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### Stock assessment for Pacific Ocean Perch (*Sebastes alutus*) in Queen Charlotte Sound, British Columbia in 2017

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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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## TABLE OF CONTENTS

ABSTRACT.....	v
1. INTRODUCTION .....	1
1.1. RANGE AND DISTRIBUTION .....	2
1.2. ASSESSMENT BOUNDARIES.....	2
2. CATCH DATA.....	3
3. FISHERIES MANAGEMENT .....	3
4. SURVEY DESCRIPTIONS.....	3
5. BIOLOGICAL INFORMATION.....	4
5.1. BIOLOGICAL SAMPLES .....	4
5.2. GROWTH PARAMETERS.....	4
5.3. MATURITY AND FECUNDITY .....	4
5.4. NATURAL MORTALITY .....	4
5.5. STEEPNESS.....	5
6. AGE-STRUCTURED MODEL .....	5
7. MODEL RESULTS.....	6
7.1. BASE CASE .....	6
7.2. SENSITIVITY ANALYSES.....	8
8. ADVICE FOR MANAGERS.....	8
8.1. REFERENCE POINTS AND CRITERIA .....	8
8.2. BASE CASE .....	8
8.3. SENSITIVITY RUNS .....	9
8.4. PROJECTION RESULTS AND DECISION TABLES .....	11
8.5. ASSESSMENT SCHEDULE.....	11
9. INVESTIGATING IMPACTS OF CLIMATIC AND ENVIRONMENTAL VARIABILITY ON RECRUITMENT .....	11
10. GENERAL COMMENTS .....	12
11. FUTURE RESEARCH AND DATA REQUIREMENTS.....	13
12. ACKNOWLEDGEMENTS .....	14
13. REFERENCES .....	14
14. FIGURES .....	17
15. TABLES .....	25
APPENDIX A. CATCH DATA.....	30
APPENDIX B. TRAWL SURVEYS .....	44
APPENDIX C. BIOLOGICAL DATA .....	78
APPENDIX D. MODEL EQUATIONS.....	103

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APPENDIX E. MODEL RESULTS.....	119
APPENDIX F. INVESTIGATING THE IMPACTS OF CLIMATIC AND ENVIRONMENTAL VARIABILITY ON RECRUITMENT OF PACIFIC OCEAN PERCH.....	205
APPENDIX G. ASSESSMENT SCHEDULE AND INTERIM YEARS BETWEEN ASSESSMENTS .....	226

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## ABSTRACT

Pacific Ocean Perch (*Sebastes alutus*, POP) is a commercially important species of rockfish that inhabits the marine canyons along the coast of British Columbia. The status of POP in Queen Charlotte Sound, British Columbia, is assessed under the assumption that it is a single stock harvested entirely in Pacific Marine Fisheries Commission (PMFC) major areas 5A, 5B, 5C, and in 5E south of 52°20'. This stock has supported a domestic trawl fishery for decades and was heavily fished by foreign fleets from the mid-1960s to mid-1970s.

We used an annual catch-at-age model tuned to two fishery-independent trawl survey series, annual estimates of commercial catch since 1940, and age composition data from the two survey series (11 years of data) and the commercial fishery (34 years of data). The model starts from an assumed equilibrium state in 1940, and the survey data cover the period 1967 to 2016 (although not all years are represented). The two-sex model was implemented in a Bayesian framework (using the Markov Chain Monte Carlo search procedure) under a scenario that estimates both sex-specific natural mortality ( $M$ ) and steepness of the stock-recruit function ( $h$ ). Seven sensitivity analyses were performed to test the effect of data inputs to the model. A bridging analysis was performed using the 2010 data from the previous assessment to determine the effect of weighting the age frequencies with a new procedure that downweights composition data instead of the 2010 procedure that uses multinomial weighting.

The base model run suggests that strong recruitment in the early 1950s sustained the foreign fishery, and that a few strong year classes spawned in the late 1970s and 1980s sustained the domestic fishery into the 1990s.

The spawning biomass (mature females only) at the beginning of 2017,  $B_{2017}$ , is estimated to be 0.27 (0.18, 0.42) of unfished biomass (median and 5th and 95th quantiles of the Bayesian posterior distribution).  $B_{2017}$  is estimated to be 1.03 (0.54, 1.96) of the spawning biomass at maximum sustainable yield,  $B_{MSY}$ .

Advice to managers is presented as decision tables that provide probabilities of exceeding limit and upper stock reference points over a five-year projection period across a range of constant catches. The DFO provisional 'Precautionary Approach compliant' reference points were used, which specify a 'limit reference point' of  $0.4B_{MSY}$  and an 'upper stock reference point' of  $0.8B_{MSY}$ . The estimated spawning biomass at the beginning of 2017 has a 0.99 probability of being above the limit reference point, and a 0.74 probability of being above the upper stock reference point. Five-year projections using a constant catch of 2500 t/y (near the recent average five-year catch of 2400 t/y) indicate that, in 2022, the spawning biomass has probabilities of 0.97 of remaining above the limit reference point, and 0.71 of remaining above the upper stock reference point.

We developed a Bayesian method to investigate potential ecosystem influences on recruitment and applied it to the estimated recruitment from the 2010 stock assessment using a suite of climatic and environmental indicators. Results show that none of the investigated indicators were able to reliably predict observed recruitment deviations, leading to the conclusion that we are unable at this time to use environmental information to improve model predictions for this stock.

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## 1. INTRODUCTION

Pacific Ocean Perch (*Sebastes alutus*, POP) is a long-lived, commercially important species of rockfish found along the rim of the North Pacific. Its commercial attractiveness stems from the bright red colour and long shelf life when properly processed. It is also the one of the most abundant rockfish species on Canada's west coast and has been the mainstay of the shelf/slope trawl fishery for decades. A distinguishing feature of POP is a prominent forward-thrusting knob on the lower jaw (Love et al. 2002).

The life history of POP follows similar patterns to other *Sebastes* species, with the live release of larvae that spend periods likely ranging from three to twelve months as free-swimming pelagic larvae before settling to the bottom as juveniles. POP reproduction appears to follow onshore-offshore migration patterns where females move onshore for insemination and then migrate deeper to the entrances of submarine gullies where they release larvae from February to May (Love et al. 2002). The larvae depend on vertical upwelling to bring them into the upper pelagic zone to facilitate growth and dispersal. The larvae can spend up to a year in the water column before settling into benthic habitat (Kendall and Lenarz 1987). Juvenile benthic habitat is shallow (100-200 m), compared to the depths occupied by adult POP, and comprises either rough rocky bottoms or high relief features such as boulders, anemones, sponges, and corals (Carlson and Straty 1981; Rooper et al. 2007).

The maximum reported age in the literature for POP is 98 years for a specimen from the Aleutian Islands (Munk 2001); however, the Fisheries and Oceans Canada (DFO) database GFBio reports two specimens older than 98 y (age 100 y: female specimen from Langara at 329 m in 1983; age 103 y: female specimen from Moresby Gully at 364 m in 2002). Values used for the natural mortality rate of POP in other published stock assessments are usually close to 0.06 (e.g., Schnute *et al.* 2001; Hanselman *et al.* 2007, 2009). In comparison, the longest-living *Sebastes* species is Rougheye Rockfish (*S. aleutianus*), with a maximum reported age of 205 years (Munk et al. 2001) and an assumed fixed natural mortality rate set to 0.035 (McDermott 1994).

Pacific Ocean Perch supports the second largest rockfish fishery (after Yellowtail Rockfish, *S. flavidus*) in British Columbia (BC), with an annual coastwide TAC (total allowable catch) in 2016 of 5,193 t and an average annual catch of 4,207 t from 2012-2016. In area 5ABC, the 2016 annual TAC was 3,231 t, the 2016 catch was 2,359 t and the 5-year mean catch was 2,397 t. The trawl fishery accounts for 99.98% of the coastwide TAC, with the remainder allocated to the hook and line fishery. Since 2006, the annual TACs have included the catches from the groundfish research programs, primarily from the synoptic surveys.

Before the previous 2010 assessment (Edwards et al. 2012), POP was assessed using a set of "slope rockfish areas" (SRFA: 3C, 3D, 5AB, 5CD, 5ES, 5EN), derived from locality codes (fishing grounds) that are recorded in the DFO catch databases. Additionally, three main gullies (slope rockfish subareas: Goose Island, Mitchell's, and Moresby) in Queen Charlotte Sound (QCS) constitute the primary fishing grounds for this species and were analysed as separate stocks. However, POP population modelling focused on Goose Island Gully (GIG) because it held the most complete set of otolith data and early surveys concentrated on this area. A detailed history of the POP fishery before the implementation of the observer trawl program in 1996 can be found in Richards and Olsen (1996). The catch-age model used to assess the stock status for GIG POP (Schnute and Richards 1995) related process error in recruitments with measurement error in the abundance index. This concept was carried forward in

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subsequent POP stock assessments (e.g., Richards and Schnute 1998) up to the 2001 assessment (Schnute et al. 2001).

In this stock assessment, we retain the approach of Edwards et al. (2012), using a modified version of the Coleraine statistical catch-at-age software (Hilborn et al. 2003) called Awatea (Appendix D). The assessment base-case model includes: (i) sex-specific parameters, (ii) three sets of proportion-at-age data (commercial catch, GIG historic surveys, QCS synoptic surveys), (iii) two survey abundance index series (GIG historic, QCS synoptic; QCS shrimp used in 2010 was excluded), (iv) an area bounded by Pacific Marine Fisheries Commission (PMFC) areas 5A, 5B, 5C, and a portion of 5E south of 52°20' (herein referred to as Anthony Island, Figure 1), (v) a maximum modelled age of 60 years with older ages accumulated into the final age class, and (vi) independent selectivities for the commercial fishery and for each of the survey indices.

The important differences between the 2010 and 2017 stock assessments are:

- removal of the QCS shrimp survey as an indicator of abundance,
- an expansion of 5ABC to include Anthony Island,
- a revised re-weighting scheme (based on the recommendations of Francis 2011) to balance abundance (Appendix B) and composition data (Appendix C),
- six additional years of data, and
- uniform priors on survey selectivity.

## 1.1. RANGE AND DISTRIBUTION

Pacific Ocean Perch occurs along the North Pacific rim, ranging from Honshu (Japan), through the Bering Sea, along the Aleutian Islands (Alaska), then southward through BC down to central Baja California (Love et al. 2002). The species appears to be most abundant north of 50°N (Allen and Smith 1988). In BC, hotspots, ( $\geq$  the 0.95 quantile) of catch per unit effort (CPUE) from trawl tows over 21 years (1996-2016) occur SE off Moresby Is. (Moresby Gully), SW off Moresby Is. (Anthony Island), NW off Graham Is. (Langara Spit), and in Dixon Entrance north of Graham Island (Figure 2). The mean CPUE in Mitchell's and in Goose Island Gullies is lower than in Moresby Gully, although all three gullies support substantial fisheries. The bulk of the commercial captures of the QCS population lies between depths 96 m and 416 m (Appendix C).

## 1.2. ASSESSMENT BOUNDARIES

This assessment includes Pacific Marine Fisheries Commission (PMFC) major areas 5A, 5B, 5C, and 5E south of 52°20' (collectively referred to as 5ABC), as shown in Figure 1. Area 5ABC accounts for the main QCS population of POP that occurs in QCS proper (the area between the southern tip of Moresby Island, northwest tip of Vancouver Island, and the mainland) and southern Hecate Strait. The PMFC areas are similar but not identical to those used by the Groundfish Management Unit (GMU), which uses combinations of DFO Pacific Fishery Management areas. We have not used the GMU areas because reported catch from these areas has only been available since 1996. In the 2010 assessment, the portion of 5E that wraps around Cape St. James and includes Anthony Island (-131.218°W, 52.095°N) was excluded from the assessment, and a TAC adjustment algorithm was presented to translate the assessed 5ABC to 5AB and 5CD TACs. For this stock assessment, the assessed area is similar to the GMU TAC areas 5AB + 5C (5C was split from 5CD in 2013), so managers can allocate any catch policy reported in this document using the simple TAC ratios  $5AB/(5AB+5C)$  and  $5C/(5AB+5C)$ .

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## 2. CATCH DATA

The methods used to prepare a catch history for this POP 5ABC stock assessment are presented in detail in Appendix A. Canadian catch reporting for POP extends back to 1951 and is credible from 1954 on; therefore, reconstruction of catch by Canadian vessels only occurs from 1940 to 1953. 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, but the estimated amounts were somewhat uncertain. All historical foreign catches (annual landings) were tracked separately from Canadian landings and added to the latter during the reconstruction process. Information about species caught concurrently with POP commercial catches are presented in Appendix C.

## 3. FISHERIES MANAGEMENT

Appendix A summarises all management actions taken for POP in QCS since 1979. Given the conclusions made by the 2010 assessment (Edwards et al 2012), DFO implemented a TAC reduction in 5AB+5CD of 258 t per year over a three year period (for a 774 t total reduction) as a conservation measure. Additional conservation measures appear in Appendix A.

## 4. SURVEY DESCRIPTIONS

Three sets of fishery independent survey indices, all located in QCS, have been considered for tracking changes in the biomass of this population (Appendix B). Only the first two were used in the current assessment's Base Case:

1. Goose Island Gully (GIG) historical – an early series of 8 indices using a fixed station design extending from 1967 to 1994. 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 GIG were used to ensure continuity across all surveys;
2. QCS synoptic – a random-stratified “synoptic” trawl survey covering all of Queen Charlotte Sound and targeting a wide range of finfish species. This survey has been repeated eight times between 2003 to 2015, using three different vessels (see Table B.6) but with a consistent design;
3. QCS shrimp – a survey targeting shrimp, operating at the head of GIG on the west and south sides of Calvert Island. This survey has been performed in each of 16 years from 1999 to 2013 and in 2016 using the research vessel *W.E. Ricker* (except in 2005 when the *Frosti* was used).

The 2010 stock assessment included the QCS shrimp survey; however, the regional peer review (RPR) participants for this assessment advised dropping it due to incomplete spatial and depth coverage and redundancy with the QCS synoptic survey. The relative biomass indices for the GIG historical and QCS synoptic surveys were used as data in the model along with the associated relative error for each index value, adjusted by a method calculating the standard deviation of normalised residuals (SDNR) to balance the relative weights of the two surveys in the model (Appendix D).



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## 5. BIOLOGICAL INFORMATION

### 5.1. BIOLOGICAL SAMPLES

In Queen Charlotte Sound, commercial catches of POP by trawl gear have been sampled for age proportions since the 1960s. However, only otoliths aged using the “break and burn” method have been included in the age samples used in this assessment because the earlier surface ageing method was known to be biased, especially with increasing age (Stanley 1987). Practically, this means that no age data were available before 1978. Commercial fishery age frequency data were summarised for each quarter, weighted by the POP 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 C for details.

Age frequency (AF) data were available from two survey series: the historical GIG series (1984 and 1994 only), and from all eight QCS synoptic surveys (spanning the years 2003 to 2015). Age frequency data from a single survey, conducted in 1995 using a similar net configuration to that in the synoptic surveys, were included in the GIG age series. The corresponding biomass index was not used in the model because it was felt that the underlying scaling parameter ( $q$  in equation E.14) would not be equivalent to the  $q$  estimated for balance of the GIG survey or the QCS synoptic survey (see Appendix B). 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, the samples were weighted by the POP catch density in sampled tows; stratum samples were then weighted by the stratum areas (described in Appendix C).

### 5.2. GROWTH PARAMETERS

Growth parameters were estimated from POP length and age data from biological samples collected from 1978 to 2015 (Appendix C). Biological samples were examined from commercial and research sampling sources in 5ABC, with the majority coming from research surveys. Only data from research surveys were used to estimate the sex-specific allometric weight-length relationship and the von Bertalanffy growth models (Appendix D).

### 5.3. 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 by partitioning the sampled specimens 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 “break and burn” method) were pooled from all 5ABC sampling sources and the observed proportion mature at each age was calculated. A monotonic increasing maturity-at-age vector was constructed by fitting a double normal function (Equation C.3, equivalent to that in Equation D.7) to the observed maturity values (Appendix C). This function was adjusted slightly by using the observed maturity values for ages less than 9. This was done because the fitted model appeared to overestimate the proportion mature at these younger ages (Figure C.8). Females older than age 25 (up to age 60) 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.

### 5.4. NATURAL MORTALITY

Male and female natural mortalities were estimated as parameters of the model (see Appendix D), using a strong informed prior based on a results from an assessment of POP in the Gulf of

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Alaska (Hanselman et al. 2009), which had used a strong informed prior on  $M$  from Archibald et al. (1981). The most probable fit and median Bayesian estimate for  $M$  from the Alaska assessment were 0.061 and 0.055, respectively. Based on these results, the previous BC POP stock assessment (Edwards et al. 2012) adopted a normal prior on  $M$  of 0.06 with a tight standard deviation of 0.006 (CV=10%), which was repeated for this stock assessment.

## 5.5. 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 D.10). Recruitments were allowed to deviate from this average (Equations D.17 and D.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  $0.2 B_0$  (Mace and Doonan 1988), where  $B_0$  is the virgin spawning biomass (mature females). The parameter  $h$  was estimated, constrained by a prior developed for west coast *Sebastes* by Forrest et al. (2010), after removing all information from the prior relevant to QCS POP (R. Forrest, DFO, pers. comm.). This prior took the form of a beta distribution with mean 0.674 and standard deviation 0.168.

## 6. AGE-STRUCTURED MODEL

A two-sex, age-structured, stochastic model was used to reconstruct the population trajectory of QCS POP from 1940 to the beginning of 2017. Ages were tracked from 1 to 60, with 60 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 both surveys and the commercial fishery 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 D.

The model was fit to the available data (2 sets of survey indices, 34 annual proportions-at-age samples (trips) from the commercial fishery and 11 proportions-at-age samples (tows) from two 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 gave sensible and reasonably consistent results. Sensitivity runs that explored the effects of all the different components of the data on model results did not seem justified, given the small amount of available data when spread over the long period of stock reconstruction (particularly in the early years) and the relative consistency seen in the interpretation of the available data under a range of model assumptions. As well, the selectivity functions for the commercial fishery and the QCS synoptic survey seemed well estimated and returned credible estimates. The 2010 stock assessment considered uncertainty in the underlying assumptions for several key model parameters, notably natural mortality  $M$  and stock-recruitment steepness  $h$ . This uncertainty was explored by alternately fixing or estimating these parameters in a pairwise pattern. Only two were brought forward for advice to managers – estimate both  $M$  and  $h$  using informed priors, and estimate  $h$  and fix  $M = 0.06$ . Similar assessments on rockfish since (Edwards et al. 2014a, b; Starr et al. 2016) have adopted the philosophy that, if both  $M$  and  $h$  can be estimated from the data, then that is the best approach to take because estimating these parameters allows for the incorporation of uncertainty associated with these parameters.

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Seven sensitivity analyses were run to see how the model predictions differed from those of the Base Case when some inputs were changed:

- **Sensitivity 1** – add the QCS shrimp survey index with fixed selectivity ( $\mu=8.069$ ,  $v_L=2.277$ ) to assess the sensitivity of dropping this data series that was used in the 2010 assessment;
- **Sensitivity 2** – add the QCS shrimp survey index with a uniform prior on domed selectivity to assess the absence of both index and age composition data available from this survey, along with adding a single age composition sample from 1999;
- **Sensitivity 3** – use the observed survey CVs without adding process error to assess the sensitivity of weighting the survey biomass indices by balancing the SDNRs to 1.0;
- **Sensitivity 4** – use a normal prior on  $M$  with mean=0.07 and SD=0.014 to assess the sensitivity of model results to an alternative  $M$  prior;
- **Sensitivity 5** – use a uniform prior on  $M$  to assess the sensitivity of model results when there is no prior expectation on  $M$ ;
- **Sensitivity 6** – halve the trawl catches during the foreign fleet period (1965-1975) to assess the sensitivity of over-estimating the catch of this fleet;
- **Sensitivity 7** – double the trawl catches during the foreign fleet period (1965-1975) to assess the sensitivity of under-estimating the catch of this fleet.

Finally, a “bridging” analysis was run which used the 2010 input data and applied the Francis (2011) reweighting procedure for age frequencies described in Section D.6.2 of Appendix D. This was done to test whether the change in the data weighting procedure, specifically for age frequencies implemented in this stock assessment, would have changed the advice generated from the 5ABC 2010 stock assessment. The previous assessment for this stock (Edwards et al. 2012) used a different weighting procedure because it preceded the publication of the Francis (2011) reweighting recommendations. At that time, an iterative reweighting procedure adjusted the relative weights of both the composition and abundance components until the standard deviation of the Pearson residuals for each data set was near 1, the theoretical value it should hold if the residual distribution were consistent with the assumed distribution for that data set.

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, sensitivity, and bridging) were judged to have converged after 6,000,000 iterations, sampling every 5,000<sup>th</sup>, to give 1,200 draws (1,000 samples after dropping the first 200).

## 7. MODEL RESULTS

### 7.1. BASE CASE

The model run for the Base Case had credible fits to the data, as demonstrated by visual examination of the MPD fits and the patterns of residuals (results in Appendix E). Fits to the survey indices were generally good (Figure E.1) and all standardised residuals were less than two standard deviations from the fit (Figures E.2 and E.3). The fits to the commercial age composition data were exceptionally good (Figure E.8) while fits to survey ages seemed to underestimate the early year classes (e.g., Figure E.16). Generally, fits to the survey age composition data were not as good 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

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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 E.19 shows that the base-case model mimics the pattern of the commercial annual mean ages very well while the model estimates of mean age for the QCS synoptic survey consistently falls below the observed mean ages.

Figure 3 illustrates the effects of re-weighting age frequencies in the composition data, where  $W_g = n_{ig}^3 / n_{ig}^0$  describes the weighting on gear  $g$  from the original number of samples  $n^0$  (number of trips for the fishery, number of tows for the surveys) to the effective number of samples  $n^3$  for the third reweight (see equation D.26). The age frequency re-weighting reduced the effective sample sizes (increasing the error bounds) for the two surveys (GIG historical  $W_g = 0.46$ , QCS synoptic  $W_g = 0.74$ ), while increasing the effective sample sizes for the commercial trawl fishery ( $W_g = 1.7$ ). These relative weights reflect the goodness of fit to the age composition data.

The MCMC results showed satisfactory convergence of the MCMC search process (Appendix E, Figures E.25-E.31) for the base-case model. Priors and marginal posteriors of the estimated parameters are presented in Figure E.32 and Table E.4. For example, natural mortality is estimated as having a median (and 5-95% credible interval) of 0.060 (0.055-0.066) for females and 0.065 (0.060-0.071) for males. Steepness is estimated to be 0.70 (0.46-0.90). The remaining MCMC results are given in Table 1 and Table 2. The median estimated ratio of spawning biomass at the start of 2017 to the equilibrium spawning biomass associated with MSY ( $B_{2017}/B_{MSY}$ ) is 1.03 (0.54-1.96). The estimated median MSY is 3,843 (2,539-5,255) t. For reference, the average catch from 2012-2016 is 2,397 t. The median estimated ratio of the spawning biomass at the start of 2017 to the unfished level ( $B_{2017}/B_0$ ) is 0.27 (0.18-0.42).

Figure 4 shows the posterior distributions of the reconstructed vulnerable biomass by year, together with the estimated historical catches. Figure 5 compares the trajectory of the estimated medians of vulnerable and spawning (mature females only) biomasses relative to their unfished values. These results demonstrate a slow decline in biomass from 1940 to 1960, followed by an increasing biomass caused by fish entering the population after a large recruitment event around 1952 (Figure 6). Heavy fishing pressure by foreign fleets (Figure 7) in the period 1965-75 caused a decline in biomass which then continued into the 1980s as the fishing pressure from the domestic Canadian trawl fleet developed after the foreign fleet left BC waters. Another good recruitment year around 1976 sustained an increase in spawning biomass until 1994, after which the biomass declined until 2005. Since then, spawning biomass has remained fairly constant to the present, coincident with a reduction in catch levels from the mid-2000s.

For area 5ABC, there have been two recruitment events with much higher recruitment than the long-term average (Figure 6). The model estimates that these events occurred around 1953 and 1977 (as 1-yr old fish), with the size of the recruitment event spread over a number of years, probably due to ageing error. This effect can be seen in Figure 6, with elevated recruitments lying on either side of the modal year, resulting in a summed overall increase on the order of 5 to 20 times the long-term average recruitment. Each of these events resulted in increases in the reconstructed vulnerable and mature biomass levels (Figure 5) as these fish matured or became old enough for capture by the fishery.

The estimated annual exploitation rate (ratio of total catch to the vulnerable biomass in the middle of the year) peaked in the mid-1960s (Figure 7) due to the large foreign catches, and then peaked again in 2007 due to increased domestic exploitation combined with lowered vulnerable biomass levels. Exploitation rates have declined since TAC reductions were put in place, beginning in 2006 (700 t for research) and in 2011-13 (774 t over three years for

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conservation concerns). The exploitation rate for 2016,  $u_{2016}$ , is estimated to be 0.056 (0.033-0.085, Table 2).

## 7.2. SENSITIVITY ANALYSES

Seven sensitivity runs (described above) were made, plus a bridging analysis repeating the 2010 stock assessment using the assumptions made by the present assessment. All sensitivity runs, including the bridging analysis, were evaluated with an MCMC search across the parameter space (6 million iterations sampled every 5000<sup>th</sup> for 1200 samples, 1000 after removing the first 200 for burn-in), with the differences among runs summarised in Sections E.5 and E.6 (Appendix E). Detailed outputs (fits to the data, MPD and MCMC results) are not provided for these runs as they mirror those for the Base Case; however, select MCMC diagnostics for each sensitivity run are provided in Appendix E. These models all fit the data well, but several of the sensitivity runs show unacceptable levels of autocorrelation. Model predictions of stock status for each sensitivity run are provided in Section 8.3.

## 8. ADVICE FOR MANAGERS

### 8.1. REFERENCE POINTS AND CRITERIA

The Sustainable Fisheries Framework (SFF, DFO 2009) established provisional reference points to guide management and assess harvest in relation to sustainability. These reference points are the Limit Reference Point (LRP) of  $0.4B_{MSY}$  and the upper stock reference point (USR) of  $0.8B_{MSY}$ , which were adopted for the previous assessment of this stock (Edwards et al., 2012) and repeated again for this stock assessment. Note that no evaluation 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  $0.4B_{MSY}$  is termed the “critical zone”, the zone lying between  $0.4B_{MSY}$  and  $0.8B_{MSY}$  is termed the “cautious zone”, and the region above the upper stock reference point ( $0.8B_{MSY}$ ) 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.,  $P(B_t > 0.4B_{MSY})$  and  $P(B_t > 0.8B_{MSY})$ . The SSF also stipulates that, when in the healthy zone, the fishing mortality must be at or below the fishing mortality associated with MSY under equilibrium conditions ( $u_{MSY}$ ), ramped down when in the cautious zone, and set equal to zero when in the critical zone.

Other jurisdictions often 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 Appendix E. 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 additional reference points:  $B_{MSY}$  and the current biomass,  $B_{2017}$  (Appendix E).

### 8.2. BASE CASE

Figure 8 shows that (based on medians), the 5ABC POP stock is estimated to have been in the healthy zone for the majority of the historical fishing period, and that the spawning biomass has remained near  $B_{MSY}$  for the past decade. It has been harvested at rates higher than  $u_{MSY}$  nine times (1966-68, 1974, 2003-04, 2006-07, 2010), and has remained below  $u_{MSY}$  since 2010. The

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current median spawning biomass  $B_{2017}$  sits at  $1.03B_{MSY}$  and the exploitation rate is at  $0.68u_{MSY}$  (Figure 8). The spawning biomass is estimated to be above  $0.4B_{MSY}$  with probability  $P(B_{2017} > 0.4B_{MSY}) = 0.99$  and above  $0.8B_{MSY}$  with probability  $P(B_{2017} > 0.8B_{MSY}) = 0.74$ . Therefore, it is in the critical zone with probability  $1 - 0.99 = 0.01$ , in the cautious zone with probability  $0.99 - 0.74 = 0.25$ , and in the healthy zone with probability  $0.74$  (Figure 9).

### 8.3. SENSITIVITY RUNS

Figure 9 demonstrates that adding the QCS shrimp survey index series lowers the stock status, regardless of whether survey selectivity is fixed (Sensitivity 1) or fitted using dome-shaped selectivity (Sensitivity 2). Median  $B_{2017} = B_{MSY}$  for the Base Case is 1.03, and this decreases to 0.75 and 0.81 for Sensitivities 1 and 2, respectively.

In the working paper presented to the RPR participants, Run08 (Sensitivity 1) was put forward as the Base Case, primarily to match the data choices made for the 2010 stock assessment (Edwards et al., 2012). However, it was noted during the peer review process that this survey does not cover the entire depth range of POP, only trawling down to  $\sim 200$  m (see Figure B.37), whereas POP typically inhabits depths down to  $\sim 400$  m (see Figure B.18), with the highest catch rates deeper than 200 m. As well, this survey only covers a relatively small portion of Goose Island Gully west of Calvert Island (e.g., Figure B.36), whereas this stock is well distributed throughout QC Sound, especially along the outer margins (e.g., Figure B.17). The shrimp survey design is optimised for shrimp, which occur at shallower depths where juvenile POP are more prevalent, and uses a fine-mesh net liner in the cod end that is designed to capture shrimp; therefore, it is likely that the QCS shrimp survey provides a relatively poor index of the adult QCS POP population. To partially address the lack of deeper, older POP in this survey, Sensitivity 2 estimated dome-shaped selectivity, with a declining vulnerability of older POP (Figure E.42), but the resulting parameter estimates differed little from those estimated when fixing selectivity (Table E.14). The insensitivity of the parameter estimates to this change in assumption may be due to the small amount of available age composition data for this survey (only one sample year). Given the limited aerial and depth coverage by this survey, and that it is redundant to the coverage by the QCS synoptic survey, which is a survey specifically designed to monitor groundfish, the RPR participants agreed to exclude this survey from the Base Case and to provide advice to managers based on the GIG historical and QCS synoptic surveys.

Sensitivity 3 explores the effect of re-weighting the survey CVs by running the model with the observed survey CVs (i.e., no additional process error). Figure E.43 shows how the survey CVs differ between the Base Case and Sensitivity 3 – the observed GIG historical survey CVs were smaller than those used in the Base Case whereas the observed QCS synoptic survey CVs were larger. The base-case reweighting effectively downweights the GIG survey while upweighting the QCS survey, constraining the fit to more closely match the latter's relative abundance. We consider the base-case weighting to be more appropriate because the historical GIG survey is a series stitched together from unconnected surveys using a fixed station design (see Section B.3) while the QCS synoptic survey is a specifically designed groundfish survey using a random stratified design (see Section B.4). Consequently, a higher weight should be given to the better designed and more recent survey series. While most of the median parameter estimates are similar to those of the Base Case (Table E.13), the median estimate of stock size, as represented by  $R_0$ , is about 2% larger than in the Base Case. This translates into a larger median estimate of  $B_{2017}$  compared to the Base Case (28,968 t vs. 24,302 t, respectively), likely reflecting differences in the posterior distributions of stock size. The consequence of the greater estimated current spawning biomass, while all else remains similar, is that stock status is estimated to be higher in this sensitivity run.

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Sensitivities 4 and 5 explore the effects of changing the priors on natural mortality  $M$ . In the Base Case, the prior for  $M$  has a mean of 0.06 with a CV of 10%, which is a tight prior and only marginally better than fixing  $M$ ; however, the posteriors for  $M$  have smaller CVs than the prior (5.6%, Figure E.44), with the posterior mean barely shifting away from the prior mean for females while increasing by 9% for males. The addition of the QCS shrimp survey did not appreciably change the means or standard deviations of the estimated  $M$  values (Figure E.45). When the prior mean was raised to 0.07 and the CV increased to 20% (Figure E.46), the model converges on a higher  $M$  for both sexes, but the mean of the posterior is 3% less than the prior mean for females and 5% greater than the prior mean for males, while the  $M$  posterior CV is less than 10% for both sexes. However, this model generates a significant amount of autocorrelation in a number of parameters, including both  $M$  parameters (Figure E.59). Similar results are obtained from a model using a uniform prior on  $M$  (no expectations, Figure E.47), with the mean of the posterior distribution for  $M$  just below 0.07 for females and at 0.075 for males with a CV near 10% for both sexes. Stock status for Sensitivity 5 is slightly higher than that in Sensitivity 4, although similar, and there is again a high level of autocorrelation among all the leading parameters (Figure E.62). The MCMC diagnostics for both of these runs indicate that this procedure has probably not converged (particularly for Sensitivity 5), leading to unreliable parameter estimates. However, it is notable that even with a uniform prior, the resulting estimates of  $M$  range from 0.057–0.080 (5-95% credible interval for females) and 0.062–0.088 (5-95% credible interval for males), indicating that the  $M$  prior used in the Base Case is consistent with the age composition data and that the constraint imposed by the base-case  $M$  prior is appropriate, given the much better MCMC diagnostics obtained for the base-case run.

Sensitivities 6 and 7 explore the effects of catch mis-specification during the period of peak foreign fleet activity. Ketchen (1980) provides minimum, intermediate, and maximum estimates of rockfish and POP caught by Russian and Japanese trawlers in Queen Charlotte Sound during the years 1965 to 1975. Traditionally, POP stock assessments have used the intermediate estimates, but these may include some bias. In Sensitivity 6, the 1965-75 catch input to the model is arbitrarily halved, while in Sensitivity 7, it is arbitrarily doubled. Predictably, stock status is shifted to the right if catches are halved, with a larger proportion of the posterior distribution of  $B_{2017}/B_{MSY}$  in the “healthy” zone. Conversely, there is a leftward shift in stock status shifts into the cautious zone when catches are doubled (Figure E.39). The median  $B_{2017}/B_{MSY}$  for the Base Case is 1.03, and this changes to 1.18 and 0.83 for Sensitivities 6 and 7, respectively. Instabilities in the MCMC chains appear when foreign catches are doubled (Figures E.66–68) but not when they are halved (Figures E.62–65).

The MCMC results of the bridging analysis, which was based on Sensitivity 1 because it included the QCS Shrimp survey (Tables E.15 and E.16), were similar to the 2010 results, but the age frequency reweighting scheme resulted in a lower stock status than was estimated in 2010 (Figure 10) – the median estimate of the 2011 stock status was 0.259 in 2010 while the same estimate using the Francis reweighting procedure on the bridging analysis model was 0.233, a drop of 10%. By de-emphasising the age composition data relative to the abundance data, the bridging analysis suggests that the data weighting procedure used in the 2010 ‘Estimate M&h’ model estimated a higher stock status, resulting in a more optimistic stock assessment compared to the current weighting procedure. However, we note that these revised results lie within the uncertainty envelope of the original model, indicating that the updated results are probably not strongly different from the 2010 results in a statistical sense. Stock assessment methodology is continually improving and we have adopted the Francis (2011) recommendations because they represent an advance on the methods used in 2010.

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## 8.4. PROJECTION RESULTS AND DECISION TABLES

Projections out to five years (Figure 11) were made for the base-case model run to evaluate the future behaviour of the population under different levels of constant catch, given the model assumptions without feedback controls. The projections, starting with the biomass at the beginning of 2017, were made over a range of constant catch strategies (0-5,000 t) for each of the 1,000 MCMC samples in the posterior, generating 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 0.9 (see Appendix D for a description of this procedure). At current average catches of 2,397 t, the catch strategy of 2,500 t in Figure 11 shows approximately how the projections would look if catch were to continue at these levels.

Decision tables are presented (in Appendix E, and in Table 3 to Table 5) with respect to the reference points outlined in Section 8.1. Each table expresses the probability that  $B_t$  (or  $u_t$ ), where  $t = 2017 \dots 2022$ , will exceed the reference point in question under each constant catch strategy. Generally, it is up to managers to choose the preferred catch 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, Table 3 indicates that 3,250 t of POP could be removed from 5ABC to be 95% certain that the spawning biomass would remain above  $0.4B_{MSY}$  at the start of 2022. Similarly, Table 4 indicates that 4,500 t could be removed to be 50% certain that the spawning biomass is above  $0.8B_{MSY}$  at the start of 2022.

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 POP 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.

## 8.5. 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 2022, as there will be three new indices from the QCS synoptic survey and five years of ageing and catch data (see Appendix G for details). Having considered the possible indicators that could be monitored in the interim years, we conclude that none are suitable for triggering an earlier-than-scheduled full assessment (see Appendix G). Note that *advice* for the interim years is explicitly included in this assessment in the form of the decision tables.

## 9. INVESTIGATING IMPACTS OF CLIMATIC AND ENVIRONMENTAL VARIABILITY ON RECRUITMENT

The provision of advice in the context of ecosystem-based fisheries management requires an understanding of how climatic and environmental processes influence fish populations. In Appendix F we develop a novel Bayesian framework to identify relationships between climatic and environmental variables and recruitment, and apply it to this stock of POP (using the MCMC recruitment estimates from the previous assessment by Edwards et al. 2012). Unlike previous



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approaches, the framework explicitly incorporates uncertainties of historical fish recruitment, which are often estimated in modern stock assessments. Furthermore, it uses multiple climatic and environmental variables, yielding conclusions that are less likely to break down over time than those based on a single variable.

We tested potential impacts using time series of nine climatic and environmental indices: East-Pacific/North-Pacific Index, pressure-adjusted sea level anomalies at Prince Rupert, standardized maximum area covered by Haida eddies, Aleutian Low Pressure Index, standardized North Pacific index, Pacific Decadal Oscillation, North Pacific Gyre Oscillation, Oceanic Niño Index and Southern Oscillation Index. However, we were unable to detect a set of conditions that appeared to strongly influence POP recruitment. We had hypothesised that favourable recruitment conditions might include basin-scale atmospheric circulations that create southward coastal winds, and medium-sized Haida eddies that may influence transport of POP larvae from marine canyons up into the shelf waters that represent favourable juvenile habitat.

Our results imply that we should currently not incorporate climatic or environmental drivers of recruitment into the stock assessment model, since there appear to be no such strong drivers. This is despite having a data-rich stock of a long-lived species, with a decades-long time series of estimated recruitment. This result may be partly due to the recruitment strategy adopted by this species, which only shows occasional pulses of strong recruitment interspersed by long periods of below average recruitment. Given that there are only two (or at the most three) episodes of strong recruitment observed in this reconstruction (in spite of the 1940 start year), the available information may simply be inadequate to discover the drivers for these rare episodes of strong recruitment. Consequently, we retain the modelling approach used in the previous assessment.

Our methods are general and have application to other stocks for which time series of potential drivers and MCMC estimates of recruitment are available.

## 10. GENERAL COMMENTS

As in previous rockfish stock assessments, this assessment depicts a slow-growing, low-productivity stock. It was severely depleted by the mid-1970s from commercial fishing by foreign fleets (Figure 5). It appears that this early fishery was sustained from a strong recruitment event that occurred in the early 1950s (Figure 6). The depletion of this stock reversed briefly in the early 1980s before resuming in the mid-1990s as the domestic bottom trawl fleet developed. Again the fishery was sustained by a few strong year classes spawned in the late 1970s and early 1980s. The declining trend appears to have halted from 2006, coincident with a 700 t reduction in the TAC in 2006 (Table A.1). After the 2010 assessment (Edwards et al 2012), management implemented a further TAC reduction in 5AB/5CD of 258 t per year over a three year period (an additional 774 t total reduction) as a conservation measure. This management action appears to have improved the 2017 stock status relative to that in 2011 (Figure 8).

Annual exploitation rates increased after the 1980s, and by the late 2000s had approached the historic high levels associated with the large catches by the foreign fleets, which occurred in the late 1960s (Figure 7). Figure 7 also shows that, after the two large TAC reductions mentioned above, there were notable declines in the exploitation rate. The median of  $B_{2017}/B_0$  is estimated to be 0.27 with 90% credible interval of (0.18, 0.42) and the median exploitation rate is 0.056 (0.033, 0.085) (Table 2). The median  $B_t/B_0$  has remained fairly constant just above 0.25 for the past 10 years (Figure 5). Examination of the decision tables (Table 3 to Table 5) and Figure 11 confirms that current catch levels are below the model predictions of surplus production, with catches around 2,750 t/year resulting in biomass predictions with  $P(B_{2022} > B_{MSY}) \approx 0.5$ .

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This model estimates that there have been no exceptional recruitment events after 1976 (1977 in Figure 6), which likely contributes to the slow recovery of this species since the 2010 stock assessment, even given the TAC reductions. The 2001 year class appears to be the largest in the last 20 years, though it was hardly exceptional. Minor upticks of age-1 fish in 2007 and 2009 are evident, although there is considerable uncertainty in estimated recruitment after 2006 because fish are not fully selected by the commercial fishery or surveys until about age 10-11.

The current spawning stock  $B_{2017}$  lies at  $1.03B_{MSY}$  and  $0.68u_{MSY}$  (Figure 8), expressed as MCMC medians (Table 2). Although,  $u_t/u_{MSY}$  has fluctuated over the past decade, the spawning biomass  $B_t$  has remained between the USR and  $B_{MSY}$  and  $u_t$  has remained below  $u_{MSY}$  since 2010 (Figure 8).

The stock status level for Sensitivity 1 (add the QCS shrimp survey) was lower than that for the Base Case (median  $B_{2017}/B_0=0.22$  compared to 0.27), demonstrating that this survey has an impact on this quantity. The use of shrimp surveys to monitor rockfish species has been questioned since the publication of the 2010 stock assessment because it is thought that the shrimp survey design and spatial coverage are not ideal for monitoring rockfish species (DFO 2015). The RPR participants agreed to exclude this survey when modelling POP in 5ABC to give advice to managers.

We note that the results of this assessment are uncertain. Although 5ABC POP is the most data-rich rockfish stock in western Canadian waters, the available historical data covering the long early catch history are uncertain before the beginning of full observer coverage in 1996. 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 all relatively recent. It is fortunate that the earliest available age data are able to provide information on year class strengths in the 1950s and 1960s, due to the long-lived nature of the species and the apparent high precision of the ageing methodology.

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 highly uncertain future recruitment values.

We expect that the results from the surveys initiated in the previous decade will continue to provide monitoring capability for POP off the BC coast. Catches in the commercial groundfish fisheries are also well-monitored. These ongoing activities give confidence that this stock is currently well-monitored, and management has demonstrated that corrective action can be taken when required.

## 11. FUTURE RESEARCH AND DATA REQUIREMENTS

The following issues should be considered when planning future stock assessments and management evaluations for Pacific Ocean Perch:

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. The use of the shrimp trawl surveys (in both QCS and off WCVI) has been contentious for various rockfish assessments since 2010. In 2014, the Yellowtail Rockfish assessment RPR

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participants (DFO 2015) recommended: “*Document changes to the design and net gear for both the West Coast Vancouver Island and Queen Charlotte Sound Shrimp trawl surveys. Evaluate the suitability, along with possible limitations, of these surveys for each groundfish species that will be assessed in future.*” The recommendation is repeated here.

3. It may be possible to construct informed priors for survey catchability parameters that can be used in Bayesian models like the catch-age model presented in this report. Such priors could be developed by placing meaningful bounds on the components of survey catchability, which in turn would help scale the biomass levels in the assessment.
4. Explore how Bayesian output from models that use environmental indices to predict biological processes (e.g., recruitment) might be incorporated into stock assessments using probability distributions.
5. Effort could be directed to studying how single populations, such as POP, 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 POP population dynamics and resilience.

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## 14. FIGURES

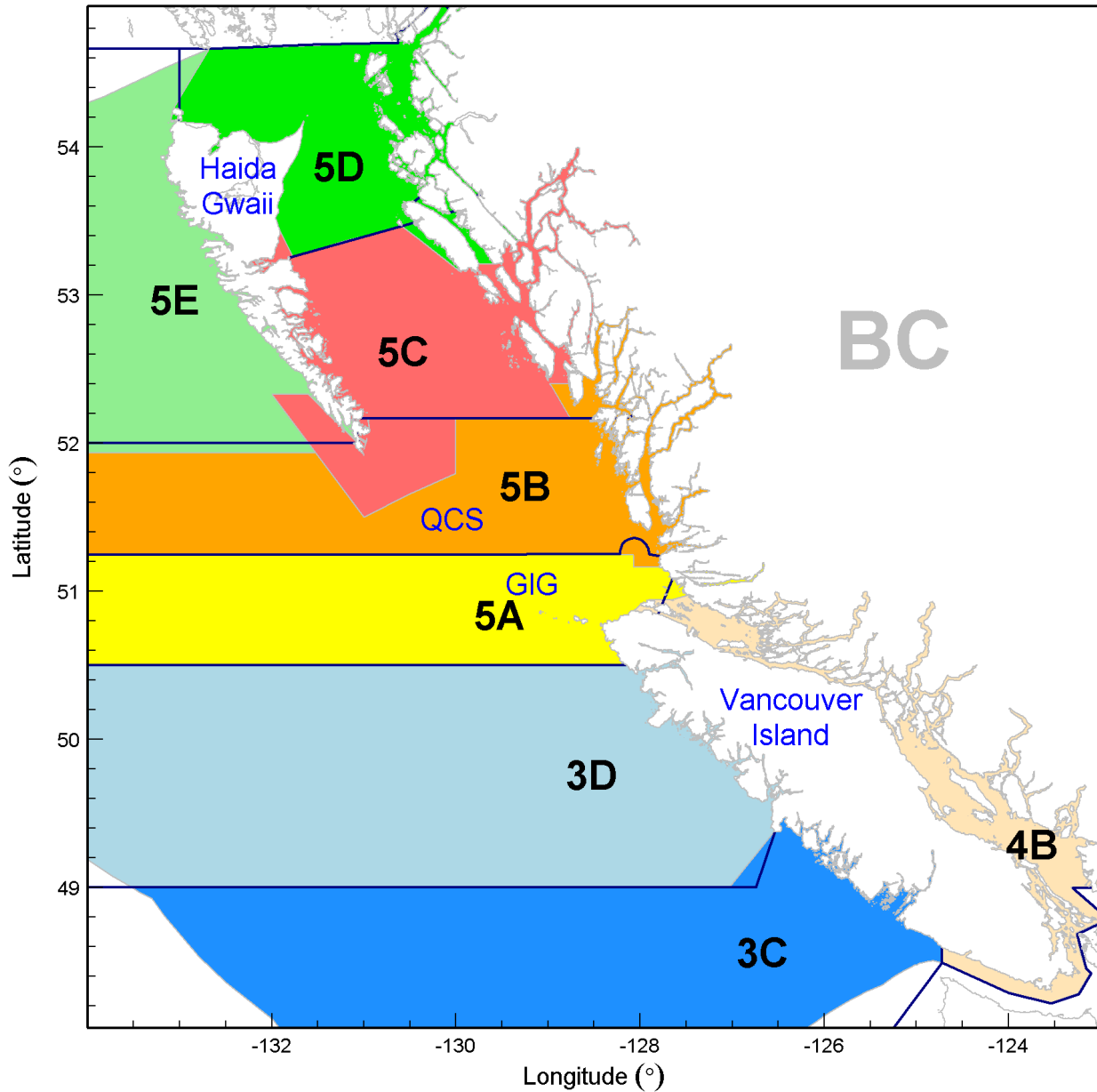


Figure 1. Pacific Marine Fisheries Commission (PMFC) major areas (outlined in dark blue) compared with Groundfish Management Unit areas for POP and Yellowmouth Rockfish (shaded). For reference, the map indicates Queen Charlotte Sound (QCS) and Goose Island Gully (GIG). This assessment is for PMFC areas 5ABC + Anthony Island (the red area to the west of the southern part of Haida Gwaii) combined.

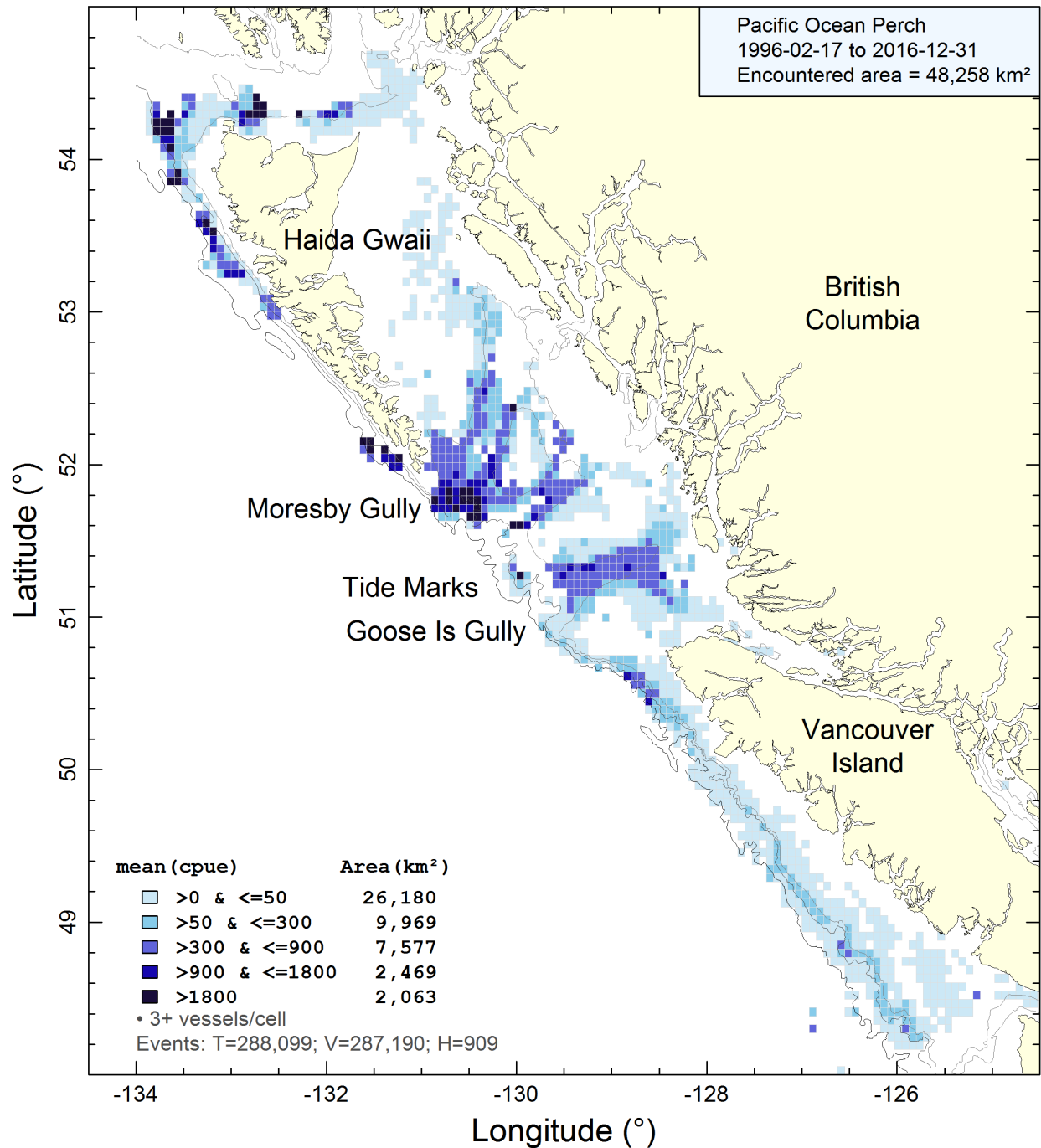


Figure 2. Aerial distribution of POP mean trawl tow catch per unit effort (kg/hour) from Feb 17, 1996 to Dec 31, 2017 in grid cells 0.075° longitude by 0.055° latitude (roughly 32 km<sup>2</sup>). Isobaths show the 200, 500, and 1200 m depth contours. Note that cells with <3 fishing vessels are not displayed.

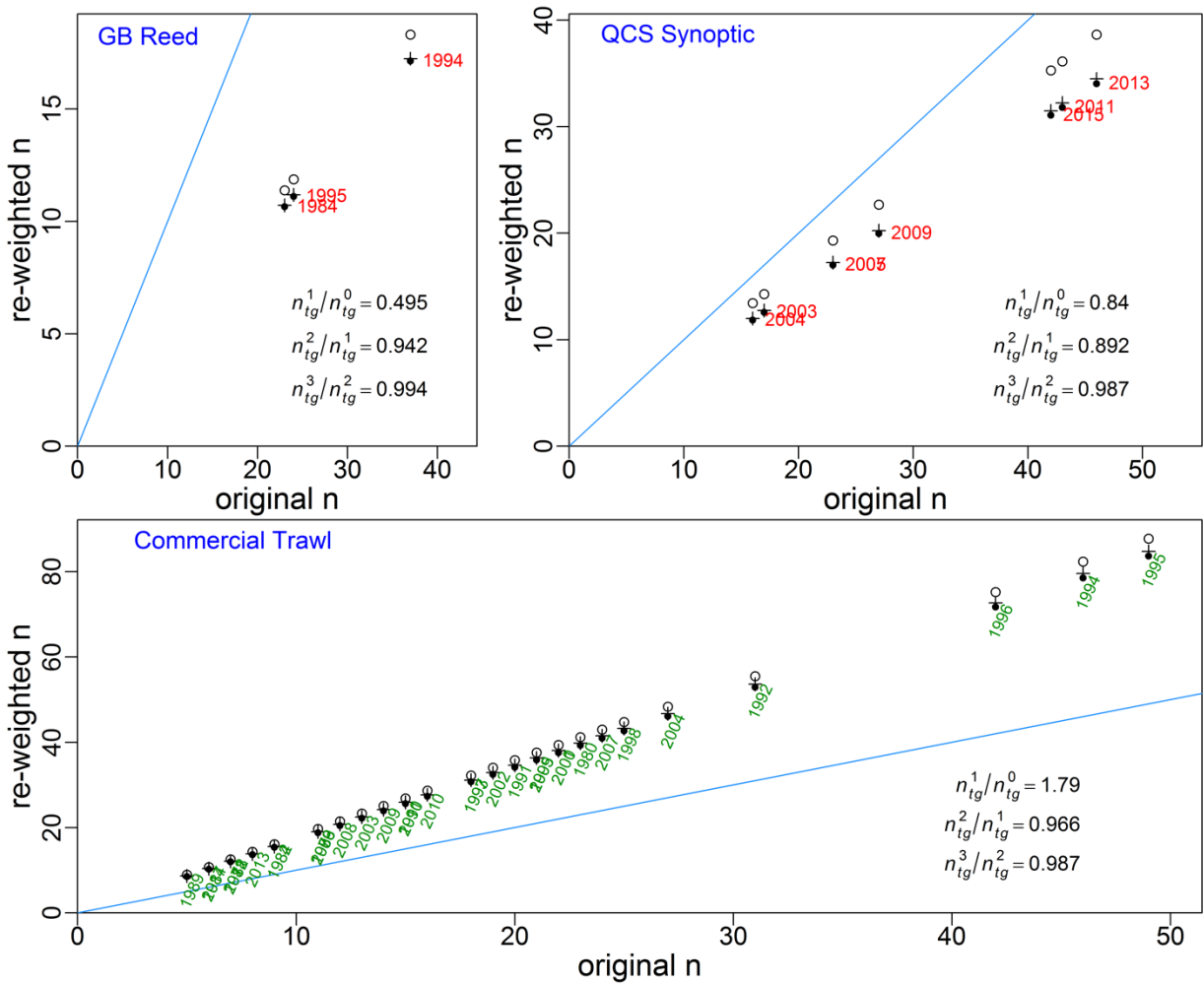


Figure 3. The effects of Francis (2011) re-weighting on age frequency effective sample size. Original sample sizes are shown on the x-axis and re-weighted sample sizes (Equation D.26) are on the y-axis, where open circles are the first re-weights, the plus symbols are the second re-weights, and the filled circles are the third re-weights used in the model. The step-wise ratios  $W_g$  are displayed in the lower right corner of each panel; the total re-weight is simply the product of the three ratios. Superscripts on  $n$  denote the re-weight number. The diagonal blue line depicts the ratio 1:1.



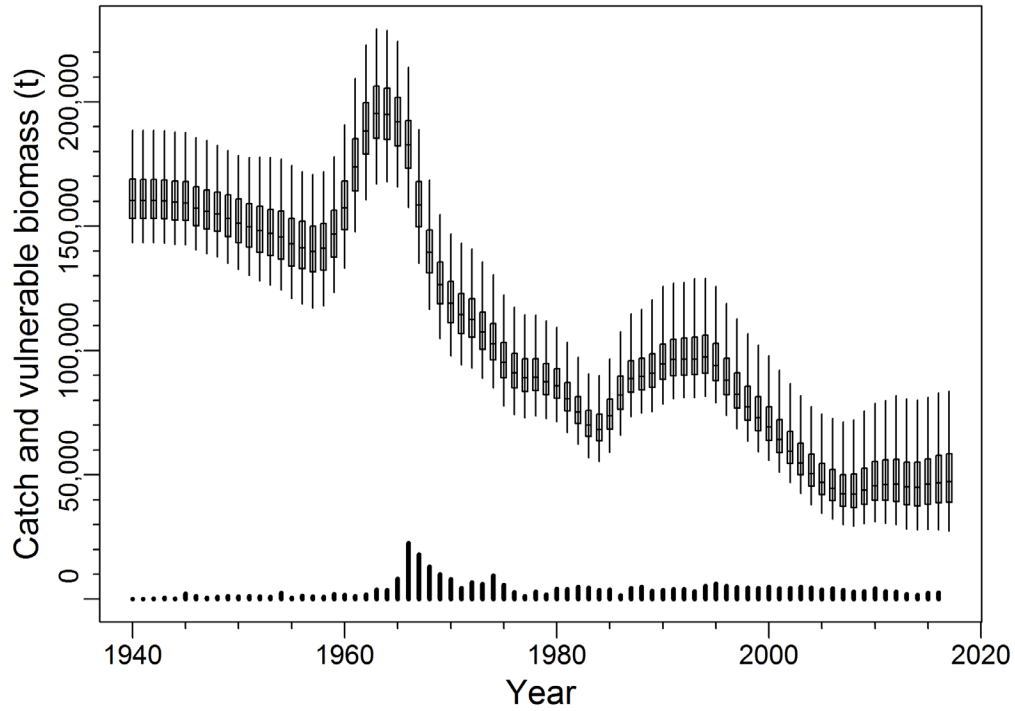


Figure 4. Vulnerable biomass (boxplots showing 2.5, 25, 50, 75 and 97.5 percentiles of the posteriors from the MCMC results) for the base-case model run. Commercial catch (vertical bars along the x-axis) are presented on the same scale.

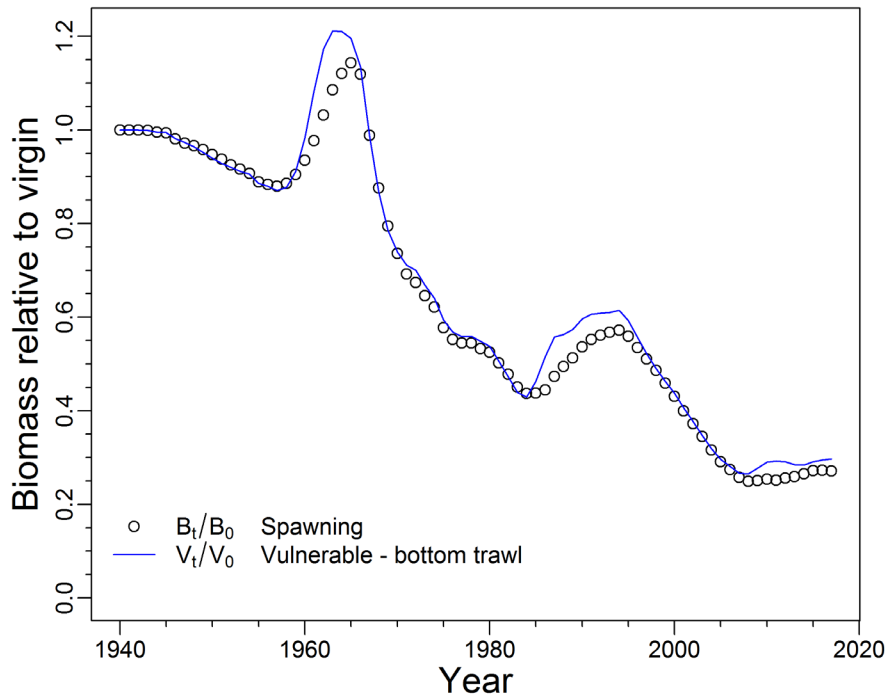


Figure 5. Trajectories of spawning and vulnerable biomass relative to virgin levels,  $B_t / B_0$  and  $V_t / V_0$  respectively, over time, shown as the medians of the MCMC posteriors for the base-case model run.

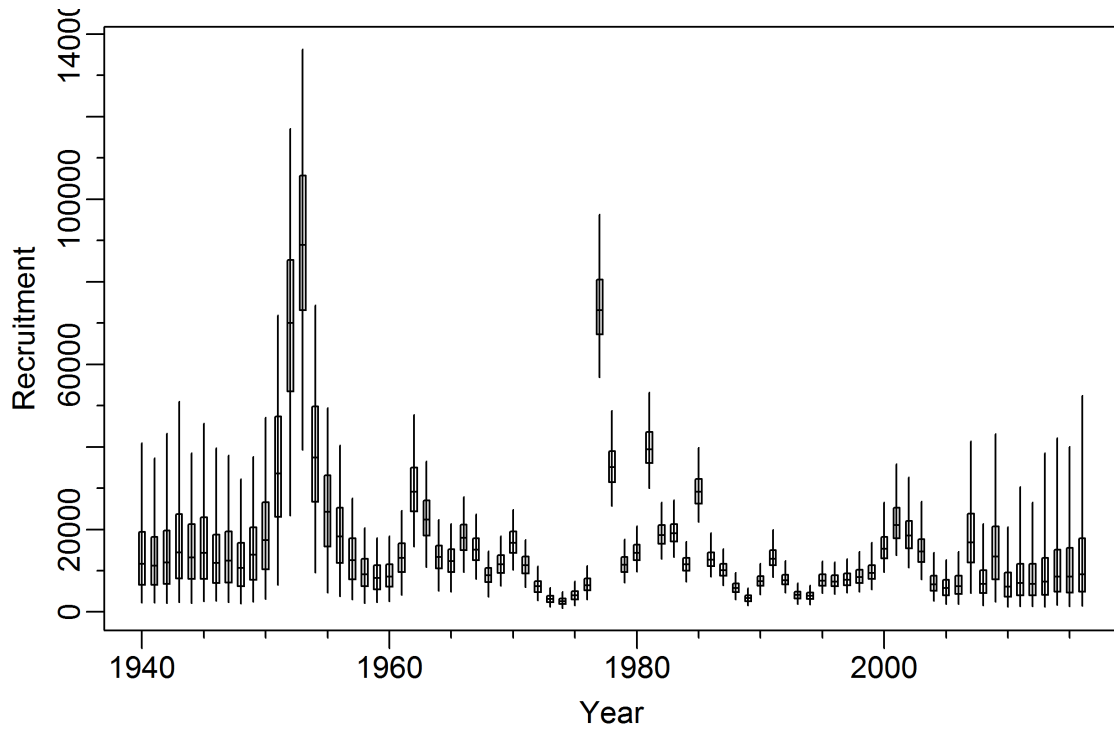


Figure 6. Marginal posterior distribution of recruitment in 1000's of age 1 fish plotted over time for the base-case model run. The boxes give the 2.5, 25, 50, 75 and 97.5 percentiles from the MCMC results.

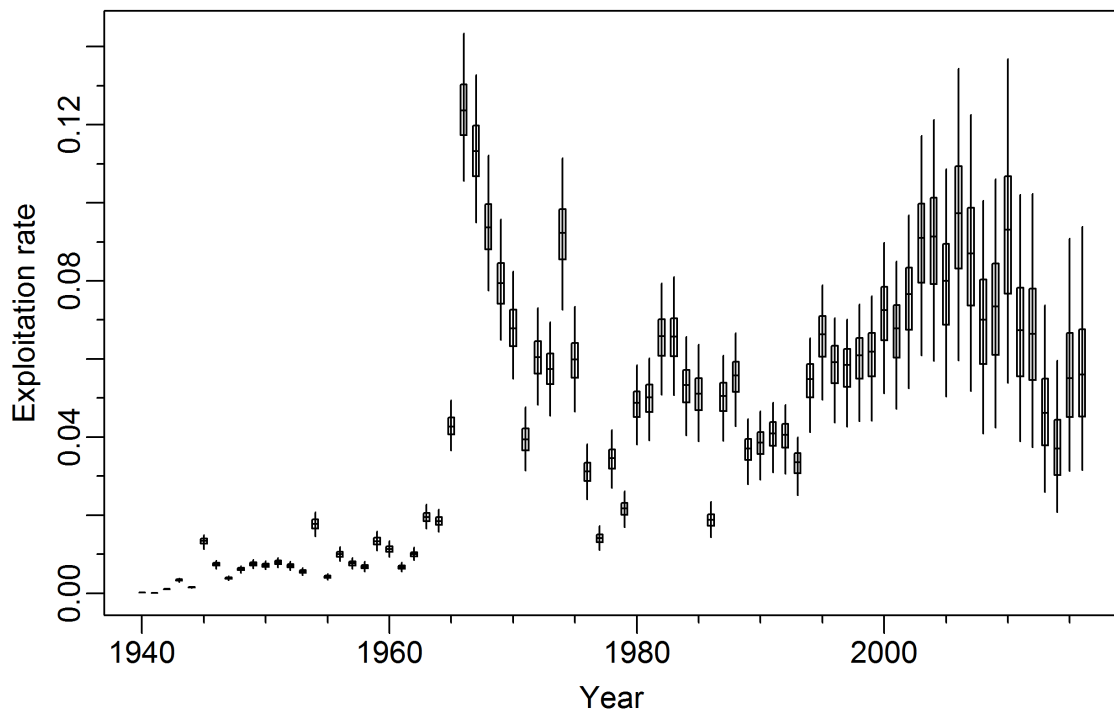


Figure 7. Marginal posterior densities of annual exploitation rate (see equation E.12) by year for the base-case model run. The boxes give the 2.5, 25, 50, 75 and 97.5 percentiles from the MCMC results.

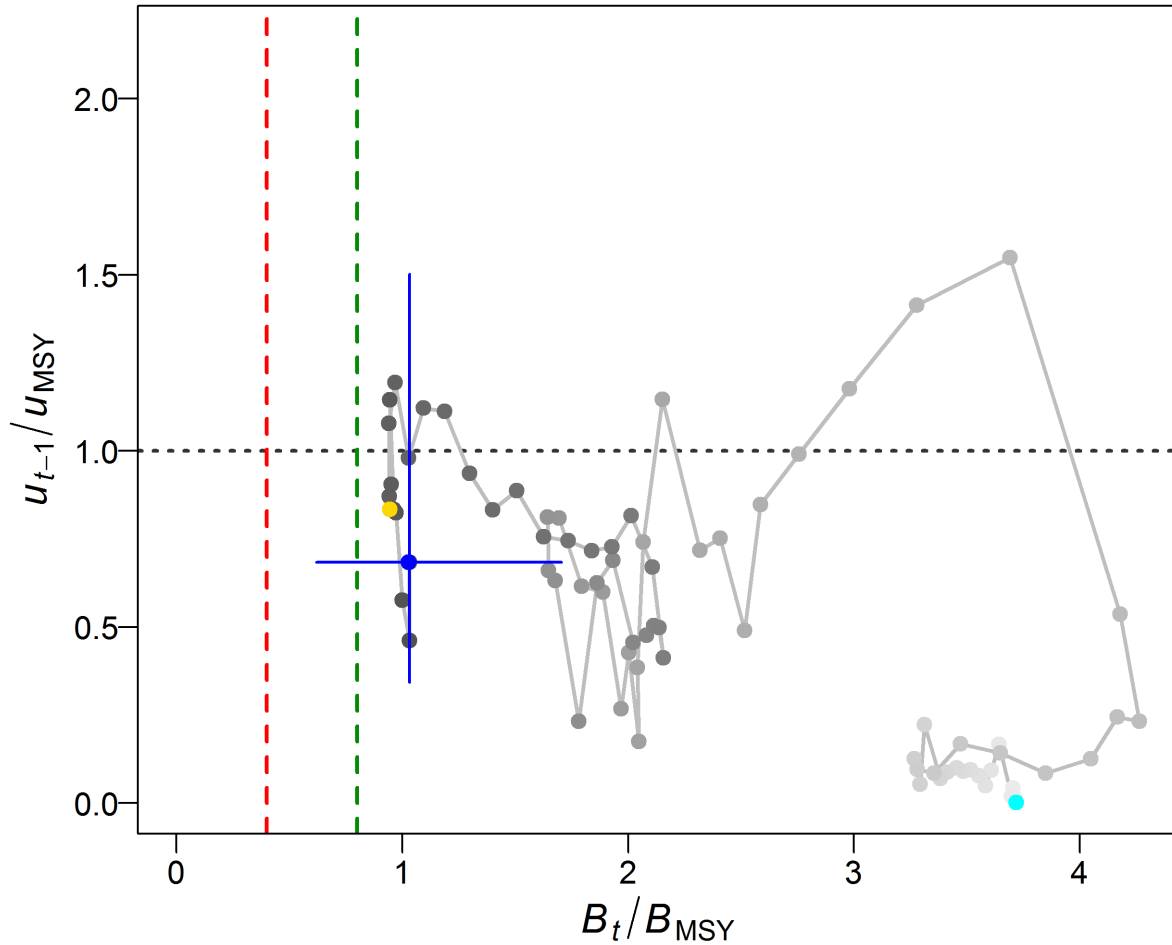


Figure 8. Phase plot through time of the medians of the ratios  $B_t/B_{MSY}$  (the spawning biomass at the start of year  $t$  relative to  $B_{MSY}$ ) and  $u_{t-1}/u_{MSY}$  (the exploitation rate in the middle of year  $t$  relative to  $u_{MSY}$ ). The filled cyan circle is the starting year (1941). Years then proceed from light grey through to dark grey with the final year (2017) 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 2011 ( $B_{2011}/B_{MSY}$ ,  $u_{2010}/u_{MSY}$ ), which coincides with the previous assessment of this stock. Red and green vertical dashed lines indicate the Precautionary Approach provisional limit and upper stock reference points of  $0.4B_{MSY}$  and  $0.8B_{MSY}$ , and the horizontal grey dotted line indicates  $u_{MSY}$ .

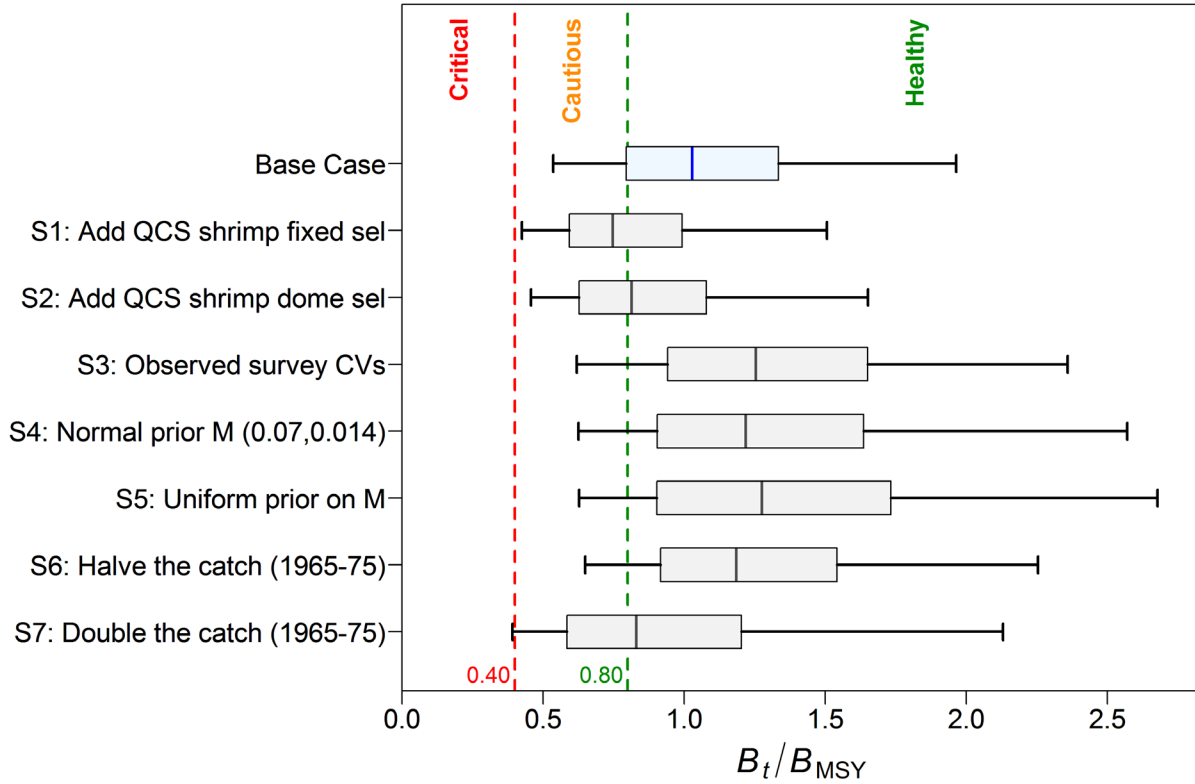


Figure 9. Status at beginning of 2017 of the 5ABC Pacific Ocean Perch stock relative to the DFO PA provisional reference points of  $0.4B_{MSY}$  and  $0.8B_{MSY}$  for the base-case (Run09) stock assessment and seven sensitivity runs: S1 = (Run08) add the QCS shrimp survey using a fixed selectivity curve; S2 = (Run15) add the QCS shrimp survey using a fitted dome-shaped selectivity curve; S3 = (Run20) use the observed survey CVs without adding process error; S4 = (Run14) use a normal prior on  $M$  with a mean of 0.07 and a standard deviation of 0.014 (CV=20%); S5 = (Run17) use a uniform prior on  $M$ ; S6 = (Run18) halve the catch in the years 1965-75 (during peak foreign fleet activity); S7 = (Run19) double the catch in the years 1965-75. Boxplots show the 5, 25, 50, 75 and 95 quantiles from the MCMC posterior. contains the details of these sensitivity runs.

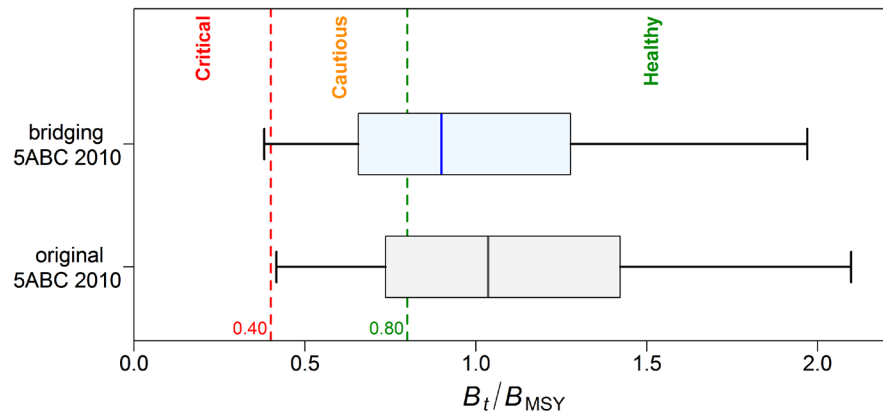


Figure 10. Status of 5ABC POP stock at the start of 2011 relative to the DFO PA provisional reference points of  $0.4B_{MSY}$  and  $0.8B_{MSY}$  for the 'Estimate M&h' model assessed in 2017 (bridging) and 2010 (original). Boxplots show the 5, 25, 50, 75 and 95 quantiles from the MCMC posterior.

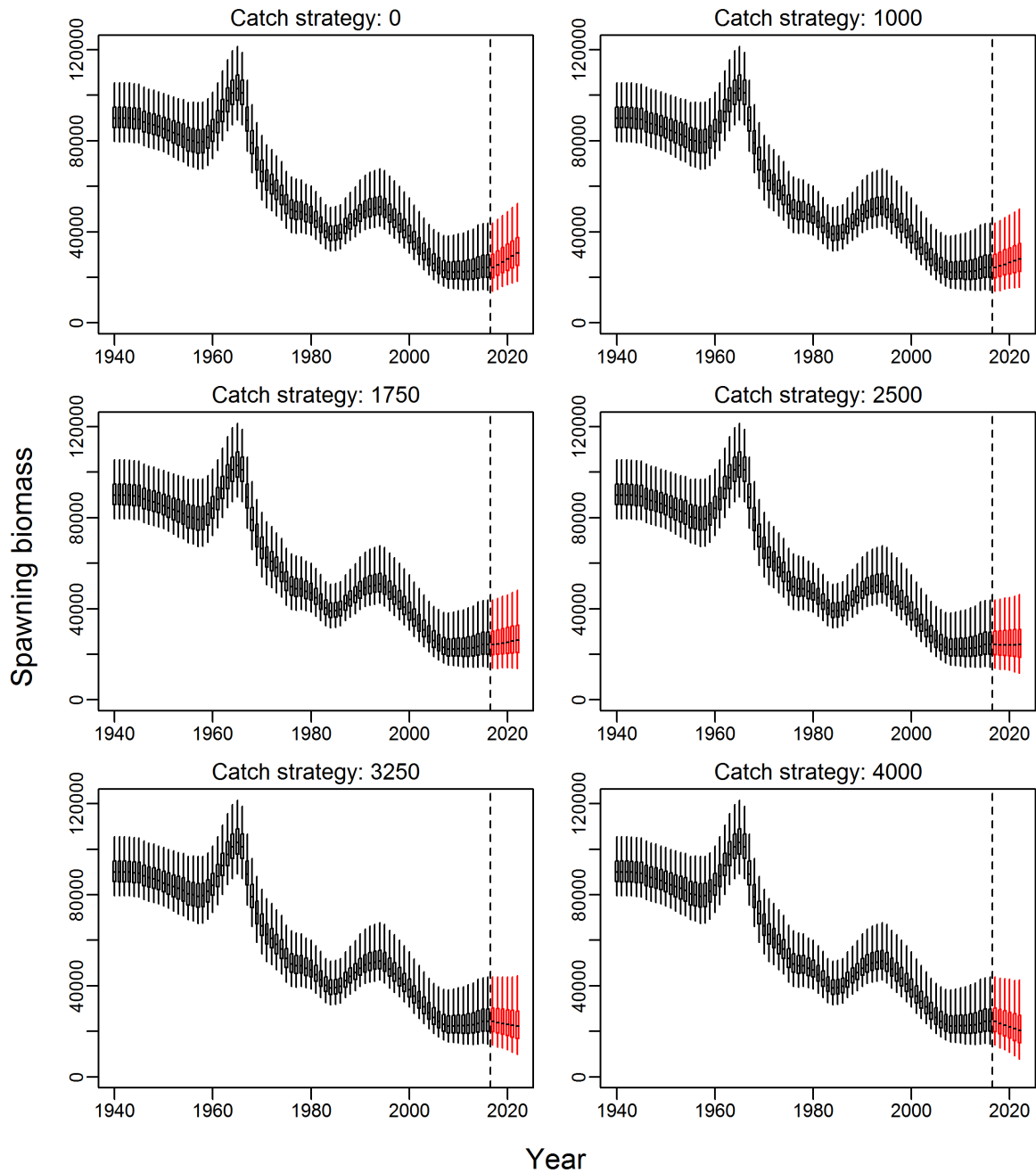


Figure 11. Projected biomass (t) under different constant catch strategies (t); boxplots show the 2.5, 25, 50, 75 and 97.5 percentiles from the MCMC results for the base-case model run. For each of the 1,000 samples from the MCMC posterior, the model was run forward in time (red, with medians in black) 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 (2012-2016) is 2,397 t.

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## 15. TABLES

Table 1. The 5th, 50th and 95th percentiles of the base-case MCMC posterior distributions for the main estimated model parameters for the 5ABC POP stock assessment. Except for  $R_0$ ,  $M_1$  and  $M_2$ , subscripts refer to the data source, where 1=GIG Historic rockfish survey, 2=Queen Charlotte Sound Synoptic survey, and 3= commercial trawl data.

<b>Value</b>	<b>5%</b>	<b>50%</b>	<b>95%</b>
$R_0$	14,387	17,516	22,025
$M_1$	0.05495	0.06020	0.06599
$M_2$	0.05951	0.06523	0.07144
$h$	0.4630	0.7018	0.8994
$q_1$	0.1046	0.1366	0.194
$q_2$	0.2156	0.3480	0.5062
$\mu_1$	11.17	17.41	28.14
$\mu_2$	12.21	15.65	21.09
$\mu_3$	10.03	10.72	11.55
$\Delta_1$	-2.678	1.264	5.818
$\Delta_2$	-1.442	-0.1227	1.124
$\Delta_3$	-0.3857	0.01853	0.4051
$\log v_{1L}$	3.016	4.603	5.904
$\log v_{2L}$	2.848	3.721	4.509
$\log v_{3L}$	1.072	1.600	2.046

Table 2. The 5th, 50th and 95th percentiles of MCMC-derived quantities from the 1,000 samples of the base-case MCMC posterior. Definitions are:  $B_0$  – unfished equilibrium spawning biomass (mature females),  $V_0$  – unfished equilibrium vulnerable biomass (males and females),  $B_{2017}$  – spawning biomass at the start of 2017,  $V_{2017}$  – vulnerable biomass in the middle of 2017,  $u_{2016}$  – exploitation rate (ratio of total catch to vulnerable biomass) in the middle of 2016,  $u_{max}$  – maximum exploitation rate (calculated for each sample as the maximum exploitation rate from 1940-2016),  $B_{MSY}$  – 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 (2012-2016) is 2397 t.

Value	Percentile		
	5%	50%	95%
From model output			
$B_0$	81,005	89,993	103,214
$V_0$	144,968	160,337	182,826
$B_{2017}$	15,312	24,302	40,768
$V_{2017}$	29,990	47,272	79,451
$B_{2017} / B_0$	0.177	0.271	0.417
$V_{2017} / V_0$	0.195	0.297	0.45
$u_{2016}$	0.033	0.056	0.085
$u_{max}$	0.108	0.124	0.142
MSY-based quantities			
MSY	2,539	3,843	5,255
$B_{MSY}$	15,743	24,116	34,771
$0.4B_{MSY}$	6,297	9,647	13,908
$0.8B_{MSY}$	12,594	19,293	27,817
$B_{2017} / B_{MSY}$	0.537	1.029	1.964
$B_{MSY} / B_0$	0.183	0.269	0.362
$V_{MSY}$	33,785	47,982	66,674
$V_{MSY} / V_0$	0.218	0.301	0.382
$u_{MSY}$	0.039	0.08	0.148
$u_{2016} / u_{MSY}$	0.292	0.684	1.798

Table 3. Decision tables for the limit reference point  $0.4B_{MSY}$  for 1-5 year base-case projections for a range of constant catch strategies (in tonnes). Values are  $P(B_t > 0.4B_{MSY})$ , 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  $B_t > 0.4B_{MSY}$ . For reference, the average catch over the last 5 years (2012-2016) is 2397 t.

Catch strategy	2017	2018	2019	2020	2021	2022
0	0.99	1.00	1.00	1.00	1.00	1.00
250	0.99	0.99	1.00	1.00	1.00	1.00
500	0.99	0.99	1.00	1.00	1.00	1.00
750	0.99	0.99	1.00	1.00	1.00	1.00
1000	0.99	0.99	0.99	1.00	1.00	1.00
1250	0.99	0.99	0.99	0.99	0.99	0.99
1500	0.99	0.99	0.99	0.99	0.99	0.99
1750	0.99	0.99	0.99	0.99	0.99	0.99
2000	0.99	0.99	0.99	0.99	0.99	0.99
2250	0.99	0.99	0.99	0.99	0.99	0.98
2500	0.99	0.99	0.99	0.99	0.98	0.97
2750	0.99	0.99	0.99	0.98	0.98	0.97
3000	0.99	0.99	0.99	0.98	0.97	0.96
3250	0.99	0.99	0.99	0.98	0.96	0.95
3500	0.99	0.99	0.98	0.97	0.95	0.94
3750	0.99	0.99	0.98	0.96	0.95	0.92
4000	0.99	0.99	0.98	0.96	0.94	0.91
4250	0.99	0.99	0.98	0.95	0.93	0.90
4500	0.99	0.99	0.97	0.95	0.91	0.87
4750	0.99	0.98	0.97	0.94	0.90	0.85
5000	0.99	0.98	0.96	0.94	0.89	0.82



Table 4. Decision tables for the upper stock reference point  $0.8B_{MSY}$  for 1-5 year base-case projections for a range of constant catch strategies (in tonnes). Values are  $P(B_t > 0.8B_{MSY})$ , i.e. the probability of the spawning biomass (mature females) at the start of year  $t$  being greater than the upper stock reference point. The probabilities are the proportion of the 1000 MCMC samples for which  $B_t > 0.8B_{MSY}$ . For reference, the average catch over the last 5 years (2012-2016) is 2397 t.

Catch strategy	2017	2018	2019	2020	2021	2022
0	0.74	0.78	0.80	0.83	0.85	0.87
250	0.74	0.78	0.80	0.82	0.84	0.85
500	0.74	0.78	0.79	0.81	0.83	0.84
750	0.74	0.77	0.79	0.80	0.81	0.82
1000	0.74	0.77	0.78	0.79	0.80	0.81
1250	0.74	0.76	0.77	0.78	0.79	0.79
1500	0.74	0.76	0.76	0.78	0.78	0.78
1750	0.74	0.75	0.76	0.77	0.77	0.77
2000	0.74	0.75	0.75	0.75	0.75	0.74
2250	0.74	0.74	0.74	0.73	0.73	0.72
2500	0.74	0.74	0.73	0.72	0.71	0.71
2750	0.74	0.73	0.71	0.71	0.70	0.68
3000	0.74	0.72	0.70	0.69	0.67	0.66
3250	0.74	0.72	0.69	0.67	0.65	0.63
3500	0.74	0.71	0.68	0.66	0.63	0.60
3750	0.74	0.70	0.67	0.64	0.61	0.58
4000	0.74	0.69	0.67	0.63	0.59	0.56
4250	0.74	0.69	0.65	0.61	0.58	0.54
4500	0.74	0.68	0.64	0.60	0.55	0.51
4750	0.74	0.68	0.63	0.59	0.53	0.48
5000	0.74	0.67	0.62	0.57	0.51	0.46

Table 5. Decision tables for the reference point  $u_{MSY}$  for 1-5 year base-case projections for a range of constant catch strategies (in tonnes). Values are  $P(u_t > u_{MSY})$ , i.e. the probability of the exploitation rate in the middle of year  $t$  being greater than the reference point. The probabilities are the proportion of the 1000 MCMC samples for which  $u_t > u_{MSY}$ . For reference, the average catch over the last 5 years (2012-2016) is 2397 t.

Catch strategy	2017	2018	2019	2020	2021	2022
0	0	0	0	0	0	0
250	0	0	0	0	0	0
500	0	0	0	0	0	0
750	0	0	0	0	0	0
1000	0.01	0.01	0.01	0.01	0.01	0.01
1250	0.02	0.02	0.02	0.02	0.02	0.03
1500	0.06	0.06	0.06	0.07	0.07	0.06
1750	0.11	0.11	0.11	0.11	0.11	0.11
2000	0.15	0.15	0.16	0.16	0.17	0.18
2250	0.19	0.19	0.20	0.21	0.22	0.22
2500	0.23	0.23	0.24	0.26	0.26	0.27
2750	0.28	0.29	0.30	0.32	0.33	0.33
3000	0.33	0.34	0.37	0.38	0.39	0.40
3250	0.39	0.40	0.42	0.43	0.45	0.46
3500	0.44	0.45	0.47	0.50	0.51	0.52
3750	0.48	0.50	0.52	0.55	0.57	0.59
4000	0.52	0.55	0.57	0.60	0.62	0.63
4250	0.57	0.59	0.62	0.65	0.67	0.68
4500	0.60	0.64	0.67	0.69	0.71	0.72
4750	0.65	0.67	0.70	0.72	0.75	0.76
5000	0.68	0.71	0.74	0.76	0.78	0.79

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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 US (1959–1980), the USSR (1965–1968), and Japan (1966–1976). The foreign vessels removed large amounts of rockfish biomass (POP included), particularly in Queen Charlotte Sound (5ABC). Canadian effort escalated in 1965 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 POP (and Yellowmouth Rockfish *Sebastes reedi*) in 1979 for GMU area 5AB (Table A.1 and Table A.2). On April 18, 1997 (one month into the IVQ program, Barry Ackerman, GMU, pers. comm.) the boundaries of GMU areas 5AB, 5CD, and 5E were adjusted to extend 5CD southwest around Cape St. James (Figure A.1) for these two species only.

In the 1980s, experimental over-harvesting of POP stocks was attempted in two regions along the BC coast (Leaman and Stanley 1993; Leaman 1998). The objectives of the experiments included

1. ground-truthing trawl survey biomass estimates,
2. estimating fishing mortality,
3. validating ageing techniques by introducing a large negative anomaly in the age composition,
4. exploring stock-recruitment relationships, and
5. involving industry in research and management.

The first experiment occurred off the WCVI where a specified overharvest was set (TAC = 500 t) from 1980 to 1984 before returning to a level deemed sustainable at 300 t (Stocker 1981). The experiment experienced no implementation problems and reporting by industry was deemed acceptable. The 3C TAC was subsequently reduced to 100 t in 1986 and remained low until 1993.

The second overharvesting experiment occurred in the Langara Spit area of PMFC 5E off the northwest coast Haida Gwaii region. This experiment differed from the WCVI one in that quotas were removed entirely in 1983 to allow five years of unrestricted fishing followed by five years of severely limited fishing. However, a scheduled closure set for 1988 did not occur because the harvesters and the region had become dependent on the higher harvest levels (Leaman 1998). Some of the fishers maintained that there was little or no evidence of over-exploitation, and misreporting of catch could not be controlled. Discussions involving harvesters, politicians, and DFO managers (excluding the original researchers) negotiated extensions of the fishery, but eventually the Langara Spit area was closed in 1993.

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In 1996, an onboard observer program was initiated, placing observers aboard all offshore trawl vessels (Option B). In 1997, an Individual Vessel Quota (IVQ) system was put in place to allocate tradable rights to each registered vessel for a share of the total allowable catch (TAC) by species. In 2001, DFO reduced the 5CD POP TAC by 300 t for research use as payment for the Hecate Strait Pacific Cod charter (over three seasons), and in 2006 DFO again reduced the 5CD POP TAC by 700 t for use in possible research programs (Table A.2). After the 2010 assessment (Edwards et al 2012), management implemented a conservation-measure TAC reduction in 5AB+5CD of 258 t per year over a three year period (for a 774 t total reduction).

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, and included: limiting the footprint of groundfish bottom trawl activities, 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).

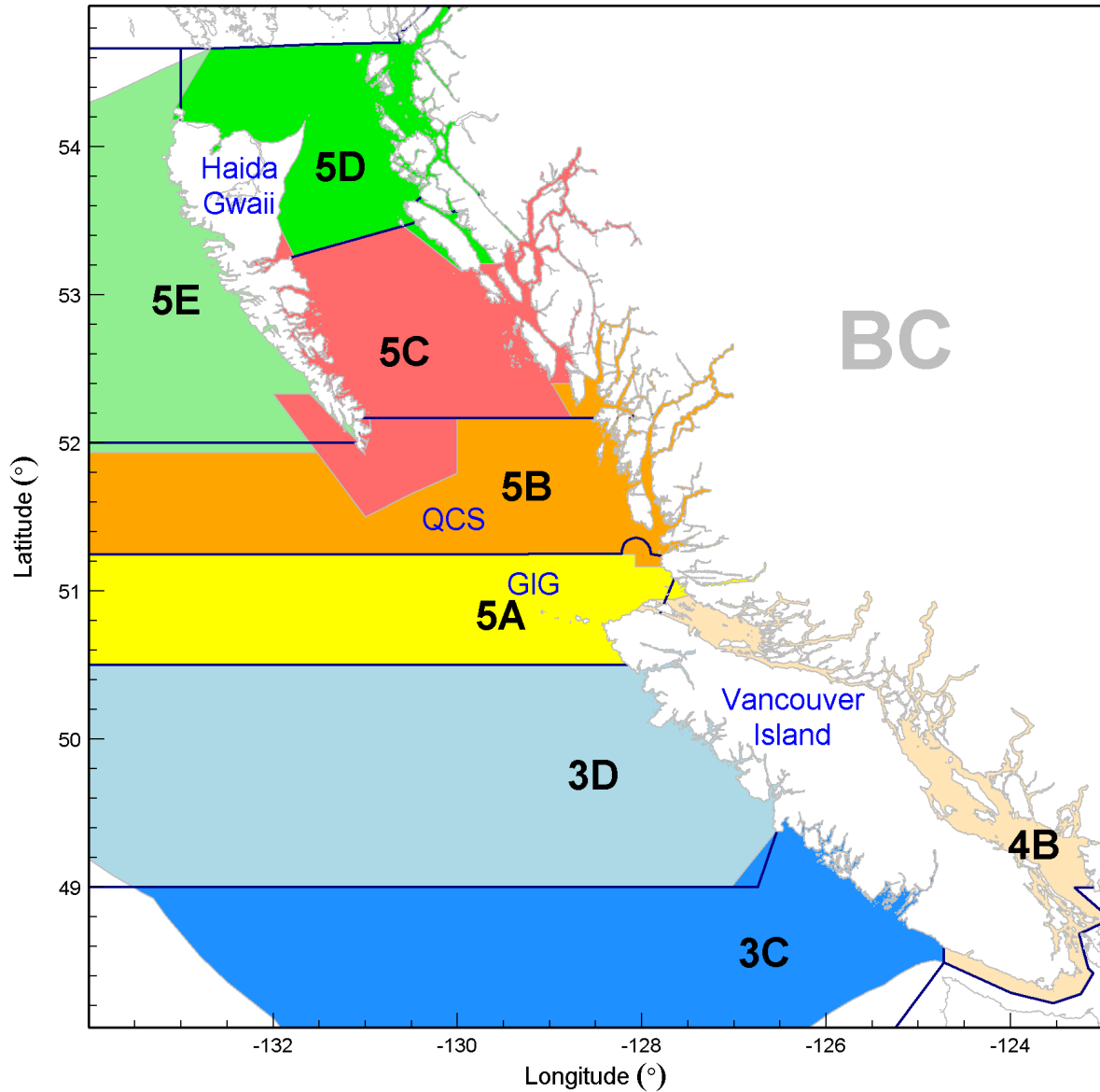


Figure A.1. Pacific Marine Fisheries Commission (PMFC) major areas (outlined in dark blue) compared with Groundfish Management Unit areas for POP and Yellowmouth Rockfish (shaded). For reference, the map indicates Queen Charlotte Sound (QCS) and Goose Island Gully (GIG). This assessment is for PMFC areas 5ABC + Anthony Island combined.

Table A.1. Annual trawl Total Allowable Catches (TACs) in tonnes for Pacific Ocean Perch in groundfish management areas. Note: year can either be calendar year (1979-1996) or fishing year (1997 on).

Year	Start	End	3C	3D	5AB	5CD	5E	Coast	Notes*
1979	1/1/1979	12/31/1979	50	-	2000	-	600	2650	-
1980	1/1/1980	12/31/1980	600	-	2200	-	800	3600	A
1981	1/1/1981	12/31/1981	500	-	1500	1800	800	4600	-
1982	1/1/1982	12/31/1982	500	250	1000	2000	800	4550	-
1983	1/1/1983	12/31/1983	500	250	1000	2000	-	3750	b
1984	1/1/1984	12/31/1984	500	250	800	2000	-	3550	c
1985	1/1/1985	12/31/1985	300	350	850	2000	-	3500	-
1986	1/1/1986	12/31/1986	100	350	500	2000	-	2950	-
1987	1/1/1987	12/31/1987	100	350	500	2000	-	2950	-
1988	1/1/1988	12/31/1988	100	350	700	3000	-	4150	-
1989	1/1/1989	12/31/1989	150	400	850	3000	400	4800	-
1990	1/1/1990	12/31/1990	150	400	850	2450	400	4250	-
1991	1/1/1991	12/31/1991	0	400	850	2150	400	3800	-
1992	1/1/1992	12/31/1992	0	400	850	2400	400	4050	-
1993	1/1/1993	12/31/1993	150	400	850	2400	400	4200	d,e
1994	1/1/1994	12/31/1994	1173	207	2177	1107	253	4917	f
1995	1/1/1995	12/31/1995	548	72	1892	1178	544	4234	-
1996	2/6/1996	3/31/1997	491	164	1500	4003	726	6884	g
1997	4/1/1997	3/31/1998	431	230	2358	2818	644	6481	h,i,j
1998	4/1/1998	3/31/1999	300	230	2070	2817	730	6147	-
1999	4/1/1999	3/31/2000	300	230	2070	2817	730	6147	-
2000	4/1/2000	3/31/2001	300	230	2070	2818	730	6148	k
2001	4/1/2001	3/31/2002	300	230	2070	2818	730	6148	l
2002	4/1/2002	3/31/2003	300	230	2070	2518	730	5848	m
2003	4/1/2003	3/31/2004	300	230	2070	2818	730	6148	-
2004	4/1/2004	3/31/2005	300	230	2070	2818	730	6148	-
2005	4/1/2005	3/31/2006	300	230	2070	2818	730	6148	-
2006	4/1/2006	3/31/2007	300	230	2070	2118	730	5448	n,o
2007	3/10/2007	3/31/2008	300	230	2070	2118	730	5448	-
2008	3/8/2008	2/20/2009	300	230	2070	2118	730	5448	-
2009	2/21/2009	2/20/2010	300	230	2070	2118	730	5448	-
2010	2/21/2010	2/20/2011	300	230	2070	2118	730	5448	-
2011	2/21/2011	2/20/2013	300	230	1942	1987	730	5189	p
2012	2/21/2011	2/20/2013	300	230	1814	1856	730	4930	q
Year	Start	End	3CD	5AB	5C	5DE	H&L	Coast	-
2013	2/21/2013	2/20/2014	750	1687	1544	1200	1	5192	r,s,t,u
2014	2/21/2014	2/20/2015	750	1687	1544	1200	1	5192	
2015	2/21/2015	2/20/2016	750	1687	1544	1200	1	5192	v
2016	2/21/2016	2/20/2017	750	1687	1544	1200	1	5192	w

\*See Table A.2 for management actions indicated by note letter.

Table A.2. Codes to notes on management actions and quota adjustments that appear in Table A.1. Abbreviations that under 'Management Actions': POP = Pacific Ocean Perch, DMP = dockside monitoring program, H&L = hook and line, IVQ = individual vessel quota, WCVI = west coast of Vancouver Island, lbs = pounds (0.4536 kg/lb).

	Year	Management Actions*
a	1980	Started experimental over-harvesting of SW Vancouver Island POP stock.
b	1983	Started experimental unlimited harvesting of Langara Spit POP stock (5EN).
c	1984	Ended experimental over-harvesting of SW Vancouver Island POP stock.
d	1993	Stopped experimental fishing of Langara Spit POP stock.
e	1993	Closed POP fishery in PMFC area 5EN (Langara Spit).
f	1994	Started DMP for Trawl fleet.
g	1996	Started 100% onboard observer program for offshore Trawl fleet.
h	1997	Started IVQ system for Trawl <i>Total Allowable Catch</i> (TAC) species (April 1, 2007)
i	1997	Implemented catch limits (15,000 lbs per trip) on combined non-TAC rockfish for the Trawl fleet.
j	1997	Permanent boundary adjustment – Pacific Ocean Perch and Yellowmouth Rockfish caught within Subarea 102-3 and those portions of Subareas 142-1, 130-3 and 130-2 found southerly and easterly of a straight line commencing at 52°20'00"N 131°36'00"W thence to 52°20'00"N 132°00'00"W thence to 51°30'00"N 131°00'00"W and easterly and northerly of a straight line commencing at 51°30'00"N 131°00'00"W thence to 51°39'20"N 130°30'30"W will be deducted from the vessel's 5CD IVQ for those two species.
k	2000	Formal discussions between the hook and line rockfish (ZN), halibut and trawl sectors were initiated in 2000 to establish individual rockfish species allocations between the sectors to replace the 92/8 split. Allocation arrangements were agreed to for rockfish species that are not currently under TAC. The agreed to splits for these rockfish will be implemented in the future when or if TACs are set for those species.
l	2001	TAC reduction (3y) for POP -- DFO reduced the 5CD POP TAC by 300 tonnes for research use as payment for the Hecate Strait Pacific Cod charter for each of the next three fishing seasons.
m	2002	Closed areas to preserve four hexactinellid (glass) sponge reefs.
n	2006	TAC reduction for POP -- DFO reduced the 5CD POP TAC by 700 tonnes for use in possible research programs.
o	2006	Introduced an <i>Integrated Fisheries Management Plan</i> ( IFMP) for most groundfish fisheries.
p	2011	TAC adjustment (3y) for POP -- combined 5ABCD POP TAC reduction to 3413 t will be achieved over a three year period through an annual reduction of 258 t. The expected catch level will be 68% of TAC.
q	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).
r	2013	To support groundfish research the Groundfish Trawl Industry agreed to the trawl TAC offsets to account for unavoidable mortality incurred in during the 2013 DFO and Trawl industry agreed upon Groundfish Trawl Multi-species surveys: POP in 5AB = 22.6 t, POP in 5C = 0.6 t.
s	2013	New Species Area Groups have been created for Pacific Ocean Perch for 3CD, 5AB, 5C and 5DE.
t	2013	POP Combine 5ABCD TACs reduction to 3413 mt is to be achieved over a three year period through an annual reduction of 258 mt. 2013/14 is the third year of this three year period. The expected catch level is to be 68% of TAC. TAC is subject to annual review.
u	2013	Pacific Ocean Perch within Subarea 127-1 and that portion of Subareas 127-2 found northerly and westerly of 50°06'00"N will be deducted from the vessel's Pacific Ocean Perch rockfish 5A/B IVQ.
v	2015	Research allocations for 2015 to account for the mortalities associated with survey catches within TACs: POP = 17 mt.
w	2016	Research allocations for 2016 to account for the mortalities associated with survey catches within TACs: POP = 57.1 mt.

\* see [Archived Integrated Fisheries Management Plans - Pacific Region](#).

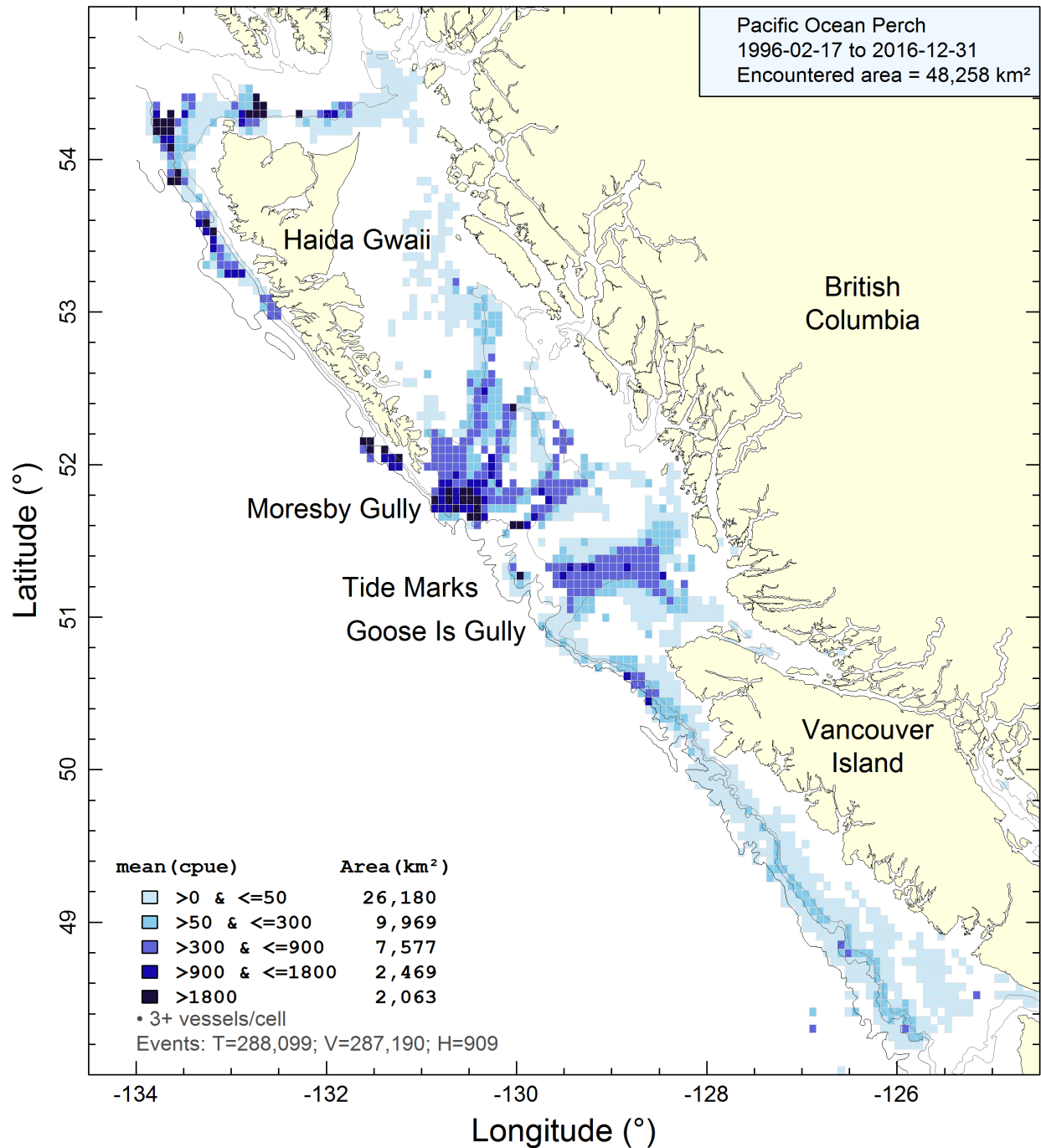


Figure A.2. Aerial distribution of Pacific Ocean Perch mean trawl tow catch per unit effort (kg/hour) from Feb 17, 1996 to Dec 31, 2017 in grid cells 0.075° longitude by 0.055° latitude (roughly 32 km<sup>2</sup>). Isobaths show the 200, 500, and 1200 m depth contours. Note that cells with <3 fishing vessels are not displayed.



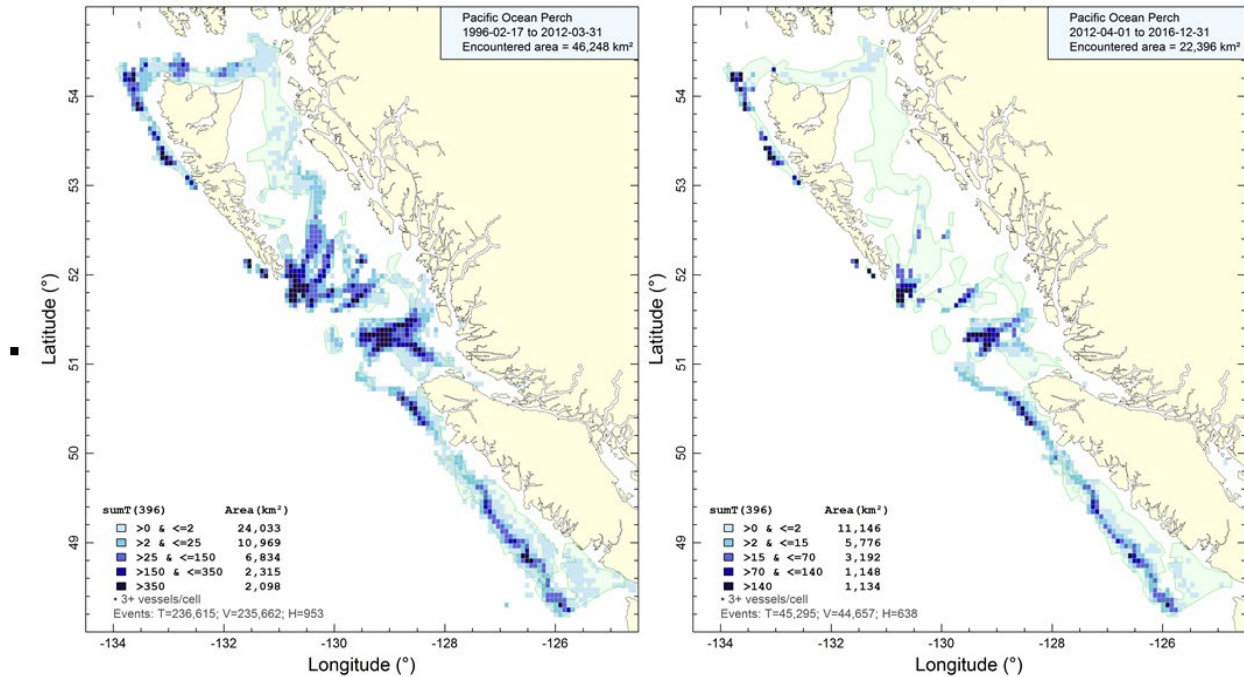


Figure A.3. Aerial distribution of accumulated Pacific Ocean Perch catch (tonnes) before (left) and after (right) the introduction of the trawl footprint in April 2012, limiting areas in which trawl vessels can operate. Note that cells with <3 fishing vessels are not displayed.

## A.2. CATCH RECONSTRUCTION

This assessment reconstructs catch back to 1918 but considers the start of the fishery to be 1940 (Figure A.4, Table A.5) 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. 1976; Leaman and Stanley 1993); however, Ketchen (1980) 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. All historical foreign catches (annual landings) were tracked separately from Canadian landings and added to the latter during the reconstruction process.

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 DFBCV9TWWASP001 server (formerly on the SVBCPBSGFIIS server). Pacific Ocean Perch 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 (2006-2016) – all fisheries and modern surveys; and
- GFBio joint-venture hake and research survey catches (1947-2016) – 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 assessment’s population model uses calendar year, requiring catch estimates to be made by calendar year. As with the previous rockfish assessments, we use “official” catch numbers whenever they have been properly recorded (see Edwards et al. 2014a,b and Yamanaka et al 2018). For POP, landings in BC are considered believable back to 1954, while for most other rockfish the landings history does not start until much later (often 1996). Because we have POP landings from Canadian vessels this far back, the reconstruction of Canadian POP landings only needs to estimate these landings for the years 1940 to 1953 using various ratios (see below), the primary one being POP/TRF landings. These ratios are also used to convert foreign landings of TRF to POP. 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.

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

**Fisheries:** there are five fisheries in the reconstruction (even though trawl dominates so completely that we use only this fishery in the model):

- groundfish trawl (bottom + midwater),
- Halibut longline,
- Sablefish trap/longline.
- Schedule II (mostly Lingcod and Dogfish longline),
- hook and line rockfish (now ZN).

**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, Pacific Ocean Perch.

**TAR:** Target species landed catch.

**gamma:** mean of annual ratios,  $\sum_i RRF_i^L / TRF_i$ , grouped by major PMFC area and fishery using reference years  $i = 1997-2005$ . Note: other RRF species might use ORF in the denominator.

**delta:** mean of annual ratios,  $\sum_i RRF_i^D / TAR_i$ , 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 ratios gamma and delta (Table A.3 and Table A.4, respectively) can be depth-stratified but these was not used in the current assessment (the differences to the reconstruction outcome were negligible). We also wanted to use ratios that would be similar to those used in the 2010 reconstruction (Edwards et al. 2012a).

For this assessment, we include catches from the Anthony Island area, which is a departure from the previous assessment. The adjustment used one of the following criteria to allocate 5E catch to 5C:

- a tow occurred in PMFC 5E with a valid latitude  $\leq 52^{\circ} 20'$  or
- a tow occurred in PMFC major 5E, minor 34, and localities 1 or 5.

The area adjustment to non-stratified catch affects gamma in 5C and 5E (Table A.3) but delta remains the same (Table A.4). The additional catches from the Anthony Island area are small compared to the total 5ABC catch (Figure A.5), and the annual increases are not likely to affect the population model greatly. In the 2010 assessment, PacHarv3 was used for all fisheries, likely inflating trawl catch already reported in GFCatch (Edwards et al. 2014b). The updated annual 5ABC POP catches by trawl fishery and those from the non-trawl fisheries appear in Table A.5. Only the trawl fishery catch was used in the population model.

*Table A.3. Estimated 'gamma' ratios for each fishery and PMFC area without and with depth stratification. The ratios without stratification are also shown for an adjustment to 5C that includes Anthony Island (AI). Only non depth-stratified gammas for adjusted 5ABC trawl (green highlight) are relevant in the catch reconstruction for the current assessment.*

Adjusted PMFC – not stratified by depth (used)					
PMFC	Trawl	Halibut	Sablefish	Dogfish/ Lingcod	H&L Rockfish
3C	0.12526	0.00228	0	0.00056	0.00042
3D	0.05910	0.00203	0	0.00030	0.00083
5A	0.19490	0.00070	0	0	0.00060
5B	0.54392	0.00157	0	0.00005	0.00111
5C+AI	0.39933	0.00017	0	0.00659	0.00318
5D	0.34989	0.00012	0	0	0.00012
5E-AI	0.35695	0.00027	0	0.00009	0.00090
Basic PMFC – not stratified by depth (not used)					
PMFC	Trawl	Halibut	Sablefish	Dogfish/ Lingcod	H&L Rockfish
3C	0.12526	0.00228	0	0.00056	0.00046
3D	0.05910	0.00203	0	0.00030	0.00087
5A	0.19490	0.00070	0	0	0.00061
5B	0.54392	0.00157	0	0.00005	0.00112
5C	0.32715	0.00007	0	2.1E-06	0.00058
5D	0.34989	0.00012	0	0	0.00013
5E	0.39464	0.00031	0	0.00459	0.00145
Basic PMFC – stratified by depth (not used)					
PMFC	Trawl	Halibut	Sablefish	Dogfish/ Lingcod	H&L Rockfish
3C	0.15415	0.00111	0	0	0.00001
3D	0.07816	0.00038	0	0	0.00030
5A	0.17242	0.00062	0	0	0.00027
5B	0.44167	0.00088	0	0	0.00045

PMFC	Trawl	Halibut	Sablefish	Dogfish/ Lingcod	H&L Rockfish
5C	0.30149	0.00006	0	0	0.00054
5D	0.09305	0.00004	0	0	0.00002
5E	0.30557	0.00007	0	0.01239	0.00156

Table A.4. Estimated 'delta' ratios for each fishery and PMFC area without and with depth stratification. The ratios without stratification are also shown for an adjustment to 5C that includes Anthony Island (AI). Only non depth-stratified deltas for adjusted 5ABC trawl (green highlight) are relevant in the catch reconstruction for the current assessment.

Adjusted PMFC – not stratified by depth (used)					
PMFC	Trawl	Halibut	Sablefish	Dogfish/ Lingcod	H&L Rockfish
3C	0.03683	0	0.00011	0	0
3D	0.03208	0	0.00018	0	0
5A	0.01611	6.9E-06	0.00003	0	0
5B	0.01671	5.0E-05	0.00020	0	0
5C+AI	0.04898	0	0	0	0
5D	0.00998	0	0	0	0
5E-AI	0.00273	1.5E-06	6.2E-06	0	0
Basic PMFC – not stratified by depth (not used)					
PMFC	Trawl	Halibut	Sablefish	Dogfish/ Lingcod	H&L Rockfish
3C	0.03683	0	0.00011	0	0
3D	0.03208	0	0.00018	0	0
5A	0.01611	6.9E-06	0.00003	0	0
5B	0.01671	5.0E-05	0.00020	0	0
5C	0.04898	0	0	0	0
5D	0.00998	0	0	0	0
5E	0.00273	1.5E-06	6.2E-06	0	0
Basic PMFC – stratified by depth (not used)					
PMFC	Trawl	Halibut	Sablefish	Dogfish/ Lingcod	H&L Rockfish
3C	0.03377	0	0.00012	0	0
3D	0.02371	0	0.00019	0	0
5A	0.01463	9.0E-06	0.00021	0	0
5B	0.01634	0.00005	0.00016	0	0
5C	0.05756	0	0	0	0
5D	0.09210	0	0	0	0
5E	0.00219	1.3E-06	4.1E-06	0	0

Table A.5. Reconstructed catches (in tonnes, landings + releases) of POP in PMFC 5ABC from all fisheries. Only those from the trawl fishery were used in the population model. Catches designated '0' are zero catches; those designated '0.000' indicate catches of less than 1 kg.

Year	Trawl	Halibut	Sablefish	Dogfish+ Lingcod	H&L Rockfish	Total
1940	27	0.001	0	0.001	0.025	27
1941	16	0.001	0	0.001	0.005	16
1942	180	0.004	0	0.000	0.003	180
1943	542	0.004	0	0.001	0.002	542
1944	249	0.011	0	0.003	0.002	249

Year	Trawl	Halibut	Sablefish	Dogfish+ Lingcod	H&L Rockfish	Total
1945	2,129	0.014	0	0.003	0.014	2,129
1946	1,170	0.022	0	0.008	0.012	1,170
1947	609	0.032	0	0.011	0.033	609
1948	961	0.005	0	0.017	0.044	961
1949	1,157	0.008	0	0.025	0.069	1,157
1950	1,091	0.011	0	0.004	0.098	1,091
1951	1,185	0.005	0	0.006	0.016	1,185
1952	1,044	0.024	0	0.008	0.025	1,044
1953	820	0.022	0	0.003	0.033	821
1954	2,583	0.007	0	0.025	0.014	2,583
1955	602	0.006	0	0.010	0.091	602
1956	1,413	0.001	0	0.003	0.051	1,413
1957	1,067	0.003	0	0.002	0.016	1,067
1958	958	0.005	0	0.003	0.012	958
1959	1,960	0.001	0	0.001	0.008	1,960
1960	1,779	0.002	0	0.001	0.006	1,779
1961	1,167	0.004	0	0.000	0.008	1,167
1962	1,882	0.005	0	0.000	0.002	1,882
1963	3,809	0.005	0	0.006	0.003	3,809
1964	3,606	0.020	0	0.002	0.021	3,607
1965	8,202	0.006	0	0.014	0.011	8,202
1966	22,594	0.003	0	0.007	0.043	22,594
1967	17,937	0.005	0	0.002	0.041	17,937
1968	13,069	0.004	0	0.006	0.014	13,069
1969	10,047	0.004	0	0.003	0.019	10,047
1970	8,076	0.013	0	0.009	0.013	8,076
1971	4,504	0.024	0	0.001	0.029	4,504
1972	6,797	0.016	0	0.014	0.008	6,798
1973	6,171	0.019	0	0.041	0.052	6,171
1974	9,477	0.008	0	0.033	0.130	9,477
1975	5,700	0.006	0	0.023	0.104	5,700
1976	2,834	0.016	0	0.020	0.081	2,835
1977	1,261	0.020	0	0.054	0.062	1,261
1978	3,088	0.025	0	0.073	0.146	3,088
1979	1,900	0.020	0	0.021	0.204	1,900
1980	4,177	0.021	0	0.036	0.077	4,177
1981	4,043	0.016	0	0.048	0.129	4,043
1982	4,953	0.012	0	0.055	0.150	4,953
1983	4,605	0.059	0	0.042	0.175	4,605
1984	3,642	0.048	0	0.031	0.132	3,642
1985	3,768	0.046	0	0.032	0.099	3,768
1986	1,545	0.176	0	0.032	0.096	1,545
1987	4,479	0.329	0	0.030	0.097	4,479
1988	4,992	0.599	0.224	0.117	0.108	4,993
1989	3,364	0.394	0.142	0.204	0.357	3,365
1990	3,654	0.488	0.212	0.249	0.666	3,656
1991	3,942	0.429	0.182	0.172	0.366	3,943
1992	3,911	0.372	0.045	0.153	0.172	3,912
1993	3,244	0.327	0.086	0.210	0.052	3,245
1994	5,332	0.448	0.109	0.181	0.746	5,334
1995	6,236	0.441	0.134	0.188	2.305	6,239
1996	5,208	0.954	0.155	0.190	0.456	5,210
1997	4,814	0.180	0.158	0.139	1.777	4,816
1998	4,706	0.210	0.096	0.471	0.403	4,708
1999	4,516	0.283	0.104	0	1.342	4,518
2000	5,016	0.303	0.144	0	1.099	5,017

Year	Trawl	Halibut	Sablefish	Dogfish+ Lingcod	H&L Rockfish	Total
2001	4,354	0.304	0.214	0.000	0.827	4,355
2002	4,549	0.501	0.158	0.583	1.129	4,552
2003	4,986	0.390	0.156	0	0.975	4,987
2004	4,611	0.367	0.134	0	1.595	4,613
2005	3,754	0.483	0.052	0	0.722	3,756
2006	4,337	0.352	0.092	0	0.524	4,338
2007	3,690	0.249	0.118	0	0.118	3,691
2008	2,956	0.264	0.559	0	0.073	2,957
2009	3,216	0.179	0.248	0.002	0.042	3,216
2010	4,252	0.120	0.001	0.001	0.013	4,252
2011	3,111	0.107	0.001	0.001	0.039	3,111
2012	3,069	0.189	0.007	0.001	0.127	3,070
2013	2,084	0.129	0.041	0.006	0.063	2,085
2014	1,666	0.067	0.055	0	0.068	1,666
2015	2,547	0.086	0.015	0	0.057	2,547
2016	2,618	0.088	0	0.001	0.015	2,618

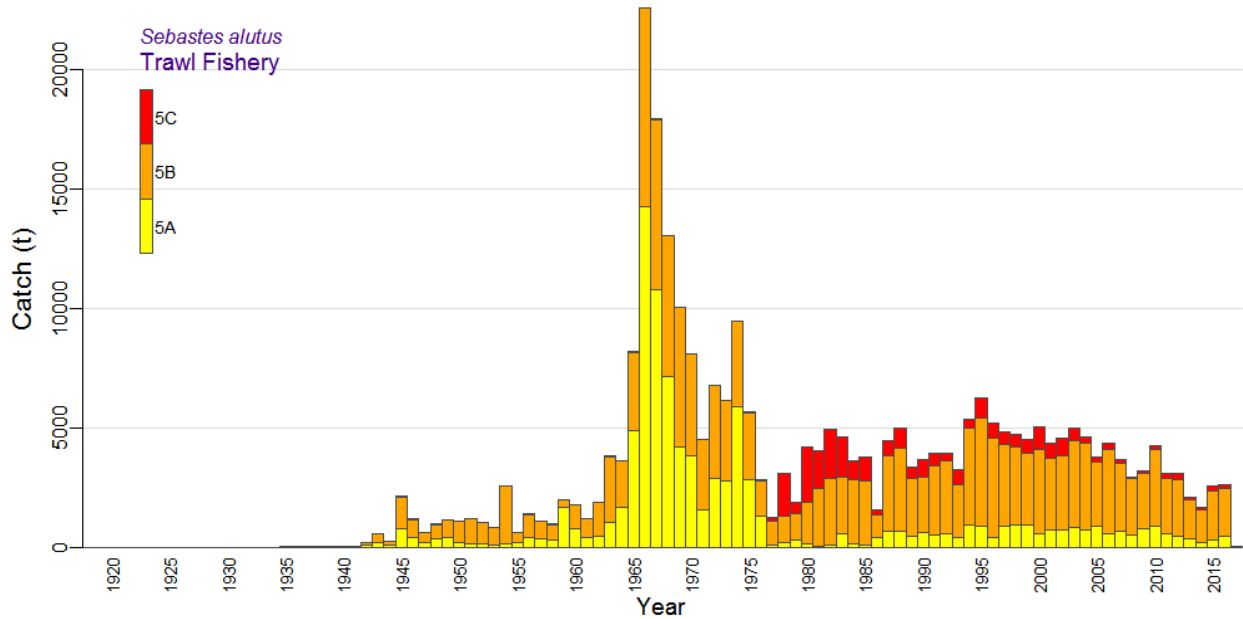


Figure A.4. Reconstructed total (landed + released) catch (t) for Pacific Ocean Perch from the trawl fishery in PMFC major areas 5A, 5B, and 5C adjusted to include Anthony Island. Catches from other fisheries were negligible.

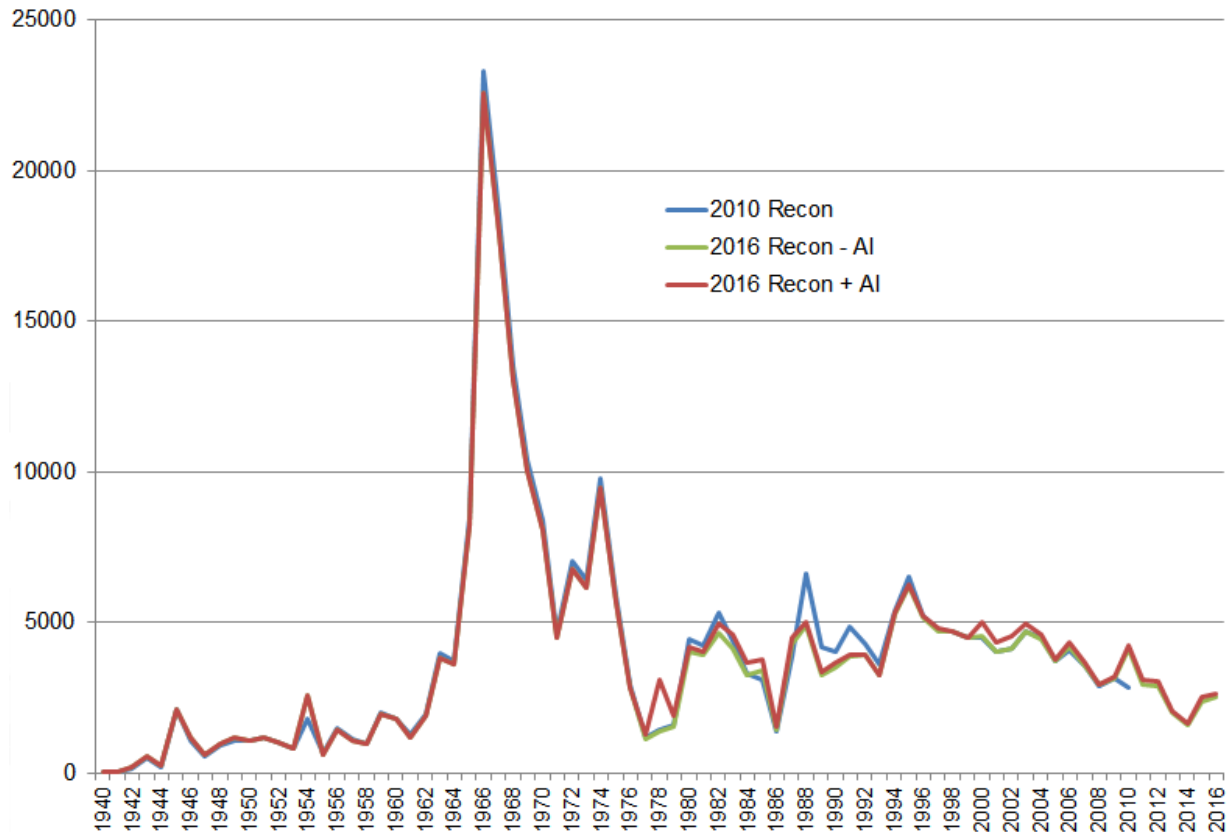


Figure A.5. Comparison of reconstructed catch (t) for 5ABC Pacific Ocean Perch from the trawl fishery for 2010 excluding Anthony Island (AI) catch (blue), 2016 excluding AI (green), and 2016 including AI (red).

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## APPENDIX B. TRAWL SURVEYS

### B.1. INTRODUCTION

This appendix summarises the derivation of the relative Pacific Ocean Perch (POP) abundance indices from the:

1. historical Goose Island Gully (GIG) surveys within Queen Charlotte Sound
2. Queen Charlotte Sound groundfish synoptic survey
3. Queen Charlotte Sound shrimp survey

### B.2. ANALYTICAL METHODS

Catch and effort data for stratum  $i$  in year  $y$  yield catch per unit effort (CPUE) values  $U_{yi}$ .

Given a set of data  $\{C_{yij}, E_{yij}\}$  for tows  $j = 1, \dots, n_{yi}$ ,

$$U_{yi} = \frac{1}{n_{yi}} \sum_{j=1}^{n_{yi}} \frac{C_{yij}}{E_{yij}}, \quad (\text{B.1})$$

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  $\delta_{yi}$  (kg/km<sup>2</sup>) using:

$$\delta_{yi} = \frac{1}{vw} U_{yi}, \quad (\text{B.2})$$

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

$w$  = average net width (m).

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

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

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 ( $B_y$ ) is then the sum of the product of CPUE densities and bottom areas across  $m$  strata:

$$B_y = \sum_{i=1}^m \delta_{yi} A_i = \sum_{i=1}^m B_{yi}, \quad (\text{B.4})$$

where  $\delta_{yi}$  = mean CPUE density (kg/km<sup>2</sup>) for stratum  $i$ , year  $y$  ;  
 $A_i$  = area (km<sup>2</sup>) 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<sup>2</sup>) follows:

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

where  $\sigma_{yi}^2$  = variance of CPUE density (kg<sup>2</sup>/km<sup>4</sup>) for stratum  $i$ , year  $y$  ;  
 $V_{yi}$  = variance of the biomass estimate (kg<sup>2</sup>) for stratum  $i$ , year  $y$  .

The coefficient of variation ( $CV_y$ ) of the annual biomass estimates ( $B_y$ ) is

$$CV_y = \frac{\sqrt{V_y}}{B_y}. \quad (\text{B.6})$$

### B.3. EARLY GIG SURVEYS IN QUEEN CHARLOTTE SOUND

#### 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 quite wide ranging, with the 1965 survey (Westrheim 1966a, 1967b) extending from near San Francisco to halfway up the Alaskan panhandle ([left panel] Figure B.1). The 1966 survey (Westrheim 1966b, 1967b) was only slightly less ambitious, ranging from the southern US-Canada border in Juan de Fuca Strait into the Alaskan panhandle ([right panel] Figure B.1). 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 surveys which were much narrower in terms of area covered and which had a much higher density of tows in GIG. This can be seen in the small number of tows used by the first two surveys in GIG (Table B.1).

The 1967 ([left panel] Figure B.2) and 1969 ([right panel] Figure B.2) surveys (Westrheim 1967a, 1969; Westrheim et al. 1968) performed tows on the west coast of Vancouver Island, the Queen Charlotte Islands 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, 1976 and 1977 surveys (Harling et al. 1973; Westrheim et al. 1976; Harling and Davenport 1977) covered both Goose Island and Mitchell Gullies in Queen Charlotte Sound ([right panel] Figure B.3 and Figure B.4).

The 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 ([left panel] Figure B.5). 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 used in the assessment.

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The 1984 survey (Nagtegaal et al. 1986) was conducted by two vessels: the *G.B. Reed* and the *Eastward Ho*. 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 – G. 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 ([right panel] Figure B.5). However, the two vessels fished more contiguously in Mitchell Gully ([right panel] Figure B.5). When the depth-stratified catch rates 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 (Hand et al. 1995), conducted by another commercial vessel (the *Ocean Selector*, Table B.2) ([left panel] Figure B.6), was used in the series without modification. This was done because the 1994 survey was executed using a design that emulated the previous *G.B. Reed* surveys as closely as possible (G. Workman, DFO, pers. comm.), as well as being supported by the conclusion that, in 1984, the research and commercial vessels did not have significantly different catch rates.

The 1995 survey (Yamanaka et al, 1996), 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 ([right panel] Figure B.6) (G. Workman, DFO, pers. comm.). This design was entirely different from that used in the previous surveys and thus this survey could not be used in the GIG series.

Given that the only area that was consistently monitored by these surveys was the GIG grounds, tows lying between 50.9°N and 51.6°N latitude from the eight acceptable survey years, covering the period from 1967 to 1994, were used to index the Queen Charlotte Sound POP population (Table B.1).

The original depth stratification of these surveys was in 20 fathom (36.1 m) intervals, with the important strata for POP ranging from 100 fathoms (183 m) to 180 fathoms (329 m). This depth range accounted for about 95% of the tows which captured POP (Table B.3). For the GIG survey series, the shallowest tow capturing POP was 121 m. Similarly, the deepest tow capturing POP was 428 m (and was also the deepest recorded tow). These depth strata were combined for analysis into three ranges: 70–100 fm, 100–120 fm and 120–160 fm, for a total of 352 tows from the eight accepted survey years (Table B.4).

A doorspread density value (B.4) was calculated for each tow based on the catch of POP, 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).

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### B.3.2. Results

Maps showing the locations where POP were caught in the GIG indicate that this species is found throughout the entire gully in all years (Figure B.7). Estimated biomass levels in the GIG for Pacific Ocean Perch from the historical GIG trawl surveys declined from the late 1960s to the end of the 1970s, with a possible recovery into the 1980s and early 1990s (Figure B.8; Table B.5). However, the long interval between surveys during this period reduces our confidence in this interpretation. The proportion of tows which caught POP is high, exceeding 95% in all survey years except for 1994 where 90% of the tows captured POP (Figure B.9). Survey relative errors are low for this species, consistent with the high frequency of this species in the tows, ranging from 0.09 to 0.21 and with seven of the eight accepted surveys below 0.20 (Table B.5).

## B.4. QUEEN CHARLOTTE SOUND SYNOPTIC TRAWL SURVEY

### B.4.1. Data selection

This survey has been conducted in eight years over the period 2003 to 2015 in Queen Charlotte Sound between Vancouver Island and Moresby Island and extending 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.11 to Figure B.17). 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.6).

The 1995 random stratified survey, described in the previous section ([right panel] Figure B.6), was considered for inclusion in this series. However, this suggestion was reviewed by a Centre for Science Advice Pacific (CSAP) meeting held in December 2009 and was not accepted. The reason for this rejection was that, while both surveys were based on a random stratified design, the 1995 survey was exclusively targeting POP while the Queen Charlotte Sound synoptic survey targets a broad range of species, including POP. The meeting concluded that this difference in survey target species would affect the way that the survey skippers fished, leading to POP catch rates that would not be comparable between the 1995 survey and the surveys that have been undertaken since 2003.

A doorspread density value (B4) was generated for each tow based on the catch of POP, 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 (B.3). A calculated value ([vessel speed] X [tow duration]) can be used for this variable if [distance travelled] is missing, but there were only two instances of this occurring in the 8 trawl surveys. Missing values for the [doorspread] field were filled in with the mean doorspread for the survey year (140 values over all years: Table B.7).

### B.4.2. Results

Pacific Ocean Perch were mainly taken at depths from 160 to 320 m, but there were sporadic observations at depths up to about 400 m (Figure B.18). The highest catch densities were found in the North stratum, but POP are present at good densities in both strata (see the right side density plots in Figure B.11 to Figure B.17).

Estimated POP doorspread biomass from this trawl survey decreased from 2003 to 2007, with the next four estimates showing no trend (Figure B.19; Table B.8). The most recent 2015 index

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showed an increase relative to the level of the previous four indices, but the confidence bounds were wide and overlapping. The estimated relative errors were reasonably low, ranging from 14 to 25% (Table B.8). The proportion of tows that captured POP was relatively higher in the North stratum, ranging from 0.63 to 0.78, while the range of proportions in the South was 0.45 to 0.69 (Figure B.20). Overall, 1194 of the 1909 valid survey tows contained POP.

## **B.5. QUEEN CHARLOTTE SOUND SHRIMP SURVEY**

### **B.5.1. Data selection**

This survey covers the SE corner of Queen Charlotte Sound extending westward from Calvert Island and Rivers Inlet into the Goose Island Gully (see left side tow distribution maps for each of 16 survey years: Figure B.21 to Figure B.36). There is also a stratum providing coverage between Calvert Island and the mainland but this stratum was not included in the biomass estimates. Five vessels took part in the first year that the survey was conducted (1998) and the timing in that year was later than in subsequent years (July instead of May/early June; Table B.9). It was decided to discard this initial survey year, given the apparent exploratory nature of the design and the potential for non-comparability among vessels in the same year and with subsequent surveys. After the initial year, the survey was conducted annually by the *W.E. Ricker* (except in 2005 when the *Frosti* was used) in May or June up to 2013. Then there was a two-year pause, followed by another survey in 2016. This assessment uses all available survey years from 1999 to 2016.

The survey is divided into three aerial strata: stratum 109 lying to the west of the outside islands and extending into Goose Island Gully; stratum 110 lying to the south of Calvert Island and stratum 111 lying between Calvert Island and the mainland. Stratum 111 has been discarded as its location does not provide good habitat for rockfish species and no POP have ever been captured here. The majority of tows occur in stratum 109 (the larger of the two remaining strata) which also samples at deeper depths, while only a few tows are placed in Stratum 110 which covers a much shallower depth range (Table B.10 Figure B.37). Only tows with usability codes of 1 (usable), 2 (fail, but all data usable), and 6 (gear torn, but all data usable) were included in the biomass estimate. Nearly 1100 usable tows have been conducted by this survey over the 16 available survey years (Table B.10).

These data were analysed using (B.1) to (B.6), which assume that tow locations were selected randomly within a stratum relative to the biomass of POP, even though the actual design of the survey is not random. One thousand bootstrap replicates with replacement were made on the survey data to estimate bias corrected 95% confidence regions for each survey year (Efron 1982).

A doorspread density value (B.3) was generated for each tow based on the catch of POP, an arbitrary doorspread (29.6 m) for the tow, and the distance travelled. The distance travelled was determined at the time of the tow, based on the bottom contact time (J. Boutillier, DFO, pers. comm.). The few missing values for this field were filled in by multiplying the vessel speed and the tow time. All tows were used regardless of depth because this survey, unlike the west coast Vancouver Island shrimp survey, has consistently sampled depths up to about 240 m (Figure B.37), so there was no need to truncate the tows at depth to ensure comparability across survey years.

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## B.5.2. Results

Catches of POP tend to be distributed along the trench of Goose Island Gully and along the shelf edge of the outside islands (see right side plots: Figure B.21 to Figure B.36). Pacific Ocean Perch were taken at depths from 140-240 m and have been taken almost entirely in Stratum 109, with the maximum catch weight in Stratum 110 being only 1.0 kg/tow (Figure B.38).

Estimated biomass levels for POP from the Queen Charlotte Sound shrimp trawl survey are reasonably consistent from 1999 to 2008, showing no strong trend. Biomass indices dropped in 2009 and remained at low levels to 2013, the lowest in the series at under 200 t. The 2016 biomass index is higher at 757 t, which is similar to 2010 index but generally lower than the pre-2009 indices. Relative error in this survey is variable but generally high, ranging between 21% and 63% (Figure B.39; Table B.11). The proportion of tows with Pacific Ocean Perch is higher in Stratum 109, with values from 0.31 to 0.93 (Figure B.40). There are usually fewer than 10 tows per year in Stratum 110 (Table B.10 and this stratum tended to sample the shallowest depths where POP rarely occur (although 2009 had a high proportion of POP in the tows from both strata: 93% in Stratum 109 and 86% in Stratum 110; Figure B.40). Note that the biomass estimate for 2009 is among the lowest in the series, in spite of the high proportion of tows which contained POP. Six hundred and sixteen tows of the 1088 valid tows conducted over 16 years held POP.

Table B.1. Number of tows in GIG and in all 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 Year	GB Reed		Southward Ho		Eastward Ho		Ocean Selector		Frosti	
	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. Number of tows by 20 fathom depth interval (in metres) in GIG and in all other areas (Other) by survey year for the 12 historical (1965 to 1995) surveys. Survey years in grey were not used in the assessment.

Survey year	Areas other than GIG									Total Tows
	146-183	184-219	220-256	257-292	293-329	330-366	367-402	403-439	440-549	
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	2	2	1	1	4	-	17
1969	-	1	-	1	-	1	-	-	-	3
1971	-	1	-	1	1	-	-	-	-	3
1973	-	-	4	3	2	2	2	-	-	13
1976	-	-	6	4	5	4	4	-	-	23
1977	-	-	3	2	5	3	2	-	-	15
1979	11	2	1	5	1	-	-	-	-	20
1984	-	-	4	10	7	7	6	-	-	34
1994	-	-	-	-	2	-	-	-	-	2
1995	-	2	-	1	-	-	-	-	-	3

Survey year	GIG									Total Tows
	146-183	184-219	220-256	257-292	293-329	330-366	367-402	403-439	440-549	
1965	-	2	4	1	1	-	-	-	-	8
1966	3	2	3	5	2	-	-	-	-	15
1967	1	6	11	5	10	-	-	-	-	33
1969	-	9	11	6	6	-	-	-	-	32
1971	-	4	15	8	9	-	-	-	-	36
1973	-	7	11	7	8	-	-	-	-	33
1976	-	7	13	8	5	-	-	-	-	33
1977	1	12	14	14	6	-	-	-	-	47
1979	23	12	18	6	-	-	-	-	-	59
1984	-	13	25	17	13	1	-	-	-	69
1994	-	15	18	20	16	-	-	-	-	69
1995	2	21	47	21	15	6	-	-	-	112

Table B.3. Catch weight (t) of Pacific Ocean Perch by 20 fathom depth interval (in metres) GIG and in all other areas (Other) by survey year for the 12 historical (1965 to 1995) surveys. Survey years in grey were not used in the assessment.

Areas other than GIG										
Survey year	20 fathom depth interval (m)									Total Weight
	146-183	184-219	220-256	257-292	293-329	330-366	367-402	403-439	440-549	
1965	0.00	8.09	13.90	29.40	2.64	4.99	0.27	0.81	0.02	60.12
1966	0.09	1.76	9.55	6.00	1.35	0.35	7.28	0.92	0.10	27.40
1967	0.00	-	0.38	1.83	1.08	0.02	0.84	5.84	-	9.99
1969	-	0.04	-	1.86	-	1.30	-	-	-	3.20
1971	-	0.01	-	0.47	0.56	-	-	-	-	1.04
1973	-	-	1.99	0.68	0.37	0.31	0.29	-	-	3.64
1976	-	-	4.04	4.66	5.76	4.72	2.62	-	-	21.80
1977	-	-	0.25	0.47	2.66	0.73	0.86	-	-	4.97
1979	0.95	0.03	0.00	0.72	0.00	-	-	-	-	1.70
1984	-	-	3.13	3.38	2.29	2.37	0.96	-	-	12.13
1994	-	-	-	-	0.00	-	-	-	-	0.00
1995	-	0.00	-	0.00	-	-	-	-	-	0.00

GIG										
Survey year	20 fathom depth interval (m)									Total Weight
	146-183	184-219	220-256	257-292	293-329	330-366	367-402	403-439	440-549	
1965	-	1.78	1.91	1.60	2.06	-	-	-	-	7.35
1966	0.66	0.31	2.18	4.17	2.43	-	-	-	-	9.75
1967	0.00	1.93	10.79	5.29	9.56	-	-	-	-	27.57
1969	-	7.84	4.88	4.27	5.45	-	-	-	-	22.44
1971	-	0.05	7.70	10.17	9.26	-	-	-	-	27.18
1973	-	1.19	3.24	2.60	3.73	-	-	-	-	10.76
1976	-	1.38	20.21	9.81	8.86	-	-	-	-	40.26
1977	0.00	0.43	5.36	4.36	1.73	-	-	-	-	11.88
1979	0.03	0.48	6.38	1.92	-	-	-	-	-	8.81
1984	-	1.39	22.87	8.52	9.29	0.24	-	-	-	42.31
1994	-	3.02	14.50	9.02	12.11	-	-	-	-	38.65
1995	0.01	12.99	22.77	18.92	13.9	4.00	-	-	-	72.59

Table B.4. Number of tows available by survey year and depth stratum for the analysis of the historical GIG trawl survey series.

Survey Year	Depth stratum			Total
	120-183 m (70-100 fm)	184-218 m (100-120 fm)	219-300 m (100-160 fm)	
1967	7	11	15	33
1969	9	11	12	32
1971	4	15	17	36
1973	7	11	15	33
1976	7	13	13	33
1977	13	14	20	47
1984	13	23	33	69
1994	14	18	37	69
Total	74	116	162	352



Table B.5. Biomass estimates for Pacific Ocean Perch from the historical Goose Island Gully trawl surveys for the years 1967 to 1994. Biomass estimates are based on three depth strata (Table B.4), 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)	Mean bootstrap biomass (t)	Lower bound biomass (t)	Upper bound biomass (t)	Bootstrap CV	Analytic CV Error! Reference source not found.
1967	19,539	19,609	15,321	24,432	0.116	0.121
1969	20,289	20,224	14,039	28,920	0.183	0.180
1971	13,799	13,795	11,579	16,462	0.092	0.093
1973	8,380	8,291	5,479	12,427	0.212	0.219
1976	11,902	11,890	9,064	15,187	0.131	0.133
1977	6,132	6,141	4,279	8,699	0.178	0.177
1984	10,409	10,454	8,625	12,321	0.096	0.098
1994	14,722	14,682	11,531	18,427	0.119	0.122

Table B.6. Number of usable tows for biomass estimation by year and depth stratum for the Queen Charlotte Sound synoptic survey over the period 2003 to 2015. Also shown is the area of each stratum and the vessel conducting the survey by survey year.

Year	Vessel	South depth strata				North stratum				Total tows
		50-125	125-200	200-330	330-500	50-125	125-200	200-330	330-500	
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	62	24	7	19	57	48	7	257
2009	Viking Storm	34	60	28	8	10	44	43	6	233
2011	Nordic Pearl	38	67	25	8	10	51	45	8	252
2013	Nordic Pearl	32	66	29	10	9	46	44	5	241
2015	Frosti	30	65	26	4	12	50	44	8	239
Area (km <sup>2</sup> )		5,072	5,432	2,712	548	1,804	4,060	3,748	1,252	24,628

Table B.7. Number of missing doorspread values by year for the Queen Charlotte Sound synoptic survey over the period 2003 to 2015 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 <sup>1</sup>	Number tows with doorspread observations <sup>2</sup>	Mean doorspread (m) used for tows with missing values <sup>2</sup>
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
Total	101	1,988	71.2

<sup>1</sup> valid biomass estimation tows only

<sup>2</sup> includes tows not used for biomass estimation

Table B.8. Biomass estimates for POP from the Queen Charlotte Sound synoptic trawl survey for the survey years 2003 to 2009. Bootstrap bias corrected confidence intervals and CVs are based on 1000 random draws with replacement.

Survey Year	Biomass (t)	Mean bootstrap biomass (t)	Lower bound biomass (t)	Upper bound biomass (t)	Bootstrap CV	Analytic CV Error! Reference source not found.
2003	22,655	22,706	17,216	29,340	0.136	0.140
2004	16,880	17,003	11,365	27,294	0.233	0.227
2005	14,547	14,727	9,849	21,662	0.193	0.195
2007	10,591	10,559	7,819	14,337	0.155	0.163
2009	12,464	12,361	7,994	20,344	0.245	0.238
2011	12,515	12,479	7,640	20,371	0.250	0.253
2013	11,419	11,323	7,619	15,923	0.183	0.186
2015	14,723	14,698	9,362	22,726	0.228	0.234

Table B.9. Number of sets made by each vessel involved in the Queen Charlotte Sound shrimp trawl by month and survey year. All Queen Charlotte Sound sets are included, not just sets used in the analysis.

Vessel and Year	Month		
	May	Jun	Jul
<b>Frosti</b>			
2005	50	-	-
<b>Ocean Dancer</b>			
1998	-	-	18
<b>Pacific Rancher</b>			
1998	-	-	18
<b>Parr Four</b>			
1998	-	-	17
<b>W. E. Ricker</b>			
1999	-	83	-
2000	84	-	-
2001	72	-	-
2002	72	-	-
2003	63	-	-
2004	65	-	-
2006	68	-	-
2007	65	-	-
2008	69	-	-
2009	66	-	-
2010	59	11	-
2011	67	-	-
2012	67	-	-
2013	67	-	-
2016	67	-	-
<b>Westerly Gail</b>			
1998	-	-	21
<b>Western Clipper</b>			
1998	-	-	18

Table B.10. Stratum designations and number of useable tows, for the Queen Charlotte Sound shrimp survey from 1999 to 2010.

Survey year	Stratum		Total
	109	110	
1999	72	10	82
2000	76	8	84
2001	65	7	72
2002	65	7	72
2003	57	6	63
2004	59	6	65
2005	41	6	47
2006	61	6	67
2007	60	5	65
2008	63	6	69
2009	57	7	64
2010	64	6	70
2011	61	6	67
2012	61	6	67
2013	61	6	67
2016	61	6	67
Total	984	104	1088
Area (km <sup>2</sup> )	2,142	159	2,301

Table B.11. Biomass estimates for Pacific Ocean Perch from the QC Sound shrimp trawl survey for the survey years 1999 to 2016. Bootstrap bias corrected confidence intervals and CVs are based on 1000 random draws with replacement. The analytic CV **Error! Reference source not found.** is based on the assumption of random tow selection within a stratum.

Survey Year	Biomass (t)	Mean bootstrap biomass (t)	Lower bound biomass (t)	Upper bound biomass (t)	Bootstrap CV	Analytic CV Error! Reference source not found.
1999	1,871	1,858	1,235	2,798	0.211	0.216
2000	1,318	1,337	685	2,283	0.307	0.303
2001	1,575	1,565	587	2,833	0.361	0.351
2002	1,199	1,182	357	2,434	0.441	0.468
2003	558	570	204	1,190	0.429	0.426
2004	1,406	1,412	754	2,246	0.265	0.269
2005	1,215	1,208	529	2,297	0.344	0.349
2006	1,896	1,901	1,069	2,884	0.239	0.245
2007	1,458	1,481	754	2,165	0.241	0.251
2008	1,158	1,149	636	1,962	0.281	0.274
2009	381	383	187	660	0.316	0.319
2010	782	783	378	1,395	0.334	0.347
2011	452	448	53	1,177	0.627	0.631
2012	501	515	95	1,260	0.532	0.519
2013	177	173	47	396	0.473	0.493
2016	757	752	388	1,373	0.331	0.342

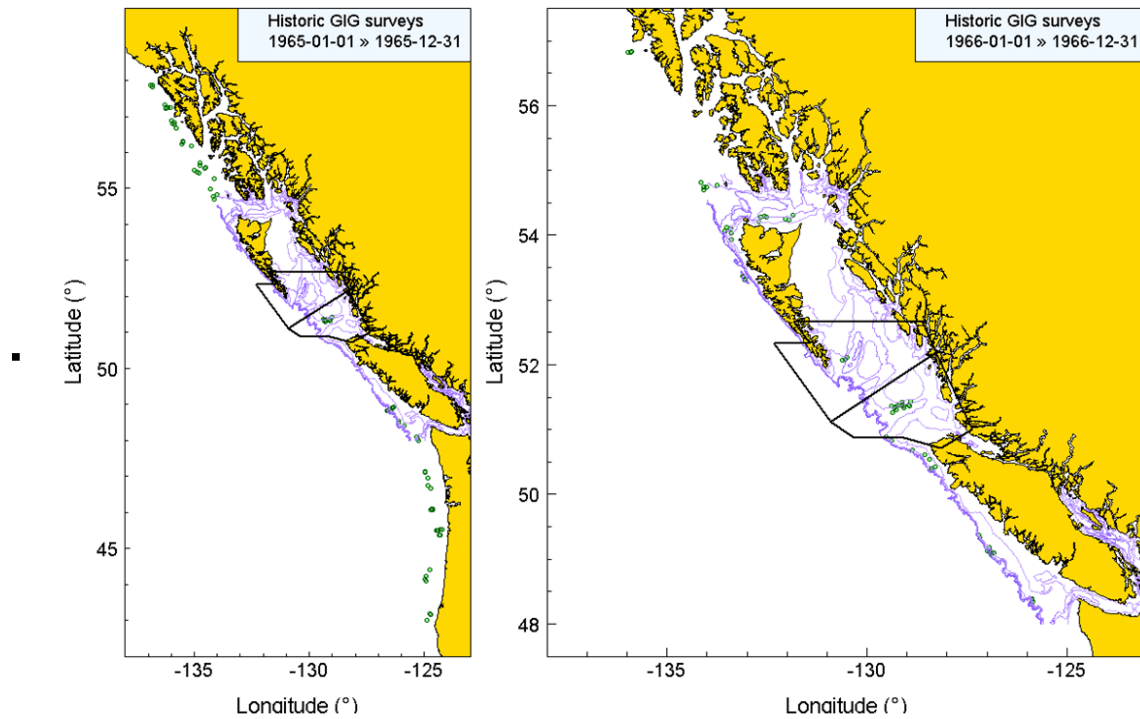


Figure B.1. Extent of the first two GB Reed surveys: [left panel] tow locations for the 1965 survey; [right panel] tow locations for the 1966 survey.

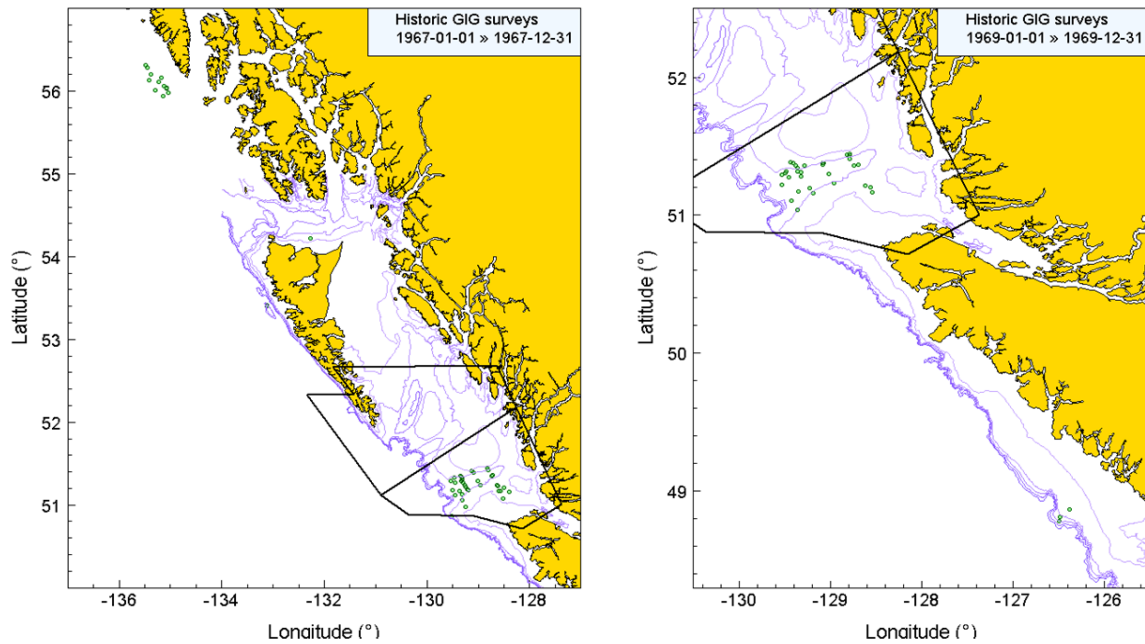


Figure B.2. Extent of the next two historical GB Reed surveys. [left panel] location of tows from the 1967 survey; [right panel] location of tows from the 1969 survey.

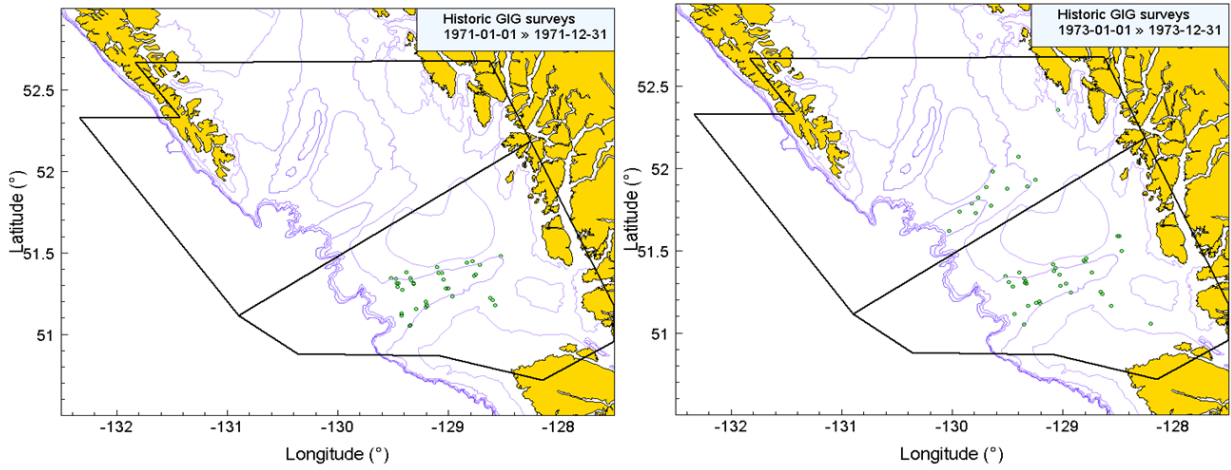


Figure B.3. Extent of the following two historical GB Reed surveys. [left panel] location of tows from the 1971 survey; [right panel] location of tows from the 1973 survey.

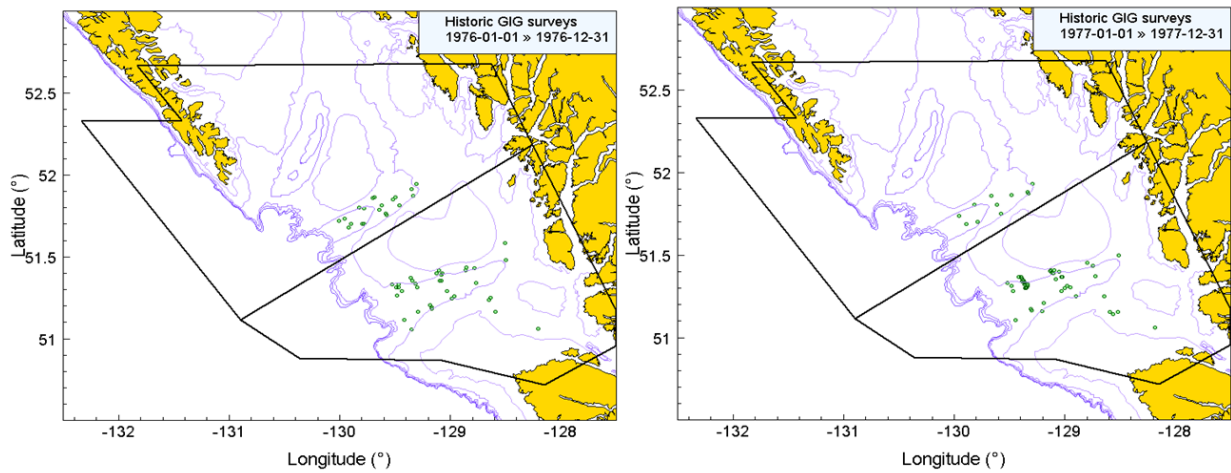


Figure B.4. Extent of the following two historical GB Reed surveys. [left panel] location of tows from the 1976 survey; [right panel] location of tows from the 1977 survey.

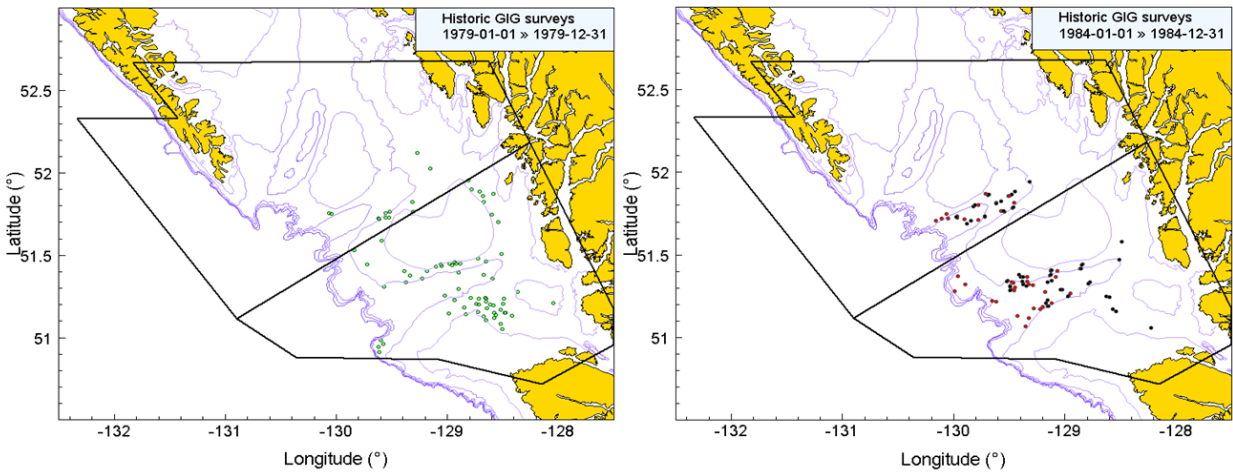


Figure B.5. Extent of the following two historical GB Reed surveys. [left panel] location of tows from the 1979 survey; [right panel] location of tows from the 1984 survey (note: GB Reed tows are black and Eastward Ho tows are red).

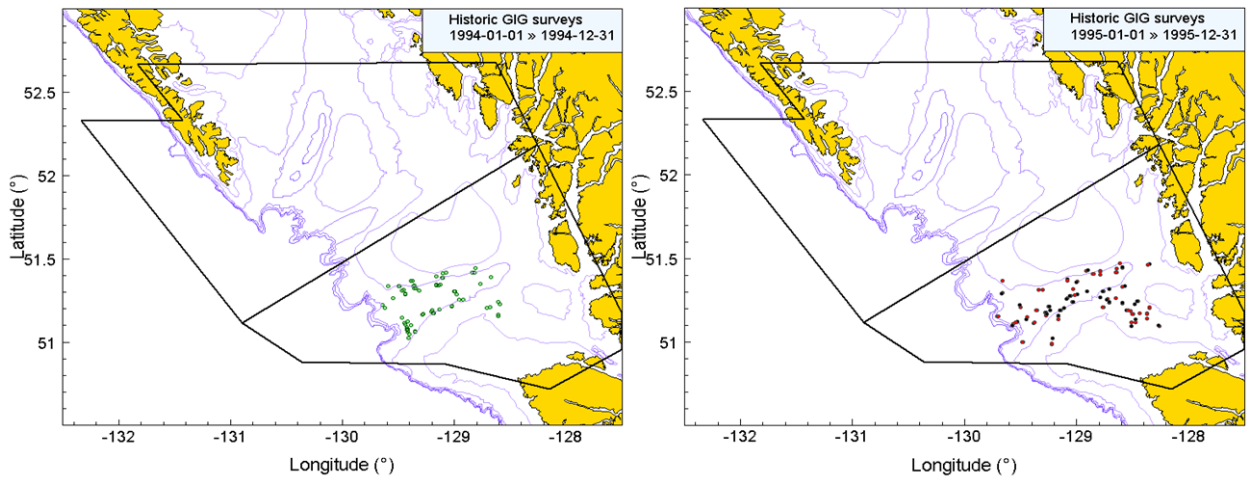
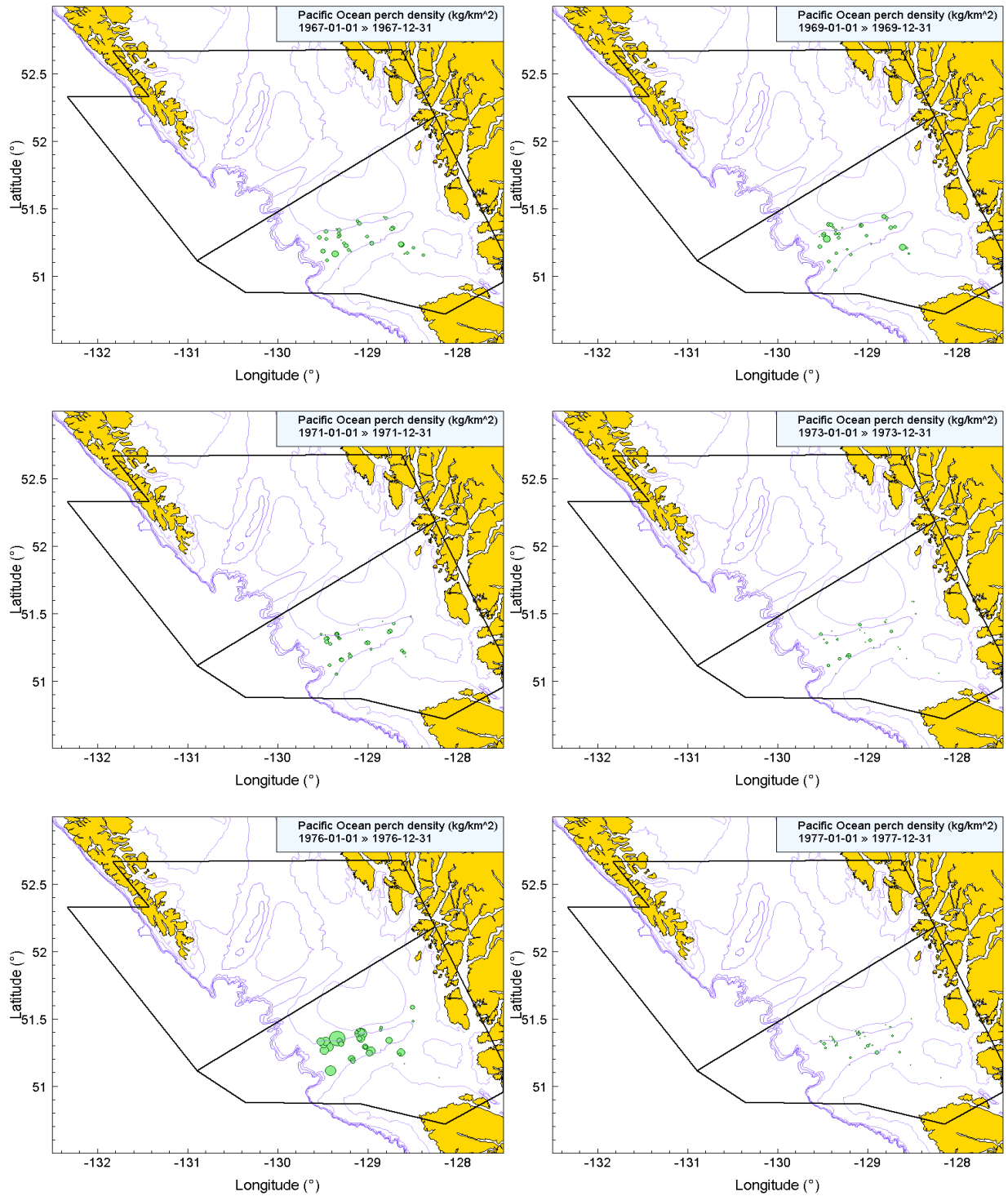


Figure B.6. Extent of the final two historical GB Reed surveys. [left panel] location of tows from the 1994 survey; [right panel] location of tows from the 1995 survey (note: Ocean Selector tows are black and Frosti tows are red).



*Figure B.7. Map of the locations of all trawls which caught Pacific Ocean Perch from the historical Goose Island Gully trawl surveys by survey year (1967–1994). Circles are proportional to POP catch density (largest circle=30,731 kg/km<sup>2</sup> in 1976). Also shown are the 100, 200, 300 and 400 m isobaths. Lines indicate the stratum boundaries for the restratified Queen Charlotte Sound synoptic survey.*

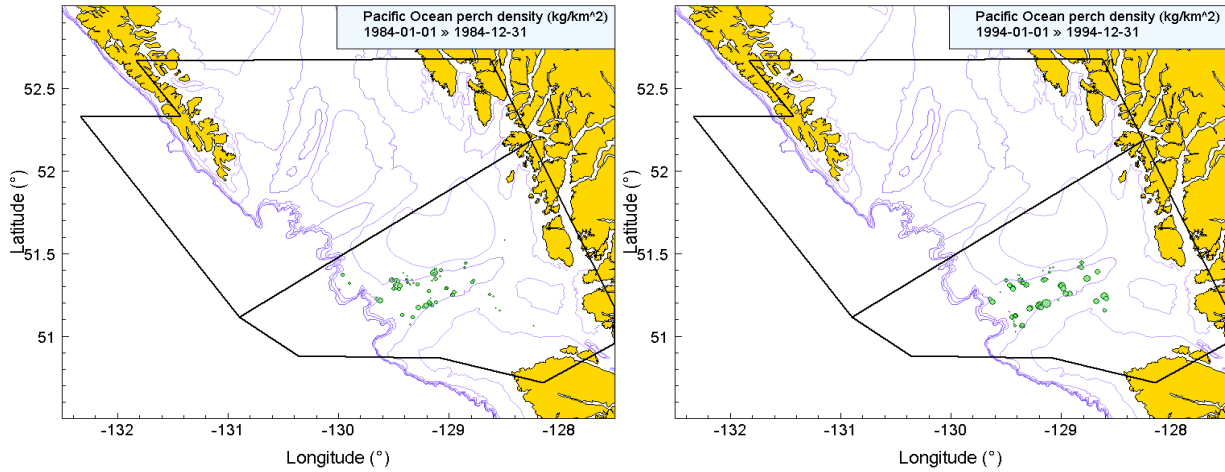


Figure B.7 (cont.).

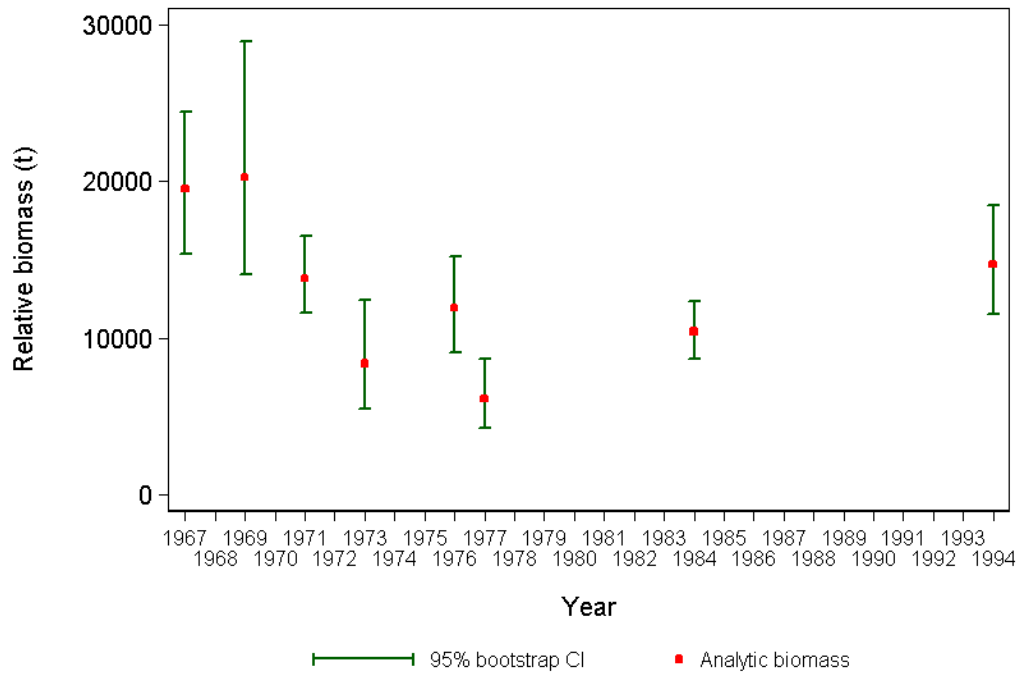


Figure B.8. Plot of biomass estimates for Pacific Ocean Perch from the historical Goose Island Gully GB Reed trawl surveys for the period 1967 to 1994. Bias corrected 95% confidence intervals from 1000 bootstrap replicates are plotted.



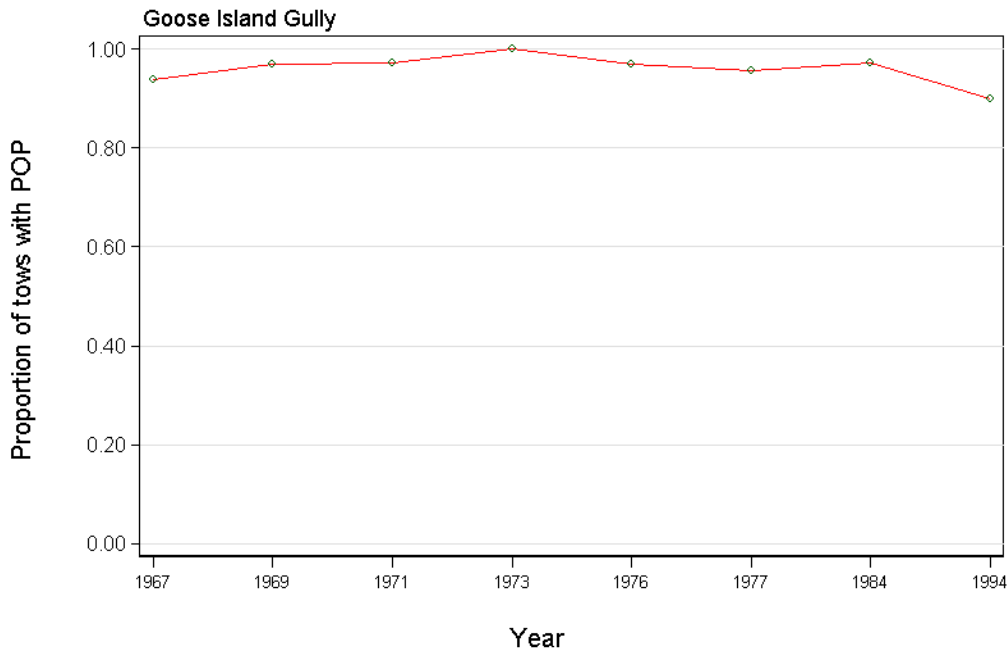


Figure B.9. Proportion of tows by year which contain POP from the usable Goose Island Gully surveys.

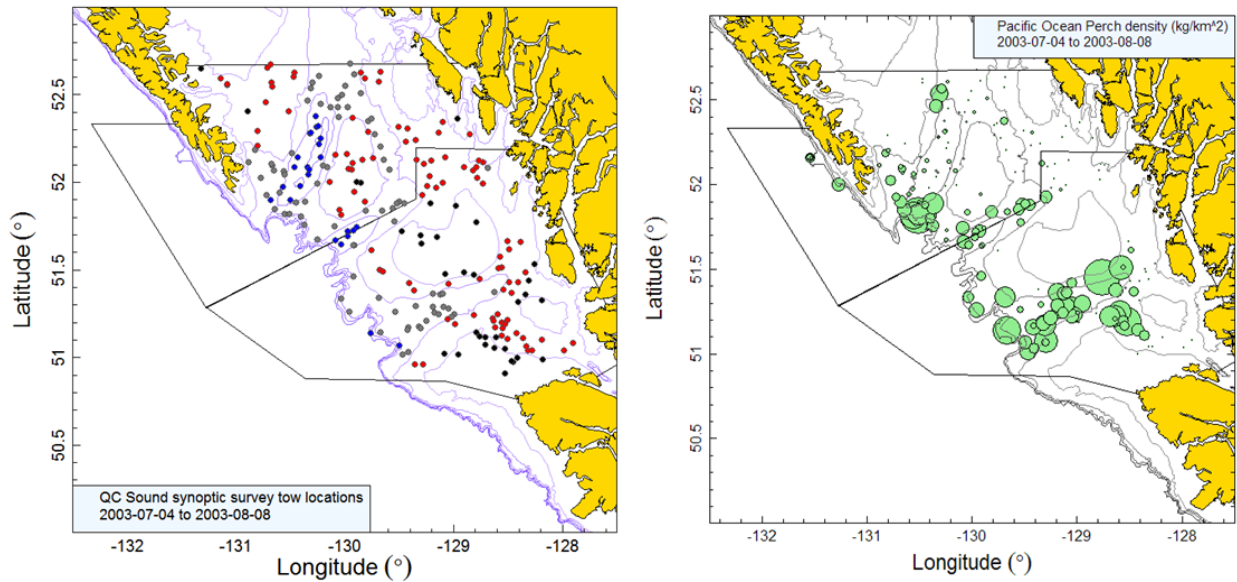


Figure B.10. Valid tow locations (50-125m stratum: black; 126-200m stratum: red; 201-330m stratum: grey; 331-500m stratum: blue) and density plots for the 2003 Queen Charlotte Sound synoptic survey. Circle sizes in the right-hand density plot scaled across all years (2003–2005, 2007, 2009, 2011, 2013, 2015), with the largest circle = 34,852 kg/km<sup>2</sup> in 2004. Boundaries delineate the North and South areal strata.

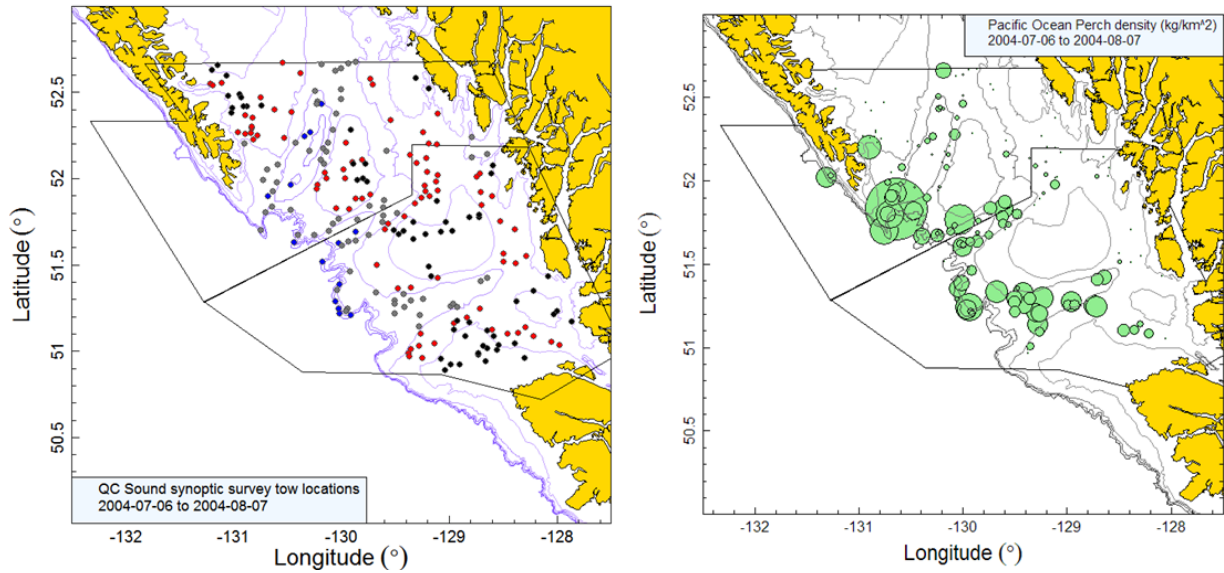


Figure B.11. Tow locations and density plots for the 2004 Queen Charlotte Sound synoptic survey (see Figure B.10 caption).

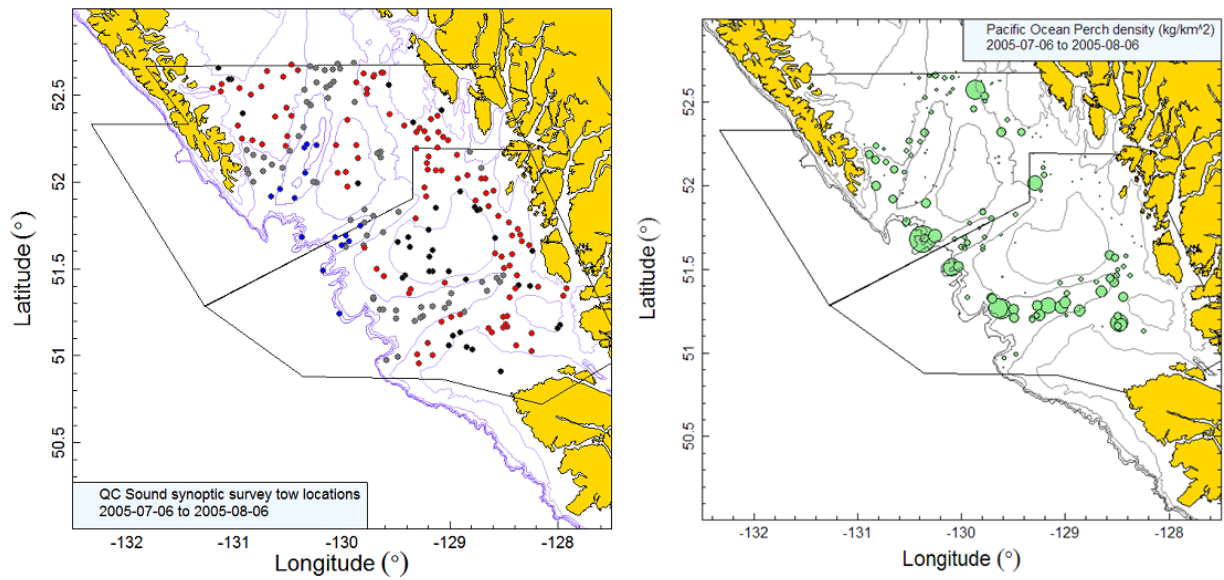


Figure B.12. Tow locations and density plots for the 2005 Queen Charlotte Sound synoptic survey (see Figure B.10 caption).

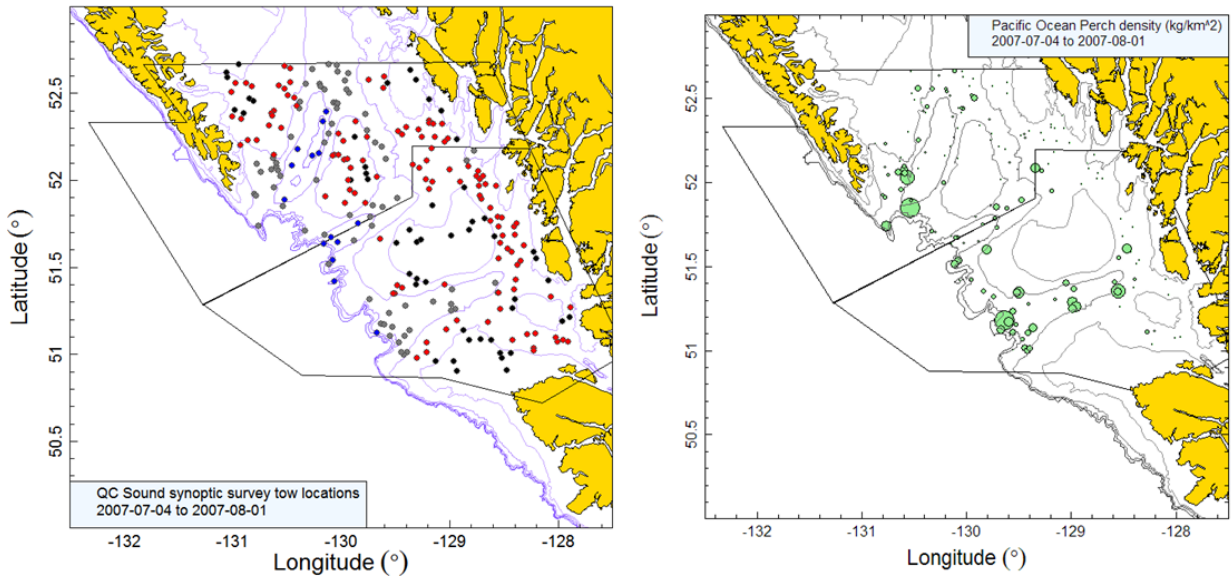


Figure B.13. Tow locations and density plots for the 2007 Queen Charlotte Sound synoptic survey (see Figure B.10 caption).

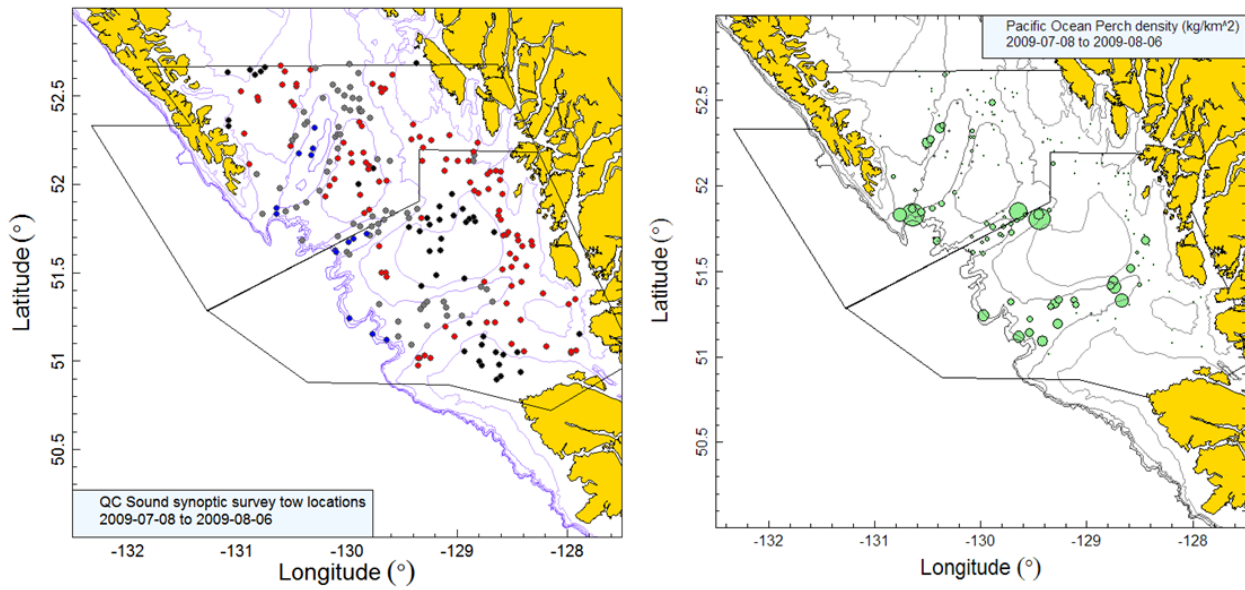


Figure B.14. Tow locations and density plots for the 2009 Queen Charlotte Sound synoptic survey (see Figure B.10 caption).

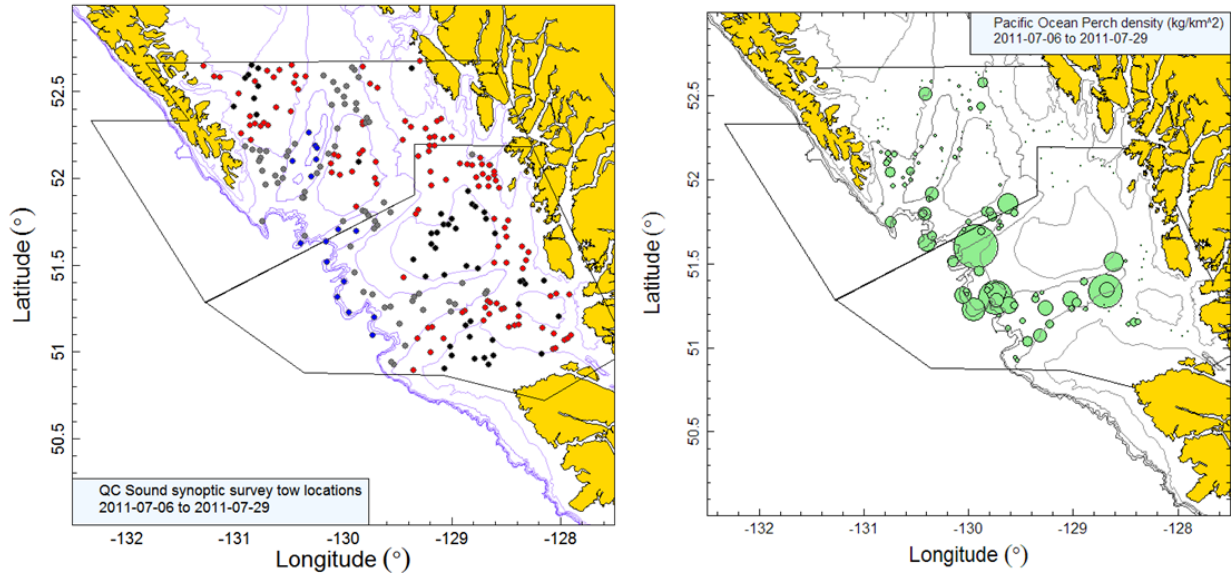


Figure B.15. Tow locations and density plots for the 2011 Queen Charlotte Sound synoptic survey (see Figure B.10 caption).

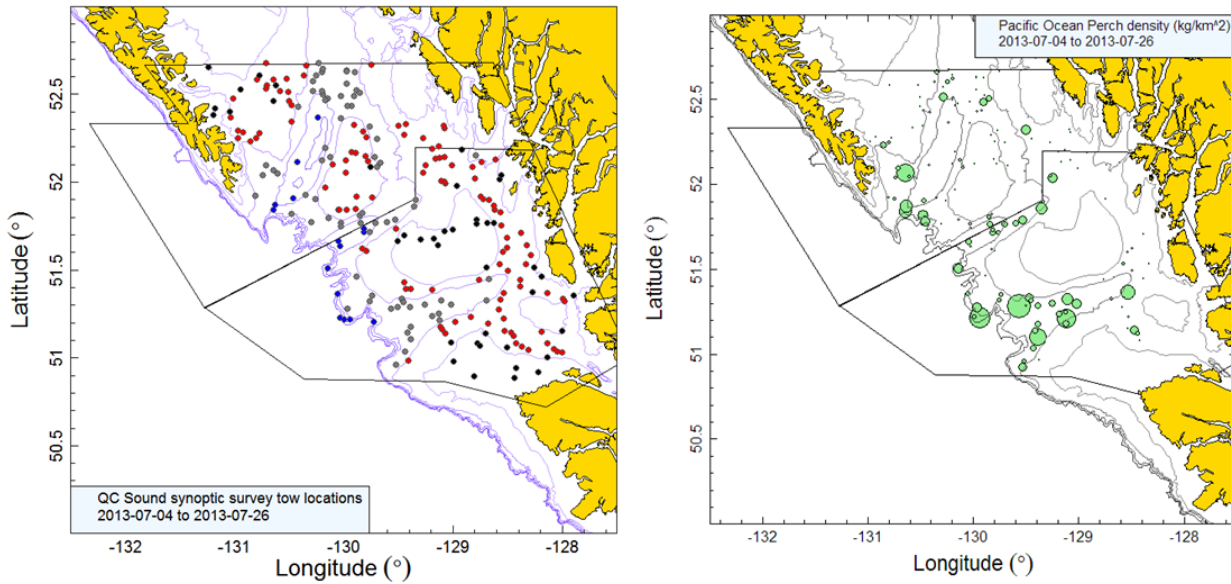


Figure B.16. Tow locations and density plots for the 2013 Queen Charlotte Sound synoptic survey (see Figure B.10 caption).

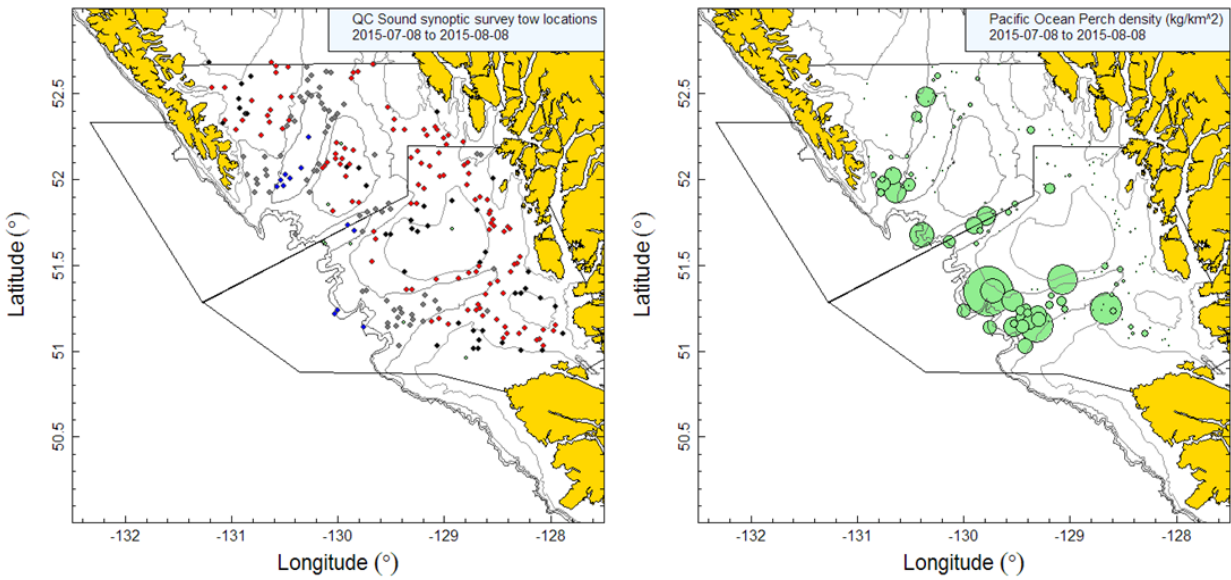


Figure B.17. Tow locations and density plots for the 2015 Queen Charlotte Sound synoptic survey (see Figure B.10 caption).

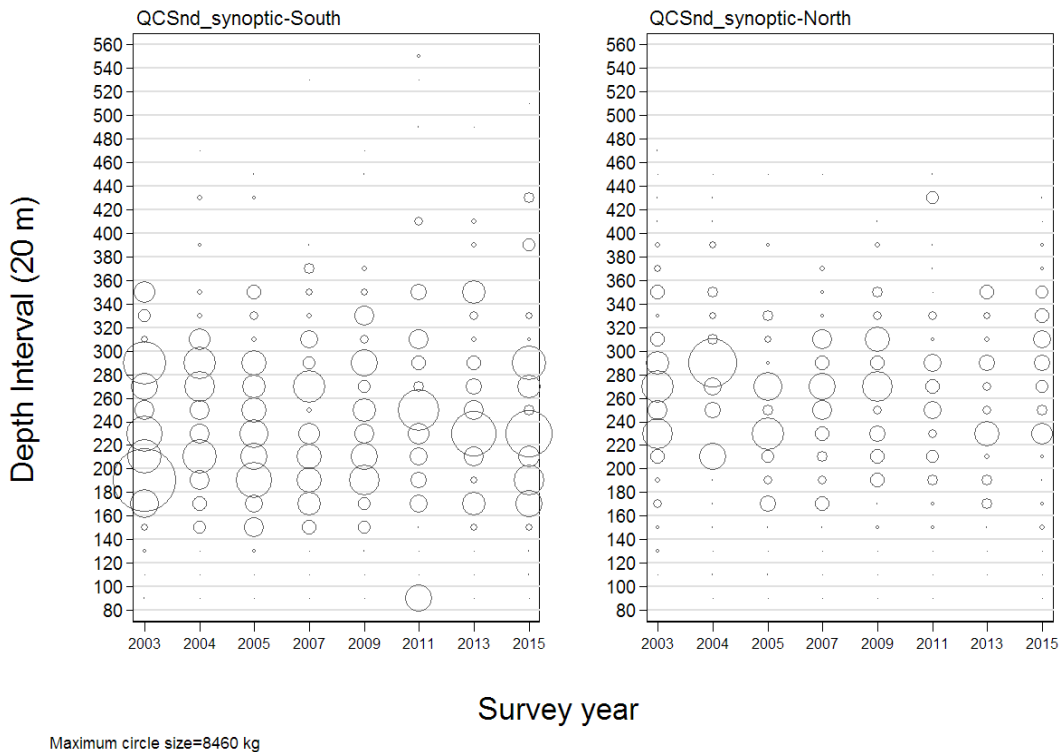


Figure B.18. Distribution of observed catch weights of Pacific Ocean Perch by the two aerial strata (Table B.6), survey year and 20 m depth zone. Depth zones are indicated by the mid point of the depth interval and circles in the panel are scaled to the maximum value in the GIG stratum (8460 kg: 180–200 m interval in 2003). Minimum depth observed for POP: 82 m; maximum depth observed for POP: 547 m. Depth is taken at the start position for each tow.

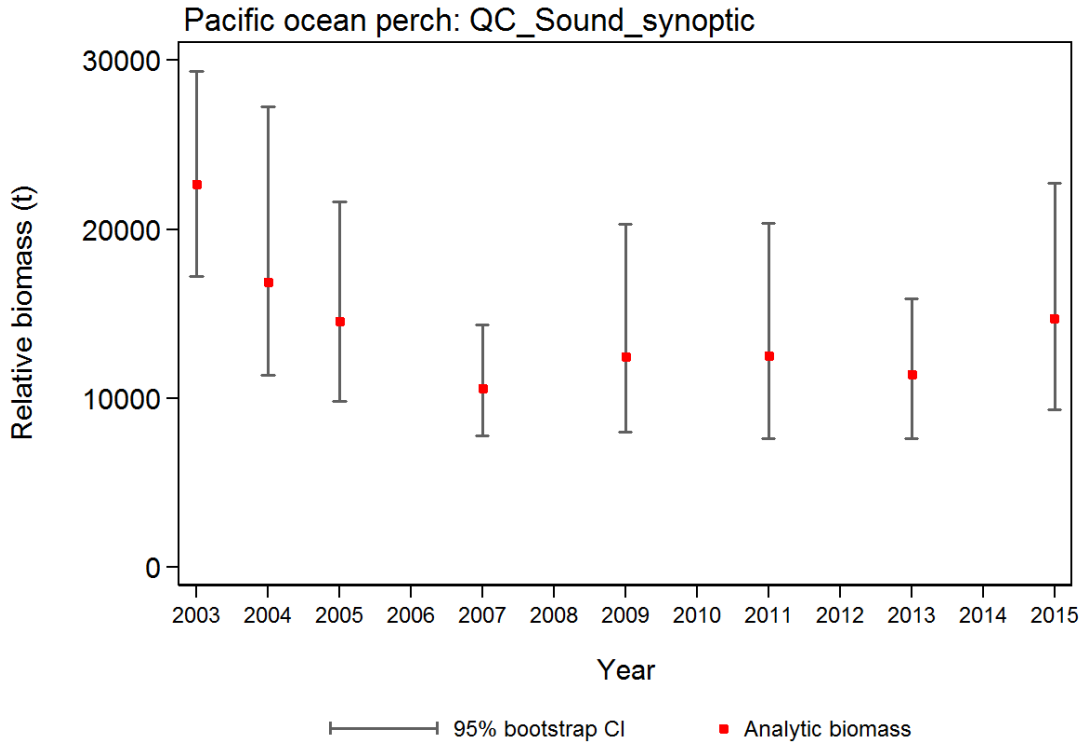


Figure B.19. Plot of biomass estimates for POP from the Queen Charlotte Sound synoptic trawl survey from 2003 to 2015. Bias corrected 95% confidence intervals from 1000 bootstrap replicates are plotted.

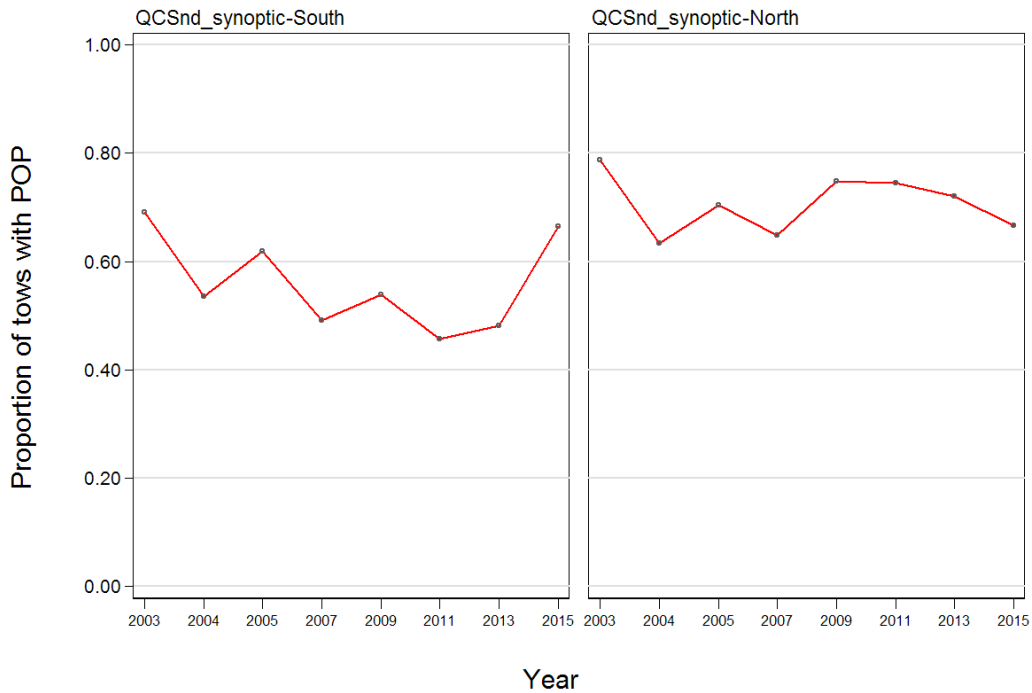


Figure B.20. Proportion of tows by stratum and year which contain POP for the Queen Charlotte Sound synoptic trawl survey.

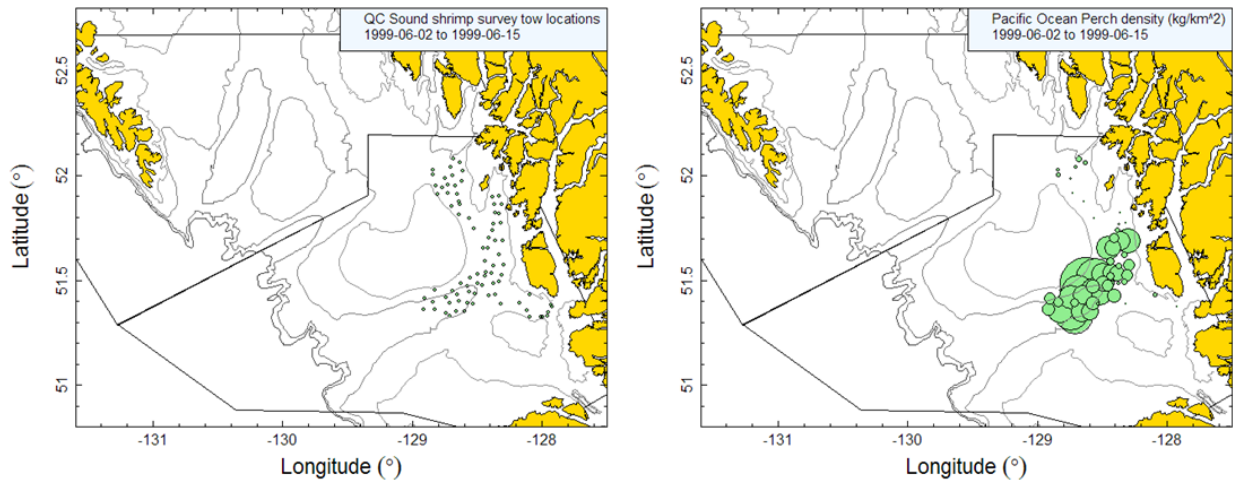


Figure B.21. Valid tow locations and density plots for the 1999 Queen Charlotte Sound shrimp survey. Circle sizes in the right-hand density plot scaled across all years (1999–2013, 2016), with the largest circle = 11,694 kg/km<sup>2</sup> in 2002. Boundaries delineate the North and South areal strata.

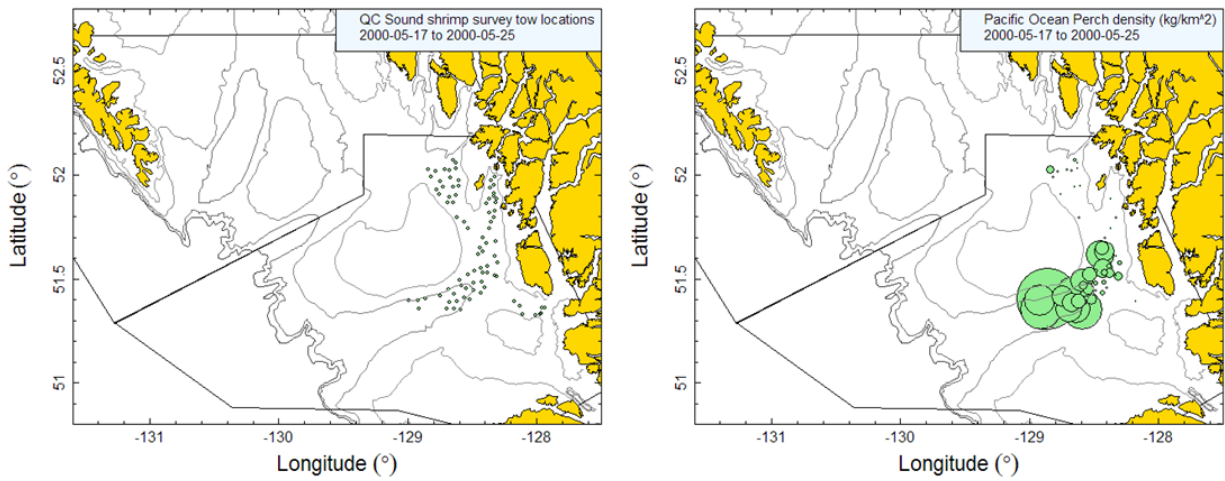


Figure B.22. Tow locations and density plots for the 2000 Queen Charlotte Sound shrimp survey (see Figure B.21 caption).

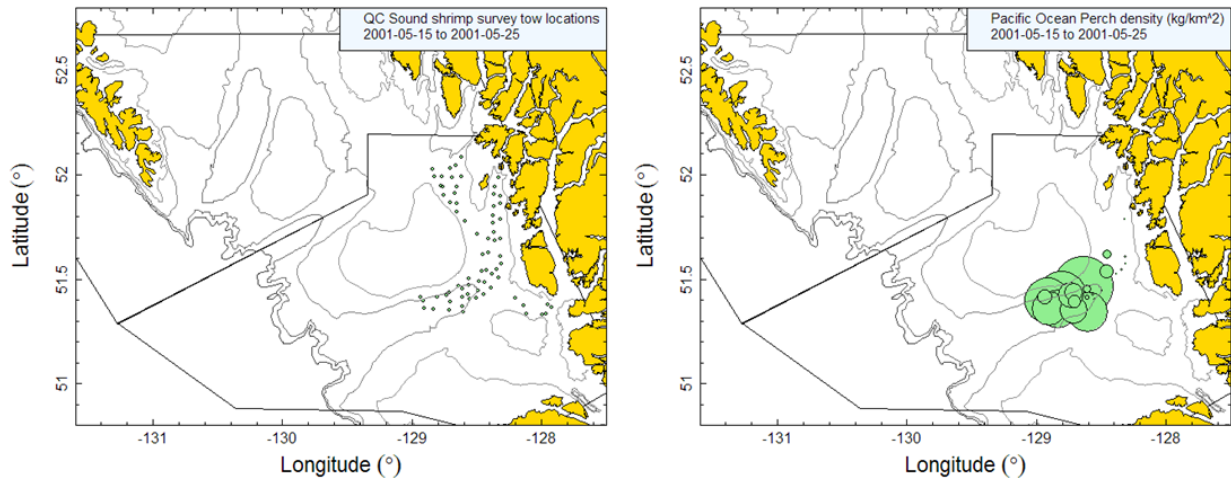


Figure B.23. Tow locations and density plots for the 2001 Queen Charlotte Sound shrimp survey (see Figure B.21 caption).

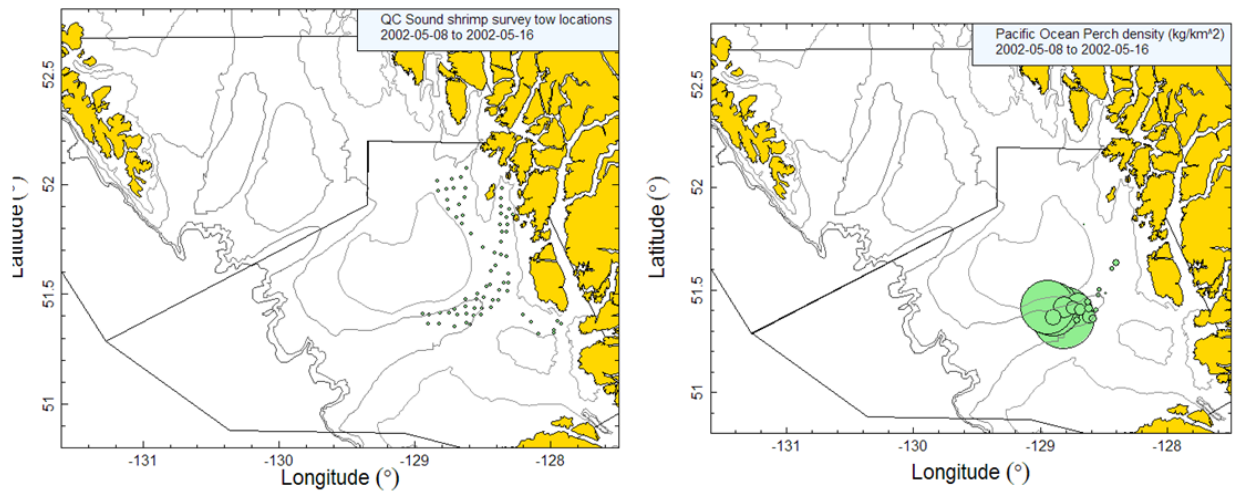


Figure B.24. Tow locations and density plots for the 2002 Queen Charlotte Sound shrimp survey (see Figure B.21 caption).



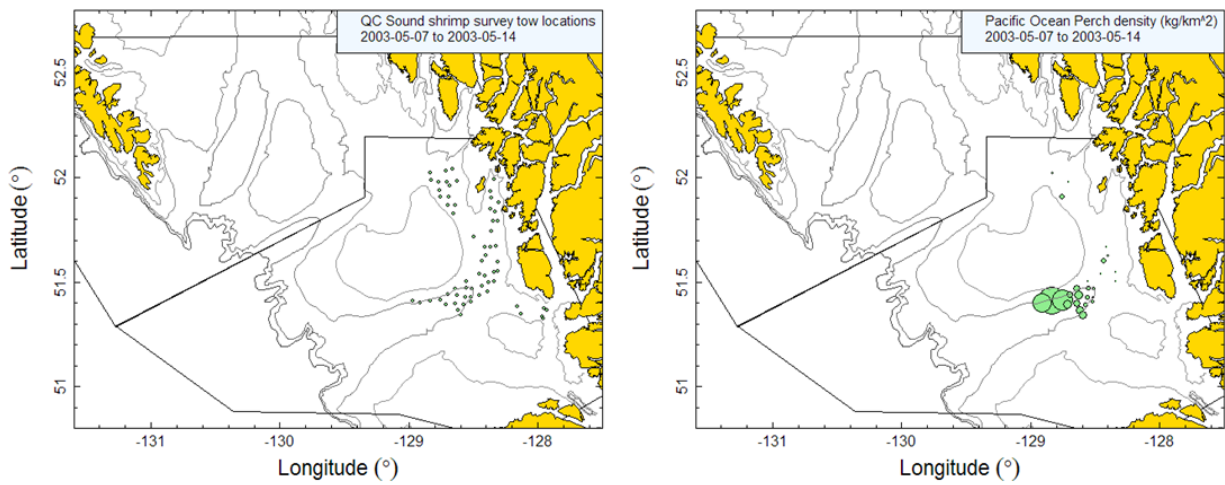


Figure B.25. Tow locations and density plots for the 2003 Queen Charlotte Sound shrimp survey (see Figure B.21 caption).

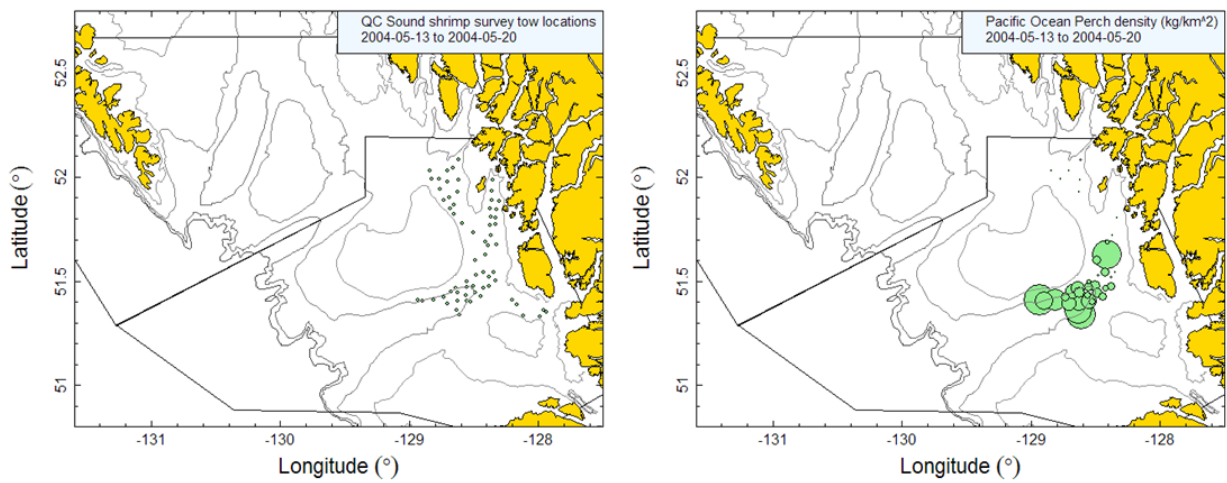


Figure B.26. Tow locations and density plots for the 2004 Queen Charlotte Sound shrimp survey (see Figure B.21 caption).

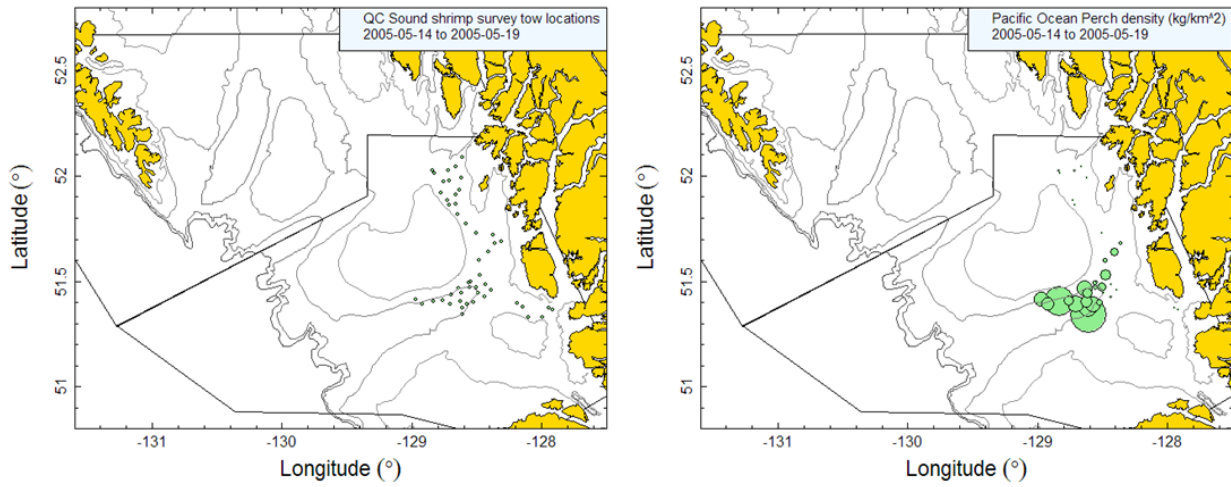


Figure B.27. Tow locations and density plots for the 2005 Queen Charlotte Sound shrimp survey (see Figure B.21 caption).

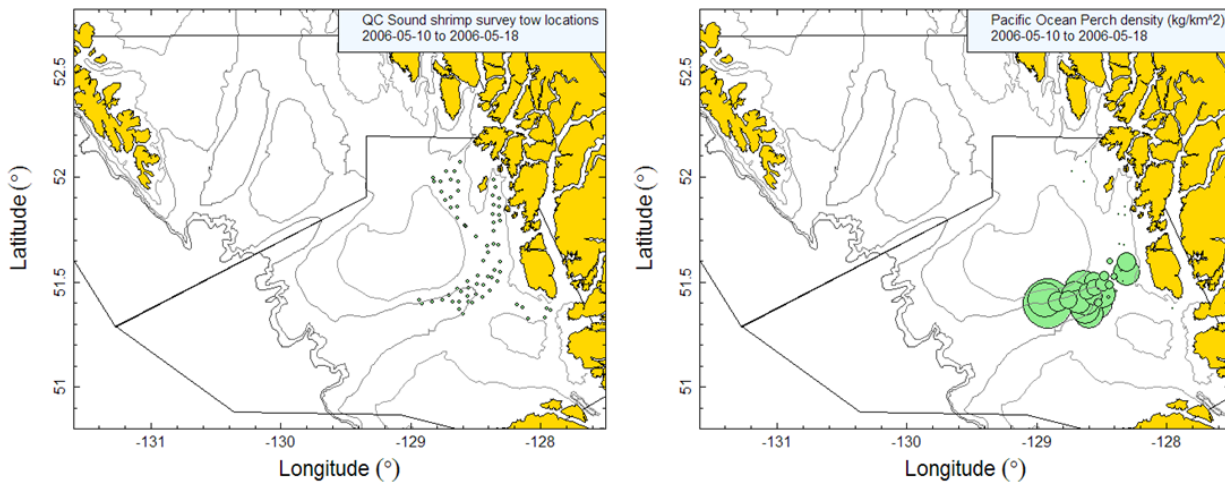


Figure B.28. Tow locations and density plots for the 2006 Queen Charlotte Sound shrimp survey (see Figure B.21 caption).

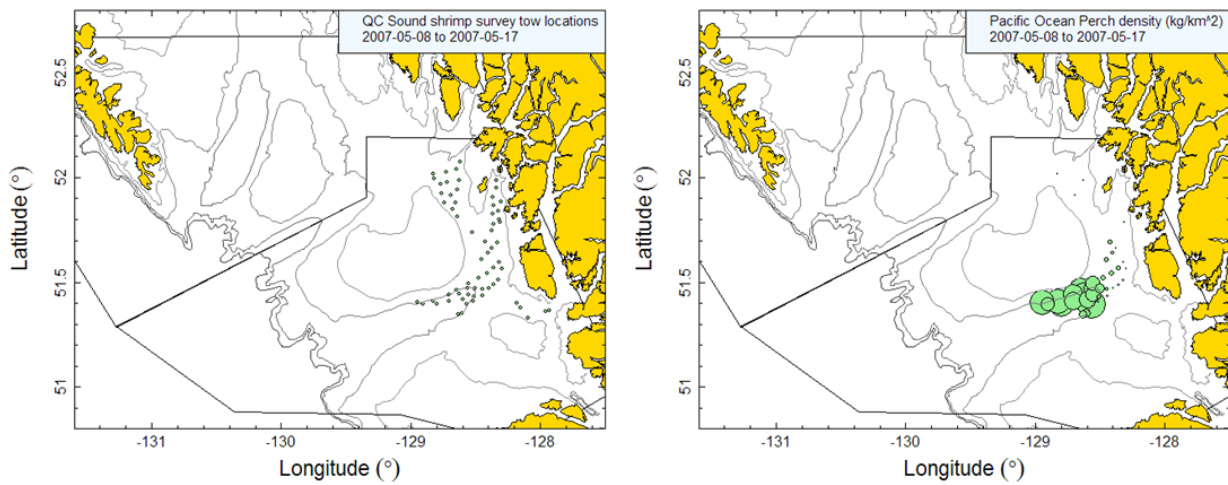


Figure B.29. Tow locations and density plots for the 2007 Queen Charlotte Sound shrimp survey (see Figure B.21 caption).

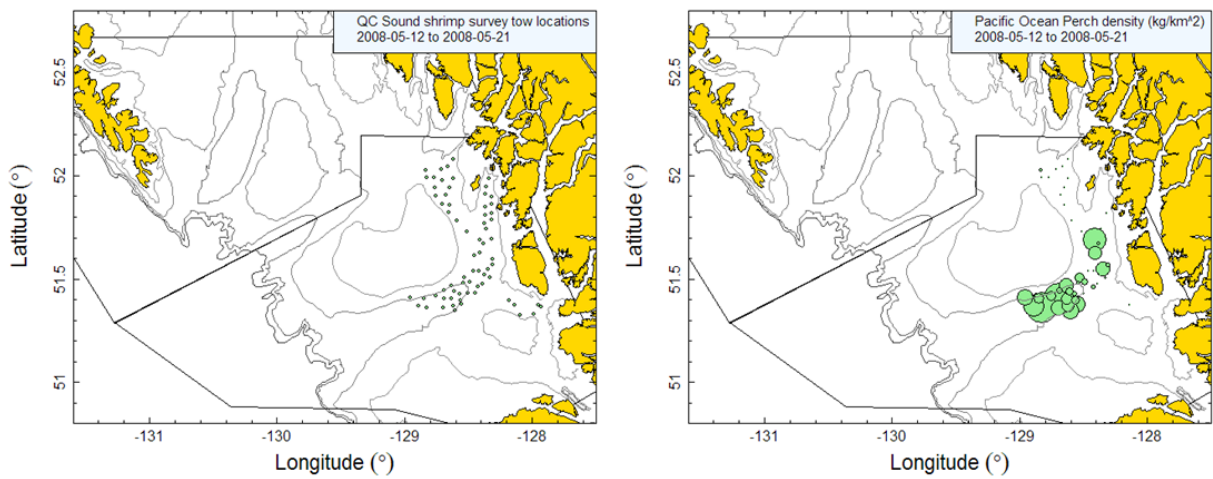


Figure B.30. Tow locations and density plots for the 2008 Queen Charlotte Sound shrimp survey (see Figure B.21 caption).

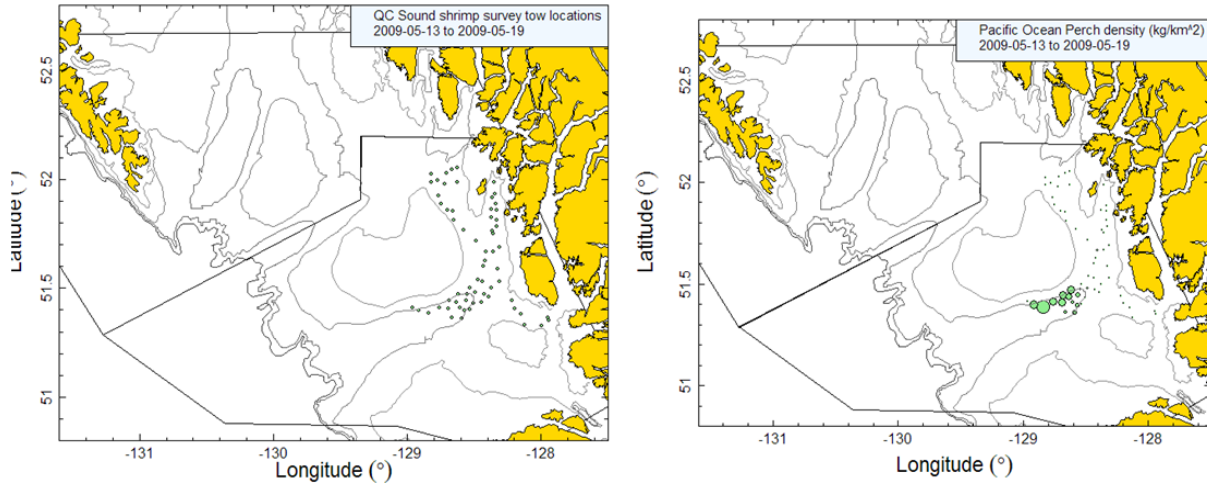


Figure B.31. Tow locations and density plots for the 2009 Queen Charlotte Sound shrimp survey (see Figure B.21caption).

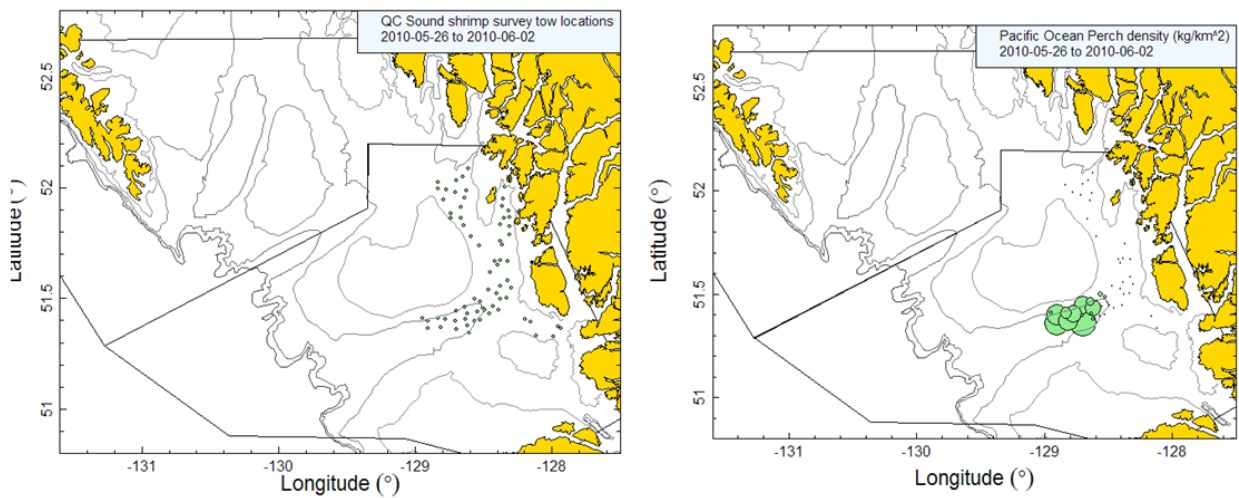


Figure B.32. Tow locations and density plots for the 2010 Queen Charlotte Sound shrimp survey (see Figure B.21 caption).

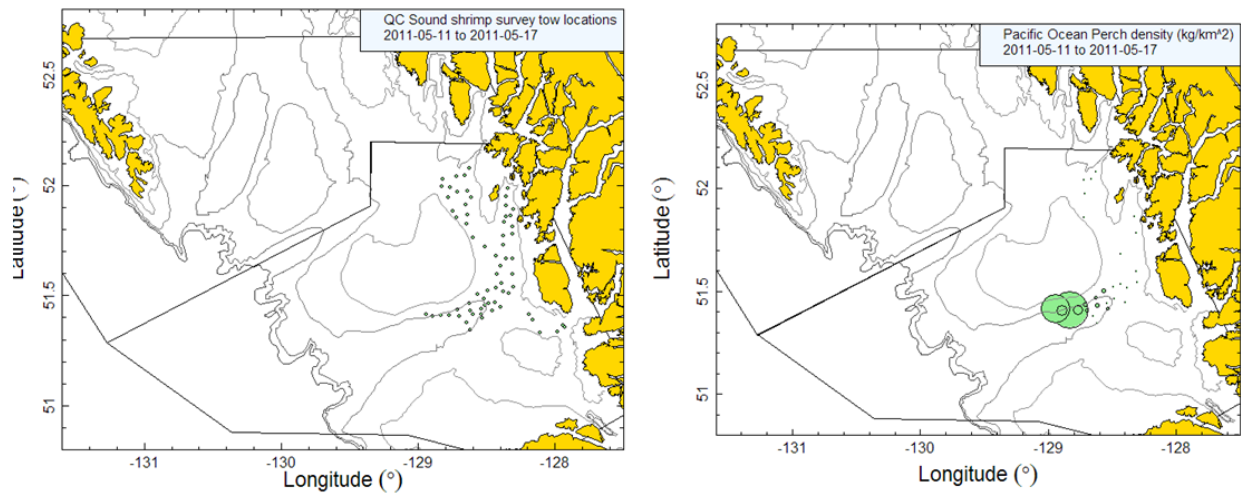


Figure B.33. Tow locations and density plots for the 2011 Queen Charlotte Sound shrimp survey (see Figure B.21 caption).

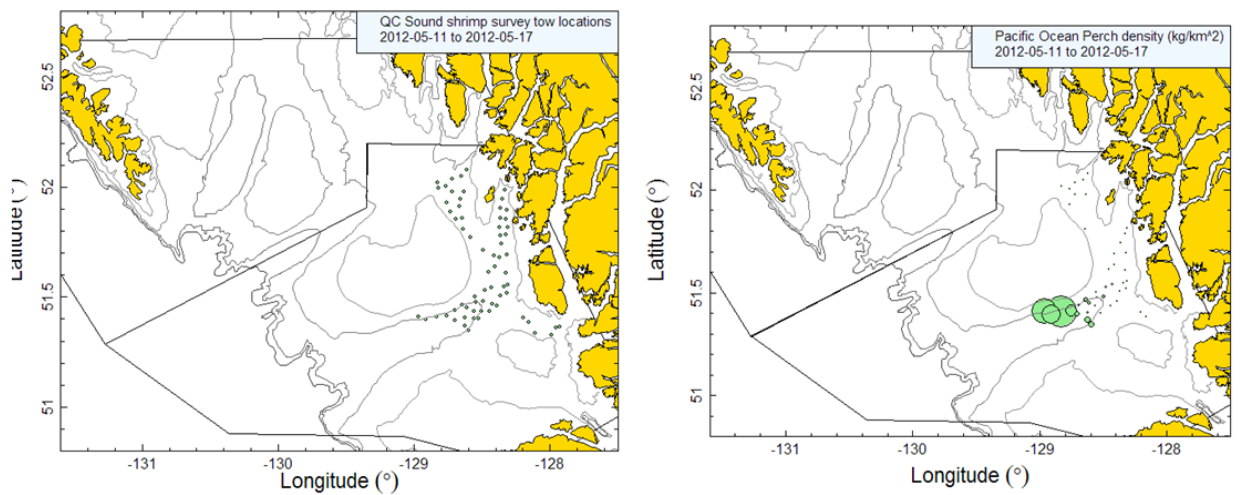


Figure B.34. Tow locations and density plots for the 2012 Queen Charlotte Sound shrimp survey (see Figure B.21 caption).

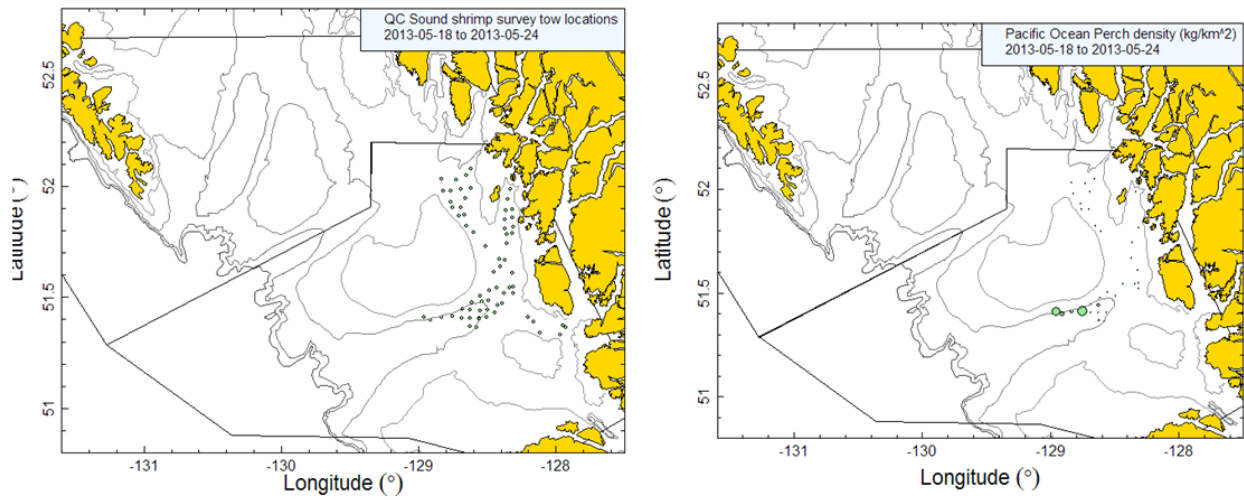


Figure B.35. Tow locations and density plots for the 2013 Queen Charlotte Sound shrimp survey (see Figure B.21 caption).

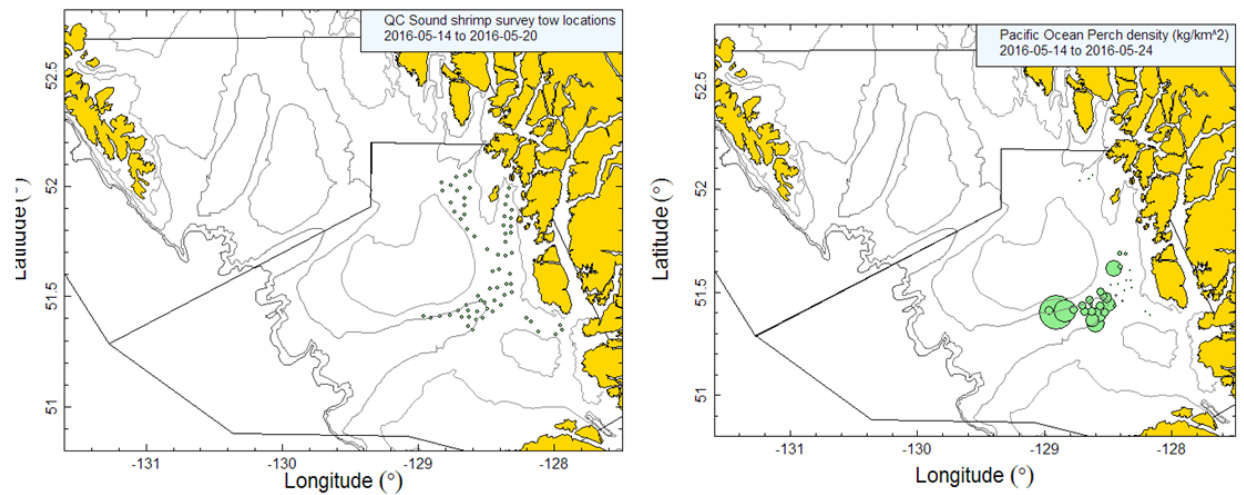


Figure B.36. Tow locations and density plots for the 2016 Queen Charlotte Sound shrimp survey (see Figure B.21 caption).

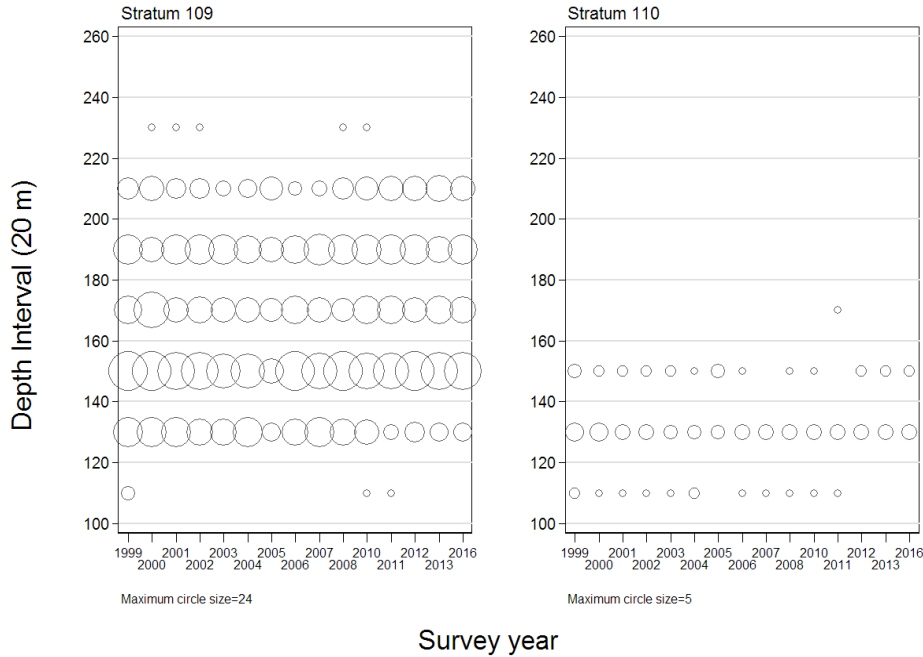


Figure B.37. Distribution of tows by stratum, survey year and 20 m depth zone for the QC Sound shrimp survey. Depth zones are indicated by the midpoint value of the depth interval, weighted by the number of tows. Depth is the start depth for the tow.

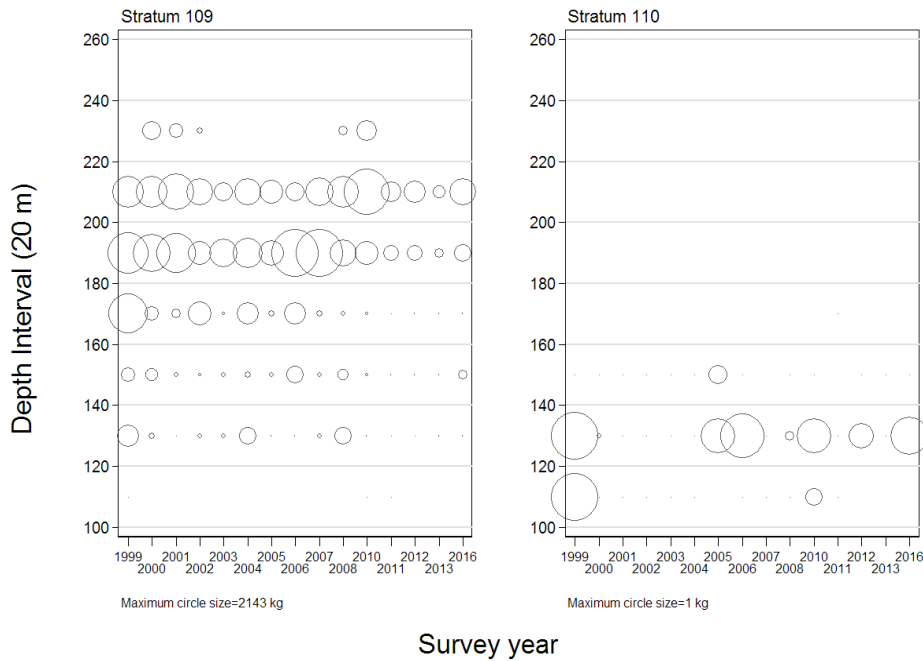


Figure B.38. Distribution of catch weight of Pacific Ocean Perch by stratum (Table B.10), survey year and 20 m depth zone for the QC Sound shrimp survey. Depth zones are indicated by the centre of the depth interval. Maximum circle size: 2143 kg (180–200 m bin in 2007 in Stratum 109). Minimum depth observed for POP: 108 m; maximum depth observed for POP: 231 m. Depth is defined as the start depth for the tow.

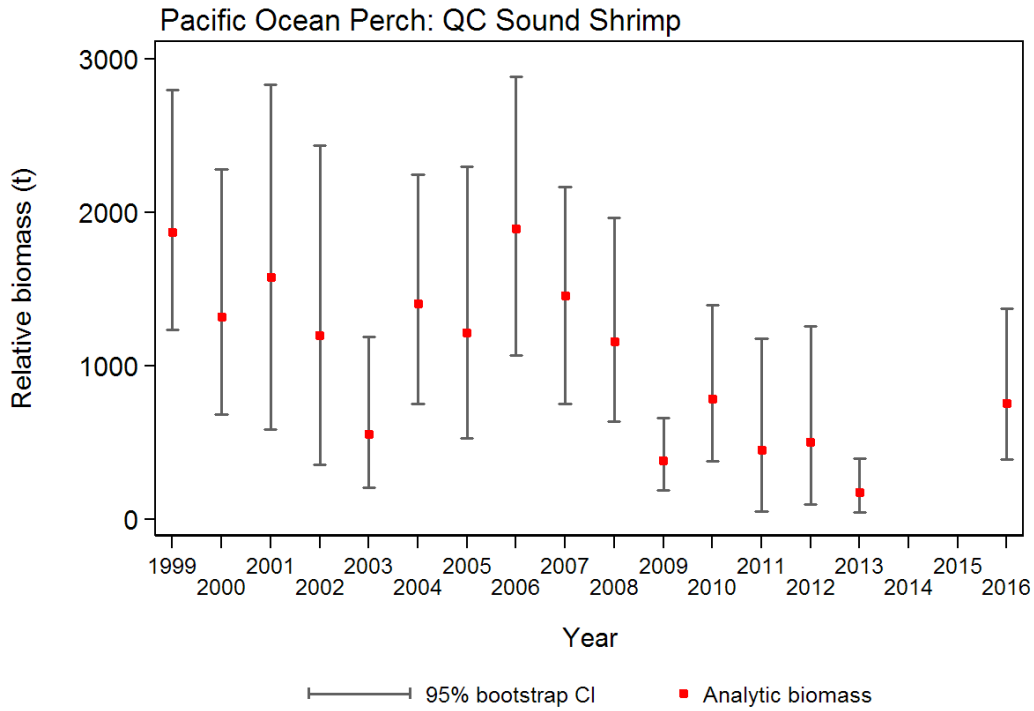


Figure B.39. Plot of biomass estimates for Pacific Ocean Perch from the QC Sound shrimp trawl survey for 1999 to 2016. Bias corrected 95% confidence intervals from 1000 bootstrap replicates are plotted.

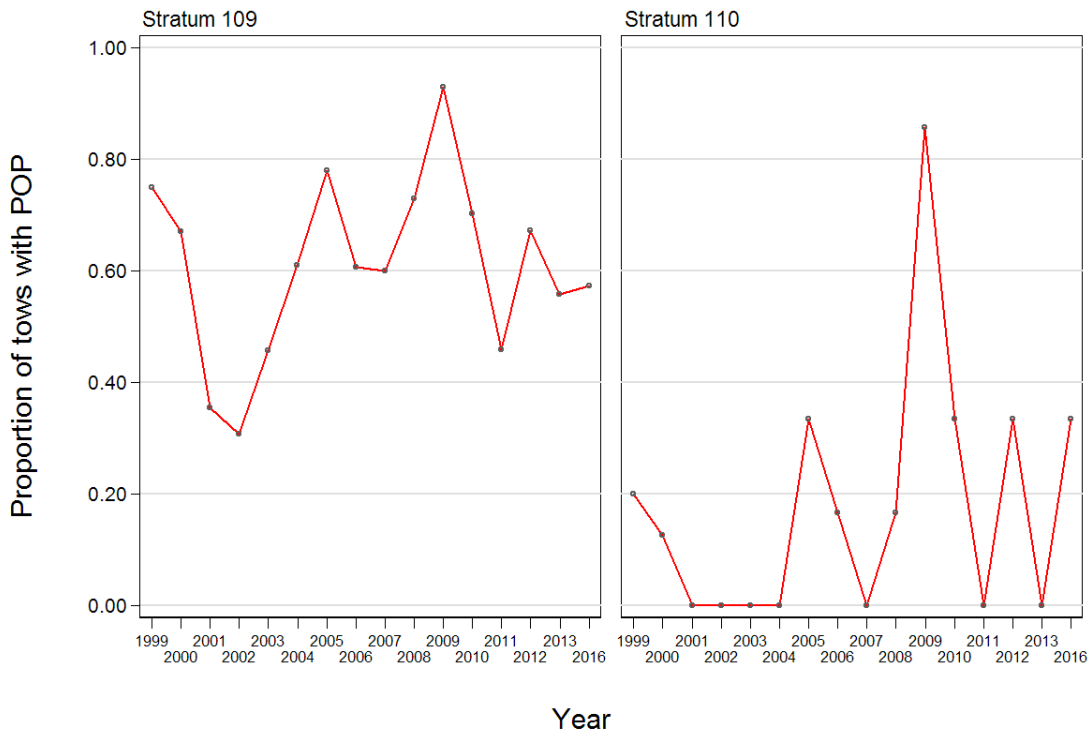


Figure B.40. Proportion of tows by stratum and year which contain Pacific Ocean Perch for the QC Sound shrimp trawl survey.



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## APPENDIX C. BIOLOGICAL DATA

Data for biological analyses were extracted from the DFO database GFBioSQL on Oct. 17, 2016. Various database codes found in the extraction appear in Table C.1. Only those specimens originating in one of the PMFC major areas 5A, 5B, 5C or in the southern tip of 5E (south of 52°20') near Anthony Island were used for analyses in this appendix. For expediency, this specimen subset is referred to as “5ABC”.

Table C.1. GFBio database codes in the data extraction for the 5ABC POP biological analyses.

Code	Description
<b>Trip types (ttype)</b>	
1	Non-observed domestic
2	Research
3	Charter
4	Observed domestic
5	Observed joint-venture (J-V)
<b>Sample types (stype)</b>	
0	Unknown
1	Total catch
2	Random
4	Selected
5	Stratified
6	Random from randomly assigned set
7	Random from set after randomly assigned set
8	Random from set requested by vessel master
<b>Ageing method (ameth)</b>	
0	Unknown
1	Otolith surface only
2	Otolith thin sectioned
3	Otolith broken & burnt
5	Otolith (unknown)

### C.1. GROWTH AND MATURITY

#### C.1.1. Length-Weight

The parameterisation of the length-weight model used in the stock assessment is:

$$W_{i,s} = \alpha_s (L_{i,s})^{\beta_s} \quad (\text{C.1})$$

where  $W_{i,s}$  = observed weight (kg) of individual  $i$  with sex  $s$ ,

$L_{i,s}$  = observed length (cm) of individual  $i$  with sex  $s$ ,

$\alpha_s$  = growth rate scalar for sex  $s$ ,

$\beta_s$  = growth rate exponent for sex  $s$ .

The above model was fit as a linear regression to the logged length-weight pairs that satisfied the following conditions (see Table C.1 for code details):

- occurred in at least one of the PMFC major areas 5A, 5B, 5C or in the southern tip of 5E (south of 52°20') near Anthony Island;
- originated from a research and/or survey trip ( $t_{type}=2:3$ ) or from a commercial trip ( $t_{type}=c(1,4)$ );
- included all available sample types;
- excluded length-weight pairs with Studentised residuals  $\geq 3.0$  (the final fit was run after these data were removed).

The resulting estimates for  $\log(\alpha_s)$  were exponentiated to provide the  $\alpha_s$  parameters used in the stock assessment.

Table C.2. Length-weight relationship parameters ( $\alpha$ ,  $\beta$ ) for 5ABC Pacific Ocean Perch collected by research surveys and by the commercial fishery, where  $s$  = sex,  $n_s$  = number of specimens by sex, and  $SE$  = standard error of the parameter.

$s$	$n_s$	$\log \alpha_s$	$SE \log \alpha_s$	$\beta_s$	$SE \beta_s$
Trip type (research: 2+3)					
Females	11,640	-11.5748	0.010906	3.111522	0.003031
Males	12,010	-11.6758	0.010864	3.144565	0.003061
F+M	23,649	-11.6101	0.007697	3.12373	0.002154
Trip type (commercial: 1+4)					
Females	1,665	-11.2795	0.071589	3.034021	0.019241
Males	1,168	-11.324	0.083796	3.046791	0.022955
F+M	2,837	-11.284	0.051765	3.035504	0.014021

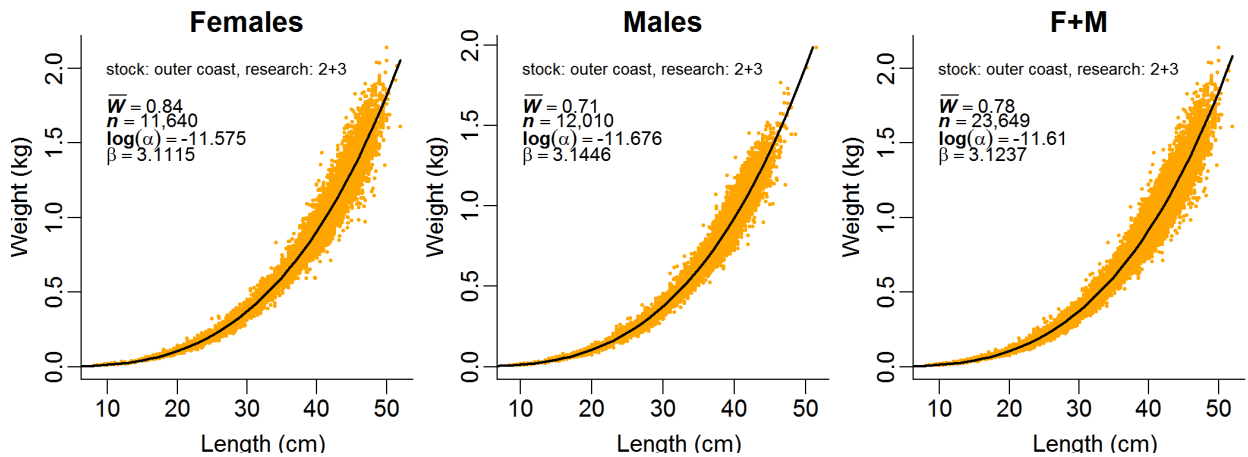


Figure C.1. Length-weight relationship for female, male, and combined POP in 5ABC from fishing events conducted by research surveys. Records with absolute value of standardised residuals  $\geq 3$  (starting with a preliminary fit) were dropped. Statistic  $\bar{W}$  indicates the arithmetic mean,  $n$  = number of specimens.

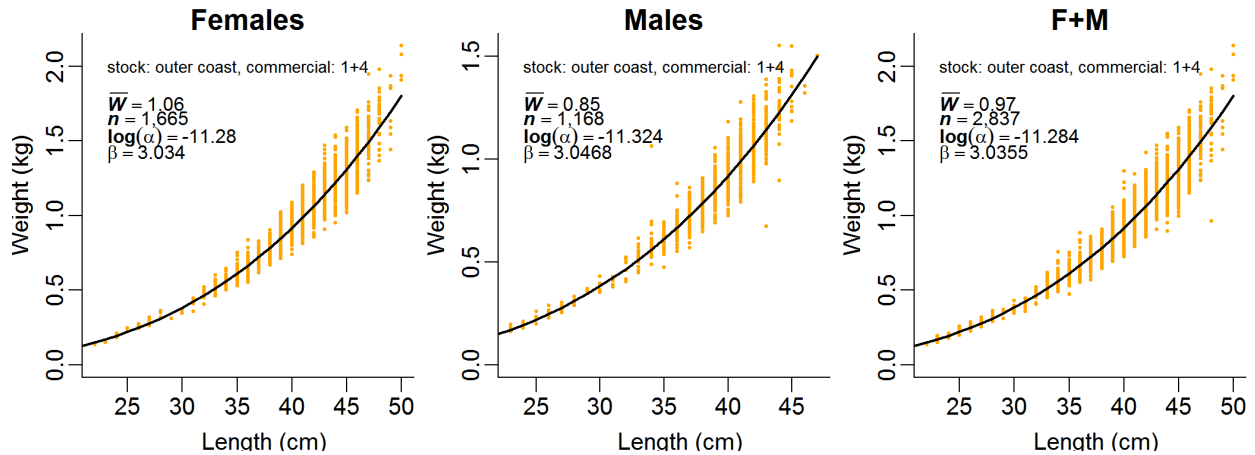


Figure C.2. Length-weight relationship for female, male, and combined POP in 5ABC from commercial fishing events. Records with absolute value of standardised residuals  $\geq 3$  (starting with a preliminary fit) were dropped. Statistic  $\bar{W}$  indicates the arithmetic mean,  $n$  = number of specimens.

### C.1.2. von Bertalanffy Growth

The parameterisation of the von Bertalanffy growth model is:

$$L_{a,s} = L_{\infty,s} \left( 1 - e^{-\kappa_s(a-t_{0,s})} \right) \quad (C.2)$$

where  $L_{a,s}$  = average length (cm) of a fish at age  $a$  and sex  $s$ ,

$L_{\infty,s}$  = average length (cm) of a fish at maximum age and sex  $s$ ,

$\kappa_s$  = growth rate coefficient for sex  $s$ ,

$t_{0,s}$  = age at which the average fish length is 0 cm for sex  $s$ .

The above model was fit using non-linear minimisation on POP age-length pairs that satisfied the following conditions (see Table C.1 for code details):

- otoliths were processed and read using the break and burn procedure (`ameth=3`) or were coded as 'unknown' (`ameth=0`) but processed in 1980 or later;
- occurred in at least one of the PMFC major areas 5A, 5B, 5C, or in the southern tip of 5E (south of 52°20') near Anthony Island;
- originated from a research survey trip (`ttype=2:3`) or from a commercial trip (`ttype=c(1,4)`);
- included only sample types `c(1,2,6,7)` (total catch, random, random from randomly assigned set, or random from set after randomly assigned set, respectively);
- excluded age-length pairs with Studentised residuals  $\geq 3.0$  (the final fit was run after these data were removed).

Non-linear von Bertalanffy models were fit to age-length pairs, with data from 1981-06-03 to 2015-08-07 coastwide for female, male and both combined (Table C.3, Figure C.3, Figure C.4) for research surveys and from 1977-06-13 to 2014-09-08 from the commercial fishery.

Generally, females attain larger sizes than do males, with  $L_{\infty}$  for females being ~3 cm larger than that for males.

Table C.3. Growth parameters ( $L_{\infty,s}$ ,  $\kappa_s$ ,  $t_{0,s}$ ) for 5ABC POP from research survey and commercial fishery specimens using the von Bertalanffy model, where  $s$  = sex,  $n_s$  = number of specimens by sex.

$s$	$n_s$	$L_{\infty,s}$	$\kappa_s$	$t_{0,s}$
Trip type: research/survey				
Female	5,134	44.161605	0.155313	-0.650378
Male	5,046	40.948744	0.178910	-0.569246
F+M	10,193	42.492337	0.167103	-0.596750
Trip type: commercial fishery				
Female	15,121	45.171667	0.132917	-2.273023
Male	15,335	41.666265	0.152907	-2.466616
F+M	30,556	43.553746	0.136227	-2.720145

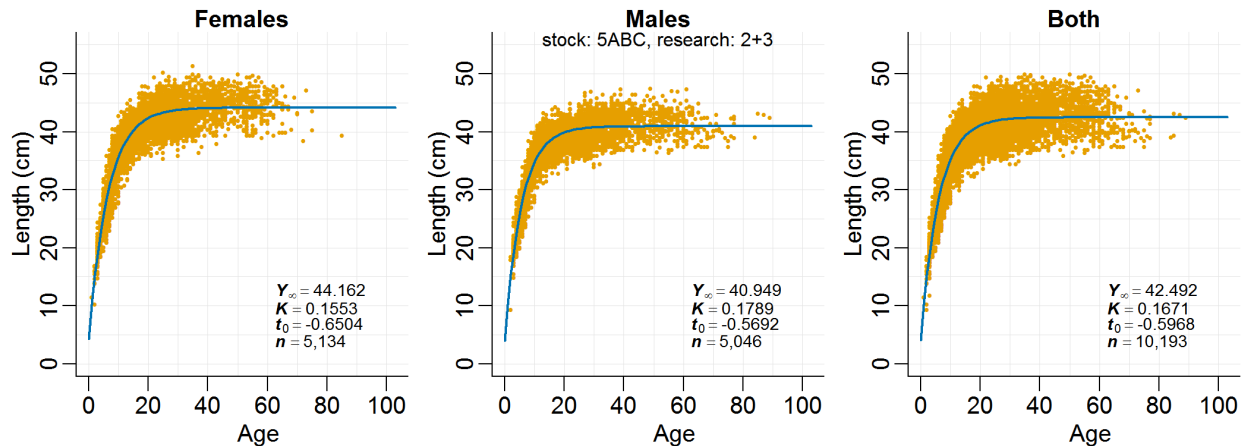


Figure C.3. Age-length relationships using the von Bertalanffy growth model for 5ABC POP specimens from research surveys, where  $Y_{\#} = L_{\infty}$  and  $n$  = number of specimens.

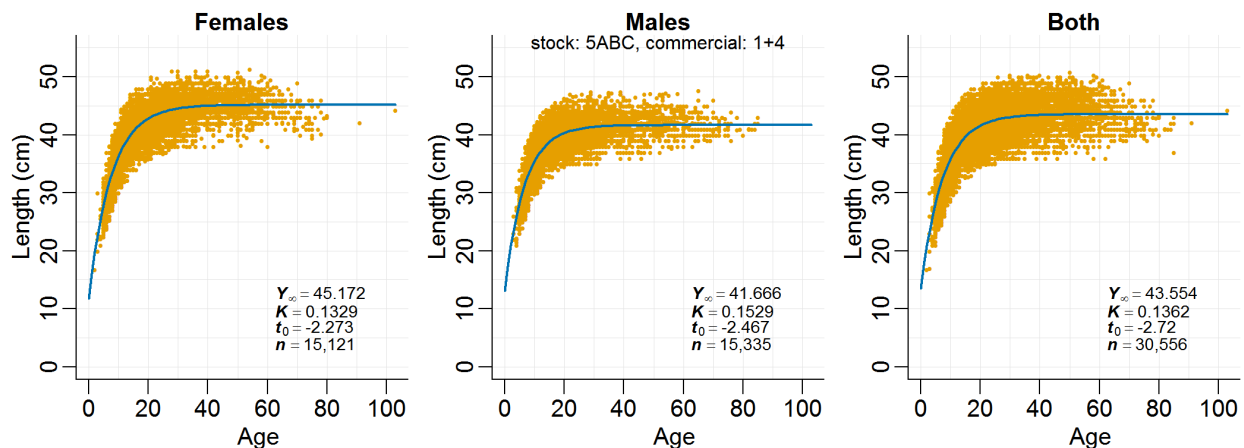


Figure C.4. Age-length relationships using the von Bertalanffy growth model for 5ABC POP specimens from the commercial fishery, where  $Y_{\#} = L_{\infty}$  and  $n$  = number of specimens.

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### C.1.3. Maturity

This analysis was based on all “staged” (examined for maturity status) females in the DFO GFBioSQL database. Maturity codes for POP in the database (Table C.4) come from `MATURITY_CONVENTION_CODE = 1`, which describes 7 maturity conditions for Rockfish (1977+).

Table C.4. GFBio maturity codes for rockfish, including 5ABC POP.

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

Maturity data were selected to satisfy the following conditions (see Table C.1 for code details):

- occurred in at least one of the PMFC major areas 5A, 5B, 5C, or in the southern tip of 5E (south of 52°20') near Anthony Island;
- originated from either a commercial trip (`ttype=c(1,4)`) or a research survey trip (`ttype=2:3`);
- included only sample types `c(1,2,6,7)` (total catch, random, random from randomly assigned set, or random from set after randomly assigned set, respectively);
- had definite identified maturity codes (`mats=1:7`).

A bubble plot of frequency data (maturity vs. month) derived from various sources (Table C.5) appears in Figure C.5. 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 January to June were used in creating the maturity curve because these months contained the majority of spawning and spent females (Figure C.5). As well, the proportion of immature fish started to rise in July concurrently with a drop in the proportion of spent fish, likely signalling the completion of spawning.

To estimate a maturity ogive, the maturity data were further qualified for female specimens that:

- were collected from January to June;
- had otoliths processed and read using the break and burn procedure (`ameth=3`) or were coded as ‘unknown’ (`ameth=0`) but processed in 1980 or later;
- came from unsorted or retained catch.

This qualification yielded 4,030 specimens with maturity readings and valid ages. Mature specimens comprised those coded 3 to 7 for rockfish (Table C.4). The proportion of mature females at each age with at least 10 observations was calculated (Table C.6). A double-normal function (C.3) was fit to the observed proportions mature at ages 2 to 25 to smooth the observations and determine an increasing monotonic function for use in the stock assessment model (Figure C.6). Following a procedure adopted by Stanley et al. (2009) for Canary Rockfish (*S. pinniger*), the observed proportions were used for ages less than 9, even though the fitted line did not appear to dramatically overestimate the proportion of mature females (Figure C.6).

The maturity ogive used in the stock assessment model (last column in Table C.6) was based on the observed proportions of mature females from ages 2 to 8 and then switched to the fitted monotonic function for ages 9 to 60, all forced to 1 (fully mature) after age 15. 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.

$$m_{a,s} = \begin{cases} e^{-(a-\mu_s)^2} / v_{sL}, & a \leq \mu_s \\ 1, & a > \mu_s \end{cases} \quad (\text{C.3})$$

where,  $m_{a,s}$  = maturity at age  $a$  for sex  $s$ ,

$\mu_s$  = age at full maturity for sex  $s$ ,

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

Table C.5. Frequency of maturity codes (columns) by month (rows) for each of the trip types.

Trip Type	Maturity Month	1	2	3	4	5	6	7
1. Comm. Non-observed	1	20	114	250	79	6	-	2
	2	16	124	168	683	304	31	2
	3	97	38	58	588	439	147	10
	4	164	102	3	62	756	519	478
	5	85	208	7	6	64	150	1184
	6	175	725	132	3	2	25	1986
	7	53	930	191	8	4	6	853
	8	45	934	346	13	1	-	409
	9	19	443	614	1	-	-	133
	10	102	486	1418	22	2	-	38
	11	26	55	432	-	-	-	1
	12	-	33	109	-	-	-	-
2. Research	2	38	-	-	-	-	-	-
	3	42	-	-	59	37	8	1
	4	9	43	-	1	16	13	242
	5	45	55	1	-	-	-	18
	6	100	120	102	42	4	25	552
	8	2	36	23	1	-	-	7
	11	6	-	-	-	-	-	-
3. Charter Survey	6	299	138	11	-	1	11	1039
	7	796	1804	1719	12	4	534	2605
	8	54	239	809	10	-	19	264
	9	11	220	513	2	-	-	87
4. Comm. Observed	1	-	2	16	6	-	-	-
	2	1	34	21	98	20	2	5
	3	5	28	9	33	52	5	11
	4	14	50	13	18	66	67	129



Trip Type	Maturity→ Month↓	1	2	3	4	5	6	7
	5	97	140	18	1	33	258	478
	6	20	184	73	-	1	197	989
	7	66	144	130	2	3	24	552
	8	24	284	484	11	1	19	333
	9	-	48	420	2	-	1	55
	10	5	42	689	3	-	-	26
	11	2	16	248	23	-	1	3
	12	-	9	71	1	25	-	-

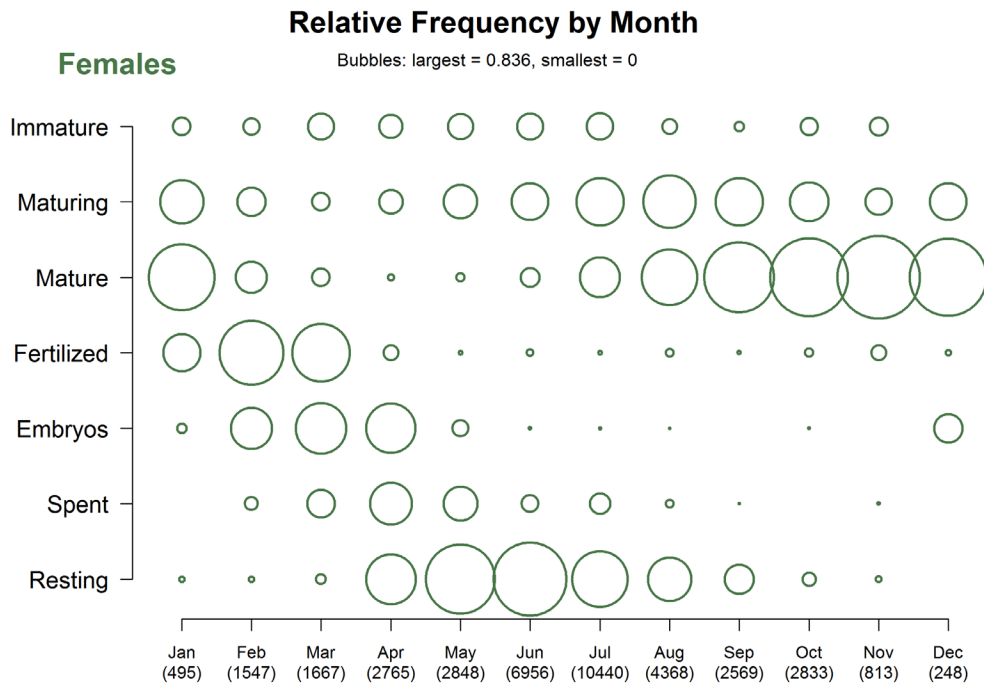


Figure C.5. Relative frequency of maturity codes by month for 5ABC POP females (data stored in DFO's GFBioSQL database). Data include maturities from commercial and research specimens. Frequencies are calculated among each maturity category for every month.

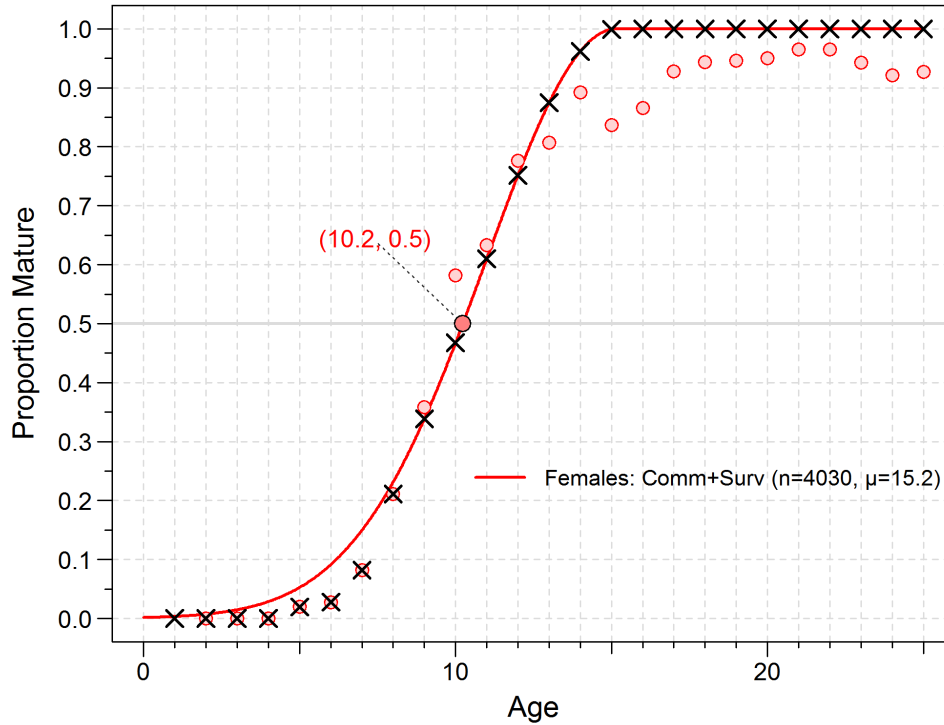


Figure C.6. Maturity ogives for 5ABC POP females (data stored in DFO's GFBioSQL database). Solid line shows the double-normal curve fit; circles denote input proportions-mature; crosses indicate values used in the model. Age at 50% maturity is indicated along the median line; age at full maturity ( $\mu$ ) is displayed in the legend.

Table C.6. 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 $m_a$	(C.3) fit $m_a$	Model $m_a$
1	0	0	0.04174	0.00330	0
2	1	0	0.05857	0.00718	0
3	16	0	0.08160	0.01477	0
4	24	0	0.11260	0.02871	0
5	51	0.01961	0.15341	0.05270	0.01961
6	36	0.02778	0.20559	0.09140	0.02778
7	61	0.08197	0.26986	0.14973	0.08197
8	161	0.21118	0.34548	0.23170	0.21118
9	201	0.35821	0.42981	0.33871	0.33871
10	287	0.58188	0.51843	0.46772	0.46772
11	382	0.63351	0.60590	0.61010	0.61010
12	429	0.77622	0.68708	0.75175	0.75175
13	347	0.80692	0.75820	0.87500	0.87500
14	307	0.89251	0.81746	0.96207	0.96207
15	239	0.83682	0.86478	0.99922	0.99922
16	253	0.86561	0.90132	1	1
17	221	0.92760	0.92880	1	1
18	232	0.94397	0.94905	1	1

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Age	# Fish	Obs. $m_a$	Logit fit $m_a$	(C.3) fit $m_a$	Model $m_a$
19	148	0.94595	0.96377	1	1
20	160	0.95000	0.97436	1	1
21	142	0.96479	0.98190	1	1
22	114	0.96491	0.98726	1	1
23	87	0.94253	0.99104	1	1
24	76	0.92105	0.99371	1	1
25	55	0.92727	0.99559	1	1

One of the questions from the review committee asked whether maturity is changing over time. Although annual data can sometimes support annual fits using (C.3), the data were grouped into 6-year epochs for expediency and the same criteria for selecting maturity records described above were applied. Figure C.7 shows maturity fits using (C.3) for six epochs of female 5ABC POP data. Although the fits indicate shifting age-at-full maturity, from a low of 13.4 y in 1985-1990 to a high of 17.3 y in 1979-1984, there is no observed one-way shift (lower or higher) in maturity over time. There is a 12-year period (1985-1996) when age-at-full maturity appears to have remained lower than during the other epochs, but there are likely issues with data quality (number of records for each epoch = 1350, 779, 1006, 654, 148, and 93) that invalidate generalisations. Additionally, fits to these data are very sensitive to the constraints placed on the parameter that determines the variance of the left-hand side of the double-normal curve (here we use the constraint 0.1 to 50).

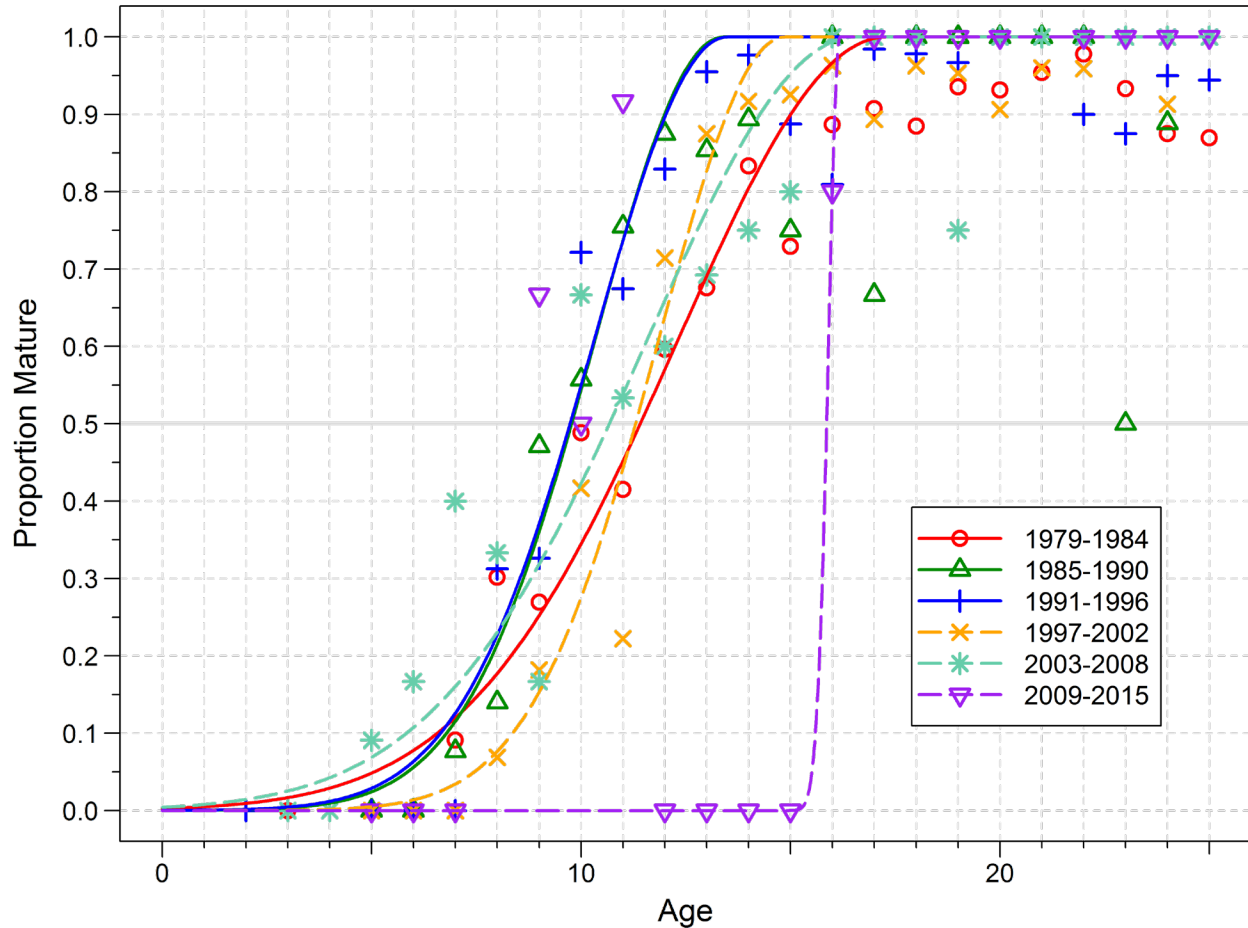


Figure C.7. Maturity ogives for 5ABC POP females for six 6-year epochs spanning 1979 to 2015.

#### C.1.4. Natural Mortality

The maximum reported age in the literature for POP is 98 years for a specimen from the Aleutian Islands (Munk 2001); however, our database (GFBio) reports two specimens older than 98 y (age 100 y: female specimen from Langara at 329 m in 1983; age 103 y: female specimen from Moresby Gully at 362 m in 2002). Archibald et al. (1981) estimated POP natural mortality to be 0.04-0.05; however, values used for the natural mortality rate of POP in other published stock assessments are usually close to 0.06 (e.g., Schnute et al. 2001, Hanselman et al. 2007, 2009). The 2010 5ABC POP assessment used an informed prior on  $M$  with a mean of 0.06 with a standard deviation of 0.006 (CV=10%) and the median estimate for females was 0.067.

A quick check for exploring natural mortality is provided by Quinn and Deriso (1999, p.361) based on Hoenig (1983):

$$M = -\ln(0.01)/t_m \quad (C.4)$$

where,  $t_m$  = maximum observed age reach by 1% of the population.

Using the maximum age observed for 5ABC in the DFO database  $t_m = 103$  y,  $M = 0.045$ , which could provide a lower bound on  $M$ , while an upper bound might be calculated using  $t_m = 59$  y

(0.99 quantile),  $M = 0.078$ . Then et al. (2015) revisited various natural mortality estimators and recommended the use of an updated Hoenig estimator based on nonlinear least squares:

$$M_{\text{est}} = 4.899 t_{\text{max}}^{-0.916} \quad (\text{C.5})$$

where  $t_{\text{max}}$  = maximum age. For POP with a maximum age of 103, the updated Hoenig estimator suggests that  $M = 0.07$ .

## C.2. 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. 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<sup>2</sup>) of the target in sampled tows. A second weighting is then applied: 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<sup>2</sup>) 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 C.7.

Table C.7. Equations for weighting age frequencies or proportions for 5ABC POP; (c) = commercial, (s) = survey.

Symbol	Description
<b>Indices</b>	
$a$	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)
<b>Data</b>	
$x_{adhi}$	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 $i$

Symbol	Description
	(s) density (t/km <sup>2</sup> ) 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 <sup>2</sup> ) 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:

$$C'_{dhi} = \frac{C_{dhi}}{\sum_d C_{dhi}}. \quad (\text{C.6})$$

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:

$$y_{ahi} = \sum_d (C'_{dhi} x_{adhi}). \quad (\text{C.7})$$

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

$$\frac{\sum_a x_{ahi}}{\sum_a y_{ahi}} \quad (\text{C.8})$$

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<sup>2</sup>) for survey ages

$$K'_{hi} = \frac{K_{hi}}{\sum_h K_{hi}} \quad (\text{C.9})$$

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

$$p_{ai} = \sum_h (K'_{hi} y_{ahi}). \quad (\text{C.10})$$

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

$$\frac{\sum_a y_{ai}}{\sum_a p_{ai}} \quad (\text{C.11})$$

to retain the original number of observations.

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

$$p'_{ai} = \frac{p_{ai}}{\sum_a p_{ai}}. \quad (\text{C.12})$$

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  $x$ .

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### C.2.1. Commercial Ages

The commercial age data for 5ABC POP are abundant and informative, with clear cohort patterns (Figure C.8). The strong 1976 year class (38 year-old fish in 2014) is still evident in the proportions-at-age data, although its presence has practically disappeared by 2014. Figure C.8 also shows that the 2000 year class contributed a large set of recruits to the population. 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 C.8) usually exceeded our criterion for using commercial age data ( $\geq 5$  trips per year); only four years (1977, 1985, 1986, and 1988) were not used in for the population model.

Table C.8. Commercial trips (trawl): number of sampled trips and 5ABC POP 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
1977	0	1	2	0	0	13.6	73.2	0	0.122	353	617	161
1978	0	3	3	1	0	73.5	94.2	49.3	0.481	267	746	356
1979	0	4	6	1	0	53.6	228	65.4	45.9	223	976	259
1980	1	10	9	3	20.8	472	405	104	27.3	1,561	1,675	711
1981	0	4	3	0	0	191	144	0	196	2,387	1,219	2.17
1982	1	7	0	1	78.1	474	0	86.4	482	2,407	1,394	358
1983	1	6	4	0	49.3	356	162	0	892	2,249	553	2.73
1984	1	7	0	1	47.9	305	0	44	893	1,327	185	587
1985	0	0	0	3	0	0	0	293	845	1,269	120	536
1986	0	1	0	1	0	39.6	0	17.6	335	493	202	254
1987	2	1	3	0	60.7	70.8	56.1	0	499	1,408	990	673
1988	2	1	1	0	40.1	31.7	19.3	0	497	1,826	901	1,099
1989	1	4	0	0	30.7	65.2	0	0	396	1,156	644	507
1990	6	6	1	2	73.6	72.9	21.7	54.5	368	1,063	751	646
1991	1	4	3	12	31.1	62.6	20.3	399	422	908	620	985
1992	4	9	13	5	69.1	135	169	21	221	1,244	1,029	173
1993	3	12	1	2	17.8	154	1.88	14.8	173	1,493	297	411
1994	0	20	17	9	0	172	210	147	163	902	1,167	1,593
1995	6	26	16	1	38.8	457	135	3.86	1,283	1,936	1,294	58.9
1996	4	23	11	4	36.1	421	101	88.1	150	2,555	725	1,723
1997	3	4	7	4	22.4	51.9	82.8	38.1	620	1,958	1,265	882
1998	4	9	8	4	54.6	75	66.8	29.8	465	2,157	1,542	529
1999	0	9	9	3	0	101	95	17.5	265	2,349	1,377	523
2000	3	11	4	4	8.52	70.1	35.5	47.9	615	1,809	1,485	572
2001	0	11	8	3	0	109	38.9	21.6	183	1,712	1,548	533
2002	0	12	5	2	0	77.1	53	15.5	305	1,376	1,869	589
2003	2	4	6	1	17.2	36.4	22.8	0.227	416	1,776	2,176	330
2004	0	14	10	3	0	34.2	38.5	11.4	278	1,576	2,056	549
2005	1	11	6	3	0.541	64.1	21.2	20.9	423	1,326	1,447	503
2006	5	3	3	0	6.64	6.04	7.18	0	614	1,366	1,780	310
2007	2	14	8	0	7.29	73.8	24.5	0	360	1,328	1,458	265
2008	1	3	6	2	2.93	29.4	59.7	20.1	361	1,063	1,106	253
2009	1	5	8	0	8.21	12.8	26.3	0	441	1,099	1,116	476
2010	2	9	4	1	51.1	24.4	18.5	3.08	342	1,544	1,654	533
2011	0	9	5	1	0	20.7	7.27	4.76	195	1,165	1,038	486
2012	0	3	3	1	0	15.6	15.8	5.53	89.4	1,132	1,132	429
2013	2	3	2	1	6	8.51	7.16	4.85	105	633	863	280
2014	2	2	2	0	0.158	0.728	21.1	0	202	378	830	141



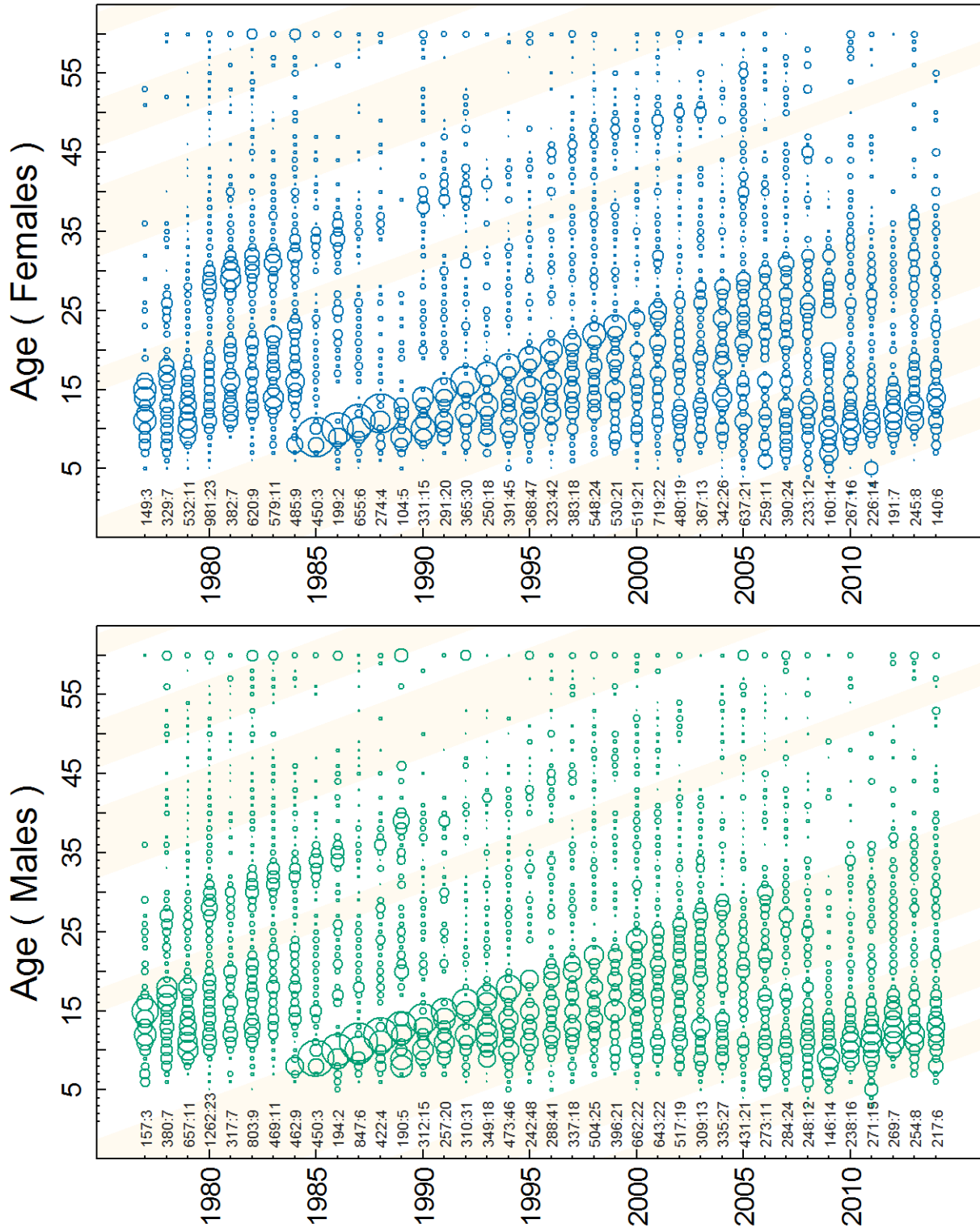


Figure C.8. Proportions-at-age for 5ABC POP caught by commercial trawl gear calculated as age frequencies weighted by trip catch within quarters and commercial catch within years. Diagonal shaded bands indicate cohorts that were born when the mean Pacific Decadal Oscillation was positive. Numbers displayed along the bottom axis indicate number of fish aged and number of samples (colon delimited) by year.

## C.2.2. Research/Survey Ages

The Queen Charlotte Sound Synoptic survey (survey series ID (SSID) 1, Figure C.9, Table C.9) has eight years of age data. The large 1976 and 2000 year classes are evident in the cohort patterns, though the signal is not as strong as that in the commercial data.

The Goose Island Gully Rockfish surveys (SSIDs 21+10, Figure C.10, Table C.10) only have three years of otolith data; however, the large 1976 year class is detectable. There also appear to be large cohorts for the following 10 years, but these readings may be confounded by age smearing.

The Queen Charlotte Sound Shrimp survey (SSID 6, Figure C.10, Table C.11) only has one year of data. In the 2010 5ABC POP assessment (Edwards et al., 2012), this single age composition sample was not used because preliminary model fits indicated that the year class information contained in this sample was not consistent with the information contained in other similar data sources, leading to unstable model behaviour and questionable model results.

Table C.9. Queen Charlotte Sound Synoptic survey: number of sampled tows and 5ABC POP density per stratum  $h$  ( $t/km^2$ ). Stratum areas: 019 = 10.7  $km^2$ ; 020 = 13  $km^2$ ; 021 = 1.5  $km^2$ ; 023 = 0.3  $km^2$ ; 024 = 12.4  $km^2$ ; 025 = 0.9  $km^2$ .

Year $h \rightarrow$	# Samples						Mean density ( $t/km^2$ )					
	019	020	021	023	024	025	019	020	021	023	024	025
2003	4	4	0	1	6	2	2.46	2.39	0	0.0213	1.08	0.105
2004	3	5	1	0	6	1	0.326	1.93	0.348	0	2.01	0.374
2005	8	4	0	4	6	1	2.12	0.530	0	0.454	1.29	2.16
2007	3	5	0	5	7	3	0.905	1.47	0	0.683	1.96	0.117
2009	5	6	2	2	9	3	0.857	3.99	0.195	0.146	2.80	2.27
2011	4	17	4	1	15	2	1.14	7.86	1.62	0.277	2.47	0.509
2013	4	20	5	3	11	3	1.07	3.94	1.17	0.521	2.40	1.04
2015	5	18	3	2	12	2	3.27	5.87	0.683	0.124	4.13	0.526

Table C.10. Goose Island Gully Rockfish survey: number of sampled tows and 5ABC POP density per stratum  $h$  ( $t/km^2$ ). Stratum areas: 121 = 1166  $km^2$ ; 122 = 1677  $km^2$ ; 123 = 731  $km^2$ ; 124 = 686  $km^2$ ; 161 = 1826  $km^2$ ; 162 = 953  $km^2$ ; 163 = 339  $km^2$ ; 185 = 2122  $km^2$ ; 186 = 1199  $km^2$ ; 187 = 1746  $km^2$ .

Year $h \rightarrow$	# Samples										
	121	122	123	124	161	162	163	185	186	187	
1984	0	0	0	0	2	2	1	4	3	4	
1994	0	0	0	0	0	0	0	6	12	19	
1995	2	11	6	5	0	0	0	0	0	0	

Year $h \rightarrow$	Mean density ( $t/km^2$ )										
	121	122	123	124	161	162	163	185	186	187	
1984	0	0	0	0	5.46	3.32	2.03	1.03	5.61	7.59	
1994	0	0	0	0	0	0	0	0.826	4.16	4.40	
1995	2.07	6.41	13.9	6.75	0	0	0	0	0	0	

Table C.11. Queen Charlotte Sound Shrimp survey: number of sampled tows and 5ABC POP density per stratum  $h$  ( $t/km^2$ ). Stratum areas: 000 = 3.6  $km^2$ ; 109 = 4.5  $km^2$ .

Year $h \rightarrow$	# Samples		Mean density ( $t/km^2$ )	
	000	109	000	109
1999	9	15	2.43	2.62

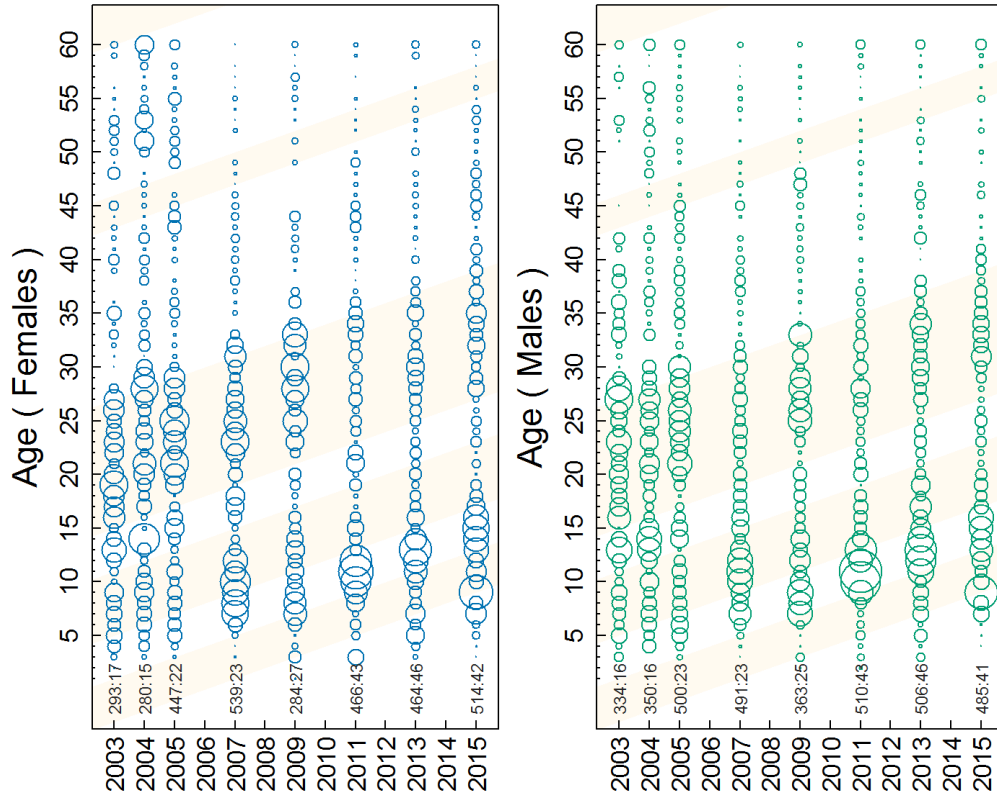


Figure C.9. Queen Charlotte Sound Synoptic survey – 5ABC POP proportions-at-age based on age frequencies weighted by mean fish density within strata and by total stratum area within survey. See Figure C.8 for details on diagonal shaded bands and displayed numbers.

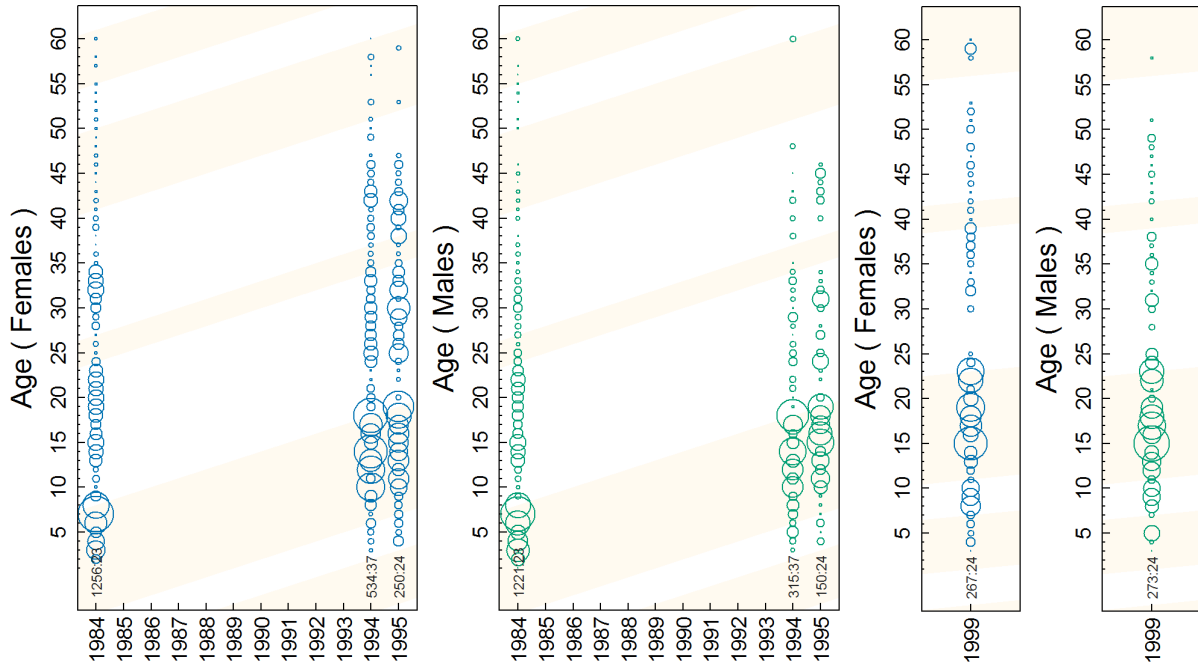


Figure C.10. Goose Island Gully Rockfish survey (left) and Queen Charlotte Sound Shrimp survey (right) – 5ABC POP proportions-at-age based on age frequencies weighted by mean fish density within strata and by total stratum area within survey. See Figure C.8 for details on displayed numbers.

### C.3. HABITAT

Pacific Ocean Perch is ubiquitous along the BC coast, with an estimated area of occupancy ranging from ~48,300 km<sup>2</sup> using trawl occurrence (Figure A.2) to ~55,000 km<sup>2</sup>, using bathymetry limits (Figure C.11). The estimated bathymetry limits are derived from POP being captured in 98% of bottom trawl tows that span depths 101 to 501 m (Figure C.12). Tows that capture POP remove other species of fish as well.

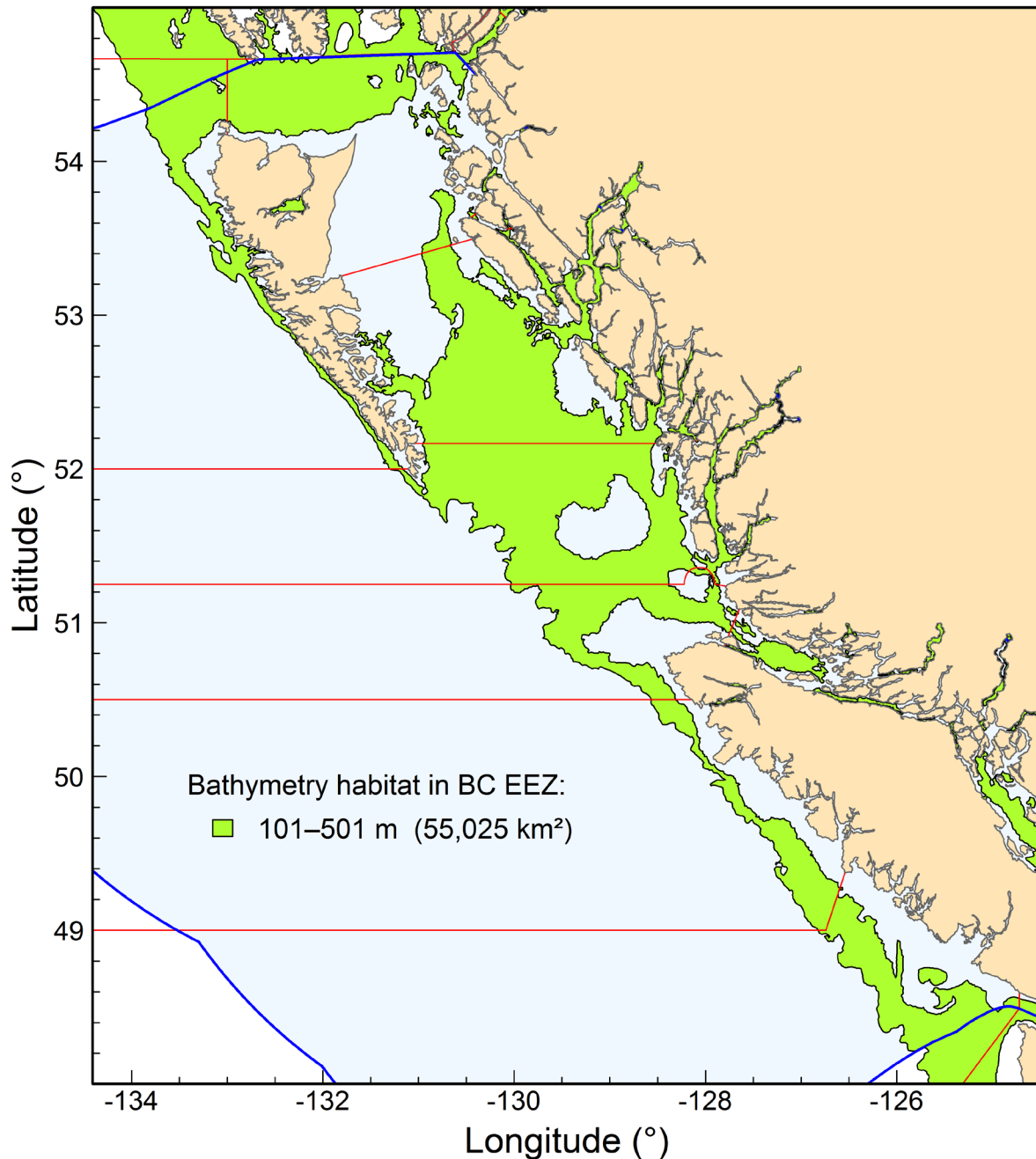


Figure C.11. Highlighted bathymetry (green) between 101 and 501 m serves as a proxy for benthic habitat for Pacific Ocean Perch along the BC coast. Within Canada’s exclusive economic zone (EEZ, blue highlighted area), the green highlighted region covers 55,025 km<sup>2</sup>. The boundaries in red delimit the PMFC areas.

The depth distribution of bottom trawl tows that captured POP in Pacific Marine Fisheries Commission (PMFC) areas 5ABC shows that 98% of the encounters lie between 96 and 416 m, with a median tow depth of 238 m and a depth-of-median-catch at 256 m (Figure C.13, data extracted from the PacHarvest and GFFOS databases). The relative distribution of POP bottom tows between 0 and 600 m differs from the total effort at these depths by the trawl fishery in 5ABC (shaded background histogram) due to a large flatfish fishery in area 5C.

The top 20 reported species caught in POP bottom tows comprise predominantly of a mixture of rockfish and flatfish (Figure C.14, Figure C.16, and Table C.12). In these tows, Pacific Ocean Perch remains the most abundant species by weight in 5ABC (29%), with important contributions from Arrowtooth Flounder *Atheresthes stomias* (19%), Yellowmouth Rockfish *Sebastes reedi* (9%), and Yellowtail Rockfish *S. flavidus* (7%). Coastwide, Arrowtooth Flounder predominates in POP tows (24%), followed by POP (19%), Yellowtail Rockfish (8%), and Dover Sole *Microstomus pacificus* (7%). Midwater POP tows captured predominantly Pacific Hake *Merluccius productus* (Figure C.15).

The rockfish species of interest to COSEWIC (Committee on the Status of Endangered Wildlife in Canada) account for varying total mortality by weight (Table C.12), with Yellowmouth Rockfish being the most caught COSEWIC species in POP tows in 5ABC (9%) and coastwide (5%). Rougheyeye Rockfish *S. aleutianus* is barely caught in POP tows in 5ABC and only minimally coastwide (2%), likely because it is more prevalent at deeper depths. Canary Rockfish *S. pinniger* accounts for only 2-3% of the catch weight in POP tows generally.

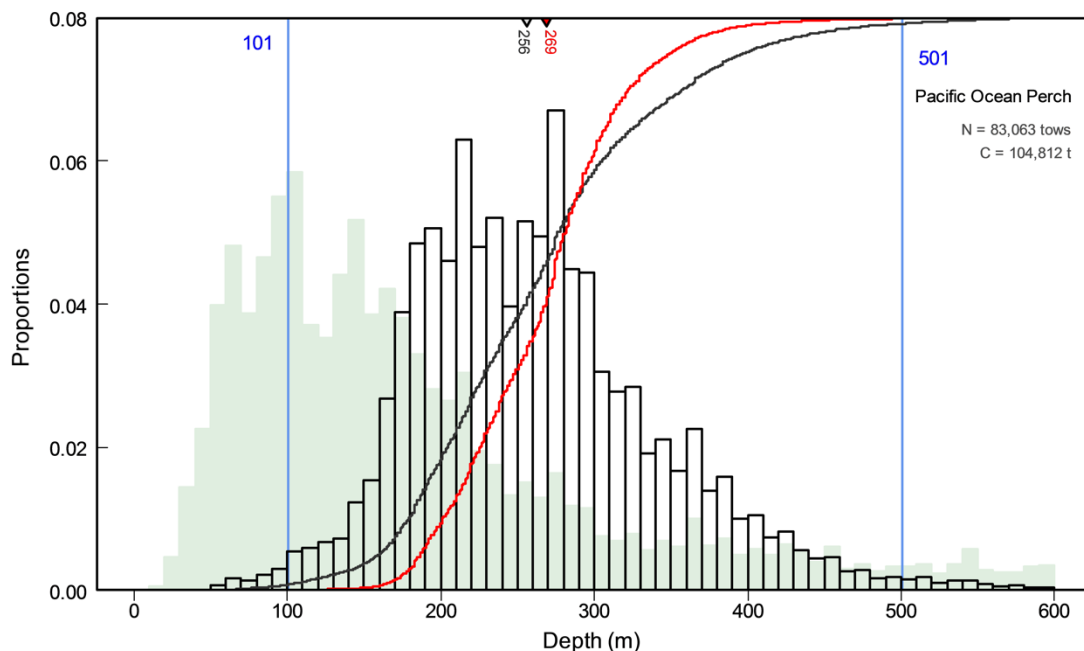


Figure C.12. BC Offshore – Depth frequency of bottom tows between 0 and 600 m that capture Pacific Ocean Perch (POP) from commercial trawl logs (1996-2007 PacHarvest, 2007-2016 GFFOS) in all PMFC major areas offshore combined (transparent histogram). The vertical solid lines denote the 1% and 99% percentiles. The black curve shows the cumulative frequency of tows that encounter POP while the red curve shows the cumulative catch of POP at depth (scaled from 0 to 1). The median depths of cumulative catch (inverted red triangle) and of POP encounters (inverted grey triangle) are indicated along the upper axis. ‘N’ reports the total number of tows; ‘C’ reports the total catch (t). The shaded histogram in the background reports the relative trawl effort on all species between 0 and 600 m for the BC offshore area.

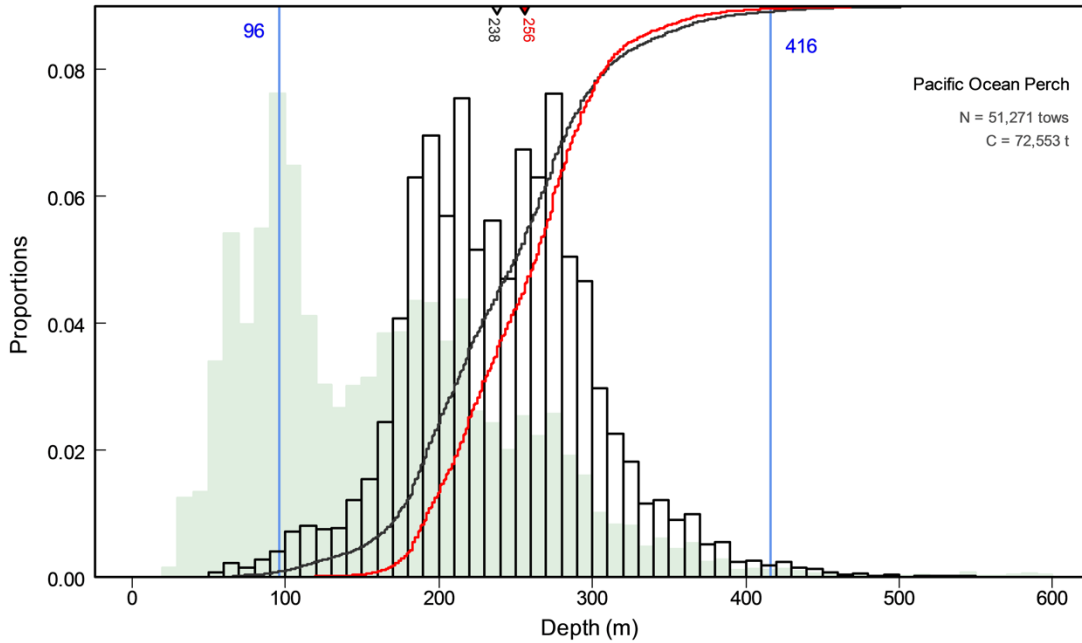


Figure C.13. QCS – Depth frequency of bottom tows that capture Pacific Ocean Perch (POP) from commercial trawl logs (1996-2007 PacHarvest, 2007-2016 GFFOS) in PMFC major areas 5ABC (transparent histogram). The shaded histogram in the background reports the relative trawl effort on all species between 0 and 600 m in 5ABC (QCS). Plot details appear in Figure C.12.

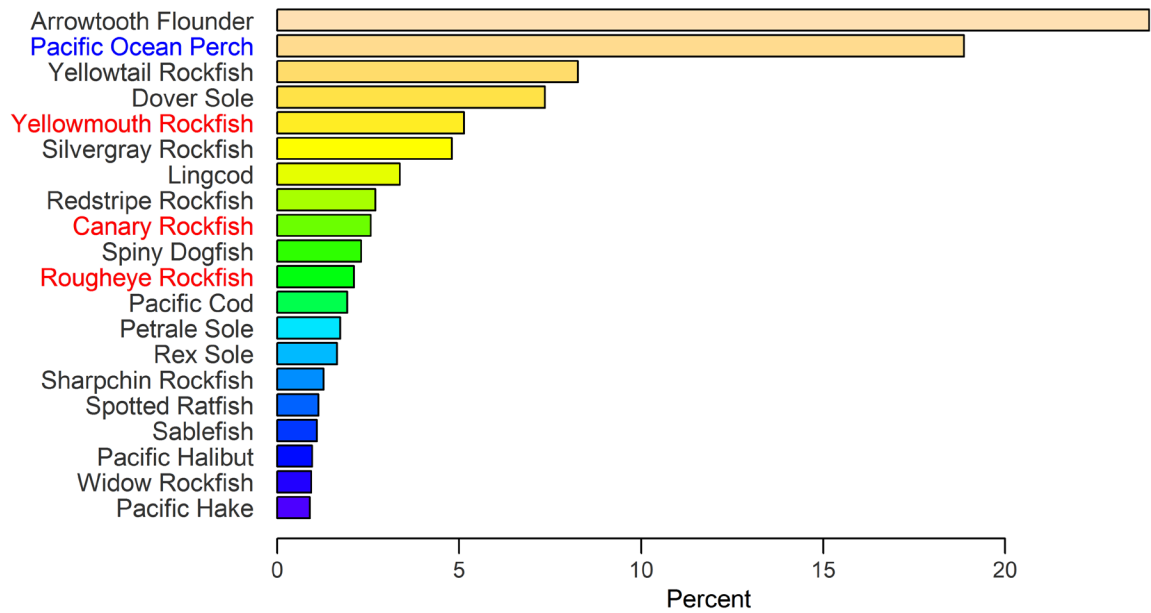


Figure C.14. BC Offshore bottom tows – Distribution of catch weights summed over the period February 1996 to June 2017 for species in bottom tows that caught at least one POP along the BC coast. Tows were selected over a depth range between 101 and 501 m (the 1% and 99% quantile range, Figure C.12). Relative concurrence is expressed as a percentage by species relative to the total catch weight summed over all species in the specified period. Pacific Ocean Perch is indicated in blue on the y-axis; other species of interest to SARA are indicated in red. The 20 species account for 93% of the total catch weight at these depths in this time period.



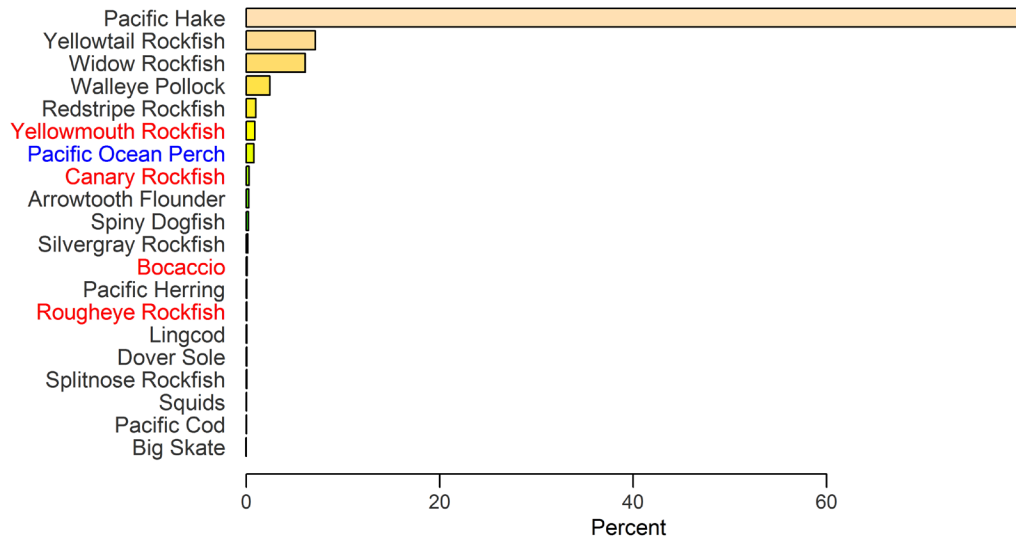


Figure C.15. BC Offshore midwater tows – Distribution of catch weights summed over the period February 1996 to June 2017 for species in midwater tows that caught at least one Pacific Ocean Perch along the BC coast. Tows were selected over a depth range between 101 and 501 m (the 1% and 99% quantile range, Figure C.12). Relative concurrence is expressed as a percentage by species relative to the total catch weight summed over all species in the specified period. Pacific Ocean Perch is indicated in blue on the y-axis; other species of interest to SARA are indicated in red. The 20 species account for 99.8% of the total catch weight at these depths in this time period; the total catch of Pacific Hake was 428,023 t

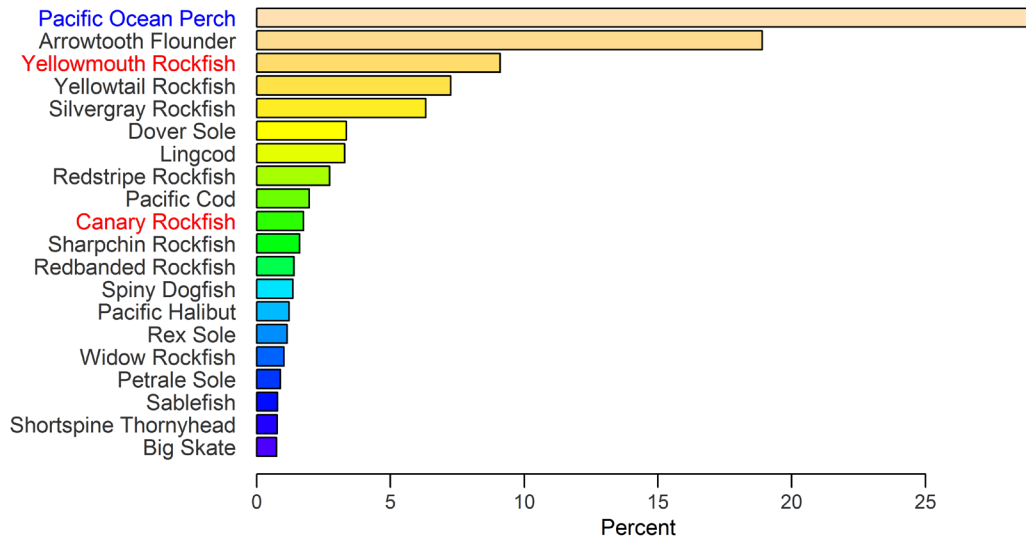


Figure C.16. QCS bottom tows – Distribution of catch weights summed over the period February 1996 to June 2017 for species in bottom tows that caught at least one Pacific Ocean Perch in PMFC 5ABC. Tows were selected over a depth range between 96 and 416 m (the 1% and 99% quantile range, Figure C.13). Relative concurrence is expressed as a percentage by species relative to the total catch weight summed over all species in the specified period. Pacific Ocean Perch is indicated in blue on the y-axis; other species of interest to SARA are indicated in red. The 20 species account for 94% of the total catch weight at these depths in this time period.

Table C.12. Top 20 species by catch weight (sum of landed + discarded from Feb 1996 to Jun 2017) that co-occur in POP bottom trawl tows along the BC coast and in PMFC 5ABC. Rockfish species of interest to COSEWIC appear in red font<sup>R</sup>, target species (must appear in every tow) appears in blue font<sup>B</sup>.

<b>Coastwide</b>				
<b>Code</b>	<b>Species</b>	<b>Latin Name</b>	<b>Catch (t)</b>	<b>Catch (%)</b>
602	Arrowtooth Flounder	<i>Atheresthes stomias</i>	134,188	23.958
<b>396</b>	<b>Pacific Ocean Perch<sup>B</sup></b>	<b><i>Sebastes alutus</i></b>	<b>105,674</b>	<b>18.867</b>
418	Yellowtail Rockfish	<i>Sebastes flavidus</i>	46,279	8.263
626	Dover Sole	<i>Microstomus pacificus</i>	41,197	7.355
<b>440</b>	<b>Yellowmouth Rockfish<sup>R</sup></b>	<b><i>Sebastes reedi</i></b>	<b>28,738</b>	<b>5.131</b>
405	Silvergray Rockfish	<i>Sebastes brevispinis</i>	26,882	4.800
467	Lingcod	<i>Ophiodon elongatus</i>	18,883	3.371
439	Redstripe Rockfish	<i>Sebastes proriger</i>	15,147	2.704
<b>437</b>	<b>Canary Rockfish<sup>R</sup></b>	<b><i>Sebastes pinniger</i></b>	<b>14,389</b>	<b>2.569</b>
044	Spiny Dogfish	<i>Squalus acanthias</i>	12,947	2.312
<b>394</b>	<b>Rougheye Rockfish<sup>R</sup></b>	<b><i>Sebastes aleutianus</i></b>	<b>11,839</b>	<b>2.114</b>
222	Pacific Cod	<i>Gadus macrocephalus</i>	10,766	1.922
607	Petrale Sole	<i>Eopsetta jordani</i>	9,703	1.732
610	Rex Sole	<i>Errex zachirus</i>	9,192	1.641
450	Sharpchin Rockfish	<i>Sebastes zacentrus</i>	7,146	1.276
066	Spotted Ratfish	<i>Hydrolagus colliei</i>	6,348	1.133
455	Sablefish	<i>Anoplopoma fimbria</i>	6,104	1.090
614	Pacific Halibut	<i>Hippoglossus stenolepis</i>	5,409	0.966
417	Widow Rockfish	<i>Sebastes entomelas</i>	5,280	0.943
225	Pacific Hake	<i>Merluccius productus</i>	5,025	0.897
<b>5ABC</b>				
<b>Code</b>	<b>Species</b>	<b>Latin Name</b>	<b>Catch (t)</b>	<b>Catch (%)</b>
<b>396</b>	<b>Pacific Ocean Perch<sup>B</sup></b>	<b><i>Sebastes alutus</i></b>	<b>75,206</b>	<b>28.826</b>
602	Arrowtooth Flounder	<i>Atheresthes stomias</i>	49,315	18.902
<b>440</b>	<b>Yellowmouth Rockfish<sup>R</sup></b>	<b><i>Sebastes reedi</i></b>	<b>23,747</b>	<b>9.102</b>
418	Yellowtail Rockfish	<i>Sebastes flavidus</i>	18,907	7.247
405	Silvergray Rockfish	<i>Sebastes brevispinis</i>	16,480	6.317
626	Dover Sole	<i>Microstomus pacificus</i>	8,754	3.355
467	Lingcod	<i>Ophiodon elongatus</i>	8,569	3.285
439	Redstripe Rockfish	<i>Sebastes proriger</i>	7,104	2.723
222	Pacific Cod	<i>Gadus macrocephalus</i>	5,130	1.966
<b>437</b>	<b>Canary Rockfish<sup>R</sup></b>	<b><i>Sebastes pinniger</i></b>	<b>4,583</b>	<b>1.757</b>
450	Sharpchin Rockfish	<i>Sebastes zacentrus</i>	4,199	1.609
401	Redbanded Rockfish	<i>Sebastes babcocki</i>	3,650	1.399
044	Spiny Dogfish	<i>Squalus acanthias</i>	3,540	1.357
614	Pacific Halibut	<i>Hippoglossus stenolepis</i>	3,164	1.213
610	Rex Sole	<i>Errex zachirus</i>	2,979	1.142
417	Widow Rockfish	<i>Sebastes entomelas</i>	2,650	1.016
607	Petrale Sole	<i>Eopsetta jordani</i>	2,308	0.885
455	Sablefish	<i>Anoplopoma fimbria</i>	2,049	0.785
451	Shortspine Thornyhead	<i>Sebastolobus alascanus</i>	2,011	0.771
056	Big Skate	<i>Raja binoculata</i>	1,920	0.736

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## APPENDIX D. MODEL EQUATIONS

### D.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 Silvergray Rockfish (Starr et al. 2016), Pacific Ocean Perch (POP) in Queen Charlotte Sound, west coast Haida Gwaii, and west coast Vancouver Island (Edwards et al. 2012b, 2014a,b), and Yellowmouth Rockfish along the Pacific coast of Canada (Edwards et al. 2012a).

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

Implementation was done using a modified version of the Coleraine statistical catch-at-age software (Hilborn et al. 2003) called Awatea (A. 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 code we wrote in R (R Core Team 2016) for the Yellowmouth Rockfish assessment (Edwards et al. 2012a), rather than using the original Excel implementation. This R code has subsequently been modified over the years. Figures and tables of output were automatically produced through R 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.

### D.2. MODEL ASSUMPTIONS

The assumptions of the model are:

1. The 5ABC stock was treated as a single stock.
2. Catches were taken by a single fishery, known without error, and occurred in the middle of the 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.

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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  $\geq 4$  samples in that year.
  11. Relative abundance indices were assumed to be proportional to the vulnerable biomass at the mid point of the year, after half of the catch and half of the natural mortality had been accounted for.
  12. The age composition samples were assumed to come from the middle of the year after half of the catch and half of the natural mortality had been accounted for.

### **D.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. Note that logarithms herein use the base  $e \approx 2.718282$  (natural logarithm). The model description is divided into the deterministic components, stochastic components and Bayesian priors. Full details of notation and equations are given after the tables.

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

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

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

Table D.1. Notation for the Awatea catch-at-age model.

<b>Indices (all subscripts)</b>	
<b>Symbol</b>	<b>Description and units</b>
$a$	age class, where $a = 1, 2, 3, \dots, A$ , and $A = 60$ is the accumulator age class
$t$	model year, where $t = 1, 2, 3, \dots, T$ , corresponds to actual years 1940, 1941, 1940, ..., 2016, and $t = 0$ represents unfished equilibrium conditions
$g$	index for data associated with survey and commercial gear: 1 – GIG historical survey series (GB Reed) 2 – Queen Charlotte Sound synoptic survey series [3] – Queen Charlotte Sound shrimp survey series [not used in Base Case] 3 – commercial trawl data
$s$	sex, 1 = females, 2 = males
<b>Index ranges</b>	
<b>Symbol</b>	<b>Description and units</b>
$A$	accumulator age-class, $A = 60$
$T$	number of model years, $T = 77$
$\mathbf{T}_g$	sets of model years for survey abundance indices from series $g$ , $g = 1, \dots, [3]$ , listed here for clarity as calendar years (subtract 1939 to give model year $t$ ): $\mathbf{T}_1 = \{1967, 1969, 1971, 1973, 1976, 1977, 1984, 1994\}$ $\mathbf{T}_2 = \{2003, 2004, 2005, 2007, 2009, 2011, 2013, 2015\}$ $\mathbf{T}_{[3]} = \{1999, \dots, 2013, 2015\}$
$\mathbf{U}_g$	sets of model years with proportion-at-age data, $g = 1, \dots, 3$ (listed here as years): $\mathbf{U}_1 = \{1984, 1994, 1995\}$ $\mathbf{U}_2 = \{2003, 2004, 2005, 2007, 2009, 2011, 2013, 2015\}$ $\mathbf{U}_{[3]} = \{1999\}$ $\mathbf{U}_3 = \{1978, \dots, 1984, 1987, 1989, \dots, 2014\}$
<b>Data and fixed parameters</b>	
<b>Symbol</b>	<b>Description and units</b>
$p_{atgs}$	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 $\sum_{a=1}^A \sum_{s=1}^2 p_{atgs} = 1$ for each $t \in \mathbf{U}_g$ , $g = 1, \dots, 3$
$n_{tg}$	assumed sample size that yields corresponding $p_{atgs}$
$C_t$	observed catch biomass (tonnes) in year $t = 1, 2, 3, \dots, T - 1$
$w_{as}$	average weight (kg) of individual of age-class $a$ and sex $s$ from fixed growth parameters
$m_a$	proportion of age-class $a$ females that are mature, fixed from data
$I_{tg}$	biomass estimates (tonnes) from surveys $g = 1, \dots, [3]$ for year $t \in \mathbf{T}_g$
$\kappa_{tg}$	standard deviation of $I_{tg}$
$\delta_{tg}$	normalised residual of $I_{tg} - \hat{I}_{tg}$ for surveys $g$ in year $t$

Symbol	Description and units
$\sigma_R$	standard deviation parameter for recruitment process error, $\sigma_R = 0.6$
<b>Estimated parameters</b>	
Symbol	Description and units
$\Theta$	set of estimated parameters
$R_0$	virgin recruitment of age-1 fish (numbers of fish, 1000s)
$M_s$	natural mortality rate for sex $s$ , $s = 1, 2$
$h$	steepness parameter for Beverton-Holt recruitment
$q_g$	catchability for survey series $g = 1, \dots, [3]$
$\mu_g$	age of full selectivity for females for series $g = 1, \dots, 3$
$\Delta_g$	shift in vulnerability for males for series $g = 1, \dots, 3$
$v_{gL}$	variance parameter for left limb of selectivity curve for series $g = 1, \dots, 3$
$s_{ags}$	selectivity for age-class $a$ , series $g = 1, \dots, 3$ , and sex $s$ , calculated from the parameters $\mu_g$ , $\Delta_g$ , and $v_{gL}$
$\alpha, \beta$	alternative formulation of recruitment: $\alpha = (1-h)B_0/(4hR_0)$ and $\beta = (5h-1)/4hR_0$
$\hat{x}$	estimated value of observed data $x$
<b>Derived states</b>	
Symbol	Description and units
$N_{ats}$	number of age-class $a$ and sex $s$ fish (1000s) 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 rate: ratio of total catch to vulnerable biomass in the middle of the year
$B_t$	spawning biomass (tonnes mature females) at the start of year $t$ , $t = 1, \dots, T$
$B_0$	virgin spawning biomass (tonnes mature females) at the start of year 0
$R_t$	recruitment of age-1 fish (1000s) in year $t$ , $t = 1, \dots, T-1$ , numbers of fish
$V_t$	vulnerable biomass (tonnes males + females) in the middle of year $t$ , $t = 1, \dots, T$
<b>Deviations and likelihood components</b>	
Symbol	Description and units
$\varepsilon_t$	Recruitment deviations arising from process error
$\log L_1(\Theta   \{\varepsilon_t\})$	log-likelihood component related to recruitment residuals
$\log L_2(\Theta   \{\hat{P}_{atgs}\})$	log-likelihood component related to estimated proportions-at-age
$\log L_3(\Theta   \{\hat{I}_{tg}\})$	log-likelihood component related to estimated survey biomass indices
$\log L(\Theta)$	total log-likelihood

<b>Prior distributions and objective function</b>	
<b>Symbol</b>	<b>Description and units</b>
$\pi_j(\Theta)$	Prior distribution for parameter $j$
$\pi(\Theta)$	Joint prior distribution for all estimated parameters
$f(\Theta)$	Objective function to be minimised

Table D.2. Deterministic components. Using the catch, weight-at-age and maturity data, with fixed values for all parameters, the initial conditions are calculated from (D.16)-(D.18), and then state dynamics are iteratively calculated through time using the main equations (D.13)-(D.15), selectivity functions (D.19) and (D.20), and the derived states (D.21)-(D.25). Estimated observations for survey biomass indices and proportions-at-age can then be calculated using (D.26) and (D.27). In Table D.3, the estimated observations of these are compared to data.

<b>State dynamics (<math>2 \leq t \leq T, s = 1, 2</math>)</b>	
$N_{1ts} = 0.5R_t$	(D.13)
$N_{ats} = e^{-M_s} (1 - u_{a-1,t-1,s}) N_{a-1,t-1,s}; 2 \leq a \leq A-1$	(D.14)
$N_{A ts} = e^{-M_s} (1 - u_{A-1,t-1,s}) N_{A-1,t-1,s} + e^{-M_s} (1 - u_{A,t-1,s}) N_{A,t-1,s}$	(D.15)
<b>Initial conditions (<math>t = 1</math>)</b>	
$N_{a1s} = 0.5R_0 e^{-M_s(a-1)}; 1 \leq a \leq A-1, s = 1, 2$	(D.16)
$N_{A1s} = 0.5R_0 \frac{e^{-M_s(A-1)}}{1 - e^{-M_s}}; s = 1, 2$	(D.17)
$B_0 = B_1 = \sum_{a=1}^A w_{a1} m_a N_{a11}$	(D.18)
<b>Selectivities (<math>g = 1, \dots, 3</math>)</b>	
$s_{ag1} = \begin{cases} e^{-(a-\mu_g)^2/vgL}, & a \leq \mu_g \\ 1, & a > \mu_g \end{cases}$	(D.19)
$s_{ag2} = \begin{cases} e^{-(a-\mu_g-\Delta_g)^2/vgL}, & a \leq \mu_g + \Delta_g \\ 1, & a > \mu_g + \Delta_g \end{cases}$	(D.20)
<b>Derived states (<math>1 \leq t \leq T-1</math>)</b>	
$B_t = \sum_{a=1}^A w_{a1} m_a N_{at1}$	(D.21)
$R_t = \frac{4hR_0 B_{t-1}}{(1-h)B_0 + (5h-1)B_{t-1}} \left( \equiv \frac{B_{t-1}}{\alpha + \beta B_{t-1}} \right)$	(D.22)
$V_t = \sum_{s=1}^2 \sum_{a=1}^A e^{-M_s/2} w_{as} s_{a4s} N_{ats}$	(D.23)



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

$$u_t = \frac{C_t}{V_t} \quad (D.24)$$

$$u_{ats} = s_{a4s} u_t; \quad 1 \leq a \leq A, \quad s = 1, 2 \quad (D.25)$$

**Estimated observations**

$$\hat{I}_{tg} = q_g \sum_{s=1}^2 \sum_{a=1}^A e^{-M_s/2} (1 - u_{ats}/2) w_{as} s_{ags} N_{ats}; \quad t \in \mathbf{T}_g, \quad g = 1, \dots, 3 \quad (D.26)$$

$$\hat{p}_{atgs} = \frac{e^{-M_s/2} (1 - u_{ats}/2) s_{ags} N_{ats}}{\sum_{s=1}^2 \sum_{a=1}^A e^{-M_s/2} (1 - u_{ats}/2) s_{ags} N_{ats}}; \quad 1 \leq a \leq A, \quad t \in \mathbf{U}_g, \quad g = 1, \dots, 3, \quad s = 1, 2 \quad (D.27)$$


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

**Estimated parameters**

$$\Theta = \{R_0; M_{1,2}; h; q_{1,\dots,[3]}; \mu_{1,\dots,3}; \Delta_{1,\dots,3}; \nu_{1,\dots,3L}\} \quad (D.28)$$

**Recruitment deviations**

$$\varepsilon_t = \log R_t - \log B_{t-1} + \log(\alpha + \beta B_{t-1}) + \sigma_R^2/2; \quad 1 \leq t \leq T-1 \quad (D.29)$$

**Log-likelihood functions**

$$\log L_1(\Theta | \{\varepsilon_t\}) = -\frac{T}{2} \log 2\pi - T \log \sigma_R - \frac{1}{2\sigma_R^2} \sum_{t=1}^{T-1} \varepsilon_t^2 \quad (D.30)$$

$$\begin{aligned} \log L_2(\Theta | \{\hat{p}_{atgs}\}) = & -\frac{1}{2} \sum_{g=1}^3 \sum_{a=1}^A \sum_{t \in \mathbf{U}_g} \sum_{s=1}^2 \log \left[ p_{atgs} (1 - p_{atgs}) + \frac{1}{10A} \right] \\ & + \sum_{g=1}^3 \sum_{a=1}^A \sum_{t \in \mathbf{U}_g} \sum_{s=1}^2 \log \left[ \exp \left\{ \frac{-(p_{atgs} - \hat{p}_{atgs})^2 n_{tg}}{2(p_{atgs} (1 - p_{atgs}) + 1/10A)} \right\} + \frac{1}{100} \right] \end{aligned} \quad (D.31)$$

$$\log L_3(\Theta | \{\hat{I}_{tg}\}) = \sum_{g=1}^3 \sum_{t \in \mathbf{T}_g} \left[ -\frac{1}{2} \log 2\pi - \log \kappa_{tg} - \frac{(\log I_{tg} - \log \hat{I}_{tg})^2}{2\kappa_{tg}^2} \right] \quad (D.32)$$

$$\log L(\Theta) = \sum_{i=1}^3 \log L_i(\Theta | \cdot) \quad (D.33)$$

**Joint prior distribution and objective function**

$$\log(\pi(\Theta)) = \sum_j \log(\pi_j(\Theta)) \quad (D.34)$$

$$f(\Theta) = -\log L(\Theta) - \log(\pi(\Theta)) \quad (D.35)$$

Table D.4. Details for estimation of parameters, including phase of the optimisation when parameter is estimated (negative values denote parameter fixed to initial value), 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  $\pi_j(\Theta)$  functions that contribute to the joint prior distribution in (D.34).

Parameter	Phase	Prior distribution	Mean, SD	Bounds	Initial value
$R_0$	1	uniform	–	[1, 1e7]	10,000
$M_{1,2}$	4	normal	0.06, 0.006	[0.01, 0.12]	0.06
$h$	5	beta	4.574, 2.212	[0.2, 0.999]	0.674
$\log q_{1,\dots,[3]}$	1	uniform	0, 0.6	[-12, 5]	-5
$\mu_{1,2}$	3	uniform	8.069, 2.421	[5, 40]	8.069
$\mu_{[3]}$	-3	uniform	8.069, 2.421	[5, 40]	8.069
$\mu_3$	3	uniform	12.289, 3.687	[5, 40]	12.289
$\log v_{1,2L}$	4	uniform	2.277, 0.683	[-15, 15]	2.277
$\log v_{[3]L}$	-4	uniform	2.277, 0.683	[-15, 15]	2.277
$\log v_{3L}$	4	uniform	2.757, 0.827	[-15, 15]	2.757
$\Delta_{1,\dots,3}$	4	uniform	0, 1	[-8, 10]	0

## D.4. DESCRIPTION OF DETERMINISTIC COMPONENTS

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

### D.4.1. Age classes

Index (subscript)  $a$  represents age classes, going from 1 to the accumulator age class,  $A$ , of 60. 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 2016.

### D.4.2. Years

Index  $t$  represents model years, going from 1 to  $T = 77$ , and  $t = 0$  represents unfished equilibrium conditions. The actual year corresponding to  $t = 1$  is 1940, and so model year  $T = 77$  corresponds to 2016. Catch data for the whole of 2016 are available (since the assessment model is being run in March 2017).

### D.4.3. Survey data

Data from three survey series were used, as described in detail in Appendix D. Here, subscript  $g = 1$  corresponds to the GB Reed historical survey series in Goose Island Gully (GIG),  $g = 2$  to the Queen Charlotte Sound synoptic survey series, and  $g = [3]$  to the Queen Charlotte Sound shrimp trawl survey series (not used in the Base Case). The years for which data are available

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for each survey are given in Table D.1;  $\mathbf{T}_g$  corresponds to years for the survey biomass estimates  $I_{tg}$  (and corresponding standard deviations  $\kappa_{tg}$ ), and  $\mathbf{U}_g$  corresponds to years for proportion-at-age data  $p_{atgs}$  (with assumed sample sizes  $n_{tg}$ ). Note that  $\mathbf{U}_{[3]}$ , with one year of age data in 1999, is only used in the Sensitivity 2 run.

#### D.4.4. Commercial data

As described in Appendix A, the commercial catch has been 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  $\mathbf{U}_3$  (Table D.1) gives the years of available ageing data from the commercial fishery. The proportions-at-age values are given by  $p_{atgs}$  with assumed sample size  $n_{tg}$ , where  $g = 3$  corresponds 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.

#### D.4.5. Sex

A two-sex model was used, with subscript  $s = 1$  for females and  $s = 2$  for males. Ageing data were partitioned by sex, as were the weights-at-age inputs. Selectivities and natural mortality were estimated by sex.

#### D.4.6. Weights-at-age

The weights-at-age  $w_{as}$  are assumed fixed over time and based on the biological data.

#### D.4.7. Maturity of females

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

#### D.4.8. State dynamics

The crux of the model is the set of dynamical equations (D.13)-(D.15) for the estimated number  $N_{ats}$  of age-class  $a$  fish of sex  $s$  at the start of year  $t$ . Equation (D.13) states that half of new recruits are males and half are females. Equation (D.14) 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 (D.15) is for the accumulator age class  $A$ , whereby survivors from this class remain in this class the following year.

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

#### D.4.9. Initial conditions

An unfished equilibrium situation at the beginning of the reconstruction is assumed, because there is no evidence of significant removals prior to 1940, and 1940 predates significant

removals by about 15 years (Appendix A). The initial conditions (D.16) and (D.17) are obtained by setting  $R_t = R_0$  (virgin recruitment),  $N_{ats} = N_{a1s}$  (equilibrium condition) and  $u_{ats} = 0$  (no fishing) into (D.13)-(D.15). The virgin spawning biomass  $B_0$  is then obtained from (D.21).

#### D.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 (D.19) and (D.20), to give selectivities  $s_{ags}$  (note that the subscript  $s$  always represents the index for sex, whereas  $s_{..}$  always represents selectivity). This permits an increase in selectivity up to the age of full selection ( $\mu_g$  for females). Given there was no evidence to suggest a dome-shaped function, it was assumed that fish older than  $\mu_g$  remain fully selected. The rate of ascent of the left limb is controlled by the parameter  $\nu_{gL}$  for females. For males, the same function is used except that the age of full selection is shifted by an amount  $\Delta_g$ , see (D.20).

#### D.4.11. Derived states

The spawning biomass (biomass of mature females, in tonnes)  $B_t$  at the start of year  $t$  is calculated in (D.21) 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 (D.25) calculates, for year  $t$ , the proportion  $u_{ats}$  of age-class  $a$  and sex  $s$  fish that are caught. This requires the commercial selectivities  $s_{a3s}$  and the ratio  $u_t$ , which equation (D.24) shows is the ratio of total catch to vulnerable biomass in the middle of the year,  $V_t$ , given by equation (D.23). So (D.24) calculates the proportion of the vulnerable biomass that is caught, and (D.25) partitions this out by sex and age.

#### D.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 (D.22) 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  $\alpha$  and  $\beta$  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.

#### D.4.13. Estimates of observed data

The model estimates of the survey biomass indices  $I_{tg}$  are denoted  $\hat{I}_{tg}$  and are calculated in (D.26). 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  $\hat{I}_{ig}$ . A 0.001 coefficient in (D.26) is not needed to convert kg into tonnes, because  $N_{ats}$  is in 1000s of fish (true also for (D.18) and (D.21)).

The estimated proportions-at-age  $\hat{p}_{atgs}$  are calculated in (D.27). 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  $\sum_{s=1}^2 \sum_{a=1}^A \hat{p}_{atgs} = 1$ .

## D.5. DESCRIPTION OF STOCHASTIC COMPONENTS

### D.5.1. Parameters

The set  $\Theta$  gives the parameters that are estimated. The estimation procedure is described in the Bayesian Computations section below.

### D.5.2. Recruitment deviations

For recruitment, a log-normal process error is assumed, such that the stochastic version of the deterministic stock-recruitment function (D.22) is

$$R_t = \frac{B_{t-1}}{\alpha + \beta B_{t-1}} e^{\varepsilon_t - \sigma_R^2/2} \quad (\text{D.36})$$

where  $\varepsilon_t \sim \text{Normal}(0, \sigma_R^2)$ , and the bias-correction term  $-\sigma_R^2/2$  in (D.36) ensures that the mean of the recruitment deviations equals 0. This then gives the recruitment deviation equation (D.29) and log-likelihood function (D.30). The value of  $\sigma_R$  was fixed at 0.6, which is typical for marine redfish (Mertz and Myers 1996).

### D.5.3. Log-likelihood functions

The log-likelihood function (D.31) 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  $\hat{p}_{atgs}$  from the Fournier et al. (1990, 1998) formulation with the observed proportions  $p_{atgs}$ , except in the  $(p_{atgs} - \hat{p}_{atgs})^2$  term (Bull et al. 2005).

The  $1/(10A)$  term in (D.31) reduces the weight of proportions that are close to or equal zero.

The  $1/100$  term reduces the weight of large residuals  $(p_{atgs} - \hat{p}_{atgs})$ . The net effect (Stanley et

al. 2009) is that residuals larger than three standard deviations from the fitted proportion are treated roughly as  $3\left(p_{atgs}(1-p_{atgs})\right)^{1/2}$ .

Lognormal error is assumed for the survey indices, resulting in the log-likelihood equation (D.32). The total log-likelihood  $\log L(\Theta)$  is then the sum of the likelihood components – see (D.33).

## D.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  $f(\Theta)$ , which equation (D.35) shows is the negative of the sum of the total log-likelihood function and the logarithm of the joint prior distribution, given by (D.34).

The procedure for the Bayesian computations is as follows:

1. minimise the objective function  $f(\Theta)$  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.

### D.6.1. Phases

The MPD estimates were obtained by minimising the objective function  $f(\Theta)$ , 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  $q_{1,\dots,[3]}$ ;

phase 2: recruitment deviations  $\varepsilon_t$  (held at 0 in phase 1);

phase 3: age of full selectivity for females  $\mu_{1,\dots,3}$ ;

phase 4: natural mortality  $M_{1,2}$  and selectivity parameters  $\Delta_g, \nu_{gL}$  for  $g = 1,\dots,3$ ;

phase 5: steepness  $h$ .

### D.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 advised. The QCS POP assessment (Edwards et al. 2012b) 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 of mean=0). This procedure did not perform well for age frequencies in the Yellowmouth Rockfish assessment (Edwards et al. 2012a), leading to spurious cohorts; therefore, the Yellowmouth assessment used the reweighting scheme proposed by Francis (2011). In this assessment, we adopt a combination approach – weighting surveys by adjusting SDNRs one time before minimisation and iteratively weighting age 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 adding process error,  $c_p = 0.2$  for example, one time only to give a reweighted coefficient of variation  $c_1$  after the first reweight:

$$c_1 = \sqrt{c_0^2 + c_p^2} \quad (D.37)$$

However, for this stock assessment we started with added process error  $c_p = 0.2$  for each survey using (B.6) and ran a preliminary set of runs to obtain a predicted index  $\hat{I}_{ig}^{(3)}$  from the third reweighted fit to the age composition data, where  $(r) = 3$  represents the reweighting iteration. These predicted indices were then used to calculate normalised residuals for each survey index:

$$\delta_{ig} = \frac{\log(I_{ig}^{(0)}) - \log(\hat{I}_{ig}^{(3)})}{c_{1ig}},$$

where  $I_{ig}^{(0)}$  = the original survey indices, and standard deviations of the normalised residuals (SDNR) for each survey  $g$ . The survey SDNRs were then used to scale  $c_{1ig}$  to derive adjusted survey CVs  $c_{ig}$  for input to the model, along with the survey indices  $I_{ig}^{(0)}$ . This procedure was a preliminary one-time adjustment to survey CVs prior to the base-case model run performed in the assessment. No further process error was added to the abundance data during subsequent reweighted model fits to the age composition data (described below).

The preliminary reweighting scheme for abundance data adopted by this approach resulted in a more appropriate set of relative weights than would have been achieved from following the Francis (2011) suggestion. The additional process error added by survey was 0.12 for the QC Sound synoptic survey, 0.25 for the GIG survey and 0.39 for the QC Sound shrimp survey. This puts more relative weight on the QC Sound synoptic survey, which is a random-stratified survey optimised for groundfish species such as POP, whereas the GIG survey was a fixed-station survey operated over a relatively limited area. The QC Sound shrimp survey was removed from the base-case runs because its depth coverage was sub-optimal for POP. Adopting the Francis (2011) approach would have placed equal weight on all three surveys which does not reflect the relative suitability of these three surveys for POP.

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

$$n_{ig}^{(r)} = W_g^{(r)} n_{ig}^{(r-1)} \quad (D.38)$$

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

The Francis (2011) weight  $W_g^{(r)}$  given to each data set takes into account deviations from the mean weight for each year, rather than the scheme used for the QCS POP assessment (Edwards et al. 2012b) that considered deviations from each proportion-at-age value. It is given by equation (TA1.8) of Francis (2011):

$$W_g^{(r)} = \left\{ \text{Var}_t \left[ \frac{\bar{O}_{ig} - \bar{E}_{ig}}{\sqrt{\theta_{ig}/n_{ig}^{(r-1)}}} \right] \right\}^{-1} \quad (\text{D.39})$$

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

$$\bar{O}_{ig} = \sum_{a=1}^A \sum_{s=1}^2 ap_{atgs} \quad (\text{D.40})$$

$$\bar{E}_{ig} = \sum_{a=1}^A \sum_{s=1}^2 a\hat{p}_{atgs} \quad (\text{D.41})$$

$$\theta_{ig} = \sum_{a=1}^A \sum_{s=1}^2 a^2 \hat{p}_{atgs} - \bar{E}_{ig}^2 \quad (\text{D.42})$$

and  $\text{Var}_t$  is the usual finite-sample variance function applied over the index  $t$ . For the Yellowmouth Rockfish assessment Edwards et al. (2012a) we used this approach iteratively with  $r = 1, \dots, 3$ , but found that reweightings after the first ( $r = 1$ ) had only a marginal effect; the reported results for this assessment were based on the third reweighting.

### D.6.3. Prior distributions

Descriptions of the prior distributions for the estimated parameters (without including recruitment deviations) are given in Table D.4. The resulting probability density functions give the  $\pi_j(\Theta)$ , whose logarithms are then summed in (D.34) to give the joint prior distribution  $\pi(\Theta)$ . 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 (D.34) of the joint prior distribution  $\pi(\Theta)$ , 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 priors for female and male natural mortality,  $M_1$  and  $M_2$  respectively, were based on previous assessments of POP that assume  $M = 0.06$  (Edwards et al. 2012b), which we use as the mean and assume a 10% CV (Table D.4).



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For steepness,  $h$ , the same prior was used as for the QCS POP assessment (Edwards et al. 2012b) – a beta distribution with values fitted to the posterior distribution for rockfish calculated by Forrest et al. (2010). Uniform priors on a logarithmic scale were used for the catchability parameters  $q_g$ .

Selectivity was estimated for the two surveys with age composition data: GIG Rockfish historical and Queen Charlotte Sound (QCS) synoptic survey series ( $g = 1,2$ ). In past assessments, informative priors were developed for the three selectivity parameters for each of these surveys,  $\mu_{1,2}$ ,  $\Delta_{1,2}$ , and  $\nu_{1,2L}$ , based on the median values for the same parameters from the matching base case POP assessments (Edwards et al. 2012b, 2014a,b). However, in this assessment, uniform distributions were assumed for the priors.

No age data were available for the QCS shrimp trawl survey series ( $g = [3]$ ), so the three selectivity parameters for this survey was fixed rather than estimated. The fixed values used for these selectivities were the posterior medians from the same survey in the 5ABC base case POP stock assessment (for the GB Reed survey series).

For the commercial selectivity ( $g = 3$ ), the priors for the three parameters were uniform (non-informative) distributions with starting values based on the median values of the posterior distributions for the 'Estimate M&h' model run of the 5ABC POP stock assessment.

#### **D.6.4. MCMC properties**

The MCMC procedure started the search from the MPD values and performed 6,000,000 iterations, sampling every 5,000<sup>th</sup> for 1,200 samples, 1,000 of which were used after removing the first 200 for a burn-in period.

### **D.7. REFERENCE POINTS, PROJECTIONS AND ADVICE TO MANAGERS**

Advice to managers is given with respect to two sets of reference points. The first set consists of the provisional reference points of the DFO Precautionary Approach (DFO 2006), namely  $0.4 B_{MSY}$  and  $0.8 B_{MSY}$  (and we also provide  $B_{MSY}$ );  $B_{MSY}$  is the estimated equilibrium spawning biomass at the maximum sustainable yield (MSY). The second set of reference points are  $0.2 B_0$  and  $0.4 B_0$ , where  $B_0$  is the estimated unfished equilibrium spawning biomass. See main text for further discussion.

To estimate  $B_{MSY}$ , the model was projected forward across a range (0 to 0.3 incremented by 0.001) of constant harvest rates ( $u_t$ ), for a maximum of 15,000 years until equilibrium was reached (with a tolerance of 0.01 t). The MSY is the largest of the equilibrium yields, and the associated exploitation rate is then  $u_{MSY}$  and the associated spawning biomass is  $B_{MSY}$ . This calculation was done for each of the 1,000 MCMC samples, resulting in marginal posterior distributions for MSY,  $u_{MSY}$  and  $B_{MSY}$ .

The probability  $P(B_{2017} > 0.4B_{MSY})$  is then calculated as the proportion of the 1,000 MCMC samples for which  $B_{2017} > 0.4B_{MSY}$  (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 2016. A range of constant catch strategies were used, from 0-5,000 t (the average catch from 2012-2016 was 2243 t). 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 (D.36) (i.e. based on lognormal recruitment

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deviations from the estimated stock-recruitment curve), using randomly generated values of  $\varepsilon_t \sim \text{Normal}(0, \sigma_R^2)$ . For each of the 1,000 MCMC samples a time series of  $\{\varepsilon_t\}$  was generated. For each MCMC sample, the same time series of  $\{\varepsilon_t\}$  was used for each catch strategy (so that, for a given MCMC sample, all catch strategies experience the same recruitment stochasticity).

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## APPENDIX E. MODEL RESULTS

### E.1. INTRODUCTION

This Appendix describes results from MPD (mode of the posterior distribution) 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 and a range of sensitivity model runs, MCMC diagnostics, and a bridging analysis to compare results using the 2010 data using the current model with results modelled in 2010. The final advice draws from the MCMC results from all runs, but the Base Case provides 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 the 2010 5ABC POP assessment, four models were explored based on combinations of  $M$  (natural mortality) and  $h$  (steepness) - estimate both  $M$  and  $h$ , estimate  $M$  and fix  $h=0.674$ , estimate  $h$  and fix  $M=0.06$ , fix  $M=0.06$  and  $h=0.674$  (Edwards et al. 2012). This assessment adopts the philosophy that both  $M$  and  $h$  can be estimated, following other DFO assessments since 2010 (Edwards et al. 2014b,a; Starr et al. 2016).

This assessment departs from the 2010 5ABC POP assessment in five important ways:

1. The RPR participants agreed that the Base Case for this assessment should use only the Goose Island Gully (GIG) historical rockfish survey (1967-1994) and the Queen Charlotte Sound (QCS) synoptic survey (2003-2015) in the population model, agreeing to drop the QCS shrimp survey because of its abbreviated depth coverage, restricted spatial coverage, and redundancy with the QCS synoptic survey.
2. Uniform priors were used for survey selectivity ( $\mu_g$ ,  $\Delta g$ ,  $vgL$  for survey gears  $g = 1, 2$ ) rather than informative priors. This was done because the model was able to find credible estimates for these parameters without the imposition of a prior assumption.
3. The assessed area was expanded to include the portion of PMFC 5E south of 52°20' as part of 5ABC. This added a small amount of catch (see Appendix A).
4. The survey CVs were re-weighted once such that the standard deviation of normalised residuals (SDNR) approximated 1.0, the theoretical value, and no additional process error was added.
5. The effective sample sizes of age frequency data were re-weighted using the mean age technique of Francis (2011).

### E.2. 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 E.1 and E.2). The MPDs became the starting points for the MCMC simulations. The following description applies to the base-case stock assessment.

The MPD fits and their residuals are shown for the survey indices (Figure E.1 and Figures E.2-E.3) and the catch-at-age data for the commercial bottom trawl fishery (Figures E.4-E.7 and Figures E.8-E.10), the Goose Island Gully (GIG) historical rockfish survey (Figure E.11 and Figures E.12-E.14), and the Queen Charlotte Sound (QCS) synoptic survey (Figure E.15 and Figures E.16-E.18). The results are able to capture the main features of the data sets fairly well, although older ages are sometimes under-represented by the fits, particularly for females. The

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available data sources are not in conflict, with reasonable fits across all data sets. Model estimates of mean age match the observed mean ages (Figure E.19) for the commercial series but 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 tend 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.

Figure E.20 shows the resulting stock-recruitment function and the MPD values of recruitment over time (though see the MCMC values of recruitment below). Figure E.21 shows that the recruitment deviations display no trend over time, and that the auto-correlation function of the deviations appears to have some periodicity with significant correlations at lags 1 and 2.

Figure E.22 gives the MPD fits for the selectivities, together with the ogive for female maturity. Survey selectivity estimated older ages at full selectivity compared to the equivalent fit for the commercial gear. This is consistent with MPD estimates made in the previous 5ABC stock assessment (Edwards et al. 2012), which estimated an age of maximum selectivity of 10.6 for the commercial fishery while estimating survey maximum selected age near to 13.5. These previous estimates of maximum selectivity for the two surveys are lower than the estimates presented in Table E.2, reflecting the shift to a uniform prior for these parameters. The previous stock assessment developed an informed prior from a published Alaskan survey and the resulting low prior mean (8.1) is not consistent with the Canadian survey age distributions. Figure E.33 shows the MPD of the relative spawning biomass ( $B_t/B_0$ ) together with catch on the same time scale, which demonstrates the impact of the large catches in the late 1960s. Figure E.24 gives the exploitation over time. The values of the log-likelihood and objective functions for the MPD fits are given in Table E.3.

### E.3. BAYESIAN MCMC RESULTS

The MCMC procedure performed 6,000,000 iterations, sampling every 5,000<sup>th</sup> 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 E.4 and E.5. The current year median estimate of  $B_{2017}$  is 24,302 t and the median estimate of  $B_{2017}/B_0$  is 0.271.

MCMC traces show acceptable convergence properties (no trend with increasing sample number) for the estimated parameters (Figure E.25), as do diagnostic analyses that split the posterior samples into three equal consecutive segments (Figure E.26) and the check for autocorrelation in the parameters out to 60 lags (Figure E.27). Some of the parameters (e.g.,  $R_0$ ) move from the initial MPD estimate to a median value that differs from the MPD (Figure E.25), indicating that the MCMC search found plausible fits to the data at higher biomass levels. The variance parameter for the left limb of the selectivity curve for the GIG historical survey ( $\log V_{LL}$ ) exhibits occasional large excursions and has more autocorrelation than the other parameters (Figure E.27), but this parameter is likely poorly estimated and not highly influential. Pairs plots of the estimated parameters (starting at Figure E.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

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spawning biomass' (Figure E.30) and recruitment (Figure E.31) also show good convergence properties.

Marginal posterior distributions and corresponding priors for the estimated parameters are shown in Figure E.32. The posterior distribution for  $h$  is almost unchanged from the informed prior, indicating that there is very little information in the model data to update the prior. Similarly, the posterior distribution for  $M_1$  closely resembles the informed prior, except for some contraction of the posterior distribution compared to the prior distribution. This indicates that the prior is consistent with the female age composition data. In the case of  $M_2$ , the posterior distribution has been shifted to the right of, but remains well within, the prior distribution, indicating that the male age composition data tend to favour a slightly higher  $M$ . Steepness  $h$  is estimated to be

0.702 (0.463-0.899) (median and 90% credible interval), which is lower than that estimated in 2010 (Figure G.23 in Edwards et al. 2012), possibly as a result of the relatively poor recruitments that have been observed since the last stock assessment. Corresponding summary statistics for the estimated parameters are given in Table E.4.

The marginal posterior distributions of vulnerable biomass and catch (Figure E.33) show a steady decline in the population from 1965 to approximately 1984, followed by a slow increase to 1994, another steady decline to 2008 and a levelling off since then. The median spawning biomass relative to unfished equilibrium values (Figure E.34) reached a minimum of 0.249 in 2008 and currently sits at 0.271. The recruitment patterns for Pacific Ocean Perch show notable upticks in 1951-54, 1962, 1977-78, 1981, and 1985 (Figure E.35). Since 1985, recruitment events have been modest with only minor increases in 2001 and 2007. Exploitation rates were higher than natural mortality during the periods 1965-75, 1982-83, and 1995-2012; they peaked in 1966 at a median value of 0.124 (Figure E.36). A phase plot of the time-evolution of spawning biomass and exploitation rate in MSY space (Figure E.37) shows a gradual progression from high biomass/low exploitation to a current position at  $B_{2017}/B_{MSY} = 1.029$  (0.537-1.964) and  $u_{2016}/u_{MSY} = 0.684$  (0.292-1.798). The figure also suggests that median POP spawning biomass has been lying along the  $B_{MSY}$  boundary for the past decade.

#### E.4. 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 2017, were made over a range of constant catch strategies (0-5,000 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 D 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 5-10 year lag before recruitment to the commercial fishery.

Resulting projections of spawning biomass are shown for a reduced range of selected catch strategies (Figure E.38). Spawning biomass  $B_{2022}$  will be greater than  $B_{2017}$  with probability greater than 0.50 at catch levels at or below 2250 t/year (Table E.9), which is lower than the recent average catch of 2397 t.

Recruitment is drawn from the estimated stock-recruitment curve with lognormal error that has a standard deviation of 0.9 and a mean of zero. This approach of using average recruitment does not accurately simulate the occasional large recruitment events that have occurred for this stock

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(Figure E.35). 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 maturation (median=10y) and the short time frame over which the projections are made. In Appendix F we investigate whether we could incorporate ecosystem information into the projections. This investigation concluded that there were no convincing relationships between ecosystem indices and POP recruitment, and so we retain the average-recruitment approach used in recent assessments.

This conclusion may be partially due to the episodic recruitment process described above, which only shows rare pulses of strong recruitment interspersed by long periods of below average recruitment. Given that there have been only two (or at the most three) episodes of strong recruitment observed over this reconstruction period (i.e., from the 1940 start year), the available information is inadequate to discover the drivers for these rare episodes of strong recruitment.

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 E.6-E.8. For example, the estimated probability that the stock is in the provisional healthy zone in 2017 under a constant catch strategy of 1,000 t is  $P(B_{2017} > 0.8B_{MSY}) = 0.74$  (row '1000' and column '2017' in Table E.7).

Table E.9 provides probabilities that projected spawning biomass  $B_t$  will exceed the current-year biomass  $B_{2017}$  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. Table E.10 shows the probabilities of projected exploitation rate  $u_t$  exceeding that at MSY ( $u_{MSY}$ ).

For the maximum sustainable yield (MSY) calculations, projections were run across a range of constant exploitation rates  $u_t$  between 0 and 0.3, with an increment value of 0.01, 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 none of the samples. Of the 301,000 projection calculations, all converged by 15,000 years.

Table E.1. Priors and MPD estimates for estimated parameters. Prior information - distributions: 0 = uniform, 1 = normal, 2 = lognormal, 5 = beta

<b><math>R_0</math> (recruitment in virgin condition)</b>					
Phase	Range	Type	(Mean, SD)	Initial	MPD
1	(1,1e+07)	0	(0,0)	10000	16133.7
<b><math>M_s</math> (natural mortality by sex <math>s</math>, where <math>s = 1</math> [female], 2 [male])</b>					
Phase	Range	Type	(Mean, SD)	Initial	MPD
4	(0.01,0.12)	1	(0.06,0.006)	0.06	0.0590018
4	(0.01,0.12)	1	(0.06,0.006)	0.06	0.0638431
<b><math>h</math> (steepness of spawner-recruit curve)</b>					
Phase	Range	Type	(Mean, SD)	Initial	MPD
5	(0.2,0.999)	5	(4.574,2.212)	0.674	0.716597
<b><math>c_t</math> (recruitment deviations)</b>					
Phase	Range	Type	(Mean, SD)	Initial	MPD
2	(-15,15)	1	(0,0.9)	0	FIG E.21
<b><math>\omega</math> (initial recruitment)</b>					
Phase	Range	Type	(Mean, SD)	Initial	MPD
-1	(0,2)	0	(1,0.1)	1	1



Table E.2. Priors and MPD estimates for index  $g$  (survey and commercial).

<b>Survey catchability mode (log <math>q_g</math>, where <math>g = 1, \dots, 2</math>)</b>							
Index $g$	Phase	Range	Type	(Mean, SD)	Initial	MPD	Exp (MPD)
1	1	(-12,5)	0	(0,0.6)	-5	-1.9856	0.13731
2	1	(-12,5)	0	(0,0.6)	-5	-0.95378	0.38528
<b>Commercial selectivity (<math>\mu_g</math>, where <math>g = 3</math>)</b>							
Index $g$	Phase	Range	Type	(Mean, SD)	Initial	MPD	Exp (MPD)
3	4	(5,40)	0	(12.2887,3.68661)	12.2887	10.783	
<b>Survey selectivity (<math>\mu_g</math>, where <math>g = 1, \dots, 2</math>)</b>							
Index $g$	Phase	Range	Type	(Mean, SD)	Initial	MPD	Exp (MPD)
1	3	(5,40)	0	(8.06889,2.42067)	8.06889	16.834	
2	3	(5,40)	0	(8.06889,2.42067)	8.06889	15.462	
<b>Variance (left) of commercial selectivity curve (log <math>v_{gL}</math>, where <math>g = 3</math>)</b>							
Index $g$	Phase	Range	Type	(Mean, SD)	Initial	MPD	Exp (MPD)
3	4	(-15,-15)	0	(2.75662,0.826987)	2.75662	1.6356	
<b>Variance (left) of survey selectivity curve (log <math>v_{gL}</math>, where <math>g = 1, \dots, 2</math>)</b>							
Index $g$	Phase	Range	Type	(Mean, SD)	Initial	MPD	Exp (MPD)
1	4	(-15,-15)	0	(2.27674,0.683022)	2.27674	4.4639	
2	5	(-15,-15)	0	(2.27674,0.683022)	2.27674	3.7309	
<b>Shift in commercial selectivity for males (<math>\Delta_g</math>, where <math>g = 3</math>)</b>							
Index $g$	Phase	Range	Type	(Mean, SD)	Initial	MPD	Exp (MPD)
3	4	(-8,-10)	0	(0,1)	0	0.012987	
<b>Shift in survey selectivity for males (<math>\Delta_g</math>, where <math>g = 1, \dots, 2</math>)</b>							
Index $g$	Phase	Range	Type	(Mean, SD)	Initial	MPD	Exp (MPD)
1	4	(-8,-10)	0	(0,1)	0	1.1936	
2	4	(-8,-10)	0	(0,1)	0	-0.080806	

Table E.3. 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	$\log L_3(\Theta / \{ \hat{I}_{t1} \})$	-6.4
Survey 2	$\log L_3(\Theta / \{ \hat{I}_{t2} \})$	-11.3
CAs 1	$\log L_2(\Theta / \{ \hat{p}_{at1s} \})$	-941.41
CAs 2	$\log L_2(\Theta / \{ \hat{p}_{at2s} \})$	-2410.18
CAC 1	$\log L_2(\Theta / \{ \hat{p}_{at3s} \})$	-10589.1
Prior	$\log L_1(\Theta / \{ \epsilon_t \}) - \log(\pi(\Theta))$	24.27
	Objective function $f(\Theta)$	-13934.1

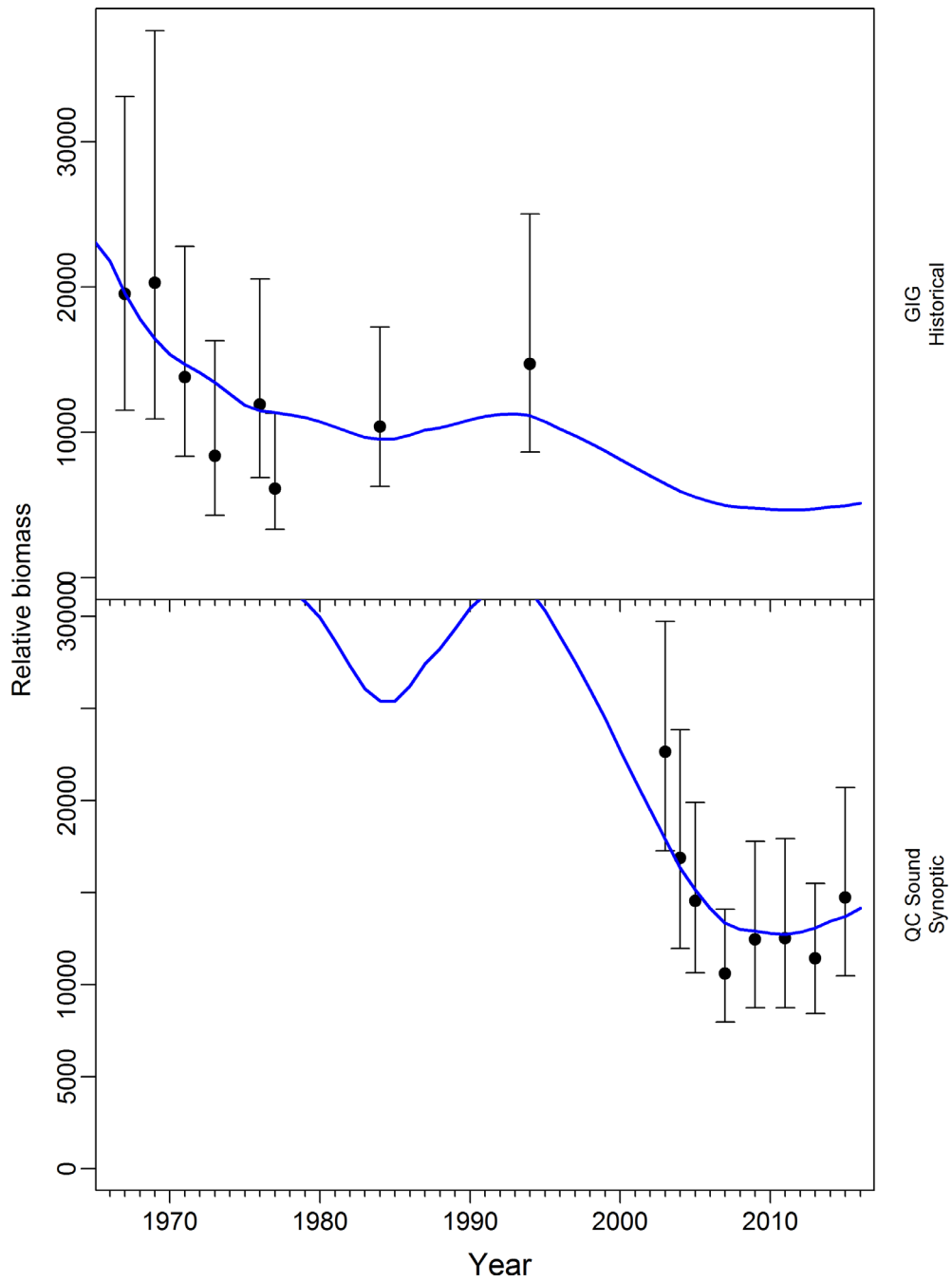


Figure E.1. Survey index values (points) with 95% confidence intervals (bars) and MPD model fits (curves) for the fishery-independent survey series.

## GIG Historical

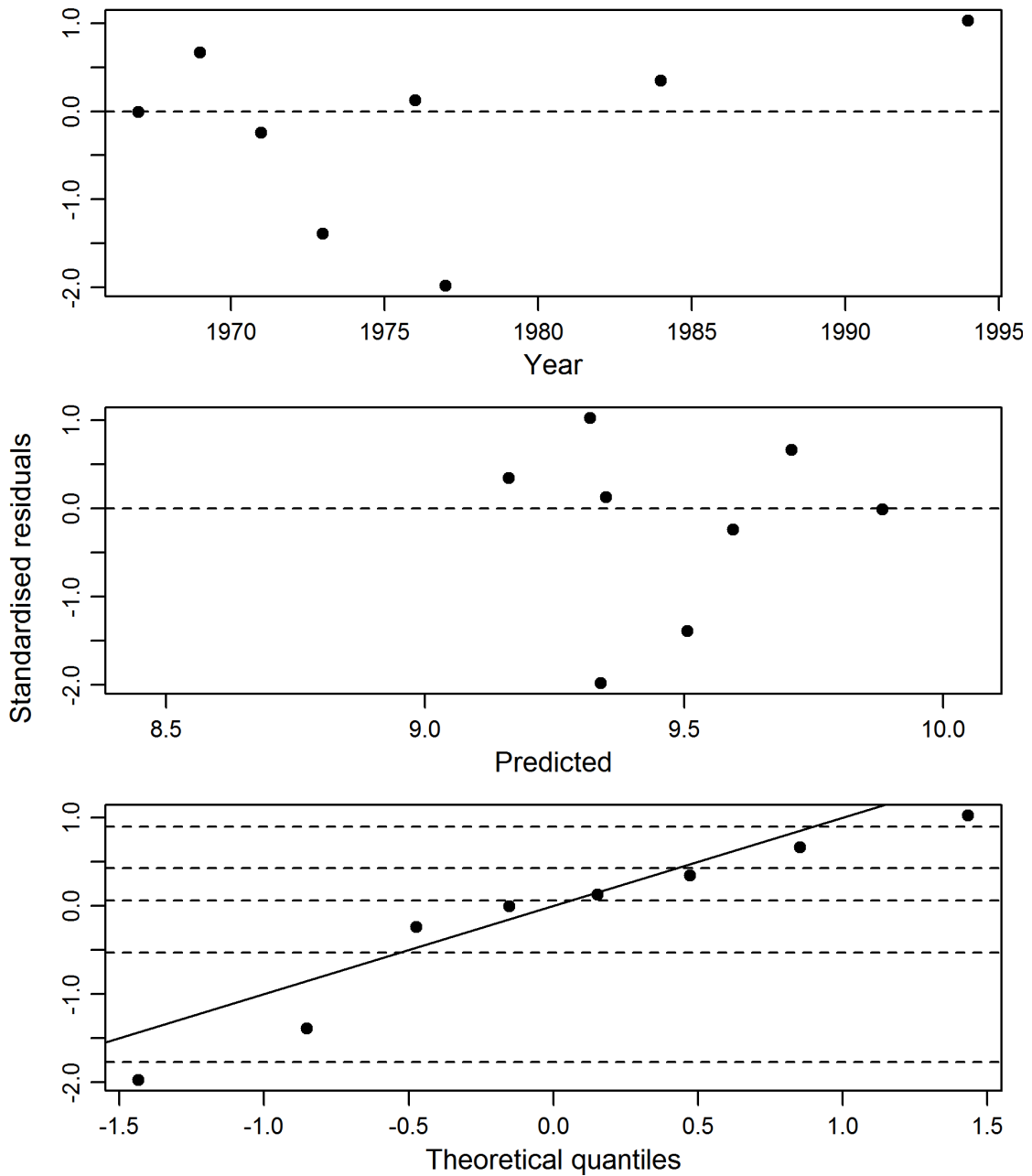


Figure E.2. Residuals of fits of model to GIG Historical survey series (MPD values). Vertical axes are standardised residuals. The three plots show, respectively, residuals by year of index, residuals relative to predicted index, and normal quantile-quantile plot for residuals (horizontal lines give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

### QC Sound Synoptic

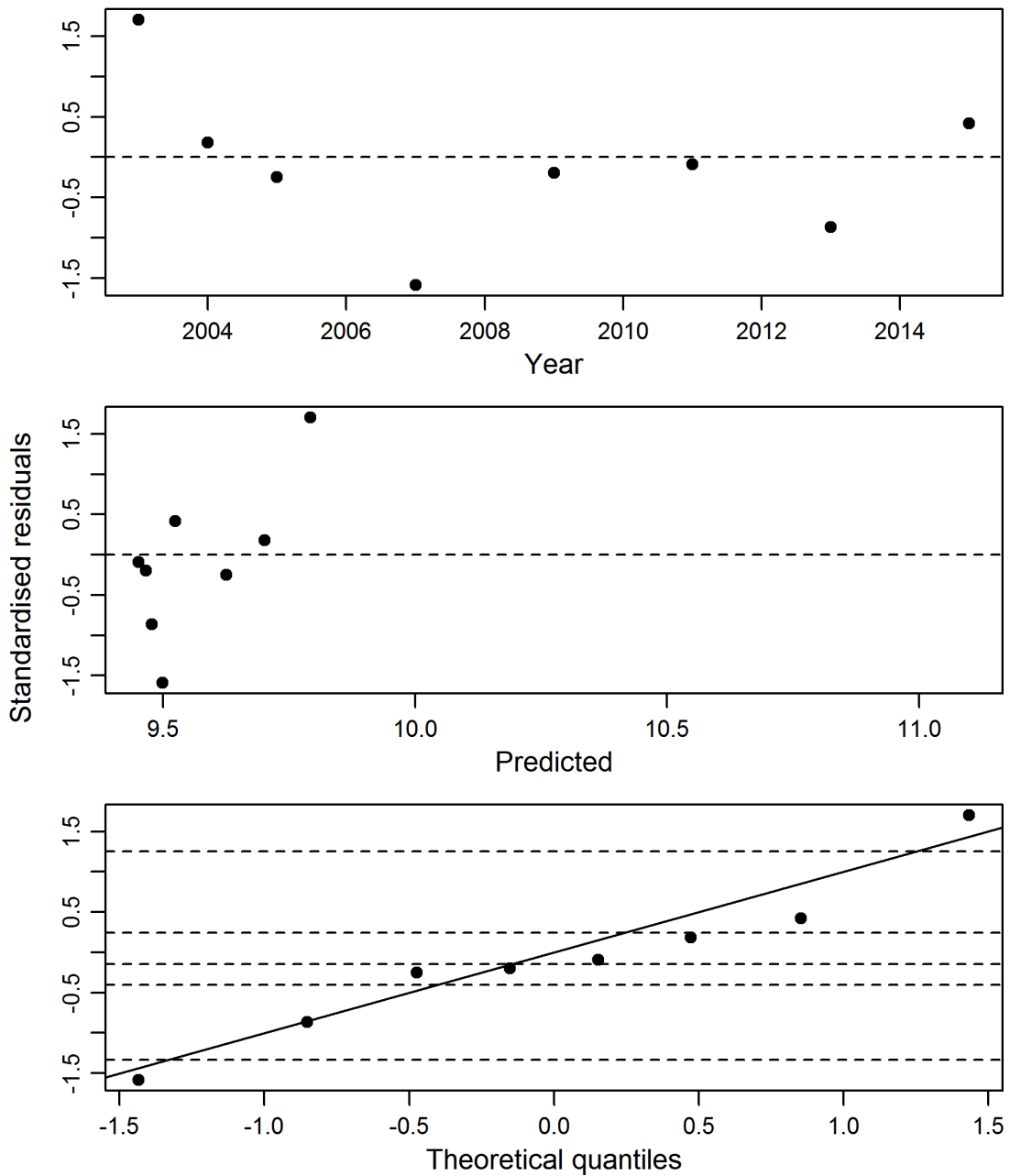


Figure E.3. Residuals of fits of model to QC Sound Synoptic survey series (MPD values). Vertical axes are standardised residuals. The three plots show, respectively, residuals by year of index, residuals relative to predicted index, and normal quantile-quantile plot for residuals (horizontal lines give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

## Bottom Trawl - Females

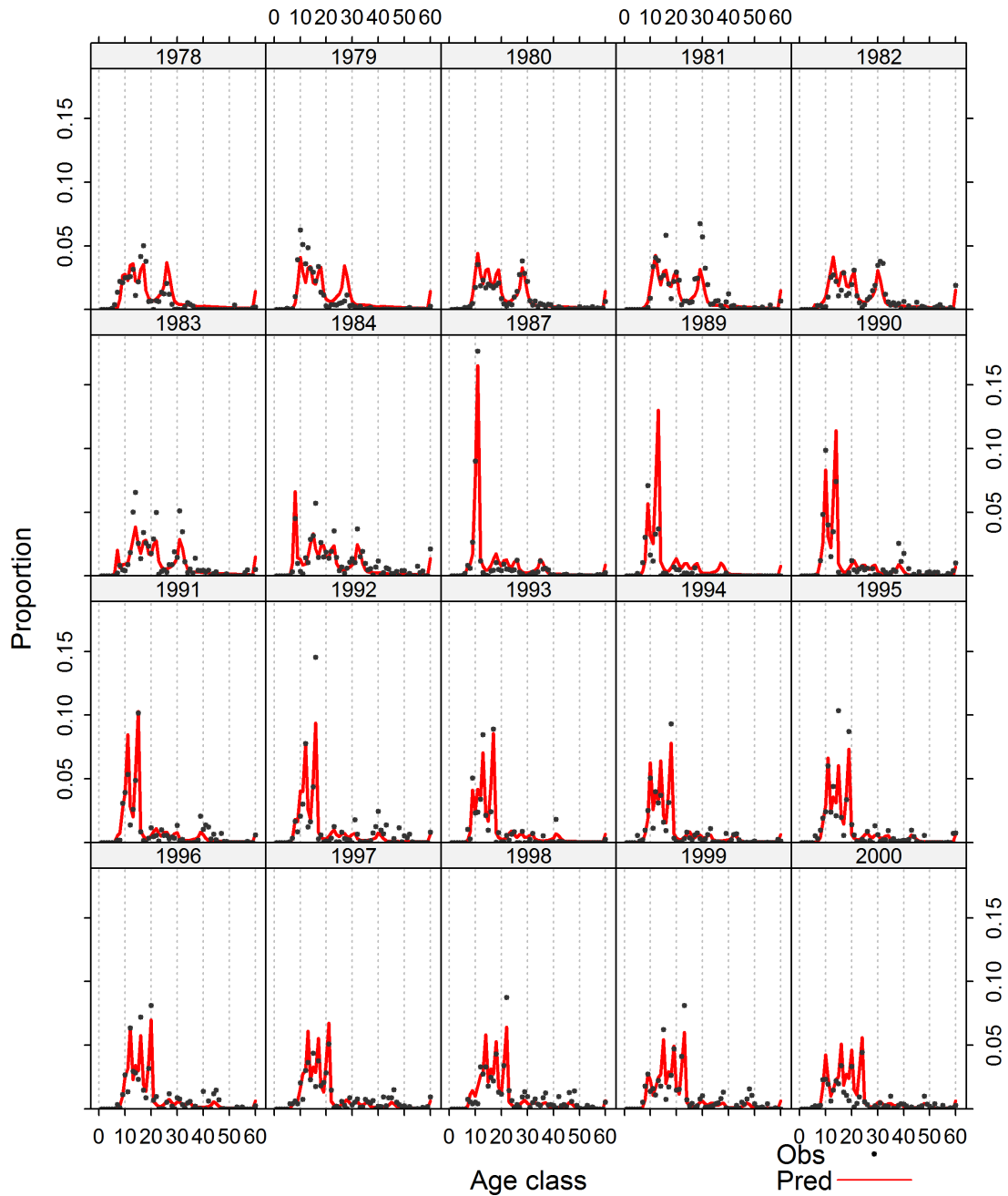


Figure E.4. Observed and predicted commercial (bottom trawl) proportions-at-age for females. Note that years are not necessarily consecutive.

## Bottom Trawl - Females

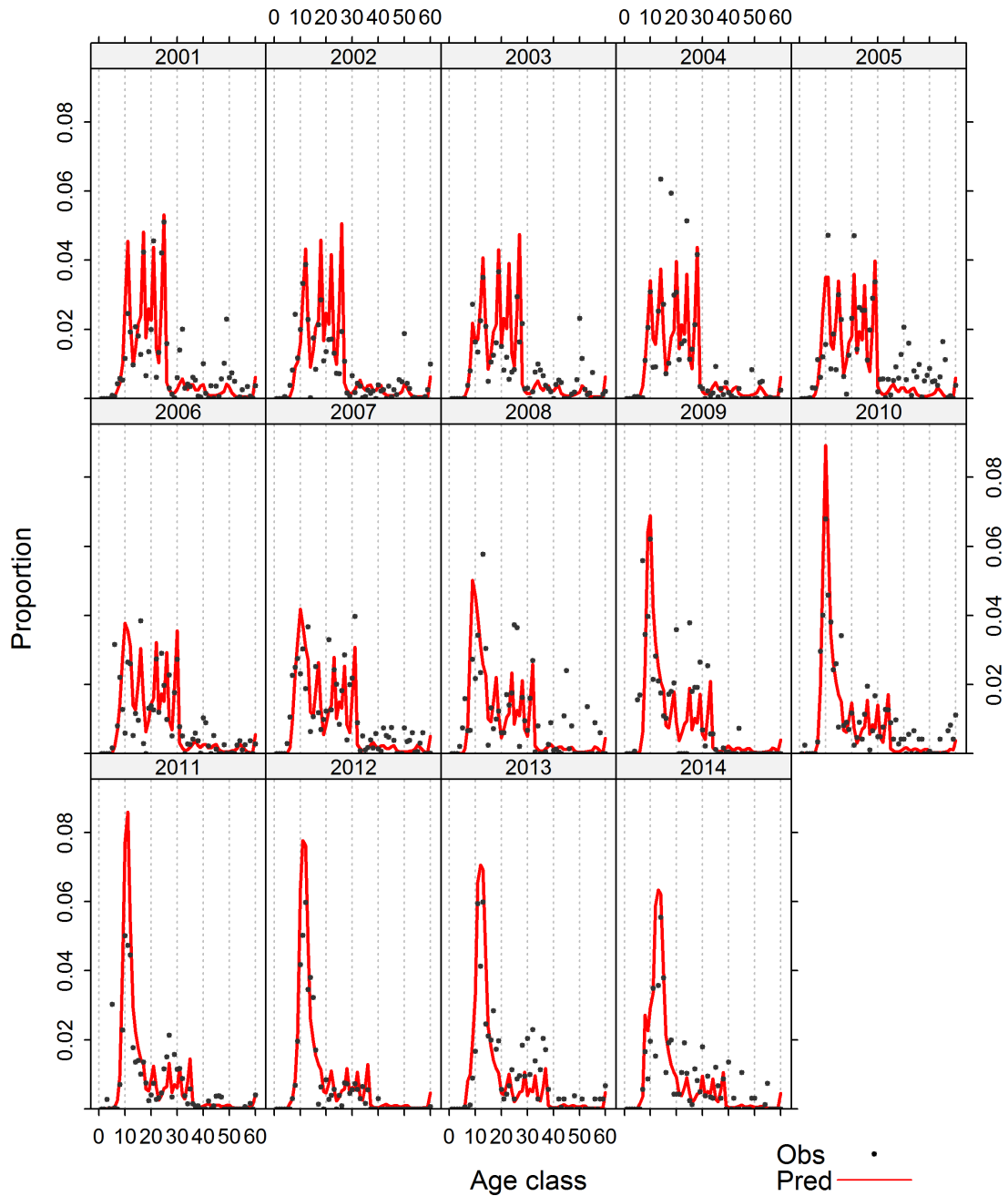


Figure E.5. Observed and predicted commercial (bottom trawl) proportions-at-age for females. Note that years are not necessarily consecutive.

## Bottom Trawl - Males

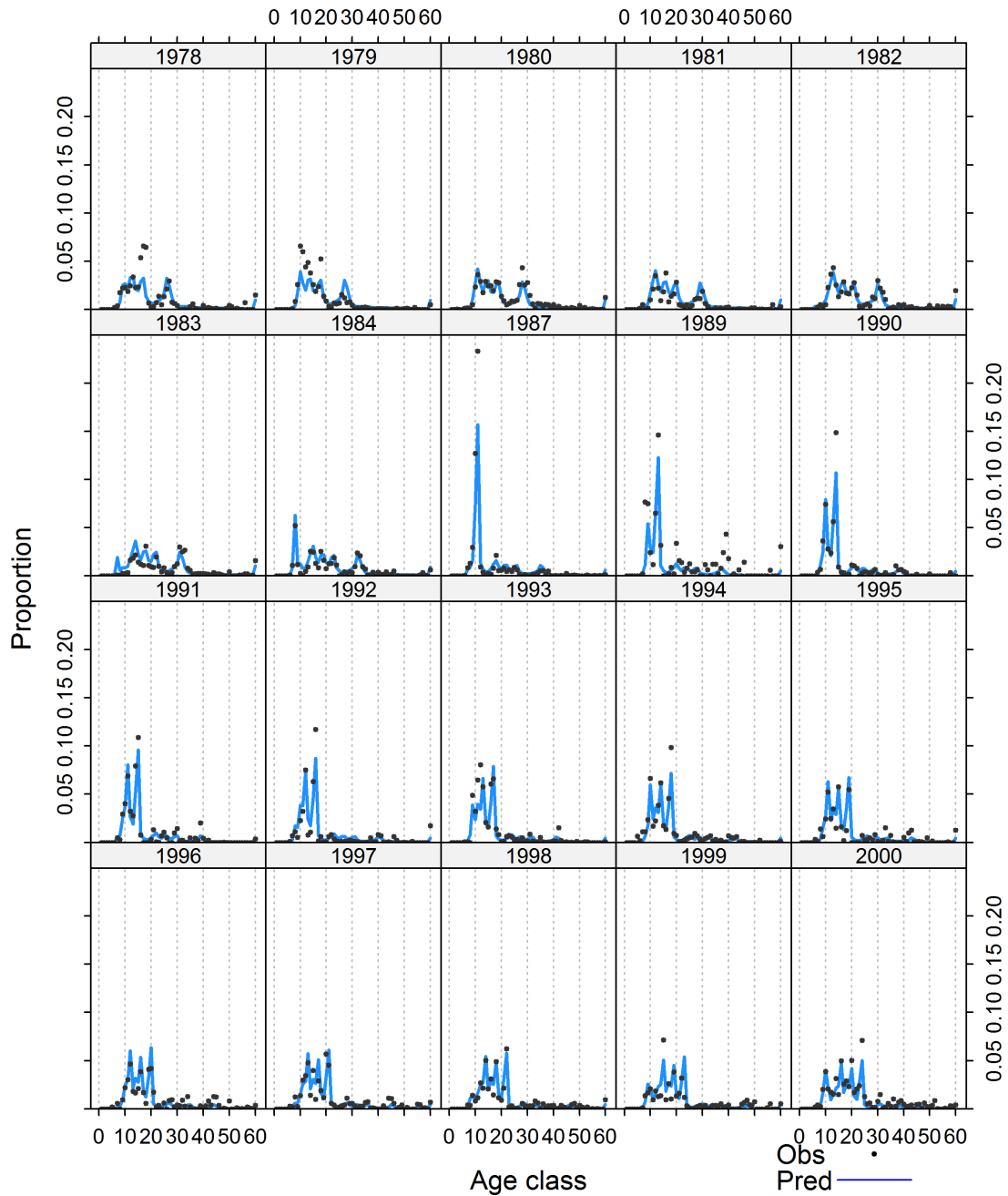


Figure E.6. Observed and predicted commercial (bottom trawl) proportions-at-age for males. Note that years are not necessarily consecutive.



## Bottom Trawl - Males

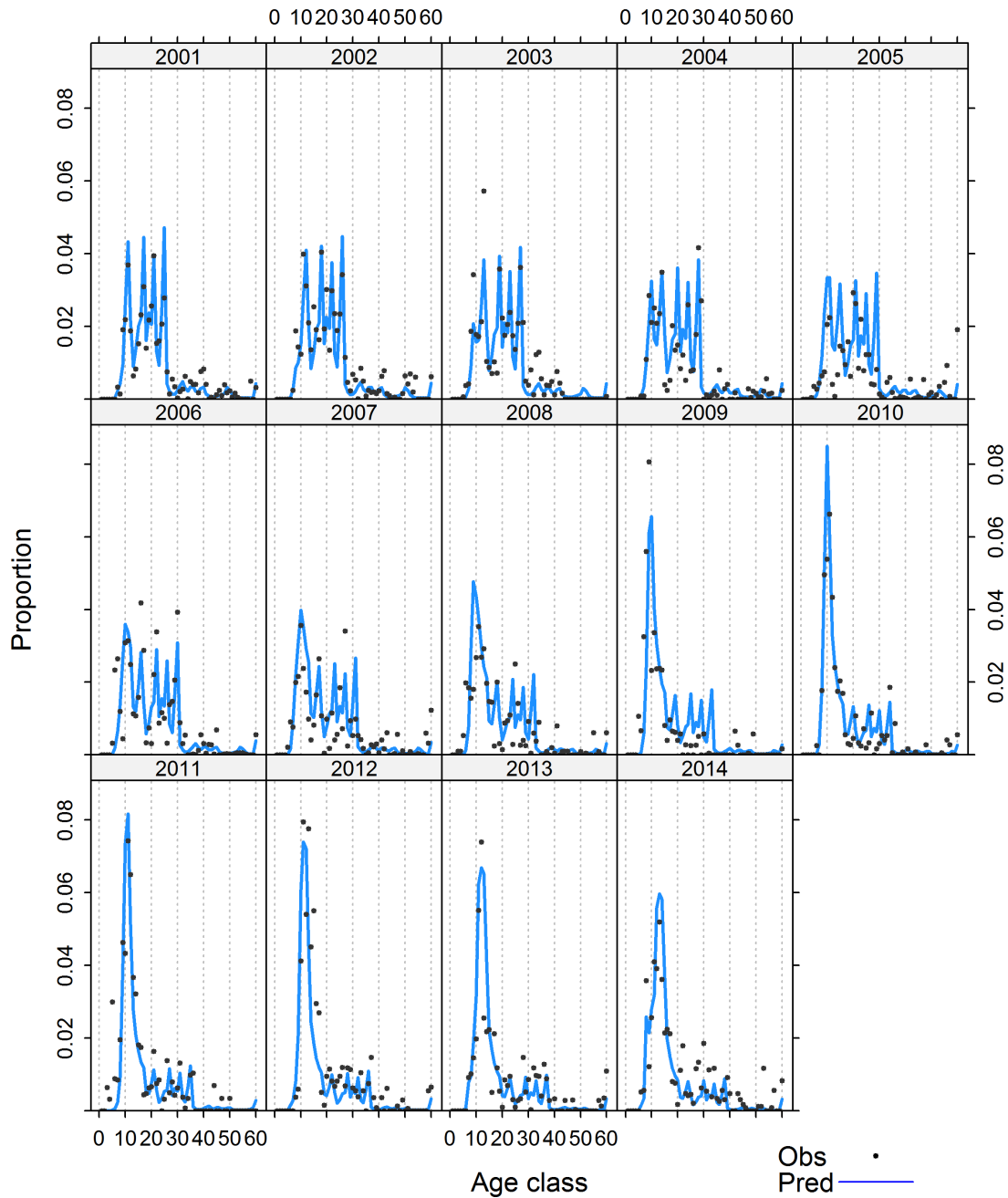


Figure E.7. Observed and predicted commercial (bottom trawl) proportions-at-age for males. Note that years are not necessarily consecutive.

## Bottom Trawl

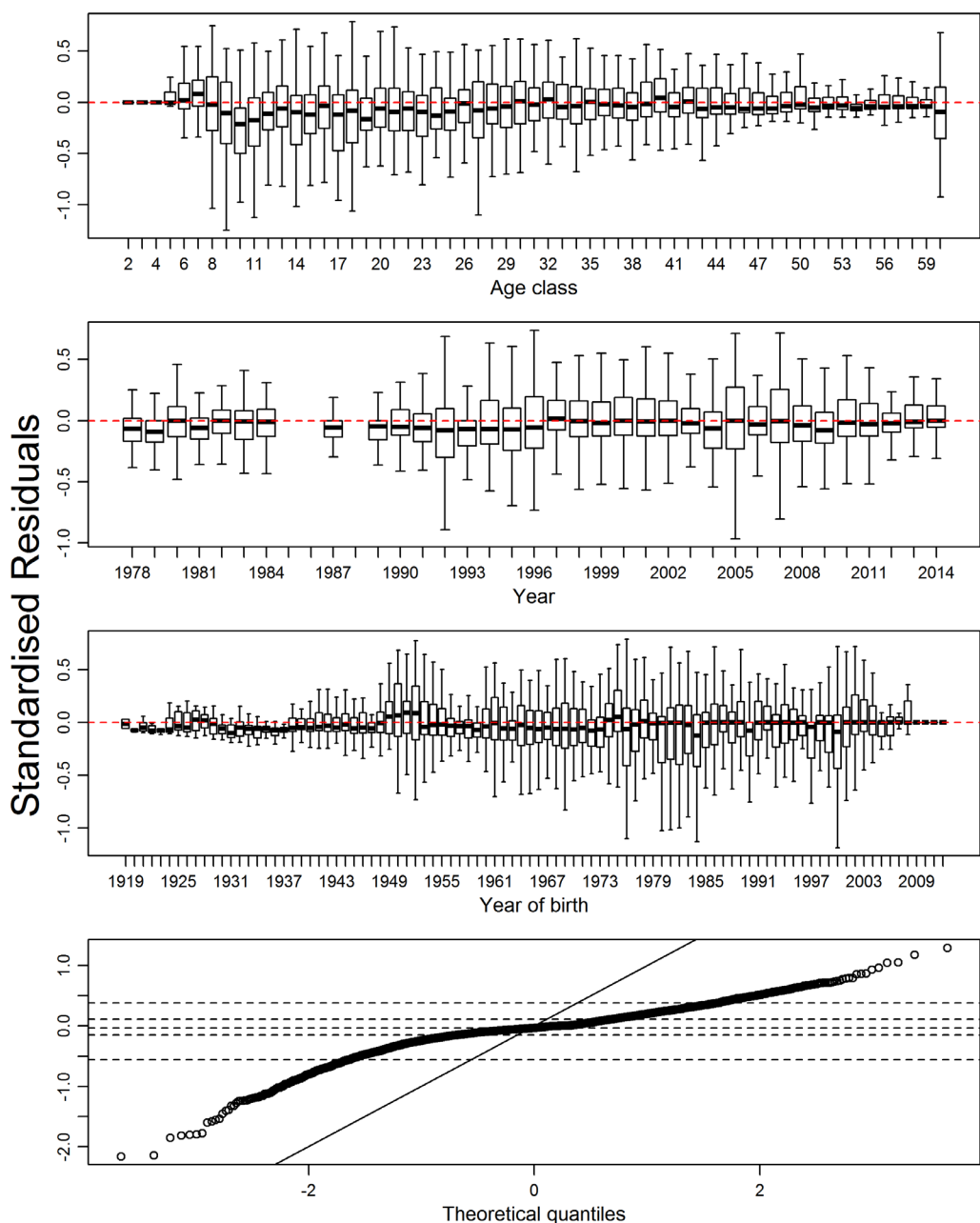


Figure E.8. Residual of fits of model to commercial proportions-at-age data (MPD values) for Bottom Trawl events. Vertical axes are standardised residuals. Boxplots show, respectively, residuals by age class, by year of data, and by year of birth (following a cohort through time). Boxes give interquartile 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 4012 residuals).

## Bottom Trawl - Female

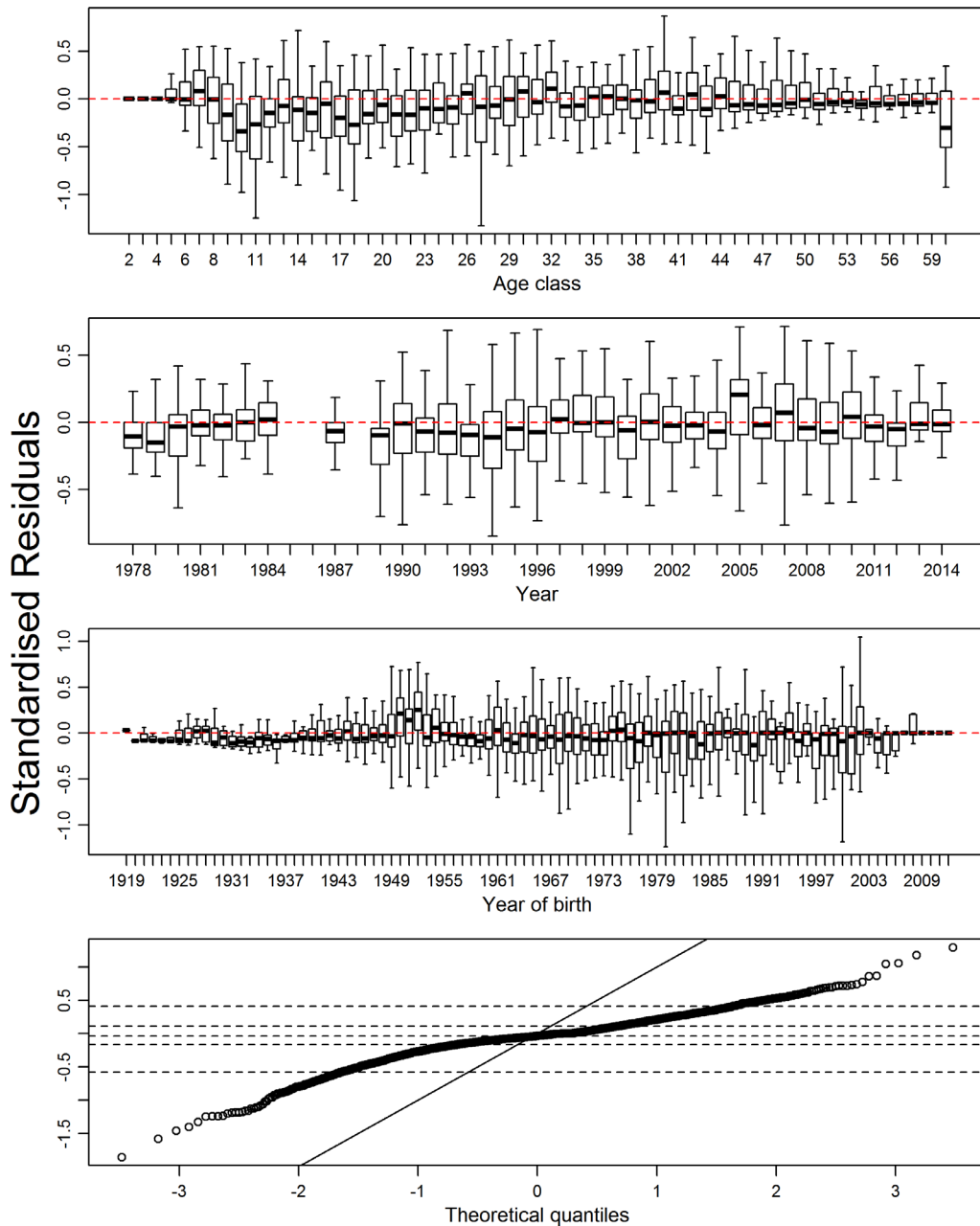


Figure E.9. Residual of fits of model to commercial proportions-at-age data (MPD values) for females (Bottom Trawl). Details as for Figure E.8, for a total of 2006 residuals.

## Bottom Trawl - Male

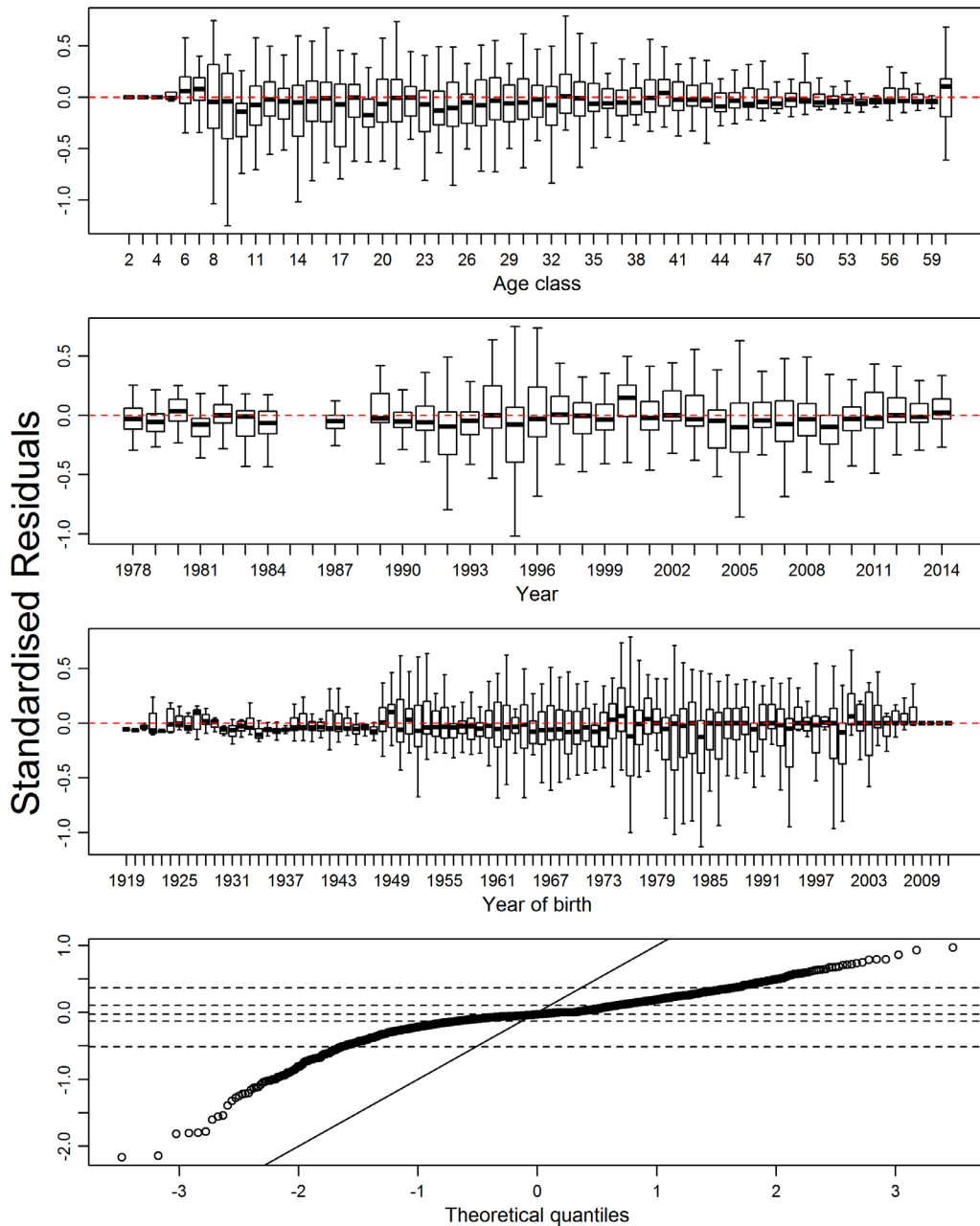
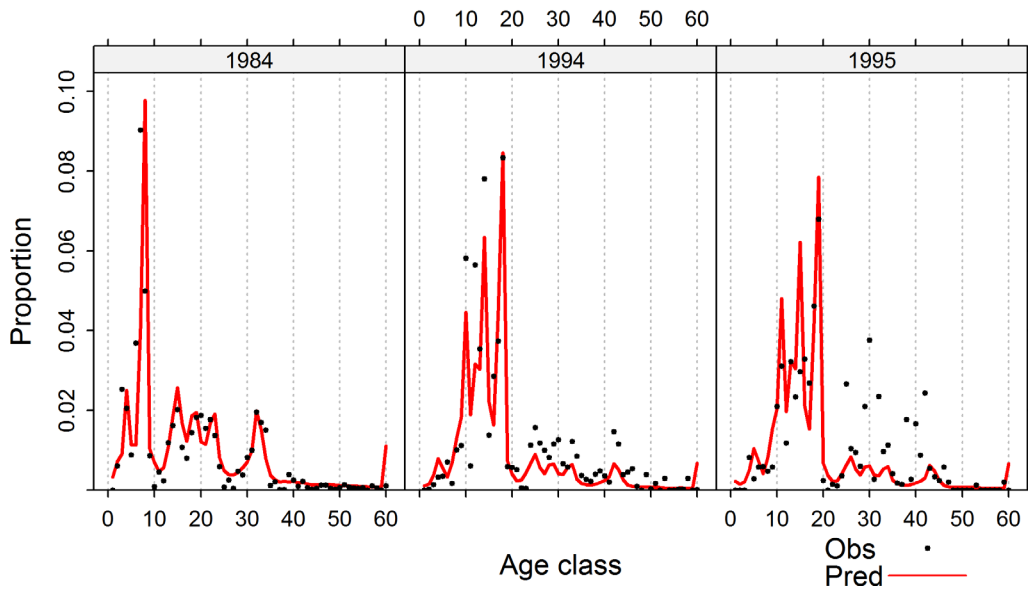


Figure E.10. Residual of fits of model to commercial proportions-at-age data (MPD values) for males (Bottom Trawl). Details as for Figure E.8, for a total of 2006 residuals.

### GIG Historical - Females



### GIG Historical - Males

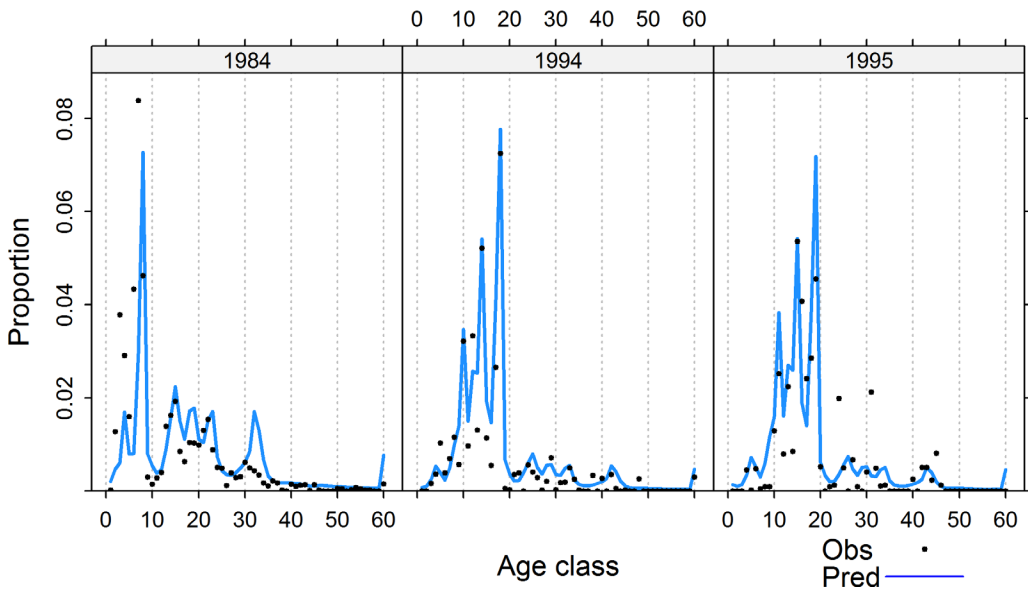


Figure E.11. Observed and predicted proportions-at-age for GIG Historical survey.

## GIG Historical

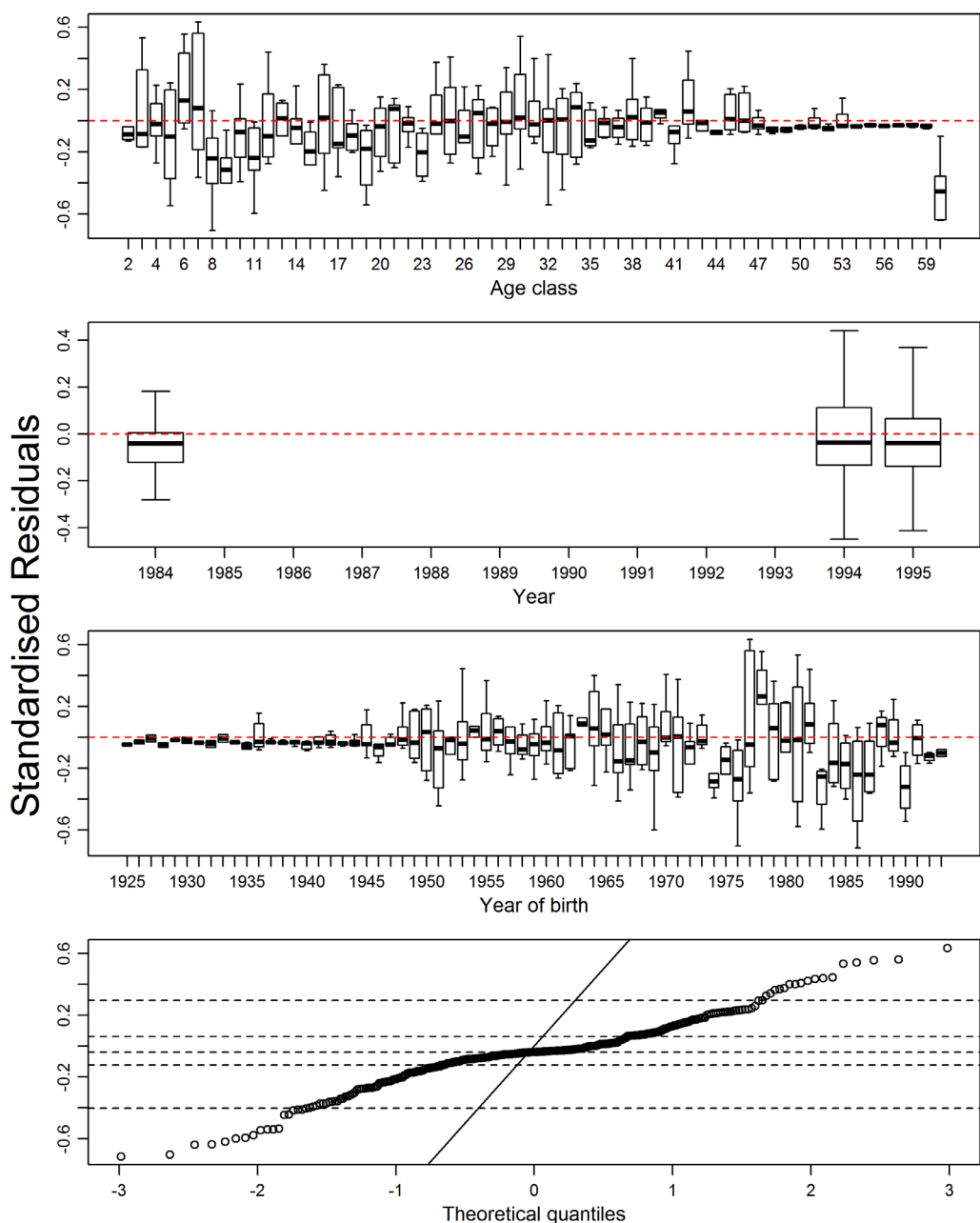


Figure E.12. Residuals of fits of model to proportions-at-age data (MPD values) from the GIG Historical survey series. Details as for Figure E.8, for a total of 354 residuals.

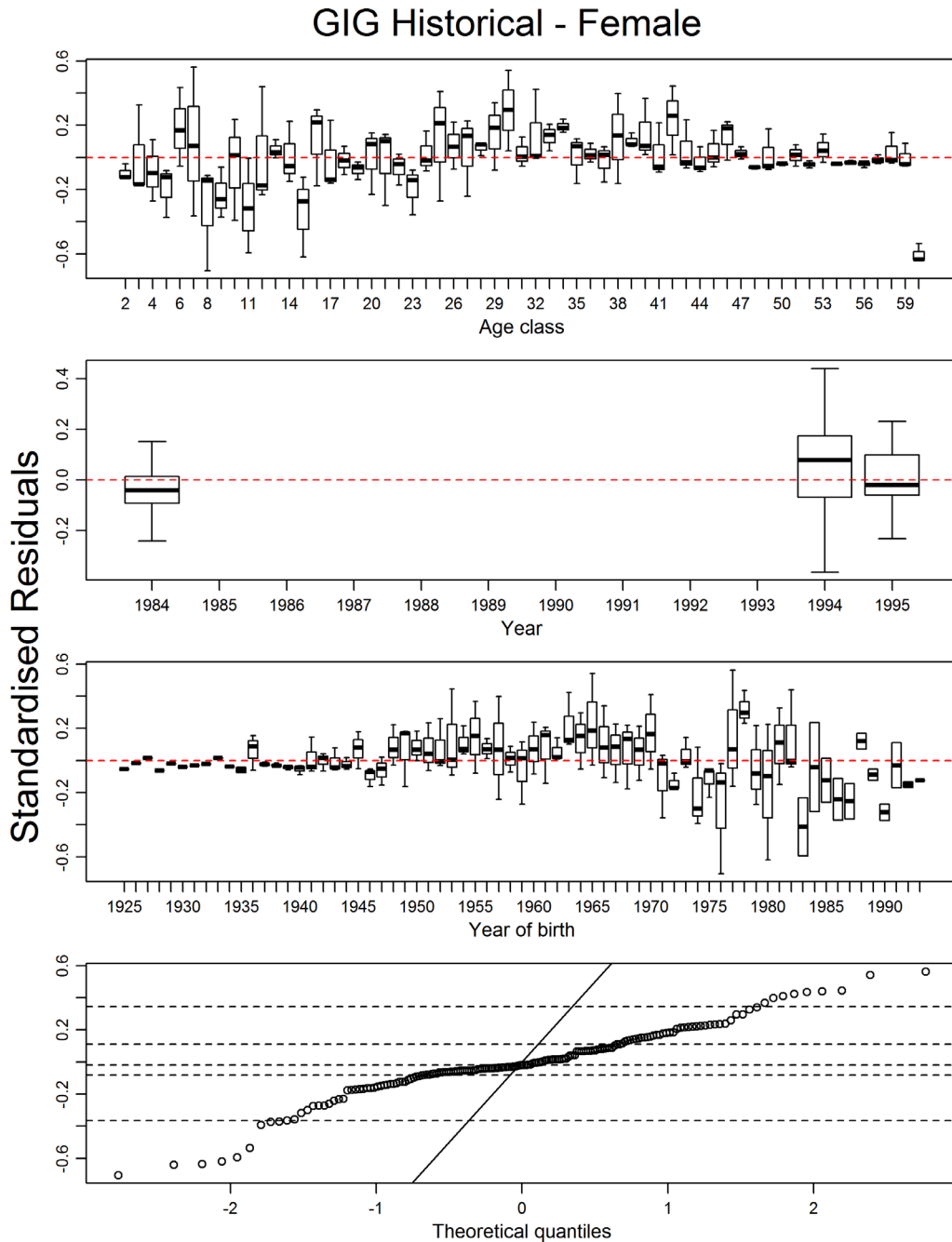


Figure E.13. Residuals of fits of model to proportions-at-age data (MPD values) for females from GIG Historical survey series. Details as for Figure E.8, for a total of 177 residuals.

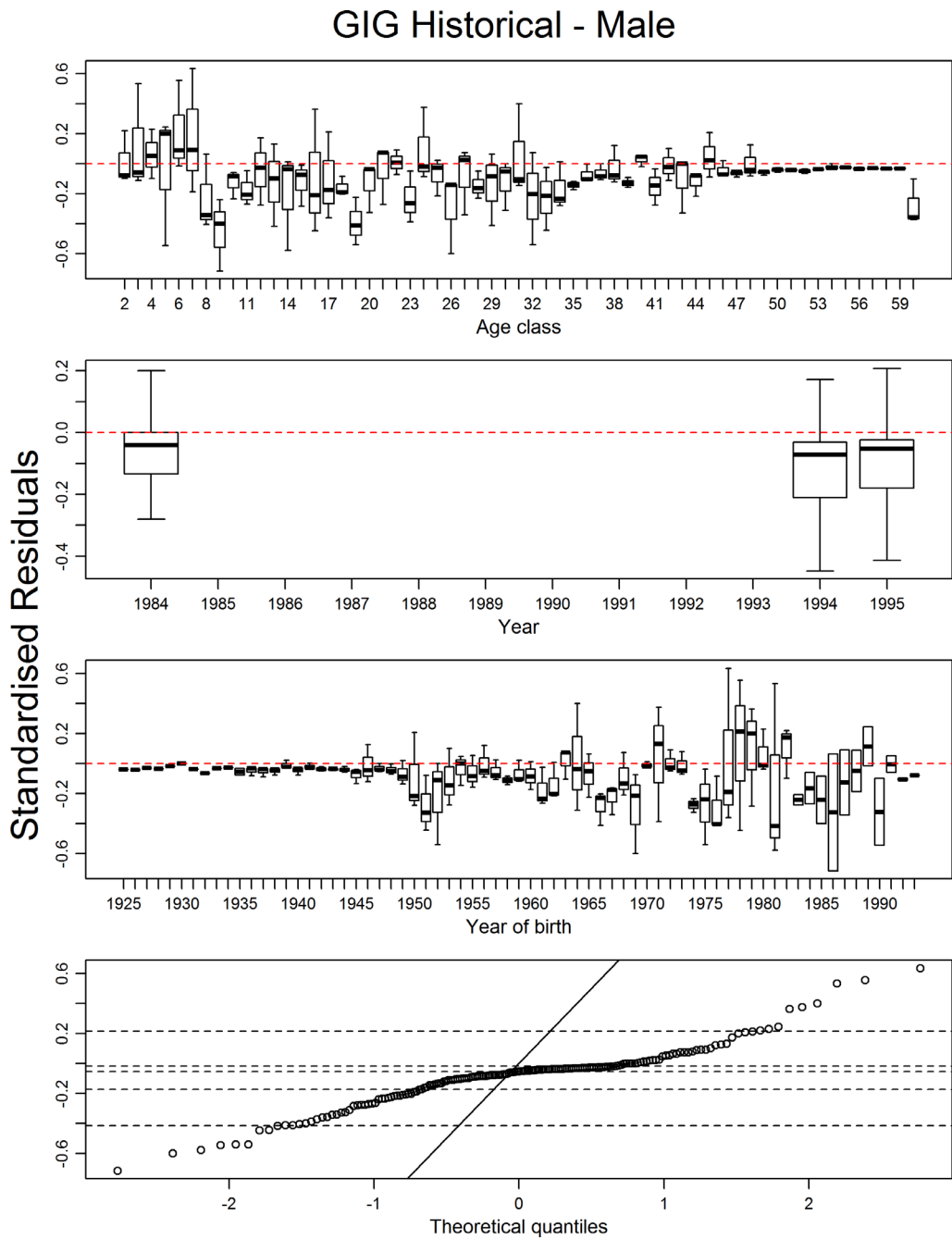


Figure E.14. Residuals of fits of model to proportions-at-age data (MPD values) for males from GIG Historical survey series. Details as for Figure E.8, for a total of 177 residuals.



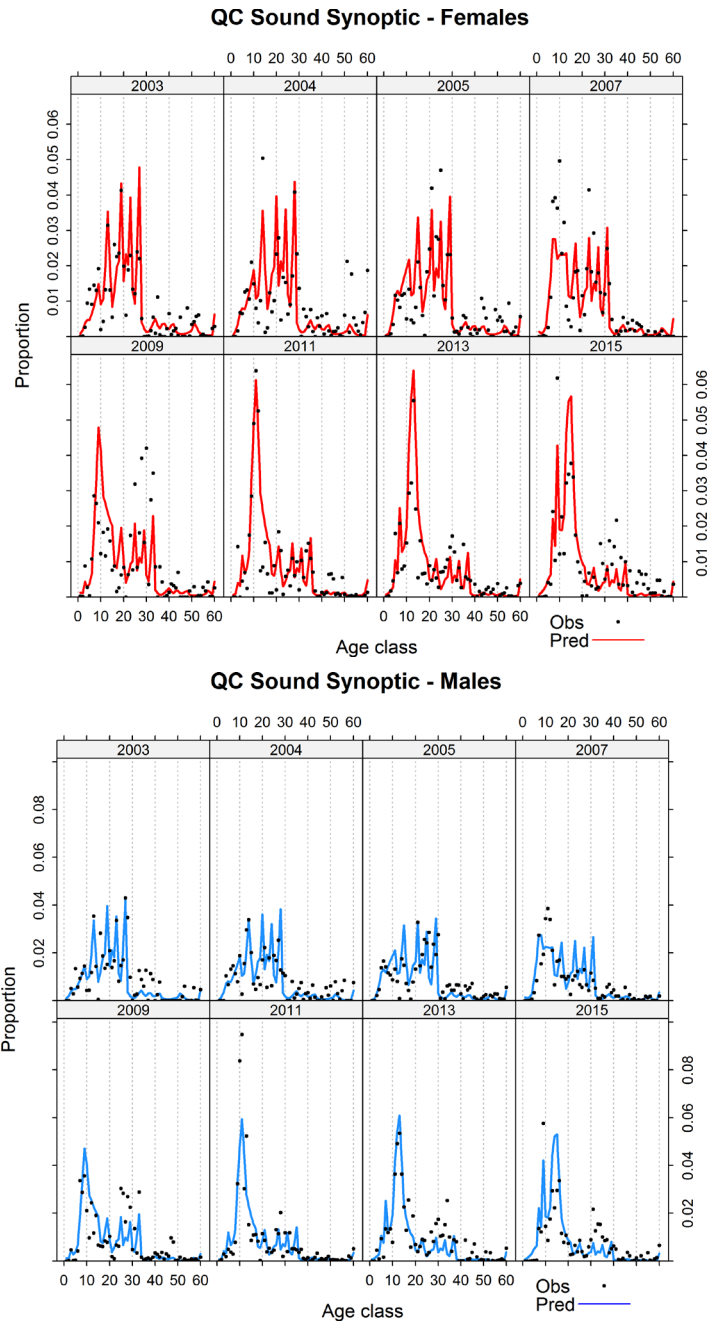


Figure E.15. Observed and predicted proportions-at-age for QC Sound Synoptic survey.

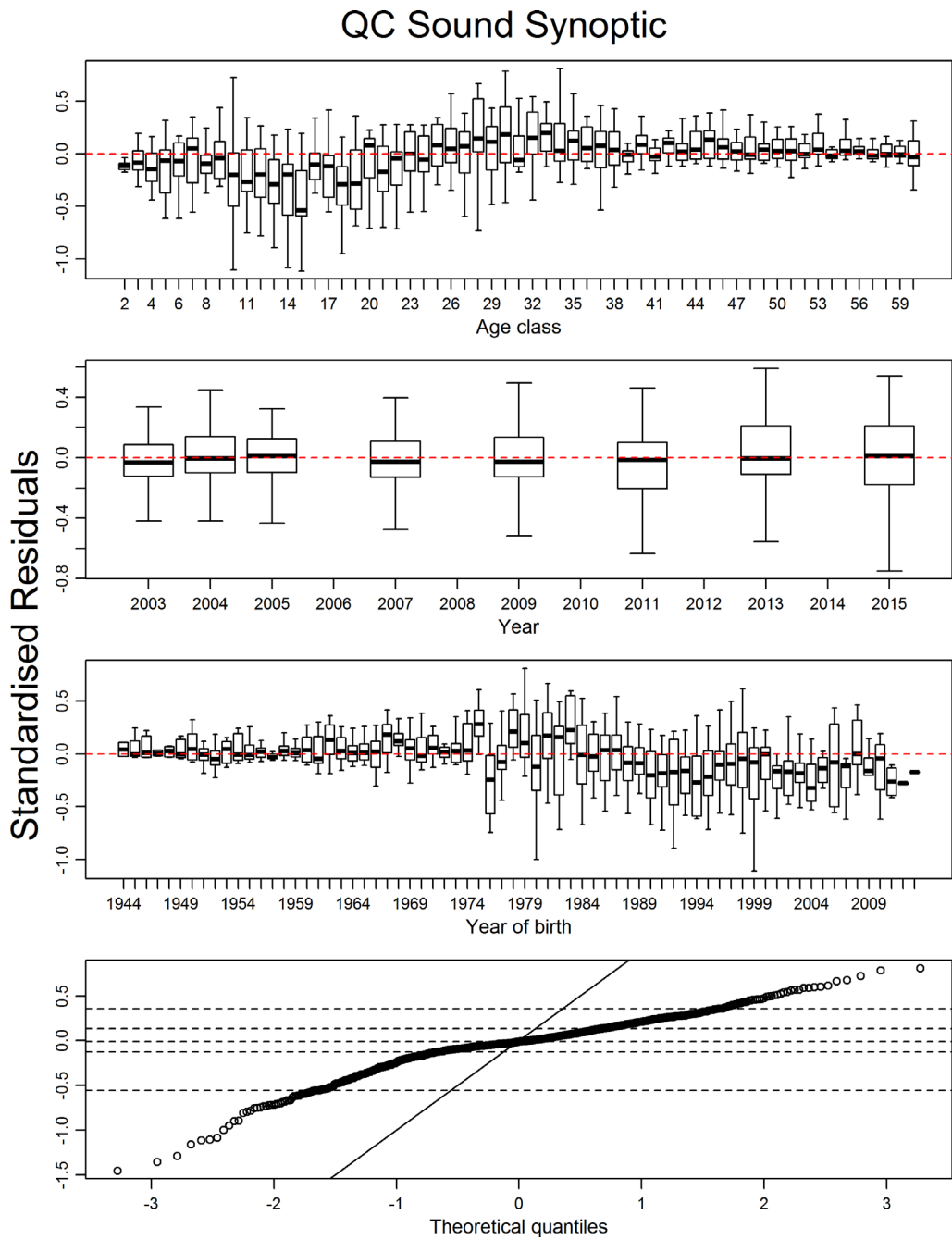


Figure E.16. Residuals of fits of model to proportions-at-age data (MPD values) from the QC Sound Synoptic survey series. Details as for Figure E.8, for a total of 944 residuals.

### QC Sound Synoptic - Female

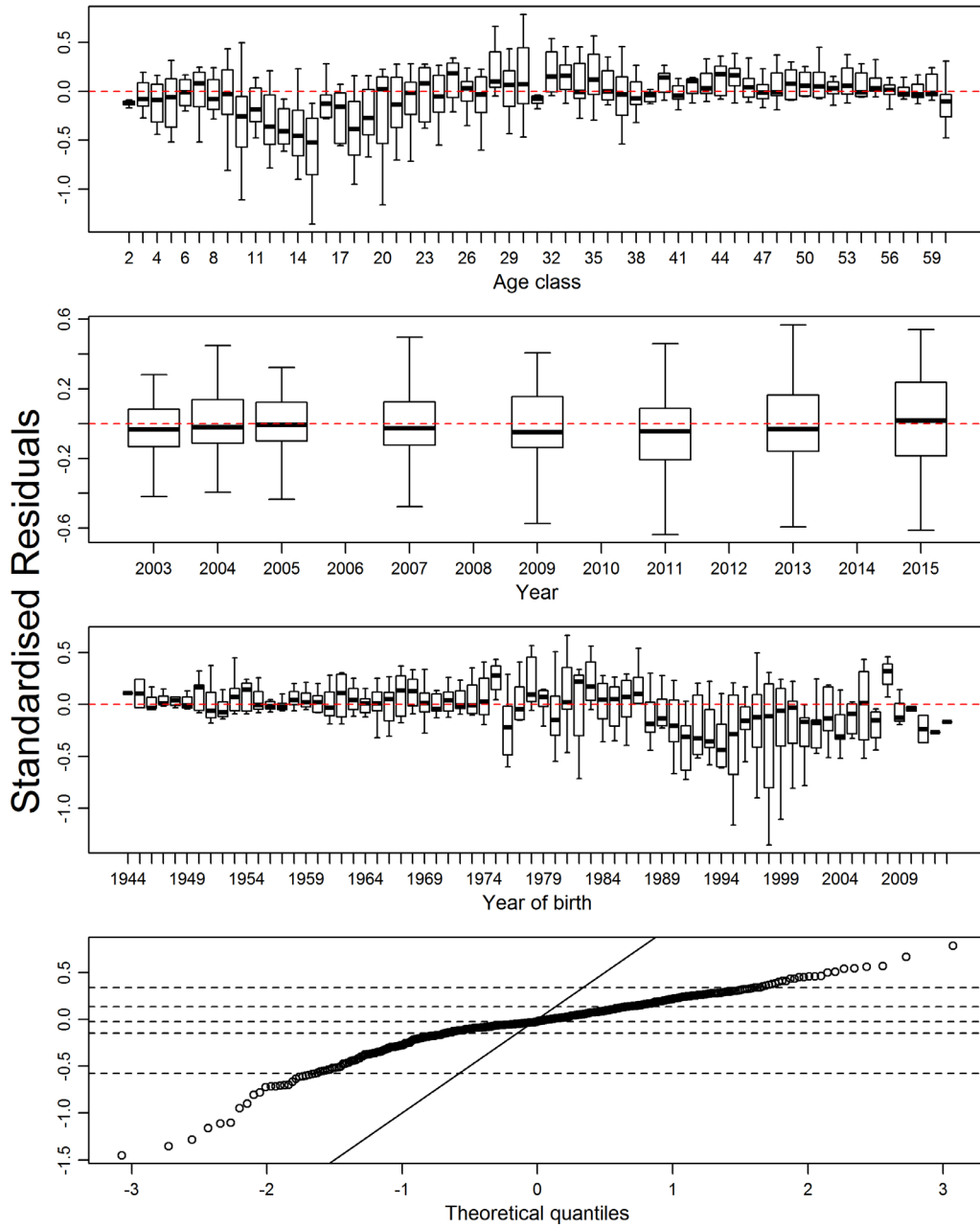


Figure E.17. Residuals of fits of model to proportions-at-age data (MPD values) for females from QC Sound Synoptic survey series. Details as for Figure E.8, for a total of 472 residuals.

### QC Sound Synoptic - Male

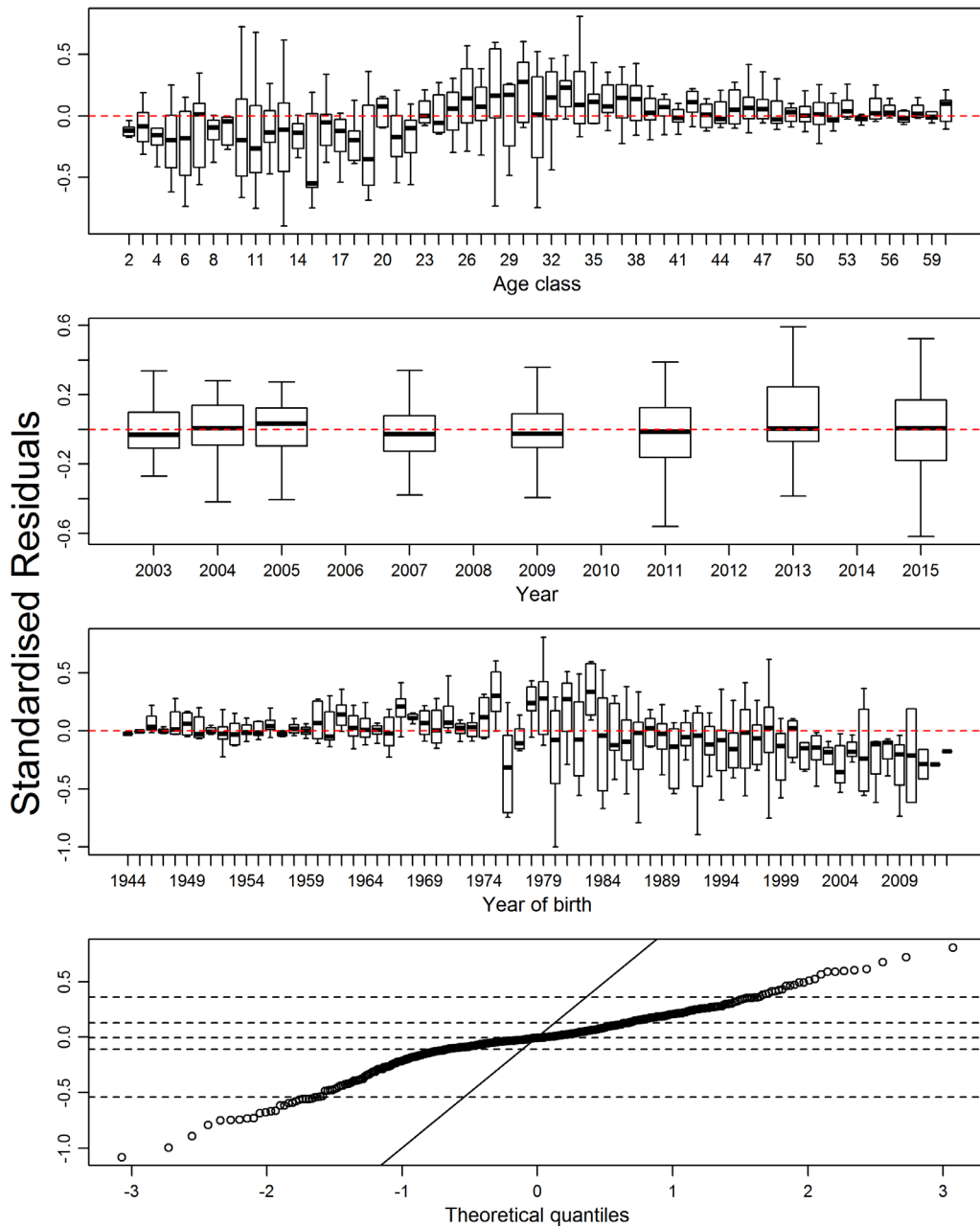


Figure E.18. Residuals of fits of model to proportions-at-age data (MPD values) for males from QC Sound Synoptic survey series. Details as for Figure E.8, for a total of 472 residuals.

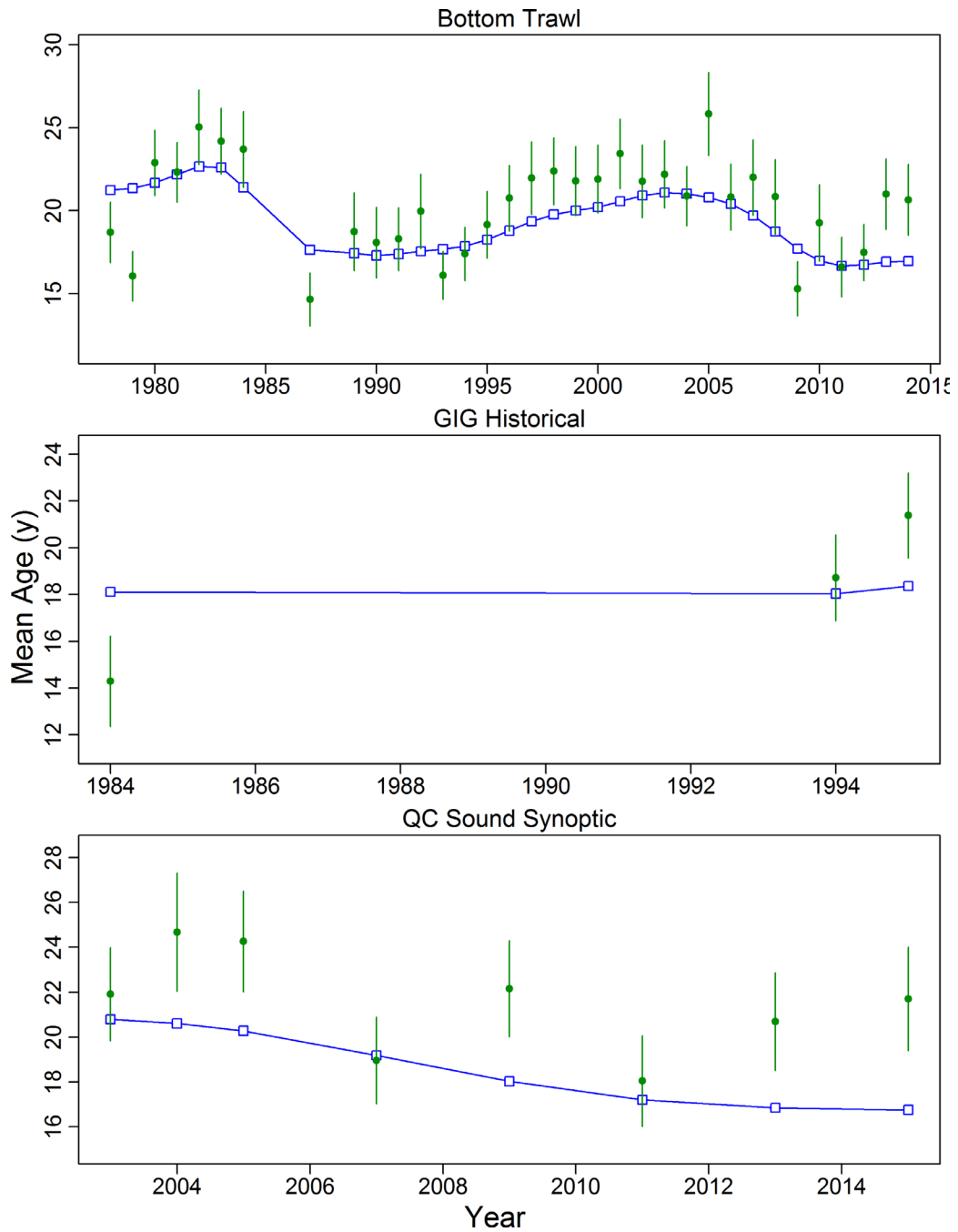


Figure E.19. Mean ages each year for the data (solid circles) with 95% confidence intervals and model estimates (joined open squares) for the commercial and survey age data.

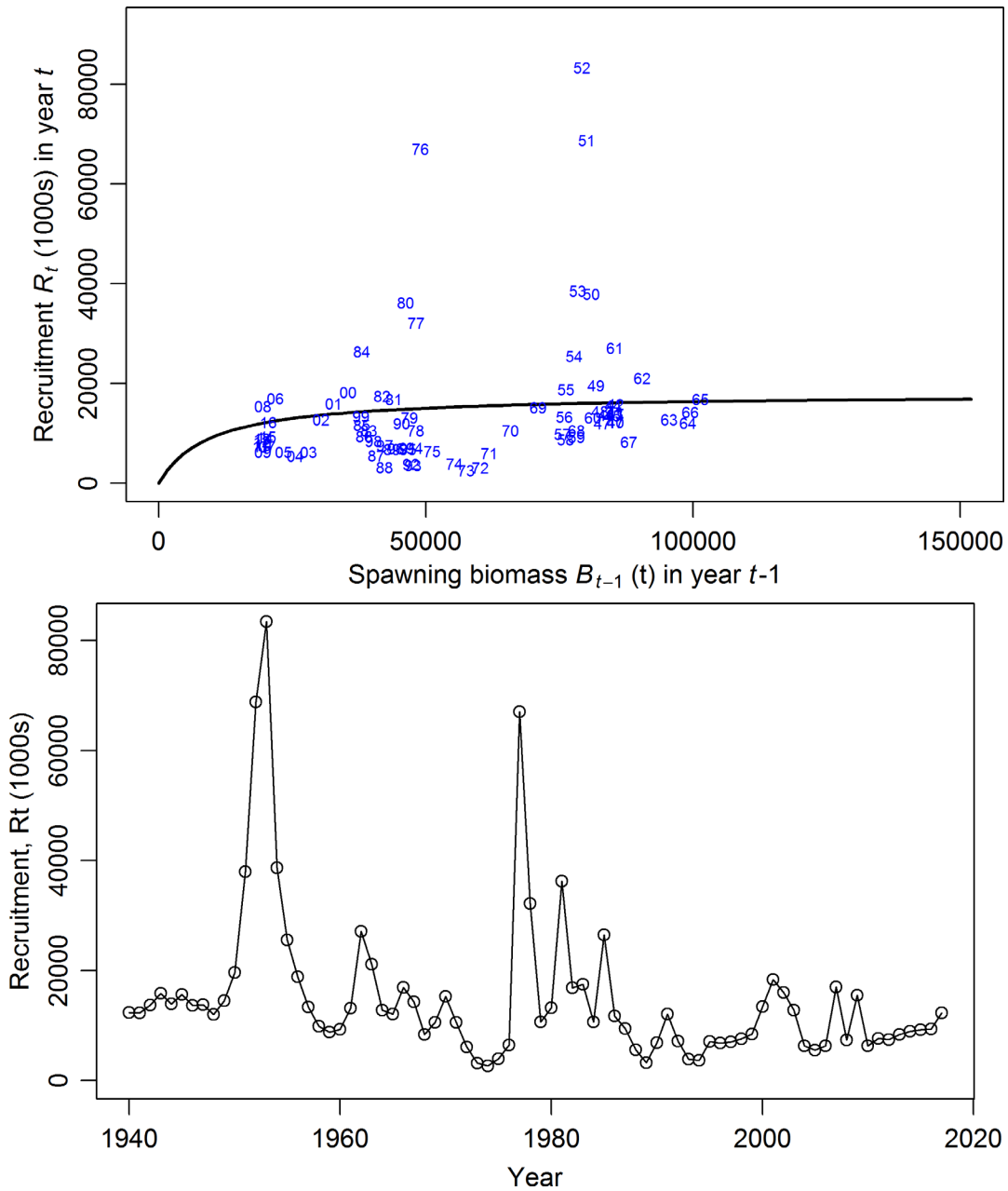


Figure E.20. Top: Deterministic stock-recruit relationship (black curve) and observed values (labelled by year of spawning) using MPD values. Bottom: Recruitment (MPD values of age-1 individuals in year  $t$ ) over time, in 1,000s of age-1 individuals, with a mean of 15,074.

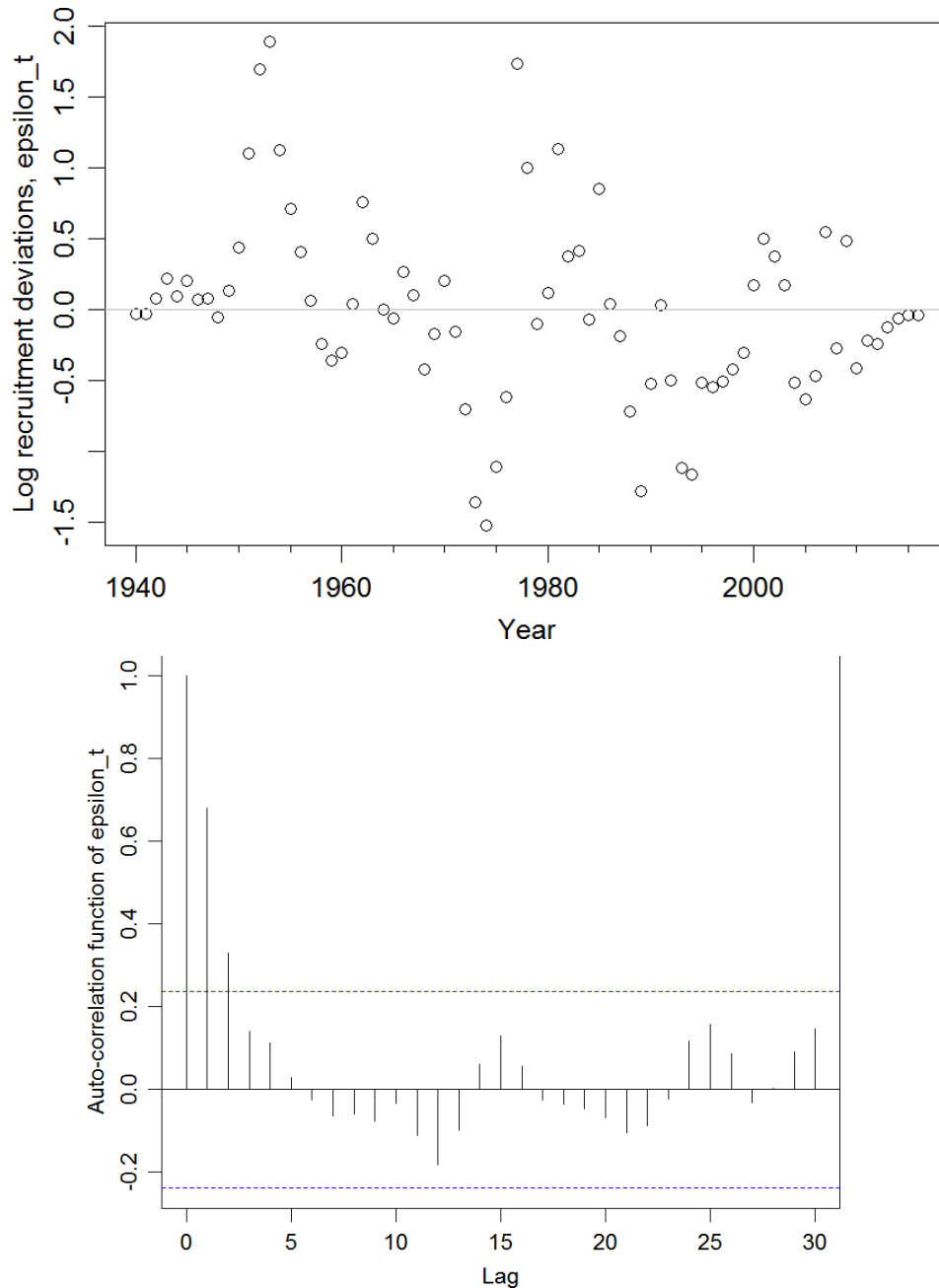


Figure E.21. Top: log of the annual recruitment deviations,  $E_t$ , where bias-corrected multiplicative deviation is  $e^{E_t - \sigma^2/2}$  where  $E \sim \text{Normal}(0, \sigma^2)$ . Bottom: Auto-correlation function of the logged recruitment deviations ( $E_t$ ), for years 1940-2007. The start of this range is calculated as the first year of commercial age data (1978) minus the accumulator age class ( $A = 60$ ) 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 (2016) minus the age for which commercial selectivity for females is 0.5 (namely 9).

## Pacific Ocean Perch Selectivity

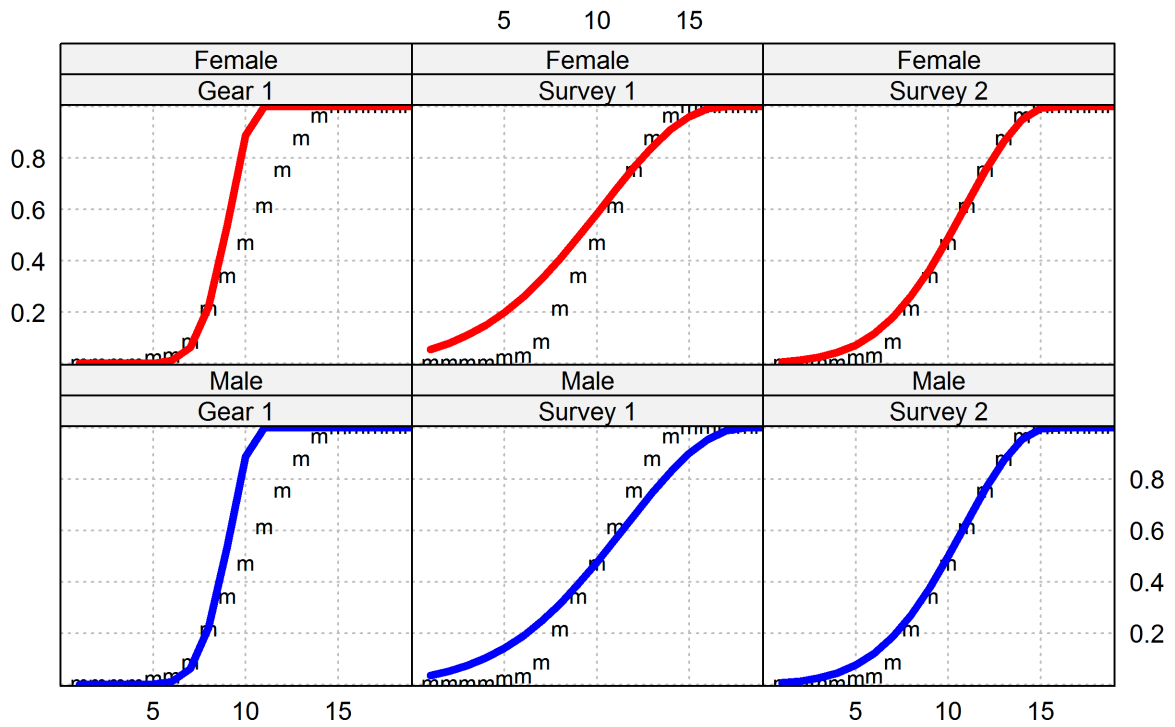


Figure E.22. Selectivities for commercial catch (Gear 1: Bottom Trawl) and surveys (all MPD values), with maturity ogive for females indicated by 'm'.



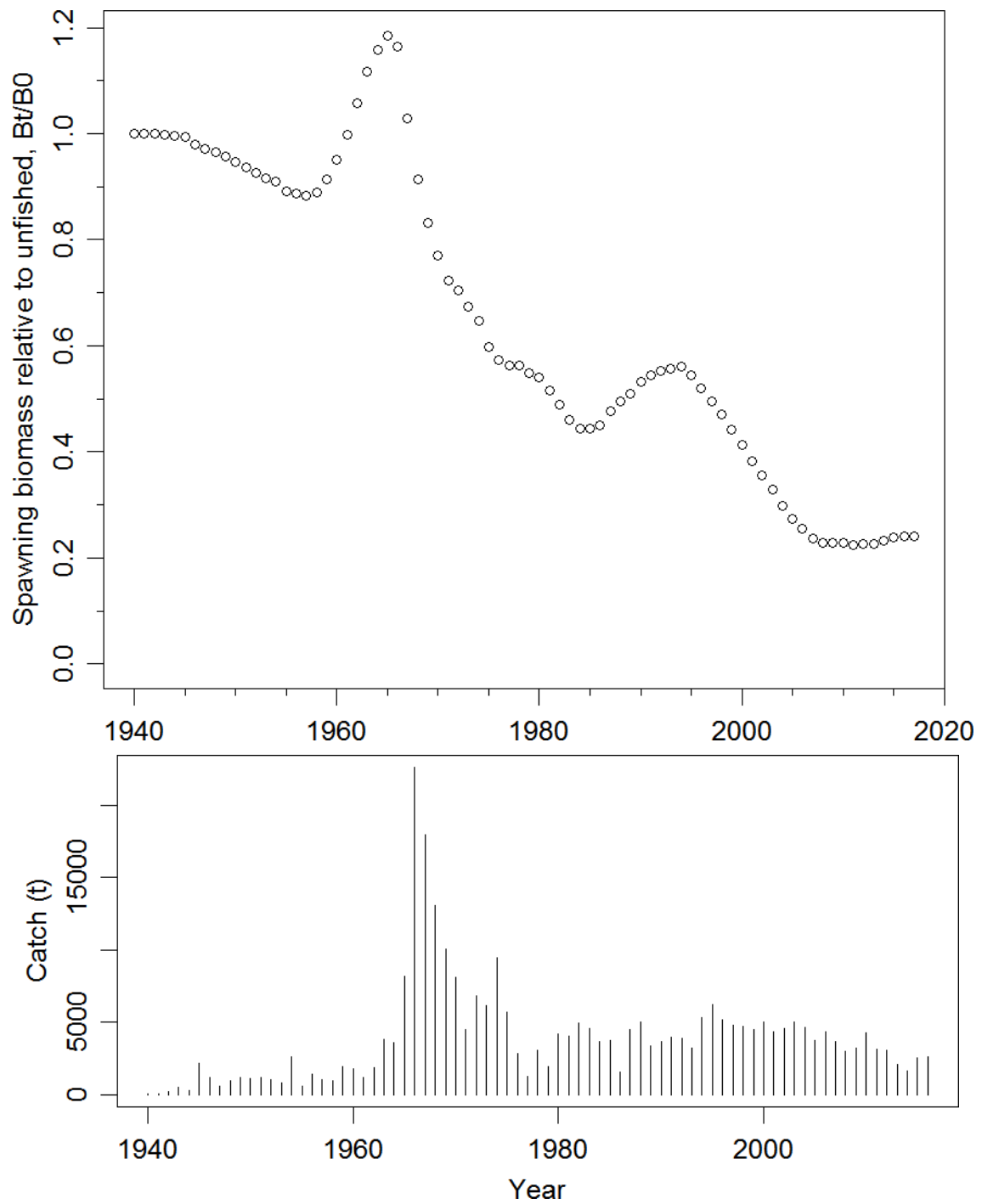


Figure E.23. Spawning biomass (mature females) relative to unfished level,  $B_t/B_0$ , and commercial catch.

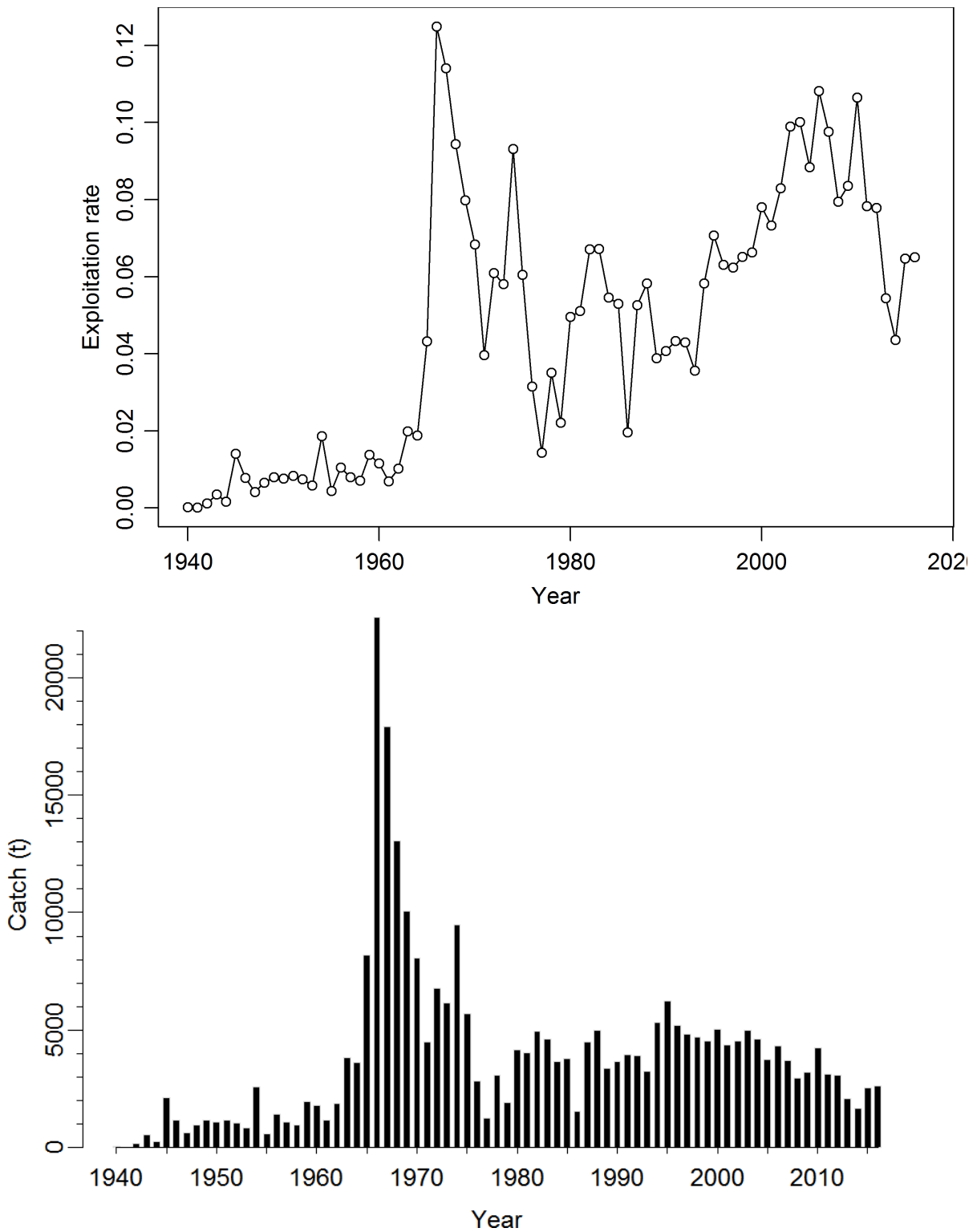


Figure E.24. Top: Exploitation rate (MPD) over time; Bottom: catch (t) by gear type.

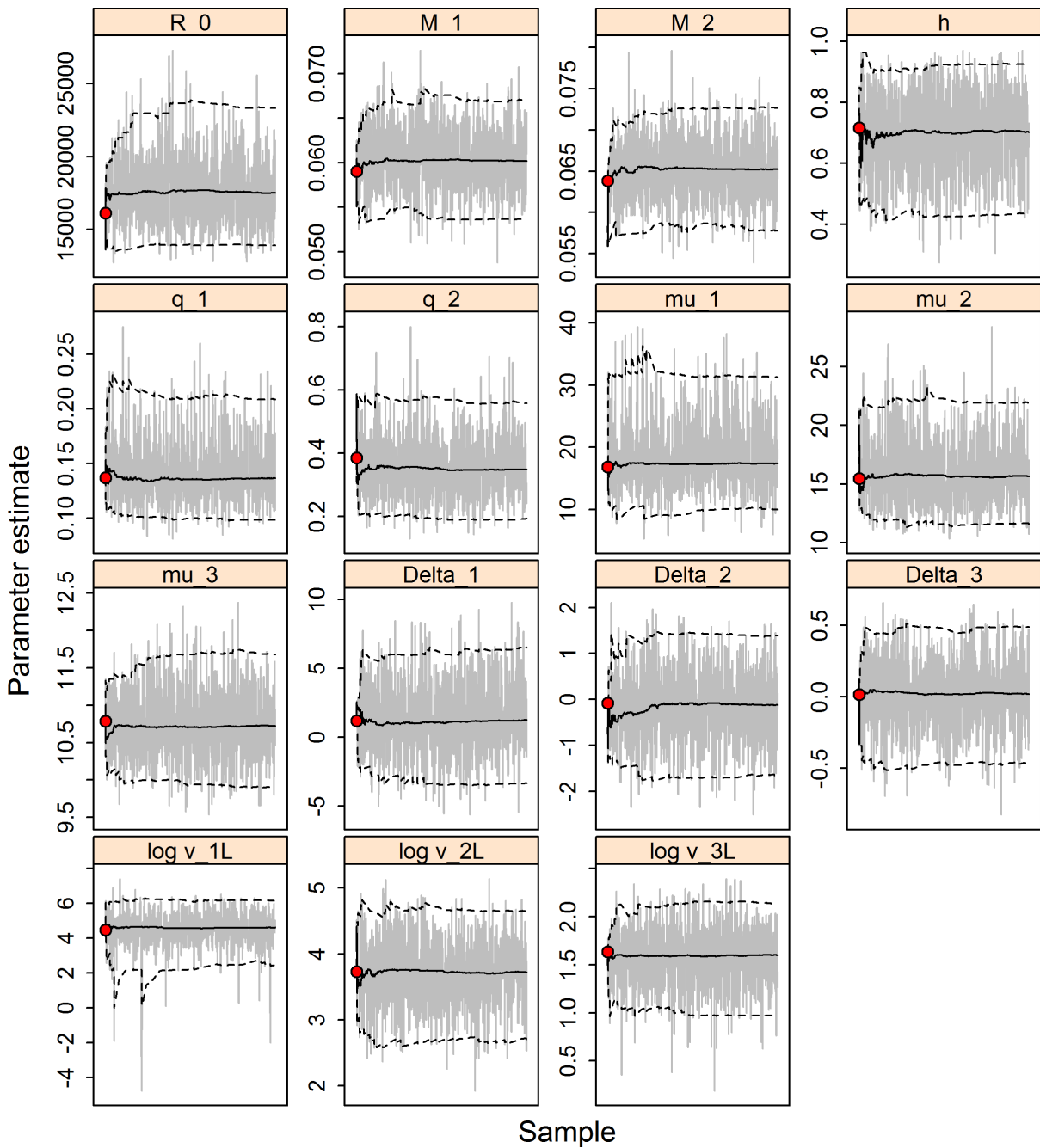


Figure E.25. MCMC traces for the estimated parameters. Grey lines show the 1,000 samples for each parameter, solid lines show the cumulative median (up to that sample), and dashed lines show the cumulative 2.5 and 97.5 quantiles. Red circles are the MPD estimates. For parameters other than  $M$  (if estimated), subscripts  $\leq 2$  correspond to fishery-independent surveys, and subscripts  $\geq 3$  denote the commercial fishery. Parameter notation is described in Appendix D.

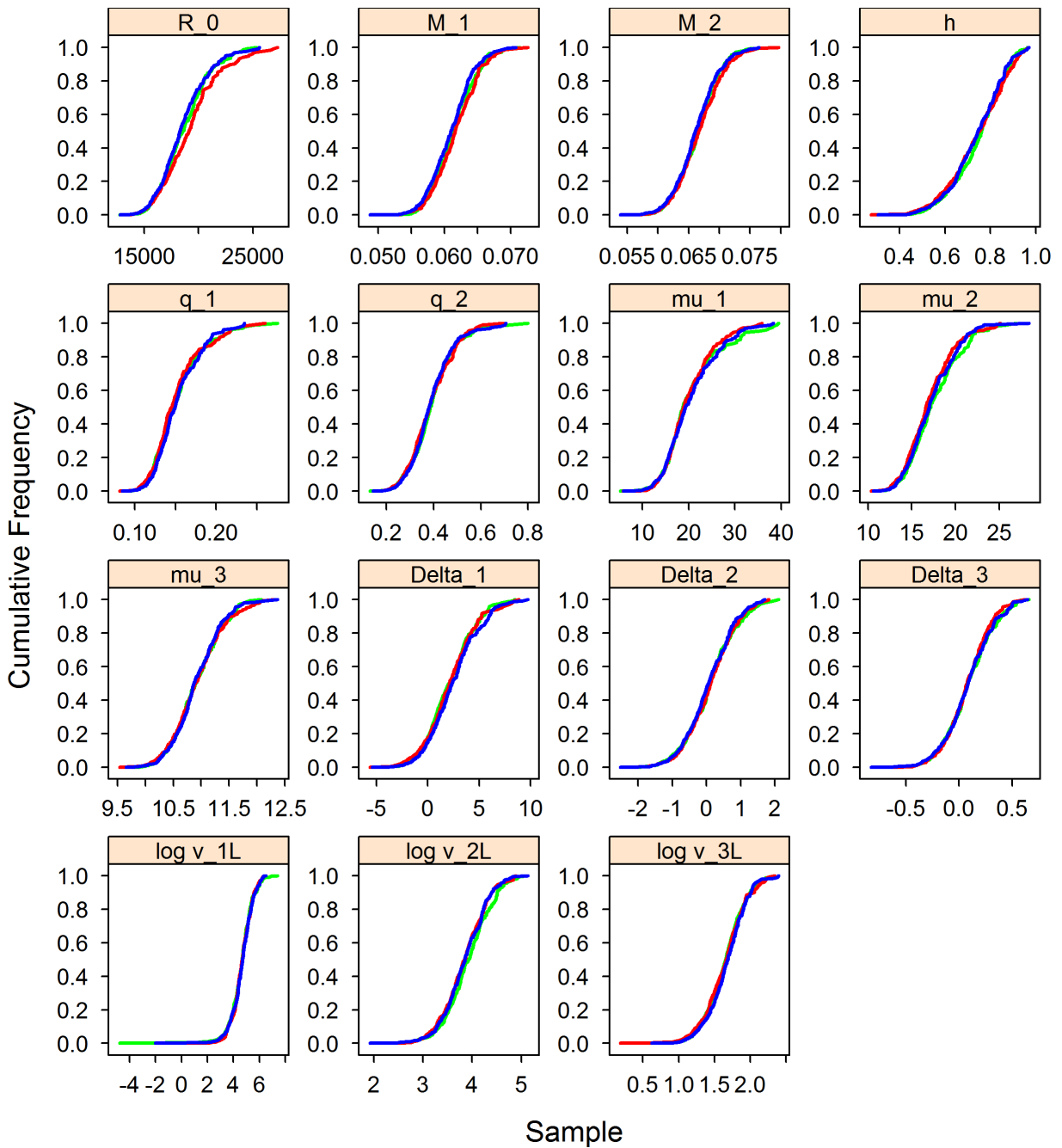


Figure E.26. Diagnostic plot obtained by dividing the MCMC chain of 1,000 MCMC samples into three segments, and overplotting the cumulative distributions of the first segment (green), second segment (red) and final segment (blue).

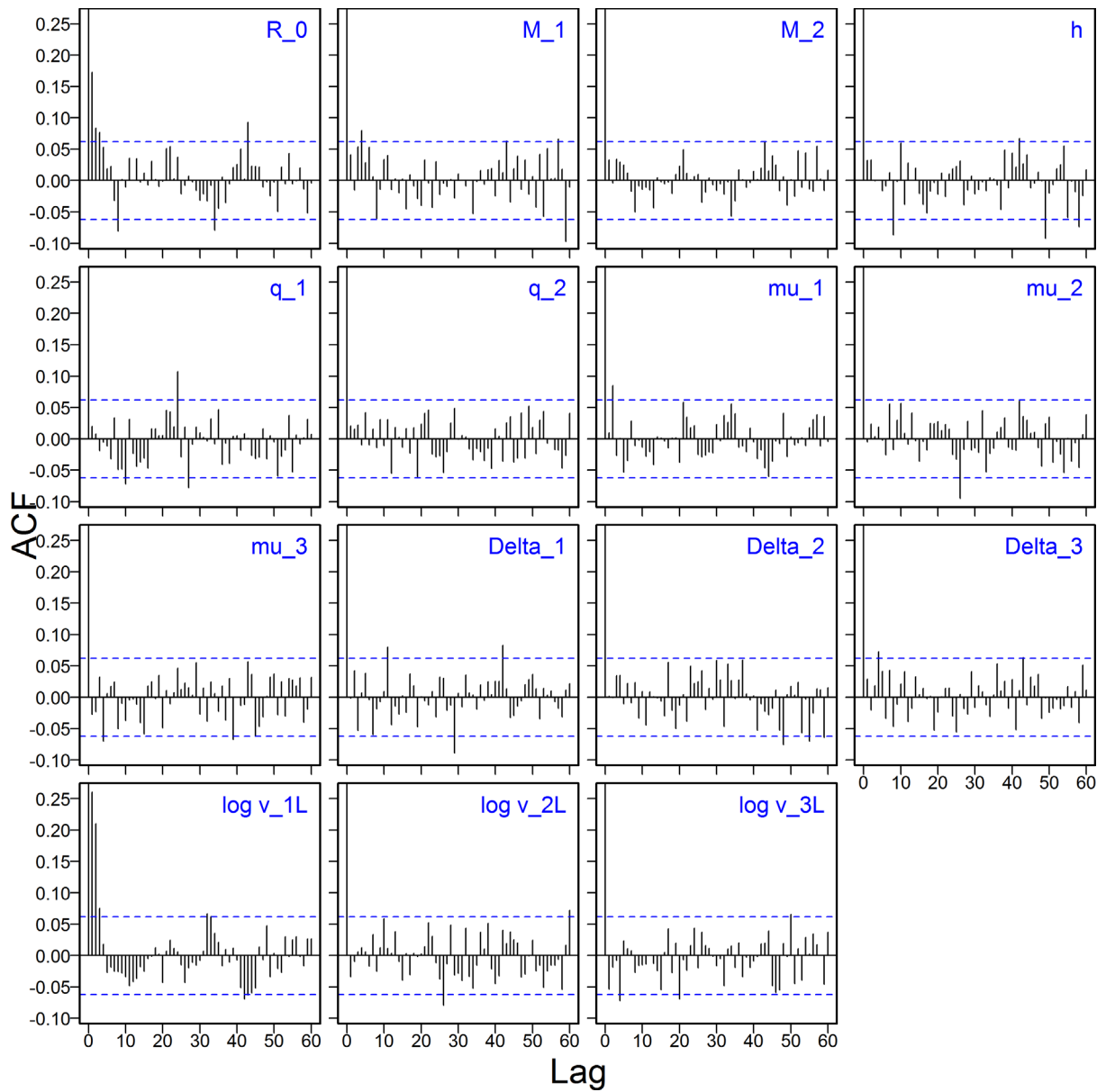


Figure E.27. Autocorrelation plots for the estimated parameters from the MCMC output. Horizontal dashed blue lines delimit the 95% confidence interval for each parameter's set of lagged correlations.

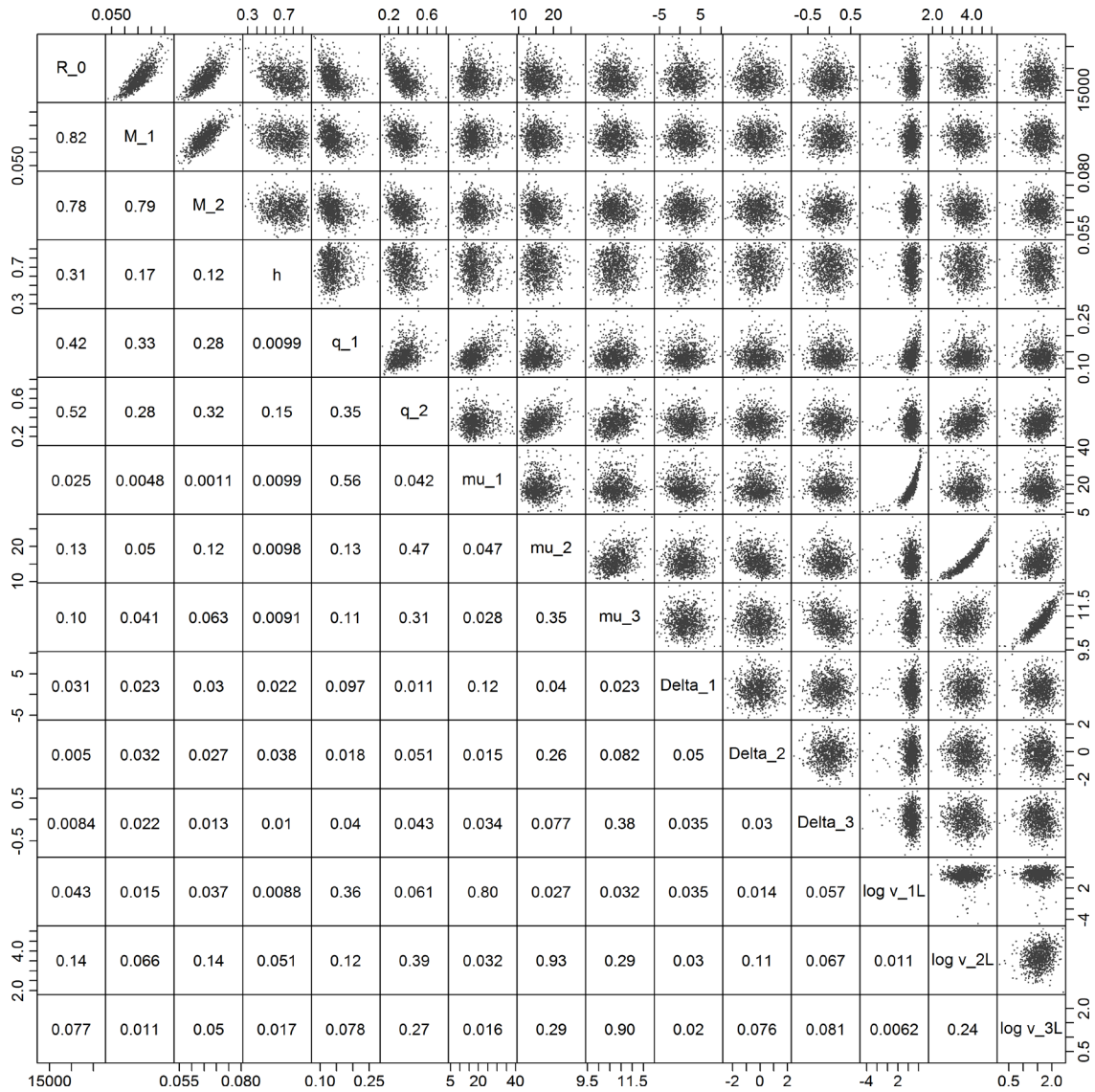


Figure E.28. Pairs plot of 1,000 MCMC samples for 15 parameters. Numbers in the lower panels are the absolute values of the correlation coefficients.

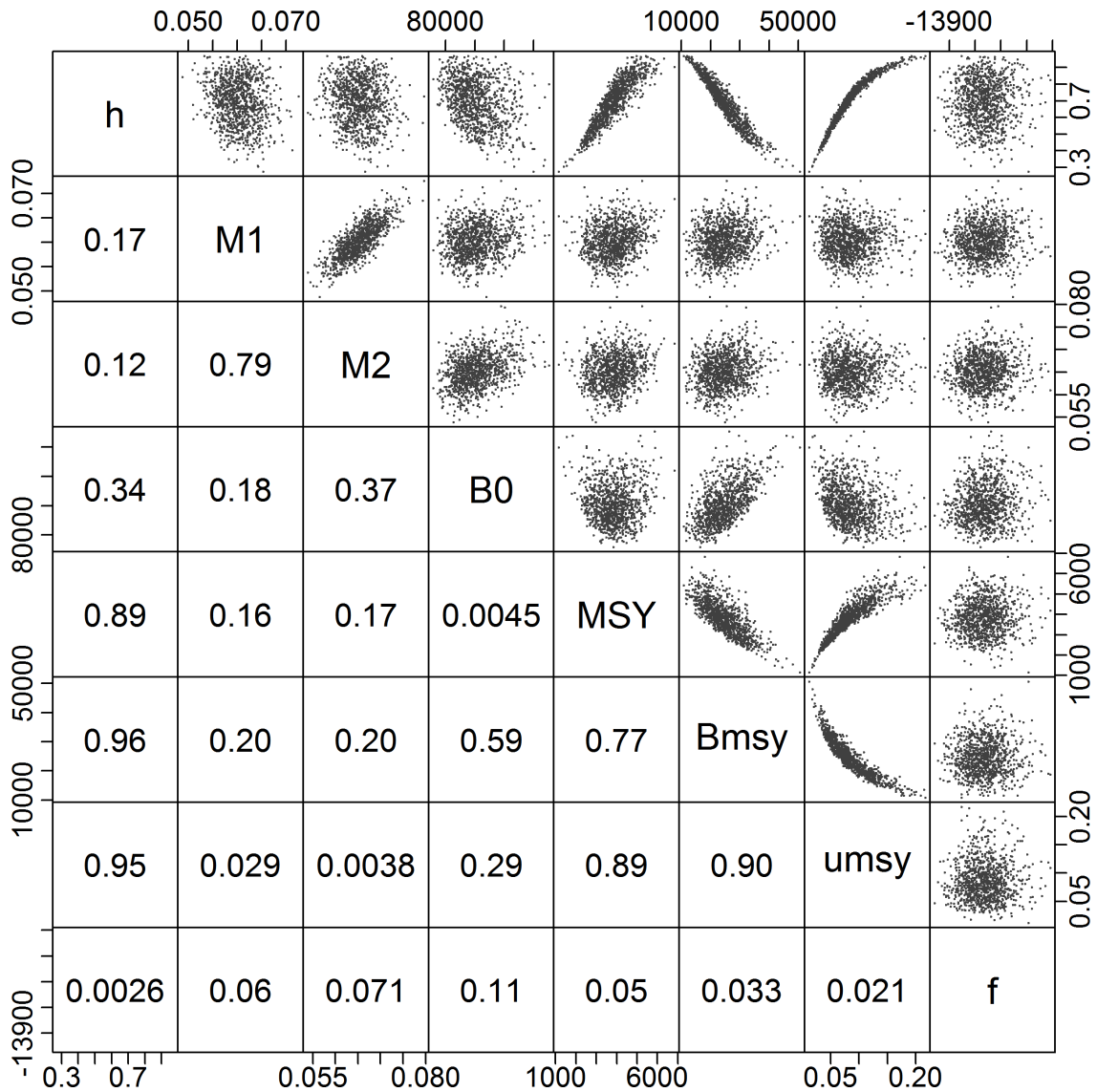


Figure E.29. Pairs plot of 1,000 MCMC samples comparing some parameters, key derived quantities, and function value ( $f$ ). Numbers in the lower panels are the absolute values of the correlation coefficients.

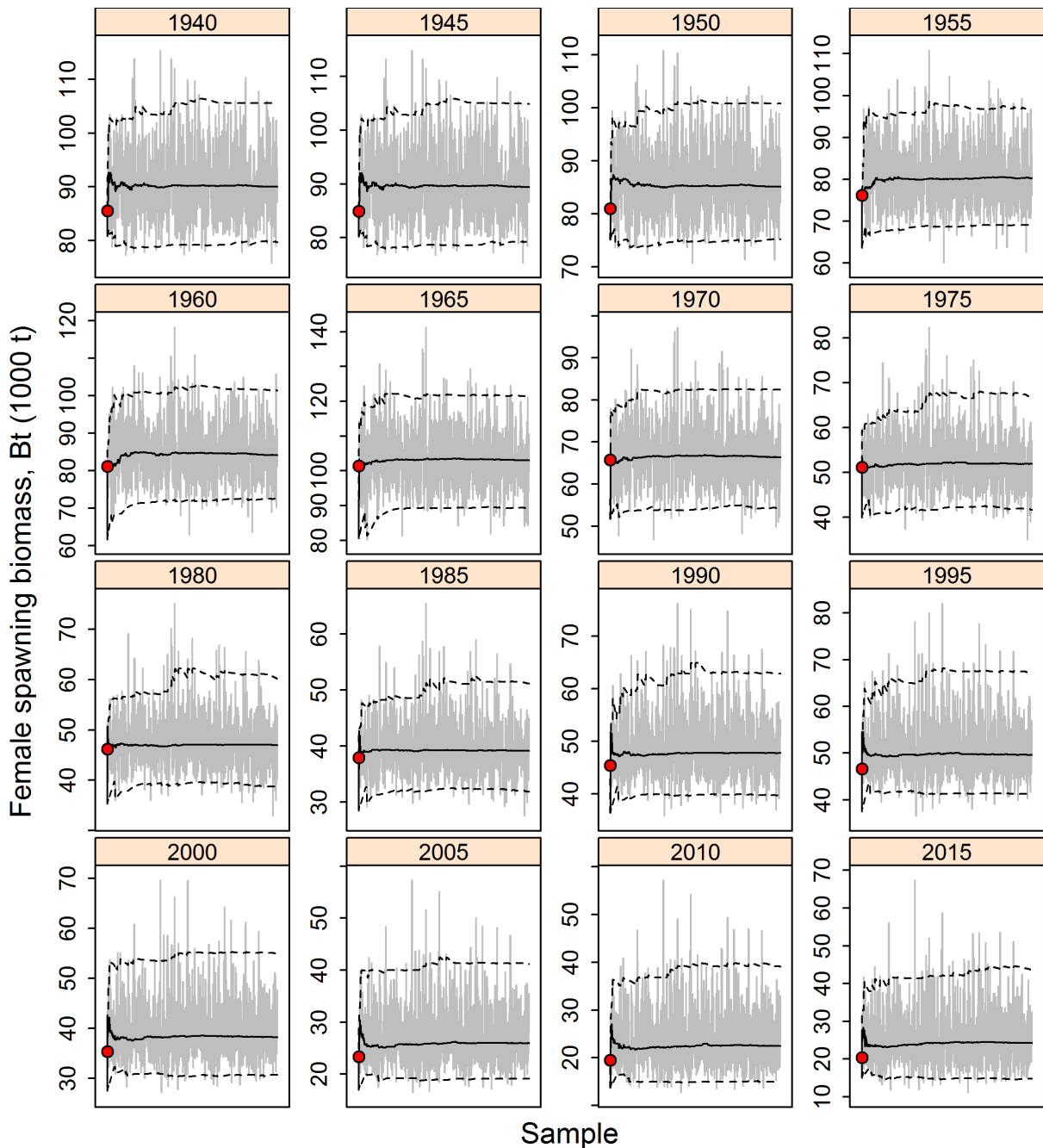


Figure E.30. MCMC traces for female spawning biomass estimates at five-year intervals. Note that vertical scales are different for each plot (to show convergence of the MCMC chain, rather than absolute differences in annual values). Grey lines show the 1,000 samples for each parameter, solid lines show the cumulative median (up to that sample), and dashed lines show the cumulative 2.5 and 97.5 quantiles. Red circles are the MPD estimates.



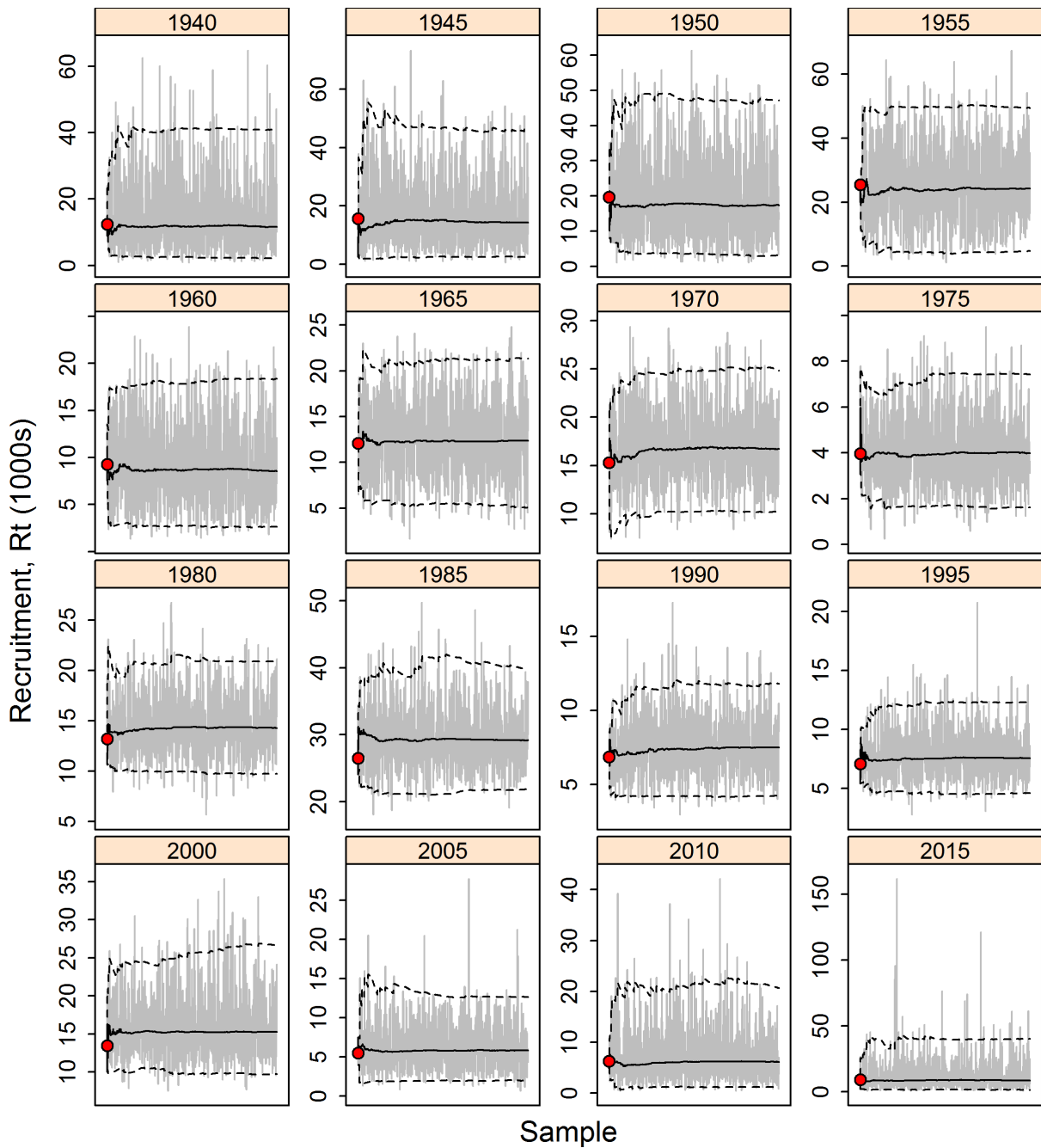


Figure E.31. MCMC traces for recruitment estimates at five-year intervals. Note that vertical scales are different for each plot (to show convergence of the MCMC chain, rather than absolute differences in annual recruitment). Grey lines show the 1,000 samples for each parameter, solid lines show the cumulative median (up to that sample), and dashed lines show the cumulative 2.5 and 97.5 quantiles. Red circles are the MPD estimates.

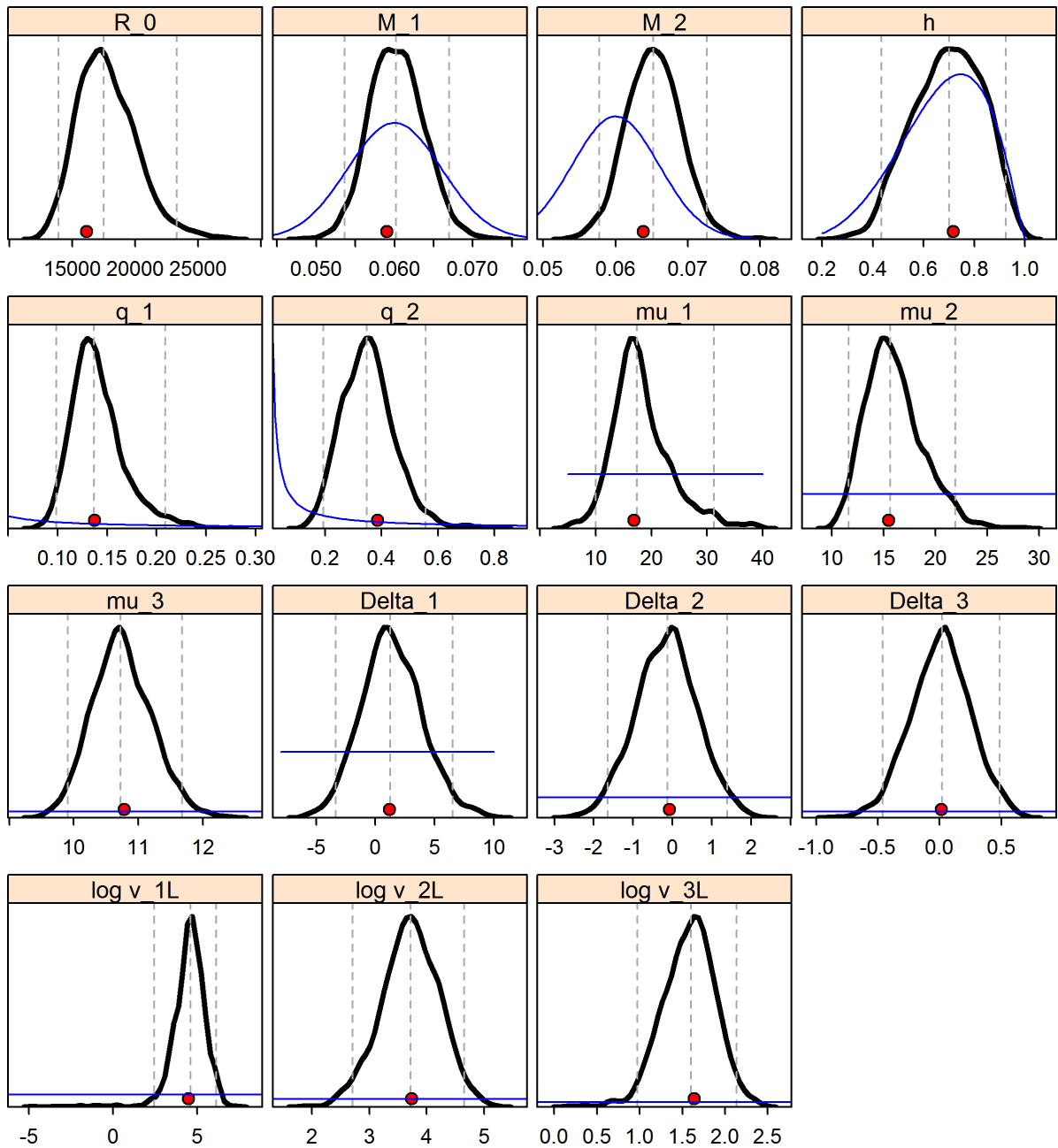


Figure E.32. Marginal posterior densities (thick black curves) and prior density functions (thin blue curves) for the estimated parameters. Vertical lines represent the 2.5, 50 and 97.5 percentiles, and red filled circles are the MPD estimates. For  $R_0$  the prior is a uniform distribution on the range  $[1, 10000000]$ . 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).

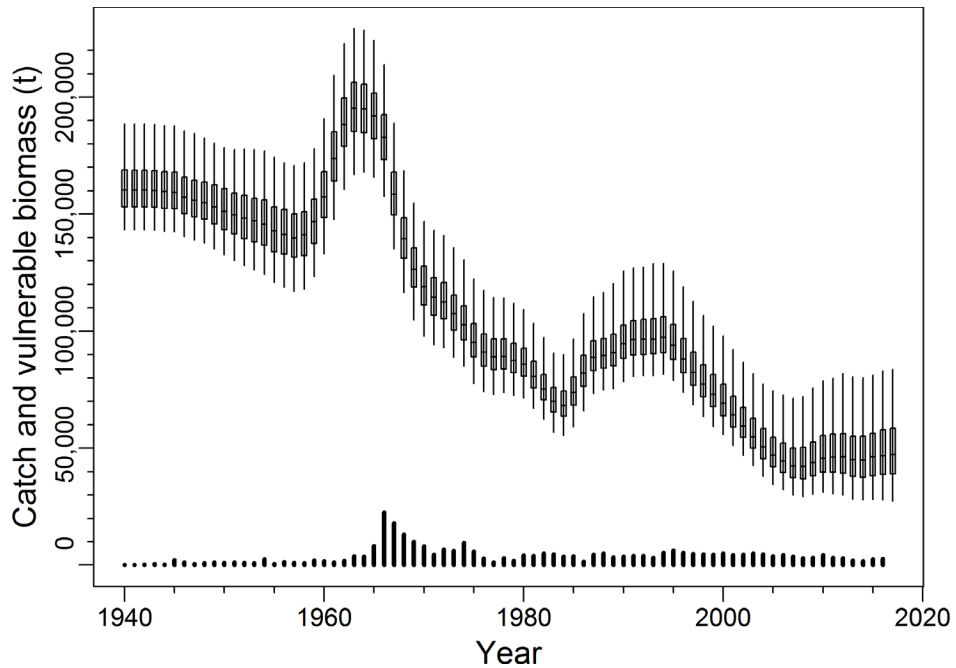


Figure E.33. Estimated vulnerable biomass (boxplots) and commercial catch (vertical bars), in tonnes, over time. Boxplots show the 2.5, 25, 50, 75 and 97.5 percentiles from the MCMC results. Catch is shown to compare its magnitude to the estimated vulnerable biomass.

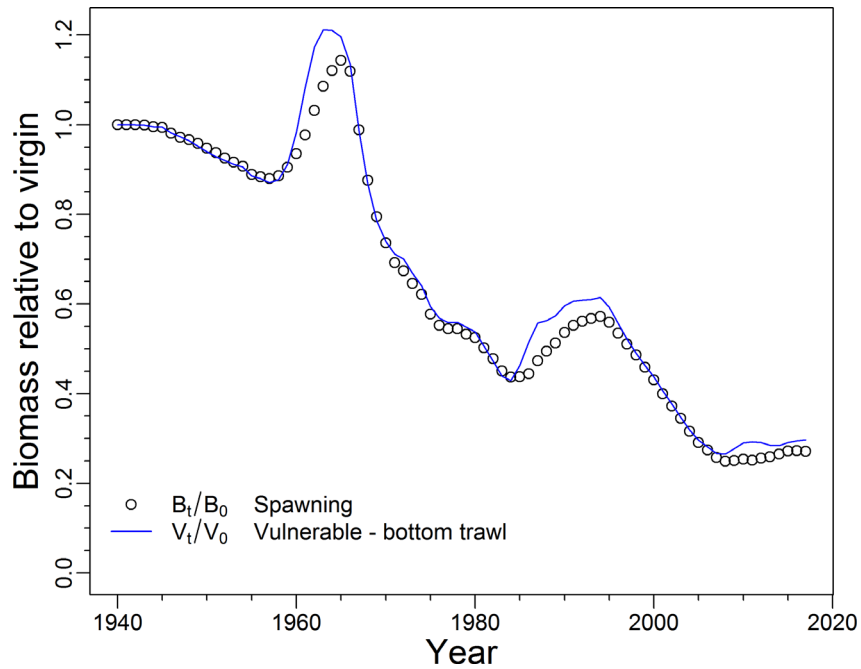


Figure E.34. Changes in  $B_t/B_0$  and  $V_t/V_0$  (spawning and vulnerable biomass relative to unfished equilibrium levels) over time, shown as the medians of the MCMC posteriors.

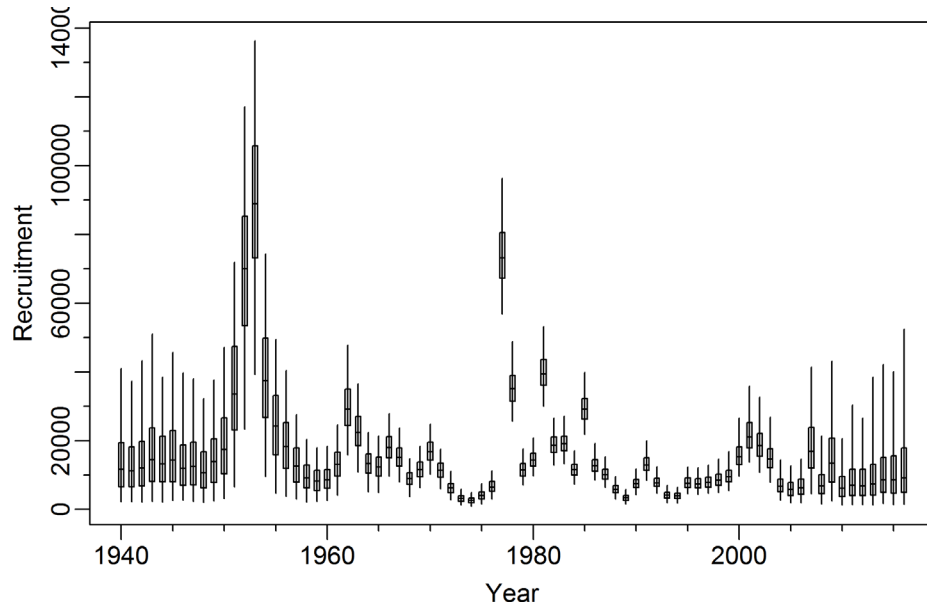


Figure E.35. Marginal posterior distribution of recruitment in 1,000s of age-1 fish over time. Boxplots show the 2.5, 25, 50, 75 and 97.5 percentiles from the MCMC results. As the first year for which there are age data is 1978, and the plus-age class is 60, there are no direct data concerning age-1 fish before 1919. Also, the final few years have no direct age-data from which to estimate recruitment, because fish are not fully selected until age 10.7 y by the commercial vessels or age 16.5 y by surveys (mean of the MCMC median ages at full selectivity for survey  $\mu_{1,2}$ ).

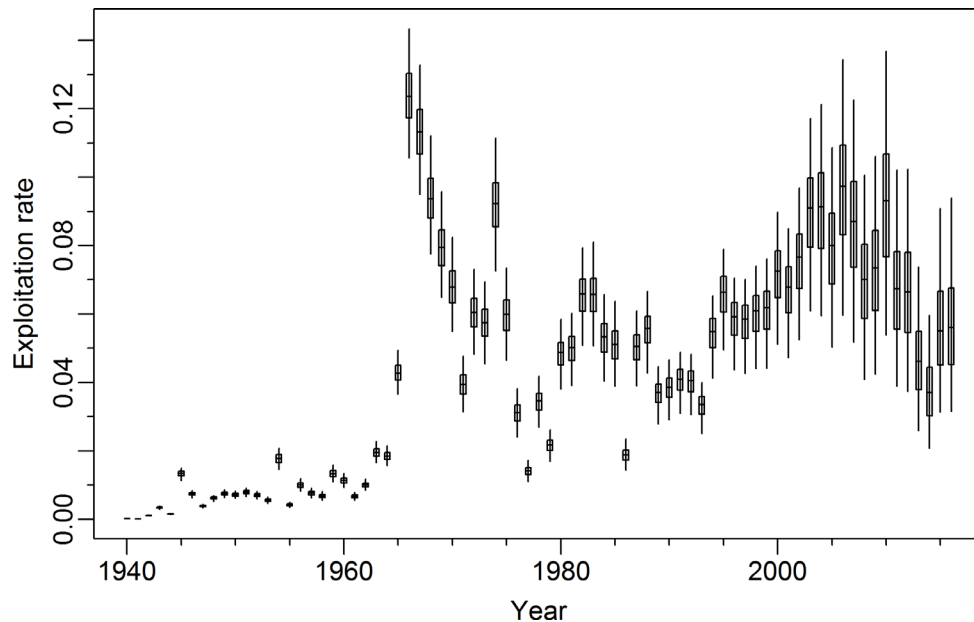


Figure E.36. Marginal posterior distribution of exploitation rate plotted over time. Boxplots show the 2.5, 25, 50, 75 and 97.5 percentiles from the MCMC results.

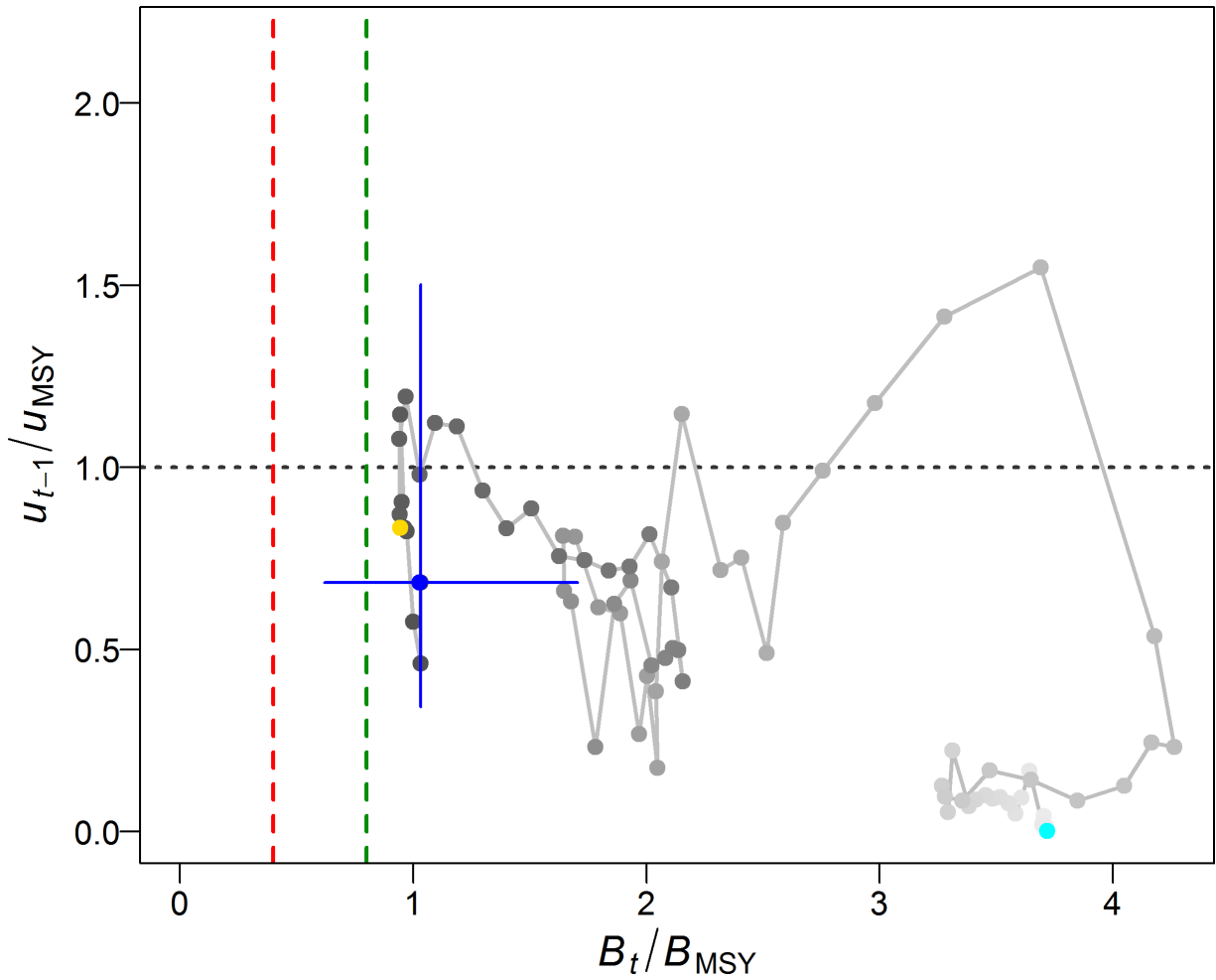


Figure E.37. Phase plot through time of the medians of the ratios  $B_t/B_{MSY}$  (the spawning biomass in year  $t$  relative to  $B_{MSY}$ ) and  $u_{t-1}/u_{MSY}$  (the exploitation rate in year  $t-1$  relative to  $u_{MSY}$ ). The filled cyan circle is the starting year (1941). Years then proceed from light grey through to dark grey with the final year (2017) 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 2011 ( $B_{2011}/B_{MSY}$ ,  $u_{2010}/u_{MSY}$ ), which coincides with the previous assessment in 2010. Red and green vertical dashed lines indicate the Precautionary Approach provisional limit and upper stock reference points ( $0.4$ ,  $0.8 B_{MSY}$ ), and the horizontal grey dotted line indicates  $u$  at  $MSY$ .

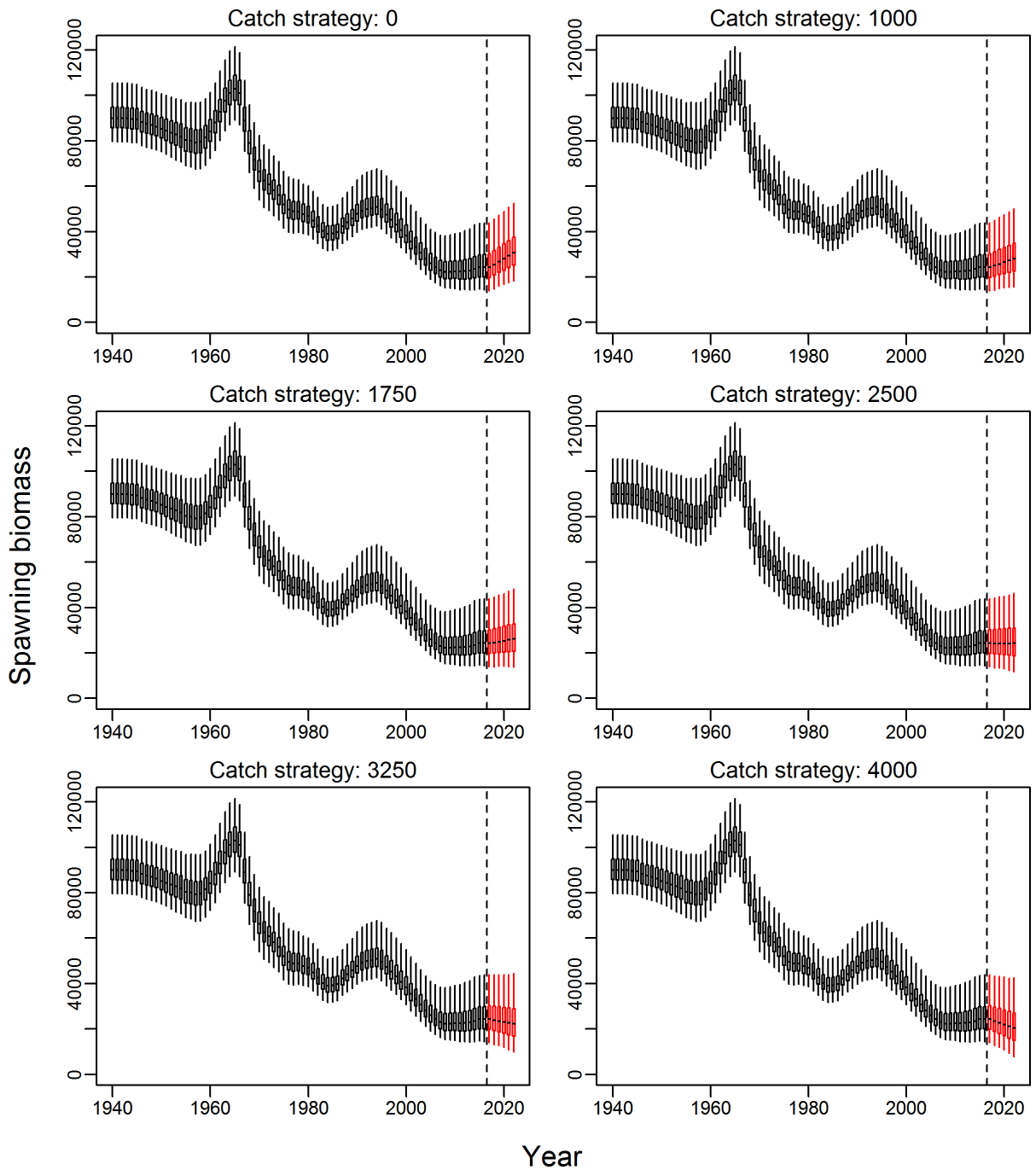


Figure E.38. Projected biomass ( $t$ ) under different constant catch strategies ( $t$ ); boxplots show the 2.5, 25, 50, 75 and 97.5 percentiles from the MCMC results. For each of the 1,000 samples from the MCMC posterior, the model was run forward in time (red, with medians in black) with a constant catch, and recruitment was simulated from the stock-recruitment function with lognormal error (see Appendix D). For reference, the average catch over the last 5 years (2012-2016) is 2397  $t$ .

Table E.4. The 5<sup>th</sup>, 50<sup>th</sup>, and 95<sup>th</sup> percentiles for model parameters derived via MCMC estimation (defined in Appendix D).

	5%	50%	95%
$R_0$	14,387	17,516	22,025
$M_1$	0.05495	0.06020	0.06599
$M_2$	0.05951	0.06523	0.07144
$h$	0.4630	0.7018	0.8994
$q_1$	0.1046	0.1366	0.1940
$q_2$	0.2156	0.3480	0.5062
$\mu_1$	11.17	17.41	28.14
$\mu_2$	12.21	15.65	21.09
$\mu_3$	10.03	10.72	11.55
$\Delta_1$	-2.678	1.264	5.818
$\Delta_2$	-1.442	-0.1227	1.124
$\Delta_3$	-0.3857	0.01853	0.4051
$\log v_{1L}$	3.016	4.603	5.904
$\log v_{2L}$	2.848	3.721	4.509
$\log v_{3L}$	1.072	1.600	2.046

Table E.5. The 5<sup>th</sup>, 50<sup>th</sup> and 95<sup>th</sup> 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),  $B_{2017}$  - spawning biomass at the start of 2017,  $V_{2017}$  - vulnerable biomass in the middle of 2017,  $u_{2016}$  - exploitation rate (ratio of total catch to vulnerable biomass) in the middle of 2016,  $u_{max}$  - maximum exploitation rate (calculated for each sample as the maximum exploitation rate from 1940-2016),  $B_{MSY}$  - 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 (2012-2016) is 2397t.

From model output			
Value	Percentile		
	5%	50%	95%
$B_0$	81,005	89,993	103,214
$V_0$	144,968	160,337	182,826
$B_{2017}$	15,312	24,302	40,768
$V_{2017}$	29,990	47,272	79,451
$B_{2017}/B_0$	0.177	0.271	0.417
$V_{2017}/V_0$	0.195	0.297	0.45
$u_{2016}$	0.033	0.056	0.085
$u_{max}$	0.108	0.124	0.142
MSY-based quantities			
Value	Percentile		
	5%	50%	95%
MSY	2,539	3,843	5,255
$B_{MSY}$	15,743	24,116	34,771
$0.4B_{MSY}$	6,297	9,647	13,908
$0.8B_{MSY}$	12,594	19,293	27,817
$B_{2017}/B_{MSY}$	0.537	1.029	1.964
$B_{MSY}/B_0$	0.183	0.269	0.362
$V_{MSY}$	33,785	47,982	66,674
$V_{MSY}/V_0$	0.218	0.301	0.382
$u_{MSY}$	0.039	0.08	0.148
$u_{2016}/u_{MSY}$	0.292	0.684	1.798



Table E.6. Decision table concerning the limit reference point  $0.4B_{MSY}$  for 1-5 year projections for a range of constant catch strategies (in tonnes). Values are  $P(B_t > 0.4B_{MSY})$ , 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  $B_t > 0.4B_{MSY}$ . For reference, the average catch over the last 5 years (2012-2016) is 2397 t.

	2017	2018	2019	2020	2021	2022
0	0.99	1.00	1.00	1.00	1.00	1.00
250	0.99	0.99	1.00	1.00	1.00	1.00
500	0.99	0.99	1.00	1.00	1.00	1.00
750	0.99	0.99	1.00	1.00	1.00	1.00
1000	0.99	0.99	0.99	1.00	1.00	1.00
1250	0.99	0.99	0.99	0.99	0.99	0.99
1500	0.99	0.99	0.99	0.99	0.99	0.99
1750	0.99	0.99	0.99	0.99	0.99	0.99
2000	0.99	0.99	0.99	0.99	0.99	0.99
2250	0.99	0.99	0.99	0.99	0.99	0.98
2500	0.99	0.99	0.99	0.99	0.98	0.97
2750	0.99	0.99	0.99	0.98	0.98	0.97
3000	0.99	0.99	0.99	0.98	0.97	0.96
3250	0.99	0.99	0.99	0.98	0.96	0.95
3500	0.99	0.99	0.98	0.97	0.95	0.94
3750	0.99	0.99	0.98	0.96	0.95	0.92
4000	0.99	0.99	0.98	0.96	0.94	0.91
4250	0.99	0.99	0.98	0.95	0.93	0.90
4500	0.99	0.99	0.97	0.95	0.91	0.87
4750	0.99	0.98	0.97	0.94	0.90	0.85
5000	0.99	0.98	0.96	0.94	0.89	0.82

Table E.7. Decision table concerning the upper stock reference point  $0.8B_{MSY}$  for 1-5 year projections, such that values are  $P(B_t > 0.8B_{MSY})$ . For reference, the average catch over the last 5 years (2012-2016) is 2397 t.

	2017	2018	2019	2020	2021	2022
0	0.74	0.78	0.80	0.83	0.85	0.87
250	0.74	0.78	0.80	0.82	0.84	0.85
500	0.74	0.78	0.79	0.81	0.83	0.84
750	0.74	0.77	0.79	0.80	0.81	0.82
1000	0.74	0.77	0.78	0.79	0.80	0.81
1250	0.74	0.76	0.77	0.78	0.79	0.79
1500	0.74	0.76	0.76	0.78	0.78	0.78
1750	0.74	0.75	0.76	0.77	0.77	0.77
2000	0.74	0.75	0.75	0.75	0.75	0.74
2250	0.74	0.74	0.74	0.73	0.73	0.72
2500	0.74	0.74	0.73	0.72	0.71	0.71
2750	0.74	0.73	0.71	0.71	0.70	0.68
3000	0.74	0.72	0.70	0.69	0.67	0.66
3250	0.74	0.72	0.69	0.67	0.65	0.63
3500	0.74	0.71	0.68	0.66	0.63	0.60
3750	0.74	0.70	0.67	0.64	0.61	0.58
4000	0.74	0.69	0.67	0.63	0.59	0.56
4250	0.74	0.69	0.65	0.61	0.58	0.54
4500	0.74	0.68	0.64	0.60	0.55	0.51
4750	0.74	0.68	0.63	0.59	0.53	0.48
5000	0.74	0.67	0.62	0.57	0.51	0.46

Table E.8. Decision table concerning the reference point  $B_{MSY}$  for 1-5 year projections, such that values are  $P(B_t > B_{MSY})$ . For reference, the average catch over the last 5 years (2012-2016) is 2397 t.

	2017	2018	2019	2020	2021	2022
0	0.53	0.58	0.63	0.67	0.71	0.74
250	0.53	0.57	0.62	0.66	0.70	0.72
500	0.53	0.57	0.61	0.64	0.68	0.70
750	0.53	0.57	0.60	0.63	0.66	0.68
1000	0.53	0.57	0.59	0.62	0.64	0.67
1250	0.53	0.56	0.58	0.60	0.62	0.64
1500	0.53	0.56	0.57	0.59	0.60	0.61
1750	0.53	0.55	0.56	0.57	0.58	0.59
2000	0.53	0.54	0.55	0.55	0.56	0.57
2250	0.53	0.53	0.54	0.54	0.55	0.55
2500	0.53	0.52	0.52	0.53	0.53	0.52
2750	0.53	0.52	0.52	0.51	0.50	0.51
3000	0.53	0.51	0.50	0.49	0.48	0.48
3250	0.53	0.51	0.49	0.48	0.47	0.46
3500	0.53	0.51	0.48	0.47	0.45	0.44
3750	0.53	0.50	0.48	0.46	0.43	0.41
4000	0.53	0.49	0.47	0.44	0.42	0.39
4250	0.53	0.49	0.47	0.43	0.40	0.37
4500	0.53	0.48	0.46	0.42	0.38	0.35
4750	0.53	0.48	0.44	0.41	0.36	0.32
5000	0.53	0.48	0.43	0.39	0.34	0.31

Table E.9. Decision table for comparing the projected biomass to the current biomass, given by probabilities  $P(B_t > B_{2017})$ . For reference, the average catch over the last 5 years (2012-2016) is 2397 t.

	2017	2018	2019	2020	2021	2022
0	0.00	1.00	1.00	1.00	1.00	1.00
250	0.00	1.00	1.00	1.00	1.00	0.99
500	0.00	0.99	0.99	0.99	0.99	0.99
750	0.00	0.98	0.97	0.97	0.97	0.97
1000	0.00	0.95	0.94	0.94	0.94	0.94
1250	0.00	0.90	0.90	0.90	0.89	0.89
1500	0.00	0.84	0.83	0.84	0.82	0.81
1750	0.00	0.74	0.75	0.74	0.74	0.73
2000	0.00	0.64	0.65	0.66	0.65	0.64
2250	0.00	0.55	0.56	0.56	0.55	0.54
2500	0.00	0.46	0.47	0.46	0.45	0.43
2750	0.00	0.37	0.37	0.36	0.35	0.35
3000	0.00	0.30	0.29	0.30	0.28	0.28
3250	0.00	0.23	0.23	0.23	0.23	0.22
3500	0.00	0.19	0.19	0.17	0.17	0.17
3750	0.00	0.14	0.15	0.14	0.14	0.14
4000	0.00	0.11	0.11	0.12	0.11	0.10
4250	0.00	0.09	0.09	0.09	0.09	0.08
4500	0.00	0.06	0.07	0.07	0.06	0.07
4750	0.00	0.05	0.05	0.05	0.05	0.05
5000	0.00	0.03	0.04	0.04	0.04	0.03

Table E.10. Decision table for comparing the projected exploitation rate to that at MSY, such that values are  $P(u_t > u_{MSY})$ , 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 (2012-2016) is 2397 t.

	2017	2018	2019	2020	2021	2022
0	0.00	0.00	0.00	0.00	0.00	0.00
250	0.00	0.00	0.00	0.00	0.00	0.00
500	0.00	0.00	0.00	0.00	0.00	0.00
750	0.00	0.00	0.00	0.00	0.00	0.00
1000	0.01	0.01	0.01	0.01	0.01	0.01
1250	0.02	0.02	0.02	0.02	0.02	0.03
1500	0.06	0.06	0.06	0.07	0.07	0.06
1750	0.11	0.11	0.11	0.11	0.11	0.11
2000	0.15	0.15	0.16	0.16	0.17	0.18
2250	0.19	0.19	0.20	0.21	0.22	0.22
2500	0.23	0.23	0.24	0.26	0.26	0.27
2750	0.28	0.29	0.30	0.32	0.33	0.33
3000	0.33	0.34	0.37	0.38	0.39	0.40
3250	0.39	0.40	0.42	0.43	0.45	0.46
3500	0.44	0.45	0.47	0.50	0.51	0.52
3750	0.48	0.50	0.52	0.55	0.57	0.59
4000	0.52	0.55	0.57	0.60	0.62	0.63
4250	0.57	0.59	0.62	0.65	0.67	0.68
4500	0.60	0.64	0.67	0.69	0.71	0.72
4750	0.65	0.67	0.70	0.72	0.75	0.76
5000	0.68	0.71	0.74	0.76	0.78	0.79

Table E. 11. Decision table for the alternative limit 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 (2012-2016) is 2397 t.

	2017	2018	2019	2020	2021	2022
0	0.88	0.92	0.95	0.97	0.98	0.98
250	0.88	0.91	0.94	0.96	0.97	0.98
500	0.88	0.91	0.94	0.95	0.96	0.97
750	0.88	0.90	0.93	0.94	0.95	0.96
1000	0.88	0.90	0.92	0.93	0.94	0.94
1250	0.88	0.90	0.90	0.92	0.92	0.93
1500	0.88	0.89	0.90	0.91	0.91	0.91
1750	0.88	0.89	0.89	0.89	0.89	0.89
2000	0.88	0.88	0.88	0.88	0.87	0.86
2250	0.88	0.87	0.87	0.85	0.84	0.83
2500	0.88	0.87	0.86	0.83	0.82	0.81
2750	0.88	0.86	0.84	0.82	0.80	0.78
3000	0.88	0.86	0.82	0.80	0.78	0.75
3250	0.88	0.85	0.81	0.78	0.76	0.72
3500	0.88	0.85	0.80	0.76	0.72	0.69
3750	0.88	0.84	0.78	0.74	0.70	0.66
4000	0.88	0.83	0.77	0.72	0.67	0.63
4250	0.88	0.82	0.76	0.70	0.65	0.59
4500	0.88	0.81	0.75	0.68	0.62	0.57
4750	0.88	0.80	0.74	0.67	0.59	0.54
5000	0.88	0.79	0.72	0.65	0.57	0.50

Table E. 12. Decision table for the alternative upper stock 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 (2012-2016) is 2397 t.

	2017	2018	2019	2020	2021	2022
0	0.07	0.10	0.13	0.17	0.22	0.27
250	0.07	0.10	0.13	0.16	0.21	0.25
500	0.07	0.10	0.12	0.15	0.19	0.22
750	0.07	0.10	0.11	0.14	0.18	0.21
1000	0.07	0.09	0.10	0.14	0.16	0.19
1250	0.07	0.09	0.10	0.13	0.15	0.17
1500	0.07	0.09	0.10	0.12	0.14	0.16
1750	0.07	0.09	0.10	0.11	0.13	0.14
2000	0.07	0.08	0.10	0.10	0.12	0.13
2250	0.07	0.08	0.09	0.10	0.10	0.12
2500	0.07	0.08	0.09	0.09	0.10	0.10
2750	0.07	0.08	0.08	0.08	0.08	0.09
3000	0.07	0.08	0.08	0.08	0.08	0.08
3250	0.07	0.08	0.08	0.07	0.07	0.07
3500	0.07	0.07	0.07	0.06	0.06	0.06
3750	0.07	0.07	0.06	0.06	0.06	0.05
4000	0.07	0.07	0.06	0.05	0.05	0.04
4250	0.07	0.07	0.06	0.05	0.04	0.04
4500	0.07	0.06	0.06	0.05	0.04	0.03
4750	0.07	0.06	0.05	0.04	0.04	0.03
5000	0.07	0.06	0.05	0.04	0.03	0.03

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## E.5. SENSITIVITY RUNS

Seven sensitivity analyses were run (with full MCMC simulations equivalent to the base-case specifications) to see how the Base Case (Run09) differed when inputs were changed:

- **Sens1** (Run08) - add QCS shrimp survey with fixed selectivity;
- **Sens2** (Run15) - add QCS shrimp survey with dome-shaped selectivity and with the addition of the single 1999 age composition sample;
- **Sens3** (Run20) - use the observed survey CVs without adding any process error;
- **Sens4** (Run14) - use an alternative normal prior on both  $M$  parameters with mean=0.07 and SD=0.014;
- **Sens5** (Run17) - use a uniform prior on  $M$ ;
- **Sens6** (Run18) - halve the trawl catches during the foreign feet period (1965-1975);
- **Sens7** (Run19) - double the trawl catches during the foreign feet period (1965-1975).

These runs used the same SDNR-adjusted survey weights as the Base Case except for Sensitivity 3, which used the nominal survey weights without additional process error. The Francis (2011) reweighting procedure for age frequencies was applied to each sensitivity run. The differences among the runs are summarised in Tables E.13 and E.14 and Figures E.39-E.41. Diagnostic plots for the sensitivity MCMCs appear in Figures E.48 to E.68.

Adding the QCS Shrimp survey index series lowers the stock status, regardless of whether survey selectivity is fixed (Sensitivity 1) or fitted using dome-shaped selectivity (Sensitivity 2). Median  $B_{2017}/B_{MSY}$  for the Base Case is 1.03, and this decreases to 0.75 and 0.81 for Sensitivities 1 and 2, respectively.

In the working paper presented to the RPR participants, Run08 (Sensitivity 1) was put forward as the Base Case, primarily to match the data choices made for the 2010 stock assessment (Edwards et al. 2012). However, it was noted during the peer review process that this survey does not cover the entire depth range of POP, only trawling down to ~200 m (see Figure B.37), whereas POP typically inhabits depths down to ~400 m (see Figure B.18), with the highest catch rates deeper than ~200 m. As well, this survey only covers a relative small portion of the Goose Island Gully west of Calvert Island (e.g., Figure B.36), whereas this stock is well distributed throughout QC Sound, especially along the outer margins (e.g., Figure B.17). The shrimp survey design is optimised for shrimp, which occur at shallower depths where juvenile POP are more prevalent and uses a fine mesh net liner in the cod end that is designed to capture shrimp; therefore, it is likely that the QCS shrimp survey provides a relatively poor index of the adult QCS POP population. To partially address the lack of deeper, older POP in this survey, Sensitivity 2 assumed dome-shaped selectivity, with a declining vulnerability of older POP (Figure E.42), but the resulting parameter estimates differed little from those estimated when assuming fixed selectivity (Table E.14). The insensitivity of the parameter estimates to this change in assumption may be due to the small amount of available age composition data for this survey (only one sample year). Given the limited areal and depth coverage by this survey, and that it is redundant to the coverage by the QCS synoptic survey, which is a survey specifically designed to monitor groundfish species, the RPR participants agreed to exclude this survey from the base-case model and to provide advice to managers based on the GIG historical and QCS synoptic surveys.

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Sensitivity 3 explores the effect of re-weighting the survey CVs by running the model with the observed survey CVs (i.e., no additional process error). Figure E.43 shows how the survey CVs differ between the Base Case and Sensitivity 3, with the observed GIG historical survey CVs being smaller than those used in the Base Case whereas the observed QCS synoptic survey CVs were larger. The base-case reweighting effectively downweights the GIG survey while upweighting the QCS survey, constraining the fit to more closely match the latter's relative abundance. We consider the base-case weighting to be more appropriate because the historical Goose Island survey is a series stitched together from unconnected surveys using a fixed station design (see Section B.3) while the QCS synoptic survey is a specifically designed groundfish survey using a random stratified design (see Section B.4). Consequently, a higher weight should be given to the better designed and more recent survey series. While most of the median parameter estimates are similar to those of the Base Case (Table E.13), the median estimate of stock size, as represented by  $R_0$ , is about 2% larger than in the Base Case. This translates into a larger median estimate of  $B_{2017}$  compared to the Base Case (28,968 vs. 24,302, respectively), likely reflecting differences in the posterior distributions of stock size. The consequence of the greater estimated current spawning biomass, while all else remains similar, is that stock status is estimated to be higher in this sensitivity run.

Sensitivities 4 and 5 explore the effects of changing the priors on natural mortality  $M$

(Figures E.40 and E.41). In the Base Case, the prior for  $M$  has a mean of 0.06 with a CV of 10%, which is a tight prior, only marginally better than fixing this parameter; however, the posteriors for  $M$  have smaller CVs than the prior (5.6%, Figure E.44), with the posterior mean barely shifting away from the prior mean for females while increasing by 9% for males. The addition of the QCS shrimp survey did not appreciably change the means or standard deviations of the estimated  $M$  values (Figure E.45). When the prior mean for  $M$  was raised to 0.07 and the CV widened to 20% (Figure E.46), the model converges on a higher  $M$  for both sexes, but the mean of the posterior is 3% less than the prior mean for females and 5% greater than the prior mean for males while the  $M$  posterior CV is less than 10% for both sexes. However, this model generates a significant amount of autocorrelation in a number of parameters, including both  $M$  parameters

(Figure E.59). Similar results are obtained from a model using a uniform prior on  $M$  (no expectations, Figure E.47), with the mean of the posterior distribution for  $M$  just below 0.07 for females and at 0.075 for males with a CV near 10% for both sexes. Stock status for Sensitivity 5 is slightly higher than that in Sensitivity 4, although similar, and there is again a high level of autocorrelation among all the leading parameters (Figure E.62). The MCMC diagnostics for both of these runs indicate that this procedure has probably not converged (particularly for

Sensitivity 5), leading to unreliable parameter estimates. However, it is notable that even with a uniform prior, the resulting estimates of  $M$  range from 0.057-0.080 (5-95% females) and

0.062-0.088 (5-95% males), indicating that the  $M$  prior used in the Base Case is consistent with the age composition data and that the constraint imposed by the base-case  $M$  prior is appropriate, given the much better MCMC diagnostics obtained for the base-case run.

Sensitivities 6 and 7 explore the effects of catch mis-specification during the period of peak foreign fleet activity. Ketchen (1980) provides minimum, intermediate, and maximum estimates of rockfish and POP caught by Russian and Japanese trawlers in Queen Charlotte Sound during the years 1965 to 1975. Traditionally, POP stock assessments have used the intermediate estimates, but these may include some bias. In Sensitivity 6, the 1965-75 catch input to the

model is arbitrarily halved, while in Sensitivity 7, it is arbitrarily doubled. Predictably, stock status is shifted to the right if catches are halved, with a larger proportion of the posterior distribution of  $B_{2017}/B_{MSY}$  in the "healthy" zone. Conversely, there is a leftward shift in stock status shifts into the cautious zone when catches are doubled (Figure E.39). The median  $B_{2017}/B_{MSY}$  for the Base Case is 1.03, and this changes to 1.18 and 0.83 for sensitivities 6 and 7, respectively.

Instabilities in the MCMC chains appear when foreign catches are doubled (Figures E.66-E.68) but not when they are halved (Figures E.63-E.65).

Table E.13. Median values of 1000 MCMC samples for the primary estimated parameters, comparing the Base Case (run 9) to sensitivity runs (8-20). R = Run, S = Sensitivity. Numeric subscripts other than those for  $R_0$  and  $M$  indicate the following gear types  $g$ : 1 = GIG historical survey, 2 = QCS synoptic survey, [3] = QCS shrimp survey, and 3 = commercial bottom trawl.

	Base(R09)	S1(R08)	S2(R15)	S3(R20)	S4(R14)	S5(R17)	S6(R18)	S7(R19)
$R_0$	17,516	16,657	16,932	17,844	22,561	23,915	15,322	23,814
$M_1$	0.0602	0.0595	0.0598	0.0599	0.0673	0.0686	0.0620	0.0595
$M_2$	0.0652	0.0644	0.0650	0.0650	0.0734	0.0748	0.0666	0.0650
$h$	0.702	0.653	0.671	0.726	0.686	0.684	0.743	0.611
$q_1$	0.137	0.143	0.141	0.134	0.117	0.117	0.145	0.117
$q_2$	0.348	0.388	0.380	0.292	0.278	0.262	0.368	0.282
$q_{[3]}$		0.0219	0.0288					
$\mu_1$	17.4	17.9	17.5	16.9	17.6	17.9	17.4	17.6
$\mu_2$	15.6	14.9	15.0	14.6	15.2	15.2	15.9	14.8
$\mu_{[3]}$			13.2					
$\mu_3$	10.7	10.7	10.7	10.6	10.7	10.7	10.8	10.6
$\Delta_1$	1.26	1.55	1.43	1.20	1.27	1.39	1.30	1.30
$\Delta_2$	-0.123	-0.0818	-0.0737	-0.0861	-0.102	-0.104	-0.128	-0.0444
$\Delta_{[3]}$			0.0567					
$\Delta_3$	0.0185	0.0260	0.0122	0.0314	0.0144	0.0122	-0.00672	0.0152
$\log v_{1L}$	4.60	4.68	4.63	4.55	4.61	4.61	4.60	4.60
$\log v_{2L}$	3.72	3.59	3.57	3.57	3.62	3.65	3.75	3.59
$\log v_{[3]L}$			1.05					
$\log v_{[3]R}$			10.4					
$\log v_{3L}$	1.60	1.56	1.57	1.50	1.56	1.55	1.60	1.52

Table E.14. The 50<sup>th</sup> 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),  $B_{2017}$  - spawning biomass at the start of 2017,  $V_{2017}$  - vulnerable biomass in the middle of 2017,  $u_{2016}$  - exploitation rate (ratio of total catch to vulnerable biomass) in the middle of 2016,  $u_{max}$  - maximum exploitation rate (calculated for each sample as the maximum exploitation rate from 1940 - 2016),  $B_{MSY}$  - 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(R09)	S1(R08)	S2(R15)	S3(R20)	S4(R14)	S1(R17)	S2(R18)	S3(R19)
$B_0$	89,993	87,245	87,856	92,397	96,338	97,524	74,848	125,119
$V_0$	160,337	155,534	156,331	164,689	170,726	173,515	134,024	221,567
$B_{2017}$	24,302	18,861	19,799	28,968	31,340	33,155	22,110	30,223
$V_{2017}$	47,272	36,794	38,693	56,080	60,355	63,211	43,165	58,554
$B_{2017}/B_0$	0.271	0.217	0.225	0.320	0.331	0.340	0.296	0.250
$V_{2017}/V_0$	0.297	0.237	0.247	0.346	0.356	0.369	0.323	0.271
$u_{2016}$	0.0560	0.0707	0.0673	0.0470	0.0437	0.0417	0.0610	0.0452
$u_{max}$	0.124	0.127	0.127	0.125	0.110	0.107	0.102	0.161
MSY	3,843	3,396	3,542	4,072	4,347	4,446	3,472	4,481
$B_{MSY}$	24,116	24,997	24,772	24,009	26,126	27,103	18,887	38,029
$0.4B_{MSY}$	9,647	9,999	9,909	9,604	10,450	10,841	7,555	15,212
$0.8B_{MSY}$	19,293	19,998	19,818	19,207	20,901	21,682	15,110	30,423
$B_{2017}/B_{MSY}$	1.03	0.748	0.815	1.26	1.22	1.28	1.18	0.831
$B_{MSY}/B_0$	0.269	0.289	0.283	0.260	0.275	0.275	0.254	0.304
$V_{MSY}$	47,982	49,186	48,731	48,419	52,485	54,083	38,170	74,017
$V_{MSY}/V_0$	0.301	0.319	0.312	0.292	0.308	0.310	0.287	0.333
$u_{MSY}$	0.0800	0.0695	0.0730	0.0850	0.0840	0.0840	0.0910	0.0620
$u_{2016}/u_{MSY}$	0.684	1.04	0.933	0.539	0.523	0.485	0.656	0.723



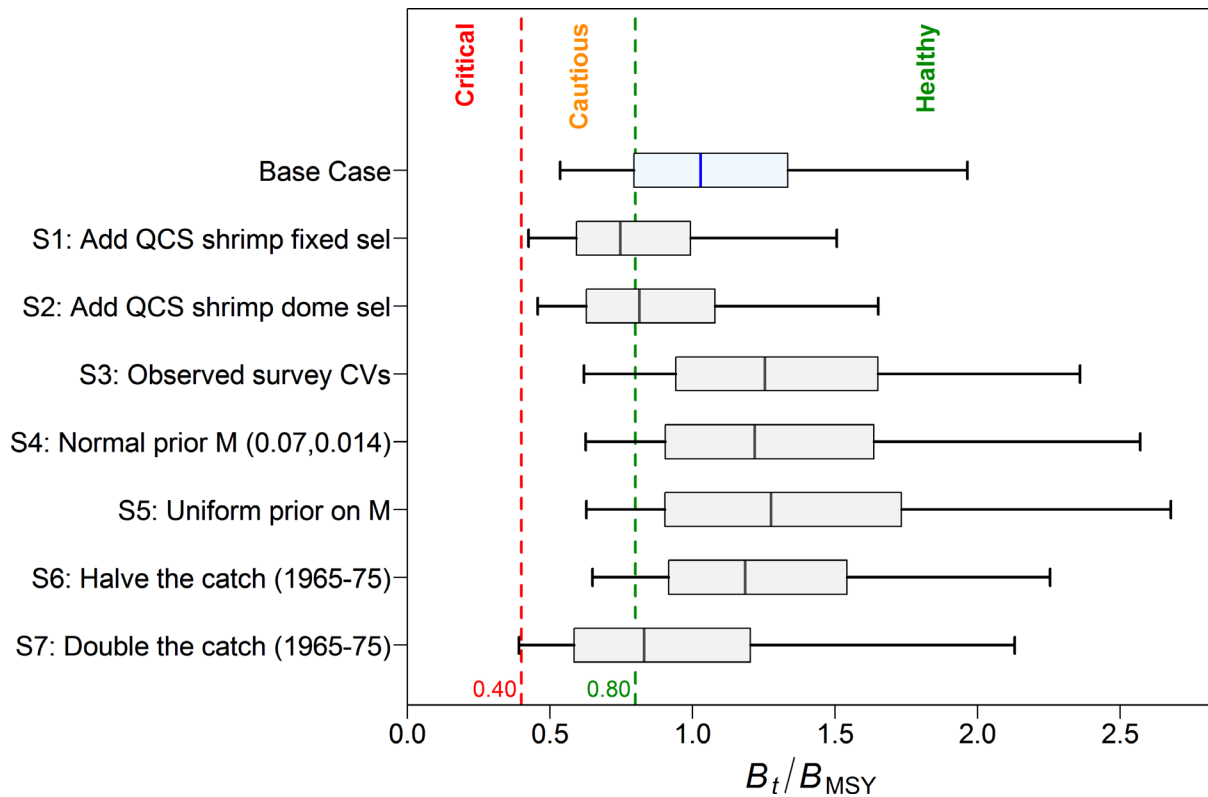


Figure E.39. Status at beginning of 2017 of the 5ABC Pacific Ocean Perch stock relative to the DFO PA provisional reference points of  $0.4B_{MSY}$  and  $0.8B_{MSY}$  for the base-case (Run09) stock assessment and seven sensitivity runs: S1 = (Run08) add the QCS shrimp survey using a fixed selectivity curve; S2 = (Run15) add the QCS shrimp survey using a fitted dome-shaped selectivity curve; S3 = (Run20) use the observed survey CVs without adding process error; S4 = (Run14) use a normal prior on  $M$  with a mean of 0.07 and a standard deviation of 0.014 (CV=20%); S5 = (Run17) use a uniform prior on  $M$ ; S6 = (Run18) halve the catch in the years 1965-75 (during peak foreign fleet activity); S7 = (Run19) double the catch in the years 1965-75. Boxplots show the 5, 25, 50, 75 and 95 quantiles from the MCMC posterior.

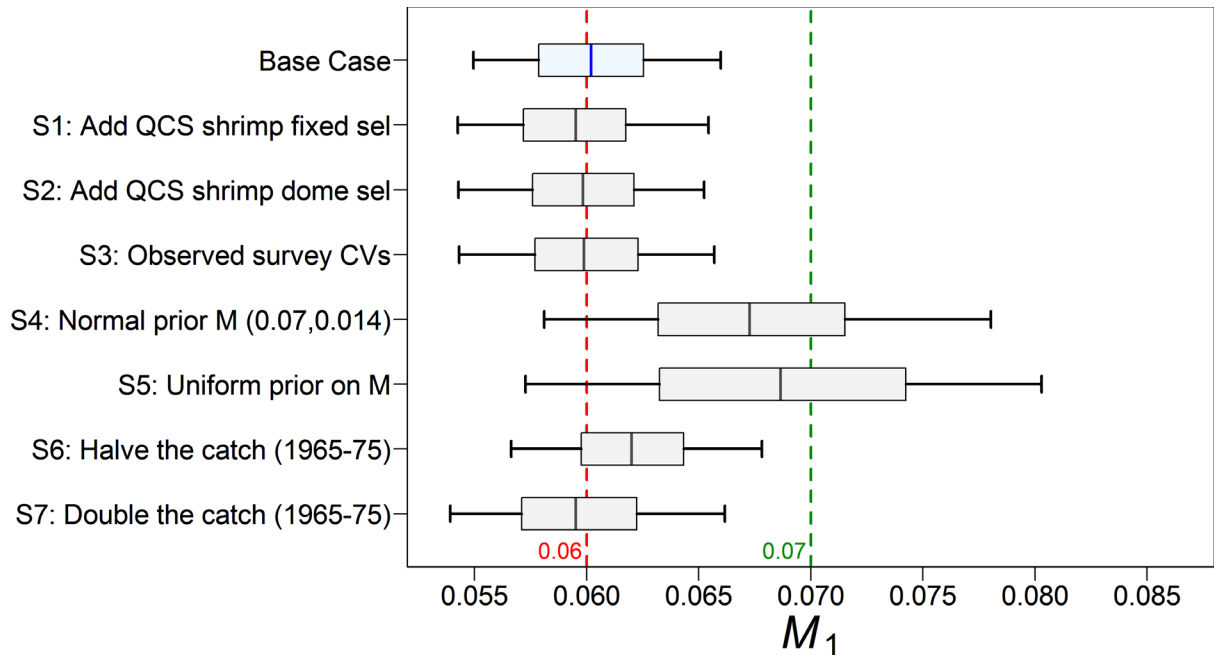


Figure E.40. Estimated female natural mortality ( $M_1$ ) at beginning of 2017 of the 5ABC Pacific Ocean Perch stock for the Base Case and seven sensitivity runs (see Figure E.39 caption for details).

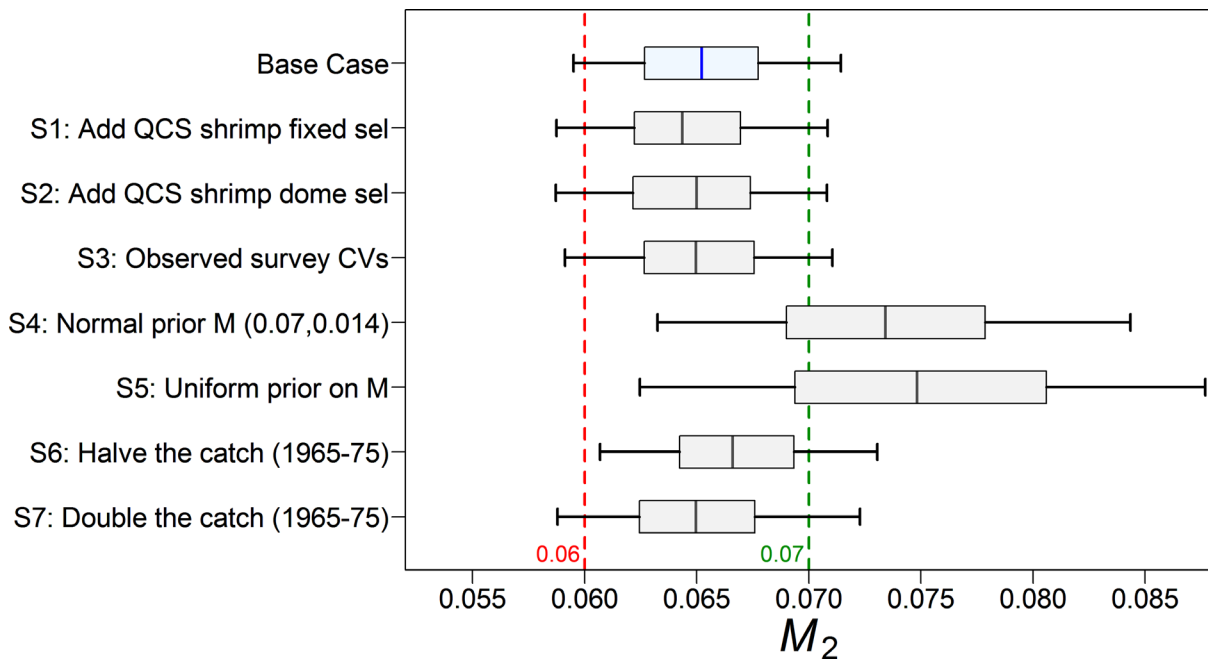


Figure E.41. Estimated male natural mortality ( $M_2$ ) at beginning of 2017 of the 5ABC Pacific Ocean Perch stock for the Base Case and seven sensitivity runs (see Figure E.39 caption for details).

## Pacific Ocean Perch Selectivity

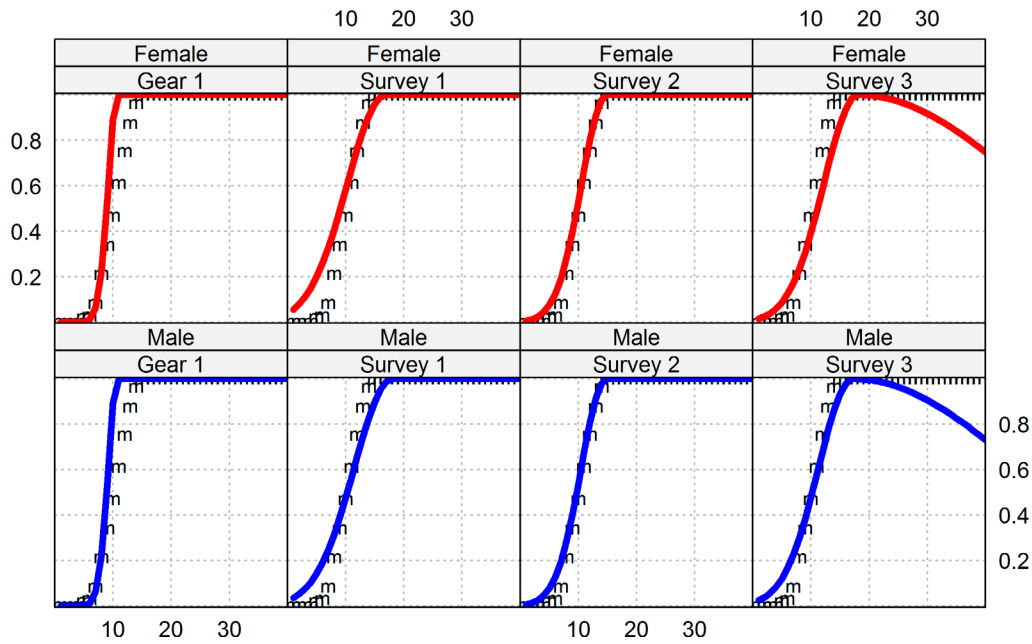


Figure E.42. Sensitivity 2: Selectivities for commercial catch (Gear 1: Bottom Trawl) and surveys (all MPD values), with maturity ogive for females indicated by 'm'.

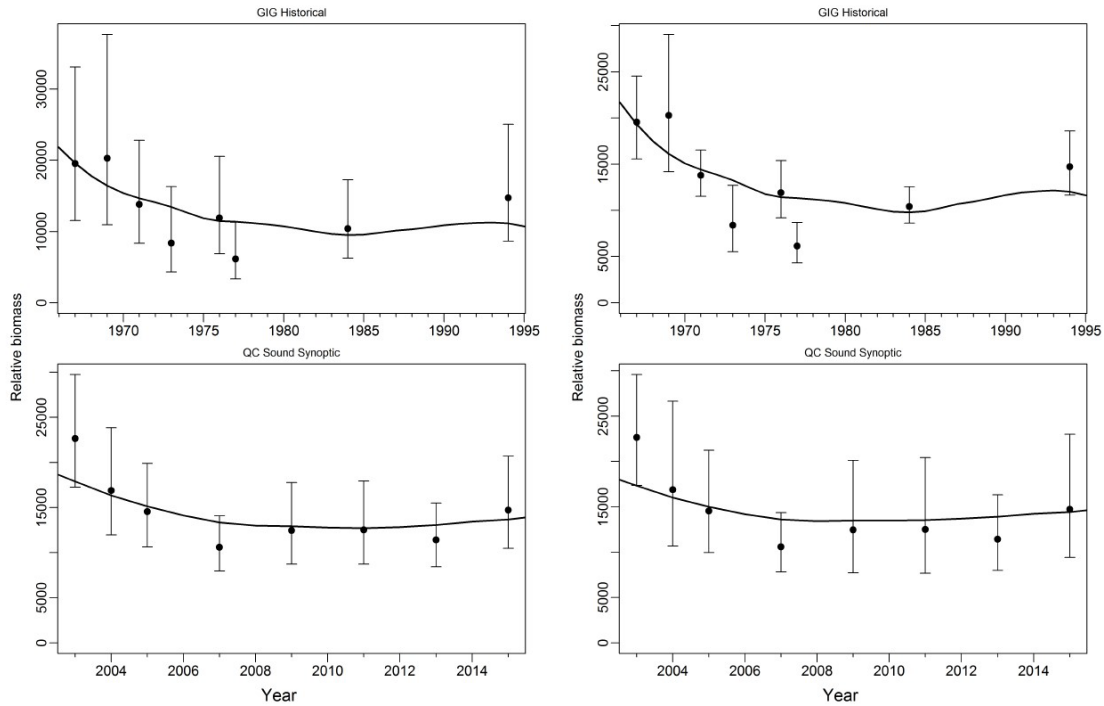


Figure E.43. Sensitivity 3: Survey index values (points) with 95% confidence intervals (bars) and MPD model fits (curves) for the fishery-independent survey series. Left: Base Case, Right: Sensitivity 3

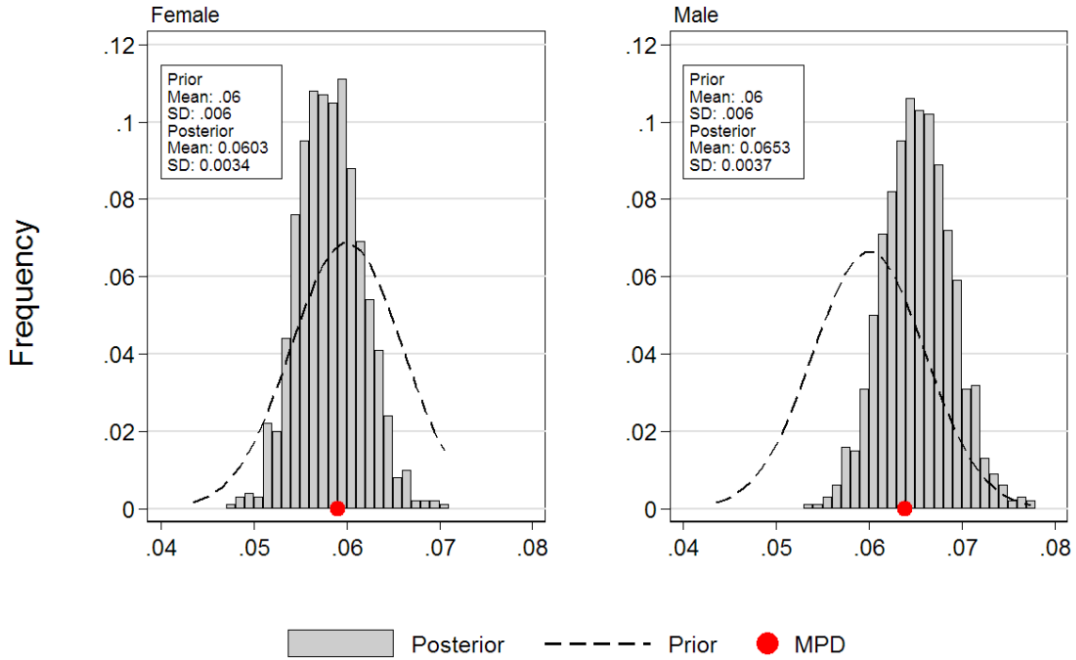


Figure E.44. Base Case: Natural mortality distributions for  $M_1$  (females) and  $M_2$  (males) comparing the means and standard deviations between the prior and posterior distributions for each sex. The MPD value is indicated by a filled red circle.

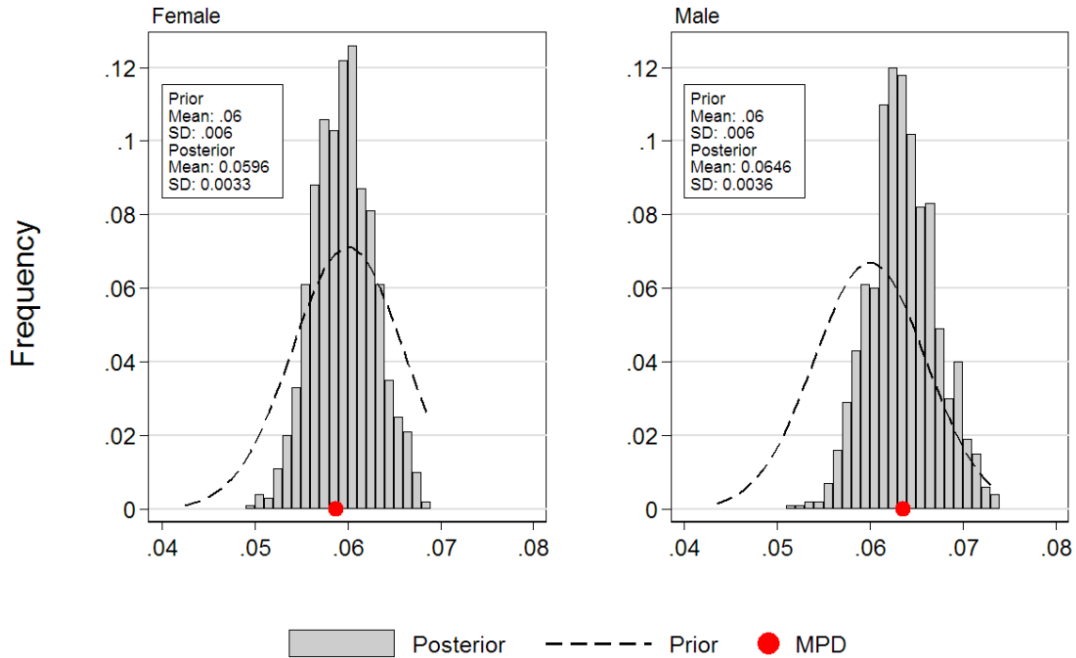


Figure E.45. Sensitivity 1: Natural mortality distributions for  $M_1$  (females) and  $M_2$  (males) comparing the means and standard deviations between the prior and posterior distributions for each sex. The MPD value is indicated by a filled red circle.

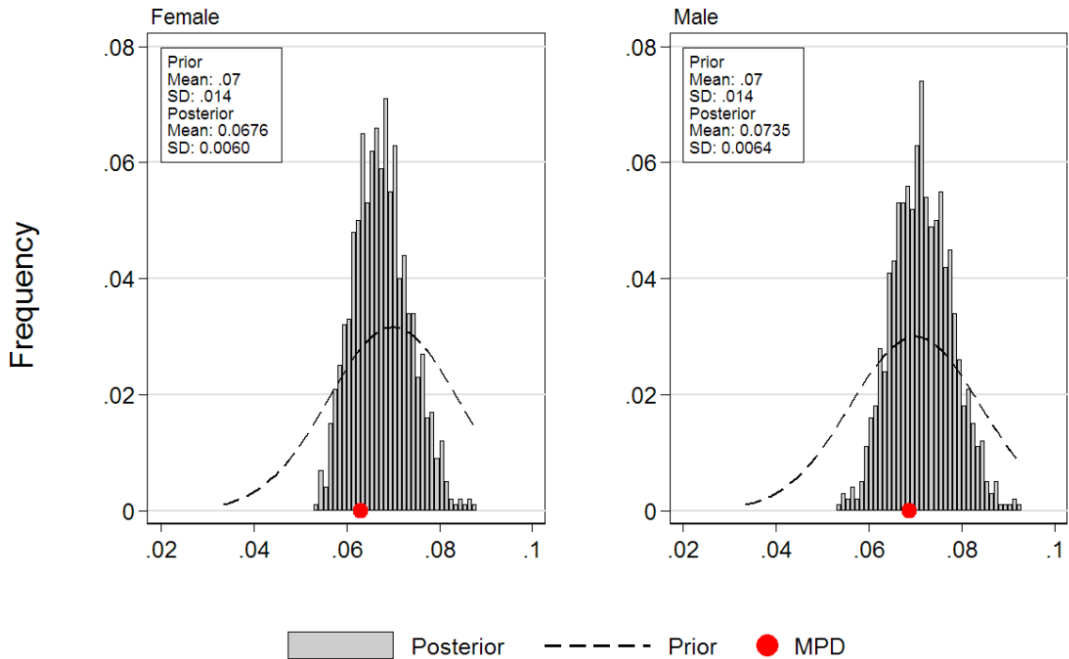


Figure E.46. Sensitivity 4: Natural mortality distributions for  $M_1$  (females) and  $M_2$  (males) comparing the means and standard deviations between the prior and posterior distributions for each sex. The MPD value is indicated by a filled red circle.

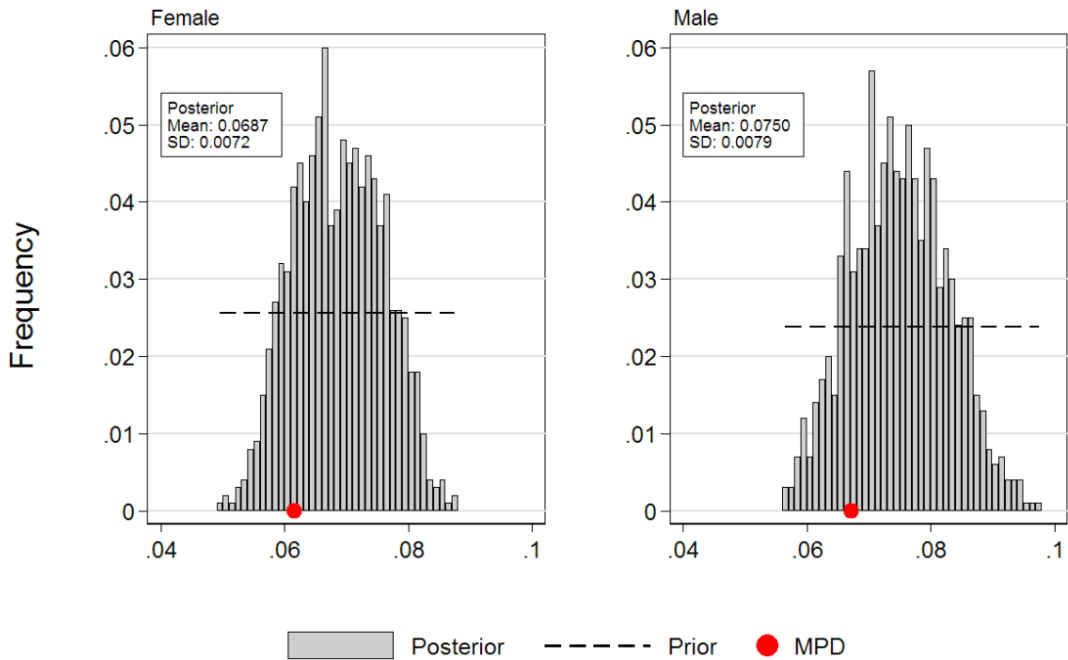


Figure E.47. Sensitivity 5: Natural mortality distributions for  $M_1$  (females) and  $M_2$  (males) comparing the means and standard deviations between the prior and posterior distributions for each sex. The MPD value is indicated by a filled red circle.

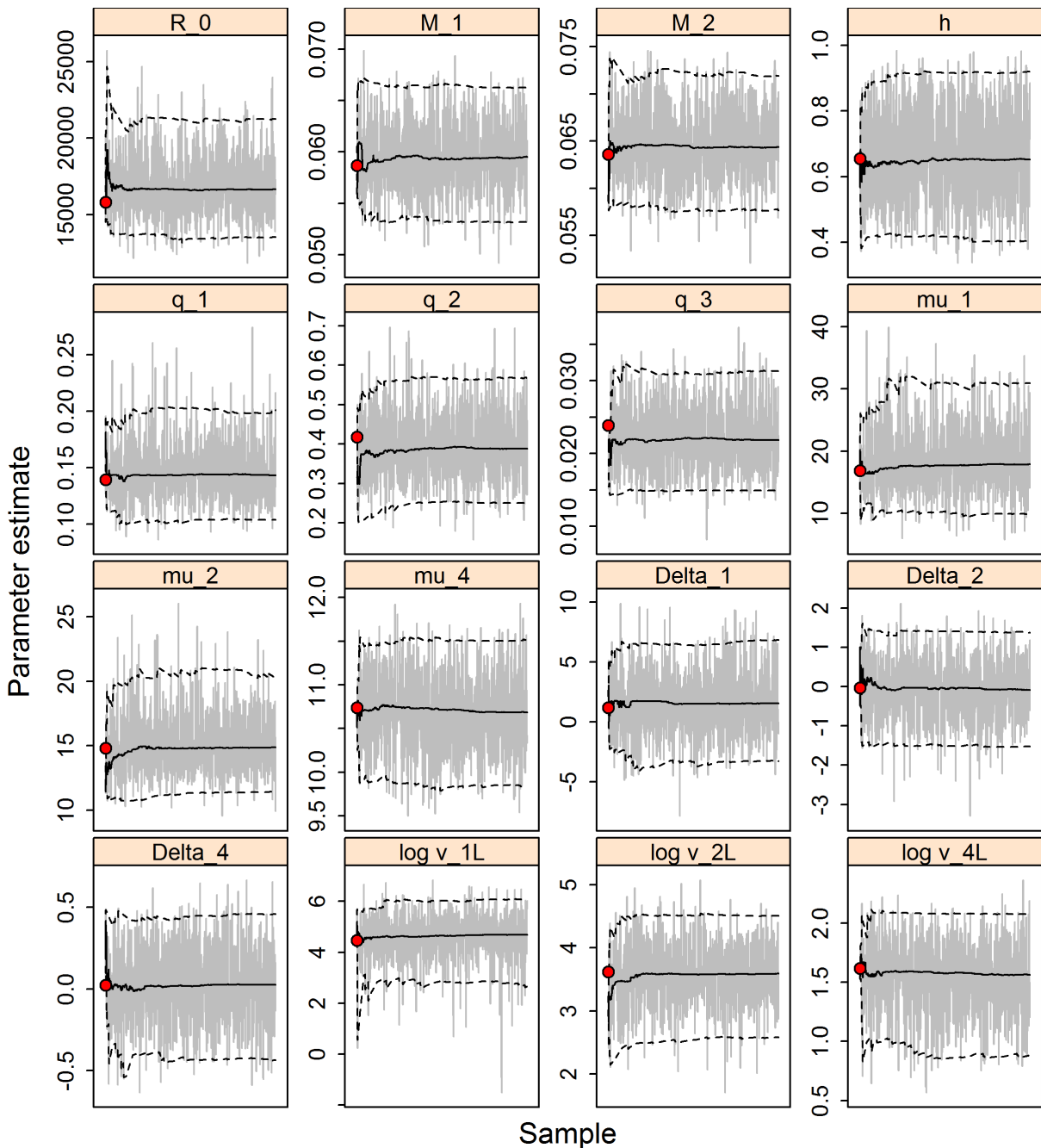


Figure E.48. Sensitivity 1: MCMC traces for the estimated parameters. Grey lines show the 1,000 samples for each parameter, solid lines show the cumulative median (up to that sample), and dashed lines show the cumulative 2.5 and 97.5 quantiles. Red circles are the MPD estimates. For parameters other than  $M$  (if estimated), subscripts  $\leq 3$  correspond to fishery-independent surveys, and subscripts  $\geq 4$  denote the commercial fishery. Parameter notation is described in Appendix D.

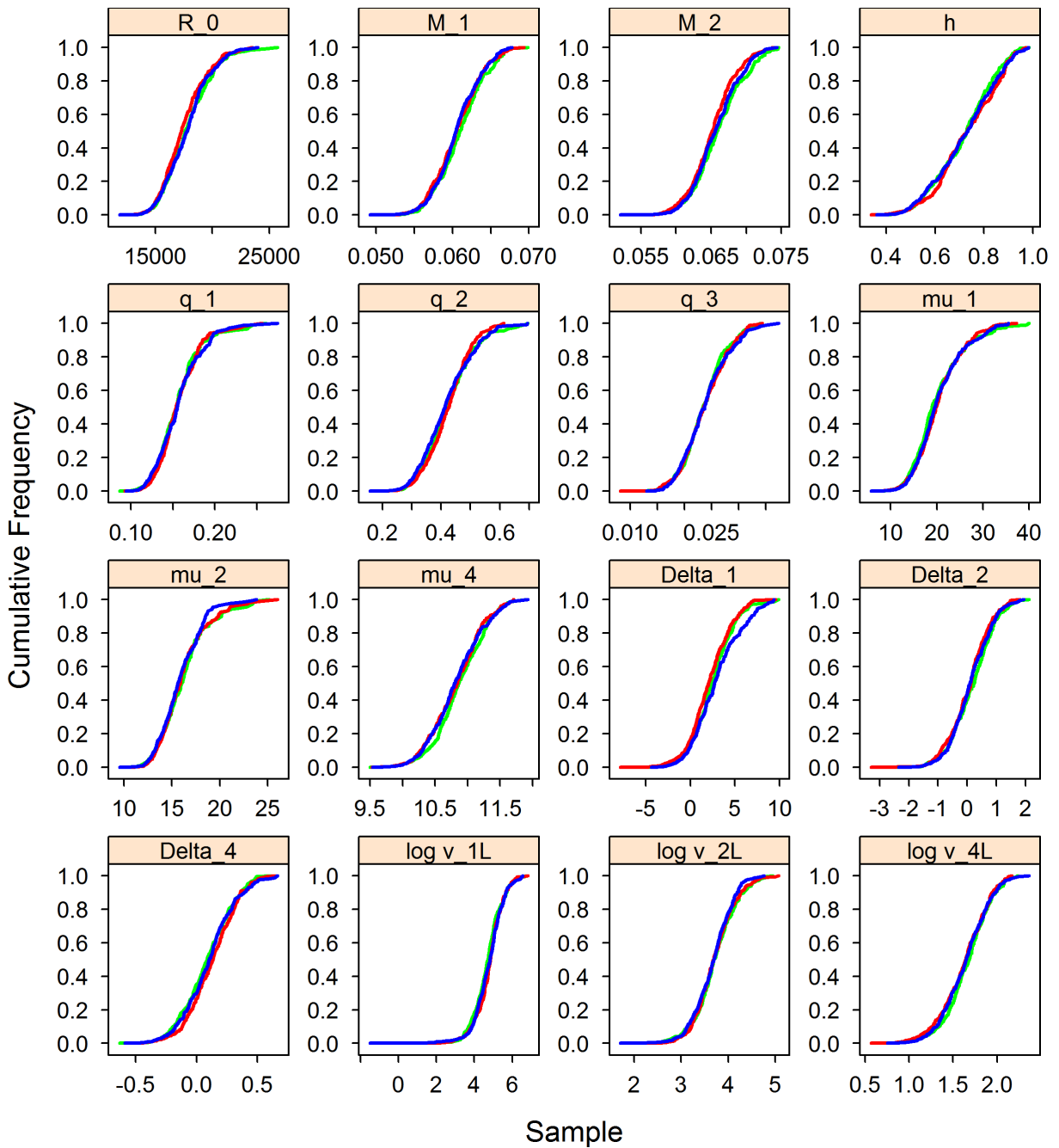


Figure E.49. Sensitivity 1: Diagnostic plot obtained by dividing the MCMC chain of 1,000 MCMC samples into three segments, and overplotting the cumulative distributions of the first segment (green), second segment (red) and final segment (blue).

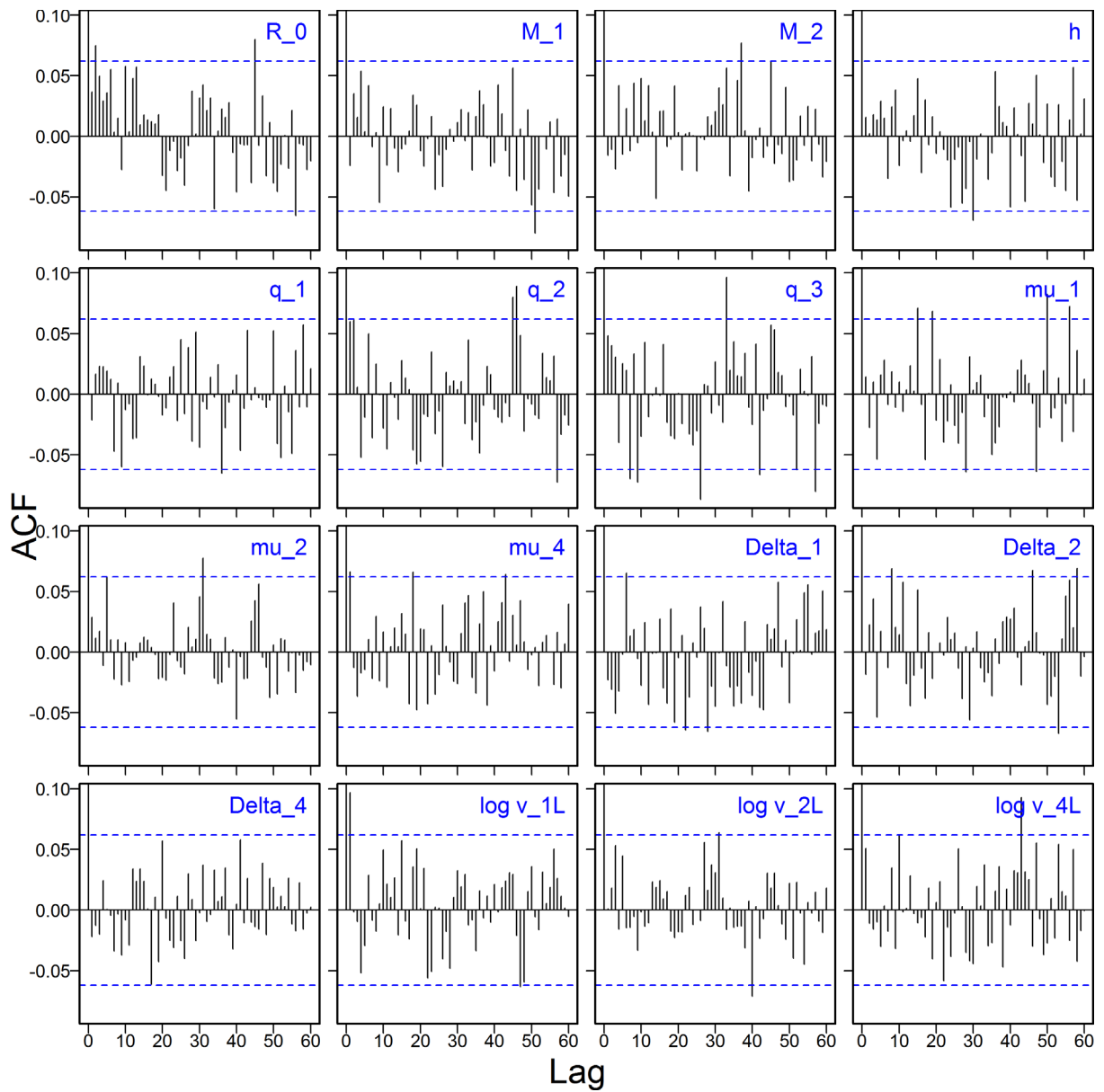


Figure E.50. Sensitivity 1: Autocorrelation plots for the estimated parameters from the MCMC output. Horizontal dashed blue lines delimit the 95% confidence interval for each parameter's set of lagged correlations.



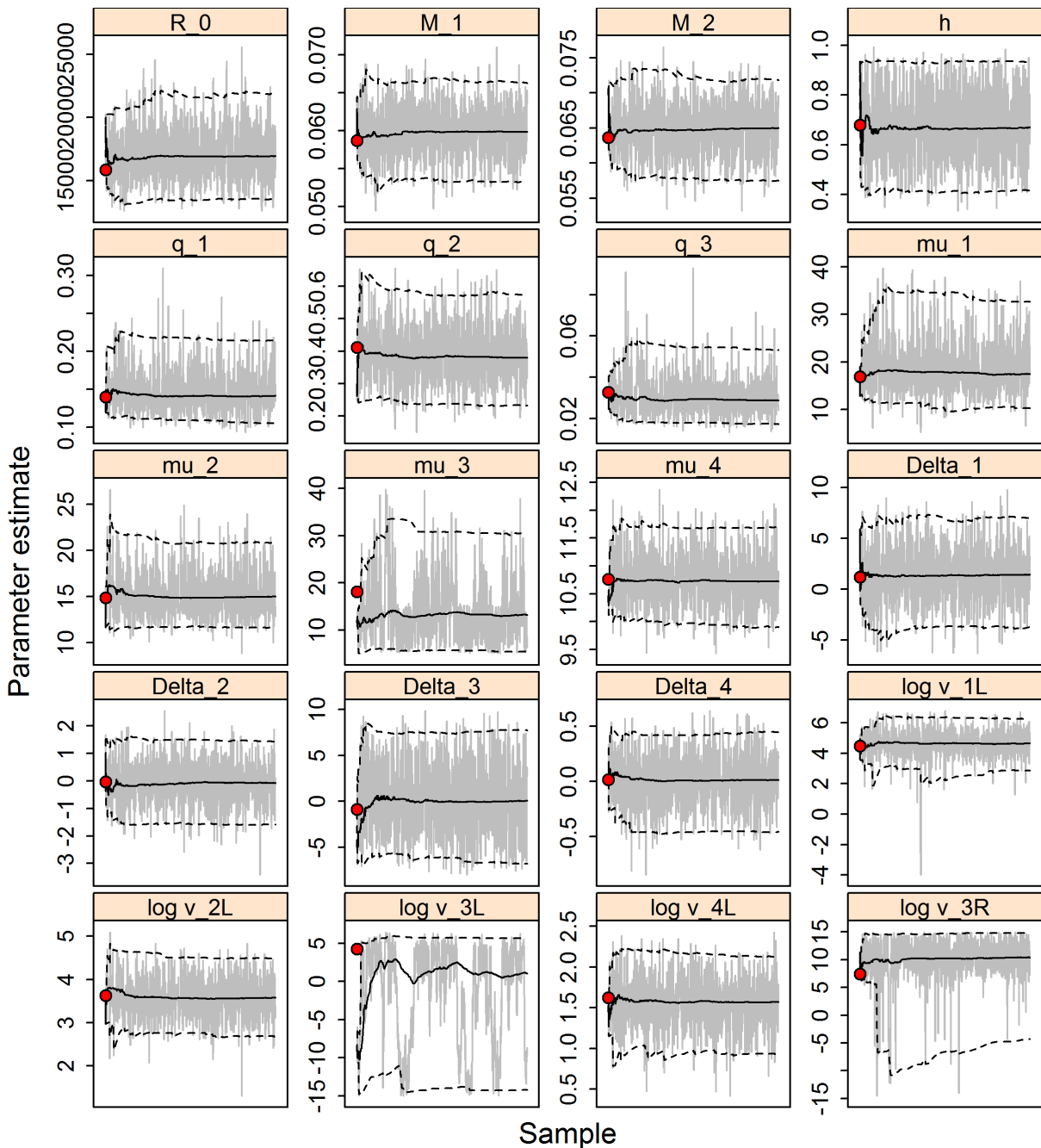


Figure E.51. Sensitivity 2: MCMC traces for the estimated parameters. Grey lines show the 1,000 samples for each parameter, solid lines show the cumulative median (up to that sample), and dashed lines show the cumulative 2.5 and 97.5 quantiles. Red circles are the MPD estimates. For parameters other than  $M$  (if estimated), subscripts  $\leq 3$  correspond to fishery-independent surveys, and subscripts  $\geq 4$  denote the commercial fishery. Parameter notation is described in Appendix D.

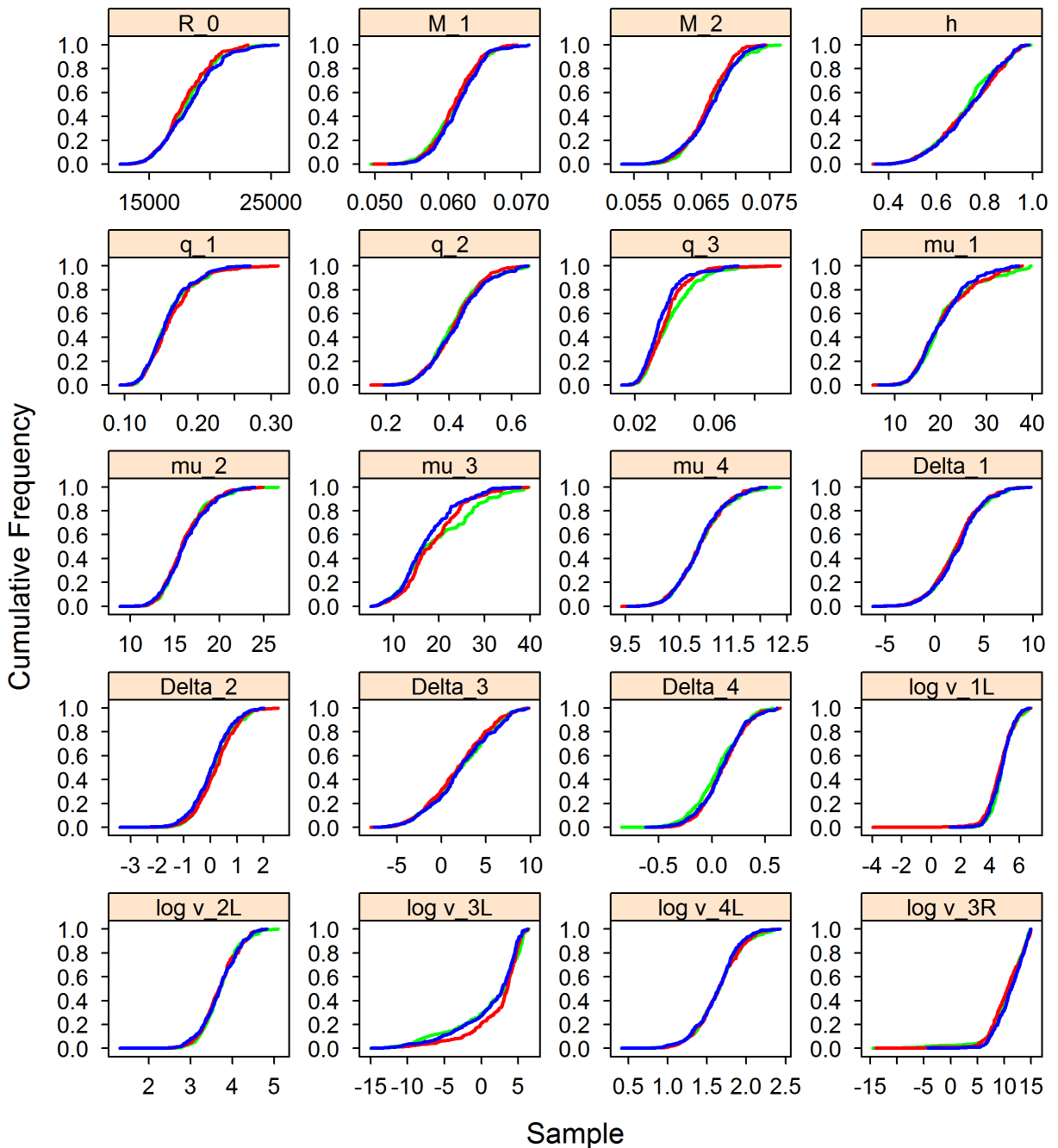


Figure E.52. Sensitivity 2: Diagnostic plot obtained by dividing the MCMC chain of 1,000 MCMC samples into three segments, and overplotting the cumulative distributions of the first segment (green), second segment (red) and final segment (blue).

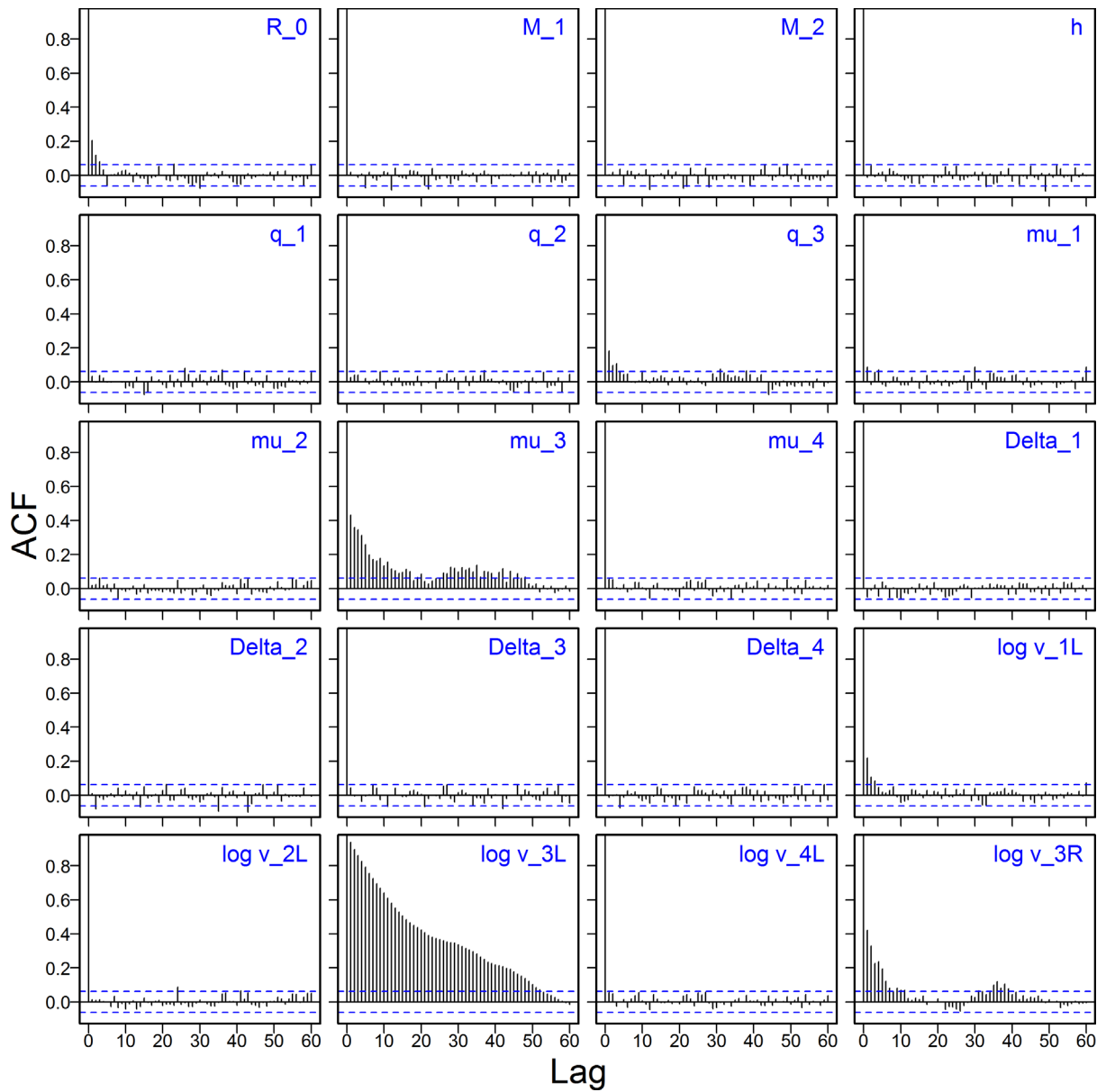


Figure E.53. Sensitivity 2: Autocorrelation plots for the estimated parameters from the MCMC output. Horizontal dashed blue lines delimit the 95% confidence interval for each parameter's set of lagged correlations.

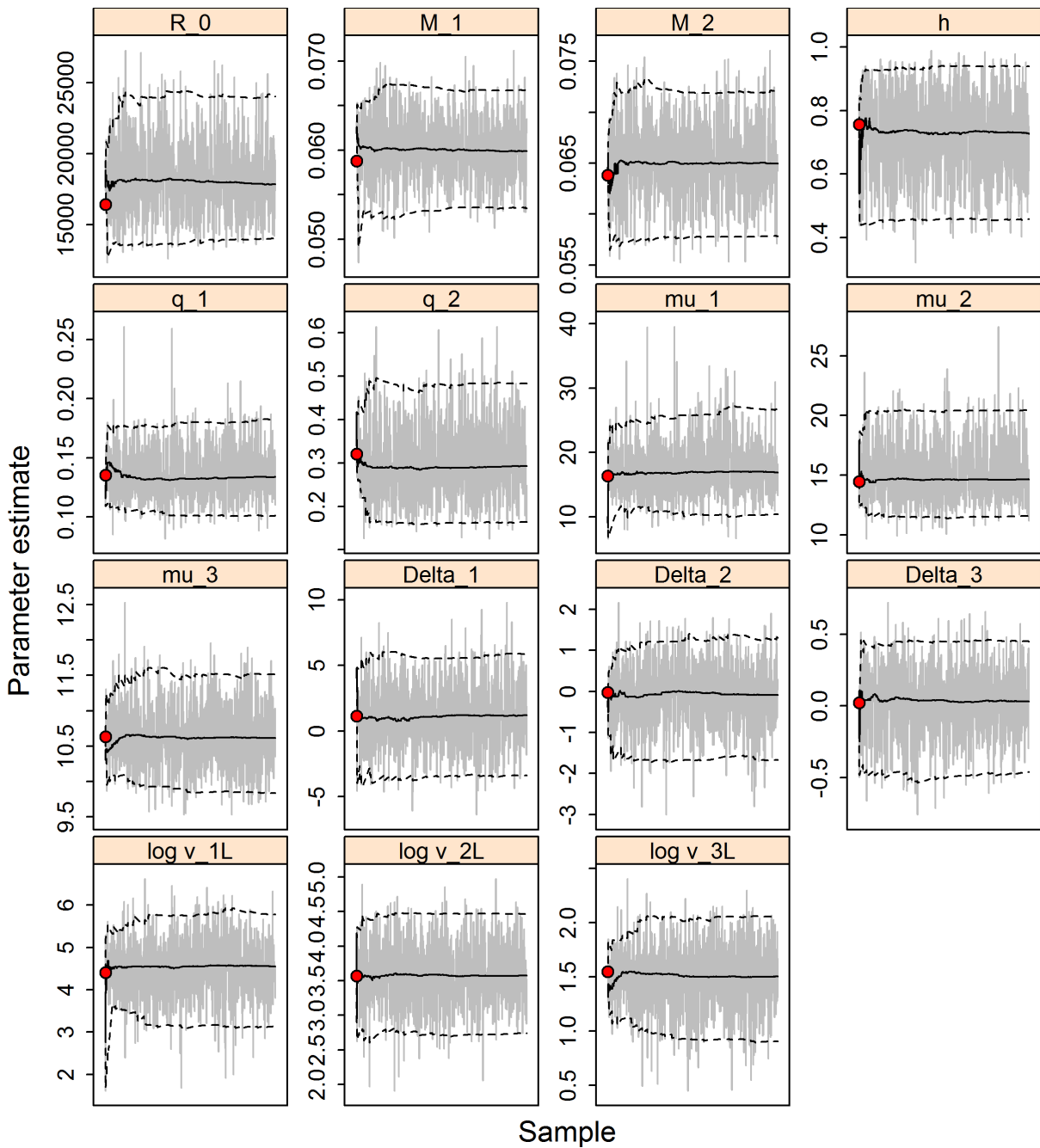


Figure E.54. Sensitivity 3: MCMC traces for the estimated parameters. Grey lines show the 1,000 samples for each parameter, solid lines show the cumulative median (up to that sample), and dashed lines show the cumulative 2.5 and 97.5 quantiles. Red circles are the MPD estimates. For parameters other than  $M$  (if estimated), subscripts  $\leq 2$  correspond to fishery-independent surveys, and subscripts  $\geq 3$  denote the commercial fishery. Parameter notation is described in Appendix D.

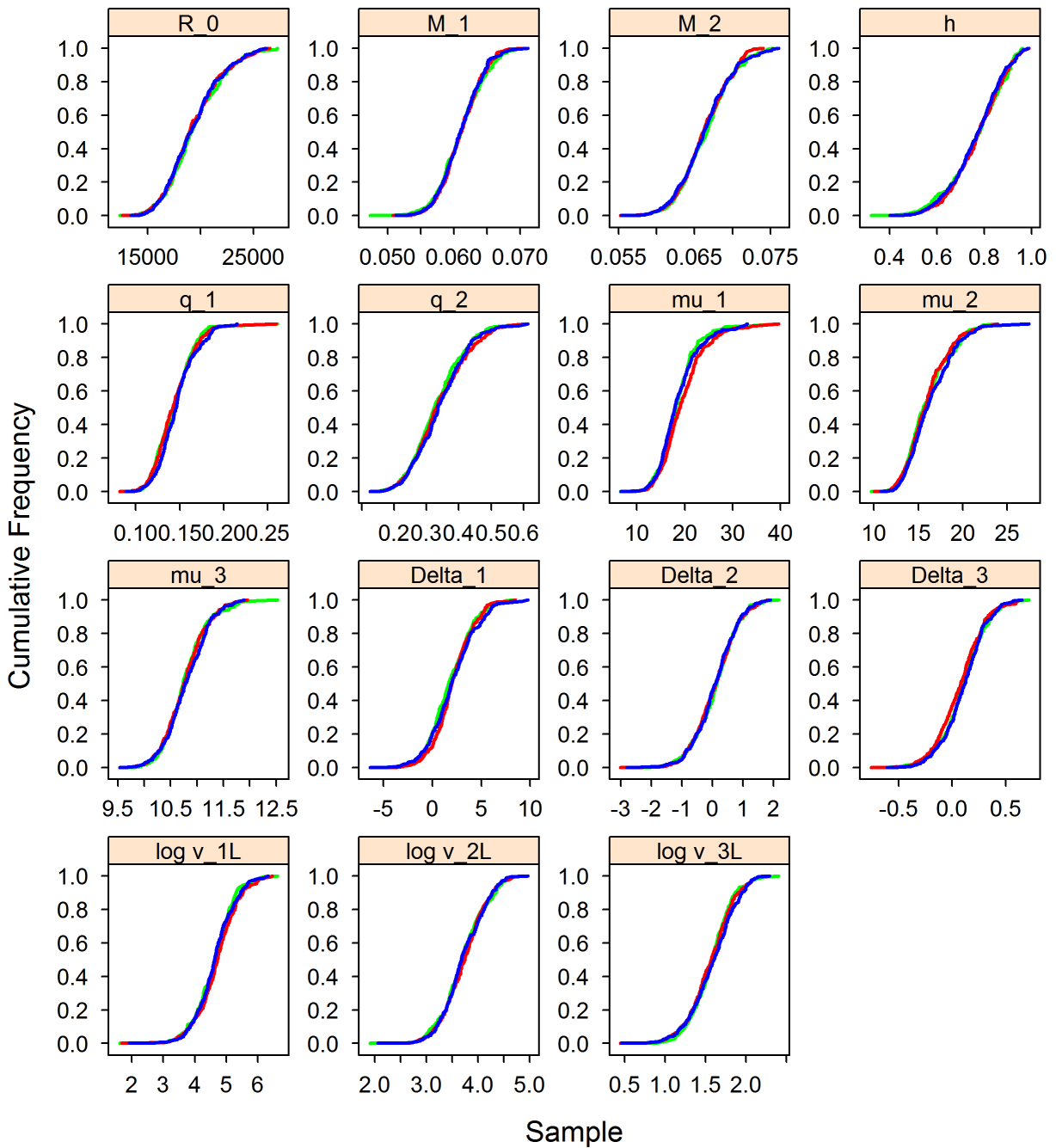


Figure E.55. Sensitivity 3: Diagnostic plot obtained by dividing the MCMC chain of 1,000 MCMC samples into three segments, and overplotting the cumulative distributions of the first segment (green), second segment (red) and final segment (blue).

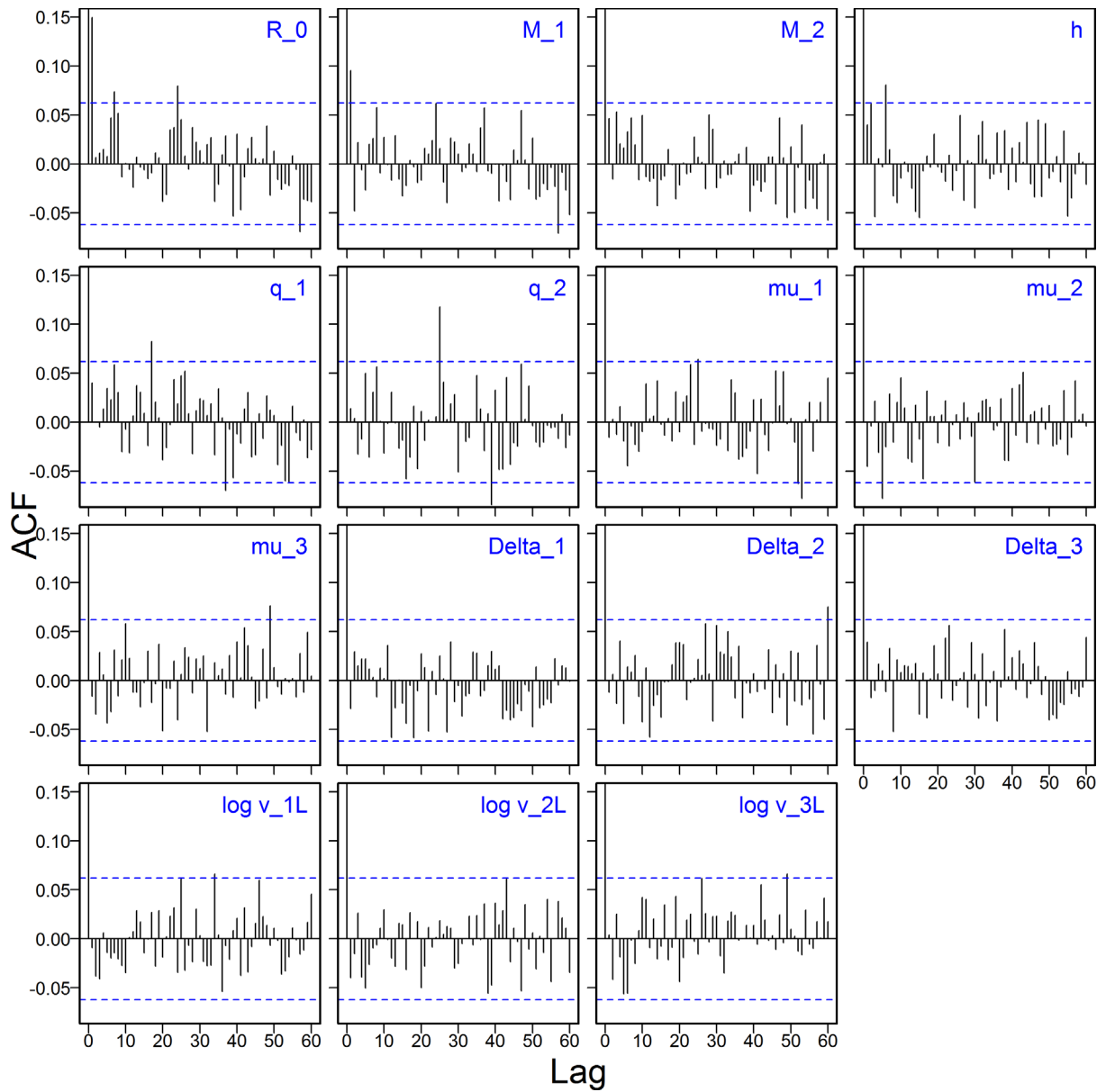


Figure E.56. Sensitivity 3: Autocorrelation plots for the estimated parameters from the MCMC output. Horizontal dashed blue lines delimit the 95% confidence interval for each parameter's set of lagged correlations.

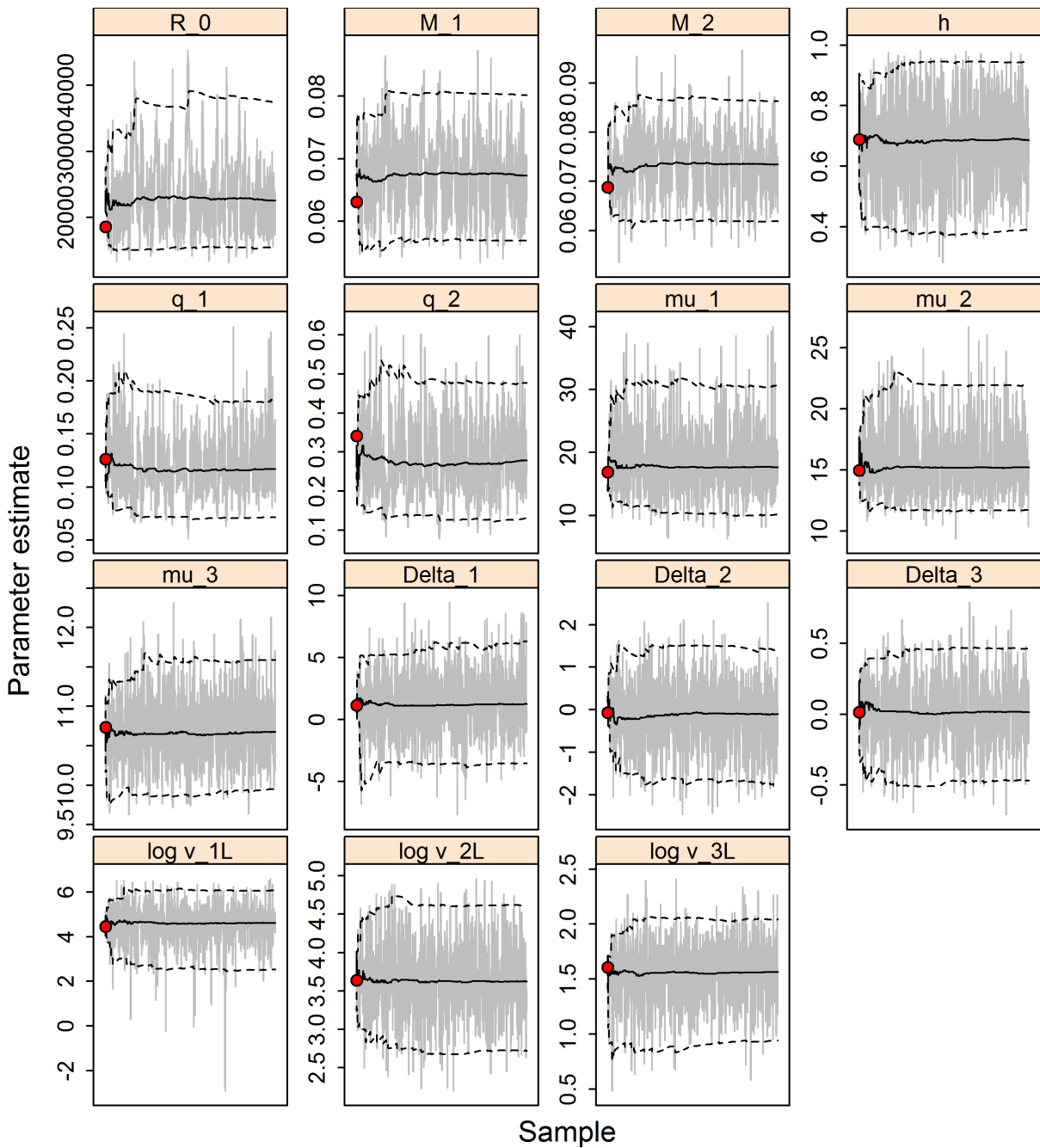


Figure E.57. Sensitivity 4: MCMC traces for the estimated parameters. Grey lines show the 1,000 samples for each parameter, solid lines show the cumulative median (up to that sample), and dashed lines show the cumulative 2.5 and 97.5 quantiles. Red circles are the MPD estimates. For parameters other than  $M$  (if estimated), subscripts  $\leq 2$  correspond to fishery-independent surveys, and subscripts  $\geq 3$  denote the commercial fishery. Parameter notation is described in Appendix D.

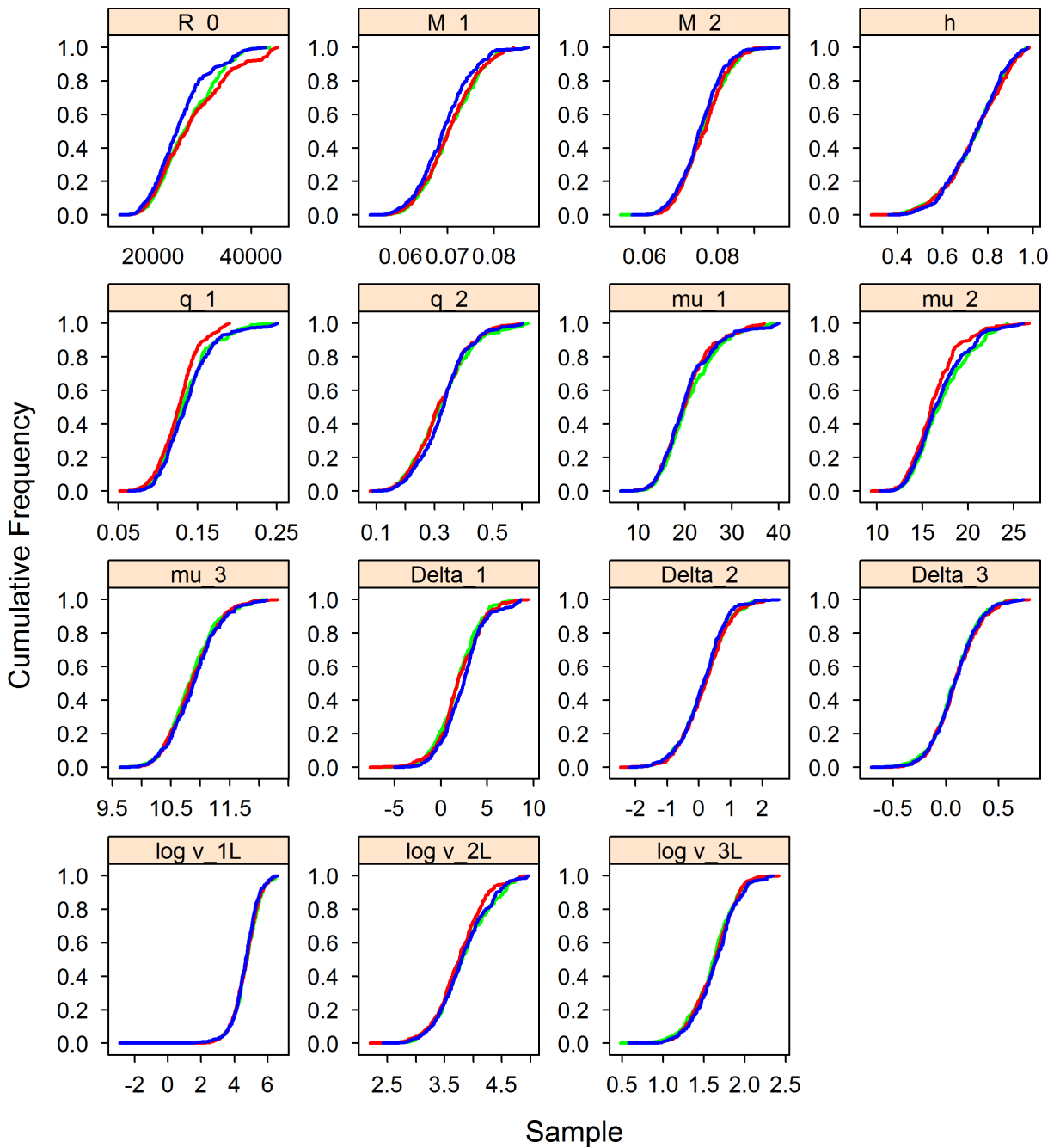


Figure E.58. Sensitivity 4: Diagnostic plot obtained by dividing the MCMC chain of 1,000 MCMC samples into three segments, and overplotting the cumulative distributions of the first segment (green), second segment (red) and final segment (blue).



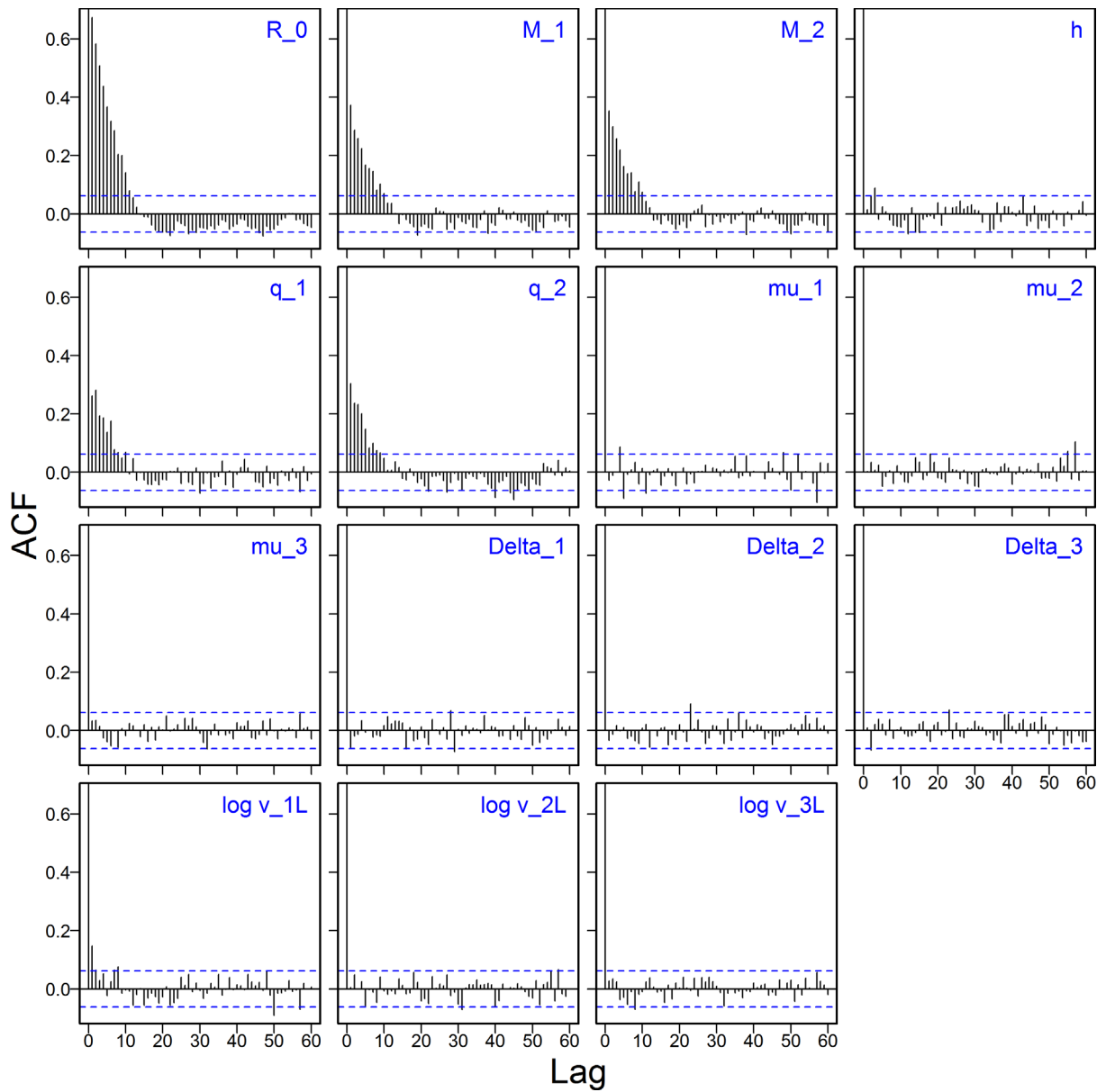


Figure E.59. Sensitivity 4: Autocorrelation plots for the estimated parameters from the MCMC output. Horizontal dashed blue lines delimit the 95% confidence interval for each parameter's set of lagged correlations.

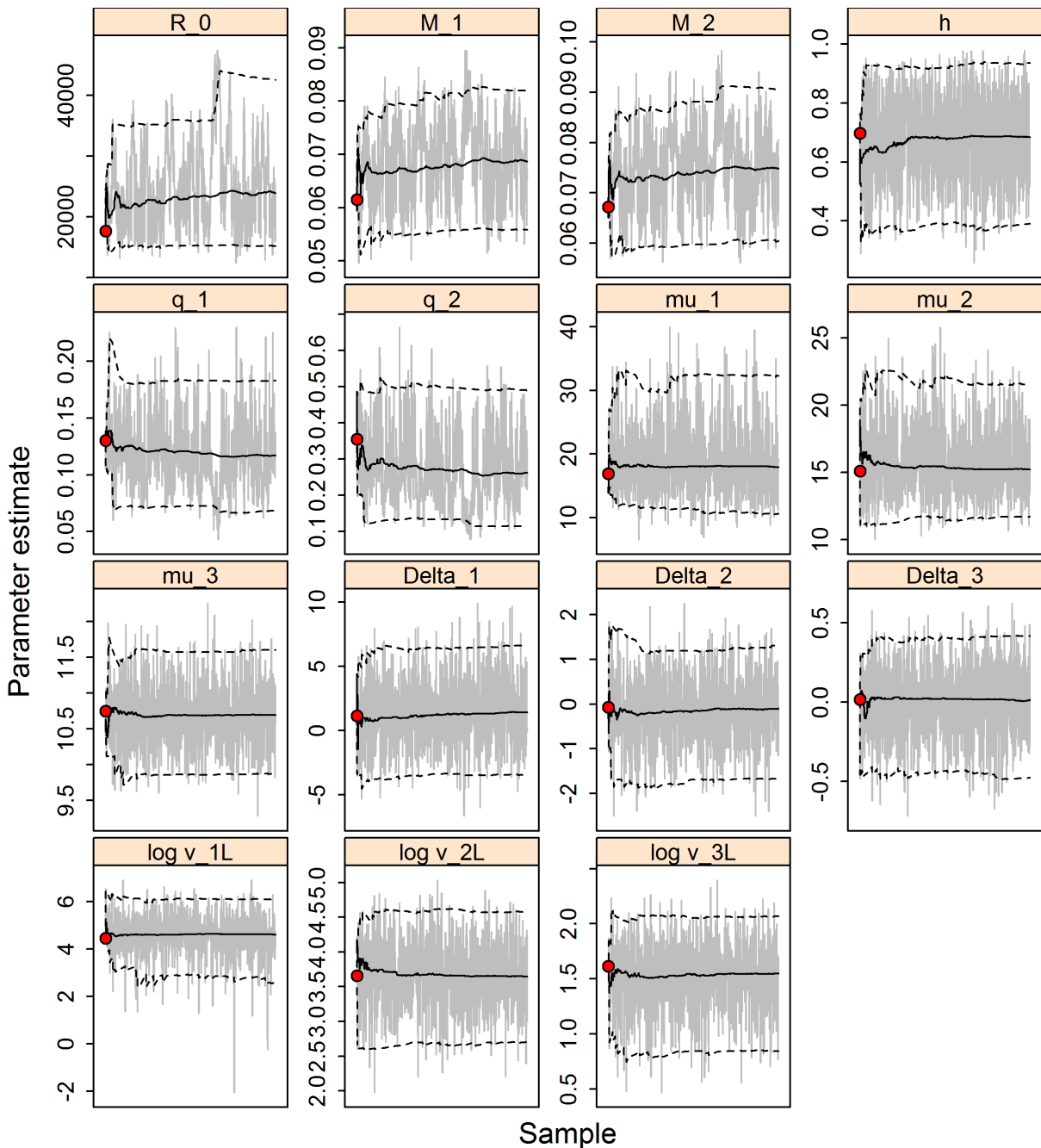


Figure E.60. Sensitivity 5: MCMC traces for the estimated parameters. Grey lines show the 1,000 samples for each parameter, solid lines show the cumulative median (up to that sample), and dashed lines show the cumulative 2.5 and 97.5 quantiles. Red circles are the MPD estimates. For parameters other than  $M$  (if estimated), subscripts  $\leq 2$  correspond to fishery-independent surveys, and subscripts  $\geq 3$  denote the commercial fishery. Parameter notation is described in Appendix D.

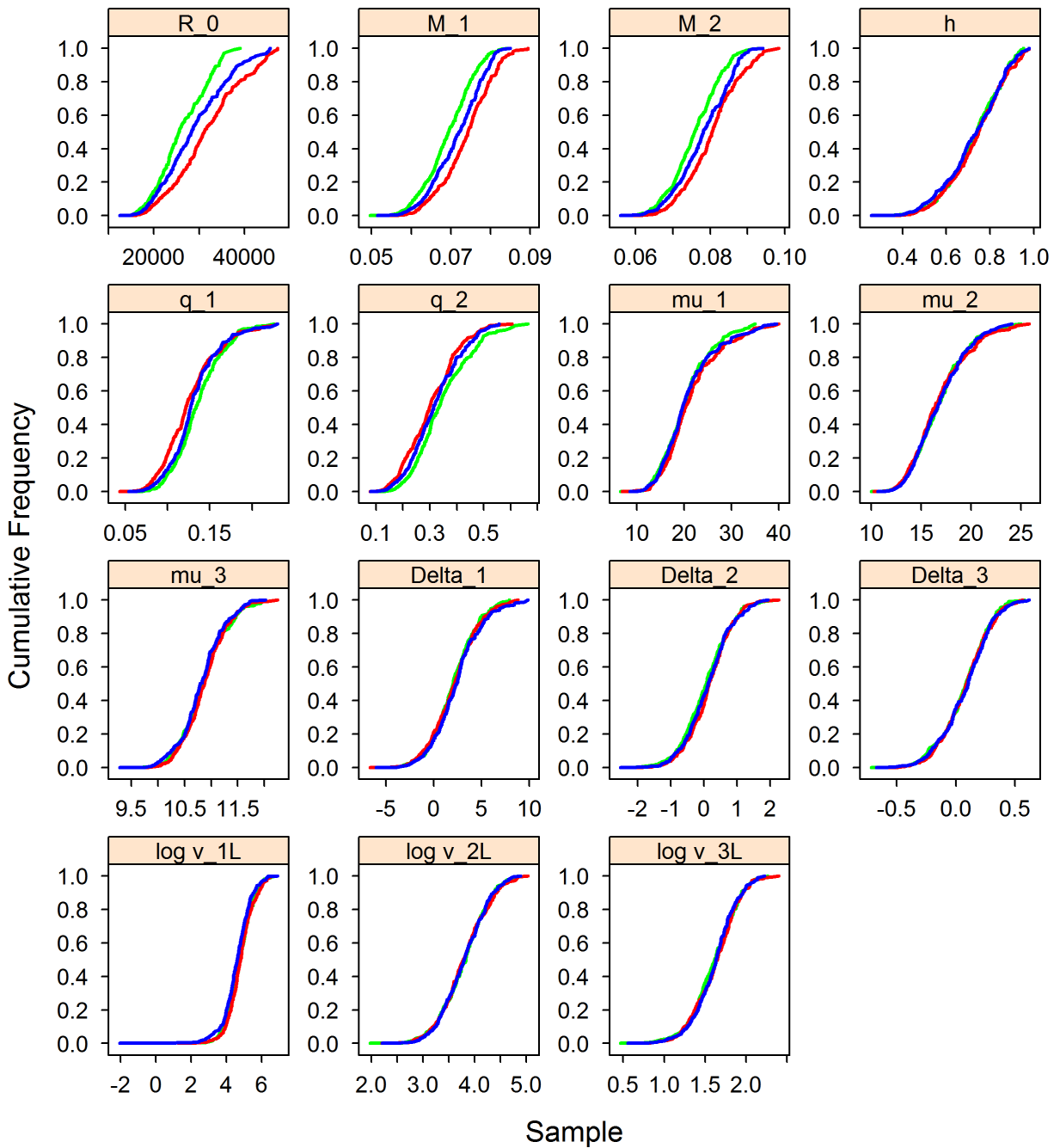


Figure E.61. Sensitivity 5: Diagnostic plot obtained by dividing the MCMC chain of 1,000 MCMC samples into three segments, and overplotting the cumulative distributions of the first segment (green), second segment (red) and final segment (blue).

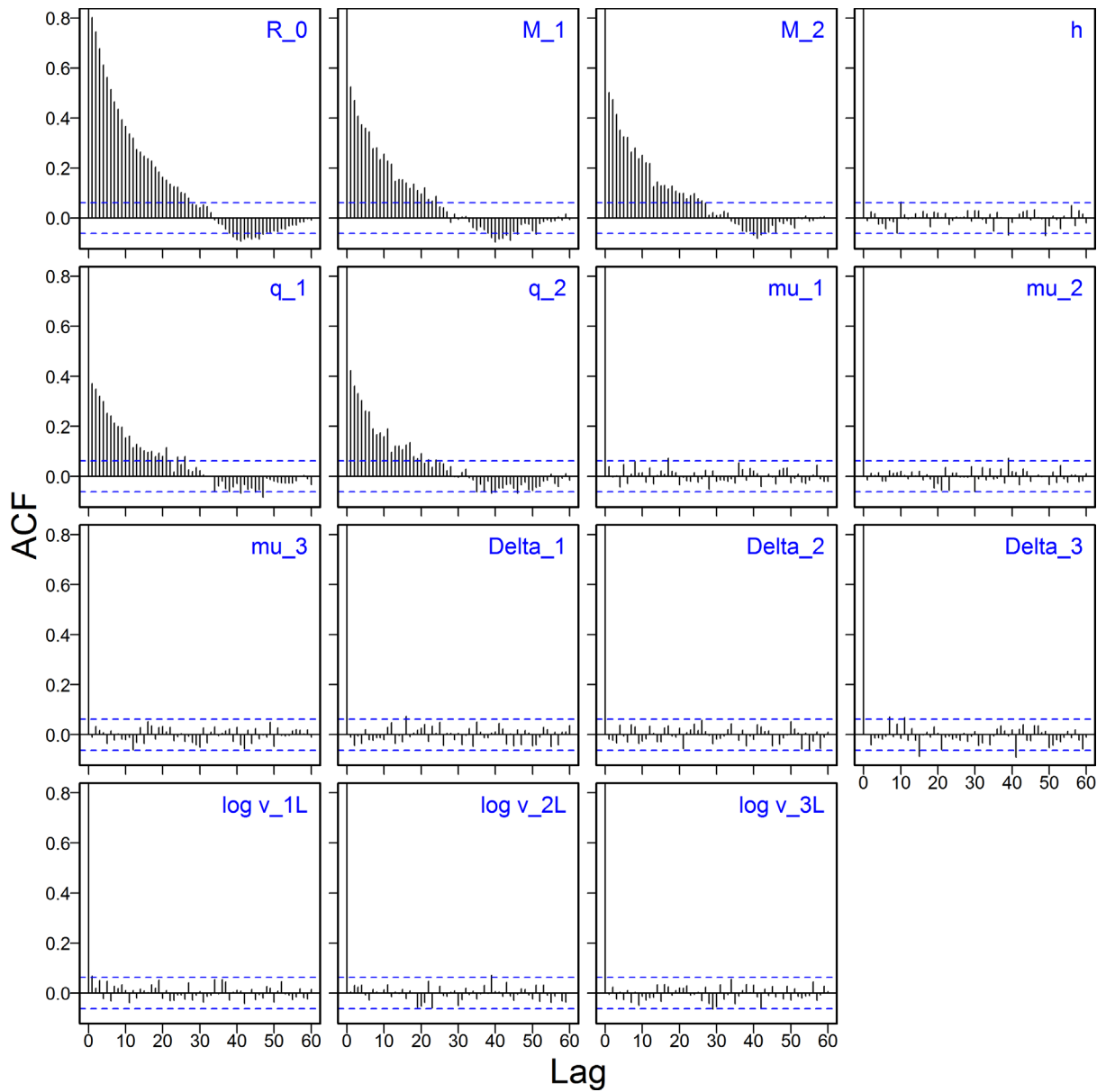


Figure E.62. Sensitivity 5: Autocorrelation plots for the estimated parameters from the MCMC output. Horizontal dashed blue lines delimit the 95% confidence interval for each parameter's set of lagged correlations.

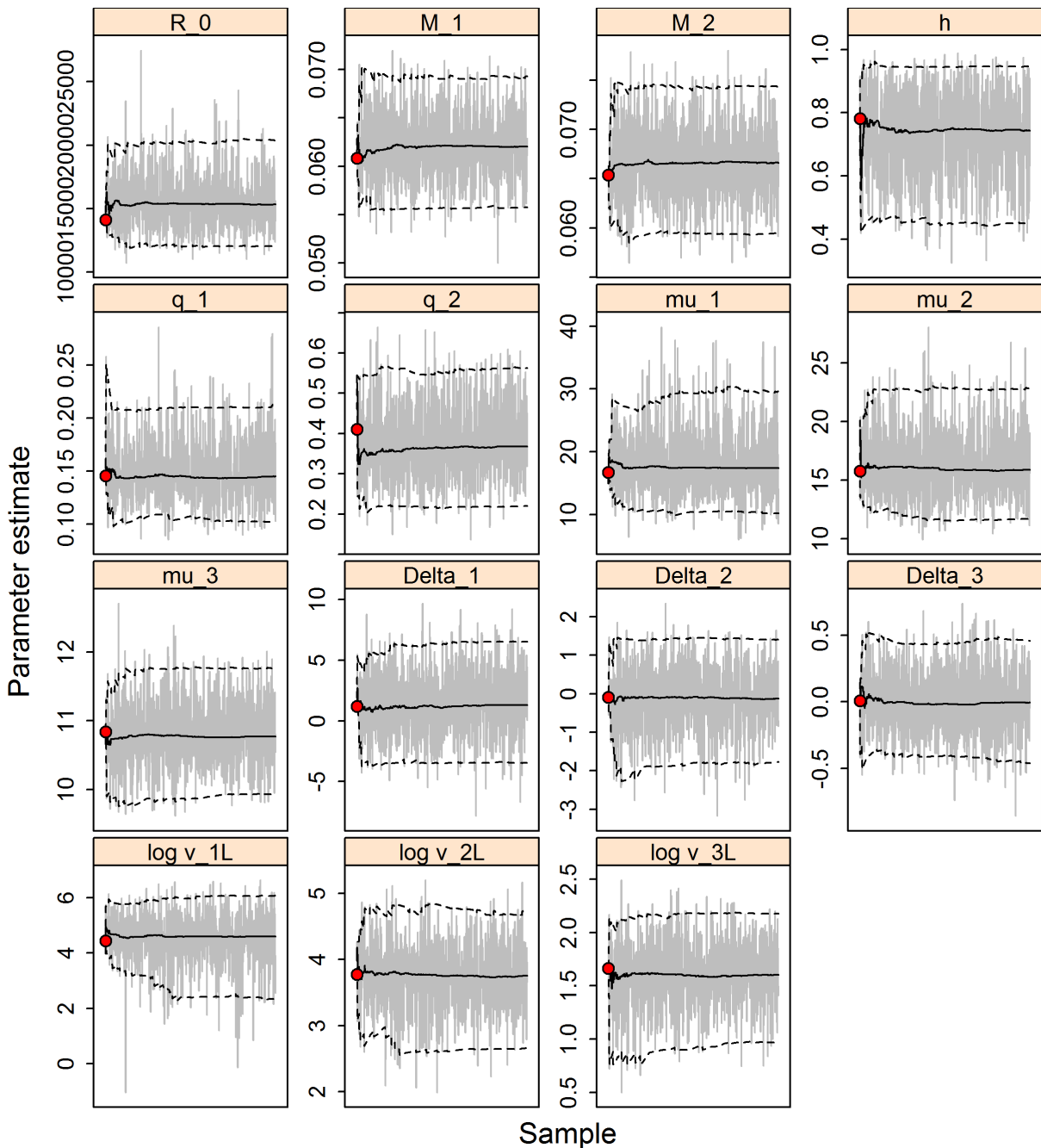


Figure E.63. Sensitivity 6: MCMC traces for the estimated parameters. Grey lines show the 1,000 samples for each parameter, solid lines show the cumulative median (up to that sample), and dashed lines show the cumulative 2.5 and 97.5 quantiles. Red circles are the MPD estimates. For parameters other than  $M$  (if estimated), subscripts  $\leq 2$  correspond to fishery-independent surveys, and subscripts  $\geq 3$  denote the commercial fishery. Parameter notation is described in Appendix D.

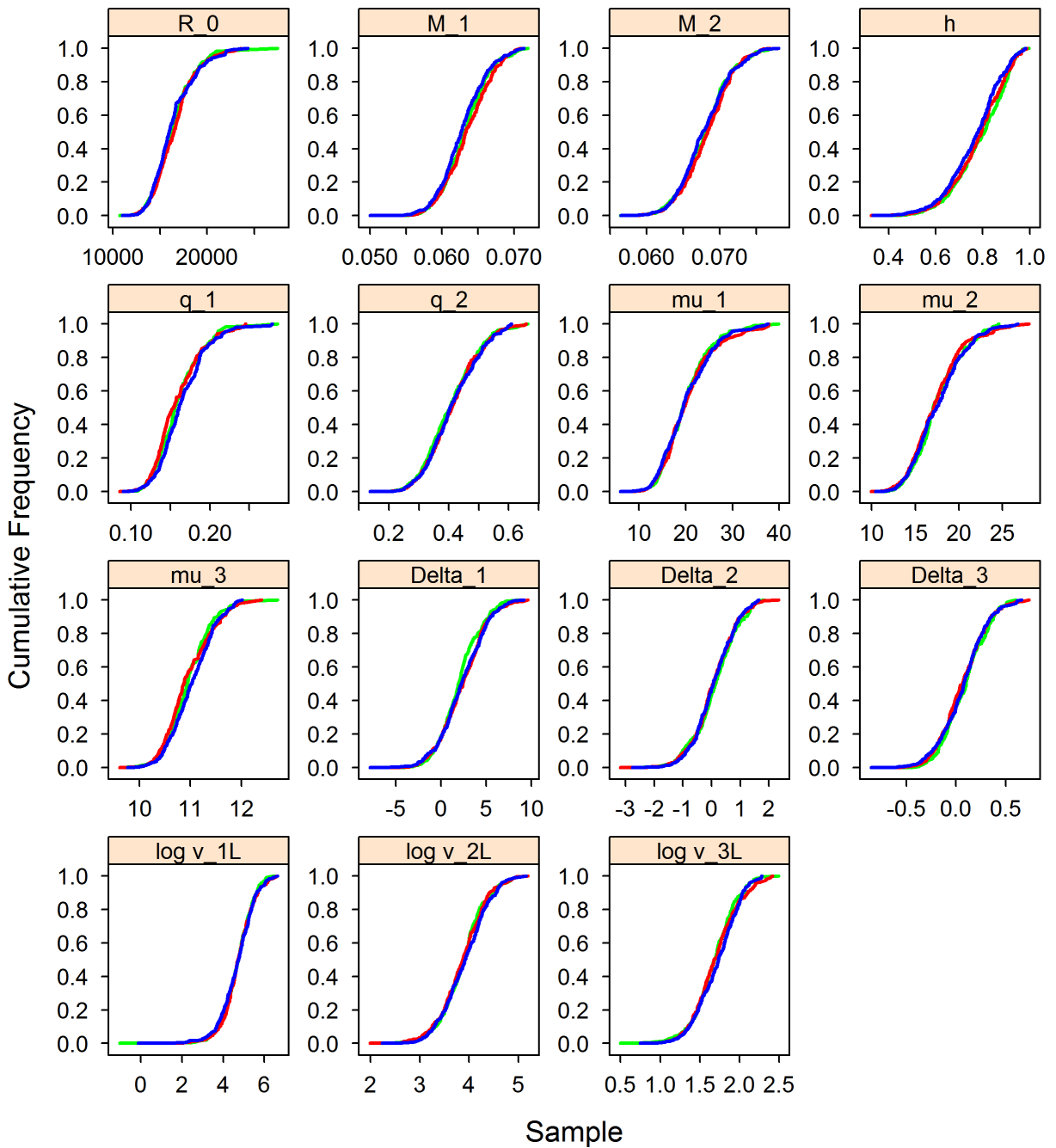


Figure E.64. Sensitivity 6: Diagnostic plot obtained by dividing the MCMC chain of 1,000 MCMC samples into three segments, and overplotting the cumulative distributions of the first segment (green), second segment (red) and final segment (blue).

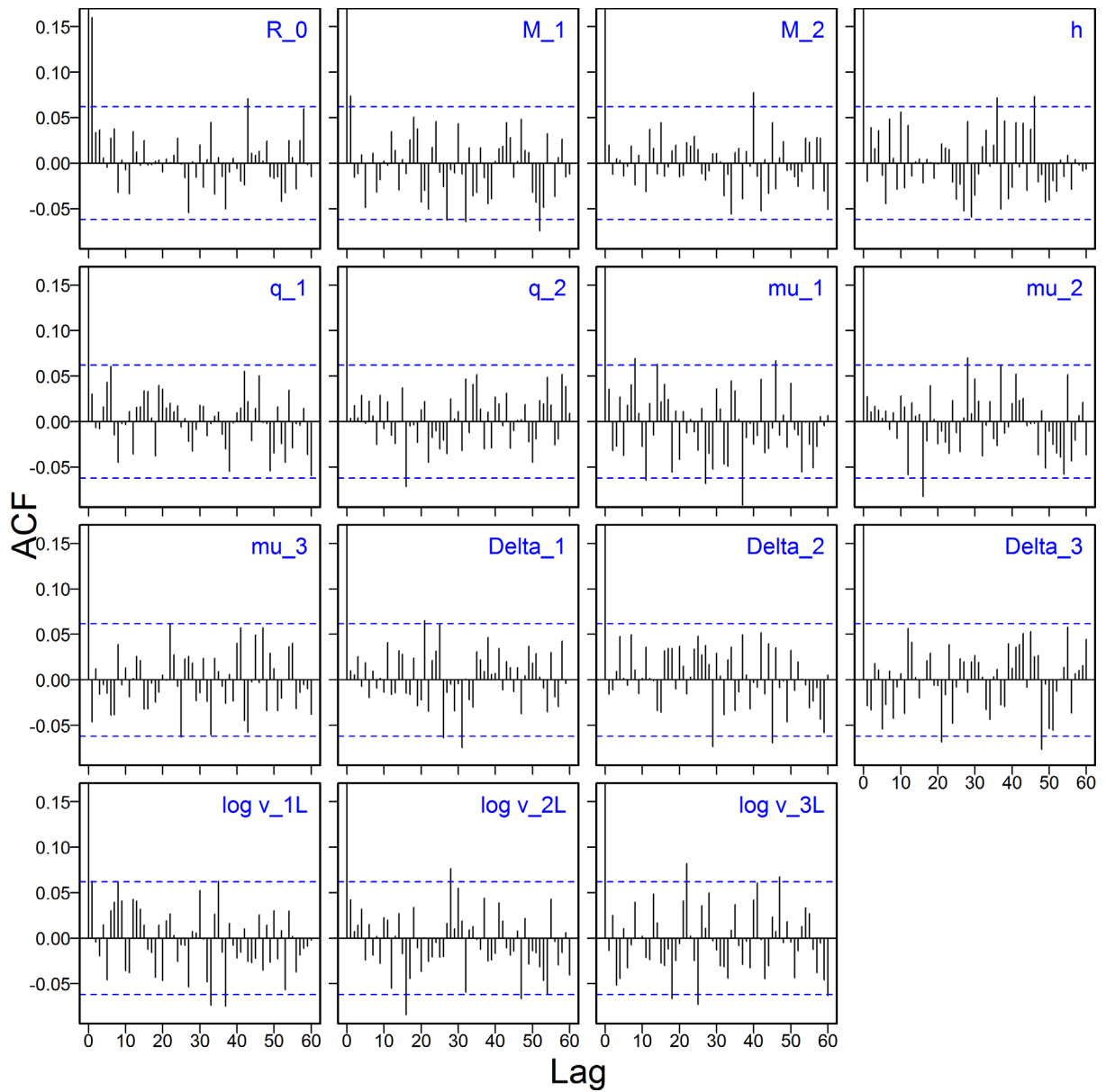


Figure E.65. Sensitivity 6: Autocorrelation plots for the estimated parameters from the MCMC output. Horizontal dashed blue lines delimit the 95% confidence interval for each parameter's set of lagged correlations.

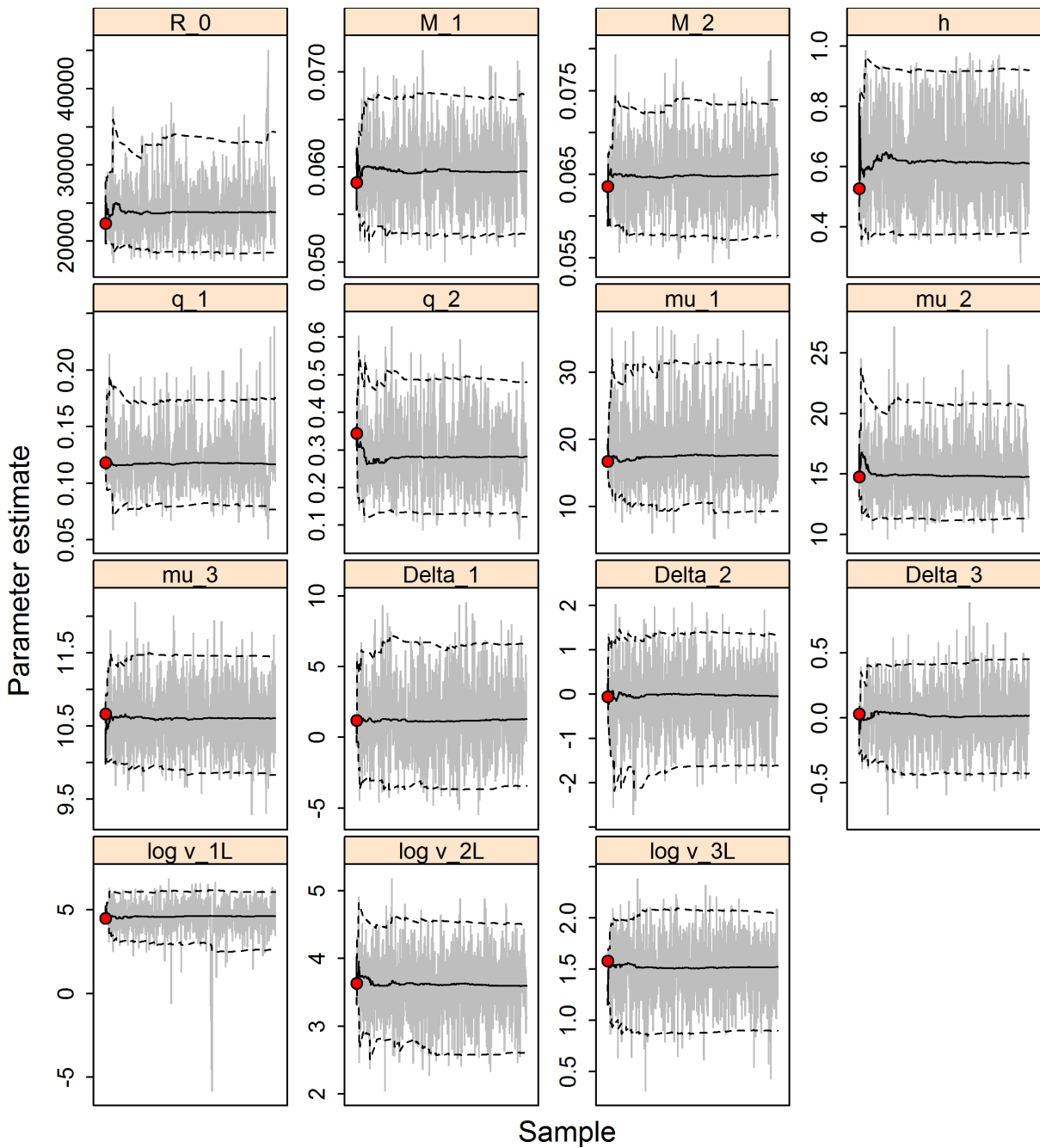


Figure E.66. Sensitivity 7: MCMC traces for the estimated parameters. Grey lines show the 1,000 samples for each parameter, solid lines show the cumulative median (up to that sample), and dashed lines show the cumulative 2.5 and 97.5 quantiles. Red circles are the MPD estimates. For parameters other than  $M$  (if estimated), subscripts  $\leq 2$  correspond to fishery-independent surveys, and subscripts  $\geq 3$  denote the commercial fishery. Parameter notation is described in Appendix D.



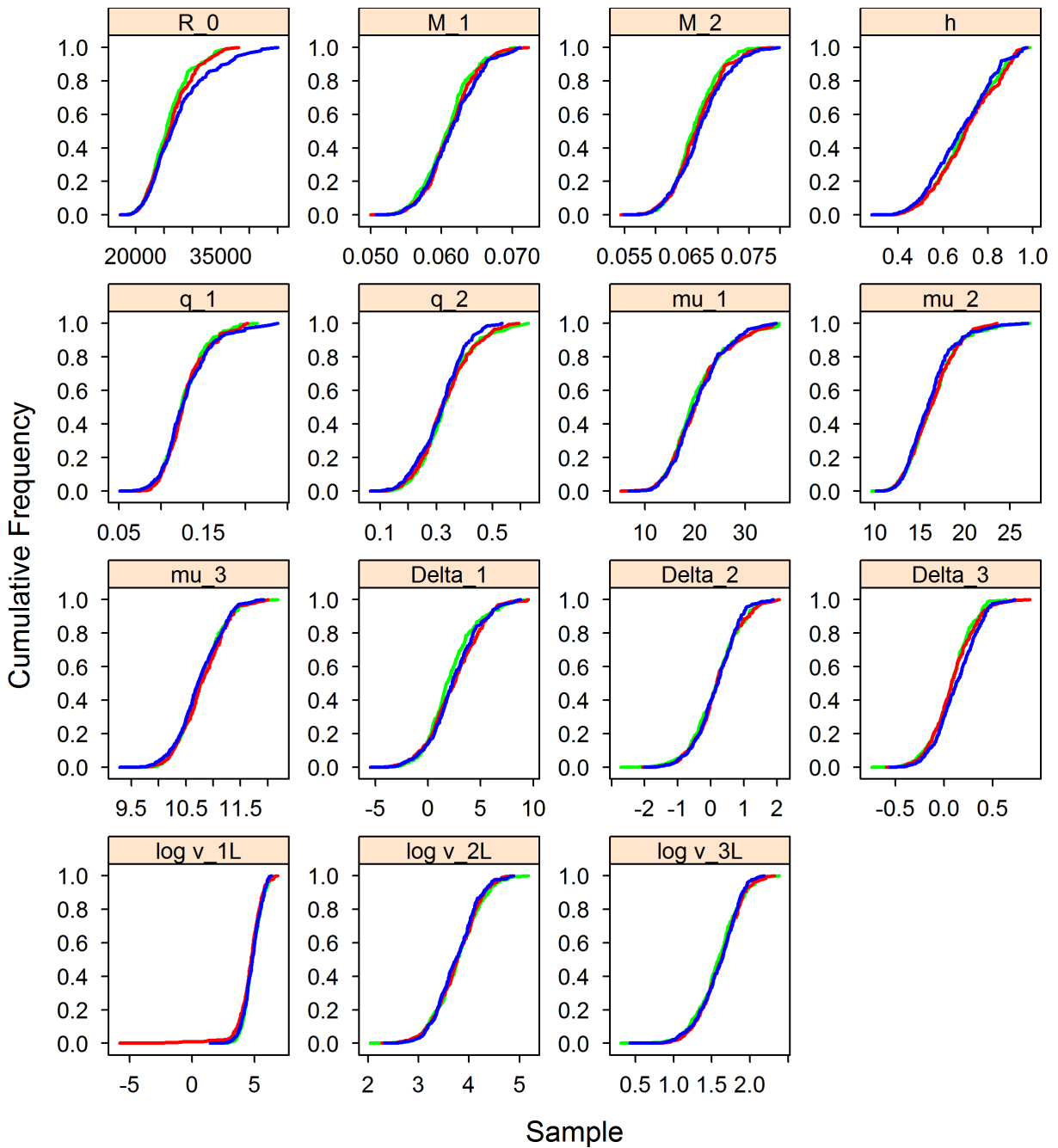


Figure E.67. Sensitivity 7: Diagnostic plot obtained by dividing the MCMC chain of 1,000 MCMC samples into three segments, and overplotting the cumulative distributions of the first segment (green), second segment (red) and final segment (blue).

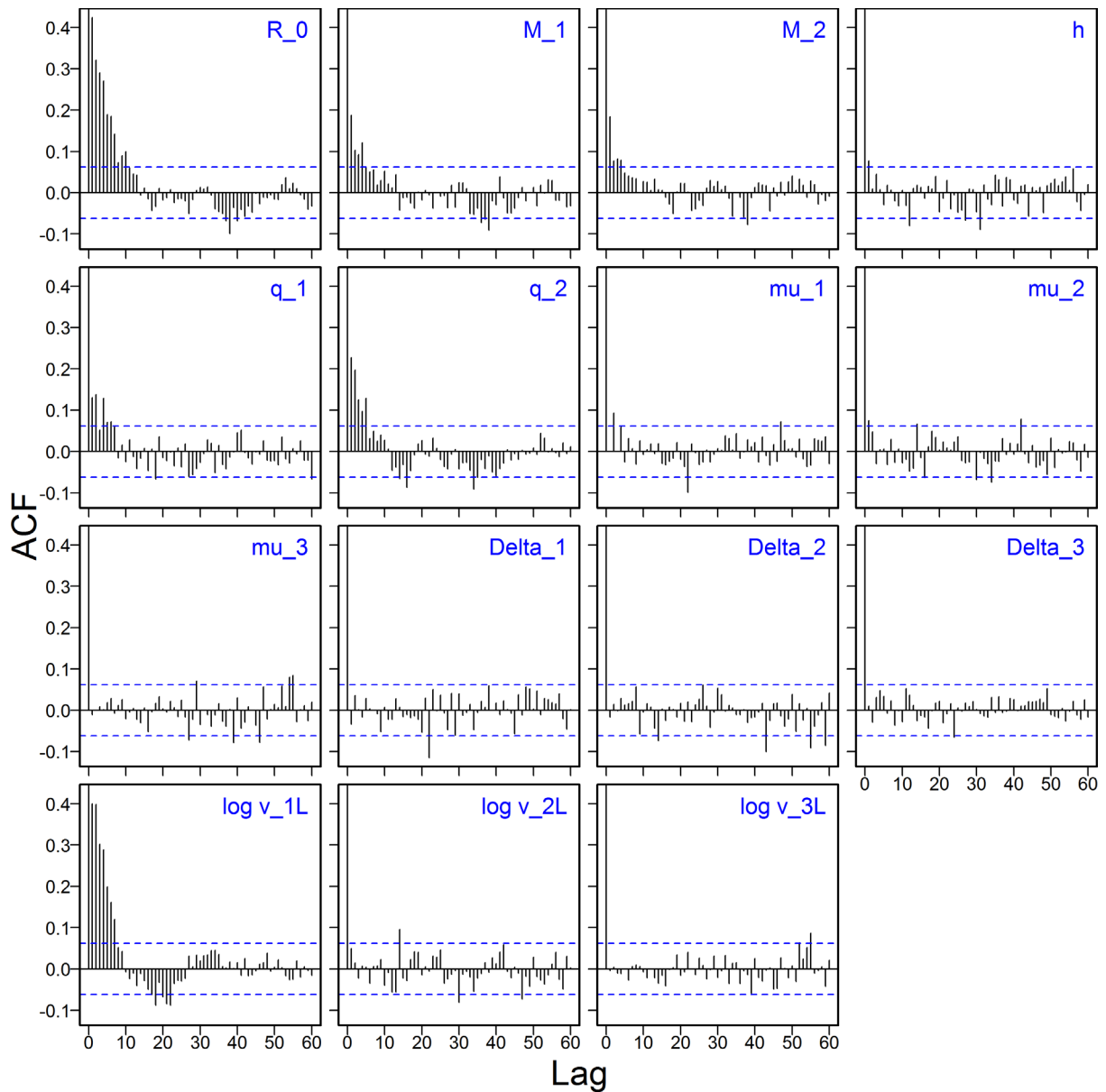


Figure E.68. Sensitivity 7: Autocorrelation plots for the estimated parameters from the MCMC output. Horizontal dashed blue lines delimit the 95% confidence interval for each parameter's set of lagged correlations.

## E.6. BRIDGING RUN USING 2010 DATA

The previous assessment for this stock (Edwards et al. 2012) preceded the publication of Francis (2011), and used an iterative reweighting approach that adjusted the relative weights until the standard deviation of normal residuals for each data source, including the composition data, was close to 1.0. Francis (2011) suggests that this approach will result in overweighting the composition data because of correlations in the proportions-at-age data. To test the impact of the change in age frequency reweighting, we re-ran the (Edwards et al. 2012) model ('Estimate M&h' run) using the Francis (2011) reweighting scheme for age frequencies after reweighting the survey CVs using the SDNR method to agree with the abundance reweighting used in 2010. We

used Sensitivity 1 to make this comparison, which included the QCS shrimp survey, because the 2010 model also used this survey.

The MCMC results of this bridging analysis (Tables E.15 and E.16) were similar to the 2010 results, but the age frequency reweighting scheme resulted in a lower stock status than was estimated in 2010 (Figure E.69) (the median estimate for the 2011 stock status was 0.259 in 2010 while the same estimate using the Francis reweighting procedure on the bridging analysis model was 0.233, a drop of 10%). By de-emphasising the age composition data relative to the abundance data, the bridging analysis suggests that the data weighting procedure used in the 2010 'Est M&h' model estimated a higher stock status, resulting in a more optimistic stock assessment compared to the current weighting procedure. However, we note that these revised results lie within the uncertainty envelope of the original model, indicating that the updated results are probably not strongly different from the 2010 results in a statistical sense. Stock assessment methodology is continually improving and we have adopted the Francis (2011) recommendations because they represent an advance on the methods used in 2010.

The diagnostic plots for the MCMCs used in the bridging analysis (Figures E.71-E.73) indicate that autocorrelation is significant for the first 6 lags in  $R_0$ , and slight trends in the median trace lines of a few parameters suggest a longer search simulation time might be warranted.

*Table E.15. Model parameters from the 2017 model using 2010 data. The 5<sup>th</sup>, 50<sup>th</sup>, and 95<sup>th</sup> percentiles for model parameters derived via MCMC estimation (defined in Appendix D).*

	5%	50%	95%
$R_0$	14,305	17,787	23,908
$M_1$	0.05514	0.06082	0.06658
$M_2$	0.05984	0.06651	0.07324
$h$	0.4786	0.7203	0.9175
$q_1$	0.08612	0.1174	0.1489
$q_2$	0.1806	0.3560	0.6280
$q_3$	0.01453	0.02744	0.04476
$\mu_1$	6.663	9.710	12.71
$\mu_2$	10.15	12.50	14.74
$\mu_4$	9.680	10.40	11.24
$\Delta_1$	-1.364	0.03246	1.500
$\Delta_2$	-1.058	0.07138	1.213
$\Delta_4$	-0.4054	0.03600	0.4388
$\log v_{1L}$	1.612	2.679	3.612
$\log v_{2L}$	2.048	2.909	3.529
$\log v_{4L}$	0.7176	1.341	1.905

Table E.16. Comparison of the 2017 model vs. the 2010 model using 2010 data in both – biomass and MSY-based quantities. The 5<sup>th</sup>, 50<sup>th</sup> and 95<sup>th</sup> 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),  $B_{2011}$  – spawning biomass at the start of 2011,  $V_{2011}$  – vulnerable biomass in the middle of 2011,  $u_{2010}$  – exploitation rate (ratio of total catch to vulnerable biomass) in the middle of 2010,  $u_{max}$  – maximum exploitation rate (calculated for each sample as the maximum exploitation rate from 1940-2010),  $B_{MSY}$  – 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 (2006-2010) is 3492 t.

Value	Percentile					
	From 2017 model			From 2010 model		
	5%	50%	95%	5%	50%	95%
$B_0$	82,536	93,905	113,164	80,667	91,595	110,024
$V_0$	147,625	166,548	200,398	143,633	163,273	196,606
$B_{2011}$	10,417	21,608	46,099	10,085	23,690	46,450
$V_{2011}$	22,307	45,064	93,457	23,963	49,668	94,728
$B_{2011}/B_0$	0.118	0.233	0.422	0.124	0.259	0.427
$V_{2011}/V_0$	0.145	0.272	0.472	0.165	0.303	0.489
$u_{2010}$	0.041	0.086	0.167	0.041	0.077	0.152
$u_{max}$	0.104	0.125	0.167	0.096	0.112	0.213
	MSY quantities (2017)			MSY quantities (2010)		
MSY	2,604	4,036	5,816	2,919	4,535	6,336
$B_{MSY}$	15,213	24,512	36,222	15,199	23,004	33,429
$0.4B_{MSY}$	6,085	9,805	14,489	6,080	9,202	13,372
$0.8B_{MSY}$	12,171	19,609	28,977	12,159	18,403	26,744
$B_{2011}/B_{MSY}$	0.381	0.899	1.970	0.417	1.040	2.100
$B_{MSY}/B_0$	0.171	0.263	0.354	0.165	0.249	0.346
$V_{MSY}$	33,060	49,265	69,333	33,045	47,272	65,259
$V_{MSY}/V_0$	0.210	0.298	0.381	0.208	0.287	0.373
$u_{MSY}$	0.041	0.082	0.156	0.048	0.0975	0.170
$u_{2010}/u_{MSY}$	0.364	1.038	3.224	0.315	0.791	2.340



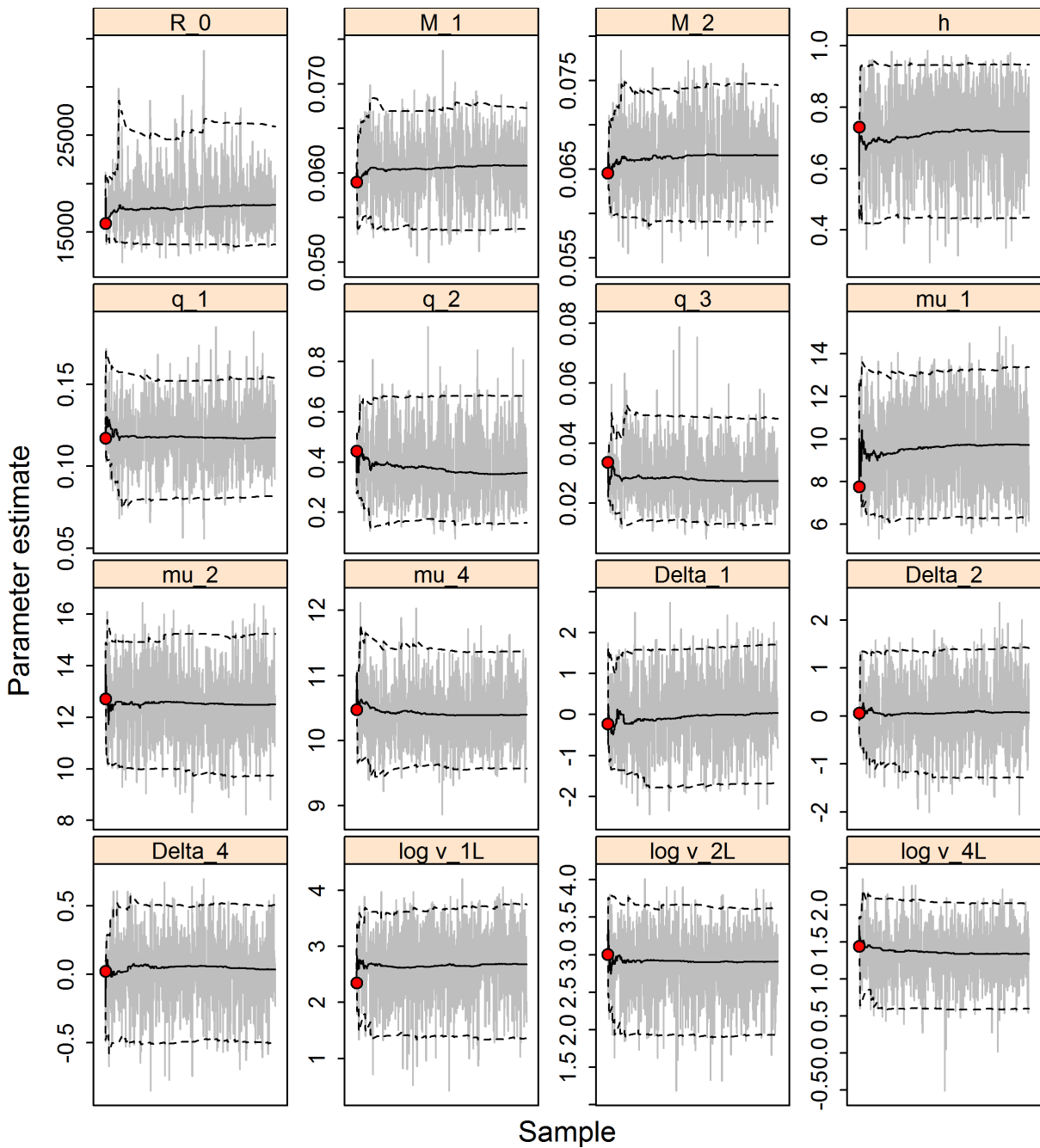


Figure E.71. Bridging: MCMC traces for the estimated parameters. Grey lines show the 1,000 samples for each parameter, solid lines show the cumulative median (up to that sample), and dashed lines show the cumulative 2.5 and 97.5 quantiles. Red circles are the MPD estimates. For parameters other than  $M$  (if estimated), subscripts  $\leq 3$  correspond to fishery-independent surveys, and subscripts  $\geq 4$  denote the commercial fishery. Parameter notation is described in Appendix D.

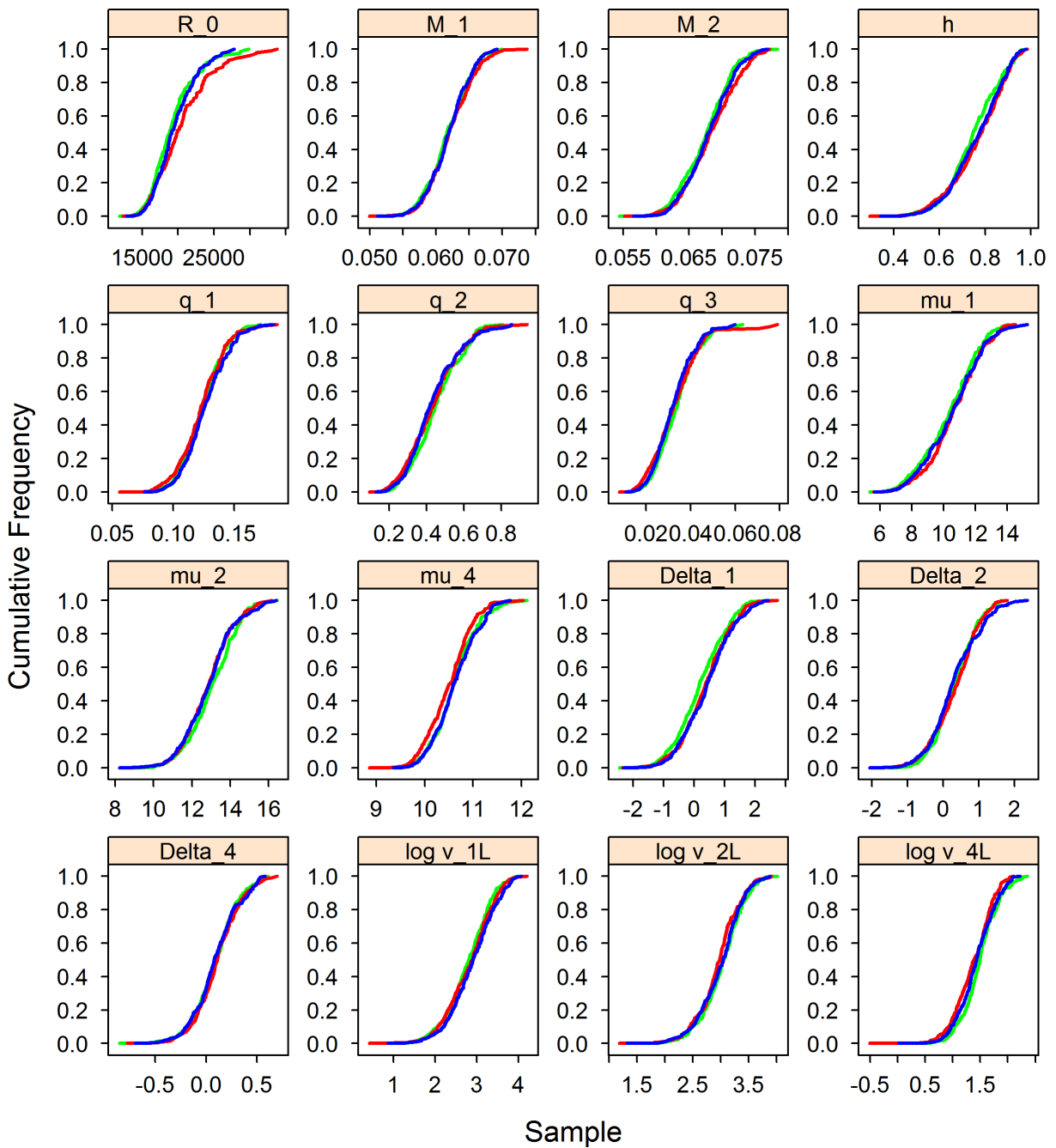


Figure E.72. Bridging: Diagnostic plot obtained by dividing the MCMC chain of 1,000 MCMC samples into three segments, and overplotting the cumulative distributions of the first segment (green), second segment (red) and final segment (blue).

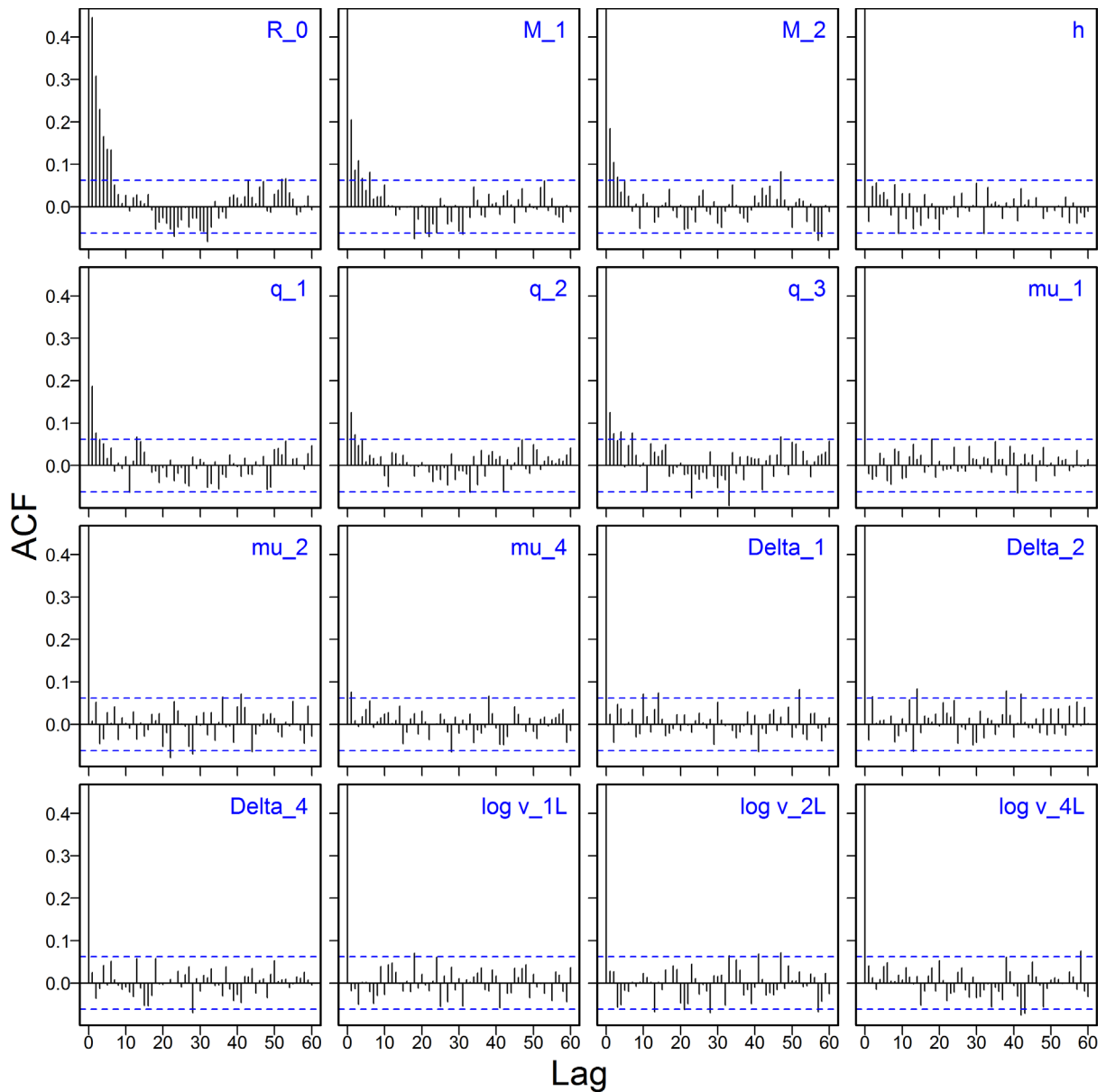


Figure E.73. Bridging: Autocorrelation plots for the estimated parameters from the MCMC output. Horizontal dashed blue lines delimit the 95% confidence interval for each parameter's set of lagged correlations.

## E.7. REFERENCES - MODEL RESULTS

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Edwards, A.M., Haigh, R. and Starr, P.J. 2014b. [Pacific Ocean Perch \(\*Sebastes alutus\*\) stock assessment for the west coast of Vancouver Island, British Columbia](#). DFO Can. Sci. Advis. Sec. Res. Doc. 2013/093. vi + 135 p. (Accessed June 5, 2018)



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- Francis, R.I.C.C. 2011. [Data weighting in statistical fisheries stock assessment models](#). Can. J. Fish. Aquat. Sci. 68(6): 1124-1138. (Accessed June 5, 2018)
- Ketchen, K.S. 1980. [Reconstruction of Pacific Ocean Perch \(\*Sebastes alutus\*\) stock history in Queen Charlotte sound. Part I. Estimation of foreign catches, 1965-1976](#). Can. Manuscr. Rep. Fish. Aquat. Sci. 1570: iv + 46 p. (Accessed June 5, 2018)
- Starr, P.J., Haigh, R. and Grandin, C. 2016. [Stock assessment for Silvergray Rockfish \(\*Sebastes brevispinis\*\) along the Pacific coast of Canada](#). DFO Can. Sci. Advis. Sec. Res. Doc. 2016/049. vi + 170 p. (Accessed June 5, 2018)

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## APPENDIX F. INVESTIGATING THE IMPACTS OF CLIMATIC AND ENVIRONMENTAL VARIABILITY ON RECRUITMENT OF PACIFIC OCEAN PERCH

### F.1. INTRODUCTION

There has been a gradual evolution towards ecosystem-based fisheries management in the last 25-30 years (King et al., 2001; Chavez et al., 2003; King and McFarlane, 2006; Marasco et al., 2007). Ecosystem-based fisheries management accounts for ecosystem processes when formulating fisheries management advice (Sissenwine and Murawski, 2004). One motivation for such interest is the growing evidence of the impacts of climate change and forcing on ecosystem states, including effects on fish abundance and population dynamics (Beamish and Bouillon, 1993; Polovina, 1996; McFarlane et al., 2000; Mantua and Hare, 2002; King, 2005). However, ecosystem-based fisheries management requires both an understanding of the mechanisms linking climate forcing to fish population dynamics and a consideration of uncertainty in the predictions of climate change and variability.

Indeed, forecasting the effects of global change on an ecosystem can be difficult (Francis et al., 1998; Dippner, 2006). Nonetheless, several studies have investigated the linkages between environmental forcing and fish populations, typically as direct inputs into a stock-recruitment relationship, and this area remains an active field of research in fisheries science (Daskalov, 1999; Fiksen and Slotte, 2002; Planque et al., 2003; Sinclair and Crawford, 2005; Arregui et al., 2006; Szuwalski and Punt, 2013). However, it can be problematic to rely on simple correlations between environmental variables and fish recruitment to draw tactical advice (Szuwalski and Punt, 2013) because often such correlations can be unreliable (Haltuch and Punt, 2011).

Generally, the environmental variables represent a proxy relationship for an unknown mechanism and hence change or break down with time (Myers, 1998; McClatchie et al., 2010). Our approach to address this limitation is to include a suite of climatic and environmental variables that represent the processes of a conceptual mechanism linking an ecosystem state to fish recruitment.

Another limitation to relating climate and environmental forcing to fish recruitment is the lack of accurate recruitment time series that are long enough to capture the time scale of climatic or environmental variability. Using long recruitment time series increases the chances of capturing changes in the ecosystem state and of identifying relationships between the environment and fish recruitment (Sinclair and Crawford, 2005). In addition, estimates from stock assessment models are more relevant than estimates derived from survey data, because they are based on all available sources of data (Szuwalski and Punt, 2013).

Here we develop a Bayesian modelling approach to explore relationships between a suite of climatic and environmental indices and fish recruitment. This approach accounts for the formal inclusion of sources of uncertainty associated with estimates of fish recruitment, and is able to highlight linear or nonlinear relationships between fish recruitment and climatic and environmental indices.

We apply our Bayesian approach to the 5ABC stock of POP using the estimates of recruitment for 1940 to 2010 calculated in the previous assessment (Edwards et al., 2012). Long-lived species, such as POP, are highly fecund and can reproduce over a long time period. This allows them to take immediate advantage of changes to more productive periods, through increased recruitment success (King and McFarlane, 2006). As a consequence, long-lived species are of particular interest when investigating climatic and environmental effects on fish recruitment.

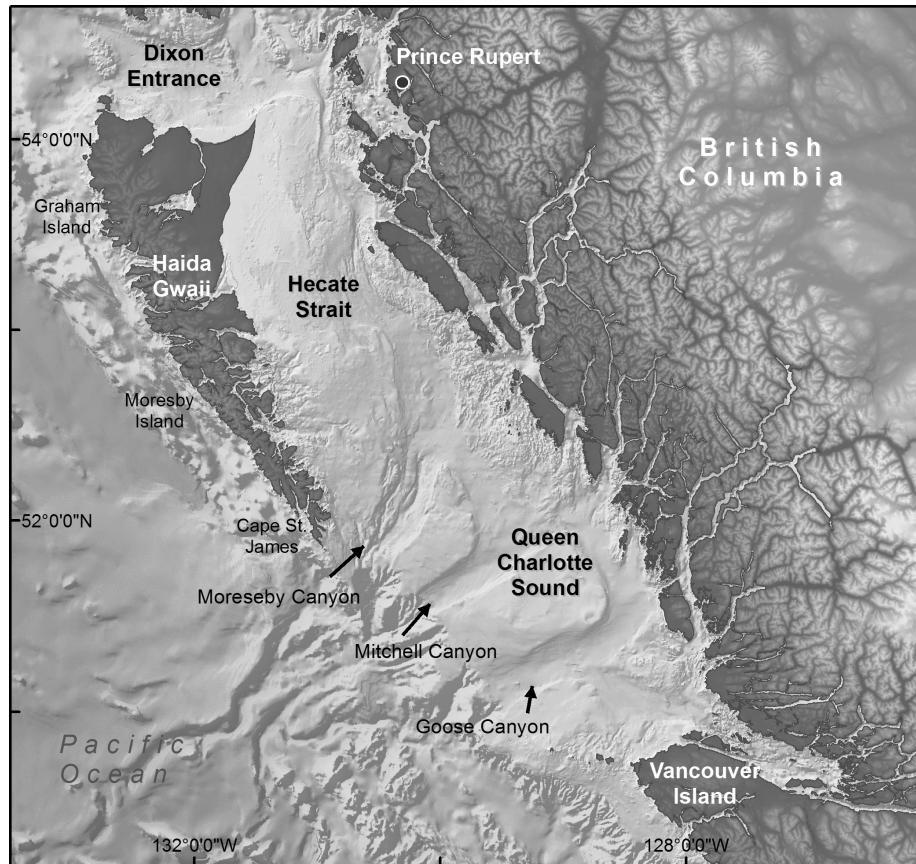


Figure F.1. Map of Queen Charlotte Sound and Hecate Strait, and surrounding waters off the west coast of British Columbia, Canada. The Pacific Ocean Perch stock studied here is for Queen Charlotte Sound and the southern half of Hecate Strait. Geographic features mentioned in the text are highlighted.

The 5ABC stock of POP inhabits Queen Charlotte Sound (QCS) and the southern half of Hecate Strait (HS, Figure F.1), a highly productive region which experiences variable water exchanges between the shelf and the open ocean (Lanson et al., 2003; Whitney et al., 2005). For this ecosystem, a mesoscale eddy, the Haida eddy, has been identified as a dominant oceanic feature that influences the physical and biological processes (Miller et al., 2005). The Haida eddy forms in late winter off Cape St James (Figure F.1) due to the wind-driven advection of warmer and fresher water masses out of QCS and HS (Di Lorenzo et al., 2005). This advection flows around the cape, generating plumes of buoyant flow and, eventually, these plumes merge to generate the larger (>40 km) Haida eddy (Di Lorenzo et al., 2005). By spring, the Haida eddy breaks off from the coast and moves westward into the Gulf of Alaska (Whitney and Robert, 2002). Haida eddies play an important role in water displacement from QCS and HS to the Gulf of Alaska (Di Lorenzo et al., 2005). Such eddies also impact zooplankton community compositions and species distributions (Miller et al., 2005; Batten and Crawford, 2005).

Previously, Sinclair and Crawford (2005) linked Haida eddy formation to physical and biological processes related to another groundfish species in this system, Pacific Cod (*Gadus macrocephalus*). They hypothesized that large eddies, which during late winter/early spring can move an estimated volume of water equivalent to that of HS and QCS combined (Whitney and Robert, 2002), resulted in displacement of pelagic Pacific Cod larvae into the open ocean and hence to poor cod recruitment. Since the Haida eddy formation is initiated by wind-driven

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advection of water movement out of HS (Di Lorenzo et al., 2005), Sinclair and Crawford (2005) used the pressure-adjusted sea level in Prince Rupert as a proxy for water displacement and Haida eddy intensity. Here we provide an index of Haida eddy intensity by developing a method that we extend from Crawford (2002). We use this Haida eddy index and the pressure-adjusted sea level along with indices that reflect regional and Pacific basin-wide atmospheric and oceanographic processes. We use our Bayesian framework to investigate the potential impacts of this suite of variables on the POP recruitment.

## **F.2. METHODS**

### **F.2.1. Pacific Ocean Perch recruitment estimates**

Estimates of recruitment (Figure F.2) of POP are taken from the statistical catch-at-age (SCA) model used in the previous the stock assessment (Edwards et al., 2012). The model is almost identical in structure to the model used in the current assessment and was used to reconstruct the population history (including recruitment and spawning biomass) from 1940 to 2010. Input data included fishery-independent survey indices, biological data and age-composition data. Specifically, we use the model run that was able to estimate the steepness of the stock-recruitment function and natural mortality (Edwards et al., 2012).

### **F.2.2. Climatic and environmental variables**

We propose a conceptual mechanism for POP recruitment success based on the following understanding of POP life history and ocean circulation in the area of larval release. The mechanism also builds upon the transport hypothesis for Pacific Cod in Hecate Strait (Tyler and Crawford, 1991) which linked winter wind direction in the area to Pacific Cod pelagic egg and larvae retention in the system (Sinclair and Crawford, 2005). Adult POP spawn in September at depths of 200-400 m (Love et al., 2002). The females retain the male milt, and internal fertilization occurs from October to November. The females do not release the larvae until February or March, by which time the females have migrated to depths of 500-700 m. Therefore, winter (December-March) environmental conditions are likely covariates that link POP recruitment to ocean processes. In our area of interest, the grounds of larvae release are on the northern sides of Moresby, Mitchell, and Goose Island Canyons (G. Workman, DFO, pers. comm.), three large submarine gullies in QCS (Figure F.1). Off British Columbia, POP larvae remain at depth for several months, transported to shelf habitat at depths of 200-275 m by upwelled waters during early spring (Love et al., 2002). In QCS, these upwelled waters are deepwater intrusions moving up through the canyons, which are linked to the movement of Haida eddies westward (Dodimead, 1980; Crawford et al., 1988). We hypothesise that westward movement of Haida eddies will positively influence, via deepwater upwelling, the transport of POP larvae from marine canyons up into the shelf waters that represent favourable juvenile habitat.

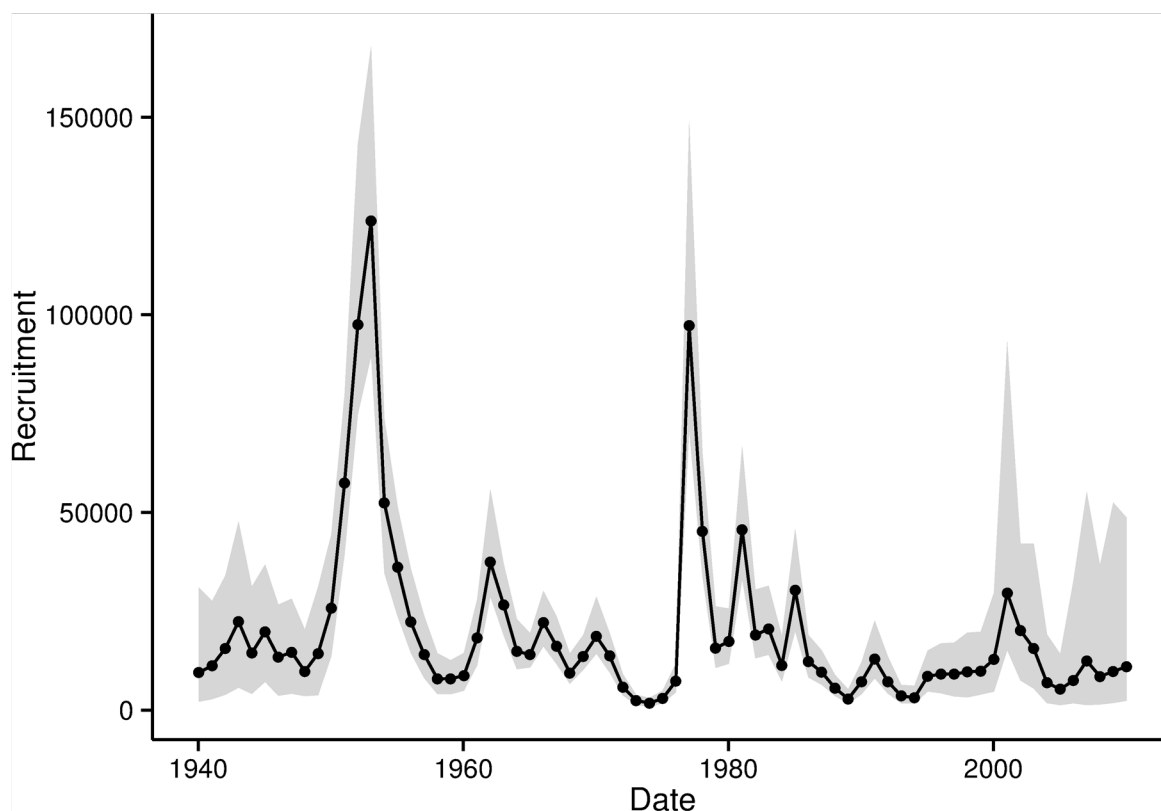


Figure F.2. Recruitment estimates of Pacific Ocean Perch in Queen Charlotte Sound and southern Hecate Strait from 1940 to 2010 from Edwards et al. (2012). Black line represents the median of the samples from the posterior distribution and the 2.5% and 97.5% quantiles are represented in grey.

Sinclair and Crawford (2005) used pressure-adjusted sea level height at the north end of HS as a proxy for surface water transport southward out of HS, where low sea level heights indicated transport of Pacific Cod eggs and larvae out of HS, with subsequent poor recruitment. Southward water movement out of HS is linked to Haida eddy formation and is determined by winter wind direction. Therefore, we include indices that represent conditions leading to Haida eddy formation and indices that represent Haida eddy intensity as suitable regional indices to investigate environmental impacts on POP recruitment. Specifically, we use an index of regional atmospheric circulation (wind direction) in winter, an index of winter surface water transport out of HS, and an index that measures the area encompassed of the Haida eddy each winter.

We also use a suite of basin-wide indices that represents atmospheric and coupled oceanographic variability, and for environmental indices we use indices that are defined on a regional scale and reflect weather patterns and oceanographic processes.

Given that regional atmospheric circulation is determined by Pacific basin-wide systems, we considered the relative intensity of the Aleutian Low pressure system in winter. The Pacific-basin atmospheric variability drives the oceanic variability captured by the sea surface spatial patterns in temperature or height (Di Lorenzo et al., 2010). These patterns of Pacific Ocean variability are coupled with the tropics, specifically El Niño teleconnections (Newman et al., 2003; Di Lorenzo et al., 2010). To capture the Pacific basin-wide climate and ocean variability, we include indices of the Aleutian Low (Aleutian Low Pressure Index, ALPI and the North Pacific

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Index, NPI), sea surface spatial patterns (Pacific Decadal Oscillation Index, PDO and the North Pacific Gyre Oscillation, NPGO) and of El Niño events (Oceanic Niño Index, ONI and Southern Oscillation Index, SOI).

### **East-Pacific/North-Pacific index**

The monthly East-Pacific/North-Pacific teleconnection index (EP-NP) is derived from a rotated principal component analysis of normalized 500-hPa height anomalies from the period 1950-2000 (available from [NOAA](#)). For each year, the winter mean (December to March) is used (Figure F.3a). A negative index is associated with a northward shift and weakening of the Pacific jet stream from eastern Asia to the eastern North Pacific, resulting in southward wind flow down through HS.

### **Pressure-adjusted sea level in Prince Rupert**

The Canadian Hydrographic Service monitors sea level along the British Columbia coast. The sea level in Prince Rupert has been recorded hourly since 1909 and is available from [DFO](#). Crawford et al. (1988) used the pressure-adjusted sea level height as a proxy for water transport out of HS. Pressure-adjusted sea level is the sum of sea level in cm and air pressure in millibars, and is expressed in units of pressure kPa (Crawford et al., 1988). Low pressure-adjusted sea level in Prince Rupert during winter is linked to southward winter winds, which increase southward advection of water out of Hecate Strait (Crawford et al., 1988; Sinclair and Crawford, 2005). Here, the pressure-adjusted sea level anomaly (PASLa) is computed for each year since 1954 by averaging monthly values over January to March (Figure F.3b).

### **Area covered by Haida eddy**

Crawford (2002) introduced an index of relative intensity of the Haida eddy for 1993-2002. The index used modelled satellite altimetry values from the Colorado Center for Astrodynamic Research and sea surface height thresholds (+10 cm and +15 cm) to estimate the monthly average area (km<sup>2</sup>) of the Haida eddies. We employ the same threshold technique for the same region of interest (150°W to 120°W, 40°N to 60°N) as Crawford (2002), but recalculate the time series for 1993-2014 with an improved version of modelled satellite altimetry data from the Colorado Center for Astrodynamic Research. We defer description of the methods to produce this index to Section F.5. As an index of the relative intensity of Haida eddy formation in winter, we use the maximum of the monthly mean areas, HEmax, (December through March) from the +10 cm threshold technique (Figure F.3c).

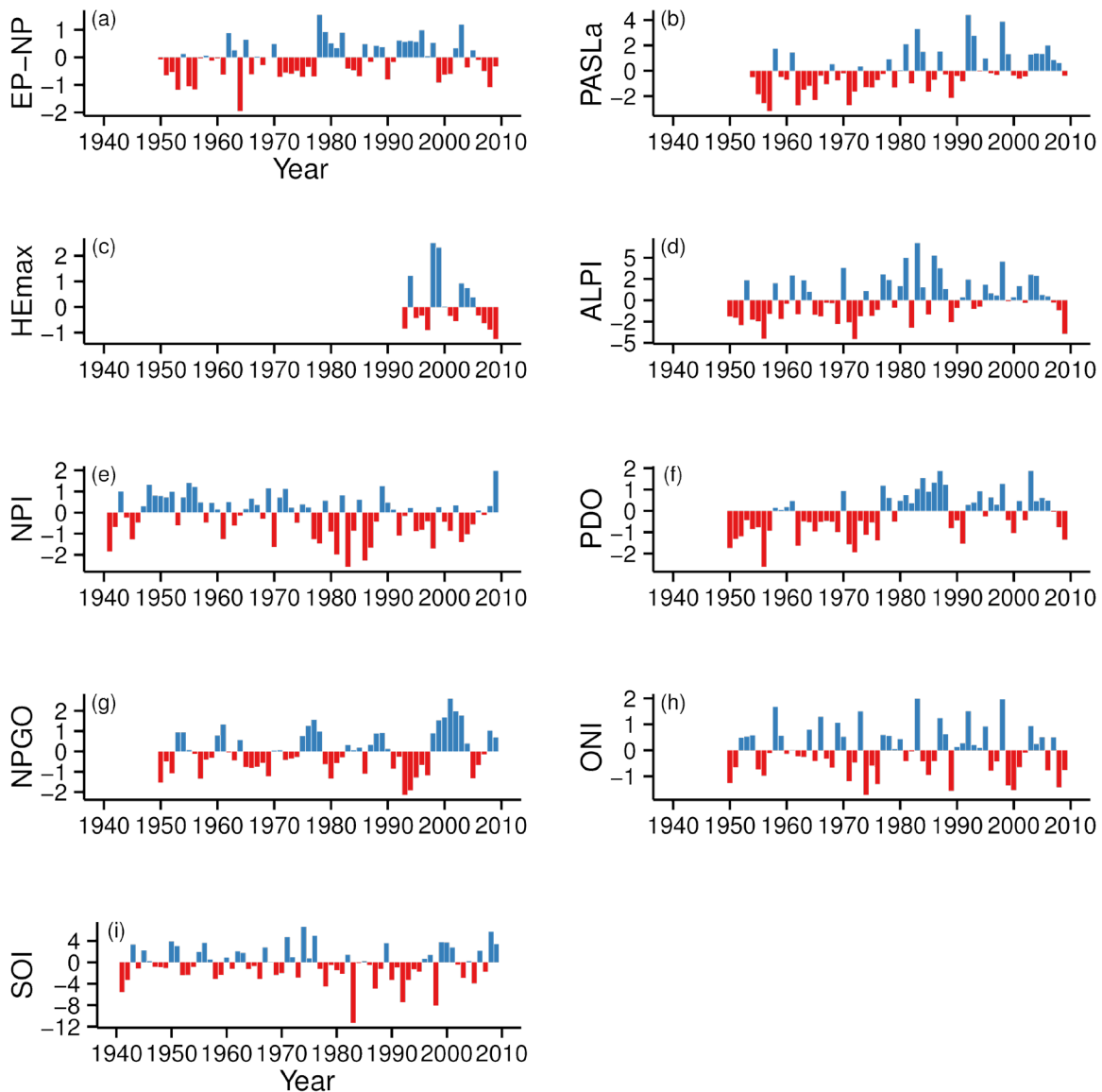


Figure F.3. Time series of climatic and environmental indices used to test influences on POP recruitment. (a) East-Pacific/North-Pacific index. (b) Pressure-adjusted sea level anomalies at Prince Rupert. (c) Standardized maximum area covered by Haida eddies. (d) Aleutian Low Pressure Index. (e) Standardized North Pacific Index. (f) Pacific Decadal Oscillation. (g) North Pacific Gyre Oscillation. (h) Oceanic Niño Index. (i) Southern Oscillation Index.

### Aleutian low pressure index

The Aleutian Low Pressure Index (ALPI) was first developed by Beamish and Bouillon (1993) as a measure of the Aleutian Low, and later modified by Beamish et al. (1997). It requires the computation of the mean area (in 106 km<sup>2</sup>) in the North Pacific that has a sea level pressure lower than 100.5 kPa in winter months (December to March). The ALPI is computed as the anomaly from a long-term mean area (1950-1997) from a gridded sea surface pressure data obtained from the National Center of Atmospheric Research (Surry and King 2015 Figure F.3d). Positive ALPI values indicate an intense Aleutian Low relative to the long-term mean. Periods of

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intense Aleutian Low are characterized by above-average south-westerly and westerly atmospheric patterns off the west coast of Canada (King et al., 2000; McFarlane et al., 2000). Changes in the Aleutian Low during the winter also capture regime-shift dynamics in the North Pacific related to the PDO (Hare and Mantua, 2000).

### **North Pacific index**

The North Pacific Index (NPI) is the area-weighted sea level pressure over the North Pacific from 30°N to 65°N and 160°E to 140°W. Like ALPI, NPI is a useful indicator of the intensity and areal extent of the Aleutian Low Pressure system. A monthly time series of this index is available from the [National Center for Atmospheric Research \(USA\)](#) based on Trenberth and Hurrell (1994) and Horel and Wallace (1981). Here we use winter-only values (averaged over December to March, Figure F.3e). The opposite pattern to ALPI is observed because a negative period of NPI indicates an intense Aleutian Low, whereas a positive period of NPI indicates a weaker Aleutian Low.

### **Pacific Decadal Oscillation**

The PDO is the first mode of an Empirical Orthogonal Function (EOF) analysis of gridded sea surface temperature in the North Pacific, (Zhang et al. 1997 and reported in Mantua et al. 1997) and is available from the [University of Washington](#). It represents sea surface temperature and sea surface height anomalies in the North Pacific and is connected to the El Niño Southern Oscillation (ENSO, Alexander et al., 2002; Newman et al., 2003). For this study, we computed the mean values of PDO over the winter months (December to March, Figure F.3f). A negative phase of the PDO is associated with unusual cold temperatures in the eastern North Pacific (Mantua et al., 1997) and a weak Aleutian Low (Di Lorenzo et al., 2010, 2013).

### **North Pacific Gyre Oscillation**

The North Pacific Gyre Oscillation (NPGO) is the second mode from an EOF analysis of gridded sea surface temperature and sea surface height anomalies in the North Pacific and is distinct from the PDO (Di Lorenzo et al. 2008). It is available from [Emanuele DiLorenzo](#). Average NPGO values over the winter months (December to March) are used here (Figure F.3g). The positive phase of the NPGO is associated with strong westerly winds over the eastern North Pacific and cool winters off the British Columbia coast, and a weak Aleutian Low (Di Lorenzo et al., 2008).

### **Oceanic Niño index**

The Oceanic Niño Index (ONI) serves as the official index of the occurrence of El Niño and La Niña episodes as determined by the NOAA Climate Prediction Center (and is available from [NOAA](#)). It is a measure of the anomaly of ocean surface temperature in the central tropical Pacific Ocean and is computed monthly. Monthly values are based on a three-month period centered over the nominal month. The NOAA Climate Prediction Center suppresses a climate change effect (warming trend) in the computation of ONI. To do so, they use multiple centered 30-year base periods to define the ONI. These 30-year base periods are used to calculate the anomalies for successive five-year periods. In this study, we use the mean values of the ONI from December to March (Figure F.3h).

### **Southern Oscillation Index**

The Southern Oscillation Index (SOI) represents the monthly anomaly of atmospheric sea surface pressure difference between the island of Tahiti and Darwin, Australia (Trenberth, 1984) and is available from the [National Center for Atmospheric Research \(USA\)](#). It usually sets up the El Niño and La Niña ocean responses. A negative SOI value indicates weak trade winds, or even a reversal of wind direction, in the tropical Pacific, and generally indicates El Niño events.



On the other hand, positive SOI values are associated with La Niña events and strong trade winds.

Average SOI values over the winter month (December-March) are used in this study (Figure F.3i).

Basin-scale and teleconnection indices (ALPI, NPI, PDO, NPGO, ONI and SOI) represent climatic variability, and regional-scale indices (PASLa, HEmax) reflect environmental variability. The East-Pacific/North-Pacific teleconnection index bridges the two spatial scales.

### F.2.3. Modelling approach

The relationships between fish recruitment and climatic and environmental variables are explored using multiple linear regressions in a Bayesian context. The number of recruits of age-1 fish in year  $t$ ,  $R_t$ , is assumed to be lognormally distributed with mean  $\mu_t$  and variance  $\sigma_2$ :

$$\log(R_t) \square \text{Normal}(\mu_t, \sigma^2) \quad (\text{F.1})$$

$$\mu_t = \alpha + \beta_1 X_{1,t-1} + \beta_2 X_{2,t-1} \quad (\text{F.2})$$

where  $\mu_t$  is a linear function of the covariates  $X_{1,t-1}$  and  $X_{2,t-1}$  and the unknown parameters  $\alpha$ ,  $\beta_1$  and  $\beta_2$ . Thus, equation (F.2) is a multiple linear regression (Dobson and Barnett, 2011). The parameter  $\alpha$  is the intercept of the linear regression, and is of less interest than  $\beta_1$  and  $\beta_2$ , which represent the influence of the covariates  $X_{1,t-1}$  and  $X_{2,t-1}$  on  $\mu_t$ . We construct multiple model formulations for which  $X_{1,t-1}$  and  $X_{2,t-1}$  correspond to different climatic and environmental indices. All variables are standardized to have a mean of zero and a standard deviation of 1 before being included in (F.1) and (F.2).

We first test whether  $X_{1,t-1}$  and  $X_{2,t-1}$  are correlated (absolute Pearson correlation score greater than 0.3), and if so consider them to account for the same climatic or environmental effect. To avoid this problem of collinearity, the two covariates are included in separate models. For some model formulations we also extend (F.2) by adding a term  $\beta_3 X_{3,t-1}$ , but for simplicity here we just discuss the formulation with  $\beta_1$  and  $\beta_2$ . Climatic and environmental covariates from year  $t_1$  are used because  $R_t$ , from Edwards et al. (2012), represents age-1 fish in year  $t$ , and we expect the climatic or environmental influences to be strongest on individuals in the year they are released live from their mothers, which is year  $t - 1$ .

If the 90% credible intervals of the parameter relating to a covariate include zero for all models in which that covariate occurs, then we consider there to be no linear relationships between POP recruitment and the covariate. We then investigate for a potential nonlinear effect. To do that, a categorical variable,  $Z_{1,t-1}$ , is created by splitting the covariate  $X_{1,t-1}$  into classes. For example, HEmax is split into three classes (for Model 6 – see Results): for a small area of 4,500-35,000 km<sup>2</sup>,  $Z_{1,t-1} = 1$ ; for a medium area of 35,000-50,000 km<sup>2</sup>,  $Z_{1,t-1} = 2$ ; and for a large area of 50,000-95,000 km<sup>2</sup>,  $Z_{1,t-1} = 3$ . The number of age-1 fish in year  $t$ ,  $R_t$ , is assumed to be lognormally distributed with mean  $\mu_{t,i}$  and variance  $\sigma_2$ :

$$\log(R_t) \square \text{Normal}(\mu_{t,i}, \sigma^2) \quad (\text{F.3})$$

$$\mu_{t,i} = \alpha + \gamma_{1,i} I(Z_{1,t-1} = i) \quad (\text{F.4})$$

where  $I(\bullet)$  is the indicator function (equalling 0 or 1 if its argument is false or true, respectively), and  $\alpha$  and  $\gamma_{1,i}$  are the unknown parameters, where the latter represents the covariate effect of class  $i$ . We set  $\gamma_{1,1} = 0$  such that effects of classes 2 and 3 are estimated relative to class 1. This

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approach can be extended for multiple covariates similarly to (F.2), by introducing parameters  $\gamma_{2,i}$ ,  $\gamma_{3,i}$  etc.

In previous studies, a point estimate,  $\bar{R}_t$ , was used to analyze the relationship between recruitment and the environment (Daskalov, 1999; Fiksen and Slotte, 2002; Planque et al., 2003; Arregui et al., 2006; Szuwalski and Punt, 2013). The point estimate,  $\bar{R}_t$ , was calculated as the mean or median of the recruitment estimated in year  $t$  from the model used for the stock assessment or from a virtual population analysis; the uncertainties associated with  $R_t$  were omitted. Omitting the variability associated with  $R_t$  impacts the parameter estimation of the model used to explore the relationship between recruitment and climatic or environmental indices. Here we explicitly account for the variability of  $R_t$  by utilizing the posterior distribution of estimated recruitment for each year. For POP, the posterior distributions come from the SCA model (Edwards et al., 2012) estimated via Markov chain Monte Carlo methods (MCMC), where each MCMC sample yields a recruitment time series (see example samples in Figure F.4).

In practice, we account for the variability of recruitment estimates by the following process:

1. draw one MCMC sample randomly (i.e. one recruitment time series) from the recruitment posterior distribution of the SCA model – see examples in Figure F.4;
2. fit model (F.2) or (F.4) to this time series to explore the climatic and/or environmental impacts on recruitment (described below);
3. store the results for this MCMC sample;
4. repeat steps 1-3 a total of 150 times (with previously drawn MCMC samples not able to be drawn again);
5. combine the 150 sets of results to obtain the posterior distributions of the parameters ( $\alpha$ ,  $\beta_1$ ,  $\beta_2$ ,  $\beta_3$  or  $\alpha$ ,  $\gamma_{1,i}$ ) of the impact of climate and/or environment on recruitment.

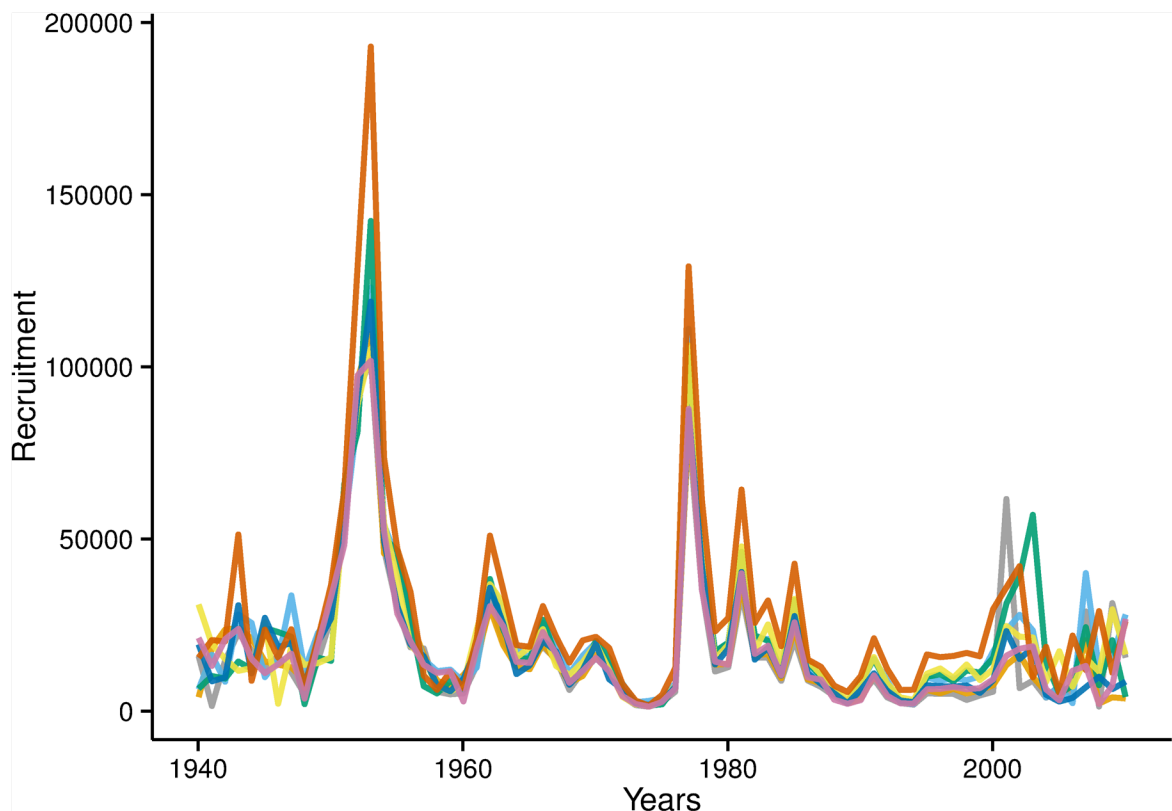


Figure F.4. Examples of individual MCMC samples for the estimates of recruitment (all samples are combined to give Figure F.2).

Steps 1 to 3 were repeated 150 times, rather than using the full 1,000 MCMC samples, to keep computational time acceptable. Other applications may allow for more repetition. Braccini et al. (2011) used a similar overall approach to integrate the uncertainties associated with catch per unit effort in a Bayesian surplus production model.

#### F.2.4. Bayesian inference

A key aspect of our framework is to fit each model in step 2 in a Bayesian framework, for which we used JAGS (Just Another Gibbs Sampler, Plummer 2003). Three chains of length 220,000 iterations were run with a burn-in period of 200,000 iterations, and 200 values were kept after a thinning of 100 iterations to eliminate autocorrelation in each chain. The samples from each chain were combined and thinned again to give a total of 200 samples (66 or 67 from each chain). Thus, at step 3 we stored the 200 values from the posterior distribution for each regression parameter ( $\alpha, \beta_1, \beta_2, \beta_3, \gamma_{1,i}$ ) associated with the particular MCMC recruitment sample drawn in step 1. The merge at step 5 is then done simply by combining, for each parameter, the 150 posterior distributions for that parameter, resulting in a full posterior distribution for each parameter consisting of 30,000 values (200 values from step 2 for each of the 150 recruitment times series).

Table F.1. Examples of models fitted to the POP recruitment estimates, including climatic and environmental variables with their corresponding time period. Models were built based on the time periods available for each covariate. Correlated covariates were not included in the same model whereas, for example,  $EP-NP_{t-1}$ ,  $NPGO_{t-1}$  and  $SOI_{t-1}$  are not correlated and so all appear in Model 5. Models 1 to 5 are formulated with respect to (F.2) and Model 6 with respect to (F.4). The parameter  $\mu_t$  estimated for each model is the mean of the lognormal distribution of the recruitments,  $\alpha$  is the intercept of the regressions and  $\beta_1$ ,  $\beta_2$ ,  $\beta_3$  and  $\gamma_{1,i}$  are the parameters accounting for the effect of the covariates. For year  $t - 1$ ,  $EP-NP_{t-1}$  is the East-Pacific/North-Pacific Index,  $PASLa_{t-1}$  is the pressure-adjusted sea level in Prince Rupert,  $PDO_{t-1}$  is the Pacific Decadal Oscillation,  $NPGO_{t-1}$  is the North Pacific Gyre Oscillation, and  $SOI_{t-1}$  is the Southern Oscillation Index. Finally,  $H\text{Emax}C_{t-1}$  is a categorical variable accounting for the maximum area covered by Haida eddy equaling 1, 2 or 3 for small, medium and large area, respectively, and  $I(\cdot)$  is the indicator function.

Model	Covariates	Period
1	$\mu_t = \alpha + \beta_1 EP-NP_{t-1}$	1950-2010
2	$\mu_t = \alpha + \beta_1 PASLa_{t-1}$	1954-2010
3	$\mu_t = \alpha + \beta_1 PDO_{t-1}$	1950-2010
4	$\mu_t = \alpha + \beta_1 NPGO_{t-1}$	1950-2010
5	$\mu_t = \alpha + \beta_1 EP-NP_{t-1} + \beta_2 NPGO_{t-1} + \beta_3 SOI_{t-1}$	1950-2010
6	$\mu_t = \alpha + \gamma_{1,i} I(H\text{Emax}C_{t-1} = i)$	1993-2010

The merging at step 5 is straightforward because of the Bayesian approach used in step 2. A non-Bayesian approach (e.g. maximum likelihood estimation or bootstrapping) at step 2 would not be straightforward, requiring assumptions about the distribution of the estimated parameters ( $\alpha$ ,  $\beta_1$ ,  $\beta_2$ ,  $\beta_3$ ,  $\gamma_{1,i}$ ) in order to merge the 150 sets of results at step 5. This whole approach then allows us to account for the uncertainties in recruitment that were estimated by the SCA model (Edwards et al., 2012).

We used common vague normal prior distributions, with a mean of zero and standard deviation of 100, for all regression parameters ( $\alpha$ ,  $\beta_1$ ,  $\beta_2$ ,  $\beta_3$ ,  $\gamma_{1,i}$ ). For the strictly positive variance parameter  $\sigma^2$  we use a weakly informative inverse-gamma distribution with a shape of 1 and a rate of 0.1. Convergence was checked using the Gelman-Rubin convergence test (Gelman and Rubin, 1992). All calculations were performed in JAGS or R version 3.2.1 (R Development Core Team, 2015). Future investigations could maybe further utilise the Bayesian results by using odds ratios.

### F.3. RESULTS

Examples of models fitted to the POP recruitment time series are provided in Table F.1. Covariates covering the same period were included in a model only if they were not correlated with each other. When there were more than two covariates available for a given time period, correlations were checked between each pair of them, and correlated covariates were not included in the same model. Note that we cannot use model-selection criteria (e.g. DIC, BIC) to select an overall most supported model, because different datasets (different period of time of recruitment) were used for different models (Burnham and Anderson, 2002).

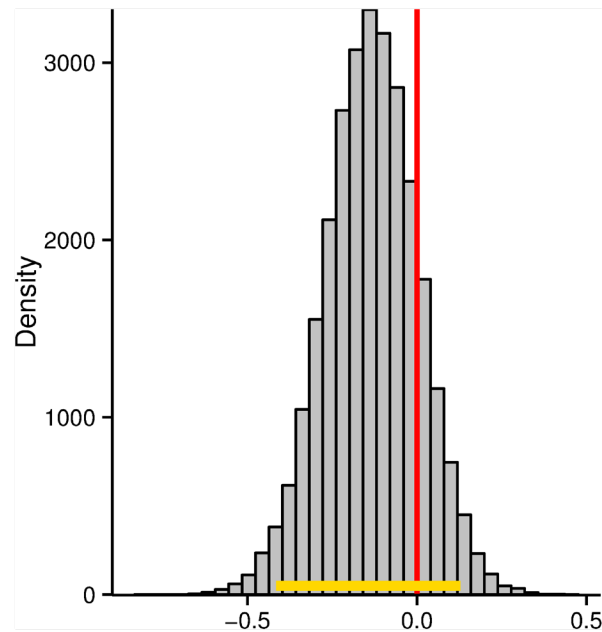


Figure F.5. For Model 1, histogram of samples from the posterior distribution of the  $\beta_1$  parameter which represents the effect of the East-Pacific/North-Pacific Index. The vertical red line represents no effect and the horizontal gold bar represents the 90% credible interval. We consider there to be an effect of a covariate if the credible interval of its corresponding parameter does not overlap zero – here (and in all results shown) the credible interval overlaps zero and so we conclude there to be no linear effect of the covariate.

Model 1 included only the EP-NP (East-Pacific/North-Pacific) index as a climatic covariate (Table F.1). The histogram of samples from the posterior distribution of the effect of the EP-NP index,  $\beta_1$ , is shown in Figure F.5. The 90% credible interval of  $\beta_1$  includes zero and so we conclude that there is no linear effect of the EP-NP index on POP recruitment.

Model 2 is for the PASLa (adjusted sea-level in Prince Rupert) and covers a shorter time period (1954-2010) than Model 1 due to the shorter time series of sea-level pressure (Table F.1). The results are similar to those for Model 1 – there appears to be no linear effect of PASLa on POP recruitment (Figure F.6).

Similar results were found for Model 3 (Figure F.7) and Model 4 (Figure F.8) for the PDO (Pacific Decadal Oscillation) and NPGO (North Pacific Gyre Oscillation), respectively.

Model 5 included three uncorrelated covariates for which the 90% credible intervals for all three effects parameters ( $\beta_1$ ,  $\beta_2$  and  $\beta_3$  for Model 5 in Table F.1) all included zero, and so no linear effects on recruitment could be ascertained (results not shown).

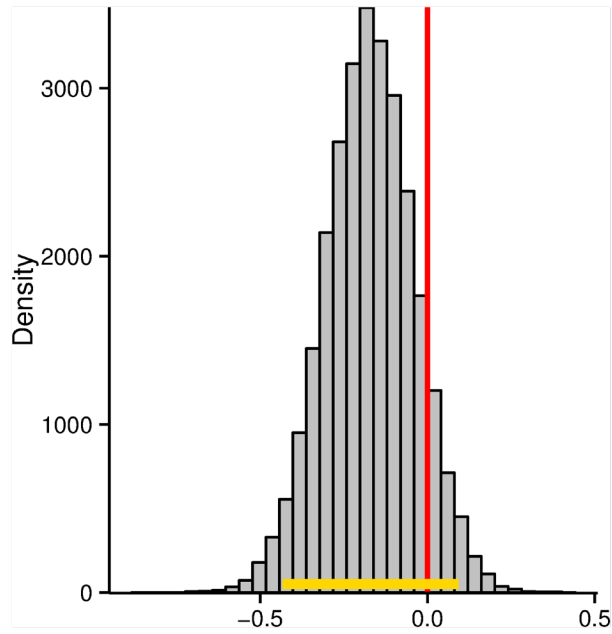


Figure F.6. As for Figure F.5 but for Model 2, for which  $\beta_1$  represents the influence of the sea level at Prince Rupert on recruitment.

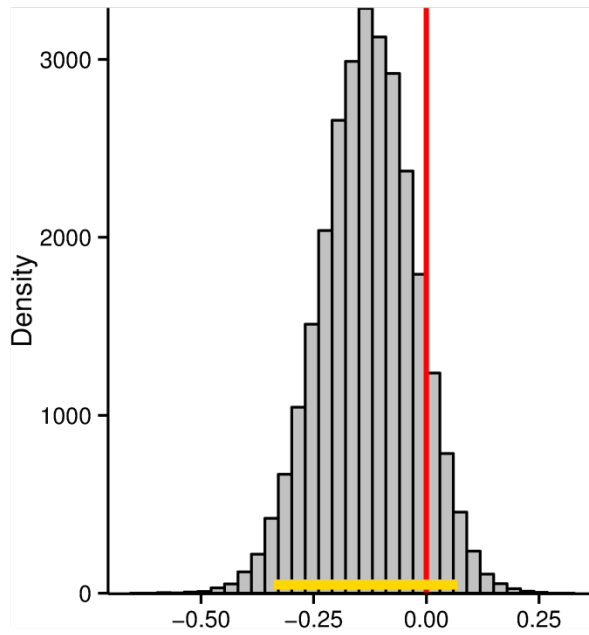


Figure F.7. As for Figure F.5 but for Model 3, for which  $\beta_1$  represents the influence of the Pacific Decadal Oscillation Index on recruitment.

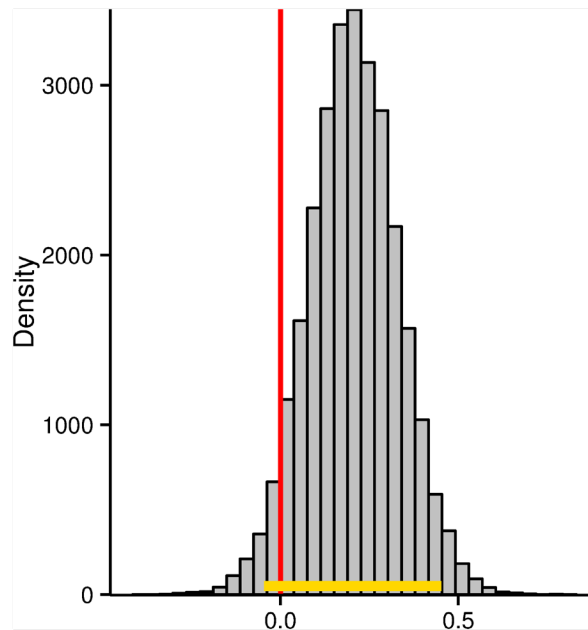


Figure F.8. As for Figure F.5 but for Model 4, for which  $\beta_1$  represents the influence of the North Pacific Gyre Oscillation on recruitment.

A linear model containing only HEmax, the maximum area of Haida eddies, also resulted in the 90% credible interval of  $\beta_1$  overlapping zero (results not shown). Thus, a categorical variable, HEmaxC, was created by splitting HEmax into three classes to capture a potential nonlinear effect, resulting in Model 6 that uses equation (F.4). The class of small eddies was set as the baseline effect ( $\gamma_{1,1} = 0$ ). Neither the medium or upper classes have an effect on POP recruitment compared to the baseline class (Figure F.9). Therefore, Model 6 demonstrates no presence of a nonlinear effect of the area of Haida eddies on POP recruitment.

These models are shown as examples of the tested models. All similar combinations of models (with uncorrelated covariates) were tested, but no linear or nonlinear effects on recruitment were found for any covariates.

## F.4. DISCUSSION

### F.4.1. Conclusions for modelling POP recruitment

With the climatic and environmental variables that we selected, we were unable to detect any conditions that appeared to strongly influence POP recruitment. We had hypothesised that favourable recruitment conditions might include basin-scale atmospheric circulations that create southward coastal winds, and medium-sized Haida eddies that may influence transport of POP larvae from marine canyons up into the shelf waters that represent favourable juvenile habitat. However, our results imply that we currently should not incorporate climatic or environmental drivers of recruitment into the stock assessment model, since we could not detect any such drivers of recruitment variability. Therefore, for this stock assessment we retain the modelling approach used in our previous assessment (Edwards et al., 2012).

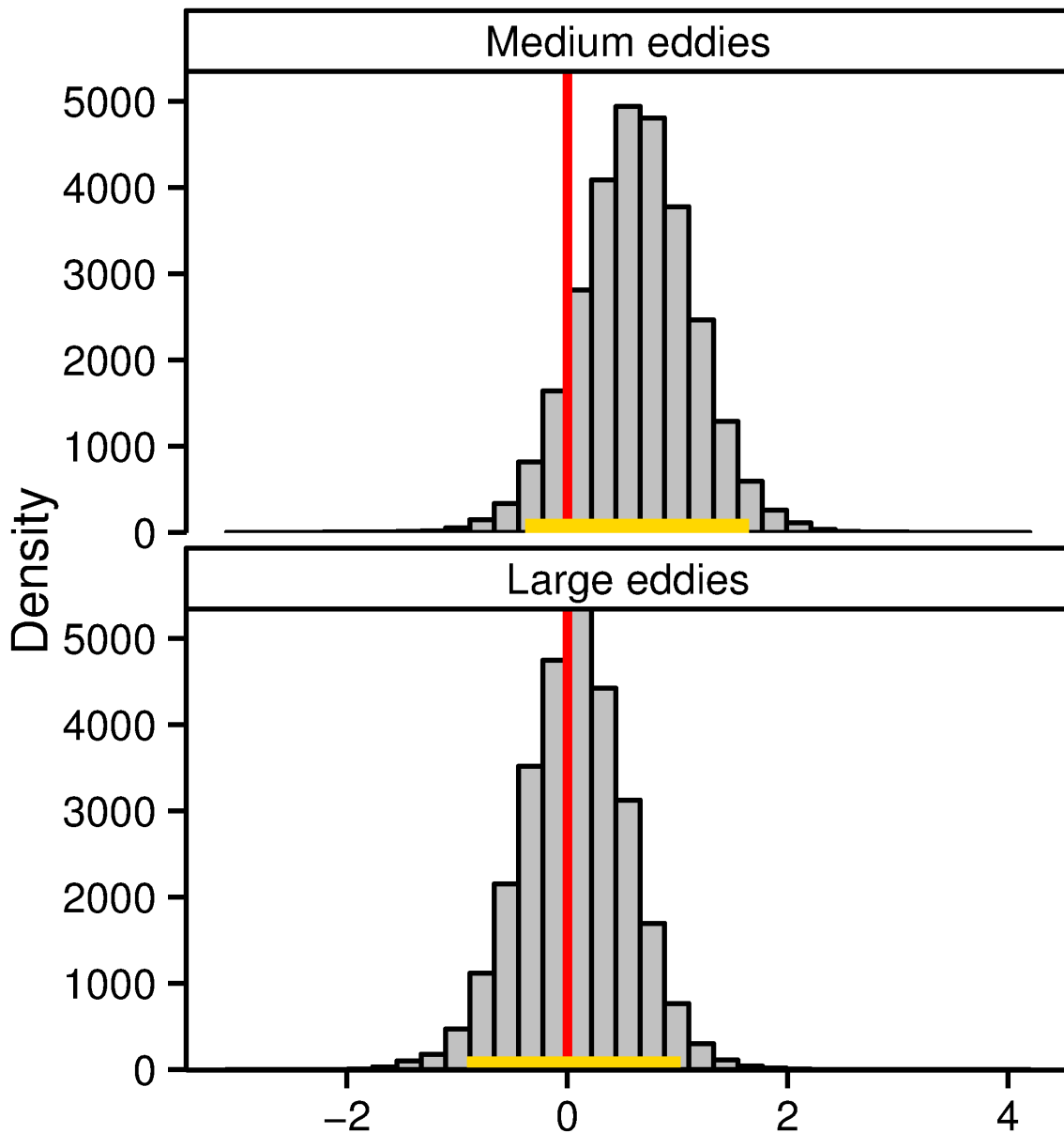


Figure F.9. For Model 6, histograms of samples from the posterior distributions of the  $\gamma_{1,2}$  and  $\gamma_{1,3}$  parameters that account, respectively, for the effect of the middle class of HEmaxC and the upper class of HEmaxC (medium and large Haida eddies, respectively). The vertical red lines represent the baseline effect of small eddies (because  $\gamma_{1,1}$  is set to 0) and the horizontal gold bars represent the 90% credible intervals. Given the red lines fall within the gold bars, we conclude there to be no influence of Haida eddies on POP recruitment.

We had anticipated that our Bayesian modelling approach might provide evidence of climatic and environmental variables that characterize ecosystem conditions associated with favourable POP recruitment. These variables are generally available within a year, whereas POP will not



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be observed in the ongoing QCS trawl survey or the commercial fishery until they are about 9-13 years old (Edwards et al., 2012). So, for example, in 2016 we may have climatic and environmental variables up until 2014-2015, but no ageing data concerning POP that were spawned after 2007. If we had found a positive influence of, say, the North Pacific index on POP recruitment then we could have used the known index from 2007-2015 to estimate whether the intervening years 2007-2015 were likely to be favourable (or unfavourable) for POP recruitment. Such information could then have been included in advice to fisheries managers. But due to the lack of any influences, such ecosystem information cannot be incorporated into advice for managers (or indeed into the stock assessment model and its projections).

#### **F.4.2. General comments on our Bayesian approach to investigating influences on recruitment**

Our proposed Bayesian approach aims to identify relationships between a suite of climatic and environmental variables and fish recruitment. It offers an elegant and theoretically consistent framework for the inclusion of recruitment uncertainty. Using a suite of climatic and environmental variables can allow utilization of more than one correlation to build a robust conceptual mechanism of the climatic and environmental processes influencing fish recruitment, potentially avoiding the pitfalls of reliance on a single, often proxy, variable (Myers, 1998). Model selection was not performed in this study because different datasets (different recruitment time periods) were used in the proposed models (Burnham and Anderson, 2002). To investigate the potential influence of the climate and the environment on recruitment, it is important to rely on multiple correlations, hence multiple models, rather than using the most supported model. Our method highlights the main characteristics of how the ecosystem can impact fish recruitment, which can easily be integrated into additional Bayesian approaches to providing advice, such as Bayesian model averaging or Bayesian decision-network models. Bayesian model averaging (Hoeting et al., 1999) has been used to provide advice when equally plausible assessment scenarios, based on the same dataset, were tested (Brodziak and Piner, 2010). Bayesian decision networks are useful tools to provide management advice under uncertainties and also have been applied in a stock assessment context (Kuikka et al., 1999; Araujo et al., 2013; Varkey et al., 2013).

A strength of the Bayesian approach in fisheries science is the ease with which it handles various sources of uncertainty and provides results (e.g. decision tables) that summarize uncertainty for decisions makers (McAllister and Kirkwood, 1998; Hammond and O'Brien, 2001; Patterson et al., 2001). The optimal approach to incorporating climatic and environmental forcing on recruitment will be to utilize a full Bayesian approach from start to finish in the stock assessment process.

The main advantages of a full Bayesian approach is that uncertainties are accounted for and are transferable across each modelling component, from identifying the conceptual mechanism, to population modelling, to the development of management options (McAllister and Kirkwood, 1998; Hammond and O'Brien, 2001; Patterson et al., 2001; Hvingel and Kingsley, 2006; Edwards et al., 2012). Our Bayesian approach can be used as the first step in an ecosystem approach to management, using climatic and environmental indicators and the quantification of uncertainty of ecosystem states to recruitment scenarios. It can be applied to other stocks for which appropriate data and estimates of recruitment are available.

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## F.5. ANNEX: DETAILS OF THE RECALCULATION OF AREA COVERED BY HAIDA EDDIES (BY ROBERT BOWEN)

The computation of the area covered by Haida eddies is based on the threshold technique from Crawford (2002) and is recalculated over the period 1993-2014. Aside from extending the time period, the new altimetry data, provided by the Colorado Center for Astrodynamics Research, were comprised of higher resolution images where pixel size = 6.48km<sup>2</sup>, compared to 20.7km<sup>2</sup> of Crawford (2002), thus enabling delineation of sea surface height anomalies with a more accurate selection of threshold boundaries. The data were also available daily, rather than once every three days. Crawford (2002) selected a wide range (-30 cm to +30 cm) for the dynamic colour interval. We selected a narrower range (0 cm to +30 cm) which led to better edge detection of threshold boundaries. The major improvement of our approach compared to Crawford (2002) is the addition of a compound warp transformation for image rectification.

The downloaded images of modelled satellite altimetry data are rectangular and do not account for the non-uniform distances between degrees of longitude with respect to latitude. We applied a two-step compound warping transformation to rectify these images to create square pixels: first the image was transformed to account for the change in longitude with respect to latitude, and then the image was transformed to account for the uneven distances between degrees of latitude. For the first step, a scaled warp template based on one-degree latitude intervals (40°N to 60°N) of diminishing distances between 150°W and 120°W was created using a vector drawing program (Coreldraw 7X). Within Photoshop CC, the downloaded images were transformed to conform to this scaled warp template. To correct for uneven distances between degrees of latitude, an evenly spaced grid (spanning 40°N to 60°N at one-degree increments) was projected onto the warped image in Photoshop CC. The image was then rubber sheeted to line up with the grid. An action script was created within Photoshop CC that systematically applied this compound warp transformation, selected all pixels within the sea surface height anomaly threshold, and summed these pixels to obtain daily eddy areas. The proposed threshold technique to compute area covered by Haida eddies can also be applied to Sitka eddies which form off the northern coast of British Columbia.

## F.6. REFERENCES – CLIMATIC IMPACTS

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## APPENDIX G. ASSESSMENT SCHEDULE AND INTERIM YEARS BETWEEN ASSESSMENTS

There is no set schedule for assessments of the POP 5ABC stock, with the most recent three assessments being for the start of 2017 (this assessment), 2010 (Edwards et al., 2012) and 2001 (for Goose Island Gully only, extrapolated to the full coast; Schnute et al. 2001). It may be expected that the next full stock assessment will therefore be in five to seven years.

Many DFO assessments are moving to a multi-year schedule (rather than being conducted every year) to provide stability to harvesters and reduce the frequency of peer-reviewed stock assessments (DFO, 2016). Consequently, DFO (2016) provided guidelines for producing updates for the interim years between full stock assessments. These guidelines include evaluating indicators that are proxies of stock status, and defining trigger values that are ‘thresholds of an indicator which if crossed would signal a change in stock status that may warrant a re-assessment ahead of schedule or changes to management measures ...’.

Potential indicators come from the data inputs to the assessment model. The QCS synoptic survey is the only ongoing survey that is explicitly designed to provide an index for groundfish species in 5ABC. The QCS shrimp survey is used in the model, but has a large coefficient of variation and provides a noisy signal that does not appear to closely track the estimated biomass of POP (Figure E.1) and therefore is not appropriate as a potential interim-year indicator. The otoliths for the ageing data are only analysed when an assessment is due, and so cannot be used on an interim basis. The other model input is the time series of annual catches, which can be updated fairly easily each year. But this is not used in the model as a stock index and so is not a suitable indicator. Similarly, catch-per-unit-effort data are not suitable as an index because, particularly in a multi-species fishery, catches of a single species can change for a variety of reasons.

Thus, only the QCS synoptic survey appears suitable as a potential indicator. The survey is currently scheduled for 2017, 2019, 2021, etc. However, even though the survey index is a prime input to the model, it is not always an accurate estimate of the estimated spawning biomass (e.g. years 2003 and 2007 Figure E.1). This suggests that a change in the survey index for a year or two may not be representative of a change in the biomass. Waiting for three survey indices means requiring the 2021 survey, by which time (or shortly after) the next full assessment will likely be requested. Also, deriving the survey estimate is not a trivial task (Appendix B).

To properly ascertain a suitable trigger point would require simulation testing to ensure that the trigger is not too easily crossed when in fact the biomass has not substantially changed, or it is not crossed when in fact the biomass has substantially changed. In particular, such simulations would have to consider the uncertainty in the survey estimate and the Bayesian uncertainty in the survey catchability parameter ( $q_2$ ). There were not resources available to conduct such simulations.

We suggest the next full stock assessment be scheduled for 2022, such that there will be three new indices from the QCS synoptic survey and five years of ageing and catch data. For reasons noted above, we are unable to propose indicators that could be monitored in the interim years. But we do note that *advice* for the interim years is explicitly included in this assessment in the form of the decision tables.

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