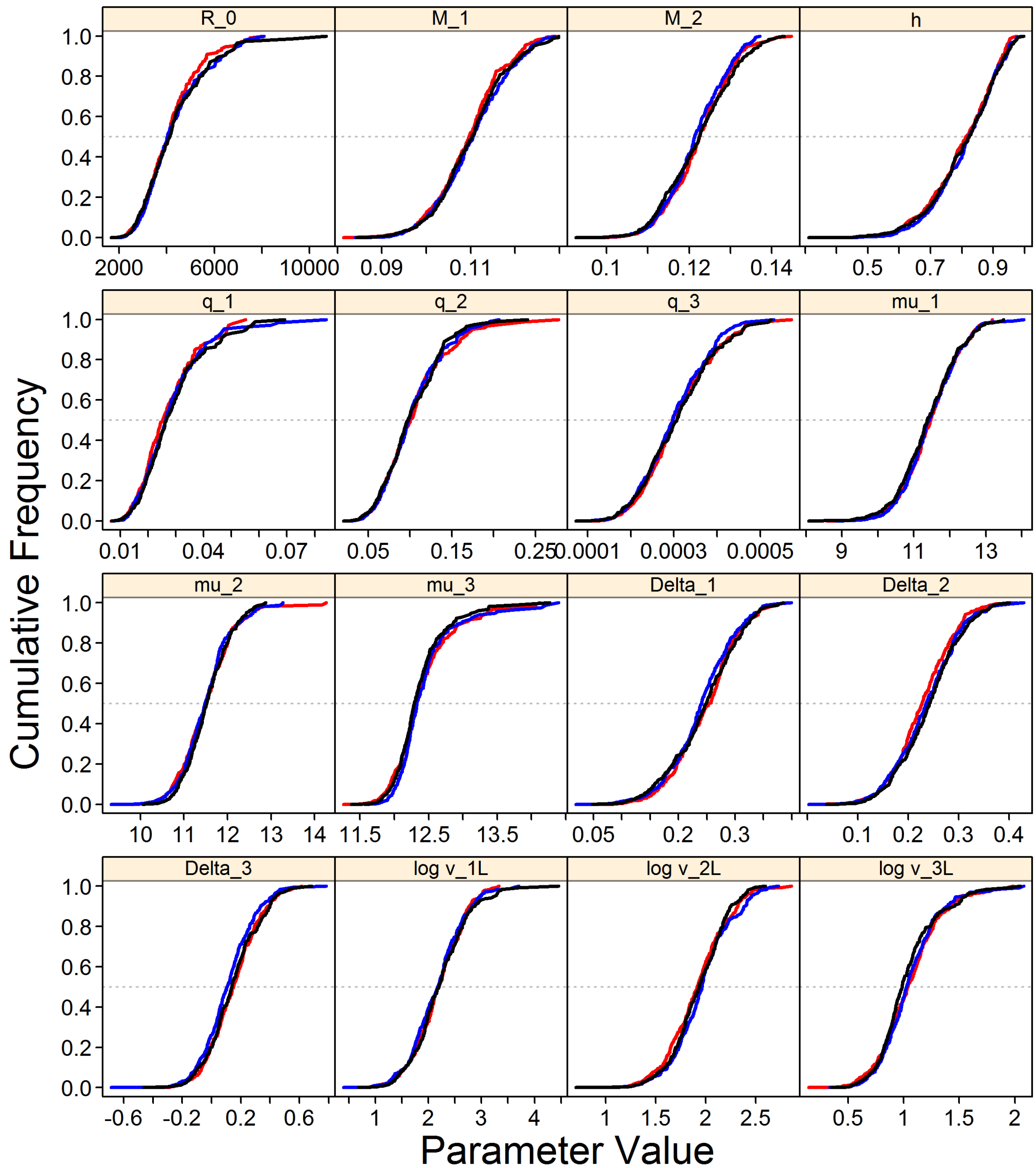


Figure F.48. BC North: Sensitivity 2: Diagnostic plot obtained by dividing the MCMC chain of 1,000 MCMC samples into three segments, and overplotting the cumulative distributions of the first segment (red), second segment (blue) and final segment (black).

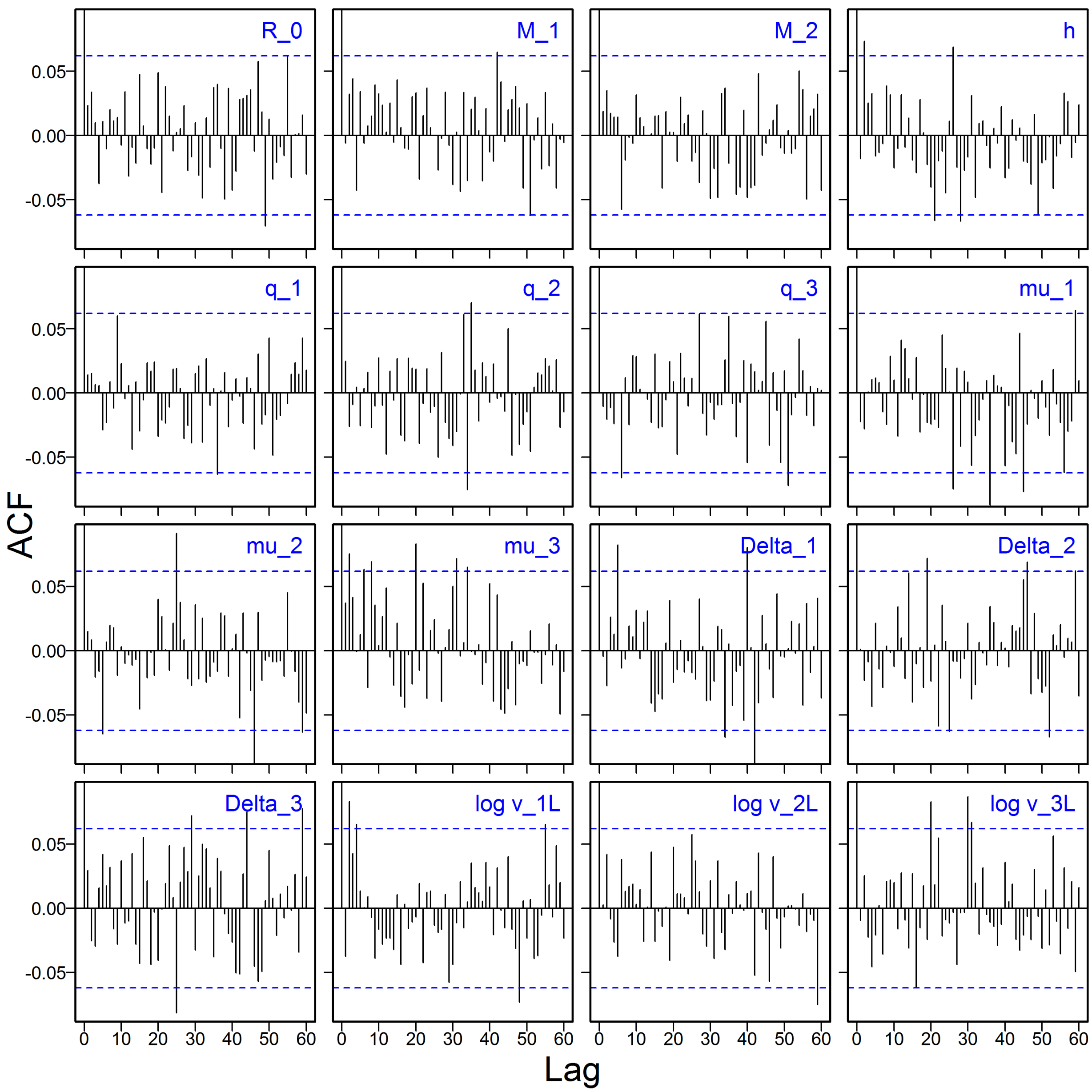


Figure F.49. BC North: Sensitivity 2: Autocorrelation plots for the estimated parameters from the MCMC output. Horizontal dashed blue lines delimit the 95% confidence interval for each parameter's set of lagged correlations.

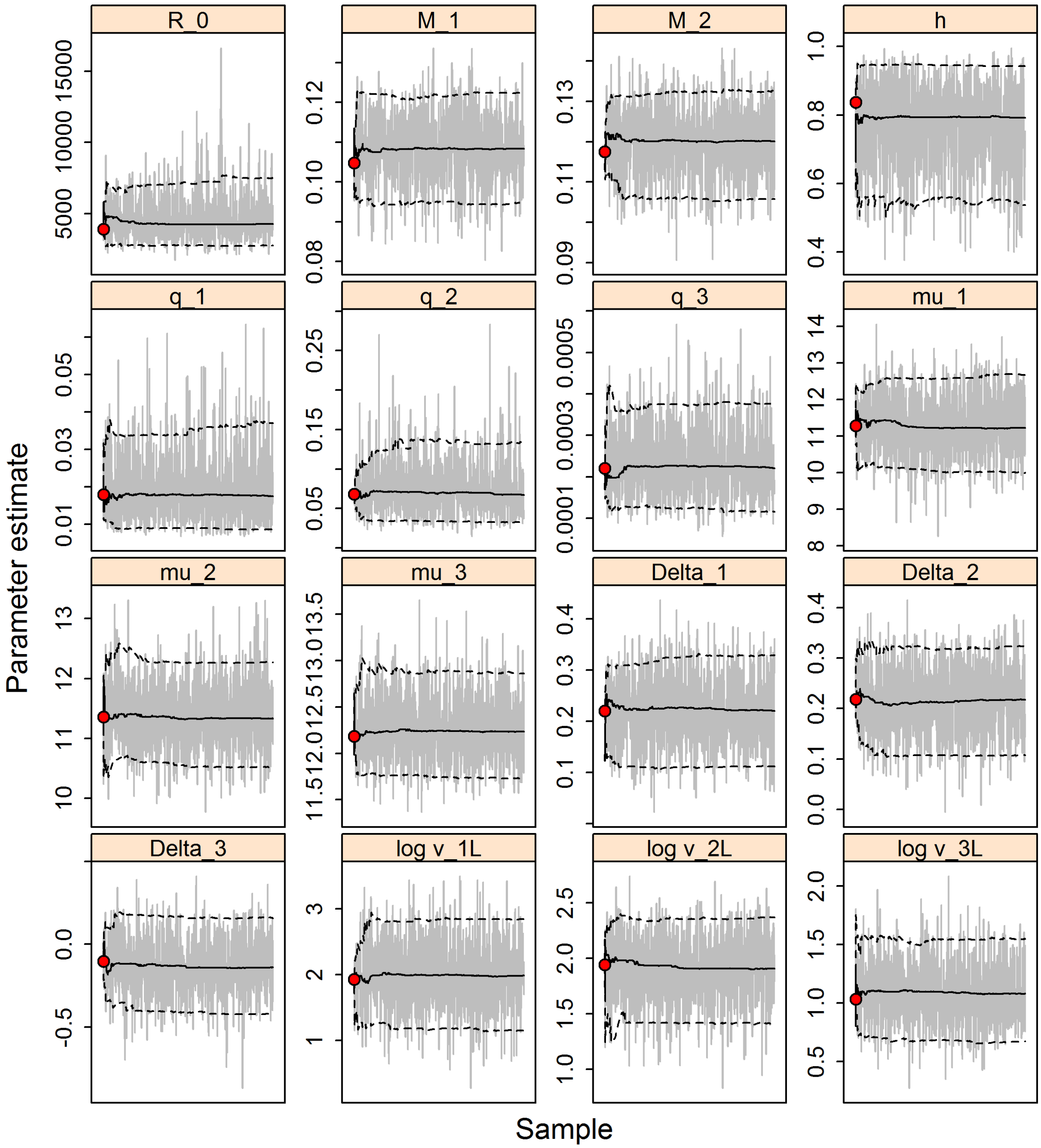


Figure F.50. BC North: Sensitivity 3: MCMC traces for the estimated parameters. Grey lines show the 1,000 samples for each parameter, solid lines show the cumulative median (up to that sample), and dashed lines show the cumulative 2.5 and 97.5 quantiles. Red circles are the MPD estimates. For parameters other than M (if estimated), subscripts ≤ 2 correspond to fishery-independent surveys, and subscripts ≥ 3 denote the commercial fishery. Parameter notation is described in Appendix E.

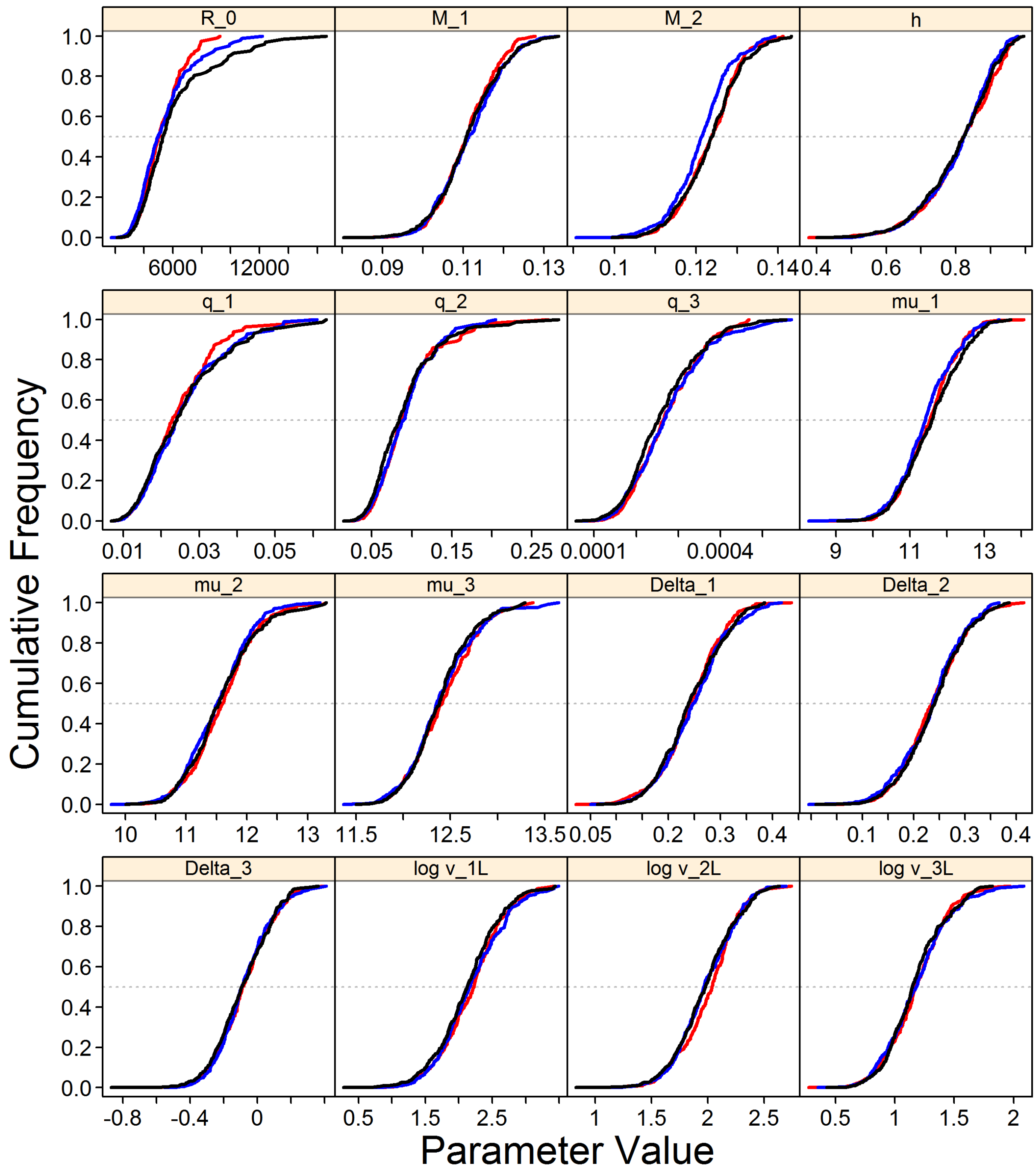


Figure F.51. BC North: Sensitivity 3: Diagnostic plot obtained by dividing the MCMC chain of 1,000 MCMC samples into three segments, and overplotting the cumulative distributions of the first segment (red), second segment (blue) and final segment (black).

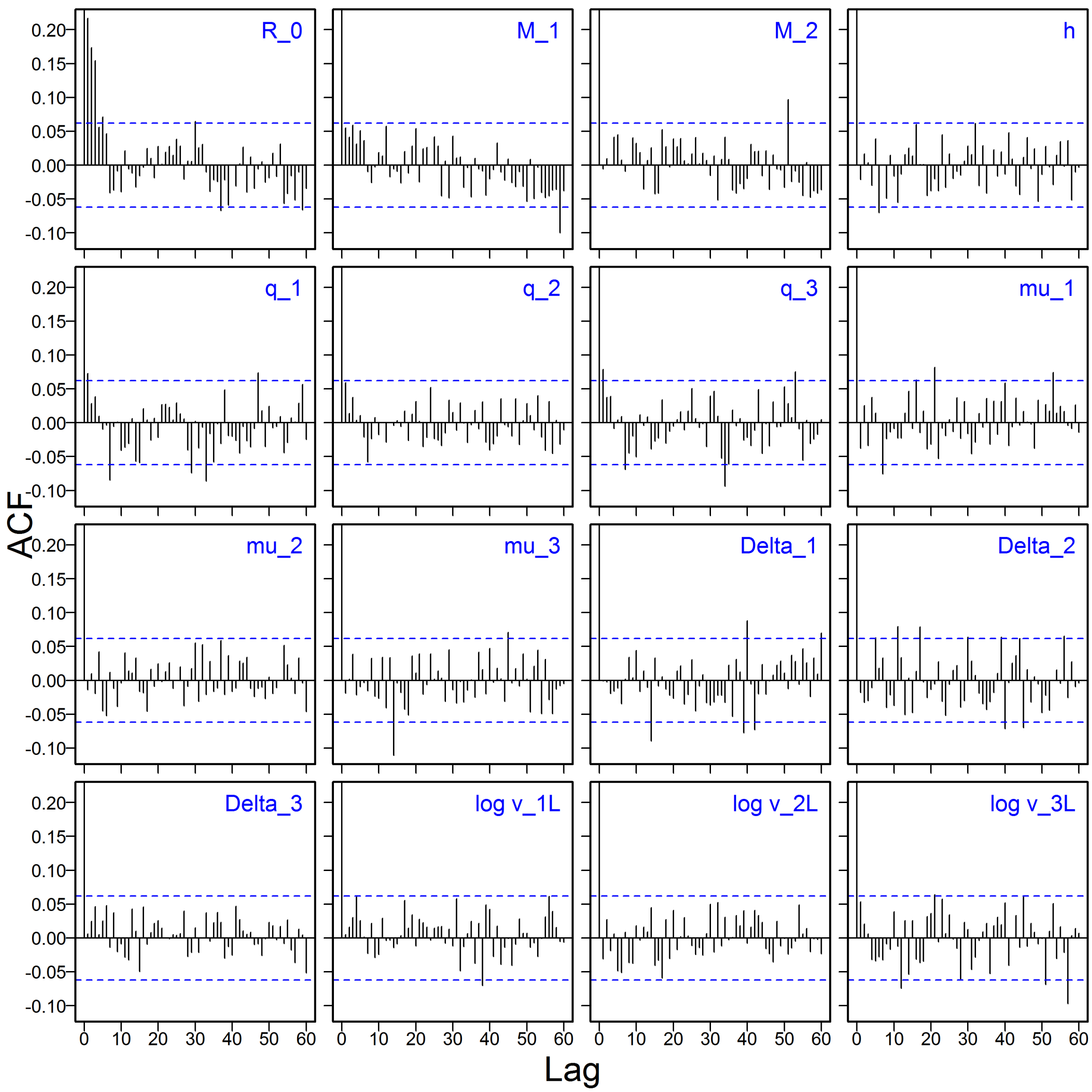


Figure F.52. BC North: Sensitivity 3: Autocorrelation plots for the estimated parameters from the MCMC output. Horizontal dashed blue lines delimit the 95% confidence interval for each parameter's set of lagged correlations.

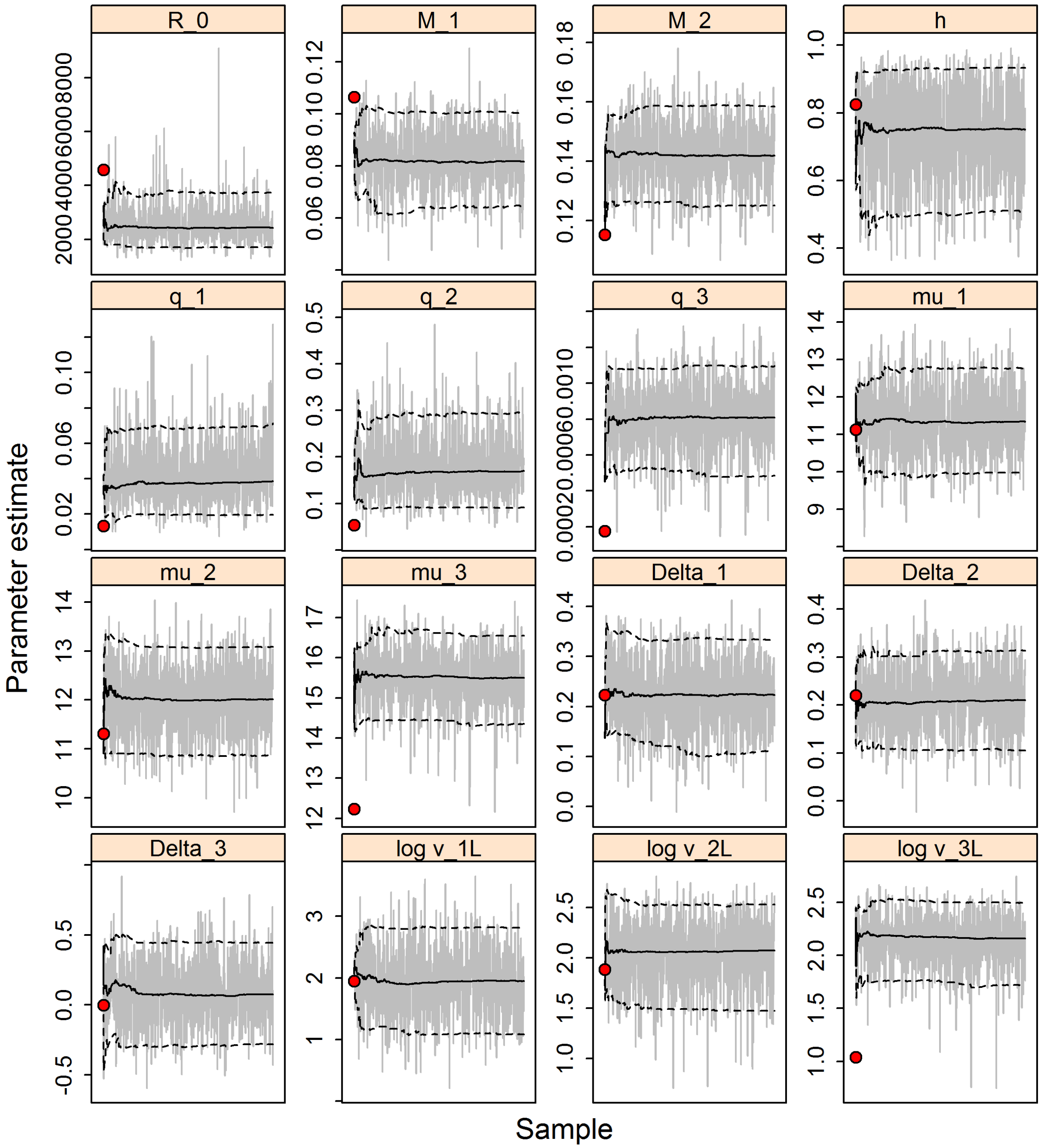


Figure F.53. BC North: Sensitivity 4: MCMC traces for the estimated parameters. Grey lines show the 1,000 samples for each parameter, solid lines show the cumulative median (up to that sample), and dashed lines show the cumulative 2.5 and 97.5 quantiles. Red circles are the MPD estimates. For parameters other than M (if estimated), subscripts ≤ 2 correspond to fishery-independent surveys, and subscripts ≥ 3 denote the commercial fishery. Parameter notation is described in Appendix E.

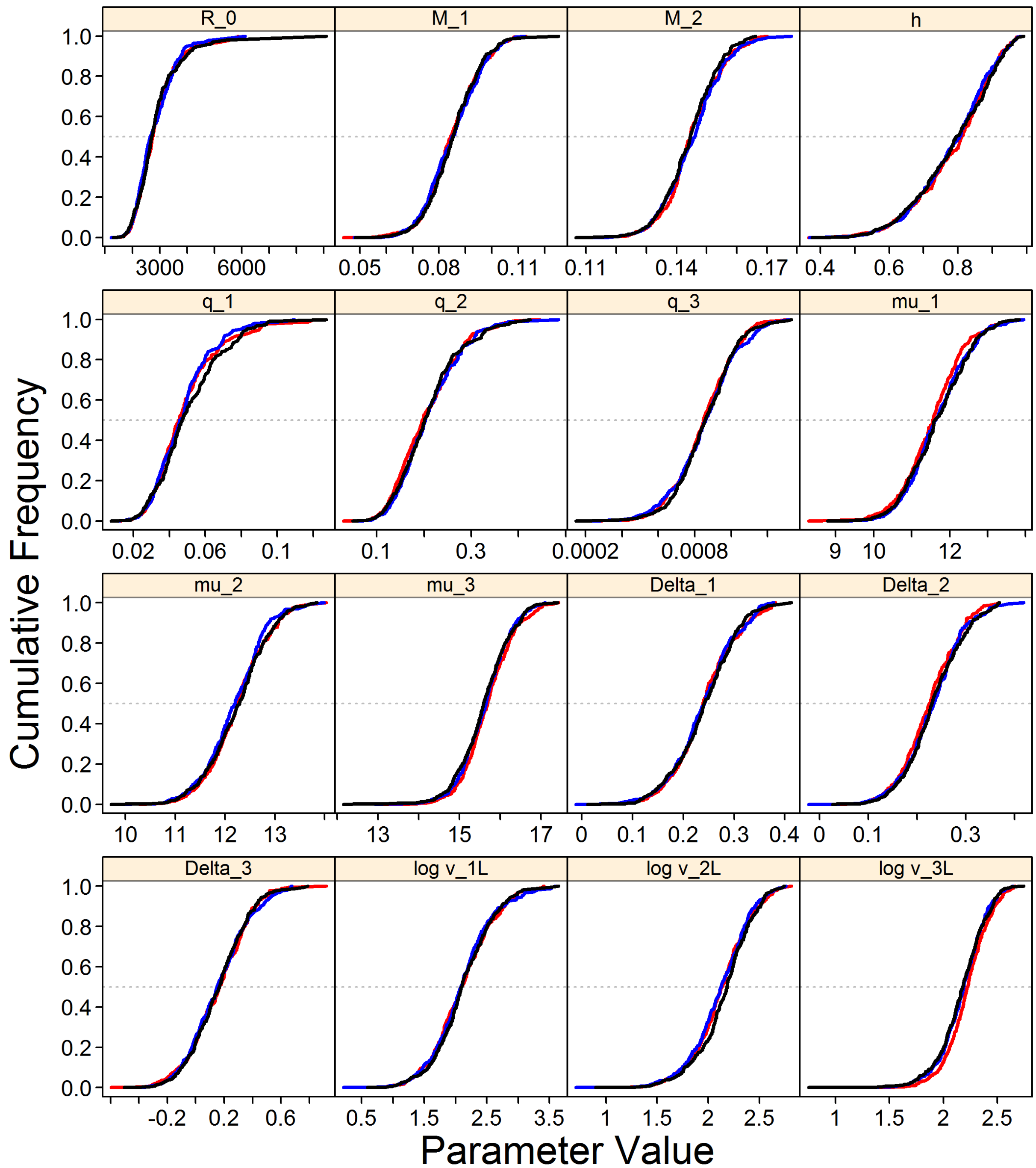


Figure F.54. BC North: Sensitivity 4: Diagnostic plot obtained by dividing the MCMC chain of 1,000 MCMC samples into three segments, and overplotting the cumulative distributions of the first segment (red), second segment (blue) and final segment (black).

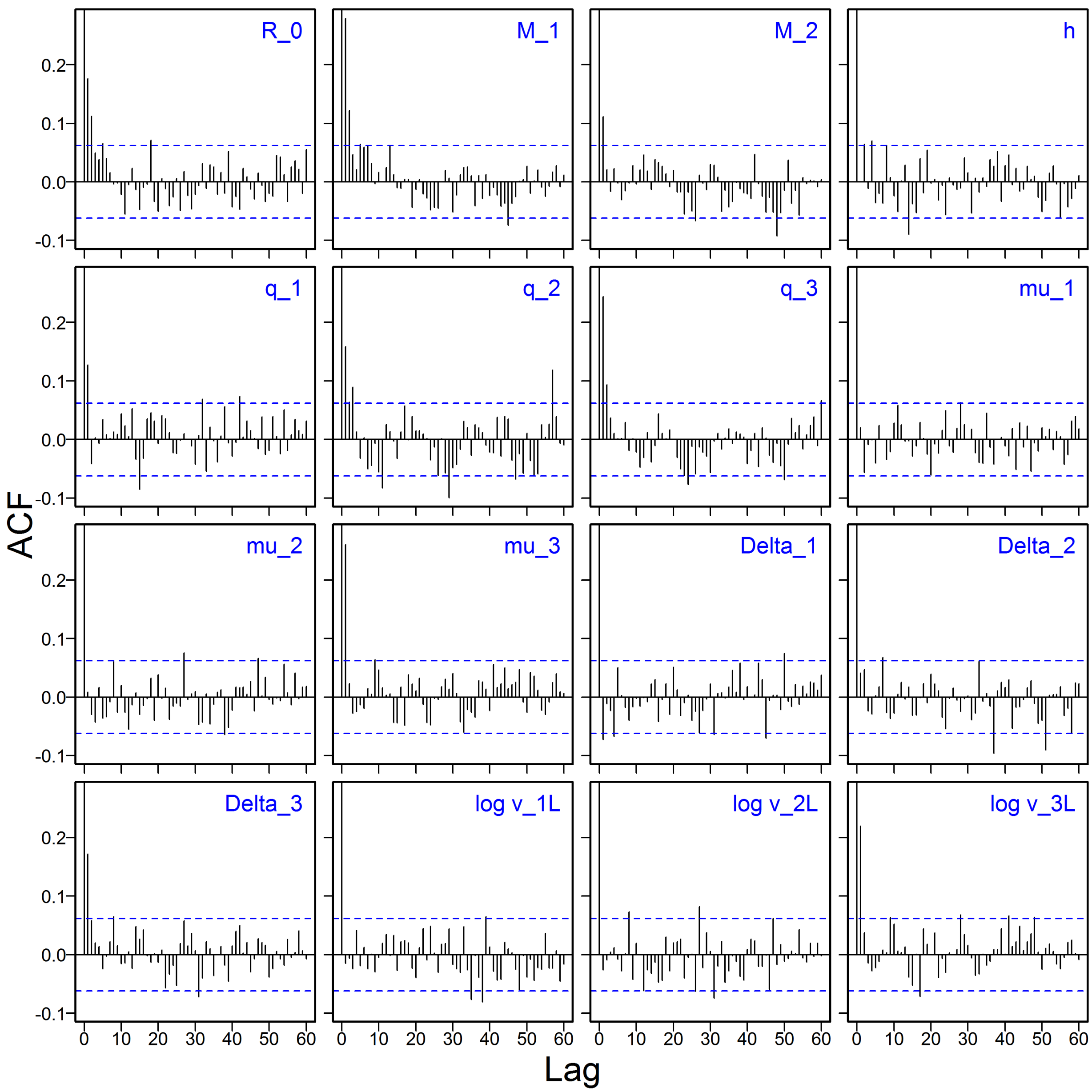


Figure F.55. BC North: Sensitivity 4: Autocorrelation plots for the estimated parameters from the MCMC output. Horizontal dashed blue lines delimit the 95% confidence interval for each parameter's set of lagged correlations.

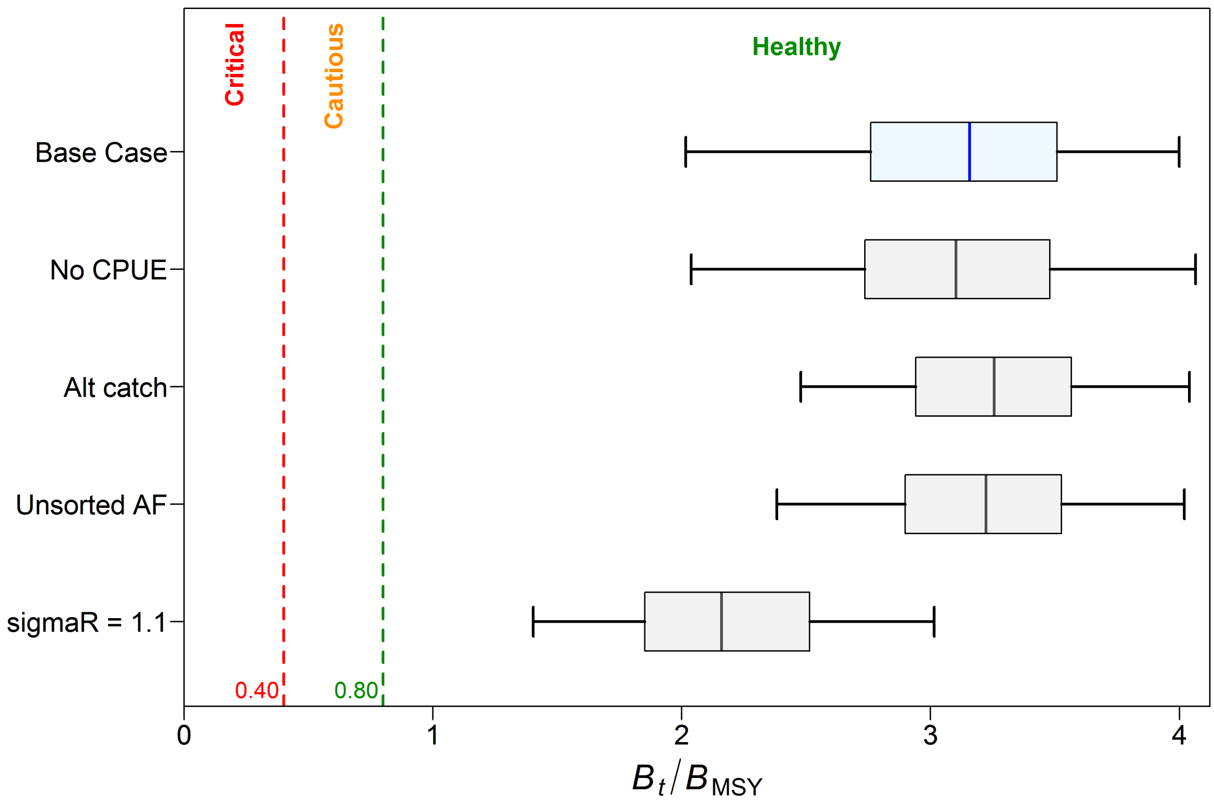


Figure F.56. BC North: status at beginning of 2018 of the Redstripe Rockfish (5DE) stock relative to the DFO PA provisional reference points of 0.4B_{MSY} and 0.8B_{MSY} for the base-case (Run16) stock assessment and 4 sensitivity runs: S1 = (Run19) remove the commercial CPUE index; S2 = (Run20) reduce the catch during periods of foreign fleet activity and during domestic fleet activity before observer coverage; S3 = (Run21) use only age frequencies from unsorted samples; S4 = (Run22) 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. BC SOUTH (BCS) STOCK

F.3.1. BCS Base Case

The base case for Redstripe Rockfish was selected from model run 16, which featured:

- 5 abundance index series: GIG Historical survey (g=1), WCVI Synoptic survey (g=2), QCS Synoptic survey (g=3), WCVI Triennial survey (g=4), and commercial trawl CPUE (g=5);
- two sexes: female (s=1) and male (s=2);
- proportions-at-age by sex for g = c(1:3,5) using all samples (unsorted + keepers);
- a normal prior for natural mortality M_s with CV = 10%;
- a normal prior for age of full selectivity for females (μ_g) with CV = 20%;
- bounds for shift in the vulnerability for males (Δ_g) and the variance parameter for the left limb of the selectivity curve ($\nu_g L$) = c(-8,10);
- abundance CVs reweighted once using cvpro = c(0.5, 0.3, 0.25, 0.5, 0.2) for the 4 surveys and the CPUE series, respectively;
- age frequency sample sizes iteratively reweighted using the Francis (2011) mean-ages method;
- a standard deviation parameter for recruitment process error (σ_R) set to 0.6.

The base-case run was reweighted three times using the procedure of Francis (2011) for age frequencies. The abundance index CVs were ajusted on the first reweight only using the process error: c_p = 0.5, 0.3, 0.25, 0.5, and 0.2 for the GIG Historical survey, WCVI Synoptic survey, QCS Synoptic survey, WCVI Triennial survey, and commercial trawl CPUE, respectively. The reweighted dataset chosen for MCMC analysis was the one where the sum of the absolute deviation from unity of the five SDNRs for the five abundance index series was the lowest (Equation E.33).

F.3.1.1. BCS Mode of the Posterior Distribution (MPD)

The procedure followed in this assessment was to first determine the best MPD fit to the data by minimising the negative log likelihood (Tables F.15 and F.16). The MPDs became the starting points for the MCMC simulations. The following description applies to the base case.

The MPD plots show:

- survey index fits (Figure F.57) and their residuals (Figures F.58–F.61);
- the bottom trawl CPUE fit (Figure F.62) and its residuals (Figures F.63);
- fits to the age frequency data by sex for the commercial trawl fishery (Figures F.64–F.65) and their residuals (Figures F.66–F.68);
- fits to the age data by sex for the Hecate Strait (HS) synoptic survey (Figure F.69) and their residuals (Figures F.70–F.72);
- fits to the age data by sex for the West Coast Haida Gwaii (WCHG) synoptic survey (Figure F.73) and their residuals (Figures F.74–F.76);
- model estimates of mean age compared to the observed mean ages (Figure F.81);
- the stock-recruitment relationship and recruitment time series (Figure F.82);
- the recruitment deviations and auto-correlation of these deviations (Figure F.83);

- fits for the gear selectivities, together with the ogive for female maturity (Figure F.84);
- the relative spawning biomass (B_t/B_0) together with catch on the same time scale (Figure F.85); and
- the exploitation over time with catch presented again for reference (Figure F.86).

The model fits to the abundance indices are good (Figures F.57 and F.62), although the fit to the QCS Synoptic survey misses the low last index in 2017. Fits to age frequency data are generally satisfactory even though prominent ages are often under-estimated for the surveys (e.g., Figure F.73). Model estimates of mean age match the observed mean ages in the centre of the commercial data, but show some lack of fit at each end of the series (Figure F.81) while there is excellent correspondence in the QCS Synoptic survey mean ages.

The stock-recruitment relationship (Figure F.82) displays the variation that rockfish typically exhibit when fitting production using a deterministic function. High, episodic recruitment occurred in 1968, 1972, 1973 and 2000. Recruit deviations fluctuate over time, with significant auto-correlation of these deviations occurring at lags 1, 2, and 22-24 (Figure F.83). The MPD estimate of survey age at full selectivity is near age 15 for the GIG and QCS surveys while the commercial fishery estimate is near age 12 and WCVI survey is near age 11 (Figure F.84). The BCS estimate of age 12 for the age at full selectivity for the commercial fishery is the same as the equivalent estimate for the BCN base case. All selectivity curves occur to the right of the maturity ogive (with the exception of the WCVI Triennial, which was fixed and follows maturity), indicating that only mature fish are captured by the commercial fishery and the three surveys.

Spawning biomass (B_t) relative to unfished equilibrium biomass (B_0) shows some depletion with a current spawning biomass (B_{2018}) at 0.614B_0 (Figure F.85). However, annual exploitation rates (u_t) are not high, only exceeding 0.08 in 4 years.

F.3.1.1.1. BCS MPD tables for base case

Table F.15. BC South: 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	(1,1e+07)	0	(0,0)	10000	11868.1
M_s **(natural mortality by sex** s**, where** $s = 1$ [female], 2 [male]**)**					
4	(0.02,0.2)	1	(0.11,0.011)	0.11	0.0923572
4	(0.02,0.2)	1	(0.11,0.011)	0.11	0.125672
h **(steepness of spawner-recruit curve)**					
5	(0.2,0.999)	5	(4.574,2.212)	0.674	0.813035
ϵ_t **(recruitment deviations)**					
2	(-15,15)	1	(0,0.6)	0	Fig F.83
ω **(initial recruitment)**					
-1	(0,2)	0	(1,0.1)	1	1

Table F.16. BC South: 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 $g = 5, ...5$)							
5	1	(-15,15)	0	(0,0.1)	-1.60944	-9.3916	8.3425e-05
Survey catchability mode ($\log q_g$, where $g = 1, ..., 4$)							
1	1	(-12,5)	0	(0,0.6)	-5	-3.5193	0.02962
2	1	(-12,5)	0	(0,0.6)	-5	-1.618	0.1983
3	1	(-12,5)	0	(0,0.6)	-5	-1.6564	0.19082
4	1	(-12,5)	0	(0,0.6)	-5	-1.4246	0.2406
Commercial selectivity (μ_g, where $g = 5$)							
5	3	(5,40)	1	(10.748,2.1496)	10.748	12.435	
Survey selectivity (μ_g, where $g = 1, ..., 4$)							
1	3	(5,40)	1	(18.232,5.28044)	18.232	15.016	
2	3	(5,40)	1	(15.6391,2.39214)	15.6391	11.424	
3	3	(5,40)	1	(15.9947,2.72092)	15.9947	15.679	
4	-3	(5,40)	0	(8.06889,2.42067)	8.06889	8.0689	
Variance (left) of commercial selectivity curve ($\log v_{gL}$, where $g = 5$)							
5	4	(-15,15)	1	(1.57823,0.305195)	1.57823	2.6422	
Variance (left) of survey selectivity curve ($\log v_{gL}$, where $g = 1, ..., 4$)							
1	4	(-15,15)	1	(4.50131,1.0652)	4.50131	3.7038	
2	4	(-15,15)	1	(3.41953,0.64788)	3.41953	3.1402	
3	4	(-15,15)	1	(3.71443,0.497083)	3.71443	3.7088	
4	-4	(-15,15)	0	(2.27674,0.683022)	2.27674	2.2767	
Shift in commercial selectivity for males (Δ_g, where $g = 5$)							
5	4	(-8,10)	1	(0.008827,0.238791)	0.008827	0.20616	
Shift in survey selectivity for males (Δ_g, where $g = 1, ..., 4$)							
1	4	(-8,10)	1	(1.3868,2.53843)	1.3868	0.22938	
2	4	(-8,10)	1	(0.221431,0.066181)	0.221431	0.21274	
3	4	(-8,10)	1	(-0.153374,0.769265)	-0.153374	-0.14482	
4	-4	(-8,10)	0	(0,1)	0	0	

Table F.17. BC South: 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 $g = 1...4$ refer to the trawl surveys and subscript $g = 5+$ refers to the commercial fishery.

Description	Negative log likelihood	Value
Survey 1	$\log \mathsf{L}_3 \left(\boldsymbol{\Theta} \middle| \left\{ \hat{I}_{t1} \right\} \right)$	4.85
Survey 2	$\log \mathsf{L}_3 \left(\boldsymbol{\Theta} \middle| \left\{ \hat{I}_{t2} \right\} \right)$	-1.51
Survey 3	$\log \mathsf{L}_3 \left(\boldsymbol{\Theta} \middle| \left\{ \hat{I}_{t3} \right\} \right)$	-3.78
Survey 4	$\log \mathsf{L}_3 \left(\boldsymbol{\Theta} \middle| \left\{ \hat{I}_{t4} \right\} \right)$	0.12
CPUE 1	$\log \mathsf{L}_3 \left(\boldsymbol{\Theta} \middle| \left\{ \hat{I}_{t1} \right\} \right)$	-23.72
CAs 1	$\log \mathsf{L}_2 \left(\boldsymbol{\Theta} \middle| \left\{ \hat{p}_{at1s} \right\} \right)$	-199.6
CAs 2	$\log \mathsf{L}_2 \left(\boldsymbol{\Theta} \middle| \left\{ \hat{p}_{at2s} \right\} \right)$	-1005.1
CAs 3	$\log \mathsf{L}_2 \left(\boldsymbol{\Theta} \middle| \left\{ \hat{p}_{at3s} \right\} \right)$	-1513.31
CAc 1	$\log \mathsf{L}_2 \left(\boldsymbol{\Theta} \middle| \left\{ \hat{p}_{at5s} \right\} \right)$	-4667.44
Prior	$\log \mathsf{L}_1 \left(\boldsymbol{\Theta} \middle| \left\{ \epsilon_t \right\} \right) - \log \left(\pi(\boldsymbol{\Theta}) \right)$	51.88
	Objective function $f(\boldsymbol{\Theta})$	-7357.63

F.3.1.1.2. BCS MPD figures for base case

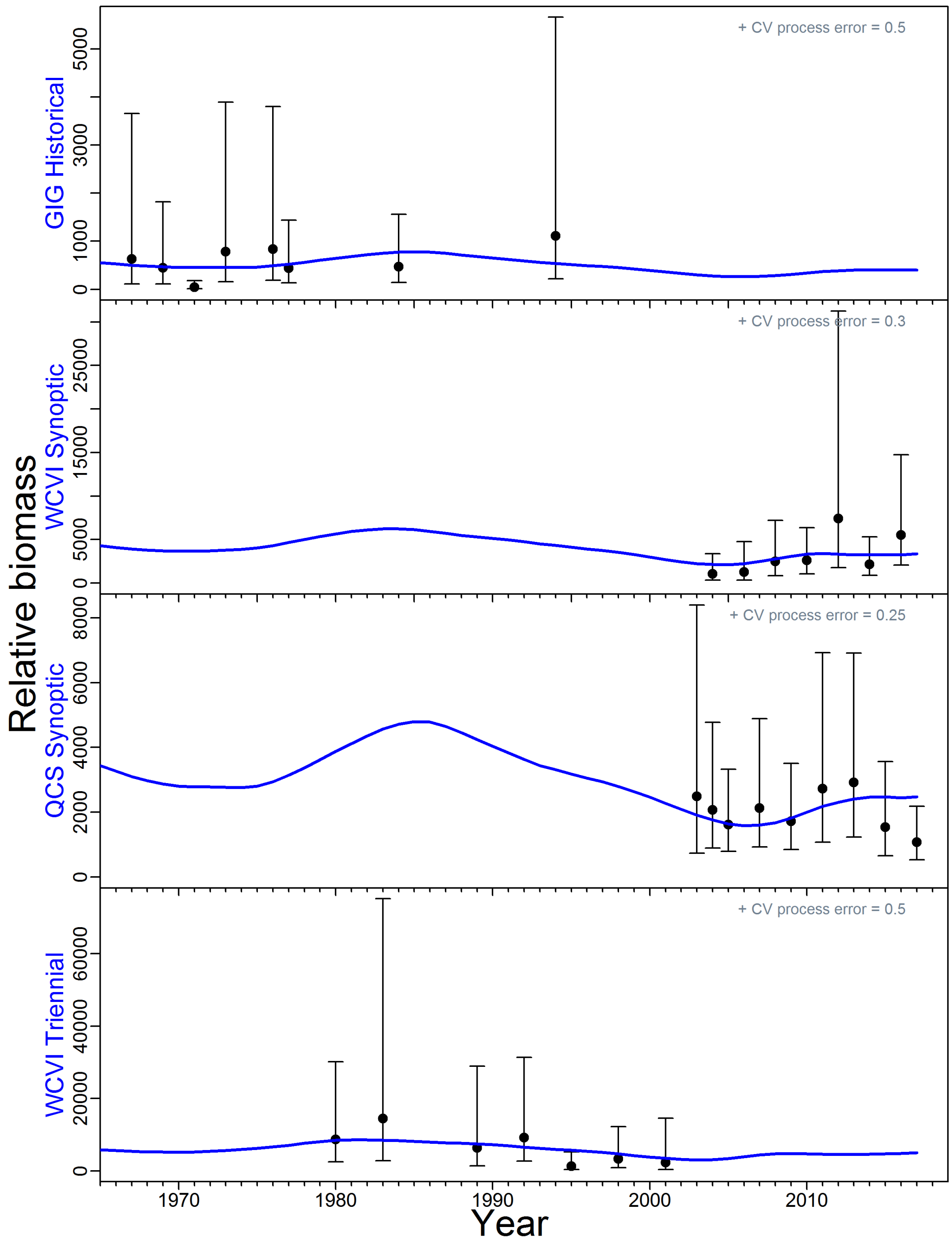


Figure F.57. BC South: Survey index values (points) with 95% confidence intervals (bars) and MPD model fits (curves) for the fishery-independent survey series.

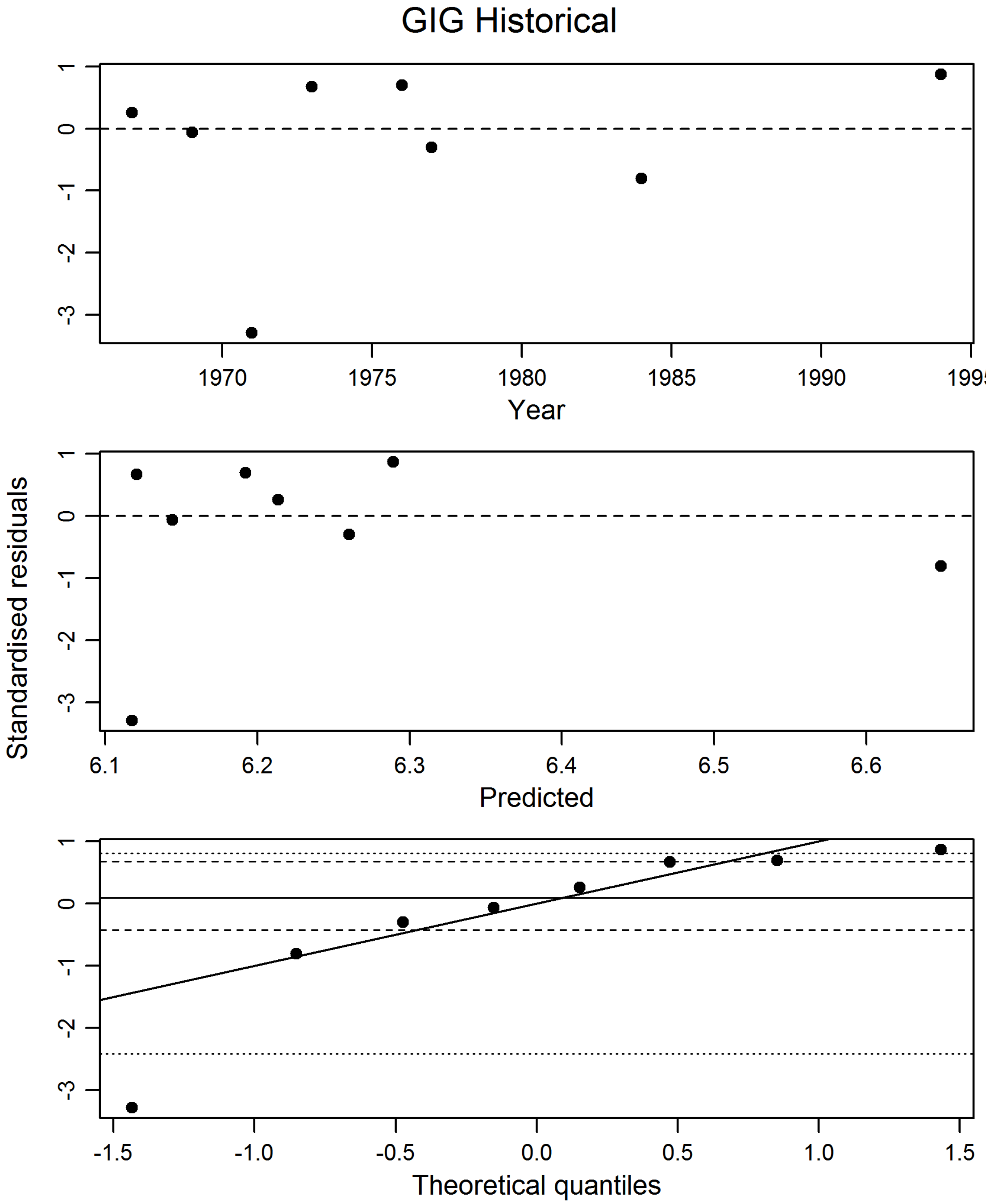


Figure F.58. BC South: Residuals of fits of model to GIG Historical survey series (MPD values). Vertical axes are standardised residuals. The three plots show, respectively, residuals by year of index, residuals relative to predicted index, and normal quantile-quantile plot for residuals (horizontal lines give 5, 25, 50, 75 and 95 percentiles).

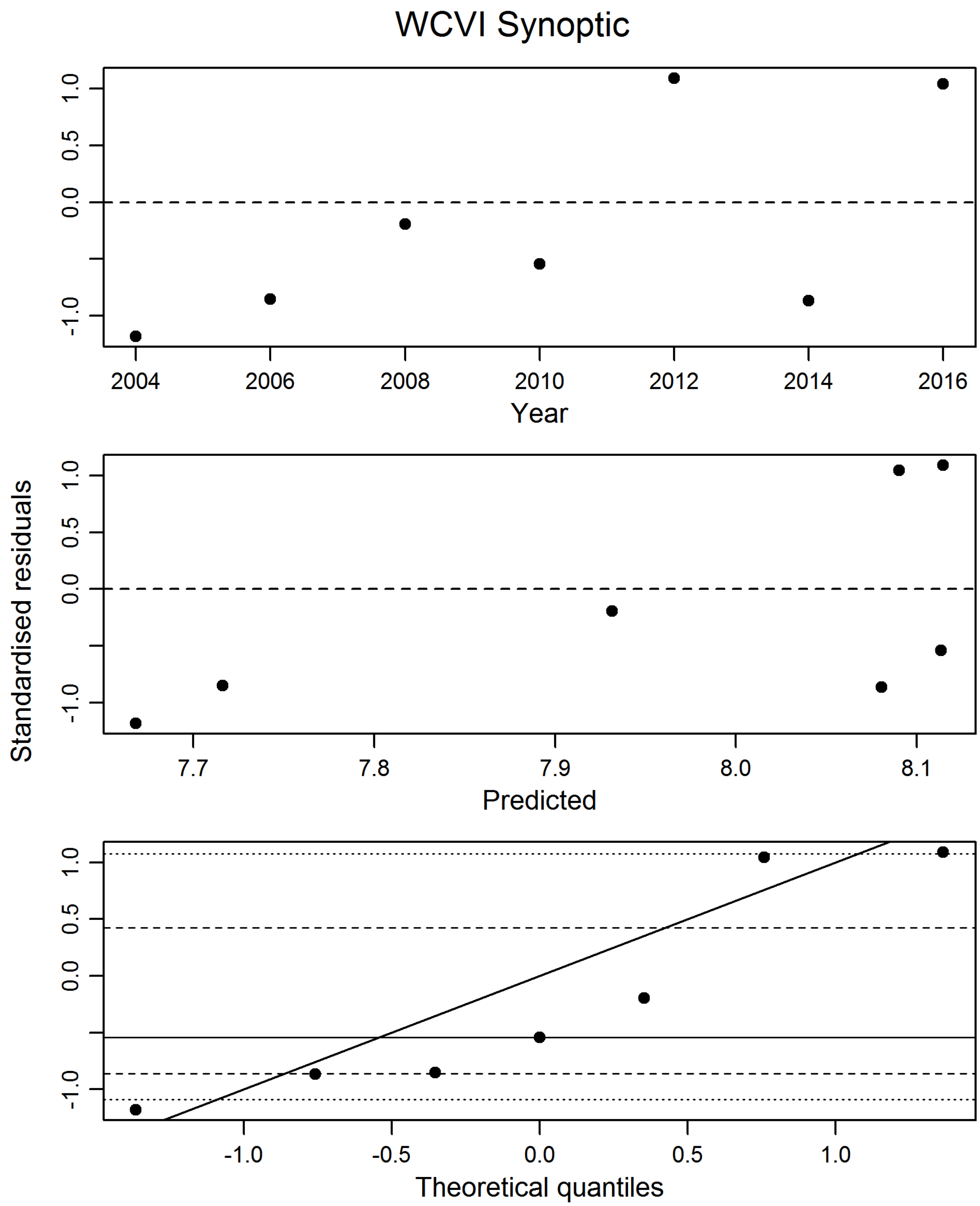


Figure F.59. BC South: Residuals of fits of model to WCVI Synoptic survey series (MPD values). Vertical axes are standardised residuals. The three plots show, respectively, residuals by year of index, residuals relative to predicted index, and normal quantile-quantile plot for residuals (horizontal lines give 5, 25, 50, 75 and 95 percentiles).

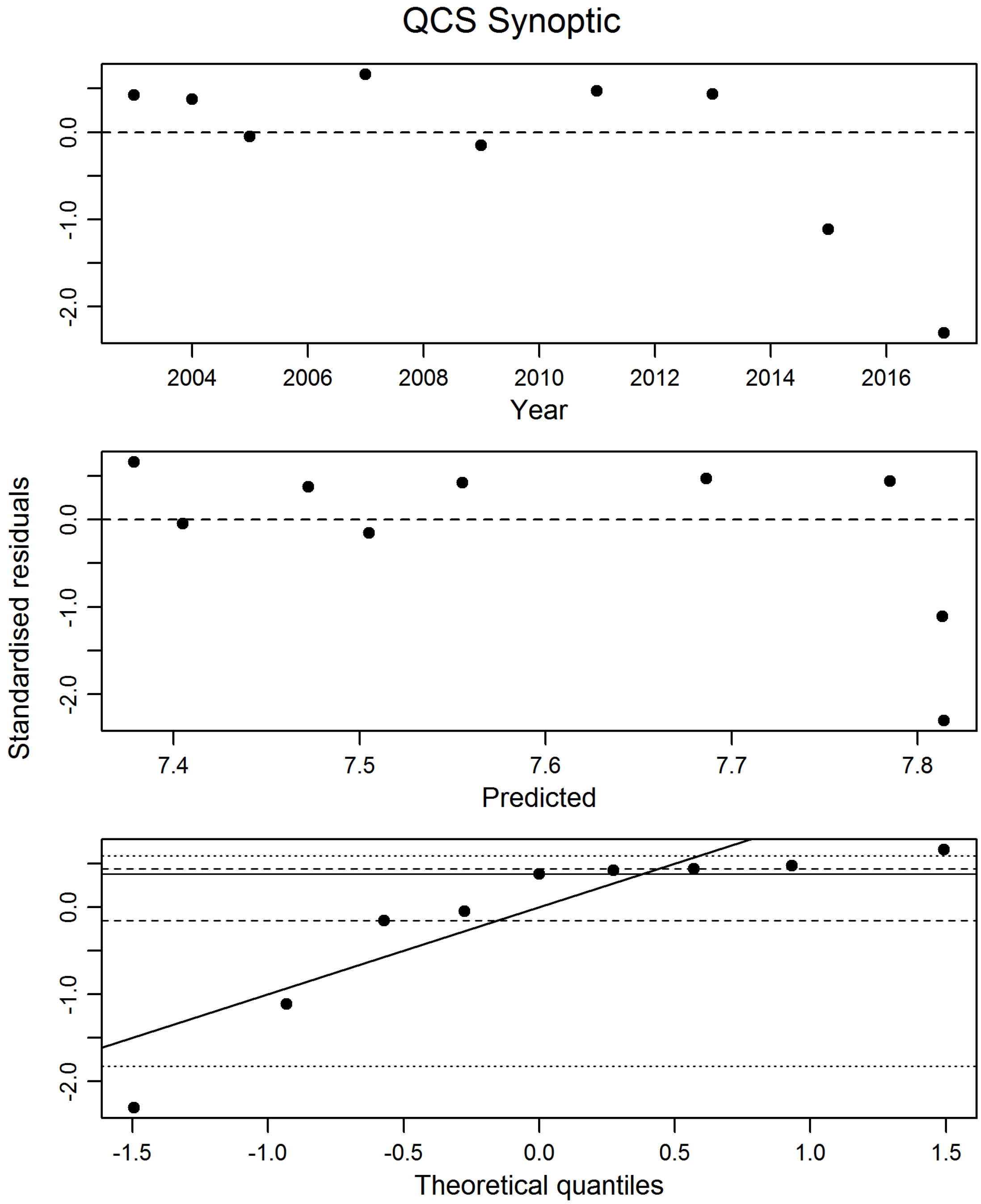


Figure F.60. BC South: Residuals of fits of model to QCS Synoptic survey series (MPD values). Vertical axes are standardised residuals. The three plots show, respectively, residuals by year of index, residuals relative to predicted index, and normal quantile-quantile plot for residuals (horizontal lines give 5, 25, 50, 75 and 95 percentiles).

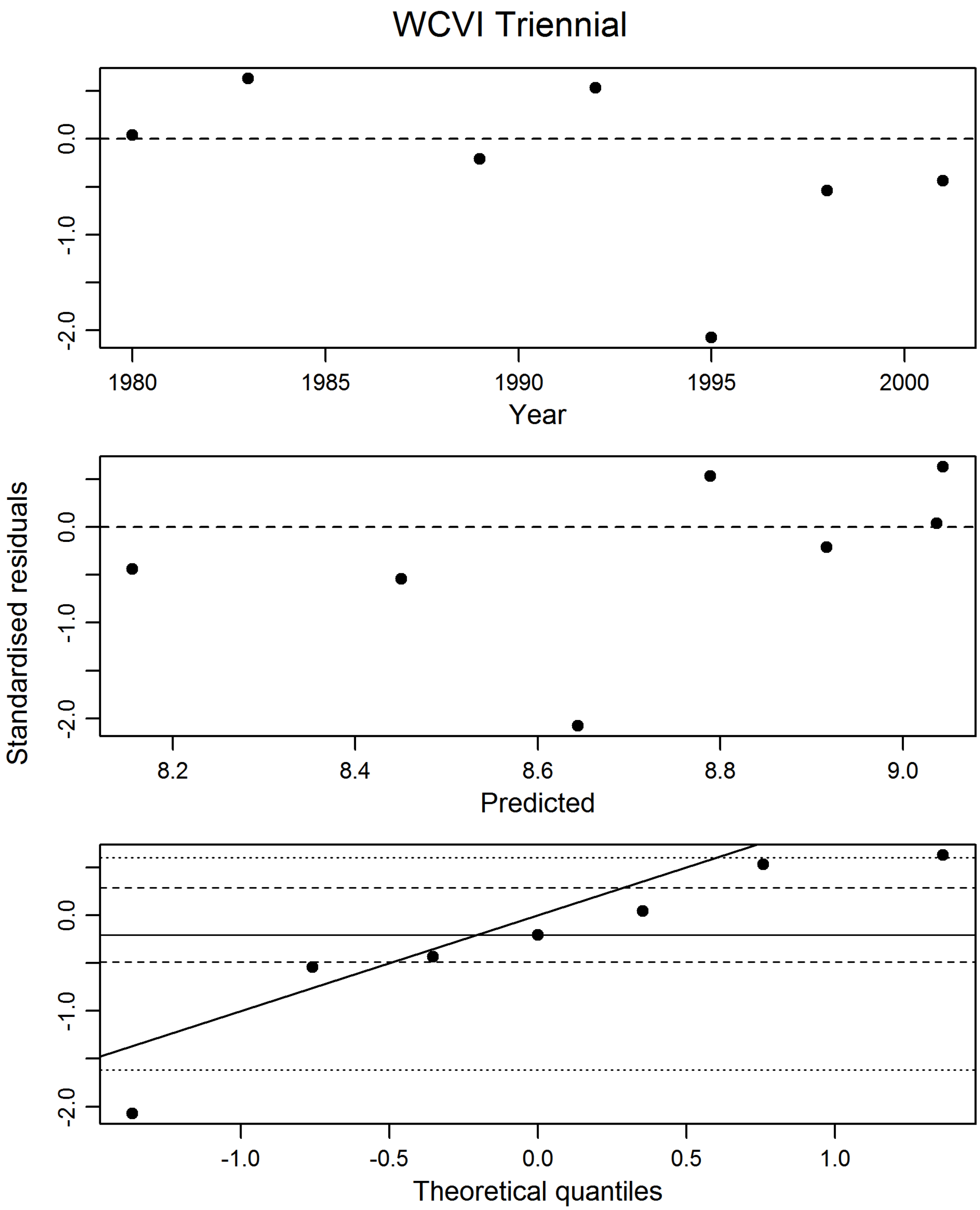


Figure F.61. BC South: Residuals of fits of model to WCVI Triennial survey series (MPD values). Vertical axes are standardised residuals. The three plots show, respectively, residuals by year of index, residuals relative to predicted index, and normal quantile-quantile plot for residuals (horizontal lines give 5, 25, 50, 75 and 95 percentiles).

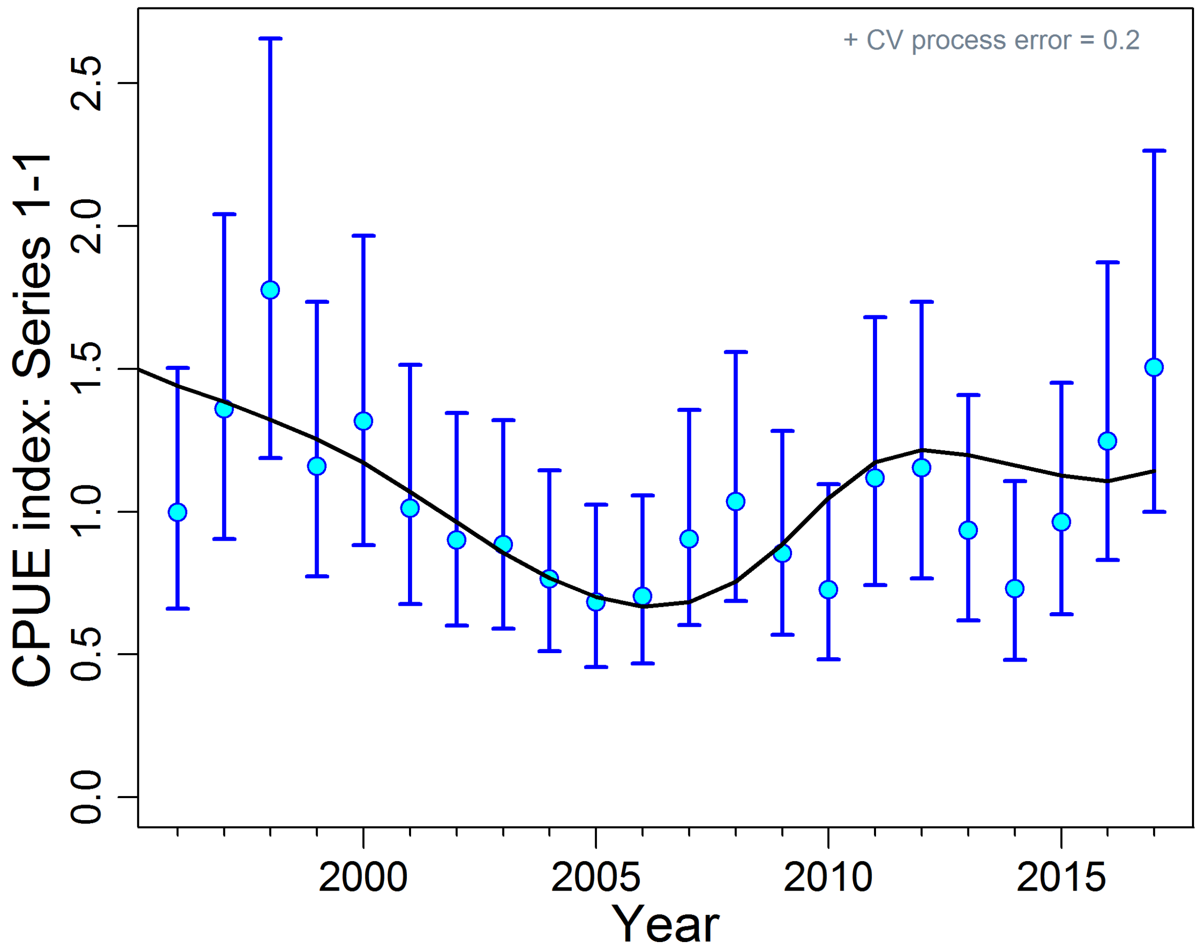


Figure F.62. BC South: CPUE index series, 90% error bars are based on lognormal assumption (double check error bars).

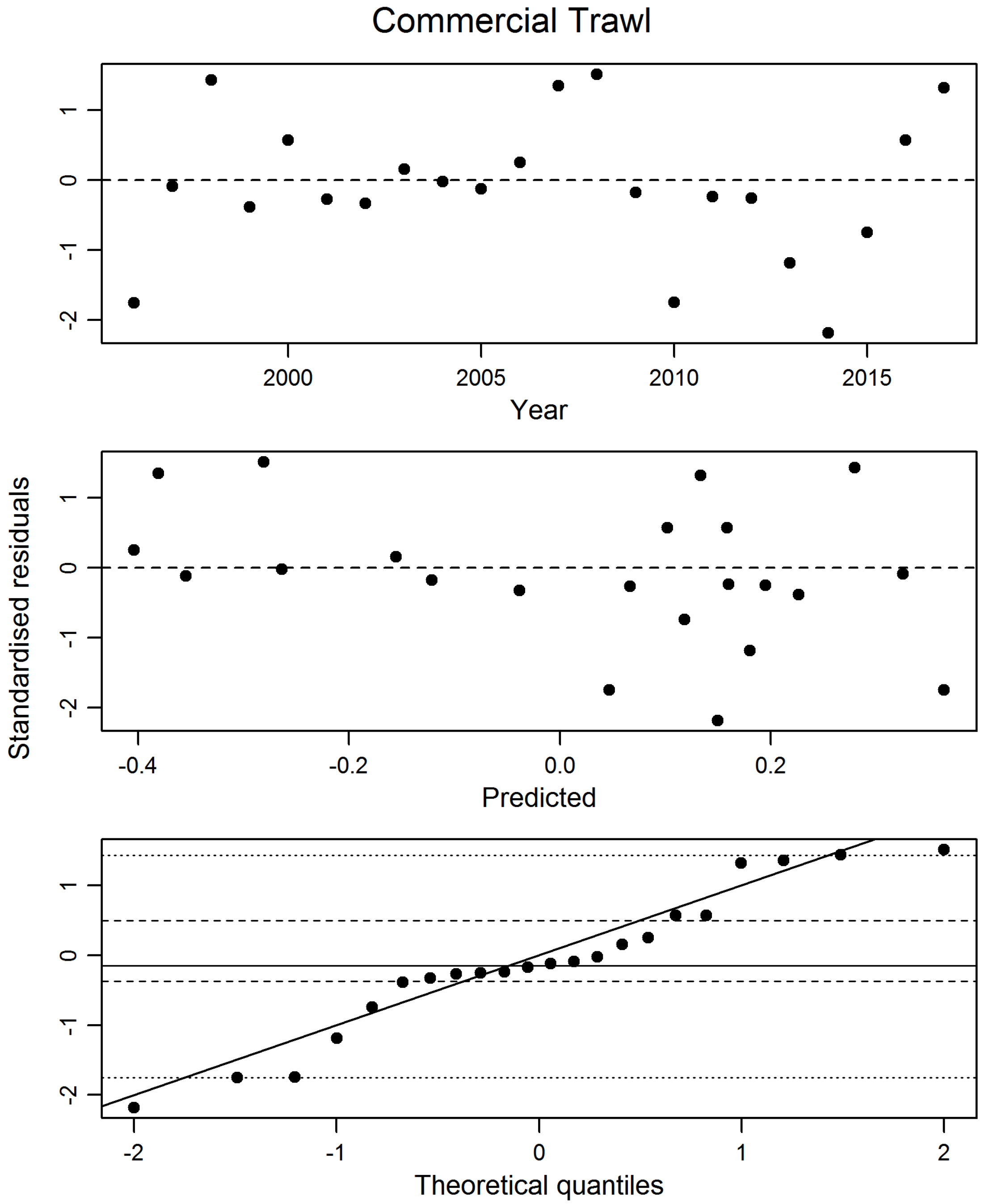


Figure F.63. BC South: Residuals of fits of model to bottom trawl CPUE series (MPD values). Vertical axes are standardised residuals. The three plots show, respectively, residuals by year of index, residuals relative to predicted index, and normal quantile-quantile plot for residuals (horizontal lines give 5, 25, 50, 75 and 95 percentiles).

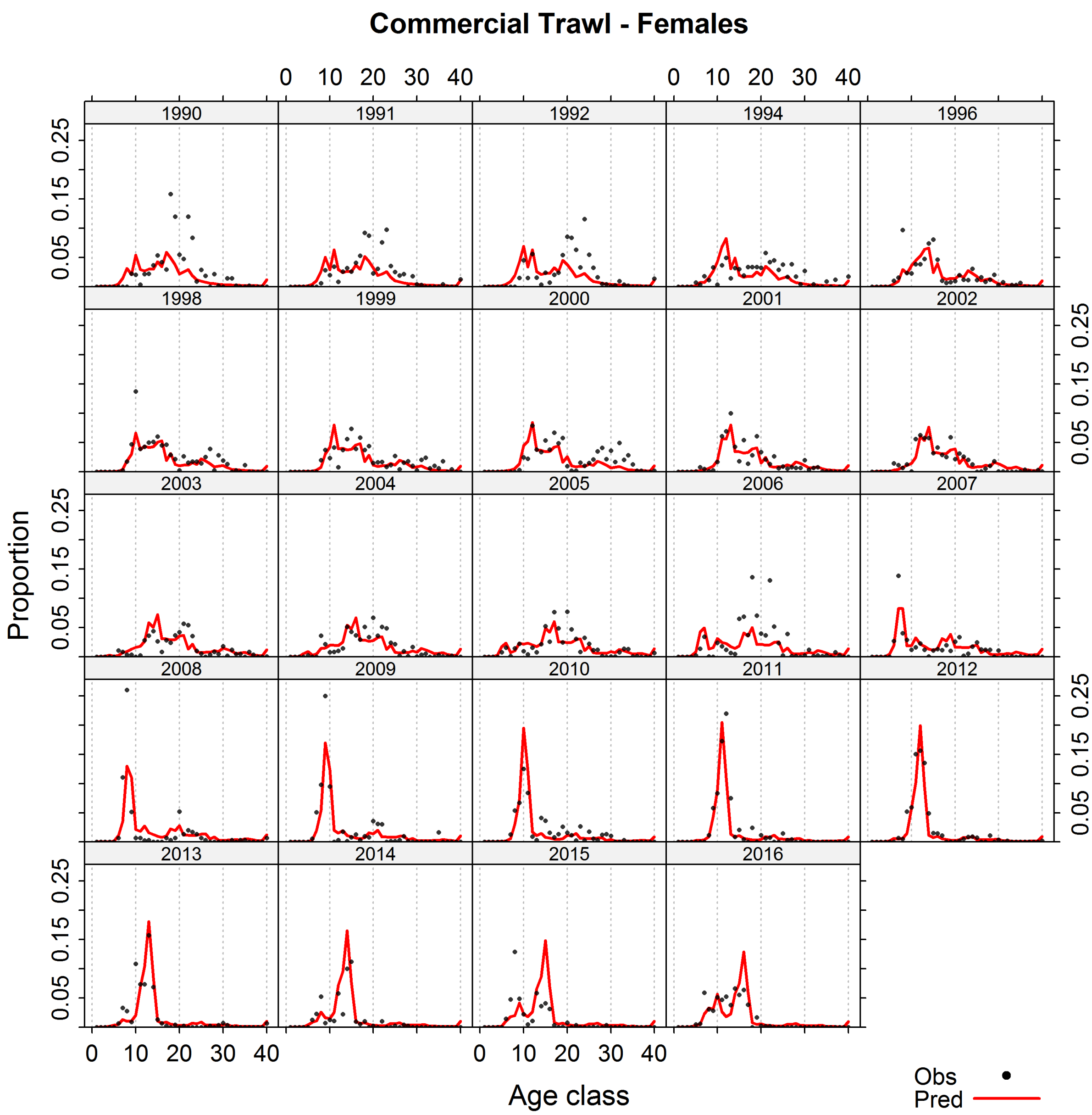


Figure F.64. BC South: Observed and predicted commercial trawl proportions-at-age for females. Note that years are not necessarily consecutive.

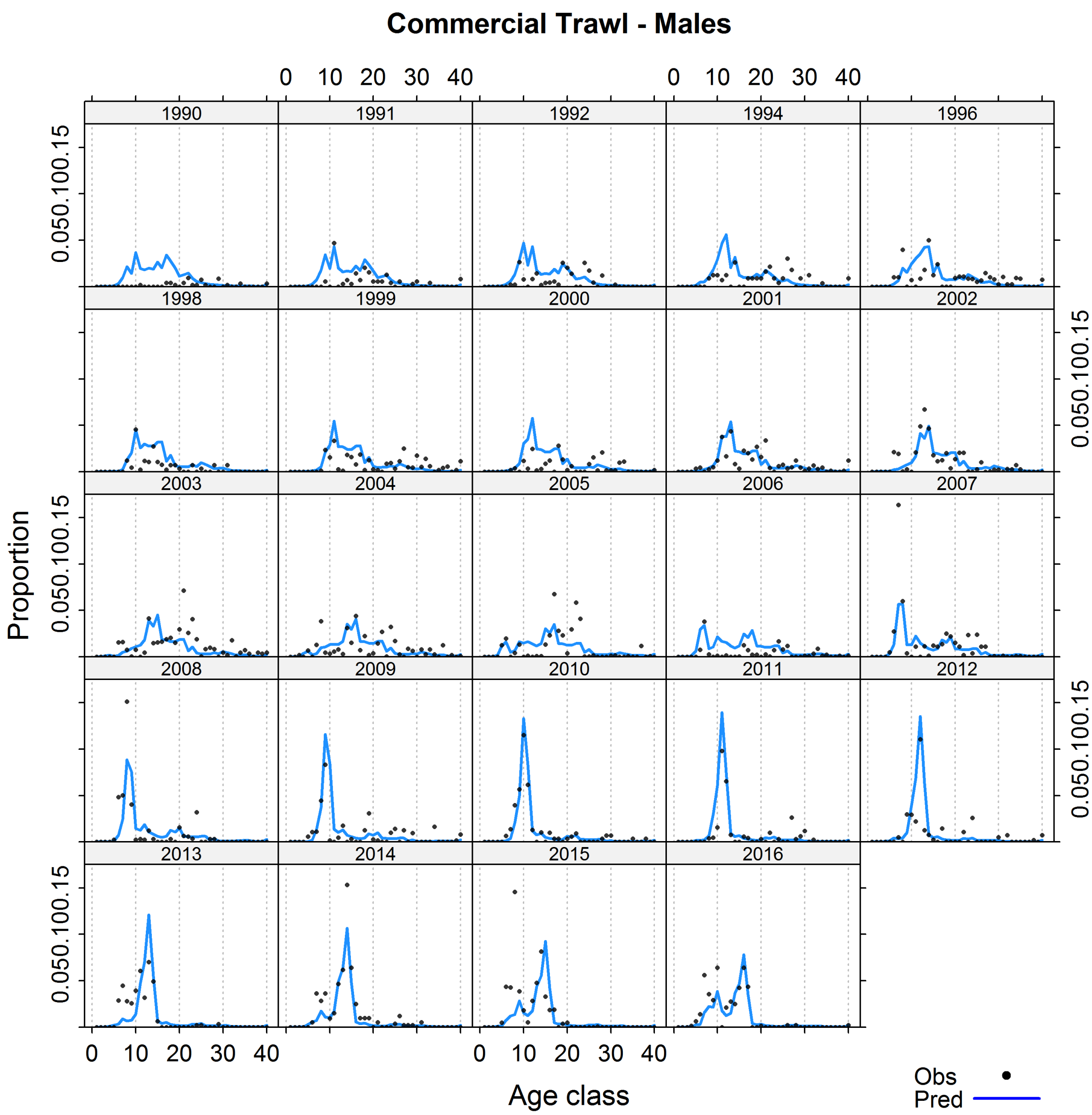


Figure F.65. BC South: Observed and predicted commercial trawl proportions-at-age for males. Note that years are not necessarily consecutive.

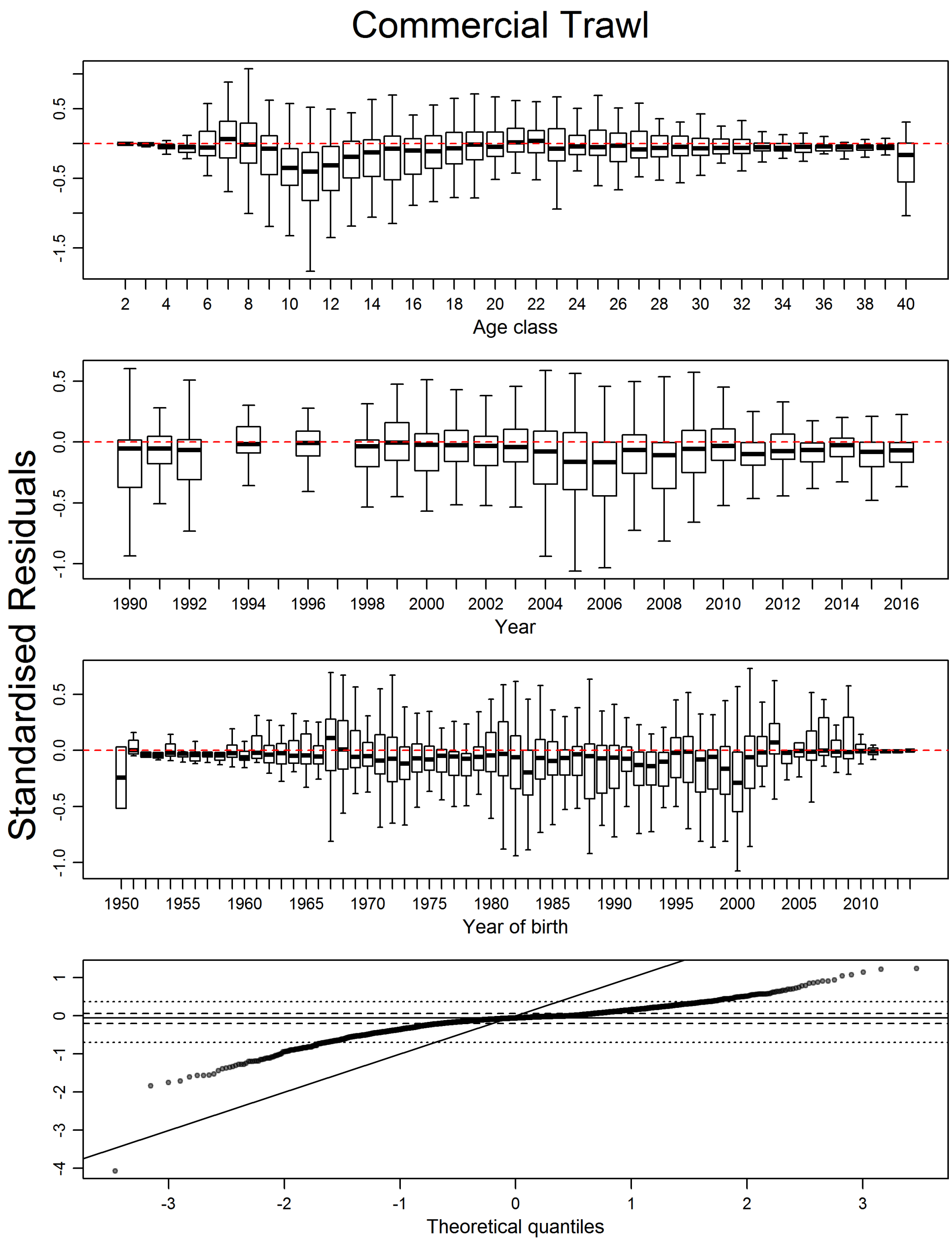


Figure F.66. BC South: Residual of fits of model to commercial proportions-at-age data (MPD values) for Commercial Trawl events. Vertical axes are standardised residuals. Boxplots show, respectively, residuals by age class, by year of data, and by year of birth (following a cohort through time). Boxes give interquartile ranges, with bold lines representing medians and whiskers extending to the most extreme data point that is <1.5 times the interquartile range from the box. Bottom panel is the normal quantile-quantile plot for residuals, with the 1:1 line, though residuals are not expected to be normally distributed because of the likelihood function used; horizontal lines give the 5, 25, 50, 75, and 95 percentiles (for a total of 1872 residuals).

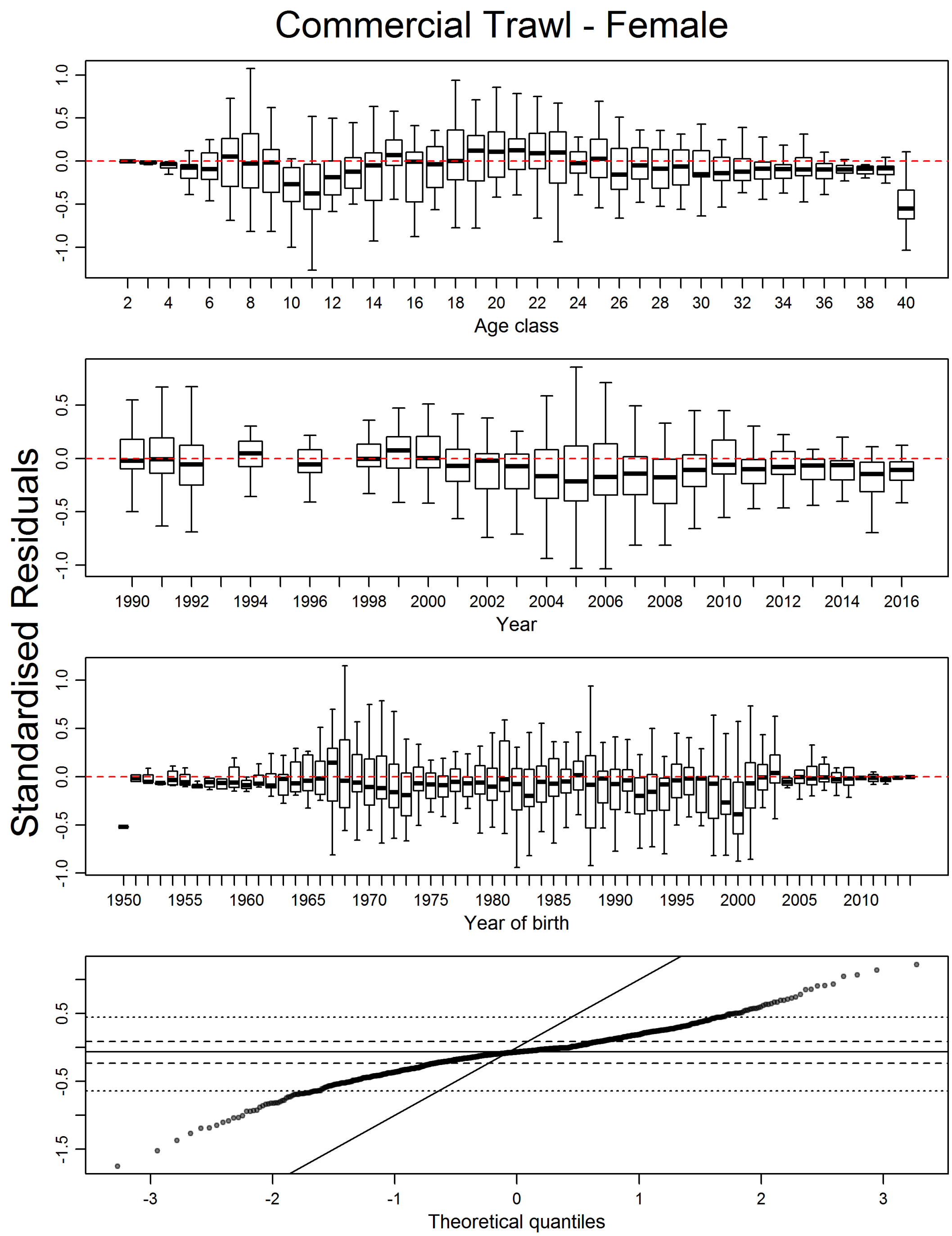


Figure F.67. BC South: Residual of fits of model to commercial proportions-at-age data (MPD values) for females (Commercial Trawl). Details as for Figure F.66, for a total of 936 residuals.

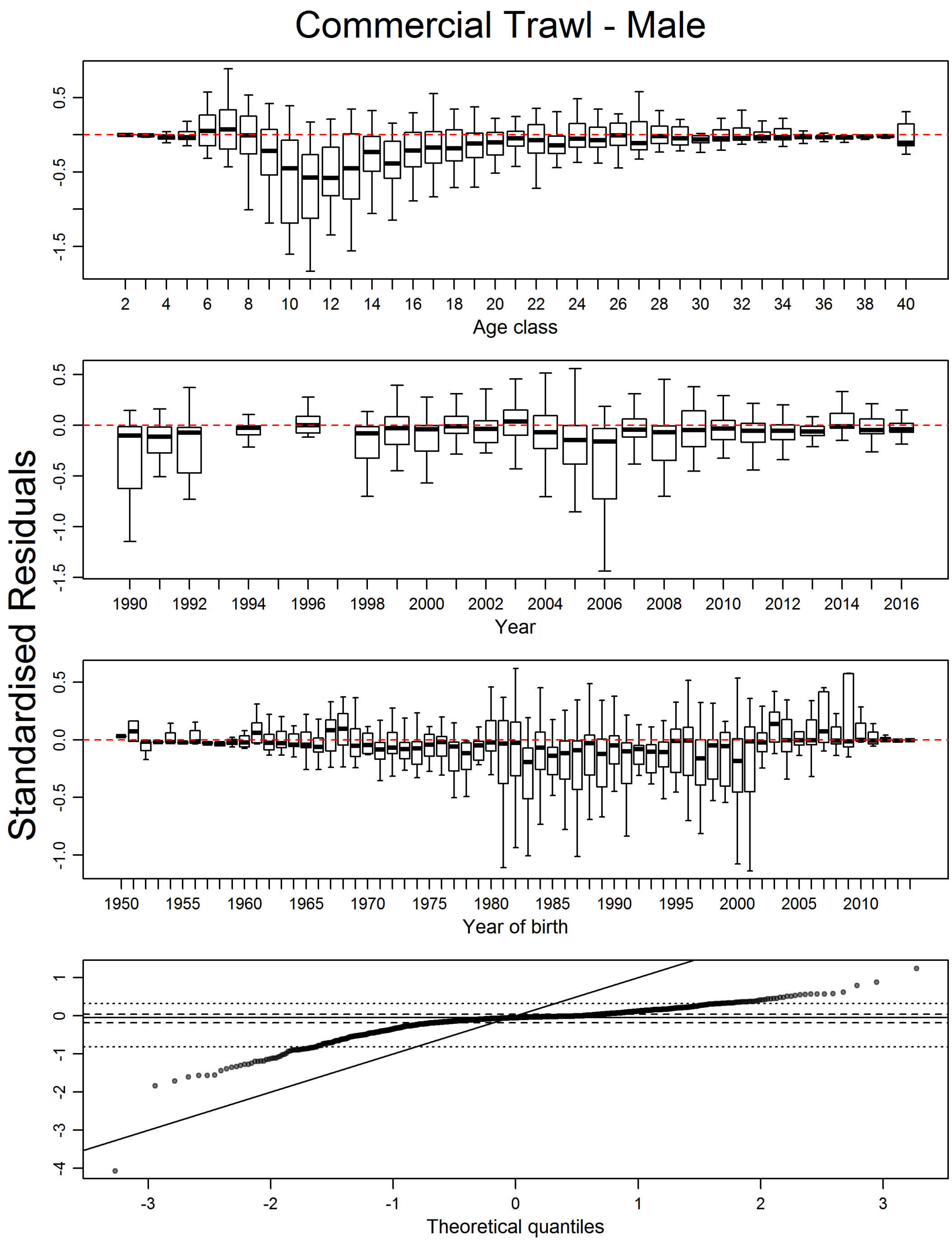
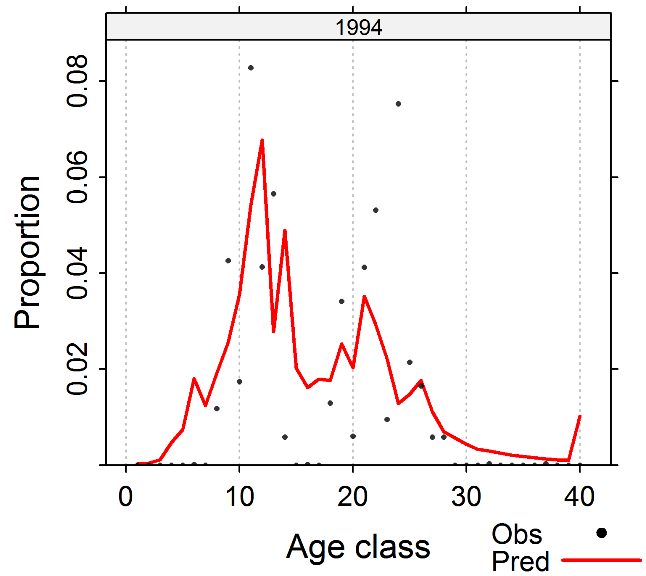


Figure F.68. BC South: Residual of fits of model to commercial proportions-at-age data (MPD values) for males (Commercial Trawl). Details as for Figure F.66, for a total of 936 residuals.

GIG Historical - Females



GIG Historical - Males

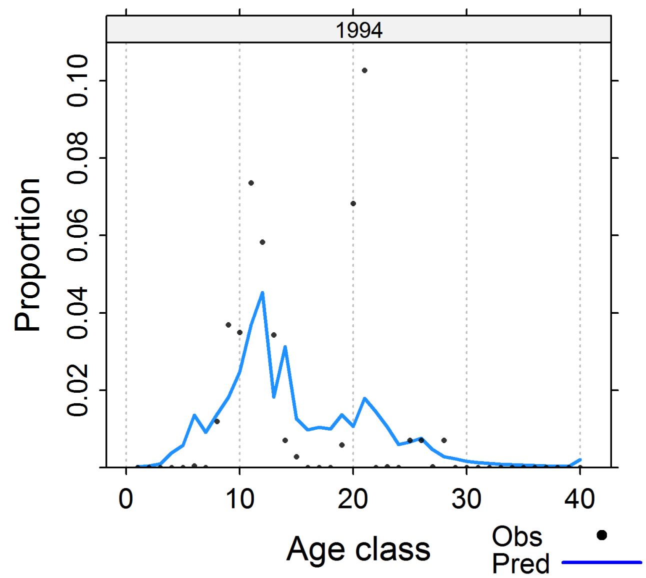


Figure F.69. BC South: Observed and predicted proportions-at-age for GIG Historical survey.

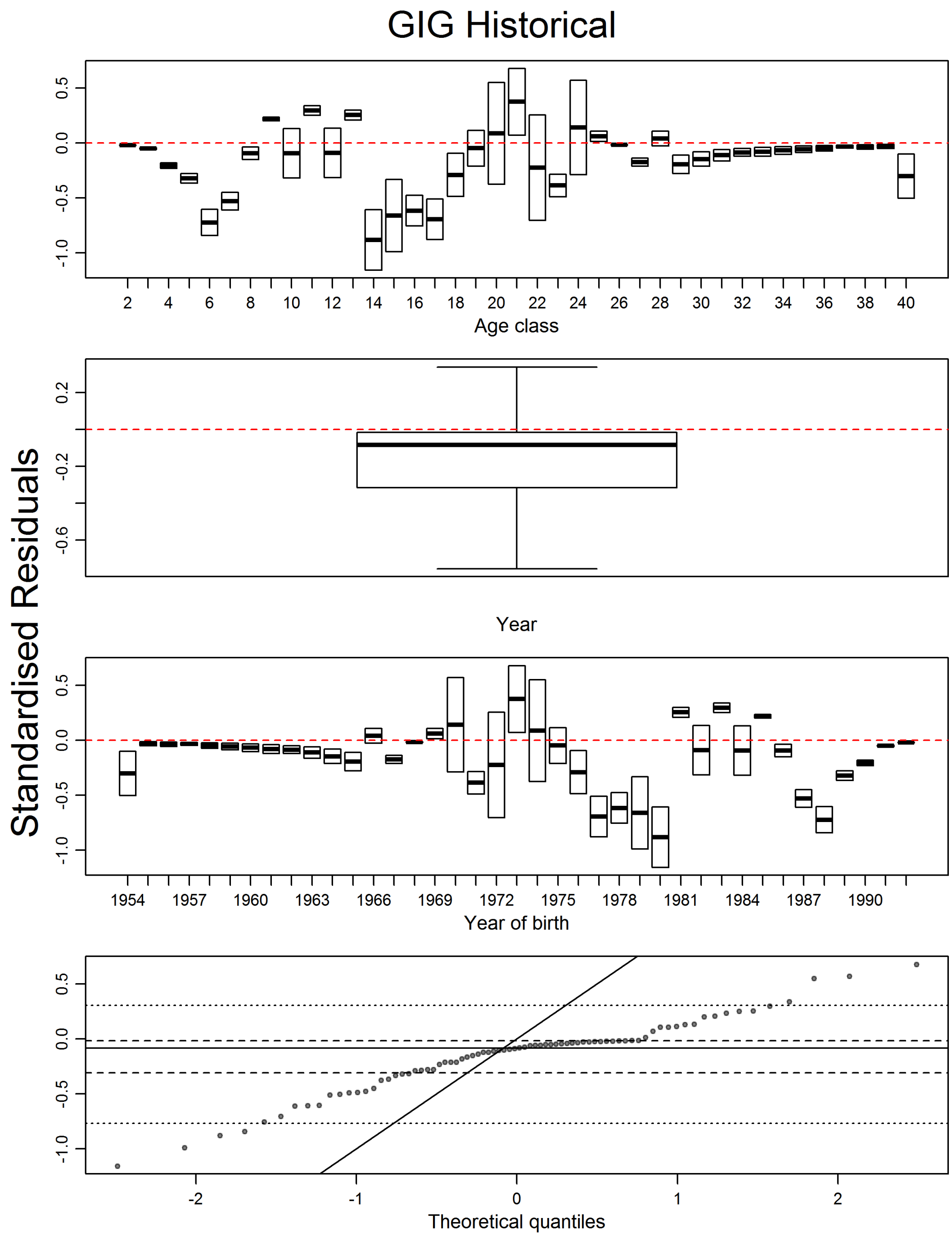


Figure F.70. BC South: Residuals of fits of model to proportions-at-age data (MPD values) from the GIG Historical survey series. Details as for Figure F.66, for a total of 78 residuals.

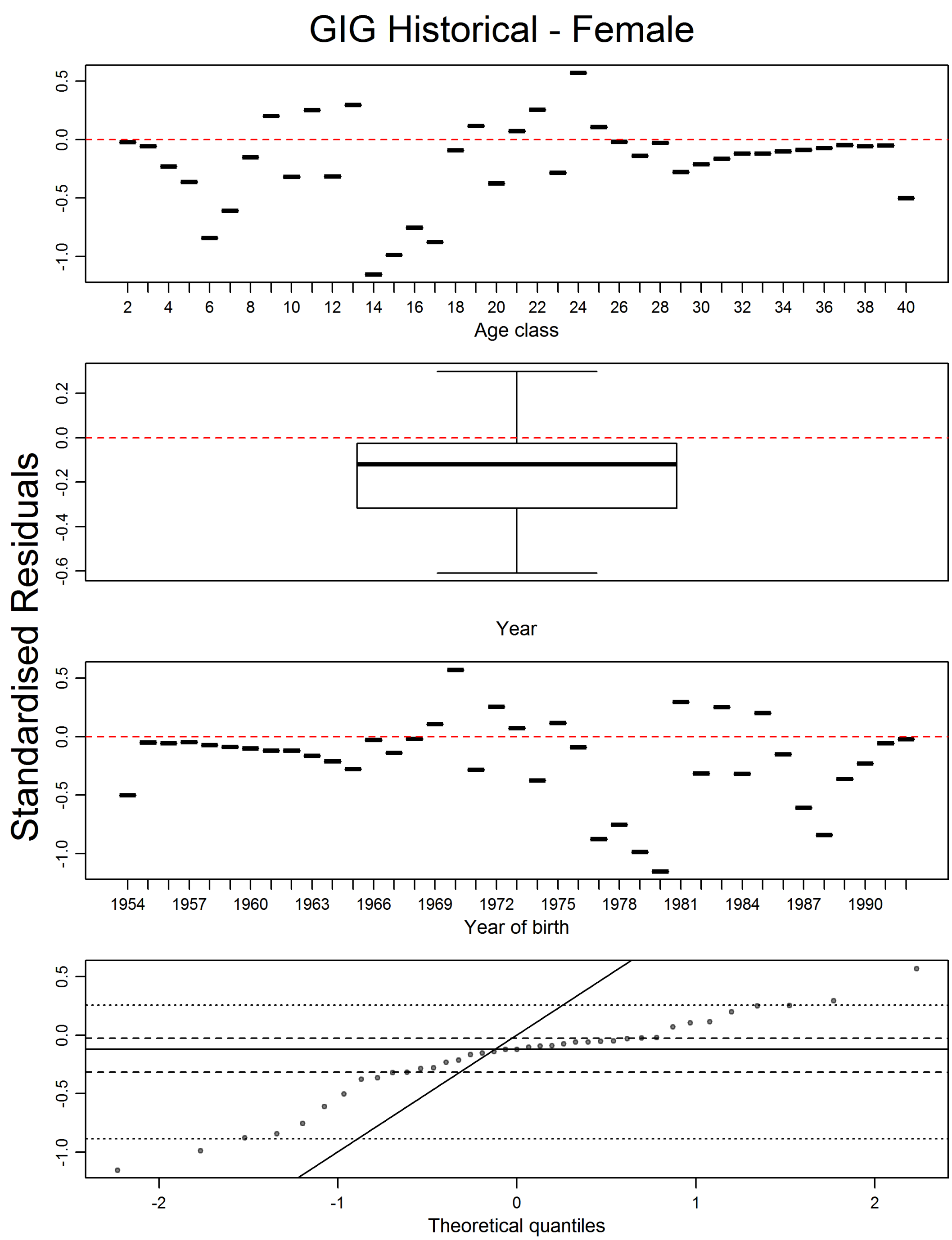


Figure F.71. BC South: Residuals of fits of model to proportions-at-age data (MPD values) for females from GIG Historical survey series. Details as for Figure F.66, for a total of 39 residuals.

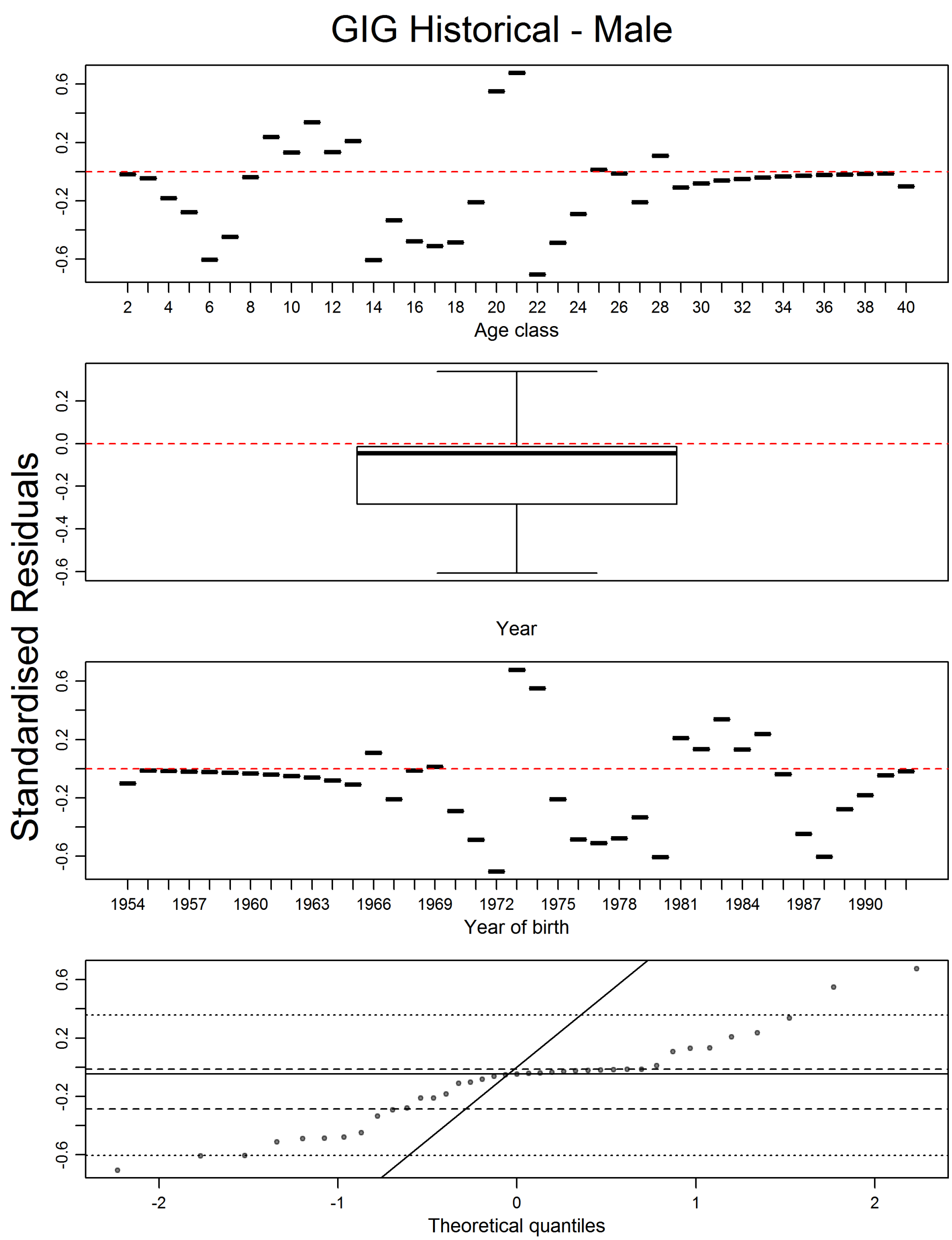


Figure F.72. BC South: Residuals of fits of model to proportions-at-age data (MPD values) for males from GIG Historical survey series. Details as for Figure F.66, for a total of 39 residuals.

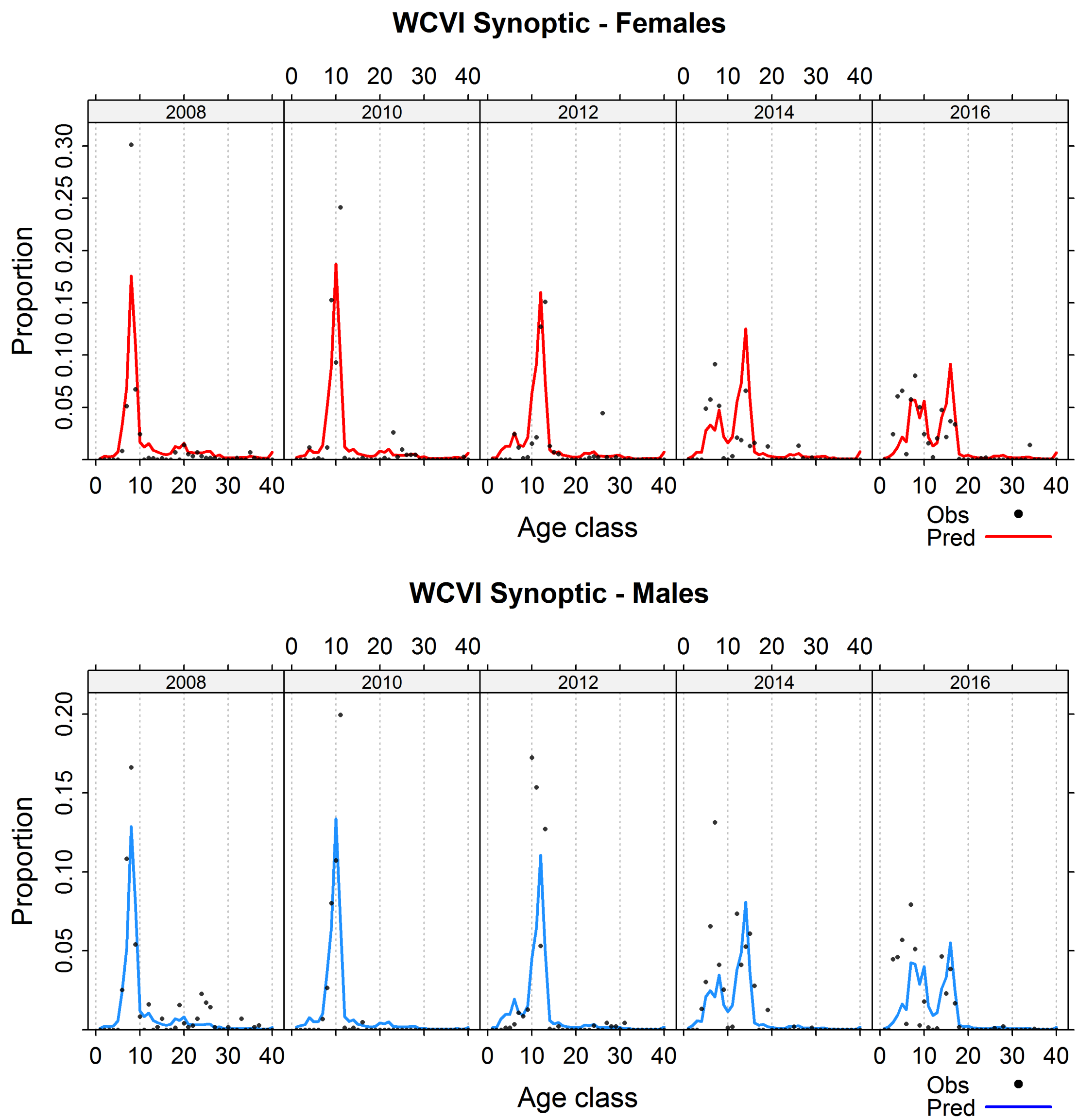


Figure F.73. BC South: Observed and predicted proportions-at-age for WCVI Synoptic survey.

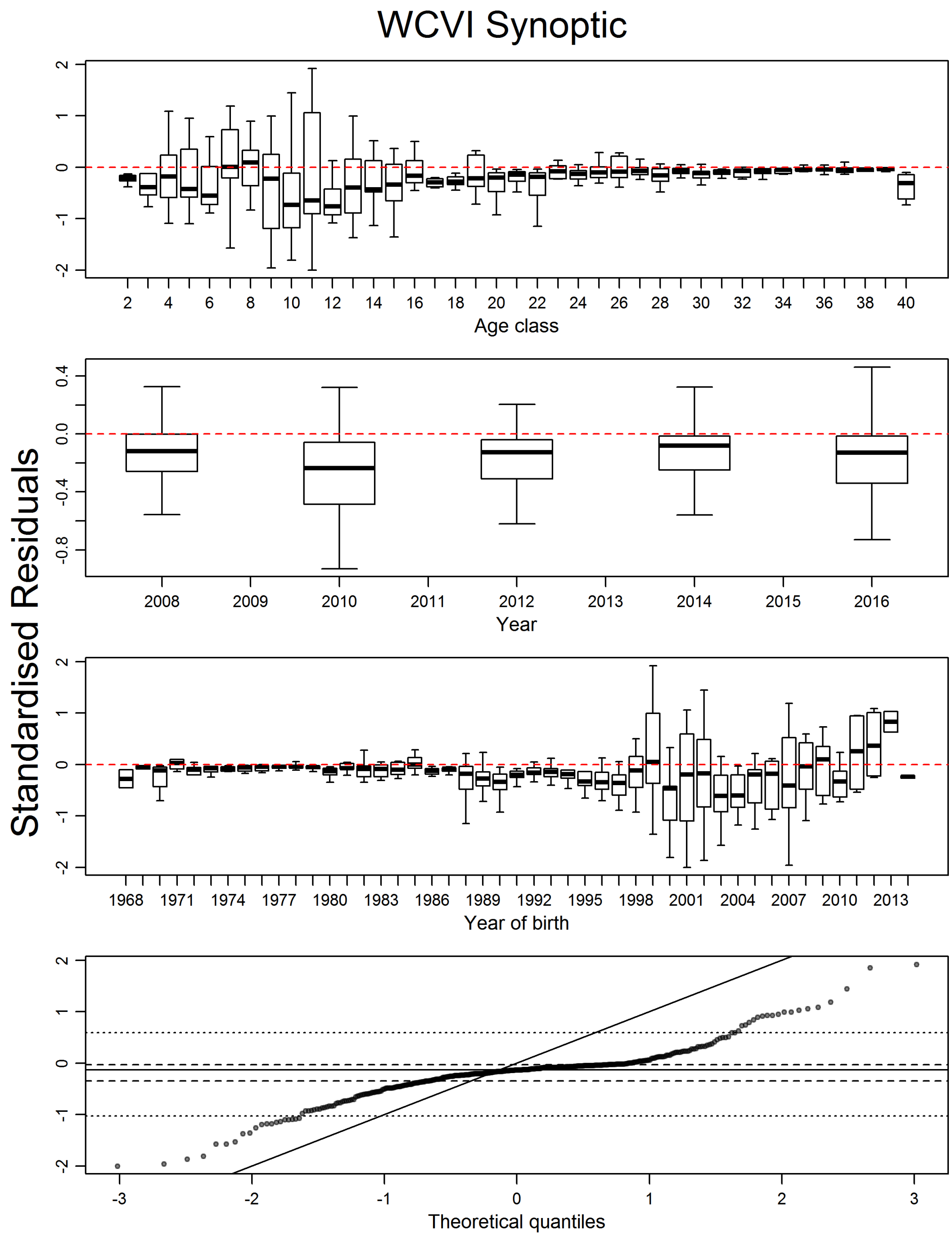


Figure F.74. BC South: Residuals of fits of model to proportions-at-age data (MPD values) from the WCVI Synoptic survey series. Details as for Figure F.66, for a total of 390 residuals.

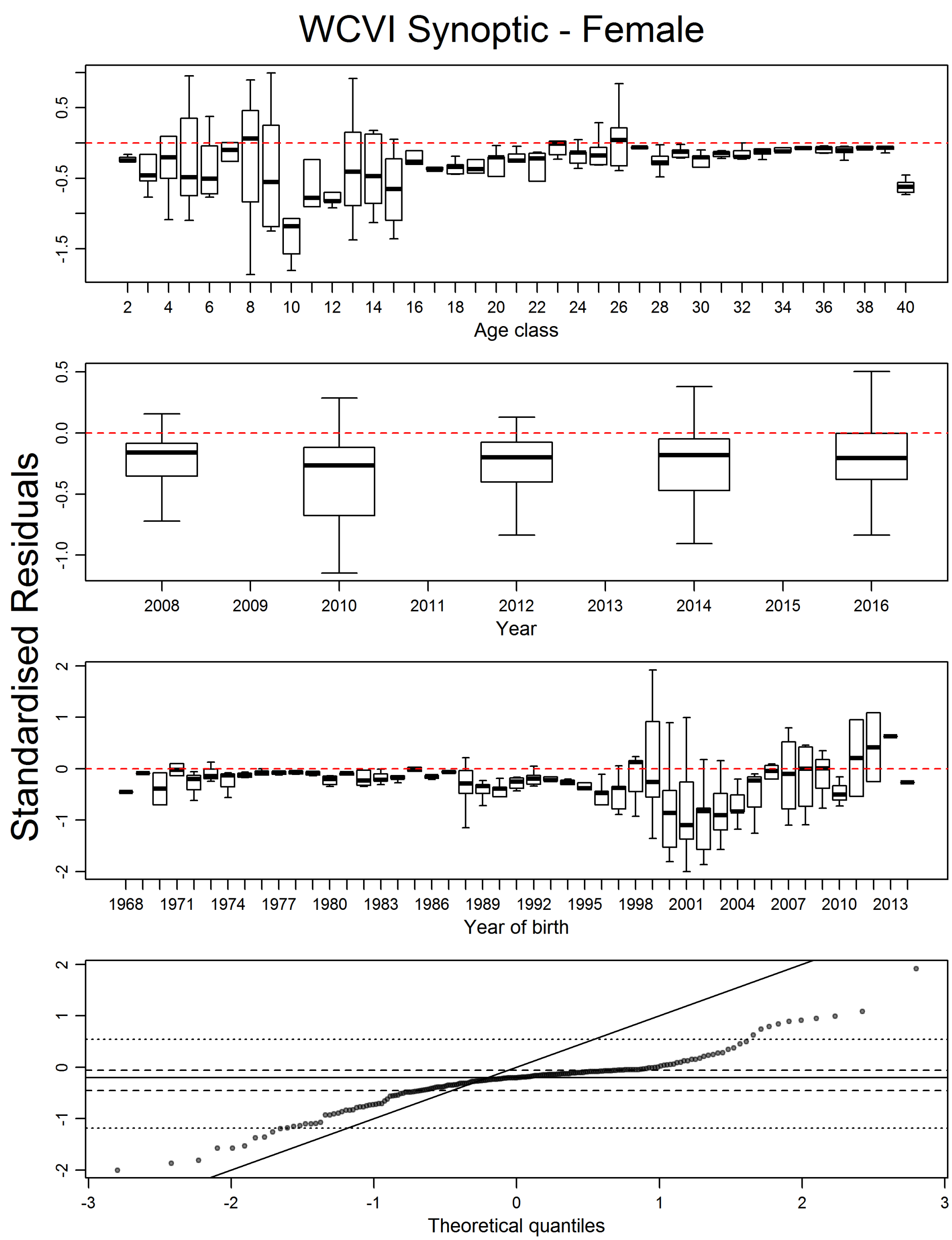


Figure F.75. BC South: Residuals of fits of model to proportions-at-age data (MPD values) for females from WCVI Synoptic survey series. Details as for Figure F.66, for a total of 195 residuals.

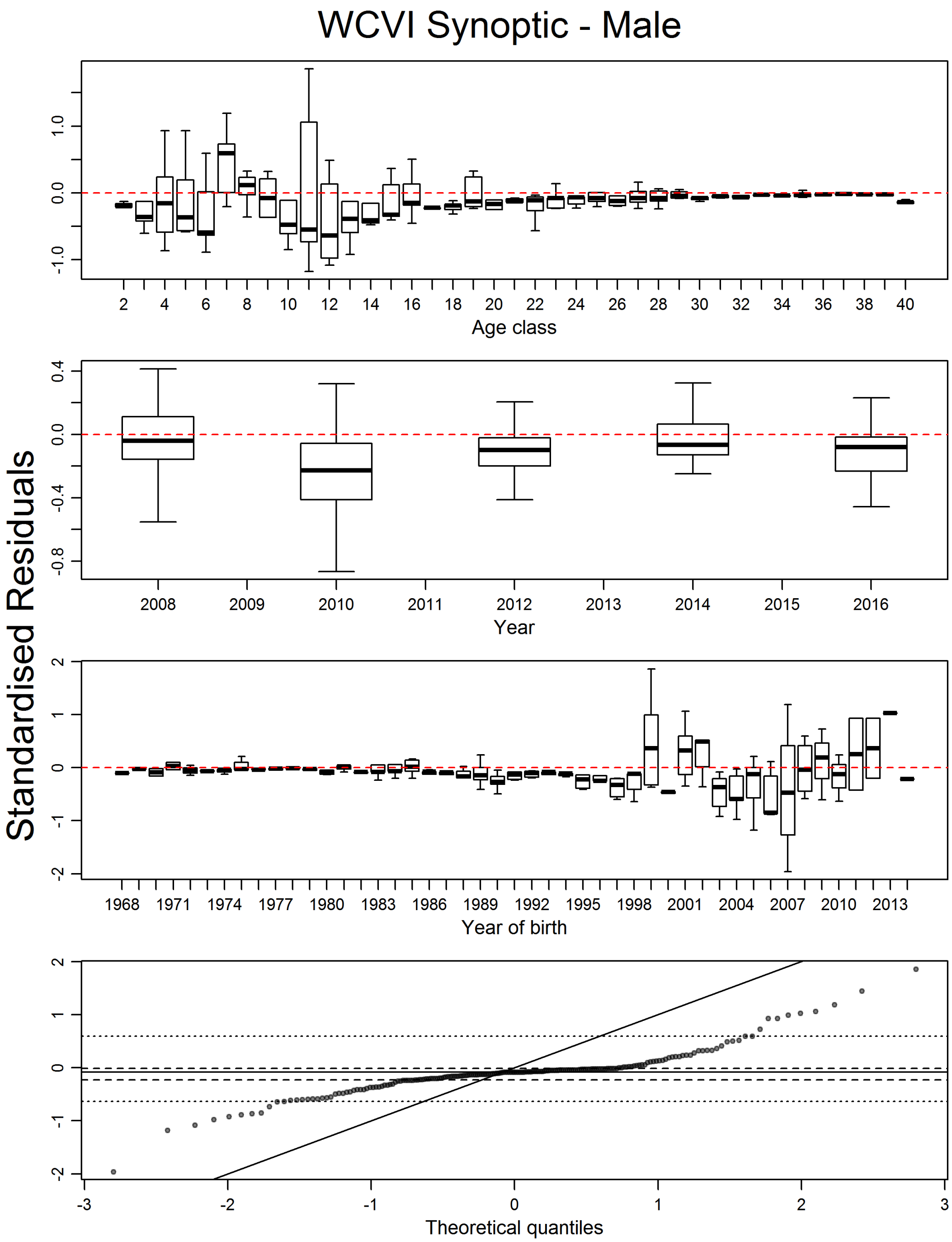
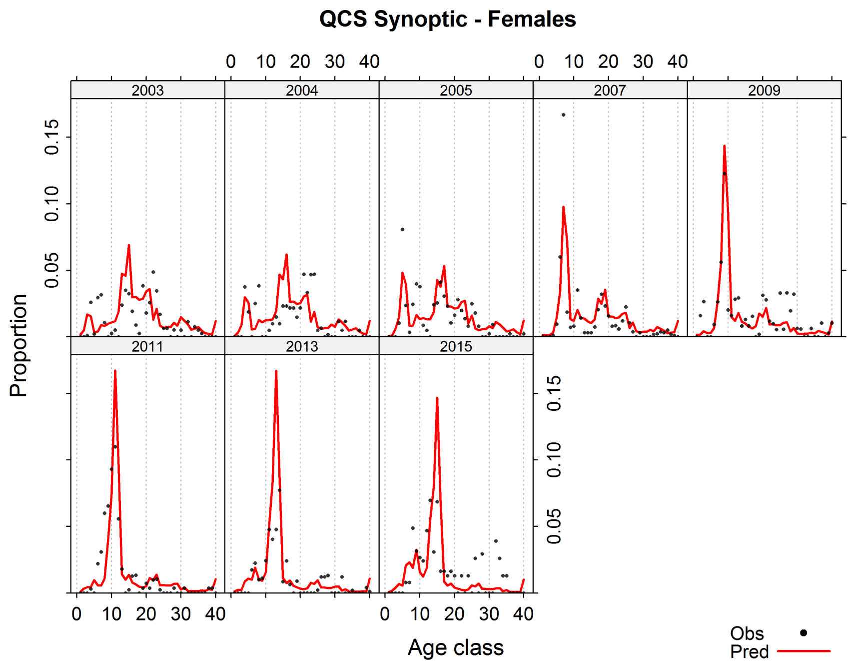


Figure F.76. BC South: Residuals of fits of model to proportions-at-age data (MPD values) for males from WCVI Synoptic survey series. Details as for Figure F.66, for a total of 195 residuals.



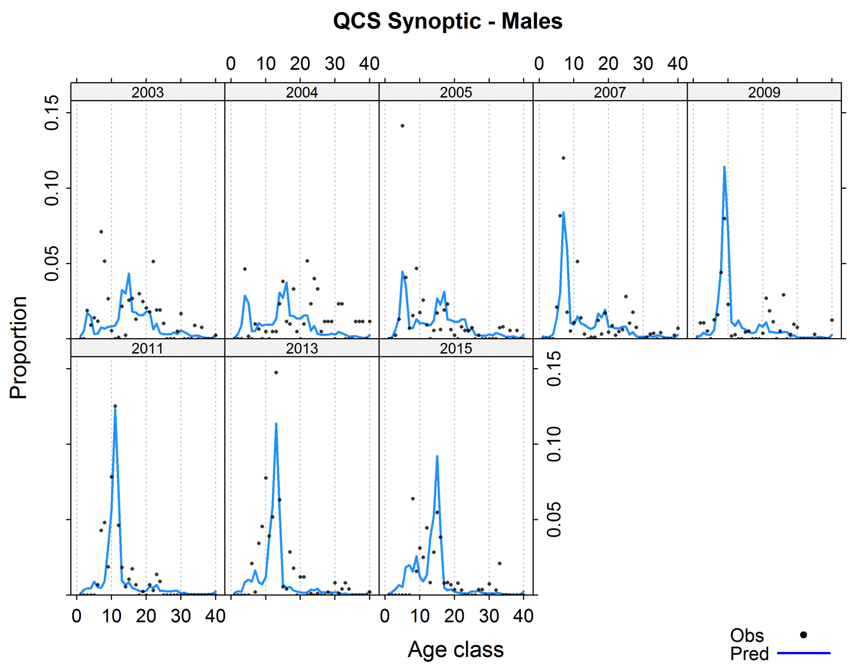


Figure F.77. BC South: Observed and predicted proportions-at-age for QCS Synoptic survey.

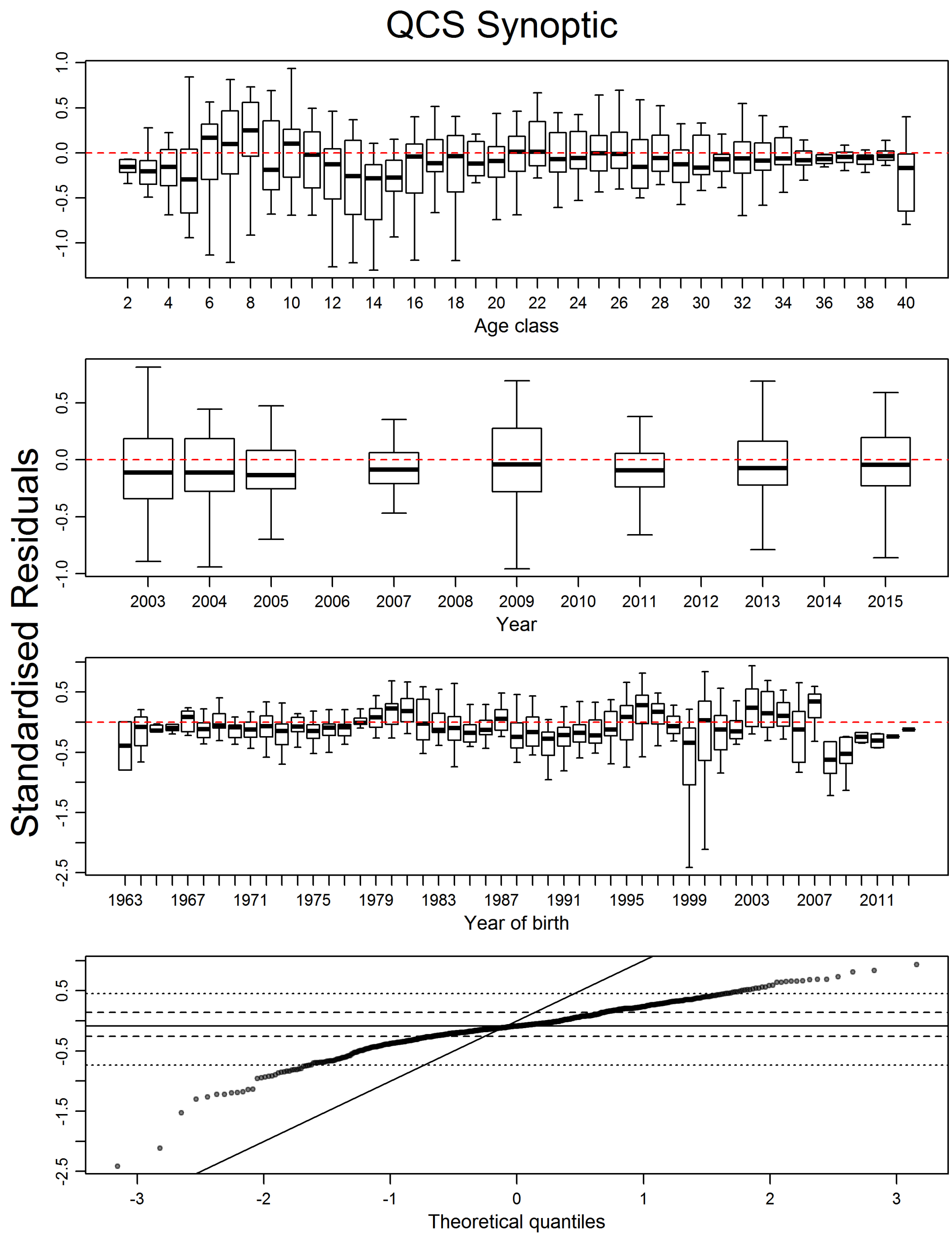


Figure F.78. BC South: Residuals of fits of model to proportions-at-age data (MPD values) from the QCS Synoptic survey series. Details as for Figure F.66, for a total of 624 residuals.

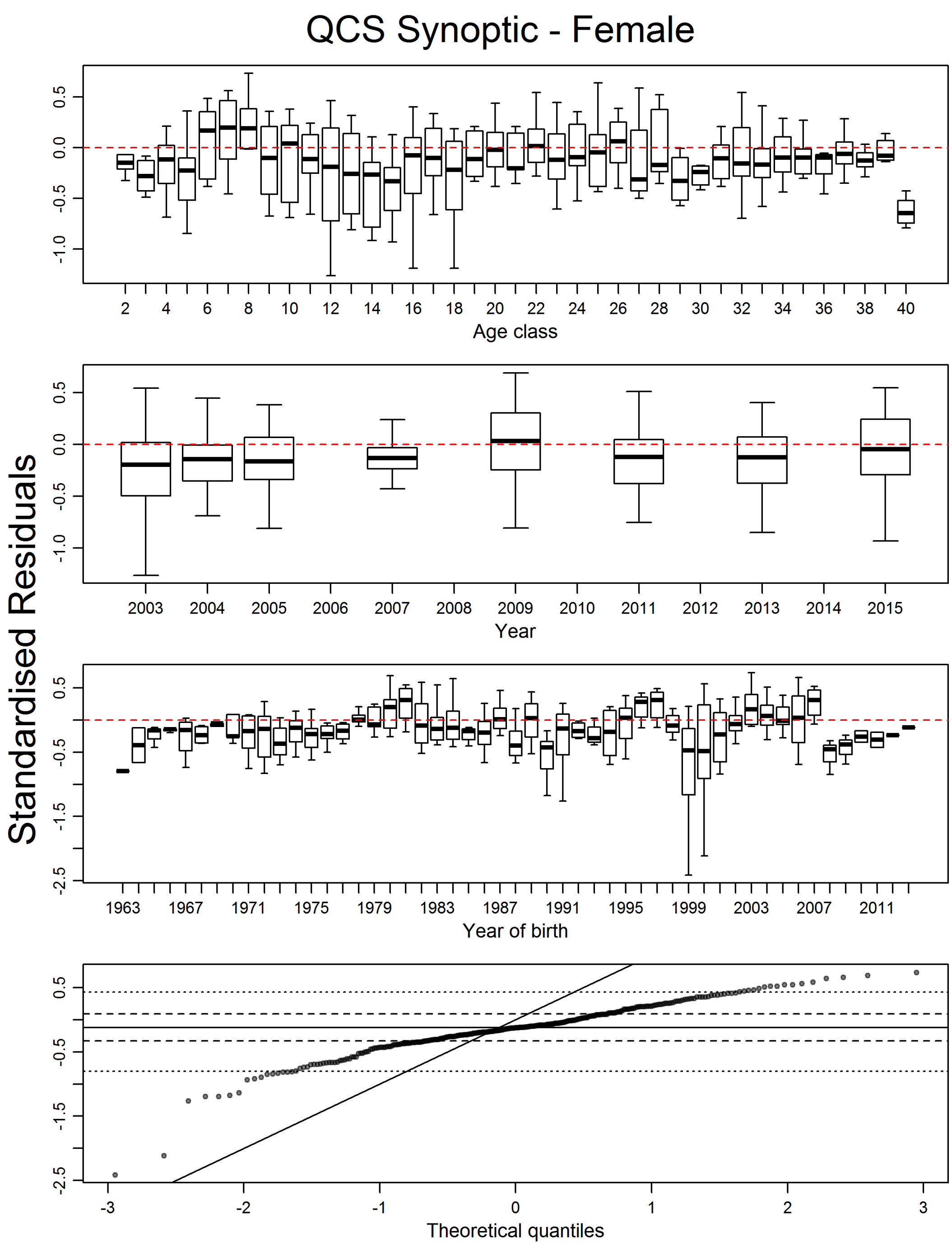


Figure F.79. BC South: Residuals of fits of model to proportions-at-age data (MPD values) for females from QCS Synoptic survey series. Details as for Figure F.66, for a total of 312 residuals.

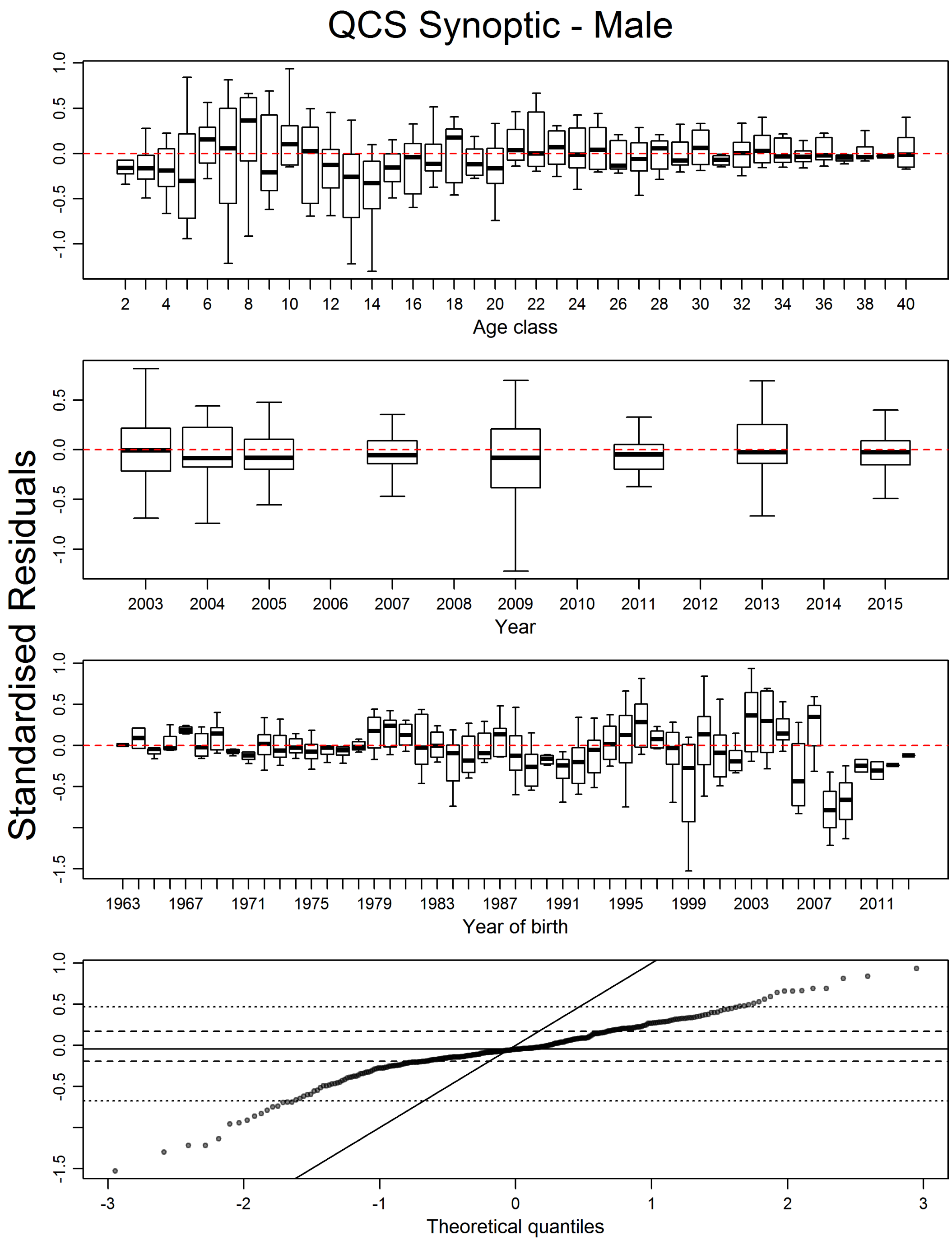


Figure F.80. BC South: Residuals of fits of model to proportions-at-age data (MPD values) for males from QCS Synoptic survey series. Details as for Figure F.66, for a total of 312 residuals.

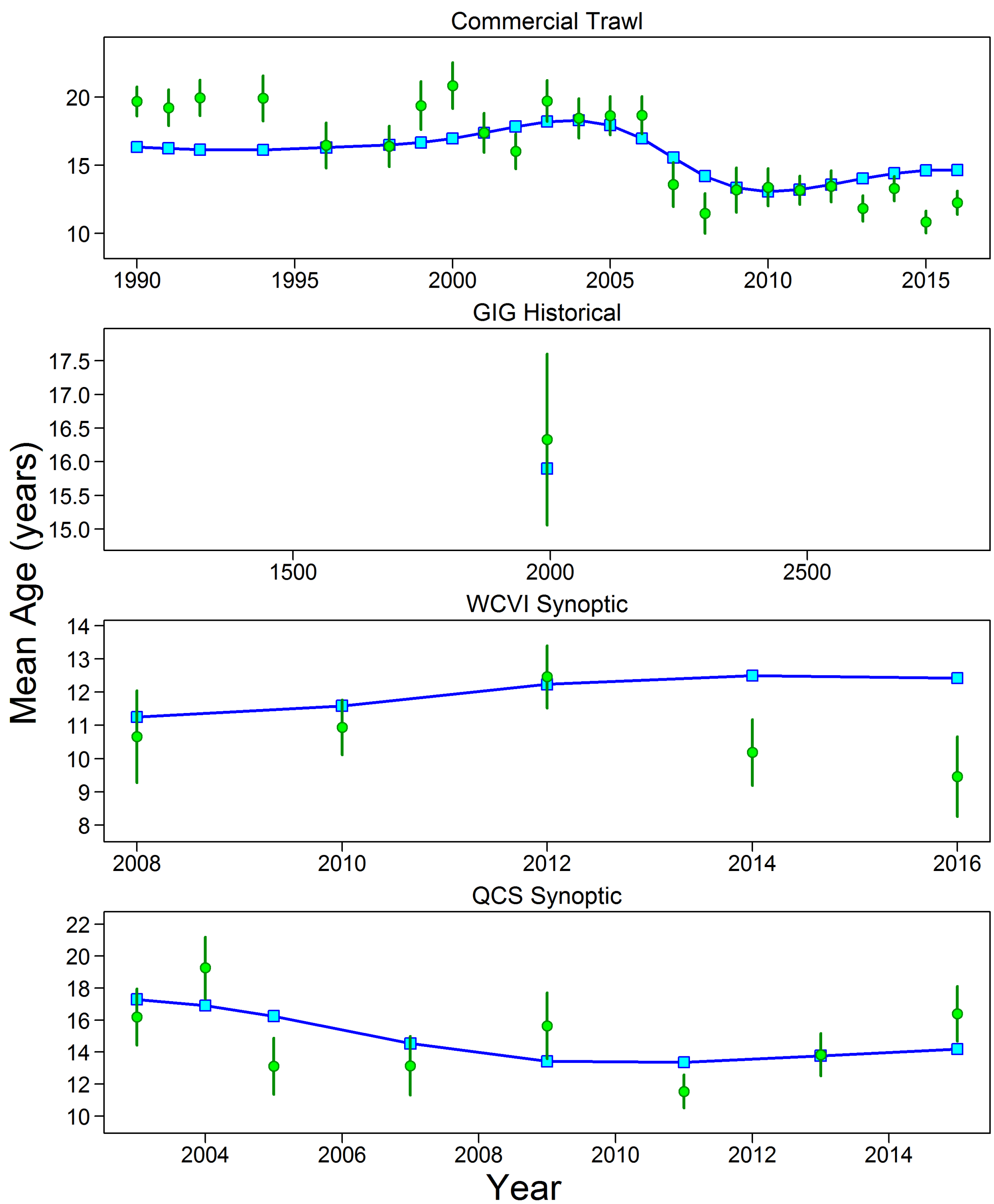


Figure F.81. BC South: Mean ages each year for the data (solid circles) with 95% confidence intervals and model estimates (joined open squares) for the commercial and survey age data.

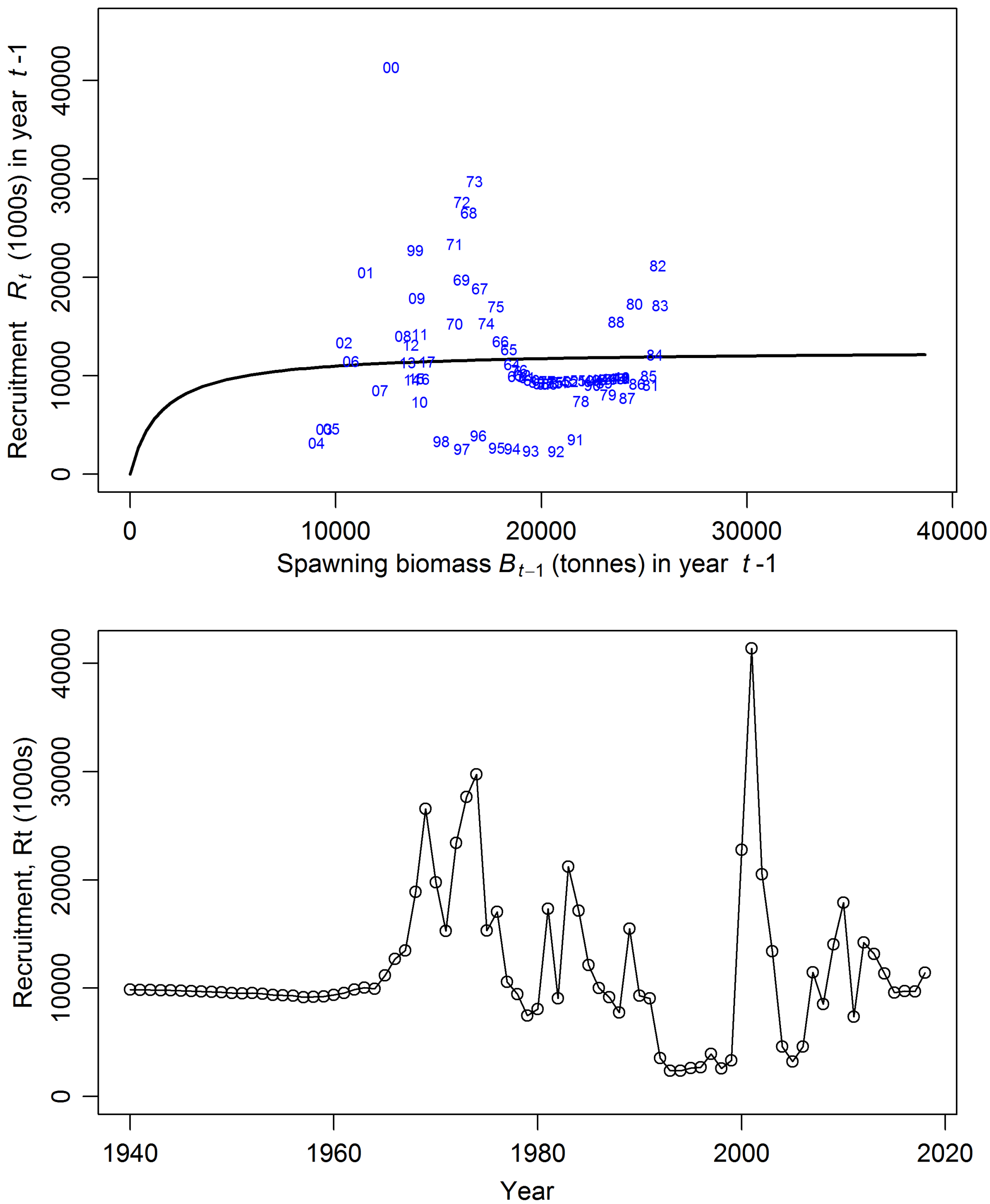


Figure F.82. BC South: Top: Deterministic stock-recruit relationship (black curve) and observed values (labelled by year of spawning) using MPD values. Bottom: Recruitment (MPD values of age-1 individuals in year t) over time, in 1,000s of age-1 individuals, with a mean of 11,612.

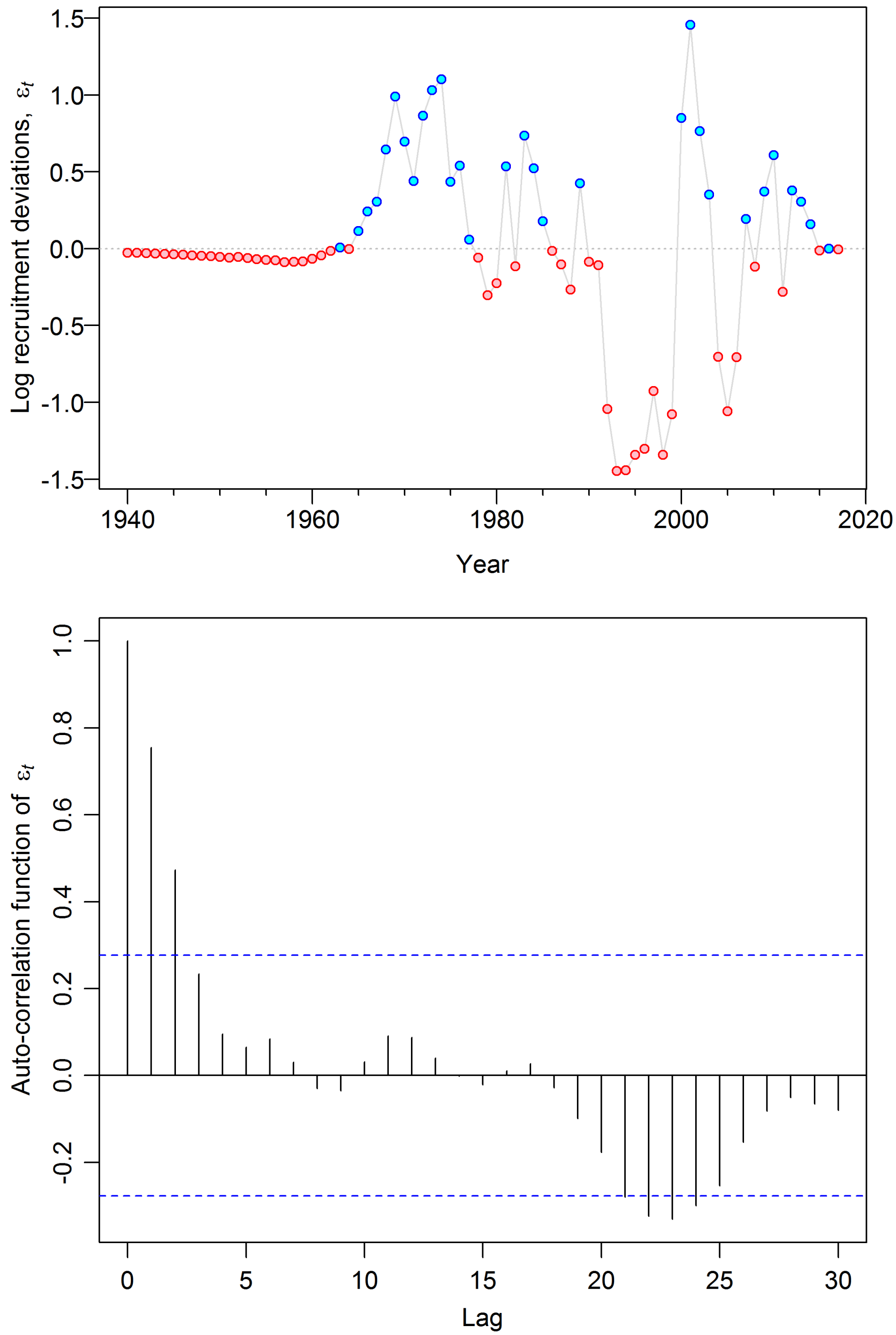


Figure F.83. BC South: Top: log of the annual recruitment deviations, ϵ_t, where bias-corrected multiplicative deviation is $e^{\epsilon_t - \sigma_R^2/2}$ where $\epsilon_t \sim$ Normal$(0, \sigma_R^2)$. Bottom: Auto-correlation function of the logged recruitment deviations (ϵ_t), for years 1959-2008. The start of this range is calculated as the first year of commercial age data (1990) minus the accumulator age class (A =40) plus the age for which commercial selectivity for females is 0.5 (namely 9); 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 (2017) minus the age for which commercial selectivity for females is 0.5 (namely 9).

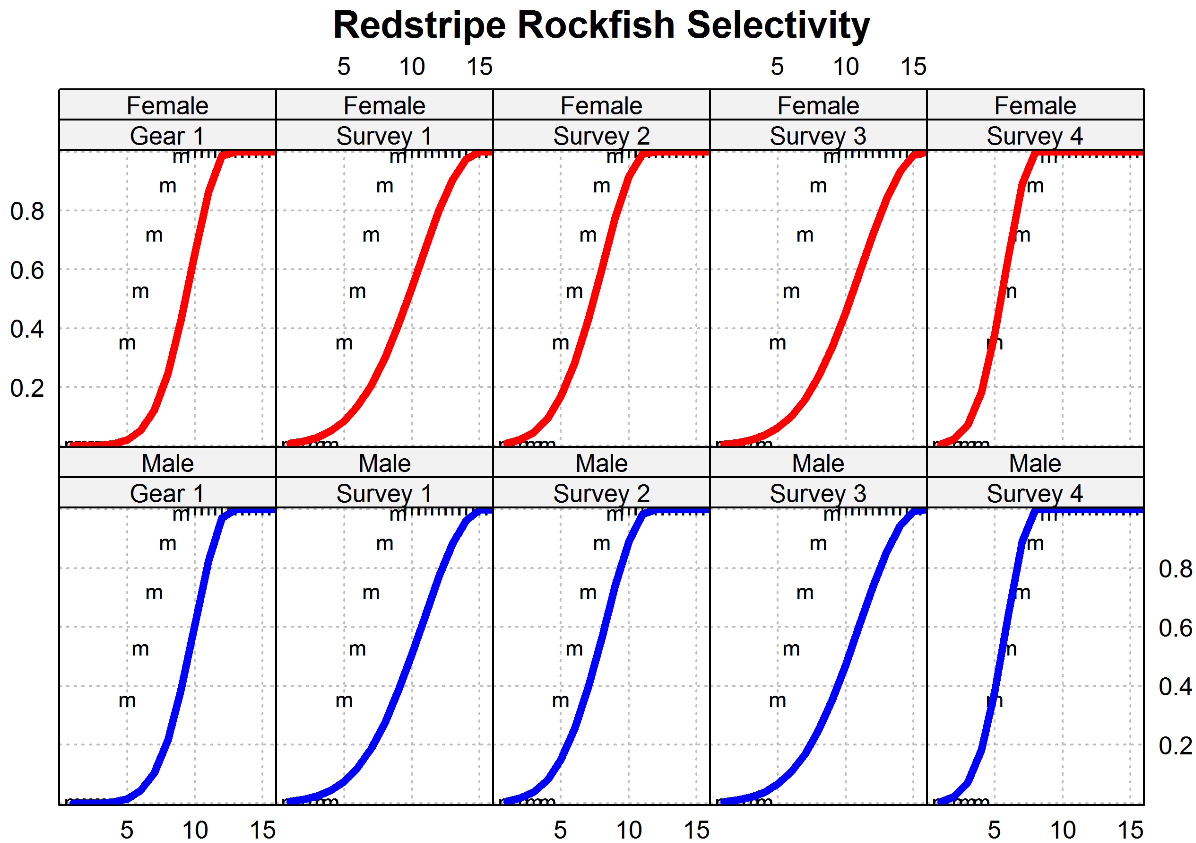


Figure F.84. BC South: Selectivities for commercial catch (Gear 1: Commercial Trawl) and surveys (all MPD values), with maturity ogive for females indicated by 'm'.

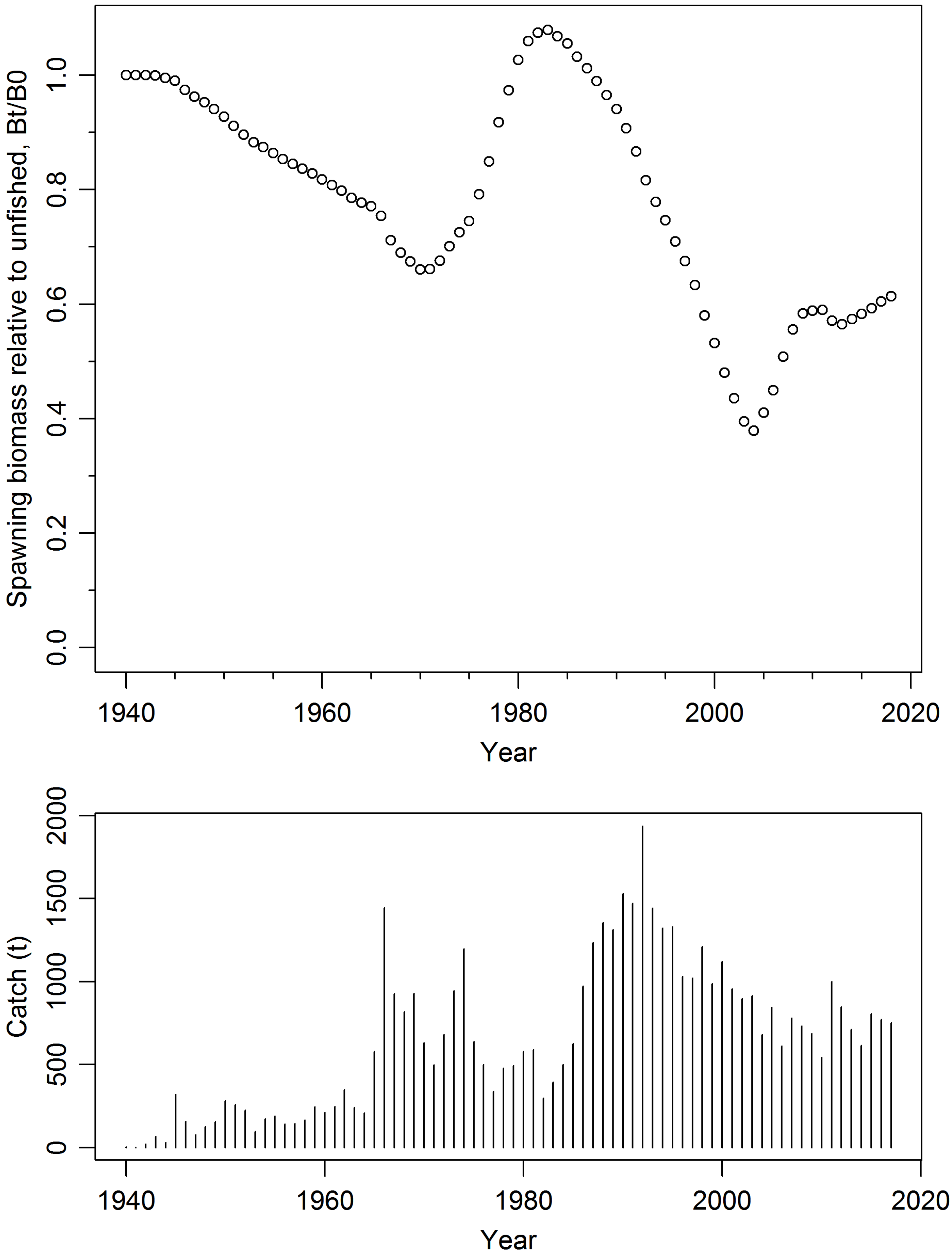


Figure F.85. BC South: Spawning biomass (mature females) relative to unfished level, B_t/B_0, and commercial catch, for run the base case.

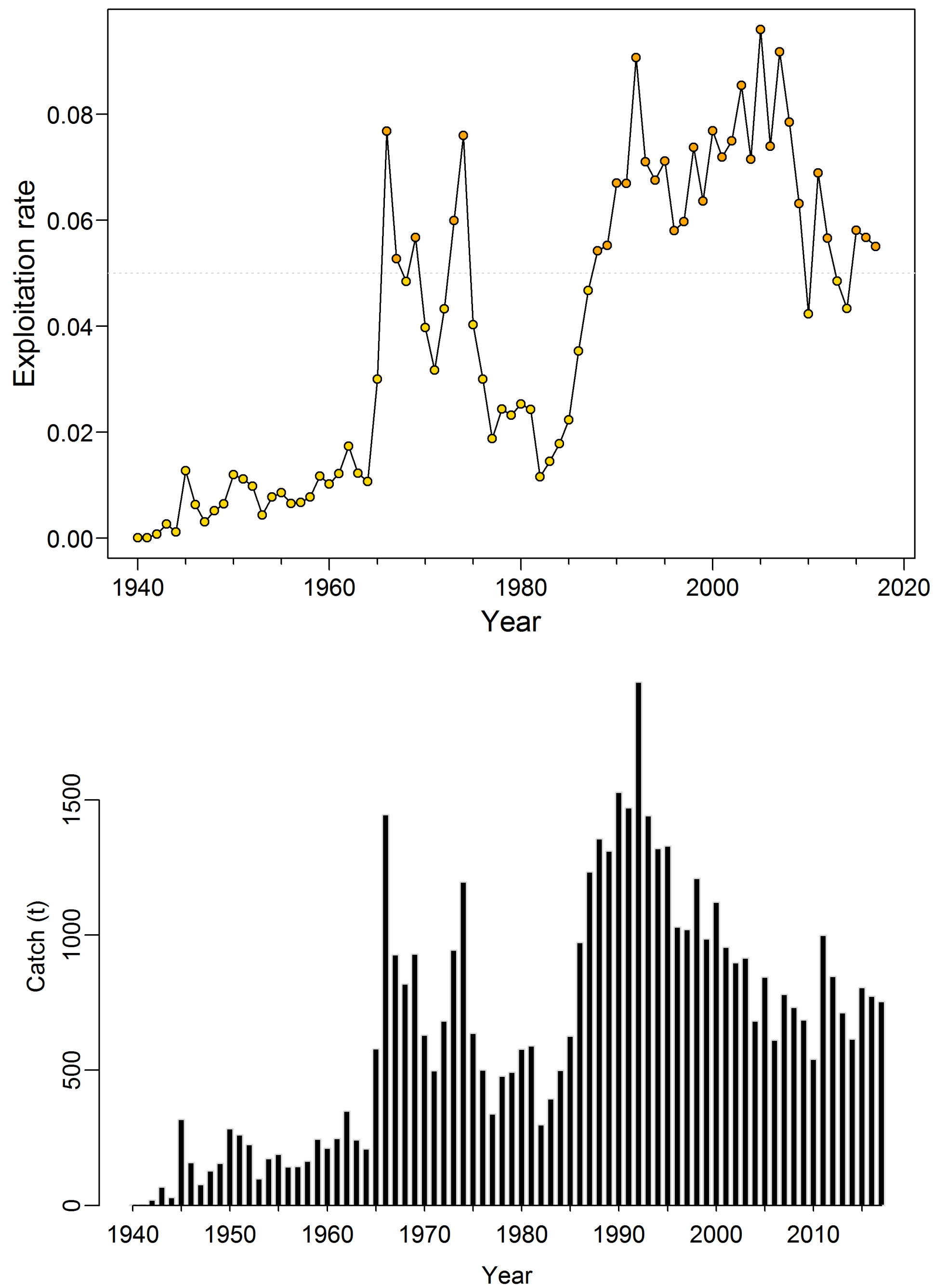


Figure F.86. BC South: TOP: Exploitation rate (MPD) over time; BOTTOM: catch (t) by gear type for run the base case.

F.3.1.2. BCS Bayesian Markov chain Monte Carlo (MCMC)

Reweight 2 was chosen for the MCMC analysis based on Equation E.33. The MCMC procedure performed 24,000,000 iterations, sampling every 20,000$^{\mathrm{th}}$ to give 1,200 MCMC samples. The first 200 samples were discarded and 1,000 samples were used for the MCMC analysis. The quantiles (0.05, 0.50, 0.95) for estimated parameters and derived quantities appear in Tables F.18 and F.19. The current year median estimate of B_{2018} is 16,235 t and the median estimate of B_{2018}/B_0 is 0.622.

The MCMC plots show:

- traces for 1,000 samples of the primary estimated parameters (Figure F.87);
- split-chain diagnostic plots for the primary estimated parameters (Figure F.88);
- auto-correlation diagnostic plots for the primary estimated parameters (Figure F.89);
- pairs plots showing how each sampled parameter relates to the others (Figure F.90);
- pairs plots showing how MSY-derived paramters relate to the others (Figure F.91);
- traces for 1,000 samples of female spawning biomass at five-year intervals (Figure F.92);
- traces for 1,000 samples of recruitment estimates at five-year intervals (Figure F.93);
- marginal posterior densities for the primary parameters compared to their respective prior density functions (Figure F.94);
- marginal posterior densities for beginning year female spawning biomass at five-year intervals (Figure F.95);
- marginal posterior densities for recruitment at five-year intervals (Figure F.96);
- estimated vulnerable biomass and catch over time (Figure F.97);
- median ratios of spawning biomass and vulnerable biomass to their respective unfished equilibrium values (Figure F.98);
- marginal posterior distribution of recruitment over time (Figure F.99);
- marginal posterior distribution of exploitation rate over time (Figure F.100);
- phase plot through time of median ratios of B_t/B_{MSY} and $u_{t\text{-}1}/u_{\mathrm{MSY}}$ (Figure F.101).

Most of the MCMC traces show acceptable convergence properties (no trend with increasing sample number) for the estimated parameters (Figure F.87), as do diagnostic analyses that split the posterior samples into three equal consecutive segments (Figure F.88) and the check for autocorrelation in the parameters out to 60 lags (Figure F.89). There is some noise and autocorrleation in the first two parameters (R_0 and M_1), but these problems are not excessive. Most of the parameters stayed fairly close to the initial MPD estimates, i.e., median values did not differ greatly from the MPD estimates (Figure F.87). Pairs plots of the estimated parameters (Figure F.90) show no undesirable or unexpected correlations between parameters. In particular, steepness h and the natural mortality parameters (M_1,M_2) show little correlation, suggesting that sufficient data exist to estimate these parameters simultaneously. Trace plots of the derived quantities 'female spawning biomass' (Figure F.92) and recruitment (Figure F.93) also show acceptable convergence properties.

The marginal posterior distribution for h shifted slightly higher from the informed prior (Figure F.94), indicating that there is little information in the model data to update the prior. In contrast, the posterior distributions for M_1 and M_2 have shifted away from the M prior – to the left (lower M) for females and to the right (higher M) for males. Corresponding summary statistics for the estimated parameters are given in Table F.18.

The marginal posterior distributions of vulnerable biomass (Figure F.97) show a steady decline in the population from 1940 to the mid 1970s, followed by a 10-year rise to levels above $B0$ by 1985. Another steady decline, steeper this time due to higher catches than previously, continued for 20 years and reached a low point in 2006. A good recruitment event occurred in 2000 (Figure F.99), causing the vulnerable biomass to show a 5-year increasing trend, followed by a stable standing stock up to the most recent year. The median female spawning biomass relative to unfished equilibrium values (Figure F.98) reached a minimum of 0.386 in 2004 and currently sits at 0.622 at the beginning of 2018.

Median exploitation rates were never higher than median female natural mortality (0.098); they peaked in 2005 at a median value of 0.086 (Figure F.100). A phase plot of the time-evolution of spawning biomass and exploitation rate in MSY space (Figure F.101) suggests that the stock is underutilized, with a current position at $B_{2018}/B_{\mathrm{MSY}}$ = 2.429 (1.509-3.768) and $u_{2017}/u_{\mathrm{MSY}}$ = 0.16 (0.049-0.496).

F.3.1.2.1. BCS MCMC tables for base case

Table F.18. BC South: The 5$^{\mathrm{th}}$, 50$^{\mathrm{th}}$, and 95$^{\mathrm{th}}$ percentiles for model parameters derived via MCMC estimation (defined in Appendix E).

	5%	50%	95%
R_0	9,980	14,312	24,249
M_1	0.08558	0.09794	0.1113
M_2	0.1176	0.1303	0.1441
h	0.5071	0.7613	0.9328
q_1	0.01465	0.02883	0.05828
q_2	0.08665	0.1723	0.2888
q_3	0.08465	0.1656	0.2806
q_4	0.1206	0.2200	0.3681
q_5	0.00004253	0.00007391	0.0001100
μ_1	11.62	17.73	25.43
μ_2	9.330	11.17	12.95
μ_3	13.04	15.36	17.98
μ_5	11.38	12.45	13.61
Δ_1	-2.647	0.5190	3.787
Δ_2	0.1081	0.2120	0.3271
Δ_3	-0.9701	-0.1333	0.6941
Δ_5	-0.1253	0.2230	0.5788
$\log v_{1L}$	2.636	4.118	5.160
$\log v_{2L}$	2.377	3.031	3.515
$\log v_{3L}$	3.186	3.660	4.075
$\log v_{5L}$	2.275	2.645	2.973

Table F.19. BC South: The 5$^{\mathrm{th}}$, 50$^{\mathrm{th}}$ and 95$^{\mathrm{th}}$ percentiles of MCMC-derived quantities from the 1,000 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_{2018} – spawning biomass at the start of 2018, V_{2018} – vulnerable biomass in the middle of 2018, u_{2017} – exploitation rate (ratio of total catch to vulnerable biomass) in the middle of 2017, $u_{\max}$ – maximum exploitation rate (calculated for each sample as the maximum exploitation rate from 1940-2017), 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 (2013-2017) is 732 t.

Value	Percentile		
	5%	50%	95%
	From model output		
B_0	21,925	26,149	36,390
$V_{0,g=5}$	22,780	27,318	38,172
B_{2018}	10,700	16,235	28,967
$V_{2018,g=5}$	10,142	15,665	27,905
B_{2018}/B_0	0.469	0.622	0.81
$V_{2018,g=5}/V_{0,g=5}$	0.424	0.574	0.764
$u_{2017,g=5}$	0.027	0.049	0.075
$u_{\max}$	0.056	0.089	0.125
	MSY-based quantities		
MSY	946	1,467	2,481
B_{MSY}	4,553	6,830	10,701
$0.4B_{\mathrm{MSY}}$	1,821	2,732	4,280
$0.8B_{\mathrm{MSY}}$	3,643	5,464	8,561
$B_{2018}/B_{\mathrm{MSY}}$	1.509	2.429	3.768
B_{MSY}/B_0	0.19	0.256	0.344
V_{MSY}	2,466	5,043	9,080
$V_{\mathrm{MSY}}/V_{0,g=5}$	0.088	0.183	0.302
u_{MSY}	0.115	0.3	0.8
$u_{2017,g=5}/u_{\mathrm{MSY}}$	0.049	0.16	0.496

F.3.1.2.2. BCS MCMC figures for base case

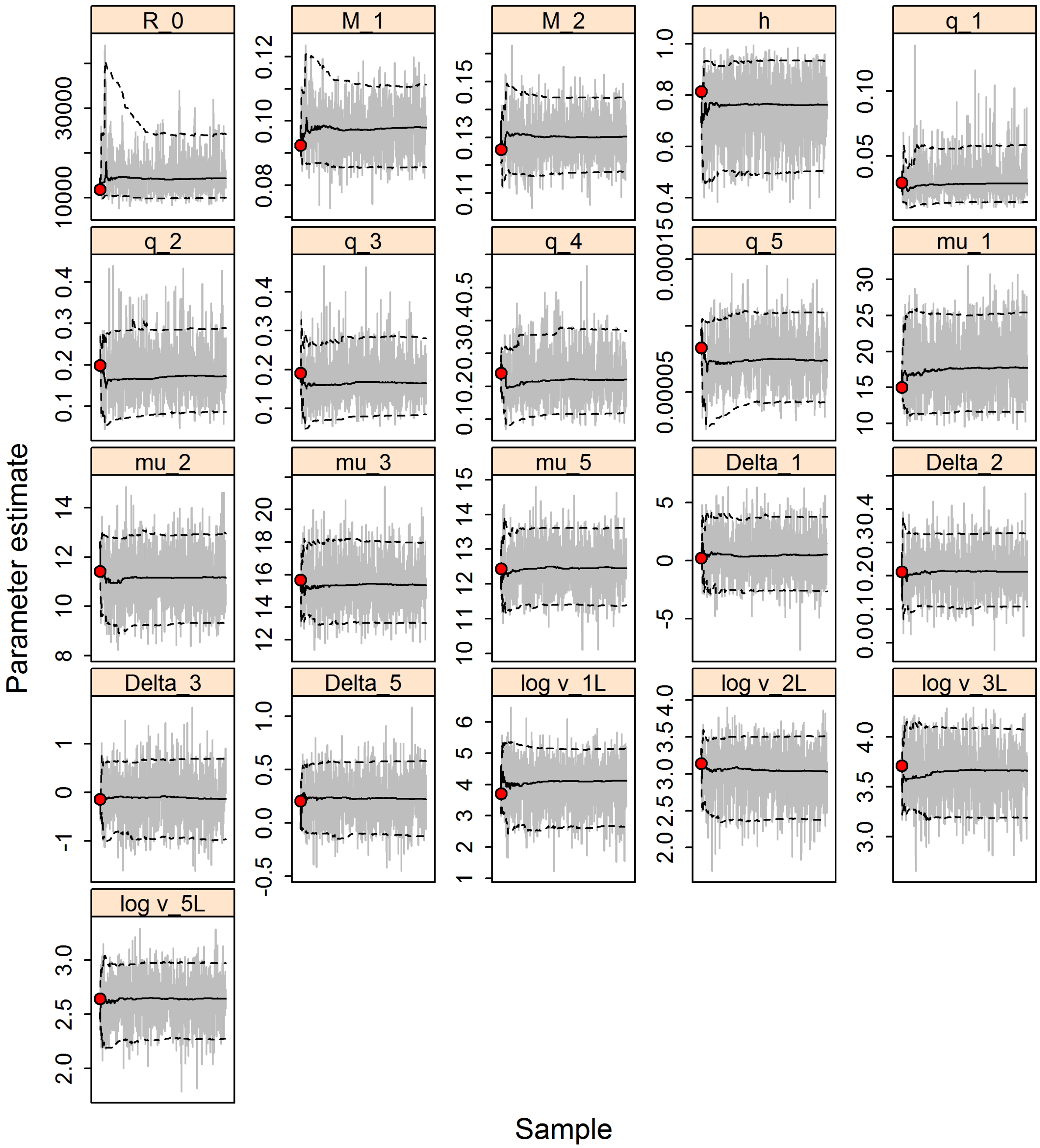


Figure F.87. BC South: MCMC traces for the estimated parameters. Grey lines show the 1,000 samples for each parameter, solid lines show the cumulative median (up to that sample), and dashed lines show the cumulative 0.05 and 0.95 quantiles. Red circles are the MPD estimates. For parameters other than M (if estimated), subscripts ≤ 4 correspond to fishery-independent surveys, and subscripts ≥ 5 denote the commercial fishery. Parameter notation is described in Appendix E.

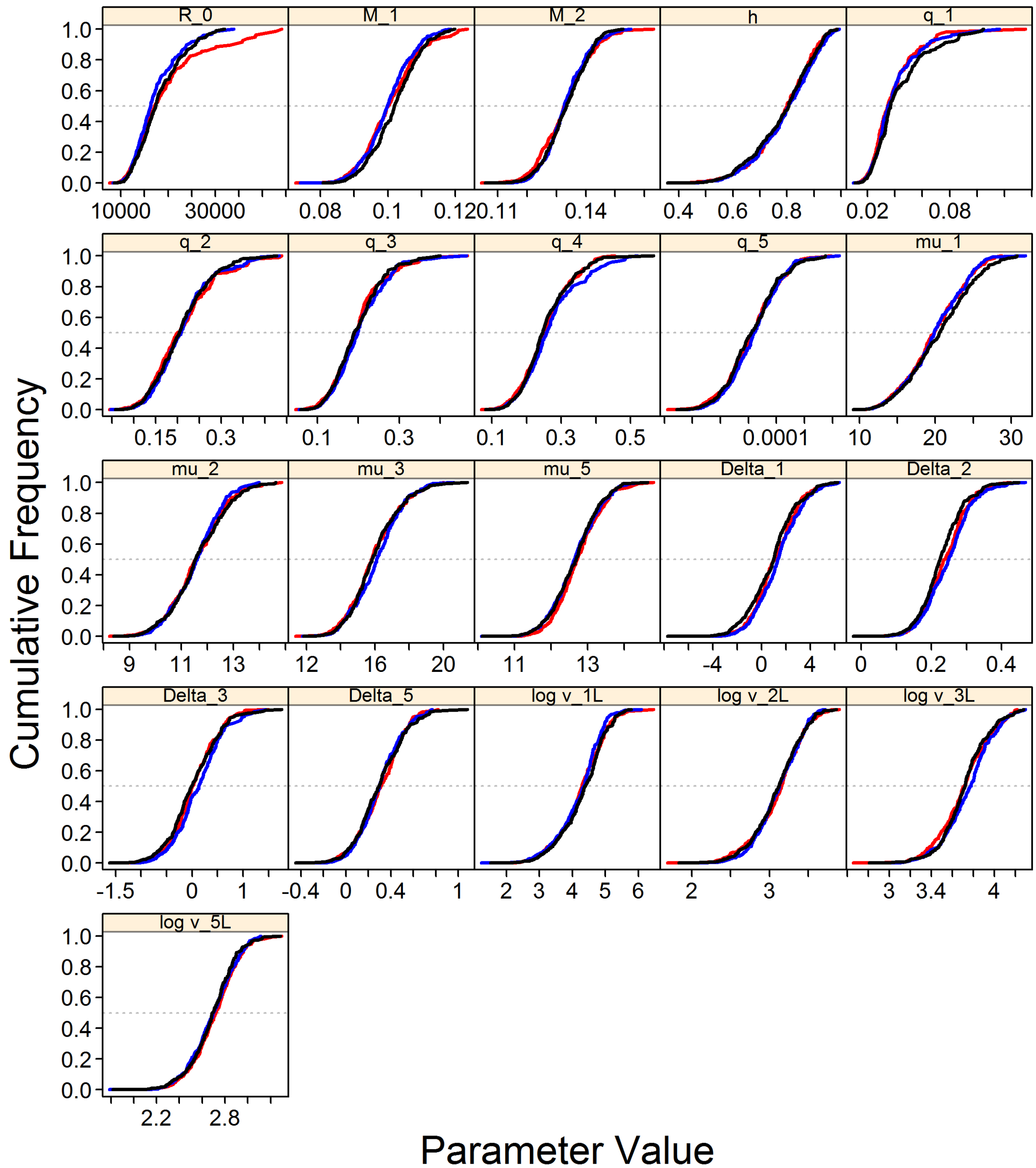


Figure F.88. BC South: Diagnostic plot obtained by dividing the MCMC chain of 1,000 MCMC samples into three segments, and overplotting the cumulative distributions of the first segment (red), second segment (blue) and final segment (black).

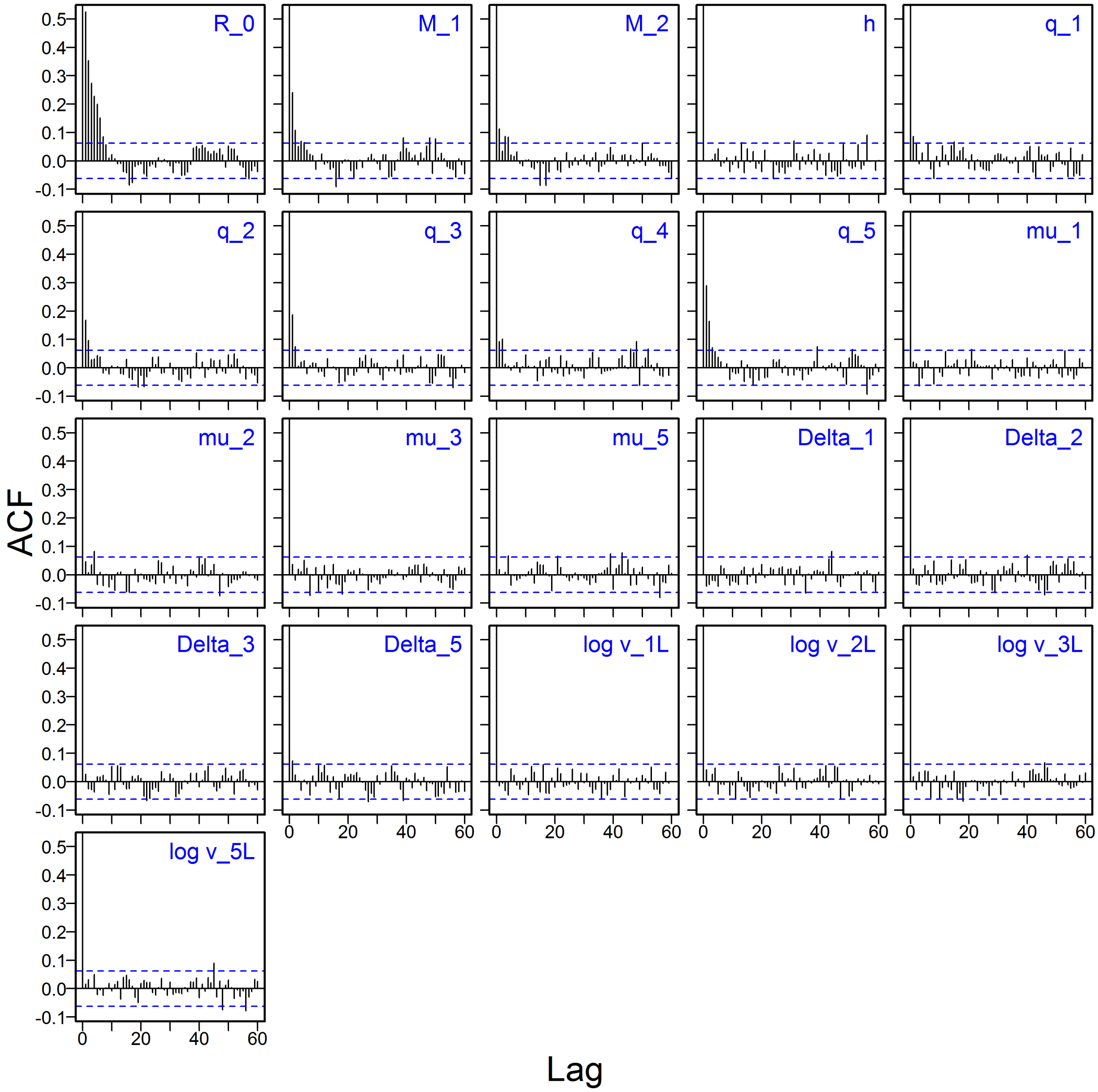


Figure F.89. BC South: Autocorrelation plots for the estimated parameters from the MCMC output. Horizontal dashed blue lines delimit the 95% confidence interval for each parameter's set of lagged correlations.

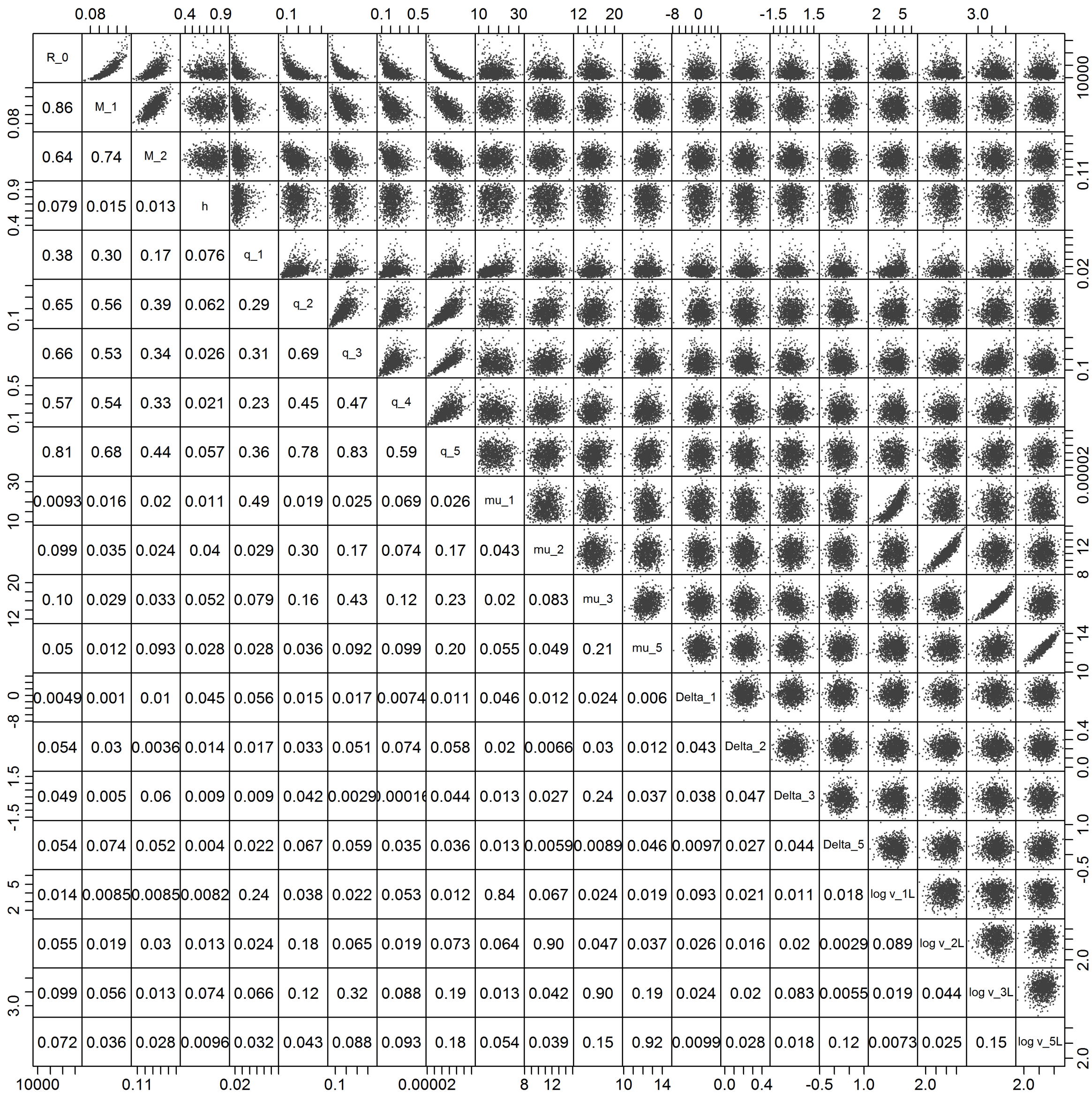


Figure F.90. BC South: Pairs plot of 1,000 MCMC samples for 21 parameters. Numbers in the lower panels are the absolute values of the correlation coefficients.

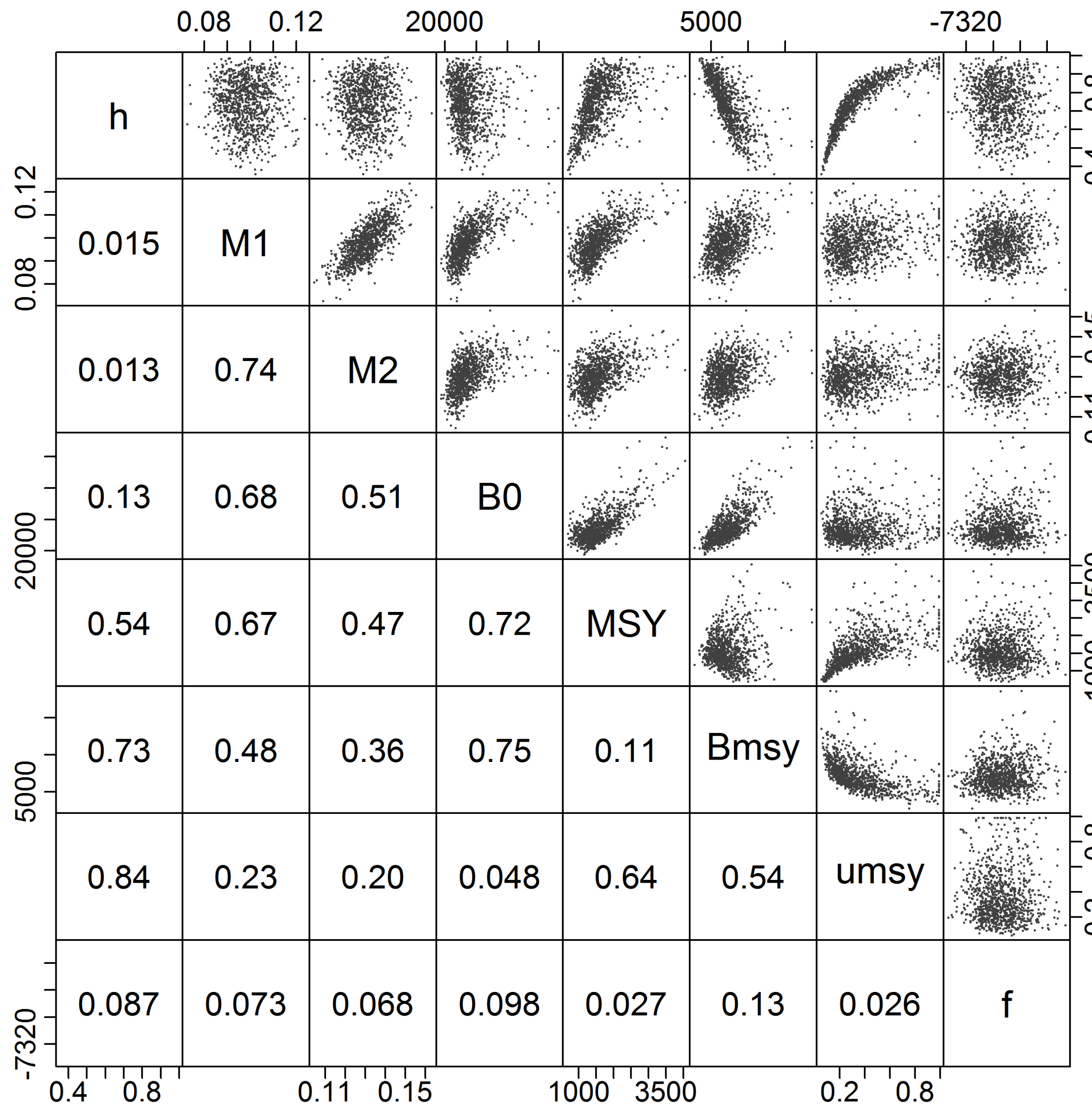


Figure F.91. BC South: Pairs plot of 1,000 MCMC samples comparing some parameters, key derived quantities, and function value (f). Numbers in the lower panels are the absolute values of the correlation coefficients.

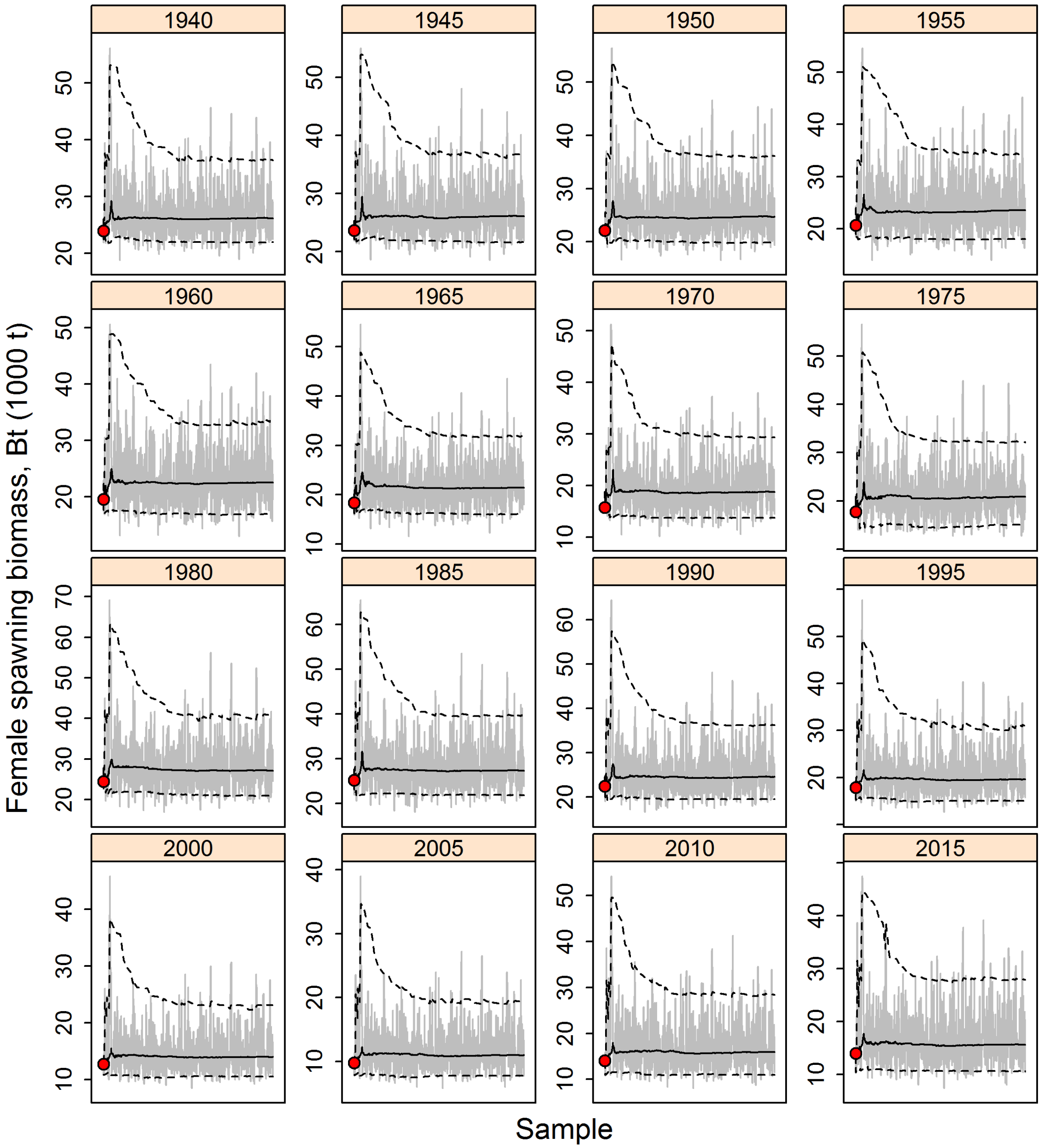


Figure F.92. BC South: MCMC traces for female spawning biomass estimates at five-year intervals. Note that vertical scales are different for each plot (to show convergence of the MCMC chain, rather than absolute differences in annual values). Grey lines show the 1,000 samples for each parameter, solid 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.

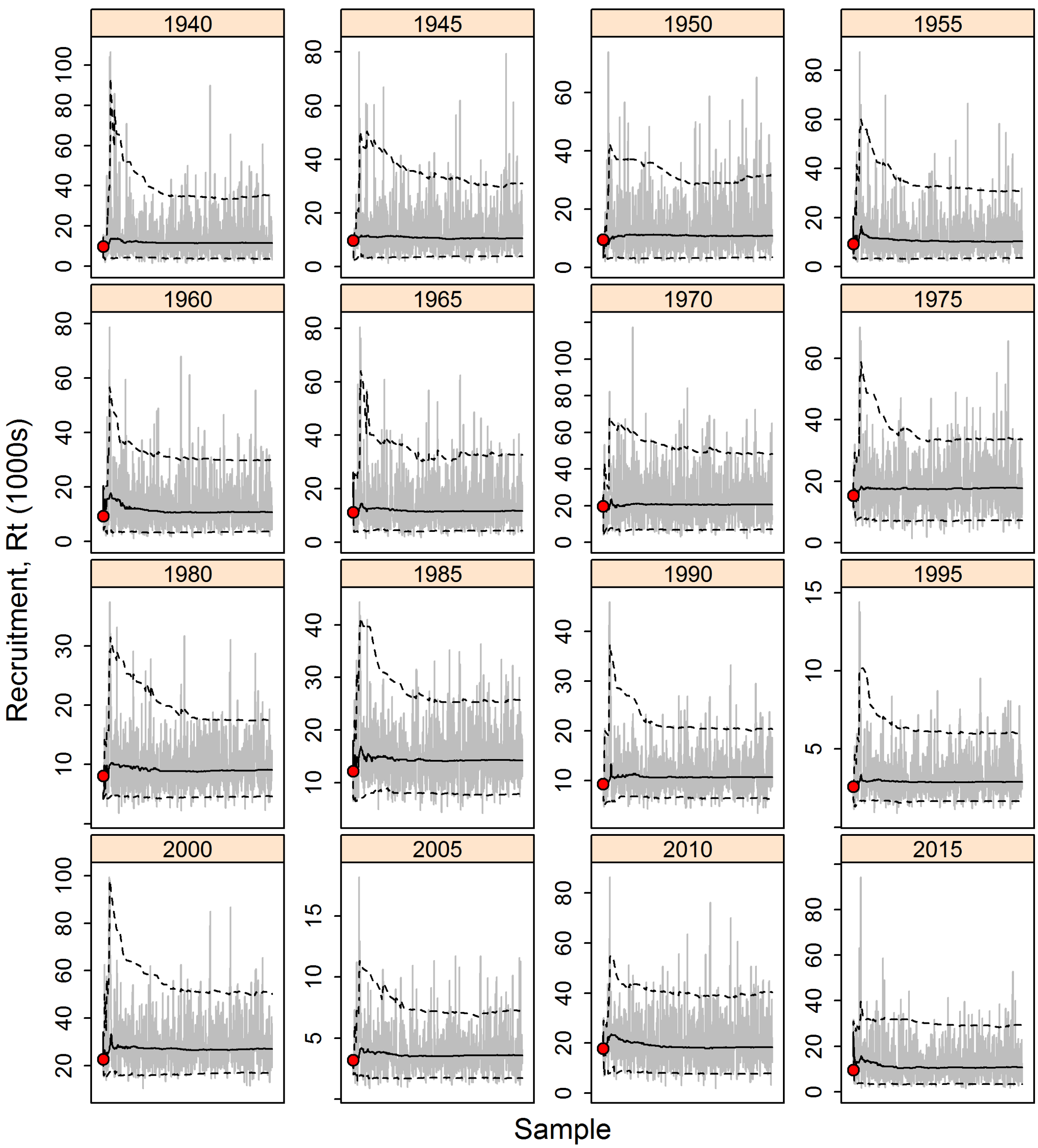


Figure F.93. BC South: MCMC traces for recruitment estimates at five-year intervals. Note that vertical scales are different for each plot (to show convergence of the MCMC chain, rather than absolute differences in annual recruitment). Grey lines show the 1,000 samples for each parameter, solid lines 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.

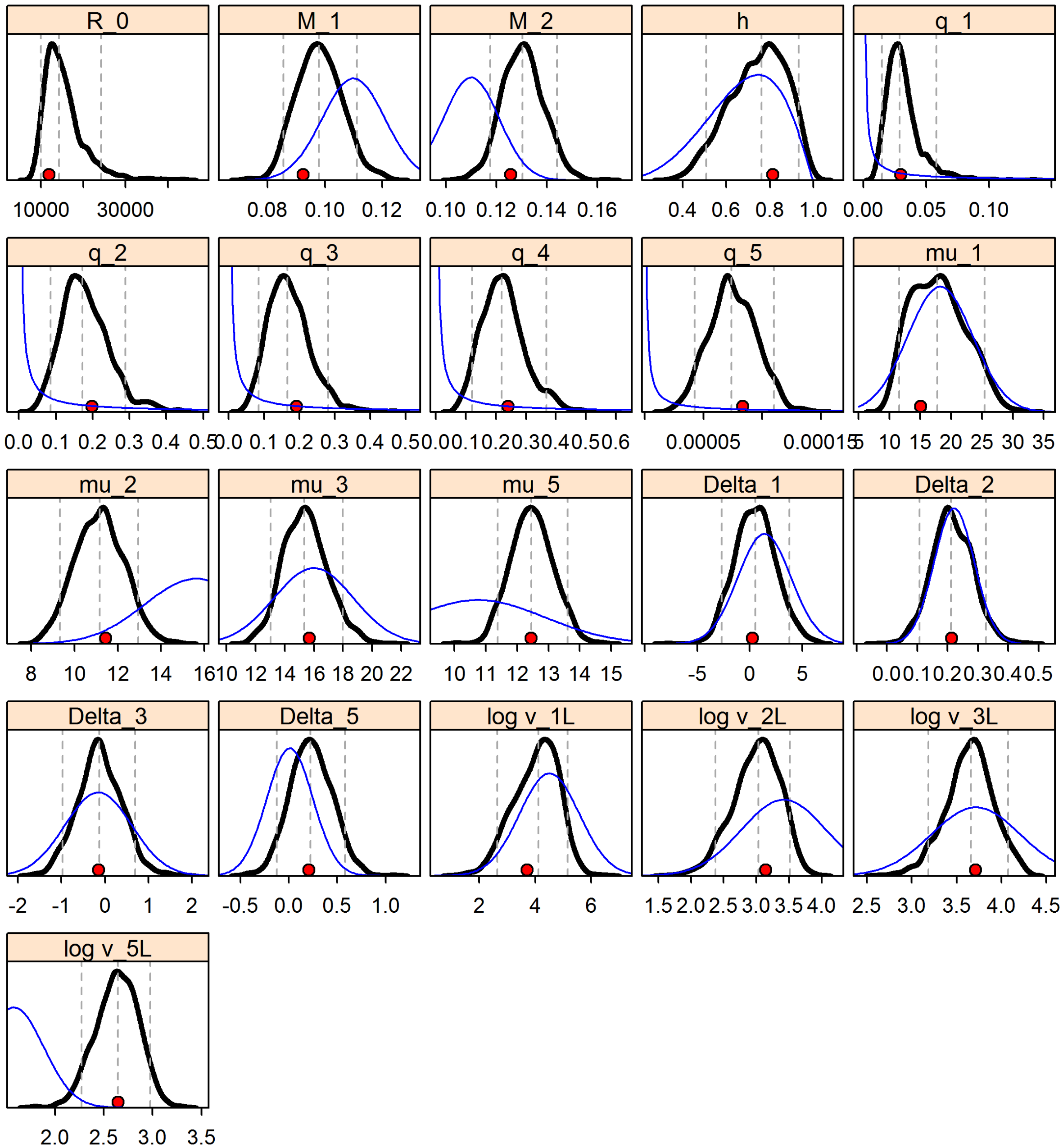


Figure F.94. BC South: Marginal posterior densities (thick black curves) and prior density functions (thin blue curves) for the estimated parameters. Vertical lines represent the 5, 50 and 95 percentiles, and red filled circles are the MPD estimates. For R_0 the prior is a uniform distribution on the range [1, 10000000]. 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).

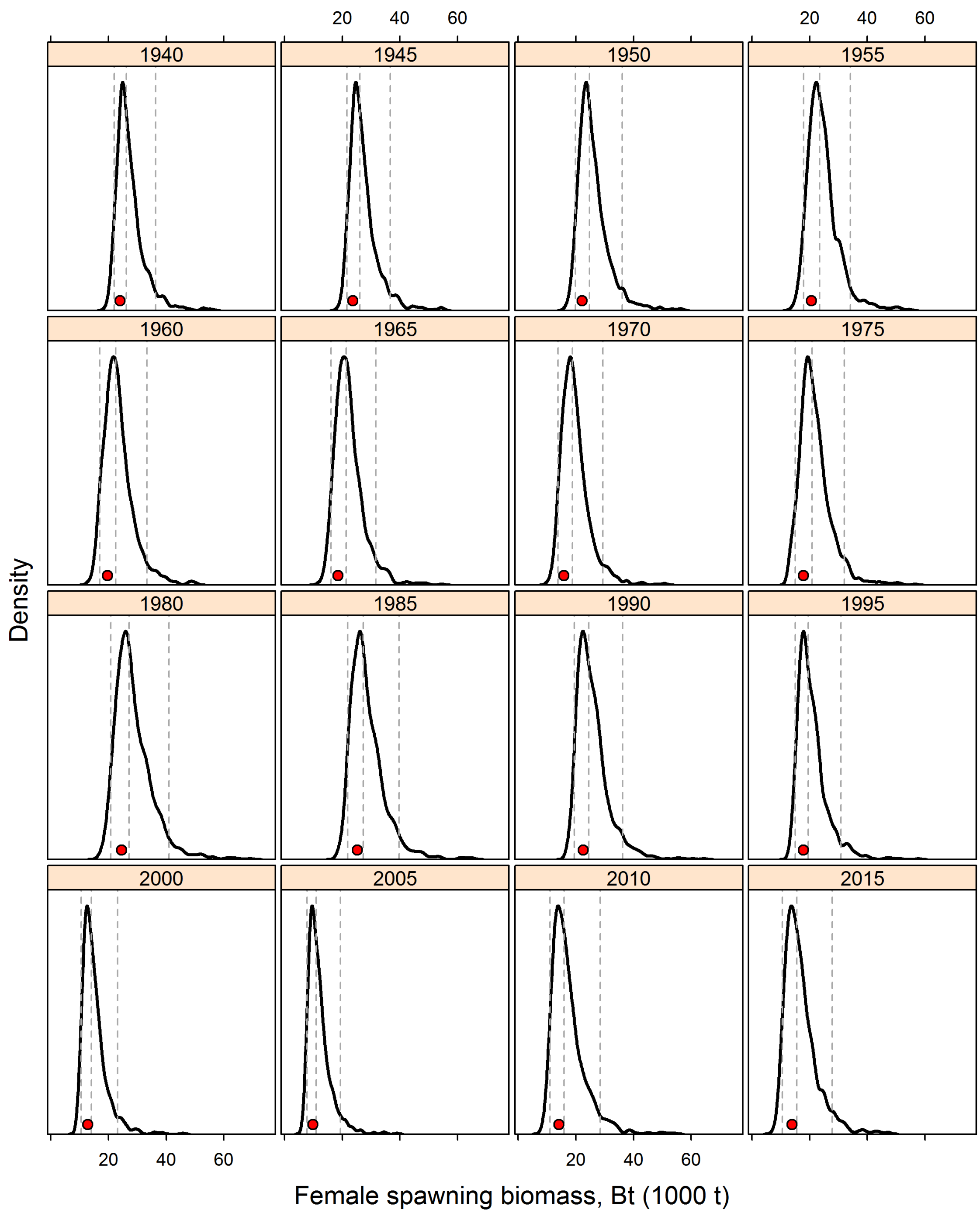


Figure F.95. BC South: Marginal posterior densities for beginning year female spawning biomass (1,000 tonnes) every 5 years starting in 1940 for the base case. Horizontal axes are all to same scale. Note that vertical axes are not to the same scale, but each is scaled to the peak of the density; with the area under each curve integrating to 1.0. Vertical lines are 5, 50 and 95 percentiles, and filled red circle indicates MPD value.

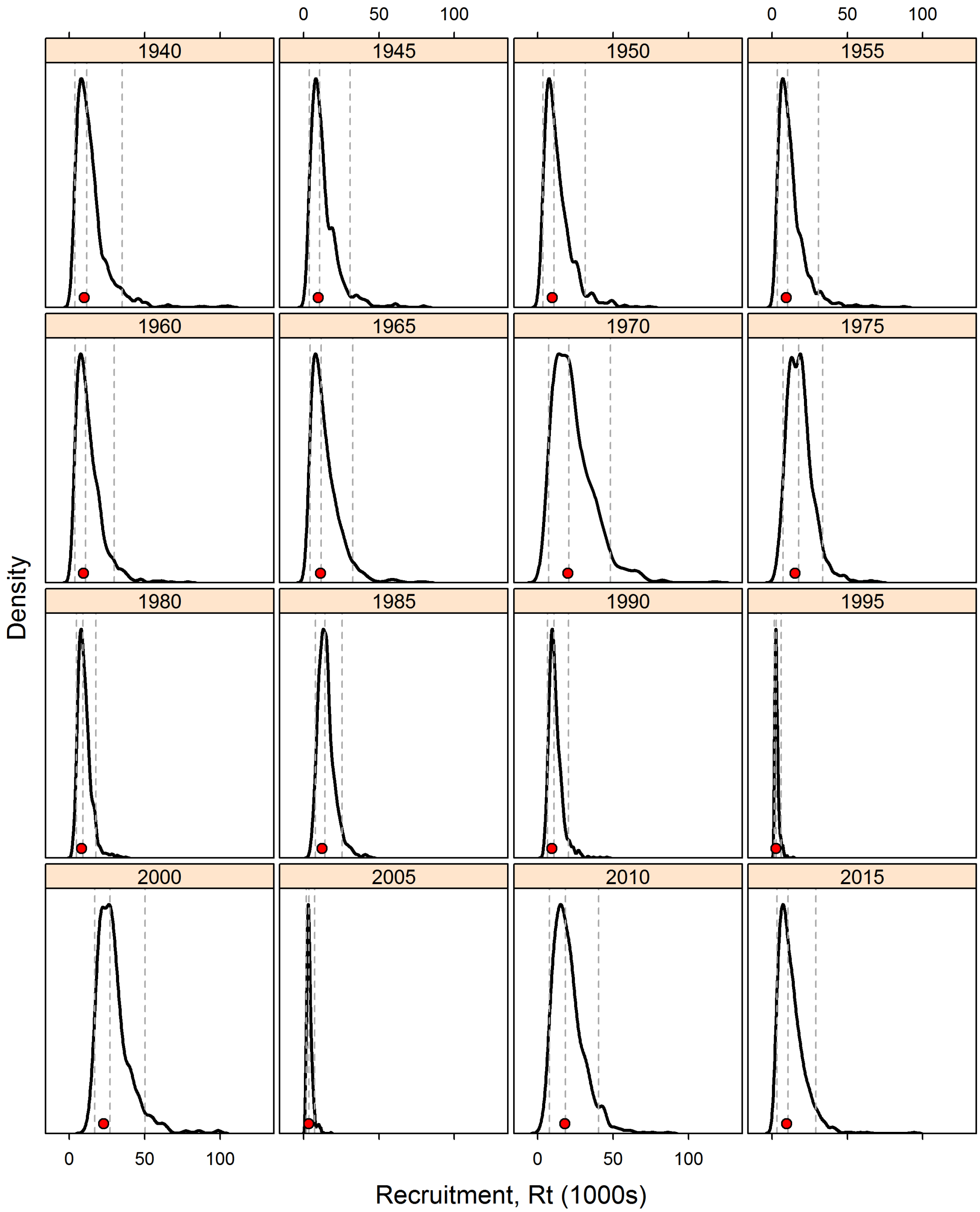


Figure F.96. BC South: Marginal posterior densities for recruitment every 5 years starting in 1940 for the base case. Horizontal axes are all to same scale, such that large recruitments in certain large years can be seen. Note that vertical axes are not to the same scale, but each is scaled to the peak of the density; areas under each curve will integrate to 1.0. Vertical lines are 5, 50 and 95 percentiles, and filled red circle indicates MPD value.

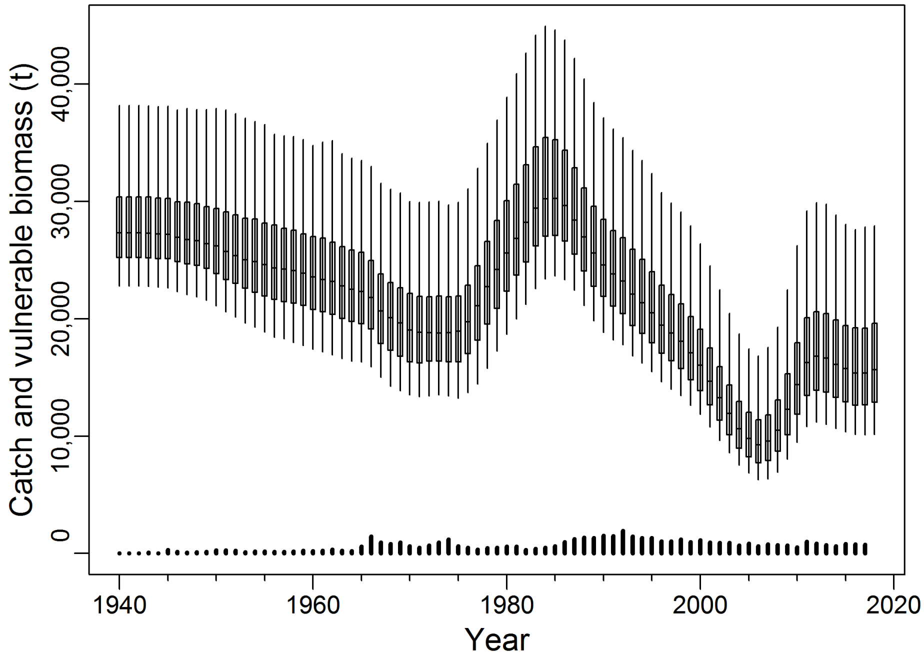


Figure F.97. BC South: Estimated vulnerable biomass (boxplots) and commercial catch (vertical bars), in tonnes, over time. Boxplots show the 5, 25, 50, 75 and 95 percentiles from the MCMC results. Catch is shown to compare its magnitude to the estimated vulnerable biomass.

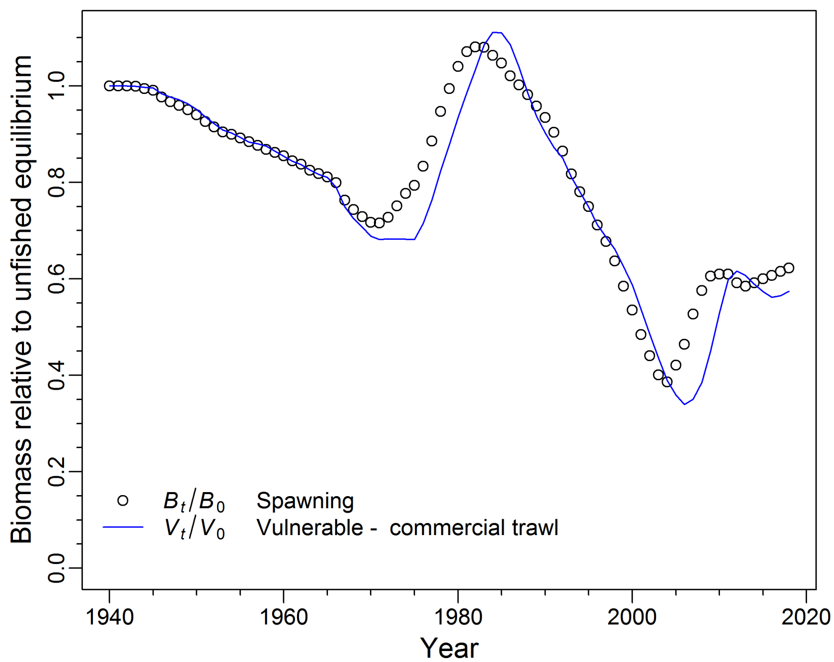


Figure F.98. BC South: Changes in B_t/B_0 and V_t/V_0 (spawning and vulnerable biomass relative to unfished equilibrium levels) over time, shown as the medians of the MCMC posteriors.

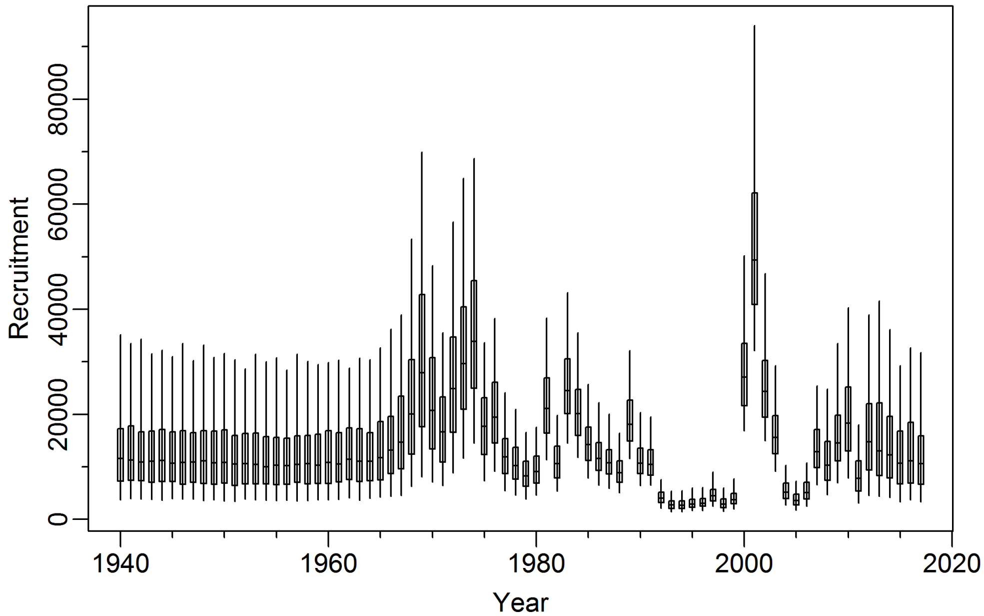


Figure F.99. BC South: Marginal posterior distribution of recruitment in 1,000s of age-1 fish plotted over time. Boxplots show the 5, 25, 50, 75 and 95 percentiles from the MCMC results. Note that the first year for which there are age data is 1990, and the plus-age class is 40, such that there are no direct data concerning age-1 fish before 1951. Also, the final few years have no direct age-data from which to estimate recruitment, because fish are not fully selected until age 12.5 by the commercial vessels or age 14.8 by surveys (mean of the MCMC median ages at full selectivity for commercial catch, μ_5, and survey $\mu_{1,2,3}$, respectively).

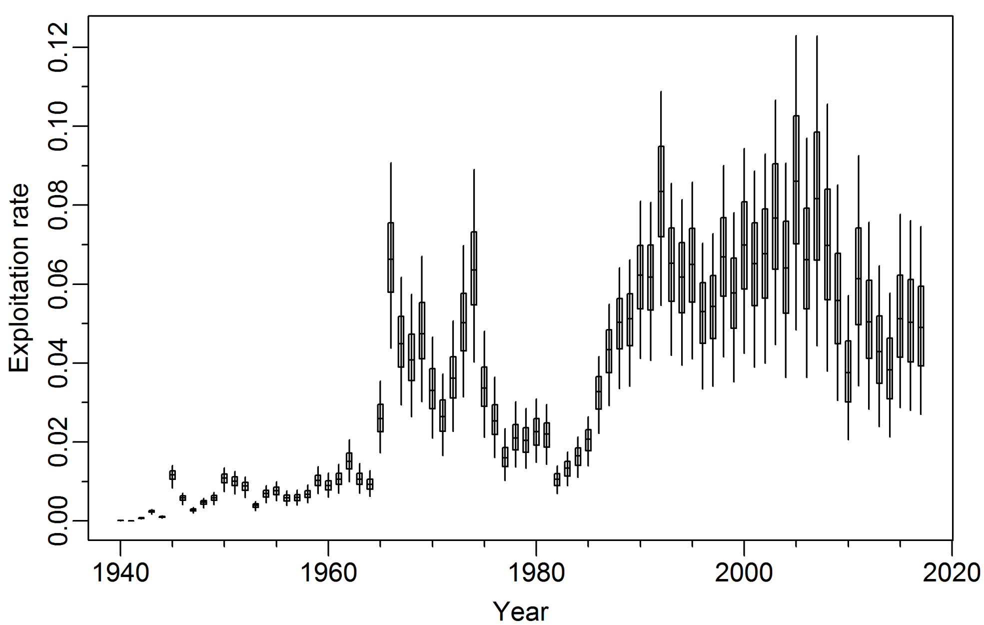


Figure F.100. BC South: Marginal posterior distribution of exploitation rate plotted over time. Boxplots show the 5, 25, 50, 75 and 95 percentiles from the MCMC results.

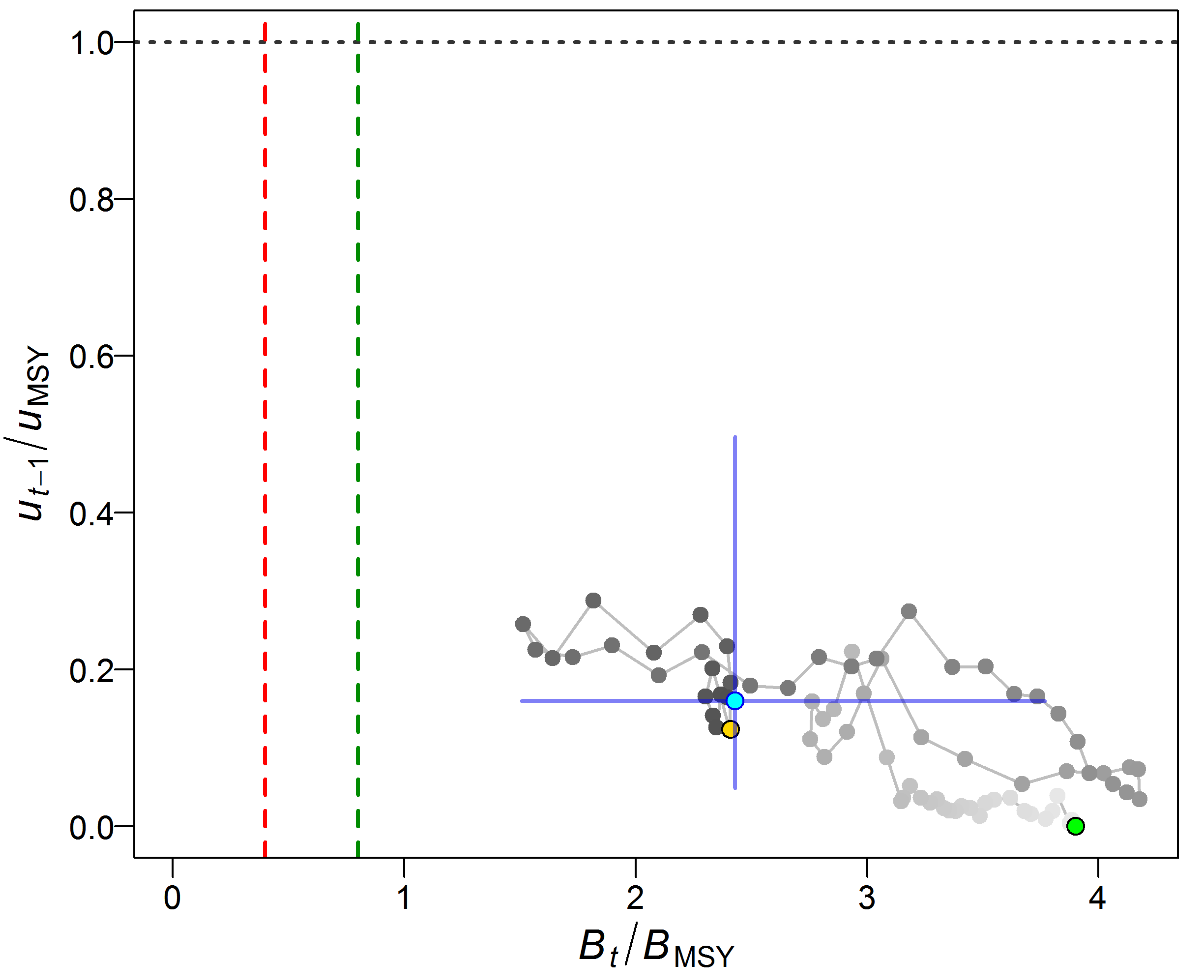


Figure F.101. BC South: Phase plot through time of the medians of the ratios B_t/B_{MSY} (the spawning biomass in year t relative to B_{MSY}) and u_{t-1}/u_{MSY} (the exploitation rate in year $t-1$ relative to u_{MSY}). The filled cyan circle is the starting year (1941). Years then proceed from light grey through to dark grey with the final year (2018) as a filled blue circle, and the blue lines represent the 10% and 90% percentiles of the posterior distributions for the final year. The filled gold circle indicates the status in 2010 ($B_{2010}/B_{\mathrm{MSY}}$, $u_{2009}/u_{\mathrm{MSY}}$), which coincides with the previous assessment in 2011. 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.

F.3.1.3. BCS Projection Results and Decision Tables

Projections were made to evaluate the future behaviour of the population under different levels of constant annual catch, given the model assumptions. The projections, starting with the biomass at the beginning of 2018, were made over a range of constant catch strategies (0-2,000 t) for each of the 1,000 MCMC samples in the posterior, generating future biomass trends by assuming random recruitment deviations. Future recruitments were generated through the stock-recruitment function using recruitment deviations drawn randomly from a lognormal distribution with zero mean and constant standard deviation (see Appendix E for full details). Projections were made for 5 years, which means that projected biomass levels will be based on recruitments estimated during the model reconstruction, rather than the stock recruitment function, given the $\sim$10 year lag before recruitment to the commercial fishery (Table F.18). Resulting projections of spawning biomass are shown for a range of selected catch strategies (Figure F.102).

The approach of obtaining future recruitments based on mean recruitment and assuming a fixed variability about that mean recruitment does not accurately simulate the occasional large recruitment events that characterise this stock and other long-lived rockfish species (Figure F.99). However, as indicated above, nearly all of the recruitments used in these projections are estimated during the stock reconstruction phase, due to the longevity of this species, the relatively late age at full maturity (estimated at 9.6 y for females, Appendix D) and the short time frame over which the projections are made.

Decision tables give the probabilities of spawning biomass exceeding various reference points in specified years, calculated by counting the proportion of MCMC samples for which the biomass exceeded the given reference point. Results for the three B_{MSY}-based reference points are presented in Tables F.20-F.22. For example, the estimated probability that the stock is in the provisional healthy zone in 2018 under a constant catch strategy of 1,000 t is P$(B_{2018} > 0.8B_{\mathrm{MSY}}) = 1$ (row '1000' and column '2018' in Table F.21).

Table F.23 provides probabilities that projected spawning biomass B_t will exceed the current-year biomass B_{2018} at the various catch levels. The first column populated by zero values simply means that the current-year biomass will never be greater than itself. If the current mean catch (732 t) is maintained until 2023, the probability that spawning biomass B_{2023} will be greater than B_{2018} is 0.614 (Table F.23).

Table F.24 shows the probabilities of projected exploitation rate u_t exceeding that at MSY (u_{MSY}). Tables F.25 and F.26 offer additional decision tables using 0.2 and 0.4B_0 as reference points, sometimes preferred by other jurisdictions.

For the maximum sustainable yield (MSY) calculations, projections were run across a range of constant exploitation rates u_t between 0 and 0.99, with an increment value of 0.005, until an equilibrium yield was reached within a tolerance of 0.01 t (or until 15,000 years had been reached). This was done for each of the 1,000 samples and the exploitation rate resulting in the highest yield would represent MSY for that MCMC draw. The lower bound of u_t was reached for none of the MCMC samples, and the upper bound was reached by 18 samples. Of the 199,000 projection calculations, all converged by 15,000 years.

F.3.1.3.1. BCS projection tables for base case

Table F.20. BC South: Decision table concerning the limit reference point $0.4B_{\mathrm{MSY}}$ for 1-5 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 1000 MCMC samples for which $B_t > 0.4B_{\mathrm{MSY}}$. For reference, the average catch over the last 5 years (2013-2017) is 732 t.

	2018	2019	2020	2021	2022	2023
0	1.000	1.000	1.000	1.000	1.000	1.000
100	1.000	1.000	1.000	1.000	1.000	1.000
200	1.000	1.000	1.000	1.000	1.000	1.000
300	1.000	1.000	1.000	1.000	1.000	1.000
400	1.000	1.000	1.000	1.000	1.000	1.000
500	1.000	1.000	1.000	1.000	1.000	1.000
600	1.000	1.000	1.000	1.000	1.000	1.000
700	1.000	1.000	1.000	1.000	1.000	1.000
800	1.000	1.000	1.000	1.000	1.000	1.000
900	1.000	1.000	1.000	1.000	1.000	1.000
1000	1.000	1.000	1.000	1.000	1.000	1.000
1100	1.000	1.000	1.000	1.000	1.000	1.000
1200	1.000	1.000	1.000	1.000	1.000	1.000
1300	1.000	1.000	1.000	1.000	1.000	1.000
1400	1.000	1.000	1.000	1.000	1.000	1.000
1500	1.000	1.000	1.000	1.000	1.000	1.000
1600	1.000	1.000	1.000	1.000	1.000	1.000
1700	1.000	1.000	1.000	1.000	1.000	1.000
1800	1.000	1.000	1.000	1.000	1.000	1.000
1900	1.000	1.000	1.000	1.000	1.000	1.000
2000	1.000	1.000	1.000	1.000	1.000	1.000

Table F.21. BC South: Decision table concerning the upper stock reference point $0.8B_{\mathrm{MSY}}$ for 1-5 year projections, such that values are P($B_t > 0.8B_{\mathrm{MSY}}$). For reference, the average catch over the last 5 years (2013-2017) is 732 t.

	2018	2019	2020	2021	2022	2023
0	1.000	1.000	1.000	1.000	1.000	1.000
100	1.000	1.000	1.000	1.000	1.000	1.000
200	1.000	1.000	1.000	1.000	1.000	1.000
300	1.000	1.000	1.000	1.000	1.000	1.000
400	1.000	1.000	1.000	1.000	1.000	1.000
500	1.000	1.000	1.000	1.000	1.000	1.000
600	1.000	1.000	1.000	1.000	1.000	1.000
700	1.000	1.000	1.000	1.000	1.000	1.000
800	1.000	1.000	1.000	1.000	1.000	1.000
900	1.000	1.000	1.000	1.000	1.000	1.000
1000	1.000	1.000	1.000	1.000	1.000	1.000
1100	1.000	1.000	1.000	1.000	1.000	0.999
1200	1.000	1.000	1.000	0.999	0.999	0.999
1300	1.000	1.000	0.999	0.999	0.999	0.999
1400	1.000	1.000	0.999	0.999	0.998	0.997
1500	1.000	1.000	0.999	0.998	0.998	0.996
1600	1.000	1.000	0.999	0.998	0.997	0.993
1700	1.000	1.000	0.999	0.998	0.997	0.992
1800	1.000	0.999	0.999	0.998	0.996	0.988
1900	1.000	0.999	0.998	0.997	0.992	0.984
2000	1.000	0.999	0.998	0.997	0.990	0.976

Table F.22. BC South: Decision table concerning the reference point B_{MSY} for 1-5 year projections, such that values are P($B_t > B_{\mathrm{MSY}}$). For reference, the average catch over the last 5 years (2013-2017) is 732 t.

	2018	2019	2020	2021	2022	2023
0	0.999	0.999	1.000	1.000	1.000	1.000
100	0.999	0.999	1.000	1.000	1.000	1.000
200	0.999	0.999	0.999	1.000	1.000	1.000
300	0.999	0.999	0.999	1.000	1.000	1.000
400	0.999	0.999	0.999	1.000	1.000	1.000
500	0.999	0.999	0.999	0.999	1.000	1.000
600	0.999	0.999	0.999	0.999	0.999	0.999
700	0.999	0.999	0.999	0.999	0.999	0.999
800	0.999	0.999	0.999	0.998	0.998	0.999
900	0.999	0.999	0.998	0.998	0.998	0.996
1000	0.999	0.999	0.998	0.998	0.997	0.995
1100	0.999	0.999	0.998	0.998	0.996	0.993
1200	0.999	0.998	0.998	0.997	0.994	0.991
1300	0.999	0.998	0.998	0.995	0.991	0.990
1400	0.999	0.998	0.998	0.993	0.990	0.986
1500	0.999	0.998	0.996	0.992	0.990	0.978
1600	0.999	0.998	0.995	0.991	0.985	0.970
1700	0.999	0.998	0.993	0.989	0.978	0.964
1800	0.999	0.998	0.993	0.985	0.973	0.958
1900	0.999	0.996	0.992	0.982	0.968	0.950
2000	0.999	0.996	0.992	0.978	0.958	0.940

Table F.23. BC South: Decision table for comparing the projected biomass to the current biomass, given by probabilities P$(B_t > B_{2018})$. For reference, the average catch over the last 5 years (2013-2017) is 732 t.

	2018	2019	2020	2021	2022	2023
0	0.000	0.967	0.970	0.969	0.971	0.968
100	0.000	0.952	0.954	0.947	0.954	0.949
200	0.000	0.934	0.938	0.929	0.928	0.923
300	0.000	0.901	0.905	0.901	0.888	0.887
400	0.000	0.854	0.866	0.847	0.839	0.845
500	0.000	0.797	0.799	0.788	0.780	0.771
600	0.000	0.735	0.734	0.712	0.692	0.693
700	0.000	0.659	0.661	0.651	0.620	0.614
800	0.000	0.581	0.595	0.561	0.548	0.534
900	0.000	0.510	0.503	0.484	0.464	0.451
1000	0.000	0.423	0.433	0.414	0.391	0.385
1100	0.000	0.355	0.369	0.334	0.325	0.306
1200	0.000	0.297	0.298	0.287	0.267	0.246
1300	0.000	0.240	0.256	0.235	0.216	0.198
1400	0.000	0.198	0.206	0.185	0.178	0.155
1500	0.000	0.161	0.173	0.153	0.141	0.132
1600	0.000	0.126	0.132	0.123	0.113	0.105
1700	0.000	0.104	0.104	0.097	0.087	0.086
1800	0.000	0.079	0.084	0.075	0.069	0.071
1900	0.000	0.057	0.062	0.060	0.057	0.054
2000	0.000	0.045	0.052	0.050	0.046	0.043

Table F.24. BC South: 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 greater than that at MSY. For reference, the average catch over the last 5 years (2013-2017) is 732 t.

	2018	2019	2020	2021	2022	2023
0	0.000	0.000	0.000	0.000	0.000	0.000
100	0.000	0.000	0.000	0.000	0.000	0.000
200	0.000	0.000	0.000	0.000	0.000	0.000
300	0.000	0.000	0.000	0.000	0.000	0.000
400	0.000	0.000	0.000	0.000	0.000	0.000
500	0.000	0.000	0.000	0.000	0.000	0.000
600	0.000	0.000	0.000	0.000	0.000	0.000
700	0.001	0.001	0.001	0.001	0.001	0.001
800	0.003	0.003	0.004	0.004	0.005	0.005
900	0.008	0.008	0.007	0.007	0.007	0.007
1000	0.009	0.010	0.011	0.011	0.015	0.016
1100	0.014	0.017	0.019	0.020	0.025	0.029
1200	0.020	0.022	0.026	0.028	0.030	0.034
1300	0.027	0.030	0.035	0.043	0.050	0.053
1400	0.036	0.041	0.049	0.055	0.064	0.070
1500	0.048	0.056	0.064	0.069	0.079	0.089
1600	0.058	0.067	0.076	0.087	0.099	0.106
1700	0.068	0.082	0.094	0.105	0.114	0.137
1800	0.082	0.096	0.107	0.120	0.141	0.159
1900	0.095	0.108	0.119	0.141	0.169	0.192
2000	0.104	0.117	0.138	0.168	0.191	0.216

Table F.25. BC South: Decision table for alternative reference point $0.2B_0$ for 1-5 year projections, such that values are P($B_t > 0.2B_0$). For reference, the average catch over the last 5 years (2013-2017) is 732 t.

	2018	2019	2020	2021	2022	2023
0	1.000	1.000	1.000	1.000	1.000	1.000
100	1.000	1.000	1.000	1.000	1.000	1.000
200	1.000	1.000	1.000	1.000	1.000	1.000
300	1.000	1.000	1.000	1.000	1.000	1.000
400	1.000	1.000	1.000	1.000	1.000	1.000
500	1.000	1.000	1.000	1.000	1.000	1.000
600	1.000	1.000	1.000	1.000	1.000	1.000
700	1.000	1.000	1.000	1.000	1.000	1.000
800	1.000	1.000	1.000	1.000	1.000	1.000
900	1.000	1.000	1.000	1.000	1.000	1.000
1000	1.000	1.000	1.000	1.000	1.000	1.000
1100	1.000	1.000	1.000	1.000	1.000	1.000
1200	1.000	1.000	1.000	1.000	1.000	1.000
1300	1.000	1.000	1.000	1.000	1.000	1.000
1400	1.000	1.000	1.000	1.000	1.000	1.000
1500	1.000	1.000	1.000	1.000	1.000	1.000
1600	1.000	1.000	1.000	1.000	1.000	1.000
1700	1.000	1.000	1.000	1.000	1.000	0.999
1800	1.000	1.000	1.000	1.000	1.000	0.997
1900	1.000	1.000	1.000	1.000	0.998	0.997
2000	1.000	1.000	1.000	1.000	0.998	0.994

Table F.26. BC South: Decision table for alternative reference point $0.4B_0$ for 1-5 year projections, such that values are P($B_t > 0.4B_0$). For reference, the average catch over the last 5 years (2013-2017) is 732 t.

	2018	2019	2020	2021	2022	2023
0	0.992	0.996	0.998	1.000	1.000	1.000
100	0.992	0.996	0.998	0.998	1.000	1.000
200	0.992	0.995	0.998	0.998	1.000	1.000
300	0.992	0.995	0.998	0.998	0.998	1.000
400	0.992	0.995	0.996	0.998	0.998	0.999
500	0.992	0.995	0.996	0.997	0.997	0.997
600	0.992	0.995	0.995	0.996	0.996	0.996
700	0.992	0.992	0.994	0.995	0.996	0.993
800	0.992	0.990	0.993	0.993	0.990	0.988
900	0.992	0.990	0.991	0.990	0.984	0.976
1000	0.992	0.989	0.987	0.984	0.976	0.965
1100	0.992	0.988	0.986	0.978	0.965	0.958
1200	0.992	0.988	0.984	0.968	0.957	0.942
1300	0.992	0.987	0.978	0.960	0.946	0.934
1400	0.992	0.985	0.976	0.956	0.937	0.911
1500	0.992	0.985	0.968	0.945	0.924	0.893
1600	0.992	0.983	0.963	0.937	0.905	0.868
1700	0.992	0.982	0.954	0.929	0.888	0.835
1800	0.992	0.982	0.947	0.916	0.862	0.809
1900	0.992	0.980	0.943	0.903	0.841	0.775
2000	0.992	0.978	0.938	0.887	0.810	0.741

F.3.1.3.2. BCS projection figures for base case

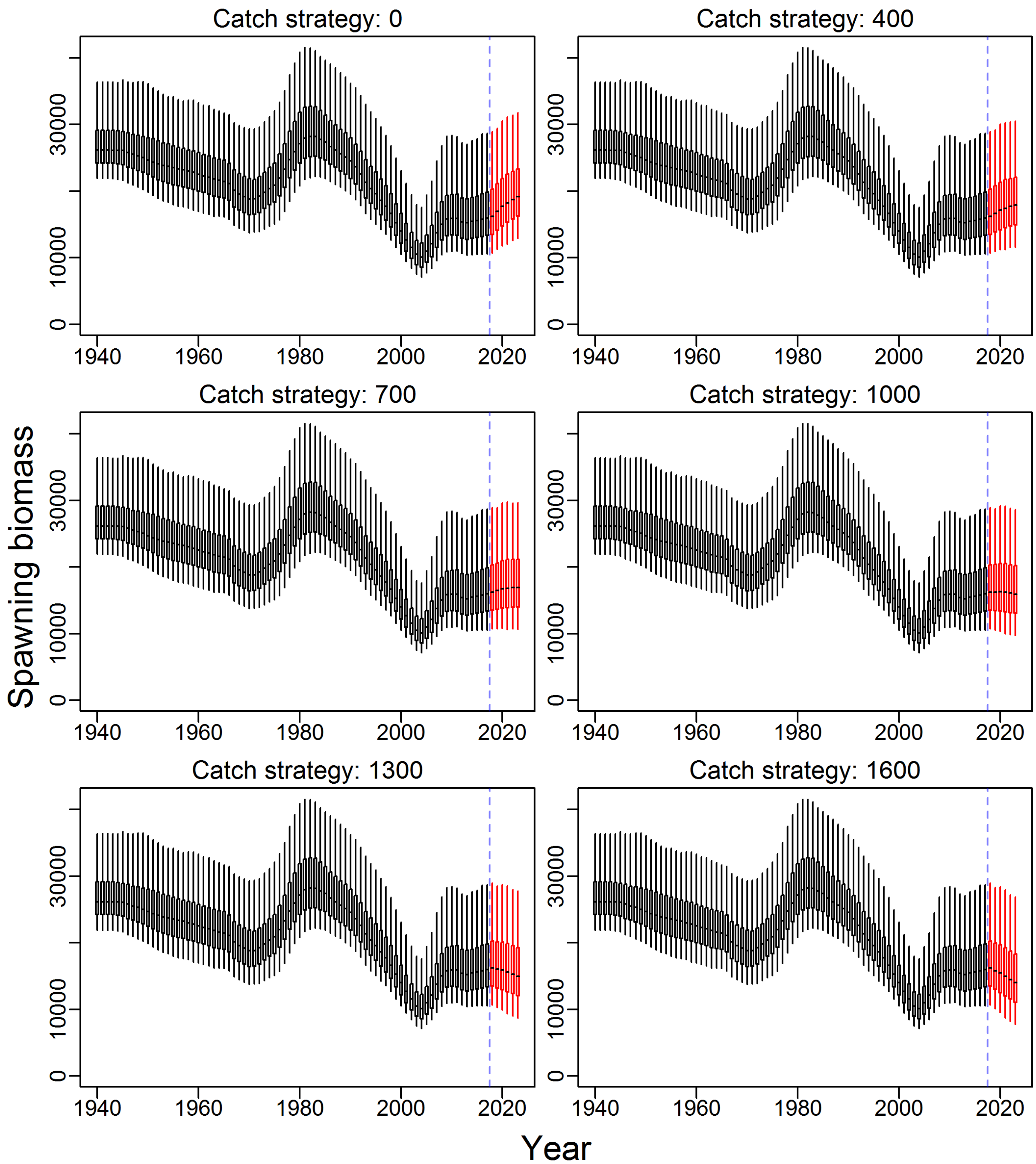


Figure F.102. BC South: Projected biomass (t) under different constant catch strategies (t); boxplots show the 2.5, 25, 50, 75 and 97.5 percentiles from the MCMC results. For each of the 1,000 samples from the MCMC posterior, the model was run forward in time (red, with medians in black) with a constant catch, and recruitment was simulated from the stock-recruitment function with lognormal error (see Appendix E). For reference, the average catch over the last 5 years (2013-2017) is 732 t.

F.3.2. BCS Sensitivity Runs

Five sensitivity analyses were run (with full MCMC simulations) relative to the base case (Run16) to test the sensitivity of the outputs to alternative model assumptions:

- **S1** (Run19) – remove the commercial CPUE index series (g=5);
- **S2** (Run20) – halve the catch during years of foreign fleet activity (1965-1976) and during years of possible misreporting by domestic fleet before observer coverage (1988-1995);
- **S3** (Run21) – use proportions-at-age from unsorted samples only;
- **S4** (Run22) – increase sigmaR (σ_R) from 0.6 to 1.1;
- **S5** (Run23) – remove the GIG Historical and WCVI Triennial surveys;

Four additional sensitivity analyses were run as diagnostics to the base case and S4:

- **D1** (Run24) – same as base case but fix $M_{1,2}$ to 0.11;
- **D2** (Run25) – same as S4 but fix $M_{1,2}$ to 0.11.
- **D3** (Run27) – same as base case but prior on $M_{1,2} \sim$ N(0.136, 0.0136) [10%CV] assuming a maximum age of 50 y instead of 61 y;
- **D4** (Run28) – same as base case but prior on $M_{1,2} \sim$ N(0.136, 0.0272) [20%CV].

Each sensitivity (including the diagnostic runs) was reweighted three times using the procedure of Francis (2011) for age frequencies. The abundance index CVs were ajusted on the first reweight only using the same process error adopted in the base case: c_p = 0.5, 0.3, 0.25, 0.5, and 0.2 for the GIG Historical survey, WCVI Synoptic survey, QCS Synoptic survey, WCVI Triennial survey, and commercial trawl CPUE, respectively. The reweighted dataset chosen for MCMC analysis was based on Equation E.33 for each sensitivity.

The differences among the runs are summarised in Tables F.27 and F.28 and Figures F.103 to F.105. Diagnostic plots for the sensitivity MCMCs appear in Figures F.106 to F.114.

Run S1 explores the effect of removing the CPUE index series. The diagnostic plots (Figures F.106–F.108) indicate that taking out CPUE destabilizes the model somewhat, but not to the extent it did in the BC North stock. The split-chain plot suggests that R_0 and q_1 are the parameters most affected (FigureF.107). Auto-correlation is a problem for a number of parameters, but does not appear much more pronounced that it did in the base case (FigureF.108). This is the most optimistic scenario regarding female spawning-biomass stock status.

Run S2 explores the effect of catch mis-specification during the period of peak foreign fleet activity and during the rise of the domestic fleet. The MCMC diagnostics for this run are good (Figures F.109–F.111), perhaps even better than those for the base case. Reducing the catch has little impact on the estimated parameters (Table F.27) or on the reference points (Table F.28).

Run S3 explores the effect of using only unsorted samples to supply the composition signal to the model. Because unsorted samples do not occur in the earlier years of age data, the model loses this information to use in the reconstruction. This limitation affects the model's performance as the MCMC diagnostics indicate some problems with autocorrelation (Figures F.112–F.114). The primary problem appears to be less ability to distinguish differences in natural mortality between the sexes (Table F.27). This scenario estimates the lowest level of current biomass relative to the unfished equilibrium female spawning biomass. However, median estimates for B_{2018}/B_0 = 0.5B_0, the 2018 stock size is nearly twice B_{MSY} and u_{2017} is 38% of u_{MSY}.

Run S4 explores the effect of a larger standard deviation for recruitment process error. This model run is perhaps the closest to the base case, and has good MCMC diagnostics (Figures F.115–F.117). Unlike this sensitivity for the BC North stock, an alternative population trajectory is not found by widening σ_R. However, when M is fixed to 0.11 at both σ_R values (diagnostic MCMC runs), the recruitment patterns change in magnitude so that the largest recruitment year in the base case, 2001, is supplanted by the 1969 recruitment event when σ_R=1.1 but is reversed when σ_R=0.6. (Figure F.105). The population trajectory remains similar among the runs, differing only in magnitude at the zenith and nadir of the trajectory.

Diagnostic runs equivalent to D1 and D2 made for the BCN stock were also run for the BCS stock (see Tables F.27 and F.28). These runs confirmed the greater relative stability of the BCS data set, with little shift in the estimates of 2018 biomass relative to the unfished equilibrium biomass (B_0) or to B_{MSY}. Biomass trajectories (Figure F.105) were also consistent with the base case or S4, differing mainly in the relative size of the strong recruitment years but not in the years with strong recruitment.

Run S5 explores the effect of removing the non-synoptic surveys. The loss of signal from the early GIG Historical survey, and perhaps that from the WCVI Triennial survey, has degraded the quality of the MCMC samples significantly (Figures F.118–F.120). Auto-correlation is unacceptably high and persistent for R_0, and other parameters suffer as well. This model scenario is not recommended for advice to managers.

The base-case stock status ($B_{2018}/B_{\mathrm{MSY}}$) of Redstripe Rockfish (3CD5ABC) is well within DFO's 'Healthy Zone' (Figure F.121), with a probability of being above 0.8B_{MSY} of 1. Sensitivities 2, 4, and 5 do not show much change in the perceived stock status. Sensitivity 3 (Unsorted AF) indicates a lower status than that for the base case and the other sensitivities; however, the probability of being above 0.8B_{MSY} is still 0.997.

As for BCN, the review meeting participants requested two additional runs (D3 and D4). The mean of these priors assumed M was based on a maximum age of 50 y instead of 61 y used in the base case. Given that these runs were made overnight at the review meeting, only the MPD results could be presented to the participants and consequently MCMC results are not reported. In BC South, the estimate of $M_{1,2}$ = (0.092, 0.126) in the base case increased to $M_{1,2}$ = (0.119, 0.151) and $M_{1,2}$ = (0.111, 0.147) for D3 and D4. Unlike for the BCN stock, the response by the BCS stock differed by sex with the two diagnostic runs estimating female M at a level lower than the prior mean while the male M estimates rose about 10% above the prior mean. These results are consistent with the MPD BCS base case results, where the M estimates by sex diverged in the same manner relative to the prior mean (see Table F.15). The shifts in spawning stock status in the final year relative to unfished equilibrium (B_{2018}/B_0) was greater for the BCS stock than for the BCN stock, with the MPD estimate of 0.61 in the base case increasing by more than 30% to 0.85 (D3) and 0.80 (D4). For both stocks, increasing the M prior mean resulted in higher levels of B_{2018} spawning stock biomass relative to B_0.

F.3.2.1. BCS tables for sensitivity runs

Table F.27. BC South: Median values of 1000 MCMC samples for the primary estimated parameters, comparing the Base Case (run 16) to sensitivity runs (19-25). R = Run, S = Sensitivity, D =Diagnostic sensitivity (M=0.11). Numeric subscripts other than those for R_0 and M indicate the following gear types g: 1 = GIG Historical survey, 2 = WCVI Synoptic survey, 3 = QCS Synoptic survey, 4 = WCVI Triennial survey, and 5 = commercial trawl CPUE.

	Base(R16)	S1(R19)	S2(R20)	S3(R21)	S4(R22)	S5(R23)	D1(R24)	D2(R25)
R_0	14,312	20,430	12,441	11,643	14,887	15,769	18,292	15,746
M_1	0.0979	0.103	0.100	0.101	0.101	0.0995	—	—
M_2	0.130	0.134	0.132	0.119	0.132	0.131	—	—
h	0.761	0.784	0.774	0.679	0.767	0.743	0.744	0.748
q_1	0.0288	0.0210	0.0336	0.0381	0.0308	—	0.0207	0.0258
q_2	0.172	0.0992	0.193	0.247	0.207	0.150	0.128	0.211
q_3	0.166	0.0896	0.185	0.269	0.233	0.137	0.116	0.230
q_4	0.220	0.157	0.244	0.309	0.233	—	0.172	0.223
q_5	0.0000739	—	0.0000816	0.0000900	0.0000940	0.0000644	0.0000537	0.0000903
μ_1	17.7	17.4	17.8	16.6	17.4	—	16.9	16.5
μ_2	11.2	12.4	11.4	9.56	9.87	11.3	10.8	9.65
μ_3	15.4	14.8	15.5	15.8	15.6	14.9	14.5	15.4
μ_5	12.4	12.4	12.5	9.16	12.4	12.3	11.8	11.9
Δ_1	0.519	0.301	0.404	0.259	0.417	—	0.756	0.627
Δ_2	0.212	0.217	0.215	0.209	0.209	0.214	0.226	0.219
Δ_3	-0.133	-0.220	-0.144	0.0377	0.0160	-0.121	0.235	0.340
Δ_5	0.223	0.269	0.256	-0.0786	0.202	0.232	0.220	0.190
$\log v_{1L}$	4.12	4.08	4.10	3.92	4.08	—	4.08	4.03
$\log v_{2L}$	3.03	3.39	3.09	2.42	2.45	3.10	2.94	2.36
$\log v_{3L}$	3.66	3.59	3.68	3.68	3.57	3.60	3.58	3.56
$\log v_{5L}$	2.64	2.58	2.64	1.64	2.59	2.58	2.54	2.54

Table F.28. BC South: The 50$^{\mathrm{th}}$ percentiles of MCMC-derived quantities from the 1000 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_{2018} – spawning biomass at the start of 2018, V_{2018} – vulnerable biomass in the middle of 2018, u_{2017} – exploitation rate (ratio of total catch to vulnerable biomass) in the middle of 2017, $u_{\max}$ – maximum exploitation rate (calculated for each sample as the maximum exploitation rate from 1940 - 2017), 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.

	Base(R16)	S1(R19)	S2(R20)	S3(R21)	S4(R22)	S5(R23)	D1(R24)	D2(R25)
B_0	26,149	34,851	21,902	20,346	25,876	28,022	27,246	23,454
V_0	27,318	35,758	22,811	26,066	26,940	29,429	34,048	29,148
B_{2018}	16,235	28,566	14,389	10,280	16,172	18,190	18,730	15,122
V_{2018}	15,665	29,232	13,833	12,686	13,444	17,924	21,885	14,390
B_{2018}/B_0	0.622	0.826	0.657	0.514	0.630	0.655	0.696	0.643
V_{2018}/V_0	0.574	0.813	0.605	0.496	0.496	0.611	0.651	0.496
u_{2017}	0.0490	0.0255	0.0552	0.0609	0.0604	0.0427	0.0350	0.0568
$u_{\max}$	0.0886	0.0641	0.0950	0.113	0.115	0.0780	0.0655	0.113
MSY	1,467	2,134	1,308	1,076	1,523	1,601	1,910	1,670
B_{MSY}	6,830	8,867	5,564	5,677	6,547	7,537	7,461	6,339
$0.4B_{\mathrm{MSY}}$	2,732	3,547	2,225	2,271	2,619	3,015	2,984	2,535
$0.8B_{\mathrm{MSY}}$	5,464	7,094	4,451	4,542	5,238	6,030	5,968	5,071
$B_{2018}/B_{\mathrm{MSY}}$	2.43	3.29	2.64	1.87	2.51	2.54	2.60	2.41
B_{MSY}/B_0	0.256	0.250	0.252	0.282	0.255	0.262	0.270	0.270
V_{MSY}	5,043	5,990	3,897	6,971	4,714	5,665	6,702	5,386
V_{MSY}/V_0	0.182	0.161	0.171	0.270	0.174	0.191	0.194	0.187
u_{MSY}	0.300	0.380	0.340	0.155	0.330	0.285	0.292	0.310
$u_{2017}/u_{\mathrm{MSY}}$	0.160	0.0661	0.157	0.377	0.180	0.141	0.116	0.180

F.3.2.2. BCS figures for sensitivity runs

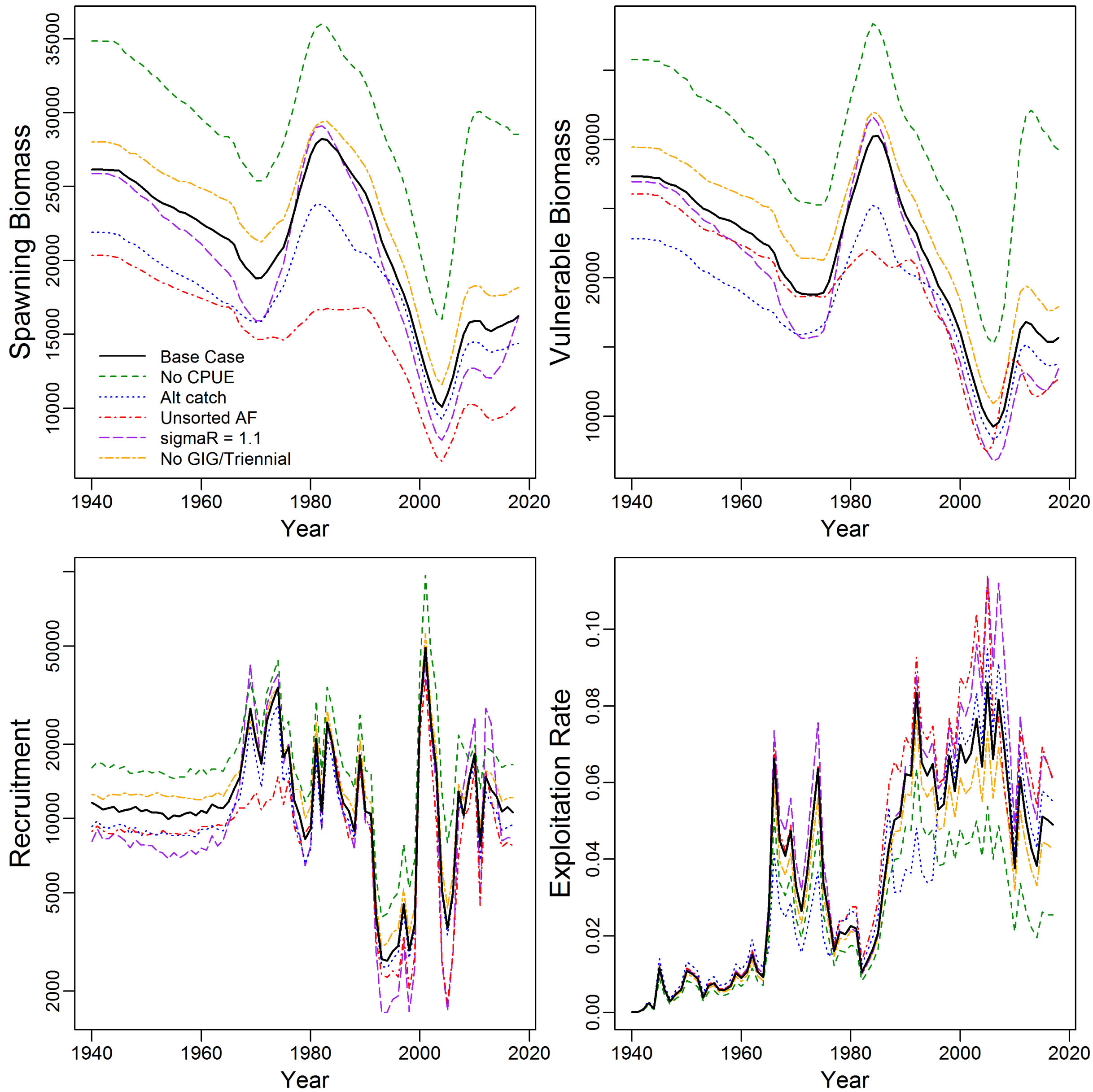


Figure F.103. BC South: Model median trajectories of spawning biomass (t), vulnerable biomass (t), recruitment (1000s fish at age 1y), and exploitation rate for the base case and 5 sensitivity runs, indicated by a legend in the first panel.

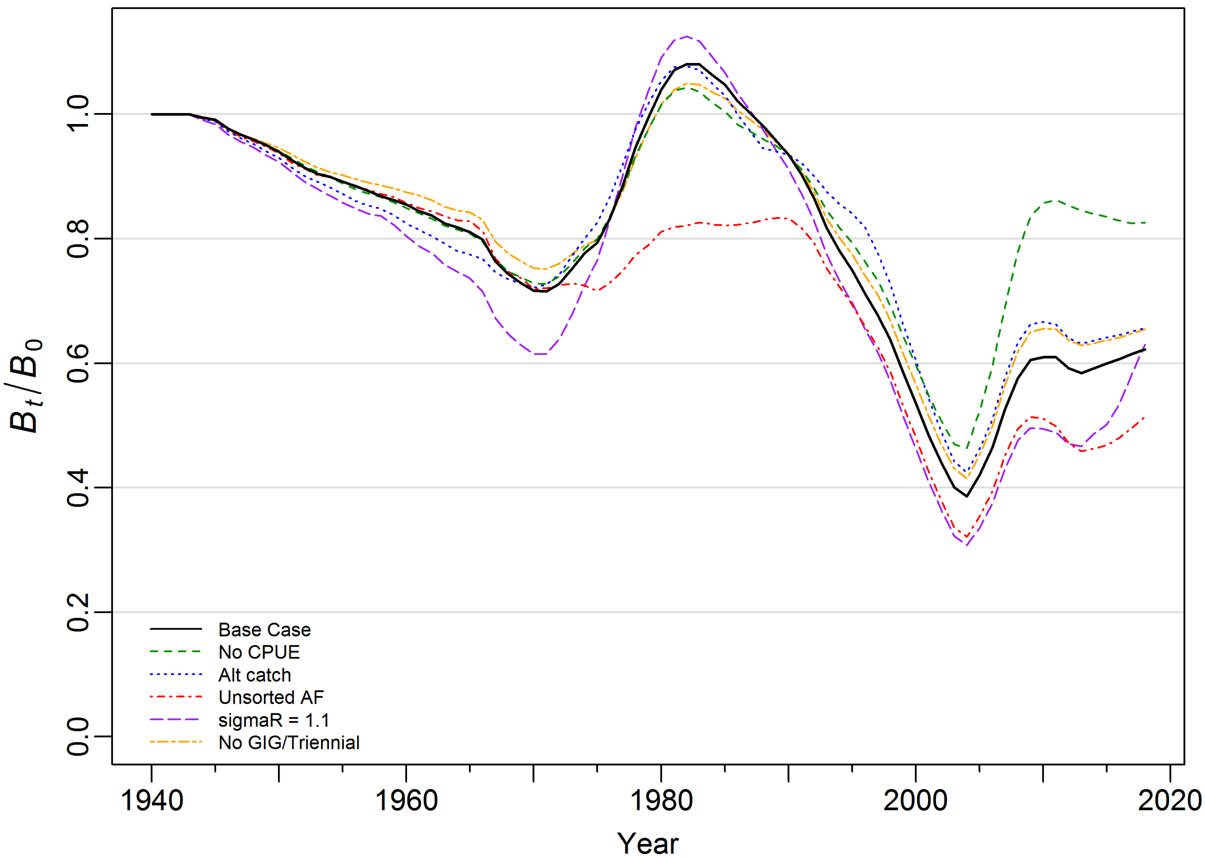


Figure F.104. BC South: Model median trajectories of spawning biomass as a proportion of unfished equilibrium biomass (B_t/B_0) for the base case and 5 sensitivity runs, indicated by a legend in the first panel.

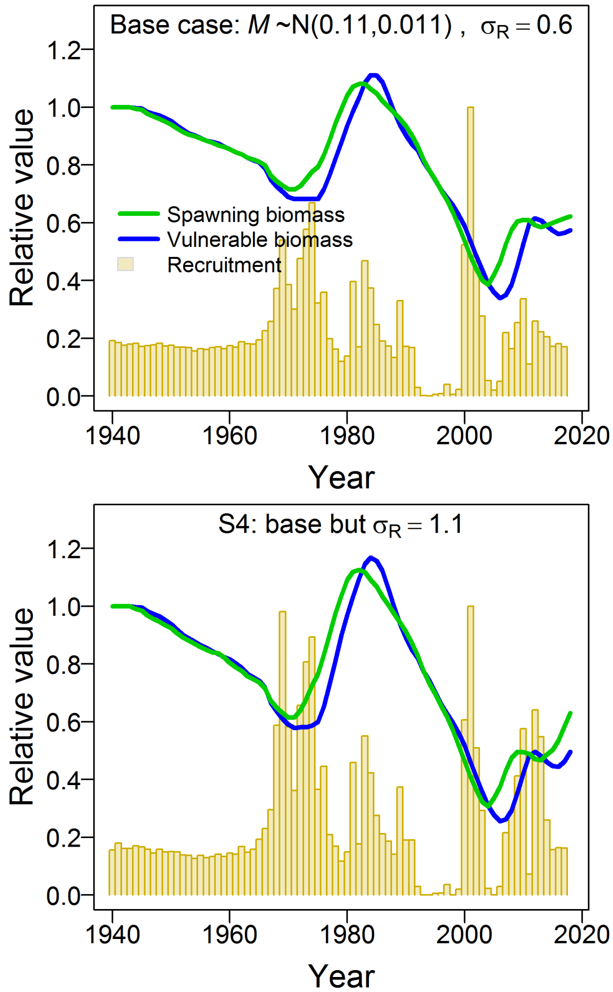


Figure F.105. BC South: Model median trajectories of spawning and vulnerable biomass relative to unfished equilibrium values (B_{2018}/B_0 and V_{2018}/V_0) and standardised median annual recruitment (bars) for the base case and sensitivity 4 (σ_R=1.1) on the left and two corresponding runs (D1 and D2) with $M_{1,2}$ fixed at 0.11 on the right.

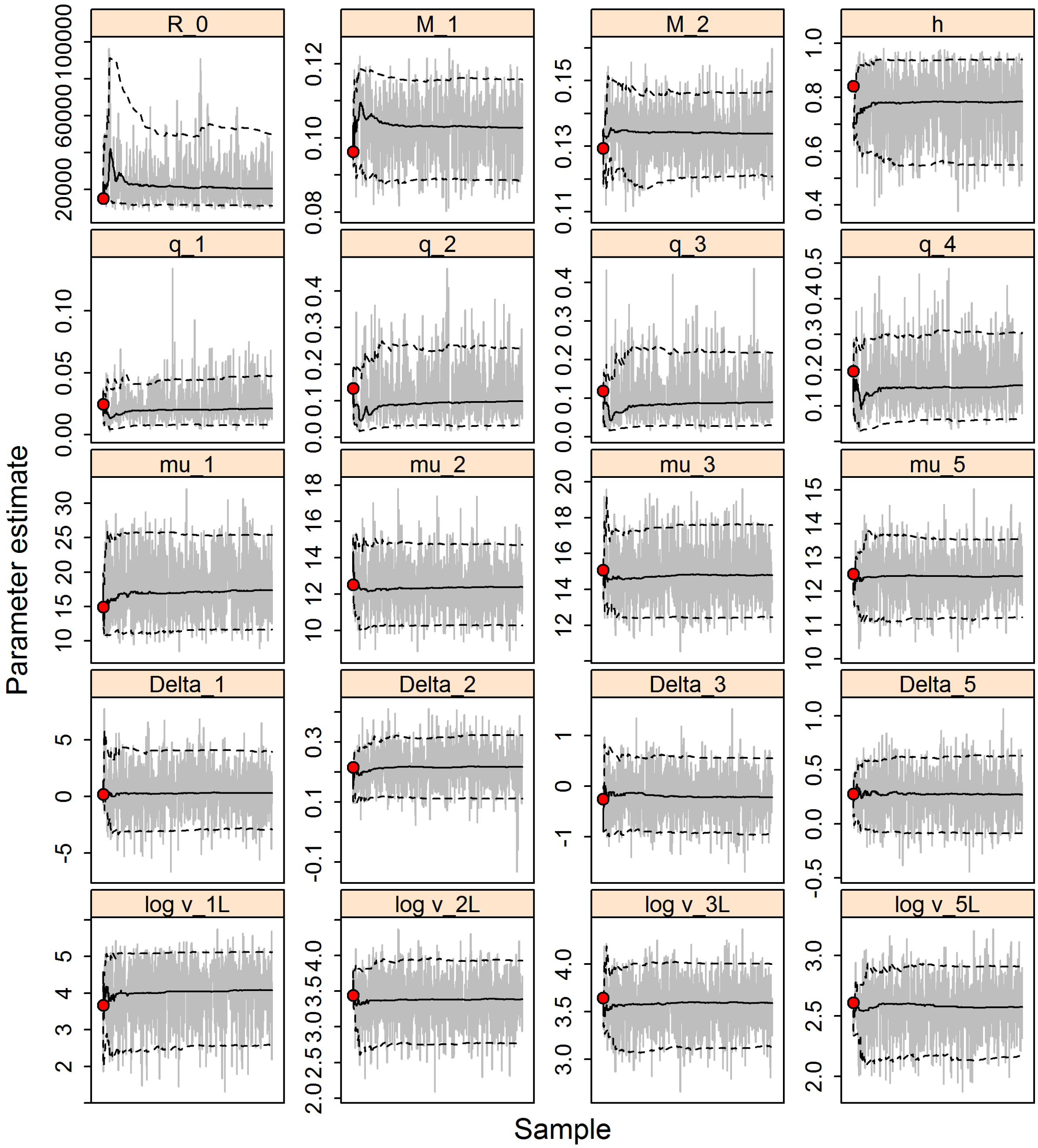


Figure F.106. BC South: Sensitivity 1: MCMC traces for the estimated parameters. Grey lines show the 1,000 samples for each parameter, solid lines show the cumulative median (up to that sample), and dashed lines show the cumulative 2.5 and 97.5 quantiles. Red circles are the MPD estimates. For parameters other than M (if estimated), subscripts ≤ 4 correspond to fishery-independent surveys, and subscripts ≥ 5 denote the commercial fishery. Parameter notation is described in Appendix E.

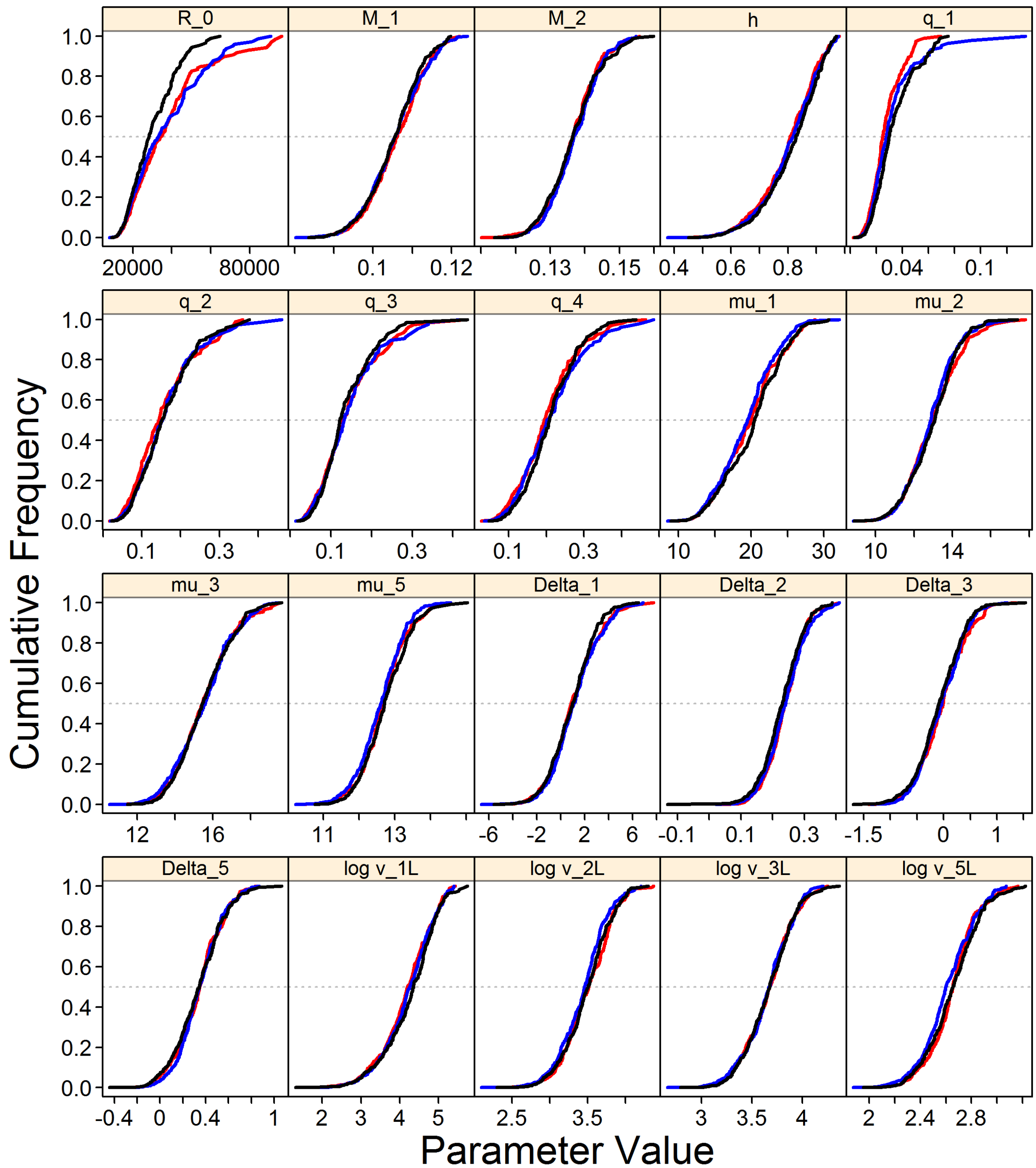


Figure F.107. BC South: Sensitivity 1: Diagnostic plot obtained by dividing the MCMC chain of 1,000 MCMC samples into three segments, and overplotting the cumulative distributions of the first segment (red), second segment (blue) and final segment (black).

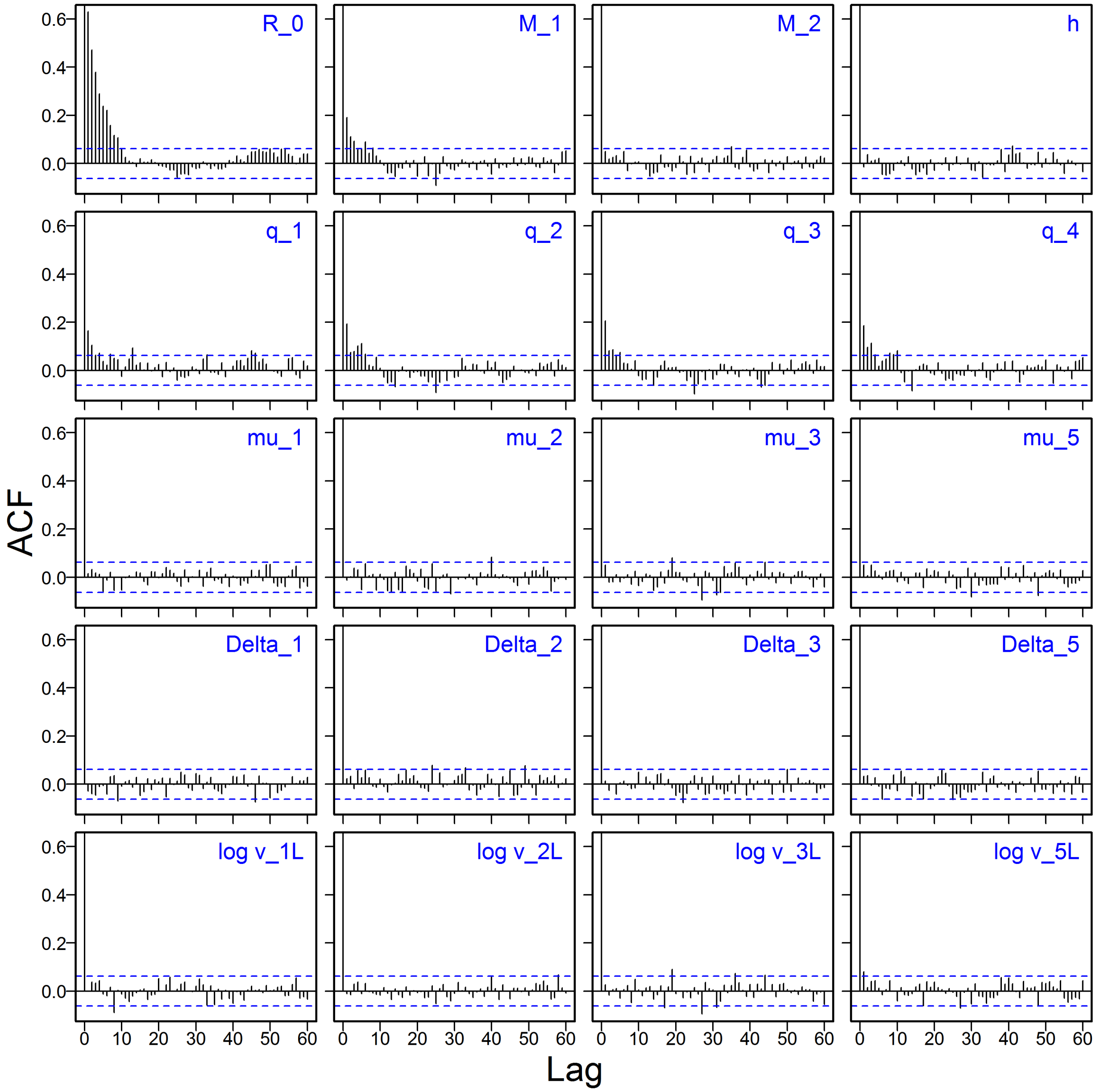


Figure F.108. BC South: Sensitivity 1: Autocorrelation plots for the estimated parameters from the MCMC output. Horizontal dashed blue lines delimit the 95% confidence interval for each parameter's set of lagged correlations.

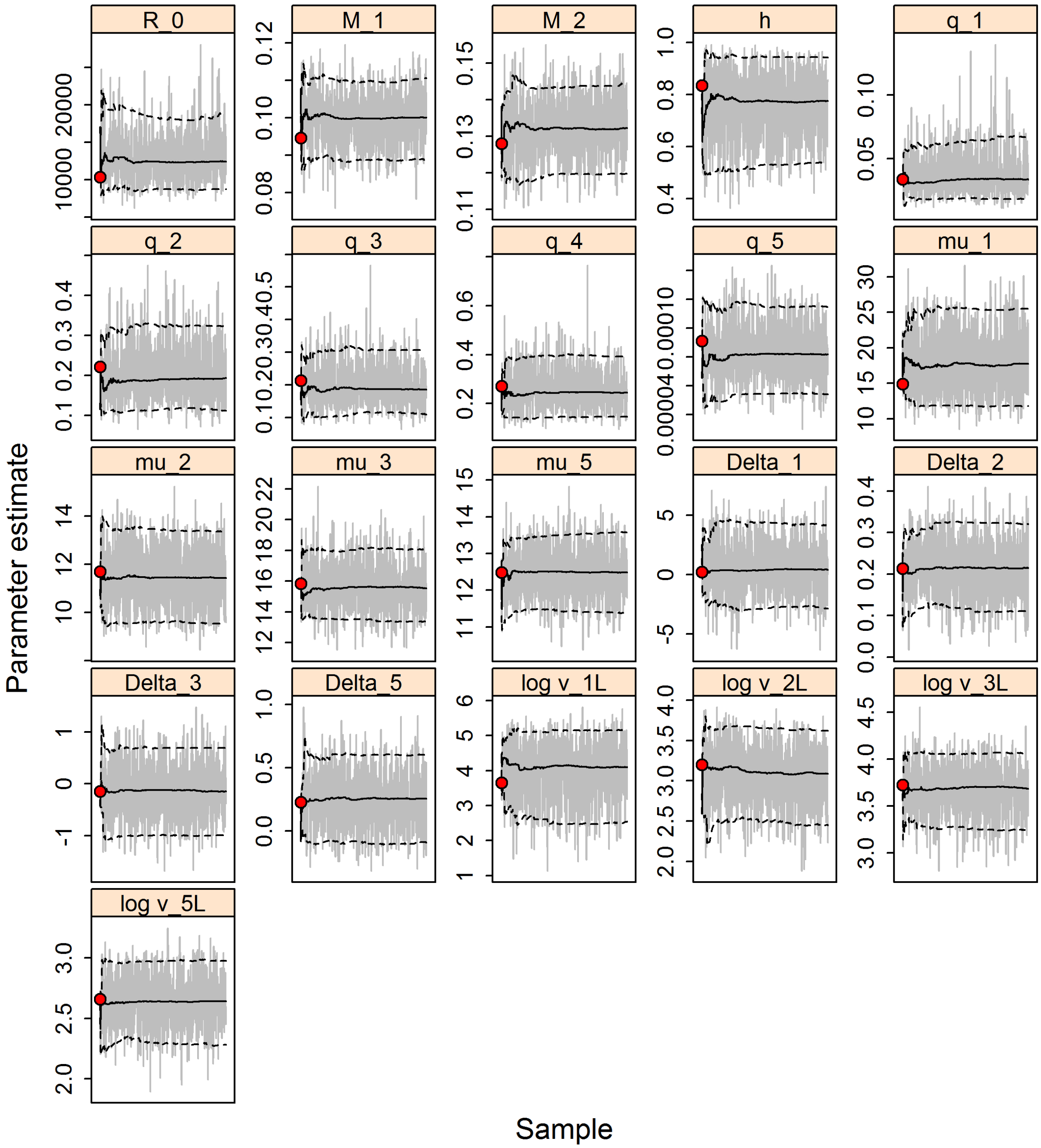


Figure F.109. BC South: Sensitivity 2: MCMC traces for the estimated parameters. Grey lines show the 1,000 samples for each parameter, solid lines show the cumulative median (up to that sample), and dashed lines show the cumulative 2.5 and 97.5 quantiles. Red circles are the MPD estimates. For parameters other than M (if estimated), subscripts ≤ 4 correspond to fishery-independent surveys, and subscripts ≥ 5 denote the commercial fishery. Parameter notation is described in Appendix E.

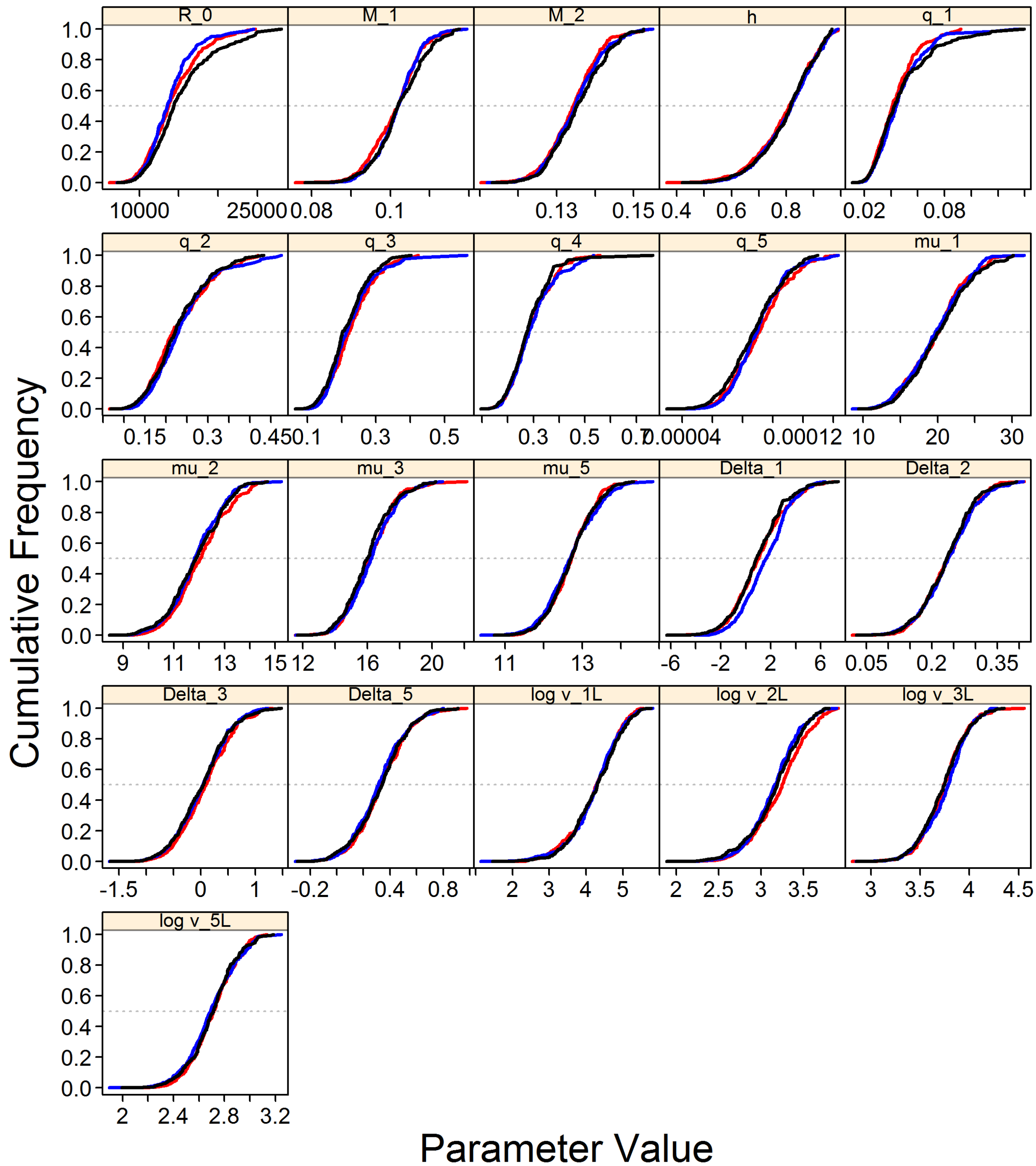


Figure F.110. BC South: Sensitivity 2: Diagnostic plot obtained by dividing the MCMC chain of 1,000 MCMC samples into three segments, and overplotting the cumulative distributions of the first segment (red), second segment (blue) and final segment (black).

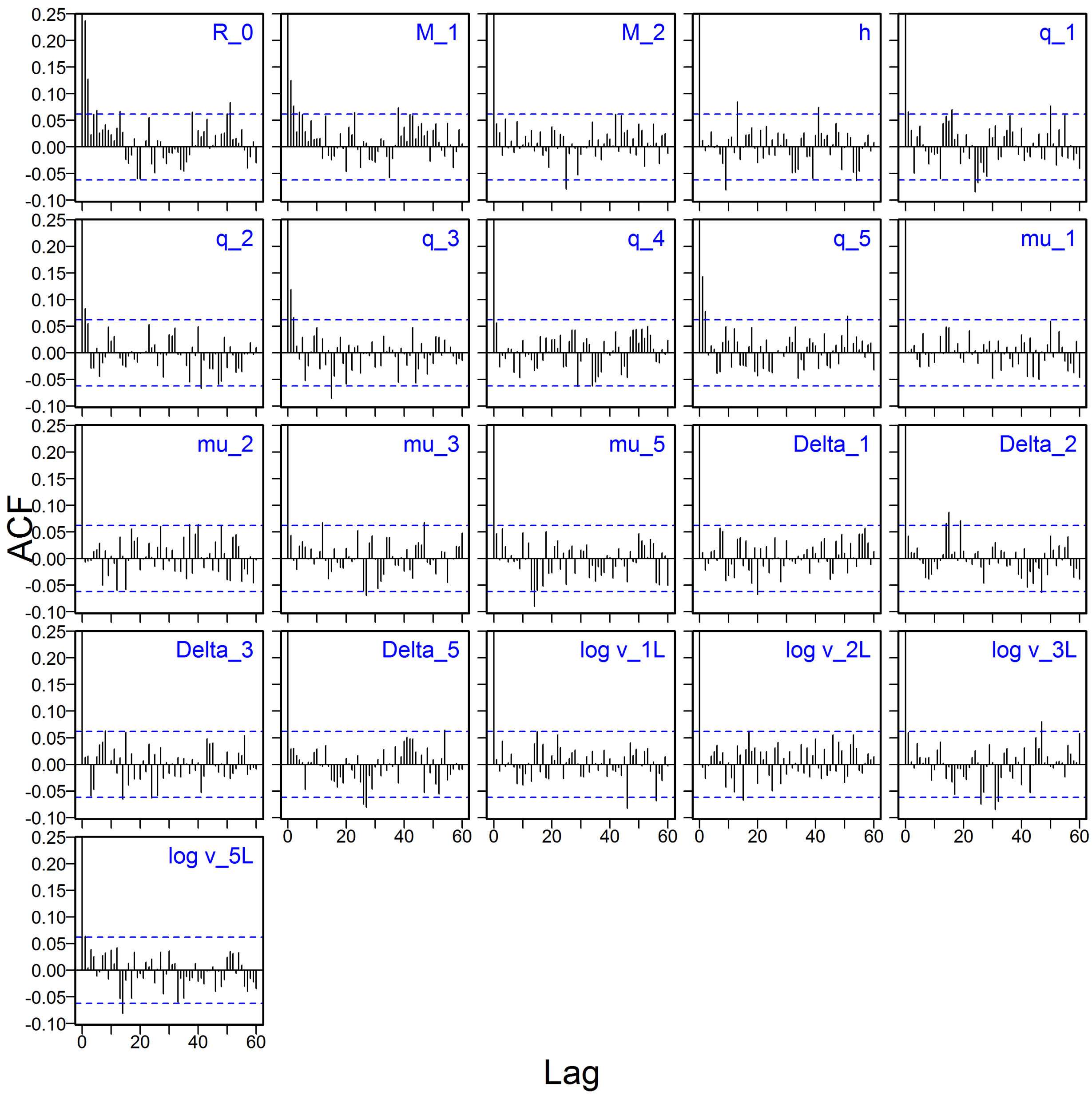


Figure F.111. BC South: Sensitivity 2: Autocorrelation plots for the estimated parameters from the MCMC output. Horizontal dashed blue lines delimit the 95% confidence interval for each parameter's set of lagged correlations.

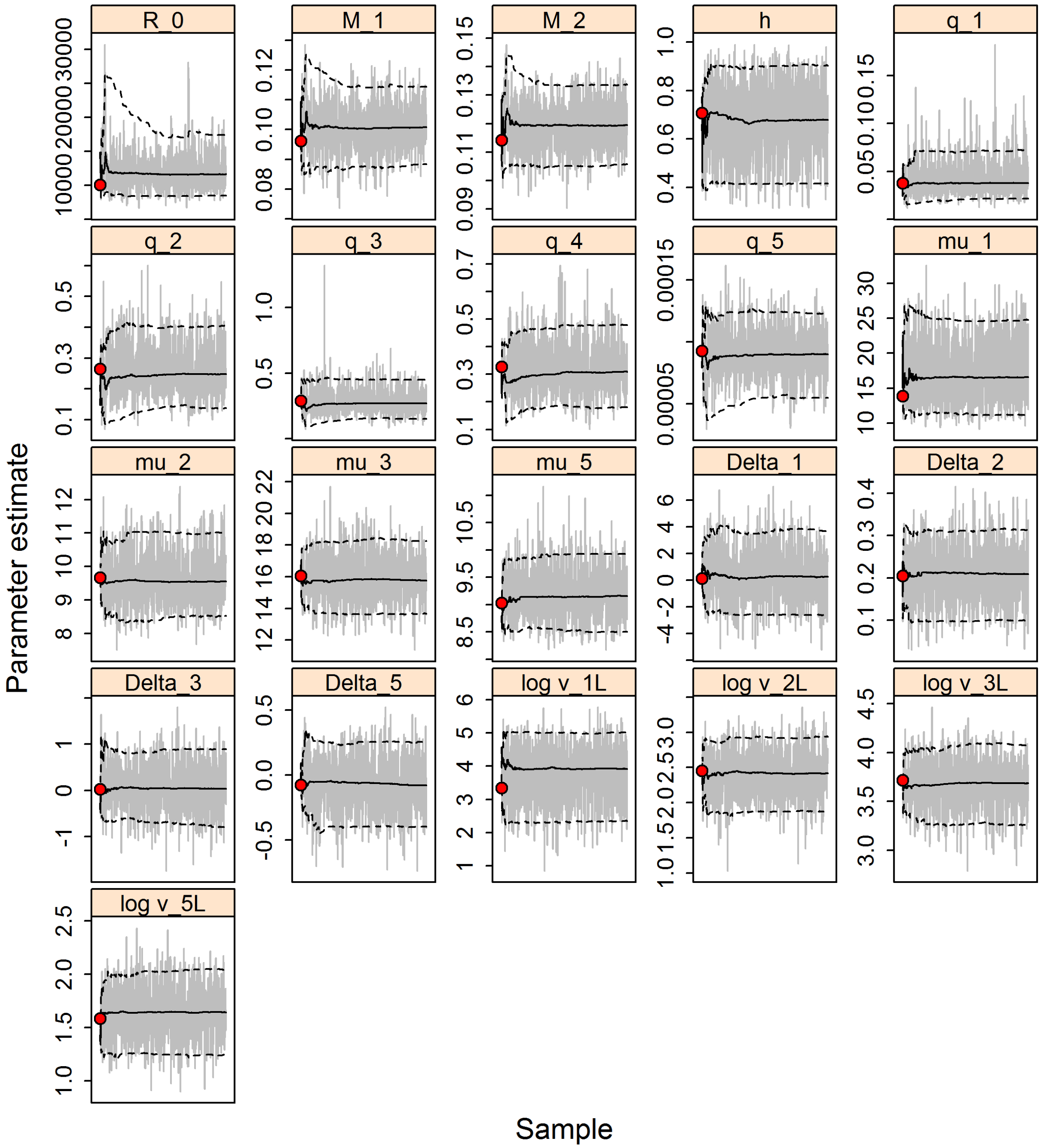


Figure F.112. BC South: Sensitivity 3: MCMC traces for the estimated parameters. Grey lines show the 1,000 samples for each parameter, solid lines show the cumulative median (up to that sample), and dashed lines show the cumulative 2.5 and 97.5 quantiles. Red circles are the MPD estimates. For parameters other than M (if estimated), subscripts ≤ 4 correspond to fishery-independent surveys, and subscripts ≥ 5 denote the commercial fishery. Parameter notation is described in Appendix E.

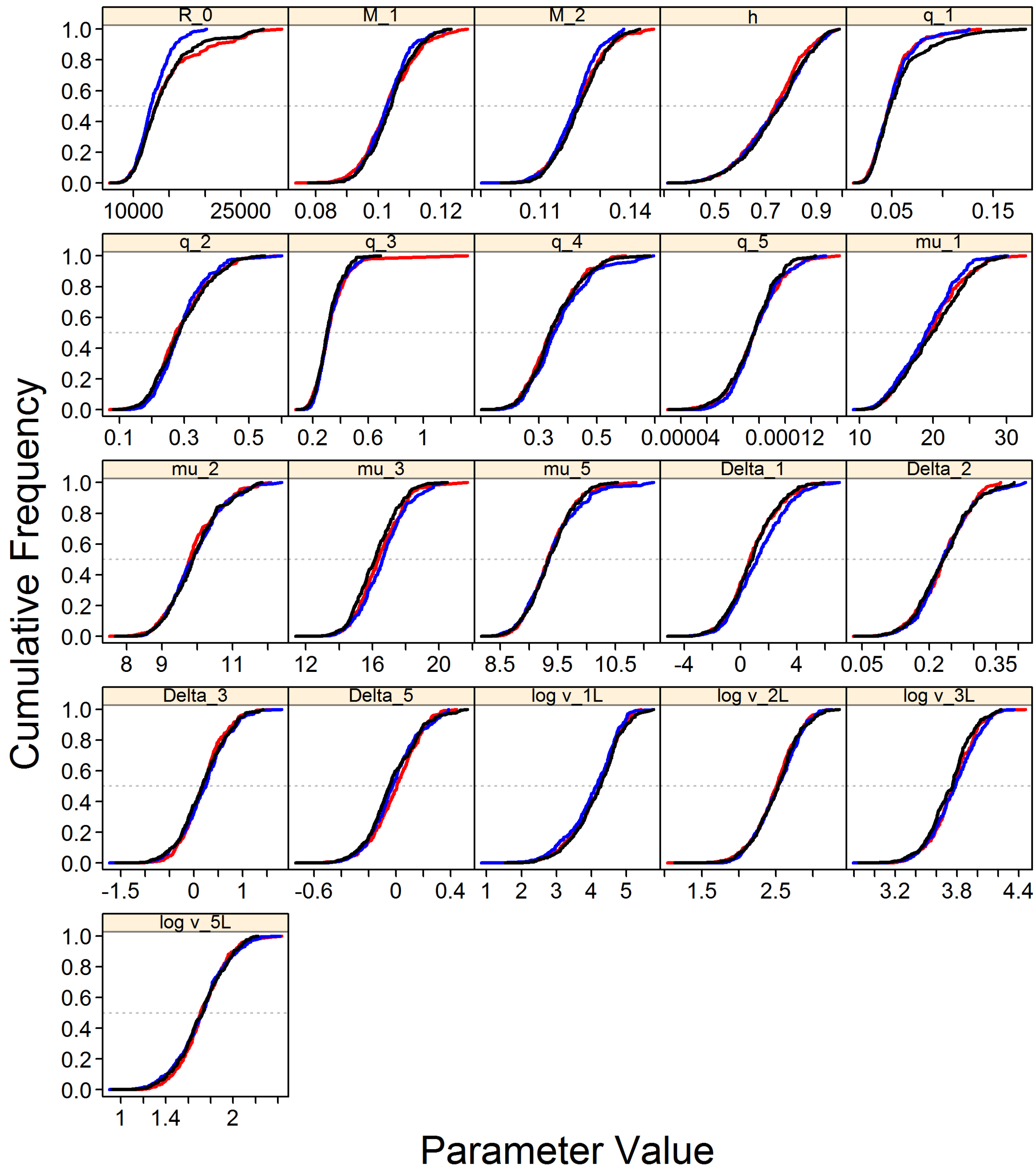


Figure F.113. BC South: Sensitivity 3: Diagnostic plot obtained by dividing the MCMC chain of 1,000 MCMC samples into three segments, and overplotting the cumulative distributions of the first segment (red), second segment (blue) and final segment (black).

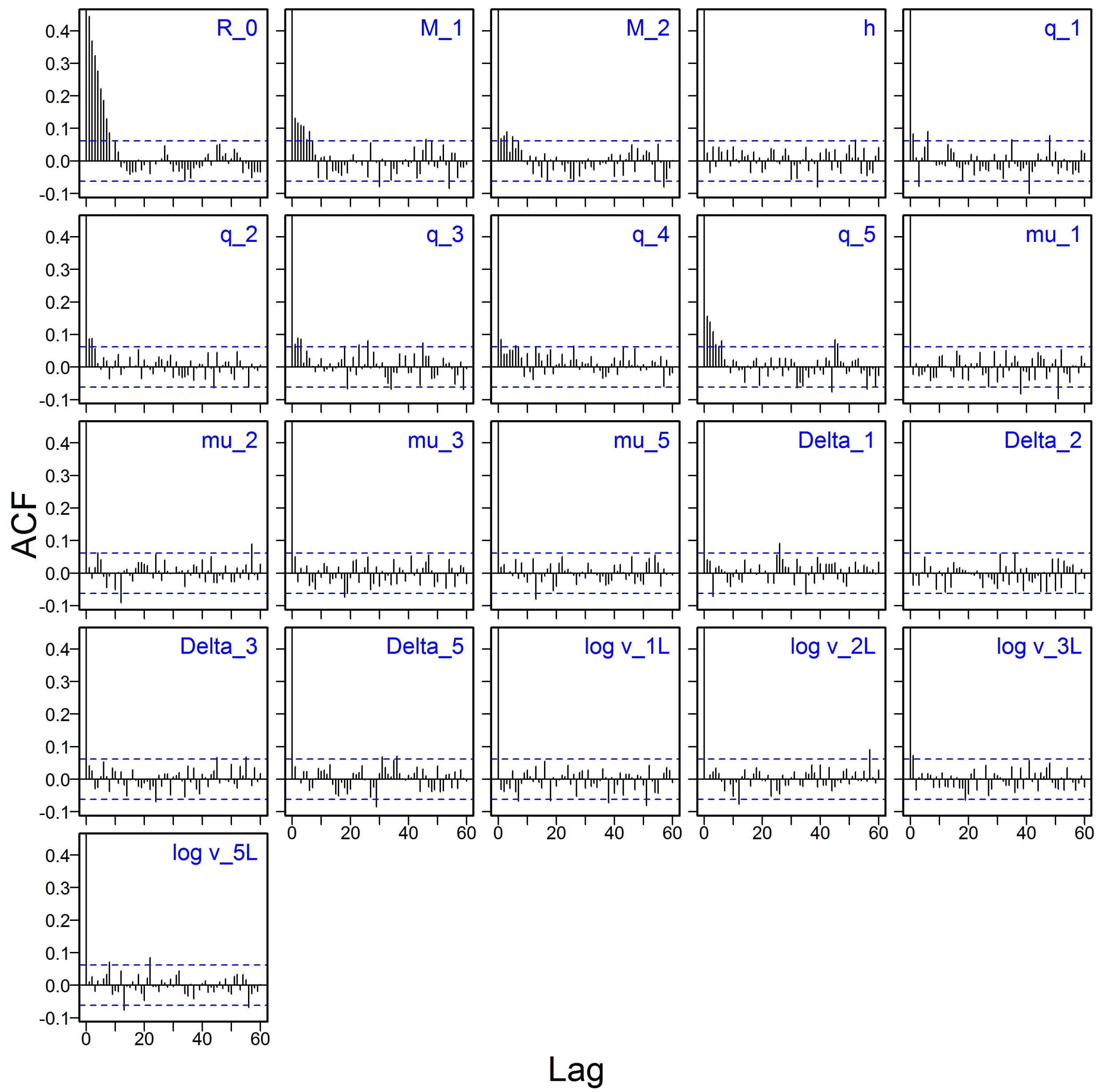


Figure F.114. BC South: Sensitivity 3: Autocorrelation plots for the estimated parameters from the MCMC output. Horizontal dashed blue lines delimit the 95% confidence interval for each parameter's set of lagged correlations.

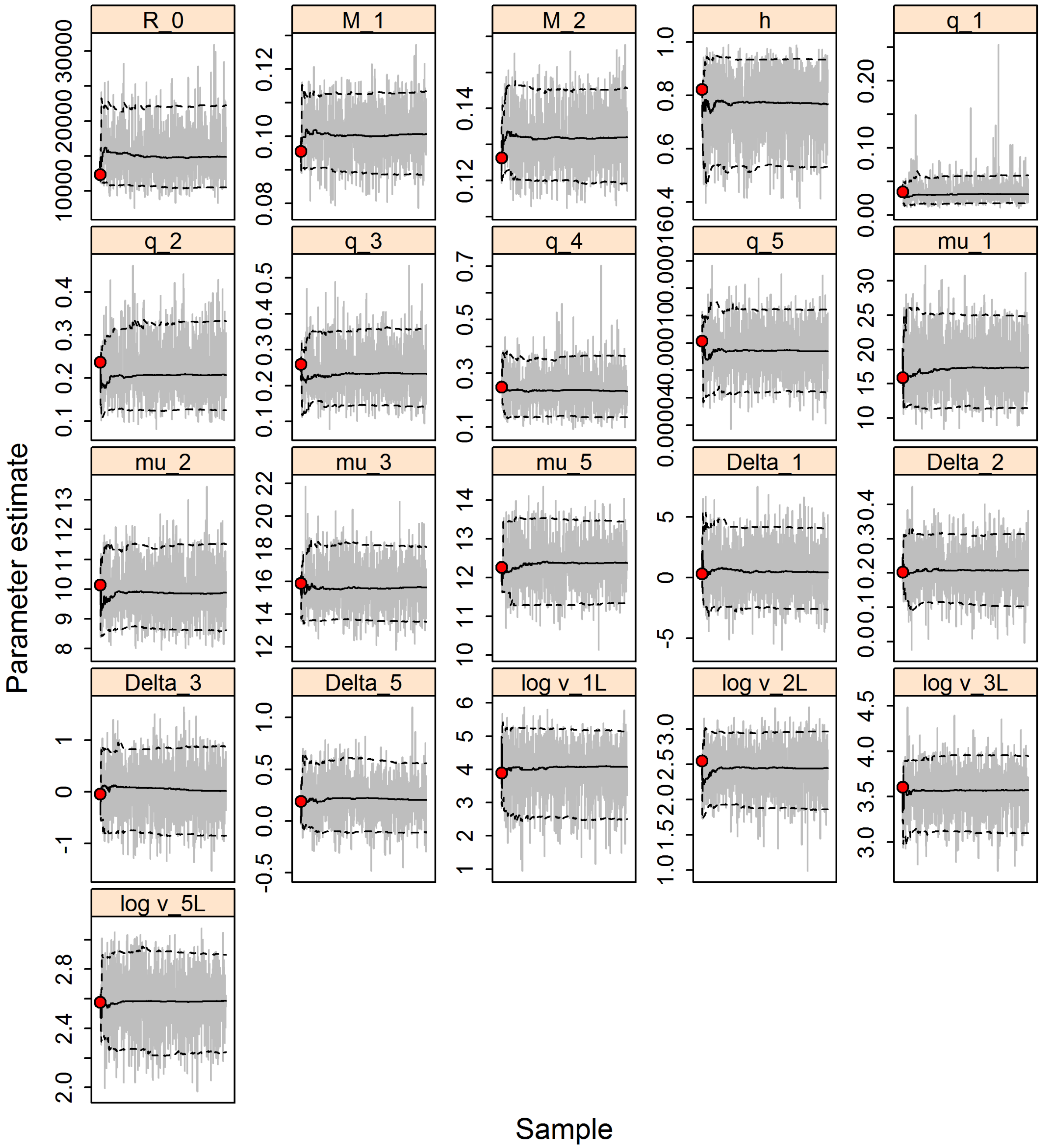


Figure F.115. BC South: Sensitivity 4: MCMC traces for the estimated parameters. Grey lines show the 1,000 samples for each parameter, solid lines show the cumulative median (up to that sample), and dashed lines show the cumulative 2.5 and 97.5 quantiles. Red circles are the MPD estimates. For parameters other than M (if estimated), subscripts ≤ 4 correspond to fishery-independent surveys, and subscripts ≥ 5 denote the commercial fishery. Parameter notation is described in Appendix E.

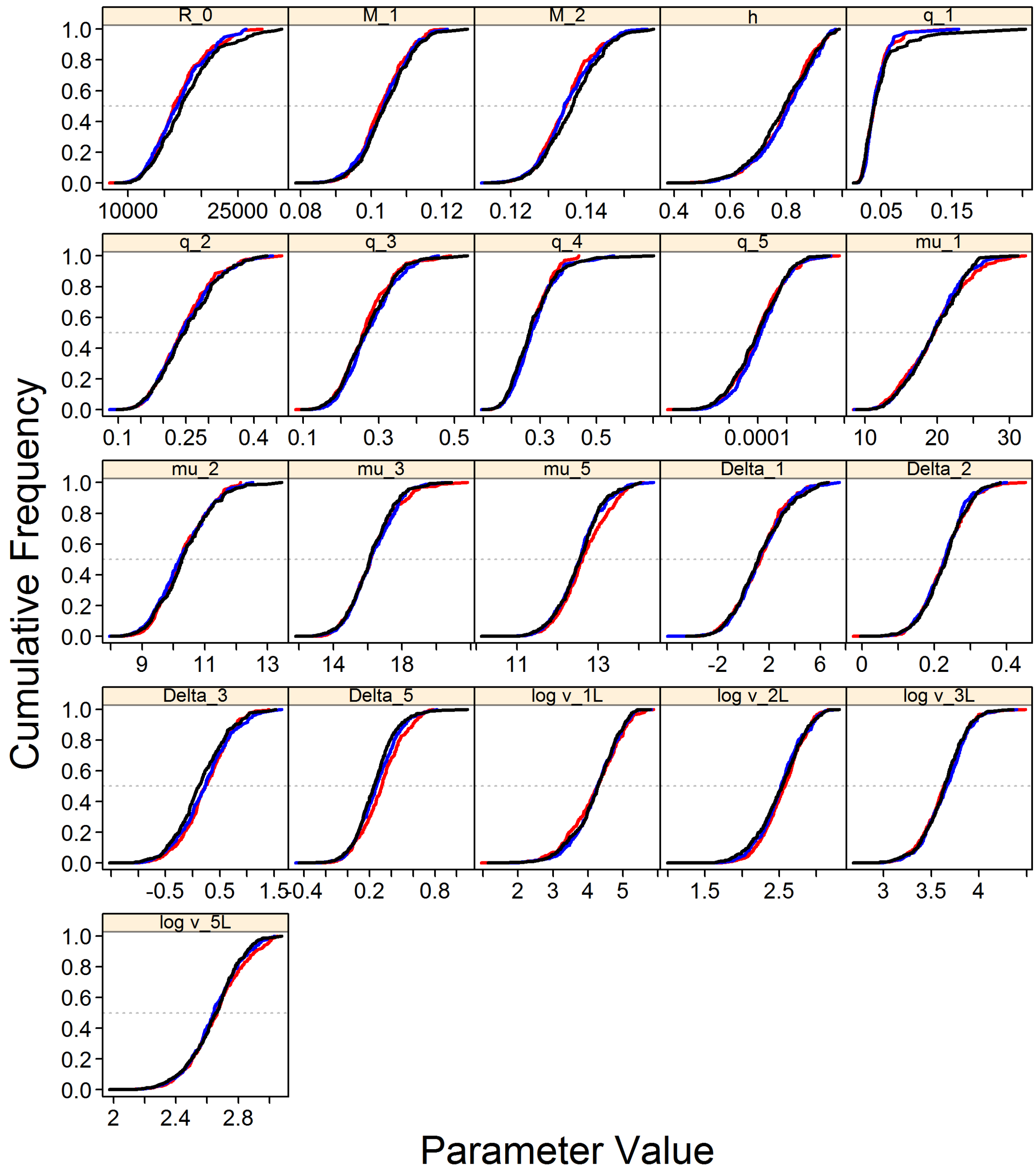


Figure F.116. BC South: Sensitivity 4: Diagnostic plot obtained by dividing the MCMC chain of 1,000 MCMC samples into three segments, and overplotting the cumulative distributions of the first segment (red), second segment (blue) and final segment (black).

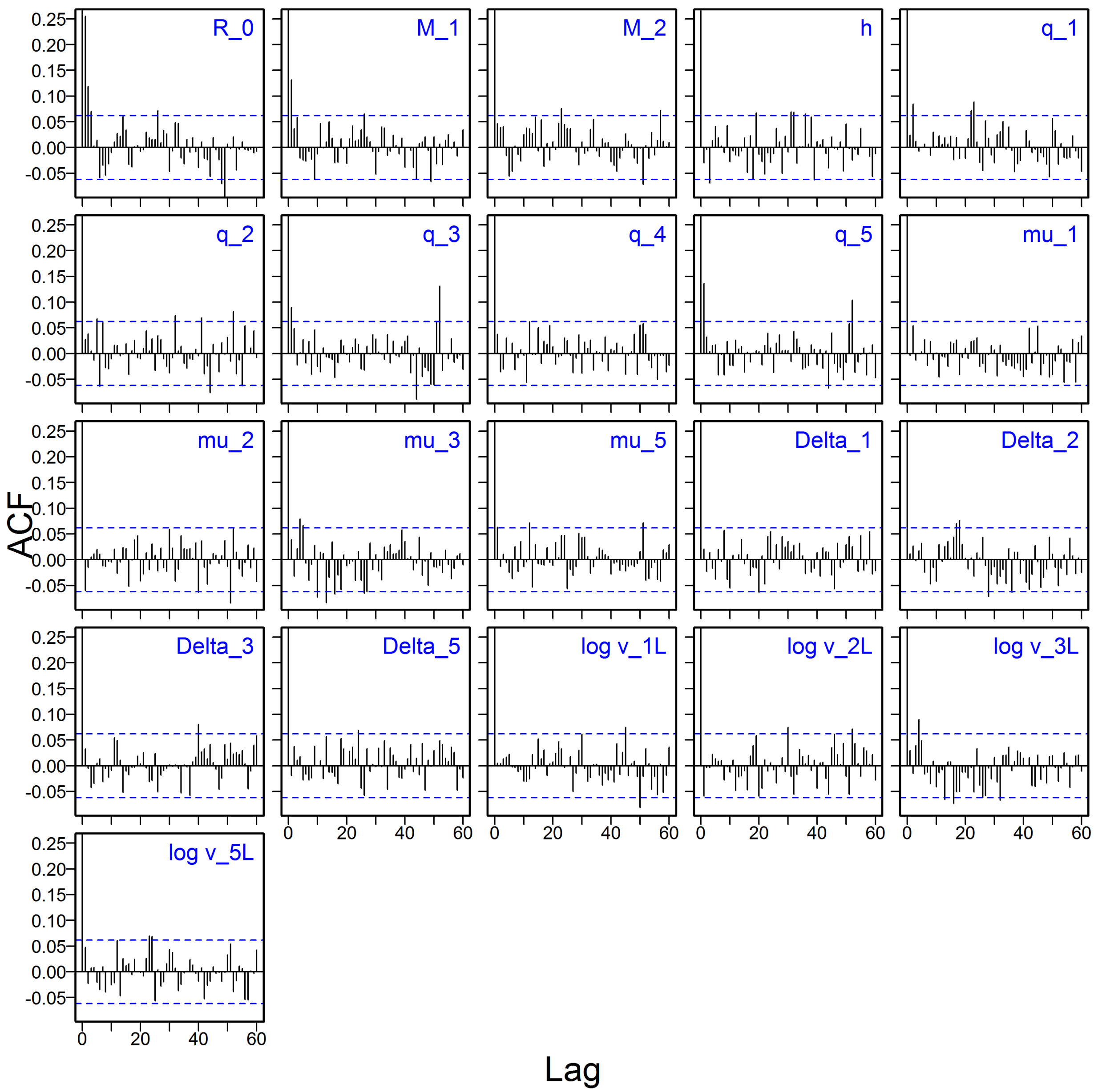


Figure F.117. BC South: Sensitivity 4: Autocorrelation plots for the estimated parameters from the MCMC output. Horizontal dashed blue lines delimit the 95% confidence interval for each parameter's set of lagged correlations.

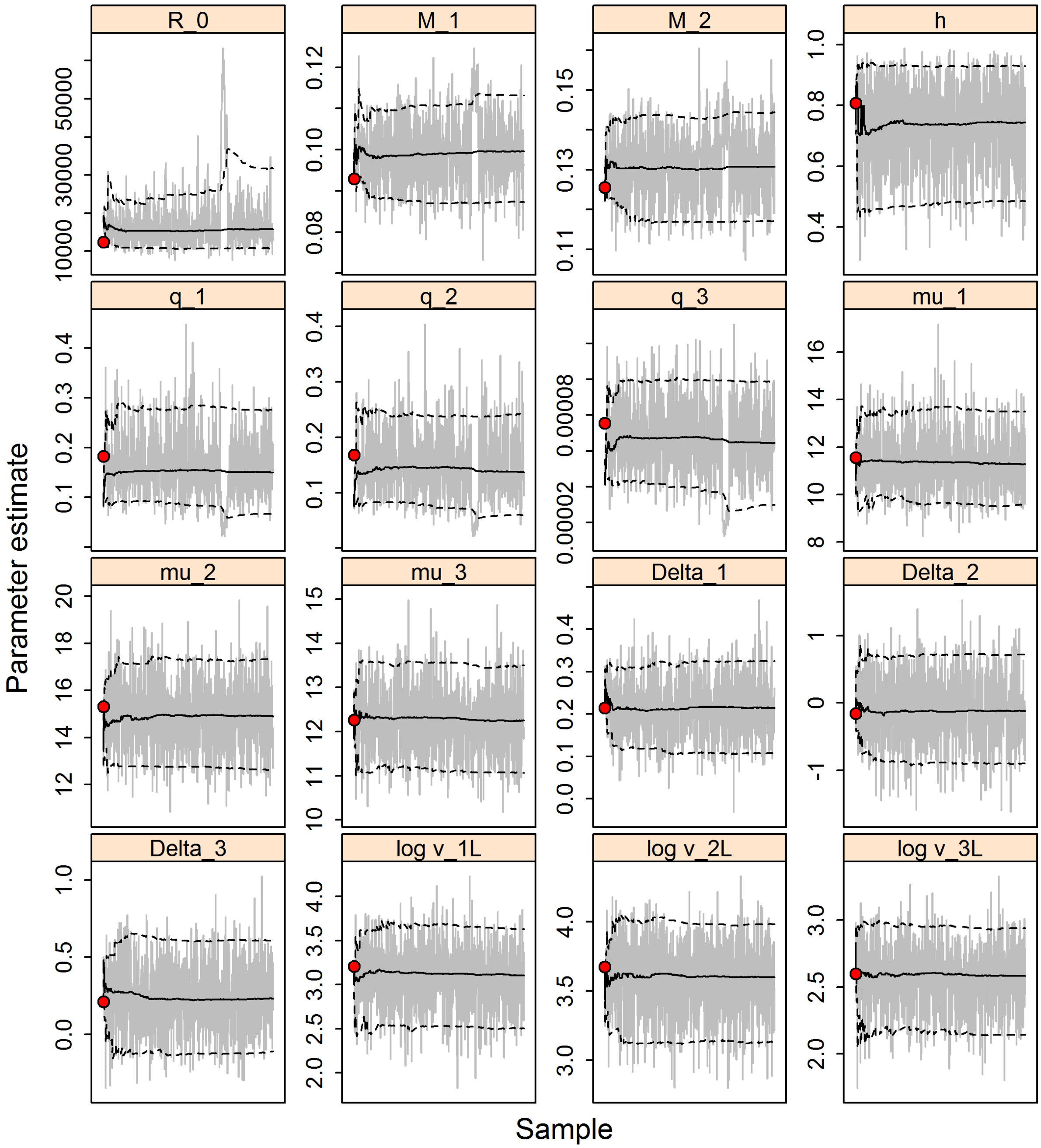


Figure F.118. BC South: Sensitivity 5: MCMC traces for the estimated parameters. Grey lines show the 1,000 samples for each parameter, solid lines show the cumulative median (up to that sample), and dashed lines show the cumulative 2.5 and 97.5 quantiles. Red circles are the MPD estimates. For parameters other than M (if estimated), subscripts ≤ 2 correspond to fishery-independent surveys, and subscripts ≥ 3 denote the commercial fishery. Parameter notation is described in Appendix E.

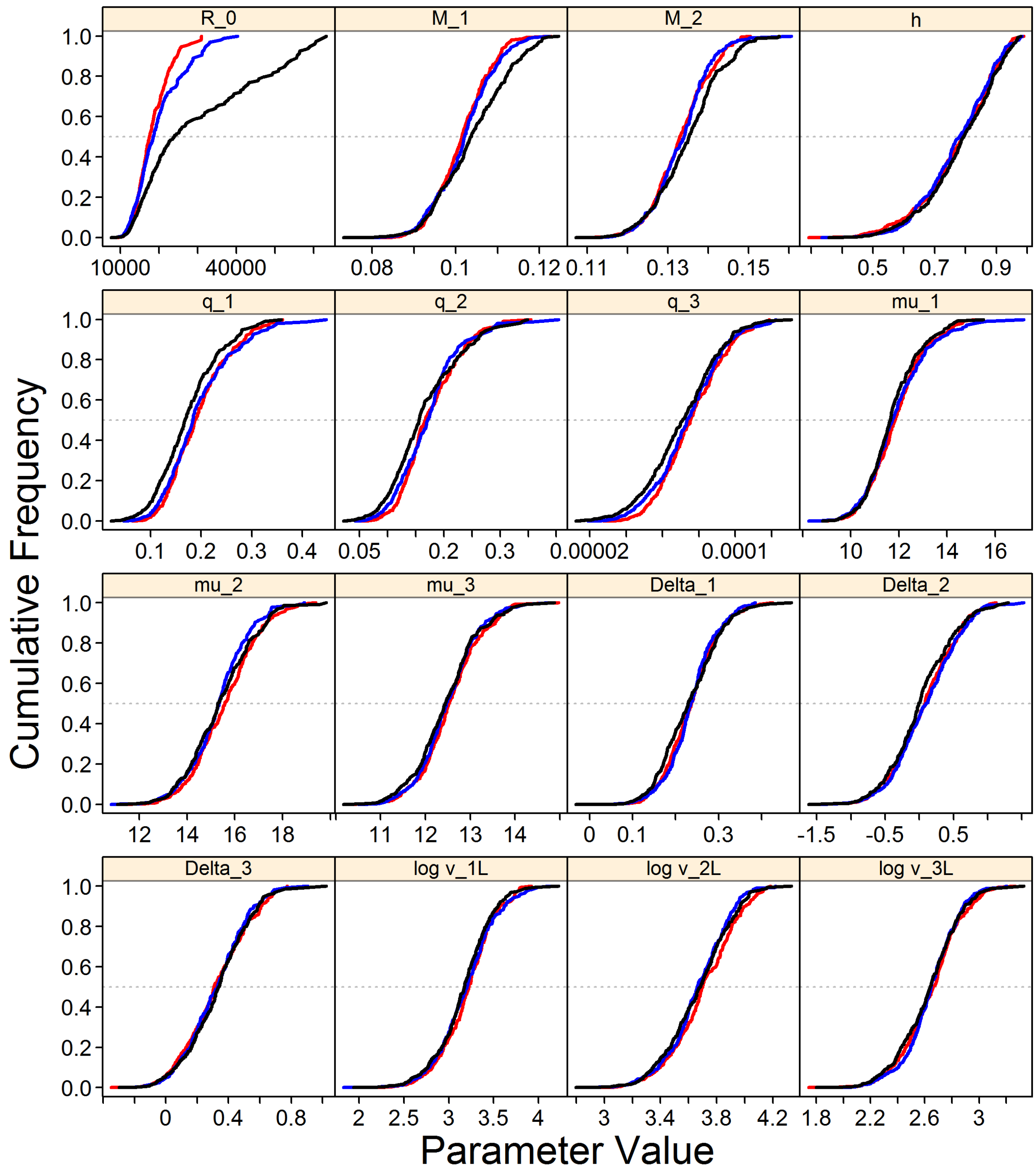


Figure F.119. BC South: Sensitivity 5: Diagnostic plot obtained by dividing the MCMC chain of 1,000 MCMC samples into three segments, and overplotting the cumulative distributions of the first segment (red), second segment (blue) and final segment (black).

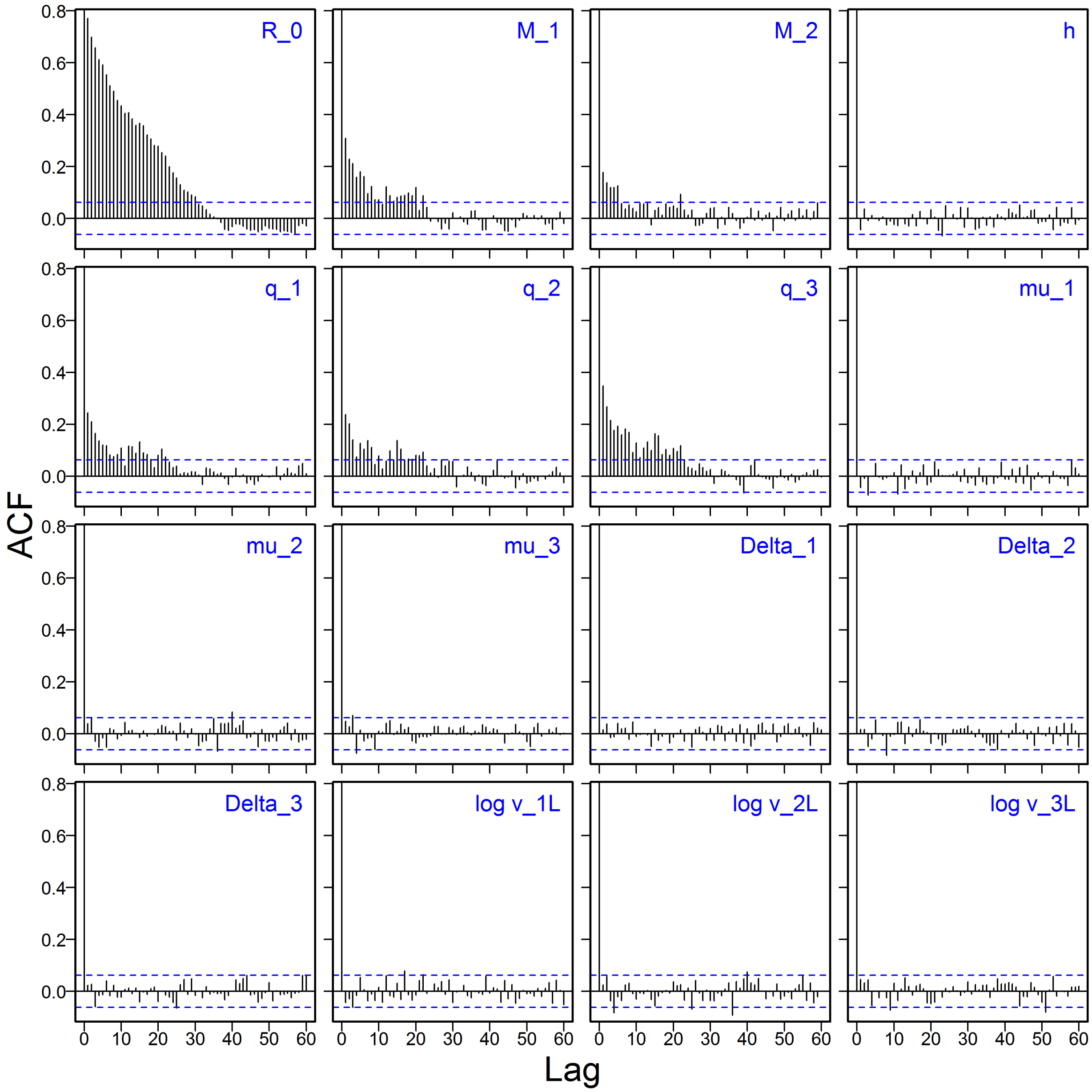


Figure F.120. BC South: Sensitivity 5: Autocorrelation plots for the estimated parameters from the MCMC output. Horizontal dashed blue lines delimit the 95% confidence interval for each parameter's set of lagged correlations.

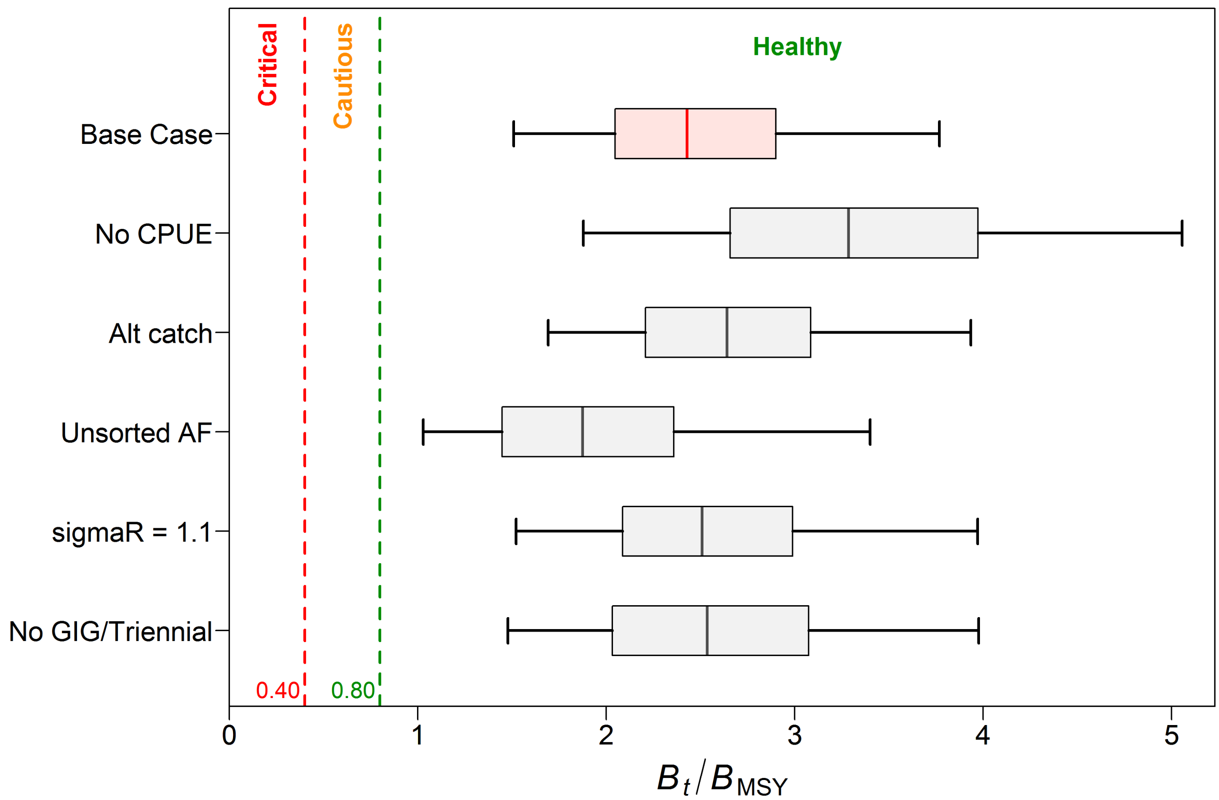


Figure F.121. BC South: Status at beginning of 2018 of the Redstripe Rockfish (3CD5ABC) stock relative to the DFO PA provisional reference points of 0.4B_{MSY} and 0.8B_{MSY} for the base-case (Run16) stock assessment and 5 sensitivity runs: S1 = (Run19) remove the commercial CPUE index; S2 = (Run20) reduce the catch during periods of foreign fleet activity and during domestic fleet activity before observer coverage; S3 = (Run21) use only age frequencies from unsorted samples; S4 = (Run22) use a larger standard deviation for recruitment process error (σ_R=1.1); S5 = (Run23) remove the GIG Historical and WCVI Triennial surveys. Boxplots show the 0.05, 0.25, 0.5, 0.75 and 0.95 quantiles from the MCMC posterior.

F.4. REFERENCES – MODEL RESULTS

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Taylor, N., Stanley, R., Starr, P., Rutherford, K. and Haigh, R. 2011. A simultaneous stock assessment of five rockfishes in British Columbia waters: Splitnose Rockfish, Greenstriped Rockfish, Redstripe Rockfish, Harlequin Rockfish, Sharpchin Rockfish. Unpubl. manuscr.

APPENDIX G. ECOSYSTEM INFORMATION

This appendix describes ecosystem information relevant to Redstripe Rockfish (RSR) along the British Columbia (BC) coast and to the two stocks identified in Appendix D: BC North (5DE) and BC South (3CD5ABC). 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 Redstripe Rockfish were refreshed on Jan 23, 2018. 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.

Redstripe Rockfish is ubiquitous along the BC coast, with an Extent of Occurrence (EO) of 169,875 km^2 (on water) if the Bowie Seamount is included in a convex hull envelope (Figure G.1). Of the bottom trawl tows capturing RSR, 99% of the tows occur between 91 m and 380 m (Figure G.2). Using this depth range as a proxy for suitable RSR benthic habitat, another estimate of the EO is 58,720 km^2 in BC's Exclusive Economic Zone (Figure G.3). To estimate the Area of Occupancy (AO), the catch of RSR was located within a grid comprising 4 km^2 cells (2km × 2km), and the cells occupied by RSR were summed to estimate an AO of 14,864 km^2 along the BC coast spanning 1996 to 2017 (Figure G.4). Figure G.5 provides another visualisation of relative catch by fishing localities along the BC coast.

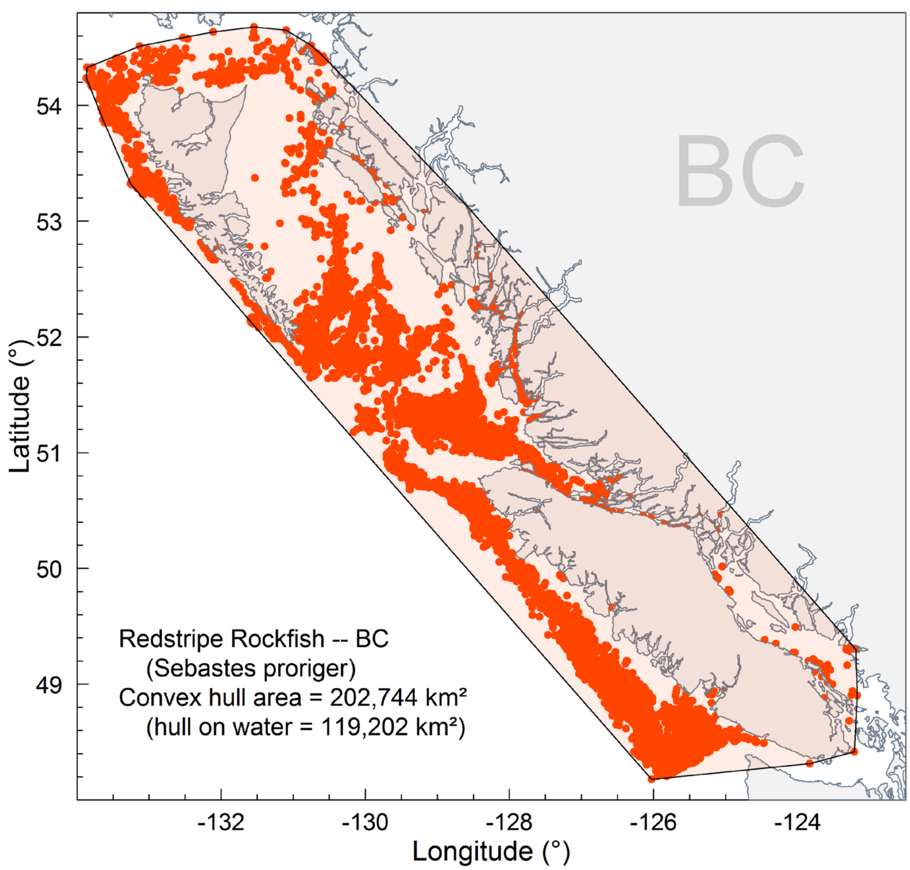

Figure G.1. Extent of Occurrence as a convex hull surrounding fishing events that caught Redstripe Rockfish along the BC coast; the shading within the hull on water covers 119,202 km^2.

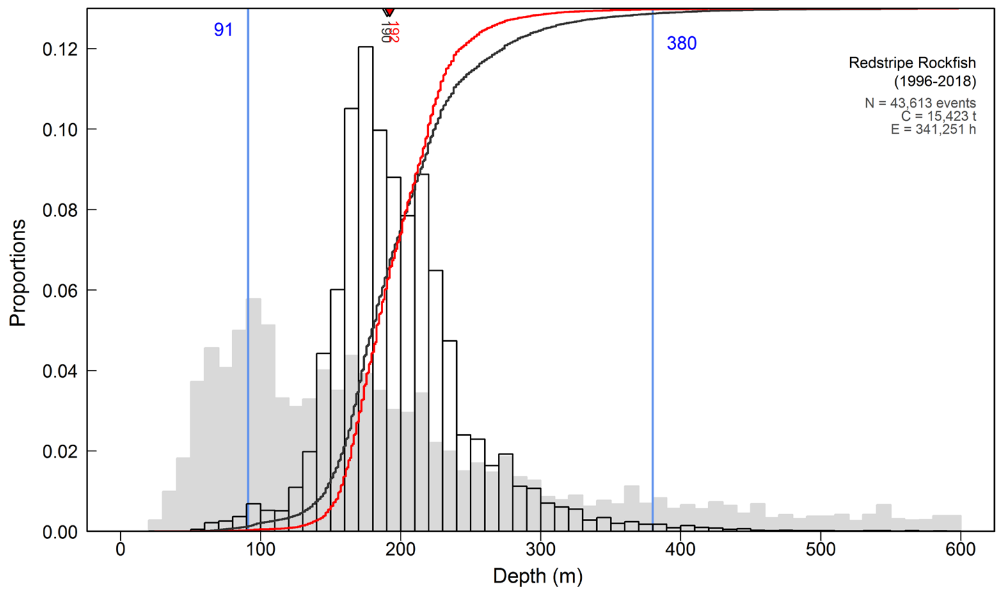

Figure G.2. BC Offshore – Depth frequency of bottom trawl tows (transparent histogram) that captured RSR from commercial logs (1996-2018 in PacHarvest and `GFFOS`*) in areas outside the Strait of Georgia. The vertical solid lines denote the 1% and 99% percentiles. The black curve shows the cumulative frequency of tows that encounter RSR while the red curve shows the cumulative catch of RSR at depth (scaled from 0 to 1). The median depths of RSR 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 for 0-800 m: N= total number of RSR tows; C= total catch (t) of RSR, E= total effort (h) of all tows.*

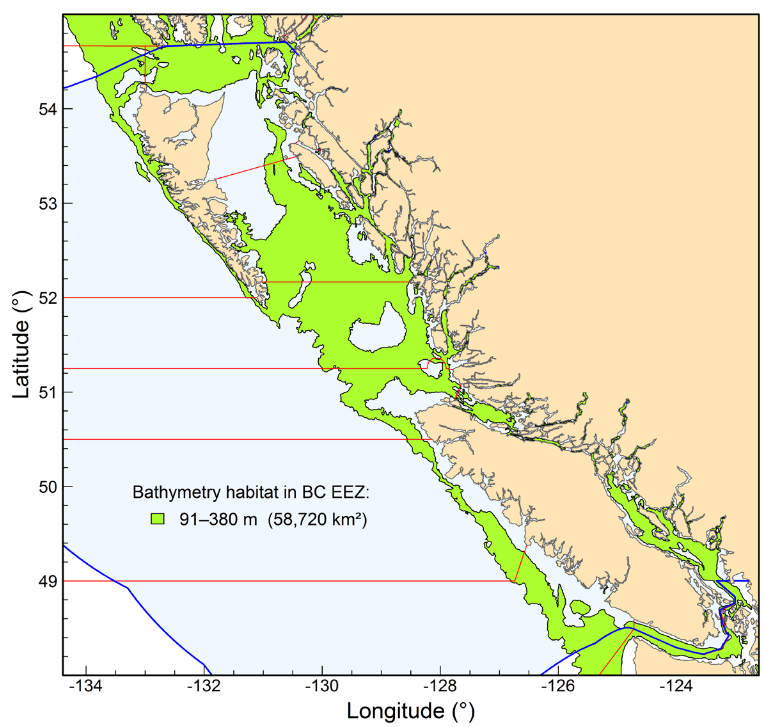

Figure G.3. Highlighted bathymetry (green) between 91 and 380 m serves as a proxy for benthic habitat for RSR along the BC coast. Within Canada's exclusive economic zone (EEZ, blue highlighted area), the green highlighted region covers 58,720 km^2*. The boundaries in red delimit PMFC areas.*

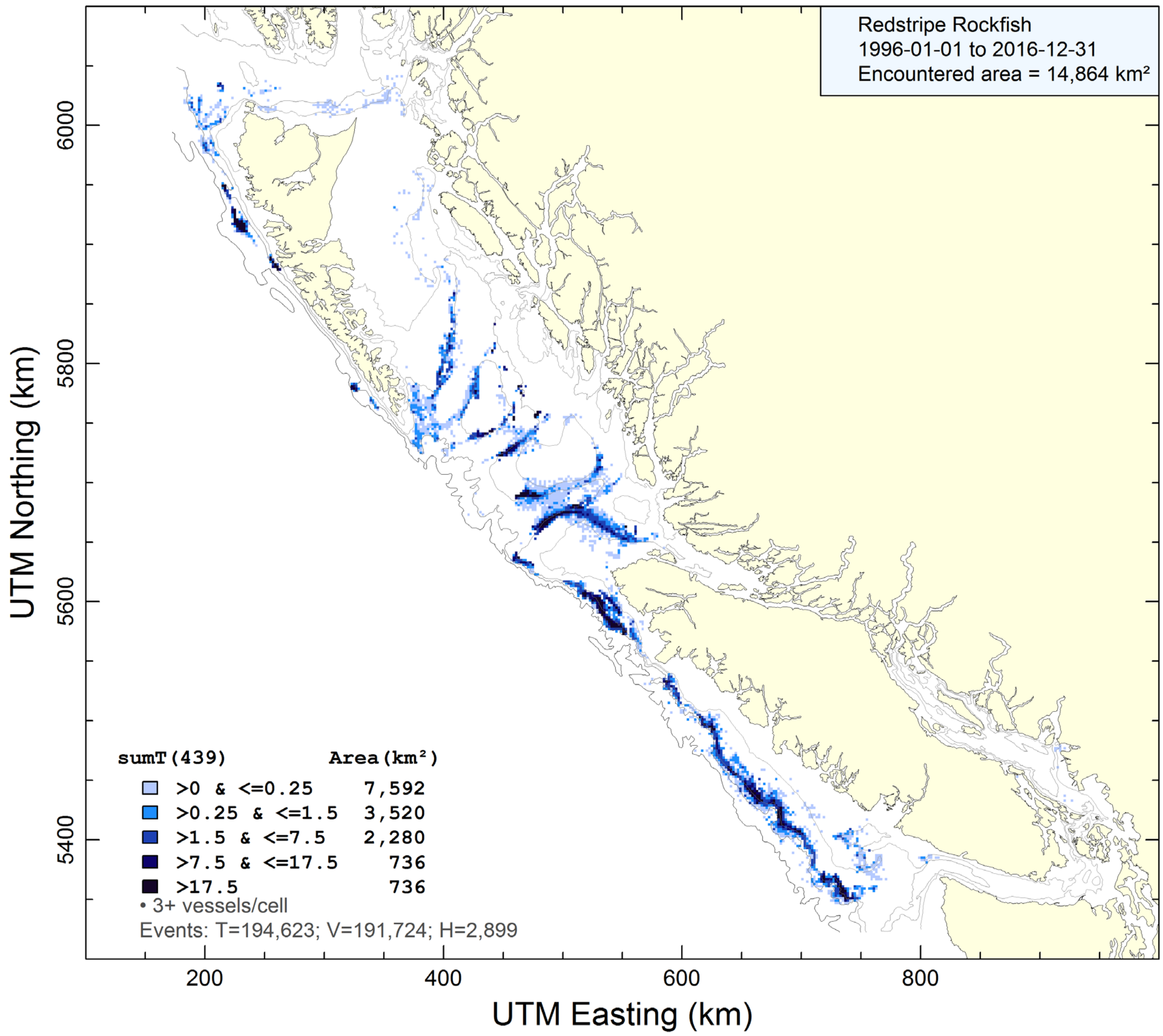

Figure G.4. Area of Occupancy (AO) determined by trawl capture of RSR in grid cells 2km × 2km. Cells with fewer than three fishing vessels are excluded. The estimated AO is 14,864 km² along the BC coast.

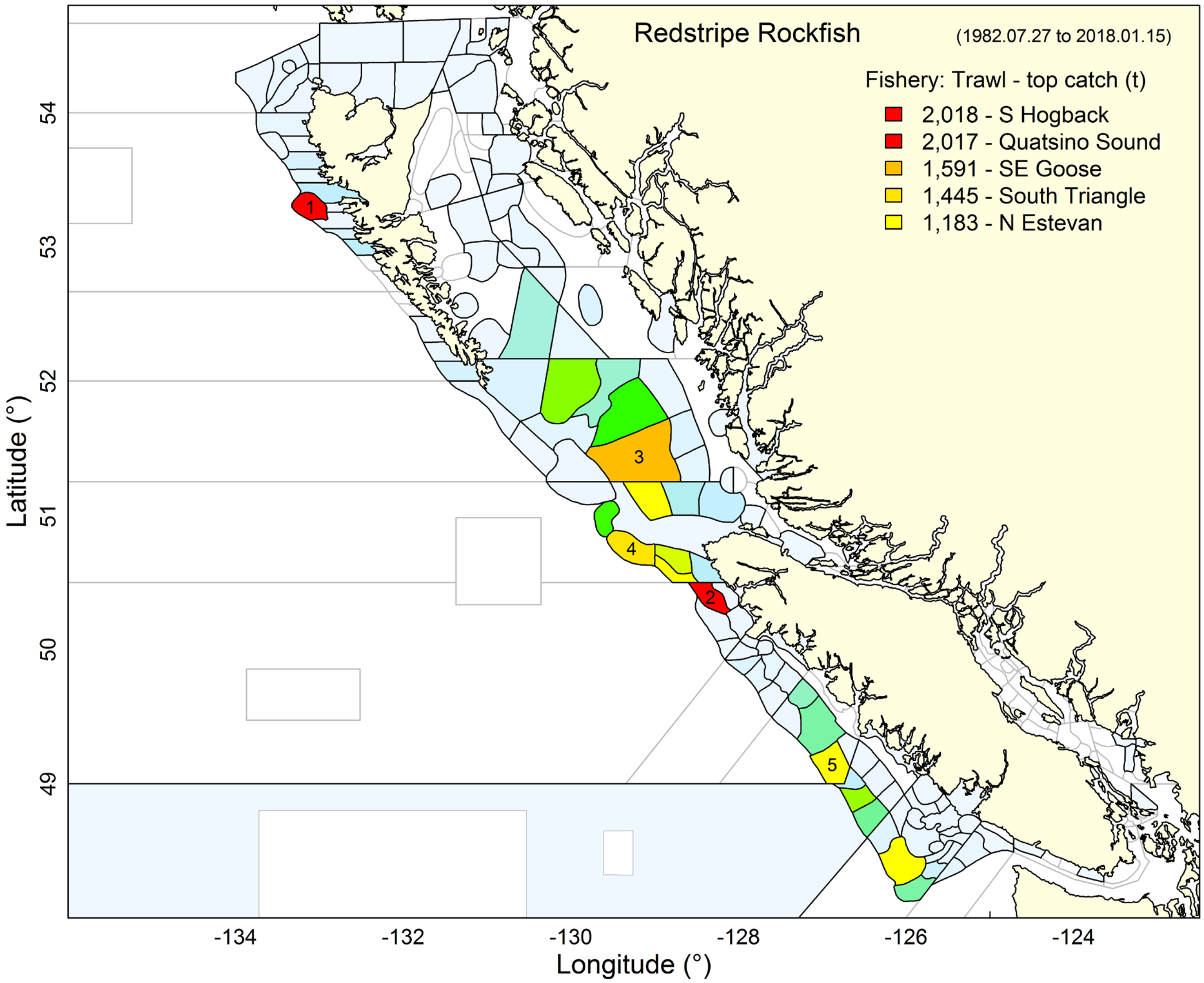

Figure G.5. Top five fishing localities where RSR was caught by the trawl fleet along the BC coast. All shaded localities indicate areas where RSR was encountered from 1982 to 2018, ranging from relatively low numbers in cool blue, through the spectrum, to relatively high catches in red.

G.2. CONCURRENT SPECIES

Species caught concurrently in coastwide bottom trawl tows that captured at least one RSR specimen, herein referred to as "redstripe tows", are dominated by seven species other than Redstripe Rockfish (only 3% of total catch, Figure G.6) – Arrowtooth Flounder *Atheresthes stomias* (21%), Pacific Ocean Perch *Sebastes alutus* (19%), Yellowtail Rockfish *S. flavidus* (9%), Dover Sole *Microstomus pacificus* (5%), Yellowmouth Rockfish *S. reedi* (5%), Silvergray Rockfish *S. brevispinis* (5%), and Lingcod *Ophiodon elongatus* (4%). Table G.1 provides more detail on the concurrent species.

Regional variations in depth distributions of redstripe tows occur along the BC coast, and species caught concurrently also vary. Here, we only examine the two stocks: BC North (PMFC areas 5DE) and BC South (PMFC areas 5ABC+3CD). The depth profiles for these stocks are not presented but the analyses yield 1% and 99% quantile limits of 113-427 m in the North and 82-444 m in the South. At these depths, concurrent species in the two stocks show some variation (Figure G.7 vs. Figure G.8); however, RSR never accounts for more than 3.5% of the catch weight in redstripe tows (Table G.2, Table G.3). Rougheye Rockfish is more prevalent in

BC North redstripe tows (8% vs. 1% in the South), while Canary Rockfish and Lingcod are more prevalent in BC South redstripe tows than in the North.

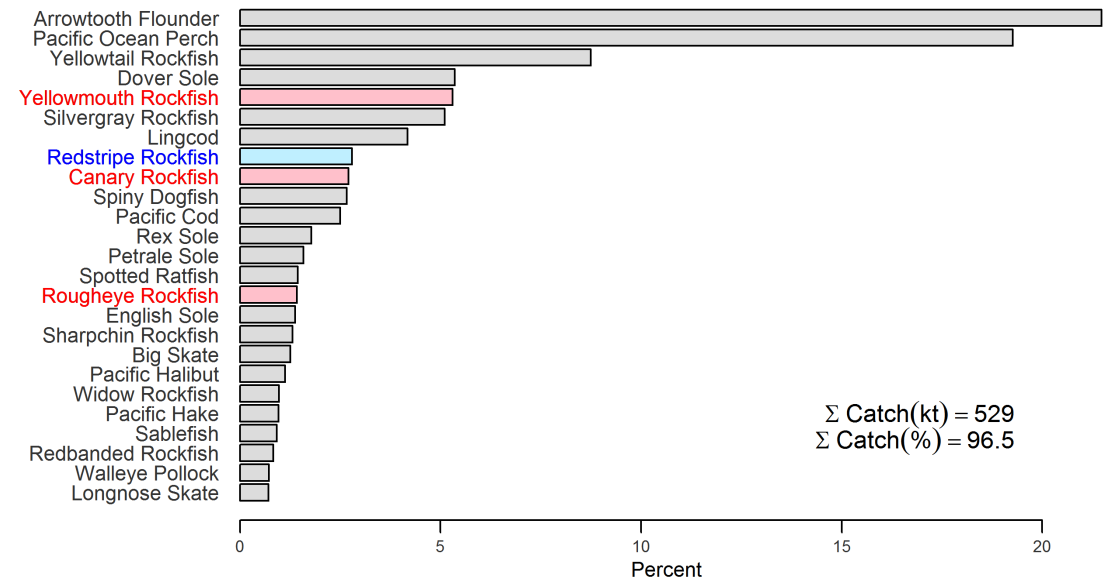

Figure G.6. BC Offshore – Distribution of RSR catch weights summed over the period February 1996 to January 2018 for important finfish species in bottom trawl tows that caught at least one Redstripe Rockfish coastwide. Tows were selected over a depth range between 91 and 380 m (the 1% and 99% quantile 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. Redstripe Rockfish is indicated in blue on the y-axis; other species of interest to COSEWIC are indicated in red.

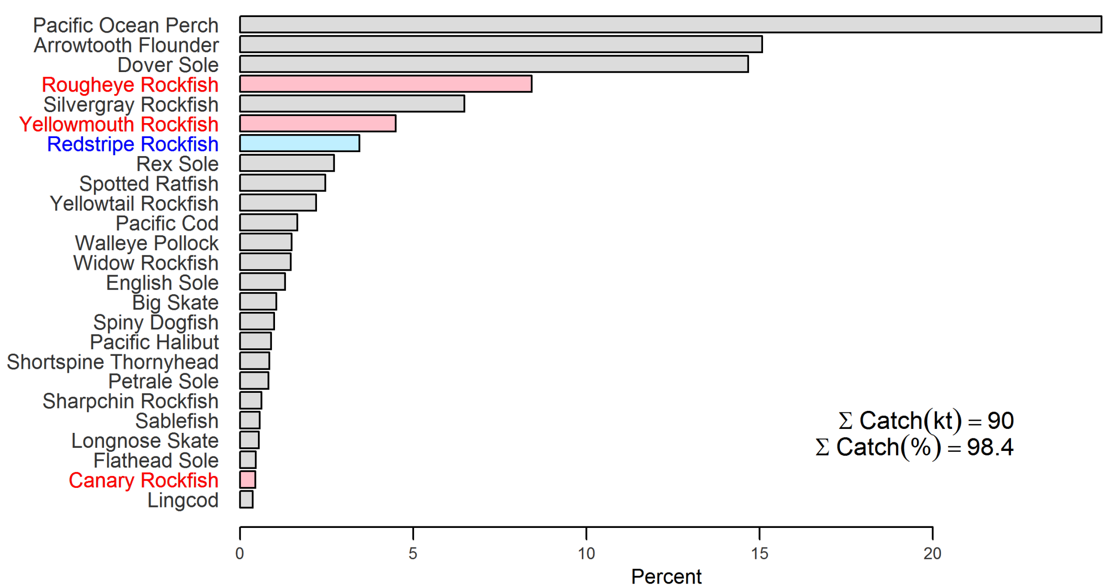

Figure G.7. BC North – Distribution of RSR catch weights for important finfish species in bottom trawl tows that caught at least one RSR in 5DE. Tows were selected over a depth range between 113 and 427 m (1% and 99% quantile range). See caption in Figure G.6 for further details.

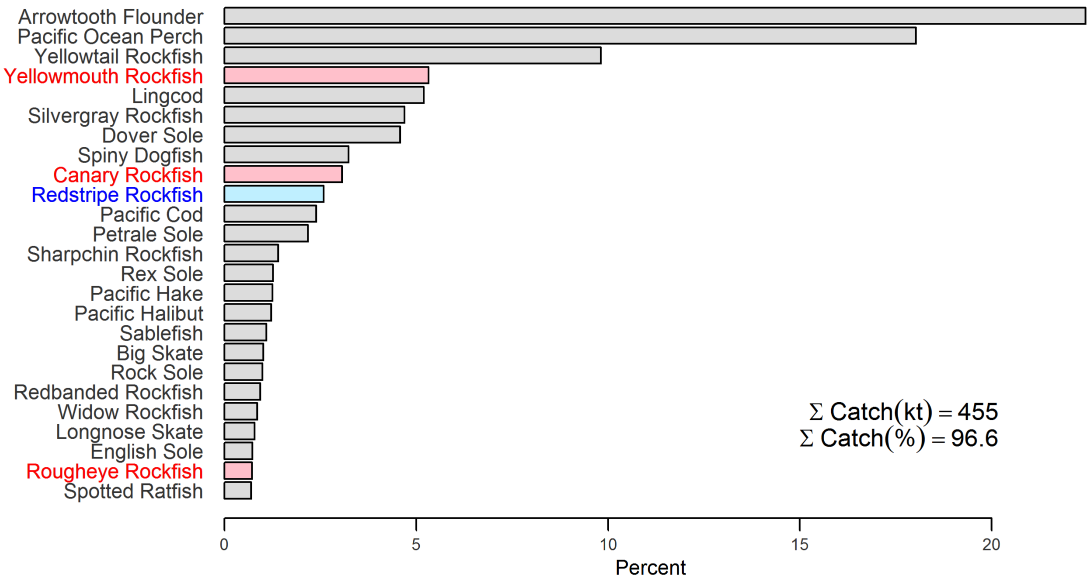

Figure G.8. BC South – Distribution of RSR catch weights for important finfish species in bottom trawl tows that caught at least one RSR in 5ABC+3CD. Tows were selected over a depth range between 82 and 444 m (1% and 99% quantile range). See caption in Figure G.6 for further details.

Table G.1. BC Offshore – Top 25 species by catch weight (sum of landed + discarded from 1996 to 2017) that co-occur in RSR bottom trawl tows along the BC coast. 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*	117,653	21.48
396	Pacific Ocean Perch	*Sebastes alutus*	105,515	19.26
418	Yellowtail Rockfish	*Sebastes flavidus*	47,906	8.75
626	Dover Sole	*Microstomus pacificus*	29,311	5.35
440	Yellowmouth Rockfish	*Sebastes reedi*	29,058	5.31
405	Silvergray Rockfish	*Sebastes brevispinis*	27,952	5.10
467	Lingcod	*Ophiodon elongatus*	22,904	4.18
439	Redstripe Rockfish	*Sebastes proriger*	15,328	2.80
437	Canary Rockfish	*Sebastes pinniger*	14,806	2.70
044	Spiny Dogfish	*Squalus acanthias*	14,589	2.66
222	Pacific Cod	*Gadus macrocephalus*	13,713	2.50
610	Rex Sole	*Errex zachirus*	9,760	1.78
607	Petrale Sole	*Eopsetta jordani*	8,702	1.59
066	Spotted Ratfish	*Hydrolagus colliei*	7,922	1.45
394	Rougheye Rockfish	*Sebastes aleutianus*	7,773	1.42
628	English Sole	*Parophrys vetulus*	7,568	1.38
450	Sharpchin Rockfish	*Sebastes zacentrus*	7,179	1.31
056	Big Skate	*Raja binoculata*	6,866	1.25
614	Pacific Halibut	*Hippoglossus stenolepis*	6,200	1.13
417	Widow Rockfish	*Sebastes entomelas*	5,351	0.98
225	Pacific Hake	*Merluccius productus*	5,253	0.96
455	Sablefish	*Anoplopoma fimbria*	5,067	0.93
401	Redbanded Rockfish	*Sebastes babcocki*	4,574	0.84
228	Walleye Pollock	*Theragra chalcogramma*	3,980	0.73
059	Longnose Skate	*Raja rhina*	3,901	0.71

Table G.2. BC North: Top 25 species by catch weight (sum of landed + discarded from 1996 to 2017) that co-occur in RSR bottom trawl tows in PMFC areas 5DE. 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 (%)
396	Pacific Ocean Perch	*Sebastes alutus*	22,625	24.87
602	Arrowtooth Flounder	*Atheresthes stomias*	13,711	15.07
626	Dover Sole	*Microstomus pacificus*	13,344	14.67
394	Rougheye Rockfish	*Sebastes aleutianus*	7,668	8.43
405	Silvergray Rockfish	*Sebastes brevispinis*	5,892	6.48
440	Yellowmouth Rockfish	*Sebastes reedi*	4,089	4.49
439	Redstripe Rockfish	*Sebastes proriger*	3,144	3.46
610	Rex Sole	*Errex zachirus*	2,472	2.72
066	Spotted Ratfish	*Hydrolagus colliei*	2,239	2.46
418	Yellowtail Rockfish	*Sebastes flavidus*	2,003	2.20
222	Pacific Cod	*Gadus macrocephalus*	1,511	1.66
228	Walleye Pollock	*Theragra chalcogramma*	1,356	1.49
417	Widow Rockfish	*Sebastes entomelas*	1,335	1.47
628	English Sole	*Parophrys vetulus*	1,187	1.30
056	Big Skate	*Raja binoculata*	961	1.06
044	Spiny Dogfish	*Squalus acanthias*	900	0.99
614	Pacific Halibut	*Hippoglossus stenolepis*	820	0.90
451	Shortspine Thornyhead	*Sebastolobus alascanus*	771	0.85
607	Petrale Sole	*Eopsetta jordani*	753	0.83
450	Sharpchin Rockfish	*Sebastes zacentrus*	569	0.63
455	Sablefish	*Anoplopoma fimbria*	516	0.57
059	Longnose Skate	*Raja rhina*	498	0.55
612	Flathead Sole	*Hippoglossoides elassodon*	417	0.46
437	Canary Rockfish	*Sebastes pinniger*	403	0.44
467	Lingcod	*Ophiodon elongatus*	343	0.38

Table G.3. BC South – Top 25 species by catch weight (sum of landed + discarded from 1996 to 2017) that co-occur in RSR bottom trawl tows in PMFC areas 5ABC+3CD. 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*	105,738	22.44
396	Pacific Ocean Perch	*Sebastes alutus*	84,899	18.02
418	Yellowtail Rockfish	*Sebastes flavidus*	46,202	9.81
440	Yellowmouth Rockfish	*Sebastes reedi*	25,093	5.33
467	Lingcod	*Ophiodon elongatus*	24,499	5.20
405	Silvergray Rockfish	*Sebastes brevispinis*	22,119	4.70
626	Dover Sole	*Microstomus pacificus*	21,614	4.59
044	Spiny Dogfish	*Squalus acanthias*	15,285	3.24
437	Canary Rockfish	*Sebastes pinniger*	14,437	3.06
439	Redstripe Rockfish	*Sebastes proriger*	12,218	2.59
222	Pacific Cod	*Gadus macrocephalus*	11,296	2.40
607	Petrale Sole	*Eopsetta jordani*	10,277	2.18
450	Sharpchin Rockfish	*Sebastes zacentrus*	6,644	1.41
610	Rex Sole	*Errex zachirus*	5,963	1.27
225	Pacific Hake	*Merluccius productus*	5,932	1.26
614	Pacific Halibut	*Hippoglossus stenolepis*	5,761	1.22
455	Sablefish	*Anoplopoma fimbria*	5,195	1.10
056	Big Skate	*Raja binoculata*	4,817	1.02
621	Rock Sole	*Lepidopsetta bilineatus*	4,692	1.00
401	Redbanded Rockfish	*Sebastes babcocki*	4,401	0.93
417	Widow Rockfish	*Sebastes entomelas*	4,042	0.86
059	Longnose Skate	*Raja rhina*	3,731	0.79
628	English Sole	*Parophrys vetulus*	3,430	0.73
394	Rougheye Rockfish	*Sebastes aleutianus*	3,389	0.72
066	Spotted Ratfish	*Hydrolagus colliei*	3,316	0.70

G.3. TROPHIC INTERACTIONS

The diet of Redstripe Rockfish includes krill, shrimp, and small fish (Love et al. 2002). A cursory look at the RSR specimens collected in Appendix D from `GFBioSQL` yields the frequency of prey items in stomach contents to be euphausiids (157), squids (25), jellyfish (6), amphipods (4), eulachon (3), unidentified fish (2), and fish eggs (2).

Marliave et al. (2009) found that shallow sponge gardens host a high number of species, including early life stages of rockfish, because they offer feeding opportunities (nursery habitat), whereas deeper sponge bioherms act more as a non-obligate hangout (providing three-dimensional relief) for some rockfish species, including *S. proriger*. There is speculation that turbulence creating by advection over bioherms might facilitate prey concentration (e.g., shoaling of euphausiids, Marliave et al. 2009). Redstripe Rockfish reportedly form dense schools over high-relief areas and migrate upwards and disperse at night (Love et al. 2002).

There are few reports of predators on *S. proriger*. Love et al. (2002) mentions “king salmon”, which refers to Chinook Salmon (*Oncorhynchus tshawytscha*); however, RSR is likely also eaten by other fish, targeting larvae and small juveniles, and some marine mammals, targeting late juvenile and adults (Tribuzio et al. 2017).

Kent and Myers (2000) reported an RSR specimen (from the mouth of Goose Island Gully, QCS) with a liver infected by a herpesvirus.

G.4. REFERENCES – ECOSYSTEM

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