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Rougheye/Blackspotted Rockfish (*Sebastes aleutianus/melanostictus*) stock assessment for British Columbia in 2020

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Foreword

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

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ABSTRACT

The Rougheye/Blackspotted Rockfish (REBS, *Sebastes aleutianus/melanostictus*) species complex is ubiquitous along the British Columbia (BC) coast, with trawl catches taken primarily from the depth range of 135-845 m. Fisheries using trawl gear find highest densities off NW Haida Gwaii, at the mouths of Moresby and Mitchell's Gullies, and off the NW coast of Vancouver Island. Fisheries using hook and line gear catch REBS along the 500 m isobath with the highest densities occurring off NW Haida Gwaii. REBS prefer soft substrata in sloping areas with frequent boulders.

In April 2007, the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) assessed the REBS complex, comprising a pair of sympatric species, as 'Special Concern'. In 2009, REBS was added to SARA's Schedule 1 as Special Concern. Since then, no changes have been made to the status of the species complex. At the time of this assessment, the taxonomy was emerging and these species were named Rougheye Rockfish Type I and Type II, where Type I corresponded to Blackspotted Rockfish (BSR) and Type II denoted Rougheye Rockfish (RER). Although procedures for separating the two species, based on genetic analyses and various biomarkers, are available, species allocation methodologies to be applied to historical data still need to be developed. In this stock assessment, the two stocks are spatially defined by Pacific Marine Fisheries Commission areas, where REBS data from areas 5DE are called 'REBS north' and REBS data from areas 3CD5AB are called 'REBS south'. REBS data from area 5C were considered to be in a zone of hybridisation and consequently were omitted from the stock assessment except to proportionately distribute the 5C catch between the two species (~65-70% in favour of REBS north).

This stock assessment evaluates two stocks along the BC coast, REBS north and REBS south, which are harvested by multiple fisheries. The assessment uses an annual catch-at-age model tuned to one fishery-independent trawl survey series for REBS north and three surveys for REBS south, a bottom trawl CPUE series for both, annual estimates of commercial catch since 1935, and age composition data from survey series (spanning 1997-2016) and commercial fisheries (spanning 1978-2018). The model starts from an assumed equilibrium state in 1935. Two fisheries are modelled: one a combined bottom and midwater 'Trawl' fishery and an 'Other' fishery, which combines halibut longline, sablefish trap, lingcod/dogfish/salmon troll, rockfish hook and line, etc. The second fishery is a compromise that acknowledges other methods capturing this species while keeping the model complexity to a minimum, given the lack of good information from these additional fisheries.

For each stock, nine base model runs using a two-sex model were implemented in a Bayesian framework (using the Markov Chain Monte Carlo procedure) under a scenario that fixed natural mortality to three levels (0.035, 0.045, 0.055) using three CPUE process errors (0.1, 0.2759 for REBS north or 0.2529 for REBS south, 0.4) each. Steepness of the stock-recruit function was fixed at 0.7; catchability for the surveys and CPUE, and selectivity for three of the four surveys and the commercial trawl fleet were estimated. Of the candidate component runs, nine were combined into a composite base case for REBS north and six were combined into a composite base case for REBS south. Each composite base case explored two major axes of uncertainty, namely, natural mortality M and CPUE process error, which modified the degree of fit to the CPUE biomass series. Sensitivity analyses were performed to test the effect of alternative model assumptions (e.g., wider ageing error matrices).

Stock status at the beginning of 2021 for the REBS north composite base case lies in the Healthy zone with a probability of 1, as do all nine component runs. The composite base case population trajectory from 1935 to 2021 and projected biomass to 2096, assuming a constant catch strategy of 600 t/y (just above the 5-year average catch of 548 t), indicates that the

median stock biomass will remain above the USR for the next 1.5 generations (75 years). The probability envelope around the constant catch strategy will extend into the Cautious and Critical zones due to a much larger cumulative removal than that under a harvest rate strategy of 0.1/year. A phase plot of the time-evolution of spawning biomass and exploitation rate in the two modelled fisheries in MSY space suggests that the stock is in the Healthy zone, with a current position at $B_{2021}/B_{\mathrm{MSY}}$ = 2.21 (1.50, 3.15), $u_{2020(\mathrm{trawl})}/u_{\mathrm{MSY}}$ = 0.06 (0.02, 0.14), and $u_{2020(\mathrm{other})}/u_{\mathrm{MSY}}$ = 0.11 (0.03, 0.32).

Stock status at the beginning of 2021 for the REBS south composite base case lies in the Healthy zone with a probability of 0.74 and in the Cautious zone with probability 0.26. The composite base case population trajectory from 1935 to 2021 and projected biomass to 2096, assuming a constant catch strategy of 300 t/y, indicates that the median stock biomass will eventually crash at the current amount of removals (5-year average catch of 291 t). The fixed harvest rate strategy appears to offer a more sustainable catch strategy, with median projected biomass remaining above the USR for the next 1.5 generations (75 years). A phase plot of the time-evolution of spawning biomass and exploitation rate in the two modelled fisheries in MSY space suggests that the stock is in the Healthy zone, with a current position at $B_{2021}/B_{\mathrm{MSY}}$ = 1.07 (0.58, 2.61), $u_{2020(\mathrm{trawl})}/u_{\mathrm{MSY}}$ = 1.17 (0.19, 2.59), and $u_{2020(\mathrm{other})}/u_{\mathrm{MSY}}$ = 0.72 (0.13, 1.77). The Trawl fishery's harvest rate is above that at u_{MSY}.

1. INTRODUCTION

In April 2007, the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) assessed the Rougheye/Blackspotted Rockfish (REBS, *Sebastes aleutianus/melanostictus*) complex, comprising a pair of sympatric species, as 'Special Concern' (COSEWIC Assessment and Status Report 2007; COSEWIC Annual Report 2007). In 2009, REBS was added to SARA's Schedule 1 as Special Concern. Since then, no changes have been made to the status of the species. The original reasons for listing REBS included:

- abundance indices and biomass estimates were uncertain and possibly compromised by short time series;
- survey techniques were not always appropriate for the species;
- strong trends were not observed in the available abundance indices;
- observed truncation of the age distribution from 1997 to 2003 suggested that mortality from all sources had doubled over that time period (0.045/year to 0.091/year);
- life-cycle vulnerability was assumed: long-lived, low-fecundity *Sebastes* species, being particularly susceptible to population collapse and recovery, could be compromised when the age and/or size distributions are truncated by fishing;
- cryptic species harm was assumed: difficulty in separating two REBS species increased the risk of potential impacts on one of the species going unnoticed.

At the time, the taxonomy was emerging (Gharrett et al. 2005) and these species were named Rougheye Rockfish Type I and Type II, where Type I corresponded to Blackspotted Rockfish (BSR) and Type II denoted Rougheye Rockfish (RER). The taxonomy separating the two species is clearer now (Orr and Hawkins 2008; Garvin et al. 2011; Harris et al. 2019) and genetic analyses can identify BSR, RER, and hybrids (F_1 or first generation hybrid = BSR×RER, F_2 or second generation hybrid = F_1×F_1).

The two REBS species are ubiquitous along the BC coast, with complete overlap in the distribution of each species and with most catches taken close to the bottom over depths of 200 to 800+ m along the shelf break. Overall, this species complex is known to range from northern Japan to southern California. These two species are among the longest lived *Sebastes*, with maximum recorded ages of 147 years (off NW Haida Gwaii) and 125 years (Moresby Gully) in BC waters, and 205 years in Southeast Alaska (Munk 2001, most likely a Type I specimen). In BC, abundance information for REBS is derived from synoptic surveys and from the commercial fishery. The two species are intercepted primarily by trawl nets, hook and line gear, and deepwater traps, and is a key species caught in the BC multispecies integrated groundfish fishery.

New methodologies must be developed before stock assessments based on reliable species-specific data can be attempted. Such stock assessments will require developing procedures capable of allocating historical catches (commercial and survey) by species. This is needed because the large majority of the historical information has been reported as RER but comprises the combined species complex REBS. Differentiating between these two species can only be done at present through genetic sampling and to a lesser degree otolith morphology; it remains difficult to identify these species by visual inspection quickly and reliably.

In the interim, while allocation methodologies are being developed, these two stocks have been delimited by Pacific Marine Fisheries Commission (PMFC[1]) areas, where REBS data from areas 5DE are called 'REBS north' and REBS data from areas 3CD5AB are called 'REBS south'.

[1] See Appendix A for historical background on the PMFC.

REBS data from area 5C are considered to be in a zone of hybridisation (Creamer 2016) and consequently omitted from the stock assessment except to proportionately distribute the 5C catch between the two stocks species (~65-70% in favour of REBS north).

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

- sex-specific parameters;
- abundance indices by year (y):
  - REBS north:
    - one synoptic survey – WCHG = west coast Haida Gwaii (8y),
    - one commercial bottom trawl CPUE (24y);
  - REBS south:
    - two synoptic surveys – QCS = Queen Charlotte Sound (10y) and WCVI = west coast Vancouver Island (8y),
    - one historical survey – NMFS Triennial = US National Marine Fisheries Service Triennial off WCVI (3y)
    - one commercial bottom trawl CPUE (24y);
- proportions-at-age data (also called age frequencies or 'AF') by year (y):
  - REBS north
    - WCHG Synoptic (7y), commercial trawl fishery (19y), commercial other fishery (6y);
  - REBS south:
    - QCS Synoptic (3y), WCVI Synoptic (3y), commercial Trawl fishery (5y), commercial Other fishery (1y);
- maximum modelled age of 80 y, with older ages accumulated into the final age class;
- estimated selectivities for the commercial fishery and for the synoptic surveys.

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

DFO Fisheries Management requested that DFO Science provide advice regarding the assessment of two stocks relative to reference points that are consistent with the DFO fishery decision-making framework incorporating the Precautionary Approach (DFO 2009), including the implications of a range of harvest strategies on stock status. In the absence of updated science advice, there is uncertainty about the risks posed to the BC stocks at current TAC (total allowable catch) levels. This stock assessment provides the first population-based model for these species and provides information on stock status and harvest advice.

1.1. ASSESSMENT BOUNDARIES

This assessment includes PMFC major areas (5DE for REBS north and 3CD5AB for REBS south) along the BC coast (Figure 1). These stocks were inferred from work by Creamer (2016) and adopted in the absence of reliable allocation methodologies based on genetics. The available biological data were examined for evidence of area and genetic differences (see Section D.3); however, the differences in allometry and growth were minimal, given the available data. There were substantial differences in selectivity by survey and fishery, some of this based on gear type (trawl, longline, and trap, Appendix D).

PMFC areas are similar but not identical to the management areas used by the Groundfish Management Unit (GMU), which uses combinations of DFO Pacific Fishery Management Areas. We have not used GMU management areas because catch reporting from these areas has only been available since 1996. However, PMFC areas are sufficiently similar to the GMU areas such that managers can prorate any catch strategy using historical catch ratios outlined in Appendix ARange and Distribution

REBS is ubiquitous along the BC coast (Figure 2), with trawl catches taken primarily from the depth range of 135-845 m (Figure G.2). Depth distributions by stock (REBS north, REBS south) do not differ greatly from the coastwide depth distribution. Fisheries using trawl gear find highest densities off NW Haida Gwaii, at the mouths of Moresby and Mitchell's Gullies, and off the NW coast of Vancouver Island (Figure 2, left). Fisheries using hook and line gear catch REBS along the 500-m isobath with the highest densities occurring off NW Haida Gwaii (Figure 2, right). REBS prefer soft substrata in areas with frequent boulders as well as slopes greater than 20° (Love at al. 2002). Boulders may act as territorial markers, current deflectors, or structures that help them hunt for prey (Krieger and Ito 1999).

Creamer (2016) developed a model, based on presumed known survey species proportional splits by tow, which predicted the BSR/RER species composition based on a range of tow characteristics, including spatial location, depth, and bottom heterogeneity (also called 'rugosity'). A similar model was then applied to commercial catch to estimate the species composition of the catch. Because the model required detailed location data from the commercial fishery, which were not available to Creamer due to confidentiality, the model was applied in 0.5 degree grids. While this study demonstrated that it is possible to use known species data to estimate species proportions in fisheries without such data, it is necessary to validate such procedures before they can be used in a stock assessment context. The most useful aspect of this work was the demonstration that there was a strong north/south cline to the species distribution, with BSR more likely to be found in the western part of BC (i.e., the west coast of Haida Gwaii).

Appendix G provides maps of catch hotspots (cumulative catch from 1996 to 2019) by fishing locality for each fishery (Figures G.7-G.11). The three top hotspots, by fishery, are:

- Trawl – Frederick Island, South Hogback, Langara Spit Outside/Whaleback;
- Halibut – Langara Spit Outside/Whaleback, Frederick Island, North Fred-Langara (deep);
- Sablefish – Langara Spit Outside/Whaleback, Fred Spot, Buck Point;
- Dogfish/Lingcod – South Hogback, Anthony Island, Flamingo Inlet;
- H&L Rockfish – South Hogback, Marble Island, Frederick Island.

Note that seamount data were excluded from this assessment. Most hotspots occur in area 5E.

Appendix G also provides species that appear concurrently in the fishery with REBS (labelled 'Rougheye Rockfish' because the fisheries only identify the two species as one). Additionally, a cluster analysis (Figure G.15) suggests that REBS is most frequently grouped with Shortspine and Longspine Thornyhead (deep-water species, >600 m), and to a lesser degree with Pacific Ocean Perch, Yellowmouth Rockfish, and Redbanded Rockfish (mid-water species, ~300 m).

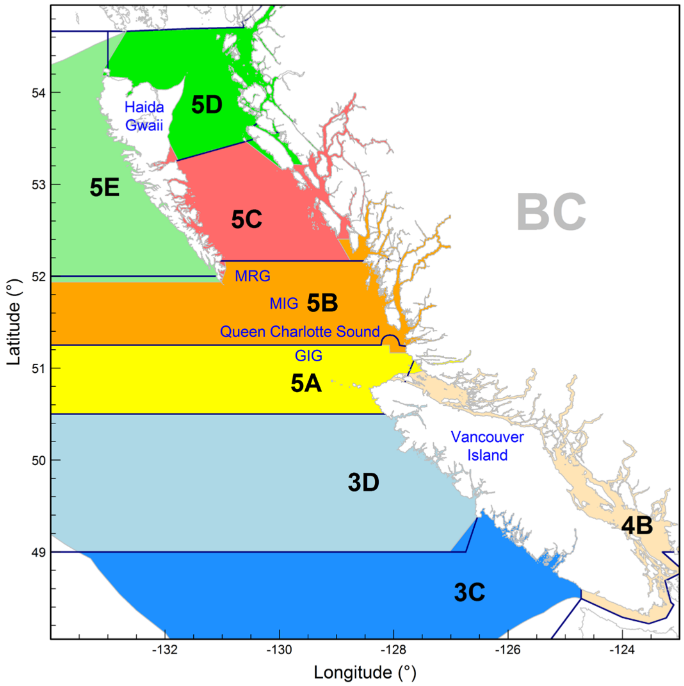

Figure 1. Pacific Marine Fisheries Commission (PMFC) major areas (outlined in dark blue) compared with Groundfish Management Unit areas (shaded). For reference, the map indicates Moresby Gully (MRG), Mitchell's Gully (MIG), and Goose Island Gully (GIG). This assessment covers 5DE for REBS north and 3CD5AB for REBS south.

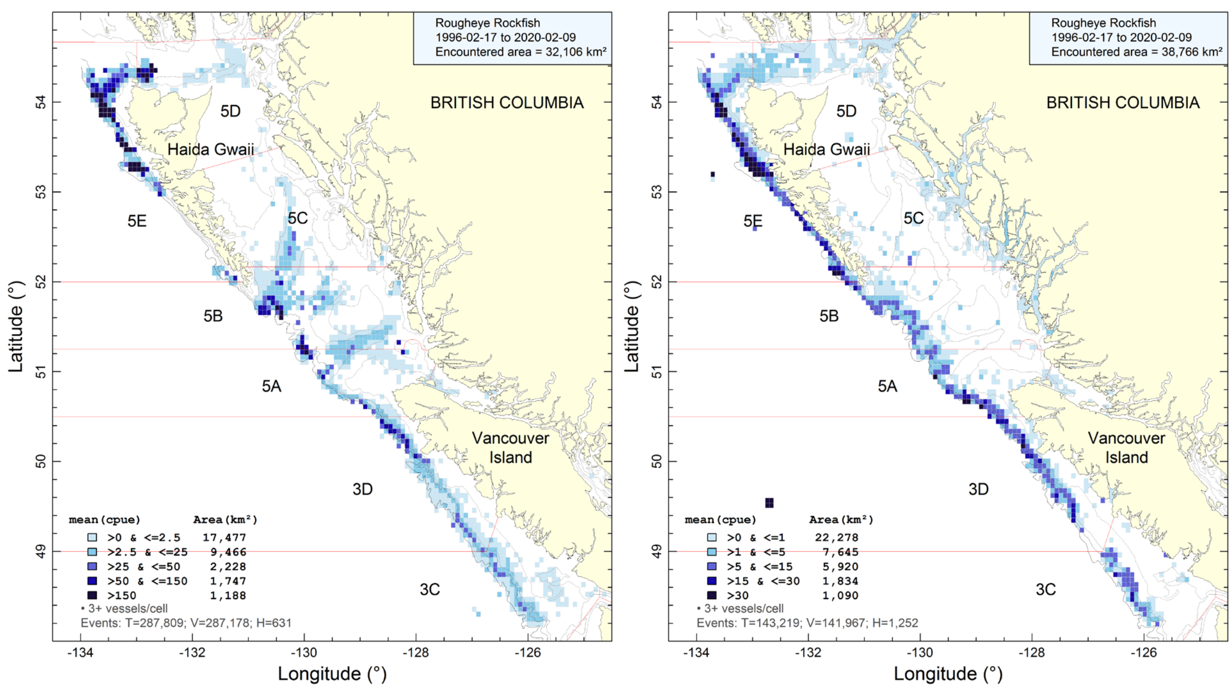

Figure 2. Density distribution of REBS (labelled 'Rougheye Rockfish') caught by bottom and midwater trawl (left) and hook and line gear (right) using mean catch per unit effort (kg/hour) from 1996 to 2020 in grid cells 0.075° longitude by 0.055° latitude (roughly 32 km² each). Isobaths show the 100, 200, 500, and 1000 m depth contours. Note that cells with <3 fishing vessels are not displayed and density scales differ between figures.

2. CATCH DATA

This stock assessment recognises two commercial fisheries: (i) 'Trawl' – a combined bottom and midwater trawl fishery (with the bottom trawl predominating), and (ii) 'Other' – fisheries using other (than trawl) capture methods, which combines halibut longline, sablefish trap, lingcod/dogfish/salmon troll, and rockfish hook and line. Recreational REBS catches were not investigated. The catch-all fishery 'Other' was needed in recognition of the significant catches of REBS by non-trawl methods, but represents a compromise regarding model complexity and lack of information to properly characterise the 'Other' fishery, particularly if this fishery is to be subdivided into several component fisheries.

The methods used to prepare a catch history for this REBS assessment, along with the full catch history, are presented in detail in Appendix A. Information about species caught concurrently with REBS commercial catches is presented in Appendix G. The average annual REBS catch for all capture methods over the most recent five years (2015-19) was 548 metric tonnes (t) for REBS north and 291 t for REBS south.

3. FISHERIES MANAGEMENT

The REBS complex is intercepted primarily by trawl nets, hook and line gear, and deepwater traps, and is a key species caught in the BC multi-species integrated groundfish fishery. The species complex has been managed as a single population of REBS, pending advice on species identification methodologies and the implications of various harvest strategies on expected stock status for each species within the complex. Differentiating between these two species is done through genetic sampling because it is not feasible to distinguish between these species by visual inspection quickly and reliably. Recent research investigating using otolith morphology to identify REBS species may offer an alternative method for determining historical catches by species.

In 2012, DFO's GMU developed a Management Plan specifically for the REBS complex and Longspine Thornyhead (Fisheries and Oceans Canada 2012), as required when species are assessed as 'Special Concern' by COSEWIC. Appendix A summarises management actions taken for REBS in BC since 1993.

4. SURVEY DESCRIPTIONS

A limited set of fishery independent survey indices has been used to track changes in the biomass of this population coastwide (Appendix B):

For REBS north:

WCHG Synoptic – a random-stratified synoptic (species comprehensive) trawl survey covering the west coast (WC) of Graham Island in Haida Gwaii (HG) and the western part of Dixon Entrance. This survey has been repeated 7 times between 2006 to 2018 using three commercial vessels and a consistent design, including the same net and targeting a wide range of finfish species. The 2014 survey has been omitted from the series because less than ½ of the tows were completed. A WCHG survey operated in 1997, which used a similar design, was also added to this series.

HS Synoptic – a random-stratified synoptic trawl survey covering all of Hecate Strait and extending into Dixon Entrance across the top of Graham Island. This survey has been repeated 8 times between 2005 to 2019 using two vessels and a consistent design, including targeting a wide range of finfish species. This survey was not used in the stock assessment because of the low incidence of REBS in the catch (less than 10% of tows), the scarcity of the deep water habitat preferred by REBS, and the lack of REBS in the commercial catch in the same area, indicating that this survey is operating in sub-optimal habitat for this species complex.

For REBS south:

QCS Synoptic – a random-stratified synoptic trawl survey covering all of Queen Charlotte Sound (QCS) and targeting a wide range of finfish species. This survey has been repeated 10 times between 2003 to 2019, using three different commercial vessels but with a consistent design, including the same net.

WCVI Synoptic – a random-stratified synoptic trawl survey covering the west coast of Vancouver Island (WCVI). This survey was repeated seven times between 2004 to 2016 using the research vessel FV *Ricker* and was conducted in 2018 using a commercial vessel after the retirement of the *Ricker*. The survey employs a consistent design, including the same net, and targets a wide range of finfish species.

NMFS Triennial – the United States National Marine Fisheries Service (NMFS) Triennial survey series covered the lower half of the west coast of Vancouver Island for seven years from 1980 to 2001. Only the Canadian portion of the Vancouver INPFC (International North Pacific Fisheries Commission) area was used. The final three years (1995, 1998 and 2001) that this survey operated were used in this stock assessment because these were the years when a deep (367–500 m) stratum was added to the survey design. The four surveys that operated before 1995 did not go deeper than 367 m, omitting an important component of the REBS depth distribution.

GIG Historical – an early composite series of eight indices extending from 1967 to 1994 in Goose Island Gully (GIG). Most of these surveys were performed by the research vessel *G.B. Reed*, but two commercial vessels (*Eastward Ho* and *Ocean Selector*) were used in 1984 and 1994 respectively. Only tows located in Goose Island Gully (GIG) are used to ensure continuity across all surveys. This survey was not used in the stock assessment because the depth coverage was inadequate to monitor REBS, with the deepest tow at 287 m and only 10% of tows were deeper than 235 m.

The following surveys were also omitted from this stock assessment because of inadequate depth coverage for REBS: Hecate Strait Multispecies Assemblage bottom trawl survey, the WCVI Shrimp Trawl survey and the QCS Shrimp Trawl survey. The IPHC Longline survey was not used because of low incidence of REBS in the catch, inconsistent identification of groundfish species across years and a truncated depth range. The Hard Bottom Longline (North and South) survey was omitted because of the truncated depth range. Finally, the Standardised Sablefish Trap survey was not used because it was unclear how to interpret the catch of REBS in this survey, in terms of population representation, given that it is a passive survey and the consequent uncertainty on whether it offered a consistent inter-annual index. It was felt that using this survey would require a substantial analytical commitment requiring resources that were not available.

The relative biomass survey indices were used as data in the models along with the associated relative error for each index value. Process error, in the form of 0.25, was added to the survey relative errors (Appendix E).

5. COMMERCIAL CPUE

Commercial catch per unit effort (CPUE) data were used to generate indices of abundance as input to the model fitting procedure. This series of indices, extending from 1996 to 2019, provided stability to the population model. In 5DE, REBS is more likely to be targeted or taken in conjunction with tows targeting Pacific Ocean Perch, whereas REBS in 3CD5AB is primarily a by-catch fishery showing up in deeper tows directed at a range of species. The use of CPUE in this model, with observations in each year beginning in 1996, stabilised the minimisation procedure as well as the MCMC simulation. Consequently, the effect of the CPUE series on the stock assessment was investigated by varying the amount of process error used when fitting the model, with low process error resulting in a close fit to the series and higher process error allowing the model to effectively ignore the series (see Appendix F).

The CPUE abundance index series was standardised for changes to vessel configuration, catch timing (seasonality), and location of catch (e.g., latitude and depth) to remove potential biases in CPUE that may result from changes in fishing practices and other non-abundance effects. This procedure was followed in two steps, with the model fitted to the positive catches assuming a lognormal distribution and to the presence/absence of REBS assuming a binomial distribution. These two models were then combined using a multiplicative “delta-lognormal” or “hurdle” model (Eq. C.4: Fletcher et al. 2005). In these models, abundance was represented as a ‘year effect’ and the explanatory variables were selected sequentially by a General Linear Model, which accounted for variation in the available data. Other factors that might affect the behaviour of fishers, particularly economic factors, do not enter these models due to a lack of applicable data, thus resulting in indices that may not entirely reflect changes in the underlying stock abundance. Appendix C provides details and diagnostics for the CPUE analyses. Three levels of process error were added to the CPUE observation errors for this stock assessment: 0.1 for a close fit to the indices, 0.2759 for REBS north and 0.2529 for REBS south to get an appropriately weighted fit (see Appendix E for derivation of these values), and 0.4 to allow the model to effectively ignore the CPUE indices.

6. BIOLOGICAL INFORMATION

6.1. BIOLOGICAL SAMPLES

Age proportion/frequency (AF) samples collected from catches of REBS by the fisheries Trawl and Other (non-trawl) were used in the model for years when the number of samples was at least two: REBS north Trawl 1978-2017 (19 years available), REBS north Other 2004-2005 (2 years), REBS south Trawl 1998-2018 (5 years), and REBS south Other 1997 (1 year). Of the synoptic surveys suitable for REBS, AF samples were used from WCHG (7 years from 1997-2016) for REBS north, and QCS (3 years from 2011-2015) and WCVI (3 years from 2012-2016) for REBS south. Only otoliths aged using the ‘break and burn’ (B&B) method (or determined by thin-sectioning in 1978 for REBS north Trawl) were included in age samples used in this assessment because an earlier surface ageing method was known to be biased, especially with increasing age. During the 2018 Redstripe Rockfish review meeting, one participant mentioned that surface ageing is currently the preferred method for ageing very young rockfish (≤ 3y), which was later confirmed by the ageing lab. Commercial fishery age frequency data were summarised for each quarter, weighted by the REBS catch weight for the sampled trip. The total quarterly samples were scaled up to the entire year using the quarterly landed commercial catch weights of REBS. See Appendix D (Section D.2.1) for details.

Sampled AFs from bottom and midwater trawl were combined after comparing length distributions for each gear type by sex and capture year and concluding that there were no consistent differences in the selectivity between the two gear types for either sex (REBS north: Figure D.28, REBS south: Figure D.29). Consequently, the model was run assuming a joint selectivity for these two trawl methods by combining the AFs and the catch data into a single Trawl fishery. Despite very limited ageing data for the Other fishery, the estimation of a separate selectivity for this fishery was possible for both stocks. The selectivity priors used for the commercial fishery are detailed in Appendix E. For REBS north, which had the better set of AF data, the Trawl fishery selectivity priors were estimated using uninformed priors. The Other fishery used an informed prior for the age at maximum selectivity (assumed at a level that seemed consistent with cumulative length frequency data) while the other two selectivity parameters (left side variable and male shift parameter) were estimated with uninformed priors. For REBS south, which had very little AF data, particularly for the Other fishery, informed priors based on the respective REBS north posteriors for each parameter were used for both commercial fisheries.

The survey AFs were scaled to represent the total survey in a manner similar to that used for the commercial samples: within an area stratum, samples were weighted by the REBS catch density in the sampled tows; stratum samples were then weighted by the stratum areas (described in Appendix D, Section D.2.2). Age frequency data were sparse for all survey years from the three synoptic survey series used in the models. For REBS north, the data were sufficient to estimate the WCHG survey selectivity using an informed prior for the age at maximum selectivity (the same prior as used for the Other fishery) while the other two selectivity parameters were estimated with uninformed priors. The MCMC posteriors for the REBS north selectivity parameters showed acceptable diagnostics. For REBS south, the model estimated credible MPD parameters for the QCS and WCVI surveys using uninformed priors but the MCMC diagnostics were not acceptable, requiring these parameters to be fixed at the MPD estimates during the MCMC simulations. There were no biological data available from the NMFS Triennial survey, which required fixing the selectivity parameters based on assumed credible values loosely based on the Pacific Ocean Perch stock assessment.

6.2. AGEING ERROR

Ageing error (AE) is a common issue in most age-structured stock assessments. Figure D.24 suggests that REBS ages estimated by the primary readers were often not reproduced consistently by secondary readers when performing spot-check analyses. The base population models for REBS north and south, by necessity, used an ageing error matrix.

After some trials, one AE matrix was adopted: ‘moderate’ error for ages 1-80 from a normal distribution with quantiles 0.01 to 0.99 spanning seven age classes (±3 ages along rows off the diagonal, Figure D.25, left). Another AE matrix was used in sensitivity runs: ‘wide’ error for ages 1-80 from a normal distribution with quantiles 0.01 to 0.99 spanning eleven age classes (±5 ages along rows off the diagonal, Figure D.25, right). A ‘narrow’ AE matrix (±1 age) was tried, but models did not converge satisfactorily.

6.3. GROWTH PARAMETERS

Allometric (length vs. weight) and growth (age vs. length) parameters were estimated from REBS data using biological samples collected from all surveys conducted between 2003 and 2019 (Appendix D). As the ageing error discussed above (see Section 6.2) might bias the estimation of the growth parameters, growth models were fit in a Bayesian context while adjusting for ageing error using the Stan probabilistic programming language. The procedure fits the von Bertalanffy model as a random effects non-linear model (Sean Anderson 2019, DFO Groundfish, pers. comm.). The model was implemented under two ageing error assumptions: (i) CV of age by age readers’ determination of age, and (ii) CV of empirical lengths at age. The resulting models differed little among each other or with the maximum likelihood model fitted without ageing error (see Table D.5). Models that used the CV of lengths at age from all surveys were used in the stock assessment because pooling survey data allowed the greatest range of lengths and ages. In trials on REBS north, restricting the survey data to synoptic surveys (WCHG and HS) truncated the larger fish and provided growth parameter fits that did not seem credible; therefore, data from all available surveys in each stock area were used for the respective stocks.

Females by stock were only slightly larger on average than males (REBS north L_∞: Female = 51.8 cm, Male = 51.0 cm; REBS south L_∞: Male = 52.7 cm, Male = 50.8 cm). Genetically determined specimens (irrespective of area) were on average slightly larger than the stocks used in the assessment (BSR L_∞: Female = 52.2 cm, Male = 51.4 cm; RER L_∞: Female = 53.8 cm, Male = 51.4 cm).

6.4. MATURITY AND FECUNDITY

The proportions of females that mature at ages 1 through 80 were computed from biological samples. Stage of maturity was determined macroscopically, partitioning the samples into one of seven maturity stages (Stanley and Kronlund 2000; described in Appendix D). Fish assigned to stages 1 or 2 were considered immature while those assigned to stages 3-7 were considered mature. Data representing staged and aged females (using the B&B method) were pooled from research and commercial trips and the observed proportion mature at each age was calculated. All months were used in creating the maturity curve because these data provided cleaner fits to the model than using a subset of months. A monotonic increasing maturity-at-age vector was constructed by fitting a half-Gaussian function (Equation D.3, equivalent to that in Equation E.7) to the observed maturity values (Appendix D, Section D.1.3). The ogive used in the model assigned proportions mature to zero for ages 1 to 11, then switched to the fitted monotonic function for ages 12 to 80, all forced to 1 (fully mature) after the estimated age at full maturity (Table D.7). This strategy follows previous BC rockfish stock assessments where it was recognised that younger ages are not well sampled and those that are tend to be larger and more likely to be mature (e.g., Stanley et al. 2009). Females older than the estimated age at full maturity were assumed to be 100% mature and maturity was assumed to be constant over time. Fecundity was assumed to be proportional to the female body weight.

6.5. NATURAL MORTALITY

We were not successful in reliably estimating REBS north natural mortality (*M*) within the model because of difficulties in finding minima, given the considerable amount of ageing error assumed in the data. Models that appeared to minimise, estimated *M* to be greater than 0.06 along with having poor MCMC diagnostics, which were not thought to be credible. The American REBS stock assessments either fix or estimate *M* at values of 0.034 and 0.036 (Hicks et al. 2014; Shotwell and Hanselman 2019). These values appeared to be possibly low for BC REBS given that the 0.99 quantile of observed ages for REBS north was 99 and for REBS south was 83.7, with no apparent trend in this statistic over time (see Table D.8). Table D.9 gives estimates of *M* based on BC REBS data using two estimators (Hoenig 1983; Gertseva 2018, Northwest Fisheries Science Center, NOAA, pers. comm. citing Then et al. 2015 and Hamel 2015) across three trial maximum ages: REBS north (100, 125, 150) and REBS south (80, 100, 125). The *M* estimates based on the REBS north trial ages (*M*=0.035, 0.045, 0.055) were adopted for component runs of the base case for both stocks. Values less than 0.035 and greater than 0.055 were not explored because they were not supported by data or because they were not credible given the longevity of these species. See Appendix D for details.

6.6. STEEPNESS

In previous rockfish assessments, a Beverton-Holt (BH) stock-recruitment function was used to generate average recruitment estimates in each year based on the biomass of female spawners (Equation E.10). Recruitments were allowed to deviate from this average (Equations E.17 and E.24) in order to improve the fit of the model to the data. The BH function was parameterised using a ‘steepness’ parameter, *h,* which specified the proportion of the maximum recruitment that was available at 0.2 B_0, where B_0 is the unfished equilibrium spawning biomass (mature females). The parameter *h* has been estimated in past stock assessments (e.g., Starr and

Haigh 2021 a,b, 2022), constrained by a prior developed for west coast rockfish by Forrest et al. (2010) after removing all information for QCS POP (Edwards et al. 2012b). This prior took the form of a beta distribution with equivalent of mean 0.674 and standard deviation 0.168. For both stock assessment models, h was fixed to 0.7, which is close to the mean of the Forrest et al. (2010) steepness prior.

7. AGE-STRUCTURED MODEL

A two-sex, age-structured, stochastic model was used to reconstruct the population trajectory for each stock from 1935 to the beginning of 2021. Ages were tracked from 1 to 80, where 80 acted as an accumulator age category. The population was assumed to be in equilibrium with average recruitment and with no fishing at the beginning of the reconstruction. Selectivities by sex for the synoptic surveys (but not the NMFS Triennial) and the two commercial fisheries (Trawl and Other) were estimated using four parameters describing paired 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 (i.e., dome-shaped selectivity was not explored). The model and its equations are described more fully in Appendix E.

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

A composite base case for both stocks comprised multiple model runs (nine for REBS north, six for REBS south), and the MCMC posterior samples from them were pooled for scientific advice to managers. Decisions made during the stock assessment of REBS north and REBS south included:

- fixed natural mortality M to three levels: 0.035, 0.045, and 0.055 and applied three process error values to the commercial CPUE index c_p for a total of nine reference models (REBS north on left used all nine component runs, REBS south on right used a subset of six component runs specified by the regional peer review meeting based on MCMC diagnostics, see Appendix F):

REBS north	REBS south
B1 (R49) – fix M=0.035, c_p=0.10;	B1 (R18) – fix M=0.035, CPUE c_p=0.10;
B2 (R50) – fix M=0.035, c_p=0.2759;	B2 (R12) – fix M=0.035, CPUE c_p=0.2529;
B3 (R51) – fix M=0.035, c_p=0.40;	B3 (R15) – fix M=0.035, CPUE c_p=0.40;
B4 (R47) – fix M=0.045, c_p=0.10;	
B5 (R46) – fix M=0.045, c_p=0.2759;	B5 (R11) – fix M=0.035, CPUE c_p=0.2529;
B6 (R48) – fix M=0.045, c_p=0.40;	B6 (R14) – fix M=0.035, CPUE c_p=0.40;
B7 (R52) – fix M=0.055, c_p=0.10;	
B8 (R53) – fix M=0.055, c_p=0.2759;	
B9 (R54) – fix M=0.055, c_p=0.40;	B9 (R16) – fix M=0.035, CPUE c_p=0.40;

- used an age plus class A=80 for both stocks;
- used one survey abundance index series (WCHG Synoptic) with AF data for REBS north, and three survey abundance index series (QCS Synoptic, WCVI Synoptic, NMFS Triennial), the first two with AF data, for REBS south;
- used one commercial fishery abundance index series (bottom trawl CPUE) for both stocks;

- assumed two commercial fisheries for both stocks, with pooled catch and AF data:
  - Trawl: bottom + midwater trawl;
  - Other: non-trawl capture methods (longline, hook and line, trap);
- assumed two sexes (females, males);
- primarily used uninformed priors for REBS north selectivity parameters, with the exception of an informed prior for the age at maximum selectivity for the Other fishery and for the WCHG survey; for REBS south, informed priors based on the REBS north posterior estimates were used for the commercial fisheries while the survey selectivity parameters were fixed to MPD values;
- applied abundance reweighting: added CV process error to index CVs, c_p=0.25 for surveys and c_p= {low=0.1, medium=$0.2759_N|0.2529_S$, high=0.4} (see first bullet) for commercial CPUE series (see Appendix E);
- applied composition reweighting: adjusted AF effective sample sizes using the TA1.8 mean-age weighting method of Francis (2011);
- fixed standard deviation of recruitment residuals (σ_R) to 0.9;
- excluded water hauls from the WCVI Triennial series;
- used the 'moderate' ageing error matrix described in Appendix D, Section D.2.3.

All model runs were reweighted (i) one time for abundance by adding process error (see above) to the index CVs for synoptic surveys and commercial CPUE, and (ii) once or twice, depending on the run, for composition using the procedure of Francis (2011) for age frequencies.

Sensitivity analyses were run (with full MCMC simulations) relative to the central run of the composite base case (REBS north Run46: M=0.045, CPUE c_p=0.2759, 'moderate' AE matrix; REBS south Run11: M=0.045, CPUE c_p=0.2529, 'moderate' AE matrix) to test the sensitivity of the outputs to alternate model assumptions (see Section 6.2 for a description of the 'wide AE matrix'):

- REBS north:
  - S01 (Run56) – estimated M using normal prior $\mathcal{N}$(0.045,0.009);
  - S02 (Run57) – reduced all commercial catch from 1965 to 1995 by 33%;
  - S03 (Run58) – increased all commercial catch from 1965 to 1995 by 50%;
  - S04 (Run59) – used wide AE matrix (±5 ages), M=0.045, and CPUE c_p=0.1;
  - S05 (Run60) – used wide AE matrix (±5 ages) , M=0.045, and CPUE c_p=0.2759;
  - S06 (Run61) – used wide AE matrix (±5 ages), M=0.045, and CPUE c_p=0.4;
  - S07 (Run62) – used wide AE matrix (±5 ages), M=0.035, and CPUE c_p=0.4;
  - S08 (Run63) – used moderate AE matrix (±3 ages) with CV increasing by age.
- REBS south:
  - S01 (Run20) – reduced all commercial catch from 1965 to 1995 by 33%;
  - S02 (Run21) – increased all commercial catch from 1965 to 1995 by 50%;
  - S03 (Run22) – used wide AE matrix (±5 ages), M=0.035, and CPUE c_p=0.2529;
  - S04 (Run23) – used wide AE matrix (±5 ages), M=0.045, and CPUE c_p=0.2529;

- S05 (Run24) – used wide AE matrix (±5 ages), M=0.055, and CPUE c_p=0.2529;
- S06 (Run25) – removed NMFS triennial survey.

The MPD (mode of the posterior distribution) or 'best fit' was used as the starting point for a Bayesian search across the joint posterior distributions of the parameters using the Monte Carlo Markov Chain (MCMC) procedure. All models (base and sensitivity runs) were judged to have converged after 6 million iterations, sampling every 5000th, to give 1200 draws (1000 samples after dropping the first 200 for burn in).

8. MODEL RESULTS

8.1. REBS NORTH

8.1.1. Central Run

The model fits to the survey abundance indices were generally satisfactory (Figures F.1 and F.2), although the 2010 index point was missed entirely. The fit to the commercial CPUE indices was basically flat, missing the 1996, 1997, and 2016 index points. This was largely a function of adding process error of 28%, which allows the model fit to ignore outlier CPUE index values (Figure F.3). Using a process error of 10% constrained the fit to follow the signal more closely, which, in the case of this REBS north series, created a more optimistic scenario based on the general upward trend in CPUE. The model runs which increased the CPUE process error to 40% generally passed through the CPUE series with little attempt to match the series deviations. Despite runs that effectively discounted the CPUE series, its removal from the suite of model data resulted in non-credible MPD parameter estimates and potentially would cause non-convergence in the MCMC simulations; this option was not further investigated by this stock assessment.

Fits to the commercial age frequency data for the Trawl fishery were generally good, with residuals indicating departures at older ages classes (Figure F.6). The fits to AFs for the Other fishery were not as good as those for the Trawl but were deemed acceptable (Figure F.8); however, they consistently missed the large plus class. Fits to the WCHG survey AFs were good but had some large negative residuals in the 2012 and 2016 surveys and in the mid-range ages of ~20-45 years (Figure F.10).

Model estimates of mean age only partially matched the observed mean ages (Figure F.11). The correspondence was greatest for the Trawl fishery, but none of the trial runs were able to fit the observed ages from the 1978 and 1982 samples which had much lower mean age than would have been expected, given the relatively early timing of the samples which implied a preponderance of older fish. The recruitment estimates appeared to be typical of those in other rockfish assessments (Figure F.12). There was some autocorrelation in the recruitment residuals, but it did not appear to be extreme (Figure F.13).

The MPD estimate for the commercial Trawl fishery selectivity was well-formed given that the parameter priors were all uniform (Figure F.14). The maturity ogive, generated from an externally fitted model (see Appendix D), has a long right-hand limb resulting in the intersection of the Trawl fishery selectivity curve with the maturity ogive at approximately age 28, indicating that sub-mature fish are harvested. Although the priors for age-at-full selectivity for the Other fishery and the WCHG survey were relatively tight (CV=20%), the estimation procedure shifted the selectivity curves to the right, such that female selectivity intercepted the maturity curve at ages 40 and 35, respectively.

MCMC traces showed acceptable convergence properties (no trend with increasing sample number) for the estimated parameters (Figure F.16), as did diagnostic analyses that split the posterior samples into three equal consecutive segments (Figure F.17) and checked for parameter autocorrelation out to 60 lags (Figure F.18). Most of the parameter medians did not move far from their initial MPD estimates (Figure F.19).

8.1.2. Composite Base Case

The composite base case comprised nine runs spanning two axes of uncertainty: $M_{1,2} \in \{0.035, 0.045, 0.055\}$ and CPUE $c_p \in \{0.1, 0.2759, 0.4\}$ for this stock assessment.

Uncertainty in M, CPUE c_p, and width of the ageing error (AE) matrix were thought to be the most important components of uncertainty in this stock assessment. The first two categories were considered to be the most important and formed the two axes of uncertainty in the composite base case. The latter category was explored in sensitivity runs.

For each component base run, 1000 MCMC samples were generated and then pooled to provide an average stock trajectory for population status and advice to managers. While estimating M was possible, the estimates were frequently higher than M=0.06, which seemed unreasonable, given the apparent maximum age for this species complex. We include a sensitivity run in the following section that demonstrates the effect of estimating M.

The nine component runs outlined above converged with no serious pathologies in the MCMC diagnostics (similar diagnostic results to those outlined for the central run). Figures F.20 to F.22 show diagnostics for the R_0 parameter in each of the component runs, and Figure F.23 shows the distribution of the estimated parameters. In most cases, the component runs had parameter estimates with overlapping distributions. The R_0 and q parameters varied with M: R_0 increasing and q decreasing with increasing M. Within each M, R_0 decreased and q increased as CPUE c_p increased. The selectivity parameters differed little among the three M estimates but changed consistently with c_p (Figure F.23).

Similar to the parameter distributions, those for derived quantities (Figure F.24) varied by M and CPUE c_p, primarily because B_0 and MSY varied by the axes of uncertainty: increasing when M increased, decreasing when CPUE c_p decreased.

The composite base case, comprising nine pooled MCMC runs, was used to calculate a set of parameter estimates (Table 1, Table F.4) and derived quantities at equilibrium and those associated with MSY (Table 2, Table F.5). The composite base case population trajectory from 1935 to 2021 and projected biomass to 2096 (Figure 3, Figure F.25), assuming a constant catch strategy of 600 t/y (and a harvest rate strategy of u=0.10/y), indicates that the median stock biomass will remain above the USR for the next 1.5 generations (75 years). The lower bound of the probability envelope around the constant catch strategy extends into the Cautious and Critical zones after about one-half generation due to a much larger cumulative removal than that under a harvest rate strategy of 0.10/year. However, most of the projection distribution lies well above these zones and we have little confidence in long-term projections which assume no active management intervention when stock size is reduced to low levels.

A phase plot of the time-evolution of spawning biomass and exploitation rate in the two modelled fisheries in MSY space (Figure 4, Figure F.29) suggests that the stock is in the Healthy zone, with a current position at $B_{2021}/B_{\mathrm{MSY}}$ = 2.21 (1.50, 3.15), $u_{2020(\mathrm{trawl})}/u_{\mathrm{MSY}}$ = 0.060 (0.023, 0.138), and $u_{2020(\mathrm{other})}/u_{\mathrm{MSY}}$ = 0.110 (0.028, 0.321).

Table 1. REBS north: quantiles of the posterior distribution based on 9000 MCMC samples for the main estimated model parameters for the composite base case stock assessment. Except for R_0, subscripts refer to the data source, where 1=WCHG Synoptic survey, 2=commercial Trawl fishery or CPUE index series, and 3=commercial Other fishery.

Value	5%	50%	95%
R_0	980	1,643	3,521
q_1	0.156	0.280	0.487
q_2	0.0000412	0.0000685	0.000109
μ_1	35.1	41.7	50.4
μ_2	28.8	33.3	37.3
μ_3	38.8	43.3	53.7
Δ_1	-3.44	-0.646	2.24
Δ_2	-2.16	-0.975	0.0997
Δ_3	-5.48	-2.00	2.30
$\log v_{1L}$	4.50	5.28	5.92
$\log v_{2L}$	3.30	4.18	4.75
$\log v_{3L}$	-13.1	5.16	5.96

Table 2. REBS north: parameter and derived parameter quantiles from 9000 samples of the MCMC posterior of the composite base case. Note that all vulnerable biomass definitions are provided using the respective fishery selectivity. Definitions: B_0 – unfished equilibrium (eq.) spawning biomass (mature females), V_0 – unfished eq. vulnerable biomass (males and females), B_{2021} – spawning biomass at the start of 2021, V_{2021} – vulnerable biomass in the middle of 2020, u_{2020} – exploitation rate (ratio of total catch to vulnerable biomass) in the middle of 2020, u_{max} – maximum exploitation rate (calculated for each sample as the maximum exploitation rate from 1935-2020), B_{MSY} – eq. spawning biomass at MSY (maximum sustainable yield), u_{MSY} – eq. exploitation rate at MSY, V_{MSY} – eq. vulnerable biomass at MSY. All biomass values (B,V,MSY) are in tonnes. Average catch over the last 5 years (2015-19) was 548 t.

From model output			
Value	**5%**	**50%**	**95%**
B_0	13,058	15,413	20,693
V_0 (trawl)	22,056	27,588	34,360
V_0 (other)	15,965	19,483	27,661
B_{2021}	5,475	9,153	17,176
V_{2021} (trawl)	9,242	15,963	30,283
V_{2021} (other)	2,493	8,970	22,357
B_{2021} / B_0	0.405	0.595	0.840
V_{2021} / V_0 (trawl)	0.387	0.590	0.903
V_{2021} / V_0 (other)	0.153	0.455	0.833
u_{2020} (trawl)	0.00823	0.0157	0.0269
u_{2020} (other)	0.00939	0.0234	0.087
$u_{\max}$ (trawl)	0.0508	0.0622	0.078
$u_{\max}$ (other)	0.0479	0.0894	0.173
MSY-based quantities			
Value	**5%**	**50%**	**95%**
MSY	474	636	1,115
B_{MSY}	3,519	4,140	5,519
$0.4B_{MSY}$	1,408	1,656	2,208
$0.8B_{MSY}$	2,815	3,312	4,415
B_{2021} / B_{MSY}	1.50	2.21	3.15
B_{MSY} / B_0	0.260	0.269	0.276
V_{MSY}	1,577	2,675	4,150
V_{MSY} / V_0 (trawl)	0.0558	0.101	0.153
V_{MSY} / V_0 (other)	0.0926	0.130	0.178
u_{MSY}	0.164	0.268	0.400
u_{2020} / u_{MSY} (trawl)	0.0234	0.0602	0.138
u_{2020} / u_{MSY} (other)	0.0281	0.110	0.321

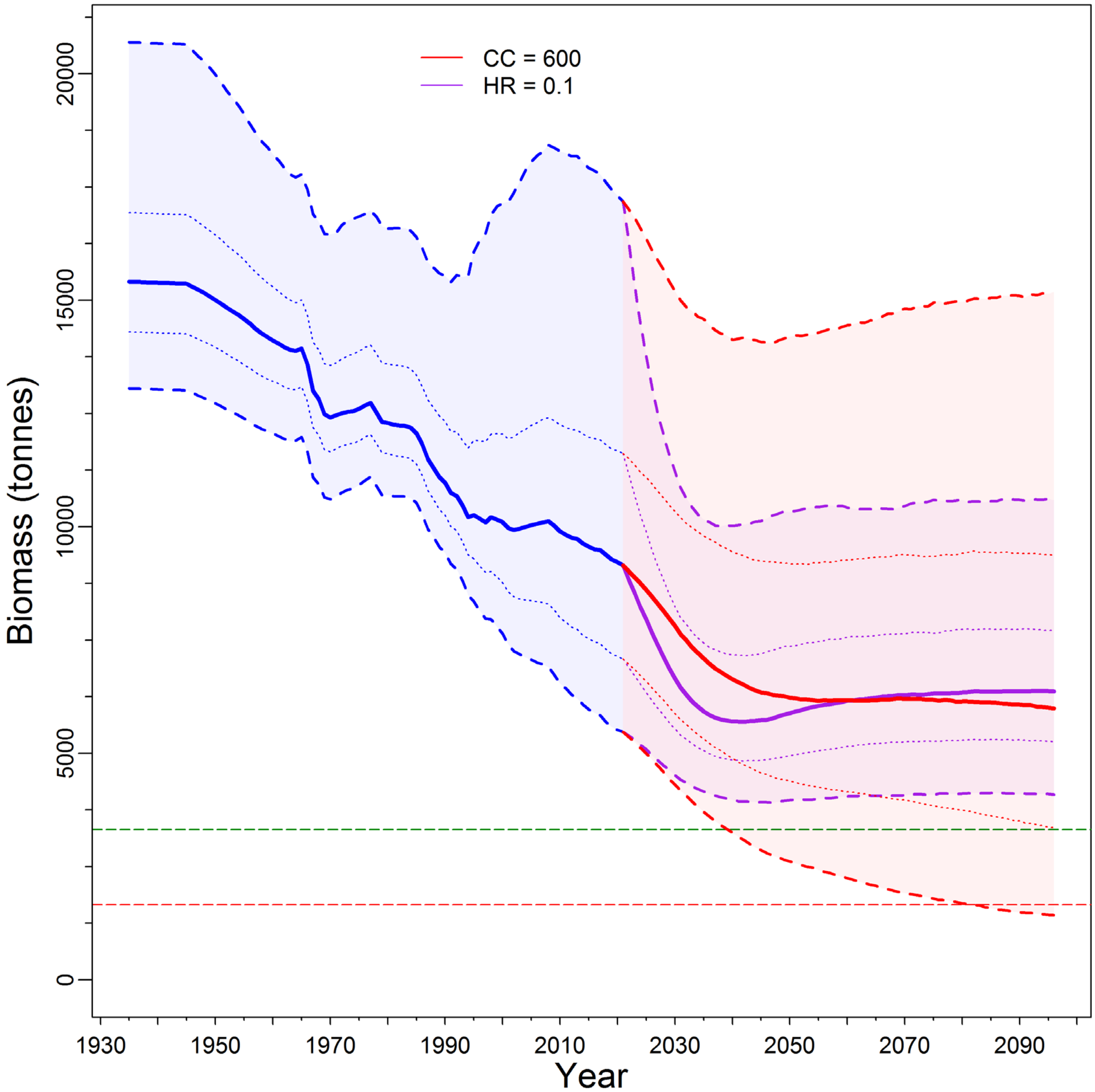

Figure 3. REBS north: estimates of spawning biomass B_t (tonnes) for the composite base case. The median biomass trajectory appears as a solid curve surrounded by a 90% credibility envelope (quantiles: 0.05-0.95) in blue and delimited by dashed lines for years t=1935-2021; projected biomass appears in red (constant catch strategy) and purple (harvest rate strategy) for years t=2022-2096. Also delimited is the 50% credibility interval (quantiles: 0.25-0.75) delimited by dotted lines. The horizontal dashed lines show the median LRP = $0.4B_{MSY}$ and USR = $0.8B_{MSY}$.

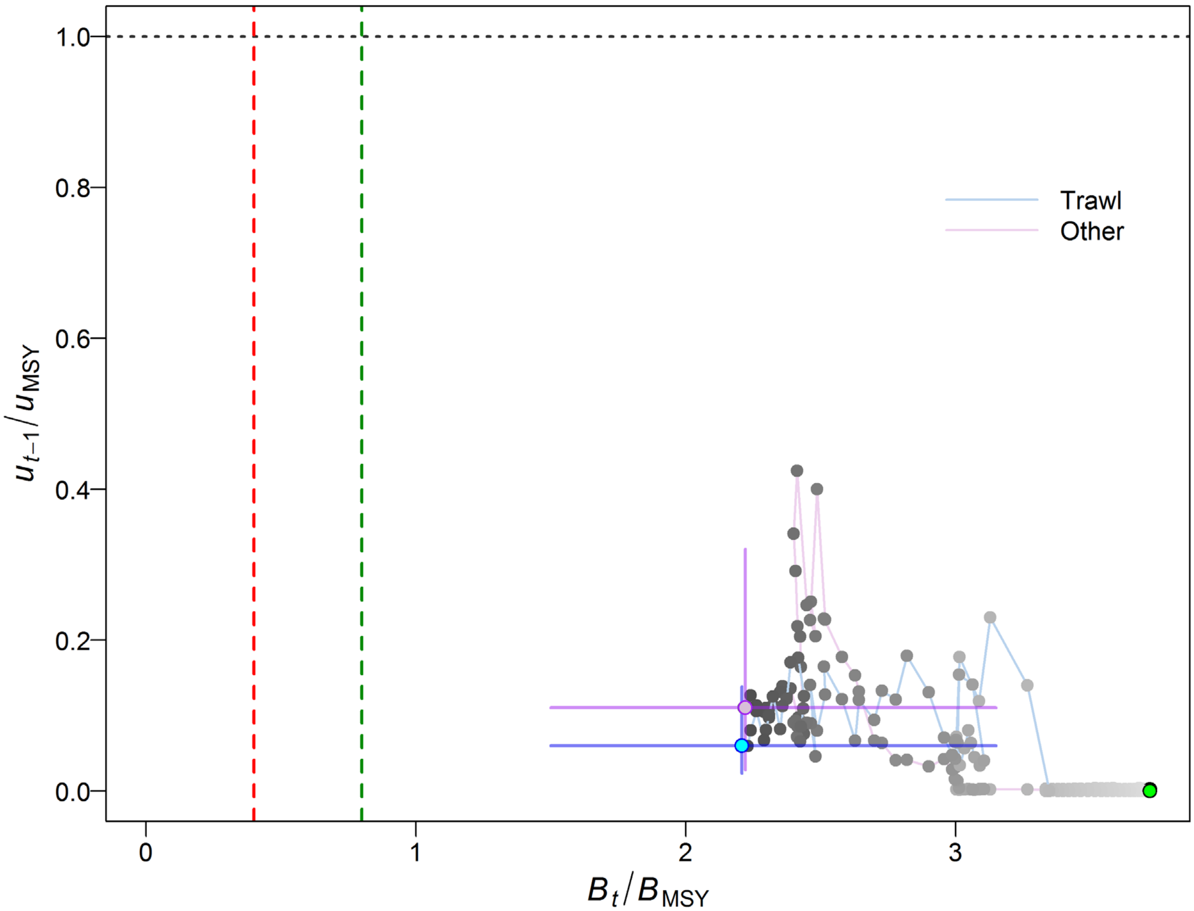

Figure 4. REBS north: phase plot through time of the medians of the ratios B_t/B_{MSY} (the spawning biomass at the start of year t relative to B_{MSY}) and two measures of fishing pressure: Trawl ($u_{t-1(trawl)}/u_{MSY}$: cyan dot) and Other ($u_{t-1(other)}/u_{MSY}$: purple dot) (both represent the exploitation rate in the middle of year t-1 relative to u_{MSY} for each fishery) for the composite base case. The filled green circle is the starting year (1935). Years then proceed from lighter to darker shades with the final year (t=2021) as a filled cyan (Trawl) or purple (Other) circle, and the crossed blue/purple lines represent the 0.05 and 0.95 quantiles of the posterior distributions for the final year. Red and green vertical dashed lines indicate the PA provisional LRP = 0.4B_{MSY} and USR = 0.8B_{MSY}, and the horizontal grey dotted line indicates u_{MSY}.

8.1.3. Sensitivity Analyses

Eight sensitivity analyses were run (with full MCMC simulations) relative to the central run (Run46: M=0.045, CPUE c_p=0.2759) to test the sensitivity of the outputs to alternative model assumptions. All sensitivity runs but one were reweighted once using the procedure of Francis (2011) for age frequencies; S01 (R56) was unstable and required that selectivity priors for the Other fishery (μ_3 and log v_{3L}) be fixed to MPD estimates. The abundance index CVs were adjusted for the first reweight only, using either that adopted in the central run (survey=0.25, CPUE=0.2759) or using specified process errors. The differences among the sensitivity runs (including the central run) are summarised in tables of median parameter estimates (Table F.62) and median MSY-based quantities (Table F.63).

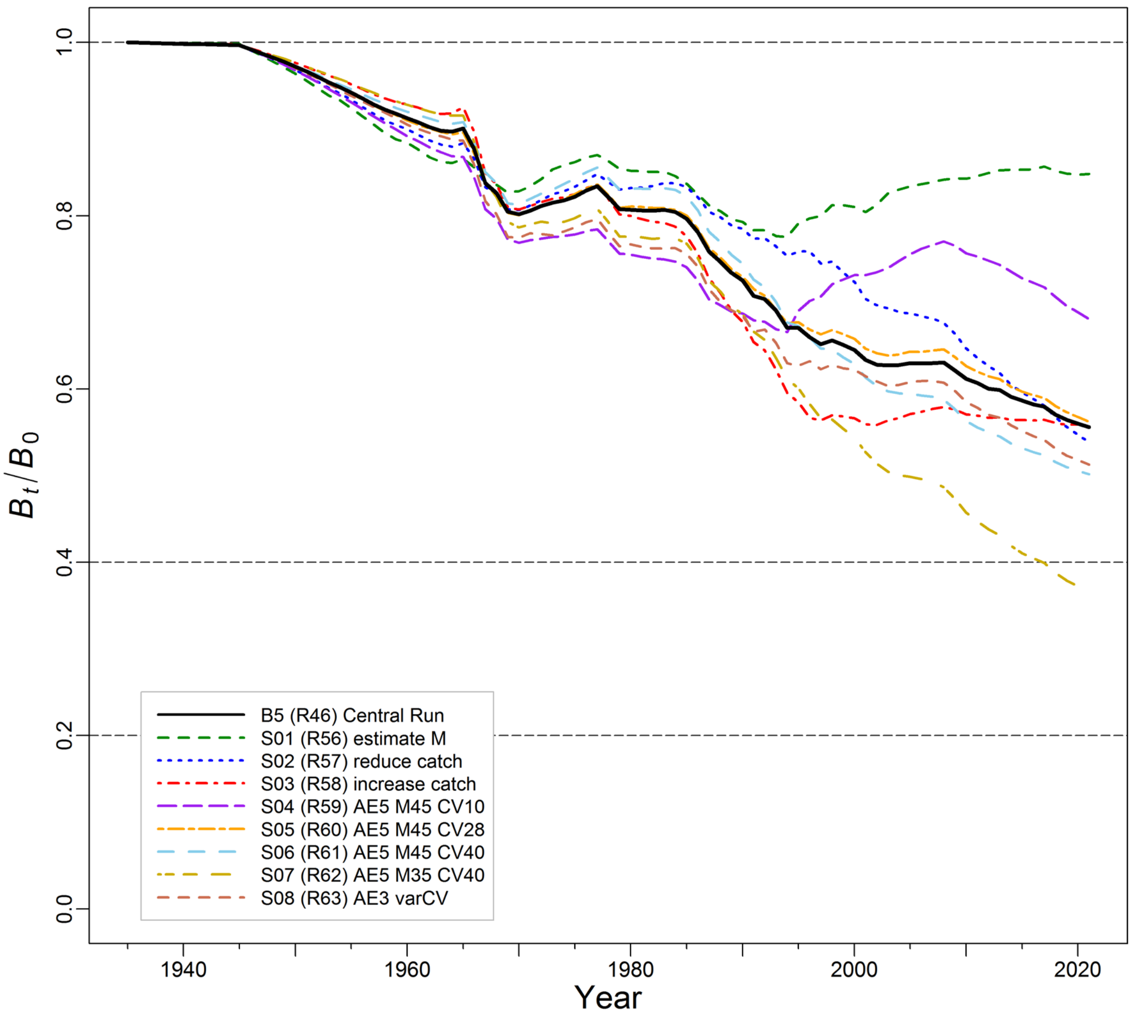

Figure 5. REBS north: model median trajectories of spawning biomass as a proportion of unfished equilibrium biomass (B_t/B_0) for the central run and eight sensitivity runs (see legend lower left). Horizontal dashed lines show alternative reference points used by other jurisdictions: $0.2B_0$ (~DFO's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

The diagnostic plots (Figures F.31 to F.33) suggest that seven sensitivity runs exhibited good MCMC behaviour, and one was poor with little credibility:

- Good – no trend in traces, split-chains align, little or no autocorrelation
  - S02 (-33% 1965-1995 commercial catch)
  - S03 (+50% 1965-1995 commercial catch)
  - S04 (wide AE, M=0.045, CPUE c_p=0.1)
  - S05 (wide AE, M=0.045, CPUE c_p=0.2759)
  - S06 (wide AE, M=0.045, CPUE c_p=0.4)
  - S07 (wide AE, M=0.035, CPUE c_p=0.4)
  - S08 (moderate AE with increasing CV with age, M=0.045, CPUE c_p=0.2759)

- Poor – trace trend fluctuates substantially or shows a persistent increase/decrease, split-chains differ from each other, substantial autocorrelation
  - S01 (estimate *M*)

The run that estimated *M* (S01) may not have converged and the marginal diagnostics suggested instability in the model. Additionally, the posterior for M_2 (males), 0.065 (0.059, 0.073), moved well above the prior ($\mathcal{N}(0.045, 0.009)$) and was deemed unrealistic given the long-lived nature of REBS.

The trajectories of the B_t medians relative to B_0 (Figure 5, Figure F.34) indicate that estimating *M* (S01) resulted in the most optimistic scenario, while the most pessimistic run was the one using a wide AE matrix, the lowest *M*, and the widest CPUE c_p (S07). Only the sensitivity run that varied from the central run by using a wide AE (S05) tended to closely reflect the central run, indicating little sensitivity to this wider level of ageing error compared to more narrow ageing error used in the composite base case. The two catch sensitivity runs (S02, S03) departed from the central run during the reconstruction years but ended with similar spawning stock depletion (B_{2021}/B_0). The two sensitivity runs that differed by CPUE ($c_p \in \{0.1, 0.4\}$) (as well as the wide AE matrix) were considerably more optimistic and pessimistic than the central run, respectively. The trajectory using an AE with increasing CV by age (S08), followed the central run up until about 1990 and then mirrored the increased-catch scenario (S02) thereafter. The overall conclusion is that, other than being sensitive to values of *M*, the model outcome is also driven by how much weight is given to the CPUE data. If the model is informed that CPUE is important, the population trajectory is more optimistic, given the generally upward trend in CPUE; while the model which discounts the CPUE index, results in a more pessimistic trajectory. The need for CPUE as a stabilising influence was also found in the latest BC Bocaccio stock assessment (Starr and Haigh 2022), which featured a monotonic decline in population until a large recruitment event in 2016.

Parameter estimates varied little among sensitivity runs (Figure F.37), with the exception of S01. Derived quantities based on MSY (Figure F.38) exhibited suspiciously high values of u_{MSY} for a long-lived species (e.g., central run u_{MSY}=0.20/y, Table F.63). The lowest u_{MSY} (0.13/y) occurred in S08 (increasing CV in AE).

The stock status ($B_{2021}/B_{\mathrm{MSY}}$) for the sensitivities (Figure F.39) all appear in the DFO Healthy zone.

8.2. REBS SOUTH

8.2.1. Central Run

The model fits to the survey abundance indices were generally satisfactory (Figures F.41 to F.44), although the 2018 WCVI index point was poorly fit. The fit to the CPUE index series was much closer when using process error of 10%, causing the biomass to follow the CPUE signal more closely, whereas higher CPUE c_p values discounted the series. The removal of the CPUE index series was not attempted for this stock because its equivalent removal for REBS north caused poor model behaviour. It was assumed that for REBS south, like REBS north, a CPUE series had a stabilising influence on the model.

Fits to the commercial age frequency data for the Trawl fishery were generally fair (Figure F.47); however, the MPD fit often underestimated the observed age proportions. The fits to AFs for the Other fishery were very poor, but there was only one AF sample which may have been non-representative (Figure F.49).

Fits to the QCS survey AFs were fair but featured many negative residuals (Figure F.51). Fits to the WCVI survey AFs were a bit better than those for the QCS survey. Both surveys suffered from a lack of data because many of the surveyed years either did not have AF data or the data had not been aged.

Model estimates of mean age only partially matched the observed mean ages (Figure F.54). As in REBS north, the observed mean weights from Trawl's initial years did not match the model's estimates, with the model estimating far more older fish than were present in the age sample, indicating that these samples may not have been representative of the fishery. The recruitment estimates appeared to be typical of those in other rockfish assessments (Figure F.55), with several large recruitment events. There was obvious autocorrelation in the recruitment residuals, which attenuated after the first 20 lags (Figure F.56).

The MPD estimate for the commercial Trawl fishery selectivity indicated that this fishery captures substantial amounts of immature fish whereas the Other fishery caught only mature fish (Figure F.57). The selectivity curves for the two synoptic surveys were well to the left of the maturity ogive, which confirmed that they intercept fairly young fish. This was especially true for the QCS synoptic survey as the AF and length frequency data indicated that this survey captured much younger fish than did the WCVI synoptic survey.

MCMC traces showed acceptable convergence properties (no trend with increasing sample number) for the estimated parameters (Figure F.59), as did diagnostic analyses that split the posterior samples into three equal consecutive segments (Figure F.60) and checked for parameter autocorrelation out to 60 lags (Figure F.61). Most of the parameter medians did not move far from their initial MPD estimates (Figure F.62).

8.2.2. Composite Base Case

During the peer review process, the participants agreed to use only six component runs (of the nine candidates) for the composite base case because the three rejected component runs had poor MCMC diagnostics. The 1000 MCMC samples from the six runs with acceptable MCMC diagnostics were pooled to create a composite posterior of 6000 samples which was used to estimate population status and to provide advice to managers. Note that all of these runs required fixing both sets of the survey selectivity parameters to their MPD values in order to obtain acceptable MCMC diagnostics.

As for REBS north, uncertainty in M, CPUE c_p, and width of the ageing error (AE) matrix were thought to be the most important components of uncertainty in this stock assessment. The first two categories were considered to be the most important and formed the two axes of uncertainty in the composite base case. The latter category was explored in sensitivity runs.

For each candidate component base run, 1000 MCMC samples were generated and then pooled to provide an average stock trajectory for population status and advice to managers. Figures F.63 to F.65 show diagnostics for the R_0 parameter in each of the component runs. The nine component runs converged with some having poor MCMC diagnostics; five of the runs exhibited frayed chains (Figure F.64) and three of these showed undesirable autocorrelation (Figure F.65).

Based on the diagnostics, a subjective ranking of the component runs would be:

- Good – no trend in traces, split-chains align, no autocorrelation
  - B2, B3, B5, and B9
- Marginal – trace trend temporarily interrupted, split-chains somewhat frayed, some autocorrelation

- B1, B4, and B6

- Poor – trace trend fluctuates substantially or shows a persistent increase/decrease, split-chains differ from each other, substantial autocorrelation
  - B7 and B8

Component runs with poor diagnostics (B7 and B8) and one with marginal diagnostics (B4) were identified by the regional peer review participants for exclusion from the candidate set of component runs for the composite base case. The chosen component runs (B1, B2, B3, B5, B6, B9) were pooled to provide an average stock trajectory for population status and advice to managers.

Figure F.66 shows box plots for the distribution of the estimated parameters. The selectivity parameters remained fairly constant across all component runs (overlapping distributions). The R_0 parameter increased in an exponential fashion from B1 through B9, with the latter two runs showing posterior distributions for R_0 that are much higher compared to the previous seven. The q parameters did not appear to vary by M, but were sensitive to differences in CPUE c_p, specifically between the low process error (c_p=0.1) and the model-based one (c_p=0.2529).

Similar to the parameter distributions, those for derived quantities (Figure F.67) varied by M and CPUE c_p; however, the difference in MSY was exaggerated by CPUE c_p for high M values.

The composite base case, comprising six pooled MCMC runs, was used to calculate a set of parameter estimates (Table 3, Table F.67) and derived quantities at equilibrium and those associated with MSY (Table 4, Table F.68). The composite base case population trajectory from 1935 to 2021 and projected biomass to 2096 (Figure 6, Figure F.68), assuming a constant catch strategy of 300 t/y (and a harvest rate strategy of u=0.06/y), indicated that the median stock biomass will eventually crash at the current amount of removals (5-year average catch of 291 t). The fixed harvest rate strategy appears to offer a more sustainable catch strategy, with median projected biomass remaining above the USR for the next 1.5 generations (75 years). We have little confidence in long-term projections which assume no active management intervention when stock size is reduced to low levels.

A phase plot of the time-evolution of spawning biomass and exploitation rate in the two modelled fisheries in MSY space (Figure 7, Figure F.72) suggests that the stock is in the Healthy zone, with a current position at B_{2021}/B_MSY = 1.07 (0.58, 2.61), $u_{2020(\mathrm{trawl})}/u_\mathrm{MSY}$ = 1.17 (0.19, 2.59), and $u_{2020(\mathrm{other})}/u_\mathrm{MSY}$ = 0.72 (0.13, 1.77). The Trawl fishery's harvest rate is above that at u_MSY.

Table 3. REBS south: quantiles of the posterior distribution based on 6000 MCMC samples for the main estimated model parameters for the composite base case stock assessment. Except for R_0, subscripts refer to the data source, where 1=QCS Synoptic survey, 2=WVCI Synoptic survey, 3=NMFS Triennial survey, 4=commercial Trawl fishery or CPUE index series, and 5=commercial Other fishery.

Value	5%	50%	95%
R_0	359	511	1,795
q_1	0.0289	0.0884	0.142
q_2	0.0128	0.0391	0.0672
q_3	0.0213	0.0567	0.138
q_4	0.000067	0.000179	0.000295
μ_4	20.6	25.3	30.7
μ_5	47.2	56.1	65.4
Δ_4	-0.84	1.45	3.78
Δ_5	-0.51	0.669	1.83
$\log v_{4\mathrm{L}}$	3.27	4.35	5.18
$\log v_{5\mathrm{L}}$	5.81	6.51	7.28

Table 4. REBS south: parameter and derived parameter quantiles from 6000 samples of the MCMC posterior of the composite base case. Note that all vulnerable biomass definitions are provided using the respective fishery selectivity. Definitions: B_0 – unfished equilibrium (eq.) spawning biomass (mature females), V_0 – unfished eq. vulnerable biomass (males and females), B_{2021} – spawning biomass at the start of 2021, V_{2021} – vulnerable biomass in the middle of 2020, u_{2020} – exploitation rate (ratio of total catch to vulnerable biomass) in the middle of 2020, u_{max} – maximum exploitation rate (calculated for each sample as the maximum exploitation rate from 1935-2020), B_{MSY} – eq. spawning biomass at MSY (maximum sustainable yield), u_{MSY} – eq. exploitation rate at MSY, V_{MSY} – eq. vulnerable biomass at MSY. All biomass values (B,V,MSY) are in tonnes. Average catch over the last 5 years (2015-19) was 291 t.

	From model output		
Value	**5%**	**50%**	**95%**
B_0	5,187	6,045	10,574
V_0 (trawl)	10,927	13,136	23,704
V_0 (other)	6,813	8,643	13,292
B_{2021}	818	1,725	7,078
V_{2021} (trawl)	1,772	3,964	15,566
V_{2021} (other)	752	2,037	7,289
B_{2021} / B_0	0.155	0.286	0.68
V_{2021} / V_0 (trawl)	0.159	0.304	0.666
V_{2021} / V_0 (other)	0.104	0.239	0.572
u_{2020} (trawl)	0.0193	0.0716	0.150
u_{2020} (other)	0.0130	0.0442	0.112
$u_{\max}$ (trawl)	0.0259	0.0717	0.150
$u_{\max}$ (other)	0.0264	0.0592	0.125
	MSY-based quantities		
Value	**5%**	**50%**	**95%**
MSY	152	193	495
B_{MSY}	1,380	1,611	2,739
$0.4B_{MSY}$	552	644	1,095
$0.8B_{MSY}$	1,104	1,289	2,191
B_{2021} / B_{MSY}	0.582	1.07	2.61
B_{MSY} / B_0	0.258	0.265	0.272
V_{MSY}	2,418	3,213	5,130
V_{MSY} / V_0 (trawl)	0.184	0.239	0.289
V_{MSY} / V_0 (other)	0.326	0.369	0.426
u_{MSY}	0.050	0.062	0.106
u_{2020} / u_{MSY} (trawl)	0.191	1.17	2.59
u_{2020} / u_{MSY} (other)	0.134	0.721	1.77

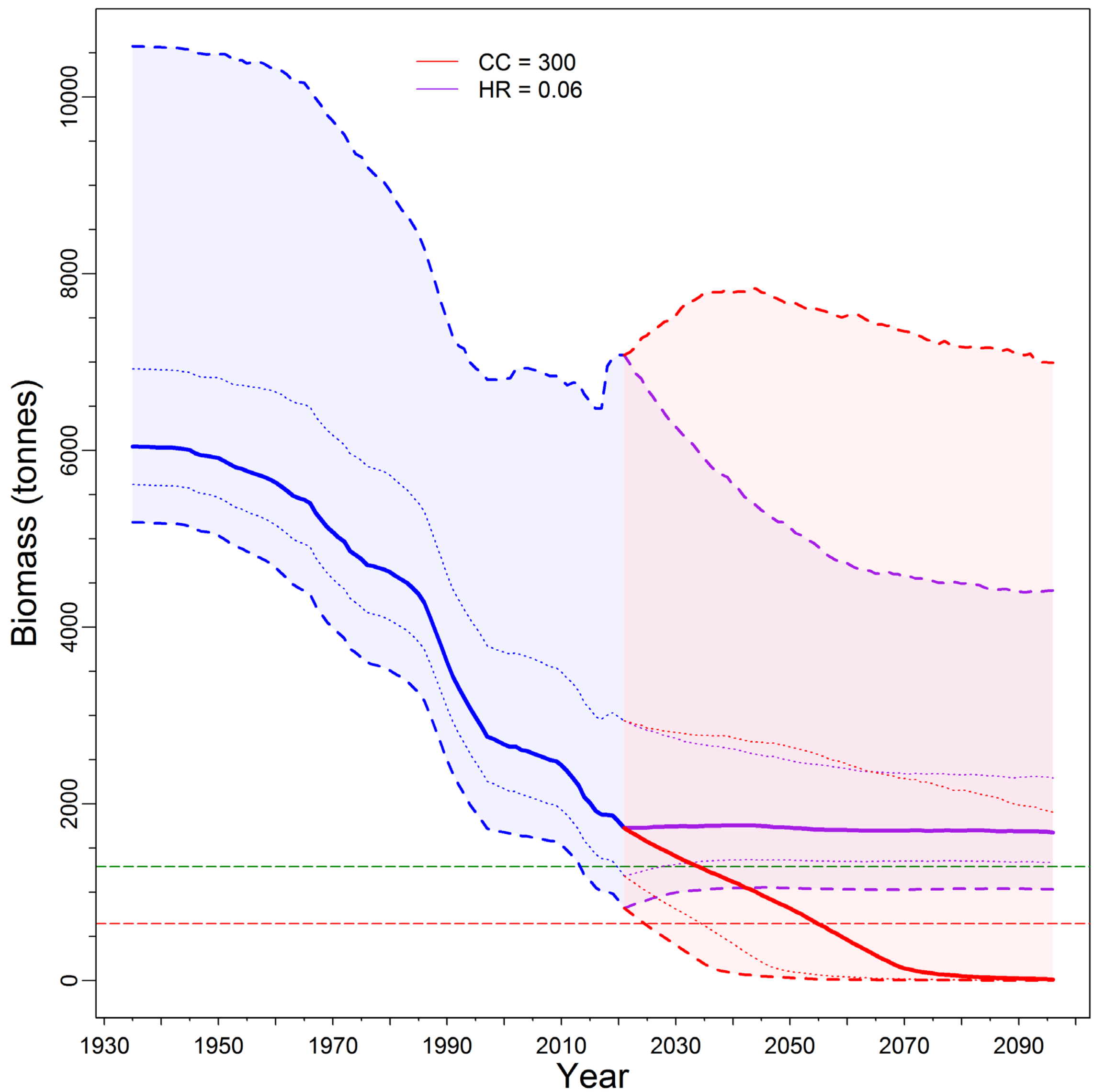

Figure 6. REBS south: estimates of spawning biomass B_t (tonnes) for the composite base case. The median biomass trajectory appears as a solid curve surrounded by a 90% credibility envelope (quantiles: 0.05-0.95) in blue and delimited by dashed lines for years t=1935-2021; projected biomass appears in red (constant catch strategy) and purple (harvest rate strategy) for years t=2022-2096. Also delimited is the 50% credibility interval (quantiles: 0.25-0.75) delimited by dotted lines. The horizontal dashed lines show the median LRP = $0.4B_{MSY}$ and USR = $0.8B_{MSY}$.

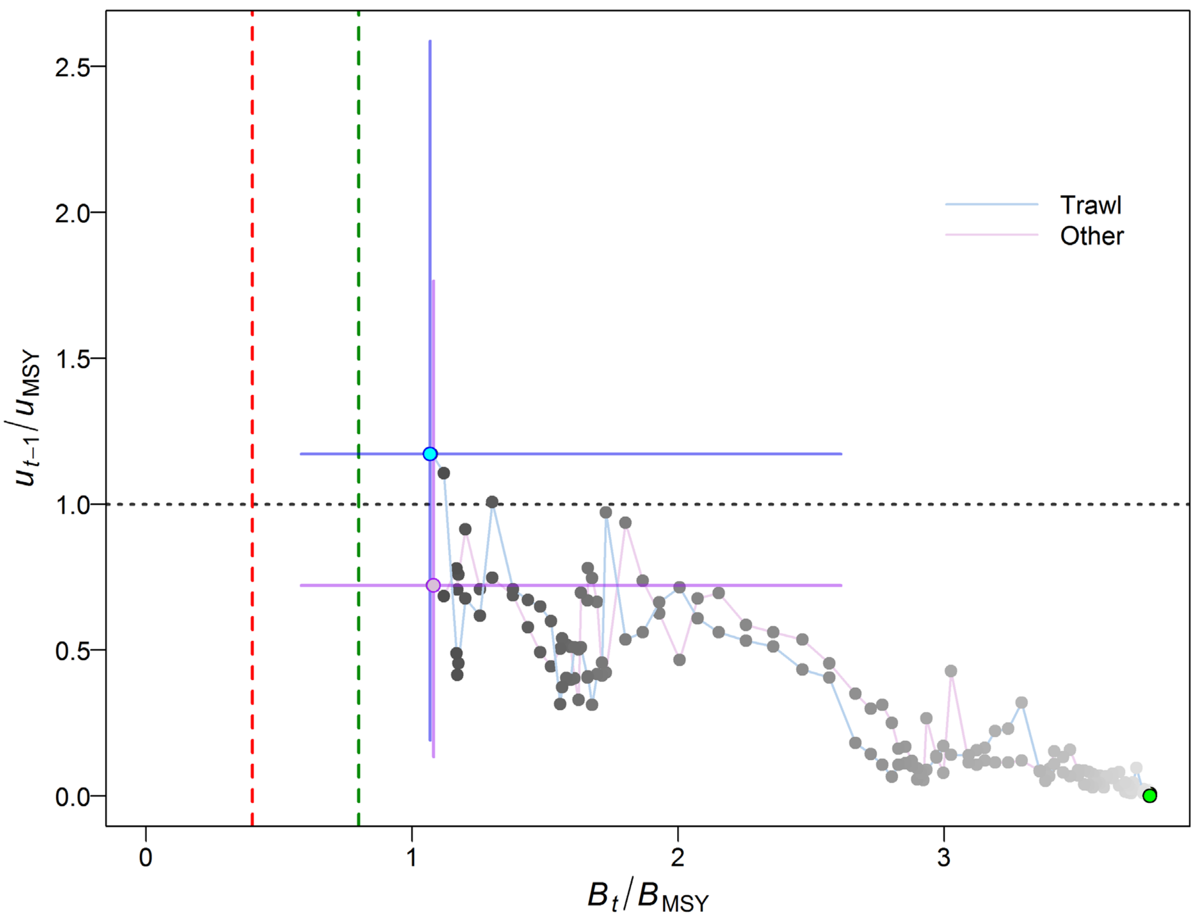

Figure 7. REBS south: phase plot through time of the medians of the ratios B_t/B_{MSY} (the spawning biomass at the start of year t relative to B_{MSY}) and two measures of fishing pressure: Trawl ($u_{t-1(trawl)}/u_{MSY}$: cyan dot) and Other ($u_{t-1(other)}/u_{MSY}$: purple dot) (both represent the exploitation rate in the middle of year t-1 relative to u_{MSY} for each fishery) for the composite base case. The filled green circle is the starting year (1935). Years then proceed from lighter to darker shades with the final year (t=2021) as a filled cyan (Trawl) or purple (Other) circle, and the crossed blue/purple lines represent the 0.05 and 0.95 quantiles of the posterior distributions for the final year. Red and green vertical dashed lines indicate the PA provisional LRP = $0.4B_{MSY}$ and USR = $0.8B_{MSY}$, and the horizontal grey dotted line indicates u_{MSY}.

8.2.3. Sensitivity Analyses

Six sensitivity analyses were run (with full MCMC simulations) relative to the central run (Run11: M=0.045, CPUE c_p=0.2529) to test the sensitivity of the outputs to alternative model assumptions. All sensitivity runs but one were reweighted twice using the procedure of Francis (2011) for age frequencies; S04 (R23) was reweighted once as the second reweight did not provide credible parameter fits. The abundance index CVs were adjusted for the first reweight only, using that adopted in the central run (surveys=0.25, CPUE=0.2529).

The diagnostic plots (Figures F.74 to F.76) suggest that four sensitivity runs exhibited good MCMC behaviour, and two were marginal but provisionally acceptable:

- Good – no trend in traces, split-chains align, no autocorrelation
  - S01 (-33% 1965-1995 commercial catch)
  - S03 (wide AE, M=0.035, CPUE c_p=0.2529)

- S05 (wide AE, M=0.055, CPUE c_p=0.2529)
- S06 (remove NMFS triennial survey)

- Marginal – trace trend temporarily interrupted, split-chains somewhat frayed, some autocorrelation
  - S02 (+50% 1965-1995 commercial catch)
  - S04 (wide AE, M=0.045, CPUE c_p=0.2529)

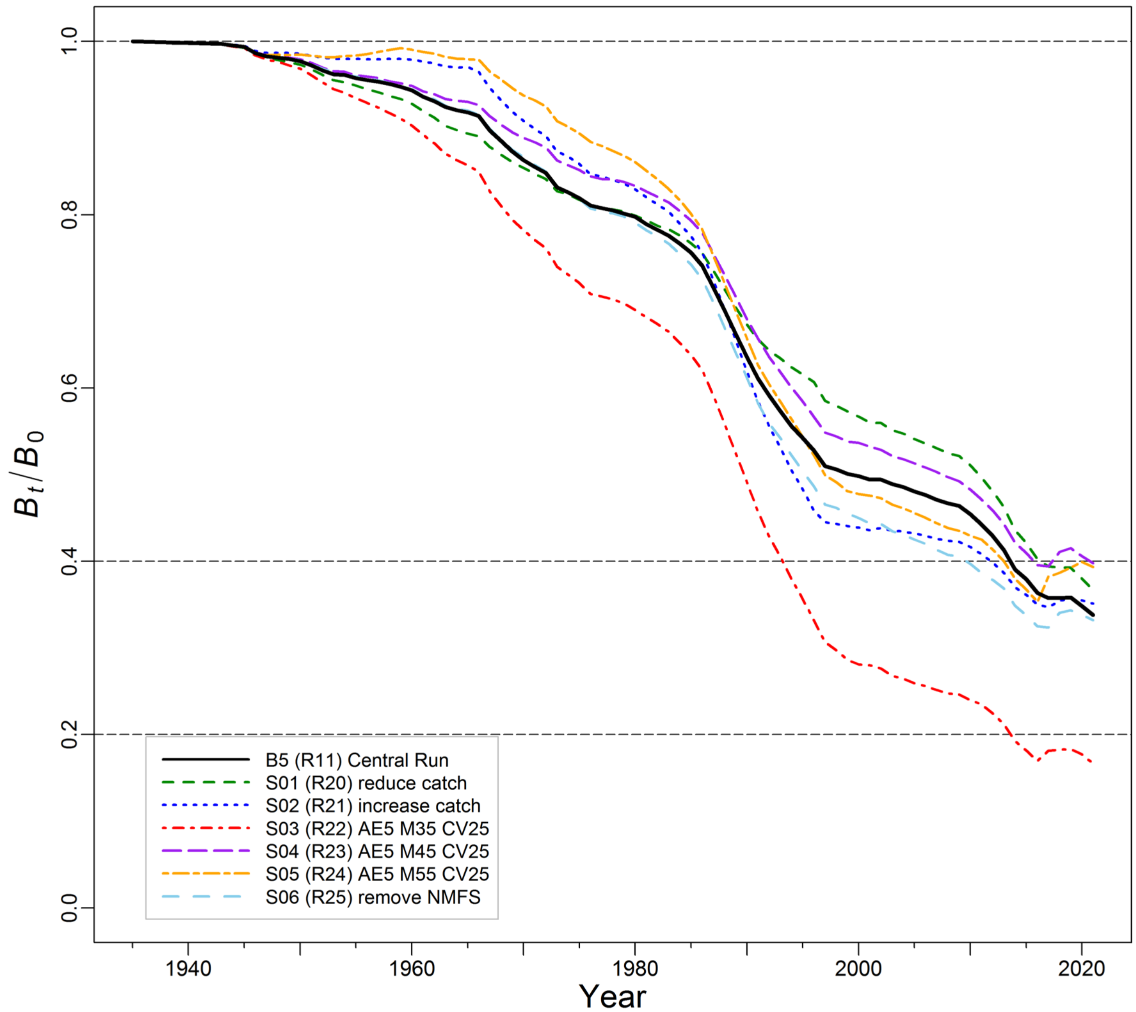

Figure 8. REBS south: model median trajectories of spawning biomass as a proportion of unfished equilibrium biomass (B_t/B_0) for the central run and six sensitivity runs (see legend lower left). Horizontal dashed lines show alternative reference points used by other jurisdictions: 0.2B_0 (~DFO's USR), 0.4B_0 (often a target level above B_{MSY}), and B_0 (equilibrium spawning biomass).

The trajectories of the B_t medians relative to B_0 (Figure 8, Figure F.77) indicate that using a wide AE matrix (S04) resulted in the most optimistic scenario, while the most pessimistic run was the one with the lowest M (S03). All sensitivity runs that adopted the same M (0.045) as the central run tended to closely reflect the central run. As with REBS north, the two catch sensitivity runs (S01, S02) departed from the central run somewhat but ended with similar spawning stock depletion (B_{2021}/B_0). Removing the NMFS triennial survey (S06) had little impact, likely because it provided only three index points and selectivity had been fixed. The overall conclusion is that the model outcome, given this limited set of sensitivities, is most sensitive to *M* and showed less sensitivity to the width of the AE matrix.

Parameter estimates varied little among sensitivity runs (Figure F.80), with the exception of S03 (*M*=0.035). Derived quantities based on MSY (Figure F.81) exhibited reasonable values of u_{MSY} (<0.10/year) for a long-lived species (Table F.126).

The stock status ($B_{2021}/B_{\mathrm{MSY}}$) for the sensitivities (Figure F.82) is clearly sensitive to *M*. All sensitivities with *M*=0.045 lie in the Healthy zone, whereas, the sensitivity with *M*=0.035 lies in the Cautious zone.

9. ADVICE FOR MANAGERS

9.1. REFERENCE POINTS

The Sustainable Fisheries Framework (SFF, DFO 2009) established provisional reference points, which incorporate the 'precautionary approach' (PA), to guide management and assess harvest in relation to sustainability. These reference points are the limit reference point (LRP) of $0.4B_{\mathrm{MSY}}$ and the upper stock reference point (USR) of $0.8B_{\mathrm{MSY}}$, which have been adopted by previous rockfish assessments (Edwards et al. 2012 a,b, 2014 a,b; Starr et al. 2014[2], 2016; Haigh et al. 2018; Starr and Haigh 2021 a,b, 2022) and so are used here. Note that, to determine the suitability of these reference points for this stock (or any *Sebastes* stock) would require a separate investigation involving simulation testing using a range of operating models.

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

The term 'stock status' should be interpreted as 'perceived stock status at the time of the assessment for the year ending in 2020 (i.e., beginning of year 2021)' because the value is calculated as the ratio of two estimated biomass values ($B_{2021}/B_{\mathrm{MSY}}$) by a specific model using the data available up to 2020. Further, the estimate of B_{MSY} depends on the model assessment of stock productivity as well as the catch split among fisheries (if there are more than one). Therefore, comparisons of stock status among various model scenarios can be misleading because the B_{MSY} space is not the same from one model to the next.

MSY-based reference points estimated within a stock assessment model can be highly sensitive to model assumptions about natural mortality, stock recruitment dynamics (Forrest et al. 2018), and the distribution of catch among the component fisheries. As a result, other jurisdictions use reference points that are expressed in terms of B_0 rather than B_{MSY} (e.g., N.Z. Ministry of Fisheries 2011), because B_{MSY} is often poorly estimated as it depends on estimated parameters and a consistent fishery distribution (although B_0 shares several of these same problems). Therefore, the reference points of $0.2B_0$ and $0.4B_0$ are also presented in Appendix F. These are default values used in New Zealand respectively as a 'soft limit', below which management

[2] Starr, P.J., Kronlund, A.R., Olsen, N. and Rutherford, K. 2014. Yellowtail Rockfish (*Sebastes flavidus*) stock assessment for the coast of British Columbia, Canada. DFO Can. Sci. Advis. Sec. Res. Doc. (unpublished working paper)

action needs to be taken, and a 'target' biomass for low productivity stocks, a mean around which the biomass is expected to vary. The 'soft limit' is equivalent to the upper stock reference (USR, 0.8B_{MSY}) in the provisional DFO Sustainable Fisheries Framework while a 'target' biomass is not specified by the provisional DFO SFF. Results are provided comparing projected biomass to B_{MSY} and to current spawning biomass B_{2021}, and comparing projected harvest rate to current harvest rate u_{2020} (Appendix F). A full suite of results based on COSEWIC indicators is also presented in Appendix.

9.2. STOCK STATUS AND DECISION TABLES

Stock status for DFO managers is usually defined as the current spawning biomass relative to the estimated spawning biomass required for maximum sustainable yield (MSY). Stock status plots depict distributions of B_{2021}/B_{MSY} in three zones (Critical, Cautious, Healthy) delimited by 0.4B_{MSY} (LRP) and 0.8B_{MSY} (USR).

We caution that, although uncertainty is built into the assessment and its projections by taking a Bayesian approach for parameter estimation and by constructing a composite base case that spans ranges of inestimable parameter values and process error, these results depend heavily on the assumed model structure, the informative priors, and data assumptions (particularly the average recruitment assumptions) used for the projections.

9.2.1. REBS North

Stock status at the beginning of 2021 for the REBS north composite base case lies in the Healthy zone with a probability of 1, as do all nine component runs (Figure 9). It is no surprise that the runs where M=0.035 tend to have the lowest stock status among these nine runs, although the degree to which the model attempts to fit the CPUE series also plays a part. The general upward trend seen in the CPUE series (notwithstanding the drop in the final three years) results in model fits that are generally more optimistic than the model runs where the CPUE is less closely fitted. Examination of the MPD fits to these models (e.g., Figure F.3) shows that, even for the central run with c_p=0.2759, the biomass trajectory passes below most of the recent indices, effectively giving more weight to the decline in CPUE in the final three years. This effect is even more pronounced for the runs where c_p=0.4, resulting in runs that are less optimistic within each suite of constant M. However, even the most pessimistic run (B3), where M=0.035 and c_p=0.4, current stock status is estimated to be in the Healthy zone.

The sensitivity runs result in similar conclusions: stock status at the beginning of 2021 for all eight sensitivity runs lie within the Healthy zone with a probability of 1 (Figure 10). Although run S01 (estimate M) did not converge properly, it is unlikely that it would return a low stock status. This run was only made to demonstrate the general tendency in the data regarding M as a free parameter and is not meant to be seriously considered. The two sensitivity runs which altered catch behaved differently, with the increased-catch run dropping to a low level in the late 1990s, only to recover to near the level of the central run in response to lower removals beginning around 2000 (Figure 5). This recovery indicates that the additional catch in the catch history raised the overall stock productivity to above current catch levels. The opposite happened for the model with reduced historical catches, with current catch levels causing an accelerated decline (Figure 5).

The four sensitivity runs which used wider ageing error (AE) matrices show that the additional freedom to fit the age data did not result in widely different results compared to the equivalent run in the composite base case. For instance, run S05 which matches the central run except for the AE matrix estimates B_{2021}/B_0=0.562 (0.470–0.653) while the central run estimates B_{2021}/B_0=0.556 (0.470–0.646). Sensitivity run S07 (the "worst case" run among these sensitivity runs), estimates B_{2021}/B_0=0.365 (0.295–0.443) while the equivalent run in the composite base case (run B03, M=0.035, c_p=0.4) estimates B_{2021}/B_0=0.421 (0.349–0.499). These two examples demonstrate that the uncertainty width of the AE matrix (ageing error spread over 7 vs. 11 ages) is not a strong source of uncertainty in the REBS north stock assessment.

Decision tables for the REBS north composite base case provide advice to managers as probabilities that current and projected biomass B_t (t = 2021, ..., 2031) will exceed biomass-based reference points (or that projected exploitation rate u_t will fall below harvest-based reference points) under constant catch policies (Table 5) or constant harvest rate policies (Table 6). These two tables present probabilities that projected B_t using the composite base case will exceed the LRP and the USR or will be less than the harvest rate at MSY. Alternative decision tables for the composite base case can be found in Appendix F (Tables F.6-F.53), including the number of years to reach the various targets (Tables F.54-F.61).

Assuming that a catch of 600 t will be taken each year for the next 10 years, Table 5 indicates that a manager would be >99% certain that both B_{2026} and B_{2031} lie above the LRP of $0.4B_{\mathrm{MSY}}$, ≥99% certain that both B_{2026} and B_{2031} lie above the USR of $0.8B_{\mathrm{MSY}}$, and >99% certain that u_{2026} and 99% certain that u_{2031} lie below u_{MSY} for the composite base case. Similarly, Table 6 indicates that under a harvest rate strategy of 0.1/year, a manager would be >99% certain that both B_{2025} and B_{2030} lie above the LRP of $0.4B_{\mathrm{MSY}}$ and above the USR of $0.8B_{\mathrm{MSY}}$, and equally certain that u_{2026} and u_{2031} lie below the u_{MSY}. Generally, it is up to managers to choose the preferred catch levels or harvest levels using their preferred risk levels. For example, it may be desirable to be 95% certain that B_{2026} exceeds an LRP whereas exceeding a USR or remaining below a target exploitation rate (u_{MSY}) might only require a 50% probability. Assuming this risk profile, all the catch policies in Table 5 and the harvest rate policies in Table 6 would satisfy the specified LRP, USR, and target exploitation constraints.

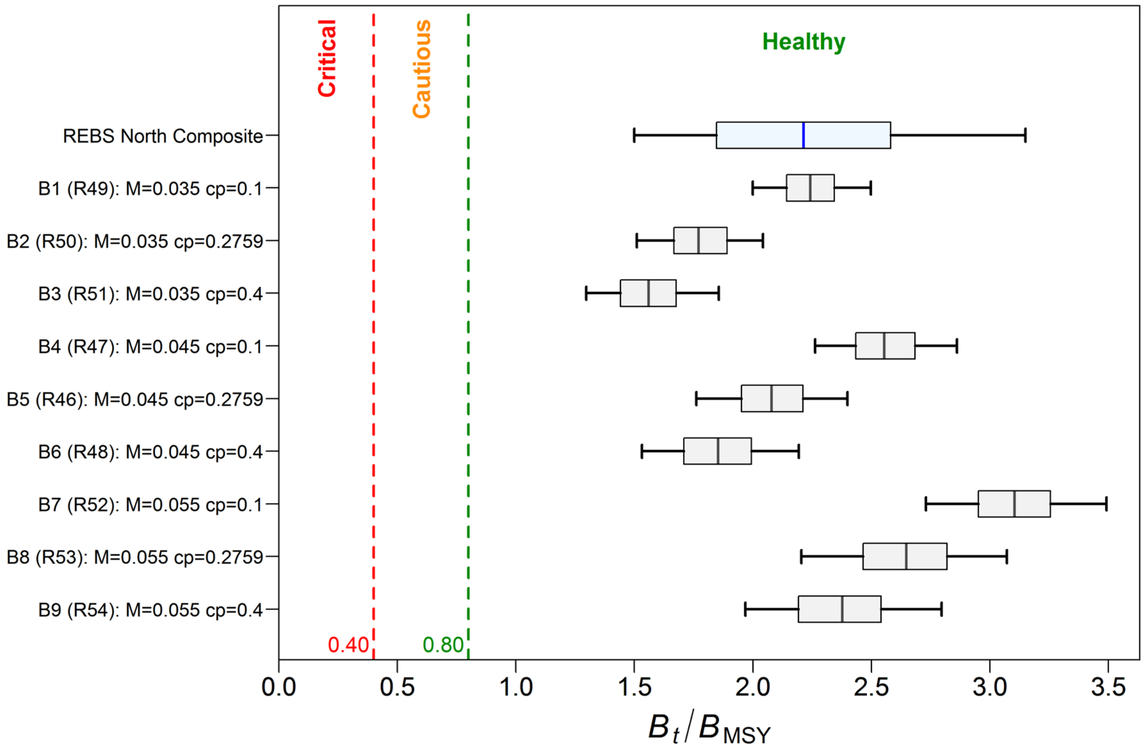

Figure 9. Status of the 2021 REBS north stock relative to the DFO PA provisional reference points of 0.4B_{MSY} and 0.8B_{MSY} for the composite base case and the component base runs that are pooled to form the composite base case. Boxplots show the 0.05, 0.25, 0.5, 0.75 and 0.95 quantiles from the MCMC posterior.

Table 5. REBS north decision tables for the reference points 0.4B_{MSY}, 0.8B_{MSY}, and u_{MSY} for 1-10 year projections for a range of constant catch policies (in tonnes) using the composite base case. Values are the probability (proportion of 9000 MCMC samples) of the female spawning biomass at the start of year t being greater than the B_{MSY} reference points, or the exploitation rate of vulnerable biomass in the middle of year t being less than the u_{MSY} reference point. For reference, the average catch over the last 5 years (2015-2019) was 548 t.

P(B_t >0.4B_{MSY})

Catch policy	Projection year 2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	1	1	1	1	1	1	1	1	1	1	1
100	1	1	1	1	1	1	1	1	1	1	1
200	1	1	1	1	1	1	1	1	1	1	1
300	1	1	1	1	1	1	1	1	1	1	1
400	1	1	1	1	1	1	1	1	1	1	1
500	1	1	1	1	1	1	1	1	1	1	1
600	1	1	1	1	1	1	1	1	1	1	1
700	1	1	1	1	1	1	1	1	1	1	1
800	1	1	1	1	1	1	1	1	1	1	1
900	1	1	1	1	1	1	1	1	1	1	1
1000	1	1	1	1	1	1	1	1	1	1	>0.99
1100	1	1	1	1	1	1	1	1	1	>0.99	>0.99
1200	1	1	1	1	1	1	1	1	1	>0.99	>0.99

P(B_t >0.8B_{MSY})

Catch policy	Projection year 2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	1	1	1	1	1	1	1	1	1	1	1
100	1	1	1	1	1	1	1	1	1	1	1
200	1	1	1	1	1	1	1	1	1	1	1
300	1	1	1	1	1	1	1	1	1	1	1
400	1	1	1	1	1	1	1	1	1	1	>0.99
500	1	1	1	1	1	1	1	>0.99	>0.99	>0.99	>0.99
600	1	1	1	1	1	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
700	1	1	1	1	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	0.99
800	1	1	1	>0.99	>0.99	>0.99	>0.99	>0.99	0.99	0.99	0.98
900	1	1	1	>0.99	>0.99	>0.99	>0.99	0.99	0.99	0.97	0.96
1000	1	1	1	>0.99	>0.99	>0.99	0.99	0.98	0.97	0.95	0.93
1100	1	1	>0.99	>0.99	>0.99	>0.99	0.99	0.97	0.95	0.92	0.88
1200	1	1	>0.99	>0.99	>0.99	0.99	0.98	0.95	0.92	0.88	0.82

P(u_t <u_{MSY})

Catch policy	Projection year 2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	1	1	1	1	1	1	1	1	1	1	1
100	1	1	1	1	1	1	1	1	1	1	1
200	1	1	1	1	1	1	1	1	1	1	1
300	1	1	1	1	1	1	1	1	1	1	1
400	1	1	1	1	1	1	1	1	1	1	1
500	1	1	>0.99	1	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
600	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	0.99	0.99	0.99
700	>0.99	>0.99	>0.99	>0.99	0.99	0.99	0.99	0.98	0.97	0.96	0.95
800	>0.99	0.99	0.99	0.99	0.98	0.97	0.95	0.94	0.91	0.89	0.87
900	0.99	0.98	0.97	0.96	0.95	0.93	0.9	0.87	0.84	0.81	0.78
1000	0.97	0.96	0.95	0.93	0.9	0.87	0.83	0.79	0.75	0.72	0.69
1100	0.95	0.93	0.91	0.88	0.85	0.8	0.76	0.72	0.68	0.65	0.62
1200	0.93	0.89	0.86	0.82	0.78	0.74	0.69	0.65	0.62	0.58	0.54

Table 6. *REBS north decision tables for the reference points 0.4B_{MSY} and 0.8B_{MSY} for 1-10 year projections for a range of constant harvest rate policies (as proportion of vulnerable biomass) using the composite base case. Values are the probability (proportion of 9000 MCMC samples) of the female spawning biomass at the start of year t being greater than the B_{MSY} reference points. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.023.*

P(B_t >0.4B_{MSY})

Catch policy	Projection year 2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	1	1	1	1	1	1	1	1	1	1	1
0.01	1	1	1	1	1	1	1	1	1	1	1
0.02	1	1	1	1	1	1	1	1	1	1	1
0.03	1	1	1	1	1	1	1	1	1	1	1
0.04	1	1	1	1	1	1	1	1	1	1	1
0.05	1	1	1	1	1	1	1	1	1	1	1
0.06	1	1	1	1	1	1	1	1	1	1	1
0.07	1	1	1	1	1	1	1	1	1	1	1
0.08	1	1	1	1	1	1	1	1	1	1	1
0.09	1	1	1	1	1	1	1	1	1	1	1
0.10	1	1	1	1	1	1	1	1	1	1	1
0.11	1	1	1	1	1	1	1	1	1	1	1
0.12	1	1	1	1	1	1	1	1	1	1	1

P(B_t >0.8B_{MSY})

Catch policy	Projection year 2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	1	1	1	1	1	1	1	1	1	1	1
0.01	1	1	1	1	1	1	1	1	1	1	1
0.02	1	1	1	1	1	1	1	1	1	1	1
0.03	1	1	1	1	1	1	1	1	1	1	1
0.04	1	1	1	1	1	1	1	1	1	1	1
0.05	1	1	1	1	1	1	1	1	1	1	1
0.06	1	1	1	1	1	1	1	1	1	1	1
0.07	1	1	1	1	1	1	1	1	1	1	1
0.08	1	1	1	1	1	1	1	1	1	1	1
0.09	1	1	1	1	1	1	1	1	1	1	1
0.10	1	1	1	1	1	1	1	1	1	1	1
0.11	1	1	1	1	1	1	1	1	1	1	1
0.12	1	1	1	1	1	1	1	1	1	1	1

P(u_t <u_{MSY})

Catch policy	Projection year 2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	1	1	1	1	1	1	1	1	1	1	1
0.01	1	1	1	1	1	1	1	1	1	1	1
0.02	1	1	1	1	1	1	1	1	1	1	1
0.03	1	1	1	1	1	1	1	1	1	1	1
0.04	1	1	1	1	1	1	1	1	1	1	1
0.05	1	1	1	1	1	1	1	1	1	1	1
0.06	1	1	1	1	1	1	1	1	1	1	1
0.07	1	1	1	1	1	1	1	1	1	1	1
0.08	1	1	1	1	1	1	1	1	1	1	1
0.09	1	1	1	1	1	1	1	1	1	1	1
0.10	1	1	1	1	1	1	1	1	1	1	1
0.11	>0.99	1	1	>0.99	1	>0.99	>0.99	>0.99	>0.99	1	>0.99
0.12	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99

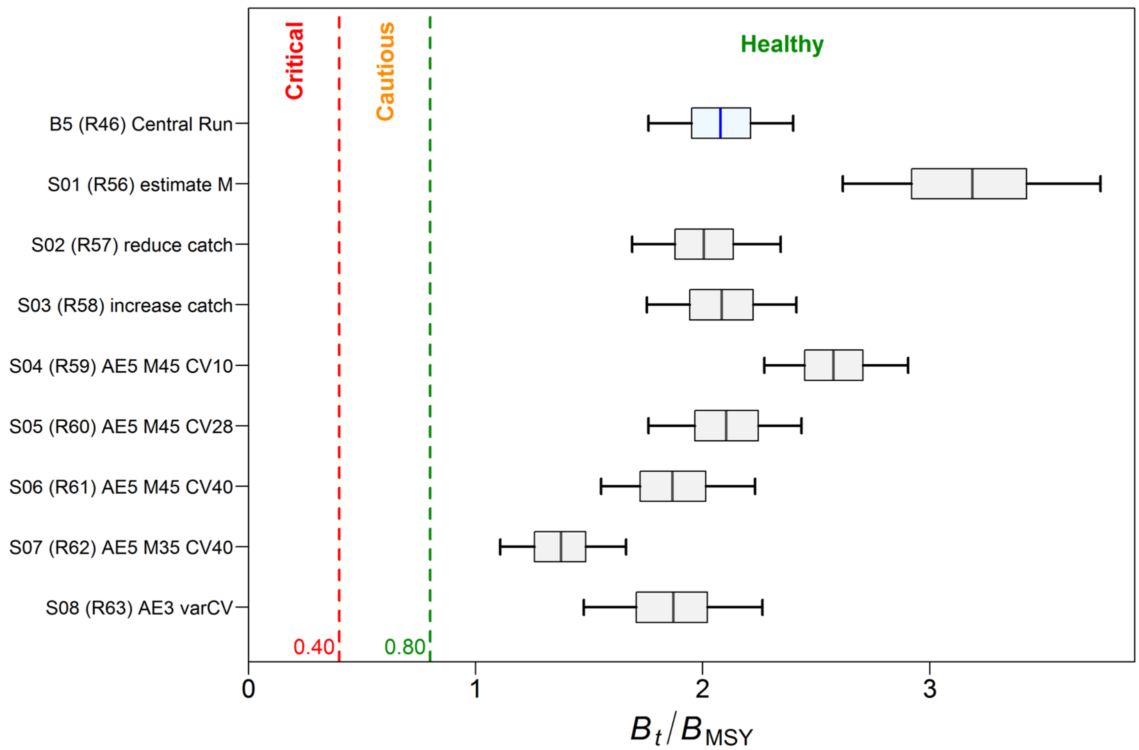

Figure 10. Status of the 2021 REBS north stock relative to the DFO PA provisional reference points of $0.4B_{MSY}$ and $0.8B_{MSY}$ for the central run of the composite base case and eight sensitivity runs (y-axis notation and sensitivity descriptions in the main text and Appendix F). Boxplots show the 0.05, 0.25, 0.5, 0.75 and 0.95 quantiles from the MCMC posterior.

9.2.2. REBS South

Stock status at the beginning of 2021 for the REBS south composite base case lies in the Healthy zone with a probability of 0.74, ranging from a low of 0.16 for component run B1 to a high of 1 for component run B9 (Figure 11). As with REBS north, the runs where M=0.035 have the lowest stock status among these six runs, although the effect of fitting the CPUE series works in the opposite direction than it did for REBS north. This is because the REBS south CPUE series trends generally downward after 2010, so the runs with c_p=0.1, which fit the downward trend more closely, will also have the lowest stock status for each M value. The MPD fit by the central run (Figure F.44), with c_p=0.2529, has the biomass trajectory passing above the final five indices, which makes the final trajectory less steep and effectively gives less weight to the declining trend in CPUE. Runs where c_p=0.1 followed the downward trend more closely than in Figure F.44 and estimated a lower stock status for the run. All the REBS south runs where M=0.035 have significant parts of the B_{2021}/B_0 posterior distribution in the Cautious zone, and run B1 (c_p=0.1) is almost entirely in the Cautious zone. On the other hand, the composite base case runs where M=0.045 or M=0.055 are either entirely or almost entirely in the Healthy zone (Figure 11). Although runs B1 and B6 have marginal MCMC diagnostics, the posterior distributions from these runs are more likely to be reliable and were accepted.

A reduced set of sensitivity runs was made for REBS south because of the scarcity of data available for this stock assessment and the difficulty when fitting alternative model runs. No attempt was made to estimate M. The sensitivity runs are all in the Healthy zone with the exception of run S03 (M=0.035) (Figure 12). The two sensitivity runs which altered catch did not diverge as much from the central run as did the equivalent REBS north runs (Figure 8). Both of these runs showed some flattening of the biomass decline during the late 1990s and 2000s, in response to the flat CPUE trend and the lack of contrast in both sets of survey biomass indices. The biomass decline steepens after 2010 in response to the decline in the CPUE series, ending at median(B_{2021}/B_0)=0.37 for S01 (reduced catch) and at median(B_{2021}/B_0)=0.35 for S02 (increased catch). The central run value for median(B_{2021}/B_0)=0.34, indicating that there is little impact to the conclusions from this stock assessment from uncertainty in the REBS south catch history.

The three sensitivity runs which used wider ageing error (AE) matrices behaved somewhat differently compared to the equivalent sensitivity runs made for the REBS north stock assessment, with the additional freedom to fit the age data resulting in a shift compared to the equivalent run in the composite base case. For instance, run S04 which matches the central run except for the wider AE matrix estimates B_{2021}/B_0=0.40 (0.28-0.55) while the central run estimates B_{2021}/B_0=0.34 (0.23-0.48). Sensitivity run S03 (the “worst case” run among these sensitivity runs), estimates B_{2021}/B_0=0.17 (0.13-0.22) while the equivalent run in the composite base case (run B02) estimates B_{2021}/B_0=0.23 (0.16-0.31). These two examples show that altering the uncertainty width of the AE matrix resulted in divergent behaviour from these two runs, suggesting that it is possible that the relative lack of REBS south data in these models may be the contributing to this result compared to the lack of sensitivity in the equivalent REBS north results.

Decision tables for the REBS south composite base case provide advice to managers as probabilities that current and projected biomass B_t (t = 2021, ..., 2031) will exceed biomass-based reference points (or that projected exploitation rate u_t will fall below harvest-based reference points) under constant-catch policies (Table 7) or constant harvest rate policies (Table 8). These two tables present probabilities that projected B_t using the composite base case will exceed the LRP and the USR or will be less than the harvest rate at MSY. Alternative decision tables for the composite base case can be found in Appendix F (Tables F.69-F.116), including the number of years to reach the various targets (Tables F.117-F.124).

Assuming that a catch of 300 t will be taken each year for the next 10 years, Table 7 indicates that a manager would be 97% certain that B_{2026} and 85% certain that B_{2031} lie above the LRP of 0.4B_{MSY}, 62% certain that B_{2026} and 53% certain that B_{2031} lie above the USR of 0.8B_{MSY}, and 33% certain that u_{2026} and 34% that u_{2031} lie below u_{MSY} for the composite base case. Similarly, Table 8 indicates that under a harvest rate strategy of 0.06/year, a manager would be >99% certain that both B_{2026} and B_{2031} lie above the LRP of 0.4B_{MSY}, 79% certain that B_{2026} and 87% that B_{2031} lie above the USR of 0.8B_{MSY}, and 60% certain that u_{2026} and u_{2031} lie below u_{MSY}. Generally, it is up to managers to choose the preferred catch levels or harvest levels using their preferred risk levels. For example, it may be desirable to be 95% certain that B_{2026} exceeds an LRP whereas exceeding a USR or remaining below a target exploitation rate (u_{MSY}) might only require a 50% probability. Assuming this risk profile, constant catch policies up to 200 t/y (constrained by target exploitation rate, Table 7) and harvest rate policies up to 0.06/y (also constrained by target exploitation rate, Table 8) would satisfy all three constraints. Ignoring target exploitation, a constant catch strategy of 300 t/y or any harvest rate strategy up to 0.12/y would satisfy the LRP and USR constraints alone.

Table 7. REBS south decision tables for the reference points $0.4B_{MSY}$, $0.8B_{MSY}$, and u_{MSY} for 1-10 year projections for a range of constant catch policies (in tonnes) using the composite base case. Values are the probability (proportion of 6000 MCMC samples) of the female spawning biomass at the start of year t being greater than the B_{MSY} reference points, or the exploitation rate of vulnerable biomass in the middle of year t being less than the u_{MSY} reference point. For reference, the average catch over the last 5 years (2015-2019) was 291 t.

$P(B_t > 0.4B_{MSY})$

Catch policy	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
		Projection year									
0	>0.99	>0.99	>0.99	>0.99	1	1	1	1	1	1	1
50	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	1	1
100	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
150	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
200	>0.99	>0.99	>0.99	>0.99	>0.99	0.99	0.99	0.99	0.99	0.99	0.98
250	>0.99	>0.99	>0.99	0.99	0.99	0.98	0.98	0.96	0.95	0.94	0.93
300	>0.99	>0.99	0.99	0.98	0.97	0.96	0.94	0.91	0.89	0.88	0.85
350	>0.99	>0.99	0.99	0.97	0.94	0.91	0.89	0.85	0.82	0.79	0.76
400	>0.99	>0.99	0.98	0.95	0.91	0.87	0.82	0.78	0.74	0.7	0.66
450	>0.99	0.99	0.97	0.93	0.87	0.82	0.76	0.71	0.66	0.62	0.58
500	>0.99	0.99	0.96	0.9	0.83	0.76	0.7	0.64	0.59	0.56	0.52
550	>0.99	0.99	0.94	0.86	0.79	0.7	0.64	0.58	0.54	0.51	0.48
600	>0.99	0.98	0.92	0.83	0.74	0.66	0.59	0.54	0.5	0.47	0.44

$P(B_t > 0.8B_{MSY})$

Catch policy	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
		Projection year									
0	0.74	0.78	0.83	0.87	0.91	0.94	0.96	0.98	0.99	>0.99	>0.99
50	0.74	0.77	0.8	0.83	0.86	0.89	0.91	0.94	0.95	0.97	0.98
100	0.74	0.76	0.77	0.79	0.81	0.83	0.85	0.87	0.88	0.89	0.91
150	0.74	0.74	0.75	0.75	0.76	0.77	0.78	0.79	0.79	0.8	0.81
200	0.74	0.73	0.72	0.72	0.71	0.71	0.7	0.7	0.7	0.7	0.69
250	0.74	0.72	0.7	0.68	0.66	0.65	0.64	0.63	0.62	0.61	0.6
300	0.74	0.7	0.67	0.65	0.62	0.6	0.58	0.57	0.55	0.54	0.53
350	0.74	0.69	0.65	0.62	0.59	0.56	0.54	0.52	0.5	0.49	0.48
400	0.74	0.68	0.63	0.59	0.55	0.53	0.5	0.48	0.47	0.45	0.44
450	0.74	0.67	0.61	0.56	0.53	0.49	0.47	0.45	0.43	0.41	0.4
500	0.74	0.65	0.59	0.54	0.5	0.47	0.44	0.41	0.4	0.38	0.36
550	0.74	0.64	0.57	0.52	0.47	0.44	0.41	0.39	0.36	0.35	0.33
600	0.74	0.63	0.55	0.5	0.45	0.41	0.38	0.36	0.34	0.32	0.3

$P(u_t < u_{MSY})$

Catch policy	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
		Projection year									
0	1	1	1	1	1	1	1	1	1	1	1
50	>0.99	>0.99	>0.99	>0.99	1	1	1	1	1	1	1
100	0.87	0.88	0.89	0.91	0.93	0.94	0.96	0.97	0.98	0.98	0.98
150	0.63	0.63	0.63	0.64	0.65	0.67	0.68	0.7	0.72	0.73	0.74
200	0.49	0.49	0.49	0.49	0.5	0.5	0.51	0.51	0.52	0.52	0.52
250	0.4	0.4	0.4	0.4	0.4	0.41	0.41	0.42	0.42	0.42	0.43
300	0.34	0.33	0.33	0.33	0.33	0.33	0.34	0.34	0.34	0.34	0.34
350	0.28	0.27	0.27	0.27	0.27	0.27	0.27	0.28	0.28	0.28	0.27
400	0.24	0.23	0.23	0.22	0.22	0.22	0.23	0.23	0.23	0.23	0.22
450	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.19
500	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.17	0.17	0.17
550	0.17	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.15	0.15
600	0.16	0.15	0.15	0.15	0.15	0.14	0.14	0.14	0.14	0.14	0.14

Table 8. REBS south decision tables for the reference points 0.4B_{MSY} and 0.8B_{MSY} for 1-10 year projections for a range of constant harvest rate policies (as proportion of vulnerable biomass) using the composite base case. Values are the probability (proportion of 6000 MCMC samples) of the female spawning biomass at the start of year t being greater than the B_{MSY} reference points. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.033.

P(B_t >0.4B_{MSY})

Catch policy	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
		Projection year									
0	>0.99	>0.99	>0.99	>0.99	1	1	1	1	1	1	1
0.01	>0.99	>0.99	>0.99	>0.99	1	1	1	1	1	1	1
0.02	>0.99	>0.99	>0.99	>0.99	>0.99	1	1	1	1	1	1
0.03	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	1	1	1	1	1
0.04	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	1	1	1	1
0.05	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	1	1
0.06	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	1	1
0.07	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
0.08	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
0.09	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
0.10	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
0.11	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
0.12	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99

P(B_t >0.8B_{MSY})

Catch policy	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
		Projection year									
0	0.74	0.78	0.83	0.87	0.91	0.94	0.96	0.98	0.99	>0.99	>0.99
0.01	0.74	0.77	0.82	0.85	0.89	0.92	0.95	0.97	0.98	0.99	0.99
0.02	0.74	0.77	0.81	0.84	0.87	0.9	0.93	0.95	0.97	0.98	0.99
0.03	0.74	0.76	0.8	0.82	0.85	0.88	0.91	0.93	0.95	0.96	0.97
0.04	0.74	0.76	0.78	0.81	0.83	0.86	0.88	0.9	0.92	0.94	0.95
0.05	0.74	0.76	0.77	0.79	0.81	0.83	0.85	0.87	0.88	0.9	0.91
0.06	0.74	0.75	0.76	0.77	0.79	0.8	0.81	0.83	0.84	0.86	0.87
0.07	0.74	0.74	0.75	0.75	0.76	0.77	0.78	0.79	0.8	0.8	0.8
0.08	0.74	0.74	0.73	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.73
0.09	0.74	0.73	0.72	0.72	0.71	0.7	0.69	0.69	0.68	0.67	0.66
0.10	0.74	0.72	0.71	0.7	0.68	0.67	0.65	0.64	0.62	0.6	0.59
0.11	0.74	0.72	0.7	0.67	0.65	0.63	0.61	0.59	0.57	0.55	0.53
0.12	0.74	0.71	0.68	0.65	0.63	0.6	0.57	0.55	0.52	0.5	0.48

P(u_t <u_{MSY})

Catch policy	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
		Projection year									
0	1	1	1	1	1	1	1	1	1	1	1
0.01	1	1	1	1	1	1	1	1	1	1	1
0.02	1	1	1	1	1	1	1	1	1	1	1
0.03	1	1	1	1	1	1	1	1	1	1	1
0.04	1	1	1	1	1	1	1	1	1	1	1
0.05	0.96	0.95	0.95	0.96	0.95	0.95	0.95	0.95	0.95	0.95	0.95
0.06	0.6	0.6	0.6	0.6	0.6	0.59	0.59	0.6	0.6	0.59	0.6
0.07	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.32
0.08	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
0.09	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
0.10	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
0.11	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
0.12	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

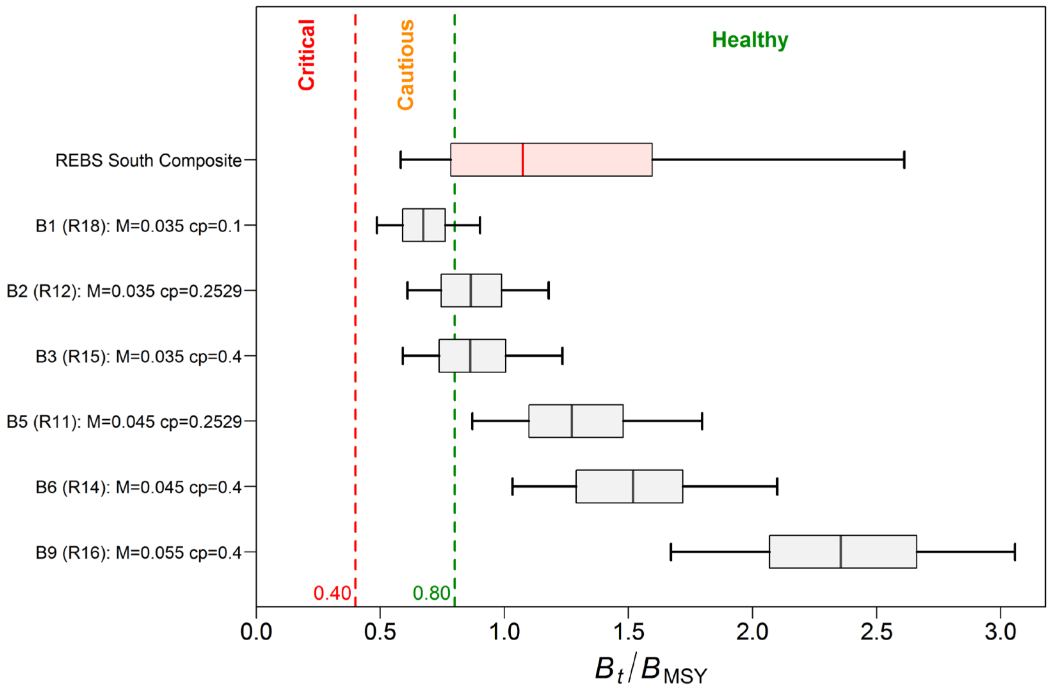

Figure 11. Status of the 2021 REBS south stock relative to the DFO PA provisional reference points of 0.4B_{MSY} and 0.8B_{MSY} for the composite base case and the component base runs that are pooled to form the composite base case. Boxplots show the 0.05, 0.25, 0.5, 0.75 and 0.95 quantiles from the MCMC posterior.

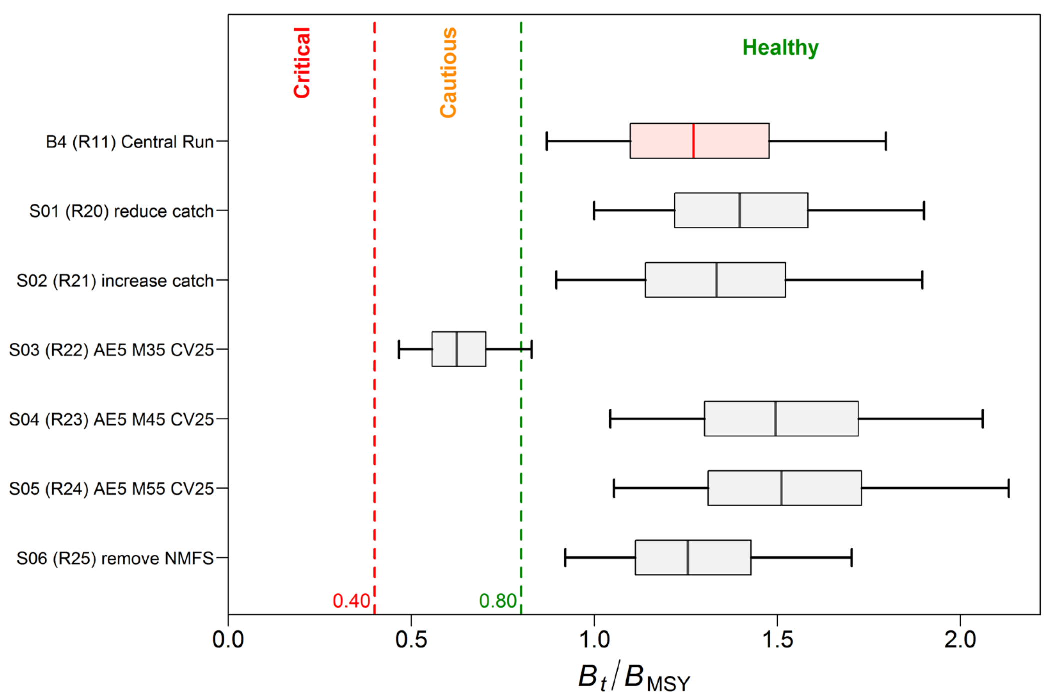

Figure 12. Status of the 2021 REBS south stock relative to the DFO PA provisional reference points of 0.4B_{MSY} and 0.8B_{MSY} for the central run of the composite base case and six sensitivity runs (y-axis notation and sensitivity descriptions in the main text and Appendix F). Boxplots show the 0.05, 0.25, 0.5, 0.75 and 0.95 quantiles from the MCMC posterior.

9.3. ASSESSMENT SCHEDULE

Advice was also requested concerning the appropriate time interval between future stock assessments and, for the interim years between stock updates, potential values of indicators that could trigger a full assessment earlier than usual (as per DFO 2016). However, it seems unlikely that any of the existing synoptic surveys would be sufficiently sensitive to changes in REBS biomass to trigger an early stock assessment of this species complex. Furthermore, there are several tasks that need to be completed before another assessment should be contemplated. First, a coastwide systematic sampling programme for the species split between BSR and RER needs to be initiated. It is unclear how useful the currently available genetic information are for splitting this species complex into its component parts because most of the data were derived from surveys and there is no current understanding on how well this information corresponds to the commercial fisheries for this species complex. Second, there remains a reasonably large number of unaged samples from the commercial fishery. The commercial AFs used in this stock assessment were only complete up to 2006. We requested additional otolith readings near the end of 2019, obtaining five new REBS north samples which represented 2016 and 2017 and one new REBS south sample from 2018. However, further ageing was interrupted by the shutdown of the ageing laboratory due to the COVID-19 response and there remain a significant number of unaged samples which should be aged before undertaking another stock assessment.

10. GENERAL COMMENTS

In common with other BC rockfish stock assessments, this stock assessment depicts two slow-growing, low productivity species/stocks. However there is reasonable evidence that there is sufficient productivity to maintain a strong (mostly target) fishery in 5DE (supporting about 700 t/year for 24 years from 1996 to 2019) and a lesser bycatch fishery in 3CD5AB (about 300 t/year over the same 24 years). There are three sets of fishery independent surveys which are used to monitor these two species/stocks and two CPUE series were developed that seem credible and helped facilitate the modelling. There is a reasonable amount of age data from the 5DE commercial fishery but much less from the 3CD5AB commercial fishery. All three primary synoptic surveys have a commendable amount of age data from most years. There are two main problems with this stock assessment. One is that this species complex is difficult to age, apparently more so than many of the other BC rockfish species. This results in variable ageing that is hard to fit without introducing substantial ageing error. This was less of a problem for the REBS north stock assessment because there were sufficient age data leading to stability in the MCMC simulations. But the REBS south assessment runs tended to be unstable, requiring fixing the survey selectivity parameters the MPD values and introducing strong priors on the commercial selectivities to obtain even moderate MCMC convergence.

The other problem was the species complex itself. We approximated the species split by using spatial definitions to define each stock. We assigned all data from the west coast of Haida Gwaii and Dixon Entrance to the more northern REBS stock. The balance of the BC data, excluding the lower part of Hecate Strait and the upper Moresby Gully, was assigned to the REBS south stock. The lower Hecate Strait/upper Moresby Gully data (PMFC 5C) were discarded except to split the catch proportionally between the two species. This approximation worked reasonably well and resulted in a credible stock assessment for REBS north and a less reliable stock assessment for REBS south. We note that the uncertainty in both stock assessments, particularly for REBS south, was much greater than the 5C catches. Consequently, managers could include 5C in either REBS stock for the purposes of management without compromising the stock assessment advice.

There was an expectation when this project was first initiated in 2018 that it would be possible to construct models to predict the species split based on information associated with the catch. While such models exist, they require high quality relevant data which do not appear to be available for REBS. Creamer (2016) constructed such a model which was used to predict the species split in the commercial fishery, beginning in 1996. This model used a suite of survey events as the training data set and then applied a form of the resulting predictive model to the commercial fishery. Because the commercial data available to Creamer were aggregated for confidentiality reasons, the final species split was based on 0.5° grids with the only parameter available being the spatial location of the grid. In effect, the Creamer species split was a finer scale version of the species split used in this stock assessment. What would be preferable is for the species information to be collected directly from the commercial fishery to better understand the distribution of the component species in the fishery before the survey data can be used to reliably split the commercial data. While the use of survey data to develop a procedure that will predict the speciation in the commercial catch is potentially a valid approach, these predictions should be validated from data in the target fishery. Alternatively, the collected commercial fishery data can be used in the predictive model. In either case, such sampling programmes should span several years in order to understand the level of interannual variability that is bound to exist in this species complex.

Foreign fleet effort in 1965-76 along the BC coast targeted POP, and REBS catch for these years was estimated as an assumed bycatch based on modern data; therefore, the magnitude of the foreign fleet removals of REBS is uncertain. Another source of uncertainty in the catch series comes from domestic landings from the mid-1980s to 1995 (pre-observer coverage) which may have misreported lesser rockfish species to bypass quota restrictions on more desirable species like POP. However, the sensitivity runs on catch (S02: -33%; S03: +50% for REBS north; S01: -33%; S02: +50% for REBS south) show that catch uncertainty did not have a major effect on the REBS north estimates of the relative stock size in 2021 but did modify the REBS north trajectories relative to the central run (Figure 5). These effects were less important for the two REBS south runs, with less modification of the biomass trajectory or the final year relative stock size estimates (Figure 10).

In the past, the use of commercial CPUE as an index of abundance was generally avoided in BC rockfish stock assessments (primarily due to uncertainty in vessel behaviour in response to regulations). However, we have successfully used CPUE based on the bycatch of the evaluated species in the BC bottom trawl fishery in four recent stock assessments (Bocaccio, Widow, Redstripe Rockfish: Starr and Haigh, 2021 a,b, 2022; Shortspine Thornyhead: Starr and Haigh 2017). The presumption in these instances was that these species were taken passively by the fishery in conjunction with a range of other finfish species. As long as the CPUE estimation model included the incidence of zero tows as well as the tows which captured the species, the resulting series would potentially track abundance. Because of the high level of observer coverage in the BC bottom trawl fishery, there is confidence that zero tows are being recorded reasonably accurately. In the case of this set of REBS stock assessments, the assumption of a bycatch fishery holds for the REBS south analysis but there is a significant component of target fishing in the REBS north fishery. We dealt with this problem differently in these stock assessments, varying the amount of process error added to the analysis, with low process error causing the model to more closely fit the CPUE series while high process error allowed the model to essentially ignore the series. In all cases, the presence of the CPUE series gave stability to models, particularly in the MCMC simulations. Consequently, the use of CPUE in these models became one of the axes of uncertainty in the composite base case.

A major source of uncertainty for this stock assessment is the inability to estimate M, given the available data. As discussed in Section 6.5, this assessment attempted to bracket plausible values of natural mortality based on the observed frequency of older ages in the data. Given the prior estimates provided by credible natural mortality estimators, we proceeded with M=0.035, 0.045 and 0.055 as the basis of this axis of uncertainty, having determined that M values outside this range had lower credibility given the observed range of available ages, Note that we chose not to investigate steepness (h). This was because the initial REBS north runs indicated that biomass levels were high and this parameter would not be tested, so it was easier to leave it out. However, we continued with this decision for the REBS south stock assessment because of the small amount of available data for this species and the corresponding fitting problems that we were having. Hopefully the next time this stock assessment is attempted there will be more ageing data available.

In addition to the uncertainties noted above in catch history accuracy, CPUE index confounding, data scarcity and projection uncertainty, there are other issues that led to uncertainty in the results. There are no biomass indices before the late-1990s. The available age composition data have a considerable amount of ageing error.

The decision tables provide guidance to the selection of short-term catch 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. These tables indicate that there is little short-term difference among the projected policies for REBS north but will need to be carefully examined for REBS south.

The REBS north stock assessment appears to be robust to a range of assumptions, including M, CPUE inclusion/exclusion, catch history and the uncertainty width of the ageing error matrix. The credible model fits to the data and the well-converged MCMC simulation behaviour for nearly every run attempted give this stock assessment a high level of credibility. This stock appears to be at fairly high relative biomass levels in spite of the long history of fishing and the projections indicate that there is little short-term concern. On the other hand, the REBS south stock assessment is much less definitive, with the runs using M=0.035 nearing or entering the Cautious zone and many of the runs, particularly those using M=0.055 having poor fits to the data with evidence of non-convergence in the MCMC simulations. That this stock is possibly at low levels is credible, given the long run of declining CPUE observations since 2010. The surveys are less clear, although the 2018 WCVI survey index is the lowest in the series and both the 2017 and 2019 QCS survey indices are also low. One possible source of optimism is the large number of young REBS observed in the QCS survey data which may indicate that there will be good recruitment to the fishery in the near future. However, while it is likely that this stock is at a low level, it is not clear how low that might be.

11. FUTURE RESEARCH AND DATA REQUIREMENTS

The following issues should be considered when planning future stock assessments and management evaluations for Rougheye/Blackspotted Rockfish[3]:

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. Implement sampling programmes (for genetic material and/or otolith morphology) in relevant commercial fisheries to explicitly estimate the REBS species composition in all BC major

[3] Many of the items in this list reflect recommendations from the May 2020 RPR meeting.

fisheries. This sampling should be implemented over a number of years to better understand variation in species proportions over years across a designed spatial scale.

3. Continue REBS species sampling (for genetic material and/or otolith morphology) in the three synoptic surveys used to monitor these two species: WCHG, QCS, and WCVI surveys. This sampling should, at a minimum, match the same years as in the commercial fishery. However, ideally this sampling should be implemented in these surveys routinely.
4. Investigate the capacity of using the longline surveys (IPHC, Hard Bottom North and South) to provide reliable relative biomass estimates for BSR and RER. If it is found that these surveys provide reliable indices of abundance, REBS species sampling should be implemented for these surveys.
5. Investigate if it is possible to derive relative biomass indices from the capture of REBS in the Sablefish trap survey. If it is found that it is possible to obtain reliable indices of abundance from this survey, REBS species sampling should be implemented in this survey.
6. Investigate the feasibility of using models to separate the REBS species complex into component species. These models should make use of the data generated by the above sampling programmes.
7. Prioritize work on otolith morphology to see if this method can be used for species specific identification.
8. Age as many as possible the unaged commercial samples beginning in 2007.
9. Obtain representative age samples from relevant commercial fisheries.
10. Analyse juvenile REBS data in more detail for growth and depth preference, particularly data from surveys that appear to have a high incidence of small REBS (e.g., Hecate Strait synoptic, Queen Charlotte Sound synoptic, Shellfish trawl).
11. Consider using a single-sex model in the next stock assessment of REBS (to avoid data dilution).
12. Investigate the feasibility of applying age-length keys to supplement years where age composition data are sparse or missing in the commercial fishery. This assumes that length data are more abundant than age data.
13. Explore using an age plus group lower than 80 in the stock assessment model.
14. Try fitting the age composition data using alternative distributions, such as the Dirichlet or logistic-normal (Schnute and Haigh 2007) or the Dirichlet-multinomial (Thorson et al. 2017).
15. Explore use of penalties on maturity at low ages (code available from one of the reviewers) rather than setting maturities to zero.
16. Try estimating steepness in the next REBS north assessment if data are sufficient.
17. Attempt retrospective analyses in the next assessment (requires different stock assessment software) if the missing age frequency data after 2006 have been updated.
18. Investigate for possible interaction effects in CPUE standardisation.
19. Look into enhanced projection methods (e.g., including autocorrelation and episodic high recruitment events).
20. Explore consequences of higher relative fecundity in females as they become larger (this can be implemented presently in Stock Synthesis, Methot et al. 2018).
21. Explore alternative random effects model for ageing error (e.g., Cope and Punt 2007).

22. Generate a 'Request for Science Information and Advice' to review existing biological sampling plans, primarily in the commercial fisheries but could also include surveys, and recommend how to improve them. This recommendation results from a clear pattern of reducing biological sampling in recent years.
23. Explore whether BSR and RER are undergoing evolutionary speciation or whether the apparent high level of hybridisation implies that the two species will not be maintained in the future as separate species.
24. Explore how single species populations, such as BSR or RER, 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 REBS population dynamics and resilience.
25. Explore the effects of climate change on REBS populations and identify how shifts in the ecosystem affect our perception of equilibrium conditions under different climate regimes. This could include exploring the use of environmental covariates as predictors of recruitment, as well as investigating the role of episodic recruitment in the evolutionary strategy used by REBS.

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13. REFERENCES

Cope, J.M. and Punt, A.E. 2007. Admitting ageing error when fitting growth curves: an example using the von Bertalanffy growth function with random effects. Can. J. Fish. Aquat. Sci. 64: 205-218.

COSEWIC. 2007. COSEWIC assessment and status report on the Rougheye Rockfish *Sebastes* sp. type I and *Sebastes* sp. type II in Canada. Tech. rep., Committee on the Status of Endangered Wildlife in Canada, Ottawa ON, viii + 36 p.

Creamer, J.M. 2016. Using genetic species identification and environmental data to distinguish historical catches of cryptic Blackspotted Rockfish (*Sebastes melanostictus*) and Rougheye Rockfish (*Sebastes aleutianus*) in British Columbia. Master's thesis, Simon Fraser University, Burnaby, BC, 40 p.

DFO. 2009. A fishery decision-making framework incorporating the Precautionary Approach. Accessed June 5, 2019.

DFO. 2012. Management plan for the Rougheye/Blackspotted Rockfish complex (*Sebastes aleutianus* and *S. melanostictus*) and Longspine Thornyhead (*Sebastolobus altivelis*) in Canada. Species at Risk Act Management Plan Series 412, Fisheries and Oceans Canada, Ottawa ON. vi + 49 p.

DFO. 2016. Guidelines for providing interim-year updates and science advice for multi-year assessments. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2016/020.

Edwards, A.M., Haigh, R. and Starr, P.J. 2012a. Stock assessment and recovery potential assessment for Yellowmouth Rockfish (*Sebastes reedi*) along the Pacific coast of Canada. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/095. iv + 188 p.

Edwards, A.M., Haigh, R. and Starr, P.J. 2014a. Pacific Ocean Perch (*Sebastes alutus*) stock assessment for the north and west coasts of Haida Gwaii, British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2013/092. vi + 126 p.

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.

Edwards, A.M., Starr, P.J. and Haigh, R. 2012b. Stock assessment for Pacific ocean perch (*Sebastes alutus*) in Queen Charlotte Sound, British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/111. viii + 172 p.

Fletcher, D., Mackenzie, D. and Villouta, E. 2005. Modelling skewed data with many zeros: A simple approach combining ordinary and logistic regression. Environmental and Ecological Statistics12, 45–54.

Forrest, R.E., McAllister, M.K., Dorn, M.W., Martell, S.J.D. and Stanley, R.D. 2010. Hierarchical Bayesian estimation of recruitment parameters and reference points for Pacific rockfishes (*Sebastes* spp.) under alternative assumptions about the stock-recruit function. Can. J. Fish. Aquat. Sci. 67: 1611–1634.

Forrest, R.E., Holt, K.R. and Kronlund, A.R. 2018. Performance of alternative harvest control rules for two Pacific groundfish stocks with uncertain natural mortality: bias, robustness and trade-offs. Fish. Res. 206: 259-286.

Francis, R.I.C.C. 2011. Data weighting in statistical fisheries stock assessment models. Can. J. Fish. Aquat. Sci. 68(6): 1124–1138.

Garvin, M.R., Marcotte, R.W., Palof, K.J., Riley, R.J., Kamin, L.M. and Gharrett, A.J. 2011. Diagnostic single-nucleotide polymorphisms identify Pacific ocean perch and delineate blackspotted and rougheye rockfish. Trans. Am. Fish. Soc. 140: 984-988.

Gharrett, A.J., Matala, A.P., Peterson, E.L., Gray, A.K., Li, Z. and Heifetz, J. 2005. Two genetically distinct forms of rougheye rockfish are different species. Trans. Am. Fish. Soc. 134: 242-260.

Haigh, R., Starr, P.J., Edwards, A.M., King, J.R. and Lecomte, J.B. 2018. Stock assessment for Pacific Ocean Perch (*Sebastes alutus*) in Queen Charlotte Sound, British Columbia in 2017. DFO Can. Sci. Advis. Sec. Res. Doc. 2018/038: v + 227 p.

Hamel, O.S. 2015. A method for calculating a meta-analytical prior for the natural mortality rate using multiple life history correlates. ICES J. Mar. Sci. 72(1): 62-69.

Harris, J.P., Hutchinson, C. and Wildes, S. 2019. Using otolith morphometric analysis to improve species discrimination of blackspotted rockfish (*Sebastes melanostictus*) and rougheye rockfish (*S. aleutianus*). Fish. Bull. 117: 234244.

Hicks, A.C., Wetzel, C. and Harms, J. 2014. The status of rougheye rockfish (*Sebastes aleutianus*) and blackspotted rockfish (*S. melanostictus*) as a complex along the U.S. West Coast in 2013. Stock Assessment and Fishery Evaluation (SAFE) , NMFS, NOAA xvi + 250 p.

Hilborn, R., Maunder, M., Parma, A., Ernst, B., Payne, J. and Starr, P. 2003. Coleraine: A generalized age-structured stock assessment model. User's manual version 2.0. University of Washington Report SAFS-UW-0116. Tech. rep., University of Washington.

Hoenig, J.M. 1983. Empirical use of longevity data to estimate mortality rates. Fish. Bull. 82(1): 898-903.

Krieger, K.J. and Ito, D.H. 1999. Distribution and abundance of shortraker rockfish, *Sebastes borealis*, and rougheye rockfish, *S. aleutianus*, determined from a manned submersible. Fish. Bull. 97(2): 264-272.

Love, M.S., Yoklavich, M. and Thorsteinson, L. 2002. The Rockfishes of the Northeast Pacific. University of California Press, Berkeley and Los Angeles, California.

New Zealand Ministry of Fisheries. 2011. Operational Guidelines for New Zealand's Harvest Strategy Standard. Ministry of Fisheries, New Zealand.

Orr, J.W. and Hawkins, S. 2008. Species of the rougheye rockfish complex: resurrection of *Sebastes melanostictus* (matsubara, 1934) and a redescription of *Sebastes aleutianus* (Jordan and Evermann, 1898) (Teleostei: Scorpaeniformes). Fish. Bull. 106: 111-134.

Schnute, J.T. and Haigh, R. 2007. Compositional analysis of catch curve data, with an application to *Sebastes maliger*. ICES J. Mar. Sci. 64(2): 218-233.

Shotwell, S.K. and Hanselman, D.H. 2019. Chapter 13: Assessment of rougheye and blackspotted rockfish in the Gulf of Alaska. In Stock Assessment and Fishery Evaluation (SAFE) Report for the Groundfish Resources of the Gulf of Alaska, chap. 12, p. 1-115. North Pacific Fishery Management Council (NPFMC).

Stanley, R.D. and Kronlund, A.R. 2000. Silvergray rockfish (*Sebastes brevispinis*) assessment for 2000 and recommended yield options for 2001/2002. DFO Can. Sci. Advis. Sec. Res. Doc. 2000/173. 116 p.

Stanley, R.D., Starr, P. and Olsen, N. 2009. Stock assessment for Canary rockfish (*Sebastes pinniger*) in British Columbia waters. DFO Can. Sci. Advis. Sec. Res. Doc. 2009/013. xxii + 198 p.

Starr, P.J. and Haigh, R. 2017. Stock assessment of the coastwide population of Shortspine Thornyhead (*Sebastolobus alascanus*) in 2015 off the British Columbia coast. DFO Can. Sci. Advis. Sec. Res. Doc. 2017/015. ix + 174 p.

Starr, P.J. and Haigh, R. 2021a. Redstripe Rockfish (*Sebastes proriger*) stock assessment for British Columbia in 2018. DFO Can. Sci. Advis. Sec. Res. Doc. 2021/014. vii + 340 p.

Starr, P.J. and Haigh, R. 2021b. Widow Rockfish (*Sebastes entomelas*) stock assessment for British Columbia in 2019. DFO Can. Sci. Advis. Sec. Res. Doc. 2021/039. viii + 238 p.

Starr, P.J. and Haigh, R. 2022. Bocaccio (*Sebastes paucispinis*) stock assessment for British Columbia in 2019, including guidance for rebuilding plans. DFO Can. Sci. Advis. Sec. Res. Doc. In press.

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. 2016/042. vi + 170 p.

Then, A.Y., Hoenig, J.M., Hall, N.G. and Hewitt, D.A. 2015. Evaluating the predictive performance of empirical estimators of natural mortality rate using information on over 200 fish species. ICES J. Mar. Sci. 72(1): 82-92.

Thorson, J.T., Johnson, K.F., Methot, R.D. and Taylor, I.G. 2017. Model-based estimates of effective sample size in stock assessment models using the Dirichlet-multinomial distribution. Fish. Res. 192: 84-93.

Walker, B. and Salt, D. 2006. Resilience Thinking: Sustaining Ecosystems and People in a Changing World. Island Press. Washington DC. 192 p.

APPENDIX A. CATCH DATA

A.1. BRIEF HISTORY OF THE FISHERY

Forrester (1969) provides a brief history of the Pacific Marine Fisheries Commission (PMFC), which is reproduced (with some modification) below. Currently, the PMFC is called the Pacific States Marine Fisheries Commission; however, this document retains the acronym 'PMFC' for historical context.

> *The Pacific Marine Fisheries Commission (PMFC) was created in 1947 when the states of Washington, Oregon, and California jointly formed an interstate agreement (called a 'compact') with the consent of the 80th Congress of the USA. In 1956, informal agreement was reached among various research agencies along the Pacific coast to establish a uniform description of fishing areas as a means of coordinating the collection and compilation of otter trawl catch statistics. This work was undertaken by the PMFC with the informal cooperation of the Fisheries Research Board of Canada. Areas 1A, 1B, and 1C encompass waters off the California coast, while Areas 2A-2D involve waters adjacent to Oregon and a small part of southern Washington. The remainder of the Washington coast and the waters off the west coast of Vancouver Island comprise Areas 3A-3D, while United States and Canadian inshore waters (Juan de Fuca Strait, Strait of Georgia, and Puget Sound) are represented by Areas 4A and 4B, respectively. Fishing grounds between the northern end of Vancouver Island and the British Columbia-Alaska boundary are represented by Areas 5A-5E. The entire Alaskan coast is designated as Area 6, but except for a small amount of fishing in inshore channels, this area has not been trawled intensively by North American nationals.*

The early history of the British Columbia (BC) trawl fleet was covered by Forrester and Smith (1972). A trawl fishery for slope rockfish has existed in BC since the 1940s. Aside from Canadian trawlers, foreign fleets targeted Pacific Ocean Perch (POP, *Sebastes alutus*) in BC waters for approximately two decades. These fleets were primarily from the USA (1959–1976), the USSR (1965–1968), and Japan (1966–1976). Consequently, the foreign vessels removed large amounts of rockfish biomass, including species other than POP, in Queen Charlotte Sound (QCS, Ketchen 1976, 1980b), off the west coast of Haida Gwaii (WCHG, Ketchen 1980a,b), and off the west coast of Vancouver Island (WCVI, Ketchen 1976, 1980a,b). All foreign fleets were excluded from Canadian waters inside of 200 nm with the declaration of the EEZ in 1977. Canadian effort escalated in 1985, and for the next decade, landings by species were often misreported to avoid species-specific trip limits.

Before 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 major finfish species. Quotas in the form of total allowable catches (TACs) were first introduced specifically for Rougheye Rockfish (RER, *Sebastes aleutianus*) in 1997 for the BC coast (Table A.1, and see Table A.2 for additional management actions). Prior to this, TACs for rockfish aggregates that included RER were set from 1994-1996. Note that the fishery catch data report all landings of Rougheye/Blackspotted Rockfish (REBS) complex as RER, and so all catches of RER are considered to comprise both species.

The REBS complex has never undergone a formal stock assessment. A pre-COSEWIC review was published in 2005 to provide data on the biology, distribution, and abundance trends for REBS (Haigh et al. 2005). Posterior model estimates of total mortality rate Z (F+M) along the

WCHG compared the survey year 1997 with commercial years 1996 and 2003. The mean mortality rate *Z* estimated from the 1997 survey was 0.048 with a 95% confidence limits of (0.039, 0.058)[4]. The estimated commercial *Z* in 1996 was equivalent with mean 0.045 (0.038, 0.054)[4]. In 2003, older age classes were truncated and younger fish predominated. The posterior distribution of *Z* had a mean of 0.091 (0.072, 0.107)[4]. It appeared that fishing mortality had doubled in this region from 1996 to 2003, assuming that natural mortality had remained constant at *M*=0.035.

In 2009, the REBS complex was listed as 'Special Concern' under SARA. This required the formation of a management plan (MP) to provide advice to jurisdictions[5] and organizations that may be involved in activities to conserve the species. The MP (Fisheries and Oceans Canada. 2012) followed extensive consultation with participants through a technical working group (TWG), held on October 2010, and posted to the DFO Pacific Region Consultation website for a public comment period from March 25 to April 28, 2011. The MP summarises various aspects relevant to the species (biology, population distribution, habitat requirements, ecological role, threats to the population) and outlines management objectives (e.g., produce peer-reviewed stock assessments) and actions (e.g., take genetic samples from all DFO Science surveys).

BSR and RER are ubiquitous along the BC coast and most catches are taken close to the bottom over depths of 200 to 800+ m along the shelf break. These two species are among the longest lived *Sebastes*, with maximum recorded ages in BC of 147 years (REBS in 5DE called 'REBS north' in this assessment) and 125 years (REBS in 3CD5AB, called 'REBS south'), and 205 years in Southeast Alaska (Munk 2001, most likely a Type I specimen). The REBS complex is intercepted by trawl nets, hook and line gear, and the Sablefish trap fishery, and is a key species caught in the BC multi-species integrated groundfish fishery. The species complex has been managed as a single population of called 'Rougheye Rockfish', pending advice on species identification methodologies and the implications of various harvest strategies on expected stock status for each species within the complex. Differentiating between these two species is done through genetic sampling because it is not feasible to distinguish between these species by visual inspection quickly and reliably.

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

[4] Visual estimate of 95% confidence limits from Figure 5 in Haigh et al. (2005)

[5] Responsible jurisdictions: Fisheries & Oceans Canada, Environment Canada, Parks Canada Agency

Table A.1. Annual Total Allowable Catch (TAC tonnes/year) for REBS caught in BC waters: year can either be calendar year (1993-1996) or fishing year (1997 on). T = Trawl, H = Halibut, ZN = ZN Outside, LL = Longline, R = Research.

TAC History				TAC by Fishery				Research			Sector Allocation		
Year	**Start**	**End**	**TAC**	**T**	**H**	**ZN**	**R**	**T**	**LL**	**ZN**	**T**	**ZN**	**H**
1993	1/1/1993	12/31/1993	-	6.8 t/trip	-	-	-	-	-	-	-	-	-
1994	1/15/1994	12/31/1994	12574	12574	-	-	-	-	-	-	-	-	-
1995	1/1/1995	12/31/1995	10451	9716	-	735	-	-	-	-	0.9297	0.0703	-
1996	2/6/1996	3/31/1997	2011	1311	-	700	-	-	-	-	0.6519	0.3481	-
1997	4/1/1997	3/31/1998	1185	380	-	805	-	-	-	-	0.3207	0.6793	-
1998	4/1/1998	3/31/1999	950	549	-	401	-	-	-	-	0.5779	0.4221	-
1999	4/1/1999	3/31/2000	950	433	-	517	-	-	-	-	0.4558	0.5442	-
2000	4/1/2000	3/31/2001	939.6	431	34.8	473.8	-	-	-	-	0.4587	0.5043	0.0370
2001	4/1/2001	3/31/2002	950	530	29	391	-	-	-	-	0.5580	0.4117	0.0303
2002	4/1/2002	3/31/2003	950	530	29	391	-	-	-	-	0.5580	0.4117	0.0303
2003	4/1/2003	3/31/2004	970	530	29	391	20	-	-	20	0.5580	0.4117	0.0303
2004	4/1/2004	3/31/2005	970	530	29	391	20	-	-	20	0.5580	0.4117	0.0303
2005	4/1/2005	3/31/2006	970	530	29	391	20	-	-	20	0.5580	0.4117	0.0303
2006	4/1/2006	3/31/2007	1140	636	35	469	-	-	-	-	0.5580	0.4117	0.0303
2007	3/10/2007	3/31/2008	1140	636	35	469	-	-	-	-	0.5580	0.4117	0.0303
2008	3/8/2008	2/20/2009	1140	636	33	451	20	-	20	-	0.5580	0.4117	0.0303
2009	2/21/2009	2/20/2010	1140	636	33	451	20	-	20	-	0.5580	0.4117	0.0303
2010	2/21/2010	2/20/2011	1140	636	33	451	20	-	20	-	0.5580	0.4117	0.0303
2011	2/21/2011	2/20/2013	1140	636	33	451	20	-	20	-	0.5580	0.4117	0.0303
2012	2/21/2011	2/20/2013	1140	636	33	451	20	-	20	-	0.5580	0.4117	0.0303
2013	2/21/2013	2/20/2014	1140	636	33	451	20	-	20	-	0.5580	0.4117	0.0303
2014	2/21/2014	2/20/2015	1140	636	33	451	20	-	20	-	0.5580	0.4117	0.0303
2015	2/21/2015	2/20/2016	1141.5	636	33	451	22	1.5	20	-	0.5580	0.4117	0.0303
2016	2/21/2016	2/20/2017	1150.3	636	33	451	30	10.3	20	-	0.5580	0.4117	0.0303
2017	2/21/2017	2/20/2018	1141.8	636	33	451	22	1.8	20	-	0.5580	0.4117	0.0303
2018	2/21/2018	2/20/2019	1158.6	636	33	451	39	14.9	23.7	-	0.5580	0.4117	0.0303
2019	2/21/2019	2/20/2020	1145	636	33	451	25	1.3	23.7	-	0.5580	0.4117	0.0303

Table A.2. Codes to notes on management actions and quota adjustments that appear in Table A.1. Abbreviations that appear under 'Management Actions': DFO = Department of Fisheries & Oceans, DMP = dockside monitoring program, GTAC =Groundfish Trawl Advisory Committee, H&L = hook and line, IFMP = Integrated Fisheries Management Plan, IVQ = individual vessel quota, MC =Mortality Cap, TAC =Total Allowable Catch. See Archived Integrated Fisheries Management Plans - Pacific Region for further details.

Year	Management Actions
1993	RER: Trip limits for trawl specified for the first time.
1994	TWL: Started a dockside monitoring program (DMP) for the Trawl fleet.
1994	TWL: As a means of both reducing at-sea discarding and simplifying the harvesting regime, rockfish aggregation was implemented. Through consultation with GTAC, the following aggregates were identified: Agg1=POP, YMR, RER, CAR, SGR, YTR; Agg2=RSR, WWR; Agg3=SKR, SST, LST; Agg4=ORF.
1995	TWL: Trawl aggregates established in 1994 changed: Agg1=CAR, SGR, YTR, WWR, RER; Agg2=POP, YMR, RSR; Agg3=SKR, SST, LST; Agg4=ORF.
1996	TWL: Started 100% onboard observer program for offshore Trawl fleet.
1996	H&L: Rockfish aggregation will continue on a limited basis in 1996: Agg1=YTR, WWR; Agg2=CAR, SGR; Agg3=POP, YMR; Agg4=RER, SKR; Agg5=RSR, SCR; Agg6=ORF incl. SST, LST
1997	TWL: Started IVQ system for Trawl Total Allowable Catch (TAC) species (April 1, 1997)
1997	H&L: All H&L rockfish, with the exception of YYR, shall be managed under the following rockfish aggregates: Agg1=QBR, CPR; Agg2=CHR, TIR; Agg3=CAR, SGR; Agg4=RER, SKR, SST, LST; Agg5=POP, YMR, RSR; Agg6=YTR, BKR, WWR; Agg7=ORF excluding YYR.
2000	H&L: Implemented formal allocation of rockfish species between Halibut and H&L sectors.
2000	ALL: 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. Splits agreed upon for these rockfish will be implemented in the future when or if TACs are set for those species.
2001	RER: Set commercial allocations among sectors (ongoing to 2019): Trawl 55.8%, H&L 41.17%, Halibut 3.03%.
2002	TWL: Closed areas to preserve four hexactinellid (glassy) sponge reefs.
2003	REBS: Species at Risk Act (SARA) came into force in 2003.
2006	ALL: Introduced an Integrated Fisheries Management Plan (IFMP) for all directed groundfish fisheries.
2006	H&L: Implemented 100% at-sea electronic monitoring and 100% dockside monitoring for all groundfish H&L fisheries.
2007	PAH: Amendment to Halibut IVQ cap for SST and RER -- reallocations can only occur in blocks up to 4000 lbs or until the vessel species cap is met. Once the first 4000 lbs has been caught additional IVQ can be reallocated onto the licence up to 4000 lbs. This can continue until the vessel species cap is met.
2009	REBS: Management plan published, with goal to maintain sustainable populations of LST and REBS within each species' known range in Canadian Pacific waters.
2012	TWL: Froze 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).
2013	TWL: To support groundfish research, the groundfish trawl industry agreed to the trawl TAC offsets to account for unavoidable mortality incurred during the joint DFO-Industry groundfish multi-species surveys in 2013.
2015	ALL: Research allocations were specified starting in 2015 to account for the mortalities associated with survey catches to be covered by TACs.

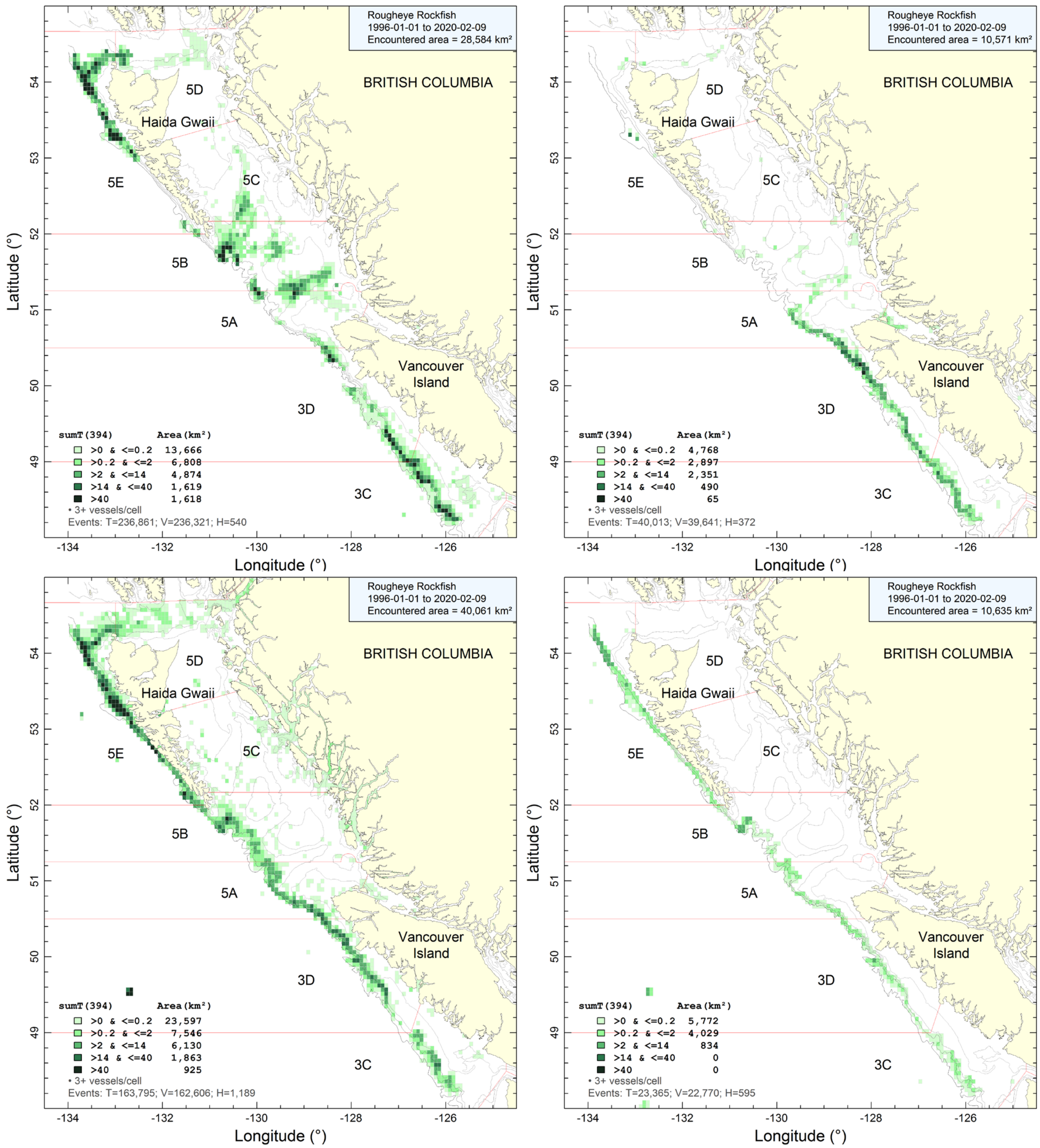

Figure A.1. Aerial distribution of accumulated REBS catch (tonnes) by bottom trawl (upper left), midwater trawl (upper right), hook and line (lower left), and trap (lower right) from 1996 to 2020 in grid cells 0.075° longitude by 0.055° latitude (roughly 32 km²). Isobaths show the 100, 200, 500, and 1200 m depth contours. Note that cells with <3 fishing vessels are not displayed.

A.2. CATCH RECONSTRUCTION

This assessment reconstructs REBS catch back to 1918 but considers the start of the fishery to be 1935 (Figure A.2) before the fishery started to increase during World War II. Prior to this, trawl catches were negligible and halibut fleet catches were estimated to be <20 tonnes per stock per year. During the period 1950–1975, US vessels routinely caught more rockfish than did Canadian vessels. Additionally, from the mid-1960s to the mid-1970s, foreign fleets (Russian and Japanese) removed large amounts of rockfish, primarily POP. These large catches were first reported by various authors (Westrheim et al. 1972; Gunderson et al. 1977; Leaman and Stanley 1993); however, Ketchen (1980a,b) re-examined the foreign fleet catch, primarily because statistics from the USSR called all rockfish 'perches' while the Japanese used the term 'Pacific ocean perch' indiscriminately. In the catch reconstruction, all historical foreign catches (annual rockfish landings) were tracked separately from Canadian REBS landings, converted to REBS (Section A.2.2), and added to the latter during the reconstruction process.

A.2.1. Data sources

Starting in 2015, all official Canadian catch tables from the databases below (except `PacHarv3`) have been merged into one table called '`GF_MERGED_CATCH`', which is available in DFO's `GFFOS` database. All groundfish DFO databases are now housed on the `DFBCV9TWVASP001` server. REBS 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 (2006-2019) – all fisheries and modern surveys; and
- `GFBioSQL` joint-venture hake and research survey catches (1947-2019) – multiple gear types. `GFBioSQL` is an SQL Server database that mirrors the `GFBio` Oracle database.

All data sources other than `PacHarv3` were superseded by `GFFOS` from 2007 on because this latter repository was designed to record all Canadian west coast 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 purpose of this procedure is to estimate the reconstructed catch of any rockfish species (generically designated as RRF) from ratios of RRF/ORF or RRF/TRF, add the estimated discards from the ratio RRF/TAR (where TAR is the target species landed by fishery), to reconstruct the total catch of species RRF.

A.2.2. Reconstruction details

A.2.2.1. Definition of terms

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

Fisheries: there are five fisheries in the reconstruction (even though trawl and hook & line dominate the REBS fishery):

- T = groundfish trawl (bottom + midwater),
- H = Halibut longline,
- S = Sablefish trap/longline,
- DL = Dogfish and Lingcod troll/longline (originally called 'Schedule II'),
- ZN = hook and line rockfish (sector called 'ZN' from 1986 to 2006 and 'Rockfish Outside' and 'Rockfish Inside' from 2007 on).

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

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

POP: Pacific Ocean Perch

RRF: Reconstructed rockfish species – in this case, REBS

TAR: Target species landed catch

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

gamma:mean of annual ratios, $\sum_i \mathrm{RRF}_i^L \big/ \mathrm{ORF}_i^L$, grouped by major PMFC area and fishery using default reference years i = 1997-2005. For REBS, the reference years were set to 1997-2005 for the trawl fishery and 2007-2009 for the non-trawl fisheries.

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

The stock assessment population model uses calendar year, requiring calendar year catch estimates. The reconstruction defaults to using 'official' (reported) catch numbers by fishery starting in years 1996 (T), 2000 (H), 2007 (S,DL), and 1986 (ZN), which are the years when these fisheries implemented reliable observer coverage. These defaults were not used for REBS. Instead, landings were reconstructed before 1996 for the trawl fishery and before 2006 for the non-trawl fisheries. Although reported data existed in earlier time periods, previous TWGs considered that reported catches of less desirable rockfish species from 1985 (start of restrictive trip limits) to 1994 (start of the DMP) were likely inflated, given the incentives for operators to misreport their catch of desirable species during this period.

The reconstruction of Canadian REBS catch estimated landings for years before those with credible records using `gamma` ratios (Table A.3). These ratios were also used to convert foreign landings of ORF to REBS. The ratios were calculated from a relatively modern period (1997-2005 for trawl, 2007-2009 for non-trawl); therefore, an obvious caveat to this procedure is that ratios derived from a modern fishery may not reflect catch ratios during the historical foreign fleet activity or regulatory regimes not using IVQs (individual vessel quotas). Consequently, we use sets of years where gamma does not fluctuate wildly in an attempt to minimise this potential issue.

After REBS landings were estimated, non-retained catch (releases or discards) were estimated and added during years identified by fishery: T = 1954-1995, H = 1918-2005, S/DL = 1950-2005, and ZN = 1986-2005. The non-retained catch was estimated using the `delta` ratios of REBS discarded by a fishery to fishery-specific landed targets (TAR): T = REBS, H = Pacific Halibut, S = Sablefish, DL = Spiny Dogfish + Lingcod, ZN = REBS (Table A.3).

The current annual REBS catches by trawl fishery and those from the non-trawl fisheries appear in Table A.4 and Figure A.2. The combined fleet catches were used in the population models as plotted in Figure A.8.

A.2.2.2. Reconstruction results

Table A.3. Estimated 'gamma' (RER/ORF) and 'delta' (discard) ratios for each fishery and PMFC area used in the catch reconstruction of REBS. Note: RER = REBS in commercial catch data.

gamma (proportion RER/ORF)

PMFC	Trawl	Halibut	Sablefish	Dogfish/ Lingcod	H&L Rockfish
3C	0.02779	0.29395	0.56921	0.00273	9.19E-05
3D	0.01590	0.27349	0.47284	0.00034	0.02350
5A	0.00298	0.09151	0.51457	0.00108	0.03210
5B	0.01515	0.15167	0.55209	0.00926	0.00638
5C	0.00724	0.02338	0.13902	0.00350	0.00715
5D	0.02197	0.09293	0.05658	7.43E-05	0.00233
5E	0.20541	0.35729	0.52004	0	0.67015

delta (discard rate)

PMFC	Trawl	Halibut	Sablefish	Dogfish/ Lingcod	H&L Rockfish
3C	0.00409	0.00016	0.02311	0	0
3D	0.00413	0.00087	0.00316	0	0
5A	0.00199	0.00022	0.00842	0	0.00196
5B	0.00655	0.00073	0.02386	0.00114	0
5C	0.00553	0.00018	0	0	0
5D	0.01936	7.44E-05	0	0	0
5E	0.00319	0.00424	0.02866	0.00166	7.26E-05

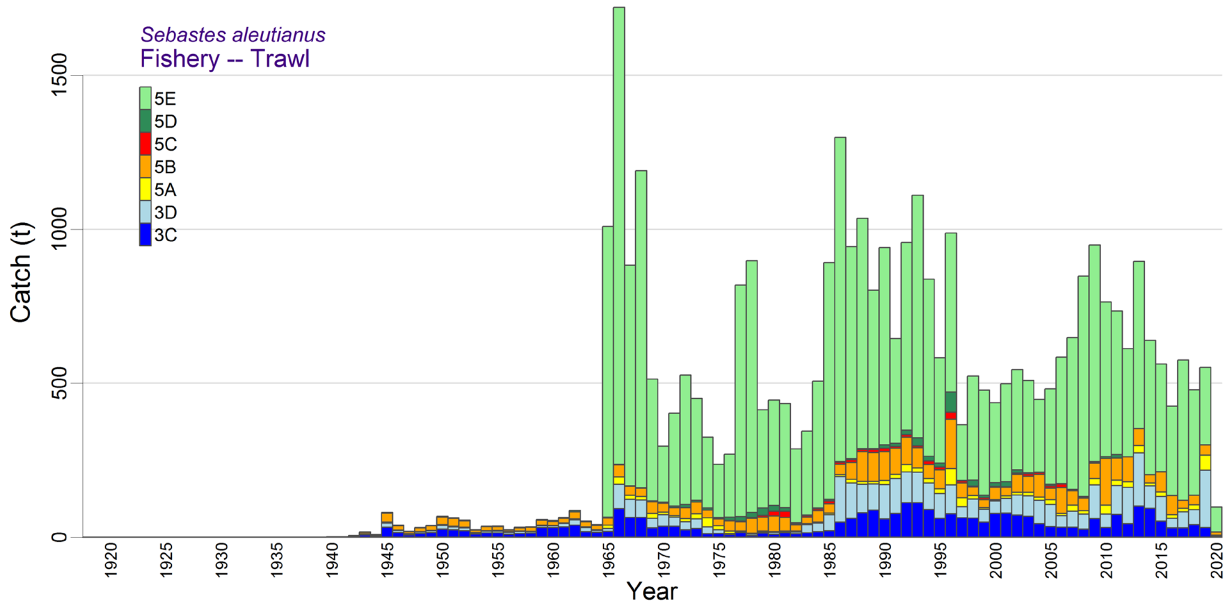

*Figure A.2. Reconstructed total (landed + released) catch (t) for REBS from the **trawl** fishery in PMFC major areas 3C to 5E.*

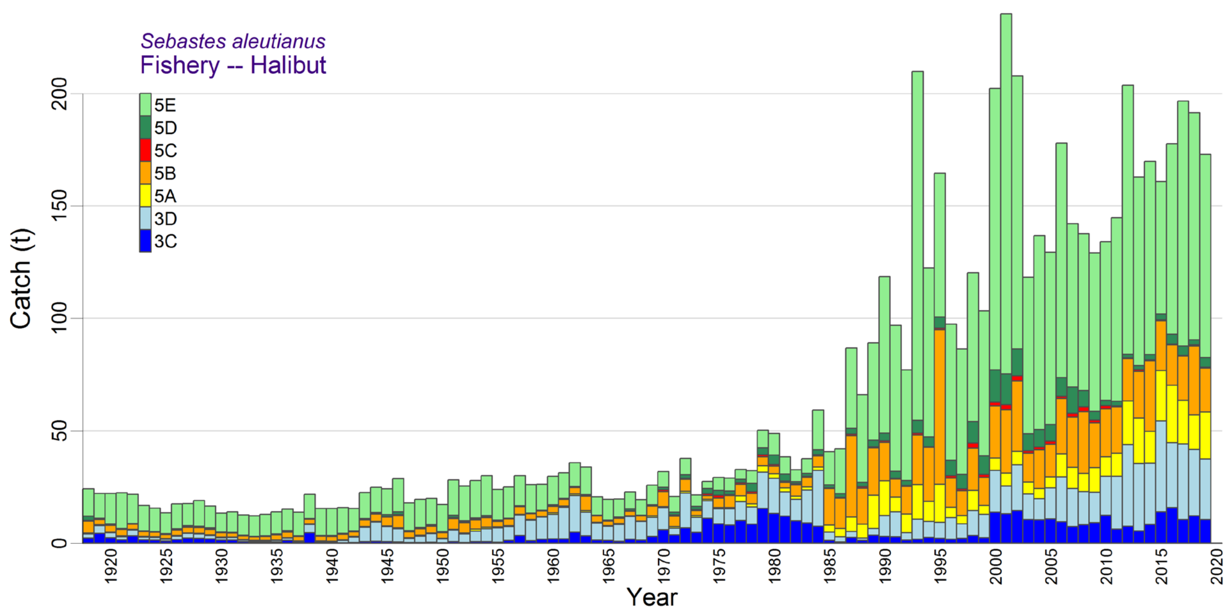

*Figure A.3. Reconstructed total (landed + released) catch (t) for REBS from the **halibut** fishery in PMFC major areas 3C to 5E.*

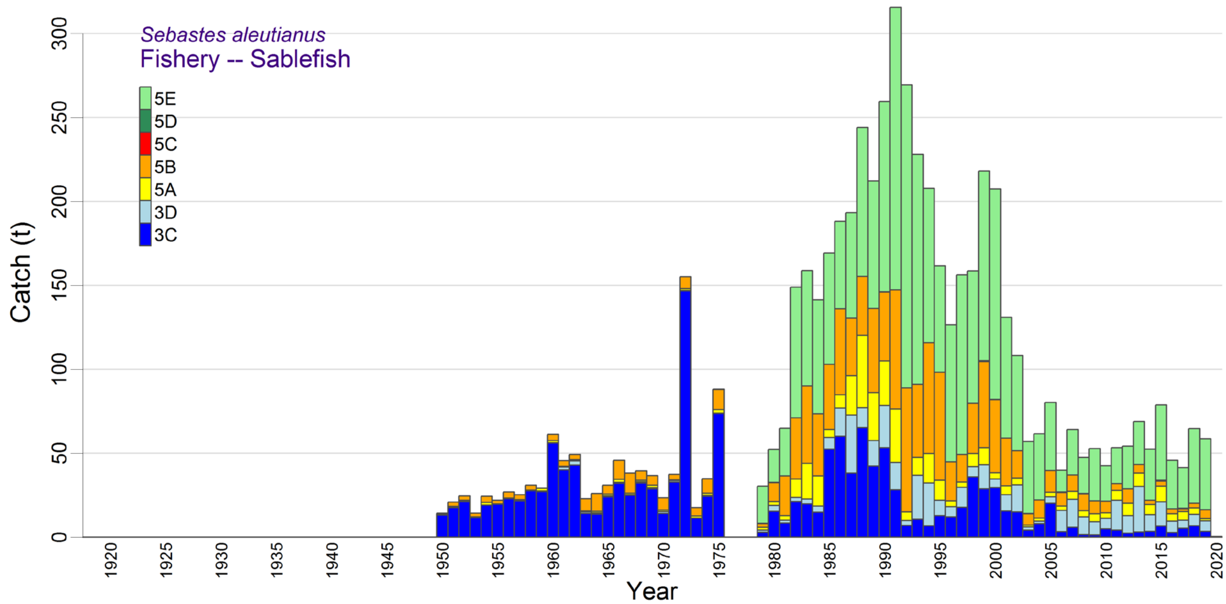

*Figure A.4. Reconstructed total (landed + released) catch (t) for REBS from the **sablefish** fishery in PMFC major areas 3C to 5E.*

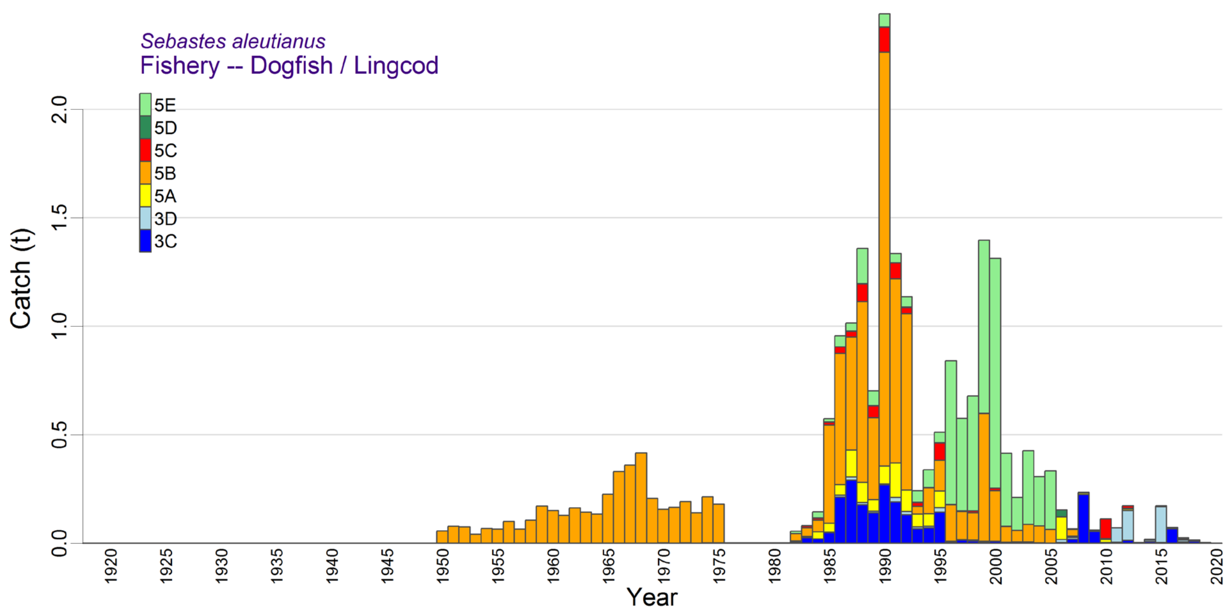

*Figure A.5. Reconstructed total (landed + released) catch (t) for REBS from the **dogfish/lingcod** fishery in PMFC major areas 3C to 5E.*

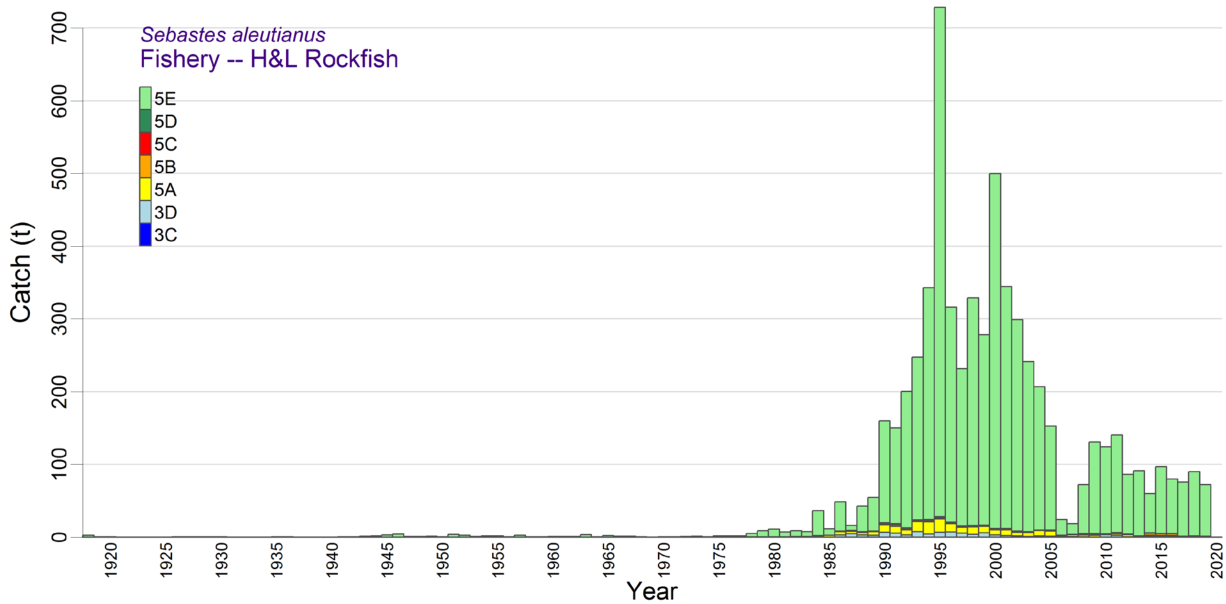

*Figure A.6. Reconstructed total (landed + released) catch (t) for REBS from the **hook and line rockfish** fishery in PMFC major areas 3C to 5E.*

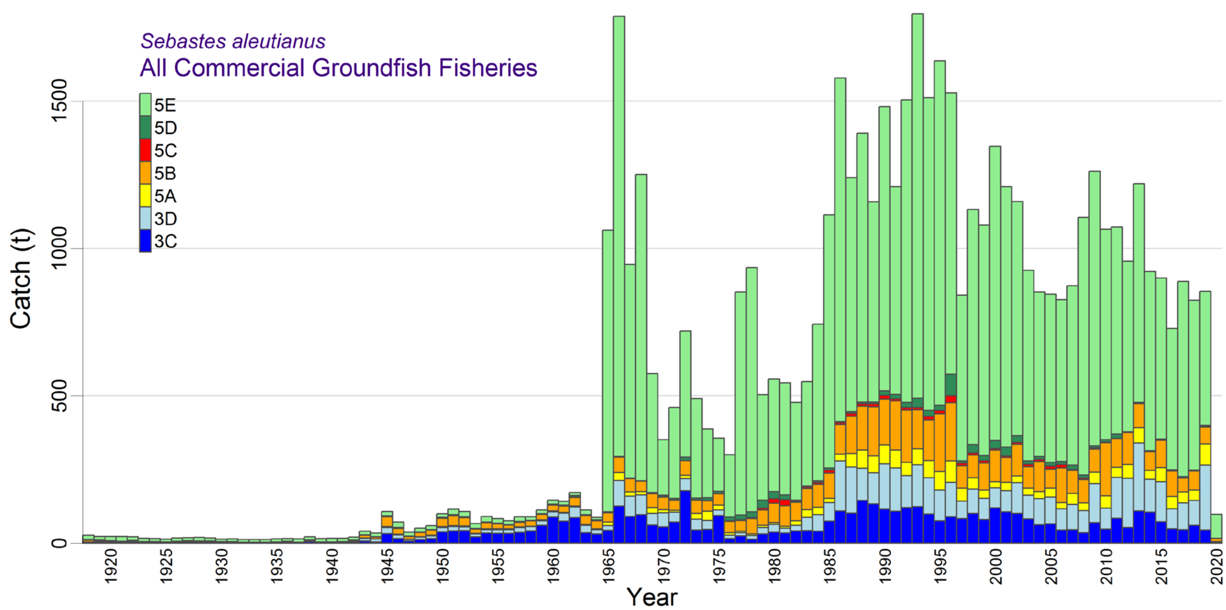

*Figure A.7. Reconstructed total (landed + released) catch (t) for REBS from the **combined** commercial groundfish fisheries in PMFC major areas 3C to 5E.*

Table A.4. Reconstructed catches (in tonnes, landings + releases) of REBS north (5DE) and south (3CD5AB) from two fisheries. Shaded columns indicate catches used in the population model, where 'Other' sums the catch by Halibut, Sablefish, Dogfish/Lingcod, and H&L Rockfish fisheries. Note: annual REBS catches in 5C are assigned to each stock based on annual proportions of catch by each stock.

Year	REBS N Trawl	REBS N Other	REBS N Coast	REBS S Trawl	REBS S Other	REBS S Coast	REBS Coast
1918	0.211	17	17	0.077	10	10	27
1919	0.024	12	12	0.073	11	11	23
1920	0.036	15	15	0.046	8.0	8.1	23
1921	0.001	16	16	0.022	6.2	6.2	22
1922	0.000	13	13	0.049	8.5	8.6	22
1923	0.003	12	12	0.023	5.2	5.2	17
1924	0.009	11	11	0.023	4.9	5.0	16
1925	0.014	9.8	9.8	0.017	3.9	3.9	14
1926	0.031	12	12	0.032	5.9	6.0	18
1927	0.048	11	11	0.047	7.1	7.2	18
1928	0.035	12	12	0.041	7.0	7.0	19
1929	0.052	11	11	0.039	6.2	6.3	17
1930	0.027	9.1	9.1	0.026	4.6	4.7	14
1931	0.004	9.5	9.5	0.021	4.5	4.5	14
1932	0.003	9.2	9.2	0.013	3.3	3.3	13
1933	0.000	9.3	9.3	0.007	2.9	2.9	12
1934	0.003	9.9	9.9	0.023	3.0	3.1	13
1935	0.033	11	11	0.146	3.7	3.8	14
1936	0.050	11	11	0.198	5.0	5.2	16
1937	0.011	11	11	0.157	3.0	3.2	14
1938	0.009	11	11	0.299	11	11	22
1939	0.017	12	12	0.292	3.2	3.5	16
1940	0.027	12	13	0.588	3.1	3.7	16
1941	0.112	12	12	0.366	3.9	4.3	17
1942	0.193	11	11	4.8	5.1	10	21
1943	0.604	13	14	16	10	27	41
1944	0.494	14	14	7.4	13	20	34
1945	2.3	15	17	78	12	89	107
1946	1.7	20	22	37	13	50	72
1947	0.545	13	14	18	5.1	23	37
1948	0.914	14	15	30	6.5	36	51
1949	1.4	14	15	37	7.6	44	59
1950	2.6	13	16	65	19	84	100
1951	1.7	21	23	61	32	93	116
1952	1.8	19	20	53	34	87	107
1953	0.741	18	19	23	25	48	67
1954	1.1	20	21	34	36	70	91
1955	1.9	16	18	34	32	66	83
1956	0.477	15	15	23	38	61	76
1957	2.0	16	18	30	42	71	89
1958	0.946	13	14	31	44	76	90
1959	2.1	12	14	54	44	98	112
1960	2.8	14	17	51	78	129	146
1961	3.2	12	16	61	65	126	142
1962	4.7	11	16	82	74	156	172
1963	2.0	16	18	50	44	94	112
1964	2.6	8.6	11	38	38	76	88
1965	947	11	959	62	41	103	1,062
1966	1,486	9.5	1,496	235	57	292	1,788

Year	REBS N Trawl	REBS N Other	REBS N Coast	REBS S Trawl	REBS S Other	REBS S Coast	REBS Coast
1967	717	9.6	727	166	53	219	945
1968	1,032	7.4	1,040	158	52	211	1,250
1969	398	9.0	407	115	54	168	576
1970	187	8.3	195	109	47	157	352
1971	306	8.6	315	96	50	146	461
1972	430	9.7	440	96	184	280	720
1973	337	7.7	344	114	33	147	491
1974	237	5.7	243	87	57	145	387
1975	178	9.7	188	59	109	169	356
1976	216	9.0	225	53	22	75	300
1977	769	7.3	776	50	27	77	853
1978	837	14	851	61	23	84	935
1979	348	42	390	66	48	114	504
1980	374	45	418	71	67	139	557
1981	367	47	414	67	64	131	544
1982	246	92	338	41	98	139	477
1983	279	83	362	66	121	186	549
1984	419	122	542	87	114	202	744
1985	783	92	875	109	131	239	1,114
1986	1,060	114	1,175	238	166	404	1,578
1987	698	108	807	245	188	434	1,240
1988	757	165	922	279	189	468	1,390
1989	523	169	692	278	188	466	1,158
1990	660	328	989	281	212	493	1,481
1991	354	369	724	291	195	486	1,209
1992	629	421	1,050	328	127	454	1,505
1993	818	523	1,341	293	162	455	1,796
1994	598	492	1,090	239	182	421	1,511
1995	359	834	1,194	222	220	443	1,637
1996	596	447	1,043	392	94	485	1,529
1997	187	388	574	179	87	266	841
1998	360	471	831	164	138	301	1,132
1999	354	450	805	123	151	274	1,079
2000	274	756	1,030	163	155	317	1,347
2001	336	581	917	162	130	292	1,209
2002	339	483	822	205	132	337	1,160
2003	308	356	663	201	61	262	925
2004	241	332	573	206	74	280	853
2005	320	269	589	161	93	254	844
2006	420	148	568	164	94	258	826
2007	498	128	625	151	97	248	873
2008	721	167	888	127	90	217	1,105
2009	708	233	941	241	79	320	1,261
2010	509	215	724	255	86	341	1,065
2011	478	240	717	256	99	355	1,072
2012	352	229	581	260	115	376	957
2013	543	202	746	353	121	474	1,219
2014	437	174	610	202	109	311	921
2015	350	199	550	212	137	350	899
2016	291	193	484	135	110	245	728
2017	456	212	668	119	101	221	889
2018	342	237	579	136	110	245	824
2019	252	209	460	299	95	395	855
2020	252	209	460	299	95	395	855

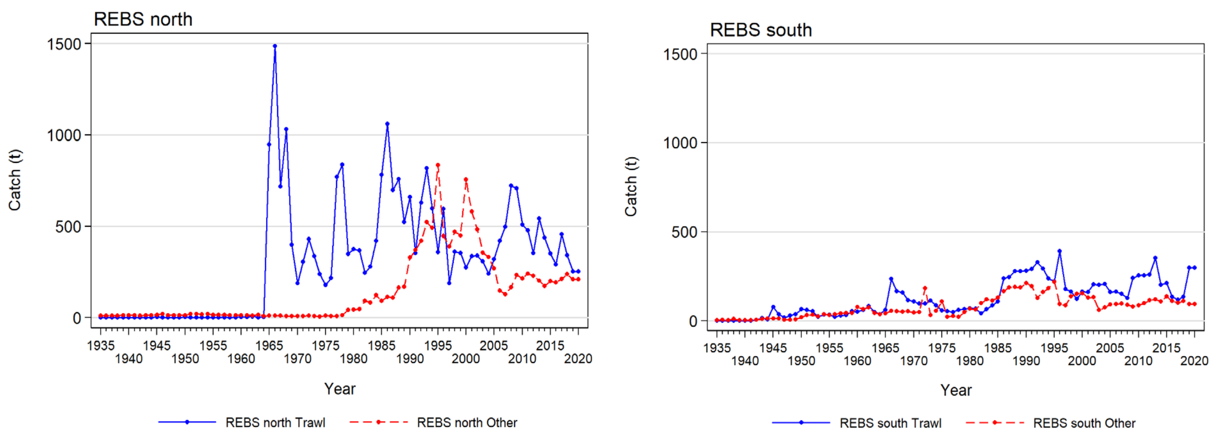

Figure A.8. Plots of model catch by fishing gear for REBS north (left panel) and REBS south (right panel) from 1935 to 2020. Data values provided in Table A.4.

A.2.3. Changes to the reconstruction algorithm since 2011

A.2.3.1. Pacific Ocean Perch (2012)

In two previous stock assessments for POP in areas 3CD and 5DE (Edwards et al. 2014a,b), the authors documented two departures from the catch reconstruction algorithm introduced by Haigh and Yamanaka (2011). The first dropped the use of trawl and trap data from the sales slip database `PacHarv3` because catches were sometimes reported by large statistical areas that could not be clearly mapped to PMFC areas. In theory, `PacHarv3` should report the same catch as that in the `GFCatch` database (Rutherford 1999), but area inconsistencies cause catch inflation when certain large statistical areas cover multiple PMFC areas. Therefore, only the `GFCatch` database for the trawl and trap records from 1954 to 1995 were used, rather than trying to mesh `GFCatch` and `PacHarv3`. The point is somewhat moot as assessments since 2015 by the Offshore Rockfish Program use the merged-catch data table (Section A.2.1). Data for the H&L fisheries from `PacHarv3` are still used as these do not appear in other databases.

The second departure was the inclusion of an additional data source for BC rockfish catch by the Japanese fleet reported in Ketchen (1980a).

A.2.3.2. Yellowtail Rockfish (2014)

The Yellowtail Rockfish assessment (Starr et al. 2014[6]) selected offshore areas that reflected the activity of the foreign fleets' impact on this species to calculate `gamma` (RRF/ORF) and `delta` ratios (RRF/TAR). This option was not used in the REBS reconstruction.

A.2.3.3. Shortspine Thornyhead (2015)

The Shortspine Thornyhead assessment (Starr and Haigh 2017) was the first to use the merged catch table (`GF_MERGED_CATCH` in `GFFOS`). Previous assessments required the meshing together of caches from six separate databases: `GFBioSQL` (research, midwater joint-venture Hake, midwater foreign), `GFCatch` (trawl and trap), `GFFOS` (all fisheries), `PacHarvest` (trawl),

[6] Starr, P.J., Kronlund, A.R., Olsen, N. and Rutherford, K. 2014. Yellowtail Rockfish (*Sebastes flavidus*) stock assessment for the coast of British Columbia, Canada. DFO Can. Sci. Advis. Sec. Res. Doc. Unpublished working paper.

PacHarvHL (hook and line), and PacHarvSable (trap and longline). See Section A.2.1 for further details.

A.2.3.4. Yelloweye Rockfish Outside (2015)

The Yelloweye Rockfish (YYR) assessment (Yamanaka et al. 2018) introduced the concept of depth-stratified gamma and delta ratios; however, this functionality has not been used for offshore rockfish to date.

Also in the YYR assessment, rockfish catch from seamounts was removed (implemented in all subsequent reconstructions, including the REBS one), as well as an option to exclude rockfish catch from the foreign fleet and the experimental Langara Spit POP fishery (neither were excluded from the REBS reconstruction). The latter option is more likely appropriate for inshore rockfish species because they did not experience historical offshore foreign fleet activity or offshore experiments.

A.2.3.5. Redstripe Rockfish (2018)

The Redstripe Rockfish assessment (Starr and Haigh, in press), introduced the use of summarising annual gamma and delta ratios from reference years (Section A.2.2) by calculating the geometric mean across years instead of using the arithmetic mean. This choice reduces the influence of single anomalously large annual ratios. The geometric mean was used in the REBS reconstruction.

Also new in 2018 was the ability to estimate RRF (using gamma) for landings later than 1996, should the user have reason to replace observed landings with estimated ones. For REBS, observed landings by fishery were used starting in 1996 for the trawl fishery and 2006 for the non-trawl fisheries; prior to these years, landings were estimated using gamma.

Another feature introduced in 2018 was the ability to specify years by fishery for discard regimes, that is, when discard ratios were to be applied. Previously, these had been fixed to 1954-1995 for the trawl fishery and 1986-2005 for the non-trawl fisheries. For REBS, discard regimes by fishery were set to T = 1954-1995, H = 1918-2005, S/DL = 1950-2005, and ZN = 1986-2005. As previously, years before the discard period assume no discarding, and years after the discard period assume that discards have been reported in the databases.

A.2.3.6. Widow Rockfish (2019)

The Widow Rockfish (WWR) assessment (Starr and Haigh, in press) found a substantial amount of WWR reported as foreign catch in the database GFBioSQL that came from midwater gear off WCVI. Subsequently, the catch reconstruction algorithm was changed to assign GFBio foreign catch to four of the five fisheries based on gear type:

- bottom and midwater trawl gear assigned to the T fishery,
- longline gear assigned to the H fishery,
- trap and line-trap mix gear assigned to the S fishery, and
- h&l gear assigned to the ZN fishery.

The assignment only happens if the user chooses to use foreign catch in the reconstruction (see Section A.2.3.3). These foreign catches occurred well after the foreign fleet activity between 1965 and the implementation of an exclusive economic zone in 1977. REBS foreign catches in GFBio occurred primarily in 1987-1989 (23 t).

A.2.3.7. Bocaccio (2019)

The Bocaccio rockfish (BOR) assessment (Starr and Haigh, in press) used advice from the technical working group, which identified specific reference years for the calculation of `gamma`: 1990-2000 for trawl (to capture the years before decreasing mortality caps for BOR were placed on the trawl fleet) and 2007-2011 for non-trawl (to capture years after some form of observer program like electronic monitoring was applied to the hook and line fleets). The catch reconstruction algorithm was previously coded to only allow one set of reference years to be applied across all fisheries. The algorithm was changed so that a user can now specify separate reference years for each fishery.

Once the merged catch table (`GF_MERGED_CATCH` in `GFFOS`) was introduced (Section A.2.3.3), catch from all databases other than `PacHarv3` have been reconciled so that caches are not double counted. In this assessment, the remaining two catch data sources (GFM and PH3, for brevity) were re-assessed by comparing ORF data, and the CR algorithm was changed in how the data sources were merged for the categories RRF landed, RRF discarded, ORF landed, POP landed, and TRF landed:

- GFM catch is the only source needed for FID 1 (Trawl fishery), as was previously assumed;
- GFM and PH3 catches appear to supplement each other for FIDs 2 (Halibut fishery), 3 (Sablefish fishery), and 4 (Dogfish/Lingcod fishery), and the catches were added in any given year up to 2005 (electronic monitoring started in 2006 and so the GFFOS database was reporting all catch for these fisheries by then);
- GFM and PH3 catches appear to be redundant for FID 5 (H&L Rockfish fishery), and so the maximum catch was used in any given year.

Also new in the BOR assessment was the introduction of historical Sablefish (SBF) and Lingcod (LIN) trawl landings from 1950 to 1975 (Ketchen 1976) for use in calculating historical discards for FIDs 3 and 4 during this period. These landings could not be used directly because they were taken by the trawl fleet; therefore, an estimation of SBF and LIN landed catch by FIDs 3 and 4, respectively, relative to SBF and LIN landed catch by FID 1 (trawl) was calculated from GFM. Annual ratios of SBF_3/SBF_1 and LIN_4/LIN_1 from 1996-2011 were chosen to calculate a geometric mean; the ratios from 2012 on started to diverge from those in the chosen period. The procedure yielded average ratios: SBF_3/SBF_1 = 10.235 and LIN_4/LIN_1 = 0.351, which were used to scale the 1950-75 trawl landings of SBF and LIN, respectively. From these estimated landings, discards of REBS were calculated by applying `delta` (see Section A.2.2.1).

Another departure was the re-allocation of PH3 records to the various catch reconstruction fisheries based on data from 1952-95. The distribution of effort (events) and catch by species for each gear type (Table A.5) led to the code revision in Table A.6.

Table A.5. PacHarv3 (PH3) number of events reportedly catching each species and catch (t) of species from 1952-95 by gear type and species code, where SCO = Scorpionfishes, POP = Pacific Ocean Perch, YTR = Yellowtail Rockfish, YMR =Yellowmouth Rockfish, YYR = Yelloweye Rockfish, SST = Shortspine Thornyhead, PAH = Pacific Halibut, SBF = Sablefish, DOG = Spiny Dogfish, and LIN = Lingcod.

Code	PH3 Gear Description	SCO	POP	YTR	YMR	YYR	SST	PAH	SBF	DOG	LIN
EVENTS		-	-	-	-		-	-	-	-	-
10	GILL NET, SALMON	55	-	-	-	17	-	-	-	-	164
11	NET, SET	-	-	-	-		-	-	-	1	-
20	SEINE, PURSE, SALMON	4	-	-	-	2	-	-	-	-	14
30	TROLL, SALMON	4281	49	69	1	2587	11	613	40	77	5201
31	TROLL, FREEZER, SALMON	614	1	14	2	294	2	91	8	31	1752
36	JIG, HAND, NON-SALMON	1126	25	241	13	914	4	1	1	152	845
40	LONGLINE	2893	109	355	100	2738	327	4484	603	1248	2377
50	TRAWL, OTTER, BOTTOM	3910	2419	2335	1521	557	1435	-	2469	748	3098

Code	PH3 Gear Description	SCO	POP	YTR	YMR	YYR	SST	PAH	SBF	DOG	LIN
51	TRAWL, MIDWATER	770	155	770	175	21	26	-	51	210	173
57	SHRIMP TRAWL	173	10	2	-	21	-	-	2	12	82
70	SEINE, BEACH	4	-		-	-	-	-	-	-	2
90	TRAP	74	-	1	1	14	18	-	753	3	34
CATCH		-	-	-	-	-	-	-	-	-	-
10	GILL NET, SALMON	3.6	-	-	-	1.0	-	-	-	-	16
11	NET, SET	-	-	-	-	-	-	-	-	2.5	-
20	SEINE, PURSE, SALMON	0.2	-	-	-	0.7	-	-	-	-	4.3
30	TROLL, SALMON	3060	1.3	5.6	0.0	925	2.0	538	20	70	5757
31	TROLL, FREEZER, SALMON	73	0.0	2.2	0.4	31	4.0	52	0.1	99	695
36	JIG, HAND, NON-SALMON	2133	5.2	40	4.6	745	0.1	0.3	1.1	175	1883
40	LONGLINE	6921	11	29	35	7922	91	48384	10785	21799	6119
50	TRAWL, OTTER, BOTTOM	117534	79327	28758	17609	1818	3468	-	6090	12637	45811
51	TRAWL, MIDWATER	17737	469	14867	735	3.3	7.7	-	7.9	1400	103
57	SHRIMP TRAWL	23	0.6	2.1	-	0.3	-	-	0.0	18	34
70	SEINE, BEACH	0.1	-	-	-	-	-	-	-	-	0.6
90	TRAP	76	-	0.0	0.6	3.6	6.4	-	50886	34	4.4

Table A.6. Code extract from Oracle SQL query ‘ph3_fcatORF.sql’ that defines catch reconstruction FIDs (1=Trawl, 2=Halibut, 3=Sablefish, 4=Dogfish/Lingcod, 5=H&L Rockfish) from gear types and dominant species caught (by weight) per event in PH3 table ‘CATCH_SUMMARY’.

FID definition in SQL query ‘ph3_fcatORF.sql’

```
(CASE -- in order of priority
  -- originally TRAWL (otter bottom, midwater, shrimp, herring)
  WHEN TAR.GR_GEAR_CDE IN (50,51,57,59) THEN 1
  -- Partition LONGLINE
  WHEN TAR.GR_GEAR_CDE IN (40) AND TAR.Target IN ('614') THEN 2
  WHEN TAR.GR_GEAR_CDE IN (40) AND TAR.Target IN ('455') THEN 3
  WHEN TAR.GR_GEAR_CDE IN (40) AND TAR.Target IN ('044','467') THEN 4
  WHEN TAR.GR_GEAR_CDE IN (40) AND TAR.Target NOT IN ('614','455','044','467')) THEN 5
  -- Partition TROLL (salmon, freezer salmon)
  WHEN TAR.GR_GEAR_CDE IN (30,31) AND TAR.Target IN ('614') THEN 2
  WHEN TAR.GR_GEAR_CDE IN (30,31) AND TAR.Target IN ('455') THEN 3
  WHEN TAR.GR_GEAR_CDE IN (30,31) AND TAR.Target IN ('044','467') THEN 4
  WHEN TAR.GR_GEAR_CDE IN (30,31) AND TAR.Target NOT IN ('614','455','044','467')) THEN 5
  -- Partition JIG (hand non-salmon)
  WHEN TAR.GR_GEAR_CDE IN (36) AND TAR.Target IN ('614') THEN 2
  WHEN TAR.GR_GEAR_CDE IN (36) AND TAR.Target IN ('455') THEN 3
  WHEN TAR.GR_GEAR_CDE IN (36) AND TAR.Target IN ('044','467') THEN 4
  WHEN TAR.GR_GEAR_CDE IN (36) AND TAR.Target NOT IN ('614','455','044','467')) THEN 5
  -- originally TRAP (experimental, salmon, longline, shrimp & prawn, crab)
  WHEN TAR.GR_GEAR_CDE IN (86,90,91,92,97,98) THEN 3
  -- Unassigned Trawl, Halibut, Sablefish, Dogfish-Lingcod, H&L Rockfish
  WHEN TAR.Target IN ('394','396','405','418','440','451') THEN 1
  WHEN TAR.Target IN ('614') THEN 2
  WHEN TAR.Target IN ('455') THEN 3
  WHEN TAR.Target IN ('044','467') THEN 4
  WHEN TAR.Target IN ('388','401','407','424','431','433','442') THEN 5
  ELSE 0 END) AS \"fid\",
```

A.2.3.8. Rougheye/Blackspotted Rockfish (2020)

During the REBS catch reconstruction, a close look at annual gammas revealed large fluctuations from 1991 to 2019 (Figure A.9). Based on these figures, the reference years chosen to calculate a geometric mean gamma by fishery were: 1997:2005 for Trawl (Figure A.10) and 2007:2009 for the non-trawl fisheries (Figure A.11). These intervals were selected to reflect times of credible data: (i) reconciled observer logs with DMP landings in PacHarvest for the trawl fishery, and (ii) least volatility in GFFOS for the non-trawl fisheries.

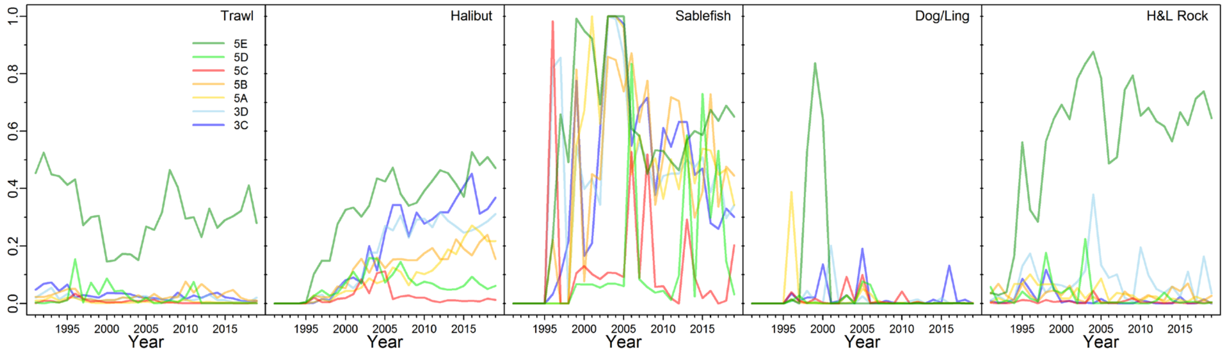

Figure A.9. Annual gamma ratios (REBS/ORF) for the five commercial groundfish fisheries.

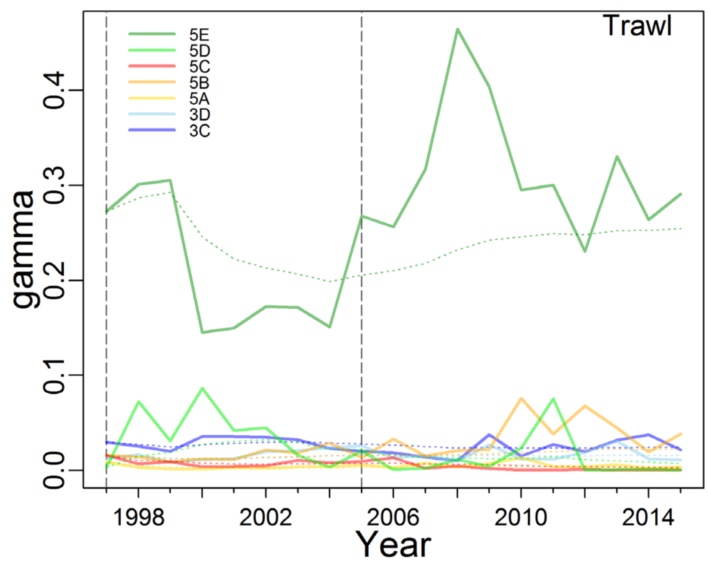

Figure A.10. Annual gamma ratios (REBS/ORF) for the trawl commercial groundfish fishery. Dotted lines trace the running geometric mean. Vertical dashed lines show interval used for gamma.

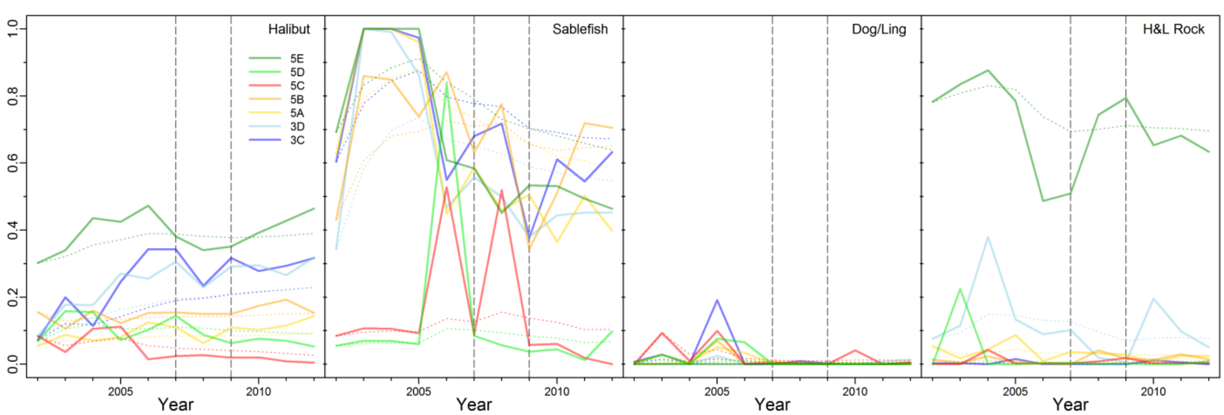

Figure A.11. Annual gamma ratios (REBS/ORF) for the four non-trawl commercial groundfish fisheries. Dotted lines trace the running geometric mean. Vertical dashed lines show interval used for gamma.

A.2.4. Caveats

The available catch data before 1996 (first year of onboard observer program) present difficulties for use in a stock assessment model without some form of interpretation, both in terms of misreporting (i.e., reporting catches of one species as another) or misidentifying species. There is also the possible existence of at-sea discarding due to catches exceeding what was permitted for retention. Although there were reports that fishermen misreported the location of catches, this issue is not a large problem for an assessment of a coastwide stock. Additionally, there was a significant foreign fishery for rockfish in BC waters, primarily by the United States, the Soviet Union and Japan from 1965 to 1976. These countries tended to report their catches in aggregate form, usually lumping rockfish into a single category. These fisheries ceased after the declaration of the 200 nm exclusive economic zone by Canada in 1977.

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

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

Many of these problems have been eliminated through the introduction of observer programs (onboard observers starting in 1996 for the offshore trawl fleet, electronic monitoring starting in 2006 for the H&L fleets), dockside [observer] monitoring, and tradeable individual vessel quotas (starting in 1997) that confer ownership of the resource to the fishing sector.

The catch reconstruction procedure does not rebuild catch by gear type (e.g., bottom trawl vs. midwater trawl, trap vs. longline). While adding this dimension is possible, it would mean splitting catches back in time using ratios observed in the modern fishery, which likely would not accurately represent historical activity by gear type (see Section A.2.2 for similar caveats regarding the use of modern catch ratios to reconstruct the catch of one species from a total rockfish catch). In this assessment, we combined the catches of REBS by bottom and midwater trawl because the biological data (Appendix D) by gear did not support two fleets in the population model and it was inconclusive whether there was a demonstrable difference in selectivity. Table A.7 and Figure A.12 show the reported coastwide catch (landings plus non-retained) by gear type.

Table A.7. Reported catch (tonnes) by gear type, sector, and fishery for the BC REBS coastwide starting when trawl fleet activity was monitored by onboard observers. BT=bottom trawl, MW=midwater trawl, HL=hook and line, GFT=groundfish trawl, ZN=license for hook and line, RO=HL rockfish outside, H=halibut longline, S=sablefish trap, HS=halibut + sablefish, DL=dogfish/lingcod.

	Gear				Sector						Fishery				
Year	BT	MW	HL	Trap	GFT	ZN	RO	H	HS	S	T	H	S	DL	HL
1996	982	0.165	170	2.3	982	165	---	3.5	---	2.7	982	3.5	2.7	1.5	165
1997	348	0.162	123	5.1	348	117	---	5.4	---	5.1	348	5.4	5.1	---	117
1998	518	0.148	243	2.9	518	225	---	15	---	2.9	518	15	2.9	2.5	225
1999	443	0.223	226	4.8	443	192	---	23	---	4.8	443	23	4.8	11	192
2000	419	8.1	588	1.6	425	520	---	67	---	2.4	425	67	2.4	---	520
2001	481	1.1	432	2.3	482	328	---	101	---	5.6	482	101	5.6	0.003	328
2002	529	9.2	442	3.5	538	355	---	86	---	4.4	538	86	4.4	0.005	355

Year	Gear				Sector						Fishery				
	BT	MW	HL	Trap	GFT	ZN	RO	H	HS	S	T	H	S	DL	HL
2003	498	3.7	376	9.9	502	306	---	67	---	14	502	67	14	0.071	306
2004	441	0.128	442	4.6	442	298	---	143	---	5.1	442	143	5.1	0.062	298
2005	475	0.287	328	14	476	195	---	131	---	16	476	131	16	0.082	195
2006	564	0.287	222	19	564	24	0.111	127	51	40	564	178	40	0.145	24
2007	627	5.4	193	28	633	---	19	85	57	61	633	142	61	0.064	19
2008	801	24	232	22	825	---	72	59	76	46	825	135	46	0.236	72
2009	915	30	287	22	945	---	130	44	84	51	945	128	51	0.061	130
2010	734	27	287	12	760	---	124	39	94	42	760	133	42	0.112	124
2011	636	87	331	7.4	723	---	140	34	111	53	723	145	53	0.071	140
2012	490	103	333	11	593	---	86	56	148	54	593	203	54	0.139	86
2013	696	180	309	14	876	---	91	36	127	69	876	163	69	0.002	91
2014	535	87	272	9.6	622	---	60	39	132	51	622	170	52	0.009	60
2015	513	46	319	17	559	---	97	39	122	78	559	160	79	0.166	97
2016	398	11	289	13	409	---	80	69	113	42	409	178	45	0.068	80
2017	525	48	302	11	573	---	75	73	123	41	573	196	41	0.010	75
2018	384	84	331	14	468	---	90	50	143	61	468	191	64	0.006	90
2019	303	238	293	11	541	---	72	56	117	58	541	173	58	0.003	72

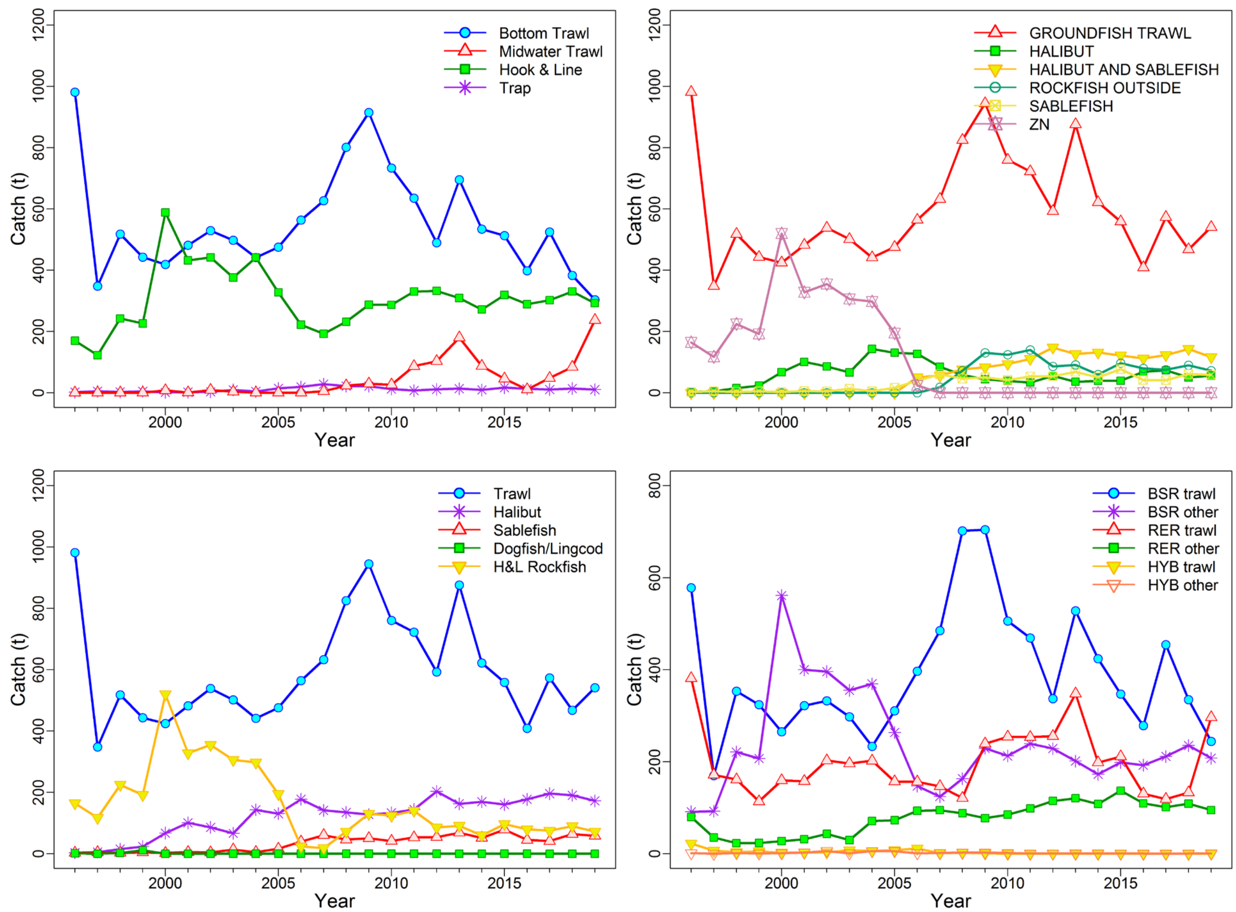

Figure A.12. Reported catch (landings + released) by gear (top left), by sector (top right), by fishery (bottom left), and by stock (bottom right) of REBS since the implementation of the trawl's onboard-observer program in 1996.

A.3. SCALING CATCH POLICY TO GMU AREA TACS

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

As this assessment covers two stocks (REBS north in 5DE and REBS south in 3CD5AB), and GMU only issues a coastwide TAC, the combined catch policies from each stock can be added because the catch in 5C was allocated to each stock based on annual proportional catch ratios in Table A.4. For example, a catch policy of 600 t REBS north and 300 t REBS south would equal a coastwide TAC for REBS of 900 t. Alternatively, if the current TAC of 1145 t were deemed sustainable from examining the decision tables, it could be split using the proportions in Table A.8, where 0.6627 (5DE), 0.0008 (5C), 0.3365 (3CD5AB) would allocate the TAC: 5DE = 759 t, 5C = 1 t, and 3CD5AB = 385 t.

Table A.8. Catch of REBS from the combined fishery in PMFC areas from the last 5 years of complete catch statistics. Annual proportions of catch by area are shown in rows marked by year. Area-specific 5-year geometric means of annual proportions (normalised) are shown in the final row.

Year	3C	3D	5A	5B	5C	5D	5E	BC
Catch(t)								
2015	72.970	135.646	47.612	93.210	0.919	3.181	545.832	899.370
2016	48.372	68.149	42.020	85.854	0.508	4.590	478.912	728.406
2017	45.347	90.680	38.072	46.569	0.334	4.676	662.826	888.503
2018	59.956	84.594	35.646	64.787	0.691	2.277	576.227	824.178
2019	44.655	220.511	70.940	58.097	0.919	4.467	455.329	854.917
Proportion								
2015	0.0811	0.1508	0.0529	0.1036	0.0010	0.0035	0.6069	1
2016	0.0664	0.0936	0.0577	0.1179	0.0007	0.0063	0.6575	1
2017	0.0510	0.1021	0.0428	0.0524	0.0004	0.0053	0.7460	1
2018	0.0727	0.1026	0.0433	0.0786	0.0008	0.0028	0.6992	1
2019	0.0522	0.2579	0.0830	0.0680	0.0011	0.0052	0.5326	1
GeoMean	0.0637	0.1307	0.0542	0.0807	0.0008	0.0044	0.6441	0.9785
Normalise	0.0650	0.1336	0.0554	0.0825	0.0008	0.0045	0.6582	1

A.4. REFERENCES – CATCH

Canada Dominion Bureau of Statistics. 1918-1950. Fisheries Statistics of Canada (British Columbia). Tech. rep., Canada Dominion Bureau of Statistics, Ottawa, ON.

Edwards, A.M., Haigh, R. and Starr, P.J. 2014a. Pacific Ocean Perch (*Sebastes alutus*) stock assessment for the north and west coasts of Haida Gwaii, British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2013/092: vi + 126 p.

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.

Fisheries and Oceans Canada. 2012. Management plan for the Rougheye/Blackspotted Rockfish complex (*Sebastes aleutianus* and *S. melanostictus*) and Longspine Thornyhead (*Sebastolobus altivelis*) in Canada. Species at Risk Act Management Plan Series 412, Fisheries and Oceans Canada, Ottawa ON, vi + 49 p.

Forrester, C.R. 1969. Results of English Sole tagging in British Columbia waters. Bull. Pac. Mar. Fish. Comm. 7: 1-10.

Forrester, C.R. and Smith, J.E. 1972. The British Columbia groundfish fishery in 1971, some aspects of its investigation and related fisheries. Fish. Res. Board Can. Tech. Rep. 338: 67 p.

Gunderson, D.R., Westrheim, S.J., Demory, R.L. and Fraidenburg, M.E. 1977. The status of Pacific Ocean Perch (*Sebastes alutus*) stocks off British Columbia, Washington, and Oregon in 1974. Fish. Mar. Serv. Tech. Rep. 690: iv + 63 p.

Haigh, R., Olsen, N. and Starr, P. 2005. A review of Rougheye Rockfish *Sebastes aleutianus* along the Pacific coast of Canada: biology, distribution, and abundance trends. DFO Can. Sci. Advis. Sec. Res. Doc. 2005/096: vi + 68 p.

Haigh, R. and Yamanaka, K.L. 2011. Catch history reconstruction for rockfish (*Sebastes* spp.) caught in British Columbia coastal waters. Can. Tech. Rep. Fish. Aquat. Sci. 2943: viii + 124 p.

Ketchen, K.S. 1976. Catch and effort statistics of the Canadian and United States trawl fisheries in waters adjacent to the British Columbia coast 1950-1975. Fisheries and Marine Service, Nanaimo, BC, Data Record 6.

Ketchen, K.S. 1980a. Assessment of groundfish stocks off the west coast of Canada (1979). Can. Data Rep. Fish. Aquat. Sci. 185: xvii + 213 p.

Ketchen, K.S. 1980b. 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.

Leaman, B.M. and Stanley, R.D. 1993. Experimental management programs for two rockfish stocks off British Columbia, Canada. In S. J. Smith, J. J. Hunt and D. Rivard, eds., Risk evaluation and biological reference points for fisheries management, p. 403-418. Canadian Special Publication of Fisheries and Aquatic Sciences 120.

Munk, K.M. 2001. Maximum ages of groundfishes in waters off Alaska and British Columbia and considerations of age determination. Alaska Fish. Res. Bull. 8: 12-21.

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

Starr, P.J. and Haigh, R. 2017. Stock assessment of the coastwide population of Shortspine Thornyhead (*Sebastolobus alascanus*) in 2015 off the British Columbia coast. DFO Can. Sci. Advis. Sec. Res. Doc. 2017/015: ix + 174 p

Starr, P.J. and Haigh, R. in press. Redstripe Rockfish (*Sebastes proriger*) stock assessment for British Columbia in 2018. DFO Can. Sci. Advis. Sec. Res. Doc. 2019/nnn: iii + xxx p.

Starr, P.J. and Haigh, R. in press. Widow Rockfish (*Sebastes entomelas*) stock assessment for British Columbia in 2019. DFO Can. Sci. Advis. Sec. Res. Doc. 2019/nnn: iii + xxx p.

Starr, P.J. and Haigh, R. 2022. Bocaccio (*Sebastes paucispinis*) stock assessment for British Columbia in 2019, including guidance for rebuilding plans. DFO Can. Sci. Advis. Sec. Res. Doc. In press.

Wallace, S., Turris, B., Driscoll, J., Bodtker, K., Mose, B. and Munro, G. 2015. Canada's Pacific groundfish trawl habitat agreement: A global first in an ecosystem approach to bottom trawl impacts. Mar. Pol. 60: 240-248.

Westrheim, S.J., Gunderson, D.R. and Meehan, J.M. 1972. On the status of Pacific Ocean Perch (*Sebastes alutus*) stocks off British Columbia, Washington, and Oregon in 1970. Fish. Res. Board Can. Tech. Rep. 326: 48 p.

Yamanaka, K.L., McAllister, M.M., Etienne, M.P., Edwards, A.M. and Haigh, R. 2018. Assessment for the outside population of Yelloweye Rockfish (*Sebastes ruberrimus*) for British Columbia, Canada in 2014. DFO Can. Sci. Advis. Sec. Res. Doc. 2018/001: ix + 150 p.

APPENDIX B. TRAWL SURVEYS

B.1. INTRODUCTION

This appendix summarises the derivation of relative Rougheye/Blackspotted Rockfish (REBS[7]) abundance indices from the following bottom trawl surveys:

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

Only surveys which were used in the REBS stock assessment are presented. The Hecate Strait multi-species survey, the WCVI shrimp and Queen Charlotte Sound shrimp surveys have been omitted because the presence of REBS in these surveys has been either sporadic or the coverage, either spatial or by depth, has been incomplete, rendering these surveys poor candidates to provide abundance series for this species. Rockfish stock assessments, beginning with Yellowtail Rockfish (DFO 2015), have explicitly omitted using the two shrimp surveys because of the truncated depth coverage, which ends at 160 m for the WCVI shrimp survey, and the constrained spatial coverage of the QC Sound shrimp survey as well as its truncated depth coverage, which ends at 231 m. For similar reasons, the early Goose Island Gully surveys used in other rockfish stock assessments (0.99 quantile of start depth=294 m; see Starr and Haigh in press for an example), the Hecate Strait synoptic survey (0.99 quantile of start depth=287 m), and the first four index years of the NMFS Triennial survey (0.99 quantile of start depth=329 m) have also been dropped.

B.2. ANALYTICAL METHODS

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

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

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

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

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

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

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

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

[7] REBS is sometimes labelled ‘RER’ or ‘Rougheye Rockfish’ in figures because the survey catch data report both species as Rougheye Rockfish (RER).

w = average net width (km).

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

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

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

D_{yij} = distance travelled (km) for tow j, stratum i, year y;

w_{yij} = net opening (km) for tow j, stratum i, year y;

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

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

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

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

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

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

m = number of strata.

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

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

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

V_{yi} = variance of the biomass estimate (kg^2) for stratum i, year y.

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

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

B.3. NMFS TRIENNIAL TRAWL SURVEY

B.3.1. Data selection

Tow-by-tow data from the US National Marine Fisheries Service (NMFS) triennial survey covering the Vancouver INPFC (International North Pacific Fisheries Commission) region were provided by Mark Wilkins (NMFS, pers. comm.) for the seven years (only the last three years which went to the deep strata are presented in this document) that the survey worked in BC waters (Table B.1; 1995: Figure B.1; 1998: Figure B.2; 2001: Figure B.3). These tows were assigned to strata by the NMFS, but the size and definition of these strata have changed over the life of the survey (Table B.2). The NMFS survey database also identified in which country the tow was located. This information was plotted and checked against the accepted

Canada/USA marine boundary: all tows appeared to be appropriately located with respect to country, based on the tow start position (Figure B.1 to Figure B.3). The NMFS designations were accepted for tows located near the marine border.

Table B.1. Number of tows by stratum and by survey year for the NFMS triennial survey. Strata coloured grey have been excluded from the analysis due to incomplete coverage across the seven survey years or were from locations outside the Vancouver INPFC area (Table B.2).

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

All usable tows had an associated median net width (with 1-99% quantiles) of 13.4 (11.3-15.7) m and median distance travelled of 2.8 (1.4-3.5) km, allowing for the calculation of the area swept by each tow. Biomass indices and the associated analytical CVs for Rougheye Rockfish were calculated for the total Vancouver INPFC region and for each of the Canadian- and US-Vancouver sub-regions, using appropriate area estimates for each stratum and year (Table B.2). Strata that were not surveyed consistently were dropped from the analysis (Table B.1; Table B.2), allowing the remaining data to provide a comparable set of data for each year (Table B.4).

Because the first four surveys have been dropped from the series used for the REBS stock assessment, it was not necessary to adjust the swept area from the 1980 and 1983 surveys to match the area used from 1989 onwards. As well, because the identified water hauls (Table B.3) all occurred before the 1995 survey, there was no need to drop any of these tows.

Table B.2. Stratum definitions by year used in the NMFS triennial survey to separate the survey results by country and by INPFC area. Stratum definitions in grey are those strata which have been excluded from the final analysis due to incomplete coverage across the seven survey years or because the locations were outside the Vancouver INPFC area.

Year	Stratum No.	Area (km^2)	Start	End	Country	INPFC area	Depth range
1980	10	3537	47°30	US-Can Border	US	Vancouver	55-183 m
1980	11	6572	US-Can Border	49°15	CDN	Vancouver	55-183 m
1980	30	443	47°30	US-Can Border	US	Vancouver	184-219 m
1980	31	325	US-Can Border	49°15	CDN	Vancouver	184-219 m
1980	50	758	47°30	US-Can Border	US	Vancouver	220-366 m
1980	51	503	US-Can Border	49°15	CDN	Vancouver	220-366 m
1983	10	1307	47°30	47°55	US	Vancouver	55-183 m
1983	11	2230	47°55	US-Can Border	US	Vancouver	55-183 m
1983	12	6572	US-Can Border	49°15	CDN	Vancouver	55-183 m
1983	30	66	47°30	47°55	US	Vancouver	184-219 m
1983	31	377	47°55	US-Can Border	US	Vancouver	184-219 m
1983	32	325	US-Can Border	49°15	CDN	Vancouver	184-219 m
1983	50	127	47°30	47°55	US	Vancouver	220-366 m
1983	51	631	47°55	US-Can Border	US	Vancouver	220-366 m
1983	52	503	US-Can Border	49 °15	CDN	Vancouver	220-366 m
1989&after	17N	1033	47°30	47°50	US	Vancouver	55-183 m
1989&after	17S	3378	46°30	47°30	US	Columbia	55-183 m
1989&after	18N	159	47°50	48°20	CDN	Vancouver	55-183 m
1989&after	18S	2123	47°50	48°20	US	Vancouver	55-183 m
1989&after	19N	8224	48°20	49°40	CDN	Vancouver	55-183 m
1989&after	19S	363	48°20	49°40	US	Vancouver	55-183 m
1989&after	27N	125	47°30	47°50	US	Vancouver	184-366 m
1989&after	27S	412	46°30	47°30	US	Columbia	184-366 m
1989&after	28N	88	47°50	48°20	CDN	Vancouver	184-366 m
1989&after	28S	787	47°50	48°20	US	Vancouver	184-366 m
1989&after	29N	942	48°20	49°40	CDN	Vancouver	184-366 m
1989&after	29S	270	48°20	49°40	US	Vancouver	184-366 m
1995&after	37N	102	47°30	47°50	US	Vancouver	367-500 m
1995&after	37S	218	46°30	47°30	US	Columbia	367-500 m
1995&after	38N	66	47°50	48°20	CDN	Vancouver	367-500 m
1995&after	38S	175	47°50	48°20	US	Vancouver	367-500 m
1995&after	39	442	48°20	49°40	CDN	Vancouver	367-500 m

Table B.3. Water haul and usable tow distribution by survey year and national stratum. Only tows used in the biomass estimation (see Table B.4) are listed.

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

Table B.4. Number of usable tows performed and area surveyed in the INPFC Vancouver region separated by the international border between Canada and the United States. Strata 18N, 28N (Table B.2) were dropped from this analysis as they were not consistently conducted over the survey period. Strata 37, 38 and 39 were added after 1995 (Table B.2). All strata occurring in the Columbia INPFC region (17S and 27S; Table B.2) were also dropped.

Survey year	Number of tows			Area surveyed (km^2)		
	CDN waters	US waters	Total	CDN waters	US waters	Total
1995	69	40	109	9,675	5,053	14,728
1998	58	44	102	9,675	5,053	14,728
2001	38	42	80	9,675	5,053	14,728
Total	165	126	291	–	–	–

B.3.2. Methods

The data were analysed using the equations in Section B.1. When calculating the variance for this survey, it was assumed that the variance and CPUE within any stratum were equal, even for strata that were split by the Canada/USA border. The total biomass $\left(B_{y_i}\right)$ within a stratum that straddled the border was split between the two countries $\left(B_{y_{i_c}}\right)$ by the ratio of the relative area within each country:

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

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

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

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

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

Biomass estimates were bootstrapped using 500 random draws with replacement to obtain bias-corrected (Efron 1982) 95% confidence intervals for each year and for the two regions (Canadian-Vancouver and US-Vancouver) based on the distribution of biomass estimates and using the above equations.

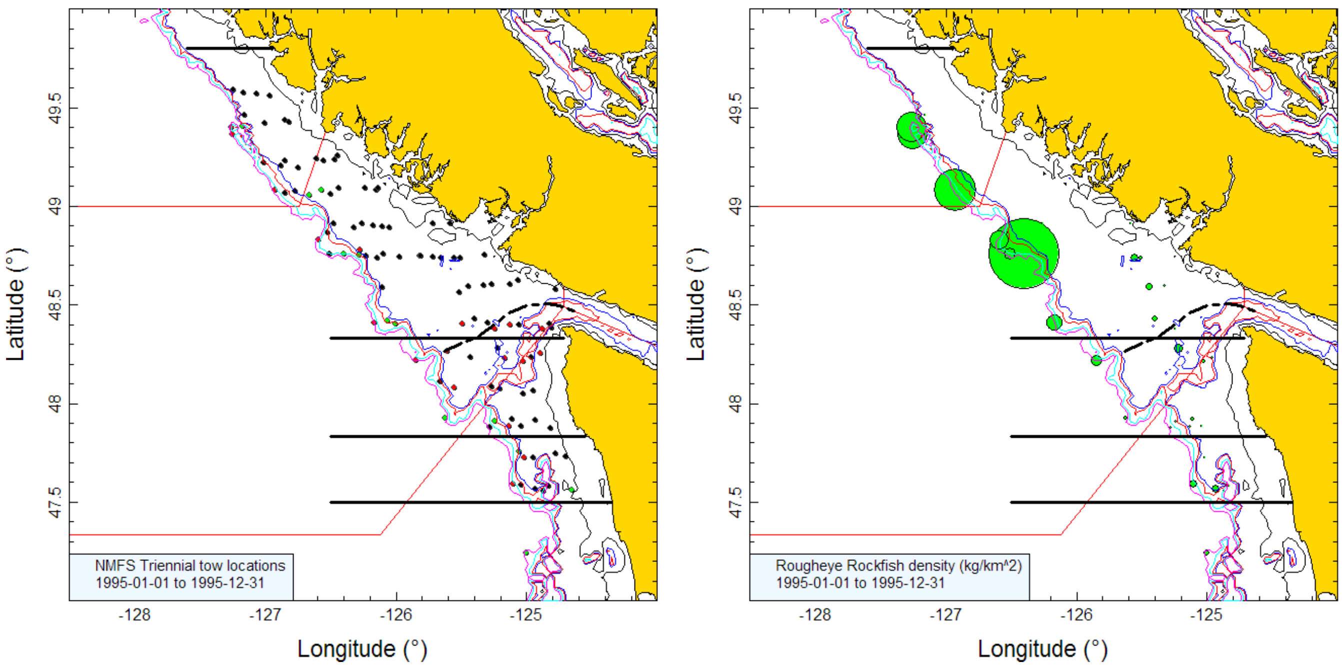

Figure B.1. [left panel]: plot of tow locations in the Vancouver INPFC region for the 1980 NMFS triennial survey in US and Canadian waters. Tow locations are colour-coded by depth range: black=55–183m; red=184-366m; green=367-500m. Dashed line shows approximate position of the Canada/USA marine boundary. Horizontal lines are the stratum boundaries: 47°30', 47°50', 48°20' and 49°50'. Tows south of the 47°30' line were not included in the analysis. [right panel]: circle sizes in the density plot are scaled across all years (1995, 1998, and 2001), with the largest circle = 17,746 kg/km² in 1995. The red solid lines indicate the boundaries between PMFC areas 3B, 3C and 3D.

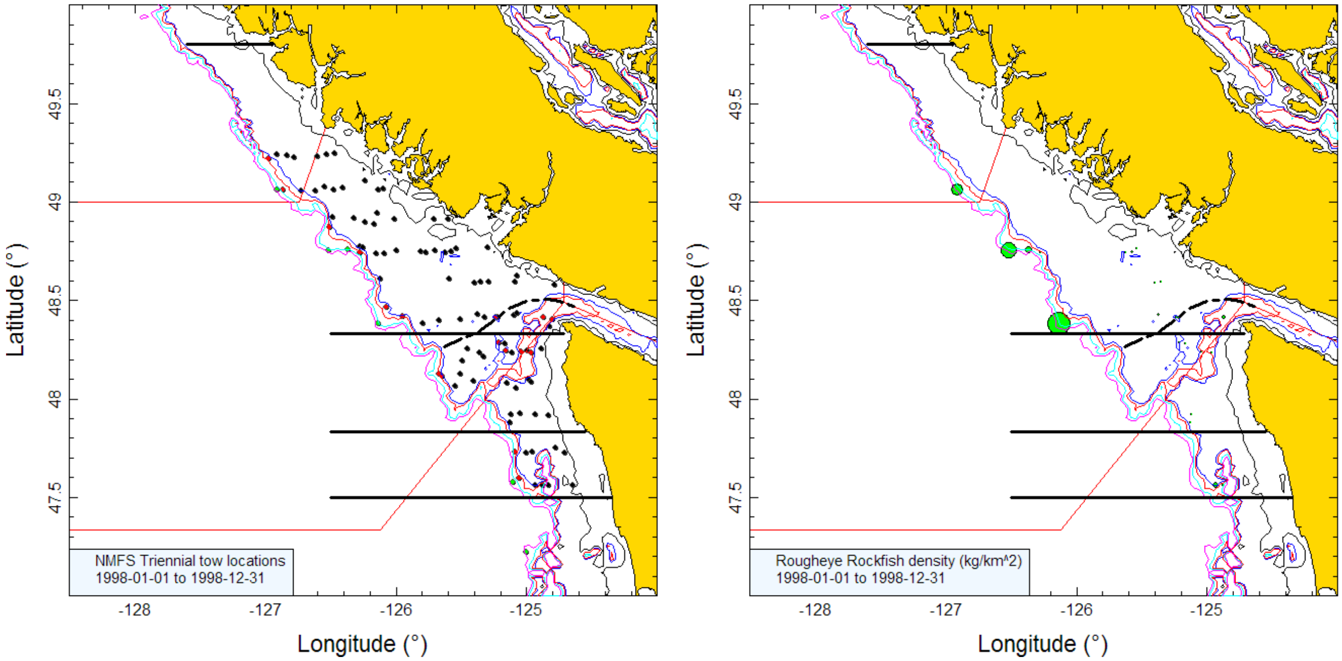

Figure B.2. Tow locations and density plots for the 1998 NMFS triennial survey in US and Canadian waters (see Figure B.1 caption).

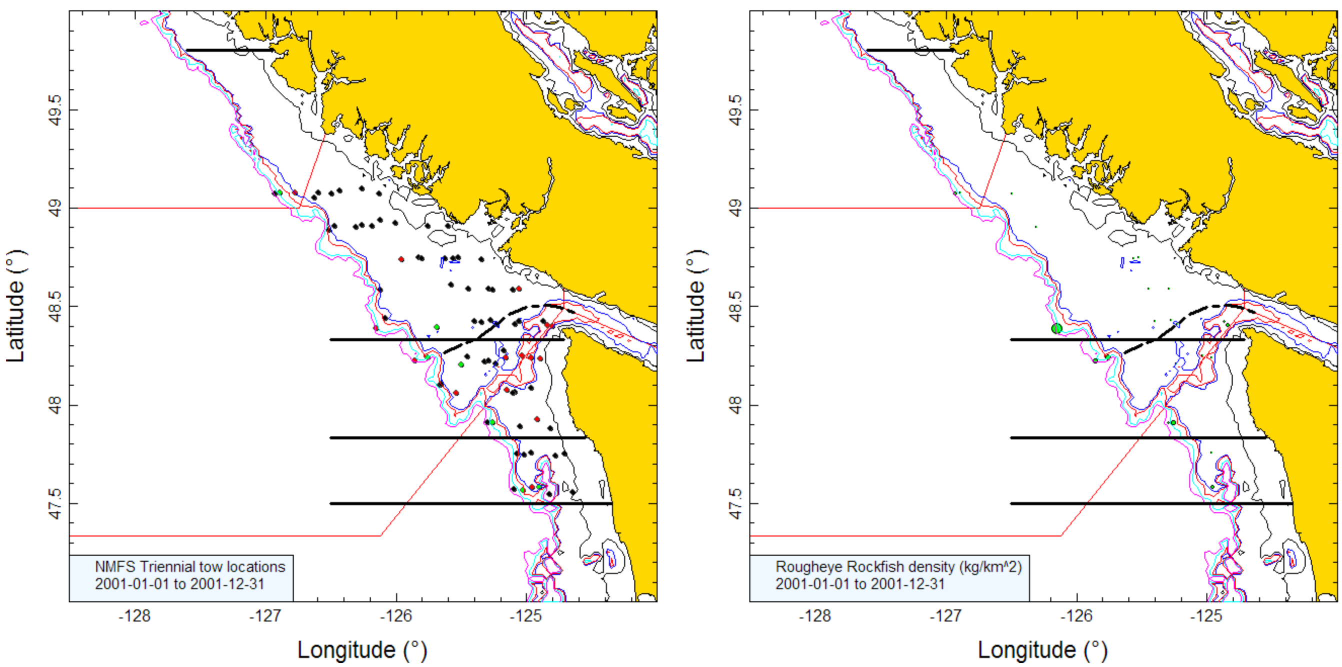

Figure B.3. Tow locations and density plots for the 2001 NMFS triennial survey in US and Canadian waters (see Figure B.1 caption).

B.3.3. Results

Rougheye/Blackspotted Rockfish (REBS) were characterised with low levels of catch in the 1980 and 1983 surveys, particularly in Canadian waters (these results are not reported here).

These surveys (and the 1989 and 1992 surveys) only covered the more shallow strata which covered depths from 55 to 366 m (Table B.2) and have been omitted from this summary as they have not been included in the stock assessment. Encounters with REBS increased from 1995 with the addition of deep (367–500 m) strata in both the US and Canadian waters. From 1995, REBS were taken along the shelf edge, particularly in Canadian waters (e.g., Figure B.3). Figure B.4 shows that this species was mainly found at depths between 152 and 458 m (1% and 99% quantiles of [`bottom_depth`]), but the largest observed catch weights occurred in the deep strata.

Rougheye Rockfish biomass estimates in both US and Canadian waters were variable without trend (Figure B.5; Table B.5). The relative error estimates were moderate to high, ranging from 0.35 in 1998 to 0.80 in 1995 in the Canadian strata (Table B.5).

The percentage of tows which captured REBS varied among survey years, with only 9% of the Canadian tows from 1980 to 1992 taking REBS (not reported here) while 26% of the tows from 1995 to 2001 captured REBS with the addition of the deep (367–500 m) stratum. The equivalent percentages for the US waters tows were 25% and 33% respectively. Overall 29% of the 291 tows used for biomass estimation after 1995 captured REBS (83 tows). The largest tow was 742 kg in 1995, taken in the deep stratum in Canadian waters. The proportion of tows from 1995 which contained REBS ranged from 21% to 29% in Canadian waters and between 23% and 45% in US, with no apparent trend (Figure B.6).

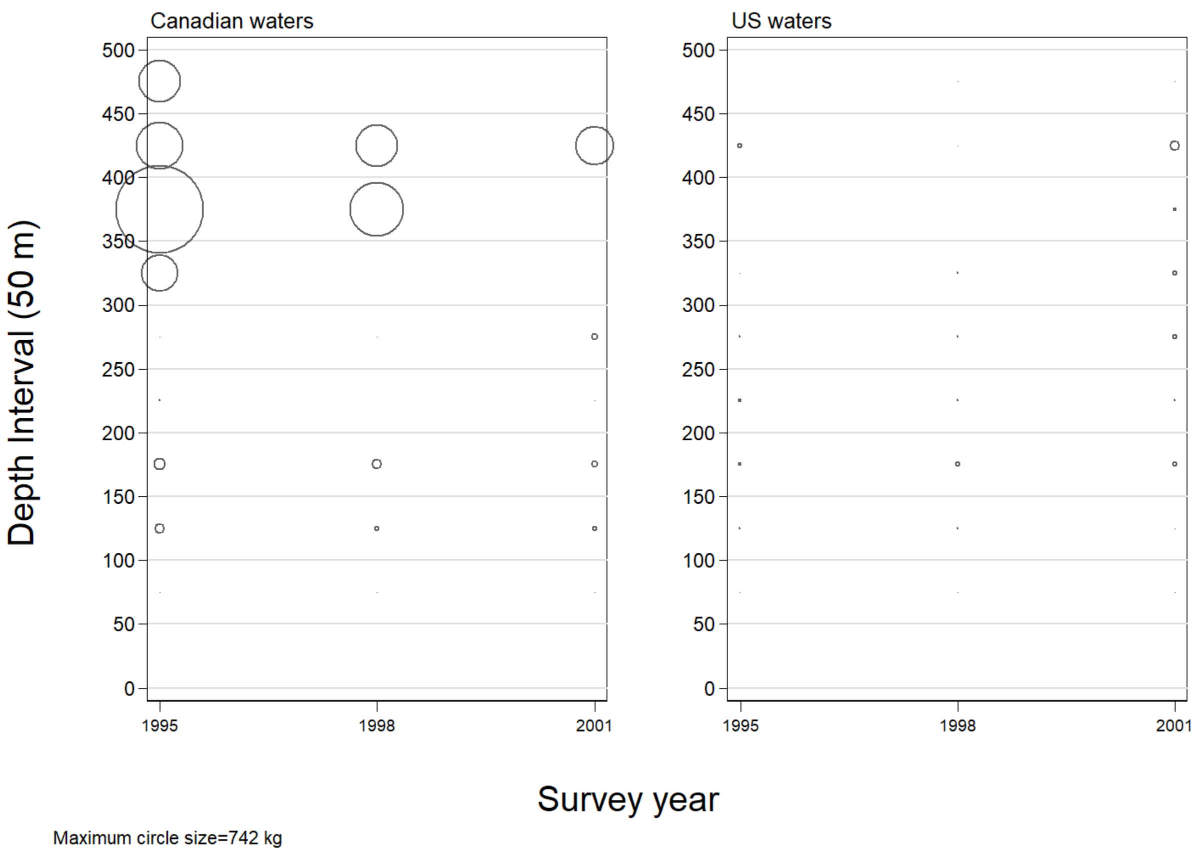

Figure B.4. Distribution of REBS catch weights for each survey year summarised into 25 m depth intervals for all tows (Table B.4) in Canadian and US waters of the Vancouver INPFC area. Catches are plotted at the mid-point of the interval.

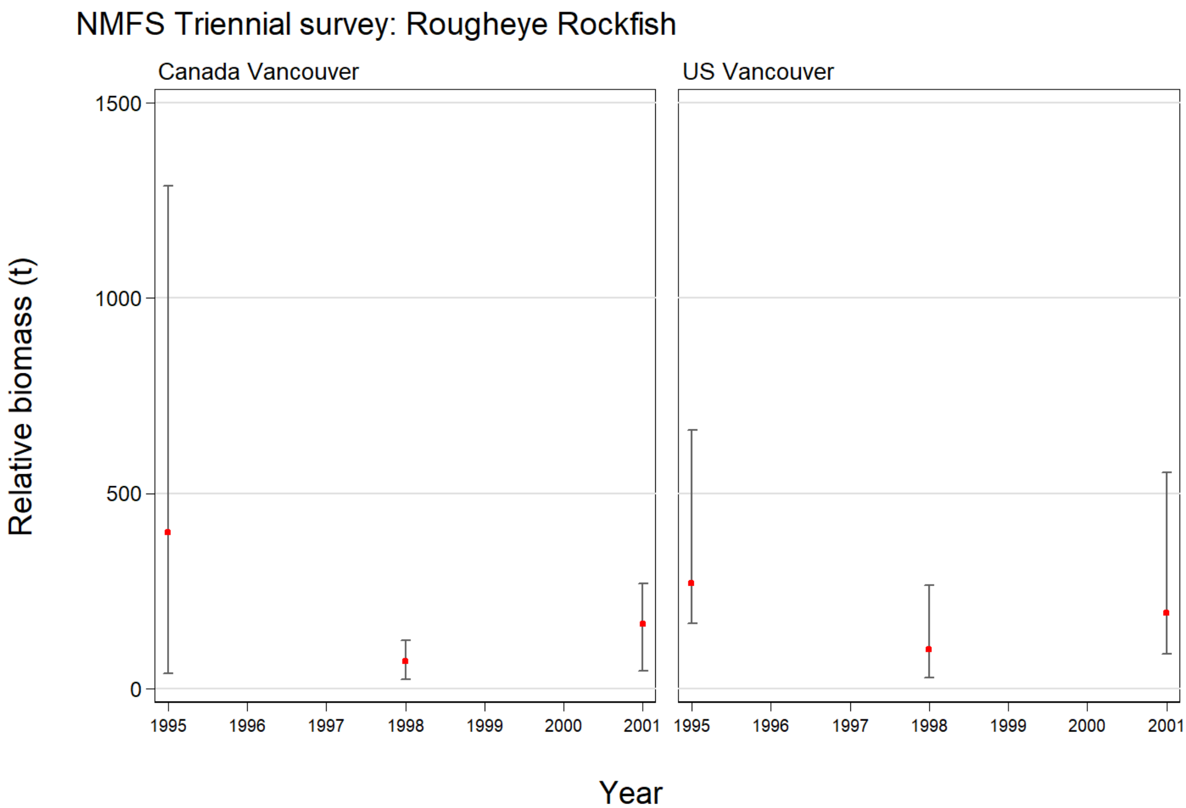

Figure B.5. Biomass estimates for REBS in the INPFC Vancouver region (Canadian waters only, US waters only) with 95% error bars estimated from 500 bootstrap random draws with replacement.

Table B.5. Two set of biomass estimates for REBS in the Vancouver INPFC region (Canadian waters; US waters) with 95% confidence bounds based on the bootstrap distribution of biomass. Bootstrap estimates are based on 1000 random draws with replacement.

Series	Year	Biomass (Eq. B.4)	Mean bootstrap biomass	Lower bound biomass	Upper bound biomass	CV bootstrap	CV Analytic (Eq. B.6)
Canada Vancouver	1995	399	391	40	1,286	0.797	0.771
	1998	71	73	23	123	0.354	0.379
	2001	165	156	45	270	0.357	0.318
US - Vancouver	1995	271	181	167	661	0.529	0.403
	1998	101	85	29	264	0.670	0.595
	2001	194	159	89	552	0.482	0.427

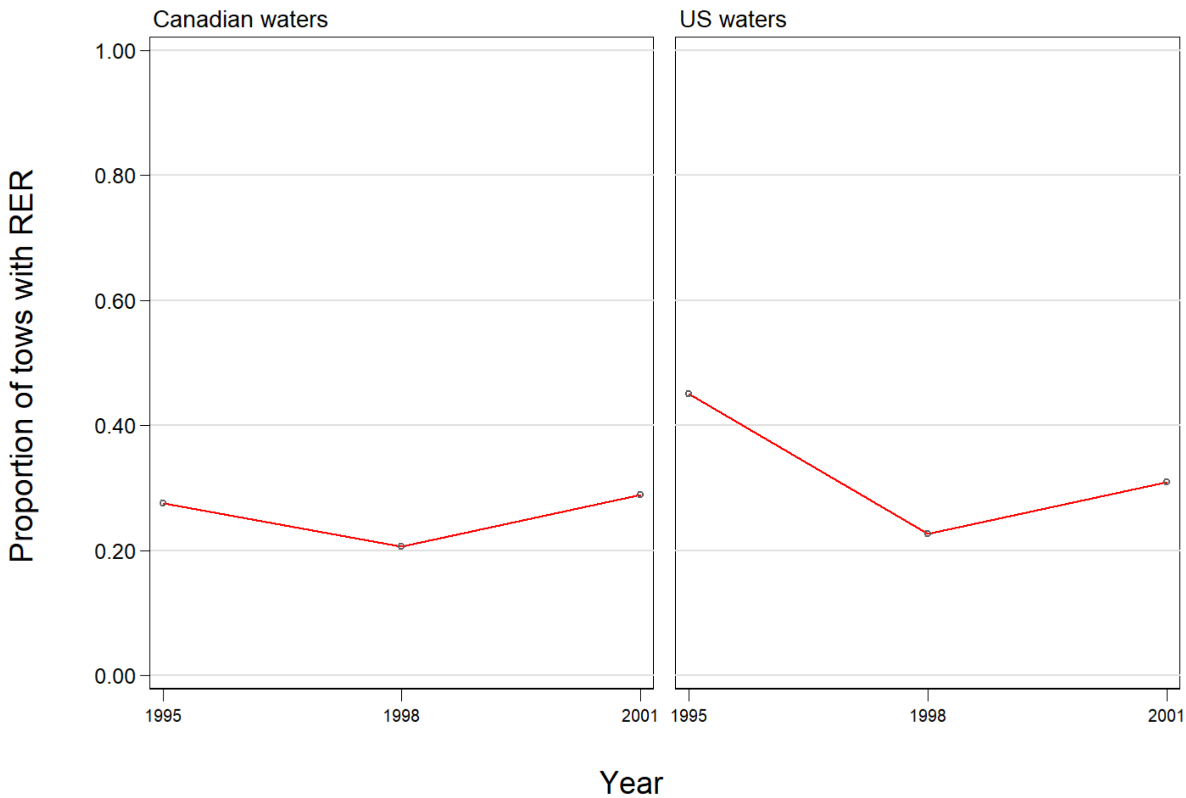

Figure B.6. Proportion of tows with REBS by year for the Vancouver INPFC region (Canadian and US waters).

B.4. QUEEN CHARLOTTE SOUND SYNOPTIC TRAWL SURVEY

B.4.1. Data selection

This survey has been conducted ten times over the period 2003 to 2019 in the Queen Charlotte Sound (QCS), which lies between the top of Vancouver Island and the southern portion of Moresby Island and extends into the lower part of Hecate Strait between Moresby Island and the mainland. The design divided the survey into two large areal strata which roughly correspond to the PMFC regions 5A and 5B while also incorporating part of 5C (all valid tow starting positions are shown by survey year in Figure B.7 to Figure B.16). Each of these two areal strata was divided into four depth strata: 50–125 m; 125–200 m; 200–330 m; and 330–500 m (Table B.6).

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 2019. Also shown is the area of each stratum for the 2019 survey and the vessel conducting the survey by survey year.

		South depth strata				North depth strata				Total
Year	**Vessel**	**50-125**	**125-200**	**200-330**	**330-500**	**50-125**	**125-200**	**200-330**	**330-500**	**tows[1]**
2003	*Viking Storm*	29	56	29	6	5	39	50	19	233
2004	*Viking Storm*	42	48	31	8	20	38	37	6	230
2005	*Viking Storm*	29	60	29	8	8	45	37	8	224
2007	*Viking Storm*	33	61	24	7	19	56	48	7	255
2009	*Viking Storm*	34	60	28	8	10	44	43	6	233
2011	*Nordic Pearl*	38	67	24	8	10	51	45	8	251
2013	*Nordic Pearl*	32	65	29	10	9	46	44	5	240
2015	*Frosti*	30	65	26	4	12	49	44	8	238
2017	*Nordic Pearl*	36	57	29	8	12	51	40	7	240
2019	*Nordic Pearl*	35	62	26	9	15	52	35	8	242
Area (km^2)[2]		5,012	5,300	2,640	528	1,740	3,928	3,664	1,236	24,048[2]

[1] GFBio usability codes=0,1,2,6 [2] Total area (km^2) for 2019 synoptic survey

Table B.7. Number of missing doorspread values by year for the Queen Charlotte Sound synoptic survey over the period 2003 to 2019 as well as showing the number of available doorspread observations and the mean doorspread value for each survey year.

Year	Number tows with missing doorspread [1]	Number tows with doorspread observations [2]	Mean doorspread (m) used for tows with missing values [2]
2003	13	236	72.1
2004	8	267	72.8
2005	1	258	74.5
2007	5	262	71.8
2009	2	248	71.3
2011	30	242	67.0
2013	42	226	69.5
2015	0	249	70.5
2017	1	264	64.7
2019	8	264	62.9
Total	110	2,516	69.7

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

A doorspread density value (Eq. B.3) was generated for each tow based on the catch of REBS (REBS) from the mean doorspread for the tow and the distance travelled. [`distance travelled`] is a database field which is calculated directly from the tow track. This field is used preferentially for the variable D_{yij} in Eq. B.3. A calculated value ([`vessel speed`]×[`tow duration`]) is used for this variable if [`distance travelled`] is missing, but there were only two instances of this occurring in the ten trawl surveys. Missing values for the [`doorspread`] field were filled in with the mean doorspread for the survey year (110 values over all years, Table B.7).

B.4.2. Results

An examination of the spatial plots provided from Figure B.7 to Figure B.16 shows that most REBS were caught along the western shelf edge along the drop-off to deeper water. In some years, small amounts of REBS were captured to the east of the shelf edge in several of the central gullies (e.g., Figure B.15). REBS were found in the deeper tows, with the 1% to 99% quantiles ranging from 187 m to 501 m (Figure B.17). The REBS biomass estimates ranged from 300 to 2,800 t, although the two years with high biomass (2011 and 2015) are also associated with the highest relative error (0.78 and 0.49 respectively) in the series (Table B.8, Figure B.18). Both of these survey years were associated with the some very large tows, which result in high levels of relative error. The remaining estimates of relative error range from 0.16 in 2005 to 0.44 in 2003 (Table B.8).

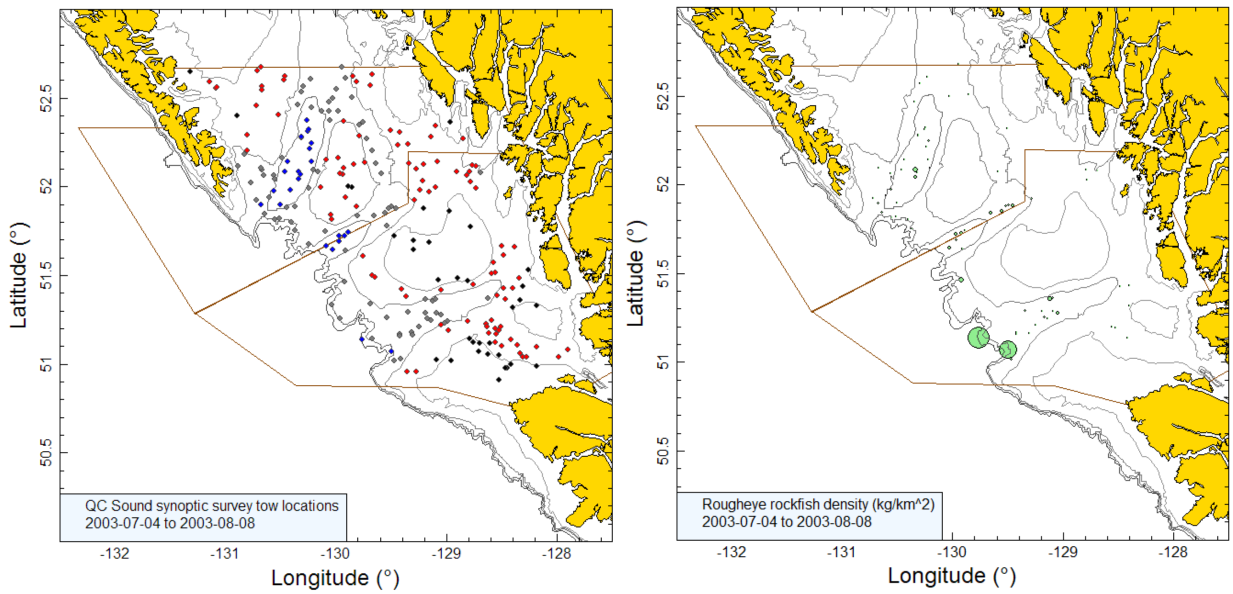

Figure B.7. Valid tow locations (50-125m stratum: black; 126-200m stratum: red; 201-330m stratum: grey; 331-500m stratum: blue) and density plots for the 2003 QC Sound synoptic survey. Circle sizes in the right-hand density plot scaled across all years (2003–2005, 2007, 2009, 2011, 2013, 2015, 2017, 2019), with the largest circle = 14,153 kg/km^2 in 2011. Boundaries delineate the North and South areal strata.

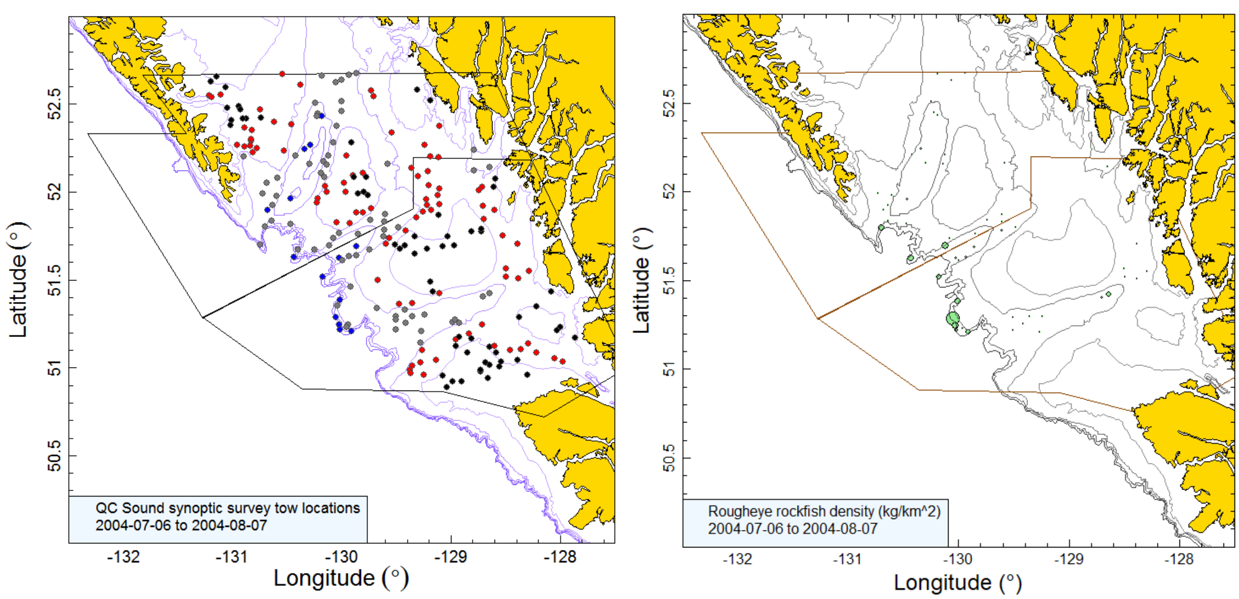

Figure B.8. Tow locations and density plots for the 2004 Queen Charlotte Sound synoptic survey (see Figure B.7 caption).

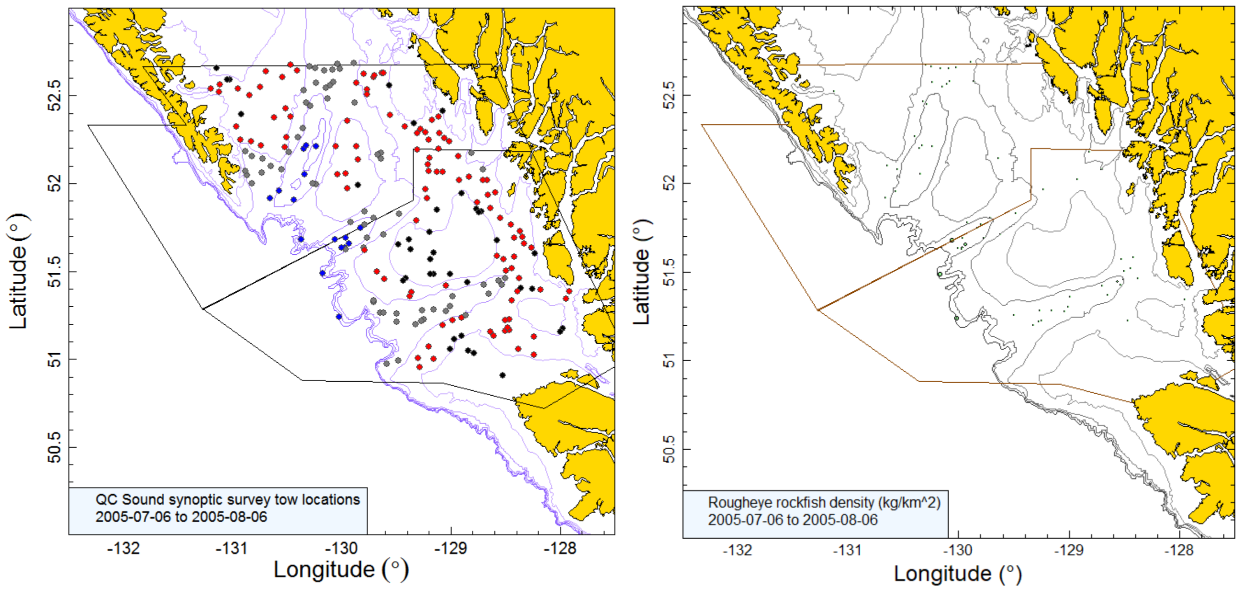

Figure B.9. Tow locations and density plots for the 2005 Queen Charlotte Sound synoptic survey (see Figure B.7 caption).

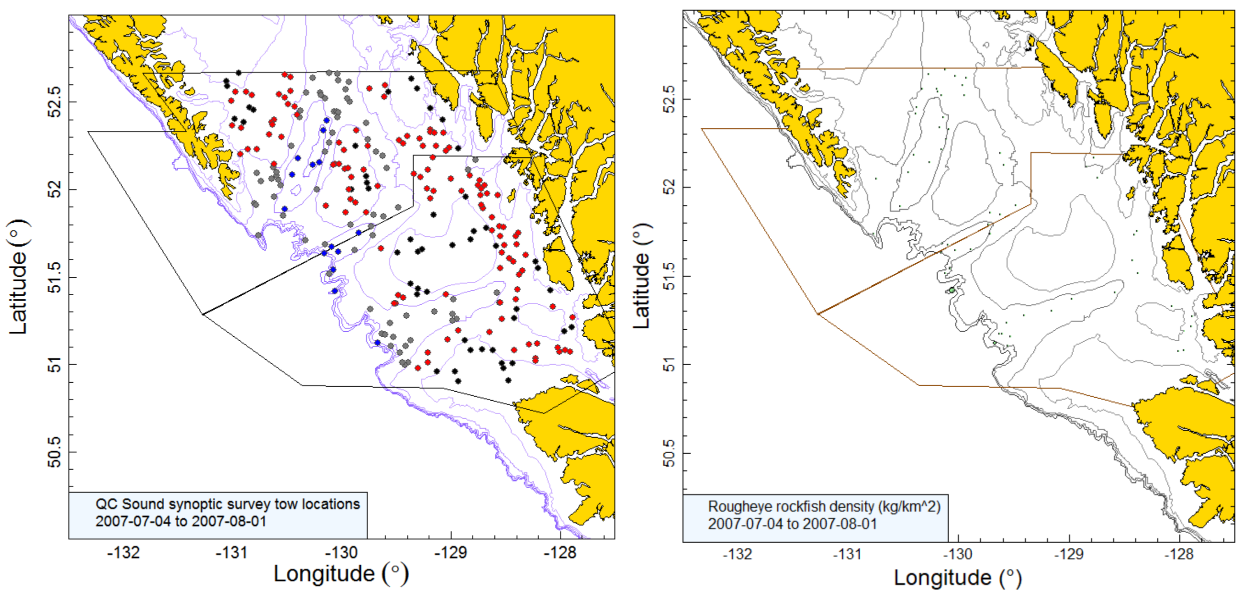

Figure B.10. Tow locations and density plots for the 2007 Queen Charlotte Sound synoptic survey (see Figure B.7 caption).

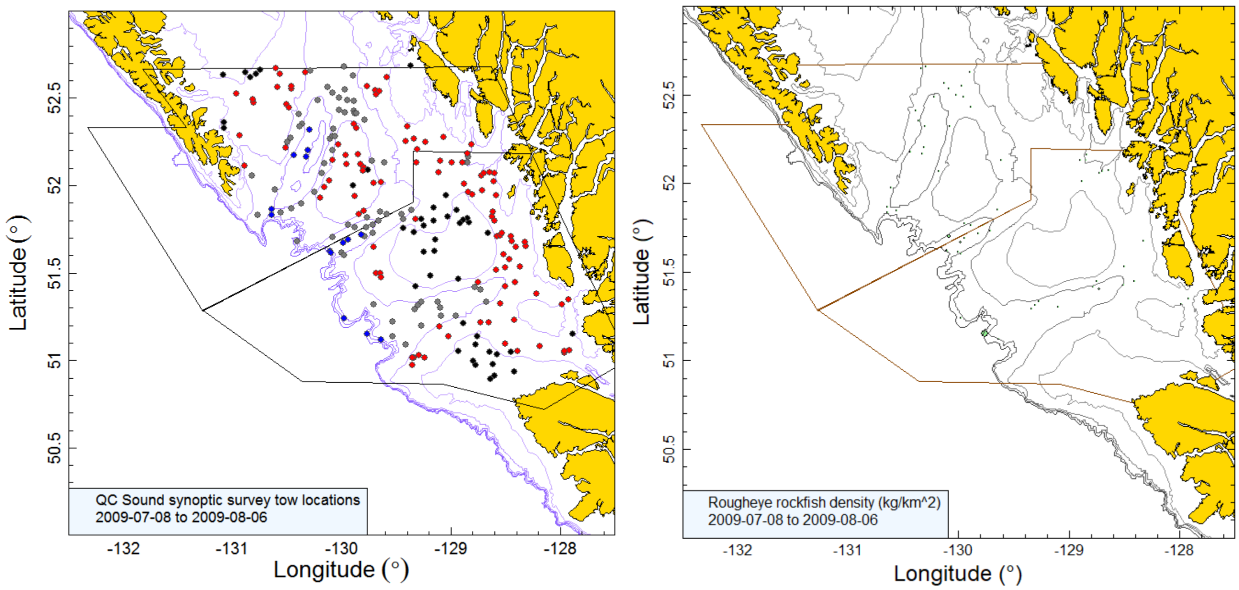

Figure B.11. Tow locations and density plots for the 2009 Queen Charlotte Sound synoptic survey (see Figure B.7 caption).

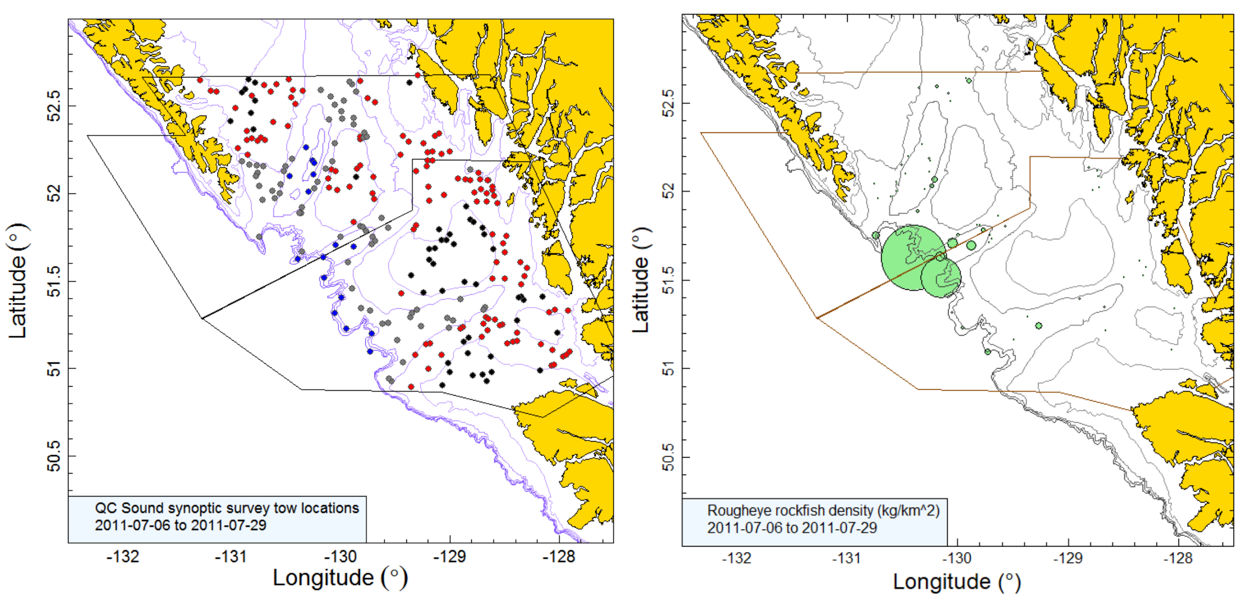

Figure B.12. Tow locations and density plots for the 2011 Queen Charlotte Sound synoptic survey (see Figure B.7 caption).

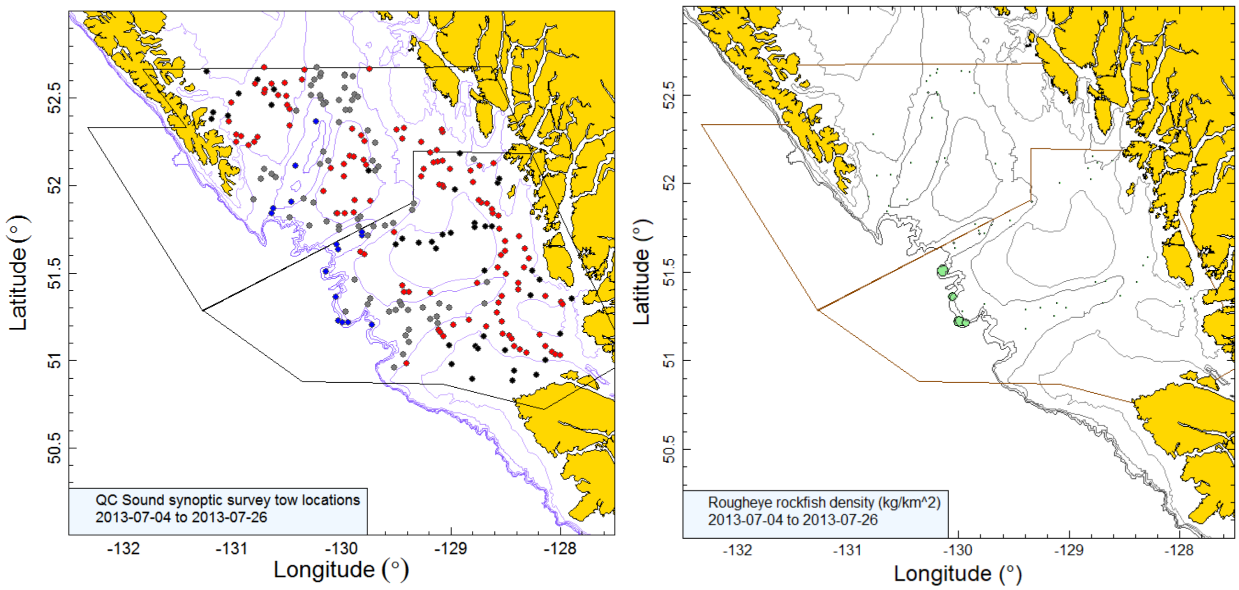

Figure B.13. Tow locations and density plots for the 2013 Queen Charlotte Sound synoptic survey (see Figure B.7 caption).

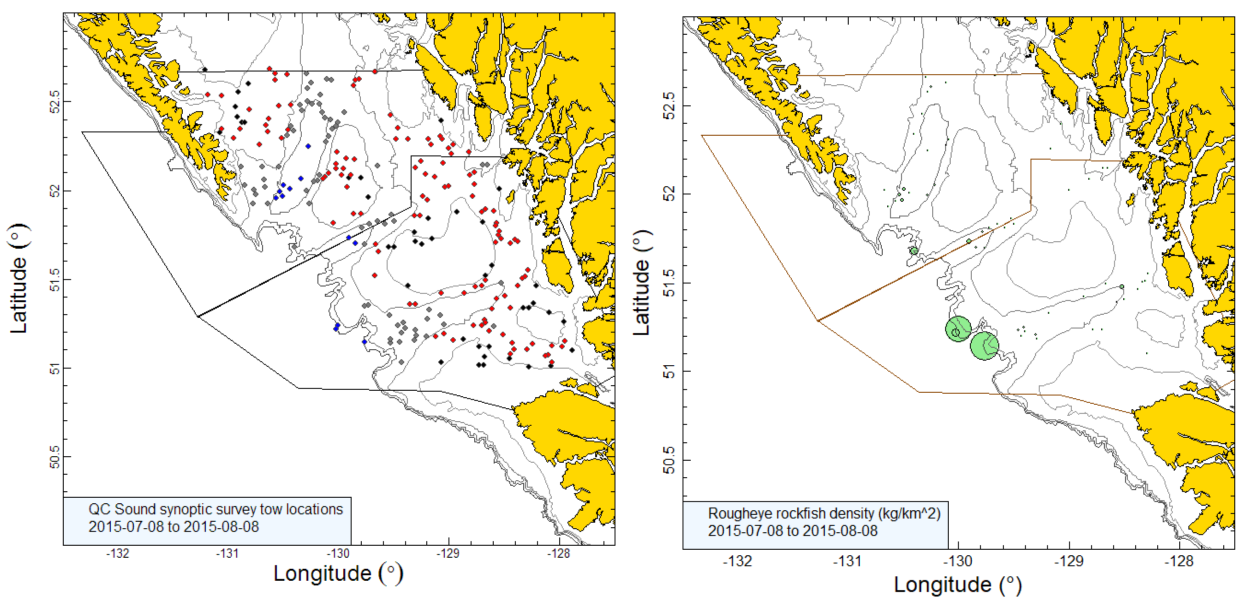

Figure B.14. Tow locations and density plots for the 2015 Queen Charlotte Sound synoptic survey (see Figure B.7 caption).

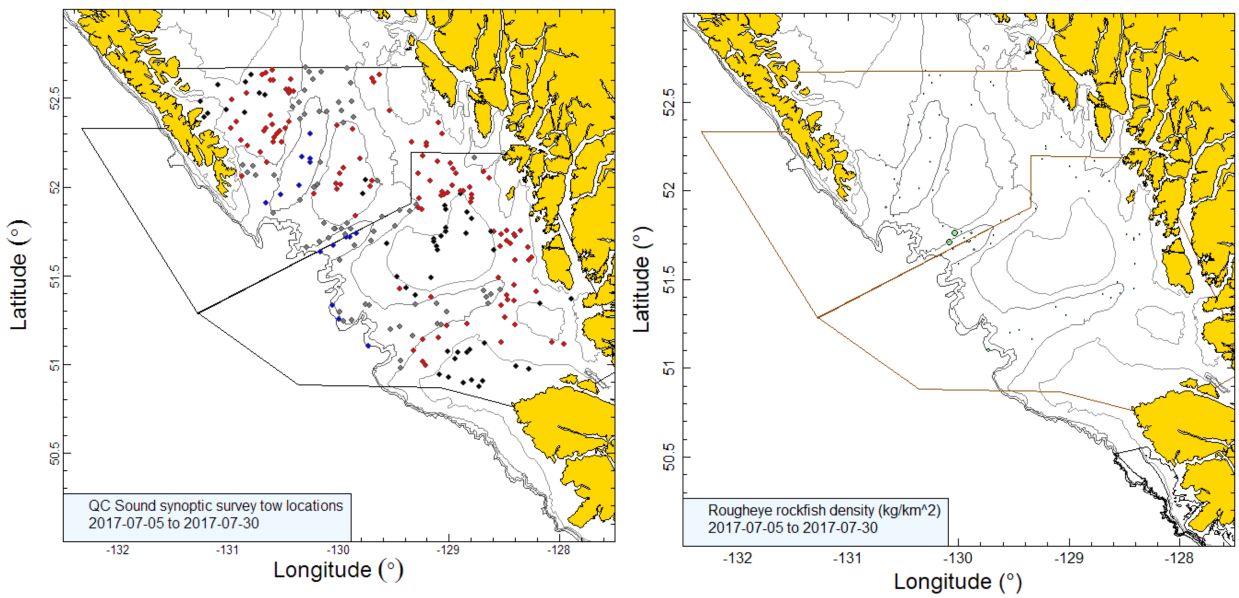

Figure B.15. Tow locations and density plots for the 2017 Queen Charlotte Sound synoptic survey (see Figure B.7 caption).

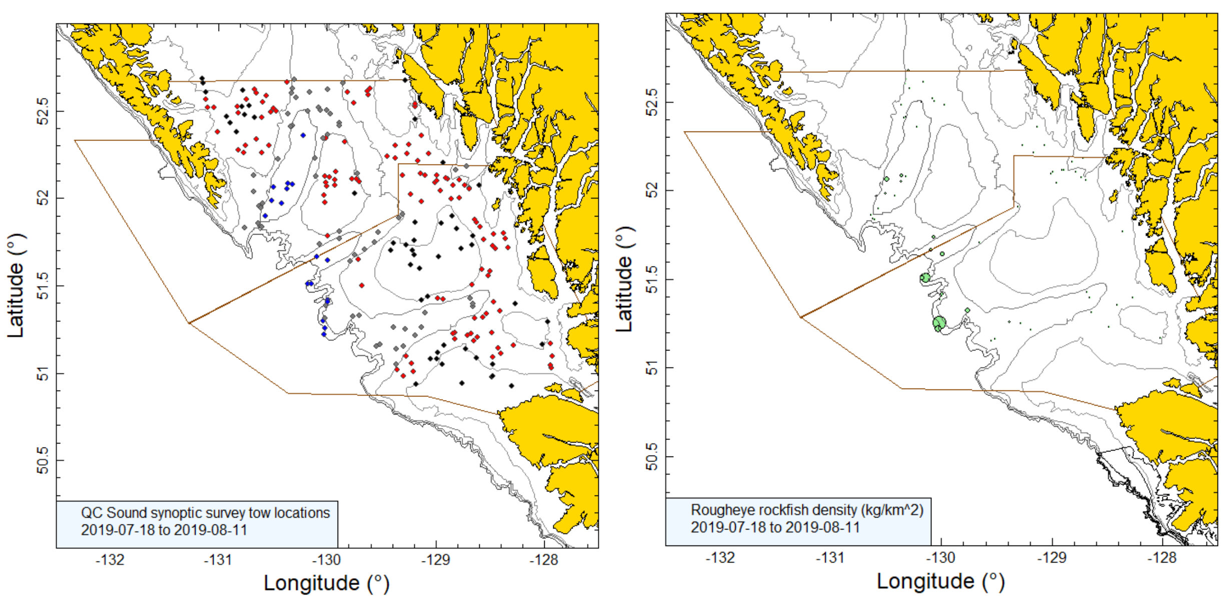

Figure B.16. Tow locations and density plots for the 2019 Queen Charlotte Sound synoptic survey (see Figure B.7 caption).

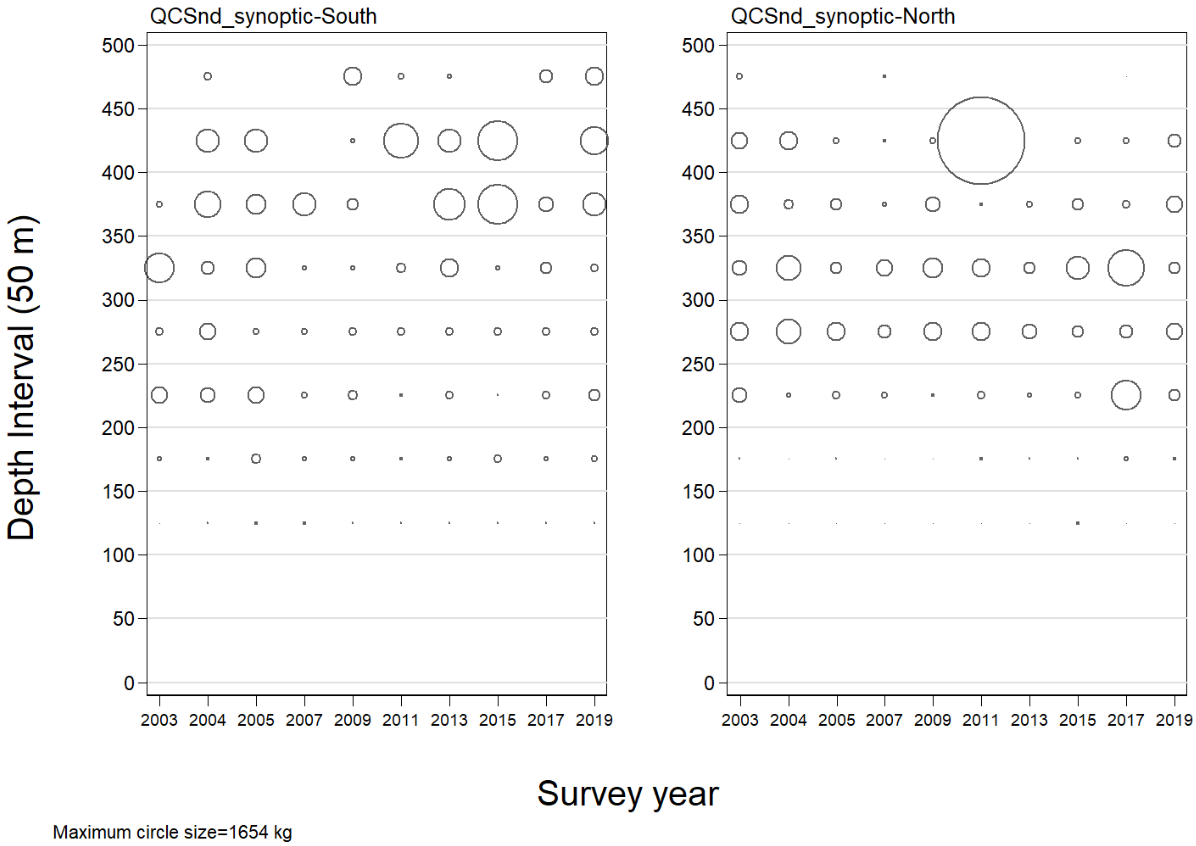

Figure B.17. Distribution of observed catch weights for tows used in biomass estimation for REBS in the two main Queen Charlotte Sound synoptic survey areal strata (Table B.6) by survey year and 50 m depth zone. Catches are plotted at the mid-point of the interval and circles in the panel are scaled to the maximum value (1654 kg) in the 400–450 m interval in the 2011 northern stratum. The 1% and 99% quantiles for the REBS start of tow depth distribution= 187 m and 501 m respectively.

Table B.8. Biomass estimates for REBS from the Queen Charlotte Sound synoptic trawl survey for the survey years 2003 to 2019. Bootstrap bias corrected confidence intervals and CVs are based on 1000 random draws with replacement.

Survey Year	**Biomass (t)** (Eq. B.4)	**Mean bootstrap biomass (t)**	**Lower bound biomass (t)**	**Upper bound biomass (t)**	**Bootstrap CV**	**Analytic CV** (Eq. B.6)
2003	974	983	256	1,893	0.444	0.451
2004	864	874	471	1,510	0.284	0.271
2005	529	531	379	695	0.158	0.157
2007	289	286	147	525	0.337	0.331
2009	369	368	221	633	0.281	0.284
2011	2,789	2,827	204	8,040	0.782	0.791
2013	565	563	276	932	0.289	0.291
2015	1,787	1,807	211	3,478	0.488	0.471
2017	606	609	325	1,055	0.294	0.292
2019	733	726	424	1,224	0.268	0.257

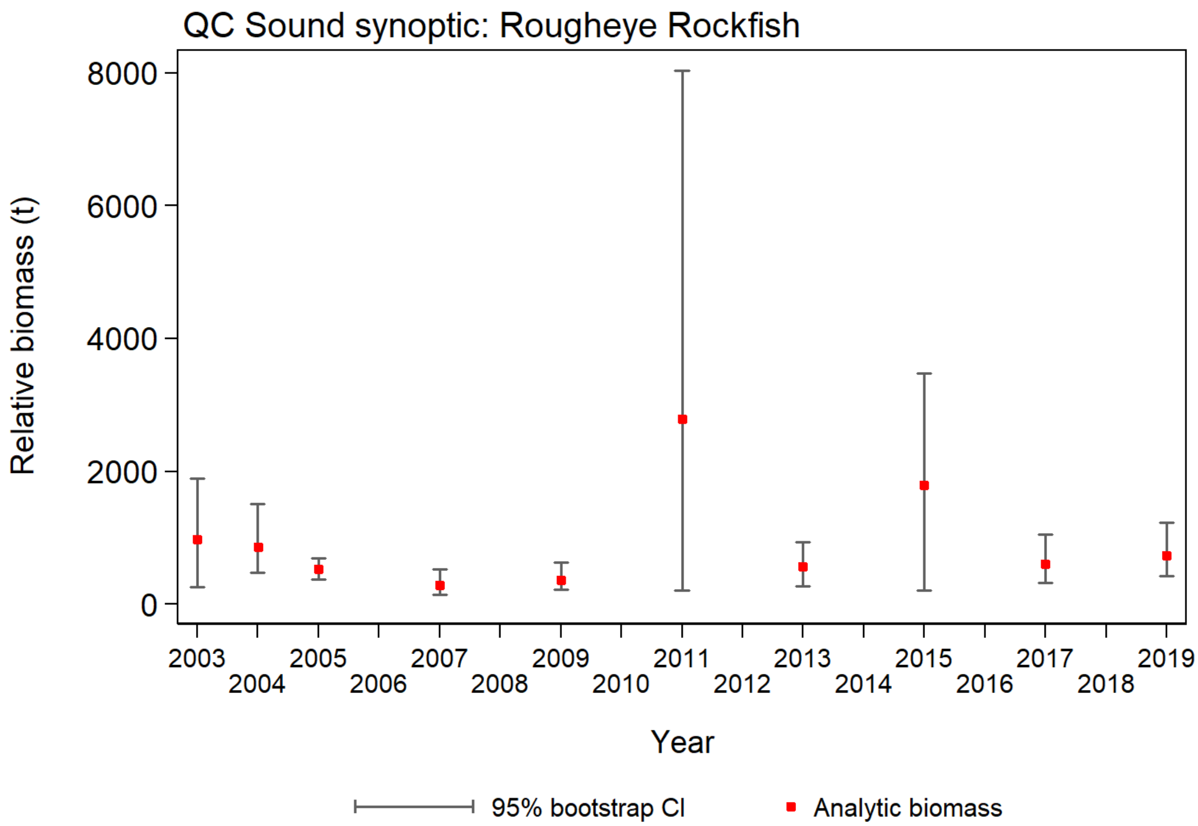

Figure B.18. Plot of biomass estimates for REBS (values provided in Table B.8) from the Queen Charlotte Sound synoptic survey over the period 2003 to 2019. Bias corrected 95% confidence intervals from 1000 bootstrap replicates are plotted.

On average, REBS were captured in around 25% of tows in both areal strata, ranging from 20% to 29% of the tows in the South stratum and 23% to 36% of the tows in the North stratum (Figure B.19). Overall, 623 of the 2,386 valid survey tows (24%) contained REBS. The median catch weight for positive tows was 2.8 kg/tow across the ten surveys, and the maximum catch weight in a tow was 1,650 kg in the 2011 survey.

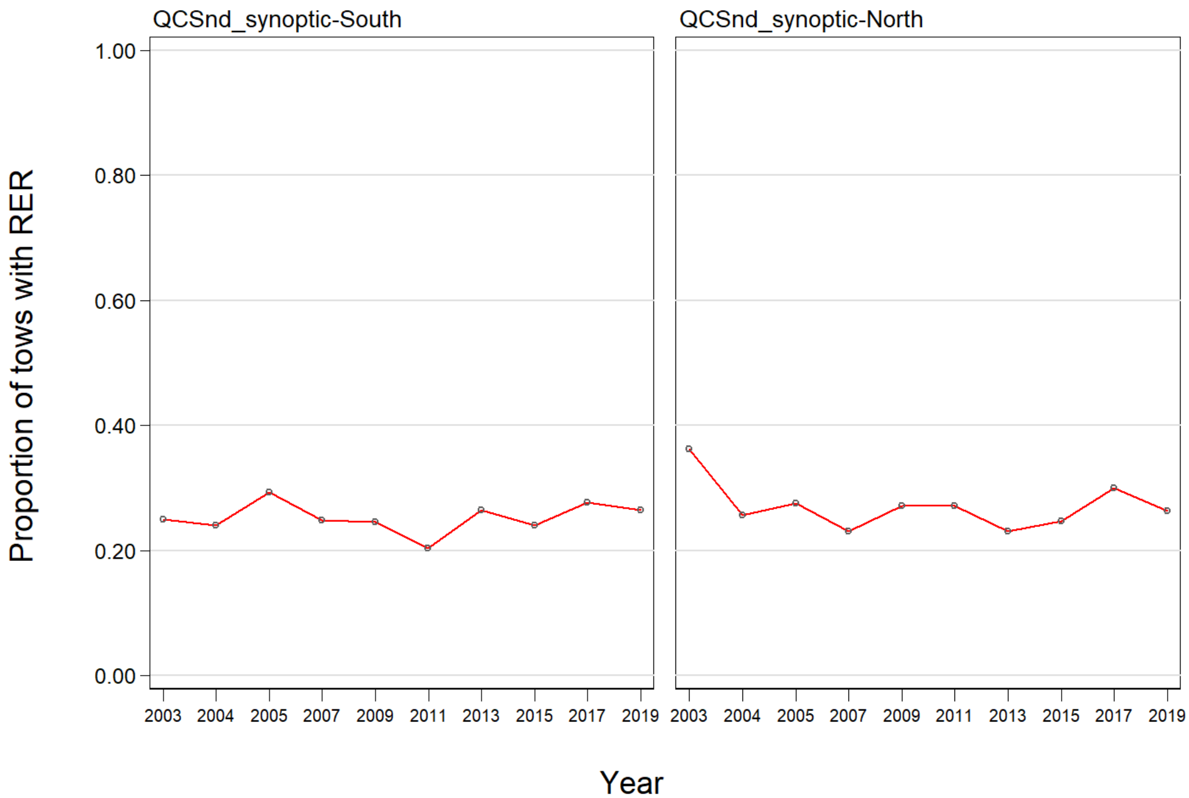

Figure B.19. Proportion of tows by stratum and year which contain REBS from the Queen Charlotte Sound synoptic survey over the period 2003 to 2019.

B.5. WEST COAST VANCOUVER ISLAND SYNOPTIC TRAWL SURVEY

B.5.1. Data selection

This survey has been conducted seven times in the period 2004 to 2016 off the west coast of Vancouver Island by RV *W.E. Ricker*. An eighth survey was conducted in 2018 by the RV *Nordic Pearl* due to the decommissioning of the *W.E. Ricker*. It comprises a single areal stratum, separated into four depth strata: 50-125 m; 125-200 m; 200-330 m; and 330-500 m (Table B.9). Approximately 150 to 200 2-km^2 blocks are selected randomly among the four depth strata when conducting each survey (Olsen et. al. 2008).

A “doorspread density” value was generated for each tow based on the catch of REBS, the mean doorspread for the tow and the distance travelled (Eq. B.3). The distance travelled was provided as a data field, determined directly from vessel track information collected during the tow. There were only two missing values in this field (in 2004 and 2010) which were filled in by multiplying the vessel speed by the time that the net was towed. There were a large number of missing values for the doorspread field, which were filled in using the mean doorspread for the survey year or a default value of 64.6 m for the three years with no doorspread data (Table B.10). The default value is based on the mean of the observed doorspread from the net mensuration equipment, averaged across the years with doorspread estimates.

Table B.9. Stratum designations, number of usable and unusable tows, for each year of the west coast Vancouver Island synoptic survey. Also shown is the area of each depth stratum in 2018 and the start and end dates for each survey.

Survey year	Stratum depth zone 50-125 m	125-200 m	200-330 m	330-500 m	Total Tows[1]	Unusable tows	Start date	End date
2004	34	34	13	8	89	17	26-May-04	09-Jun-04
2006	61	62	28	13	164	12	24-May-06	18-Jun-06
2008	54	50	32	23	159	19	27-May-08	21-Jun-08
2010	58	47	22	9	136	8	08-Jun-10	28-Jun-10
2012	60	46	25	20	151	6	23-May-12	15-Jun-12
2014	55	49	29	13	146	7	29-May-14	20-Jun-14
2016	54	41	26	19	140	7	25-May-16	15-Jun-16
2018	69	64	36	21	190	12	19-May-18	12-Jun-18
Area (km^2)	5,716	3,768	708	572	10,764[2]	–	–	–

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

Table B.10. Number of tows with and without doorspread measurements by survey year for the WCVI synoptic survey. Mean doorspread values for those tows with measurements are provided.

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

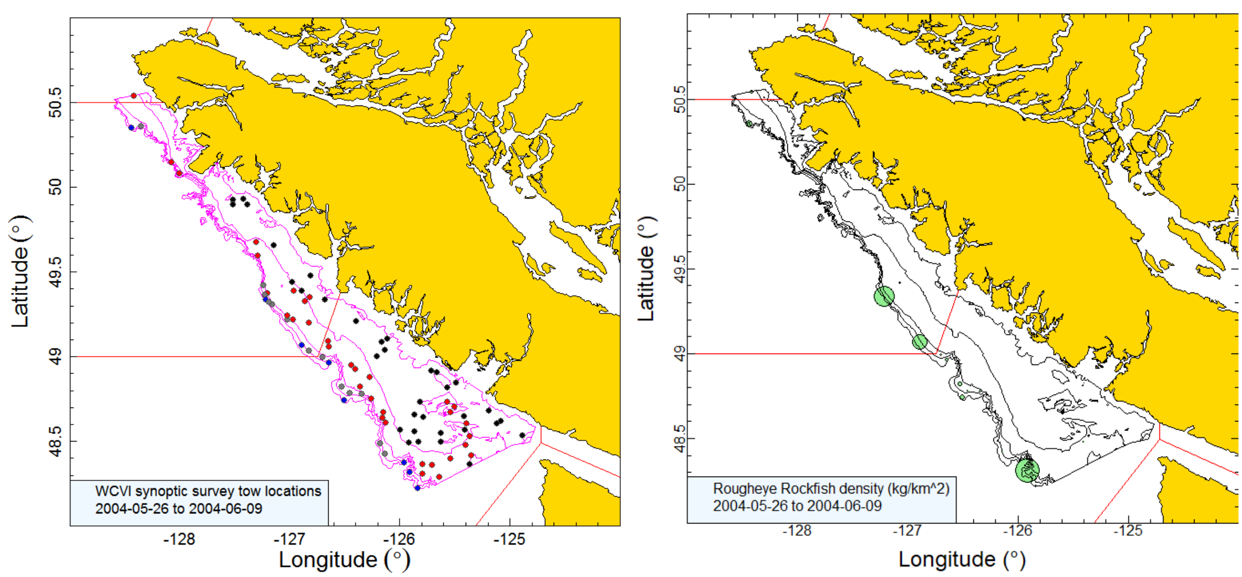

Figure B.20. Valid tow locations (50-125m stratum: black; 126-200m stratum: red; 201-330m stratum: grey; 331-500m stratum: blue) and density plots for the 2004 west coast Vancouver Island synoptic survey. Circle sizes in the right-hand density plot scaled across all years (2004, 2006, 2008, 2010, 2012, 2014, 2016, 2018), with the largest circle = 4,950 kg/km^2 in 2018. The red solid lines indicate the boundaries for PMFC areas 3C, 3D and 5A.

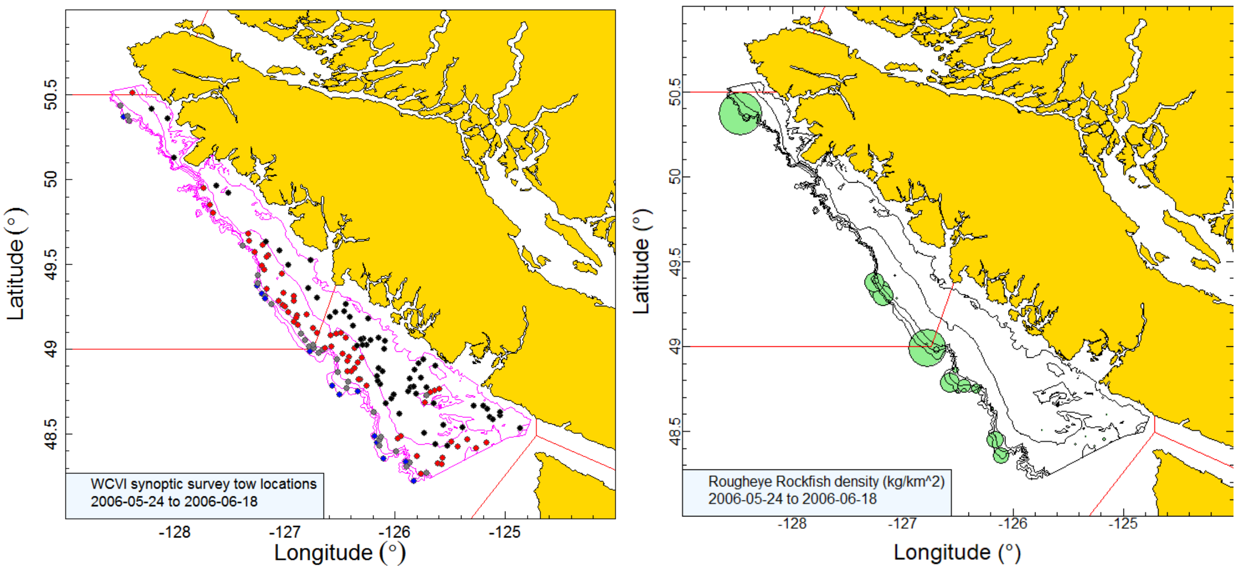

Figure B.21. Tow locations and density plots for the 2006 west coast Vancouver Island synoptic survey (see Figure B.20 caption).

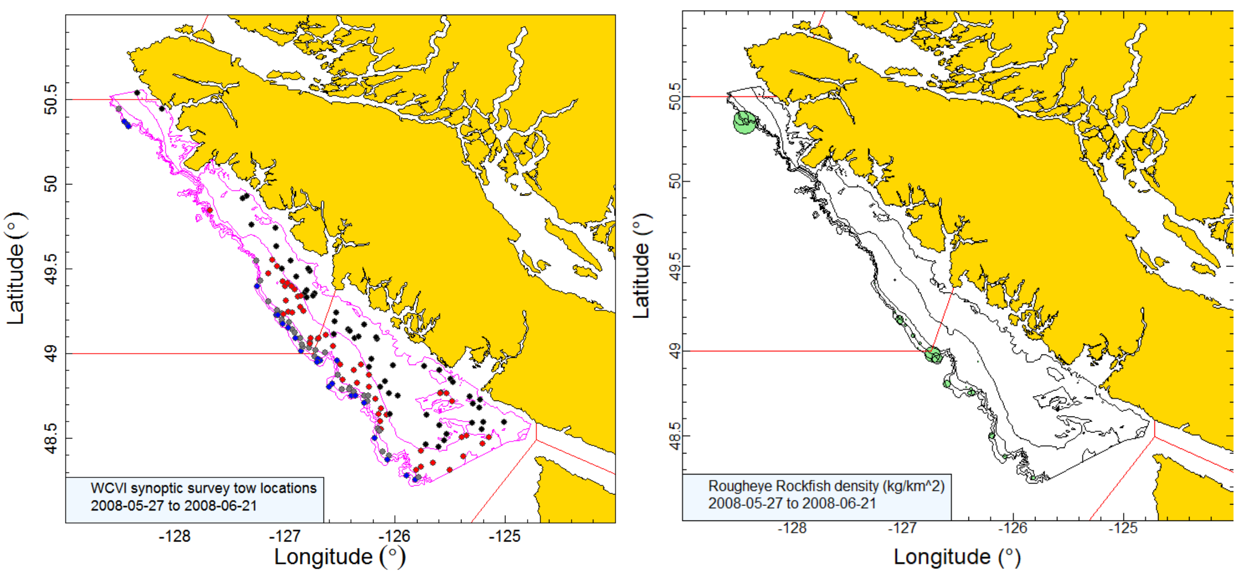

Figure B.22. Tow locations and density plots for the 2008 west coast Vancouver Island synoptic survey (see Figure B.20 caption).

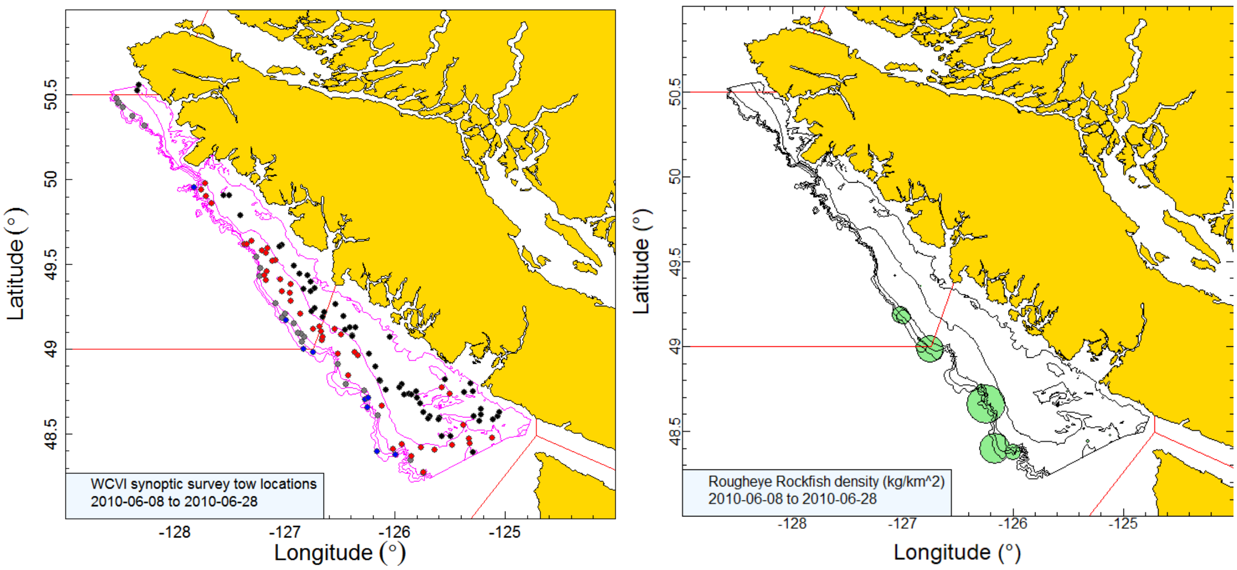

Figure B.23. Tow locations and density plots for the 2010 west coast Vancouver Island synoptic survey (see Figure B.20 caption).

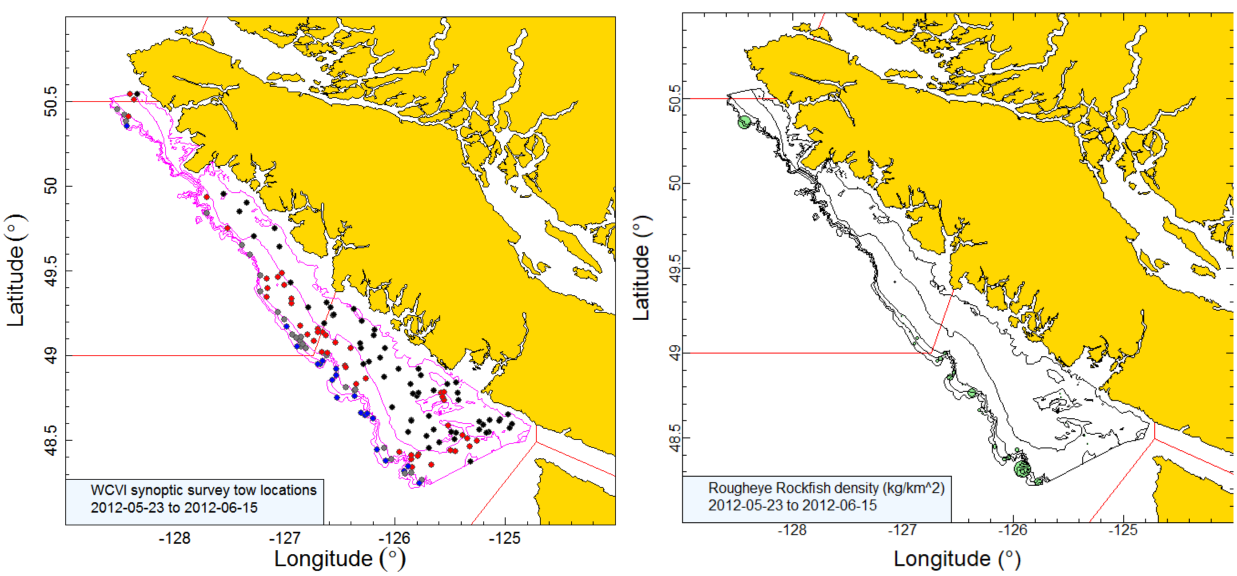

Figure B.24. Tow locations and density plots for the 2012 west coast Vancouver Island synoptic survey (see Figure B.20 caption).

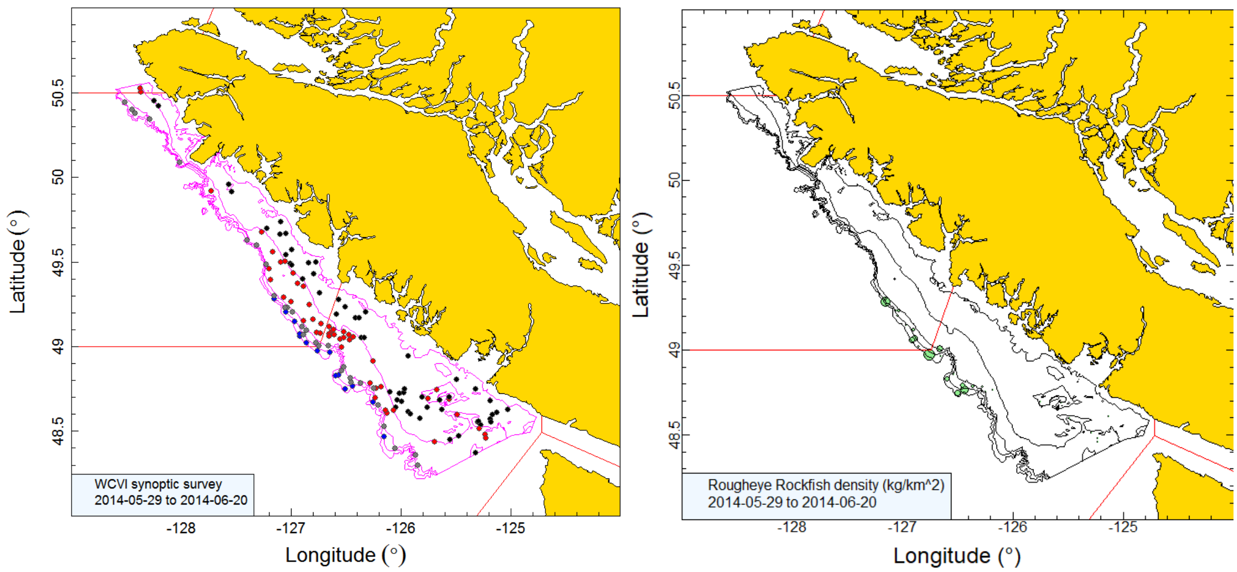

Figure B.25. Tow locations and density plots for the 2014 west coast Vancouver Island synoptic survey (see Figure B.20 caption).

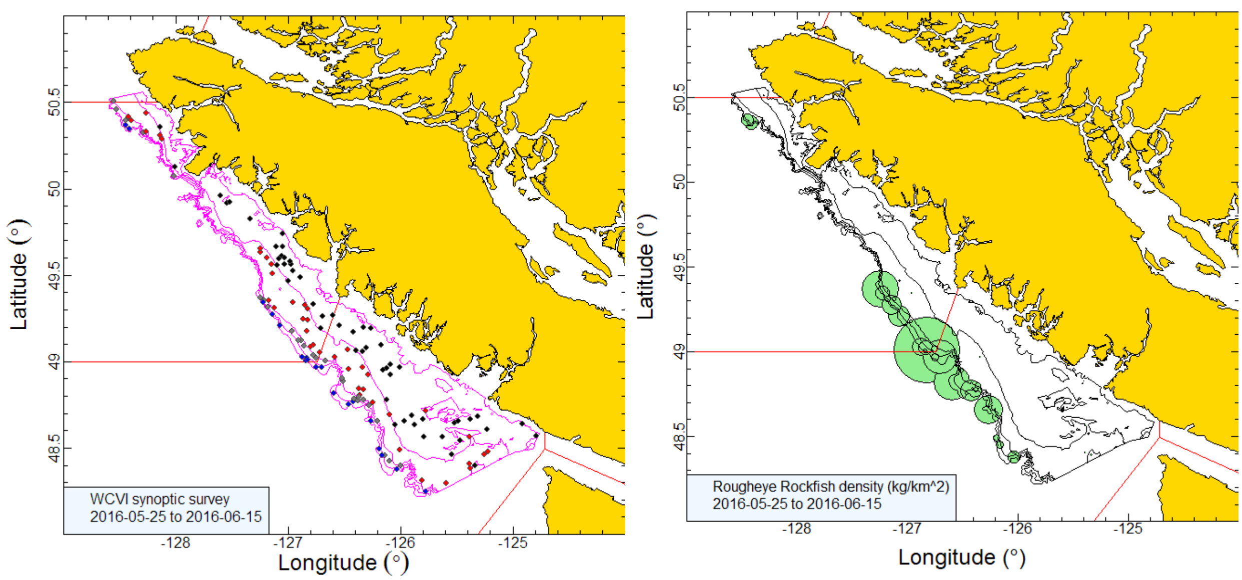

Figure B.26. Tow locations and density plots for the 2016 west coast Vancouver Island synoptic survey (see Figure B.20 caption).

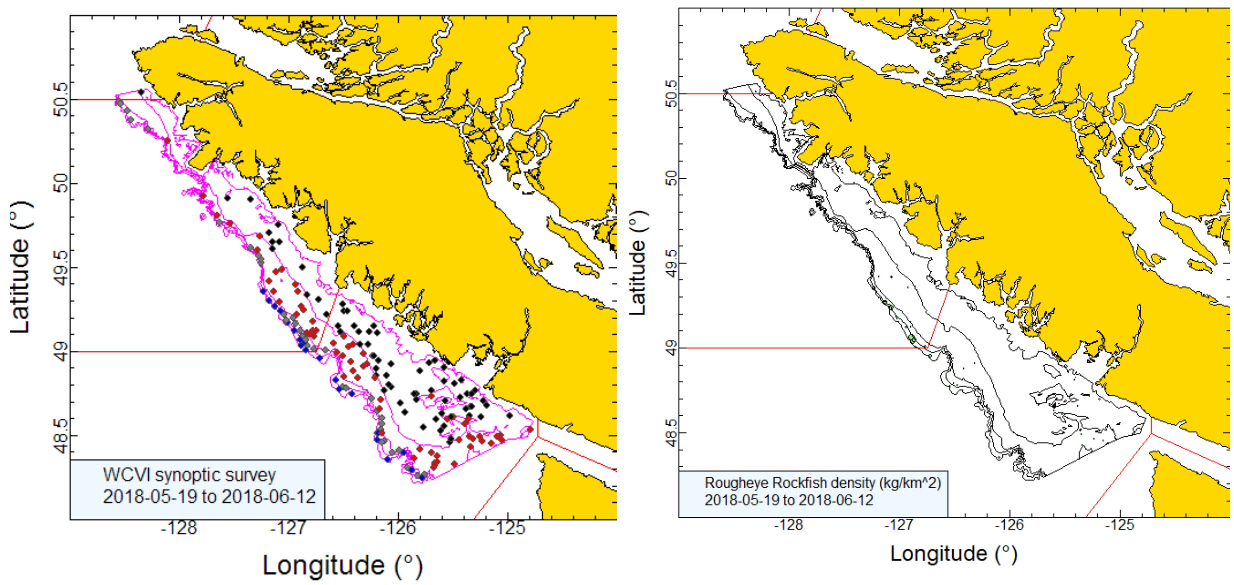

Figure B.27. Tow locations and density plots for the 2018 west coast Vancouver Island synoptic survey (see Figure B.20 caption).

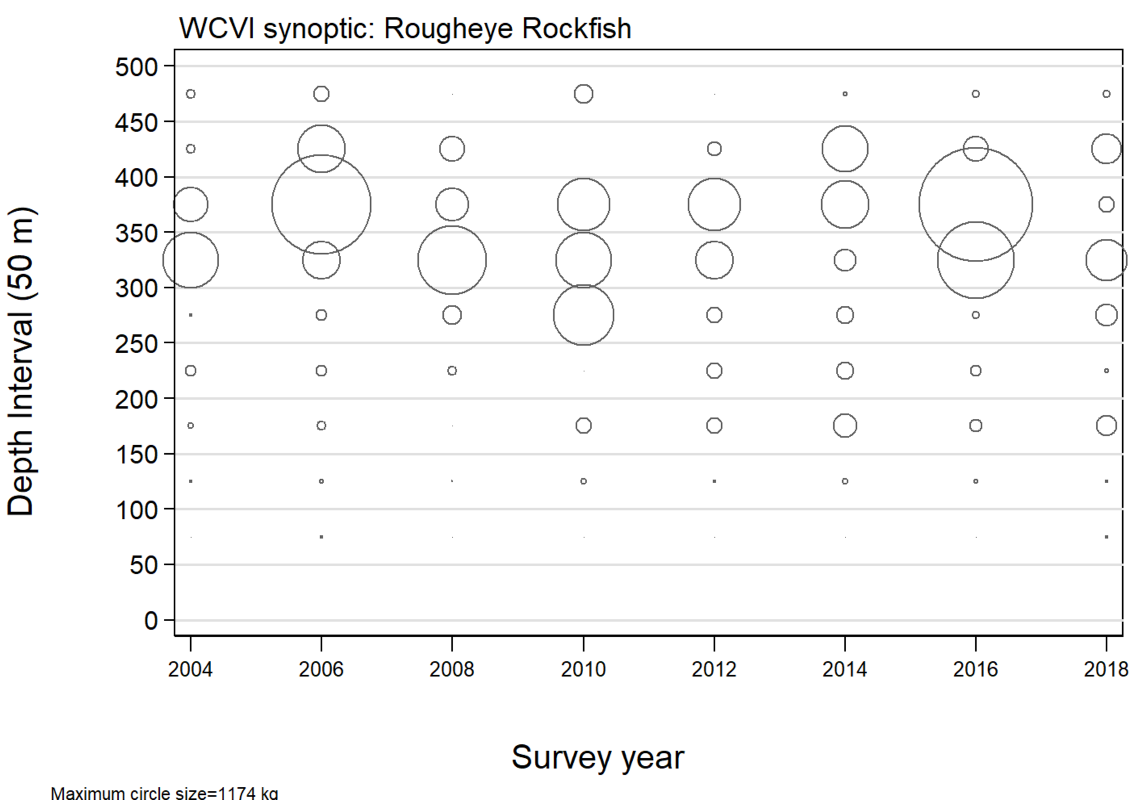

Figure B.28. Distribution of observed weights of REBS by survey year and 50 m depth zone. Catches are plotted at the mid-point of the interval and circles in the panel are scaled to the maximum value (1,174 kg) in the 350-400 m interval in 2016. The 1st and 99th percentiles for the REBS start of tow depth distribution = 173 m and 467 m, respectively.

B.5.2. Results

REBS were taken exclusively along the shelf edge from near the US border to above Brooks Peninsula near the top of Vancouver Island (Figure B.20 to Figure B.27). The distribution appeared to predominate in the lower half of Vancouver Island. REBS were mainly taken at deeper depths, ranging from 265 to 427 m (5–95 percentiles). This species tends to be found at depths greater than 300 m, with observations up to 500 m (Figure B.28). Relative biomass levels for REBS from this trawl survey were not particularly high, ranging from 130 to 500 t, with moderate to high relative errors, which range from 0.31 to 0.47 except for 2018, where a low estimate of 86 t had an associated CV=0.19 (Figure B.29; Table B.11).

The proportion of tows capturing REBS was low, but shows little year-to-year variation, ranging between 10 and 21% over the eight surveys and with a mean value of 19% (Figure B.30). Two hundred twenty-two of the 1175 usable tows (19%) from this survey contained REBS, with a median catch weight for positive tows of 5.7 kg/tow and maximum catch weight across all eight surveys of 621 kg (in 2016).

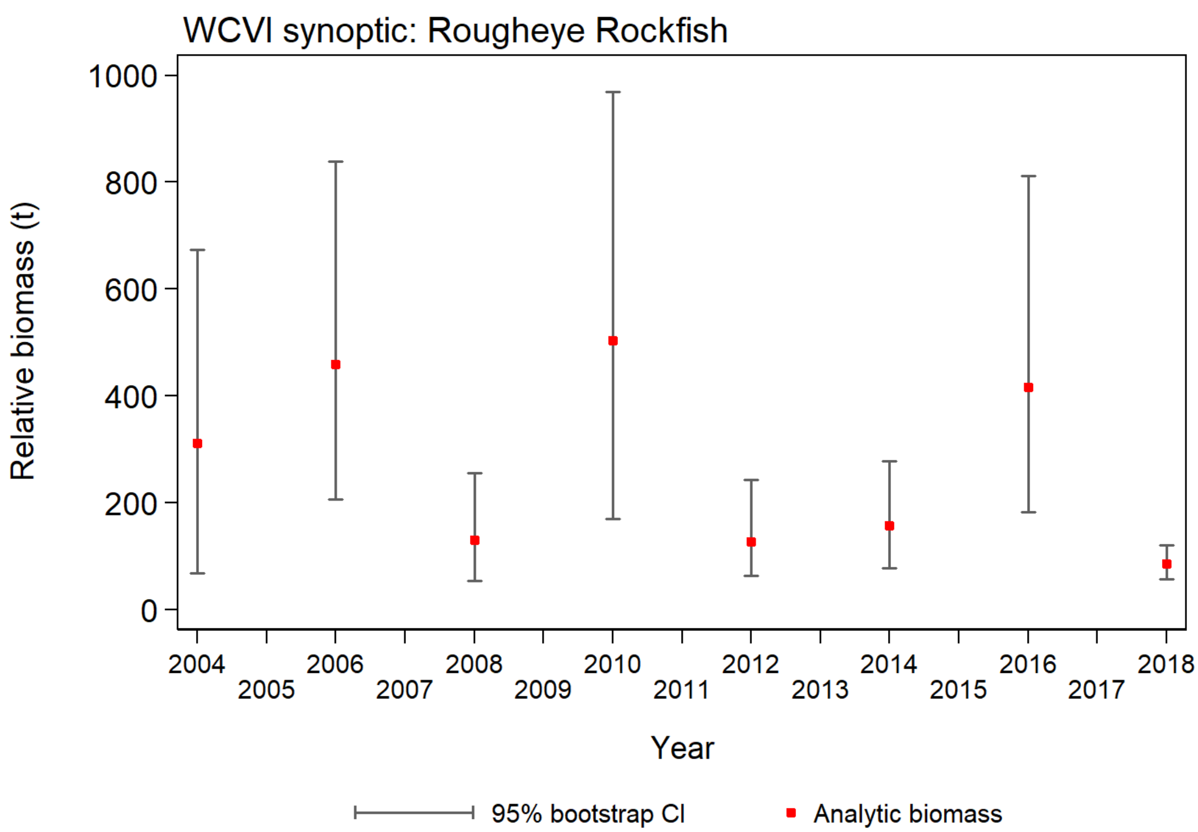

Figure B.29. Plot of biomass estimates for REBS from the 2004 to 2018 west coast Vancouver Island synoptic trawl surveys (Table B.11). Bias-corrected 95% confidence intervals from 1000 bootstrap replicates are plotted.

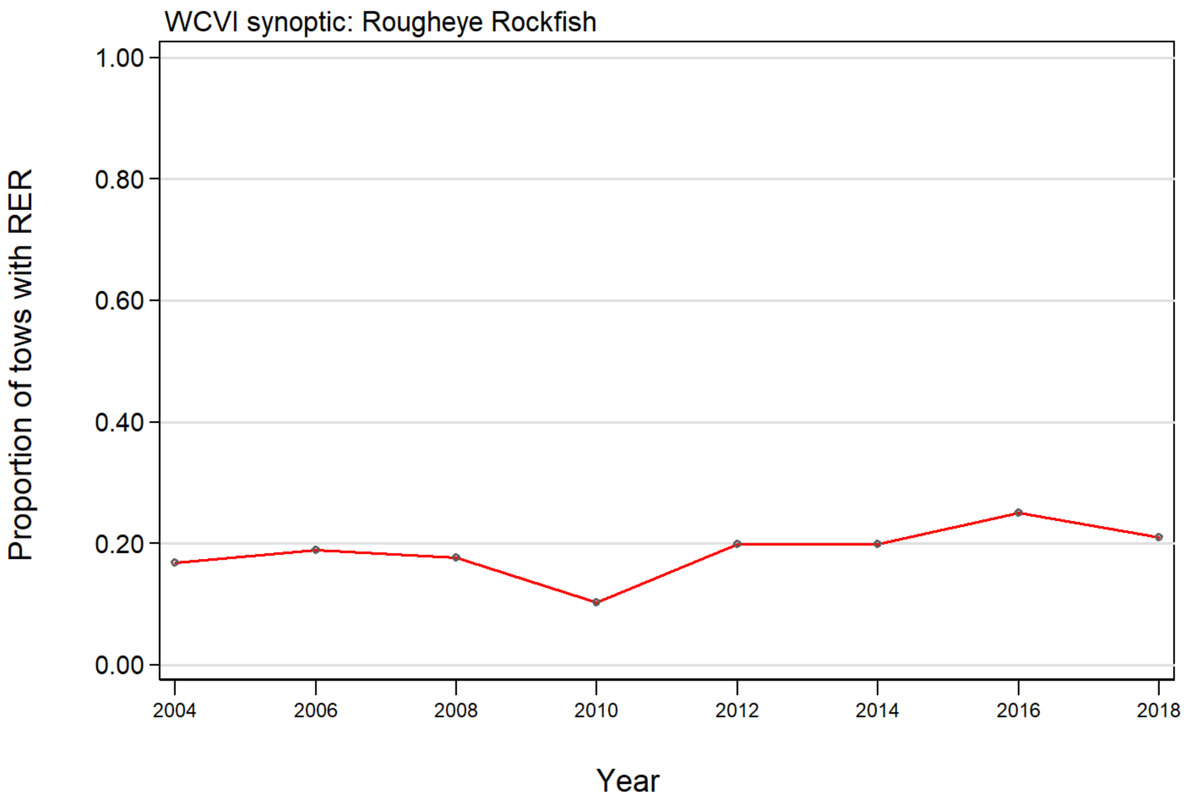

Figure B.30. Proportion of tows by stratum and year capturing REBS in the WCVI synoptic trawl surveys, 2004–2018.

Table B.11. Biomass estimates for REBS from the WCVI synoptic trawl survey for the survey years 2004 to 2018. Bootstrap bias-corrected confidence intervals and CVs are based on 1000 random draws with replacement.

Survey Year	Biomass (t) (Eq. B.4)	Mean bootstrap biomass (t)	Lower bound biomass (t)	Upper bound biomass (t)	Bootstrap CV	Analytic CV (Eq. B.6)
2004	312	318	68	674	0.470	0.458
2006	460	467	207	839	0.342	0.346
2008	131	131	55	256	0.371	0.370
2010	504	496	171	969	0.400	0.389
2012	128	128	64	243	0.335	0.328
2014	157	159	79	279	0.309	0.307
2016	417	415	184	812	0.377	0.372
2018	86	86	58	122	0.192	0.194

B.6. WEST COAST HAIDA GWAII SYNOPTIC TRAWL SURVEY

B.6.1. Data selection

The west coast Haida Gwaii (WCHG) survey has been conducted eight times in the period 2006 to 2018 off the west coast of Haida Gwaii. This includes a survey conducted in 2014 which did not complete a sufficient number of tows for it to be considered comparable to the remaining surveys and which is consequently omitted from Table B.12. An earlier survey, conducted in 1997, also using a random stratified design similar to the current synoptic survey design along with an Atlantic Western II box trawl net (Workman et al. 1998), has been included in this time series. This survey comprises a single areal stratum extending from 53°N to the BC-Alaska border and east to 133°W (e.g., Olsen et al. 2008). The 1997 survey (depth stratification: 180-275 m, 275-365 m, 365-460 m, 460-625 m) and the 2006 survey (depth stratification: 150–200 m, 200–330 m, 330–500 m, 500–800 m, and 800–1300 m) have been re-stratified into the four depth strata used from 2007 onwards: 180–330 m; 330–500 m; 500–800 m; and 800–1300 m, based on the mean of the beginning and end depths of each tow (Table B.12). All tows S of 53°N from the two earlier surveys have been dropped from biomass estimation. Plots of the locations of all valid tows by year and stratum are presented in Figure B.31 (1997), Figure B.32 (2006), Figure B.33 (2007), Figure B.34 (2008), Figure B.35 (2010), Figure B.36 (2012), Figure B.37 (2016) and Figure B.38 (2018). Note that the depth stratum boundaries for this survey differ from those used for the Queen Charlotte Sound (Edwards et al. 2012) and west coast Vancouver Island (Edwards et al. 2014) synoptic surveys due to the considerable difference in the seabed topography of the area being surveyed. The deepest stratum (800–1300 m) has been omitted from this analysis because of lack of coverage in 2007.

Table B.12. Stratum designations, vessel name, number of usable and unusable tows, for each completed year of the west coast Haida Gwaii synoptic survey. Also shown are the dates of the first and last survey tow in each year.

		Depth stratum							
Survey year	**Vessel**	**180-330m**	**330-500m**	**500-800m**	**800-1300m**	**Total tows[1]**	**Unusable tows**	**Minimum date**	**Maximum date**
1997	*Ocean Selector*	39	57	6	0	90	5	07-Sep-97	21-Sep-97
2006	*Viking Storm*	55	26	16	13	97	13[2]	30-Aug-06	22-Sep-06
2007	*Nemesis*	68	34	9	0	111	5	14-Sep-07	12-Oct-07
2008	*Frosti*	71	31	8	8	110	9	28-Aug-08	18-Sep-08
2010	*Viking Storm*	82	29	12	6	123	2	28-Aug-10	16-Sep-10
2012	*Nordic Pearl*	75	29	10	16	114	11	27-Aug-12	16-Sep-12
2016	*Frosti*	69	28	5	10	101	8	28-Aug-16	24-Sep-16
2018	*Nordic Pearl*	67	31	10	11	108	11	05-Sep-18	20-Sep-18
Area (km^2)		1104	1024	956	2248	5,332[3]	–	–	–

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

Table B.13. Number of valid tows with doorspread measurements, the mean doorspread values (in m) from these tows for each survey year and the number of valid tows without doorspread measurements.

Year	Tows with doorspread	Tows missing doorspread	Mean doorspread (m)
1997	107	0	61.6
2006	93	30	77.7
2007	113	3	68.5
2008	123	4	80.7
2010	129	2	79.1
2012	92	49	73.8
2016	105	15	74.1
2018	130	0	67.0
Total/Average	892	103	73.1[1]

[1] average 2006–2018: all observations

A doorspread density (Eq. B.3) was generated for each tow based on the catch of REBS (REBS) from the mean doorspread for the tow and the distance travelled. [`distance travelled`] is a database field which is calculated directly from the tow track. This field is used preferentially for the variable D_{yij} in Eq. B.3. A calculated value ([`vessel speed`]×[`tow duration`]) is used for this variable if [`distance travelled`] is missing, but there were no instances of this occurring in the eight trawl surveys. Missing values for the [`doorspread`] field were filled in with the mean doorspread for the survey year (103 values over all years, Table B.13).

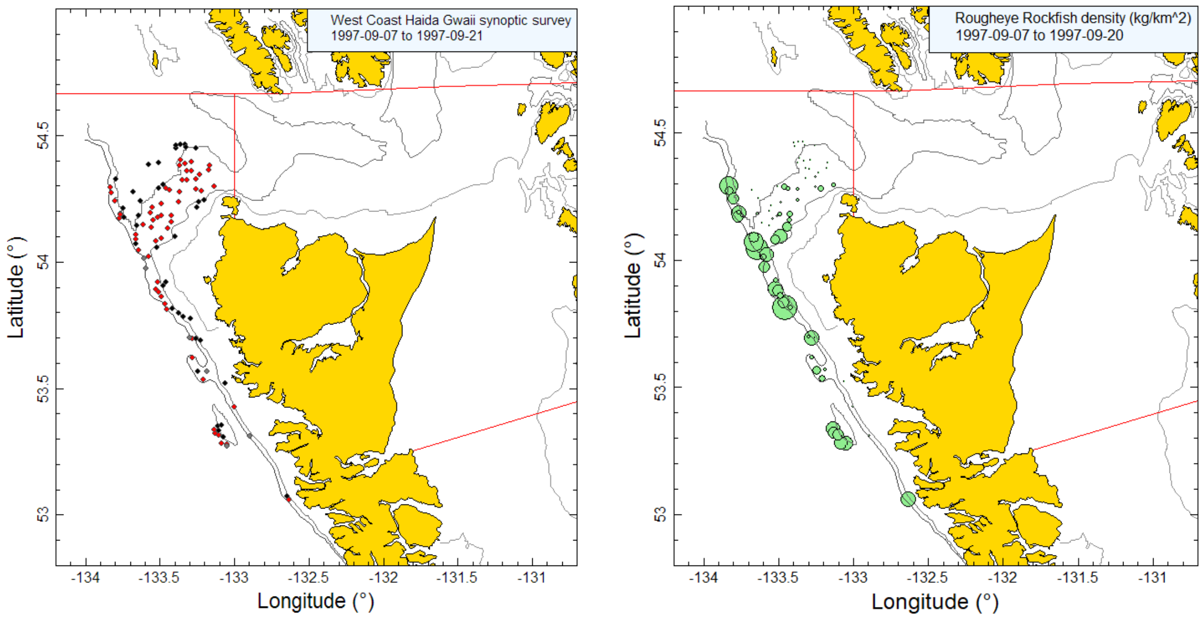

Figure B.31. Valid tow locations by stratum (180-330m: black; 330-500m: red; 500-800m: grey; 800-1300m: blue) and density plots for the 1997 Ocean Selector synoptic survey. Circle sizes in the right-hand density plot scaled across all years (2006–2018), with the largest circle =47,497 kg/km² in 2012. The red lines show the Pacific Marine Fisheries Commission 5E and 5D major area boundaries.

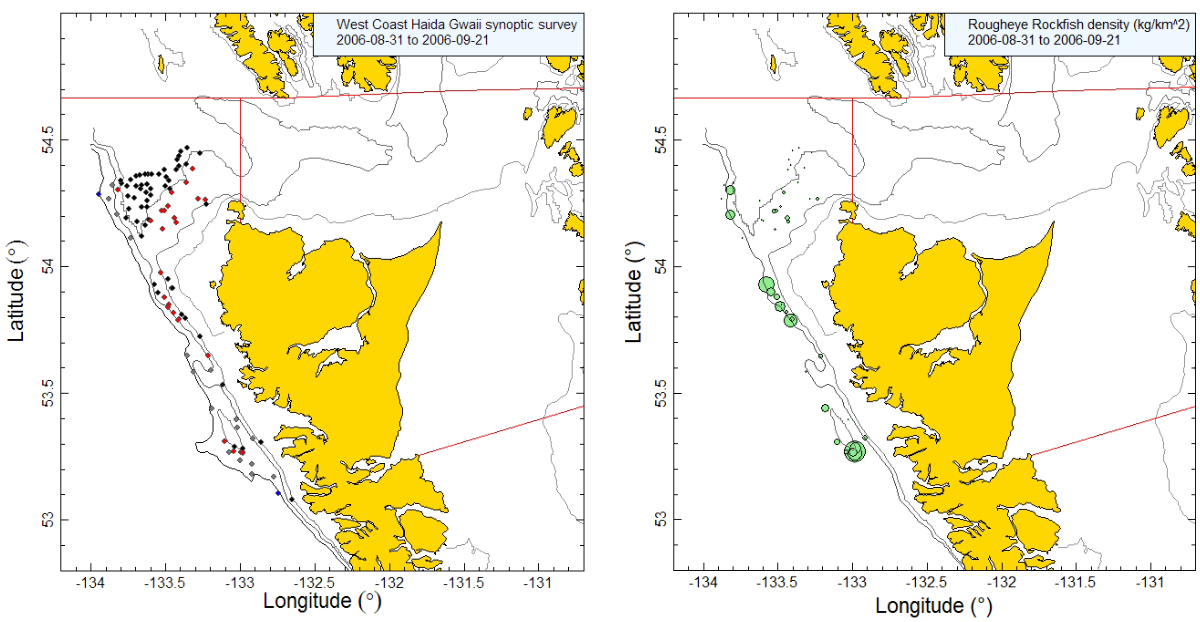

Figure B.32. Tow locations and density plots for the 2006 Viking Storm synoptic survey (see Figure B.31 caption).

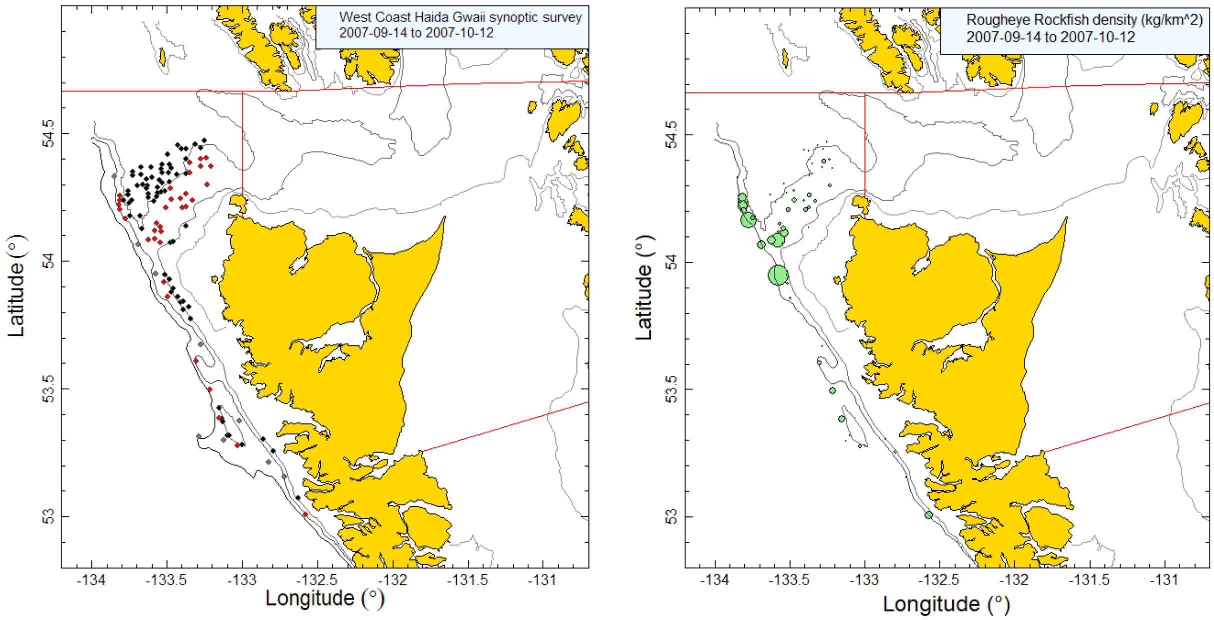

Figure B.33. Tow locations and density plots for the 2007 Nemesis synoptic survey (see Figure B.31 caption).

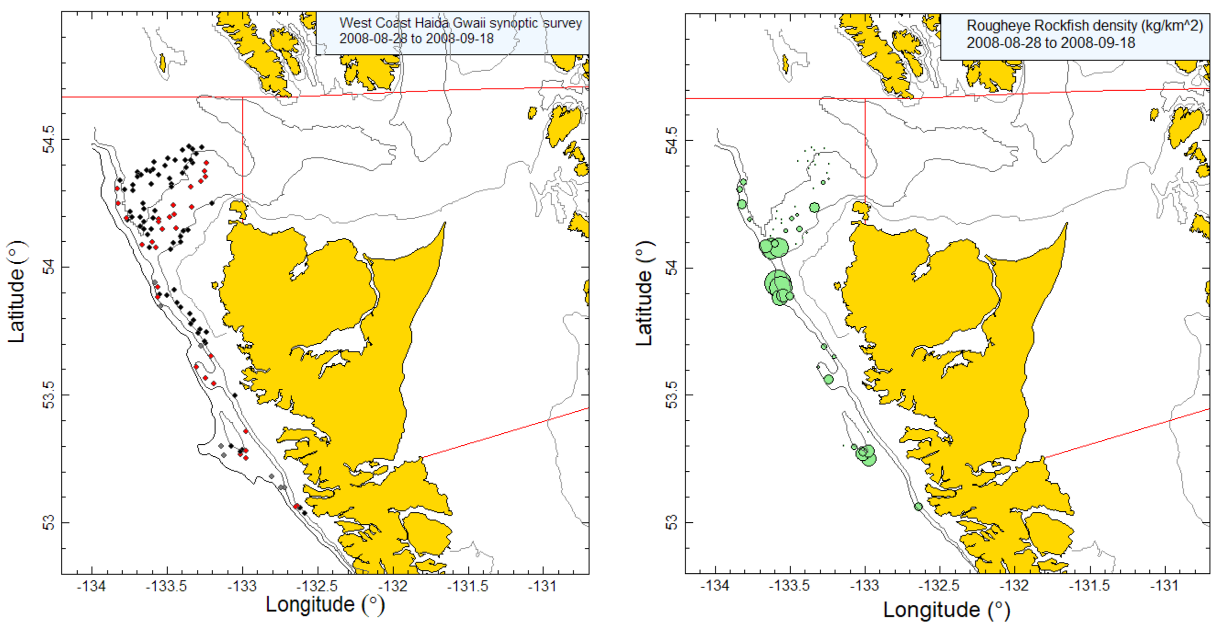

Figure B.34. Tow locations and density plots for the 2008 Frosti synoptic survey (see Figure B.31 caption).

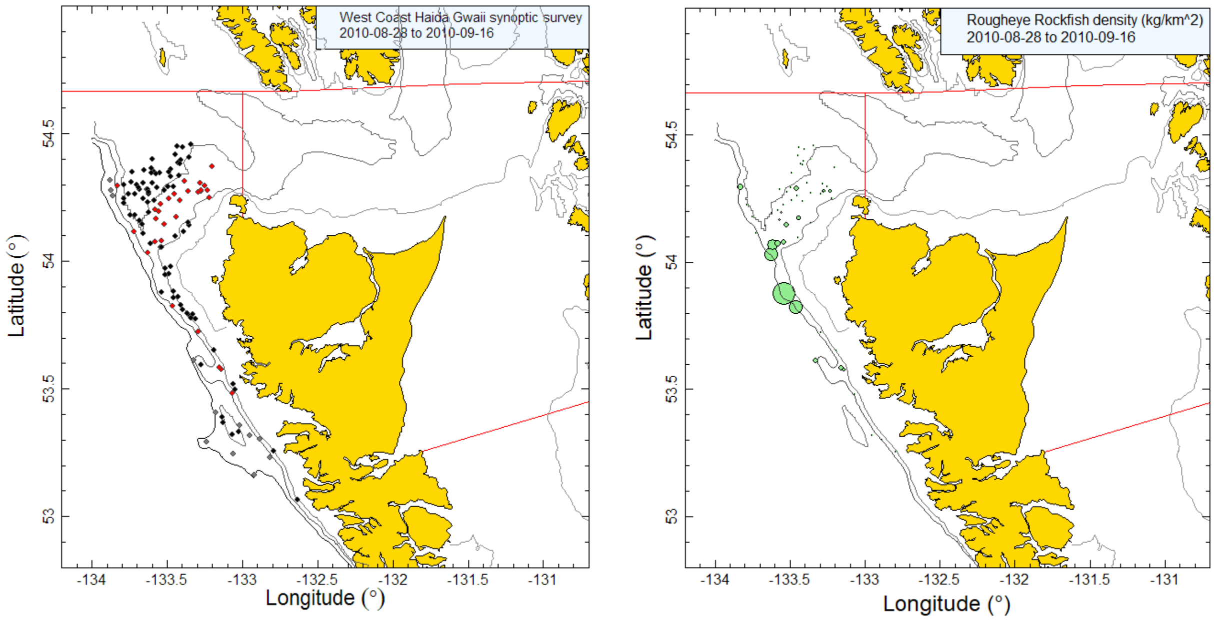

Figure B.35. Tow locations and density plots for the 2010 Viking Storm synoptic survey (see Figure B.31 caption).

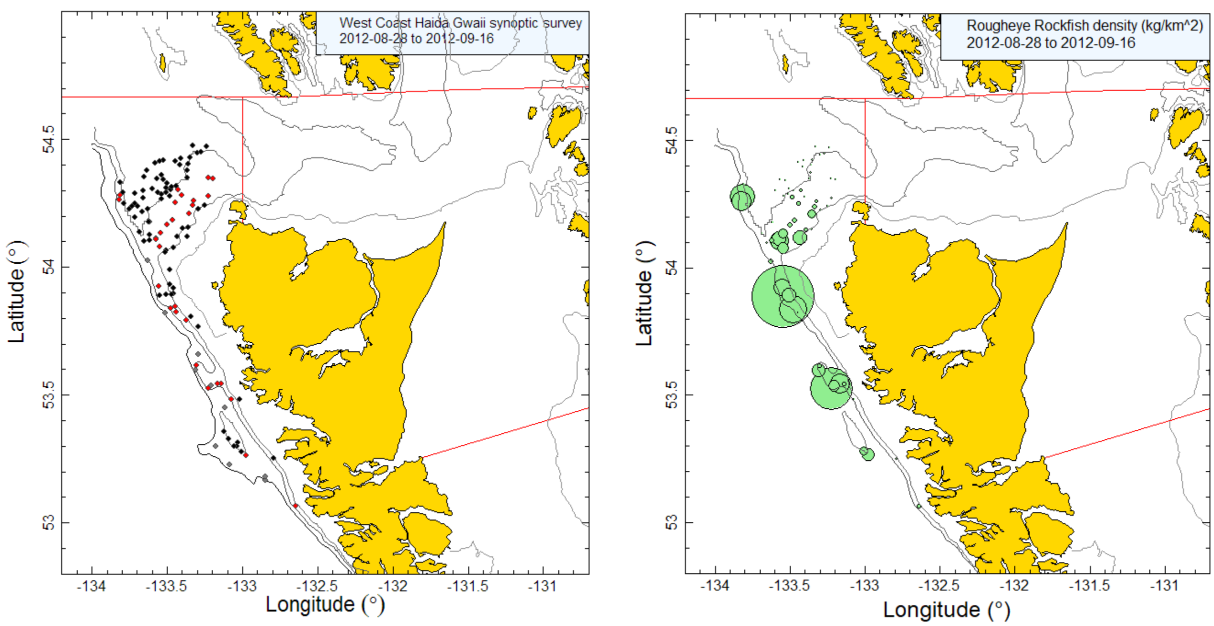

Figure B.36. Tow locations and density plots for the 2012 Nordic Pearl synoptic survey (see Figure B.31 caption).

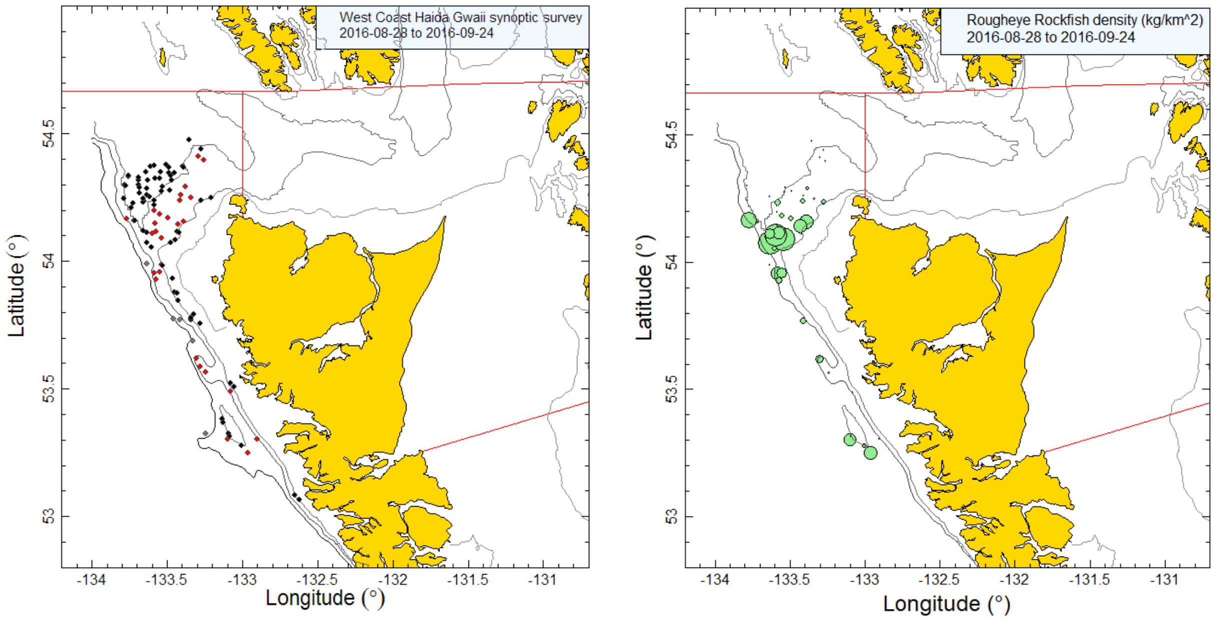

Figure B.37. Tow locations and density plots for the 2016 Frosti synoptic survey (see Figure B.31 caption).

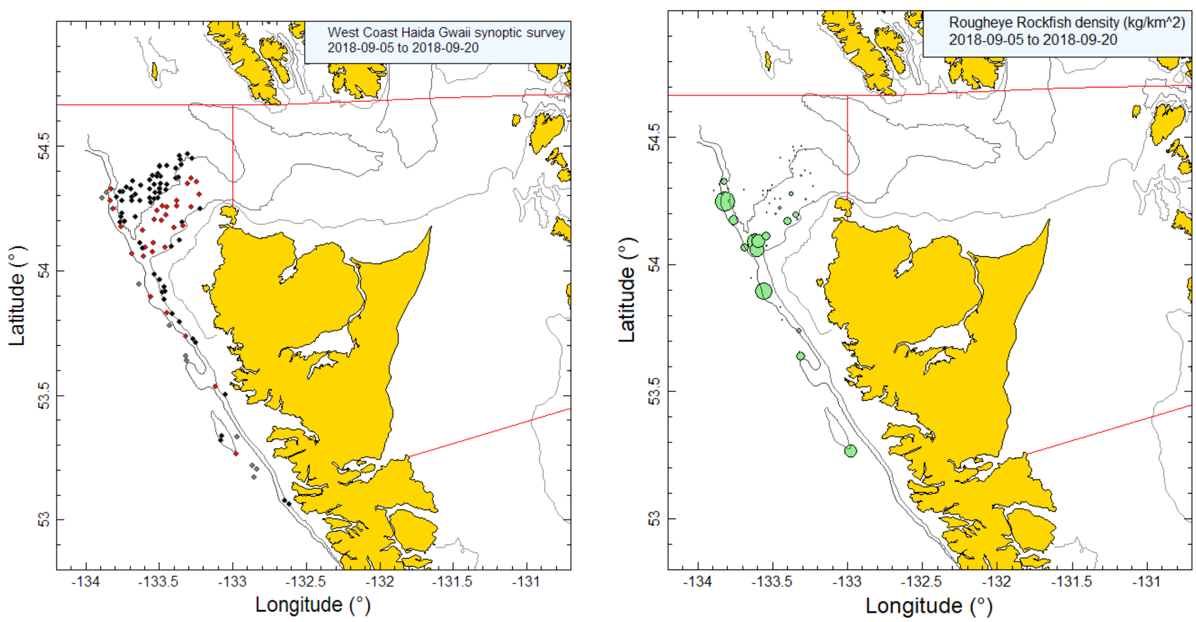

Figure B.38. Tow locations and density plots for the 2018 Nordic Pearl synoptic survey (see Figure B.31 caption).

B.6.2. Results

All eight usable surveys have taken REBS along the shelf edge off the west coast of Graham Island, down to 53°N, the southernmost extent of this survey and into the western reaches of Dixon Entrance (Figure B.31 to Figure B.38). REBS were mainly taken at depths from 303 m to 472 m (5 to 95% quantiles of the starting tow depth), with the 50% of the observations lying between 338 m and 400 m depth (25–75% quantiles, Figure B.39). There were 75 REBS observations greater than 500 m in capture depth, using valid survey tows, distributed among the eight survey years.

The proportion of tows that captured REBS fluctuated near 50% without trend, ranging from 46 to 78% of tows over the eight survey years and with an overall mean of 54% (469 of 868 tows)(Figure B.41). The median REBS catch weight for positive tows was 23.3 kg/tow and the maximum catch weight across the eight surveys was 6,189 kg in 2018.

Estimated biomass levels for REBS from these trawl surveys are reasonably high and show no overall trend (ranging from 1,100 t in 2010 to 5,500 t in 2008) (Figure B.40; Table B.14). The estimated relative errors (RE) for these surveys are variable and often large, ranging from 0.19 in 1997 to 0.47 in 2006 (Table B.14).

Table B.14. Biomass estimates for REBS from the seven west coast Haida Gwaii synoptic surveys used in the stock assessment. Bootstrap bias-corrected confidence intervals and coefficients of variation (CVs) are based on 1000 random draws with replacement.

Survey Year	Biomass (t) (Eq. B.4)	Mean bootstrap biomass (t)	Lower bound biomass (t)	Upper bound biomass (t)	Bootstrap CV	Analytic CV (Eq. B.6)
1997	4,372	4,378	2,889	6,205	0.193	0.195
2006	2,702	2,691	1,554	4,524	0.265	0.272
2007	3,560	3,587	1,379	7,526	0.474	0.469
2008	5,477	5,420	2,271	12,361	0.463	0.466
2010	1,128	1,115	546	1,976	0.328	0.343
2012	3,663	3,672	1,877	6,366	0.307	0.309
2016	3,857	3,852	2,254	5,842	0.245	0.250
2018	2,772	2,769	1,459	4,647	0.289	0.276

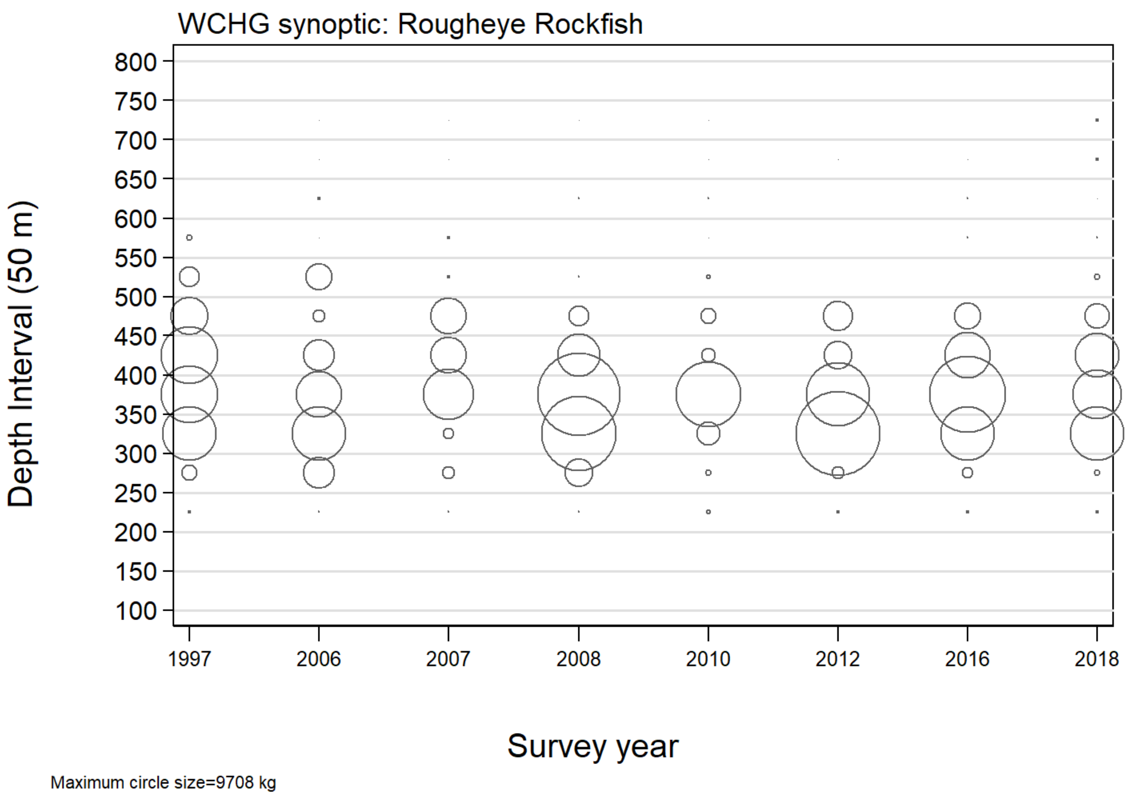

Figure B.39. Distribution of observed weights of REBS by survey year and 40 m depth zone intervals. Catches are plotted at the mid-point of the interval and circles in the each panel are scaled to the maximum value (60 kg – 200-240 m interval in 2018). Minimum and maximum depths observed for REBS: 195 m and 451 m, respectively.

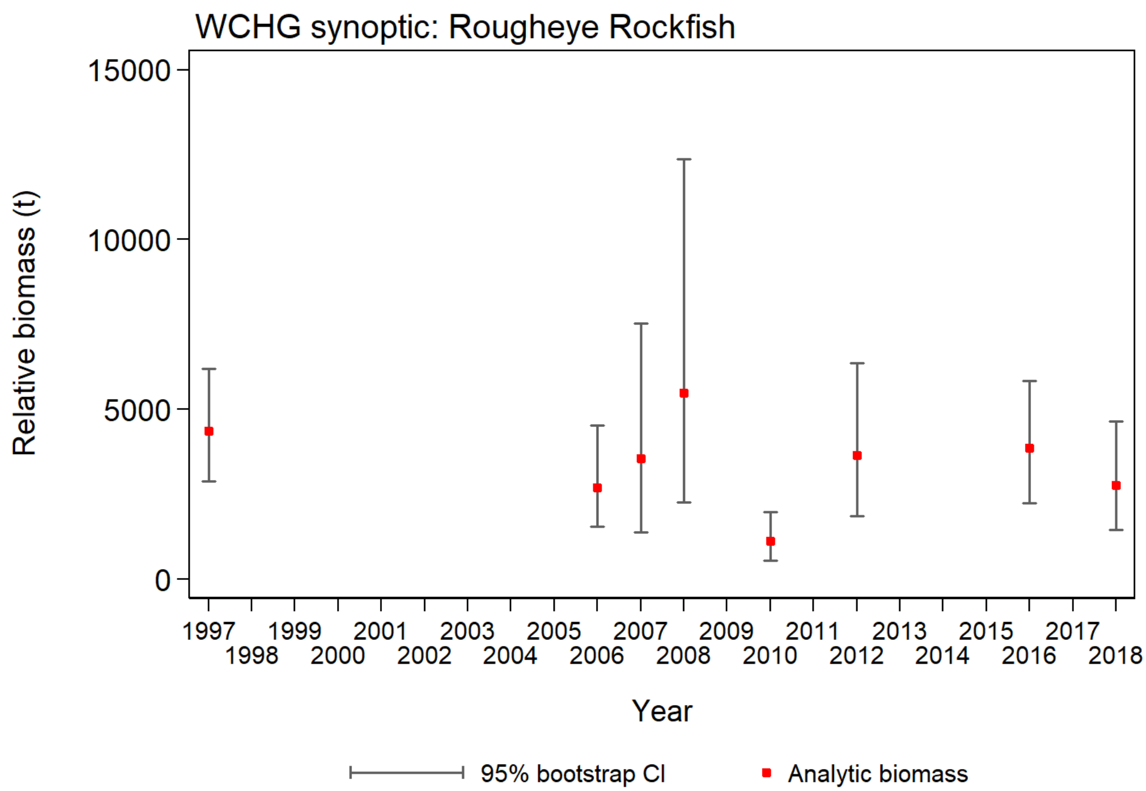

Figure B.40. Biomass estimates for REBS from the 2006 to 2018 west coast Haida Gwaii synoptic surveys (Table B.14). Bias-corrected 95% confidence intervals from 1000 bootstrap replicates are plotted.

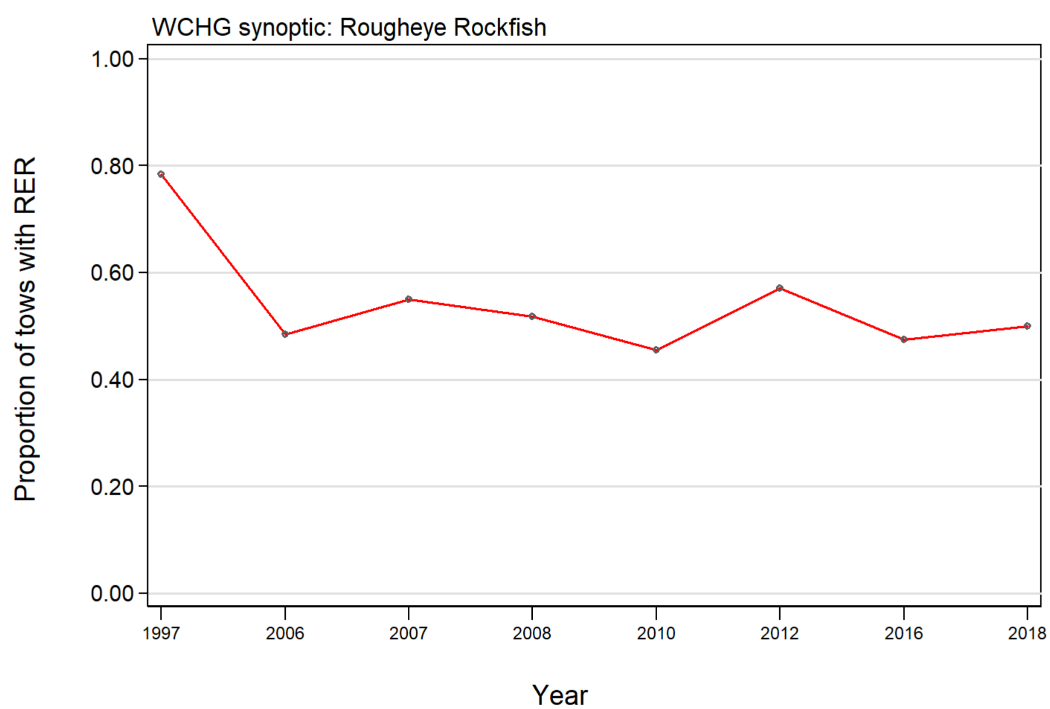

Figure B.41. Proportion of tows by year that contain REBS for the seven west coast Haida Gwaii synoptic surveys.

B.7. REFERENCES – SURVEYS

DFO. 2015. Proceedings of the Pacific regional peer review on Stock assessment for Yellowtail Rockfish (*Sebastes flavidus*) in British Columbia; November 18-19, 2014. DFO Can. Sci. Advis. Sec. Proceed. Ser. 2015/020.

Edwards, A.M., Haigh, R. and Starr, P.J. 2014. 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 pp.

Edwards, A.M., Starr, P.J. and Haigh, R. 2012. Stock assessment for Pacific ocean perch (*Sebastes alutus*) in Queen Charlotte Sound, British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/111: viii + 172 pp.

Efron, B. 1982. The Jackknife, the Bootstrap and Other Resampling Plans. No. 38 in CBMS-NSF Regional Conference Series in Applied Mathematics. Society for Industrial and Applied Mathematics.

Olsen, N., Rutherford, K.L. and Stanley, R.D. 2008. West Coast Queen Charlotte Islands groundfish bottom trawl survey, August 25th to September 21st , 2008. Can. Manuscr. Rep. Fish. Aquat. Sci. 2858: vii + 50 pp.

Starr, P.J. and Haigh, R. in press. Bocaccio (*Sebastes paucispinis*) stock assessment for British Columbia in 2019, including guidance for rebuilding plans. DFO Can. Sci. Advis. Sec. Res. Doc. 2020/nnn: vi + xxx p.

Workman, G.D., Olsen, N. and Kronlund, A.R. 1998. Results from a bottom trawl survey of rockfish stocks off the west coast of the Queen Charlotte Islands, September 5 to 23, 1997. Can. Manuscr. Rep. Fish. Aquat. Sci. 2457: viii + 86 p.

APPENDIX C. COMMERCIAL TRAWL CPUE

C.1. INTRODUCTION

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

This Appendix documents standardised CPUE analyses for two stocks of Rougheye/Blackspotted Rockfish (REBS), one in the north (PMFC areas 5DE) and one in the south (PMFC areas 3CD5AB), which were subsequently used in species stock assessments based on the same spatial definitions.

C.2. METHODS

C.2.1. Arithmetic and Unstandardised CPUE

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

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

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

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

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

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

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

C.2.2. Standardised CPUE

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

C.2.2.1. Lognormal Model

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

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

where I_i = C_i or catch;

B = the intercept;

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

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

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

ε_i = an error term.

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

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

Canonical coefficients and standard errors were calculated for each categorical variable (Francis 1999[8]). Standardised analyses typically set one of the coefficients to 1.0 without an error term and estimate the remaining coefficients and the associated error relative to the fixed coefficient. This is required because of parameter confounding. The Francis (1999[8]) procedure rescales all coefficients so that the geometric mean of the coefficients is equal to 1.0 and calculates a standard error for each coefficient, including the fixed coefficient.

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

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

C.2.2.2. Binomial Logit Model

The procedure described by Eq. C.3 is necessarily confined to the positive catch observations in the data set because the logarithm of zero is undefined. Observations with zero catch were modelled by fitting a logit regression model based on a binomial distribution and using the presence/absence of REBS north as the dependent variable (where 1 is substituted for $\ln(I_i)$ in Eq. C.3 if it is a successful catch record and 0 if it is not successful) and using the same data set. Explanatory factors were estimated in the model in the same manner as described in Eq. C.3. Such a model provides an alternative series of standardised coefficients of relative annual changes that is analogous to the series estimated from the lognormal regression.

C.2.2.3. Combined Model

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

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

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

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

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

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

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

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

C.3. REBS NORTH/SOUTH STOCK SEPARATION

At present, it is not possible to visually separate Blackspotted Rockfish (BSR) and Rougheye Rockfish (RER) accurately; instead genetic (DNA) sampling is required to determine the species. Such sampling has been undertaken in BC waters since 2010 in research surveys and from 2012 in the commercial fishery, but with unknown sampling strategies, so it is not possible to gauge the representativeness of the available data. Furthermore, there was no sampling at all before 2010 which means that it will not be easy to determine the historical split of these two species. Mathematical procedures can be applied to this task (e.g., Creamer 2016), but these procedures require broad data coverage, both spatially and temporally, and should be validated before they can be used in a stock assessment. As a first approximation, the Terms of Reference have chosen to define the species separation by designating all REBS[9] catch from the west coast of Haida Gwaii (PMFC Area 5E) and Dixon Entrance (PMFC Area 5D) as ‘REBS north’. REBS catches in PMFC areas 3C to 5B (see Appendix Figure A.1 for map locations of these areas) are designated as ‘REBS south’. The small amount of REBS catch in

[9] all commercial catch of REBS is labelled ‘RER’ in the DFO catch databases.

PMFC Area 5C was ignored in this analysis because of the assumption that this area represented a high level of hybridisation. The justification for this spatial separation from the available genetic data is provided in Section D.3 in Appendix D.3

C.4. PRELIMINARY INSPECTION OF THE DATA

The analyses reported in this Appendix are based on tow-by-tow total catch (landings + discards) data collected over the period 1996–2019 for which detailed positional data for every tow are available. Each tow will have an estimate of retained and discarded catch because of the presence of an observer on board the vessel. These data are held in the DFO PacHarvTrawl (PacHarvest) and GFFOS databases (Fisheries and Oceans Canada, Pacific Region, Groundfish Data Unit).

C.4.1. REBS north – 5DE BT

Tow-by-tow catch and effort data for the REBS north stock from the BC trawl fishery operating from 1996 to 2019 were selected using the following criteria:

- Tow start date between 1 January 1996 and 31 December 2019;
- Bottom trawl type (includes ‘unknown’ trawl gear);
- Fished in PMFC regions: 5D or 5E;
- Fishing success code <=1 (code 0= unknown; code 1= useable);
- Catch of at least one fish or invertebrate species (no water hauls or inanimate object tows);
- Valid depth field;
- Valid latitude and longitude co-ordinates;
- Valid estimate of time towed that was > 0 hours and <= 12 hours.

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

As indicated above, the catch and effort data from Areas 5D and 5E were treated as a single area representing the catch of REBS north, based on the declared distribution of bottom trawl catches (see Appendix A). Only bottom trawl data were used as this is the most prevalent capture method for this species. Figure C.1 plots the distribution of depth for all successful REBS north bottom trawl tows in the designated region. A depth range for this analysis was selected from this plot and is summarised in Table C.1.

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

Analysis	Trawl Gear	First year	Depth range (m)	Upper bound effort (h)	Minimum bin + records	N depth bins	N latitude bins	N locality bins
5DE	Bottom trawl	1996	100–800	12	100	14	14	15

Vessel qualification criteria for the bottom trawl fisheries were based on number of trips per year and number of years fishing to avoid including vessels which only occasionally captured REBS. The vessel qualification criteria used in this analysis appear in Table C.2 and the distribution of positive tows by vessel and year is presented in Figure C.2. Once a vessel was selected, all data for the qualifying vessel were included, regardless of the number of trips in a year.
Table C.2 shows the number of vessels used in this analysis and the fraction (89%) of the total catch represented in the core fleet. While there were only 14 vessels in the analysis, 9 of these

vessels were in the fishery for 19 years or more, and 6 of these were in the fishery for 23 or 24 years, giving good vessel overlap in the analysis.

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

Analysis	Trawl Gear	Vessel selection criteria			Data set characteristics				
		N years	N trips	Minimum positive Records	N vessels	% total catch[1]	catch (t)	Total records	Positive records
5DE	Bottom	3	2	150	14	89	8,040	25,471	8,324

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

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

Variable	**Data type**
Year	24 categories (calendar years)
Hours fished	continuous: 3rd order polynomial
Month	12 categories
DFO locality	Fishing locality areas identified by Rutherford (1999) (includes a final aggregated category) (Table C.1)
Latitude	Latitude aggregated by 0.1° bands starting at 48°N (includes a final aggregated category) (Table C.1)
Vessel	See Table C.2 for number of categories by analysis (no final aggregated category) (Table C.2)
Depth	See Table C.1 for number of categories by analysis (no final aggregated category) (Table C.1)

Table C.4. Summary data for the REBS north bottom trawl fishery (in 5DE) by year for the core data set (after applying all data filters and selection of core vessels).

Year	Number vessels[1]	Number trips[1]	Number tows[1]	Number records[1]	Number records[2]	% zero records[2]	Total catch (t)[1]	Total hours[1]	CPUE (kg/h) (Eq. C.1)
1996	14	54	466	466	1,144	59.3	301.8	1,051	287.1
1997	13	46	238	238	986	75.9	101.9	532	191.6
1998	12	73	409	409	1,411	71.0	322.5	984	327.7
1999	10	44	219	219	1,023	78.6	222.3	458	485.5
2000	12	71	394	394	1,592	75.3	171.1	963	177.6
2001	10	70	452	452	1,389	67.5	244.5	1,330	183.9
2002	13	85	425	425	1,441	70.5	245.7	1,226	200.4
2003	13	75	315	315	1,123	72.0	201.9	903	223.6
2004	11	78	450	450	1,402	67.9	215.5	1,645	131.0
2005	10	63	293	293	1,500	80.5	298.9	494	605.5
2006	12	76	360	360	1,011	64.4	369.9	1,096	337.4
2007	10	68	412	412	1,057	61.0	435.5	1,155	377.1
2008	9	70	472	472	1,069	55.8	665.6	964	690.6
2009	10	79	540	540	1,057	48.9	640.1	1,233	519.0
2010	11	84	492	492	1,113	55.8	453.2	1,514	299.3
2011	10	73	416	416	1,001	58.4	461.5	1,118	412.6
2012	11	62	308	308	875	64.8	317.2	1,356	233.9
2013	11	74	426	426	1,066	60.0	493.2	1,718	287.1
2014	9	58	301	301	800	62.4	383.1	960	399.1
2015	8	49	187	187	669	72.0	283.0	487	581.1
2016	7	41	134	134	607	77.9	265.2	325	814.6
2017	9	66	251	251	836	70.0	393.3	570	690.4
2018	7	43	191	191	590	67.6	309.9	347	894.2
2019	6	50	173	173	709	75.6	243.0	252	963.5

[1] calculated for tows with REBS north catch >0; [2] calculated for all tows

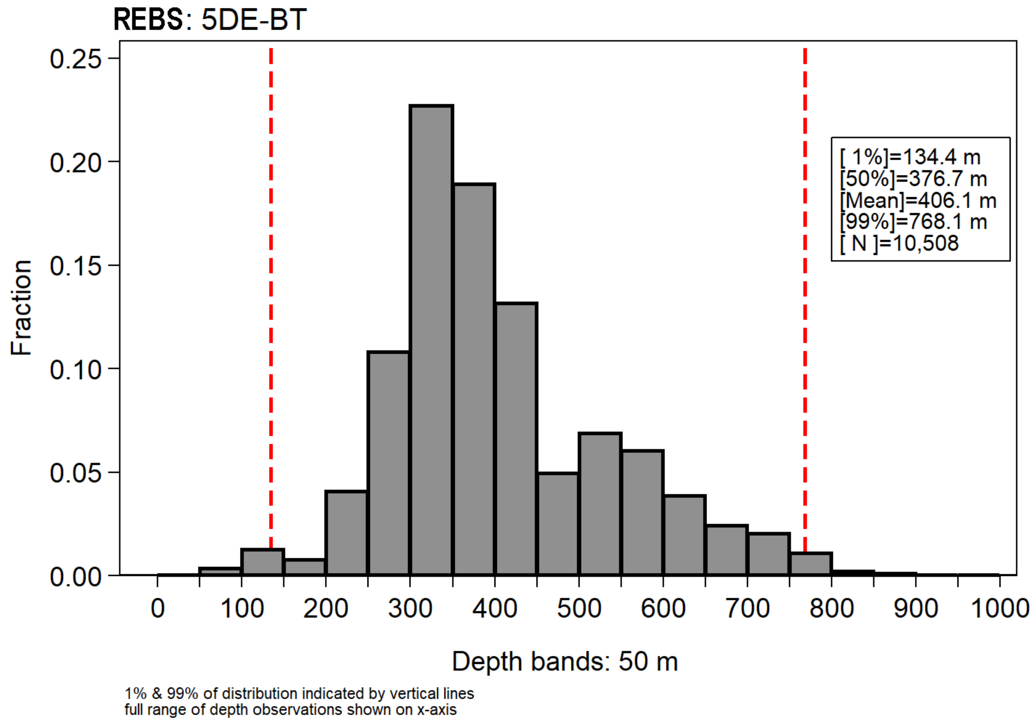

Figure C.1. Depth distribution of tows capturing REBS for the 5DE bottom trawl (BT) GLM analyses from 1996 to 2019 using 50 m intervals (each bin is labelled with the upper bound of the interval). Vertical lines indicate the 1% and 99% percentiles.

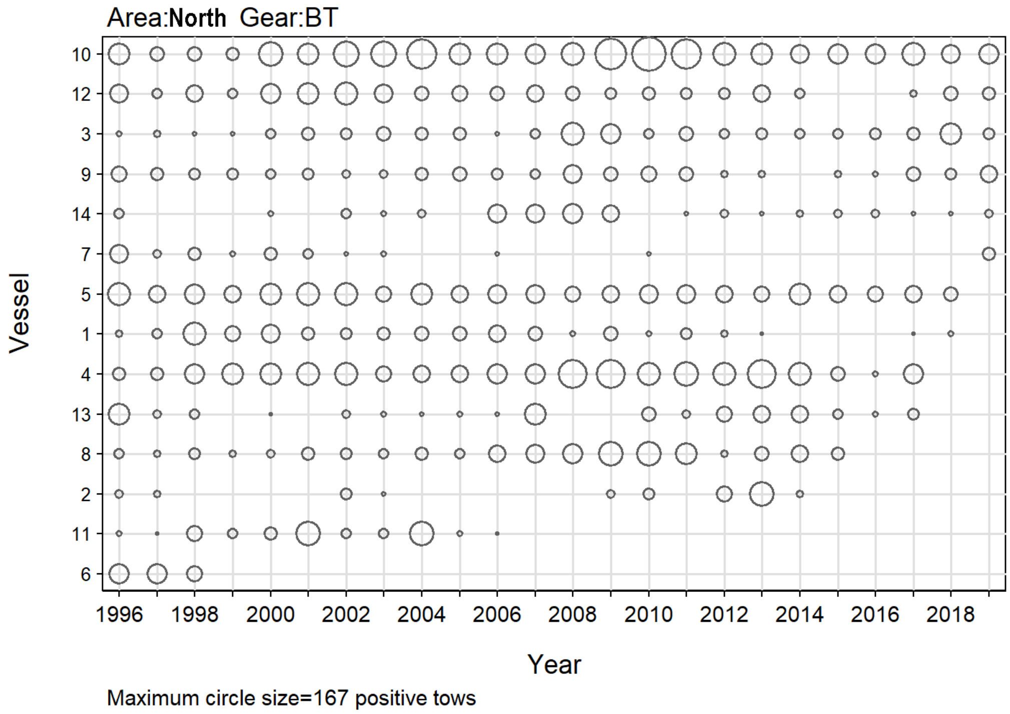

Figure C.2. Bubble plot showing vessel participation (number positive REBS tows) by the core fleet in the 5DE BT GLM analyses. Vessels are coded in ascending order total effort by year.

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

C.4.2. REBS south – 3CD5AB BT

Tow-by-tow catch and effort data for the REBS south stock from the BC trawl fishery operating from 1996 to 2019 were selected using the following criteria:

- Tow start date between 1 January 1996 and 31 December 2019;
- Bottom trawl type (includes ‘unknown’ trawl gear);
- Fished in PMFC regions: 3C, 3D, 5A or 5B;
- Fishing success code <=1 (code 0= unknown; code 1= useable);
- Catch of at least one fish or invertebrate species (no water hauls or inanimate object tows);
- Valid depth field;
- Valid latitude and longitude co-ordinates;
- Valid estimate of time towed that was > 0 hours and <= 12 hours.

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

As indicated above, the catch and effort data from Areas 3C, 3D, 5A and 5B were treated as a single area representing the catch of the REBS south stock, based on the declared distribution of bottom trawl catches (see Appendix A). Only bottom trawl data were used as this is by far the most prevalent capture method for this species. Figure C.3 plots the distribution of depth for all successful REBS bottom trawl tows in the designated region. A depth range for this analysis was selected from this plot and is summarised in Table C.5.

Table C.5. Depth bins used in CPUE analyses of REBS south by gear.

Analysis	Trawl Gear	First year	Depth range (m)	Upper bound effort (h)	Minimum bin + records	N depth bins	N latitude bins	N locality bins
3CD5AB	Bottom trawl	1996	100–700	11	150	12	24	23

Vessel qualification criteria for the bottom trawl fisheries were based on number of trips per year and number of years fishing to avoid including vessels which only occasionally captured REBS. The vessel qualification criteria used in this analysis appear in Table C.6 and the distribution of tows by vessel and year is presented in Figure C.4. Once a vessel was selected, all data for the qualifying vessel were included, regardless of the number of trips in a year. Table C.6 shows the number of vessels used in this analysis and the fraction (90%) of the total catch represented in the core fleet. There was good vessel overlap across years (Figure C.4) in the fishery, where 13 of the 41 core vessels participated in the fishery for either 23 or 24 years and a further 6 vessels were in the fishery for 20–22 years.

Table C.6. Vessel qualification criteria used in CPUE analyses of REBS south by gear.

Analysis	Trawl Gear	Vessel selection criteria			Data set characteristics				
		N years	N trips	Minimum positive Records	N vessels	% total catch[1]	catch (t)	Total records	Positive records
3CD5AB	Bottom	5	5	100	41	90	3,351	128,422	24,213

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

Table C.7. Explanatory variables offered to the REBS south CPUE model, based on the tow-by-tow information.

Variable	Data type
Year	24 categories (calendar years)
Hours fished	continuous: 3rd order polynomial
Month	12 categories
DFO locality	Fishing locality areas identified by Rutherford (1999) (includes a final aggregated category) (Table C.5)
Latitude	Latitude aggregated by 0.1° bands starting at 48°N (includes a final aggregated category) (Table C.5)
Vessel	See Table C.2 for number of categories by analysis (no final aggregated category) (Table C.6)
Depth	See Table C.1 for number of categories by analysis (no final aggregated category) (Table C.5)

Table C.8. Summary data for the REBS south bottom trawl fishery (in 3CD5AB) by year for the core data set (after applying all data filters and selection of core vessels).

Year	Number vessels[1]	Number trips[1]	Number tows[1]	Number records[1]	Number records[2]	% zero records[2]	Total catch (t)[1]	Total hours[1]	CPUE (kg/h) (Eq. C.1)
1996	34	180	817	817	4,110	80.1	251.2	1,908	131.7
1997	34	201	735	735	4,995	85.3	95.5	1,743	54.8
1998	32	242	865	865	5,782	85.0	113.6	2,103	54.0
1999	31	251	928	928	6,103	84.8	93.7	2,388	39.2
2000	33	299	1,146	1,146	7,049	83.7	144.5	2,847	50.8
2001	32	320	1,267	1,267	6,404	80.2	142.4	3,156	45.1
2002	31	323	1,256	1,256	6,958	81.9	184.2	3,153	58.4
2003	31	315	1,090	1,090	7,039	84.5	178.0	2,555	69.6
2004	32	339	1,151	1,151	6,752	83.0	177.7	2,712	65.5
2005	33	311	996	996	7,301	86.4	142.8	2,351	60.8
2006	30	309	1,103	1,103	6,287	82.5	134.0	2,538	52.8
2007	30	270	1,003	1,003	5,611	82.1	131.1	2,436	53.8
2008	28	219	781	781	4,633	83.1	93.7	1,844	50.8
2009	28	263	1,049	1,049	5,190	79.8	206.2	2,574	80.1
2010	25	268	1,220	1,220	5,382	77.3	218.6	2,987	73.2
2011	28	241	1,135	1,135	5,046	77.5	159.8	3,027	52.8
2012	25	207	1,038	1,038	4,356	76.2	142.6	2,710	52.6
2013	25	198	1,169	1,169	4,561	74.4	162.3	2,890	56.2
2014	27	206	1,036	1,036	4,693	77.9	113.8	2,697	42.2
2015	24	186	973	973	4,911	80.2	148.1	2,485	59.6
2016	21	171	978	978	4,431	77.9	115.8	2,506	46.2
2017	22	167	885	885	3,936	77.5	86.6	2,280	38.0
2018	19	155	834	834	3,917	78.7	61.1	1,742	35.1
2019	15	127	758	758	2975	74.5	54.1	1448	37.3

[1] calculated for tows with REBS south catch >0; [2] calculated for all tows

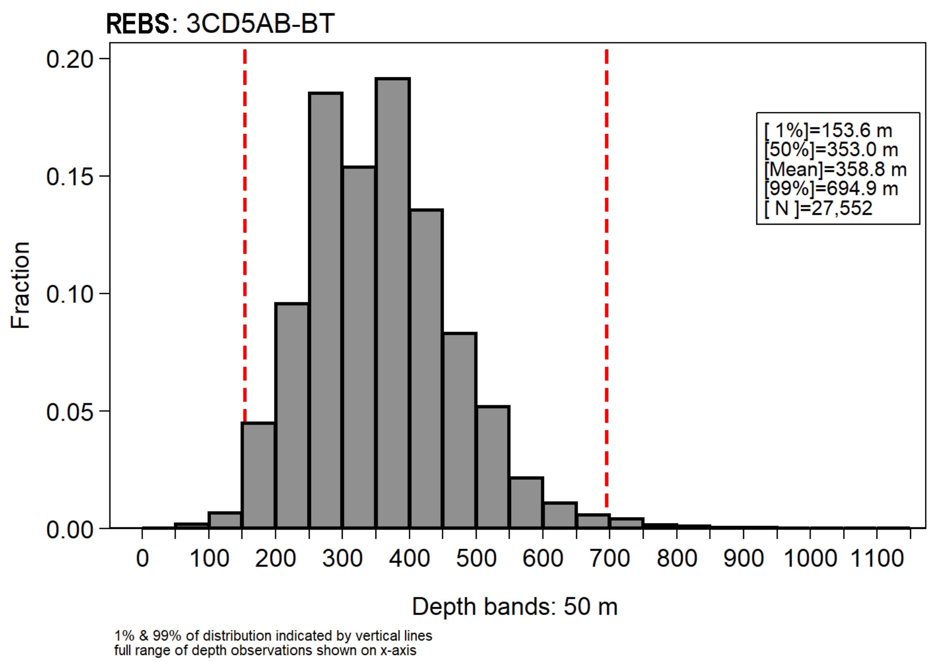

Figure C.3. Depth distribution of tows capturing REBS for the 3CD5AB bottom trawl (BT) GLM analyses from 1996 to 2019 using 50 m intervals (each bin is labelled with the upper bound of the interval). Vertical lines indicate the 1% and 99% percentiles.

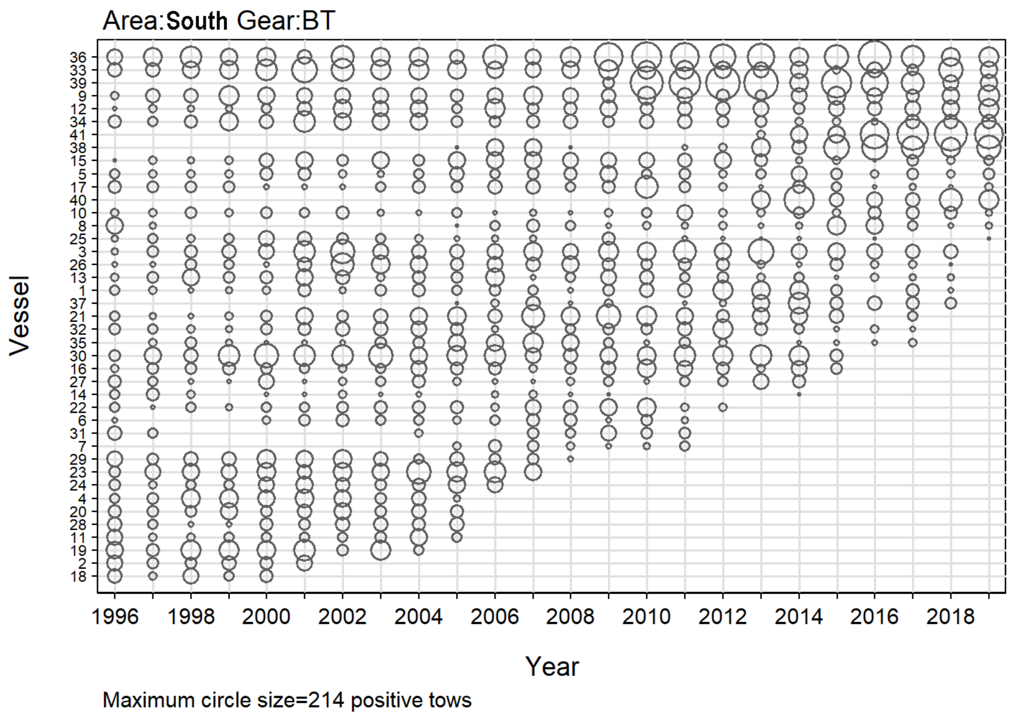

Figure C.4. Bubble plot showing vessel participation (number positive REBS tows) by the core fleet in the 3CD5AB BT GLM analyses. Vessels are coded in ascending order total effort by year.

Table C.7 reports the explanatory variables offered to the model, based on the tow-by-tow information in each record, with the number of available categories varying as indicated in Table C.5, Table C.6 and Table C.7. Table C.8 summarises the core vessel data used in the analysis by calendar year, including the number of records, the total hours fished and the associated REBS catch. This table also tracks the proportion of tows which did not report REBS.

C.5. RESULTS

C.5.1. REBS north – 5DE

C.5.1.1. Bottom trawl fishery: positive lognormal model

A standardised lognormal General Linear Model (GLM) analysis was performed on positive catch records from the bottom trawl tow-by-tow data set generated as described in Section C.4.1 above. Seven explanatory variables (Table C.3) were offered to the model and `Ln(catch)` was used as the dependent variable, where catch is the total by weight of landed plus discarded REBS in each record (tow) (Eq. C.3). The resulting CPUE index series is presented in Figure C.5.

The `[Year]` categorical variable was forced as the first variable in the model without regard to its effect on the model deviance. The remaining six variables were offered sequentially, with a stepwise acceptance of the remaining variables with the best AIC. This process was continued until the improvement in the model R^2 was less than 1% (Table C.9). This model selected five of the six remaining explanatory variables, including `[Depth bands]`, `[0.1°Latitude_bands]`, `[Vessel]`, `[Month] and [DFO locality] in` addition to `[Year]`. The final lognormal model accounted for 54% of the total model deviance (Table C.9), with the year variable explaining about 5% of the model deviance.

Model residuals showed a satisfactory fit to the underlying lognormal distributional assumption, with some skewness in the body of the distribution and deviations in the tails outside of +/- 2 standard errors (Figure C.6).

A stepwise plot showing the effect on the year indices as each explanatory variable was introduced into the model shows that the standardisation procedure made some major adjustments to the unstandardised series throughout the series after the introduction of the `[Depth bands]`, resulting in a relatively smooth annual trend (Figure C.7). The addition of the `[0.1°Latitude_bands]` variable completed the smoothing process, giving a rising trend to the series up to 2016, followed by a decline over the next three years.

*Table C.9. Order of acceptance of variables into the lognormal model of positive total mortalities (verified landings plus discards) of REBS in the 5DE bottom trawl fishery with the amount of explained deviance (R^2) for each variable. Variables accepted into the model are identified in bold with an *. Year was forced as the first variable.*

Variable	1	2	3	4	5	6	7
Year*	**0.0487**	-	-	-	-	-	-
Depth bands*	0.3342	**0.3602**	-	-	-	-	-
0.1° Latitude bands*	0.3372	0.3551	**0.4974**	-	-	-	-
Vessel*	0.1159	0.1525	0.4049	**0.5136**	-	-	-
Month*	0.0565	0.1040	0.3774	0.5097	**0.5265**	-	-
DFO locality*	0.3147	0.3337	0.4766	0.5106	0.5248	**0.5371**	-
Hours fished	0.1454	0.1868	0.3864	0.4981	0.5143	0.5283	0.5391
Improvement in deviance	0.0000	0.3115	0.1372	0.0162	0.0129	0.0106	0.0020

CDI plots of the five explanatory variables introduced to the model in addition to `[Year]` show strong standardisation effects in the series with the addition of the first two variables. Much of the adjustment to the unstandardised series shown in Figure C.7 occurred with the addition of the variable `[Depth bands]` (Figure C.8), which indicates that there was a lot of variation in the preferred depth between years. Similarly, the `[0.1°Latitude_bands]` (Figure C.9) variable shows variation between years, particularly near the end of the series where latitudes 53.9° and 54° seem to predominate. The remaining three explanatory variables (`[Vessel]` (Figure C.10), `[Month]` (Figure C.11) and `[DFO locality]` (Figure C.12)) had much less impact on the overall series.

The lognormal year indices show a rising trend from the beginning of the series to 2016, with a sharp decline in the final three years of the series (Figure C.5). This model has reasonable diagnostics and shows major changes from the unstandardised series, particularly in the final three years which change from a continuation of the rising trend to a decline.

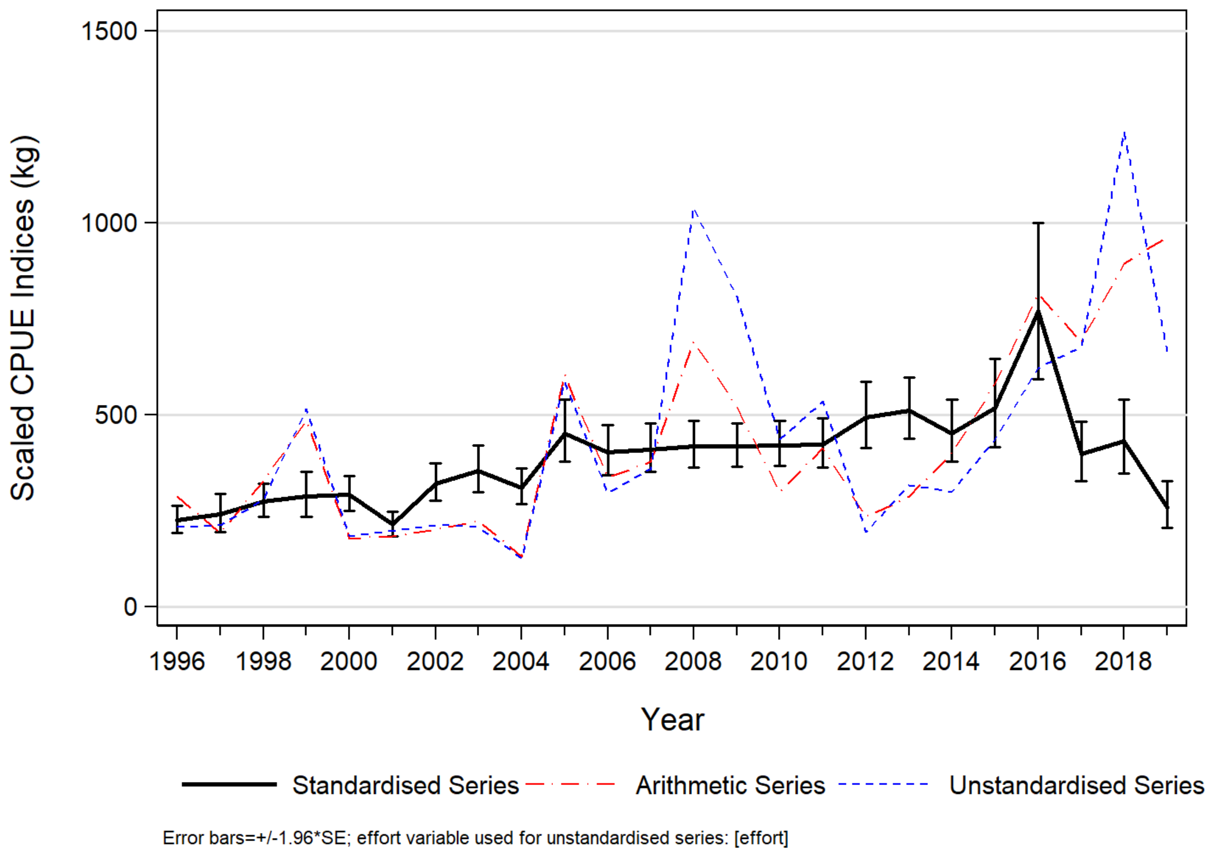

Figure C.5. Three positive catch CPUE series for REBS from 1996 to 2019 in the 5DE bottom trawl fishery. The solid line is the standardised CPUE series from the lognormal model (Eq. C.3). The arithmetic series (Eq. C.1) and the unstandardised series (Eq. C.2) are also presented. All three series have been scaled to same geometric mean.

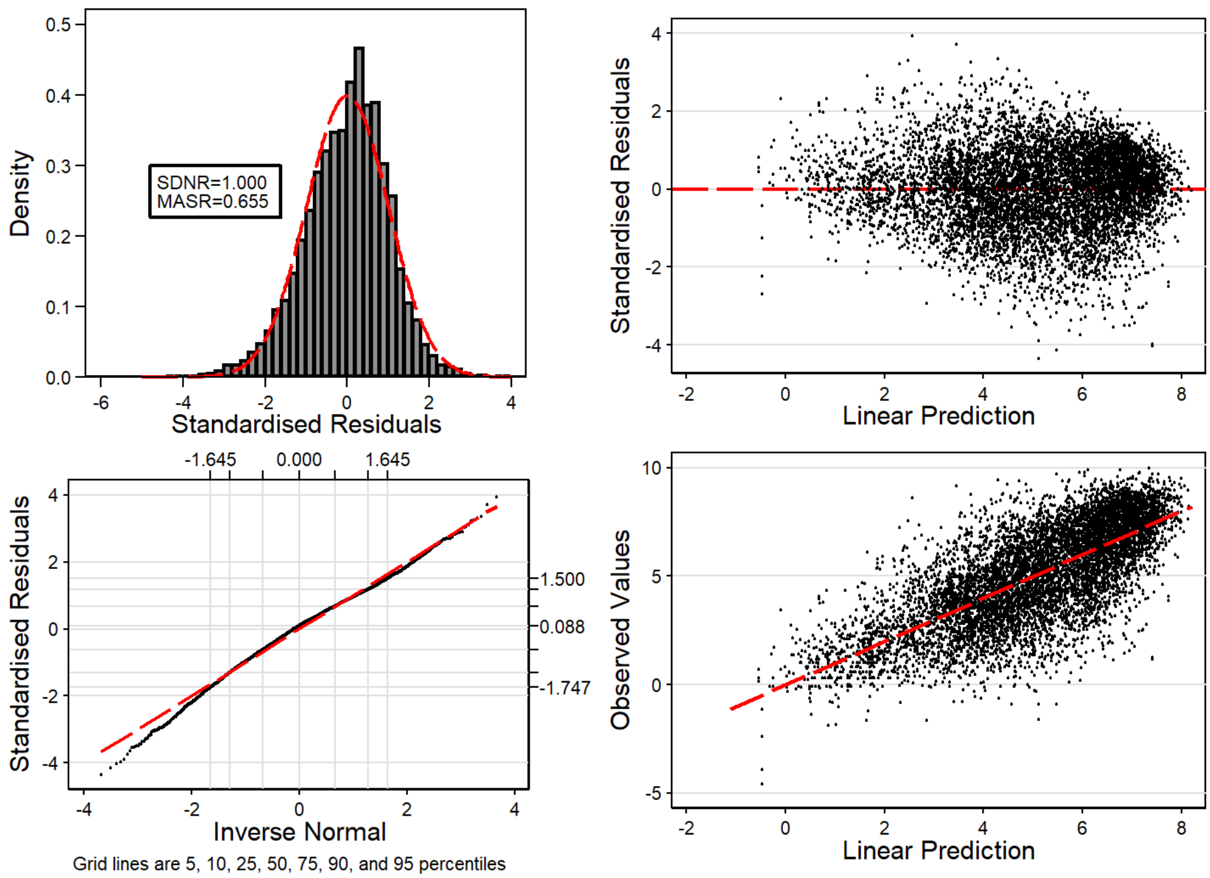

Figure C.6. Residual diagnostic plots for the GLM lognormal analysis for REBS in the 5DE bottom trawl fishery. Upper left: histogram of the standardised residuals with overlaid lognormal distribution (SDNR = standard deviation of normalised residuals. MASR = median of absolute standardised residuals). Lower left: Q-Q plot of the standardised residuals with the outside horizontal and vertical lines representing the 5th and 95th percentiles of the theoretical and observed distributions. Upper right: standardised residuals plotted against the predicted CPUE. Lower right: observed CPUE plotted against the predicted CPUE.

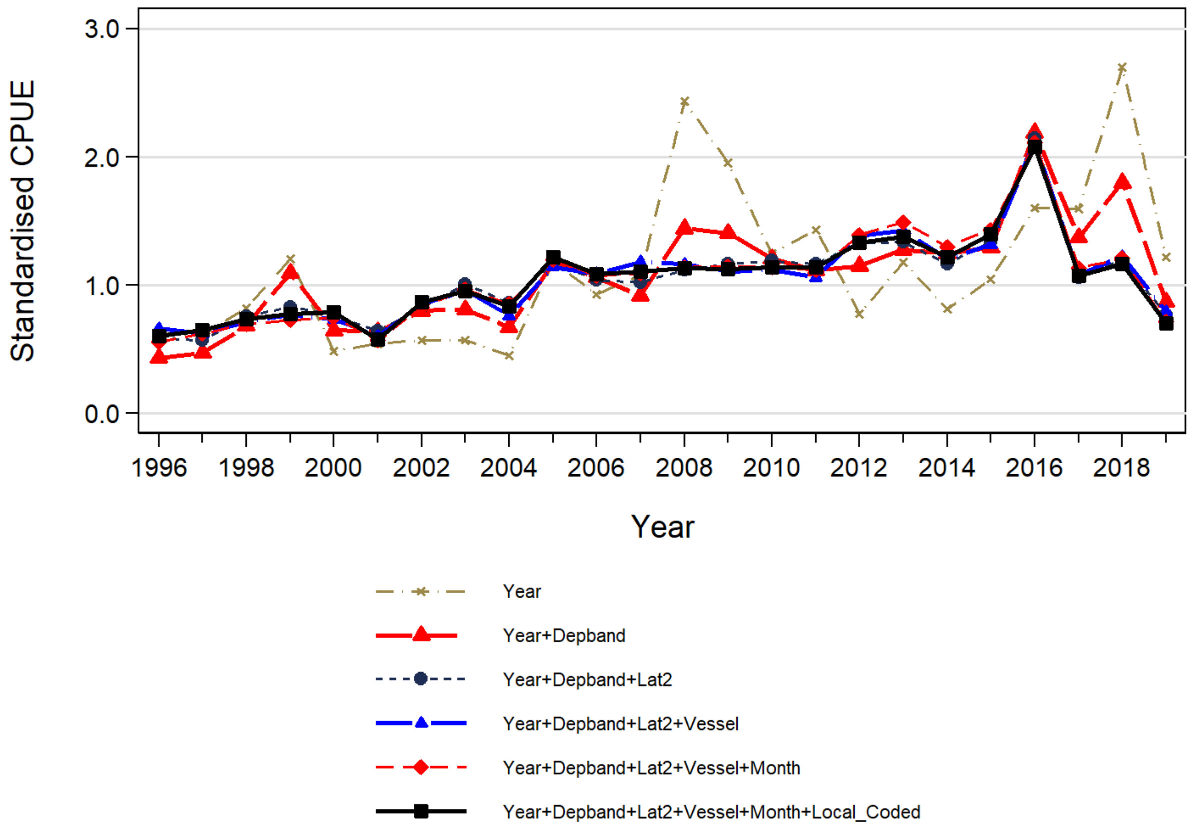

Figure C.7. Plot showing the year coefficients after adding each successive term of the standardised lognormal regression analysis for REBS in the 5DE bottom trawl fishery. The final model is shown with a thick solid black line. Each line has been scaled so that the geometric mean equals 1.0.

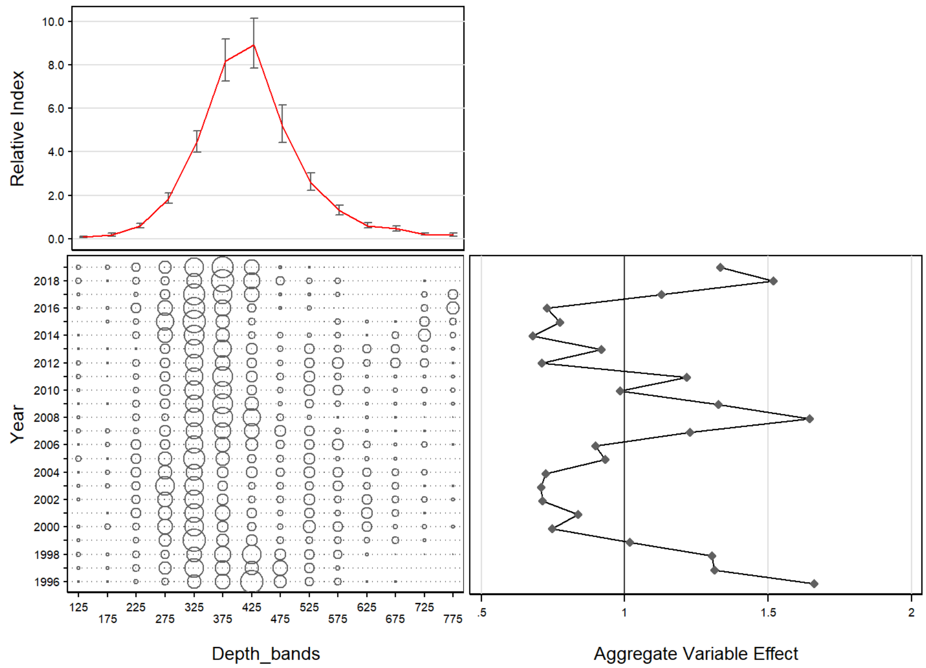

Figure C.8. CDI plot showing the effect of introducing the categorical variable [Depth_bands] to the lognormal regression model for REBS in the 5DE bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution by year of variable records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

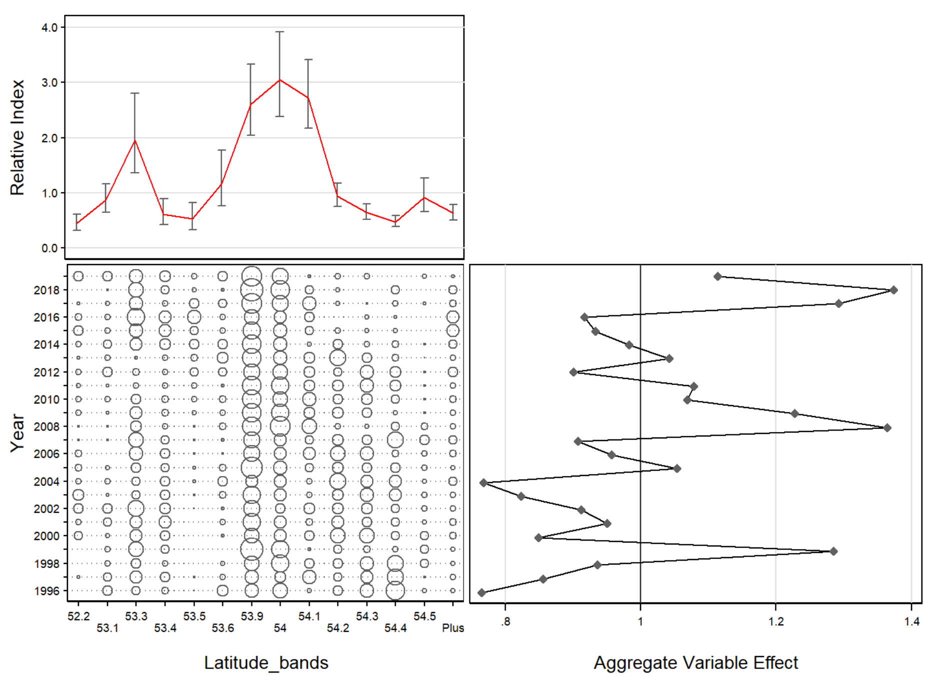

Figure C.9. CDI plot showing the effect of introducing the categorical variable [Latitude_bands] to the lognormal regression model for REBS in the 5DE bottom trawl fishery. Table C.10 provides the definitions for the coded values used for each locality in the above plot. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution by year of variable records (bottom left), and the cumulative effect of variable by year (bottom right).

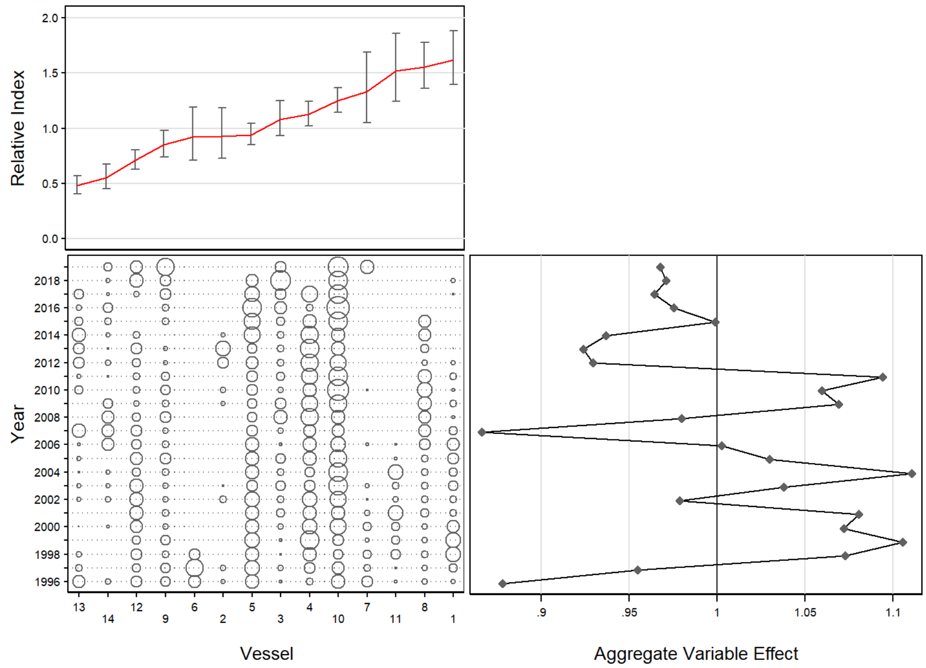

Figure C.10. CDI plot showing the effect of introducing the categorical variable [Vessel] to the lognormal regression model for REBS in the 5DE bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution by year of variable records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

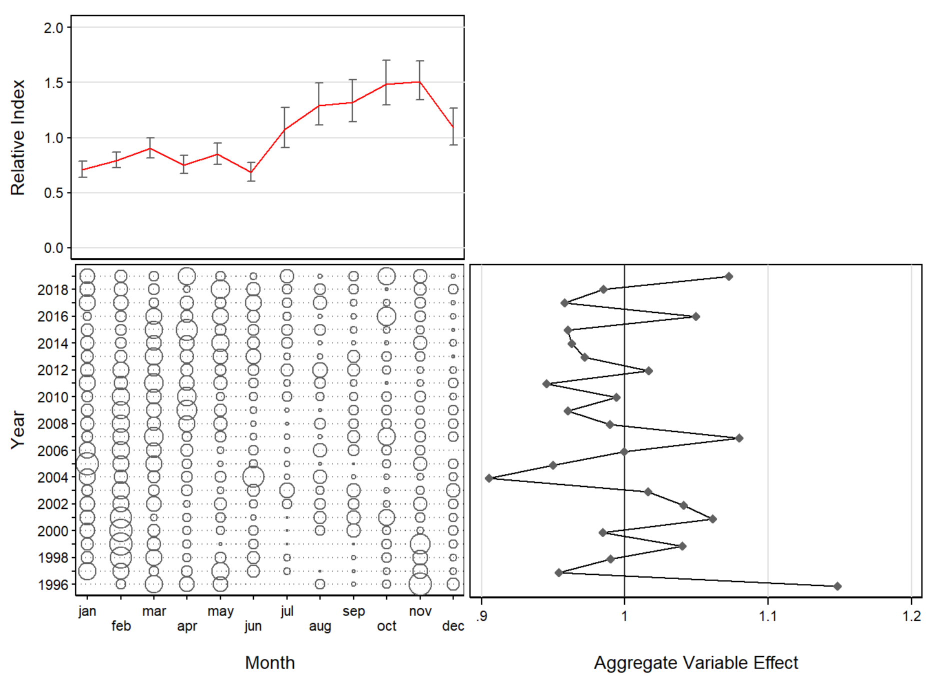

Figure C.11. CDI plot showing the effect of introducing the categorical variable [Month] to the lognormal regression model for REBS in the 5DE bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution by year of variable records (bottom left), and the cumulative effect of variable by year (bottom right).

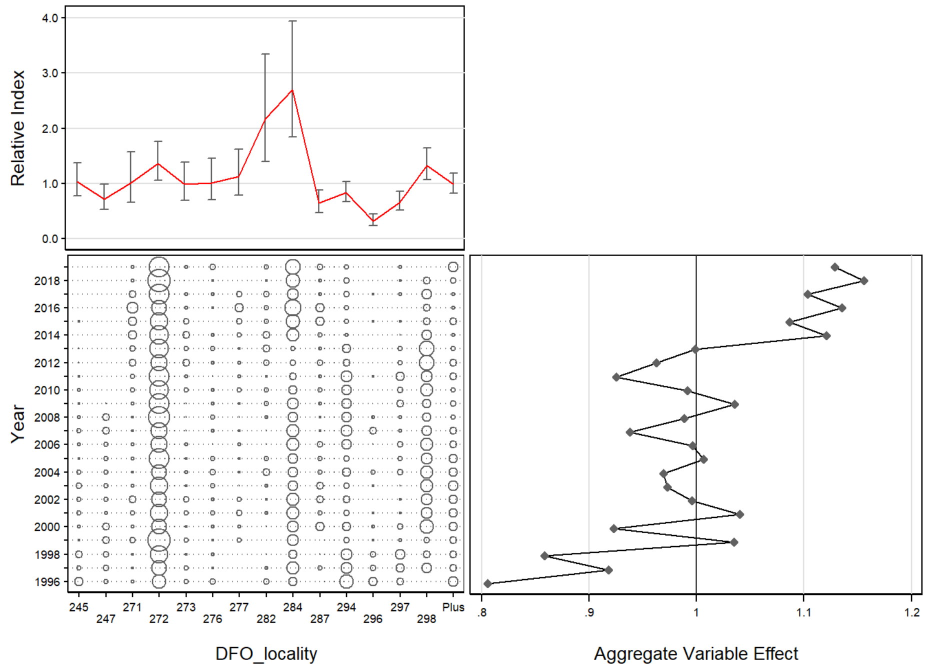

Figure C.12. CDI plot showing the effect of introducing the categorical variable [DFO_locality] to the lognormal regression model for REBS in the 5DE bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution by year of variable records (bottom left), and the cumulative effect of variable by year (bottom right).

Table C.10. Definition of locality codes used in Figure C.12.

Code	PFMC Major	DFO Minor	Minor Name	Locality Name	Lognormal Index
245	5D	3	1 EAST-DIXON ENTRANCE	NE LANGARA	1.028
247	5D	3	1 EAST-DIXON ENTRANCE	DIXON ENTRANCE	0.722
271	5E	31	2A WEST – RENNELL SOUND	RENNELL SOUND	1.012
272	5E	31	2A WEST – RENNELL SOUND	FREDERICK ISLAND	1.362
273	5E	31	2A WEST – RENNELL SOUND	BUCK POINT	0.981
276	5E	31	2A WEST – RENNELL SOUND	FRED SPOT	1.013
277	5E	31	2A WEST – RENNELL SOUND	MARBLE ISLAND	1.131
282	5E	31	2A WEST – RENNELL SOUND	HIPPA ISLAND	2.166
284	5E	31	2A WEST – RENNELL SOUND	SOUTH HOGBACK	2.695
287	5E	34	2B WEST – ANTHONY ISLAND	ANTHONY ISLAND	0.643
294	5E	35	1 WEST – LANGARA	N FRED-LANGARA (DEEP)	0.833
296	5E	35	1 WEST – LANGARA	NW LANGARA (133 DEGREES)	0.321
297	5E	35	1 WEST – LANGARA	LANGARA`SPIT INSIDE/COMPASS RO	0.663
298	5E	35	1 WEST – LANGARA	LANGARA`SPIT INSIDE/COMPASS RO	1.321

C.5.1.2. Bottom trawl fishery: binomial logit model

The same explanatory variables used in the lognormal model were offered sequentially to this model, beginning with the year categorical variable, until the improvement in the model R^2 was less than 1% (Table C.11). A binary variable which equalled 1 for positive catch tows and 0 for zero catch tows was used as the dependent variable. The final binomial model accounted for 53% of the total model deviance, with the year variable explaining just over 2% of the model deviance. The resulting CPUE index series is presented in Figure C.13.

*Table C.11. Order of acceptance of variables into the binomial model of presence/absence of verified landings plus discards of REBS north in 5DE bottom trawl fishery with the amount of explained deviance (R^2) for each variable. Variables accepted into the model are marked in bold with an *. Year was forced as the first variable.*

Variable	1	2	3	4
Year*	**0.0240**	-	-	-
Depth bands*	0.4972	**0.5011**	-	-
0.1° Latitude bands*	0.2449	0.2577	**0.5258**	-
Vessel	0.0504	0.0725	0.5064	0.5310
Hours fished	0.0158	0.0370	0.5045	0.5270
Month*	0.0598	0.0811	0.5037	0.5283
DFO locality*	0.3361	0.3409	0.5250	0.5297
Improvement in deviance	0.0000	0.4772	0.0246	0.0053

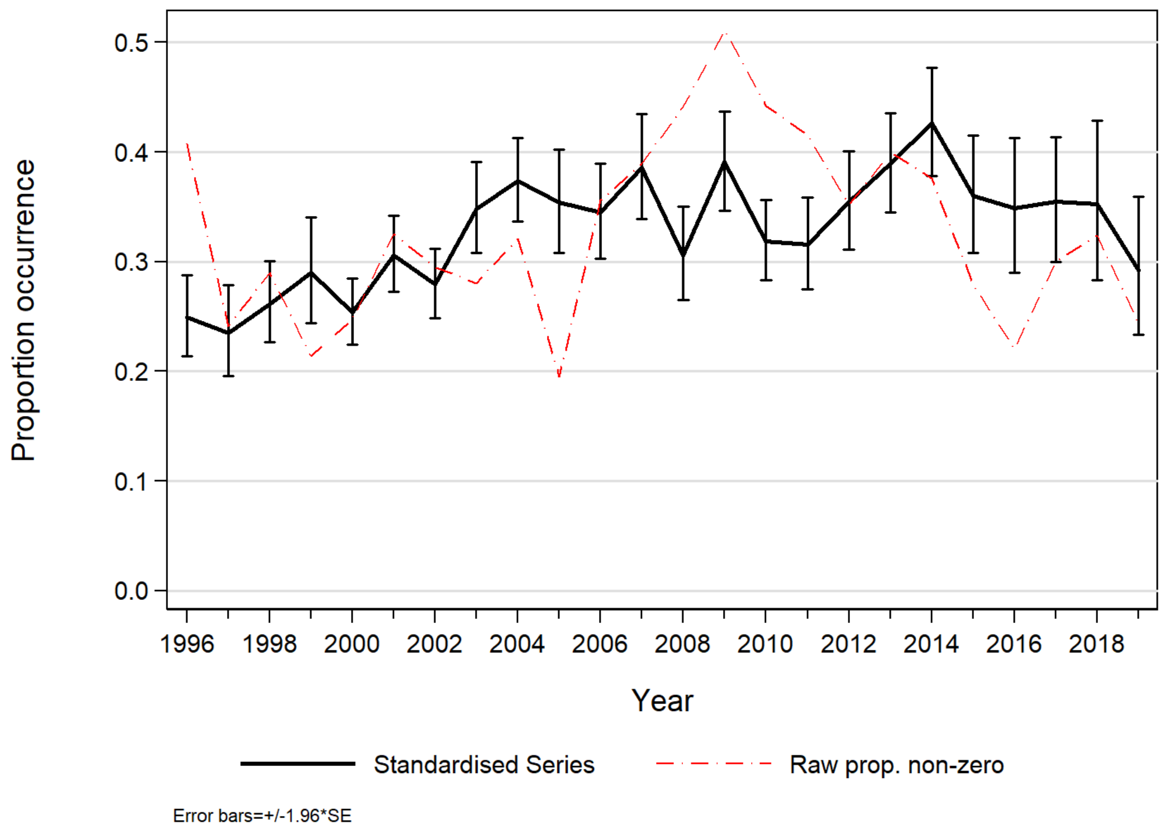

Figure C.13. Binomial index series for the REBS north 5DE bottom trawl fishery also showing the trend in proportion of zero tows from the same data set.

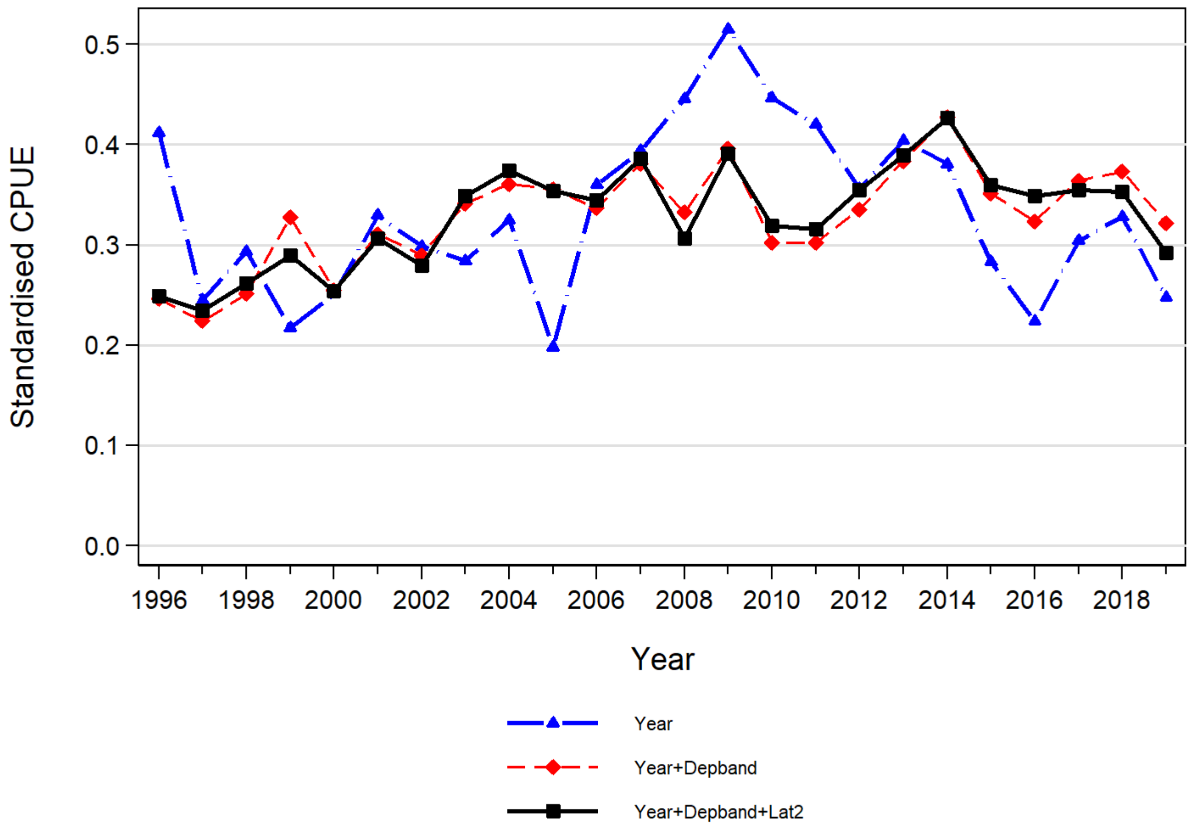

Figure C.14. Plot showing the year coefficients after adding each successive term of the standardised binomial regression analysis for REBS in the 5DE bottom trawl fishery. The final model is shown with a thick solid black line. Each line has been scaled so that the geometric mean equals 1.0.

The selected explanatory variables only included `[Depth_bands]` and `[0.1°Latitude_bands]`, the same two variables that first entered the lognormal model (see Table C.9), in addition to `[Year]`. This model shows a trend similar to the lognormal model, generally increasing up to the mid-2010s and then decreasing over the next four to five years (Figure C.13). A stepwise plot (Figure C.14), showing the effect of adding each successive explanatory variable, indicates that there were strong changes effected from the binomial standardisation, with the unstandardised "occurrence" function showing much annual variation compared to the much smoother standardised binomial series (Figure C.13).

As with the lognormal model, the effect of the standardisation was to smooth the series. The addition of the `[Depth_bands]` (Figure C.15) took out much of the interannual variability, as was seen for the lognormal model. There was less standardisation impact with the addition of the `[0.1°Latitude_bands]` (Figure C.16) variable.

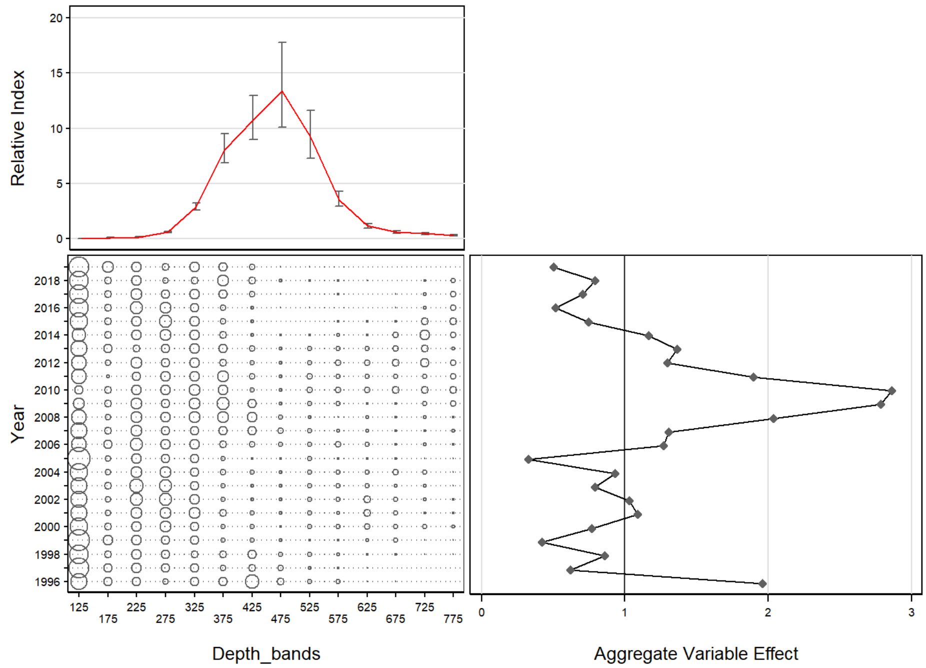

Figure C.15. CDI plot showing the effect of introducing the categorical variable [Depth bands] to the binomial regression model for REBS in the 5DE bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution by year of variable records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

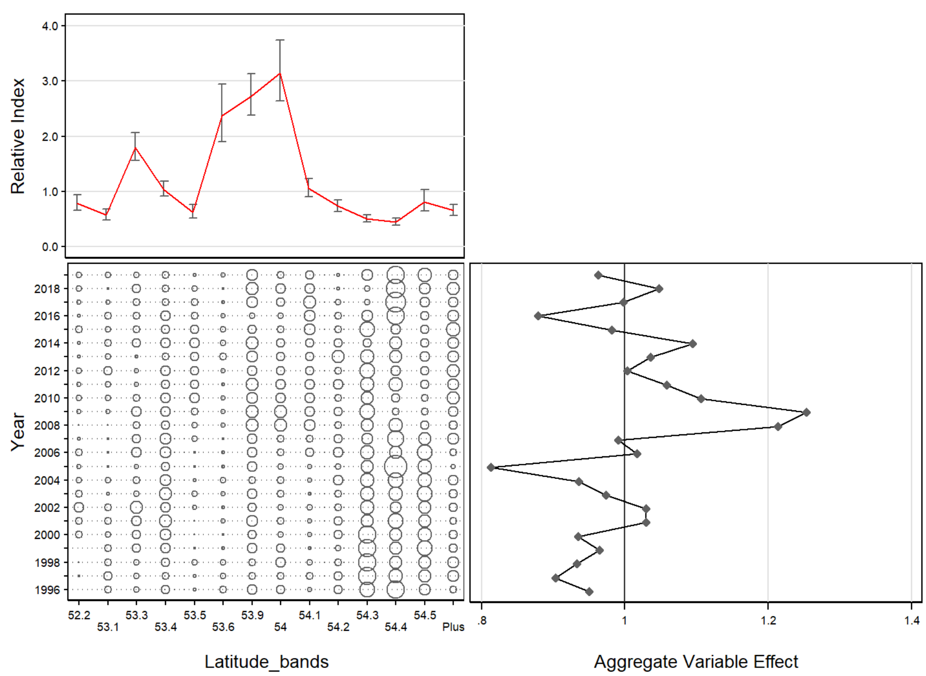

Figure C.16. CDI plot showing the effect of introducing the categorical variable [Latitude bands] to the binomial regression model for REBS in the 5DE bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution by year of variable records (bottom left), and the cumulative effect of variable by year (bottom right).

C.5.1.3. Bottom trawl fishery: combined model

While the lognormal and binomial models show similar trends over the entire period, the combined model (Eq. C.4) tracks the lognormal model, increasing up to 2016, followed by a drop in the final three years of the series (Figure C.17).

C.5.2. REBS north relative indices of abundance

Table C.12 summarises the suite of relative abundance indices and associated standard errors derived from this REBS north CPUE analysis. The CPUE indices used in the age-structured stock assessment model appear as the delta-lognormal (combined) indices from the bottom trawl data (Figure C.17, Table C.12). The associated bootstrap standard errors (SE) were used as the initial CVs when fitting the stock assessment model, which were then modified by adding various levels of process error which changed the relative fit of the model to these indices.

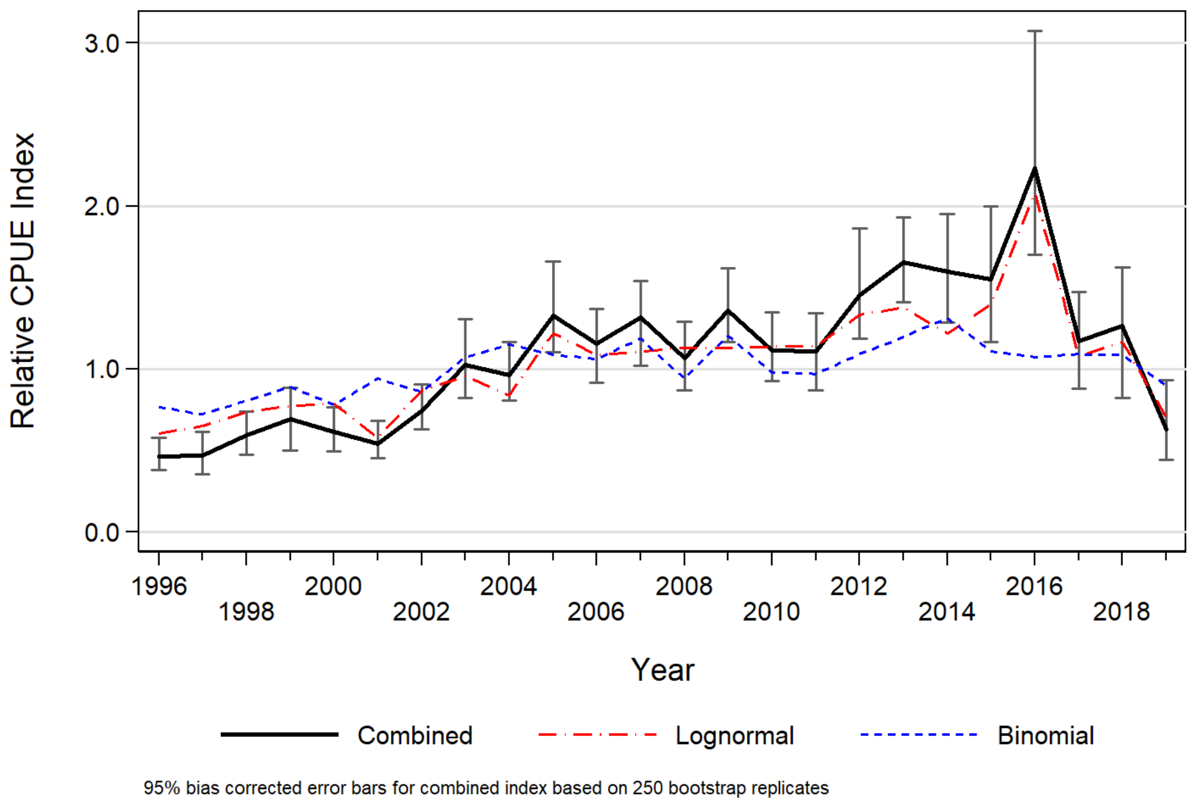

Figure C.17. Combined index series (Eq. C.4) for the REBS north 5DE bottom trawl fishery also showing the contributing lognormal and binomial index series. Confidence bounds based on 250 bootstrap replicates.

C.5.3. Comparison of REBS north combined series with west coast Haida Gwaii synoptic survey

Figure C.18 compares the REBS north combined series (Figure C.17, Table C.12) with the relative biomass series from the west coast Haida Gwaii synoptic survey (see Appendix B, Section B.4). This comparison shows general agreement between the two series, with a slowly increasing trend over the first 20 years covered, followed by a suggestion of a downturn in the 2018 survey observation which matches the recent three-year decline observed in the CPUE series.

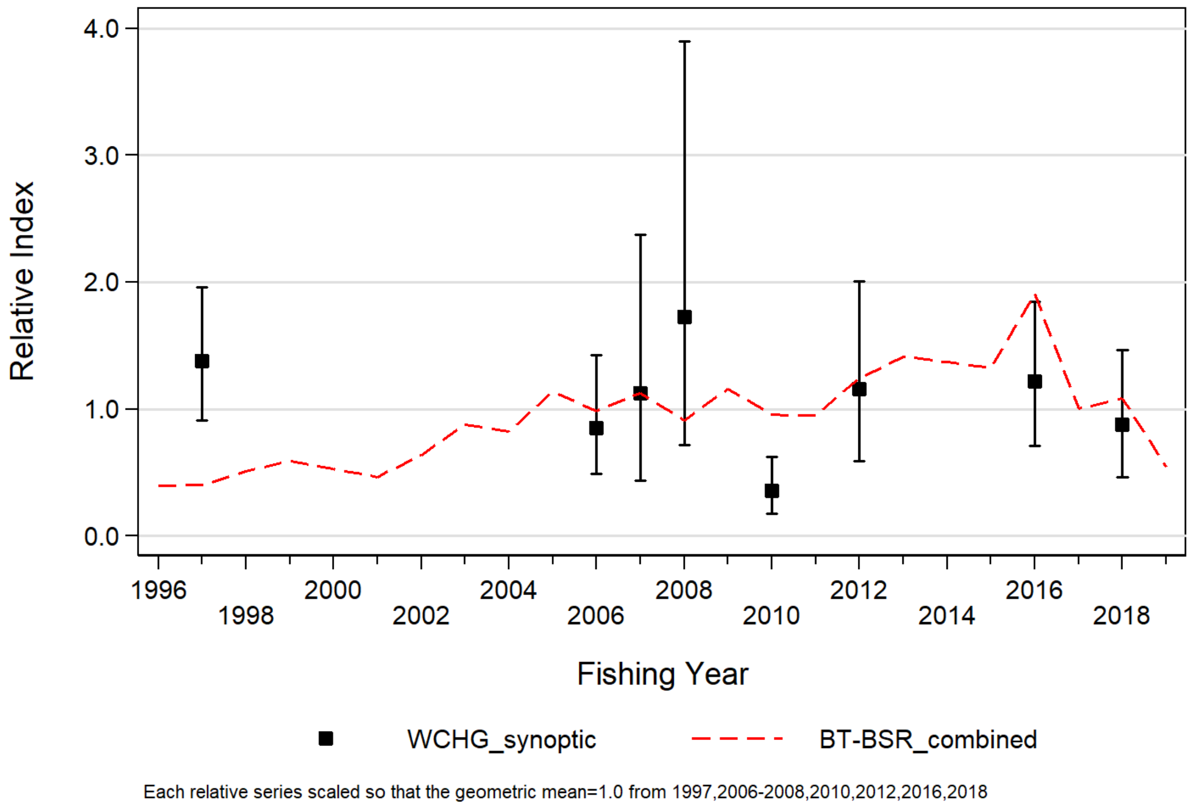

Figure C.18. Comparison of the west coast Haida Gwaii synoptic survey series with the combined index series (Eq. C.4) for the REBS 5DE bottom trawl fishery. Survey confidence bounds based on 1000 bootstrap simulations.

Table C.12. Relative indices of annual CPUE from the arithmetic, unstandardised, lognormal models of non-zero bottom trawl catches of REBSin 5DE. Also shown are the indices from the binomial model of presence/absence in this fishery and the combined delta-lognormal model (Eq. C.4). All indices are scaled so that their geometric means equal 1.0. Upper and lower 95% analytic confidence bounds and associated standard error (SE) are presented for the lognormal model, while bootstrapped (250 replicates) upper and lower 95% confidence bounds and the associated SE are presented for the combined model.

	Arithmetic	Geometric	Lognormal (Eq. C.3)				Binomial	Combined (Eq. C.4)			
Year	Index (Eq. C.1)	Index (Eq. C.2)	Index	Lower bound	Upper bound	SE	Index (Eq. C.3)	Index	Lower bound	Upper bound	SE
1996	0.776	0.560	0.607	0.518	0.711	0.0806	0.766	0.465	0.381	0.581	0.1126
1997	0.518	0.575	0.649	0.529	0.797	0.1047	0.722	0.469	0.357	0.615	0.1339
1998	0.886	0.753	0.740	0.632	0.866	0.0803	0.805	0.596	0.472	0.740	0.1122
1999	1.312	1.393	0.775	0.631	0.952	0.1049	0.892	0.691	0.502	0.887	0.1389
2000	0.480	0.496	0.789	0.674	0.923	0.0802	0.781	0.616	0.497	0.764	0.1082
2001	0.497	0.535	0.577	0.497	0.670	0.0761	0.942	0.544	0.454	0.680	0.1088
2002	0.542	0.577	0.868	0.747	1.008	0.0765	0.860	0.746	0.631	0.906	0.1023
2003	0.604	0.559	0.957	0.805	1.137	0.0882	1.072	1.026	0.825	1.309	0.1146
2004	0.354	0.340	0.839	0.722	0.975	0.0767	1.151	0.966	0.806	1.167	0.0986
2005	1.637	1.585	1.220	1.022	1.456	0.0904	1.089	1.328	1.104	1.662	0.1051
2006	0.912	0.800	1.087	0.924	1.279	0.0828	1.062	1.154	0.916	1.368	0.0961
2007	1.019	0.971	1.107	0.949	1.293	0.0789	1.187	1.315	1.018	1.539	0.1023
2008	1.867	2.809	1.132	0.980	1.308	0.0737	0.942	1.066	0.872	1.291	0.1003
2009	1.403	2.183	1.128	0.987	1.291	0.0685	1.203	1.358	1.164	1.620	0.0819
2010	0.809	1.178	1.138	0.990	1.308	0.0712	0.981	1.117	0.925	1.347	0.0941
2011	1.115	1.446	1.141	0.982	1.327	0.0769	0.971	1.108	0.869	1.342	0.1044
2012	0.632	0.525	1.332	1.119	1.587	0.0891	1.092	1.455	1.186	1.862	0.1102
2013	0.776	0.857	1.380	1.181	1.614	0.0796	1.198	1.653	1.408	1.931	0.0829
2014	1.079	0.809	1.218	1.020	1.456	0.0908	1.313	1.600	1.285	1.952	0.1072
2015	1.571	1.178	1.400	1.123	1.745	0.1126	1.108	1.551	1.168	1.999	0.1426
2016	2.202	1.681	2.079	1.600	2.703	0.1338	1.074	2.232	1.701	3.074	0.1548
2017	1.866	1.829	1.073	0.885	1.301	0.0983	1.091	1.171	0.880	1.472	0.1159
2018	2.417	3.341	1.168	0.936	1.457	0.1128	1.085	1.268	0.824	1.622	0.1603
2019	2.604	1.796	0.701	0.556	0.886	0.1189	0.900	0.631	0.441	0.931	0.1981

C.5.4. REBS south – 3CD5AB

C.5.4.1. Bottom trawl fishery: positive lognormal model

A standardised lognormal General Linear Model (GLM) analysis was performed on positive catch records from the bottom trawl tow-by-tow data set generated as described in C.4.2 above. Seven explanatory variables (Table C.7) were offered to the model and `Ln(catch)` was used as the dependent variable, where catch is the total by weight of landed plus discarded REBS south in each record (tow) (Eq. C.3). The resulting CPUE index series is presented in Figure C.19.

The `[Year]` categorical variable was forced as the first variable in the model without regard to its effect on the model deviance. The remaining six variables were offered sequentially, with a stepwise acceptance of the remaining variables with the best AIC. This process was continued until the improvement in the model R^2 was less than 1% (Table C.13). This model selected five of the six remaining explanatory variables, including `[Depth bands]`, `[0.1°Latitude_bands]`, `[Vessel]`, `[Month] and [Hours fished] in` addition to `[Year]`. The final lognormal model accounted for 26% of the total model deviance (Table C.13), with the year variable explaining about 2% of the model deviance.

Model residuals showed a satisfactory fit to the underlying lognormal distributional assumption, with very little skewness in the body of the distribution and only small deviations in the tails outside of +/- 2 standard errors (Figure C.20).

A stepwise plot showing the effect on the year indices as each explanatory variable was introduced into the model shows that the standardisation procedure only made relatively small downward adjustments to the unstandardised series at various stages in the series, resulting in a relatively smooth continuous downward trend (Figure C.21).

*Table C.13. Order of acceptance of variables into the lognormal model of positive total mortalities (verified landings plus discards) of REBS 3CD5AB bottom trawl fishery with the amount of explained deviance (R^2) for each variable. Variables accepted into the model are identified in bold with an *. Year was forced as the first variable.*

Variable	1	2	3	4	5	6	7
Year*	**0.0178**	-	-	-	-	-	-
Depth bands*	0.1137	**0.1330**	-	-	-	-	-
0.1° Latitude bands*	0.0836	0.1003	**0.1995**	-	-	-	-
Vessel*	0.0351	0.0490	0.1601	**0.2233**	-	-	-
Month*	0.0105	0.0275	0.1581	0.2184	**0.2407**	-	-
Hours fished*	0.0222	0.0400	0.1524	0.2195	0.2386	**0.2552**	-
DFO locality	0.0611	0.0782	0.1885	0.2059	0.2288	0.2452	0.2582
Improvement in deviance	0.0000	0.1152	0.0665	0.0238	0.0174	0.0145	0.0031

CDI plots of the five explanatory variables introduced to the model in addition to `[Year]` show standardisation effects to the series coming from the addition of these variables. Some adjustment to the unstandardised series occurred with the addition of the variable `[Depth bands]` (Figure C.22), which shows a trend of increasing depth in the fishery in the latter half of the series which drops the year indices because the expected CPUE at these depths is greater. Similarly, the `[0.1°Latitude_bands]` (Figure C.23) variable shows variation between years, particularly in the first year and the last three years of the series where the more northern latitudes seem to predominate which tend to have higher CPUE. The `[Vessel] explanatory variable` (Figure C.24) has an opposite trend to `[0.1°Latitude_bands] variable, with a` number of less effective vessels entering the fishery in the final six years of the series and which raise the CPUE. The effect of the [Month] variable (Figure C.25) appears to be small, with the possible exception of 1996 where the high CPUE in that first year was pulled down by the addition of this variable (as well as the [Depth bands] and [0.1°Latitude_bands] variables). Finally, the [Hours fished] variable (Figure C.26)) shows a strong drop in the length of tows, which results in pulling up the indices in these last two years because shorter tows have a lower expected CPUE.

The lognormal year indices show a continuously declining trend from the beginning of the series up to 2019, with some variation in the centre of the series (Figure C.19). This model has good diagnostics and does not change much from the unstandardised series.

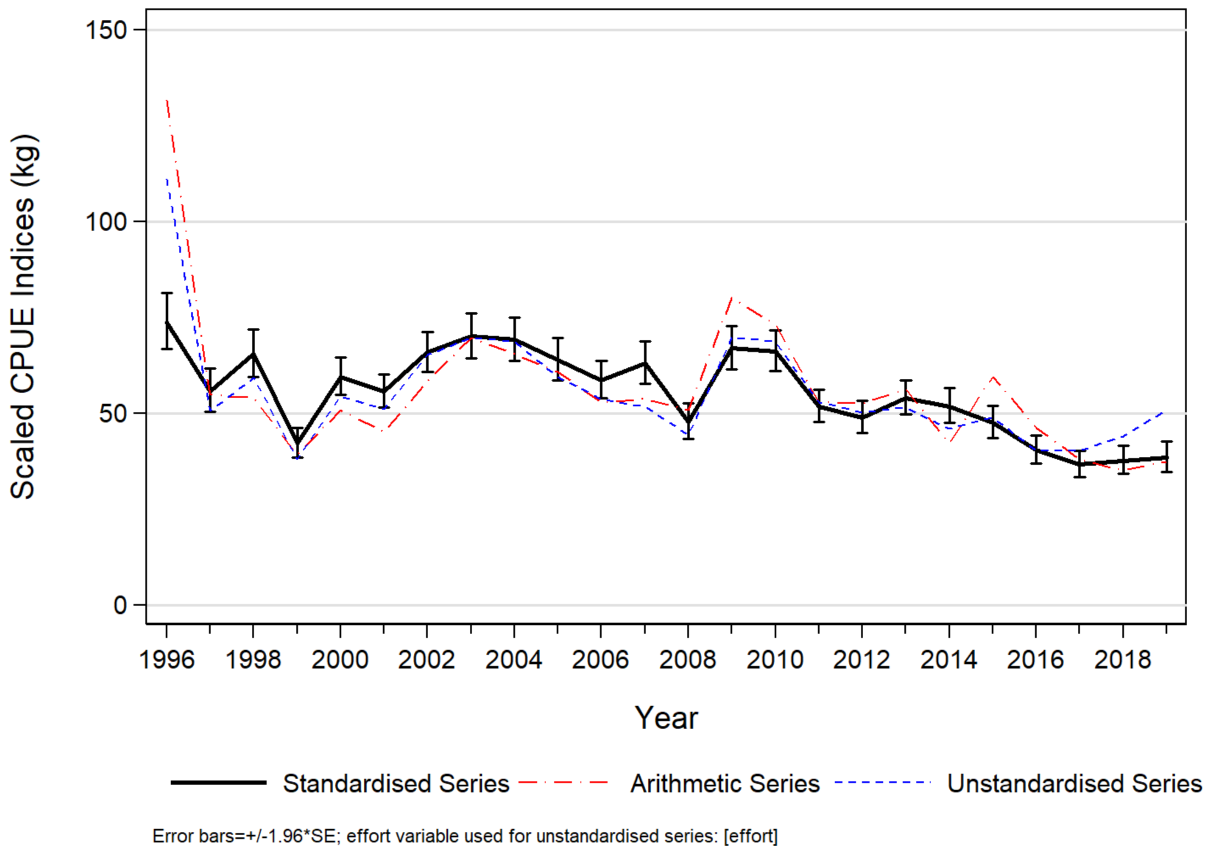

Figure C.19. Three positive catch CPUE series for REBS from 1996 to 2019 in the 3CD5AB bottom trawl fishery. The solid line is the standardised CPUE series from the lognormal model (Eq. C.3). The arithmetic series (Eq. C.1) and the unstandardised series (Eq. C.2) are also presented. All three series have been scaled to same geometric mean.

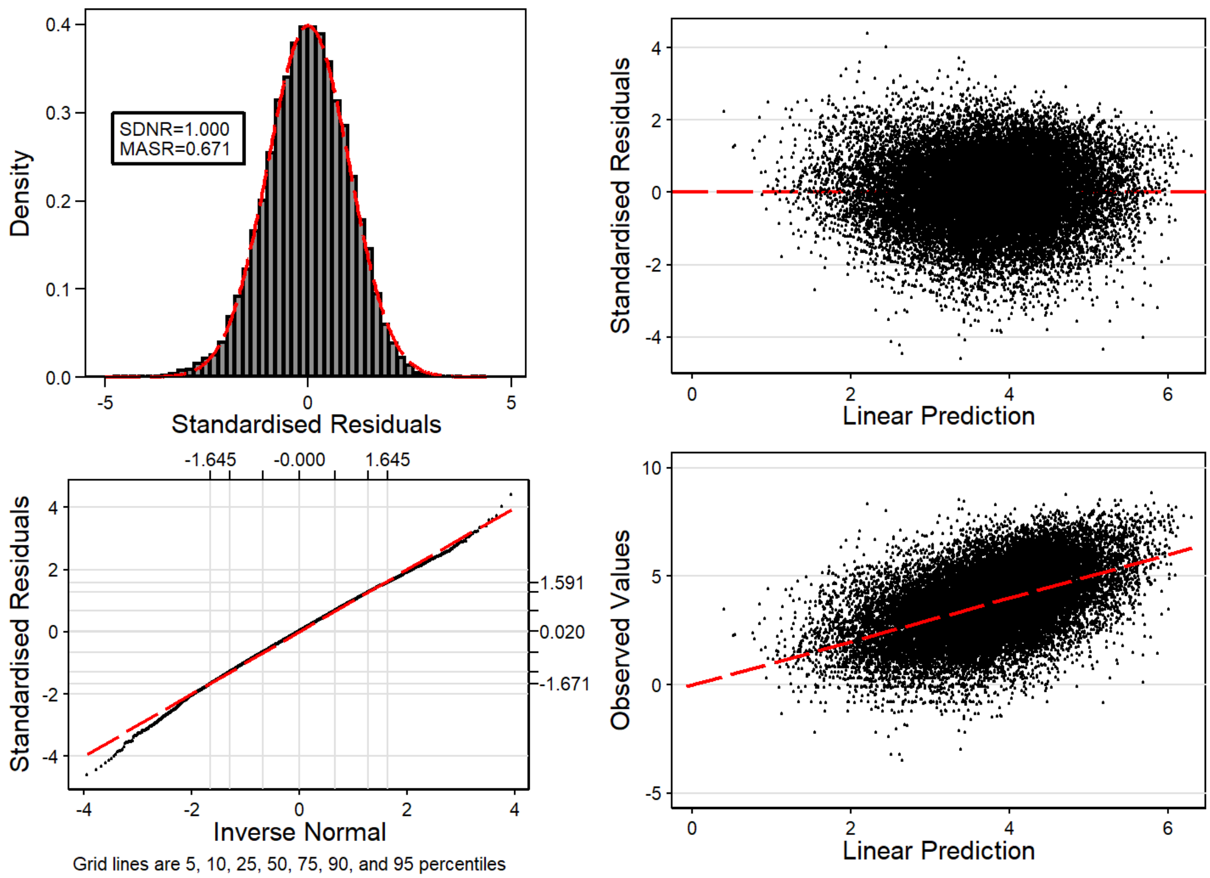

Figure C.20. Residual diagnostic plots for the GLM lognormal analysis for REBS in the 3CD5AB bottom trawl fishery. Upper left: histogram of the standardised residuals with overlaid lognormal distribution (SDNR = standard deviation of normalised residuals. MASR = median of absolute standardised residuals). Lower left: Q-Q plot of the standardised residuals with the outside horizontal and vertical lines representing the 5th and 95th percentiles of the theoretical and observed distributions. Upper right: standardised residuals plotted against the predicted CPUE. Lower right: observed CPUE plotted against the predicted CPUE.

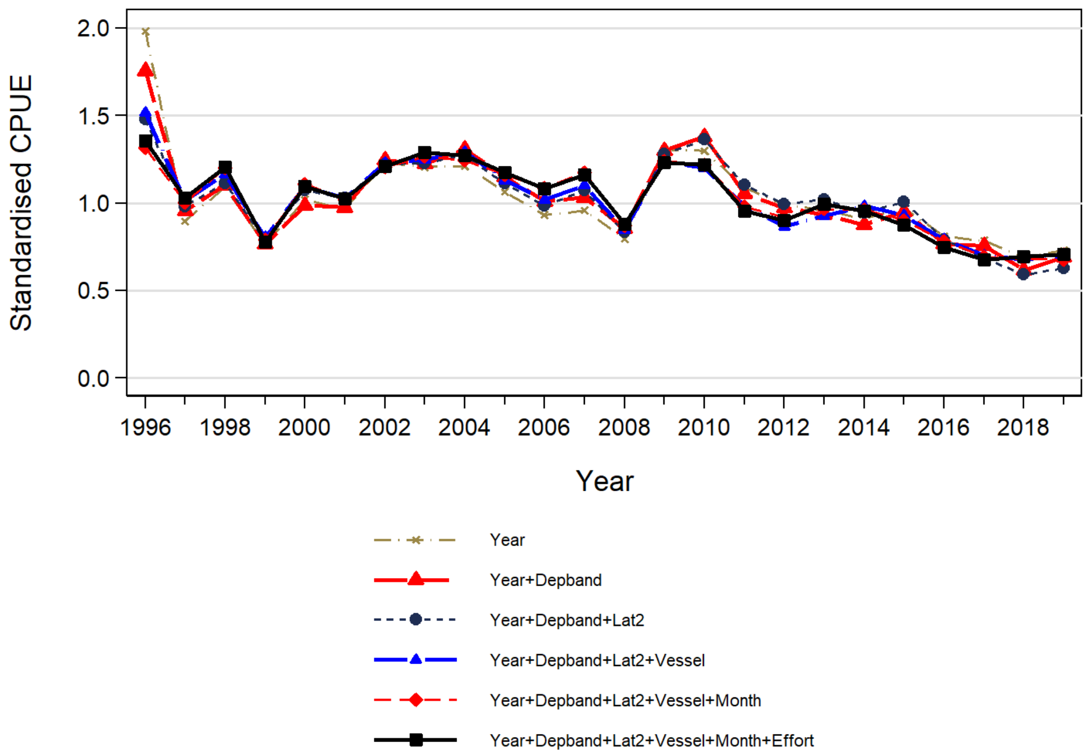

Figure C.21. Plot showing the year coefficients after adding each successive term of the standardised lognormal regression analysis for REBS in the 3CD5AB bottom trawl fishery. The final model is shown with a thick solid black line. Each line has been scaled so that the geometric mean equals 1.0.

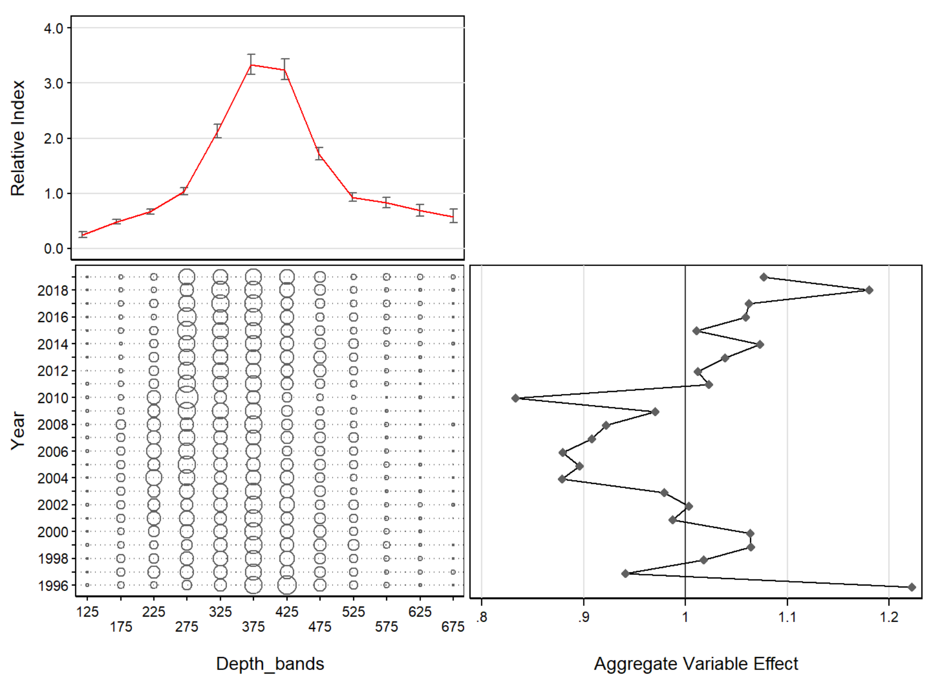

Figure C.22. CDI plot showing the effect of introducing the categorical variable [Depth_bands] to the lognormal regression model for REBS in the 3CD5AB bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution by year of variable records (bottom left), and the cumulative effect of variable by year (bottom right).

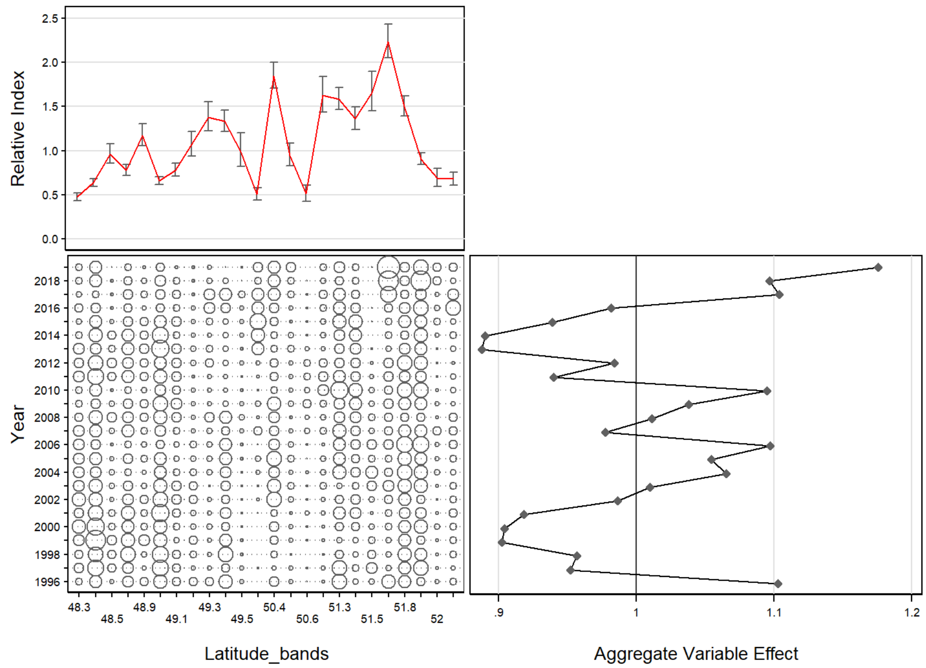

Figure C.23. CDI plot showing the effect of introducing the categorical variable [Latitude_bands] to the lognormal regression model for REBS in the 3CD5AB bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution by year of variable records (bottom left), and the cumulative effect of variable by year (bottom right).

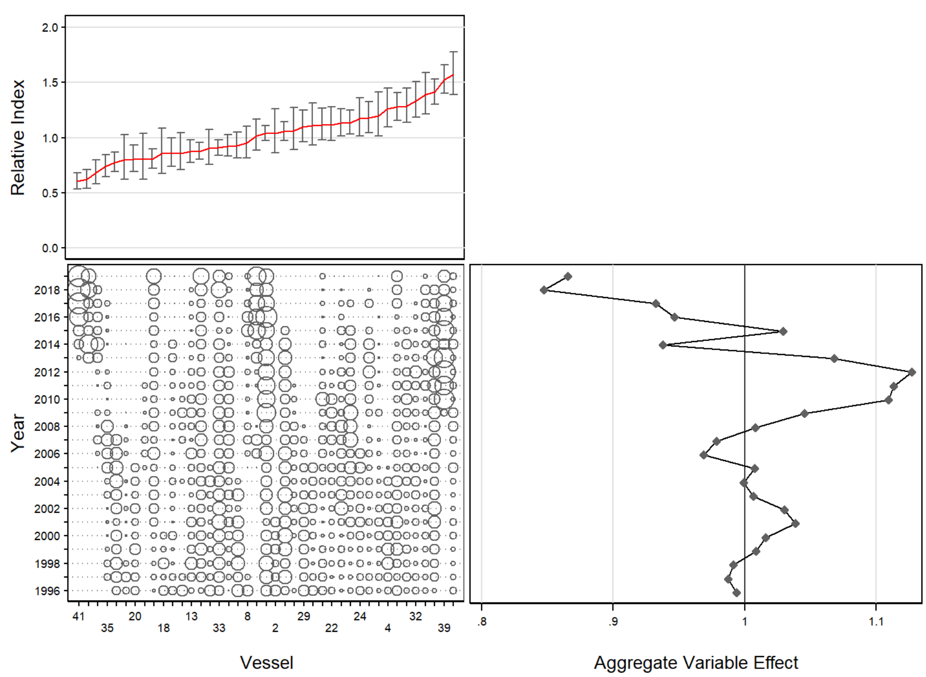

Figure C.24. CDI plot showing the effect of introducing the categorical variable [Vessel] to the lognormal regression model for REBS in the 3CD5AB bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution by year of variable records (bottom left), and the cumulative effect of variable by year (bottom right).

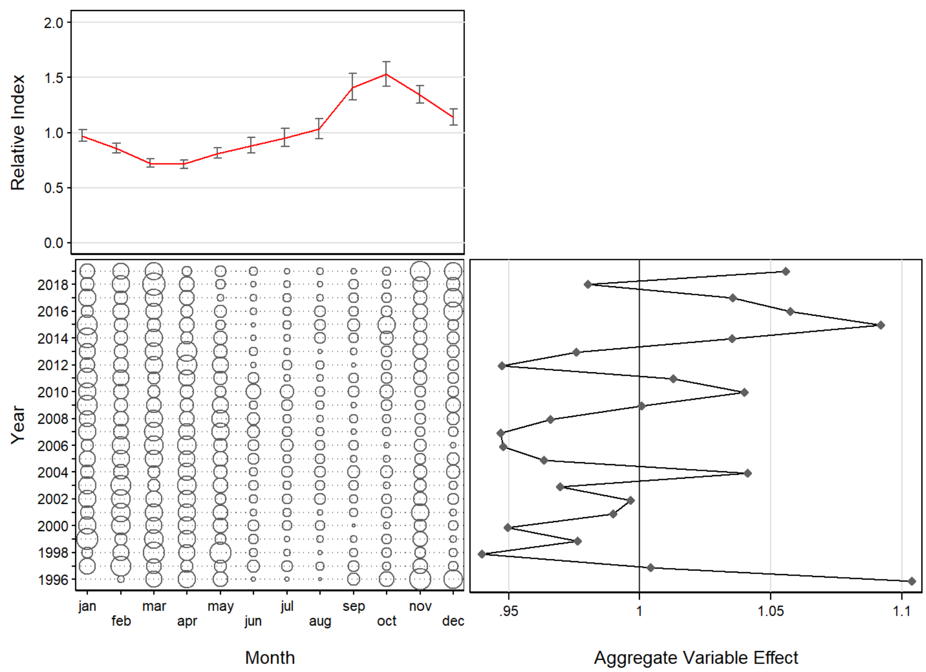

Figure C.25. CDI plot showing the effect of introducing the categorical variable [Month] to the lognormal regression model for REBS in the 3CD5AB bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution by year of variable records (bottom left), and the cumulative effect of variable by year (bottom right).

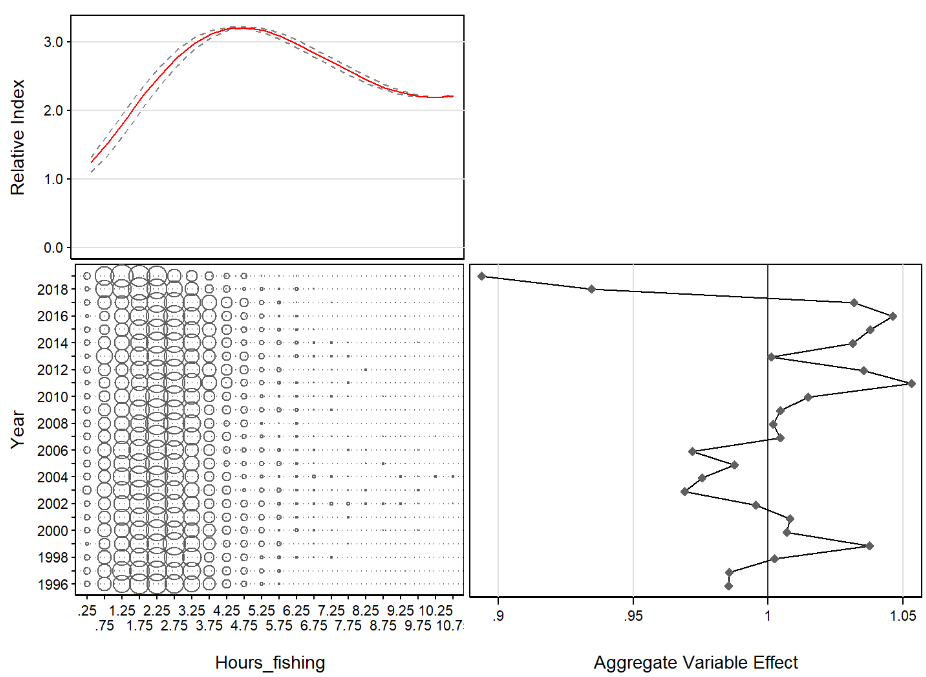

Figure C.26. CDI plot showing the effect of introducing the categorical variable [Hours fishing] to the lognormal regression model for REBS in the 3CD5AB bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution by year of variable records (bottom left), and the cumulative effect of variable by year (bottom right).

C.5.4.2. Bottom trawl fishery: binomial logit model

The same explanatory variables used in the lognormal model were offered sequentially to this model, beginning with the year categorical variable, until the improvement in the model R^2 was less than 1% (Table C.14). A binary variable which equalled 1 for positive catch tows and 0 for zero catch tows was used as the dependent variable. The final binomial model accounted for 40% of the total model deviance, with the year variable explaining less than 1% of the model deviance. The resulting CPUE index series is presented in Figure C.27.

*Table C.14. Order of acceptance of variables into the binomial model of presence/absence of verified landings plus discards of REBS south in 3CD5AB bottom trawl fishery with the amount of explained deviance (R^2) for each variable. Variables accepted into the model are marked in bold with an *. Year was forced as the first variable.*

Variable	1	2	3	4	5
Year*	**0.0075**	-	-	-	-
Depth bands*	0.3531	**0.3581**	-	-	-
0.1° Latitude bands*	0.1011	0.1061	**0.3844**	-	-
Vessel*	0.0498	0.0535	0.3735	**0.3976**	-
Hours fished	0.0301	0.0378	0.3737	0.3961	0.4072
Month	0.0384	0.0446	0.3662	0.3929	0.4049
DFO locality*	0.1175	0.1237	0.3819	0.3911	0.4043
Improvement in deviance	0	0.3506	0.0263	0.0132	0.0096

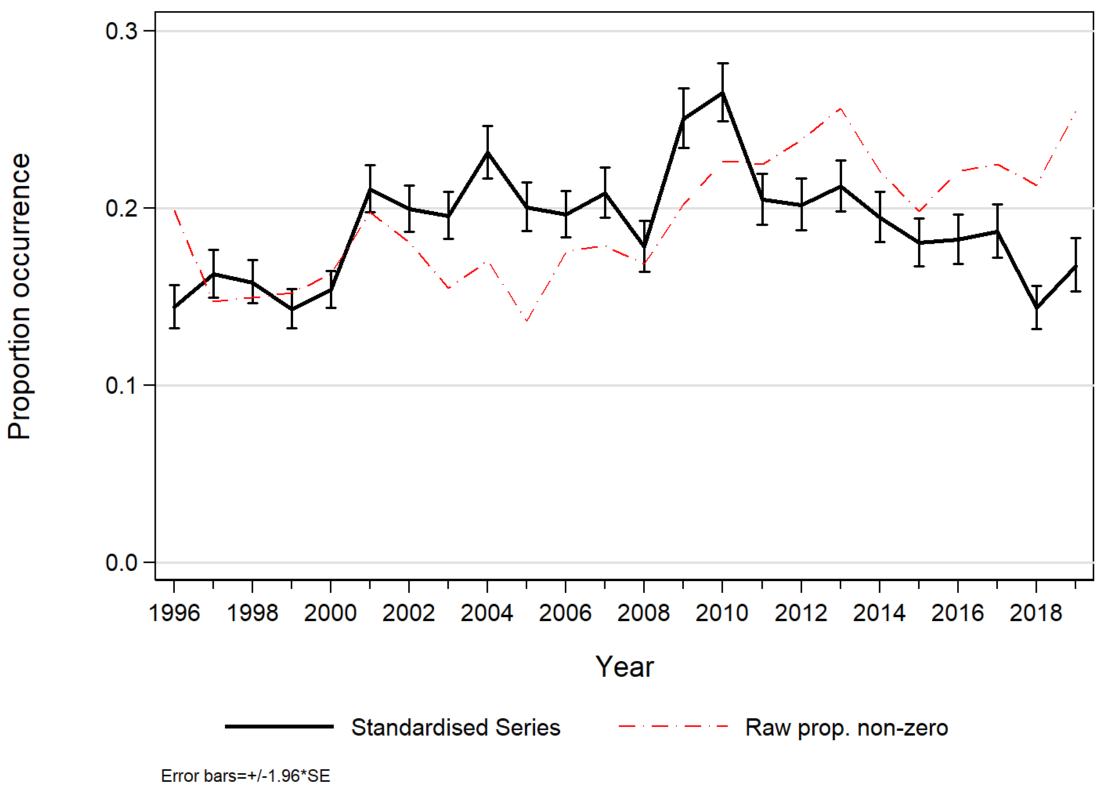

Figure C.27. Binomial index series for the REBS south 3CD5AB bottom trawl fishery also showing the trend in proportion of zero tows from the same data set.

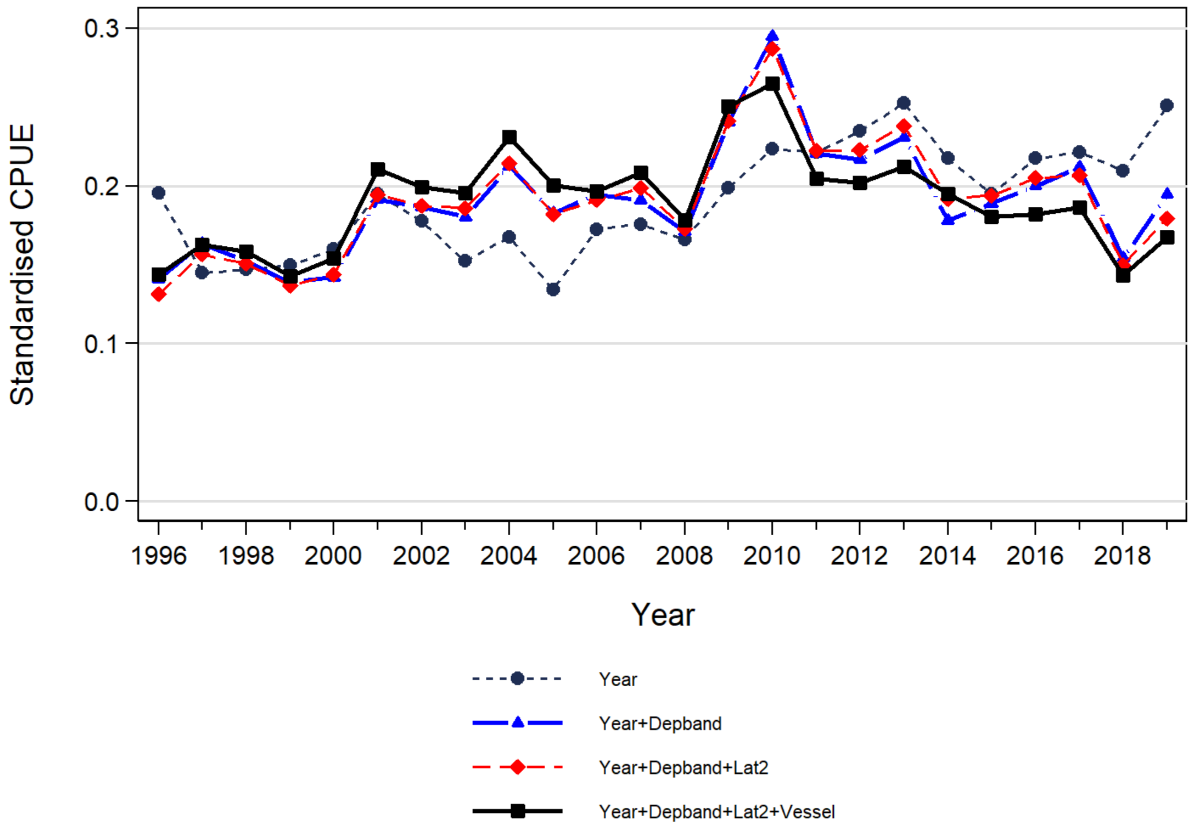

Figure C.28. Plot showing the year coefficients after adding each successive term of the standardised binomial regression analysis for REBS in the 3CD5AB bottom trawl fishery. The final model is shown with a thick solid black line. Each line has been scaled so that the geometric mean equals 1.0.

The selected explanatory variables included `[0.1°Latitude_bands]`, `[Depth_bands]` and `[Vessel]`, in addition to `[Year]`. This binomial standardised series differs from the lognormal series, in that it is generally increasing to the early 2010s and then decreases to the end of the series (Figure C.27). The binomial series also changes quite a bit from the unstandardised series, which is generally increasing over the entire period. A stepwise plot (Figure C.28) showing the effect of adding each successive explanatory variable, indicates that much of the shift away from the unstandardised series occurs with the addition of the first `[Depth_bands]` variable (Figure C.29), which has a trend of increasing depth (with corresponding increase in occurrence) in the latter half of the series. There is also a strong downward movement of occurrence in 1996, the first year of the series. The addition of the `[0.1°Latitude_bands]` variable (Figure C.30) has a variable effect on the series, jumping above and below the 1.0 line annually. There is a more systematic effect with the addition of the `[Vessel]` variable (Figure C.31), with a strong trending effect of moving from predominantly less successful to more successful vessels, culminating in the final standardised trend.

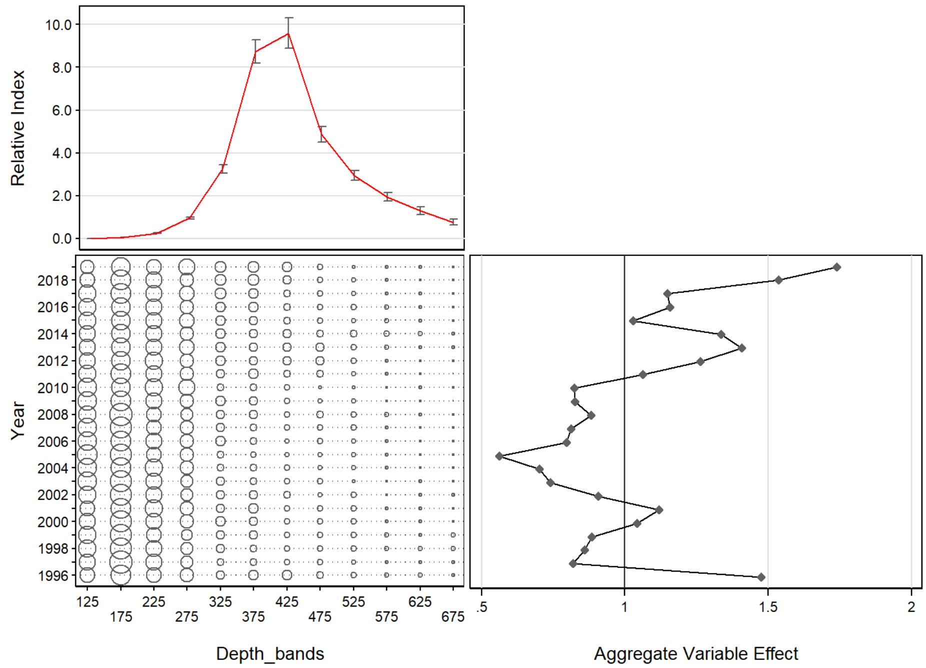

Figure C.29. CDI plot showing the effect of introducing the categorical variable [Depth bands] to the binomial regression model for REBS in the 3CD5AB bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution by year of variable records (bottom left), and the cumulative effect of variable by year (bottom right).

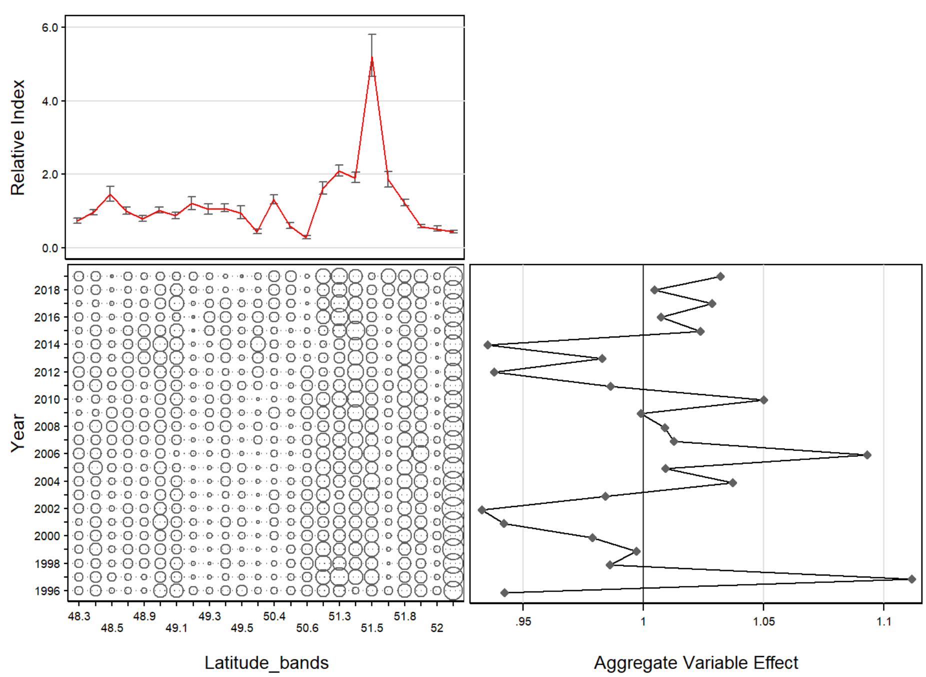

Figure C.30. CDI plot showing the effect of introducing the categorical variable [Latitude bands] to the binomial regression model for REBS in the 3CD5AB bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution by year of variable records (bottom left), and the cumulative effect of variable by year (bottom right).

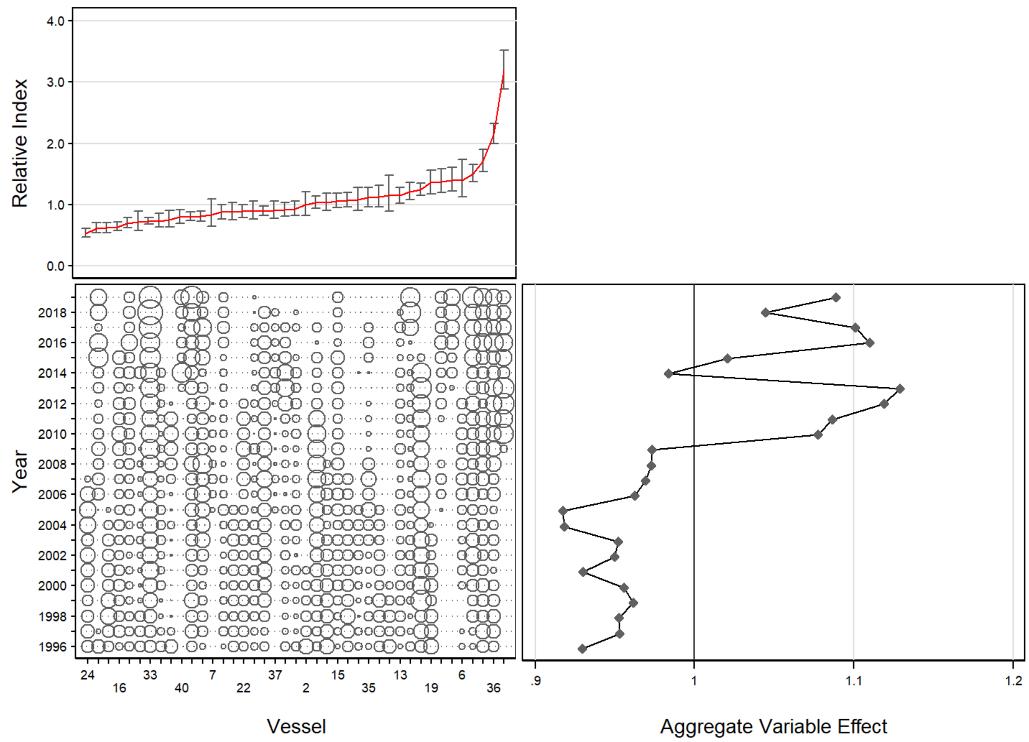

Figure C.31. CDI plot showing the effect of introducing the categorical variable [Vessel] to the binomial regression model for REBS in the 3CD5AB bottom trawl fishery. Each plot consists of subplots showing the effect by level of variable (top left), the relative distribution by year of variable records (bottom left), and the cumulative effect of variable by year (bottom right).

C.5.4.3. Bottom trawl fishery: combined model

The two series show a combination of effects from the two contributing models when they are combined using equation Eq. C.4 (Figure C.32). The first part of the resulting series resembles the binomial component, showing a slightly increasing trend up to a peak around 2010, followed by a declining trend to the end of the series, which more closely resembles the lognormal component.

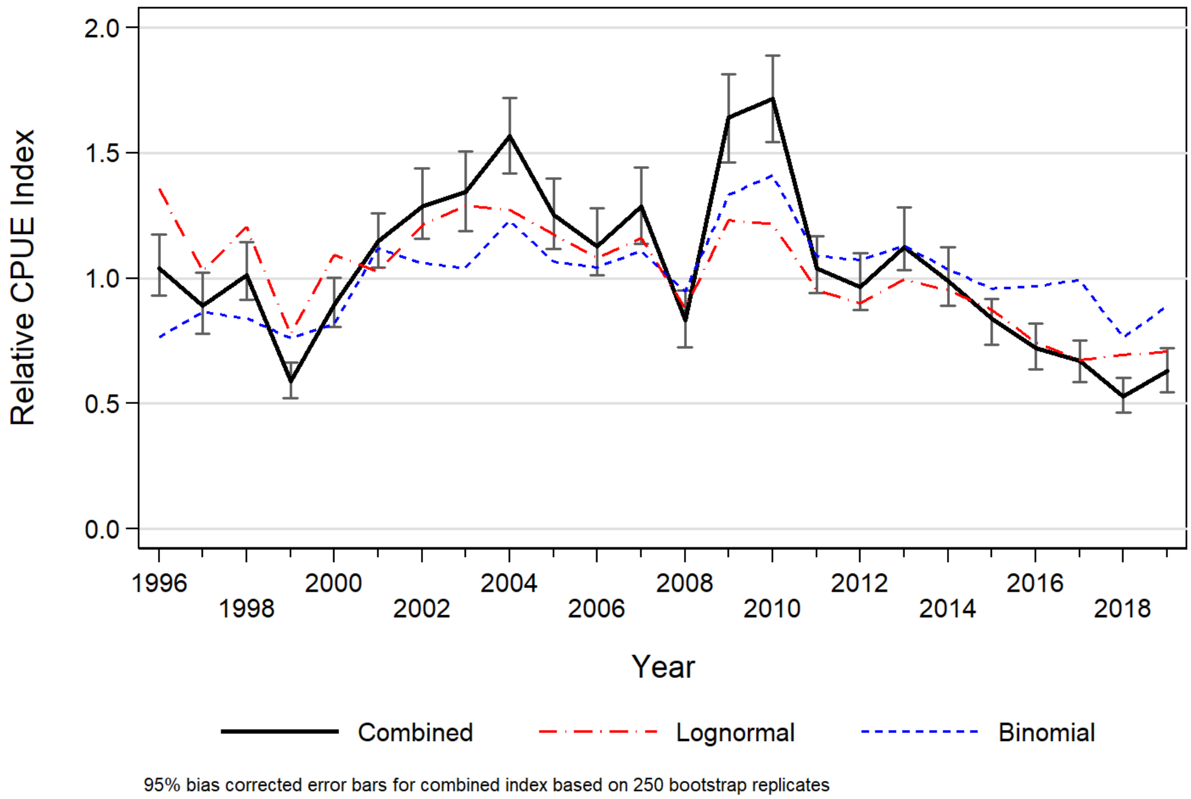

Figure C.32. Combined index series (Eq. C.4) for the REBS south 3CD5AB bottom trawl fishery also showing the contributing lognormal and binomial index series. Confidence bounds based on 250 bootstrap replicates.

C.5.5. REBS south relative indices of abundance

Table C.15 summarises the suite of relative abundance indices and associated standard errors derived from this REBS south CPUE analysis. The CPUE indices used in the age-structured stock assessment model appear as the delta-lognormal (combined) indices from the bottom trawl data (Figure C.32, Table C.15). The associated bootstrap standard errors (SE) were used as the initial CVs when fitting the stock assessment model, which were then modified by adding various levels of process error which changed the relative fit of the model to these indices.

Table C.15. Relative indices of annual CPUE from the arithmetic, unstandardised, lognormal models of non-zero bottom trawl catches of REBS south in 3CD5AB. Also shown are the indices from the binomial model of presence/absence in this fishery and the combined delta-lognormal model (Eq. C.4). All indices are scaled so that their geometric means equal 1.0. Upper and lower 95% analytic confidence bounds and associated standard error (SE) are presented for the lognormal model, while bootstrapped (250 replicates) upper and lower 95% confidence bounds and the associated SE are presented for the combined model.

Year	Arithmetic Index (Eq. C.1)	Geometric Index (Eq. C.2)	Lognormal (Eq. C.3)				Binomial Index (Eq. C.3)	Combined (Eq. C.4)			
			Index	Lower bound	Upper bound	SE		Index	Lower bound	Upper bound	SE
1996	2.425	2.044	1.357	1.228	1.498	0.0507	0.766	1.039	0.932	1.175	0.0599
1997	1.009	0.932	1.028	0.930	1.137	0.0513	0.865	0.889	0.780	1.023	0.0714
1998	0.995	1.092	1.205	1.096	1.324	0.0481	0.841	1.014	0.913	1.145	0.0613
1999	0.722	0.700	0.776	0.708	0.850	0.0464	0.761	0.590	0.520	0.665	0.0640
2000	0.935	1.002	1.095	1.009	1.188	0.0417	0.818	0.896	0.806	1.001	0.0513
2001	0.831	0.941	1.026	0.948	1.109	0.0399	1.121	1.149	1.044	1.260	0.0482
2002	1.076	1.202	1.212	1.121	1.311	0.0399	1.061	1.286	1.157	1.438	0.0548
2003	1.282	1.284	1.290	1.187	1.402	0.0425	1.041	1.343	1.189	1.508	0.0604
2004	1.206	1.265	1.273	1.174	1.381	0.0415	1.230	1.566	1.418	1.719	0.0521
2005	1.119	1.095	1.175	1.077	1.282	0.0443	1.067	1.254	1.116	1.399	0.0568
2006	0.973	0.989	1.081	0.995	1.175	0.0423	1.045	1.129	1.012	1.279	0.0537
2007	0.991	0.952	1.161	1.064	1.266	0.0442	1.109	1.287	1.140	1.441	0.0575
2008	0.936	0.817	0.881	0.799	0.971	0.0495	0.948	0.835	0.726	0.951	0.0691
2009	1.475	1.288	1.233	1.132	1.342	0.0432	1.333	1.643	1.464	1.813	0.0548
2010	1.347	1.264	1.217	1.124	1.318	0.0407	1.411	1.717	1.545	1.888	0.0503
2011	0.972	0.975	0.954	0.879	1.035	0.0415	1.089	1.039	0.941	1.169	0.0530
2012	0.969	0.924	0.901	0.827	0.981	0.0437	1.073	0.967	0.873	1.100	0.0584
2013	1.034	0.949	0.996	0.918	1.080	0.0417	1.130	1.125	1.032	1.282	0.0537
2014	0.777	0.846	0.953	0.874	1.040	0.0446	1.036	0.988	0.891	1.123	0.0579
2015	1.097	0.900	0.875	0.800	0.957	0.0457	0.960	0.840	0.735	0.919	0.0564
2016	0.851	0.742	0.745	0.681	0.816	0.0463	0.969	0.722	0.638	0.820	0.0619
2017	0.699	0.739	0.675	0.614	0.741	0.0481	0.993	0.670	0.586	0.752	0.0611
2018	0.646	0.812	0.694	0.629	0.766	0.0504	0.764	0.530	0.464	0.602	0.0651
2019	0.688	0.936	0.707	0.638	0.784	0.0529	0.890	0.630	0.547	0.720	0.0701

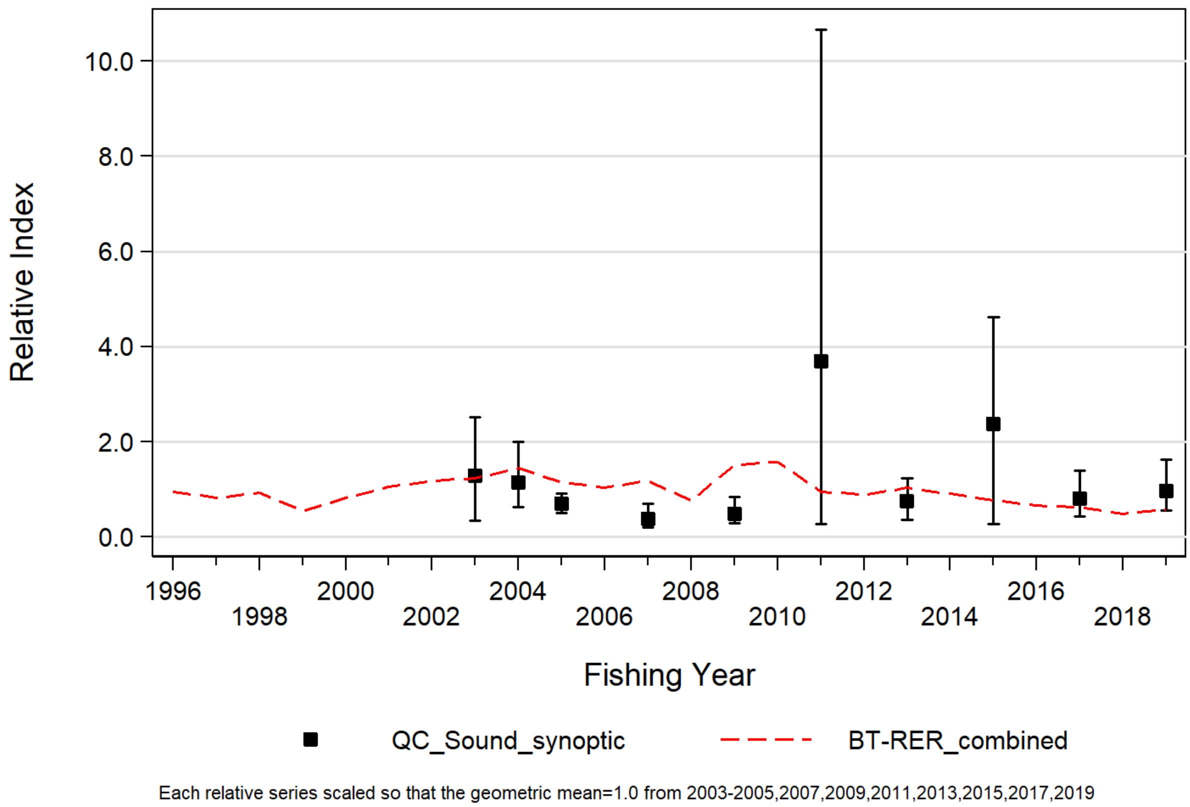

Figure C.33. Comparison of the Queen Charlotte Sound synoptic survey series with the combined index series (Eq. C.4) for the REBS south 3CD5AB bottom trawl fishery. Survey confidence bounds based on 1000 bootstrap simulations.

C.5.6. Comparison of REBS south combined series with synoptic surveys

C.5.6.1. Queen Charlotte Sound survey

Figure C.33 compares the REBS south combined series (Figure C.32, Table C.15) with the relative biomass series from the Queen Charlotte Sound synoptic survey (see Appendix B, Section B.2). This comparison is difficult to evaluate, given the very large error bars associated with the 2011 index. However, there is general agreement between the two series, given the high level of variability that seems to be associated with this survey.

C.5.6.2. West coast Vancouver Island survey

Figure C.34 compares the REBS south combined series (Figure C.32, Table C.15) with the relative biomass series from the west coast Vancouver Island synoptic survey (see Appendix B, Section B.3). This comparison is also difficult to evaluate, given the large error bars associated with the higher indices in 2004, 2006, 2010 and 2016. The 2018 index is the lowest in the series while the 2012 and 2014 indices are also low. This run of low indices, notwithstanding the higher 2016 index, tends to corroborate the declining trend from 2010 in the CPUE series.

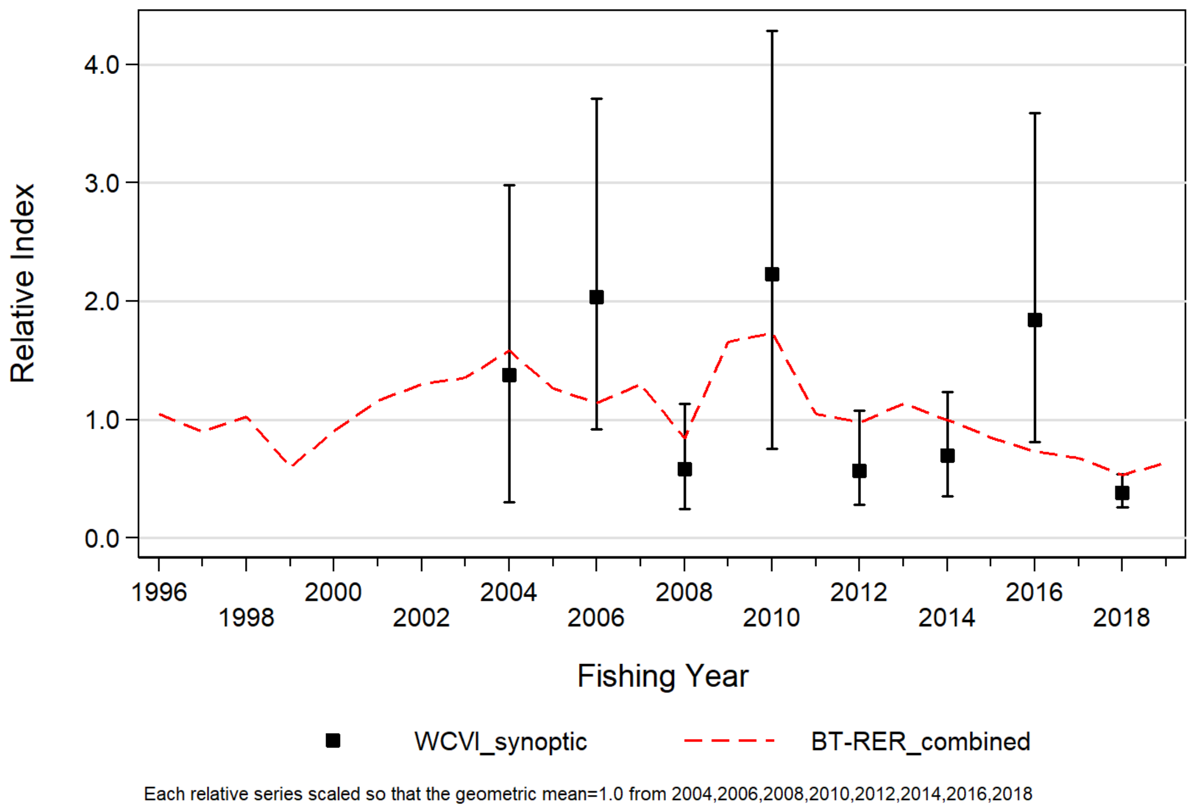

Figure C.34. Comparison of the west coast Vancouver Island synoptic survey series with the combined index series (Eq. C.4) for the REBS south 3CD5AB bottom trawl fishery. Survey confidence bounds based on 1000 bootstrap simulations.

C.6. COMPARISON OF REBS NORTH AND REBS SOUTH COMBINED SERIES

Figure C.35 compares the combined series for REBS north (areas 5DE) with the equivalent series for REBS south (areas 3CD5AB). While they both end up at the same place at the end of the series (about 60% of the series mean), they take quite different trajectories to get there. The REBS north series climbs to more than double the series mean in 2016, followed by a sharp drop to 60% of the mean by 2019. The REBS south series peaks around 2010 at 50-60% greater than the series mean and then gradually declines to 60% of the mean in 2019.

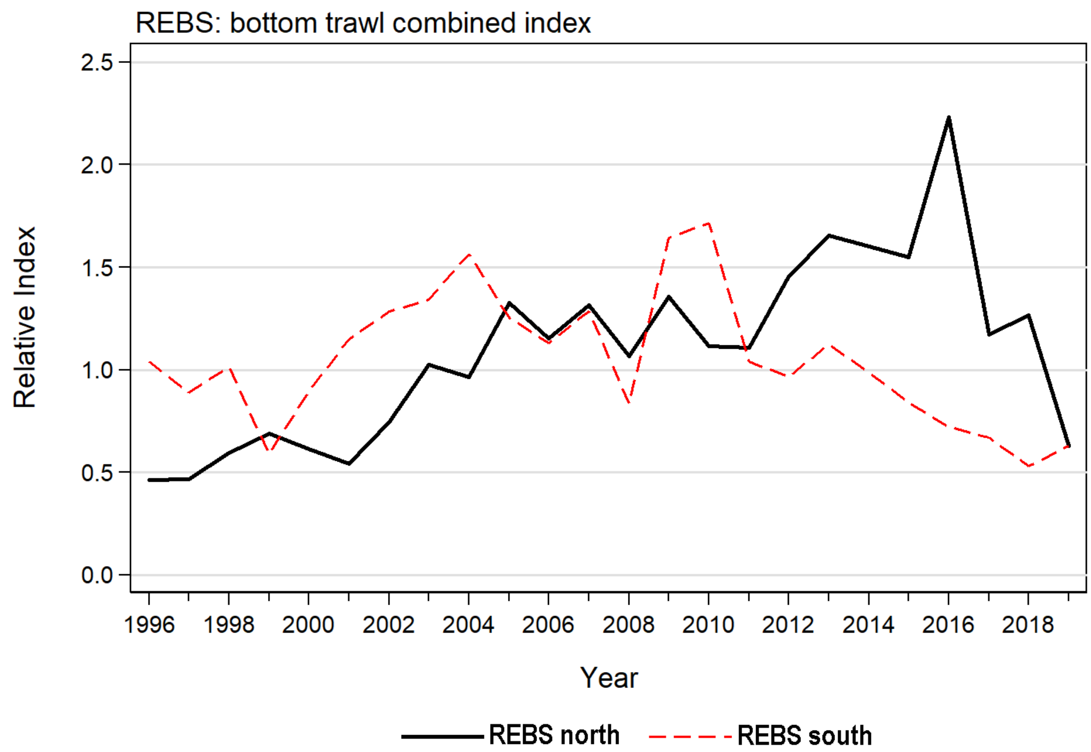

Figure C.35. Comparison of the REBS north 5DE BT combined index series with the REBS south 3CD5AB BT combined index.

C.7. REFERENCES – CPUE

Bentley, N., Kendrick, T.H., Starr, P.J., and Breen, P.A. 2012. Influence plots and metrics: tools for better understanding fisheries catch-per-unit-effort standardizations. ICES J. Mar. Sci. 69(1): 84-88.

Creamer, J.M. 2016. Using genetic species identification and environmental data to distinguish historical catches of cryptic Blackspotted Rockfish (*Sebastes melanostictus*) and Rougheye Rockfish (*Sebastes aleutianus*) in British Columbia. Master's thesis, Simon Fraser University, Burnaby, BC, 40 p.

Fletcher, D., Mackenzie, D. and Villouta, E. 2005. Modelling skewed data with many zeros: A simple approach combining ordinary and logistic regression. Environmental and Ecological Statistics12, 45–54.

Francis, R.I.C.C. 2001. Orange roughy CPUE on the South and East Chatham Rise. N.Z. Fish. Ass. Rep. 2001/26: 30 pp.

Quinn, T.R. and R.B. Deriso. 1999. Quantitative Fish Dynamics. Oxford University Press. 542 pp.

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

APPENDIX D. BIOLOGICAL DATA

This appendix describes analyses of biological data for two stocks of the Rougheye/ Blackspotted (REBS) complex along the British Columbia (BC) coast: 'REBS north' for REBS in PMFC[10] areas 5DE and 'REBS south' for REBS in 3CD5AB. Rougheye Rockfish (RER, GFBio code 394[11]) and Blackspotted Rockfish (BSR, GFBio code 425) co-mingle throughout the range of REBS; however, definitive analyses separating the two species spatially have yet to be developed. In the appendix, 'BSR' refers to genetically-determined Blackspotted Rockfish and 'RER' refers to genetically determined Rougheye Rockfish.

The analyses in this appendix include length-weight relationships, von Bertalanffy growth models, maturity schedules, natural mortality, and age proportions for use in the REBS catch-at-age stock assessment models (see Sections 0 and D.2). As well, these data were investigated for differences between area-based stocks (REBS north, REBS south) and genetically determined species (Section D.3). All biological analyses are based on REBS data extracted from the Fisheries and Oceans Canada (DFO) Groundfish database `GFBioSQL` on 2020-02-28 (72,789 records). General data selection criteria for most analyses are summarised in Table D.1, although data selection sometimes varied depending on the analysis.

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

Field	Criterion	Notes
Trip type	`[trip_type] == c(2,3)`	Definition of research observations.
	`[trip_type] == c(1,4,5)`	Definition of commercial observations
Sample type	`[sample_type] == c(1,2,6,7,8)`	Only random or total samples.
Ageing method	`[agemeth] == c(3, 17) or== (0 & [year]>=1980) or == 1 for ages 1:3`	Break & burn|bake method unknown from 1980 on (assumed B&B) surface readings for young fish
Species category code	`[SPECIES_CATEGORY_CODE]==1 (or 3)`	1 = Unsorted samples 3 = Sorted (keeper) samples
Sex code	`[sex] == c(1,2)*`	Clearly identified sex (1=male or 2=female).
Area code	`[stock]` select stock area (5DE or 3CD5AB)	PMFC major area codes 8:9 or 3:6

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

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[10] See Appendix A for historical background on the Pacific Marine Fisheries Commission (PMFC).

[11] GFBio changed the code for RER to '009', keeping code '394' for the REBS complex; however, most records are still recorded as '394'.

D.1. LIFE HISTORY

D.1.1. Allometry – Weight vs. Length

A log-linear relationship with additive errors was fit to females (*s*=2), males (*s*=1), and combined to all valid weight and length data pairs i, $\left\{W_{is}, L_{is}\right\}$:

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

where α_s and β_s are the intercept and slope parameters for each sex s.

Commercial and research survey samples, regardless of gear type, were used independently to derive length-weight parameters for consideration in the model (Table D.2); however, only research/survey data coastwide were adopted for use (Figure D.1, Figure D.2). Commercial fishery weight data were not as abundant as those from research surveys and tended to represent midsize fish (40-60 cm) more than other sizes.

*Table D.2. Length-weight parameter estimates, standard errors (SE) and number of observations (n) for REBS (females, males and combined) from survey and commercial samples, regardless of gear type from 1988 to 2019. W_i = weight (kg) of specimen i, W_{pred} = predicted weight from fitted data set. (**S**): survey data; (**C**): commercial data.*

Stock	Sex	*n*	ln(*a*)	SE ln(*a*)	*b*	SE *b*	mean W_i	SD W_i	min W_i	max W_i	mean W_{pred}
REBS N	F	4,965	-11.586	0.029	3.133	0.008	1.746	0.828	0.015	11.470	1.800
5DE	M	5,340	-11.493	0.028	3.104	0.007	1.694	0.711	0.012	9.915	1.713
(**S**)	F+M	10,306	-11.538	0.020	3.118	0.005	1.719	0.770	0.012	11.470	1.755
BSR	F	1,811	-11.589	0.031	3.132	0.008	1.524	0.918	0.014	11.470	1.537
genetic	M	1,920	-11.608	0.031	3.136	0.008	1.447	0.764	0.012	9.615	1.465
(**S**)	F+M	3,728	-11.582	0.022	3.130	0.006	1.485	0.843	0.014	11.470	1.500
REBS N	F	1,826	-10.776	0.073	2.924	0.019	1.697	0.638	0.250	8.147	1.774
5DE	M	1,672	-10.877	0.075	2.945	0.020	1.610	0.554	0.527	6.561	1.740
(**C**)	F+M	3,499	-10.859	0.053	2.943	0.014	1.657	0.603	0.250	8.147	1.758
REBS S	F	3,612	-11.404	0.018	3.086	0.005	1.377	0.843	0.007	11.015	1.404
3CD5AB	M	4,199	-11.382	0.016	3.076	0.004	1.332	0.674	0.005	4.835	1.454
(**S**)	F+M	7,809	-11.389	0.012	3.080	0.003	1.353	0.757	0.005	11.015	1.433
RER	F	1,184	-11.474	0.030	3.111	0.008	1.502	0.911	0.007	5.935	1.505
genetic	M	1,423	-11.447	0.024	3.100	0.006	1.428	0.815	0.005	6.600	1.434
(**S**)	F+M	2,608	-11.466	0.019	3.107	0.005	1.462	0.861	0.005	6.600	1.466
REBS S	F	1,240	-7.917	0.185	2.180	0.048	1.625	0.414	0.500	4.900	1.634
3CD5AB	M	1,136	-7.793	0.172	2.146	0.045	1.574	0.399	0.500	4.200	1.597
(**C**)	F+M	2,373	-7.881	0.125	2.170	0.033	1.599	0.405	0.500	4.900	1.615

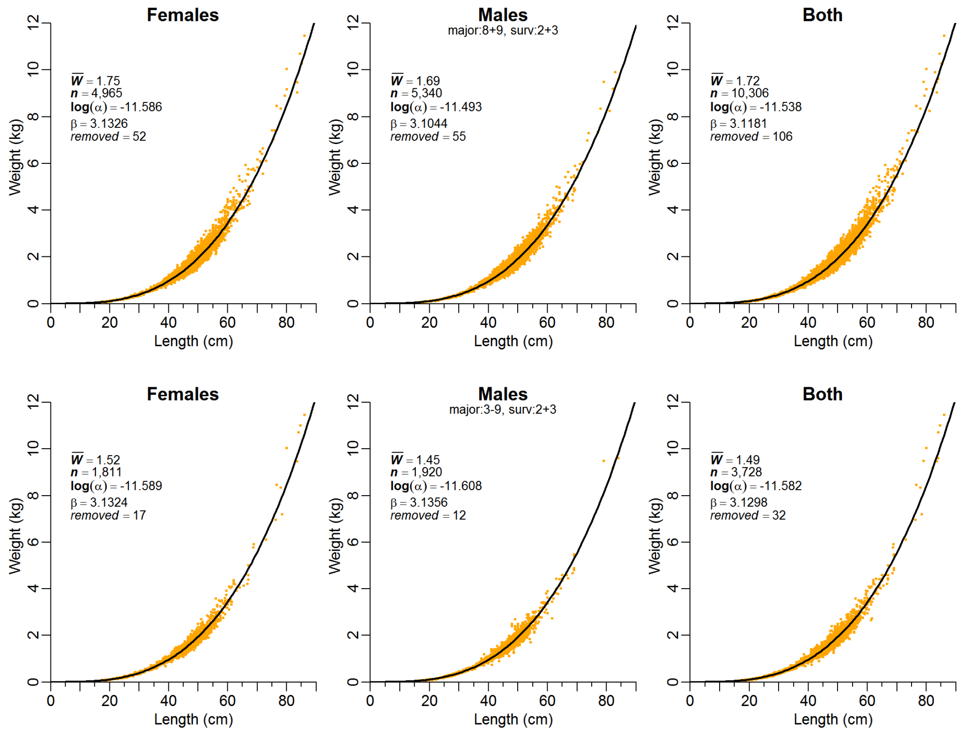


Figure D.1. Length-weight relationship for REBS north by area (top) and BSR by genetics (bottom) from research survey samples. Records with absolute value of standardised residuals >3 (starting with a preliminary fit) were dropped.

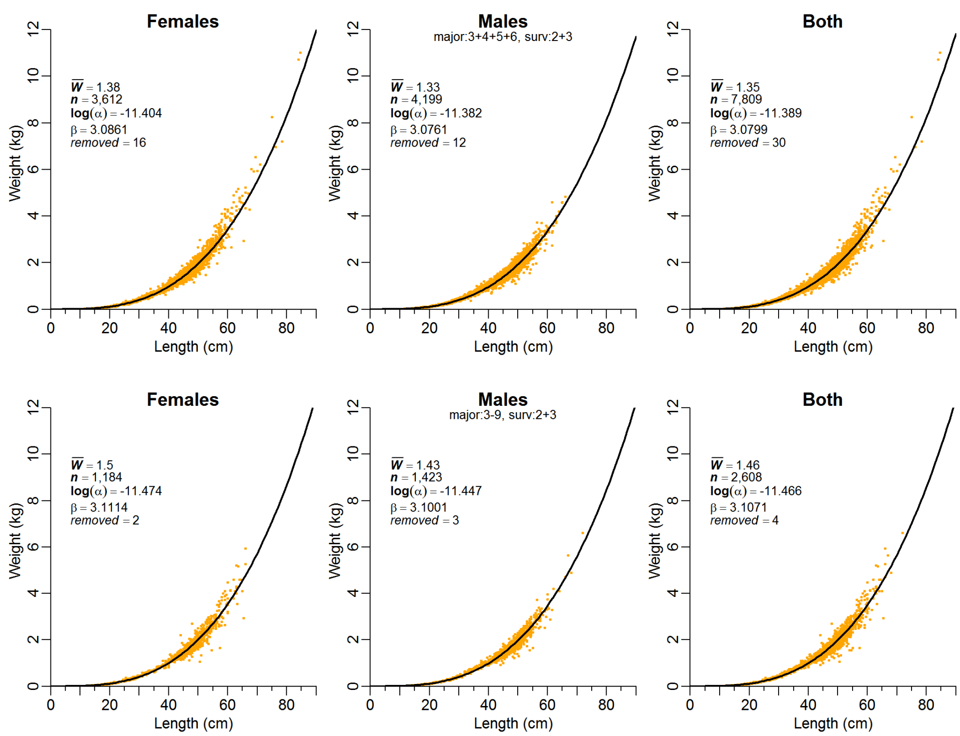


Figure D.2. Length-weight relationship for REBS south by area (top) and RER by genetics (bottom) from research survey samples. Records with absolute value of standardised residuals >3 (starting with a preliminary fit) were dropped.

D.1.2. Growth – Length vs. Age

Otolith age data were abundant for both surveys and commercial fishing trips; therefore, data from the survey were used in determining growth for the model. Of the 15211 records with age data, 15204 records had concurrent length data, 15038 records were suitable for growth analysis by sex, and 7683 of the latter came from research surveys and were used in the REBS growth analyses (females = 3608 specimens, males = 4075 specimens). The majority of these ages were determined using the break-and-burn (B&B) method (MacLellan 1997). The number of specimens by stock were REBS north = 4116 and REBS south = 3214. Of the 7683 records used for growth analysis, 2441 were genetically determined to be Blackspotted (BSR) and 2193 were genetically determined to be Rougheye (RER). Table D.3 summarises the availability of all REBS otoliths.

Table D.3. Number of REBS specimen otoliths aged by various methods. Number of samples appear in parentheses and are not additive between the sexes (i.e. otoliths by sex usually come from the same sample). The 'Charter' samples are from research surveys conducted on commercial vessels. These otoliths were collected over the period 1967 to 2018.

Trip Type	Activity	Age method	Female	Male	Unknown
Non-obs domestic	commercial	unknown	---	1 (1)	---
Non-obs domestic	commercial	thin section	82 (2)	110 (2)	---
Non-obs domestic	commercial	break & burn	1272 (49)	1471 (49)	1 (1)
Research	survey	surface read	8 (4)	14 (12)	31 (17)
Research	survey	break & burn	842 (263)	992 (286)	23 (16)
Charter	survey	thin section	1 (1)	1 (1)	---
Charter	survey	break & burn	2762 (495)	3071 (517)	13 (10)
Obs domestic	commercial	break & burn	2182 (92)	2282 (92)	52 (8)

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

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

where for each sex s,

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

κ_s = growth rate coefficient, and

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

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

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

D.1.2.1. Maximum Likelihood Estimation

Various maximum likelihood estimation (MLE) fits were made for the length vs. age data. Two growth models were used on the full set of survey data (Table D.4): von Bertalanffy and that of Schnute (1981). The von Bertalanffy fits to area-based stocks and genetically determined stocks appear in Figure D.3 (REBS north, BSR) and Figure D.4 (REBS south, RER). However, comparing cumulative length frequencies of the synoptic surveys to those from the Sablefish trap survey (which was substantially sampled), it was obvious that the latter only caught large fish (Figure D.5). The decision was made to use all survey data to determine growth parameters for potential use in the population model (Figure D.6), primarily because the synoptic surveys lacked data on older ages.

Table D.4. Age-length parameter estimates for REBS (females, males, both combined) from fits using the von Bertalanffy and Schnute growth models (Quinn and Deriso 1999, Schnute 1981) using specimens from research surveys: either all surveys or area-relevant synoptic surveys (HS = Hecate, WCHG = west coast Haida Gwaii, QCS = Queen Charlotte Sound, WCVI = west coast Vancouver Island).

MLE Model	Data Source	Sex	n	Linf (cm)	K	t_0 (cm)
REBS north vonB	All surveys	Female	1881	52.5	0.0628	-5
		Male	2021	51.4	0.0750	-2.21
		Both	3904	52.1	0.0662	-4.28
REBS north Schnute	All surveys	Female	1883	53.5	0.0436	5.56
		Male	2022	52.0	0.0580	4.54
		Both	3905	52.9	0.0485	5.42
REBS north vonB	HS + WCHG	Female	895	50.0	0.0874	-1.13
		Male	1134	49.9	0.0946	0.33
		Both	2029	49.9	0.0926	-0.03
BSR vonB	All surveys	Female	1157	52.1	0.0671	0.18
		Male	1254	51.3	0.0738	1.02
		Both	2408	51.6	0.0711	0.69
BSR Schnute	All surveys	Female	1157	52.4	0.0626	1.48
		Male	1254	50.3	0.0994	-23.9
		Both	2407	51.0	0.0849	-4.88
REBS south vonB	All surveys	Female	1413	52.0	0.0761	-1.35
		Male	1761	50.4	0.0839	-1.13
		Both	3179	51.0	0.0809	-1.20
REBS south Schnute	All surveys	Female	1413	51.8	0.0792	-1.91
		Male	1761	50.1	0.0928	-3.19
		Both	3178	50.7	0.0884	-2.80
REBS south vonB	QCS + WCVI	Female	736	52.2	0.0760	-0.87
		Male	952	50.4	0.0840	-0.80
		Both	1688	50.9	0.0820	-0.73
RER vonB	All surveys	Female	999	53.3	0.0779	-1.07
		Male	1170	51.0	0.0868	-0.92
		Both	2169	52.0	0.0829	-0.98
RER Schnute	All surveys	Female	998	52.4	0.1008	-8.65
		Male	1168	50.7	0.1033	-6.46
		Both	2172	51.4	0.1032	-7.69

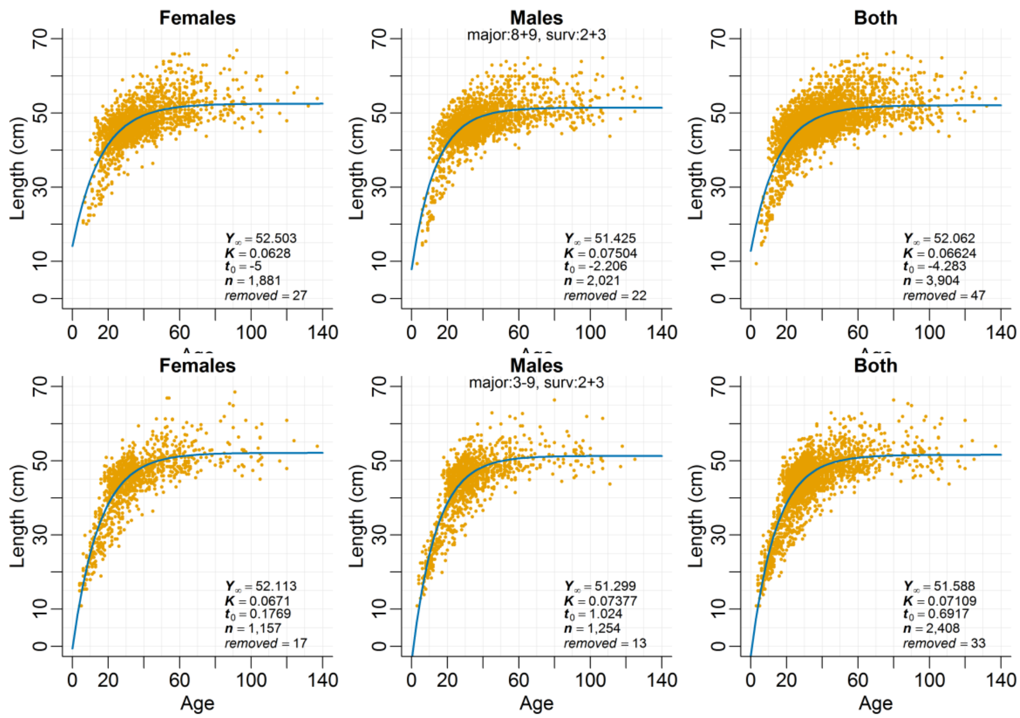


Figure D.3. Growth specified by age-length relationship: von Bertalanffy fits to REBS north ages (top) and by BSR ages (bottom). Data records come from research surveys determined by break-and-burn otoliths and surface-read otoliths from ages 1 to 3. Records with absolute value of standardised residuals >3 (starting with a preliminary fit) were dropped.

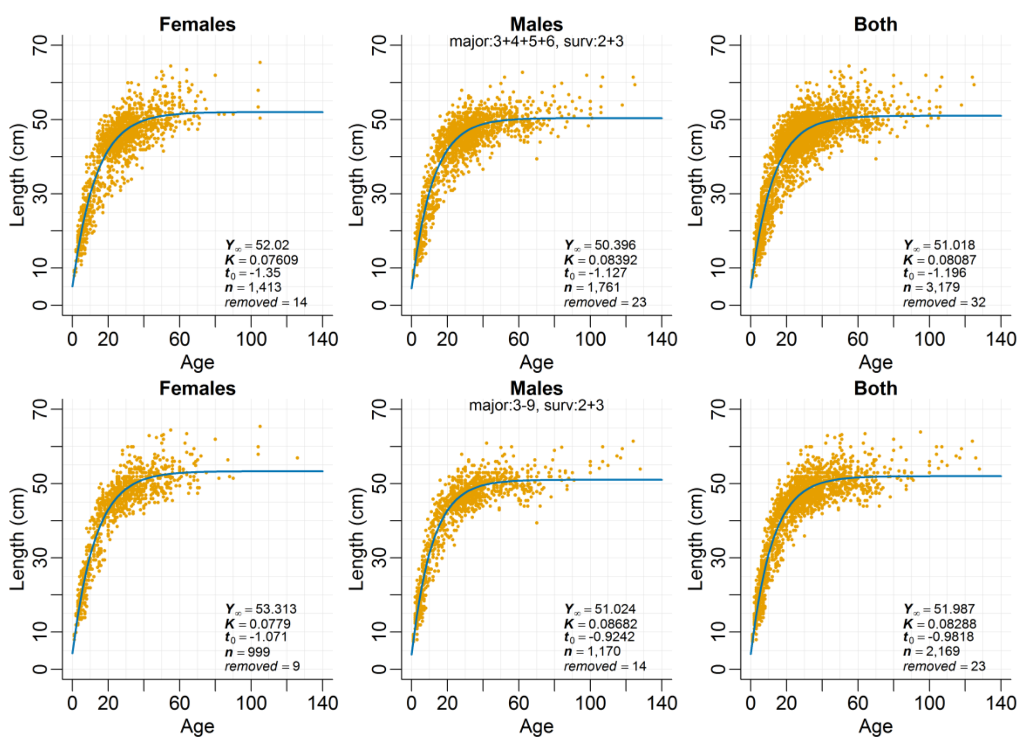


Figure D.4. Growth specified by age-length relationship: von Bertalanffy fits to REBS south ages (top) and RER ages (bottom). See caption in Figure D.3 for additional details.

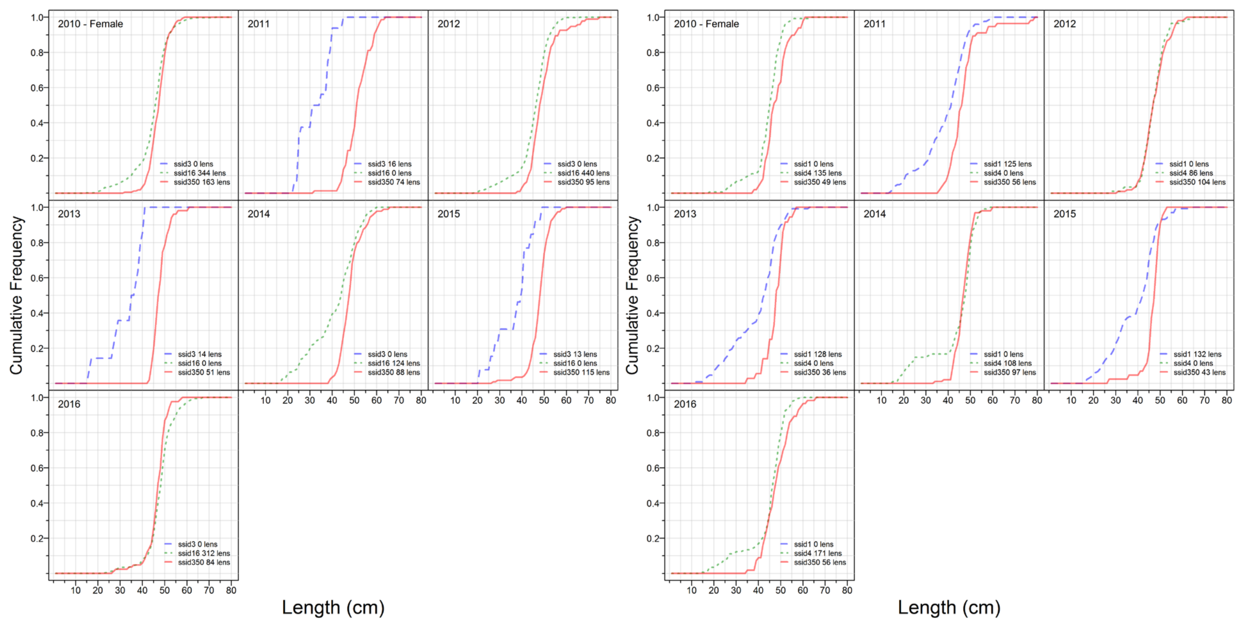


Figure D.5. Cumulative length frequencies for females (left: REBS north, right: REBS south) comparing synoptic surveys (ssid 1=QCS, ssid 3=HS, ssid 4=WCVI, ssid 16=WCHG) to the Sablefish trap survey (ssid 350).

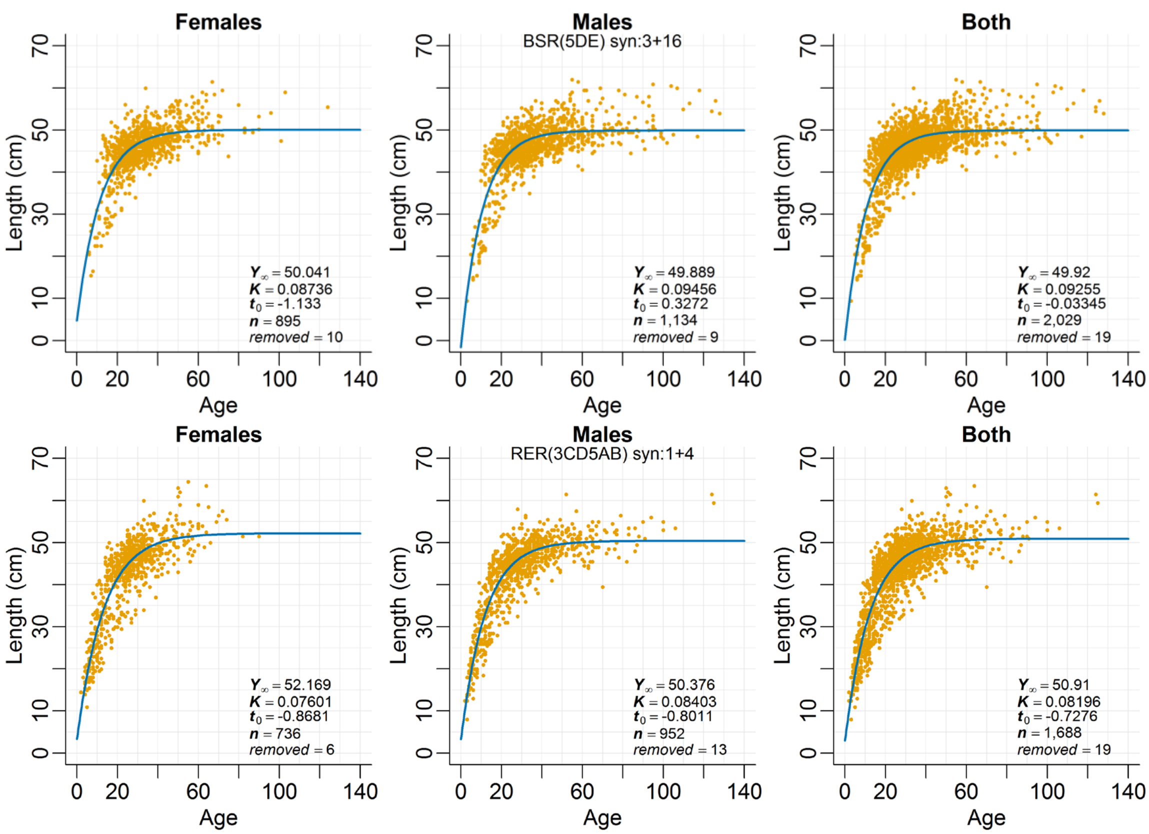


Figure D.6. Growth specified by age-length relationship: von Bertalanffy fits to data for REBS north from the HS and WCHG synoptic surveys (top) and for REBS south from the QCS and WCVI synoptic surveys (bottom). See caption in Figure D.3 for additional details.

D.1.2.2. Growth adjusted for ageing error

In the Bocaccio assessment, a method (provided by Sean Anderson, 2019, DFO Groundfish, pers. comm.) for fitting growth curves while adjusting for ageing error in [Stan probabilistic programming language]() was implemented in R using the package `rstan` (Stan Development Team 2018). We computed two measurements of ageing error: (i) CV of age by age readers' determination of accepted age (best age given uncertainty), and (ii) CV of lengths at accepted age (Figure D.7, Figure D.8). Each were used in a Bayesian fit to von Bertalanffy parameters using the random-effects Stan model on data that had been fit previously using non-linear methods (MLE or maximum likelihood estimation) to remove observations >3 standard deviations from the fit. The median parameter estimates from 4000 MCMC samples were compared to the MLE fits of the same data (i.e., outliers removed), and the median parameter estimates from the model using CVs from length-at-age were used in the Awatea population model.

Table D.5. Estimated von Bertalanffy parameters from maximum likelihood estimation (MLE) and median parameter estimates from 4000 MCMC samples. Note, the Stan model that sets CV=0.005 is considered to have no ageing error. Models highlighted in green were used in the base runs of the REBS north and REBS south stock assessments. REBS north = REBS in 5DE, REBS south = REBS in 3CD5AB, BSR = genetically determined Blackspotted, RER = genetically determined Rougheye. Synoptic surveys: HS = Hecate, WCHG = west coast Haida Gwaii, QCS = Queen Charlotte Sound, WCVI = west coast Vancouver Island.

Model	Data Source	Age Error	Female Linf	Female K	Female t0	Male Linf	Male K	Male t0
REBS N MLE	All surveys	---	52.50	0.0628	-5.000	51.42	0.0750	-2.206
REBS N MLE	HS + WCHG	---	50.04	0.0874	-1.133	49.89	0.0946	0.327
REBS N MCMC RE	All surveys	CV=0.005	52.25	0.0660	-4.140	50.78	0.0891	0.311
REBS N MCMC RE	All surveys	CV length-at-age	51.78	0.0794	0.359	50.99	0.0897	1.635
REBS N MCMC RE	All surveys	CV age readers	51.86	0.0743	-1.663	50.74	0.0910	0.727
REBS N MCMC RE	HS + WCHG	CV=0.005	49.50	0.1006	0.691	49.75	0.0989	0.880
REBS N MCMC RE	HS + WCHG	CV length-at-age	49.61	0.1085	2.998	49.75	0.1073	3.114
BSR MLE	All surveys	---	52.11	0.0671	0.177	51.30	0.0738	1.024
BSR MCMC RE	All surveys	CV=0.005	52.59	0.0632	-0.443	52.54	0.0633	-0.439
BSR MCMC RE	All surveys	CV length-at-age	52.19	0.0687	1.252	51.42	0.0750	1.955
REBS S MLE	All surveys	---	52.02	0.0761	-1.350	50.40	0.0839	-1.127
REBS S MLE	QCS + WCVI	---	52.17	0.0760	-0.868	50.38	0.0840	-0.801
REBS S MCMC RE	All surveys	CV=0.005	52.53	0.0722	-1.678	50.78	0.0799	-1.400
REBS S MCMC RE	All surveys	CV length-at-age	52.71	0.0715	-1.154	50.84	0.0798	-0.981
REBS S MCMC RE	All surveys	CV age readers	51.86	0.0743	-1.663	50.74	0.0910	0.727
REBS S MCMC RE	QCS + WCVI	CV=0.005	53.03	0.0697	-1.493	50.54	0.0821	-0.983
REBS S MCMC RE	QCS + WCVI.	CV length-at-age	52.48	0.0756	-0.138	50.39	0.0861	-0.033
RER MLE	All surveys	---	53.31	0.0779	-1.071	51.02	0.0868	-0.924
RER MCMC RE	All surveys	CV=0.005	54.15	0.0713	-1.607	51.50	0.0815	-1.251
RER MCMC RE	All surveys	CV length-at-age	53.72	0.0753	-0.903	51.37	0.0836	-0.752

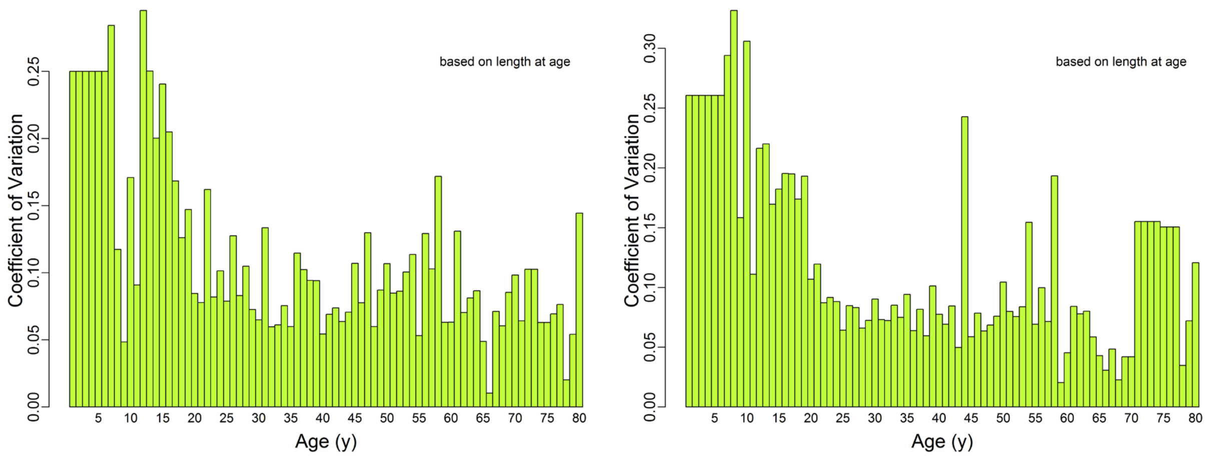


Figure D.7. Estimated ageing error for REBS north females (left) and REBS north males (right) as CVs for lengths-at-age from all surveys. Ageing error determined as CVs by age reader precision tests (not shown here) were also tried. Note: distributions have been truncated at age 80 but extend to age 135 for the von Bertalanffy fits.

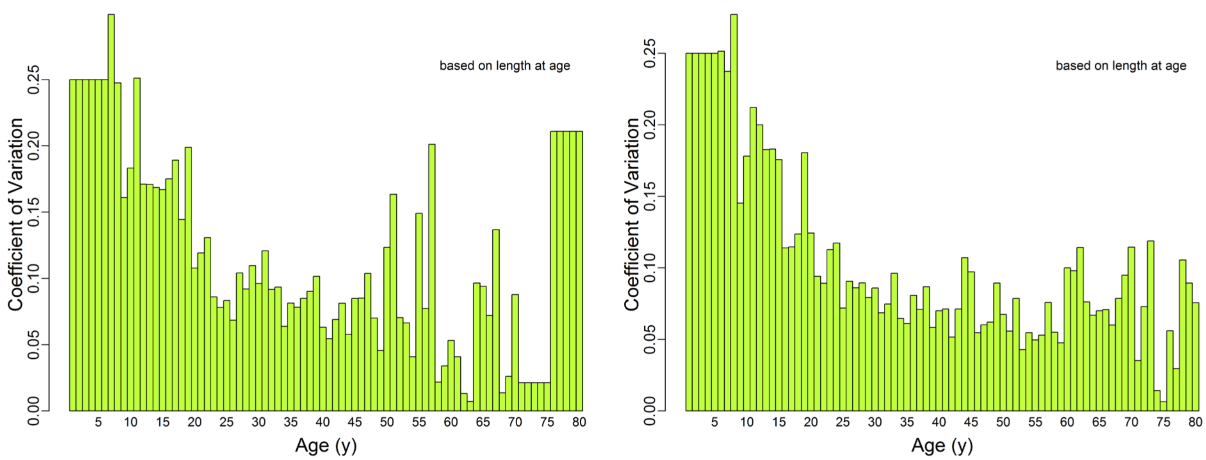


Figure D.8. Estimated ageing error for REBS south females (left) and REBS south males (right) as CVs for lengths-at-age from all surveys. Ageing error determined as CVs by age reader precision tests (not shown here) were also tried. Note: distributions have been truncated at age 80 but extend to age 135 for the von Bertalanffy fits.

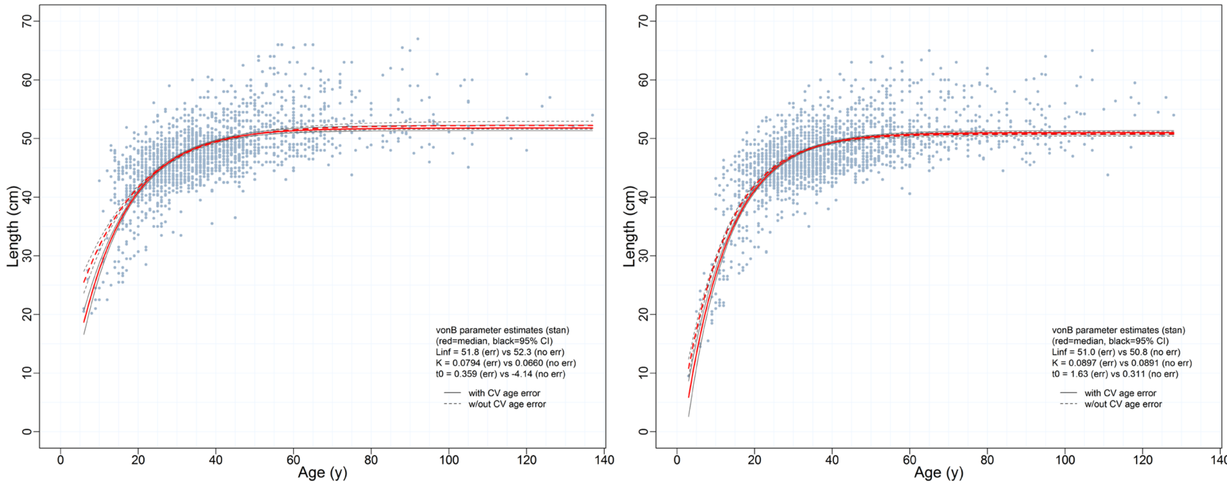


Figure D.9. REBS north: von Bertalanffy fits (left: female, right: male) using Stan to incorporate random effects error from CVs of lengths-at-age from all surveys (see Figure D.7).

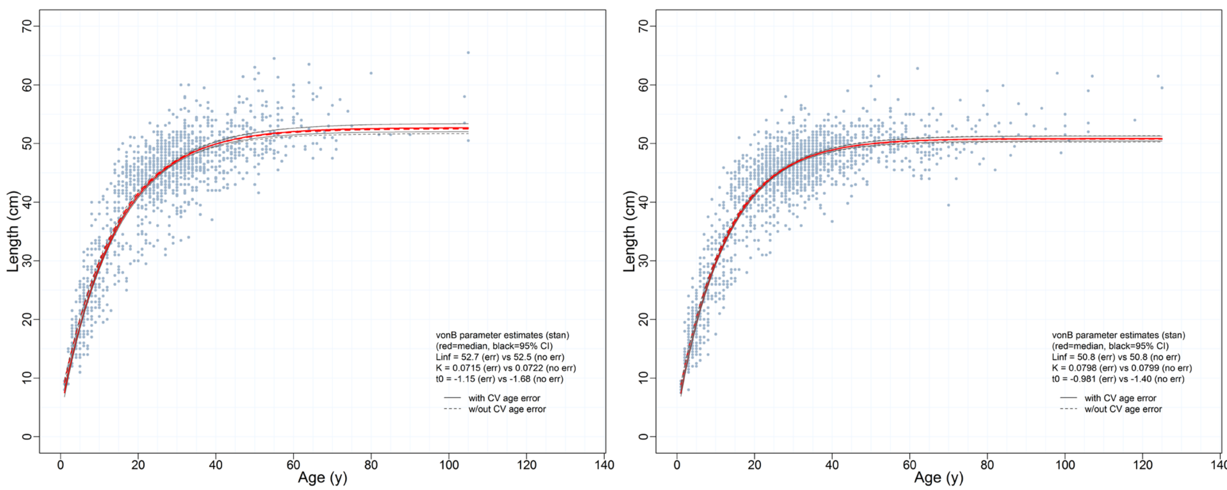


Figure D.10. REBS south: von Bertalanffy fits (left: female, right: male) using Stan to incorporate random effects error from CVs of lengths-at-age from all surveys (see Figure D.8).

D.1.3. Maturity

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

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

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

Bubble plots of frequency data (maturity vs. month) derived from various sources appear in Figure D.11 for REBS north and Figure D.13 for REBS south. Mature (stage 3) REBS north females are evident from October to February, with fertilised females in February and March and females with embryos from March to May; the pattern is similar for REBS south females. Ideally, lengths- and ages-at-maturity are calculated at times of peak development stages (males: insemination season, females: parturition season; Westrheim 1975). However, all months were used in creating the maturity curve because these data provided cleaner fits than using a subset of months.

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

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

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

ν_s = age of full maturity for sex s,

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

To estimate a maturity ogive, the biological data records (recs) were qualified as follows:

• `stocks – REBS north|south`	`major = 8:9	3:6`	`47,866|23,341 recs`
• ageing method (see note below)	`ameth = c(0,1,3,17)`	`10,251|4,233 recs`
• years	`year = 1996:2020`	`7,439|4,227 recs`
• `sample type – total catch/random`	`stype = c(1,2,6,7)`	`7,286|4,177 recs`
• `sex – females only`	`sex = 2`	`3,587|1,860 recs`
• maturity codes for rockfish	`mats = c(1:7)`	`2,806|1,591 recs`
• `ogive age limits`	`age = c(0,80)`	`2,725|1,577 recs`
• `trip type – survey + commercial`	`ttype = 1:5`	`2,725|1,577 recs`
• month – all months	`month = 1:12`	`2,725|1,577 recs`

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

The above qualification yielded 2725 REBS north and 1577 REBS south female specimens from research surveys and the commercial fishery with maturity readings and valid ages. (The commercial fishery lacked data for younger ages to determine ogives separately from survey data.) Mature specimens comprised those coded 3 to 7 for rockfish (Table D.6). The empirical proportion of mature females at each age was calculated (REBS north: Figure D.12, REBS south: Figure D.14). A double-normal function (Eq. D.3) was fit to the observed proportions mature at ages 1 to 80 to smooth the observations and determine an increasing monotonic function for use in the stock assessment model (Figure D.12). Additionally, a logistic function used by Vivian Haist (VH) for length models in New Zealand rock lobster assessments (Haist et al. 2009) was used to compare with the double normal model.

Following a procedure adopted by Stanley et al. (2009) for Canary Rockfish (*S. pinniger*), the proportions mature for young ages fitted by Eq. D.3 were not used because the fitted line may overestimate the proportion of mature females (Figure D.12). Therefore, the maturity ogive used in the stock assessment models (columns marked 'Mod m_a' in Table D.7) set proportion mature to zero for ages 1 to 11, then switched to the fitted monotonic function for ages 12 to 80, all forced to 1 (fully mature) after the estimated age at full maturity. This strategy follows previous BC rockfish stock assessments where it was recognised that younger ages are not well sampled and those that are, tend to be larger and more likely to be mature. The function of this ogive in the stock assessment model is to calculate the spawning biomass used in the Beverton-Holt stock recruitment function, and is treated as a constant known without error. The ages at 50% and full maturity are estimated from the double-normal fit at 24 y and 61.5 y, respectively, for REBS north and 25.6 y and 52.3 y, respectively, for REBS south. Empirically, the age at full maturity occurs at age 54 y for REBS north (Figure D.12) and 45 y for REBS south (Figure D.14).

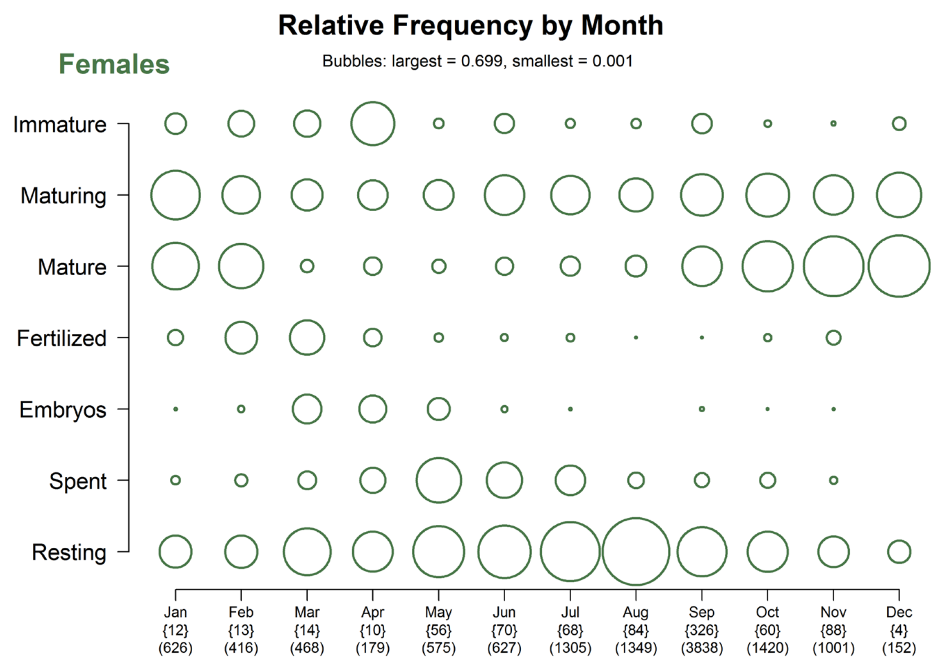


Figure D.11. Relative frequency of maturity codes by month for REBS north females. Data include maturities from commercial and research specimens. Frequencies are calculated among each maturity category for every month.

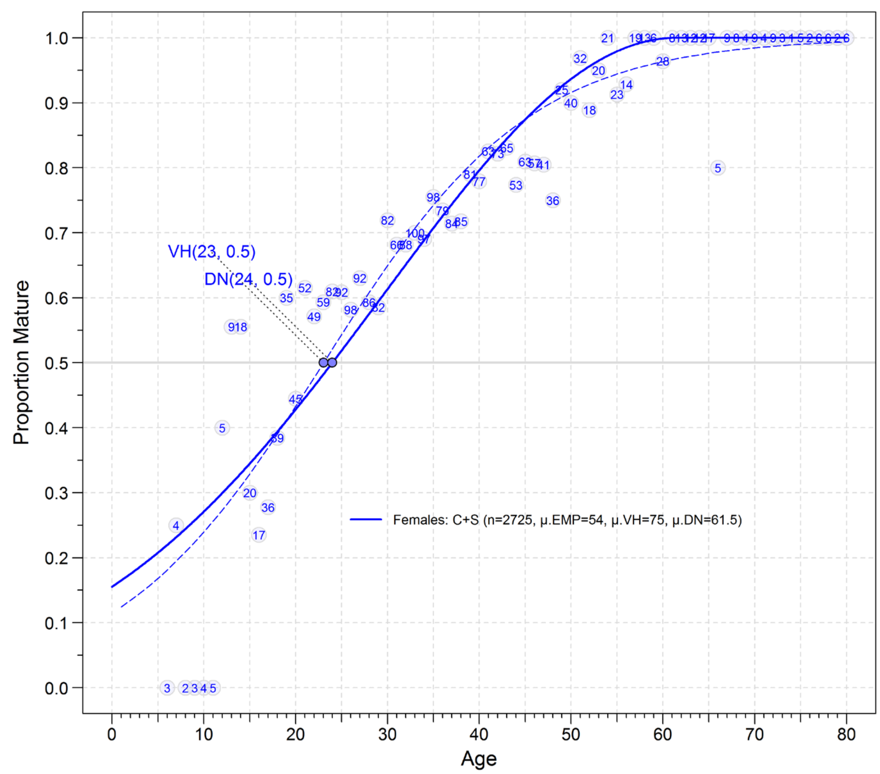


Figure D.12. Maturity ogives for REBS north females. Solid line shows double-normal (DN) curve fit; dashed line shows logistic model fit (VH = Vivian Haist); numbers in circles denote number of female specimens used to calculate the input proportions-mature (EMP =empirical). Estimated ages at 50% maturity are indicated near the median line; ages at full maturity (µ.VH, µ.DN) are displayed in the legend.

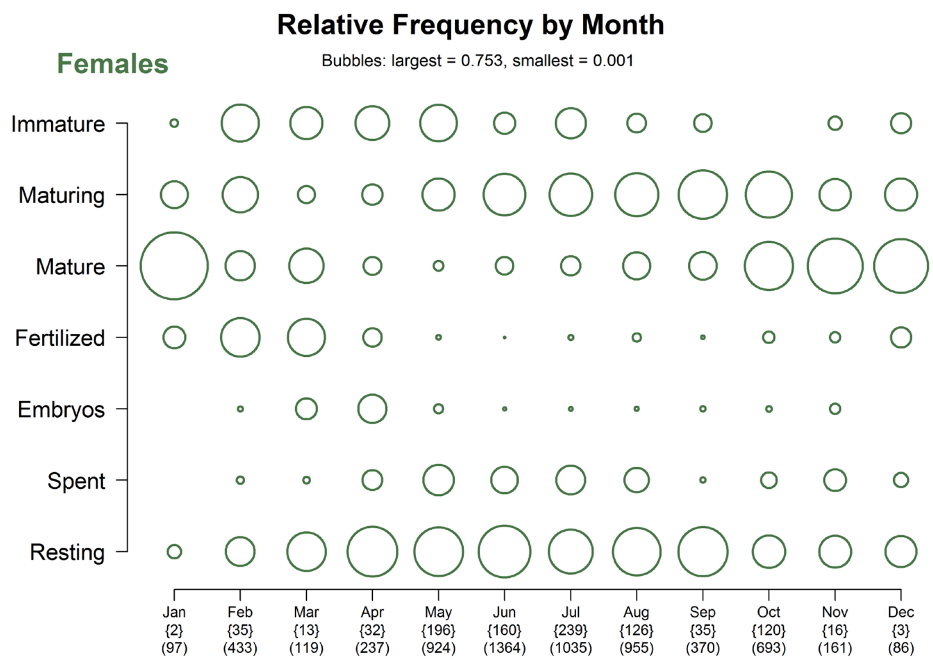


Figure D.13. Relative frequency of maturity codes by month for REBS south females. Data include maturities from commercial and research specimens. Frequencies are calculated among each maturity category for every month.

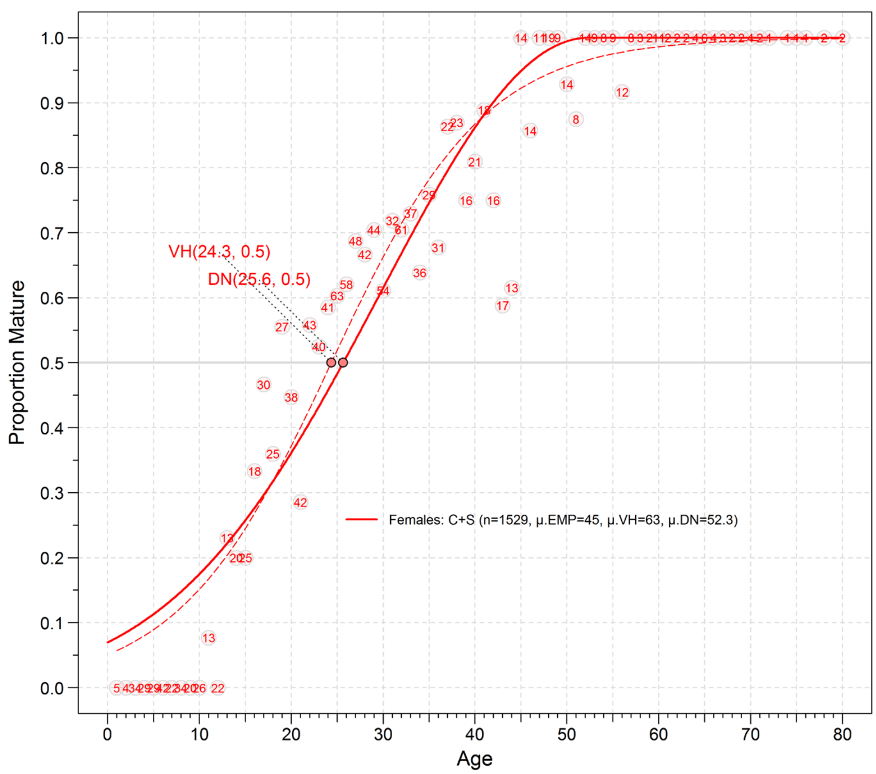


Figure D.14. Maturity ogives for REBS south females. See Figure D.12 caption for details.

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

	REBS north						REBS south					
Age	# Fish	EMP m_a	BL m_a	VH m_a	DN m_a	Mod m_a	# Fish	EMP m_a	BL m_a	VH m_a	DN m_a	Mod m_a
1	0	0	0.186	0.124	0.165	0	5	0	0.045	0.057	0.077	0
2	0	0	0.197	0.134	0.175	0	4	0	0.051	0.064	0.085	0
3	0	0	0.209	0.145	0.186	0	34	0	0.057	0.072	0.094	0
4	0	0	0.221	0.156	0.196	0	29	0	0.065	0.080	0.103	0
5	0	0	0.234	0.168	0.208	0	29	0	0.073	0.089	0.113	0
6	3	0	0.247	0.181	0.220	0	42	0	0.082	0.100	0.124	0
7	4	0.250	0.261	0.195	0.232	0	22	0	0.092	0.111	0.135	0
8	2	0	0.275	0.209	0.244	0	34	0	0.104	0.123	0.148	0
9	3	0	0.290	0.224	0.257	0	20	0	0.116	0.137	0.161	0
10	4	0	0.305	0.240	0.271	0	26	0	0.130	0.152	0.175	0
11	5	0	0.321	0.256	0.285	0.285	13	0.077	0.145	0.168	0.190	0.190
12	5	0.400	0.337	0.273	0.299	0.299	22	0	0.162	0.185	0.205	0.205
13	9	0.556	0.354	0.291	0.314	0.314	13	0.231	0.180	0.204	0.222	0.222
14	18	0.556	0.371	0.310	0.329	0.329	20	0.200	0.200	0.224	0.239	0.239
15	20	0.300	0.388	0.329	0.345	0.345	25	0.200	0.222	0.246	0.258	0.258
16	17	0.235	0.405	0.349	0.361	0.361	18	0.333	0.245	0.269	0.277	0.277
17	36	0.278	0.423	0.369	0.377	0.377	30	0.467	0.269	0.293	0.297	0.297
18	39	0.385	0.441	0.390	0.394	0.394	25	0.360	0.295	0.318	0.318	0.318
19	35	0.600	0.459	0.411	0.411	0.411	27	0.556	0.323	0.345	0.339	0.339
20	45	0.444	0.477	0.433	0.428	0.428	38	0.447	0.352	0.372	0.362	0.362
21	52	0.615	0.496	0.455	0.446	0.446	42	0.286	0.382	0.401	0.385	0.385
22	49	0.571	0.514	0.477	0.464	0.464	43	0.558	0.412	0.430	0.409	0.409
23	59	0.593	0.532	0.499	0.482	0.482	40	0.525	0.444	0.460	0.433	0.433
24	82	0.610	0.550	0.521	0.500	0.500	41	0.585	0.476	0.490	0.458	0.458
25	92	0.609	0.568	0.543	0.519	0.519	63	0.603	0.508	0.520	0.483	0.483
26	98	0.582	0.586	0.565	0.537	0.537	58	0.621	0.540	0.549	0.509	0.509
27	92	0.630	0.604	0.587	0.556	0.556	48	0.688	0.572	0.579	0.536	0.536
28	86	0.593	0.621	0.608	0.575	0.575	42	0.667	0.603	0.608	0.562	0.562
29	82	0.585	0.638	0.629	0.594	0.594	44	0.705	0.634	0.636	0.589	0.589
30	82	0.720	0.655	0.649	0.613	0.613	54	0.611	0.663	0.663	0.615	0.615
31	66	0.682	0.671	0.669	0.632	0.632	32	0.719	0.691	0.690	0.642	0.642
32	88	0.682	0.687	0.689	0.651	0.651	61	0.705	0.718	0.715	0.669	0.669
33	100	0.700	0.703	0.707	0.670	0.670	37	0.730	0.743	0.739	0.695	0.695
34	97	0.691	0.718	0.725	0.689	0.689	36	0.639	0.767	0.761	0.721	0.721
35	98	0.755	0.732	0.743	0.707	0.707	29	0.759	0.789	0.782	0.746	0.746
36	79	0.734	0.746	0.759	0.726	0.726	31	0.677	0.810	0.802	0.771	0.771
37	84	0.714	0.760	0.775	0.744	0.744	22	0.864	0.829	0.820	0.795	0.795
38	85	0.718	0.773	0.790	0.762	0.762	23	0.870	0.847	0.837	0.819	0.819
39	81	0.790	0.786	0.804	0.779	0.779	16	0.750	0.863	0.853	0.841	0.841
40	77	0.779	0.798	0.818	0.796	0.796	21	0.810	0.877	0.867	0.862	0.862
41	63	0.825	0.809	0.831	0.813	0.813	18	0.889	0.890	0.881	0.882	0.882
42	73	0.822	0.820	0.843	0.829	0.829	16	0.750	0.902	0.893	0.901	0.901
43	65	0.831	0.831	0.854	0.845	0.845	17	0.588	0.913	0.904	0.919	0.919
44	53	0.774	0.841	0.865	0.860	0.860	13	0.615	0.923	0.914	0.935	0.935
45	63	0.810	0.850	0.875	0.874	0.874	14	1	0.932	0.923	0.949	0.949
46	57	0.807	0.859	0.884	0.888	0.888	14	0.857	0.939	0.931	0.962	0.962
47	41	0.805	0.868	0.893	0.901	0.901	11	1	0.946	0.938	0.973	0.973
48	36	0.750	0.876	0.901	0.914	0.914	19	1	0.952	0.945	0.982	0.982
49	25	0.920	0.884	0.909	0.926	0.926	9	1	0.958	0.951	0.989	0.989
50	40	0.900	0.891	0.916	0.937	0.937	14	0.929	0.963	0.956	0.995	0.995
51	32	0.969	0.898	0.922	0.947	0.947	8	0.875	0.967	0.961	0.998	0.998
52	18	0.889	0.905	0.929	0.956	0.956	14	1	0.971	0.965	1	1.000
53	20	0.950	0.911	0.934	0.965	0.965	9	1	0.974	0.969	1	1
54	21	1	0.916	0.939	0.972	0.972	8	1	0.977	0.972	1	1
55	23	0.913	0.922	0.944	0.979	0.979	9	1	0.980	0.975	1	1
56	14	0.929	0.927	0.949	0.985	0.985	12	0.917	0.982	0.978	1	1
57	19	1	0.932	0.953	0.990	0.990	8	1	0.985	0.981	1	1
58	13	1	0.936	0.957	0.994	0.994	3	1	0.986	0.983	1	1
59	6	1	0.940	0.960	0.997	0.997	2	1	0.988	0.985	1	1
60	28	0.964	0.944	0.964	0.999	0.999	11	1	0.989	0.986	1	1
61	8	1	0.948	0.967	1	1	2	1	0.991	0.988	1	1

	REBS north						REBS south					
Age	# Fish	EMP m_a	BL m_a	VH m_a	DN m_a	Mod m_a	# Fish	EMP m_a	BL m_a	VH m_a	DN m_a	Mod m_a
62	13	1	0.952	0.969	1	1	2	1	0.992	0.989	1	1
63	12	1	0.955	0.972	1	1	2	1	0.993	0.990	1	1
64	12	1	0.958	0.974	1	1	4	1	0.994	0.992	1	1
65	17	1	0.961	0.976	1	1	6	1	0.994	0.992	1	1
66	5	0.800	0.963	0.978	1	1	4	1	0.995	0.993	1	1
67	9	1	0.966	0.980	1	1	3	1	0.996	0.994	1	1
68	8	1	0.968	0.982	1	1	2	1	0.996	0.995	1	1
69	4	1	0.970	0.983	1	1	2	1	0.997	0.995	1	1
70	9	1	0.972	0.985	1	1	4	1	0.997	0.996	1	1
71	4	1	0.974	0.986	1	1	2	1	0.997	0.996	1	1
72	9	1	0.976	0.987	1	1	1	1	0.998	0.997	1	1
73	3	1	0.978	0.988	1	1	0	0	0.998	0.997	1	1
74	1	1	0.979	0.989	1	1	1	1	0.998	0.997	1	1
75	5	1	0.981	0.990	1	1	1	1	0.998	0.998	1	1
76	2	1	0.982	0.991	1	1	1	1	0.999	0.998	1	1
77	6	1	0.983	0.992	1	1	0	0	0.999	0.998	1	1
78	6	1	0.984	0.992	1	1	2	1	0.999	0.998	1	1
79	2	1	0.986	0.993	1	1	0	0	1	0.999	1	1
80	6	1	0.987	0.994	1	1	2	1	1	0.999	1	1

D.1.4. Natural Mortality

Natural mortality (M) estimates for REBS from the literature include:

- 0.03-0.039 – estimated for REBS from the Aleutian Islands south to Oregon (including BC) by McDermott (1994) based on a gonadosomatic index;
- 0.036 – estimated for Gulf of Alaska REBS by Shotwell and Hanselman (2019) using a normal prior $\mathcal{N}(0.03, 0.003)$;
- 0.034 (0.037-0.047) – estimated for US west coast REBS by Hicks et al. (2014) using several lognormal priors: 0.03365 (CV=0.58), 0.02134 (CV=0.60), and 0.0605 (CV=0.44).

There have been no previous DFO stock assessments for REBS. A DFO review of REBS (Haigh et al. 2005) estimated median total mortality Z (M+F) from commercial data to be 0.045 in 1996 and 0.091 in 2003. While the analysis suggested a doubling of total mortality within seven years (primarily due to the disappearance of older ages and a new recruitment pulse from a 25-year old cohort), it is likely that non-representative sampling accounted for the perceived difference in proportion-at-age data.

In the DFO database GFBioSQL, the maximum ages for REBS stocks are 147 for REBS north (5DE), 138 for 'hybrids' (5C), and 125 for REBS south (3CD5ABC). Of the genetically resolved specimens, the maximum ages are 137 for BSR, 128 for RER, 102 for first-generation hybrids, and 125 for second-generation hybrids. The mean age for REBS north is 39.4 y (n=10,445), the median age is 36 y, and the 0.025. 0.975, and 0.99 quantiles are 17, 87, and 99 y, respectively. The mean age for REBS south is 28.9 y (n=4,233), the median age is 27 y, and the 0.025. 0.975, and 0.99 quantiles are 3, 70, and 83.7 y, respectively. Table D.8 indicates that there has been no long term change in the upper end of the age distribution of either REBS stock, with the 99th percentile of the most recent REBS north survey data showing no attenuation in this age statistic relative to earlier data. This statistic may be diminishing for REBS south, but this calculation may be affected by the large number of young REBS that are taken in the QCS synoptic survey (see Figure D.22).

Table D.8. 99th percentile of age by year, REBS species category (determined from PFMC spatial definition) and commercial/research category. Also shown are the number of samples and number of otoliths used when calculating the 99th percentile. Dash '–' indicates no data.

	Number samples						Number otoliths						99th percentile(age)					
	Commercial			Research			Commercial			Research			Commercial			Research		
Year	5DE	5C	3CD 5AB	5DE	5C	3CD 5AB	5DE	5C	3CD 5AB	5DE	5C	3CD 5AB	5DE	5C	3CD 5AB	5DE	5C	3CD 5AB
1979	1	–	–	–	–	–	99	–	–	–	–	–	90	–	–	–	–	–
1980	–	–	–	5	–	–	–	–	–	271	–	–	–	–	–	92	–	–
1982	1	–	–	–	1	1	198	–	–	–	6	5	70	–	–	–	9	8
1983	1	–	–	–	–	–	100	–	–	–	–	–	81.5	–	–	–	–	–
1987	1	–	–	–	–	–	102	–	–	–	–	–	105	–	–	–	–	–
1990	2	–	–	–	–	–	92	–	–	–	–	–	147	–	–	–	–	–
1991	9	–	–	–	–	–	455	–	–	–	–	–	87	–	–	–	–	–
1992	7	–	–	–	–	–	346	–	–	–	–	–	95	–	–	–	–	–
1993	6	–	–	3	–	–	341	–	–	112	–	–	80	–	–	98	–	–
1994	5	–	–	–	–	–	300	–	–	–	–	–	100.5	–	–	–	–	–
1995	7	–	–	–	–	–	402	–	–	–	–	–	98	–	–	–	–	–
1996	4	–	1	1	–	6	351	–	50	41	–	70	98	–	90	72	–	99
1997	5	–	2	25	–	–	270	–	100	429	–	–	96	–	93.5	101	–	–
1998	6	–	1	–	–	–	358	–	81	–	–	–	95	–	72	–	–	–
1999	3	–	1	–	–	–	204	–	61	–	–	–	60	–	90	–	–	–
2000	5	–	1	4	–	–	277	–	34	153	–	–	90	–	49	82	–	–
2001	5	–	4	–	–	4	277	–	194	–	–	8	105	–	79	–	–	65
2002	2	–	1	–	–	7	120	–	67	–	–	17	70	–	108	–	–	85
2003	9	–	3	–	–	–	479	–	170	–	–	–	60	–	55	–	–	–
2004	9	–	1	–	–	–	476	–	60	–	–	–	77	–	50	–	–	–
2005	9	–	1	–	–	–	457	–	47	–	–	–	93	–	70	–	–	–
2006	4	1	2	4	–	–	238	52	92	196	–	–	100	138	108	90	–	–
2007	–	–	–	11	–	–	–	–	–	513	–	–	–	–	–	96	–	–
2008	–	–	–	10	–	–	–	–	–	447	–	–	–	–	–	78	–	–
2010	–	–	–	25	–	–	–	–	–	209	–	–	–	–	–	103	–	–
2011	–	–	–	20	25	72	–	–	–	148	145	502	–	–	–	95	65	97
2012	–	–	–	89	7	103	–	–	–	606	35	612	–	–	–	105	92	84
2013	–	–	–	16	22	93	–	–	–	133	87	396	–	–	–	115	115	78
2014	–	–	–	11	–	55	–	–	–	157	–	509	–	–	–	107	–	80
2015	–	–	–	32	31	89	–	–	–	297	88	482	–	–	–	116	107	70
2016	2	–	–	63	–	106	53	–	–	405	–	624	63	–	–	117	–	72
2017	3	–	–	–	–	–	151	–	–	–	–	–	81	–	–	–	–	–
2018	–	–	2	–	–	–	–	–	106	–	–	–	–	–	71	–	–	–
Total	106	1	20	319	86	536	6,146	52	1,062	4,117	361	3,225	96	138	83	103	92	84

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

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

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

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

where $t_{\max}$ = maximum age.

During the review process for Redstripe Rockfish (DFO 2022), one of the principal reviewers, Vladlena Gertseva (2018, Northwest Fisheries Science Center, NOAA, pers. comm.), noted that Then et al. (2015) did not consistently apply a log transformation. In real space, one might expect substantial heteroscedasticity in both the observation and process errors associated with the relationship of M to $t_{\max}$. Re-evaluating the data used in Then et al. (2015) by fitting the one-parameter $t_{\max}$ model using a log-log transformation (such that the slope is forced to be -1 in the transformed space, as in Hamel 2015), Gertseva recalculated the point estimate for M as:

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

In past assessment meetings, participants have been averse to adopting a maximum age that comes from a single, usually isolated individual, preferring instead to observe the tail distribution of ages (REBS north: Figure D.15, REBS south: Figure D.16). For REBS, this suggests that age 100 y might be a more appropriate value for REBS north $t_{\max}$, while 80 y looks more appropriate for REBS south. Using these ages (~0.99 quantiles) as the lower bounds for the stocks and the observed maximum ages as upper bounds, Table D.9 calculates possible M values based on the Hoenig (1983) and Gertseva (2018) estimators. In this assessment, M is fixed to three values (0.035, 0.045, 0.055) for a range of reasons discussed in the main document.

Table D.9. Estimates of BSR natural mortality using equations based on fish longevity. Three upper age values (t_{max}) are used to illustrated the variability in M based on maximum age.

Stock by PMFC	Equation	low $t_{\max}$	mid $t_{\max}$	high $t_{\max}$
REBS north		100 y	125 y	150 y
Hoenig (1983)	M = -LN(0.01)/tmax	0.046	0.037	0.031
Gertseva (2018)	M = 5.4/tmax	0.054	0.043	0.036
REBS south		80 y	100 y	125 y
Hoenig (1983)	M = -LN(0.01)/tmax	0.058	0.046	0.037
Gertseva (2018)	M = 5.4/tmax	0.068	0.054	0.043

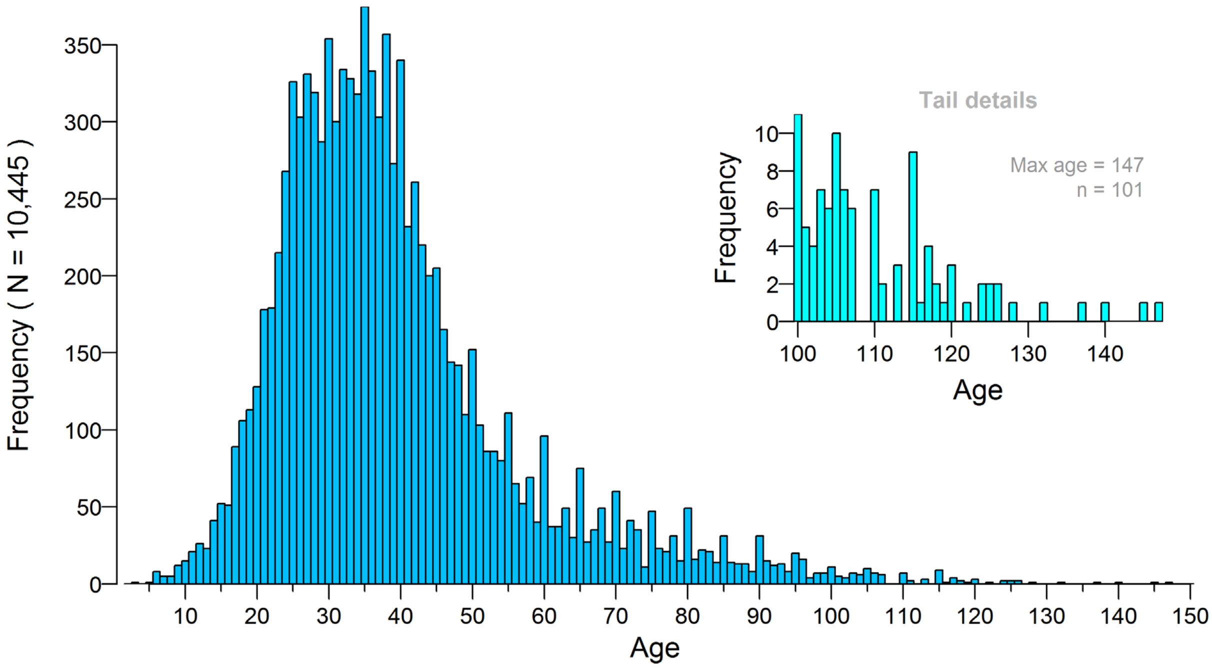


Figure D.15. Distribution of REBS north female + male ages; inset shows details for ages >=100 y old, which is the 0.991 quantile of the complete age data set.

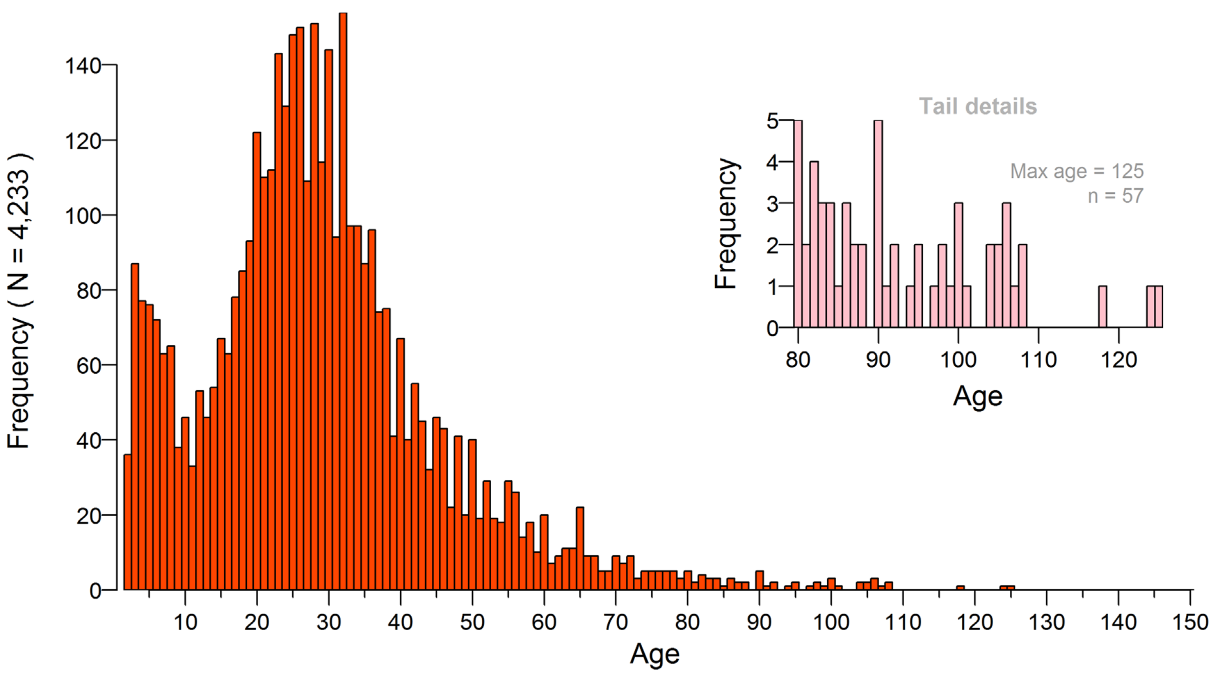


Figure D.16. Distribution of REBS south female + male ages; inset shows details for ages >=80 y old, which is the 0.987 quantile of the complete age data set.

D.1.5. Generation Time

Generation time t_G is assumed to be the average age of adults (males and females) in the population, and takes the form:

Eq. D.7 $$t_G = k + \frac{1}{e^M - 1}$$

where k = age at 50% maturity,

M = instantaneous rate of natural mortality.

COSEWIC uses a rough approximation to generation time:

Eq. D.8 $$t_G = k + \frac{1}{M}$$

From Section D.1.3, k = 24.0 y for REBS north and 25.6 y for REBS south. If we assume that M = 0.036 for REBS north and 0.043 for REBS south (using oldest age in Table D.9), then the COSEWIC estimates of generation time t_G = 51.8 y and 48.9 y, respectively for the two stocks. For simplicity, we adopt t_G = 50 years.

D.2. WEIGHTED AGE PROPORTIONS

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

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

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

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

For simplicity, the weighting of age frequencies x_a is used for illustration, unless otherwise specified. The weighting occurs at two levels: h (quarters for commercial ages, strata for survey ages) and i (years if commercial, stratum areas if survey). Notation is summarised in Table D.10.

Table D.10. Equations for weighting age frequencies or proportions; (c) = commercial, (s) = survey.

Indices

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

Data

Symbol	**Description**
x_{adhi}	observations-at-age a for sample unit d in quarter‖stratum h of year‖survey i
x'_{adhi}	proportion-at-age a for sample unit d in quarter‖stratum h of year‖survey i
C_{dhi}	(c) commercial catch (tonnes) of the target for sample unit d in quarter h of year i
	(s) density (t/km²) 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 (km²) of stratum h in survey i
K'_{hi}	K_{hi} as a proportion of total catch‖area $K_i = \sum_h K_{hi}$
p_{ai}	weighted frequencies at age a in year‖survey i
p'_{ai}	weighted proportions at age a in year‖survey i

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

Eq. D.9 $$C'_{dhi} = C_{dhi} \Big/ \sum_d C_{dhi} .$$

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:

Eq. D.10 $$y_{ahi} = \sum_{d} \left(C'_{dhi} x_{adhi} \right).$$

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

Eq. D.11 $$\sum\nolimits_a x_{ahi} \Big/ \sum\nolimits_a y_{ahi}$$

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

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

Eq. D.12 $$K'_{hi} = K_{hi} \Big/ \sum\nolimits_h K_{hi}$$

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

Eq. D.13 $$p_{ai} = \sum_{h} \left(K'_{hi} y_{ahi} \right).$$

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

Eq. D.14 $$\sum\nolimits_a y_{ai} \Big/ \sum\nolimits_a p_{ai}$$

to retain the original number of observations.

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

Eq. D.15 $$p'_{ai} = p_{ai} \Big/ \sum\nolimits_a p_{ai}\ .$$

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

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

D.2.1. Commercial Ages

For both stocks, sampled age frequencies (AF) from commercial bottom and midwater trawls were combined for the 'trawl' fishery (only RER in 2018 had midwater samples); the shrimp trawl data were not used. Therefore, the model was run assuming a joint selectivity for the two trawl fishing methods (the catch data were also combined into a single trawl fishery). For the 'other' fishery, commercial longline and trap data were combined due to the low number of aged fish, especially from the trap fishery (Table D.11). In 1978, ages from commercial trips were determined using thin-sectioning, which are used for the weighted age proportions to extend the REBS north time series back one year. Additionally for this stock, the data were pooled for 1982 and 1983 (into 1982) to increase sample size. See Section D.1.3 for information on the ageing methodologies typically used in DFO stock assessments.

The 2018 stock assessment of Redstripe Rockfish (Starr and Haigh, 2021a) did not separate sorted (by size or sex) and unsorted samples when introducing proportions-at-age into the model. This practice was also followed for the 2019 BOR stock assessment after exploratory runs using only sorted and only unsorted samples were examined. Usually the sorted samples occur earlier in the time series than do the unsorted samples. Consequently, dropping sorted samples loses information about early recruitment strength. This stock assessment uses combined sorted and unsorted samples for REBS AFs.

Table D.11. Number of REBS aged specimens from commercial trips by area (North=5DE, South=3CD5AB) and gear type (BT= bottom trawl, MW= midwater trawl, ST= shrimp trawl, LL= longline).

Year	North BT	North ST	North LL	North Trap	South BT	South MW	South LL
1978	192	---	---	---	---	---	---
1979	99	---	---	---	---	---	---
1982	199	---	---	---	---	---	---
1983	100	---	---	---	---	---	---
1987	---	---	---	102	---	---	---
1990	92	---	---	---	---	---	---
1991	410	---	---	45	---	---	---
1992	200	---	56	83	---	---	---
1993	341	---	---	---	---	---	---
1994	300	---	---	---	---	---	---
1995	202	---	200	---	---	---	---
1996	300	---	50	---	---	---	50
1997	127	---	142	---	---	---	100
1998	257	---	101	---	81	---	---
1999	204	---	---	---	61	---	---
2000	277	---	---	---	---	---	---
2001	277	---	---	---	194	---	---
2002	120	---	---	---	67	---	---
2003	479	---	---	---	170	---	---
2004	214	---	262	---	60	---	---
2005	303	---	53	100	45	---	---
2006	197	---	41	---	85	---	---
2016	---	53	---	---	---	---	---
2017	151	---	---	---	---	---	---
2018	---	---	---	---	---	106	---

Table D.12. Commercial trip quarterly data from the 'Trawl' and 'Other' fisheries used to weight REBS north and REBS south proportions-at-age: number of sampled trips, REBS catch (t) by sampled trip and by all trips.

REBS north Trawl Fishery

Year	# Trips | # Samples				Sampled catch (t)				Fishery catch (t)			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1978	---	---	2 | 2	---	---	---	58.76	---	2	7	82	48
1979	1 | 1	---	---	---	2.50	---	---	---	88	32	87	3
1982	---	1 | 1	---	---	---	40.87	---	---	262	80	0	1
1983	1 | 1	---	---	---	18.16	---	---	---	158	21	12	10
1990	---	1 | 2	---	---	---	1.59	---	---	141	163	514	147
1991	3 | 3	2 | 2	1 | 1	2 | 2	16.80	14.53	4.99	13.62	130	199	83	230
1992	1 | 1	2 | 2	---	1 | 1	8.17	18.39	---	10.50	372	351	211	139
1993	2 | 2	2 | 2	1 | 1	1 | 1	11.12	11.12	6.36	6.81	250	450	208	287
1994	---	4 | 4	1 | 1	1 | 1	---	34.67	5.45	11.35	205	294	155	384
1995	5 | 5	---	---	---	47.45	---	---	---	407	202	9	---
1996	---	2 | 2	3 | 3	---	---	20.93	36.32	---	57	203	90	228
1997	1 | 1	---	---	1 | 1	4.09	---	---	9.53	54	39	12	66
1998	4 | 4	---	1 | 1	2 | 2	22.25	---	6.13	14.53	148	41	29	135
1999	---	---	---	4 | 4	---	---	---	24.38	175	22	10	116
2000	2 | 2	1 | 1	---	2 | 2	11.14	0.42	---	7.20	145	37	42	39
2001	3 | 3	---	---	2 | 2	7.79	---	---	9.79	132	34	64	93
2002	---	---	---	2 | 2	---	---	---	18.20	87	23	87	136
2003	3 | 3	1 | 1	6 | 6	2 | 2	8.50	0.11	29.17	7.08	86	14	118	80
2004	2 | 2	2 | 2	---	---	12.77	7.26	---	---	99	47	35	51
2005	3 | 3	---	---	3 | 3	20.39	---	---	16.27	160	22	15	114
2006	1 | 1	1 | 1	1 | 1	---	7.57	6.35	0.28	---	166	67	50	113
2016	1 | 1	---	1 | 1	---	2.09	---	3.52	---	118	92	14	55
2017	**1 | 1**	**2 | 2**	**---**	**---**	**4.31**	**3.03**	**---**	**---**	**199**	**110**	**45**	**100**

REBS north Other Fishery

Year	# Trips | # Samples				Sampled catch (t)				Fishery catch (t)			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1987	---	1 | 1	---	---	---	1.14	---	---	---	1	---	---
1991	---	---	---	1 | 1	---	---	---	0.20	2	10	5	1
1992	---	---	2 | 4	---	---	---	0.34	---	4	4	1	0
1995	---	---	3 | 5	---	---	---	10.57	---	78	334	104	0
1996	---	---	1 | 1	---	---	---	0.00	---	39	45	6	1
1997	---	---	3 | 3	---	---	---	34.05	---	12	55	98	68
1998	---	---	2 | 2	---	---	---	45.40	---	3	95	272	15
2004	1 | 1	2 | 2	1 | 1	1 | 1	0.38	11.59	5.44	0.23	107	144	78	47
2005	---	1 | 2	---	1 | 1	---	0.38	---	3.04	29	112	81	38
2006	1 | 1	---	---	---	2.27	---	---	---	63	29	19	32

REBS south Trawl Fishery

Year	# Trips | # Samples				Sampled catch (t)				Fishery catch (t)			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1998	---	1 | 1	---	1 | 1	---	0.38	---	0.32	62	67	8	14
1999	---	---	1 | 1	---	---	---	4.09	---	49	27	14	20
2001	2 | 2	2 | 2	---	---	0.54	0.40	---	---	68	38	12	32
2002	---	---	---	1 | 1	---	---	---	2.72	69	47	29	49
2003	2 | 2	---	1 | 1	---	2.03	---	2.72	---	77	64	20	23
2004	1 | 1	---	---	---	2.16	---	---	---	46	57	31	58
2005	1 | 1	---	---	---	0.31	---	---	---	40	62	14	25
2006	1 | 1	1 | 1	---	---	0.09	0.28	---	---	61	42	26	21
2018	---	---	---	1 | 2	---	---	---	0.83	32	21	22	43

REBS south Other Fishery

Year	# Trips | # Samples				Sampled catch (t)				Fishery catch (t)			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1996	---	---	1 | 1	---	---	---	0.00	---	1	98	70	64
1997	---	---	1 | 1	1 | 1	---	---	0.00	0.00	84	238	55	0

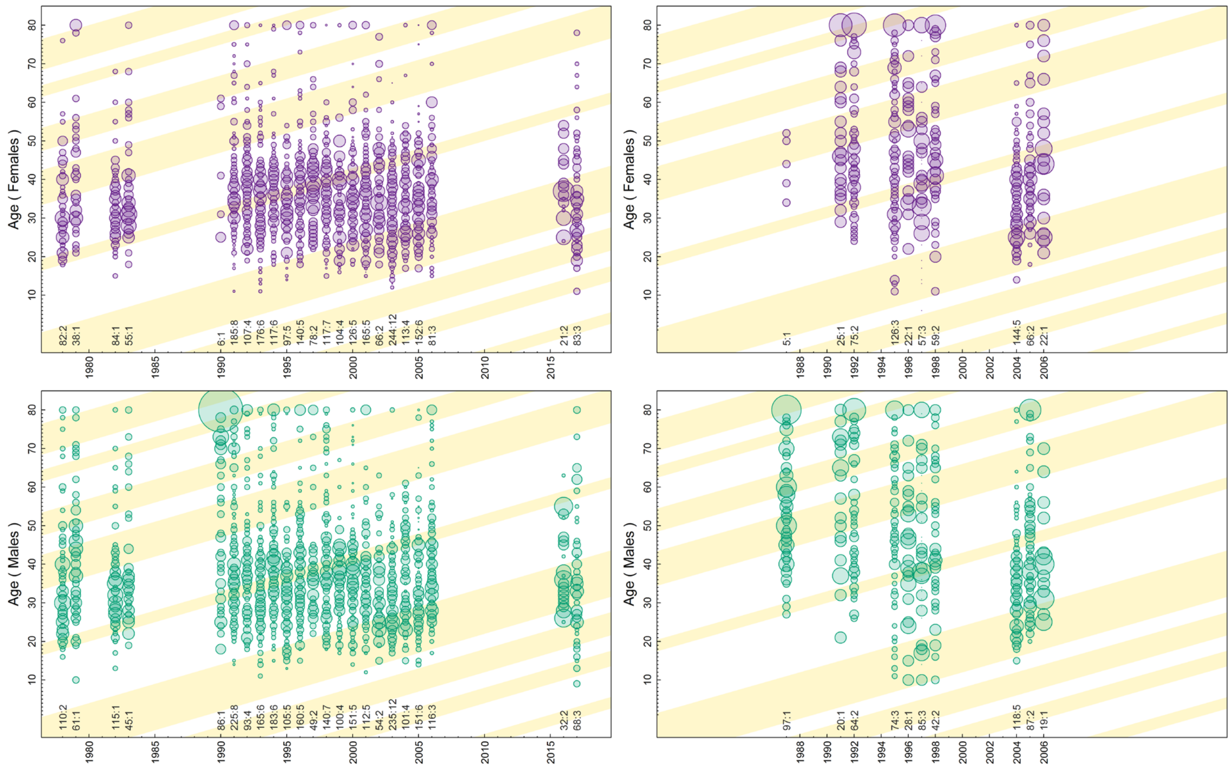


Figure D.17. Proportions-at-age for REBS north caught by commercial trawl gear (left) and gear other than trawl (right) calculated as age frequencies weighted by trip catch within quarters and commercial catch within years. Diagonal shaded bands indicate cohorts that were born when the mean Pacific Decadal Oscillation was positive. Numbers displayed along the bottom axis indicate number of fish aged and number of samples (colon delimited) by year.

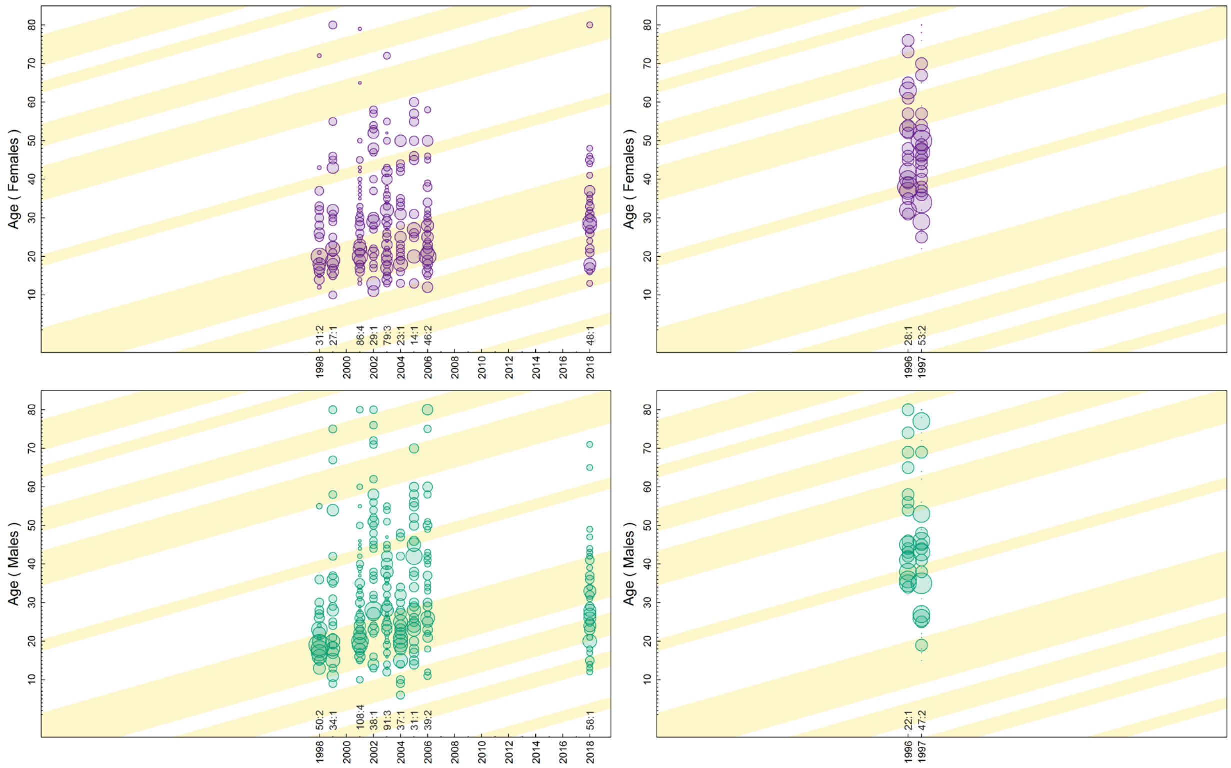


Figure D.18. Proportions-at-age for REBS south caught by commercial trawl gear (left) and gear other than trawl (right) calculated as age frequencies weighted by trip catch within quarters and commercial catch within years. See Figure D.17 for details on diagonal shaded bands and displayed numbers.

D.2.2. Research/Survey Ages

Age data for REBS from the surveys cover years from 1996 to 2016 (Table D.13). Age cohort patterns are not easily discernible, likely due to low numbers of specimens to represent species that appear to live to 150 years.

REBS north stock is covered by five surveys in 5DE:

- WCHG Synoptic (6 years) from 1997-2016 (Figure D.19);
- HS Synoptic (3 years) from 2011-2015 (Figure D.20);
- IPHC Longline (2 years) from 2012 and 2015 (Figure D.20);
- Hard-bottom Longline North (2 years) from 2012 and 2015 (Figure D.21);
- Standardised Sablefish Trap (6 years) from 2011-2016 (Figure D.21).

REBS south stock is covered by four surveys in 3CD5AB:

- QCS Synoptic (3 years) from 2011-2015 (Figure D.22);
- WCVI Synoptic (4 years) from 1996-2016 (Figure D.22);
- IPHC Longline (3 years) from 2011-2015 (Figure D.23);
- Standardised Sablefish Trap (6 years) from 2011-2015.

Table D.13. Number of REBS age samples (s) collected from surveys and REBS density (d=kg/km^2) by survey stratum identifier (h); stratum area is shown in parentheses. Note: d=1.000 usually indicates the absence of catch data in GFBioSQL for a specific survey.

Surv/Year	**Survey Strata – REBS north**				
WCHG	h=115 (892 km2)	h=116 (744 km2)	h=117 (372 km2)	h=127 (1,090 km2)	h=128 (927 km2)
1997	s=16, d=3.939	s=22, d=3.391	s=11, d=2.398	-	-
2006	-	-	-	s=4, d=6.933	s=1, d=2.333
WCHG Syn	h=151 (1,076 km2)	h=152 (1,004 km2)	h=153 (952 km2)	h=154 (2,248 km2)	-
2007	s=1, d=0.846	s=11, d=2.954			-
2008	s=5, d=4.897	s=9, d=4.658	s=2, d=10.984		-
2010	s=8, d=2.819	s=15, d=1.390	s=2, d=0.471		-
2012	s=35, d=1.595	s=27, d=2.637	s=3, d=1.460	s=1, d=0.034	-
2016	s=22, d=1.206	s=25, d=3.617	s=2, d=0.606	s=1, d=0.012	-
HS Syn	h=73 (2,992 km2)	h=74 (2,400 km2)	h=75 (1,816 km2)	-	-
2011	-	s=4, d=0.020	s=5, d=0.023	-	-
2013	-	s=5, d=0.011	s=3, d=0.046	-	-
2015	s=1, d=0.012	s=5, d=0.018	s=4, d=0.052	-	-
IPHC LL	h=134 (19,417 km2)	-	-	-	-
2012	s=7, d=1.000	-	-	-	-
2015	s=8, d=1.000	-	-	-	-
HBLL N	h=322 (5,485 km2)	h=323 (3,705 km2)	-	-	-
2012	s=1, d=1.000	s=5, d=1.000	-	-	-
2015	s=1, d=1.000	s=2, d=1.000	-	-	-
SBF Trap	h=59 (9,477 km2)	h=60 (9,477 km2)	h=62 (9,477 km2)	h=63 (9,477 km2)	h=441 (9,477 km2)
2011	s=5, d=0.101	-	s=4, d=0.499	s=2, d=0.096	-
2012	s=4, d=0.280	s=2, d=0.116	s=4, d=1.774	s=2, d=0.635	-
2013	s=4, d=0.296	-	s=2, d=0.352	s=2, d=0.497	-
2014	s=2, d=0.419	-	s=4, d=0.779	s=3, d=0.604	s=2, d=0.035
2015	s=5, d=0.508	s=2, d=0.153	s=2, d=0.327	s=2, d=0.473	-
2016	s=5, d=0.174	s=2, d=0.037	s=5, d=0.778	s=1, d=0.241	-

Surv/Year	**Survey Strata – REBS south**				
QCS Syn	h=19 (5,300 km2)	h=20 (2,640 km2)	h=21 (528 km2)	h=24 (3,664 km2)	h=25 (1,236 km2)
2011	s=10, d=0.004	s=10, d=0.030	s=7, d=0.917	s=16, d=0.044	s=5, d=2.919
2013	s=11, d=0.011	s=15, d=0.034	s=9, d=0.924	s=6, d=0.021	s=4, d=0.037
2015	s=13, d=0.006	s=12, d=0.032	s=4, d=2.994	s=9, d=0.084	s=6, d=0.084
WCVI RF	h=119 (497 km2)	h=120 (600 km2)	-	-	-
1996	s=1, d=0.098	s=5, d=0.157	-	-	-
WCVI Syn	h=65 (5,716 km2)	h=66 (3,768 km2)	h=67 (708 km2)	h=68 (572 km2)	-
2012	-	s=6, d=0.020	s=8, d=0.060	s=16, d=0.230	-
2014	-	s=8, d=0.009	s=10, d=0.105	s=11, d=0.288	-
2016	s=1, d=0.008	s=7, d=0.011	s=7, d=0.246	s=19, d=0.630	-
IPHC LL	h=131 (15,891 km2)	h=132 (15,526 km2)	h=133 (17,073 km2)	-	-
2011	s=2, d=1.000	-	s=6, d=1.000	-	-
2012	s=2, d=1.000	s=2, d=1.000	s=8, d=1.000	-	-
2015	s=2, d=1.000	s=2, d=1.000	s=3, d=1.000	-	-
SBF Trap	h=0 (10,752 km2)	h=50 (10,752 km2)	h=51 (10,752 km2)	h=53 (10,752 km2)	h=54 (10,752 km2)
2011	s=2, d=0.008	s=2, d=0.130	-	s=3, d=0.113	-
2012	-	s=6, d=0.260	-	s=4, d=0.127	-
2013	-	s=3, d=0.056	-	s=2, d=0.338	s=2, d=0.129
2014	-	s=2, d=0.380	s=1, d=0.152	s=5, d=0.247	--
2015	-	s=4, d=0.135	s=2, d=0.035	s=2, d=0.045	s=2, d=0.054
2016	-	s=3, d=0.371	s=1, d=0.021	s=3, d=0.101	s=1, d=0.023
SBF Trap	h=56 (10,752 km2)	h=57 (10,752 km2)	h=59 (10,752 km2)	h=60 (10,752 km2)	h=335 (10,752 km2)
2011	s=8, d=0.133	s=1, d=0.023	s=1, d=0.039	-	-

Surv/Year	Survey Strata – REBS south				
2012	s=6, d=0.236	s=2, d=0.052	-	s=1, d=0.038	s=1, d=0.020
2013	s=5, d=0.041	s=3, d=0.055	-	-	-
2014	s=4, d=0.720	s=3, d=0.101	s=2, d=0.284	-	-
2015	s=2, d=0.782	-	-	-	-
2016	s=4, d=0.284	s=3, d=0.035	-	-	s=1, d=0.056

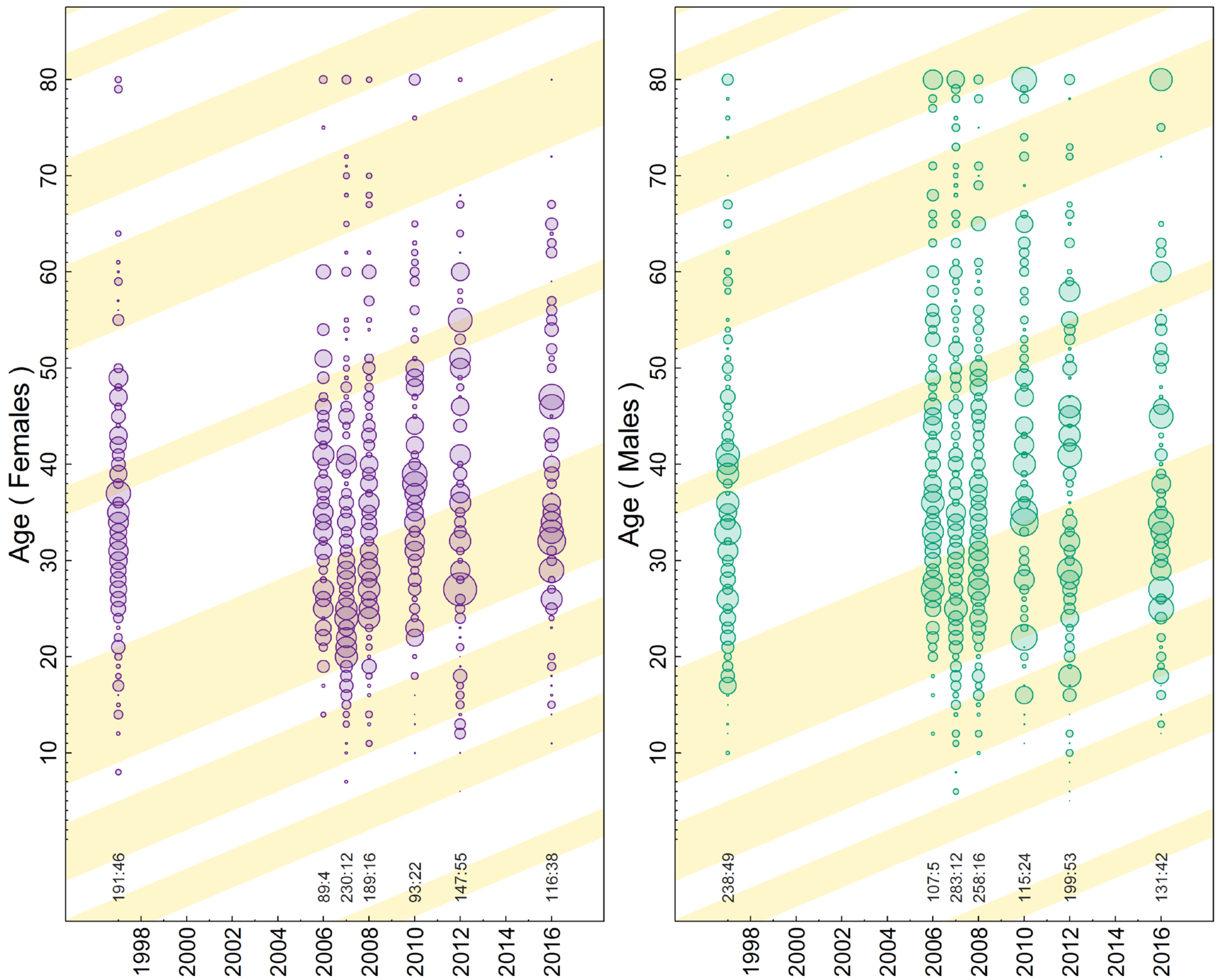


Figure D.19. REBS north surveys: WCHG Synoptic (2006 on) and WCQCI rockfish (1997) – proportions-at-age based on age frequencies weighted by mean fish density within strata and by total stratum area within survey (Table D.13). See Figure D.17 for details on diagonal shaded bands and displayed numbers.

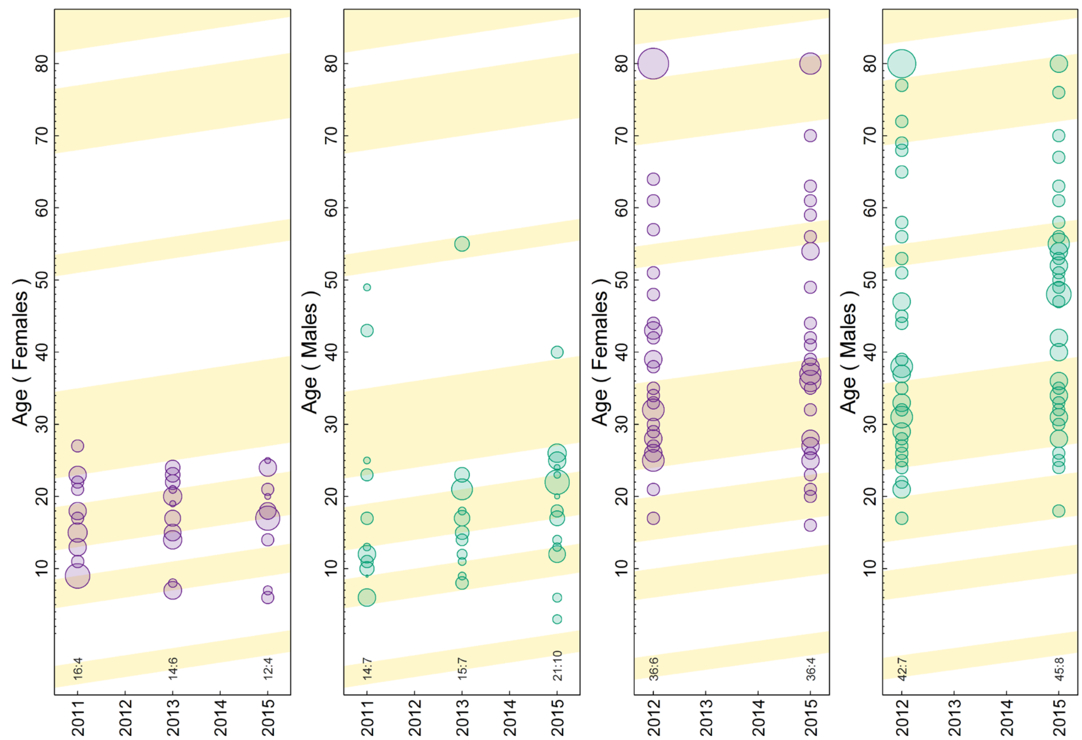


Figure D.20. REBS north surveys: HS Synoptic (left) and IPHC Longline (right) – proportions-at-age based on age frequencies weighted by mean fish density within strata and by total stratum area within survey (Table D.13). See Figure D.17 for details on displayed numbers.

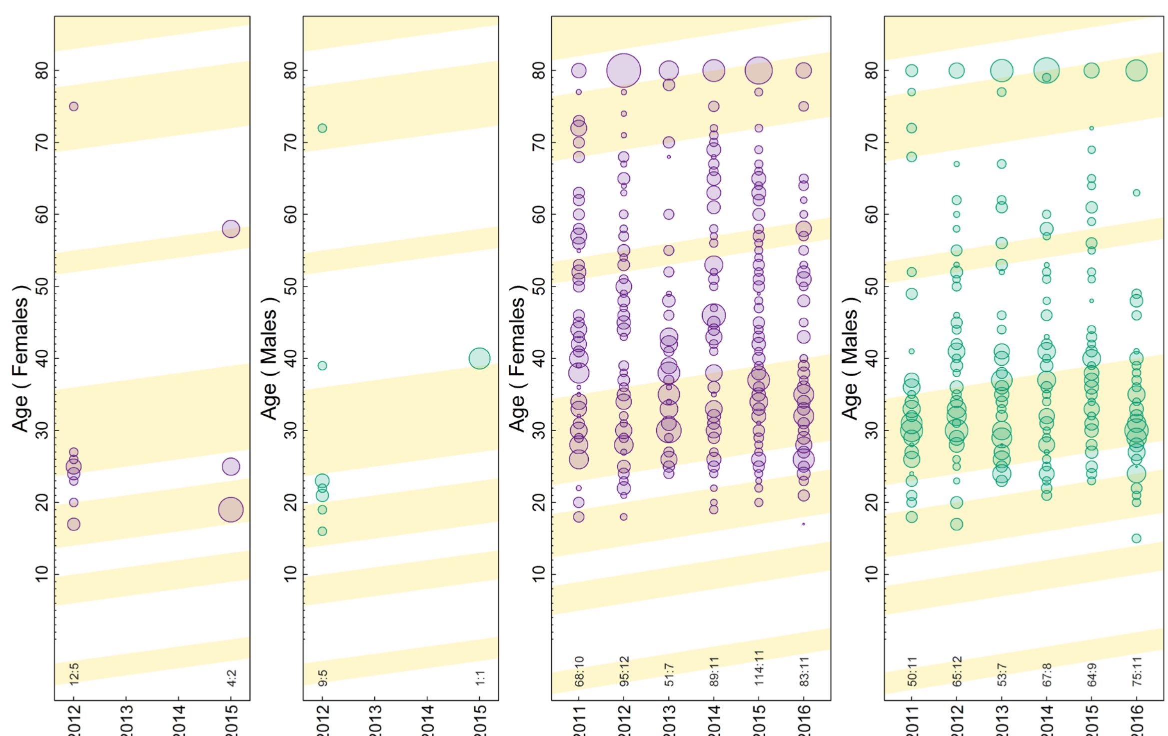


Figure D.21. REBS north surveys: Hard-bottom Longline North (left) and Standardised Sablefish Trap (right) – proportions-at-age based on age frequencies weighted by mean fish density within strata and by total stratum area within survey (Table D.13). See Figure D.17 for details on displayed numbers.

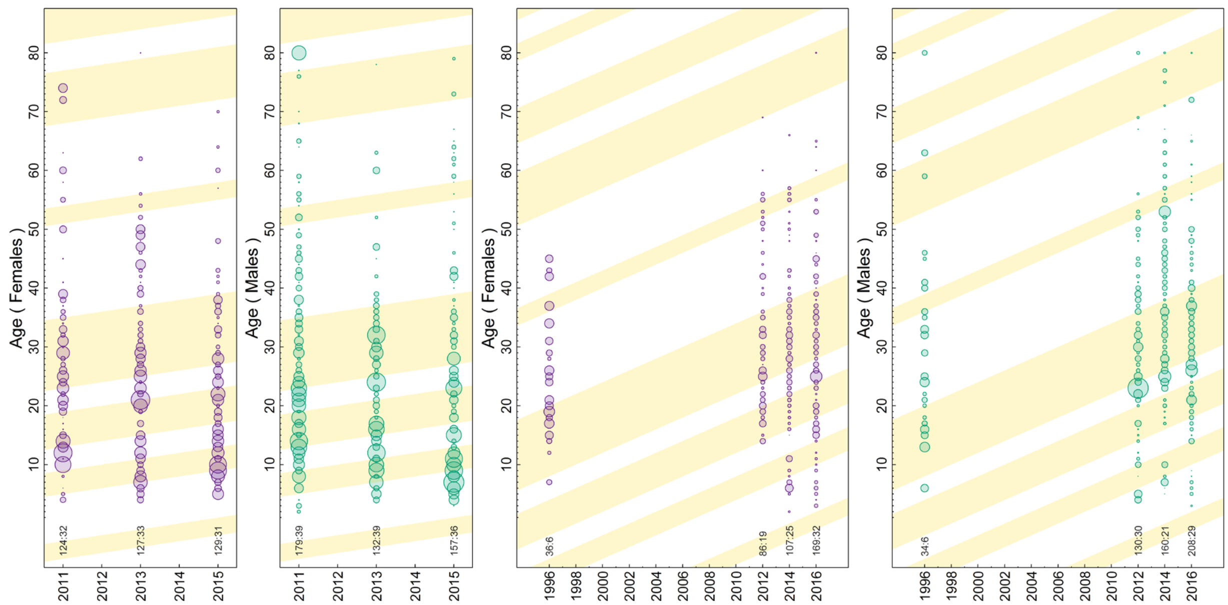


Figure D.22. REBS south surveys: QCS Synoptic (left) and WCVI Synoptic (right) – proportions-at-age based on age frequencies weighted by mean fish density within strata and by total stratum area within survey (Table D.13). See Figure D.17 for details on displayed numbers.

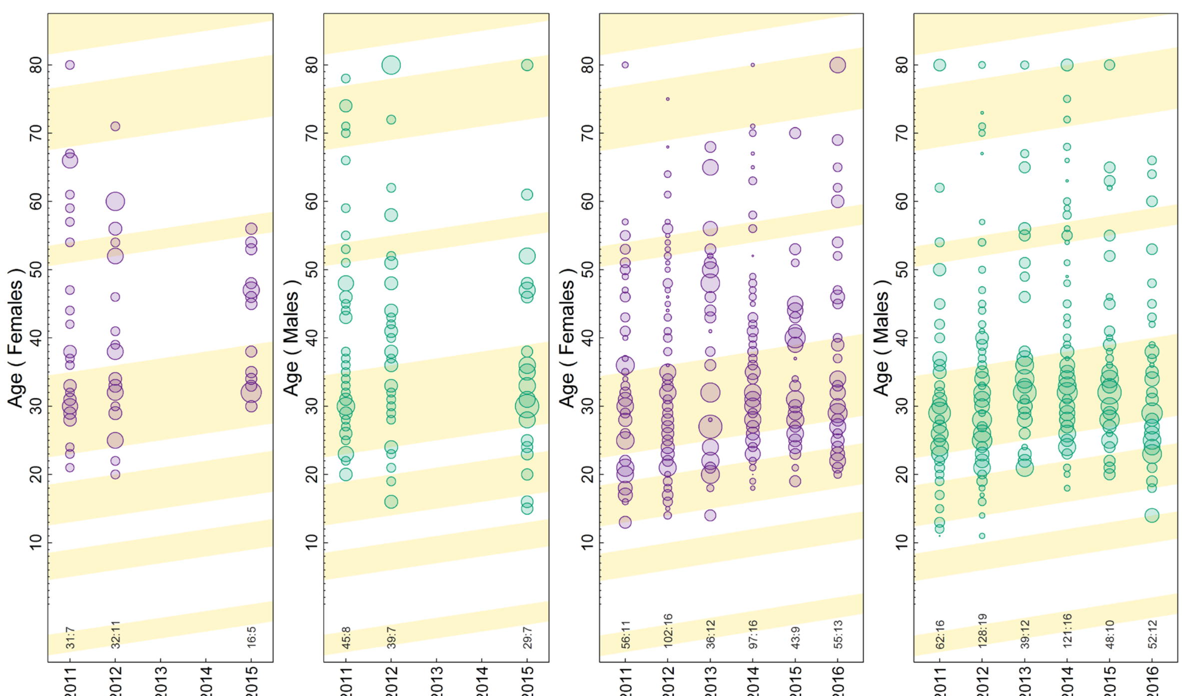


Figure D.23. REBS south surveys: IPHC Longline (left) and Standardised Sablefish Trap (right) – proportions-at-age based on age frequencies weighted by mean fish density within strata and by total stratum area within survey (Table D.13). See Figure D.17 for details on displayed numbers.

D.2.3. Ageing Error

Ageing error routinely arises as an issue in stock assessments. Figure D.24 suggests that REBS ages by primary readers are often not reproduced consistently by secondary readers when performing spot-check analyses. The base case population models for REBS, by necessity, both use an ageing error (AE) matrix.

After some trials, one AE matrix was adopted: 'moderate' error for ages 1-80 from a normal distribution with quantiles 0.01 to 0.99 spanning seven age classes (±3 ages along rows off the diagonal, Figure D.25, left). Another AE matrix was used in sensitivity runs: 'wide' error for ages 1-80 from a normal distribution with quantiles 0.01 to 0.99 spanning eleven age classes (±5 ages along rows off the diagonal, Figure D.25, right). A 'narrow' AE matrix (±1 age) was tried, but models did not converge satisfactorily.

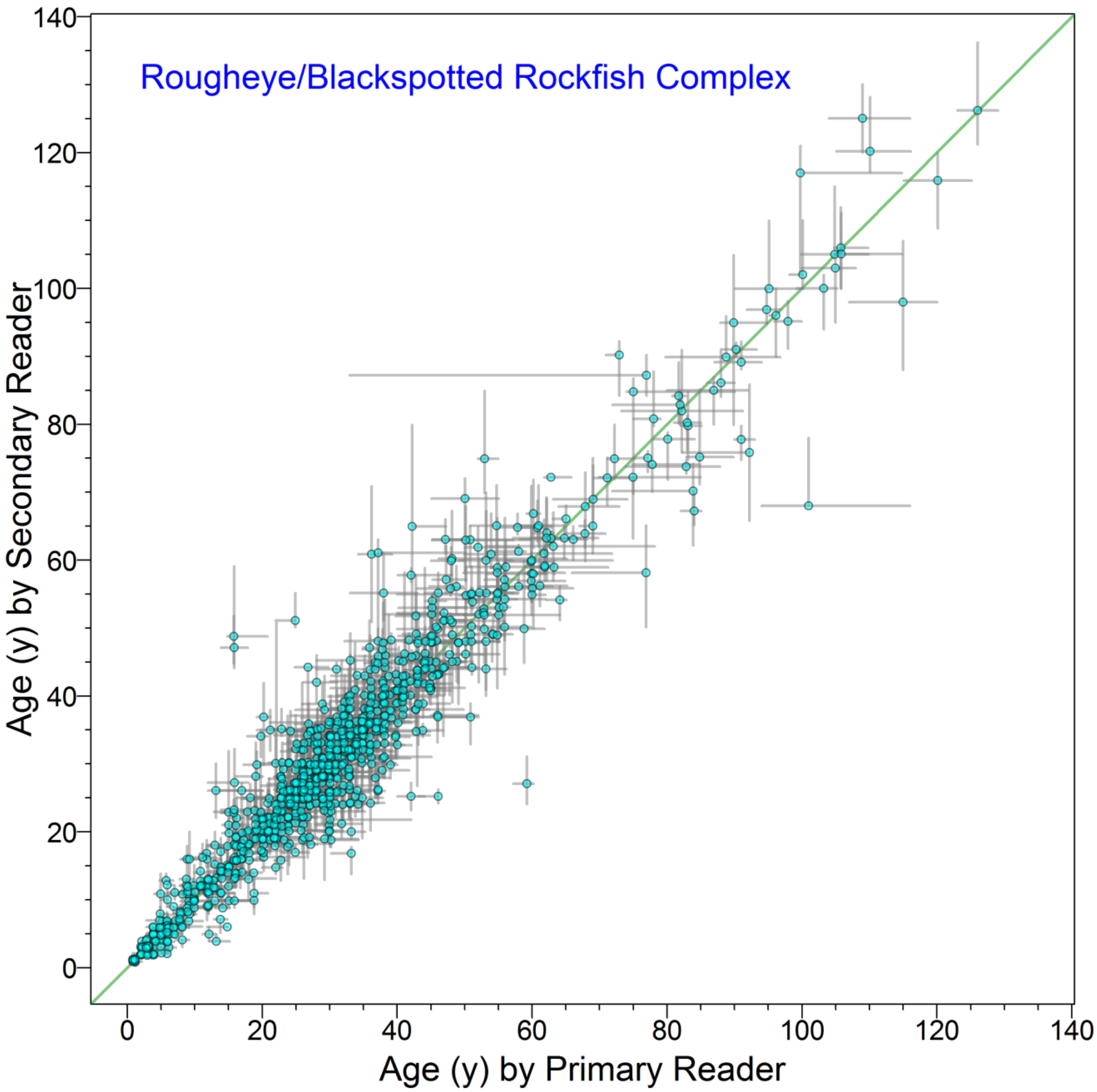


Figure D.24. Ageing error of REBS specified as the range between minimum and maximum age (grey bars) determined by primary and secondary readers for each accepted age (points). The data are jittered using a random uniform distribution between -0.25 and 0.25 y.

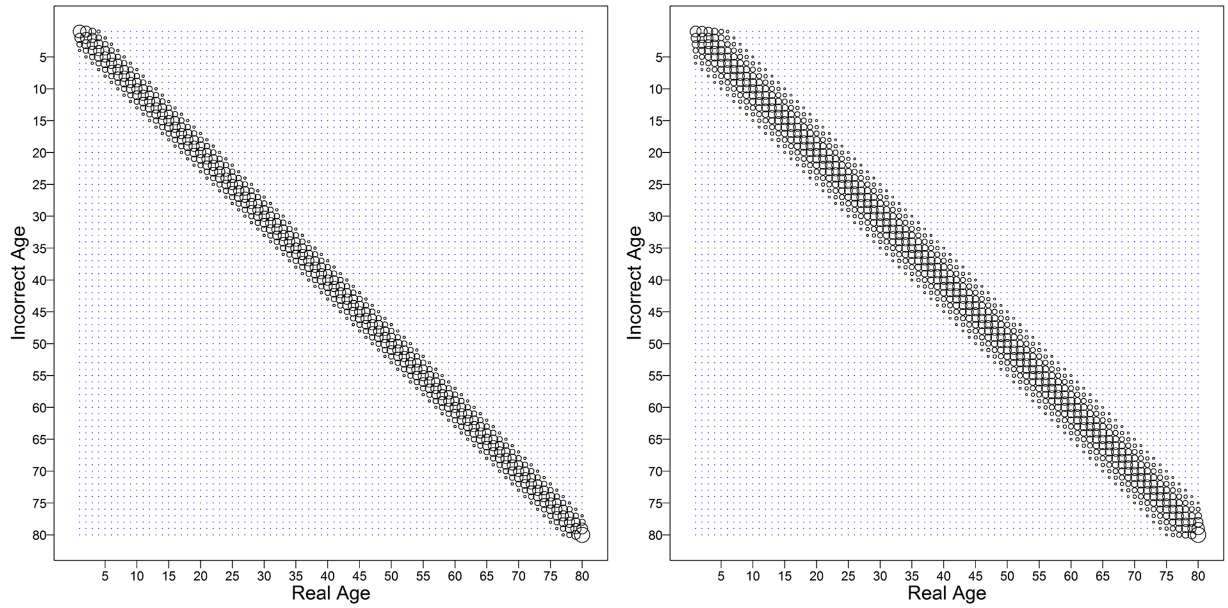


Figure D.25. Ageing error misclassification matrix (Hilborn et al. 2003) used for REBS north and south by Awatea in this assessment. Left: 'moderate' error structure adopted for all composite base case runs. Right: 'wide' error structure used in the sensitivity runs.

D.3. STOCK STRUCTURE

D.3.1. Genetics

Gharrett et al. (2005) concluded that the REBS complex comprised two distinct genetic types based on differences at one microsatellite locus (µSma 6) out of eight tested. Type I (Blackspotted Rockfish or BSR) were homozygous for the *177 allele at µSma 6 and Type II (Rougheye Rockfish or RER) were homozygous at the *183 allele. These differences correlated to different mitochondrial-DNA haplotypes (group of alleles that are inherited together). In their study, Type I were predominant in western waters but extended throughout the range sampled (along the Pacific rim from the Aleutian Island south to Oregon). Type II fish were most prevalent in the central and eastern Gulf of Alaska, and were largely absent from waters west of 170°W in the Bering Sea and Aleutian Islands.

Using genetically determined REBS specimens based on the Sma 6 locus identified by Gharrett et al. (2005), Harris et al. (2019) developed a predictive logistic regression model using age, six otolith metrics (area, perimeter, minor axis length, otolith length, otolith width, otolith weight), and fork length. A striking discovery was that for all six otolith measurements, RER was larger on average than BSR for any given age. Their predictive model, fitted using one set of training data, was tested on a separate set of data and correctly identified 97% of BSR and 86% of RER. Compared to field identification, their results showed a slight improvement for BSR (97% vs. 92-94% accurate in field) and a substantial improvement for RER (86% vs. 66-68% accurate in field). Assuming that growth rates do not change substantially over time and that ageing is fairly accurate, this method was suggested to be useful for hindcasting species taxonomy using archived otoliths, and would be independent of year and species range. The PBS ageing lab is currently conducting an otolith morphology study, which may also yield predictive capabilities.

D.3.2. Stock Definition

At present, it is not possible to visually separate BSR and RER with great accuracy; instead genetic (DNA) sampling is required to determine the species. Such sampling has been undertaken in BC waters since 2010 in research surveys and from 2012 in the commercial fishery (Table D.14), but with variable sampling strategies. As well, almost all the available genetic sampling has come from research surveys (Table D.14), so it is not straightforward to extrapolate from these disparate data to general observations of coastwide species distribution. As a first approximation, the Terms of Reference chose to define the species separation by designating all REBS observations (from the commercial fishery or from surveys) from the west coast of Haida Gwaii (PMFC Area 5E) and Dixon Entrance (PMFC Area 5D) as BSR; however, the peer review participants requested that this spatial set be identified as a REBS north stock to reflect the fact that specimens comprised both BSR and RER in the data. Similarly, REBS catches in PMFC areas 3C to 5B (see Appendix Figure A.1 for map locations of these areas) were to be designated as RER, but the review meeting wanted this spatial set identified as a REBS south stock. The small amount of REBS catch in PMFC Area 5C was divided proportionately (~70:30 north:south based on catch) between the two stocks because of the assumed high level of hybridisation in this area. These areal designations follow Creamer (2016), who found that longitude was the strongest predictor of BSR proportion, with the more westerly longitudes (i.e., west coast Haida Gwaii) favouring BSR. Note that in BC, longitude is correlated with latitude due to the diagonal nature of the coastline.

Table D.14 shows that genetic analyses have been performed on 8668 specimens. Of these, 4903 have been determined as BSR, 2730 as RER, 153 as hybrids by first generation or later, 273 as hybrids by second generation or later, and 609 failed resolutions (either through spoiled genetic material or failure of automated equipment to supply genetic material to testing well). Genetically determined BSR accounts for 3815/(631+3815+80+93) = 82.6%, of the genetically determined specimens (excluding failed tests) in the REBS north stock area, while genetically determined RER accounts for 2011/(2011+892+65+146) = 64.6% of the genetically determined specimens in the REBS south stock area (3CD5AB, Table D.15). While the assumed hybrid stock (5C) is not used in the population model (other than allocating 5C catch to the other two stocks), genetically determined hybrids account for only (8+34)/(87+196+8+34) = 12.9% of the genetically determined specimens in 5C.

Genetically determined BSR and RER occur in all regions along the BC coast (Figure D.26). There are indications that BSR occurs more frequently in areas 5A-E than in areas 3CD, but the reverse is not true for RER, which exhibits hotspots off NW Haida Gwaii, in Moresby/Goose Island Gullies, and off SW Vancouver Island. The absolute frequency of specimens might be misleading as there are twice as many genetically determined BSR as RER. Figure D.27 presents the proportion of BSR (pBSR) specimens to BSR+RER specimens in area groups, specifically by PMFC major and minor areas. The highest pBSR occurs in 5E, but 5A and 5C also feature high pBSR. Broken down by minor area, the highest pBSR occurs in minor area 34 near Anthony Island, followed by hotspots in areas 31 and 35 off Haida Gwaii and areas 2 and 7 clustered near the head of Moresby Gully. The latter seems anomalous because BSR is generally considered to occur deeper than RER; however, the same cluster appears in Creamer (2016, Fig. 1)[12]. Despite the noisy data, there is a general attenuation of pBSR from north to south.

[12] Creamer (2016) found that depth alone was a poor predictor of the BSR/RER species split.

Table D.14. Extent of available genetic information for the BSR/RER species complex by data source and year. '–': no data

	Sample year							
Data source↓	2010	2011	2012	2013	2014	2015	2016	Total
Commercial fishery	–	–	54	65	227	236	318	900
Queen Charlotte Sound Synoptic	–	362	–	335	–	323	–	1,020
Hecate Strait Synoptic	–	106	–	42	–	63	–	211
West Coast Vancouver Island Synoptic	–	–	213	–	267	–	379	859
IPHC Longline	–	88	114	–	–	129	129	460
West Coast Haida Gwaii Synoptic	731	–	859	–	264	–	685	2,539
Hard Bottom Longline Outside North	–	–	56	–	–	20	–	76
Hard Bottom Longline Outside South	–	1	–	–	3	–	1	5
Strait of Georgia Synoptic	–	–	1	–	–	–	–	1
Joint Canada/US Hake Acoustic	–	–	–	1	9	26	–	36
Standardised Sablefish Trap	420	239	395	154	371	270	268	2,117
Shrimp Bottom Trawl	–	28	123	63	31	59	140	444
Total	1,151	824	1,815	660	1,172	1,126	1,920	8,668

Table D.15. Genetic composition of the assessment stocks (BSR=Blackspotted, RER=Rougheye, HY1=first-generation hybrids, HY2=second-generation hybrids, FAIL=failed genetic tests).

stock→ genetics↓	REBS north	REBS south	5C 'hybrids'
BSR	3815	892	196
RER	631	2011	87
FAIL	349	235	25
HY1	80	65	8
HY2	93	146	34

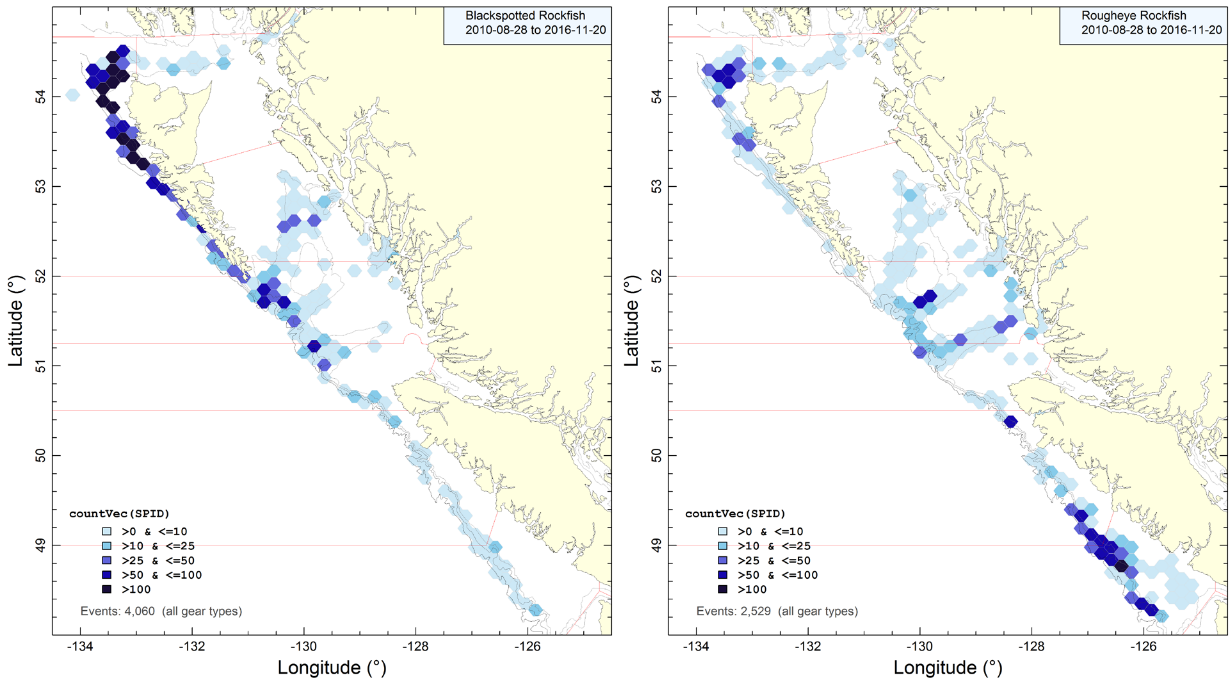


Figure D.26. Distribution of genetically determined BSR (left) and RER (right) by all gear types.

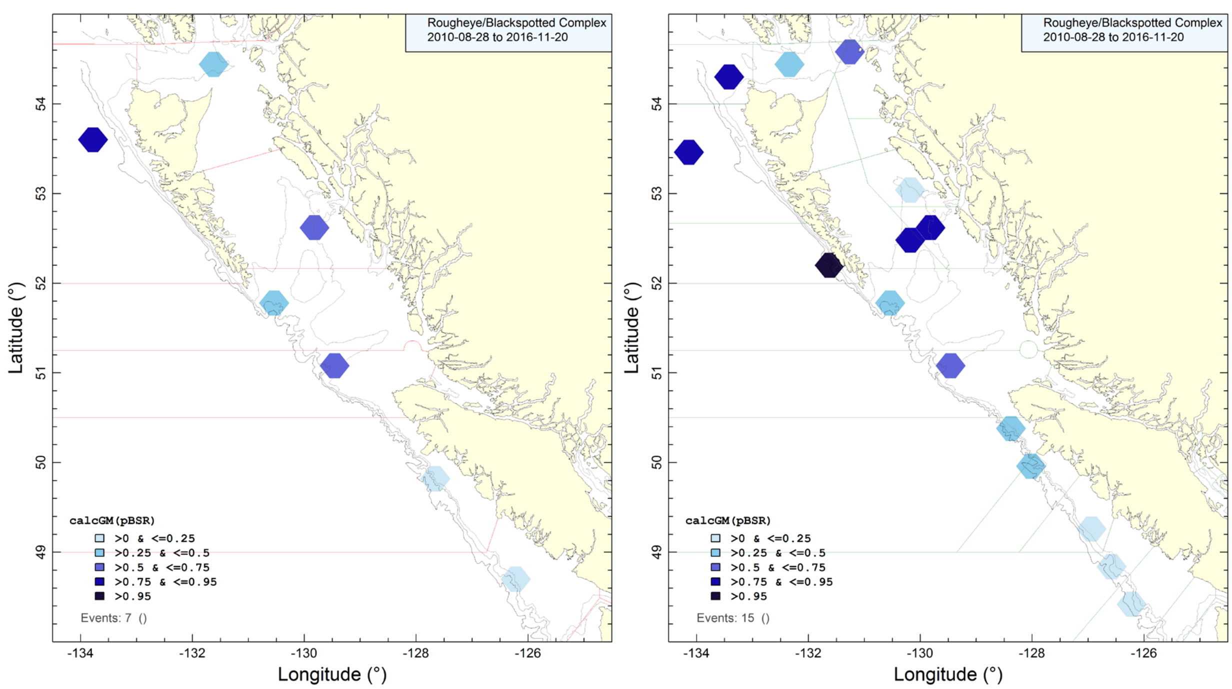


Figure D.27. Proportion of specimens genetically identified as BSR grouped by PMFC major areas (left) and PMFC minor areas (right) by all gear.

The species distribution information presented in Figure D.26 and Figure D.27 treat all observations as if they were independent representations of the true species distribution, without regard to interannual variation. These data indicate that these two species are highly comingled throughout BC waters and they clearly interbreed successfully. However, it is not correct to consider that these genetic observations, summarised across a range of surveys and collected over seven years, are representative of the underlying distribution of these two species. Even the Creamer (2016) statistical model, which attempted to predict the species distribution based on only two variables (longitude and 'rugosity'), makes the underlying assumption that the distribution of REBS species is static and can be predicted across years using external data. However, the true species distribution is much more likely to be dynamic and variable, responding to a range of environmental cues. If it is important to understand the split between these two species, we should actively sample the catch across a range of fisheries in every part of the occupied habitat. Until several years of comprehensive species information are collected, it will not be possible to understand how best to disaggregate historical catches of REBS into the component species.

The areal stock separation for REBS used in this stock assessment also aligns with previous stock assessments (Starr and Haigh 2021 a,b), with one stock north of 52°N and one south of this latitude. This separation may be caused by the North Pacific Current bifurcation (Pickard and Emery 1982, Freeland 2006, Cummins and Freeland 2006, Batten and Freeland 2007) whereby free-swimming larvae from the two regions are kept apart.

D.3.3. Fish Length Distributions

Simple comparisons of commercial length distributions by stock from the two trawl fisheries (bottom and midwater) show no evidence that length frequency distributions are markedly different between capture methods by stock based on area (REBS north: Figure D.28, REBS south: Figure D.29). This suggests that it is likely reasonable to combine data from bottom and midwater trawl gear. The trap and longline data suggest that lengths by non-trawl capture methods might be higher than those from trawl; however, the population model treats the non-trawl fisheries as an 'Other' fishery.

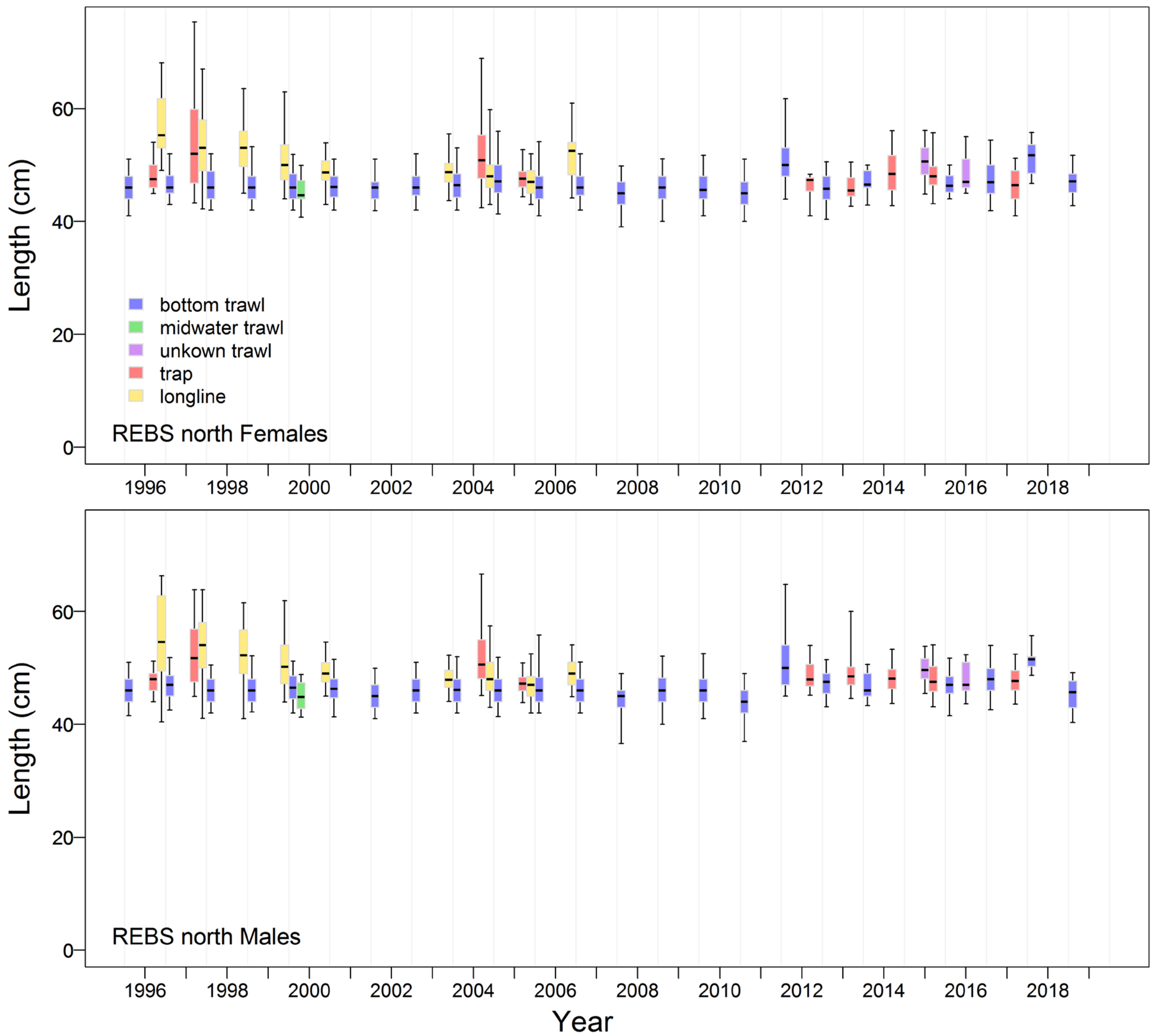


Figure D.28. Comparison of annual distributions of REBS north length by sex among gear types in the commercial fisheries. Boxplot quantiles: 0.05, 0.25, 0.5, 0.75, 0.95.

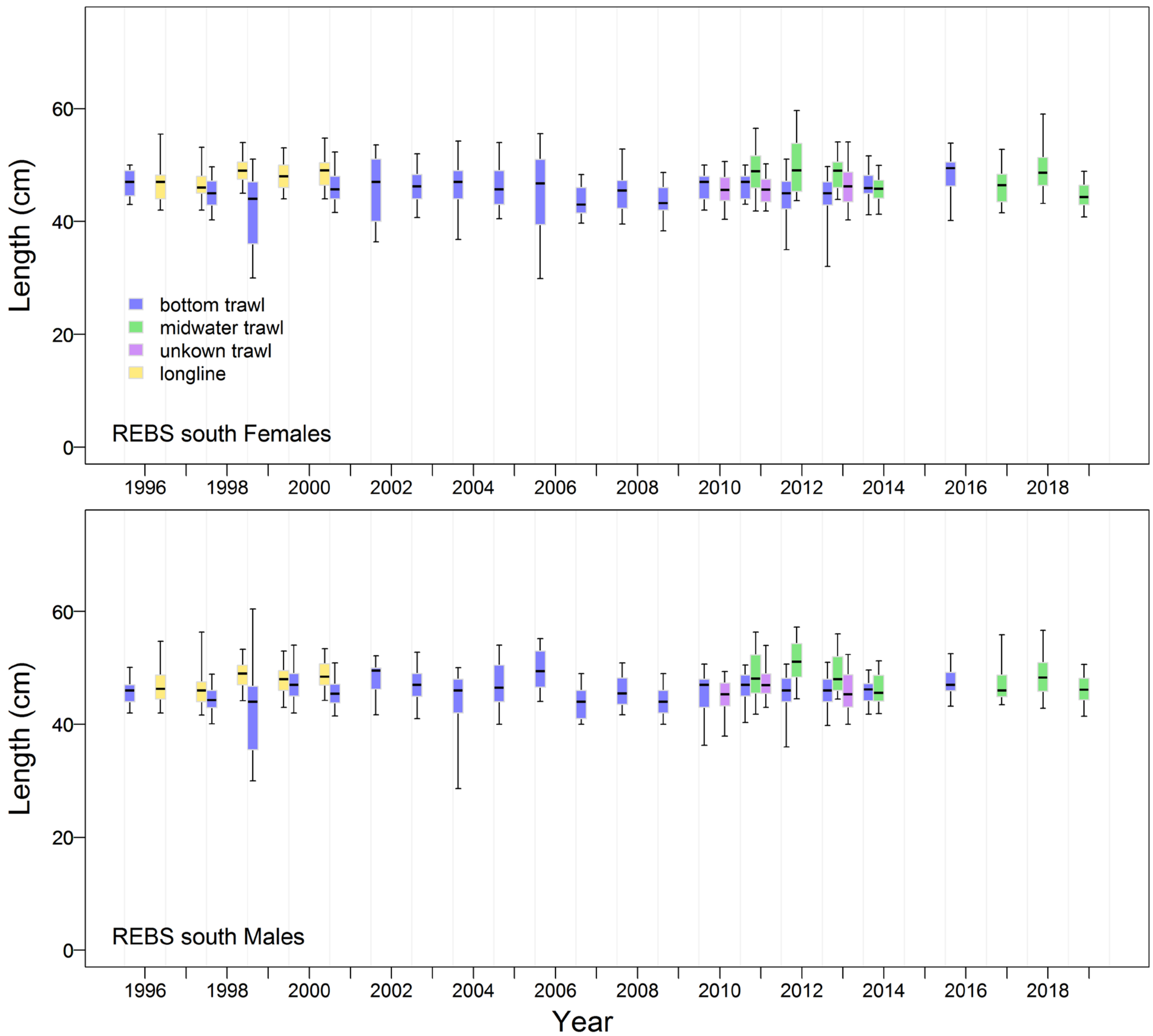


Figure D.29. Comparison of annual distributions of REBS south length by sex among gear types in the commercial fisheries. Boxplot quantiles: 0.05, 0.25, 0.5, 0.75, 0.95.

The distribution of lengths from a variety of surveys (REBS north: Figure D.30, REBS south: Figure D.31) show inter-survey differences in mean length that likely stem from survey selectivity differences:

- surveys WCHG synoptic, IPHC longline, and Sablefish trap show similar REBS length distributions while those from the HS synoptic are smaller (and younger);
- four of six surveys show similar REBS length distributions with QCS synoptic catching smaller fish on average and the Shrimp trawl survey catching much smaller (and younger) fish.

The selectivity differences are probably more related to depth rather than latitude.

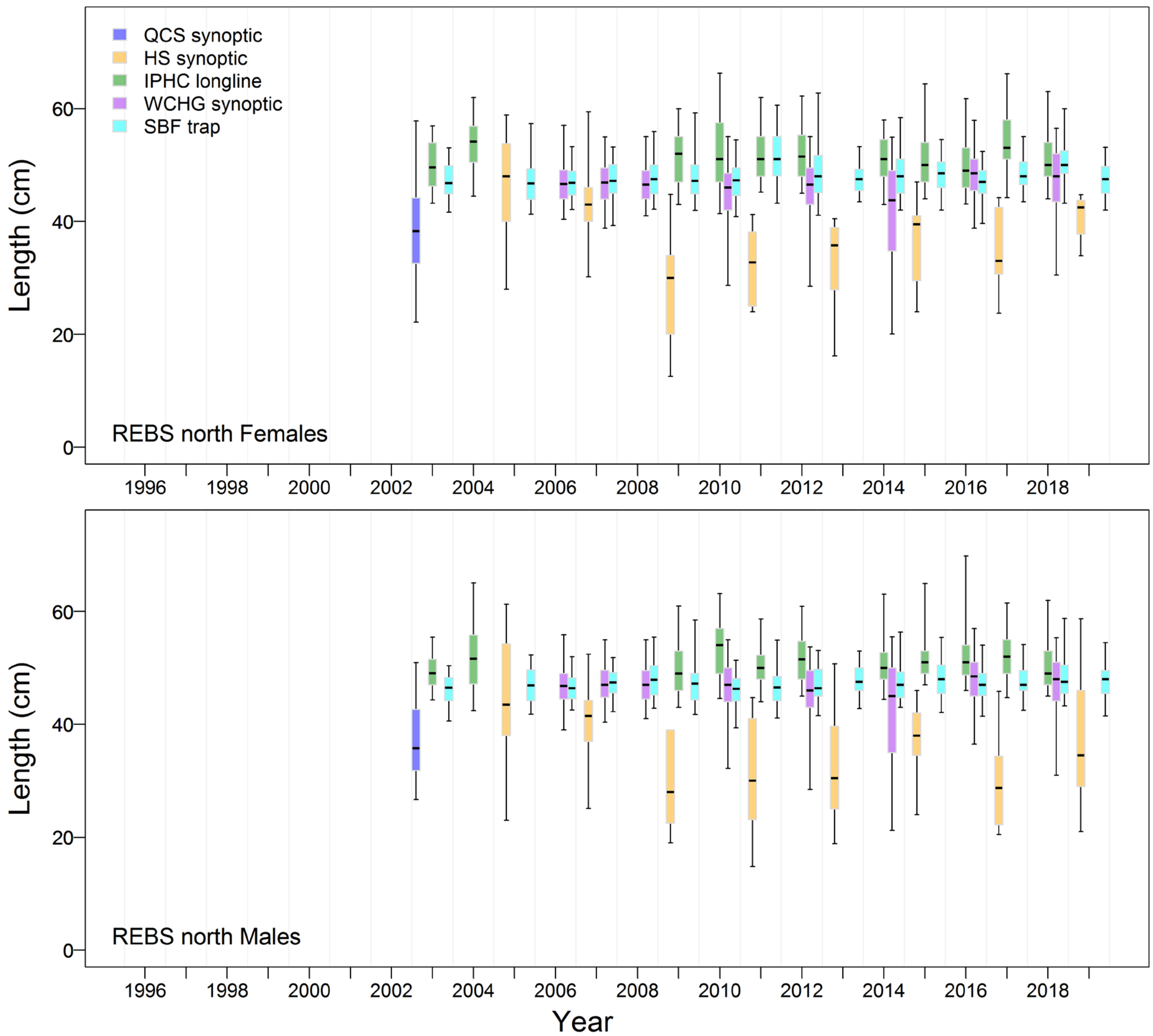


Figure D.30. Comparison of annual distributions of REBS north length among five surveys (three trawl, one halibut longline, and one sablefish trap). Boxplot quantiles: 0.05, 0.25, 0.5, 0.75, 0.95.

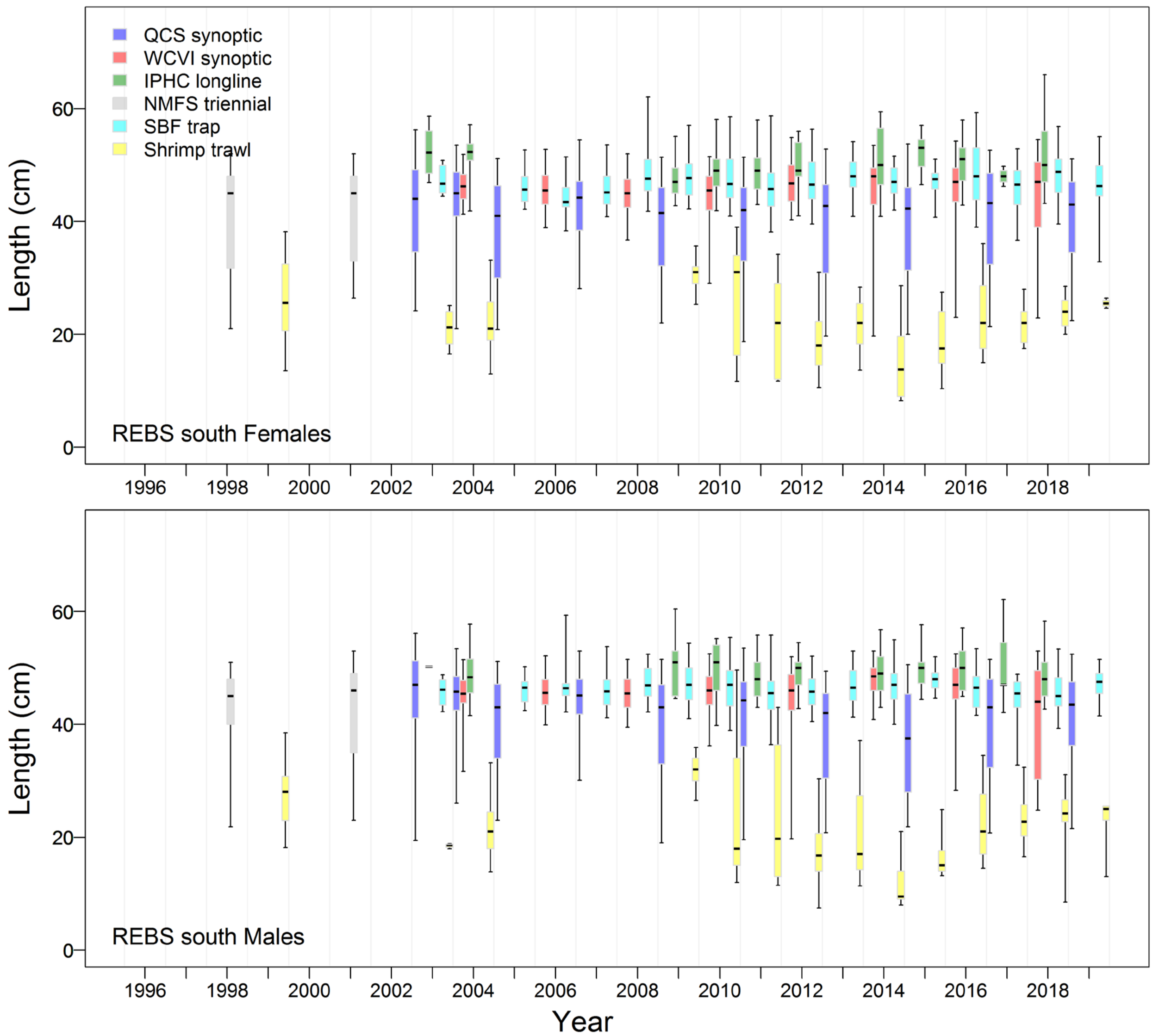


Figure D.31. Comparison of annual distributions of REBS south length among six surveys (four trawl, one halibut longline, and one sablefish trap). Boxplot quantiles: 0.05, 0.25, 0.5, 0.75, 0.95.

D.3.4. Comparison of Growth Models

A comparison of growth models between stocks (REBS north vs. REBS south) and genetically determined species (BSR and RER) in Figure D.32 suggests a few differences:

- females are larger than males;
- genetically determined females and males are larger that their area-based counterparts for both stocks;
- males determined by genetics (BSR and RER) are the same size;
- males determined by area (REBS north and REBS south) are the same size.

Figure D.32 also shows how the two other parameters (K, t_0) vary with L_∞. Despite these differences, a comparison of growth curves (Figure D.33) shows that growth does not vary a great deal amongst stocks, genetics, and sex.

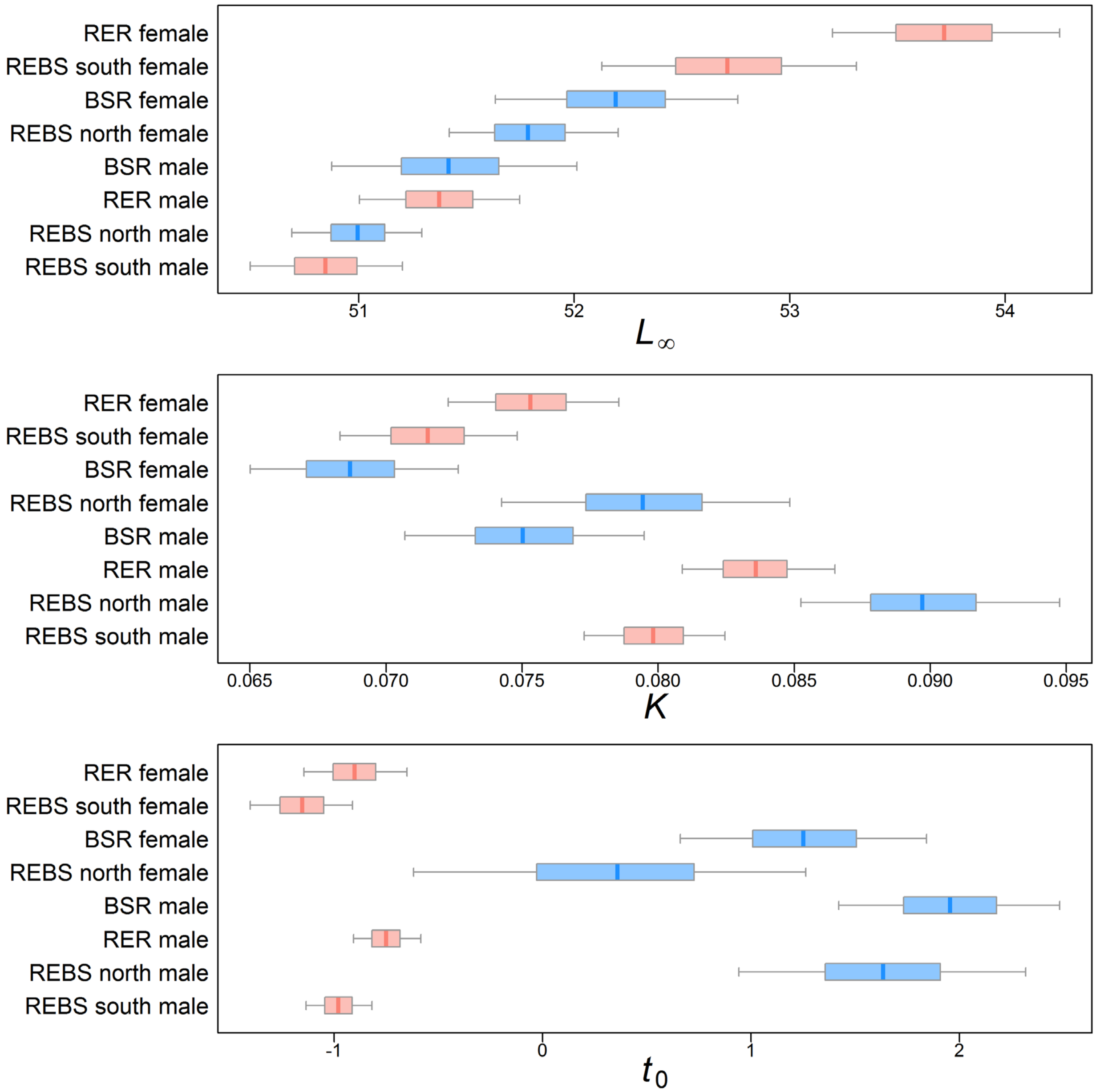


Figure D.32. MCMC samples (4 chains, 1000 each) for von Bertalanffy parameters using survey REBS length-age data by stock (REBS north and south) and genetics (BSR, RER). Boxplots (blue = REBS north and BSR; red = REBS south and RER) show 0.05, 0.25, 0.5, 0.75, and 0.95 quantiles.

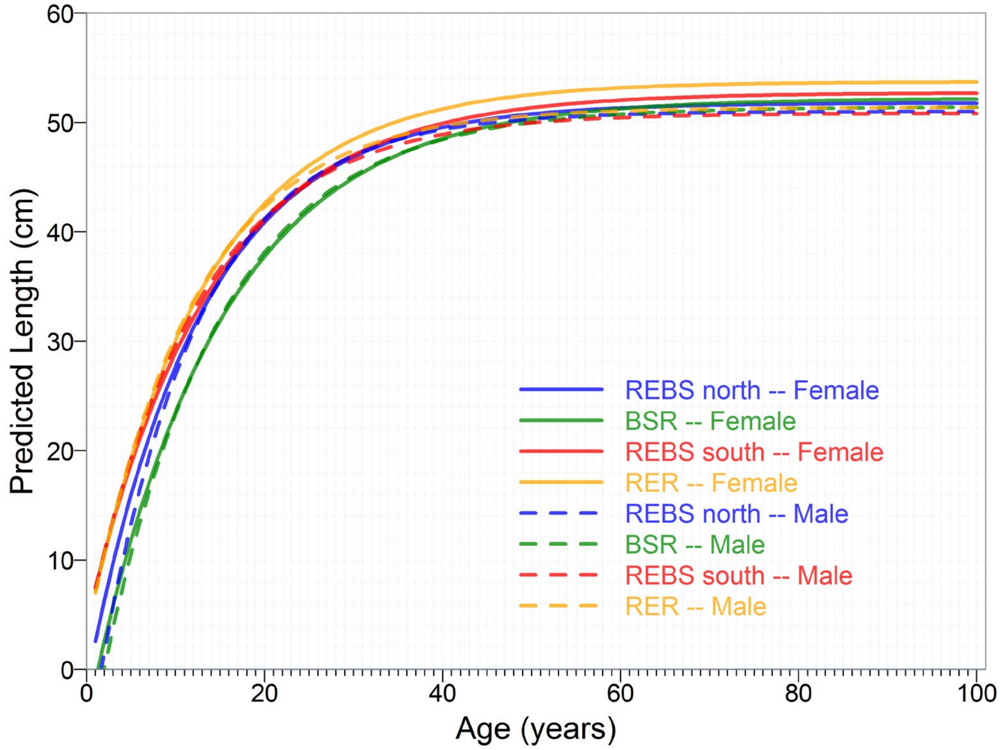


Figure D.33. von Bertalanffy fits using median parameter estimates from the rstan model fit to survey REBS length-age data by stock and genetics region using ageing error (CVs of length-at-age). Line colour indicates stock/genetics (blue=REB north, red=REBS south, green=BSR, orange=RER); line type indicates sex (solid=female, dashed=male).

D.4. REFERENCES – BIOLOGY

Batten, S.D. and Freeland, H.J. 2007. Plankton populations at the bifurcation of the North Pacific Current. Fisheries Oceanography 16(6): 536-546.

Creamer, J.M. 2016. Using genetic species identification and environmental data to distinguish historical catches of cryptic Blackspotted Rockfish (*Sebastes melanostictus*) and Rougheye Rockfish (*Sebastes aleutianus*) in British Columbia. Master's thesis, Simon Fraser University, Burnaby, BC, 40 p.

Cummins, P.F. and Freeland, H.J. 2007. Variability of the North Pacific Current and its bifurcation. Progress in Oceanography 75(2): 253-265.

DFO. 2022. Proceedings of the Pacific regional peer review of the Redstripe Rockfish (*Sebastes proriger*) stock assessment for British Columbia in 2018; June 13-14, 2018. DFO Can. Sci. Advis. Sec. Proceed. Ser. In press.

Freeland, H.J. 2006. What proportion of the North Pacific Current finds its way into the Gulf of Alaska? Atmosphere-Ocean 44(4): 321-330.

Gharrett, A.J., Matala, A.P., Peterson, E.L., Gray, A.K., Li, Z. and Heifetz, J. 2005. Two genetically distinct forms of rougheye rockfish are different species. Trans. Am. Fish. Soc. 134: 242-260.

Haigh, R., Olsen, N. and Starr, P. 2005. A review of Rougheye Rockfish *Sebastes aleutianus* along the Pacific coast of Canada: biology, distribution, and abundance trends. DFO Can. Sci. Advis. Sec. Res. Doc. 2005/096. vi + 68 p.

Haist, V., Breen, P.A. and Starr, P.J. 2009. A multi-stock, length-based assessment model for New Zealand rock lobster (*Jasus edwardsii*). N.Z. J. Mar. Freshw. Res. 43: 355-371.

Hamel, O.S. 2015. A method for calculating a meta-analytical prior for the natural mortality rate using multiple life history correlates. ICES J. Mar. Sci. 72(1): 62-69.

Harris, J.P., Hutchinson, C. and Wildes, S. 2019. Using otolith morphometric analysis to improve species discrimination of blackspotted rockfish (*Sebastes melanostictus*) and rougheye rockfish (*S. aleutianus*). Fish. Bull. 117: 234-244.

Hicks, A.C., Wetzel, C. and Harms, J. 2014. The status of rougheye rockfish (*Sebastes aleutianus*) and blackspotted rockfish (*S. melanostictus*) as a complex along the U.S. West Coast in 2013. Stock Assessment and Fishery Evaluation (SAFE) , NMFS, NOAA xvi + 250 p.

Hilborn, R., Maunder, M., Parma, A., Ernst, B., Payne, J. and Starr, P. 2003. Coleraine: A generalized age-structured stock assessment model. User's manual version 2.0. University of Washington Report SAFS-UW-0116. Tech. rep., University of Washington.

Hoenig, J.M. 1983. Empirical use of longevity data to estimate mortality rates. Fish. Bull. 82(1): 898-903.

MacLellan, S.E. 1997. How to age rockfish (*Sebastes*) using *S. alutus* as an example – the otolith burnt section technique. Can. Tech. Rep. Fish. Aquat. Sci. 2146: 39 p.

Pickard, G.L. and Emery, W.J. 1982. Descriptive Physical Oceanography, an Introduction. Pergamon Press, Oxford UK, 4th (SI) enlarged ed.

Quinn, T.J.I. and Deriso, R.B. 1999. Quantitative Fish Dynamics. Oxford University Press, New York, NY.

Schnute, J.T. 1981. A versatile growth model with statistically stable parameters. Can. J. Fish. Aquat. Sci. 38(9): 1128-1140.

Shotwell, S.K. and Hanselman, D.H. 2019. Chapter 13: Assessment of rougheye and blackspotted rockfish in the Gulf of Alaska. In Stock Assessment and Fishery Evaluation (SAFE) Report for the Groundfish Resources of the Gulf of Alaska, chap. 12, p. 1-115. North Pacific Fishery Management Council (NPFMC).

Stan Development Team. 2018. rstan: the R interface to Stan. R package version 2.18.2.

Stanley, R.D., Starr, P. and Olsen, N. 2009. Stock assessment for Canary rockfish (*Sebastes pinniger*) in British Columbia waters. DFO Can. Sci. Advis. Sec. Res. Doc. 2009/013: xxii + 198 p.

Starr, P.J. and Haigh, R. 2021a. Redstripe Rockfish (*Sebastes proriger*) stock assessment for British Columbia in 2018. DFO Can. Sci. Advis. Sec. Res. Doc. 2021/014. vii + 340 p.

Starr, P.J. and Haigh, R. 2021b. Walleye Pollock (*Theragra chalcogramma*) stock assessment for British Columbia in 2017. DFO Can. Sci. Advis. Sec. Res. Doc. 2021/004. vii + 265 p.

Then, A.Y., Hoenig, J.M., Hall, N.G. and Hewitt, D.A. 2015. Evaluating the predictive performance of empirical estimators of natural mortality rate using information on over 200 fish species. ICES J. Mar. Sci. 72(1): 82-92.

Westrheim, S. 1975. Reproduction, maturation, and identification of larvae of some *Sebastes* (Scorpaenidae) species in the northeast Pacific Ocean. J. Fish. Res. Bd. Can. 32: 2399-2411.

APPENDIX E. MODEL EQUATIONS

E.1. INTRODUCTION

The stock assessment of Rougheye/Blackspotted Rockfish uses a sex-specific, age-structured model called 'Awatea' in a Bayesian framework to reconstruct a population trajectory and its uncertainty. The model can simultaneously estimate the steepness of the stock-recruitment function and separate mortalities for the sexes. This approach follows that used in BC stock assessments since 2010:

- 2019 – Bocaccio for the coast of BC (Starr and Haigh 2022),
- 2019 – Widow Rockfish for the coast of BC (Starr and Haigh 2021*a*),
- 2018 – Redstripe Rockfish in PMFC areas 5DE and 3CD5ABC (Starr and Haigh 2021*b*),
- 2017 – Pacific Ocean Perch (POP) in Queen Charlotte Sound (Haigh et al. 2018*a*),
- 2014 – Yellowtail Rockfish for the coast of BC (DFO 2015),
- 2013 – Silvergray Rockfish along the Pacific coast of Canada (Starr et al. 2016),
- 2013 – Rock Sole in BC (Holt et al. 2016),
- 2012 – POP off the west coast of Vancouver Island (Edwards et al. 2014*b*),
- 2012 – POP off the west coast of Haida Gwaii (Edwards et al. 2014*a*),
- 2011 – Yellowmouth Rockfish along the Pacific coast of Canada (Edwards et al. 2012*a*),
- 2010 – POP in Queen Charlotte Sound (Edwards et al. 2012*b*).

The model structure is the same as that used previously, and, as for all the assessments above except 5ABC POP in 2010, this assessment used the weighting scheme of Francis (2011) described in Section E.6.2.

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

Running of Awatea is streamlined using custom R code (Haigh et al. 2018*b*), rather than through the original Microsoft Excel 97/2000 implementation (Hilborn et al. 2003). Figures and tables of output were automatically produced in R, an environment for statistical computing and graphics (R Core Team 2019), using code adapted from the R packages `scape` (Magnusson 2009) and `plotMCMC`, previously called `scapeMCMC` (Magnusson and Stewart 2020). The R function `Sweave` (Leisch 2002) automatically collates, via LaTeX, the large amount of figures and tables into a single '`.pdf`' file for each model run.

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

E.2. MODEL ASSUMPTIONS

The assumptions of the model are:

1. The assessed BC population of Rougheye/Blackspotted Rockfish (REBS) comprised two stocks in PMFC areas 5DE and 3CD5AB.

2. Annual catches were taken by two fisheries: ‘Trawl’ (bottom and midwater) and ‘Other’ (halibut longline, sablefish trap, lingcod & salmon troll, and rockfish hook & line), known without error, and occurred in the middle of each year.
3. The Beverton-Holt stock-recruitment relationship was time-invariant, with a log-normal error structure.
4. Selectivity was different among surveys but the same between sexes, and remained invariant over time. Selectivity parameters were estimated when ageing data were available.
5. Natural mortality M was fixed at three values (0.035, 0.045, 0.055) for females and males, and held invariant over time.
6. Growth parameters were fixed and invariant over time.
7. Maturity-at-age parameters for females were fixed and invariant over time. Male maturity did not need to be considered, because it was assumed that there were always sufficient mature males.The mature male population is not tracked by this model, with spawning biomass expressed as mature females only.
8. Recruitment at age 1 was 50% females and 50% males.
9. Fish ages determined using the preferred otolith break-and-burn methodology (MacLellan 1997) were aged without error. Ages determined by surface ageing methods (chiefly before 1978) are biased (Beamish 1979) and not generally used. This methodology was deemed suitable, however, for very young rockfish (ages 1-3): fourteen surface-read REBS south specimens were used.
10. Commercial samples of catch-at-age in a given year were representative of the fishery if there were $\geq$2 samples in that year.
11. Relative abundance indices were proportional to the vulnerable biomass at the mid point of the year, after half the catch and half the natural mortality had been accounted for.
12. The age composition samples came from the middle of the year after half the catch and half the natural mortality had been accounted for.

E.3. MODEL NOTATION AND EQUATIONS

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

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

Given that fixed values are not known for all parameters, many of them need to be estimated, and stochasticity needs to be added 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.3). This function is derived from the deterministic, stochastic and prior components of the model.

Table E.1. *Notation for the Awatea catch-at-age model (continued overleaf). Note:* $\mathrm{N_vS}$ *denotes 'REBS north or REBS south'.*

Symbol	Description and units
	Indices (all subscripts)
a	age class, where $a = 1, 2, 3, ...A$, and $A \in \{80, 80\}$ is the accumulator age class for REBS north and REBS south
t	model year, where $t = 1, 2, 3, ...T$, corresponds to actual years: 1935, ..., 2021, and $t = 0$ represents unfished equilibrium conditions
g	index for series (abundance|composition) data: REBS north: 1 – WCHG Synoptic trawl survey series 2 – Trawl fishery|CPUE index 3 – Other fishery index REBS south: 1 – QCS Synoptic trawl survey series 2 – WCVI Synoptic trawl survey series 3 – NMFS Triennial trawl survey series 4 – Trawl fishery|CPUE index 5 – Other fishery index
s	sex, $1 =$ females, $2 =$ males
	Index ranges
A	accumulator age-class, $A \in \{80, 80\}$
T	number of model years, $T = 87$
$\mathbf{T}_g$	sets of model years for survey abundance indices from series g, listed here for clarity as actual years (subtract 1934 to give model year t): REBS north: $\mathbf{T}_1$ = {1997, 2006:2008, 2010, 2012, 2016, 2018} $\mathbf{T}_2$ = {1996, ..., 2019} REBS south: $\mathbf{T}_1$ = {2003:2005, 2007, 2009, 2011, 2013, 2015, 2017, 2019} $\mathbf{T}_2$ = {2004, 2006, 2008, 2010, 2012, 2014, 2016, 2018} $\mathbf{T}_3$ = {1995, 1998, 2001} $\mathbf{T}_4$ = {1996, ..., 2019}
$\mathbf{U}_g$	sets of model years with proportion-at-age data for series g: REBS north: $\mathbf{U}_1$ = {1997, 2006:2008, 2010, 2012, 2016} $\mathbf{U}_2$ = {1978, 1982, 1991:2006, 2017} $\mathbf{U}_3$ = {2004:2005} REBS south: $\mathbf{U}_1$ = {2011, 2013, 2015} $\mathbf{U}_2$ = {2012, 2014, 2016} $\mathbf{U}_4$ = {1998, 2001, 2003, 2006, 2018} $\mathbf{U}_5$ = {1997}

Symbol	Description and units
	Data and fixed parameters
p_{atgs}	observed weighted proportion of fish from series g in each year $t \in \mathbf{U}_g$ that are age-class a and sex s; so $\Sigma_{a=1}^{A}\Sigma_{s=1}^{2} p_{atgs} = 1$ for each $t \in \mathbf{U}_g$
n_{tg}	effective sample size that yields corresponding p_{atgs}
C_t	observed catch biomass (tonnes) in year $t = 1, 2, ..., T-1$
w_{as}	average weight (kg) of individual of age-class a of sex s from fixed parameters
m_a	proportion of age-class a females that are mature, fixed from data
I_{tg}	biomass estimates (tonnes) from surveys $g = 1, ..., \{1_{\mathrm{N}} \vee 3_{\mathrm{S}}\}$, for year $t \in \mathbf{T}_g$, tonnes
κ_{tg}	standard deviation of I_{tg}
σ_R	standard deviation parameter for recruitment process error, $\sigma_R = 0.9$
	Estimated parameters
$\mathbf{\Theta}$	set of estimated parameters
R_0	virgin recruitment of age-1 fish (numbers of fish, 1000s)
M_s	natural mortality rate for sex $s = 1, 2$ (M fixed for the REBS assessment)
h	steepness parameter for Beverton-Holt recruitment
q_g	catchability for survey series $g = 1, ..., \{1_{\mathrm{N}} \vee 3_{\mathrm{S}}\}$
μ_g	age of full selectivity for females for series $g = {\scriptstyle \mathrm{N}\{1,2,3\} \vee \mathrm{S}\{1,2,4,5\}}$
Δ_g	shift in vulnerability for males for series $g = {\scriptstyle \mathrm{N}\{1,2,3\} \vee \mathrm{S}\{1,2,4,5\}}$
v_{gL}	variance parameter for left limb of selectivity curve for series $g = {\scriptstyle \mathrm{N}\{1,2,3\} \vee \mathrm{S}\{1,2,4,5\}}$
s_{ags}	selectivity for age-class a, series $g = {\scriptstyle \mathrm{N}\{1,2,3\} \vee \mathrm{S}\{1,2,4,5\}}$, and sex s, calculated from the parameters μ_g, Δ_g and v_{gL}
α, β	alternative formulation of recruitment: $\alpha = (1-h)B_0/(4hR_0)$ and $\beta = (5h-1)/4hR_0$
$\widehat{x}$	estimated value of observed data x
	Derived states
N_{ats}	number of age-class a fish (1000s) of sex s at the start of year t
u_{ats}	proportion of age-class a and sex s fish in year t that are caught
u_t	exploitation ratio of total catch to vulnerable biomass in the middle of the year t
B_t	spawning biomass (tonnes mature females) at the start of year $t = 1, 2, 3, ..., T$
B_0	virgin spawning biomass (tonnes mature females) at the start of year 0
R_t	recruitment of age-1 fish (numbers of fish, 1000s) in year $t = 1, 2, ..., T-1$
V_t	vulnerable biomass (tonnes males + females) in the middle of year $t = 1, 2, 3, ..., T$

Symbol	Description and units
	Deviations and likelihood components
ϵ_t	Recruitment deviations arising from process error
$\log L_1(\mathbf{\Theta}\|\{\epsilon_t\})$	log-likelihood component related to recruitment residuals
$\log L_2(\mathbf{\Theta}\|\{\widehat{p}_{atgs}\})$	log-likelihood component related to estimated proportions-at-age
$\log L_3(\mathbf{\Theta}\|\{\widehat{I}_{tg}\})$	log-likelihood component related to estimated survey biomass indices
$\log L(\mathbf{\Theta})$	total log-likelihood
	Prior distributions and objective function
$\pi_j(\mathbf{\Theta})$	Prior distribution for parameter j
$\pi(\mathbf{\Theta})$	Joint prior distribution for all estimated parameters
$f(\mathbf{\Theta})$	Objective function to be minimised

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

Deterministic components

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

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

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

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

Initial conditions ($t = 1$)

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

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

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

Selectivities ($g = 1, \ldots$)

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

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

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

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

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

$$V_t = \sum_{s=1}^{2} \sum_{a=1}^{A} e^{-M_s/2}\, w_{as}\, s_{a,g=\{2_{\mathrm{N}} \vee 4_{\mathrm{S}}\},\ldots,\{3_{\mathrm{N}} \vee 5_{\mathrm{S}}\},s}\, N_{ats} \tag{E.11}$$

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

$$u_{ats} = s_{a,g=\{2_{\mathrm{N}} \vee 4_{\mathrm{S}}\},\ldots,\{3_{\mathrm{N}} \vee 5_{\mathrm{S}}\},s}\, u_t\,; \quad 1 \leq a \leq A,\ s = 1, 2 \tag{E.13}$$

Estimated observations

$$\widehat{I}_{tg} = q_g \sum_{s=1}^{2} \sum_{a=1}^{A} e^{-M_s/2}(1 - u_{ats}/2) w_{as} s_{ags} N_{ats}\,; \quad t \in \mathbf{T}_g,\ g = {\scriptstyle \mathrm{N}\{1,2\} \vee \mathrm{S}\{1,2,3,4\}} \tag{E.14}$$

$$\widehat{p}_{atgs} = \frac{e^{-M_s/2}(1 - u_{ats}/2) s_{ags} N_{ats}}{\sum_{s=1}^{2} \sum_{a=1}^{A} e^{-M_s/2}(1 - u_{ats}/2) s_{ags} N_{ats}}\,;\ {\scriptstyle 1 \leq a \leq A,\ t \in \mathbf{U}_g,\ g = \mathrm{N}\{1,2,3\} \vee \mathrm{S}\{1,2,4,5\},\ s = 1,2} \tag{E.15}$$

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

Stochastic components

Estimated parameters

$$\boldsymbol{\Theta} = \{R_0; M_{1,2}; h; q_{\mathrm{N}\{1,2\}\vee\mathrm{S}\{1,2,3,4\}}; \mu_{\mathrm{N}\{1,2,3\}\vee\mathrm{S}\{1,2,4,5\}}; \Delta_{\mathrm{N}\{1,2,3\}\vee\mathrm{S}\{1,2,4,5\}}; \upsilon_{\mathrm{N}\{1,2,3\}\vee\mathrm{S}\{1,2,4,5\}L}\} \tag{E.16}$$

Recruitment deviations

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

Log-likelihood functions

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

$$\begin{aligned}\log L_2(\boldsymbol{\Theta}|\{\widehat{p}_{atgs}\}) = &-\frac{1}{2}\sum_{g=\mathrm{N}\{1,2,3\}\vee\mathrm{S}\{1,2,4,5\}}\sum_{a=1}^{A}\sum_{t\in\mathbf{U}_g}\sum_{s=1}^{2}\log\left[p_{atgs}(1-p_{atgs}) + \frac{1}{10A}\right] \\ &+ \sum_{g=\mathrm{N}\{1,2,3\}\vee\mathrm{S}\{1,2,4,5\}}\sum_{a=1}^{A}\sum_{t\in\mathbf{U}_g}\sum_{s=1}^{2}\log\left[\exp\left\{\frac{-(p_{atgs}-\widehat{p}_{atgs})^2\, n_{tg}}{2\left(p_{atgs}(1-p_{atgs}) + \frac{1}{10A}\right)}\right\} + \frac{1}{100}\right]\end{aligned} \tag{E.19}$$

$$\log L_3(\boldsymbol{\Theta}|\{\widehat{I}_{tg}\}) = \sum_{g=\mathrm{N}\{1,2,3\}\vee\mathrm{S}\{1,2,4,5\}}\sum_{t\in\mathbf{T}_g}\left[-\frac{1}{2}\log 2\pi - \log\kappa_{tg} - \frac{(\log I_{tg} - \log\widehat{I}_{tg})^2}{2\kappa_{tg}^2}\right] \tag{E.20}$$

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

Joint prior distribution and objective function

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

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

Table E.4. Details for estimation of parameters, including prior distributions with corresponding means and standard deviations, bounds between which parameters are constrained, and initial values to start the minimisation procedure for the MPD (mode of the posterior density) calculations. For uniform prior distributions, the bounds completely parameterise the prior. The resulting non-uniform prior probability density functions are the $\pi_j(\mathbf{\Theta})$ functions that contribute to the joint prior distribution in (E.3).

Parameter	Phase	Prior distribution	Mean, SD	Bounds	Initial value
REBS north					
R_0	1	uniform	—	[1, 10e7]	10e4
M_1, M_2	-	fixed	—	—	{0.035,0.045,0.055}
h	-	fixed	—	—	0.7
$\log \epsilon_t$	2	normal	0, 0.9	[-15, 15]	0
$\log q_1$	1	normal	0, 0.6	[-12, 5]	-5
$\log q_2$	2	normal	0, 0.1	[-15, 15]	-1.60944
μ_1	3	normal	36, 7.2	[5, 70]	36
μ_2	3	uniform	35, 3.5	[5, 60]	26
μ_3	3	normal	36, 7.2	[5, 70]	36
$\log v_{1,2,3}$	4	uniform	2.5, 2.5	[-15, 15]	2.5
$\Delta_{1,2,3}$	4	uniform	0, 1	[-8. 10]	0
REBS south					
R_0	1	uniform	—	[1, 10e7]	10e4
M_1, M_2	-	fixed	—	—	{0.035,0.045,0.055}
h	-	fixed	—	—	0.7
$\log \epsilon_t$	2	normal	0, 0.9	[-15, 15]	0
$\log q_{1,2,3}$	1	uniform	0, 0.6	[-5, 5]	-1.6
$\log q_4$	1	uniform	0, 0.1	[-15, 15]	-1.60944
$\mu_{1,2}$	3	uniform	36, 7.2	[5, 70]	36
μ_3	-	fixed	—	—	36
μ_4	3	uniform	33.6, 2.36	[5, 60]	33.6
μ_5	3	uniform	56.5, 5.65	[5, 70]	56.5
$\log v_{1,2,4}$	4	uniform	2.5, 2.5	[-15, 15]	2.5
$\log v_3$	-	fixed	—	—	2.5
$\log v_5$	4	normal	6, 0.6	[-15, 15]	6
$\Delta_{1,2,4}$	4	uniform	0, 1	[-8. 10]	0
Δ_3	-	fixed	—	—	0
Δ_5	4	normal	0.6, 0.6	[-8. 10]	0.6

E.4. DESCRIPTION OF DETERMINISTIC COMPONENTS

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

E.4.1. Age classes

Index (subscript) a represents age classes, going from 1 to the accumulator age class A of 80. 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 2021.

E.4.2. Years

Index t represents model years, going from 1 to $T = 87$, and $t = 0$ represents unfished equilibrium conditions. The actual year corresponding to $t = 1$ is 1935, and so model year $T = 87$ corresponds to 2021. The interpretation of year depends on the model's derived state or data input:

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

E.4.3. Survey Data

Data from $1, ..., \{1_\mathrm{N} \vee 3_\mathrm{S}\}$ series were used, as described in detail in Appendix B. For the two REBS stocks, indices g denote the surveys: North g=1: West Coast Haida Gwaii (WCHG) Synoptic; South g=1: Queen Charlotte Sound (QCS) Synoptic; South g=2: West Coast Vancouver Island (WCVI) Synoptic; South g=3: NMFS Triennial. The years for which data were available for each survey are given in Table E.1; $\mathbf{T}_g$ corresponds to years for the survey biomass estimates I_{tg} (and corresponding standard deviations κ_{tg}), and $\mathbf{U}_g$ corresponds to years for proportion-at-age data p_{atgs} (with effective sample sizes n_{tg}). Note that sample size refers to the number of samples, where each sample comprises multiple specimens, typically $\sim$30-350 fish.

E.4.4. Commercial Data

As described in Appendix A, the commercial catch was reconstructed back to 1918 for five fisheries. In this assessment, two fisheries are used – Trawl and Other (comprising the non-trawl fisheries: halibut longline, sablefish trap|logline, dogfish|lingcod|salmon troll, and hook & line rockfish outside of PMFC area 4B). Given the negligible catches in the early years, the model was started in 1935, and catches prior to 1935 were not considered. The time series for catches is denoted C_t. The set $\mathbf{U}_{\mathrm{N}\{1,2,3\} \vee \mathrm{S}\{1,2,4,5\}}$ (Table E.1) gives the years of available ageing data from the commercial fishery. The proportions-at-age values are given by p_{atgs} with effective sample size n_{tg}, where $g = \{2_\mathrm{N} \vee 4_\mathrm{S}\}, ..., \{3_\mathrm{N} \vee 5_\mathrm{S}\}$ (to correspond to the commercial data). These proportions are the weighted proportions calculated using the stratified weighting scheme described in Appendix D, that adjusts for unequal sampling effort across temporal and spatial strata.

E.4.5. Sex

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

E.4.6. Weights-at-age

The weights-at-age w_{as} were assumed fixed over time and were based on sex-specific allometric (length-weight) and growth (age-length) model parameters derived from the biological data (see Appendix D for details). The equation to calculate w_{as} incorporates a bias correction into the conversion from length to weight using CVs of lengths-at-age (c_{as}):

$$w_{as} = \alpha_s \bar{l}_{as}^{\,\beta_s} \;\; e^{0.5\beta_s (\sigma_{\bar{l}_{as}})^2 (\beta_s - 1)} \tag{E.24}$$

where α_s and β_s are the intercept and slope parameters for each sex s of the allometric equation (D.1), and mean length-at-age ($\bar{l}_{as}$) and standard deviation of $\bar{l}_{as}$, respectively are:

$$\bar{l}_{as} = L_{\infty,s}\left[1 - e^{-\kappa_s(a-t_{0,s})}\right] \text{ ; and} \tag{E.25}$$

$$\sigma_{\bar{l}_{as}} = c_{a=1,s} + \left[(c_{a=A,s} - c_{a=1,s})/(A-1)\right](a-1)\ . \tag{E.26}$$

E.4.7. Maturity of females

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

E.4.8. State dynamics

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

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

E.4.9. Initial conditions

An unfished equilibrium situation at the beginning of the reconstruction was assumed because there was no evidence of significant removals prior to 1935. The initial conditions (E.2) and (E.2) were obtained by setting $R_t = R_0$ (virgin recruitment), $N_{ats} = N_{a1s}$ (equilibrium condition) and $u_{ats} = 0$ (no fishing) into (E.2)-(E.2). The virgin spawning biomass B_0 was then obtained from (E.2).

E.4.10. Selectivities

Separate selectivities were modelled for the commercial fishery and for each survey series (except NMFS Triennial). For REBS north, which had the better set of AF data, the Trawl fishery selectivity priors were estimated using uninformed priors. The Other fishery used an informed prior for the age at maximum selectivity (arbitrarily assumed at a level that seemed reasonable) while the other two selectivity parameters (left side variable and male shift parameter) were estimated with uninformed priors. For REBS south, which had very little AF data, particularly for the Other fishery, informed priors based on the respective REBS north posteriors for each parameter were used for both commercial fisheries.

For REBS north, the data were sufficient to estimate the WCHG survey selectivity using an informed prior for the age at maximum selectivity (the same prior as used for the Other fishery) while the other two selectivity parameters were estimated with uninformed priors. The MCMC posteriors for the REBS north selectivity parameters showed acceptable diagnostics. For REBS south, the model estimated credible MPD parameters for the QCS and WCVI surveys using uninformed priors but the MCMC diagnostics were not acceptable, requiring these parameters to be fixed at the MPD estimates during the MCMC simulations. There were no biological data available from the NMFS Triennial survey, which required fixing the selectivity parameters based on assumed credible values loosely based on the Pacific Ocean Perch stock assessment.

A half-Gaussian formulation was used, as given in (E.2) and (E.2), to give selectivities s_{ags}. (Note that the subscript $\cdot_s$ always represents the index for sex, whereas $s_{\dots}$ always represents selectivity). This results in an increasing selectivity up to the age of full selection (μ_g for females). Given there was no evidence to suggest a dome-shaped function, it was assumed that fish older than μ_g remained fully selected. The rate of ascent of the left limb is controlled by the parameter v_{gL} for females. For males, the same function is used except that the age of full selection is shifted by an amount Δ_g, see (E.2).

E.4.11. Derived states

The spawning biomass (biomass of mature females, in tonnes) B_t at the start of year t is calculated in (E.2) by multiplying the numbers of females N_{at1} by the proportion that are mature (m_a), and converting to biomass by multiplying by the weights-at-age w_{a1}.

Equation (E.2) calculates, for year t, the proportion u_{ats} of age-class a and sex s fish that are caught. This requires the commercial selectivities $s_{a,g=\{2_\mathrm{N} \vee 4_\mathrm{S}\},\dots,\{3_\mathrm{N} \vee 5_\mathrm{S}\},s}$ and the ratio u_t, which equation (E.2) shows is the ratio of total catch (assumed taken all at once mid-year) to vulnerable biomass in the middle of the year, V_t, given by equation (E.2). Therefore, (E.2) calculates the proportion of the vulnerable biomass that is caught, and (E.2) partitions this out by sex and age.

E.4.12. Stock-recruitment function

A Beverton-Holt recruitment function is used, parameterised in terms of steepness, h, which is the proportion of the long-term unfished recruitment obtained when the stock abundance is reduced to 20% of the virgin level (Mace and Doonan 1988; Michielsens and McAllister 2004). This was done so that a prior for h could be taken from Forrest et al. (2010). The formulation shown in (E.2) comes from substituting $\alpha = (1-h)B_0/(4hR_0)$ and $\beta = (5h-1)/4hR_0$ into the Beverton-Holt equation $R_t = B_{t-1}/(\alpha + \beta B_{t-1})$, where α and β are from the standard formulation given in the Coleraine manual (Hilborn et al. 2003; see also Michielsens and McAllister 2004), R_0 is the virgin recruitment, R_t is the recruitment in year t, B_t is the spawning biomass at the start of year t, and B_0 is the virgin spawning biomass.

E.4.13. Estimates of observed data

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

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

E.5. DESCRIPTION OF STOCHASTIC COMPONENTS

E.5.1. Parameters

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

E.5.2. Recruitment deviations

For recruitment, a log-normal process error is assumed, such that the stochastic version of the deterministic stock-recruitment function (E.2) is

$$R_t = \frac{B_{t-1}}{\alpha + \beta B_{t-1}} e^{\epsilon_t - \sigma_R^2/2} \tag{E.27}$$

where $\epsilon_t \sim$ Normal$(0, \sigma_R^2)$, and the bias-correction term $-\sigma_R^2/2$ term in (E.27) ensures that the mean of the recruitment deviations equals 0. This then gives the recruitment deviation equation (E.3) and log-likelihood function (E.3). In this assessment, the value of σ_R was fixed at 0.9 based on trials with $\sigma_R \in \{0.6, 0.9, 1.2\}$. Previous assessments have used σ_R = 0.6 following an assessment of Silvergray Rockfish (Starr et al. 2016) in which the authors stated that the value was typical for marine 'redfish' (Mertz and Myers 1996). An Awatea model of Rock Sole used σ_R = 0.6 (Holt et al. 2016), citing that it was a commonly used default for finfish assessments (Beddington and Cooke 1983). In other rockfish assessments, authors have adopted σ_R = 0.9 based on an empirical model fit consistent with the age composition data for 5ABC POP (Edwards et al. 2012*b*). A study by Thorson et al. (2014) examined 154 fish populations and estimated σ_R = 0.74 (SD=0.35) across seven taxonomic orders; the marginal value for Scorpaeniformes was σ_R=0.78 (SD=0.32) but was only based on 7 stocks.

E.5.3. Log-likelihood functions

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

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

Lognormal error is assumed for the survey indices, resulting in the log-likelihood equation (E.3). The total log-likelihood $\log L(\boldsymbol{\Theta})$ is then the sum of the likelihood components – see (E.3).

E.6. BAYESIAN COMPUTATIONS

Estimation of parameters compares the estimated (model-based) observations of survey biomass indices and proportions-at-age with the data, and minimises the recruitment deviations. This is done by minimising the objective function $f(\boldsymbol{\Theta})$, which equation (E.3) shows is the negative of the sum of the total log-likelihood function and the logarithm of the joint prior distribution, given by (E.3).

The procedure for the Bayesian computations is as follows:

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

E.6.1. Phases

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

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

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

E.6.2. Reweighting

Given that sample sizes are not comparable between different types of data, a procedure that adjusts the relative weights between data sources (abundance vs. composition) is required. The QCS POP assessment (Edwards et al. 2012*b*) used an iterative reweighting scheme based on adjusting the standard deviation of normal (Pearson) residuals (SDNRs) of data sets until these standard deviations were approximately 1 (which is the predicted standard deviation of a normal distribution with μ=0). This procedure did not perform well for the Yellowmouth Rockfish assessment (Edwards et al. 2012*a*), leading to spurious cohorts; therefore, the Yellowmouth assessment used the reweighting scheme proposed by Francis (2011). Rockfish stock assessments using the Awatea model since 2011, including this one, have adopted the Francis (2011) reweighting approach – adding series-specific process error to abundance index CVs on the first reweight, and iteratively reweighting age frequency (composition data) sample size by mean age on the first and subsequent reweights (see Section E.6.2.). For the Rougheye/Blackspotted Rockfish data set, one reweight using mean age was performed for most of the REBS north model runs, and two reweights were used for most of the REBS south model runs.

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

$$c_1 = \sqrt{c_0^2 + c_\mathrm{p}^2}\,. \tag{E.28}$$

For each model run, the abundance index CVs were adjusted on the first reweight only using the process error c_p = 0.25 and 0.2759 in REBS north (g=1,2) and 0.25, 0.25, 0.25, and 0.2529 in REBS south (g=1,...,4). The c_p value adopted for the CPUE indices was based on an estimated CV of residuals to the indices after a smoothing function was fitted to the CPUE series, giving an approximation of the eventual fit to the indices (see Section E.6.2.1.).

Francis (2011) maintains that correlation effects are usually strong in age composition data. Each age composition data set has a sample size n_{tg} ($g = _{\mathrm{N}\{1,2,3\} \vee \mathrm{S}\{1,2,4,5\}}$, $t \in \mathbf{U}_g$), which is typically in the range 3-20.Equation (T3.4) of Francis (2011) is used to iteratively reweight the sample size as

$$n_{tg}^{(r)} = W_g^{(r)} n_{tg}^{(r-1)} \tag{E.29}$$

where $r = 1, 2, 3$ represents the reweighting iteration, $n_{tg}^{(r)}$ is the effective sample size for reweighting r, $W_g^{(r)}$ is the weight applied to obtain reweighting r, and $n_{tg}^{(0)} = n_{tg}$. Therefore, a single-value weight $W_g^{(r)}$ is calculated for each series $g = _{\mathrm{N}\{1,2,3\} \vee \mathrm{S}\{1,2,4,5\}}$ for reweighting r.

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

$$W_g^{(r)} = \left\{ \mathrm{Var}_t \left[\frac{\overline{O}_{tg} - \overline{E}_{tg}}{\sqrt{\theta_{tg} / n_{tg}^{(r-1)}}} \right] \right\}^{-1} \tag{E.30}$$

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

$$\overline{O}_{tg} = \sum_{a=1}^{A} \sum_{s=1}^{2} a p_{atgs} \tag{E.31}$$

$$\overline{E}_{tg} = \sum_{a=1}^{A} \sum_{s=1}^{2} a \widehat{p}_{atgs} \tag{E.32}$$

$$\theta_{tg} = \sum_{a=1}^{A} \sum_{s=1}^{2} a^2 \widehat{p}_{atgs} - \overline{E}_{tg}^2 \tag{E.33}$$

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

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

$$\delta_{tg}^{(r)} = \frac{\log I_{tg}^{(r-1)} - \log \widehat{I}_{tg}^{(r)} + 0.5 \log(1 + c_{tg}^2)^2}{\sqrt{\log(1 + c_{tg}^2)}}, \tag{E.34}$$

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

$$\sigma_{\delta_g}^{(r)} = \sqrt{\frac{\sum_t (\delta_{tg}^{(r)} - \overline{\delta}_{tg}^{(r)})^2}{\eta_g - 1}} \tag{E.35}$$

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

The reweighted dataset chosen for MCMC analysis is typically the one where the sum of the absolute deviation from unity of the SDNRs for the 1 abundance index series was the lowest (E.36); however, the first or second reweight was chosen for all model runs in this assessment, including the sensitivity runs, based on model fits to mean age and survey age composition.

$$r' = \min_{r \in 1:3} \sum_{g=\mathrm{N}\{1,2\} \vee \mathrm{S}\{1,2,3,4\}} |1 - \sigma^{(r)}_{\delta_g}|. \tag{E.36}$$

E.6.2.1. Process error for commercial CPUE

A procedure was developed for estimating process error c_p to add to the commercial CPUE using a spline-smoother analysis. Francis (2011), citing Clark and Hare (2006), recommends using a smoothing function to determine the appropriate level of process error to add to CPUE data, with the goal of finding a balance between rigorously fitting the indices while not removing the majority of the signal in the data. An arbitrary sequence of length 50, comprising degrees of freedom (DF, ν_i), where $i = 2, ..., N$ and N = number of CPUE values U_t from $t = 1996, ..., 2019$, was used to fit the CPUE data with a spline smoother. At $i = N$, the spline curve fit the data perfectly and the residual sum of squares (RSS, ρ_N) was 0. Using spline fits across a range of trial DF ν_i, values of RSS ρ_i formed a logistic-type curve with an inflection point at $i = k$ (Figure E.1, REBS north on left, REBS south on right). The difference between point estimates of ρ_i (proxy for the slope δ_i) yielded a concave curve with a minimum δ_i, which occurred close to the inflection point k. At the inflection point k, ν_k=2.449 for both REBS north and REBS south, corresponding to $\rho_k = \{1.984_\mathrm{B} \vee 1.544_\mathrm{R}\}$, which was converted to $c_\mathrm{p} = \{0.2759_\mathrm{B} \vee 0.2529_\mathrm{R}\}$ using:

$$c_\mathrm{p} = \sqrt{\frac{\rho_k}{N-2}} \left[\frac{1}{N} \sum_{t=1996}^{2019} U_t \right]^{-1}. \tag{E.37}$$

E.6.3. Prior distributions

Descriptions of the prior distributions for the estimated parameters (without including recruitment deviations) are given in Table E.4. The resulting probability density functions give the $\pi_j(\boldsymbol{\Theta})$, whose logarithms are then summed in (E.3) to give the joint prior distribution $\pi(\boldsymbol{\Theta})$. Since uniform priors are, by definition, constant across their bounded range (and zero outside), their contributions to the objective function can be ignored. Thus, in the calculation (E.3) of the joint prior distribution $\pi(\boldsymbol{\Theta})$, only those priors that are not uniform need to be considered in the summation.

A uniform prior over a large range was used for R_0. Normal priors for female and male natural mortality, M_1 and M_2 respectively, were explored using the natural mortality estimators of Hoenig (1983) and Gertseva (2018, pers. comm., based on Then et al. 2015; Hamel 2015) at observed ages $A_\mathrm{max} \in \{100, 125, 150\}$ for REBS north and $A_\mathrm{max} \in \{80, 100, 125\}$ for REBS south (Appendix D). Natural mortality M appears to range from 0.03 to 0.07 for Rougheye/Blackspotted Rockfish, depending on the stock.

Steepness was not estimated in this model, but was fixed h=0.7. Uniform priors on a logarithmic scale were used for the catchability parameters q_g. Selectivity is discussed more fully in Section E.4.10. Most selectivity priors were uniform with bounds based on previous stock assessments. Some informed selectivity priors (means and standard deviations) were based on values that were considered reasonable based on experience in previouis stock assessments.

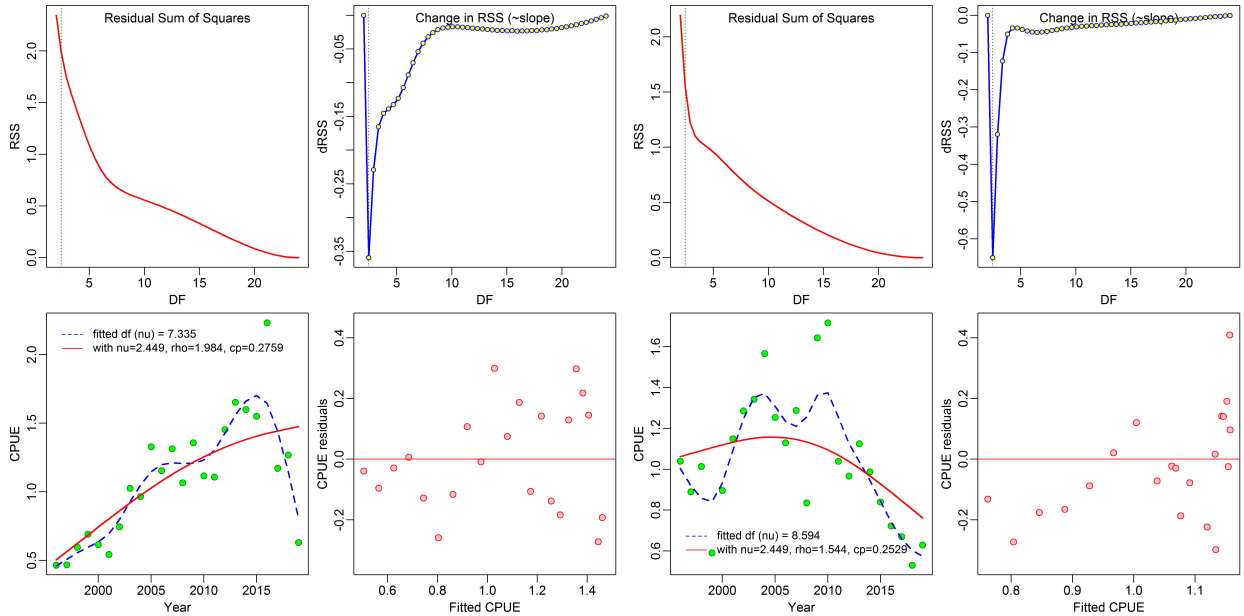


Figure E.1. Estimating process error to add to commercial CPUE data (REBS north on left, REBS south on right). For each stock: top left – residual sum of squares (RSS) from spline-smoother at various degrees of freedom; top right – slope of RSS (∼ first derivative), vertical dotted line at DF where slope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

E.6.4. MCMC properties

The MCMC procedure started the search from the MPD values and performed 6 million iterations, sampling every 5000$^{\text{th}}$ for 1200 samples, 1000 of which were used after removing the first 200 for a burn-in period.

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

Advice to managers is given with respect to a suite of reference points. The first set is based on MSY (maximum sustainable yield) and includes the provisional reference points of the DFO Precautionary Approach (DFO 2006), namely 0.4B_{MSY} and 0.8B_{MSY} (and also provided are B_{MSY} and u_{MSY}, which denote the estimated equilibrium spawning biomass and harvest rate at MSY, respectively). A second set of reference points, the current spawning biomass B_{2021} and harvest rate u_{2020}, is used to show the probability of increasing from the current female spawning biomass or decreasing from the current harvest rate. A third set of reference points, 0.2B_0 and 0.4B_0, is based on the estimated unfished equilibrium spawning biomass B_0. See main text for further discussion.

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

The probability $\mathrm{P}(B_{2021} > 0.4B_{\text{MSY}})$ is then calculated as the proportion of the 1000 MCMC samples for which $B_{2021} > 0.4B_{\text{MSY}}$ (and similarly for the other biomass-based reference points).

For harvest rates, the probability $\mathrm{P}(u_{2020} < u_{\mathsf{MSY}})$ is calculated so that both B- and u-based stock status indicators (and projections when $t = 2021, ..., 2031$) state the probability of being in a 'good' place.

Projections were made for 10 years starting with the biomass and age structure calculated for the start of 2021. A range of constant catch strategies were used, from 0 to N:1200∨S:600 t at N:100∨S:50 t increments (the average catch from 2015 to 2019 was 548 t and 291 t in 5DE and 3CD5AB). For each strategy, projections were performed for each of the 1000 MCMC samples (resulting in posterior distributions of future spawning biomass). Recruitments were randomly calculated using (E.27) (i.e. based on lognormal recruitment deviations from the estimated stock-recruitment curve), using randomly generated values of $\epsilon_t \sim$ Normal$(0, \sigma_R^2)$. For each of the 1000 MCMC samples a time series of $\{\epsilon_t\}$ was generated. For each MCMC sample, the same time series of $\{\epsilon_t\}$ was used for each catch strategy (so that, for a given MCMC sample, all catch strategies experience the same recruitment stochasticity).

E.8. REFERENCES – MODEL RESULTS

ADMB Project. 2009. AD Model Builder: Automatic Differentiation Model Builder. Developed by David Fournier and freely available from admb-project.org.

Beamish, R.J. 1979. New information on the longevity of Pacific ocean perch (*Sebastes alutus*). Can. J. Fish. Aquat. Sci. 36(11). 1395–1400.

Beddington, J.R. and Cooke, J.G. 1983. The potential yield of fish stocks. FAO Fish. Tech. Paper 242. v + 47 p.

Bull, B., Francis, R.I.C.C., Dunn, A., McKenzie, A., Gilbert, D.J. and Smith, M.H. 2005. CASAL (C++ algorithmic stock assessment laboratory), user manual v2.07-2005/08/21. NIWA Tech. Rep. 127. 274 p.

Caswell, H. 2001. Matrix Population Models: Construction, Analysis and Interpretation. Sinauer Associates, Massachusetts.

Clark, W.G. and Hare, S.R. 2006. Assessment and management of Pacific halibut: data, methods, and policy. Sci. Rep. 83, International Pacific Halibut Commission, Seattle, WA.

DFO. 2006. A harvest strategy compliant with the precautionary approach. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2006/023. 7 p.

DFO. 2015. Yellowtail Rockfish (*Sebastes flavidus*) stock assessment for the coast of British Columbia, Canada. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2015/010. 14 p.

Edwards, A.M., Haigh, R. and Starr, P.J. 2014*a*. Pacific Ocean Perch (*Sebastes alutus*) stock assessment for the north and west coasts of Haida Gwaii, British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2013/092. vi + 126 p.

Edwards, A.M., Haigh, R. and Starr, P.J. 2014*b*. 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.

Edwards, A.M., Haigh, R. and Starr, P.J. 2012*a*. Stock assessment and recovery potential assessment for Yellowmouth Rockfish (*Sebastes reedi*) along the Pacific coast of Canada. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/095. iv + 188 p.

Edwards, A.M., Starr, P.J. and Haigh, R. 2012*b*. Stock assessment for Pacific ocean perch (*Sebastes alutus*) in Queen Charlotte Sound, British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/111. viii + 172 p.

Forrest, R.E., McAllister, M.K., Dorn, M.W., Martell, S.J.D. and Stanley, R.D. 2010. Hierarchical Bayesian estimation of recruitment parameters and reference points for Pacific rockfishes (*Sebastes* spp.) under alternative assumptions about the stock-recruit function. Can. J. Fish. Aquat. Sci. 67. 1611–1634.

Fournier, D.A., Hampton, J. and Sibert, J.R. 1998. MULTIFAN-CL: a length-based, age-structured model for fisheries stock assessment, with application to South Pacific albacore, *Thunnus alalunga*. Can. J. Fish. Aquat. Sci. 55(9). 2105–2116.

Fournier, D.A., Sibert, J.R., Majkowski, J. and Hampton, J. 1990. MULTIFAN a likelihood-based method for estimating growth parameters and age composition from multiple length frequency data sets illustrated using data for southern bluefin tuna (*Thunnus maccoyii*). Can. J. Fish. Aquat. Sci. 47(2). 301–317.

Francis, R.I.C.C. 2011. Data weighting in statistical fisheries stock assessment models. Can. J. Fish. Aquat. Sci. 68(6). 1124–1138.

Gelman, A., Carlin, J.B., Stern, H.S. and Rubin, D.B. 2004. Bayesian Data Analysis, 2nd edition. Chapman and Hall/CRC, New York.

Haigh, R., Starr, P.J., Edwards, A.M., King, J.R. and Lecomte, J.B. 2018*a*. Stock assessment for Pacific Ocean Perch (*Sebastes alutus*) in Queen Charlotte Sound, British Columbia in 2017. DFO Can. Sci. Advis. Sec. Res. Doc. 2018/038. v + 227 p.

Haigh, R., Edwards, A.M. and Starr, P.J. 2018*b*. PBSawatea: Tools for Running Awatea and Visualizing the Results. R package version 1.4.2.

Hamel, O.S. 2015. A method for calculating a meta-analytical prior for the natural mortality rate using multiple life history correlates. ICES J. Mar. Sci. 72(1). 62–69.

Hilborn, R., Maunder, M., Parma, A., Ernst, B., Payne, J. and Starr, P. 2003. Coleraine: A generalized age-structured stock assessment model. User's manual version 2.0. University of Washington Report SAFS-UW-0116. Tech. rep., University of Washington.

Hoenig, J.M. 1983. Empirical use of longevity data to estimate mortality rates. Fish. Bull. 82(1). 898–903.

Holt, K.R., Starr, P.J., Haigh, R. and Krishka, B. 2016. Stock assessment and harvest advice for Rock Sole (*Lepidopsetta* spp.) in British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2016/009. ix + 256 p.

Leisch, F. 2002. Sweave: dynamic generation of statistical reports using literate data analysis. In W. Härdle and B. Rönz, eds., Compstat 2002 - Proceedings in Computational Statistics, p. 575–580. Physica Verlag, Heidelberg.

Mace, P.M. and Doonan, I.J. 1988. A generalized bioeconomic simulation for fish population dynamics. NZ Fish. Assess. Res. Doc. 88/4. 51 p.

MacLellan, S.E. 1997. How to age rockfish (*Sebastes*) using *S. alutus* as an example – the otolith burnt section technique. Can. Tech. Rep. Fish. Aquat. Sci. 2146. 39 p.

Magnusson, A. 2009. Scape – statistical catch-at-age plotting environment. R package .

Magnusson, A. and Stewart, I. 2020. plotMCMC: MCMC diagnostic plots. R package version 2.0.1.

Mertz, G. and Myers, R. 1996. Influence of fecundity on recruitment variability of marine fish. Can. J. Fish. Aquat. Sci. 53(7). 1618–1625.

Michielsens, C.G.J. and McAllister, M.K. 2004. A Bayesian hierarchical analysis of stock-recruit data: quantifying structural and parameter uncertainties. Can. J. Fish. Aquat. Sci. 61(6). 1032–1047.

R Core Team. 2019. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Stanley, R.D., Starr, P. and Olsen, N. 2009. Stock assessment for Canary Rockfish (*Sebastes pinniger*) in British Columbia waters. DFO Can. Sci. Advis. Sec. Res. Doc. 2009/013. xxii + 198 p.

Starr, P.J. and Haigh, R. 2021*a*. Widow Rockfish (*Sebastes entomelas*) stock assessment for British Columbia in 2019. DFO Can. Sci. Advis. Sec. Res. Doc. 2021/039. vi + 238 p.

Starr, P.J. and Haigh, R. 2022. Bocaccio (*Sebastes paucispinis*) stock assessment for British Columbia in 2019, including guidance for rebuilding plans. DFO Can. Sci. Advis. Sec. Res. Doc. *In press*.

Starr, P.J. and Haigh, R. 2021*b*. Redstripe Rockfish (*Sebastes proriger*) stock assessment for British Columbia in 2018. DFO Can. Sci. Advis. Sec. Res. Doc. 2021/014. vii + 340 p.

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. 2016/042. vi + 170 p.

Then, A.Y., Hoenig, J.M., Hall, N.G. and Hewitt, D.A. 2015. Evaluating the predictive performance of empirical estimators of natural mortality rate using information on over 200 fish species. ICES J. Mar. Sci. 72(1). 82–92.

Thorson, J.T., Jensen, O.P. and Zipkin, E.F. 2014. How variable is recruitment for exploited marine fishes? A hierarchical model for testing life history theory. Can. J. Fish. Aquat. Sci. 71(7). 973–983.

APPENDIX F. MODEL RESULTS

F.1. INTRODUCTION

This appendix describes results for two stocks of Rougheye/Blackspotted Rockfish (REBS, *Sebastes aleutianus/melanostictus*): 'REBS north' in PMFC areas 5DE and 'REBS south' in PMFC areas 3CD5AB. Broadly, the results include:

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

Note that MCMC diagnostics are rated using the following subjective criteria:

- Good – no trend in traces, split-chains align, no autocorrelation
- Marginal – trace trend temporarily interrupted, split-chains somewhat frayed, some autocorrelation
- Poor – trace trend fluctuates substantially or shows a persistent increase/decrease, split-chains differ from each other, substantial autocorrelation
- Unacceptable – trace trend shows a persistent increase/decrease that has not levelled, split-chains differ markedly from each other, substantial autocorrelation

The final advice consists of a composite base case which provides the primary guidance. A range of sensitivity runs are presented to show the effect of some of the main modelling assumptions. Estimates of major quantities and advice to management (decision tables) are presented here and in the main text.

F.2. REBS NORTH (5DE)

The base case for REBS north was selected from model runs 46-54 and pooled. Important decisions made during the assessment of REBS north included:

- fixed natural mortality M to three levels: 0.035, 0.045, and 0.055, each with CPUE process error c_p of 0.1, 0.2759, and 0.4, for a total of nine reference models using two axes of uncertainty:
  - B1 (R49): M=0.035, CPUE c_p=0.1
  - B2 (R50): M=0.035, CPUE c_p=0.2759
  - B3 (R51): M=0.035, CPUE c_p=0.4
  - B4 (R47): M=0.045, CPUE c_p=0.1
  - B5 (R46): M=0.045, CPUE c_p=0.2759
  - B6 (R48): M=0.045, CPUE c_p=0.4
  - B7 (R52): M=0.055, CPUE c_p=0.1
  - B8 (R53): M=0.055, CPUE c_p=0.2759
  - B9 (R54): M=0.055, CPUE c_p=0.4
- set plus class A to 80 years;
- used one survey abundance index series (WCHG Synoptic), with age frequency (AF) data;

- used one commercial bottom trawl fishery abundance index series (bottom trawl CPUE index, 1996–2019);
- assumed two fisheries (1 = ‘Trawl’ – commercial bottom + midwater trawl; 2 = ‘Other’ – halibut longline, sablefish trap, lingcod longline, inshore longline, salmon troll), each with pooled catches and AF data);
- assumed two sexes (females, males);
- used uniform priors for the three selectivity parameters (μ_g, Δ_g, $v_{g\mathrm{L}}$) for both fisheries and survey, except for a normal prior on $\mu_g \sim \mathcal{N}(36, 7.2)$ for the Other fishery and the WCHG survey;
- applied abundance reweighting: added CV process error to index CVs, c_p=0.25 for surveys and $c_\mathrm{p} \in \{0.1, 0.2759, 0.4\}$ for commercial CPUE series (see Appendix E);
- applied composition reweighting: adjusted AF effective sample sizes using the TA1.8 mean-age weighting method of Francis (2011);
- fixed standard deviation of recruitment residuals (σ_R) to 0.9;
- used ‘moderate’ ageing error matrix depicted as a normal distribution spanning three ages on either side of ‘true age’ (matrix diagonal), described in Appendix D, Section D.2.3 and plotted in Figure D.26 (left panel).

Three fixed M values and three CPUE c_p values produced nine separate model runs, with the respective posterior distributions pooled as a base case for advice to managers. The central run of the composite base case (Run46: M=0.045, c_p=0.2759) was used as an example reference case against which eight sensitivity runs were compared.

All model runs were reweighted (i) one time for abundance, by adding process error c_p to the index CVs for the WCHG Synoptic and commercial trawl CPUE, respectively, and (ii) once or twice for composition (effective sample size for AF data) using the mean-age procedure of Francis (2011).

F.2.1. REBS North – Central Run MPD

The modelling procedure used here first determines the best fit (MPD) to the data by minimising the negative log likelihood. Because the REBS north composite base case examined nine models, only the central run (M=0.045, CPUE c_p=0.2759, moderate AE matrix) was used as an example (Tables F.1 and F.2). These MPD runs became the starting points for the MCMC simulations. The following plot references apply to the central run.

- Figure F.1 – survey index fits across all survey years;
- Figures F.2 – individual survey fits and residuals (only WCHG synoptic for REBS north);
- Figure F.3 – bottom trawl CPUE fit and its residuals;
- Figures F.4-F.6 model fits to the female and male age frequency data for the commercial Trawl fishery and combined-sex residuals;
- Figures F.7-F.8 model fits to the female and male age frequency data for the commercial Other fishery and combined-sex residuals;
- Figure F.9 and F.10 – model fits and residuals to the age data for the West Coast Haida Gwaii (WCHG) synoptic survey;
- Figure F.11 – model estimates of mean age compared to the observed mean ages;
- Figure F.12 – the stock-recruitment relationship and recruitment time series;
- Figure F.13 – the recruitment deviations and auto-correlation of these deviations;
- Figure F.14 – estimated gear selectivities, together with the ogive for female maturity;

- Figure F.15 – exploitation rates and catches by gear type over time.

The model fits to the survey abundance indices were generally satisfactory (Figures F.1 and F.2), although the 2010 index point was missed entirely. The fit to the commercial CPUE indices was essentially flat, missing the 1996, 1997, and 2016 index points. This was largely a function of adding process error of 28%, which allowed the model fit to ignore outlier CPUE index values (Figure F.3). Using process error of 10%restricted the fit to follow the signal more closely, which in the case of this REBS north series created a more optimistic scenario based on the general upward trend in CPUE (apart from the final three years). The model runs which increased the CPUE process error to 40% generally passed through the CPUE series with little attempt to match the series deviations. Despite runs that effectively discounted the CPUE series, its removal from model data resulted in non-credible MPD parameter estimates and potentially would cause non-convergence in the MCMC simulations; this option was not further investigated by this stock assessment.

Fits to the commercial age frequency data for the Trawl fishery were generally good, with residuals indicating departures at older ages classes (Figure F.6). The fits to AFs for the Other fishery were not as good as those for the Trawl but were deemed acceptable (Figure F.8).

Fits to the WCHG survey AFs were good but had some large negative residuals in the 2012 and 2016 surveys and in the mid-range ages of $\sim$20-45 years (Figure F.10).

Model estimates of mean age only partially matched the observed mean ages (Figure F.11). The correspondence was greatest for the Trawl fishery (which had the most data), but none of the trial runs were able to fit the observed ages from the 1978 and 1982 samples which had much lower mean age than was realistic, given the relatively early timing of the samples. Model runs where the model mean age matches the observed mean age are desirable. The recruitment estimates appeared to be typical of those in other rockfish assessments (Figure F.12). There was some autocorrelation in the recruitment residuals, but it did not appear to be extreme (Figure F.13).

The fit for the commercial Trawl fishery selectivity was well-formed despite using uniform priors on all parameters (Figure F.14). The maturity ogive, generated from an externally fitted model (see Appendix D), has a long right-hand limb resulting in the intersection of the Trawl fishery selectivity curve with the maturity ogive at approximately age 28, indicating that sub-mature fish are harvested. The relatively tight (CV=20%) priors of age-at-full selectivity for the Other fishery and the WCHG survey shifted these selectivity curves to the right, such that female selectivity intercepted the maturity curve at ages 40 and 35, respectively.

F.2.1.1. Tables – REBS north CR MPD

Table F.1. REBS north CR.46.01: priors and MPD estimates for estimated parameters. Prior information – distributions: 0 = uniform, 1 = normal, 2 = lognormal, 5 = beta

Phase	Range	Type	(Mean,SD)	Initial	MPD
R_0 **(recruitment in virgin condition)**					
1	(1,1e+07)	0	(0,0)	10000	1572.92
M_s **(natural mortality by sex** s**, where** $s = 1$ [female], 2 [male]**)**					
-3	(0.02,0.15)	1	(0.035,0.01)	0.045	0.045
-3	(0.02,0.15)	1	(0.035,0.01)	0.045	0.045
h **(steepness of spawner-recruit curve)**					
-1	(0.01,5)	0	(0.7,0.6)	0.7	0.7
ϵ_t **(recruitment deviations)**					
2	(-15,15)	1	(0,0.9)	0	Fig F.13
ω **(initial recruitment)**					
-1	(0,2)	0	(1,0.1)	1	1

Table F.2. REBS north CR.46.01: priors and MPD estimates for index g (survey and commercial).

Index g	Phase	Range	Type	(Mean,SD)	Initial	MPD	exp (MPD)
CPUE catchability mode ($\log q_g$ **where** $g = 2, ...3$**)**							
2	1	(-15,15)	0	(0,0.1)	-1.60944	-9.335	8.8276e-05
Survey catchability mode ($\log q_g$**, where** $g = 1, ..., 1$**)**							
1	1	(-12,5)	0	(0,0.6)	-5	-0.9978	0.36869
Commercial selectivity (μ_g**, where** $g = 2, 3$**)**							
2	3	(5,60)	0	(35,3.5)	26	34.908	
3	3	(5,70)	1	(36,7.2)	36	47.399	
Survey selectivity (μ_g**, where** $g = 1, ..., 1$**)**							
1	3	(5,70)	1	(36,7.2)	36	43.678	
Variance (left) of commercial selectivity curve ($\log v_{gL}$**, where** $g = 2, 3$**)**							
2	4	(-15,15)	0	(2.5,2.5)	2.5	4.4382	
3	4	(-15,15)	0	(2.5,2.5)	2.5	5.5071	
Variance (left) of survey selectivity curve ($\log v_{gL}$**, where** $g = 1, ..., 1$**)**							
1	4	(-15,15)	0	(2.5,2.5)	2.5	5.3974	
Shift in commercial selectivity for males (Δ_g**, where** $g = 2, 3$**)**							
2	4	(-8,10)	0	(0,1)	0	-1.052	
3	4	(-8,10)	0	(0,1)	0	-2.2689	
Shift in survey selectivity for males (Δ_g**, where** $g = 1, ..., 1$**)**							
1	4	(-8,10)	0	(0,1)	0	-1.0081	

Table F.3. REBS north CR.46.01: negative log-likelihoods and objective function from the MPD results for the two models. Parameters and likelihood symbols are defined in Appendix F. For indices ($\hat{I}_{tg}$) and proportions-at-age ($\hat{p}_{atgs}$), subscripts $g = 1...1$ refer to the trawl surveys and subscript $g = 2+$ refers to the commercial fishery.

Description	Negative log likelihood	Value
Survey 1	$\log \mathsf{L}_3 \left(\mathbf{\Theta} \middle\| \left\{\hat{I}_{t1}\right\}\right)$	-2.96
CPUE 1	$\log \mathsf{L}_3 \left(\mathbf{\Theta} \middle\| \left\{\hat{I}_{t1}\right\}\right)$	-6.3
CAs 1	$\log \mathsf{L}_2 \left(\mathbf{\Theta} \middle\| \{\hat{p}_{at1s}\}\right)$	-3057.77
CAc 1	$\log \mathsf{L}_2 \left(\mathbf{\Theta} \middle\| \{\hat{p}_{at2s}\}\right)$	-8431
CAc 2	$\log \mathsf{L}_2 \left(\mathbf{\Theta} \middle\| \{\hat{p}_{at3s}\}\right)$	-898.6
Prior	$\log \mathsf{L}_1 \left(\mathbf{\Theta} \middle\| \{\epsilon_t\}\right) - \log\left(\pi(\mathbf{\Theta})\right)$	8.51
	Objective function $f(\mathbf{\Theta})$	-12388.1

F.2.1.2. Figures – REBS north CR MPD

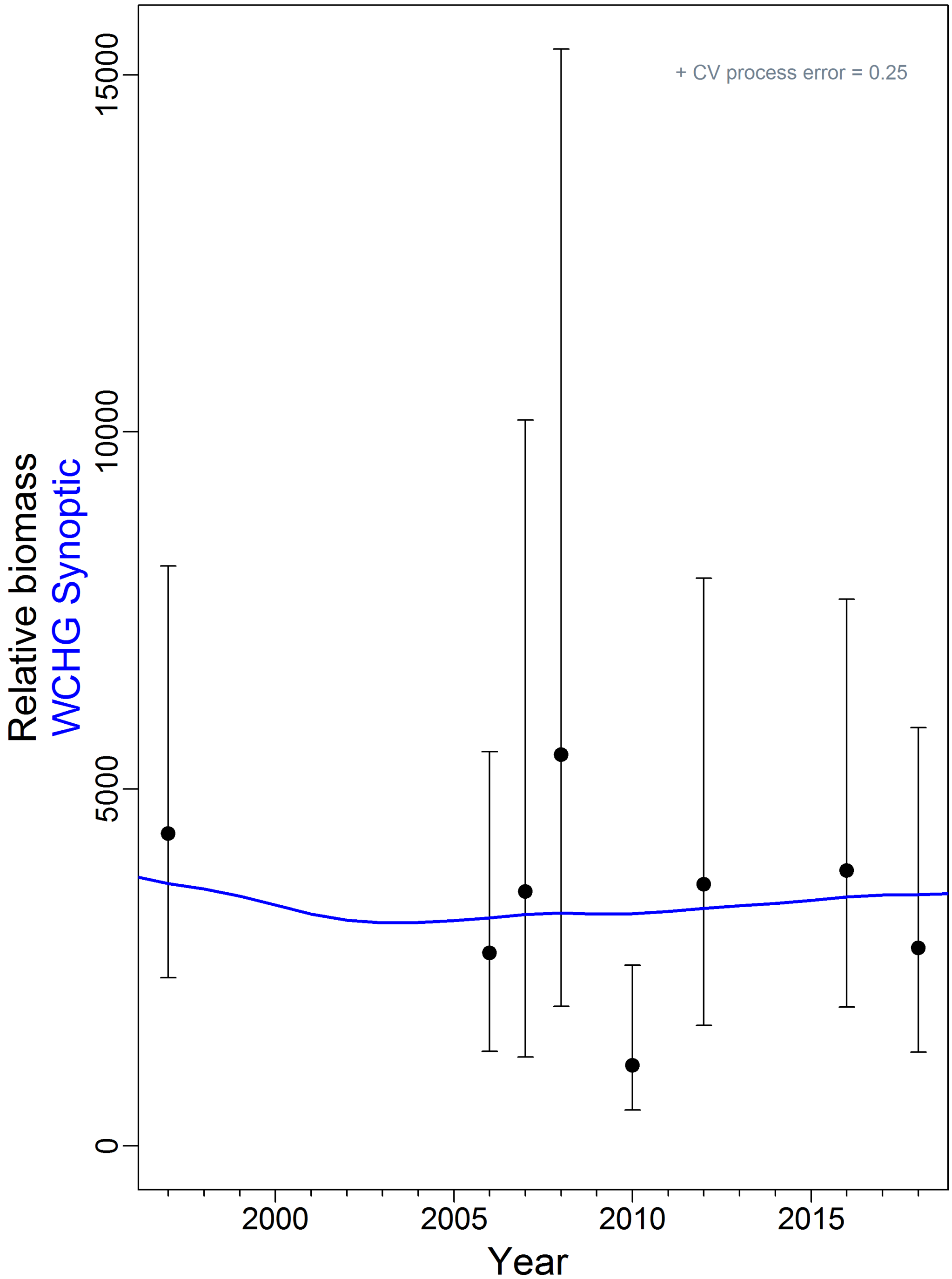


Figure F.1. REBS north CR.46.01: survey index values (points) with 95% confidence intervals (bars) and MPD model fits (curves) for the fishery-independent survey series.

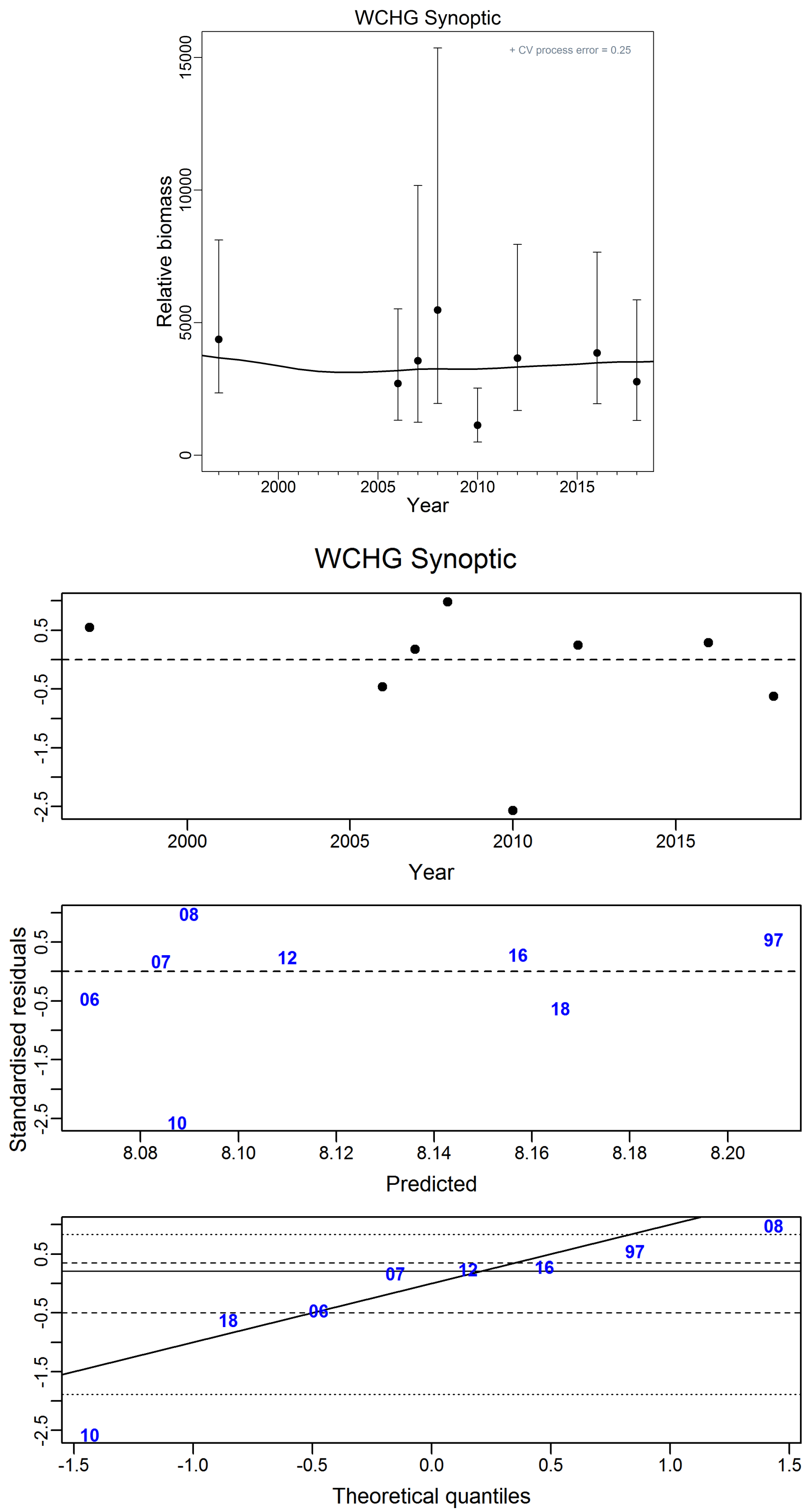


Figure F.2. REBS north CR.46.01: fit (top) and standardised residuals of fits (bottom) of model to WCHG Synoptic survey series (MPD values). Vertical axes are standardised residuals. The three plots show, respectively, residuals by year of index, residuals relative to predicted index, and normal quantile-quantile plot for residuals (horizontal lines give 5, 25, 50, 75 and 95 percentiles).

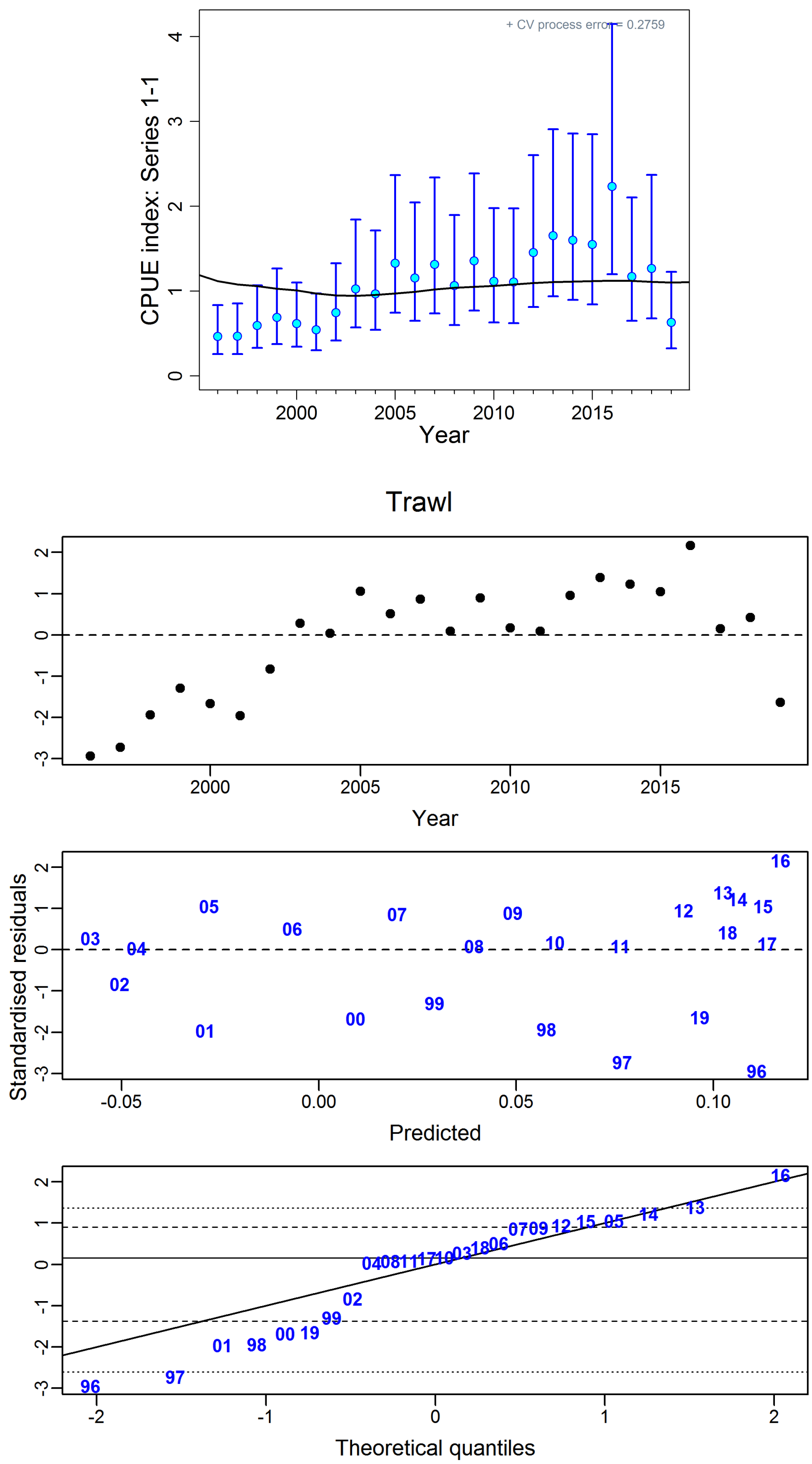


Figure F.3. REBS north CR.46.01: fit (top) and standardised residuals of fits (bottom) of model to Bottom Trawl CPUE series (MPD values). The three residuals plots show, respectively, residuals by year of index, residuals relative to predicted index, and normal quantile-quantile plot for residuals (horizontal lines give 5, 25, 50, 75 and 95 percentiles).

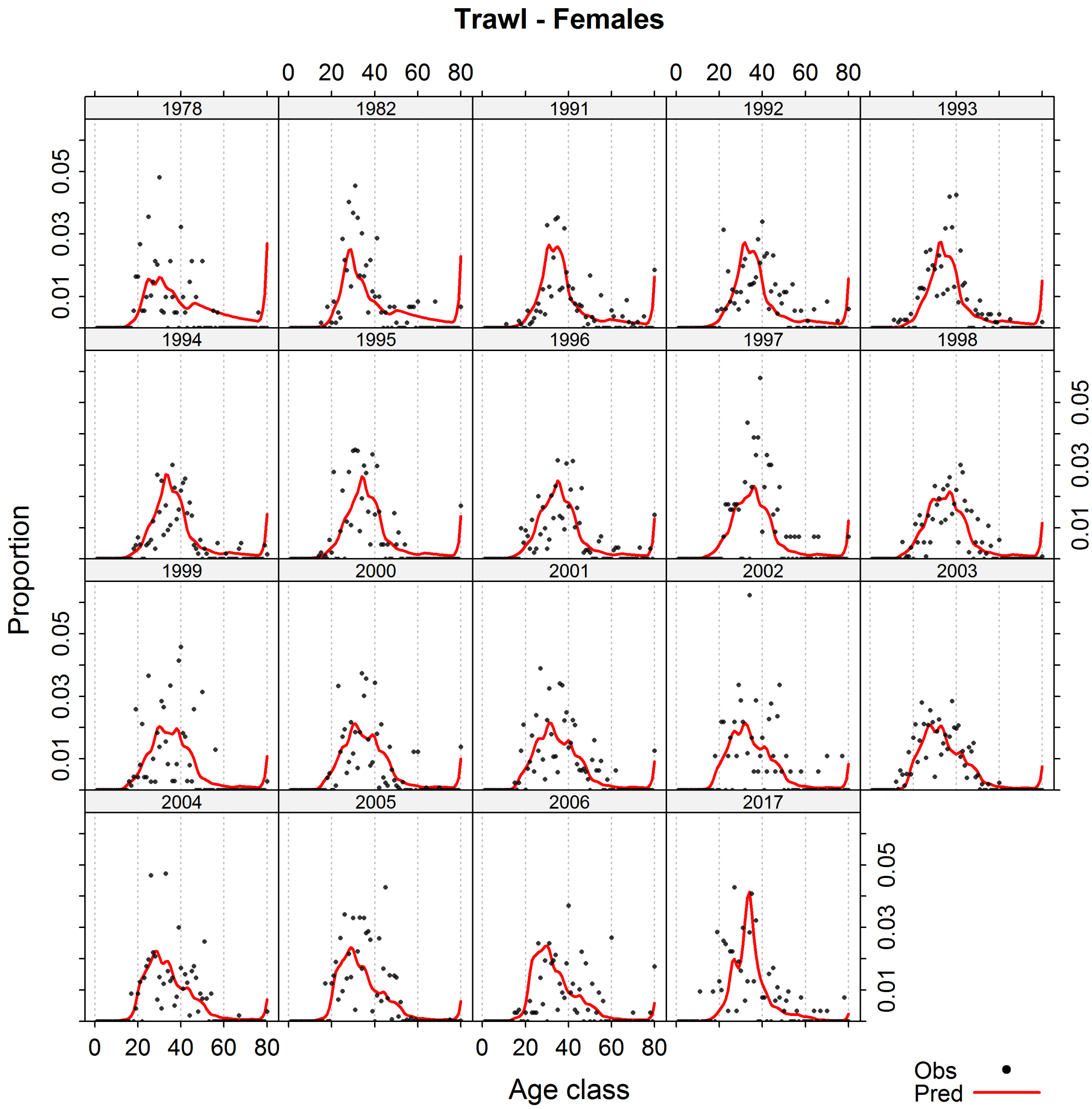


Figure F.4. REBS north CR.46.01: observed and predicted commercial (trawl) proportions-at-age for females. Note that years are not necessarily consecutive.

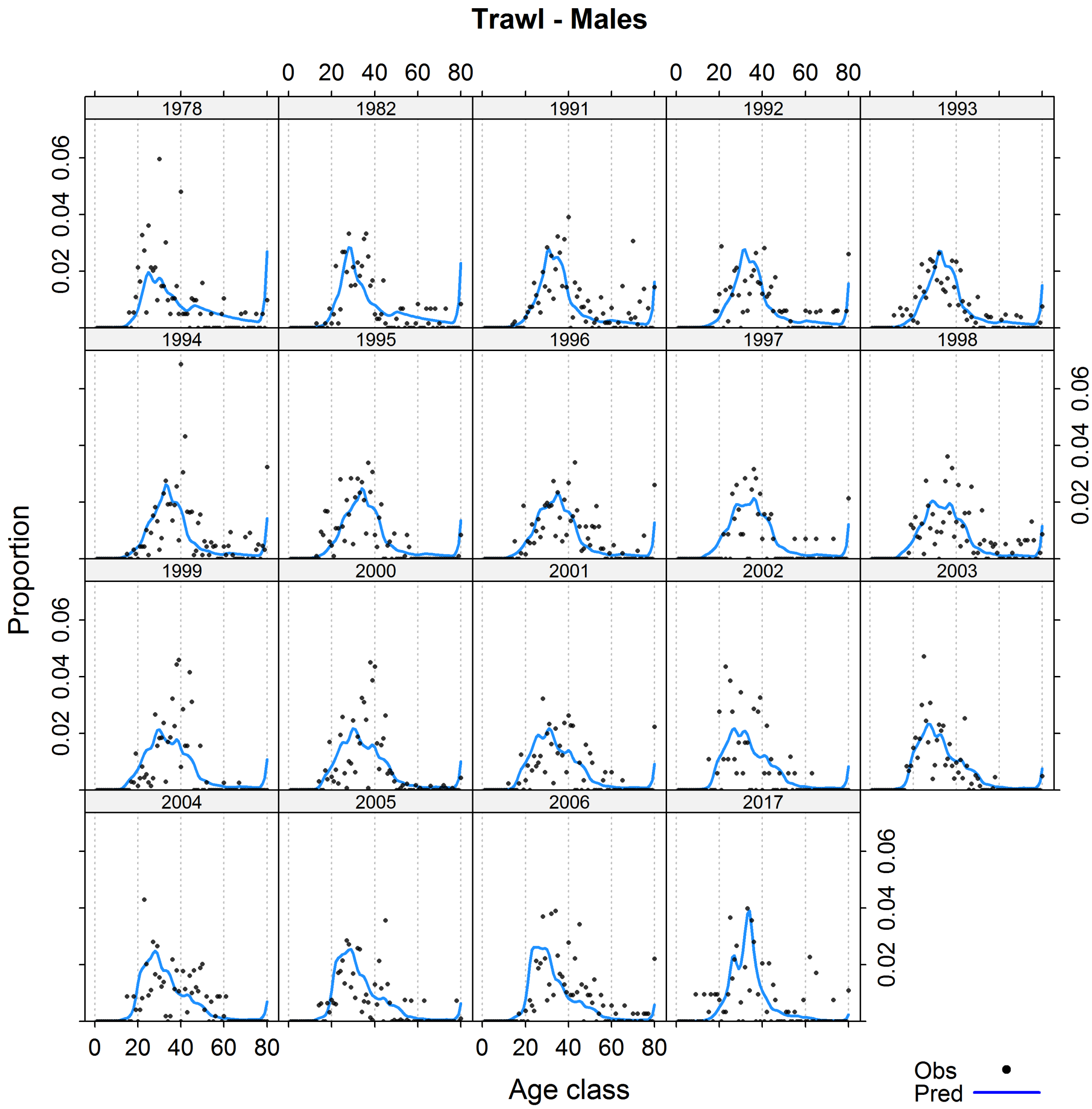


Figure F.5. REBS north CR.46.01: observed and predicted commercial (trawl) proportions-at-age for males. Note that years are not necessarily consecutive.

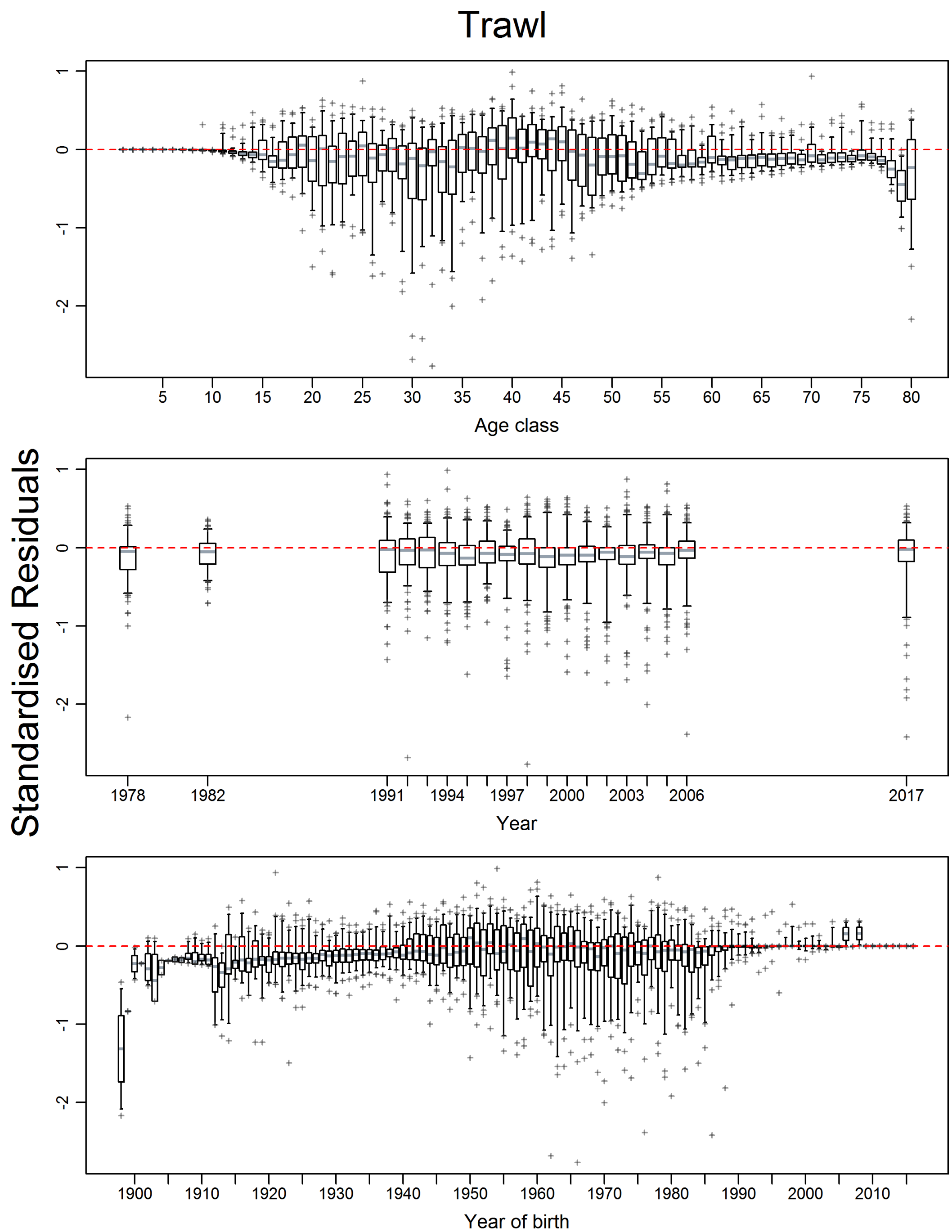


Figure F.6. REBS north CR.46.01: residuals (3002 in total) of model fits to commercial proportion-at-age data (MPD values) for Trawl events. Vertical axes are standardised residuals. Boxplots show, respectively, residuals by age class, by year of data, and by year of birth (following a cohort through time). Boxes give quantile ranges (0.25-0.75) with horizontal lines at medians, vertical whiskers extend to the the 0.05 and 0.95 quantiles, and outliers appear as plus signs.

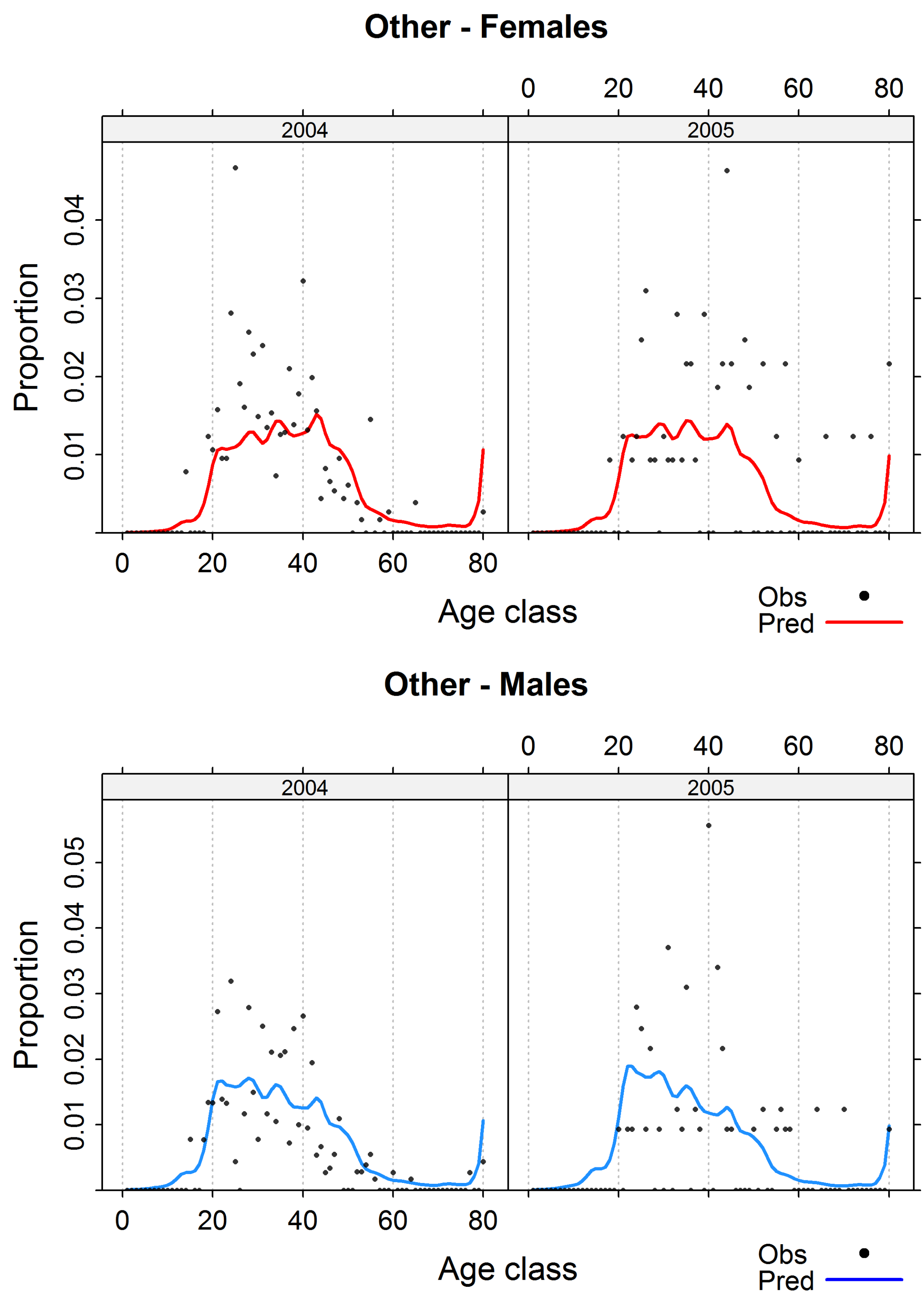


Figure F.7. REBS north CR.46.01: observed and predicted commercial (other) proportions-at-age for females (top) and males (bottom).

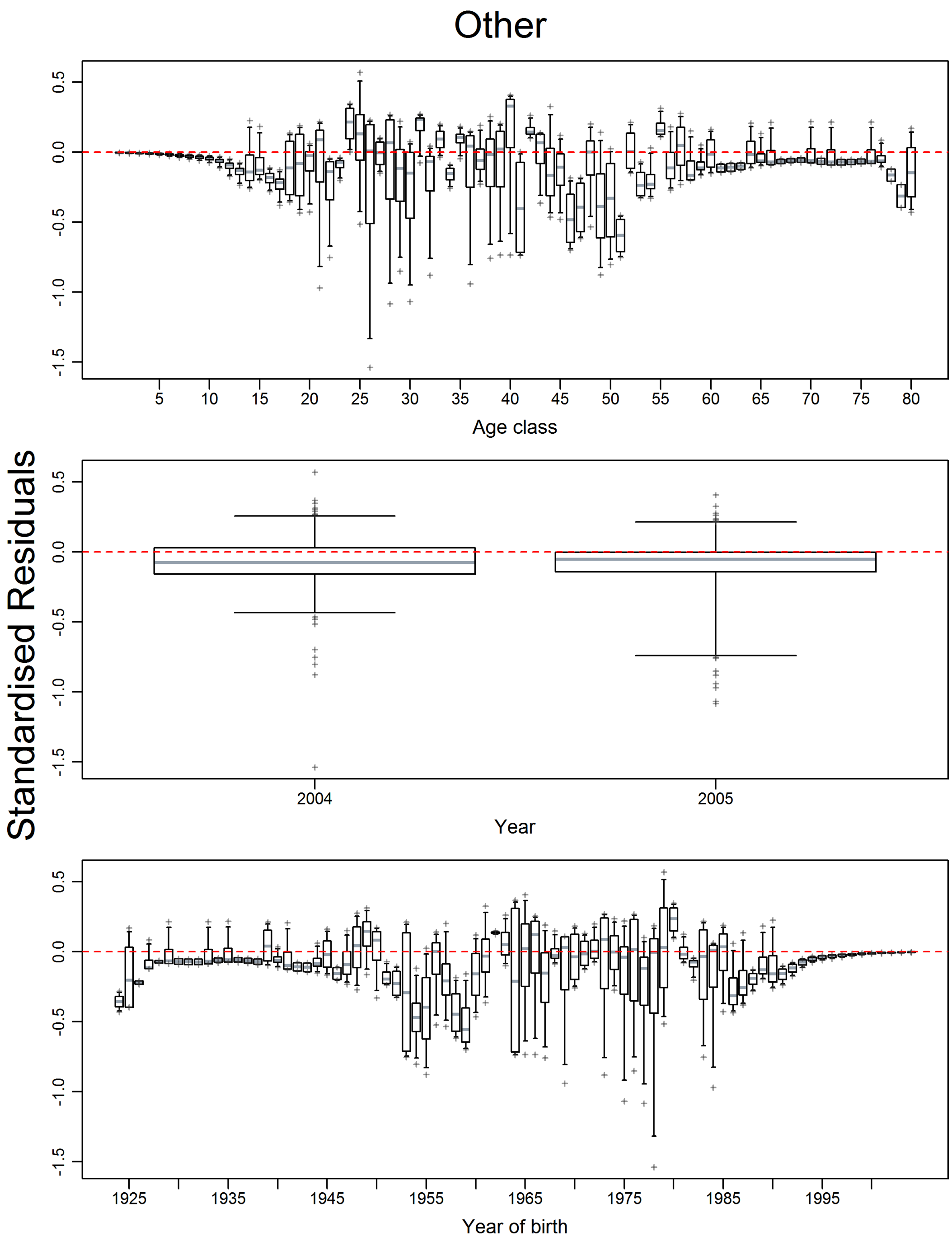
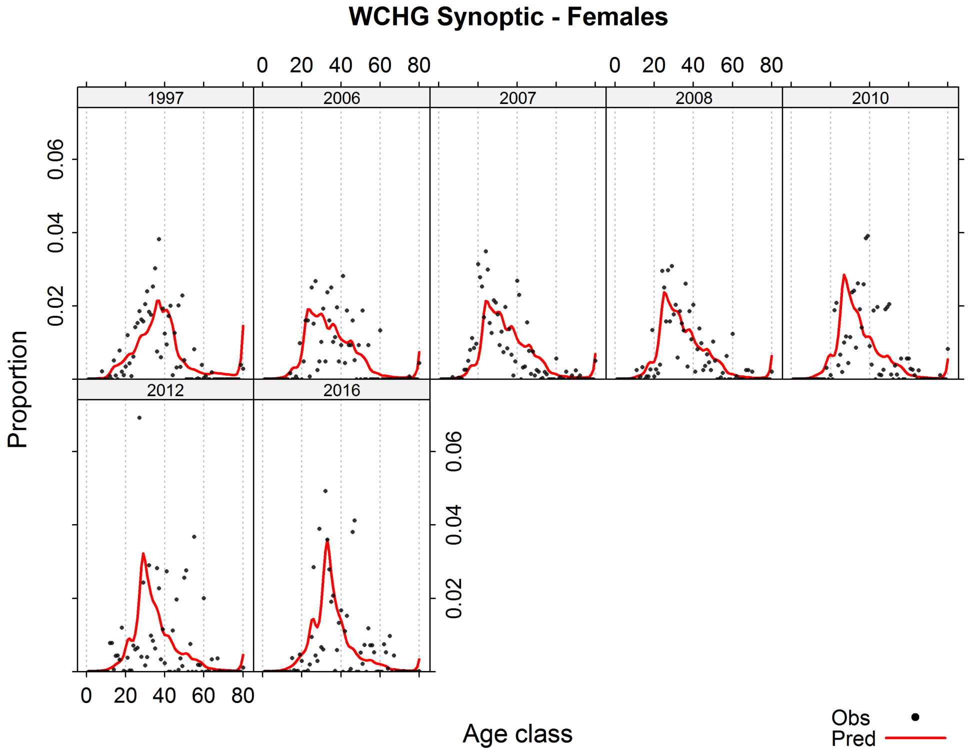


Figure F.8. REBS north CR.46.01: residuals (316 in total) of model fits to commercial proportion-at-age data (MPD values) for Other events. Vertical axes are standardised residuals. Boxplots show, respectively, residuals by age class, by year of data, and by year of birth (following a cohort through time). Boxes give quantile ranges (0.25-0.75) with horizontal lines at medians, vertical whiskers extend to the the 0.05 and 0.95 quantiles, and outliers appear as plus signs.



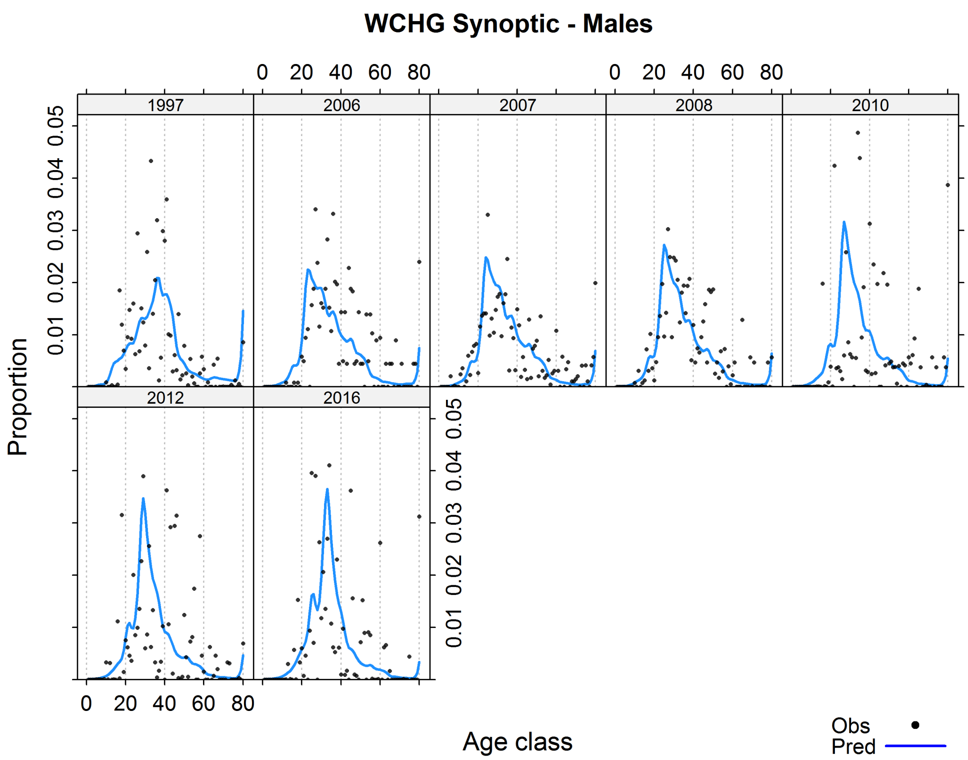


Figure F.9. REBS north CR.46.01: observed and predicted proportions-at-age for WCHG Synoptic survey: females (top) and males (bottom).

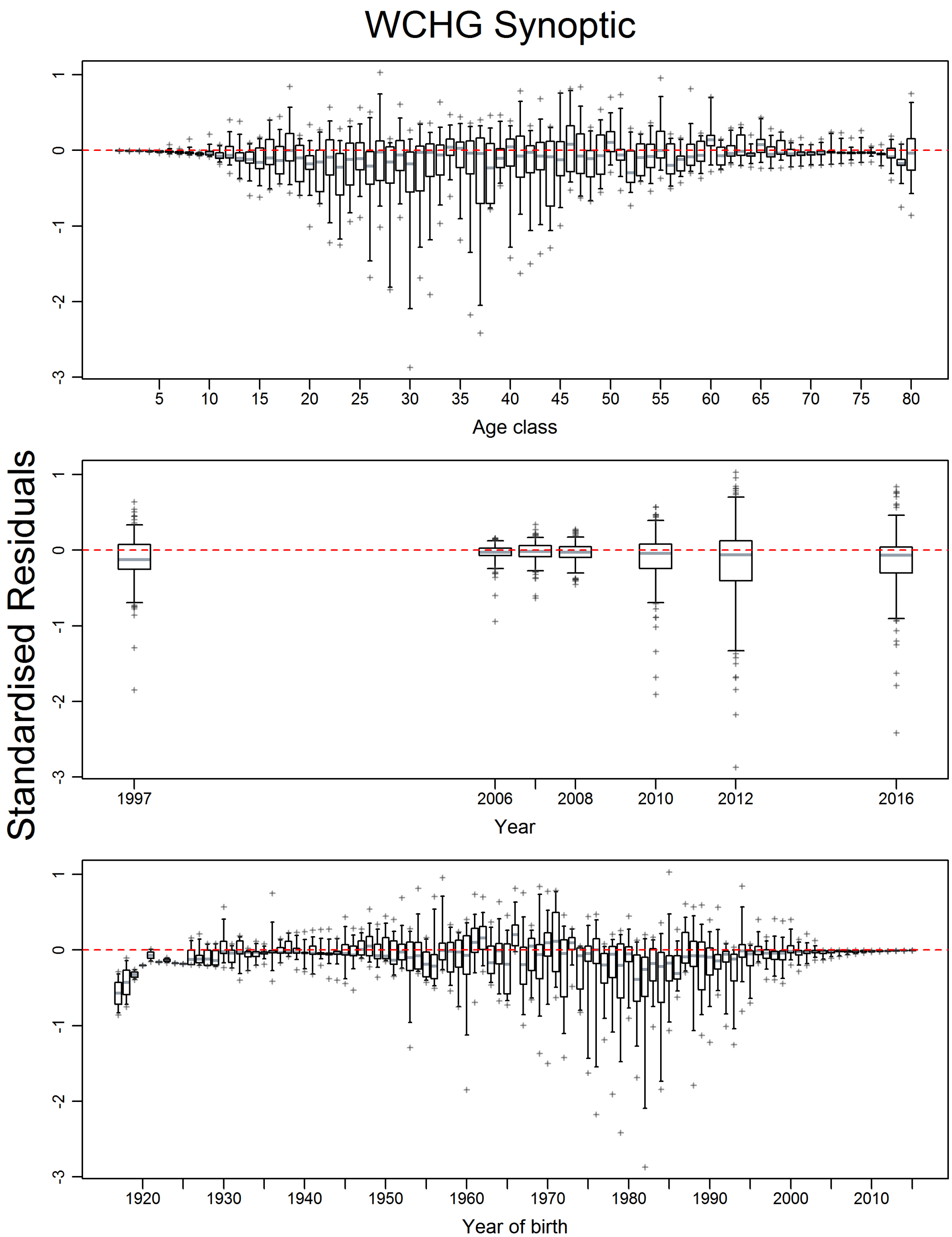


Figure F.10. REBS north CR.46.01: residuals of model fits to proportion-at-age data (MPD values) from the WCHG Synoptic survey series. Details as for Figure F.6, for a total of 1106 residuals.

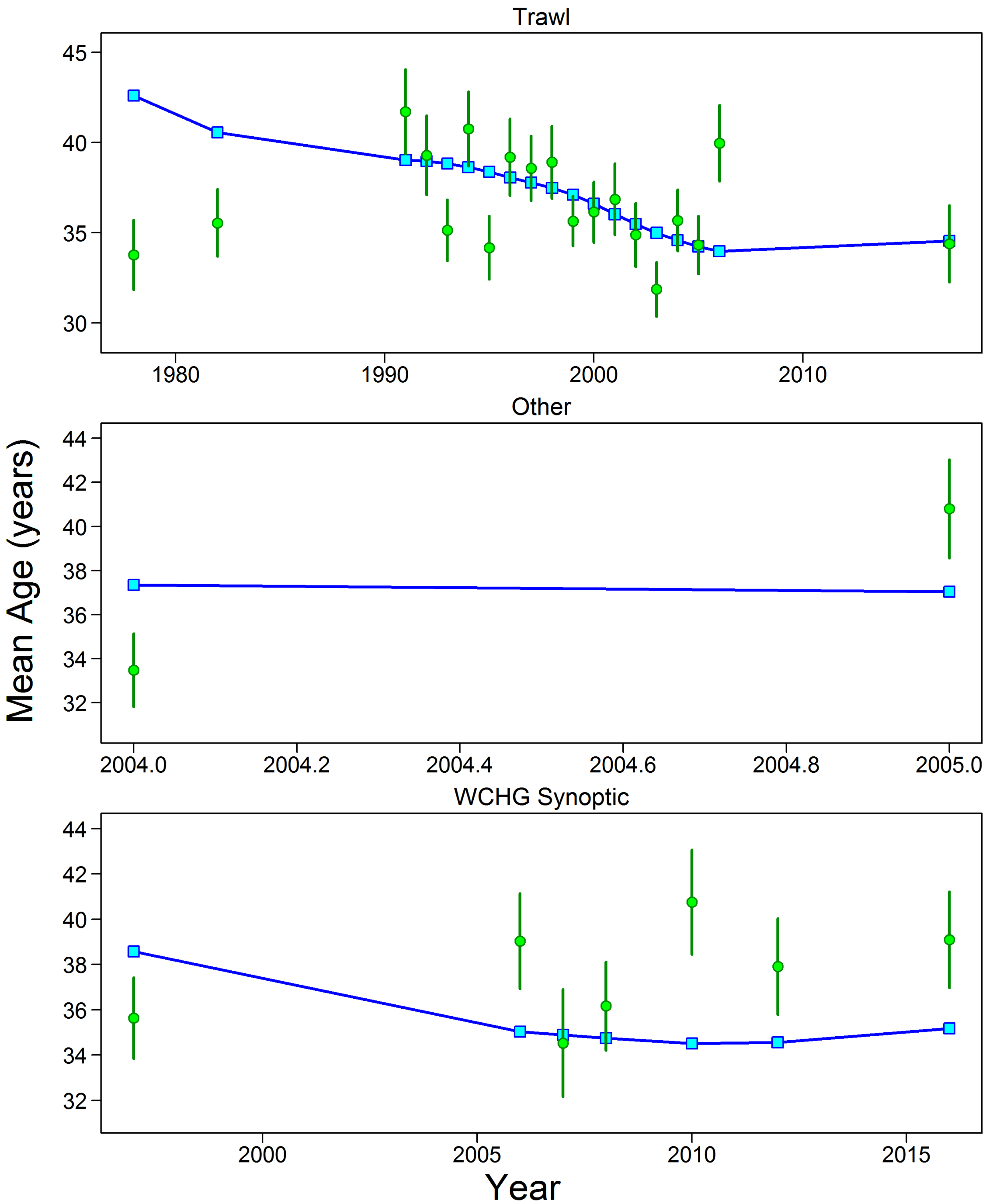
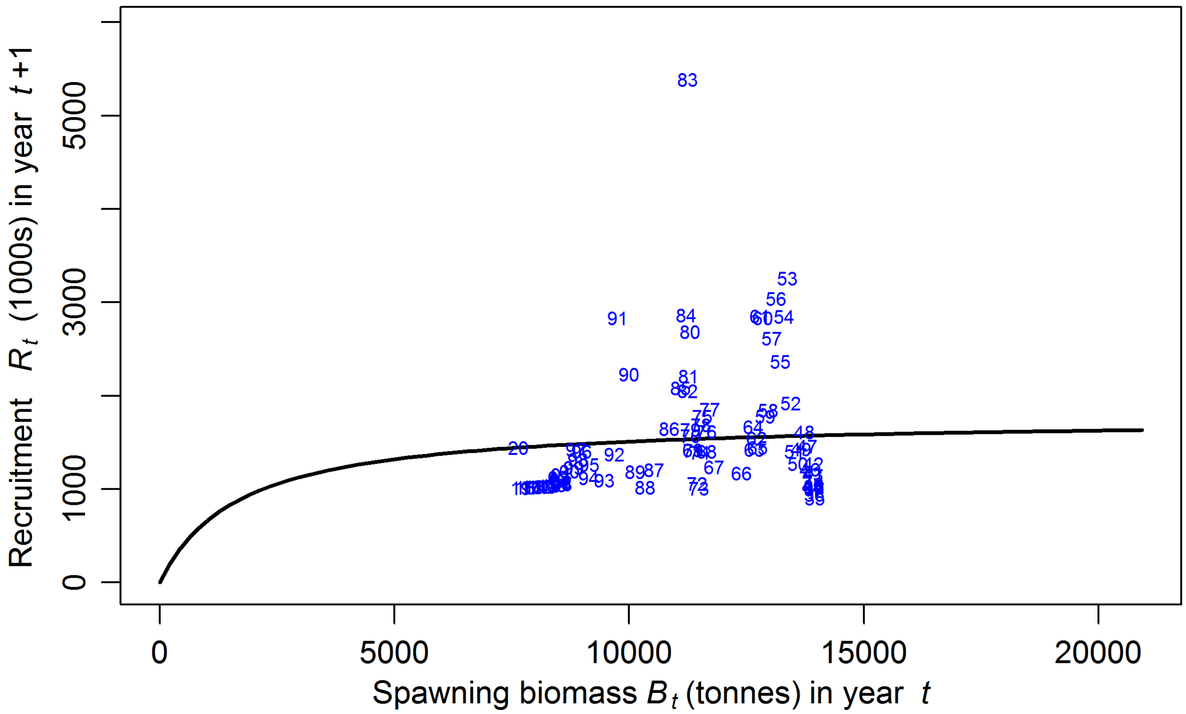


Figure F.11. REBS north CR.46.01: mean ages each year for the data (solid circles) with 95% confidence intervals and model estimates (joined open squares) for the commercial and survey age data.



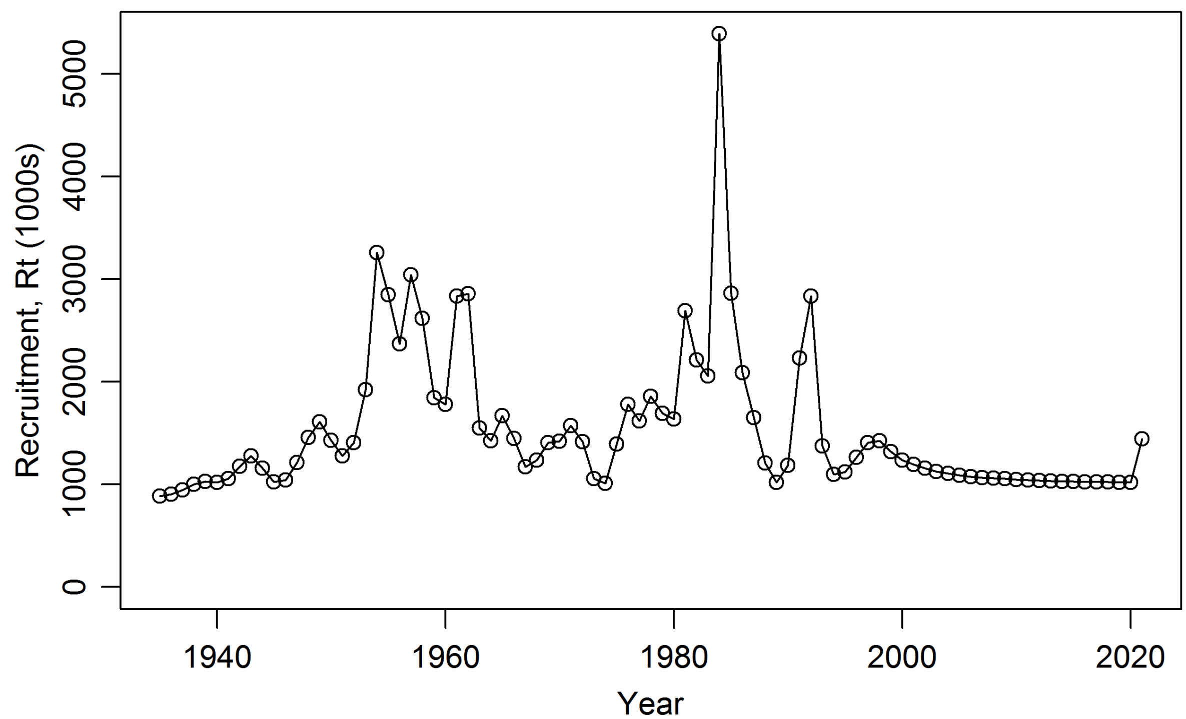


Figure F.12. REBS north CR.46.01: (top) deterministic stock-recruit relationship (black curve) and observed values (labelled by year of spawning) using MPD values; (bottom) recruitment (MPD values of age-1 individuals in year t) over time, in 1,000s of age-1 individuals, with a mean of 1,528.9.

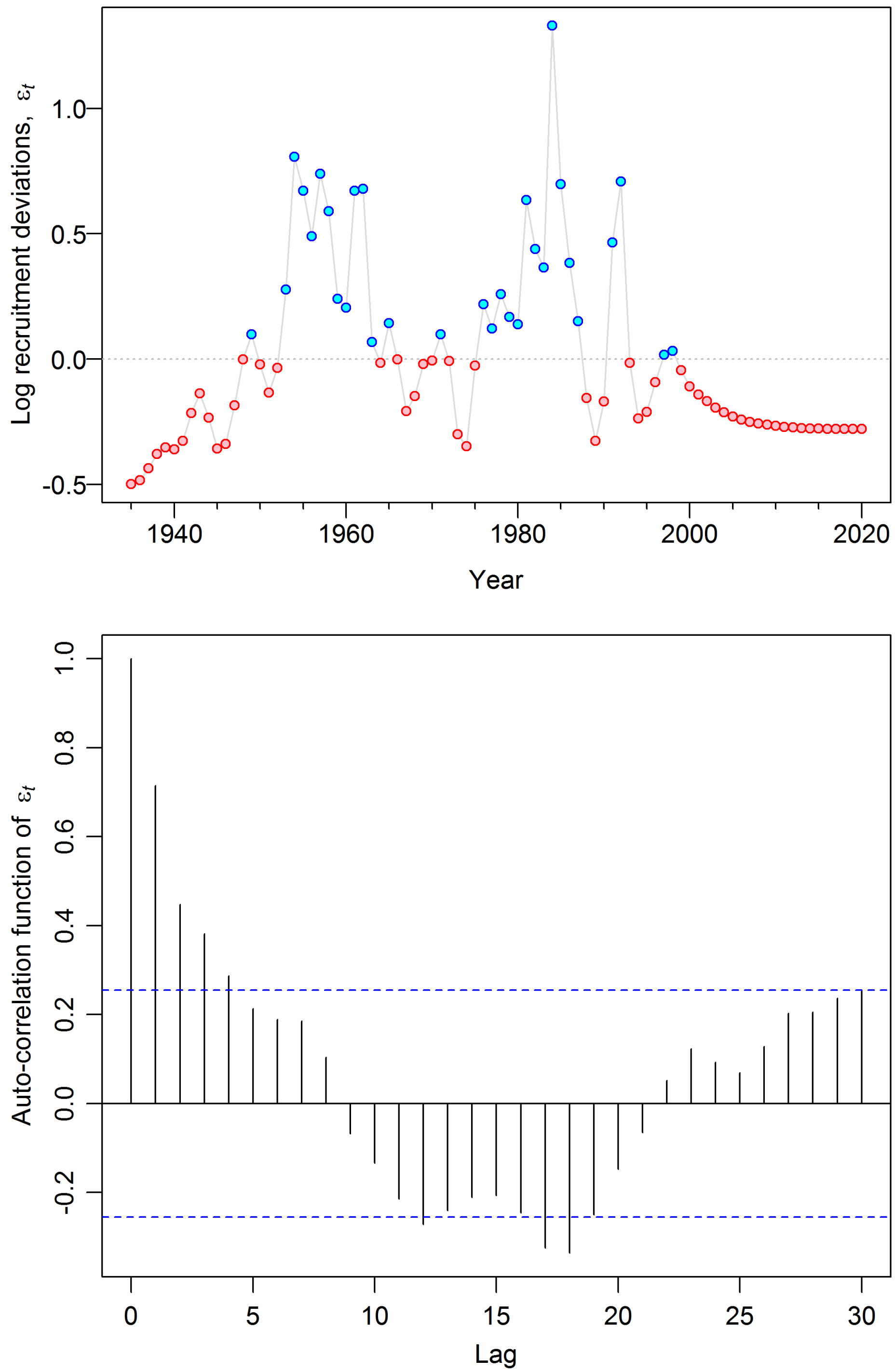


Figure F.13. REBS north CR.46.01: (top) log of the annual recruitment deviations, ϵ_t, where bias-corrected multiplicative deviation is e$^{\epsilon_t - \sigma_R^2/2}$ where $\epsilon_t \sim$ Normal$(0, \sigma_R^2)$; (bottom) auto-correlation function of the logged recruitment deviations (ϵ_t), for years 1935-1993. The start of this range is calculated as the first year of commercial age data (1978) minus the accumulator age class (A =80) plus the age for which commercial selectivity for females is 0.5 (namely 27); if the result is earlier than the model start year (1935), then the model start year is used. The end of the range is the final year that recruitments are calculated (2020) minus the age for which commercial selectivity for females is 0.5 (namely 27).

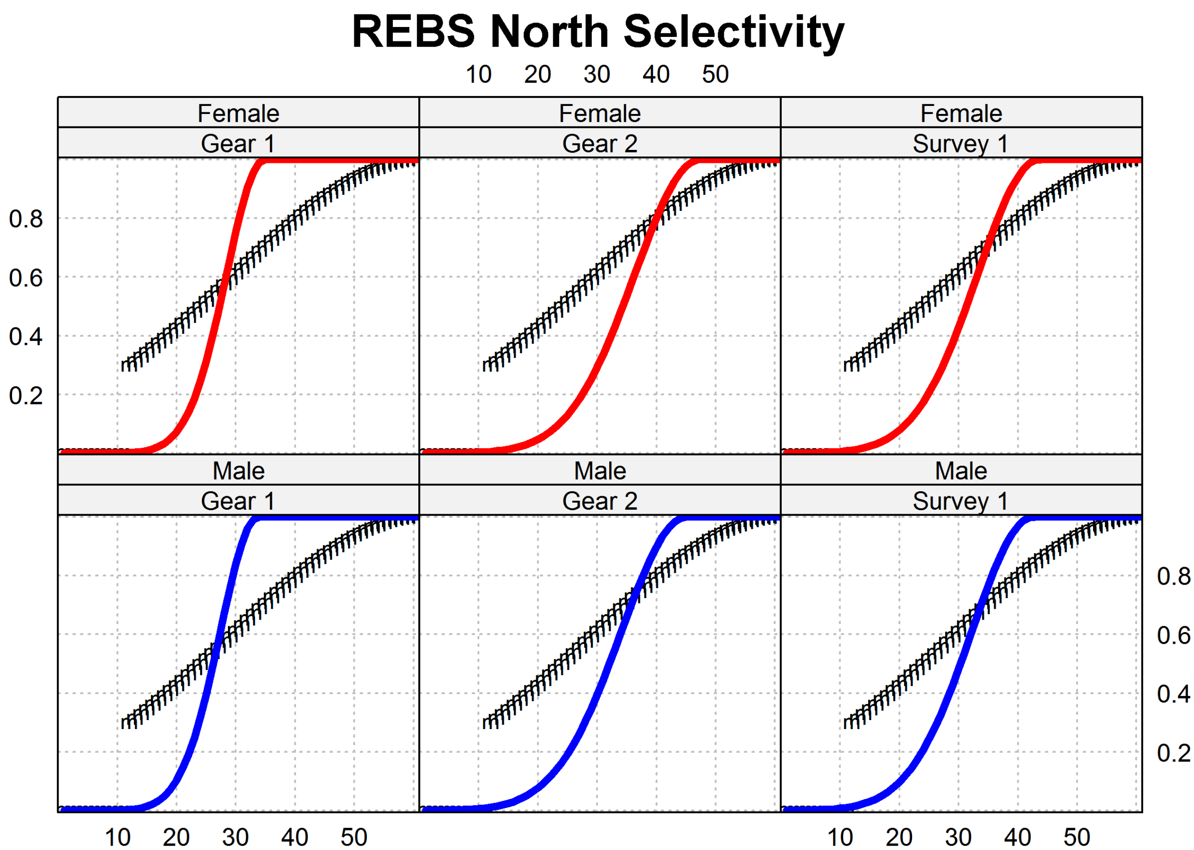


Figure F.14. REBS north CR.46.01: selectivities for commercial catch (Gear 1: Trawl, Gear 2: Other) and surveys (all MPD values), with maturity ogive for females indicated by 'm'.

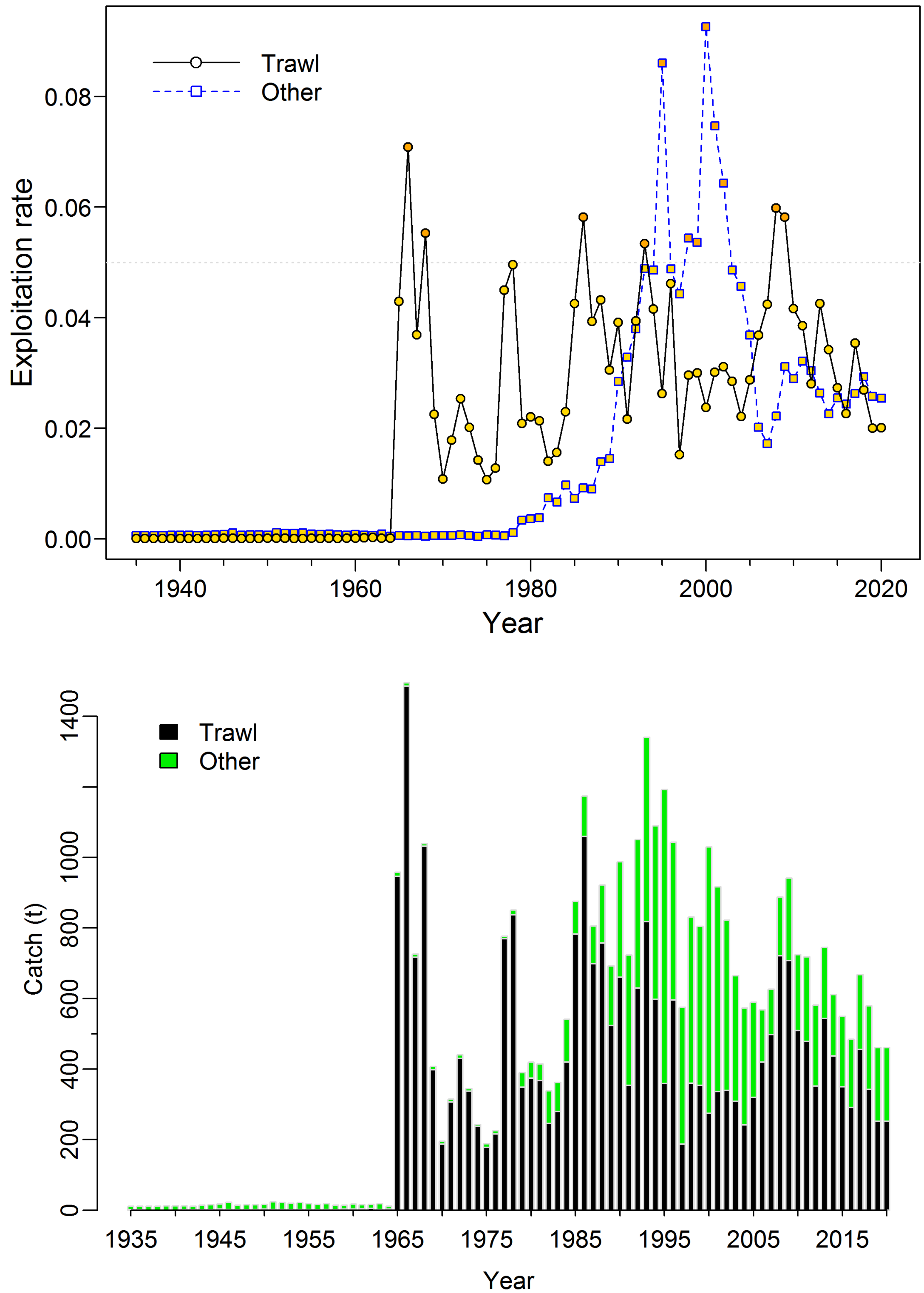


Figure F.15. REBS north CR.46.01: (top) exploitation rate (MPD) over time; (bottom) catch (t) by gear type.

F.2.2. REBS North – Central Run MCMC

The MCMC procedure performed 6 million iterations, sampling every 5000^{th} to give 1200 MCMC samples. The first 200 samples were discarded and the remaining 1000 samples were used for the MCMC analysis.

The MCMC plots show:

- Figure F.16 – traces for 1000 samples of the primary estimated parameters;
- Figure F.17 – split-chain diagnostic plots for the primary estimated parameters;
- Figure F.18 – auto-correlation diagnostic plots for the primary estimated parameters;
- Figure F.19 – marginal posterior densities for the primary parameters compared to their respective prior density functions.

MCMC traces showed acceptable convergence properties (no trend with increasing sample number) for the estimated parameters (Figure F.16), as did diagnostic analyses that split the posterior samples into three equal consecutive segments (Figure F.17) and checked for parameter autocorrelation out to 60 lags (Figure F.18). Most of the parameter medians did not move far from their initial MPD estimates (Figure F.19).

F.2.2.1. Figures – REBS north CR MCMC

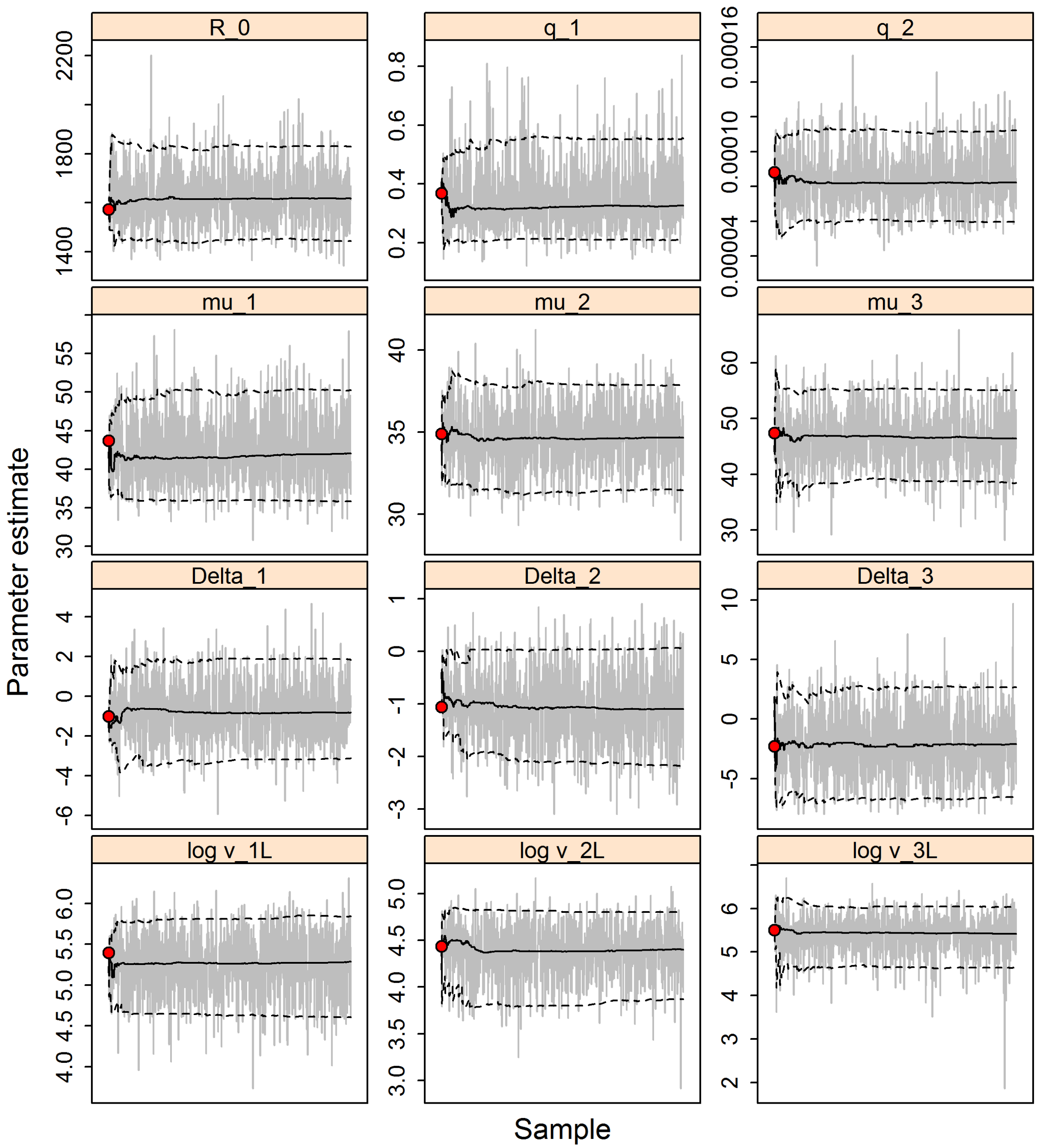


Figure F.16. REBS north CR.46.01: MCMC traces for the estimated parameters. Grey lines show the 1000 samples for each parameter, solid lines show the cumulative median (up to that sample), and dashed lines show the cumulative 0.05 and 0.95 quantiles. Red circles are the MPD estimates. For parameters other than M (if estimated), subscripts ≤ 1 correspond to fishery-independent surveys, and subscripts ≥ 2 denote the commercial fishery. Parameter notation is described in Appendix E.

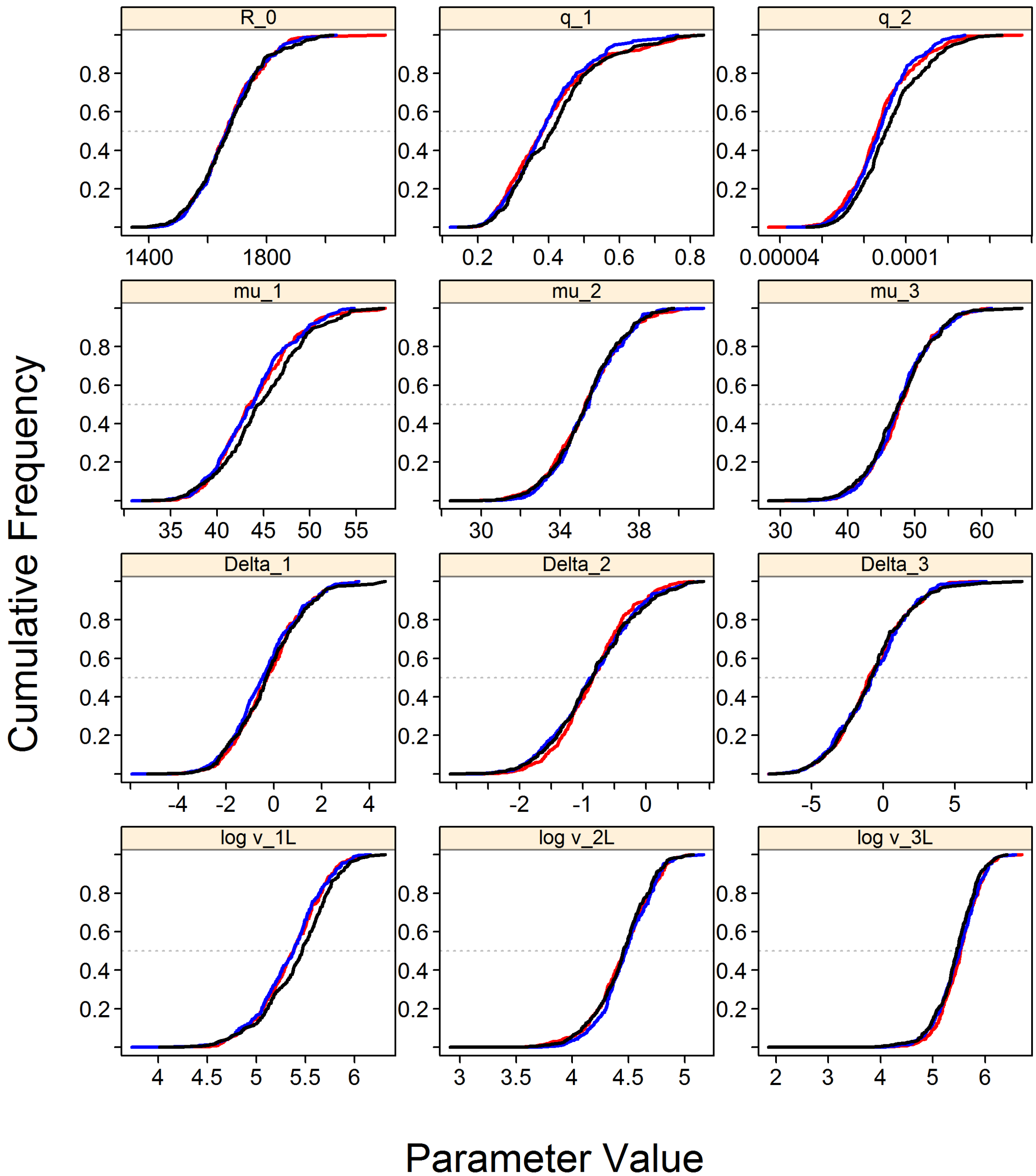


Figure F.17. REBS north CR.46.01: diagnostic plot obtained by dividing the MCMC chain of 1000 MCMC samples into three segments, and overplotting the cumulative distributions of the first segment (red), second segment (blue) and final segment (black).

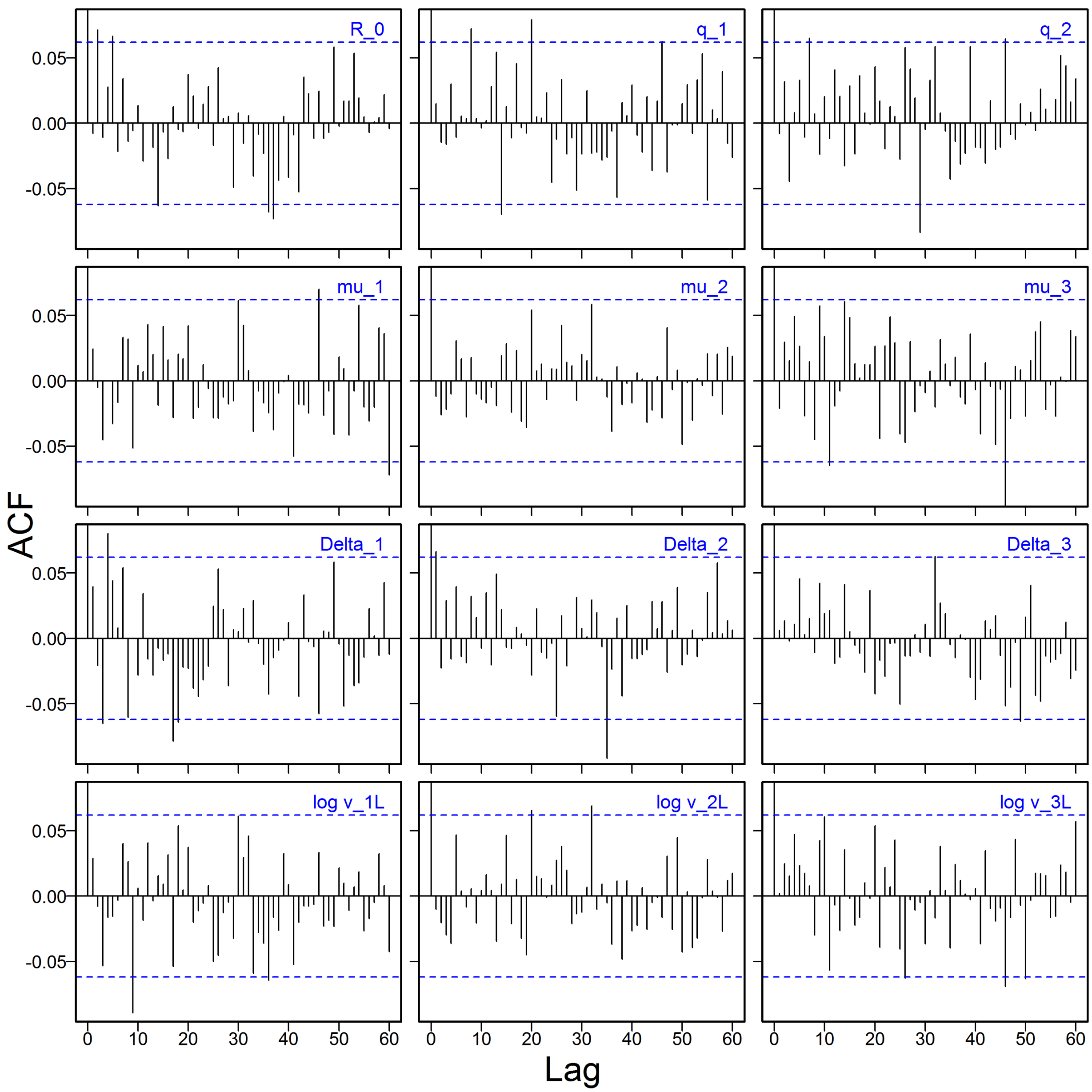


Figure F.18. REBS north CR.46.01: autocorrelation plots for the estimated parameters from the MCMC output. Horizontal dashed blue lines delimit the 95% confidence interval for each parameter's set of lagged correlations.

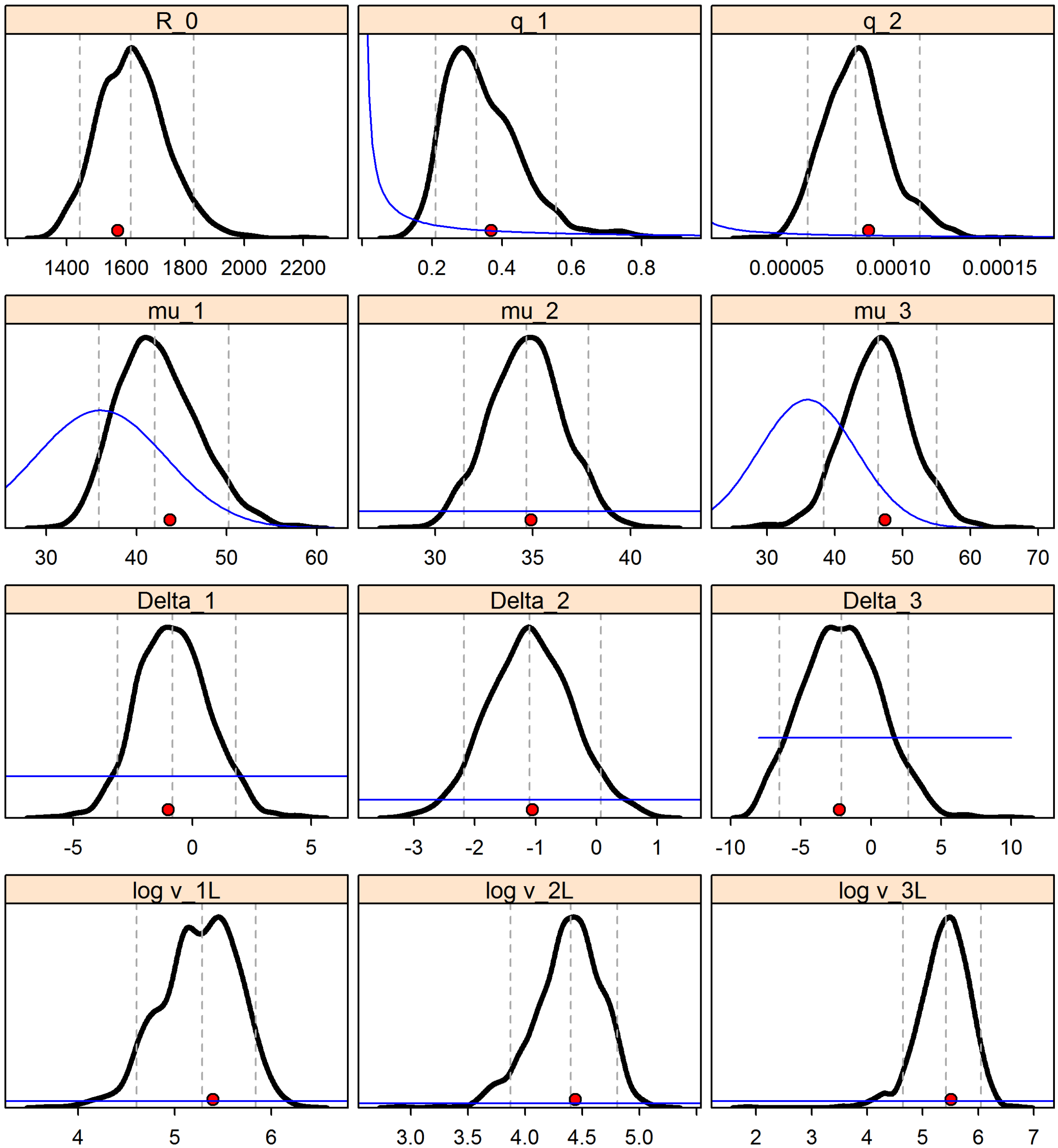


Figure F.19. REBS north CR.46.01: marginal posterior densities (thick black curves) and prior density functions (thin blue curves) for the estimated parameters. Vertical lines represent the 0.05, 0.5, and 0.95 quantiles, and red filled circles are the MPD estimates. For R_0 the prior is a uniform distribution on the range [1, 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).

F.2.3. REBS North – Composite Base Case

The composite base case examined nine runs which spanned two axes of uncertainty (M and CPUE c_{p}) for this stock assessment:

- **B1** (Run49) – fixed $M_{1,2} = 0.035$ and CPUE $c_p = 0.1$;
- **B2** (Run50) – fixed $M_{1,2} = 0.035$ and CPUE $c_p = 0.2759$
- **B3** (Run51) – fixed $M_{1,2} = 0.035$ and CPUE $c_p = 0.4$
- **B4** (Run47) – fixed $M_{1,2} = 0.045$ and CPUE $c_p = 0.1$;
- **B5** (Run46) – fixed $M_{1,2} = 0.045$ and CPUE $c_p = 0.2759$
- **B6** (Run48) – fixed $M_{1,2} = 0.045$ and CPUE $c_p = 0.4$
- **B7** (Run52) – fixed $M_{1,2} = 0.055$ and CPUE $c_p = 0.1$;
- **B8** (Run53) – fixed $M_{1,2} = 0.055$ and CPUE $c_p = 0.2759$
- **B9** (Run54) – fixed $M_{1,2} = 0.055$ and CPUE $c_p = 0.4$

The 1000 MCMC samples from each of the above runs were pooled to create a composite posterior of 9000 samples, which was used to estimate population status and to provide advice to managers. Estimating M provided non-credible fits given the uninformative nature of the data, with MPD estimates occurring at values of M greater than 0.06. MCMC runs that estimated M exhibited unstable behaviour with poor diagnostics. Note that some of these runs, notably B1, B2, B3 and B9, demonstrated unacceptable MCMC diagnostics for the selectivity parameters associated with the Other (non-trawl) commercial fishery. Consequently, these parameters were fixed to their MPD values when the MCMC simulations for these four component runs were conducted.

Composite base case median parameter estimates appear in Table F.4, and derived quantities at equilibrium and associated with maximum sustainable yield (MSY) appear in Table F.5. The differences among the component base runs are summarised by various figures:

- Figure F.20 – MCMC traces of R_0 for the 9 candidate base runs;
- Figure F.21 – three chain segments of R_0 MCMC chains;
- Figure F.22 – autocorrelation plots for R_0 MCMC output;
- Figure F.23 – quantile plots of parameter estimates from 9 component base runs;
- Figure F.24 – quantile plots of selected derived quantities from 9 component base runs.

In this assessement, projections extend to 2096 which equals 1.5 generations (75 years), where one generation was determined to be 50 years (see Appendix D). Various model trajectories and final stock status for the composite base case appear in the figures:

- Figure F.25 – estimates of spawning biomass B_t (tonnes) from pooled model posteriors spanning 1935-2096;
- Figure F.26 – estimates of vulnerable biomass V_t (tonnes) from pooled model posteriors;
- Figure F.27 – estimates of exploitation rate u_t from pooled model posteriors;
- Figure F.28 – estimates of reconstructed (1935-2021) and projected (2022-2096) recruitment R_t (1000s age-1 fish) from pooled model posteriors;
- Figure F.29 – phase plot through time of median B_t/B_{MSY} and u_{t-1}/u_{MSY} relative to DFO's Precautionary Approach (PA) provisional reference points;
- Figure F.30 – REBS north stock status at beginning of 2021.

Uncertainty in M, CPUE c_{p}, and width of the ageing error (AE) matrix were thought to be the most important components of uncertainty in this stock assessment. The first two categories were considered to be the most important and formed the two axes of uncertainty in the composite base case. The latter category was explored in sensitivity runs.

For each component base run, 1000 MCMC samples were generated then pooled to provide an average stock trajectory for population status and advice to managers. While estimating M was possible, the estimates were frequently higher than M=0.06, which seemed unreasonable, given the maximum age for this species complex. We include a sensitivity run in the following section that demonstrated the effect of estimating M.

The nine component runs outlined above converged with no serious pathologies in the MCMC diagnostics (similar diagnostic results to those outlined for the central run). Figures F.20 to F.22 show diagnostics for the R_0 parameter in each of the component runs, and Figure F.23 shows the distribution of all the estimated parameters. In most cases, the component runs had parameter estimates with overlapping distributions. The R_0 and q parameters varied with M: R_0 increasing and q decreasing with increasing M. Within each M, R_0 decreased and q increased as CPUE c_{p} increased. The selectivity parameters differed little among the three M estimates but changed consistently with c_{p} (Figure F.23).

Similar to the parameter distributions, those for derived quantities (Figure F.24) varied by M and CPUE c_{p}, primarily because B_0 and MSY varied by the axes of uncertainty: increasing when M increased, decreasing when CPUE c_{p} increased.

The composite base case, comprising nine pooled MCMC runs, was used to calculate a set of parameter estimates (Table F.4) and derived quantities at equilibrium and those associated with MSY (Table F.5). The composite base case population trajectory from 1935 to 2021 and projected biomass to 2096 (Figure F.25), assuming a constant catch policy of 600 t/y (and a harvest rate policy of u=0.1/y), indicated that the median stock biomass will remain above the USR for the next 1.5 generations (75 years). The lower bound of the probability envelope around the constant catch policy is predicted to enter the Cautious and Critical zones after about one-half generation due to a much larger cumulative removal than that under a harvest rate policy of 0.1/year. However, most of the projection distribution lies well above these zones and we have little confidence in long-term projections which assume no active management intervention when stock size is reduced to low levels.

A phase plot of the time-evolution of spawning biomass and exploitation rate in the two modelled fisheries in MSY space (Figure F.29) suggests that the stock is firmly in the Healthy Zone, with a current position at $B_{2021}/B_{\mathrm{MSY}}$ = 2.214 (1.5, 3.149), $u_{2020(\mathrm{trawl})}/u_{\mathrm{MSY}}$ = 0.06 (0.023, 0.138), and $u_{2020(\mathrm{other})}/u_{\mathrm{MSY}}$ = 0.11 (0.028, 0.321).

Table F.4. REBS north: the 0.05, 0.5, and 0.95 quantiles for pooled model parameters (defined in Appendix E) from MCMC estimation of 9 base model runs.

	5%	50%	95%
R_0	980	1,643	3,521
q_1	0.156	0.280	0.487
q_2	0.0000412	0.0000685	0.000109
μ_1	35.1	41.7	50.4
μ_2	28.8	33.3	37.3
μ_3	38.8	43.3	53.7
Δ_1	-3.44	-0.646	2.24
Δ_2	-2.16	-0.975	0.0997
Δ_3	-5.48	-2.00	2.30
$\log v_{1L}$	4.50	5.28	5.92
$\log v_{2L}$	3.30	4.18	4.75
$\log v_{3L}$	-13.1	5.16	5.96

Table F.5. REBS north: the 0.05, 0.5, and 0.95 quantiles of MCMC-derived quantities from 9000 samples pooled from 9 MCMC posteriors. Definitions are: B_0 – unfished equilibrium spawning biomass (mature females), V_0 – unfished equilibrium vulnerable biomass (males and females), B_{2021} – spawning biomass at the start of 2021, V_{2021} – vulnerable biomass in the middle of 2021, u_{2020} – exploitation rate (ratio of total catch to vulnerable biomass) in the middle of 2020, $u_{\max}$ – maximum exploitation rate (calculated for each sample as the maximum exploitation rate from 1935-2020), 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 (2015-2019) was 548 t.

	5%	50%	95%
B_0	13,058	15,413	20,693
V_0 (trawl)	22,056	27,588	34,360
V_0 (other)	15,965	19,483	27,661
B_{2021}	5,475	9,153	17,176
V_{2021} (trawl)	9,242	15,963	30,283
V_{2021} (other)	2,493	8,970	22,357
B_{2021}/B_0	0.405	0.595	0.840
V_{2021}/V_0 (trawl)	0.387	0.590	0.903
V_{2021}/V_0 (other)	0.153	0.455	0.833
u_{2020} (trawl)	0.00823	0.0157	0.0269
u_{2020} (other)	0.00939	0.0234	0.0870
$u_{\max}$ (trawl)	0.0508	0.0622	0.0780
$u_{\max}$ (other)	0.0479	0.0894	0.173
MSY	474	636	1,115
B_{MSY}	3,519	4,140	5,519
$0.4B_{2021}$	1,408	1,656	2,208
$0.8B_{2021}$	2,815	3,312	4,415
$B_{2021}/B_{\mathrm{MSY}}$	1.50	2.21	3.15
B_{MSY}/B_0	0.260	0.269	0.276
V_{MSY}	1,577	2,675	4,150
V_{MSY}/V_0 (trawl)	0.0558	0.101	0.153
V_{MSY}/V_0 (other)	0.0926	0.130	0.178
u_{MSY}	0.164	0.268	0.400
$u_{2020}/u_{\mathrm{MSY}}$ (trawl)	0.0234	0.0602	0.138
$u_{2020}/u_{\mathrm{MSY}}$ (other)	0.0281	0.110	0.321

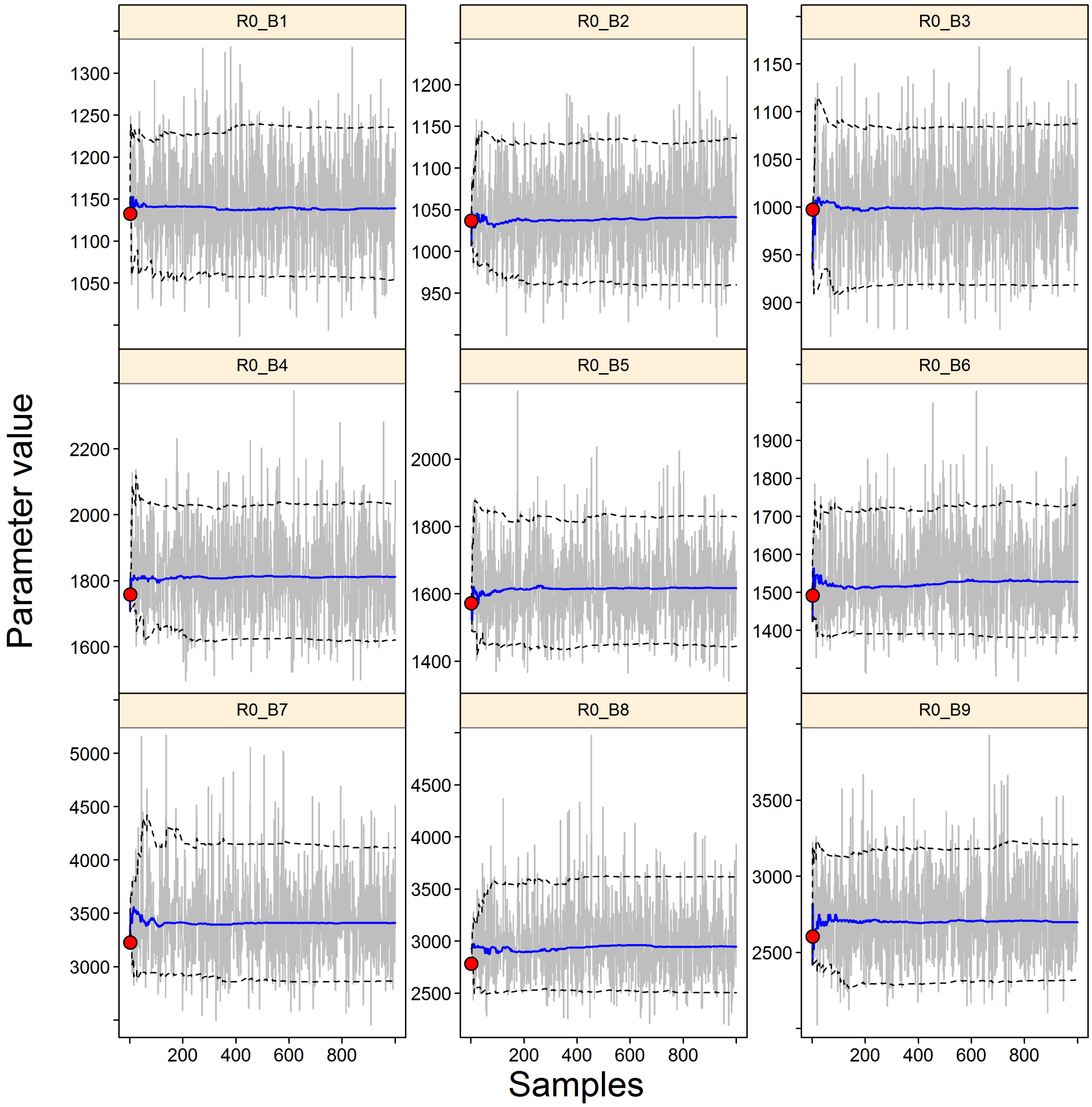


Figure F.20. REBS north base candidates: MCMC traces of R_0 for the 9 candidate base runs. Grey lines show the 1000 samples for the R_0 parameter, solid lines show the cumulative median (up to that sample), and dashed lines show the cumulative 0.05 and 0.95 quantiles. Red circles are the MPD estimates.

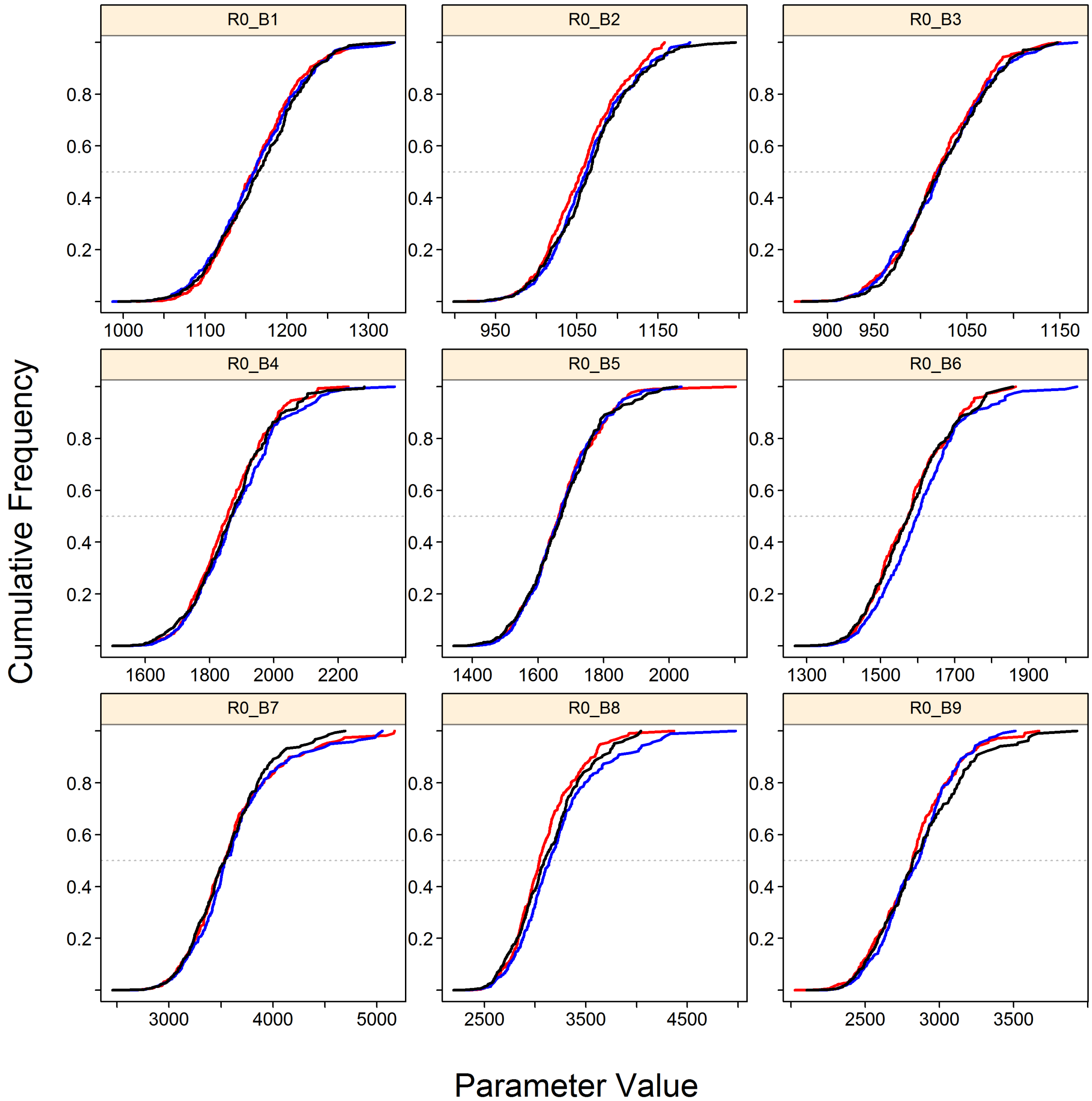


Figure F.21. REBS north base candidates: diagnostic plots obtained by dividing the R_0 MCMC chains of 1000 MCMC samples into three segments, and overplotting the cumulative distributions of the first segment (red), second segment (blue) and final segment (black).

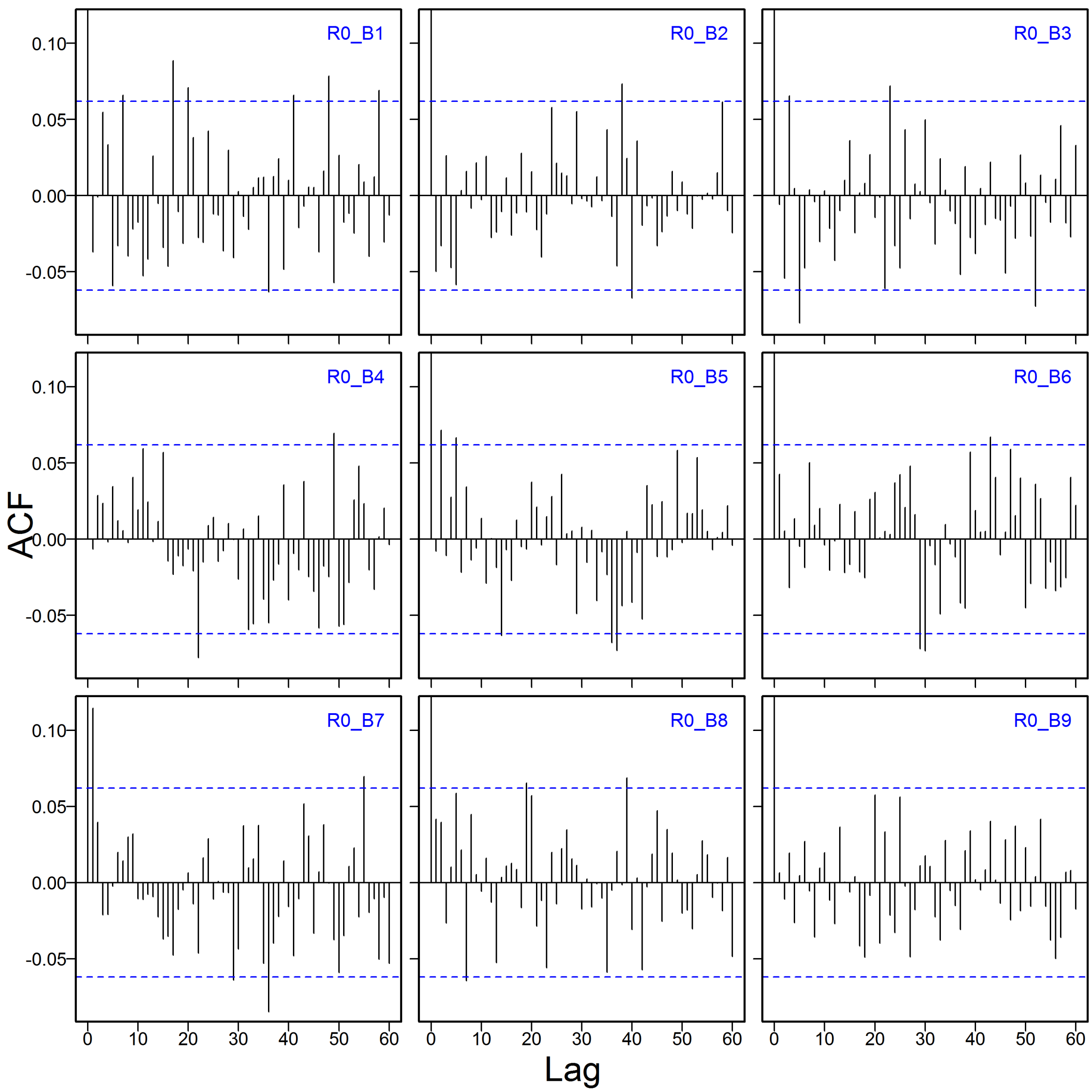


Figure F.22. REBS north base candidates: autocorrelation plots for the R_0 parameters from the MCMC output. Horizontal dashed blue lines delimit the 95% confidence interval for each parameter's set of lagged correlations.

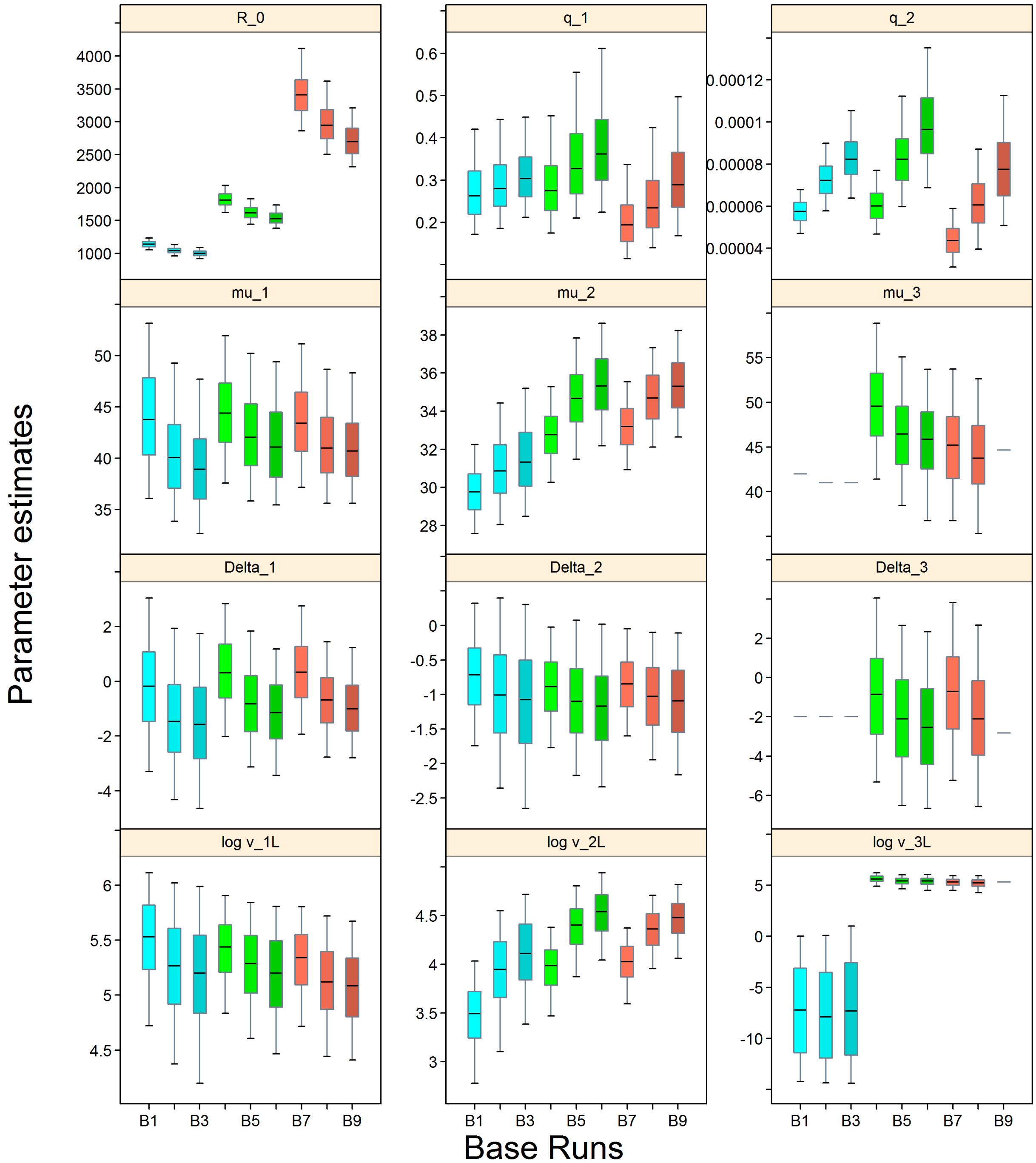


Figure F.23. REBS north base composite: quantile plots of the parameter estimates from 9 component runs of the base case, where blue boxes denote M=0.035, green boxes denote M=0.045, and red boxes denote M=0.055. The boxplots delimit the 0.05, 0.25, 0.5, 0.75, and 0.95 quantiles. Horizontal lines with no variation indicate parameters which were fixed at the MPD value for the MCMC simulation.

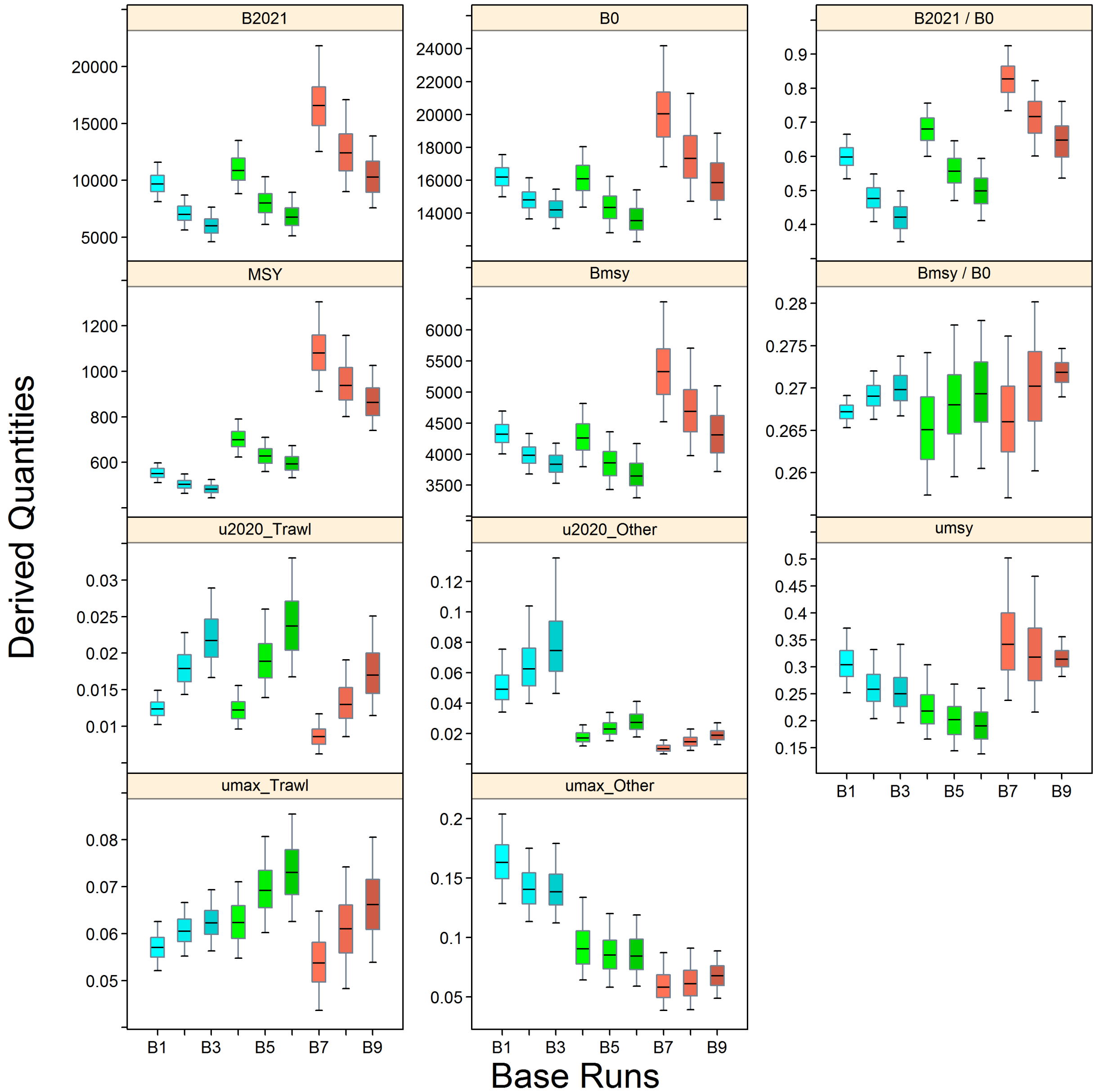


Figure F.24. REBS north base composite: quantile plots of selected derived quantities (B_{2021}, B_0, B_{2021}/B_0, MSY, B_{MSY}, B_{MSY}/B_0, u_{2020}, u_{MSY}, $u_{\max}$) from 9 component runs of the base case, where blue boxes denote M=0.035, green boxes denote M=0.045, and red boxes denote M=0.055. The boxplots delimit the 0.05, 0.25, 0.5, 0.75, and 0.95 quantiles.

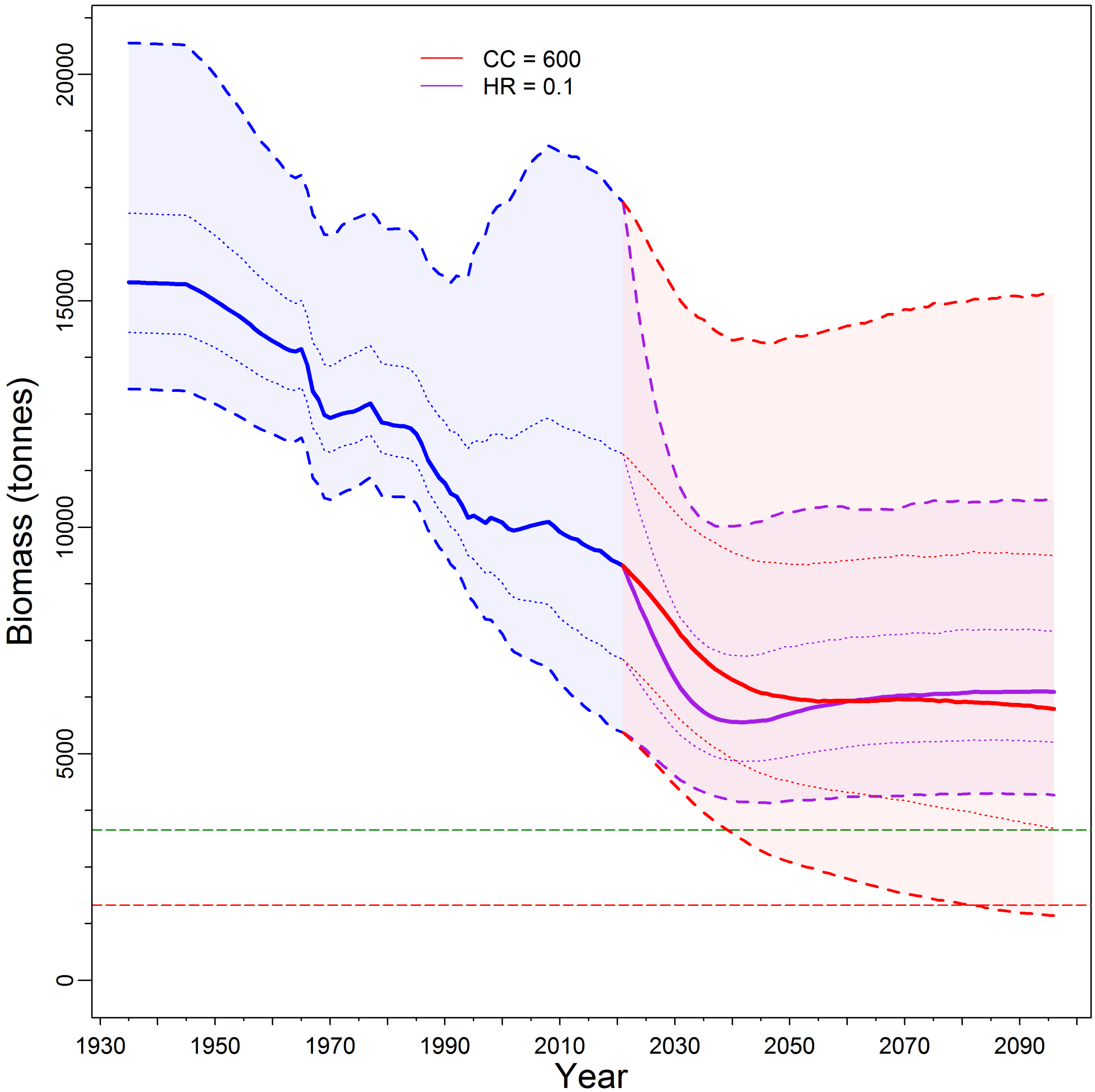


Figure F.25. REBS north base composite: estimates of spawning biomass B_t (tonnes) from pooled model posteriors. The median biomass trajectory appears as a solid curve surrounded by a 90% credibility envelope (quantiles: 0.05-0.95) in light blue and delimited by dashed lines for years t=1935:2021; projected biomass appears in light red for years t=2022:2096. Also delimited is the 50% credibility interval (quantiles: 0.25-0.75) delimited by dotted lines. The horizontal dashed lines show the median LRP and USR.

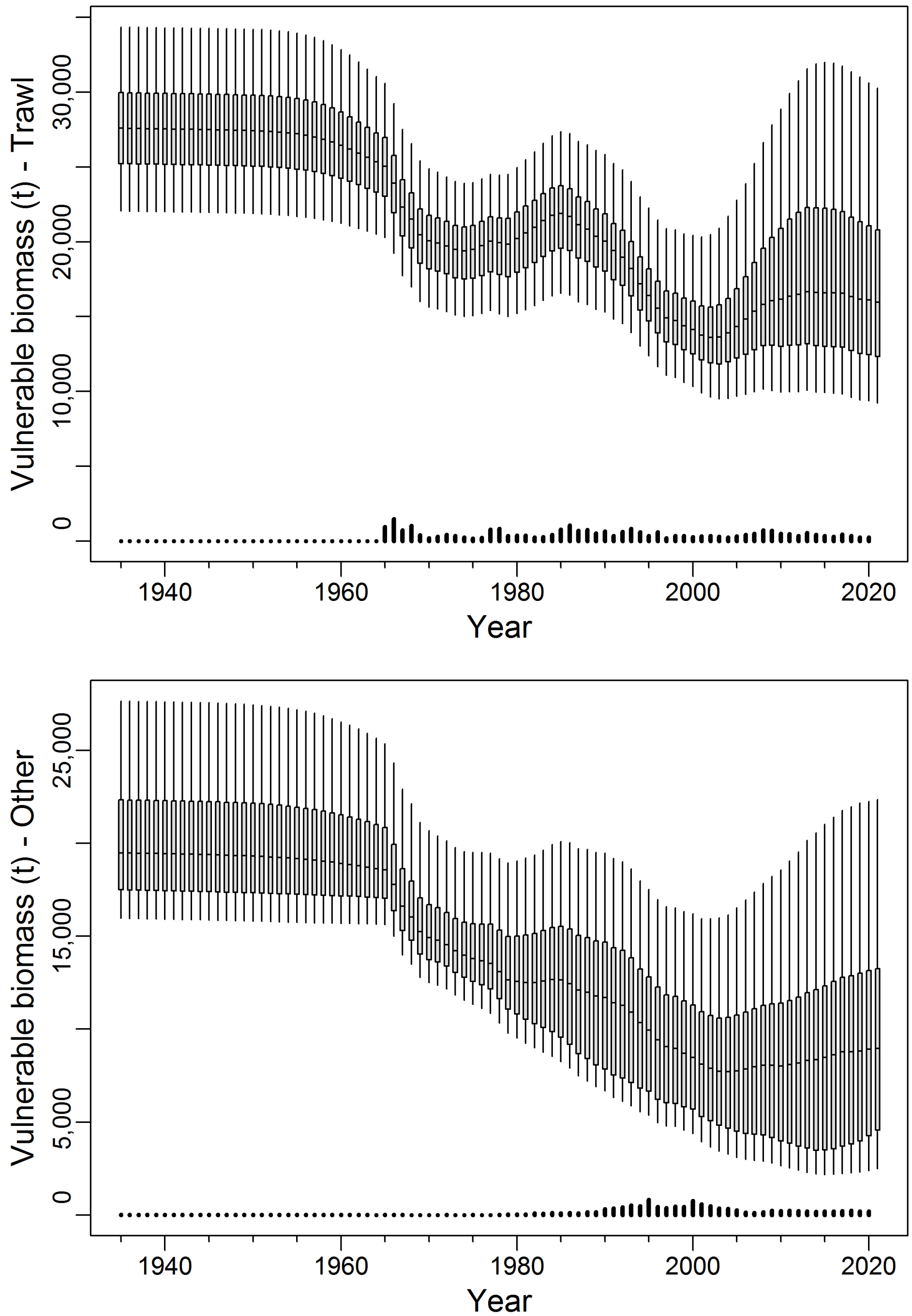


Figure F.26. REBS north base composite: estimated vulnerable biomass trajectory for two fisheries (boxplots) and commercial catch history (vertical bars), in tonnes. Boxplots show the 0.05, 0.25, 0.5, 0.75, and 0.95 quantiles from the MCMC results.

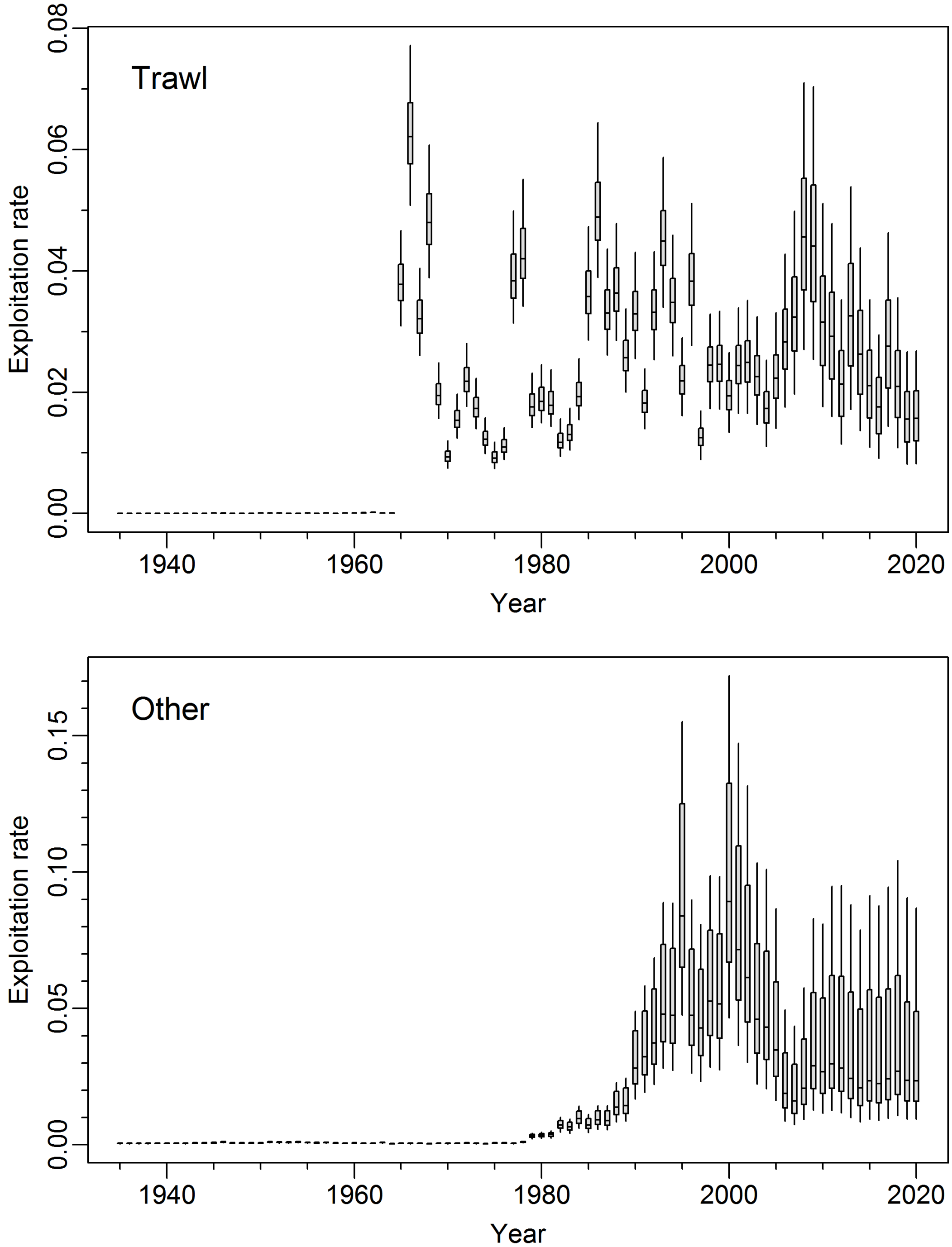


Figure F.27. REBS north base composite: marginal posterior distribution of exploitation rate trajectory for two fisheries. Boxplots show the 0.05, 0.25, 0.5, 0.75, and 0.95 quantiles from the MCMC results.

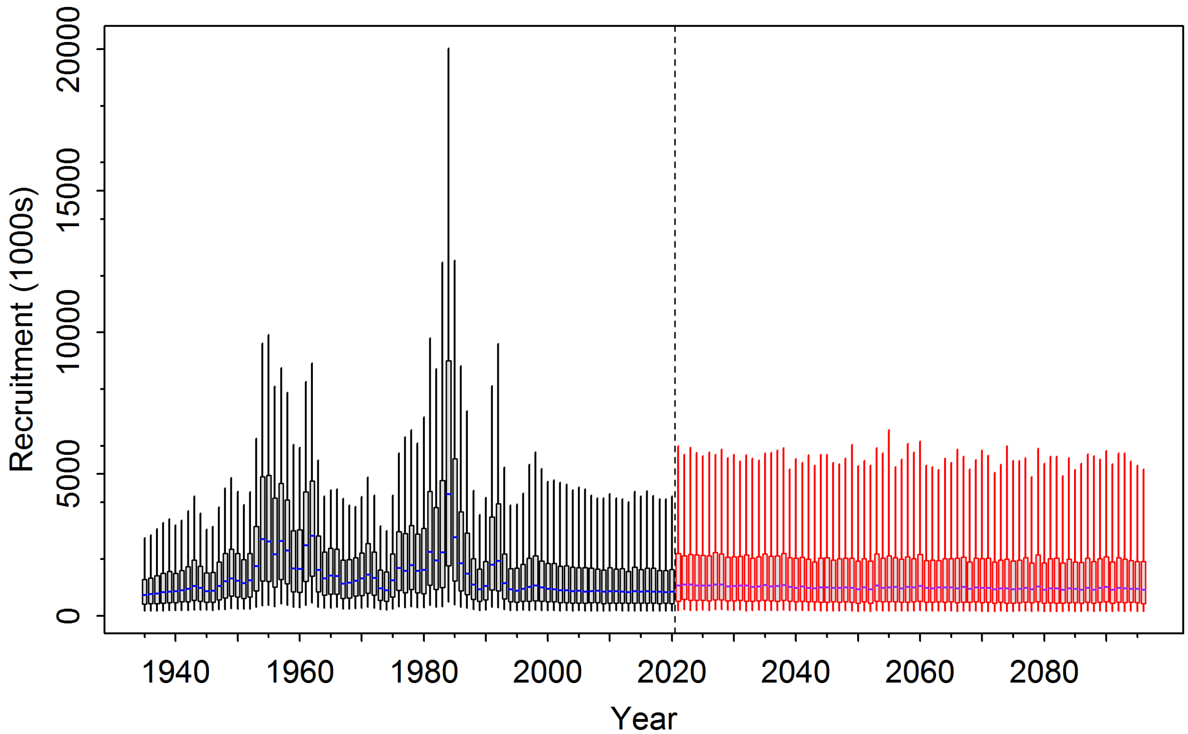


Figure F.28. REBS north base composite: marginal posterior distribution of recruitment trajectory (reconstructed: 1935-2021, projected: 2022-2096) in 1,000s of age-1 fish.

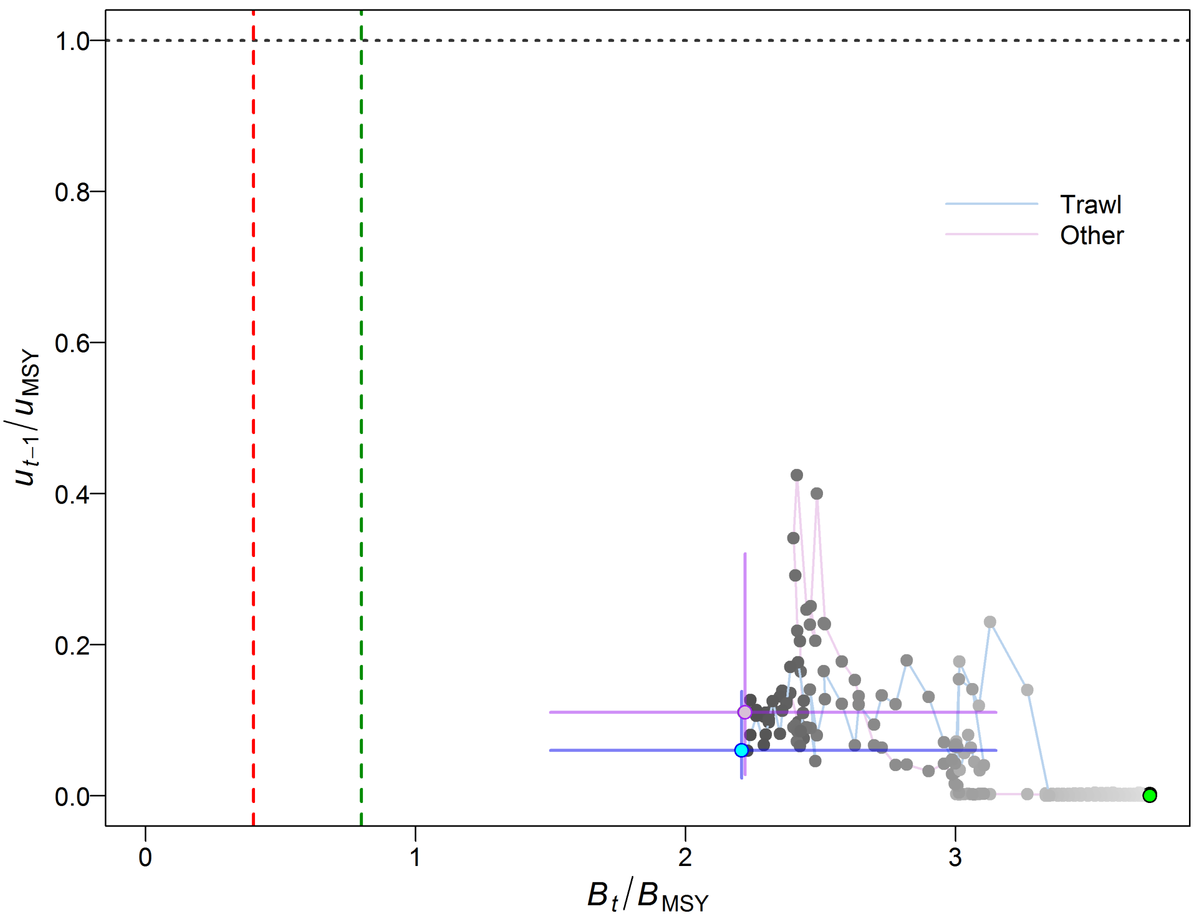


Figure F.29. REBS north base composite: phase plot through time of the medians of the ratios B_t/B_{MSY} (the spawning biomass in year t relative to B_{MSY}) and u_{t-1}/u_{MSY} (the exploitation rate in year $t-1$ relative to u_{MSY}) for two fisheries (trawl/other). The filled green circle is the starting year (1936). Years then proceed along lines gradually darkening from light grey/blue, with the final year (2021) as a filled cyan/purple circle, and the blue/purple cross lines represent the 0.05 and 0.95 quantiles of the posterior distributions for the final year. Red and green vertical dashed lines indicate the PA provisional limit and upper stock reference points (0.4, 0.8 B_{MSY}), and the horizontal grey dotted line indicates u at MSY.

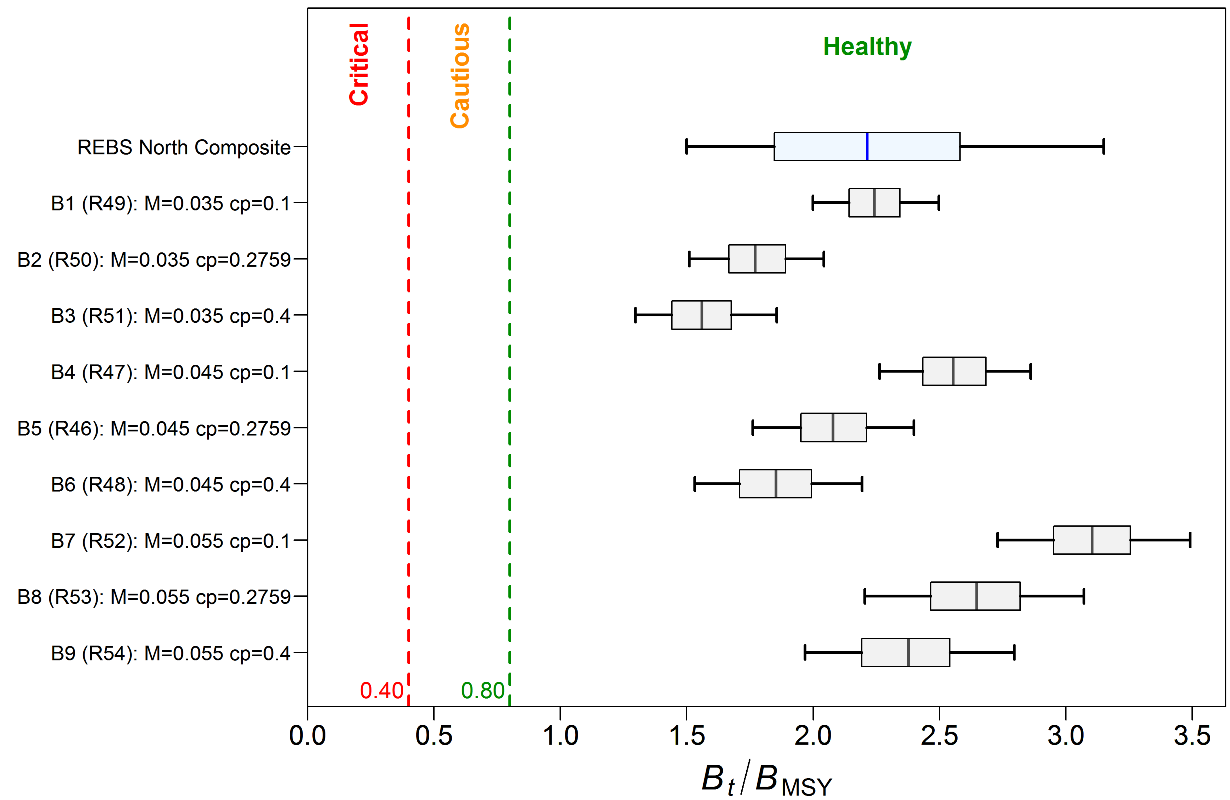


Figure F.30. REBS north base composite: stock status at beginning of 2021 relative to the PA provisional reference points of 0.4B_{MSY} and 0.8B_{MSY} for a base case comprising 9 model runs. The top quantile plot shows the composite distribution and below are the 9 contributing runs. Quantile plots show the 0.05, 0.25, 0.5, 0.75, and 0.95 quantiles from the MCMC posteriors.

F.2.4. REBS North – Decision Tables

F.2.4.1. GMU – Guidance for setting TACs

Decision tables for the composite base case provide advice to managers as probabilities that current and projected biomass B_t ($t = 2021, ..., 2031$) will exceed biomass-based reference points (or that projected exploitation rate u_t will fall below harvest-based reference points) under constant catch (CC) and harvest rate (HR) policies. Specifically:

- Tables F.6 & F.7 – probability of B_t exceeding the LRP, P$(B_t > 0.4B_{\text{MSY}})$, under CC and HR policies;
- Tables F.8 & F.9 – probability of B_t exceeding the USR, P$(B_t > 0.8B_{\text{MSY}})$, under CC and HR policies;
- Tables F.10 & F.11 – probability of B_t exceeding biomass at MSY, P$(B_t > B_{\text{MSY}})$, under CC and HR policies;
- Tables F.12 & F.13 – probability of u_t falling below harvest rate at MSY, P$(u_t < u_{\text{MSY}})$, under CC and HR policies;
- Tables F.14 & F.15 – probability of B_t exceeding current-year biomass, P$(B_t > B_{2021})$, under CC and HR policies;
- Tables F.16 & F.17 – probability of u_t falling below current-year harvest rate, P$(u_t < u_{2020})$, under CC and HR policies;
- Tables F.18 & F.19 – probability of B_t exceeding a non-DFO 'soft limit', P$(B_t > 0.2B_0)$, under CC and HR policies;
- Tables F.20 & F.21 – probability of B_t exceeding a non-DFO 'target' biomass, P$(B_t > 0.4B_0)$, under CC and HR policies.

MSY-based reference points estimated within a stock assessment model can be highly sensitive to model assumptions about natural mortality and stock recruitment dynamics (Forrest et al. 2018). As a result, other jurisdictions use reference points that are expressed in terms of B_0 rather than B_{MSY} (e.g., N.Z. Min. Fish. 2011), because B_{MSY} is often poorly estimated as it depends on estimated parameters and a consistent fishery (although B_0 shares several of these same problems). Therefore, the reference points of 0.2B_0 and 0.4B_0 are also presented here. These are default values used in New Zealand respectively as a 'soft limit', below which management action needs to be taken, and a 'target' biomass for low productivity stocks, a mean around which the biomass is expected to vary. The 'soft limit' is equivalent to the upper stock reference (USR, 0.8B_{MSY}) in the provisional DFO Sustainable Fisheries Framework while a 'target' biomass is not specified by the provisional DFO SFF. Additionally, results are provided comparing projected biomass to B_{MSY} and to current spawning biomass B_{2021}, and comparing projected harvest rate to current harvest rate u_{2020}.

Table F.6. REBS north: decision table for the limit reference point $0.4B_{MSY}$ for 1-10-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 9000 MCMC samples for which $B_t > 0.4B_{MSY}$. For reference, the average catch over the last 5 years (2015-2019) was 548 t.*

CC	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	1	1	1	1	1	1	1	1	1	1	1
100	1	1	1	1	1	1	1	1	1	1	1
200	1	1	1	1	1	1	1	1	1	1	1
300	1	1	1	1	1	1	1	1	1	1	1
400	1	1	1	1	1	1	1	1	1	1	1
500	1	1	1	1	1	1	1	1	1	1	1
600	1	1	1	1	1	1	1	1	1	1	1
700	1	1	1	1	1	1	1	1	1	1	1
800	1	1	1	1	1	1	1	1	1	1	1
900	1	1	1	1	1	1	1	1	1	1	1
1000	1	1	1	1	1	1	1	1	1	1	>0.99
1100	1	1	1	1	1	1	1	1	1	>0.99	>0.99
1200	1	1	1	1	1	1	1	1	1	>0.99	>0.99

Table F.7. REBS north: decision table for the limit reference point $0.4B_{MSY}$ for 1-10-year projections for a range of **harvest rate** *strategies. 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 9000 MCMC samples for which $B_t > 0.4B_{MSY}$. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.023.*

HR	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	1	1	1	1	1	1	1	1	1	1	1
0.01	1	1	1	1	1	1	1	1	1	1	1
0.02	1	1	1	1	1	1	1	1	1	1	1
0.03	1	1	1	1	1	1	1	1	1	1	1
0.04	1	1	1	1	1	1	1	1	1	1	1
0.05	1	1	1	1	1	1	1	1	1	1	1
0.06	1	1	1	1	1	1	1	1	1	1	1
0.07	1	1	1	1	1	1	1	1	1	1	1
0.08	1	1	1	1	1	1	1	1	1	1	1
0.09	1	1	1	1	1	1	1	1	1	1	1
0.1	1	1	1	1	1	1	1	1	1	1	1
0.11	1	1	1	1	1	1	1	1	1	1	1
0.12	1	1	1	1	1	1	1	1	1	1	1

Table F.8. REBS north: decision table for the upper stock reference point $0.8B_{MSY}$ for 1-10-year projections for a range of **constant catch** *strategies (in tonnes), such that values are P$(B_t > 0.8B_{MSY})$. For reference, the average catch over the last 5 years (2015-2019) was 548 t.*

CC	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	1	1	1	1	1	1	1	1	1	1	1
100	1	1	1	1	1	1	1	1	1	1	1
200	1	1	1	1	1	1	1	1	1	1	1
300	1	1	1	1	1	1	1	1	1	1	1
400	1	1	1	1	1	1	1	1	1	1	>0.99
500	1	1	1	1	1	1	1	>0.99	>0.99	>0.99	>0.99
600	1	1	1	1	1	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
700	1	1	1	1	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	0.99
800	1	1	1	>0.99	>0.99	>0.99	>0.99	>0.99	0.99	0.99	0.98
900	1	1	1	>0.99	>0.99	>0.99	>0.99	0.99	0.99	0.97	0.96
1000	1	1	1	>0.99	>0.99	>0.99	0.99	0.98	0.97	0.95	0.93
1100	1	1	>0.99	>0.99	>0.99	>0.99	0.99	0.97	0.95	0.92	0.88
1200	1	1	>0.99	>0.99	>0.99	0.99	0.98	0.95	0.92	0.88	0.82

Table F.9. REBS north: decision table for the upper stock reference point $0.8B_{MSY}$ for 1-10-year projections for a range of **harvest rate** *strategies, such that values are P$(B_t > 0.8B_{MSY})$. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.023.*

HR	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	1	1	1	1	1	1	1	1	1	1	1
0.01	1	1	1	1	1	1	1	1	1	1	1
0.02	1	1	1	1	1	1	1	1	1	1	1
0.03	1	1	1	1	1	1	1	1	1	1	1
0.04	1	1	1	1	1	1	1	1	1	1	1
0.05	1	1	1	1	1	1	1	1	1	1	1
0.06	1	1	1	1	1	1	1	1	1	1	1
0.07	1	1	1	1	1	1	1	1	1	1	1
0.08	1	1	1	1	1	1	1	1	1	1	1
0.09	1	1	1	1	1	1	1	1	1	1	1
0.1	1	1	1	1	1	1	1	1	1	1	1
0.11	1	1	1	1	1	1	1	1	1	1	1
0.12	1	1	1	1	1	1	1	1	1	1	1

Table F.10. REBS north: decision table for the reference point B_{MSY} for 1-10-year projections-year projections for a range of **constant catch** strategies (in tonnes), such that values are P($B_t > B_{MSY}$). For reference, the average catch over the last 5 years (2015-2019) was 548 t.

CC	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	>0.99	1	1	1	1	1	1	1	1	1	1
100	>0.99	1	1	1	1	1	1	1	1	1	1
200	>0.99	1	1	1	1	1	1	1	1	1	1
300	>0.99	1	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
400	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
500	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
600	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	0.99	0.99	0.98
700	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	0.99	0.99	0.98	0.97	0.96
800	>0.99	>0.99	>0.99	>0.99	>0.99	0.99	0.99	0.98	0.96	0.94	0.92
900	>0.99	>0.99	>0.99	>0.99	>0.99	0.99	0.97	0.96	0.93	0.91	0.88
1000	>0.99	>0.99	>0.99	>0.99	0.99	0.98	0.96	0.93	0.90	0.86	0.81
1100	>0.99	>0.99	>0.99	>0.99	0.99	0.97	0.94	0.90	0.85	0.80	0.75
1200	>0.99	>0.99	>0.99	0.99	0.98	0.95	0.91	0.86	0.80	0.75	0.69

Table F.11. REBS north: decision table for the reference point B_{MSY} for 1-10-year projections-year projections for a range of **harvest rate** strategies, such that values are P($B_t > B_{MSY}$). For reference, the average harvest rate over the last 5 years (2015-2019) was 0.023.

HR	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	>0.99	1	1	1	1	1	1	1	1	1	1
0.01	>0.99	1	1	1	1	1	1	1	1	1	1
0.02	>0.99	1	1	1	1	1	1	1	1	1	1
0.03	>0.99	1	1	1	1	1	1	1	1	1	1
0.04	>0.99	1	1	1	1	1	1	1	1	1	1
0.05	>0.99	1	1	1	1	1	1	1	1	1	1
0.06	>0.99	1	1	1	1	1	1	1	1	1	1
0.07	>0.99	1	1	1	1	1	1	1	1	1	1
0.08	>0.99	1	1	1	>0.99	1	1	1	>0.99	>0.99	>0.99
0.09	>0.99	1	1	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
0.1	>0.99	1	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
0.11	>0.99	1	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
0.12	>0.99	1	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	0.99

Table F.12. REBS north: decision table comparing the projected exploitation rate to that at MSY for a range of **constant catch** *strategies, such that values are P*$(u_t < u_{\mathrm{MSY}})$*, i.e. the probability of the exploitation rate in the middle of year* t *being less than that at MSY. For reference, the average catch over the last 5 years (2015-2019) was 548 t.*

CC	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	1	1	1	1	1	1	1	1	1	1	1
100	1	1	1	1	1	1	1	1	1	1	1
200	1	1	1	1	1	1	1	1	1	1	1
300	1	1	1	1	1	1	1	1	1	1	1
400	1	1	1	1	1	1	1	1	1	1	1
500	1	1	>0.99	1	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
600	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	0.99	0.99	0.99
700	>0.99	>0.99	>0.99	>0.99	0.99	0.99	0.99	0.98	0.97	0.96	0.95
800	>0.99	0.99	0.99	0.99	0.98	0.97	0.95	0.94	0.91	0.89	0.87
900	0.99	0.98	0.97	0.96	0.95	0.93	0.90	0.87	0.84	0.81	0.78
1000	0.97	0.96	0.95	0.93	0.90	0.87	0.83	0.79	0.75	0.72	0.69
1100	0.95	0.93	0.91	0.88	0.85	0.80	0.76	0.72	0.68	0.65	0.62
1200	0.93	0.89	0.86	0.82	0.78	0.74	0.69	0.65	0.62	0.58	0.54

Table F.13. REBS north: decision table comparing the projected exploitation rate to that at MSY for a range of **harvest rate** *strategies, such that values are P*$(u_t < u_{\mathrm{MSY}})$*, i.e. the probability of the exploitation rate in the middle of year* t *being less than that at MSY. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.023.*

HR	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	1	1	1	1	1	1	1	1	1	1	1
0.01	1	1	1	1	1	1	1	1	1	1	1
0.02	1	1	1	1	1	1	1	1	1	1	1
0.03	1	1	1	1	1	1	1	1	1	1	1
0.04	1	1	1	1	1	1	1	1	1	1	1
0.05	1	1	1	1	1	1	1	1	1	1	1
0.06	1	1	1	1	1	1	1	1	1	1	1
0.07	1	1	1	1	1	1	1	1	1	1	1
0.08	1	1	1	1	1	1	1	1	1	1	1
0.09	1	1	1	1	1	1	1	1	1	1	1
0.1	1	1	1	1	1	1	1	1	1	1	1
0.11	>0.99	1	1	>0.99	1	>0.99	>0.99	>0.99	>0.99	1	>0.99
0.12	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99

Table F.14. REBS north: decision table comparing the projected biomass to current biomass for a range of **constant catch** *strategies, given by probabilities P$(B_t > B_{2021})$. For reference, the average catch over the last 5 years (2015-2019) was 548 t.*

CC	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	0	0.91	0.91	0.91	0.91	0.90	0.90	0.90	0.89	0.88	0.87
100	0	0.82	0.83	0.82	0.82	0.81	0.80	0.79	0.77	0.75	0.74
200	0	0.63	0.64	0.63	0.62	0.60	0.58	0.57	0.55	0.53	0.52
300	0	0.38	0.37	0.37	0.35	0.34	0.33	0.31	0.30	0.28	0.27
400	0	0.21	0.20	0.18	0.18	0.16	0.15	0.14	0.13	0.13	0.13
500	0	0.13	0.11	0.09	0.09	0.08	0.08	0.07	0.07	0.07	0.06
600	0	0.08	0.06	0.05	0.05	0.04	0.04	0.04	0.04	0.03	0.03
700	0	0.05	0.04	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.02
800	0	0.03	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01
900	0	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	<0.01	<0.01
1000	0	0.02	0.01	0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
1100	0	0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
1200	0	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

Table F.15. REBS north: decision table (REBS north) comparing the projected biomass to current biomass for a range of **harvest rate** *strategies, given by probabilities P$(B_t > B_{2021})$. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.023.*

HR	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	0	0.91	0.91	0.91	0.91	0.90	0.90	0.90	0.89	0.88	0.87
0.01	0	0.77	0.78	0.77	0.76	0.75	0.74	0.72	0.71	0.69	0.68
0.02	0	0.61	0.61	0.59	0.58	0.56	0.54	0.52	0.51	0.49	0.48
0.03	0	0.45	0.44	0.42	0.40	0.38	0.37	0.35	0.34	0.33	0.32
0.04	0	0.32	0.31	0.29	0.27	0.25	0.24	0.23	0.22	0.21	0.20
0.05	0	0.22	0.21	0.19	0.17	0.16	0.15	0.14	0.13	0.12	0.12
0.06	0	0.15	0.13	0.12	0.11	0.10	0.09	0.08	0.08	0.08	0.07
0.07	0	0.10	0.09	0.08	0.07	0.06	0.06	0.05	0.05	0.04	0.04
0.08	0	0.07	0.06	0.05	0.05	0.04	0.04	0.03	0.03	0.03	0.02
0.09	0	0.05	0.04	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.02
0.1	0	0.03	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01
0.11	0	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
0.12	0	0.02	0.01	0.01	0.01	0.01	0.01	0.01	<0.01	<0.01	0.01

Table F.16. REBS north: decision table comparing the projected exploitation rate to that in 2020 for a range of **constant catch** *strategies, such that values are P$(u_t < u_{2020})$. For reference, the average catch over the last 5 years (2015-2019) was 548 t.*

CC	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	1	1	1	1	1	1	1	1	1	1	1
100	1	1	1	1	1	1	1	1	1	1	1
200	0.95	>0.99	1	1	1	>0.99	>0.99	0.99	0.99	0.98	0.96
300	0	0	<0.01	0.01	0.05	0.07	0.08	0.08	0.08	0.08	0.08
400	0	0	0	0	0	<0.01	<0.01	0	0	0	0
500	0	0	0	0	0	0	0	0	0	0	0
600	0	0	0	0	0	0	0	0	0	0	0
700	0	0	0	0	0	0	0	0	0	0	0
800	0	0	0	0	0	0	0	0	0	0	0
900	0	0	0	0	0	0	0	0	0	0	0
1000	0	0	0	0	0	0	0	0	0	0	0
1100	0	0	0	0	0	0	0	0	0	0	0
1200	0	0	0	0	0	0	0	0	0	0	0

Table F.17. REBS north: decision table comparing the projected exploitation rate to that in 2020 for a range of **harvest rate** *strategies, such that values are P$(u_t < u_{2020})$. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.023.*

HR	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	1	1	1	1	1	1	1	1	1	1	1
0.01	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91
0.02	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53
0.03	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
0.04	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
0.06	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
0.07	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
0.08	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
0.09	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
0.1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
0.11	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
0.12	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

Table F.18. REBS north: decision table for the alternative limit reference point $0.2B_0$ for 1-10 year projections for a range of **constant catch** *strategies, such that values are P$(B_t > 0.2B_0)$. For reference, the average catch over the last 5 years (2015-2019) was 548 t.*

CC	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	1	1	1	1	1	1	1	1	1	1	1
100	1	1	1	1	1	1	1	1	1	1	1
200	1	1	1	1	1	1	1	1	1	1	1
300	1	1	1	1	1	1	1	1	1	1	1
400	1	1	1	1	1	1	1	1	1	1	1
500	1	1	1	1	1	1	1	1	>0.99	>0.99	>0.99
600	1	1	1	1	1	1	>0.99	>0.99	>0.99	>0.99	>0.99
700	1	1	1	1	1	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
800	1	1	1	1	>0.99	>0.99	>0.99	>0.99	>0.99	0.99	0.99
900	1	1	1	1	>0.99	>0.99	>0.99	>0.99	0.99	0.98	0.97
1000	1	1	1	>0.99	>0.99	>0.99	>0.99	0.99	0.98	0.97	0.95
1100	1	1	1	>0.99	>0.99	>0.99	0.99	0.98	0.97	0.94	0.91
1200	1	1	1	>0.99	>0.99	>0.99	0.99	0.97	0.94	0.90	0.86

Table F.19. REBS north: decision table for the alternative limit reference point $0.2B_0$ for 1-10 year projections for a range of **harvest rate** *strategies, such that values are P$(B_t > 0.2B_0)$. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.023.*

HR	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	1	1	1	1	1	1	1	1	1	1	1
0.01	1	1	1	1	1	1	1	1	1	1	1
0.02	1	1	1	1	1	1	1	1	1	1	1
0.03	1	1	1	1	1	1	1	1	1	1	1
0.04	1	1	1	1	1	1	1	1	1	1	1
0.05	1	1	1	1	1	1	1	1	1	1	1
0.06	1	1	1	1	1	1	1	1	1	1	1
0.07	1	1	1	1	1	1	1	1	1	1	1
0.08	1	1	1	1	1	1	1	1	1	1	1
0.09	1	1	1	1	1	1	1	1	1	1	1
0.1	1	1	1	1	1	1	1	1	1	1	1
0.11	1	1	1	1	1	1	1	1	1	1	1
0.12	1	1	1	1	1	1	1	1	1	1	1

Table F.20. REBS north: decision table for the alternative upper stock reference point $0.4B_0$ for 1-10 year projections for a range of **constant catch** strategies, such that values are P$(B_t > 0.4B_0)$. For reference, the average catch over the last 5 years (2015-2019) was 548 t.

CC	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	0.96	0.97	0.97	0.98	0.99	0.99	0.99	>0.99	>0.99	>0.99	>0.99
100	0.96	0.96	0.97	0.98	0.98	0.98	0.99	0.99	0.99	0.99	0.99
200	0.96	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.98	0.98
300	0.96	0.96	0.96	0.96	0.96	0.95	0.95	0.95	0.95	0.94	0.94
400	0.96	0.95	0.95	0.95	0.94	0.93	0.93	0.92	0.91	0.90	0.89
500	0.96	0.95	0.94	0.93	0.92	0.91	0.89	0.88	0.86	0.84	0.82
600	0.96	0.94	0.93	0.92	0.90	0.88	0.85	0.83	0.81	0.78	0.76
700	0.96	0.94	0.92	0.90	0.87	0.85	0.81	0.78	0.75	0.72	0.69
800	0.96	0.94	0.91	0.88	0.85	0.81	0.77	0.73	0.70	0.66	0.62
900	0.96	0.93	0.90	0.86	0.82	0.77	0.73	0.69	0.65	0.60	0.56
1000	0.96	0.93	0.89	0.84	0.79	0.74	0.69	0.65	0.60	0.54	0.49
1100	0.96	0.92	0.87	0.82	0.76	0.71	0.66	0.60	0.55	0.49	0.44
1200	0.96	0.92	0.86	0.80	0.74	0.68	0.62	0.56	0.49	0.43	0.39

Table F.21. REBS north: decision table for the alternative upper stock reference point $0.4B_0$ for 1-10 year projections for a range of **harvest rate** strategies, such that values are P$(B_t > 0.4B_0)$. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.023.

HR	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	0.96	0.97	0.97	0.98	0.99	0.99	0.99	>0.99	>0.99	>0.99	>0.99
0.01	0.96	0.96	0.97	0.98	0.98	0.99	0.99	0.99	>0.99	>0.99	>0.99
0.02	0.96	0.96	0.97	0.98	0.98	0.98	0.99	0.99	0.99	0.99	0.99
0.03	0.96	0.96	0.97	0.97	0.97	0.98	0.98	0.98	0.98	0.98	0.98
0.04	0.96	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97
0.05	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.95	0.95	0.94
0.06	0.96	0.96	0.96	0.96	0.95	0.95	0.94	0.94	0.93	0.92	0.90
0.07	0.96	0.95	0.95	0.95	0.94	0.93	0.92	0.91	0.89	0.87	0.85
0.08	0.96	0.95	0.95	0.94	0.93	0.92	0.90	0.88	0.84	0.81	0.77
0.09	0.96	0.95	0.94	0.93	0.92	0.90	0.87	0.83	0.79	0.74	0.68
0.1	0.96	0.95	0.94	0.92	0.90	0.87	0.83	0.78	0.73	0.66	0.59
0.11	0.96	0.95	0.93	0.91	0.88	0.84	0.79	0.73	0.66	0.58	0.51
0.12	0.96	0.94	0.93	0.90	0.86	0.81	0.74	0.67	0.59	0.50	0.42

F.2.4.2. GMU – Long-term guidance

Table F.22. REBS north: decision table for the limit reference point $0.4B_{MSY}$ for selected projection years over 1.5 generations (75 years) and for a range of **constant catch** *strategies, such that values are $P(B_t > 0.4B_{MSY})$. For reference, the average catch over the last 5 years (2015-2019) was 548 t.*

CC	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	1	1	1	1	1	1	1	1	1	1	1
100	1	1	1	1	1	1	1	1	1	1	1
200	1	1	1	1	1	1	1	1	1	1	1
300	1	1	1	1	1	1	1	1	1	1	1
400	1	1	1	1	1	1	>0.99	>0.99	>0.99	>0.99	>0.99
500	1	1	1	1	1	>0.99	>0.99	>0.99	>0.99	0.99	0.99
600	1	1	1	1	>0.99	>0.99	>0.99	0.99	0.97	0.96	0.94
700	1	1	1	>0.99	>0.99	>0.99	0.98	0.96	0.93	0.90	0.86
800	1	1	1	>0.99	>0.99	0.99	0.97	0.92	0.87	0.83	0.78
900	1	1	1	>0.99	0.99	0.98	0.94	0.87	0.82	0.76	0.71
1000	1	1	1	0.99	0.98	0.96	0.92	0.83	0.77	0.72	0.66
1100	1	1	>0.99	0.99	0.97	0.95	0.89	0.79	0.74	0.69	0.63
1200	1	1	>0.99	0.98	0.96	0.94	0.86	0.77	0.72	0.66	0.61

Table F.23. REBS north: decision table for the limit reference point $0.4B_{MSY}$ for selected projection years over 1.5 generations (75 years) and for a range of **harvest rate** *strategies, such that values are $P(B_t > 0.4B_{MSY})$. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.023.*

HR	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	1	1	1	1	1	1	1	1	1	1	1
0.01	1	1	1	1	1	1	1	1	1	1	1
0.02	1	1	1	1	1	1	1	1	1	1	1
0.03	1	1	1	1	1	1	1	1	1	1	1
0.04	1	1	1	1	1	1	1	1	1	1	1
0.05	1	1	1	1	1	1	1	1	1	1	1
0.06	1	1	1	1	1	1	1	1	1	1	1
0.07	1	1	1	1	1	1	1	1	1	1	1
0.08	1	1	1	1	1	1	1	1	1	1	1
0.09	1	1	1	1	1	1	1	1	1	1	1
0.1	1	1	1	1	1	1	1	1	1	1	1
0.11	1	1	1	1	1	1	1	1	1	1	1
0.12	1	1	1	1	1	1	1	1	1	1	1

Table F.24. REBS north: decision table for the upper stock reference $0.8B_{MSY}$ for selected projection years over 1.5 generations (75 years) and for a range of **constant catch** *strategies, such that values are* $P(B_t > 0.8B_{MSY})$. *For reference, the average catch over the last 5 years (2015-2019) was 548 t.*

CC	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	1	1	1	1	1	1	1	1	1	1	1
100	1	1	1	1	1	1	1	1	1	1	1
200	1	1	1	1	1	1	1	1	1	1	1
300	1	1	1	1	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
400	1	1	1	>0.99	>0.99	>0.99	>0.99	>0.99	0.99	0.99	0.99
500	1	1	>0.99	>0.99	0.99	0.99	0.97	0.96	0.95	0.93	0.92
600	1	1	>0.99	0.99	0.97	0.94	0.90	0.86	0.82	0.80	0.77
700	1	>0.99	>0.99	0.97	0.91	0.86	0.78	0.72	0.67	0.63	0.60
800	1	>0.99	0.99	0.93	0.83	0.75	0.66	0.58	0.53	0.49	0.47
900	1	>0.99	0.97	0.87	0.74	0.65	0.55	0.47	0.43	0.39	0.36
1000	1	>0.99	0.95	0.79	0.64	0.56	0.47	0.39	0.35	0.31	0.29
1100	1	>0.99	0.92	0.71	0.55	0.48	0.40	0.33	0.29	0.25	0.22
1200	1	>0.99	0.88	0.63	0.48	0.43	0.34	0.27	0.23	0.20	0.18

Table F.25. REBS north: decision table for the upper stock reference $0.8B_{MSY}$ for selected projection years over 1.5 generations (75 years) and for a range of **harvest rate** *strategies, such that values are* $P(B_t > 0.8B_{MSY})$. *For reference, the average harvest rate over the last 5 years (2015-2019) was 0.023.*

HR	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	1	1	1	1	1	1	1	1	1	1	1
0.01	1	1	1	1	1	1	1	1	1	1	1
0.02	1	1	1	1	1	1	1	1	1	1	1
0.03	1	1	1	1	1	1	1	1	1	1	1
0.04	1	1	1	1	1	1	1	1	1	1	1
0.05	1	1	1	1	1	1	1	1	1	1	1
0.06	1	1	1	1	1	1	1	1	1	1	1
0.07	1	1	1	1	1	1	1	1	1	1	1
0.08	1	1	1	1	1	1	1	1	>0.99	>0.99	1
0.09	1	1	1	1	1	>0.99	1	>0.99	>0.99	>0.99	>0.99
0.1	1	1	1	1	1	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
0.11	1	1	1	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
0.12	1	1	1	>0.99	>0.99	>0.99	>0.99	0.99	0.99	0.99	0.99

Table F.26. REBS north: decision table for biomass at maximum sustainable yield B_{MSY} for selected projection years over 1.5 generations (75 years) and for a range of **constant catch** *strategies, such that values are P$(B_t > B_{MSY})$. For reference, the average catch over the last 5 years (2015-2019) was 548 t.*

CC	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	>0.99	1	1	1	1	1	1	1	1	1	1
100	>0.99	1	1	1	1	1	1	1	1	1	1
200	>0.99	1	1	1	>0.99	>0.99	>0.99	1	1	1	1
300	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
400	>0.99	>0.99	>0.99	>0.99	0.99	0.99	0.98	0.98	0.98	0.98	0.98
500	>0.99	>0.99	>0.99	0.99	0.97	0.94	0.92	0.90	0.89	0.88	0.87
600	>0.99	>0.99	0.99	0.95	0.90	0.85	0.80	0.76	0.74	0.71	0.69
700	>0.99	>0.99	0.97	0.90	0.81	0.74	0.66	0.61	0.58	0.55	0.53
800	>0.99	>0.99	0.94	0.82	0.70	0.62	0.54	0.49	0.45	0.43	0.40
900	>0.99	>0.99	0.91	0.74	0.60	0.52	0.45	0.39	0.36	0.33	0.31
1000	>0.99	0.99	0.86	0.66	0.51	0.44	0.37	0.32	0.28	0.26	0.23
1100	>0.99	0.99	0.80	0.57	0.44	0.38	0.31	0.26	0.22	0.20	0.17
1200	>0.99	0.98	0.75	0.50	0.38	0.33	0.26	0.20	0.17	0.14	0.12

Table F.27. REBS north: decision table for biomass at maximum sustainable yield B_{MSY} for selected projection years over 1.5 generations (75 years) and for a range of **harvest rate** *strategies, such that values are P$(B_t > B_{MSY})$. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.023.*

HR	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	>0.99	1	1	1	1	1	1	1	1	1	1
0.01	>0.99	1	1	1	1	1	1	1	1	1	1
0.02	>0.99	1	1	1	1	1	1	1	1	1	1
0.03	>0.99	1	1	1	1	1	1	1	1	1	1
0.04	>0.99	1	1	1	1	1	1	1	1	1	1
0.05	>0.99	1	1	1	1	1	1	1	1	>0.99	1
0.06	>0.99	1	1	1	1	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
0.07	>0.99	1	1	1	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
0.08	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	0.99	0.99	>0.99	>0.99	0.99
0.09	>0.99	>0.99	>0.99	>0.99	0.99	0.99	0.98	0.99	0.99	0.99	0.99
0.1	>0.99	>0.99	>0.99	0.99	0.98	0.97	0.97	0.97	0.98	0.98	0.97
0.11	>0.99	>0.99	>0.99	0.99	0.96	0.95	0.95	0.95	0.96	0.96	0.96
0.12	>0.99	>0.99	>0.99	0.97	0.93	0.91	0.93	0.93	0.93	0.94	0.93

Table F.28. REBS north: decision table for harvest rate at maximum sustainable yield u_{MSY} for selected projection years over 1.5 generations (75 years) and for a range of **constant catch** *strategies, such that values are P$(u_t < u_{MSY})$. For reference, the average catch over the last 5 years (2015-2019) was 548 t.*

CC	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	1	1	1	1	1	1	1	1	1	1	1
100	1	1	1	1	1	1	1	1	1	1	1
200	1	1	1	1	1	1	1	1	1	1	1
300	1	1	1	1	1	1	1	>0.99	>0.99	>0.99	>0.99
400	1	1	1	>0.99	>0.99	>0.99	>0.99	0.99	0.99	0.99	0.99
500	1	>0.99	>0.99	>0.99	0.98	0.96	0.92	0.91	0.90	0.89	0.88
600	>0.99	>0.99	0.99	0.96	0.90	0.84	0.76	0.74	0.72	0.70	0.69
700	>0.99	0.99	0.96	0.88	0.77	0.68	0.59	0.57	0.54	0.52	0.51
800	>0.99	0.98	0.89	0.76	0.63	0.52	0.46	0.44	0.41	0.40	0.38
900	0.99	0.95	0.81	0.66	0.50	0.41	0.37	0.35	0.33	0.31	0.30
1000	0.97	0.90	0.72	0.56	0.41	0.35	0.31	0.28	0.25	0.24	0.22
1100	0.95	0.85	0.65	0.46	0.35	0.29	0.25	0.22	0.19	0.17	0.16
1200	0.93	0.78	0.58	0.39	0.29	0.25	0.20	0.16	0.13	0.12	0.10

Table F.29. REBS north: decision table for harvest rate at maximum sustainable yield u_{MSY} for selected projection years over 1.5 generations (75 years) and for a range of **harvest rate** *strategies, such that values are P$(u_t < u_{MSY})$. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.023.*

HR	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	1	1	1	1	1	1	1	1	1	1	1
0.01	1	1	1	1	1	1	1	1	1	1	1
0.02	1	1	1	1	1	1	1	1	1	1	1
0.03	1	1	1	1	1	1	1	1	1	1	1
0.04	1	1	1	1	1	1	1	1	1	1	1
0.05	1	1	1	1	1	1	1	1	1	1	1
0.06	1	1	1	1	1	1	1	1	1	1	1
0.07	1	1	1	1	1	1	1	1	1	1	1
0.08	1	1	1	1	1	1	1	1	1	1	1
0.09	1	1	1	1	1	1	1	1	1	1	1
0.1	1	1	1	1	1	1	1	1	1	1	1
0.11	>0.99	1	1	1	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
0.12	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99

Table F.30. *REBS north: decision table for comparing projected biomass to current biomass B_{2021} for selected projection years over 1.5 generations (75 years) and for a range of* **constant catch** *strategies, such that values are P($B_t > B_{2021}$). For reference, the average catch over the last 5 years (2015-2019) was 548 t.*

CC	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	0	0.91	0.88	0.87	0.88	0.89	0.92	0.94	0.96	0.97	0.97
100	0	0.82	0.75	0.75	0.76	0.78	0.83	0.88	0.91	0.93	0.94
200	0	0.62	0.53	0.53	0.55	0.58	0.68	0.75	0.81	0.85	0.86
300	0	0.35	0.28	0.29	0.32	0.36	0.45	0.55	0.63	0.67	0.69
400	0	0.18	0.13	0.14	0.16	0.20	0.26	0.33	0.39	0.42	0.45
500	0	0.09	0.07	0.07	0.09	0.11	0.15	0.18	0.21	0.23	0.24
600	0	0.05	0.03	0.04	0.05	0.06	0.08	0.09	0.11	0.11	0.11
700	0	0.03	0.02	0.02	0.03	0.03	0.05	0.05	0.05	0.06	0.06
800	0	0.02	0.01	0.01	0.02	0.02	0.03	0.03	0.03	0.03	0.03
900	0	0.01	<0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01
1000	0	0.01	<0.01	<0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
1100	0	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	0.01	<0.01
1200	0	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

Table F.31. *REBS north: decision table for comparing projected biomass to current biomass B_{2021} for selected projection years over 1.5 generations (75 years) and for a range of* **harvest rate** *strategies, such that values are P($B_t > B_{2021}$). For reference, the average harvest rate over the last 5 years (2015-2019) was 0.023.*

HR	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	0	0.91	0.88	0.87	0.88	0.89	0.92	0.94	0.96	0.97	0.97
0.01	0	0.76	0.69	0.68	0.69	0.72	0.78	0.84	0.87	0.89	0.90
0.02	0	0.58	0.49	0.49	0.50	0.53	0.62	0.69	0.73	0.76	0.77
0.03	0	0.40	0.33	0.32	0.34	0.38	0.46	0.54	0.59	0.62	0.63
0.04	0	0.27	0.21	0.20	0.23	0.26	0.34	0.41	0.46	0.49	0.49
0.05	0	0.17	0.12	0.13	0.15	0.18	0.25	0.31	0.35	0.37	0.38
0.06	0	0.11	0.08	0.08	0.10	0.12	0.19	0.23	0.27	0.28	0.29
0.07	0	0.07	0.04	0.05	0.06	0.09	0.14	0.17	0.20	0.22	0.22
0.08	0	0.05	0.03	0.03	0.04	0.06	0.10	0.13	0.15	0.17	0.17
0.09	0	0.03	0.02	0.02	0.03	0.05	0.08	0.10	0.12	0.12	0.13
0.1	0	0.02	0.01	0.01	0.02	0.04	0.06	0.07	0.09	0.10	0.10
0.11	0	0.01	0.01	0.01	0.02	0.03	0.05	0.06	0.07	0.08	0.08
0.12	0	0.01	<0.01	0.01	0.01	0.02	0.04	0.05	0.05	0.06	0.07

Table F.32. REBS north: decision table for comparing projected harvest rate to current harvest rate u_{2020} for selected projection years over 1.5 generations (75 years) and for a range of **constant catch** strategies, such that values are P($u_t < u_{2020}$). For reference, the average catch over the last 5 years (2015-2019) was 548 t.

CC	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	1	1	1	1	1	1	1	1	1	1	1
100	1	1	1	1	1	1	1	1	1	1	1
200	0.95	1	0.98	0.91	0.85	0.82	0.83	0.87	0.90	0.92	0.93
300	0	0.05	0.08	0.07	0.05	0.06	0.09	0.15	0.22	0.28	0.33
400	0	0	0	<0.01	<0.01	<0.01	<0.01	0.01	0.01	0.02	0.02
500	0	0	0	0	0	0	<0.01	<0.01	<0.01	<0.01	<0.01
600	0	0	0	0	0	0	0	0	0	<0.01	<0.01
700	0	0	0	0	0	0	0	0	0	0	<0.01
800	0	0	0	0	0	0	0	0	0	0	0
900	0	0	0	0	0	0	0	0	0	0	0
1000	0	0	0	0	0	0	0	0	0	0	0
1100	0	0	0	0	0	0	0	0	0	0	0
1200	0	0	0	0	0	0	0	0	0	0	0

Table F.33. REBS north: decision table for comparing projected harvest rate to current harvest rate u_{2020} for selected projection years over 1.5 generations (75 years) and for a range of **harvest rate** strategies, such that values are P($u_t < u_{2020}$). For reference, the average harvest rate over the last 5 years (2015-2019) was 0.023.

HR	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	1	1	1	1	1	1	1	1	1	1	1
0.01	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91
0.02	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53
0.03	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
0.04	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
0.06	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
0.07	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
0.08	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
0.09	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
0.1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
0.11	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
0.12	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

Table F.34. REBS north: decision table for alternative limit reference point $0.2B_0$ for selected projection years over 1.5 generations (75 years) and for a range of **constant catch** *strategies, such that values are P($B_t > 0.2B_0$). For reference, the average catch over the last 5 years (2015-2019) was 548 t.*

CC	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	1	1	1	1	1	1	1	1	1	1	1
100	1	1	1	1	1	1	1	1	1	1	1
200	1	1	1	1	1	1	1	1	1	1	1
300	1	1	1	1	1	1	>0.99	>0.99	>0.99	>0.99	>0.99
400	1	1	1	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	0.99	0.99
500	1	1	>0.99	>0.99	>0.99	0.99	0.98	0.97	0.96	0.95	0.93
600	1	1	>0.99	>0.99	0.98	0.96	0.92	0.88	0.85	0.82	0.79
700	1	1	>0.99	0.98	0.94	0.89	0.81	0.75	0.70	0.66	0.62
800	1	>0.99	0.99	0.95	0.87	0.79	0.70	0.61	0.56	0.52	0.49
900	1	>0.99	0.98	0.90	0.77	0.69	0.59	0.50	0.46	0.41	0.38
1000	1	>0.99	0.97	0.83	0.68	0.60	0.50	0.42	0.38	0.34	0.31
1100	1	>0.99	0.94	0.75	0.59	0.53	0.44	0.35	0.32	0.27	0.25
1200	1	>0.99	0.90	0.67	0.52	0.47	0.38	0.30	0.26	0.22	0.20

Table F.35. REBS north: decision table for alternative limit reference point $0.2B_0$ for selected projection years over 1.5 generations (75 years) and for a range of **harvest rate** *strategies, such that values are P($B_t > 0.2B_0$). For reference, the average harvest rate over the last 5 years (2015-2019) was 0.023.*

HR	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	1	1	1	1	1	1	1	1	1	1	1
0.01	1	1	1	1	1	1	1	1	1	1	1
0.02	1	1	1	1	1	1	1	1	1	1	1
0.03	1	1	1	1	1	1	1	1	1	1	1
0.04	1	1	1	1	1	1	1	1	1	1	1
0.05	1	1	1	1	1	1	1	1	1	1	1
0.06	1	1	1	1	1	1	1	1	1	1	1
0.07	1	1	1	1	1	1	1	1	1	1	1
0.08	1	1	1	1	1	1	1	1	1	1	1
0.09	1	1	1	1	1	1	1	>0.99	1	>0.99	1
0.1	1	1	1	1	1	>0.99	1	>0.99	>0.99	>0.99	>0.99
0.11	1	1	1	1	1	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
0.12	1	1	1	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99

Table F.36. REBS north: decision table for alternative upper stock reference $0.4B_0$ for selected projection years over 1.5 generations (75 years) and for a range of **constant catch** *strategies, such that values are P$(B_t > 0.4B_0)$. For reference, the average catch over the last 5 years (2015-2019) was 548 t.*

CC	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	0.96	0.99	>0.99	>0.99	>0.99	1	1	1	1	1	1
100	0.96	0.98	0.99	>0.99	>0.99	>0.99	>0.99	>0.99	1	1	1
200	0.96	0.97	0.98	0.98	0.98	0.99	0.99	0.99	>0.99	>0.99	>0.99
300	0.96	0.96	0.94	0.93	0.92	0.92	0.93	0.95	0.96	0.97	0.97
400	0.96	0.94	0.90	0.86	0.82	0.80	0.80	0.82	0.84	0.85	0.85
500	0.96	0.92	0.84	0.77	0.70	0.66	0.64	0.65	0.67	0.67	0.67
600	0.96	0.90	0.78	0.67	0.58	0.53	0.51	0.50	0.51	0.50	0.49
700	0.96	0.87	0.72	0.58	0.48	0.44	0.41	0.39	0.38	0.37	0.36
800	0.96	0.85	0.66	0.49	0.40	0.36	0.33	0.30	0.29	0.27	0.26
900	0.96	0.82	0.60	0.42	0.34	0.30	0.26	0.23	0.21	0.20	0.19
1000	0.96	0.79	0.54	0.37	0.29	0.24	0.20	0.17	0.16	0.14	0.13
1100	0.96	0.76	0.49	0.32	0.25	0.20	0.16	0.13	0.11	0.10	0.08
1200	0.96	0.74	0.43	0.28	0.20	0.16	0.11	0.09	0.08	0.06	0.05

Table F.37. REBS north: decision table for alternative upper stock reference $0.4B_0$ for selected projection years over 1.5 generations (75 years) and for a range of **harvest rate** *strategies, such that values are P$(B_t > 0.4B_0)$. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.023.*

HR	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	0.96	0.99	>0.99	>0.99	>0.99	1	1	1	1	1	1
0.01	0.96	0.98	>0.99	>0.99	>0.99	>0.99	1	1	1	1	1
0.02	0.96	0.98	0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	1
0.03	0.96	0.97	0.98	0.99	0.99	0.99	0.99	>0.99	>0.99	>0.99	>0.99
0.04	0.96	0.97	0.97	0.97	0.96	0.95	0.96	0.97	0.98	0.98	0.98
0.05	0.96	0.96	0.95	0.92	0.89	0.87	0.89	0.92	0.94	0.95	0.95
0.06	0.96	0.95	0.92	0.85	0.77	0.75	0.81	0.85	0.88	0.89	0.89
0.07	0.96	0.94	0.87	0.73	0.64	0.63	0.71	0.77	0.79	0.81	0.81
0.08	0.96	0.93	0.81	0.61	0.52	0.52	0.61	0.68	0.70	0.71	0.71
0.09	0.96	0.92	0.74	0.50	0.42	0.43	0.52	0.59	0.61	0.62	0.62
0.1	0.96	0.90	0.66	0.41	0.35	0.36	0.45	0.51	0.52	0.54	0.53
0.11	0.96	0.88	0.58	0.33	0.29	0.31	0.38	0.43	0.45	0.46	0.45
0.12	0.96	0.86	0.50	0.28	0.24	0.26	0.33	0.36	0.37	0.39	0.39

F.2.4.3. COSEWIC – Reference criteria

Table F.38. REBS north: decision table for probabilities of satisfying the A2 criterion of $\leq 50\%$ decline over 1.5 generations (75 years) for 10-year projections and for a range of **constant catch** *strategies. For reference, the average catch over the last 5 years (2015-2019) was 548 t.*

CC	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	0.75	0.78	0.80	0.83	0.85	0.88	0.90	0.91	0.93	0.94	0.95
100	0.75	0.77	0.79	0.81	0.82	0.84	0.86	0.87	0.89	0.90	0.91
200	0.75	0.76	0.78	0.79	0.80	0.80	0.82	0.83	0.83	0.84	0.85
300	0.75	0.76	0.76	0.77	0.77	0.77	0.77	0.78	0.78	0.78	0.78
400	0.75	0.75	0.75	0.74	0.74	0.74	0.73	0.73	0.72	0.72	0.71
500	0.75	0.74	0.73	0.72	0.71	0.70	0.69	0.68	0.67	0.66	0.64
600	0.75	0.73	0.72	0.70	0.69	0.67	0.66	0.64	0.62	0.60	0.57
700	0.75	0.73	0.71	0.69	0.66	0.64	0.61	0.59	0.56	0.53	0.51
800	0.75	0.72	0.69	0.66	0.64	0.61	0.57	0.54	0.51	0.47	0.45
900	0.75	0.72	0.68	0.64	0.61	0.57	0.54	0.50	0.46	0.42	0.40
1000	0.75	0.71	0.67	0.62	0.58	0.54	0.49	0.45	0.41	0.38	0.35
1100	0.75	0.70	0.65	0.60	0.56	0.51	0.45	0.41	0.37	0.34	0.31
1200	0.75	0.69	0.64	0.59	0.53	0.47	0.42	0.37	0.33	0.30	0.28

Table F.39. REBS north: decision table for probabilities of satisfying the A2 criterion of $\leq 50\%$ decline over 1.5 generations (75 years) for 10-year projections and for a range of **harvest rate** *strategies. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.023.*

HR	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	0.75	0.78	0.80	0.83	0.85	0.88	0.90	0.91	0.93	0.94	0.95
0.01	0.75	0.77	0.79	0.81	0.83	0.85	0.87	0.88	0.90	0.91	0.92
0.02	0.75	0.77	0.78	0.80	0.81	0.83	0.84	0.85	0.86	0.87	0.88
0.03	0.75	0.76	0.77	0.78	0.79	0.80	0.80	0.81	0.81	0.82	0.83
0.04	0.75	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76
0.05	0.75	0.75	0.75	0.74	0.74	0.73	0.72	0.71	0.70	0.69	0.68
0.06	0.75	0.74	0.74	0.72	0.71	0.70	0.68	0.66	0.64	0.62	0.59
0.07	0.75	0.74	0.72	0.71	0.69	0.66	0.64	0.61	0.57	0.54	0.50
0.08	0.75	0.73	0.71	0.68	0.66	0.63	0.59	0.55	0.50	0.45	0.41
0.09	0.75	0.72	0.70	0.66	0.63	0.59	0.54	0.49	0.43	0.38	0.34
0.1	0.75	0.72	0.68	0.64	0.60	0.55	0.49	0.42	0.37	0.31	0.28
0.11	0.75	0.71	0.67	0.62	0.57	0.51	0.44	0.36	0.30	0.26	0.23
0.12	0.75	0.71	0.65	0.60	0.54	0.47	0.38	0.30	0.25	0.21	0.18

Table F.40. REBS north: decision table for probabilities of satisfying the A2 criterion of $\leq 30\%$ decline over 1.5 generations (75 years) for 10-year projections and for a range of **constant catch** *strategies. For reference, the average catch over the last 5 years (2015-2019) was 548 t.*

CC	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	0.25	0.27	0.29	0.32	0.34	0.36	0.39	0.41	0.43	0.45	0.47
100	0.25	0.26	0.28	0.30	0.31	0.33	0.35	0.36	0.38	0.39	0.40
200	0.25	0.26	0.27	0.28	0.29	0.30	0.31	0.32	0.33	0.34	0.35
300	0.25	0.25	0.26	0.27	0.27	0.28	0.29	0.29	0.29	0.29	0.30
400	0.25	0.25	0.25	0.25	0.25	0.25	0.26	0.26	0.26	0.25	0.26
500	0.25	0.24	0.24	0.24	0.23	0.23	0.23	0.23	0.22	0.22	0.22
600	0.25	0.24	0.23	0.22	0.22	0.21	0.21	0.20	0.19	0.19	0.18
700	0.25	0.23	0.22	0.21	0.20	0.19	0.18	0.17	0.16	0.16	0.15
800	0.25	0.23	0.21	0.19	0.19	0.17	0.16	0.15	0.14	0.13	0.13
900	0.25	0.22	0.20	0.19	0.17	0.16	0.15	0.13	0.12	0.11	0.10
1000	0.25	0.22	0.19	0.18	0.16	0.14	0.13	0.12	0.10	0.09	0.08
1100	0.25	0.22	0.19	0.17	0.15	0.13	0.11	0.10	0.08	0.07	0.06
1200	0.25	0.21	0.18	0.16	0.14	0.12	0.10	0.08	0.06	0.05	0.04

Table F.41. REBS north: decision table for probabilities of satisfying the A2 criterion of $\leq 30\%$ decline over 1.5 generations (75 years) for 10-year projections and for a range of **harvest rate** *strategies. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.023.*

HR	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	0.25	0.27	0.29	0.32	0.34	0.36	0.39	0.41	0.43	0.45	0.47
0.01	0.25	0.26	0.28	0.29	0.30	0.32	0.33	0.34	0.36	0.37	0.38
0.02	0.25	0.25	0.26	0.26	0.27	0.28	0.28	0.29	0.29	0.29	0.30
0.03	0.25	0.24	0.24	0.24	0.24	0.24	0.23	0.23	0.23	0.22	0.23
0.04	0.25	0.24	0.22	0.21	0.21	0.20	0.19	0.18	0.17	0.16	0.16
0.05	0.25	0.23	0.21	0.19	0.18	0.16	0.15	0.13	0.12	0.10	0.09
0.06	0.25	0.22	0.19	0.17	0.15	0.13	0.11	0.09	0.07	0.06	0.05
0.07	0.25	0.21	0.18	0.15	0.12	0.09	0.07	0.05	0.04	0.03	0.02
0.08	0.25	0.21	0.17	0.13	0.10	0.06	0.04	0.03	0.02	0.01	0.01
0.09	0.25	0.20	0.15	0.11	0.07	0.04	0.03	0.02	0.01	0.01	0.01
0.1	0.25	0.19	0.14	0.09	0.05	0.03	0.01	0.01	0.01	<0.01	<0.01
0.11	0.25	0.18	0.13	0.07	0.03	0.02	0.01	<0.01	<0.01	<0.01	<0.01
0.12	0.25	0.18	0.12	0.06	0.02	0.01	<0.01	<0.01	<0.01	<0.01	<0.01

Table F.42. *REBS north: decision table for reference criterion $0.5B_0$ for 10-year projections and for a range of* **constant catch** *strategies, such that values are P($B_t > 0.5B_0$). For reference, the average catch over the last 5 years (2015-2019) was 548 t.*

CC	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	0.74	0.77	0.79	0.80	0.82	0.85	0.86	0.88	0.89	0.90	0.92
100	0.74	0.76	0.77	0.78	0.79	0.81	0.82	0.83	0.84	0.84	0.85
200	0.74	0.75	0.76	0.76	0.77	0.77	0.77	0.78	0.78	0.78	0.78
300	0.74	0.74	0.74	0.74	0.74	0.74	0.73	0.73	0.72	0.71	0.71
400	0.74	0.74	0.73	0.72	0.71	0.70	0.69	0.68	0.67	0.65	0.63
500	0.74	0.73	0.72	0.70	0.69	0.67	0.65	0.63	0.61	0.58	0.56
600	0.74	0.72	0.70	0.68	0.66	0.64	0.61	0.58	0.55	0.52	0.49
700	0.74	0.72	0.69	0.66	0.63	0.60	0.57	0.53	0.50	0.46	0.42
800	0.74	0.71	0.68	0.64	0.61	0.57	0.53	0.48	0.44	0.41	0.37
900	0.74	0.70	0.66	0.62	0.58	0.53	0.48	0.44	0.40	0.36	0.33
1000	0.74	0.70	0.65	0.60	0.55	0.50	0.44	0.40	0.35	0.32	0.29
1100	0.74	0.69	0.63	0.58	0.53	0.46	0.41	0.36	0.32	0.29	0.26
1200	0.74	0.68	0.62	0.56	0.50	0.43	0.37	0.32	0.29	0.26	0.23

Table F.43. *REBS north: decision table for reference criterion $0.5B_0$ for 10-year projections and for a range of* **harvest rate** *strategies, such that values are P($B_t > 0.5B_0$). For reference, the average harvest rate over the last 5 years (2015-2019) was 0.023.*

HR	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	0.74	0.77	0.79	0.80	0.82	0.85	0.86	0.88	0.89	0.90	0.92
0.01	0.74	0.76	0.78	0.79	0.80	0.82	0.83	0.84	0.85	0.86	0.87
0.02	0.74	0.75	0.76	0.77	0.78	0.79	0.79	0.80	0.80	0.80	0.80
0.03	0.74	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.74	0.74	0.73
0.04	0.74	0.74	0.74	0.74	0.73	0.72	0.71	0.70	0.68	0.67	0.64
0.05	0.74	0.74	0.73	0.72	0.70	0.69	0.67	0.64	0.61	0.58	0.55
0.06	0.74	0.73	0.71	0.70	0.67	0.65	0.62	0.58	0.55	0.49	0.45
0.07	0.74	0.72	0.70	0.67	0.65	0.61	0.57	0.52	0.46	0.41	0.36
0.08	0.74	0.72	0.69	0.65	0.62	0.57	0.52	0.46	0.39	0.33	0.29
0.09	0.74	0.71	0.67	0.63	0.59	0.53	0.47	0.39	0.32	0.27	0.23
0.1	0.74	0.70	0.66	0.61	0.56	0.49	0.41	0.32	0.26	0.21	0.17
0.11	0.74	0.70	0.65	0.59	0.53	0.44	0.35	0.27	0.21	0.15	0.12
0.12	0.74	0.69	0.63	0.57	0.49	0.39	0.29	0.22	0.16	0.11	0.08

Table F.44. REBS north: decision table for reference criterion $0.7B_0$ for 10-year projections and for a range of **constant catch** *strategies, such that values are P($B_t > 0.7B_0$). For reference, the average catch over the last 5 years (2015-2019) was 548 t.*

CC	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	0.24	0.25	0.26	0.28	0.29	0.30	0.31	0.32	0.33	0.34	0.34
100	0.24	0.25	0.25	0.26	0.27	0.27	0.28	0.28	0.29	0.29	0.29
200	0.24	0.24	0.24	0.24	0.25	0.25	0.25	0.25	0.25	0.25	0.24
300	0.24	0.23	0.23	0.23	0.23	0.22	0.22	0.22	0.21	0.21	0.20
400	0.24	0.23	0.22	0.21	0.21	0.20	0.19	0.19	0.18	0.17	0.16
500	0.24	0.22	0.21	0.20	0.19	0.18	0.17	0.16	0.15	0.14	0.12
600	0.24	0.22	0.20	0.19	0.18	0.16	0.15	0.14	0.12	0.11	0.09
700	0.24	0.22	0.20	0.18	0.16	0.15	0.13	0.12	0.10	0.08	0.07
800	0.24	0.21	0.19	0.17	0.15	0.13	0.12	0.10	0.08	0.06	0.05
900	0.24	0.21	0.18	0.16	0.14	0.12	0.10	0.08	0.06	0.05	0.03
1000	0.24	0.20	0.17	0.15	0.13	0.10	0.08	0.06	0.04	0.03	0.02
1100	0.24	0.20	0.17	0.14	0.12	0.09	0.07	0.05	0.03	0.02	0.01
1200	0.24	0.19	0.16	0.13	0.10	0.08	0.06	0.04	0.02	0.01	0.01

Table F.45. REBS north: decision table for reference criterion $0.7B_0$ for 10-year projections and for a range of **harvest rate** *strategies, such that values are P($B_t > 0.7B_0$). For reference, the average harvest rate over the last 5 years (2015-2019) was 0.023.*

HR	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	0.24	0.25	0.26	0.28	0.29	0.30	0.31	0.32	0.33	0.34	0.34
0.01	0.24	0.24	0.25	0.25	0.25	0.26	0.26	0.26	0.26	0.26	0.26
0.02	0.24	0.23	0.23	0.23	0.22	0.22	0.21	0.20	0.20	0.19	0.18
0.03	0.24	0.23	0.21	0.20	0.19	0.18	0.16	0.15	0.13	0.11	0.10
0.04	0.24	0.22	0.20	0.18	0.16	0.14	0.12	0.10	0.07	0.06	0.04
0.05	0.24	0.21	0.18	0.16	0.13	0.11	0.08	0.05	0.04	0.02	0.02
0.06	0.24	0.20	0.17	0.14	0.11	0.07	0.05	0.03	0.02	0.01	0.01
0.07	0.24	0.19	0.16	0.12	0.08	0.05	0.02	0.01	0.01	<0.01	<0.01
0.08	0.24	0.19	0.14	0.10	0.06	0.03	0.01	0.01	<0.01	<0.01	<0.01
0.09	0.24	0.18	0.13	0.08	0.04	0.02	0.01	<0.01	<0.01	<0.01	<0.01
0.1	0.24	0.17	0.12	0.06	0.02	0.01	<0.01	<0.01	<0.01	<0.01	0
0.11	0.24	0.17	0.10	0.05	0.02	<0.01	<0.01	<0.01	<0.01	0	0
0.12	0.24	0.16	0.09	0.03	0.01	<0.01	<0.01	<0.01	0	0	0

Table F.46. REBS north: decision table for probabilities of satisfying the A2 criterion of $\leq 50\%$ decline over 1.5 generations (75 years) for selected projection years and for a range of **constant catch** *strategies. For reference, the average catch over the last 5 years (2015-2019) was 548 t.*

CC	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	0.75	0.85	0.94	0.98	0.99	>0.99	>0.99	1	1	1	1
100	0.75	0.82	0.90	0.94	0.96	>0.99	>0.99	>0.99	1	1	1
200	0.75	0.80	0.84	0.88	0.89	0.97	0.98	>0.99	1	1	1
300	0.75	0.77	0.78	0.79	0.79	0.90	0.91	0.97	>0.99	>0.99	>0.99
400	0.75	0.74	0.72	0.70	0.68	0.78	0.79	0.88	0.95	0.97	0.99
500	0.75	0.71	0.66	0.61	0.56	0.66	0.65	0.74	0.82	0.85	0.88
600	0.75	0.69	0.60	0.51	0.47	0.54	0.51	0.59	0.64	0.64	0.68
700	0.75	0.66	0.53	0.44	0.39	0.44	0.41	0.46	0.48	0.46	0.48
800	0.75	0.64	0.47	0.38	0.33	0.36	0.32	0.35	0.35	0.32	0.33
900	0.75	0.61	0.42	0.33	0.28	0.29	0.25	0.27	0.25	0.23	0.23
1000	0.75	0.58	0.38	0.29	0.23	0.24	0.19	0.20	0.18	0.16	0.16
1100	0.75	0.56	0.34	0.25	0.19	0.20	0.15	0.15	0.13	0.11	0.10
1200	0.75	0.53	0.30	0.21	0.16	0.16	0.11	0.11	0.09	0.06	0.06

Table F.47. REBS north: decision table for probabilities of satisfying the A2 criterion of $\leq 50\%$ decline over1.5 generations (75 years) for selected projection years and for a range of **harvest rate** *strategies. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.023.*

HR	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	0.75	0.85	0.94	0.98	0.99	>0.99	>0.99	1	1	1	1
0.01	0.75	0.83	0.91	0.96	0.98	>0.99	>0.99	1	1	1	1
0.02	0.75	0.81	0.87	0.92	0.94	0.99	0.99	>0.99	1	>0.99	>0.99
0.03	0.75	0.79	0.82	0.86	0.86	0.97	0.98	>0.99	>0.99	>0.99	>0.99
0.04	0.75	0.76	0.76	0.76	0.75	0.92	0.94	0.99	>0.99	>0.99	>0.99
0.05	0.75	0.74	0.69	0.65	0.62	0.83	0.86	0.97	0.99	0.98	0.99
0.06	0.75	0.71	0.62	0.53	0.50	0.73	0.78	0.93	0.97	0.97	0.98
0.07	0.75	0.69	0.54	0.42	0.40	0.62	0.69	0.88	0.94	0.94	0.96
0.08	0.75	0.66	0.45	0.34	0.32	0.51	0.60	0.82	0.90	0.90	0.94
0.09	0.75	0.63	0.38	0.28	0.26	0.42	0.52	0.75	0.85	0.86	0.91
0.1	0.75	0.60	0.31	0.22	0.21	0.36	0.44	0.68	0.80	0.82	0.87
0.11	0.75	0.57	0.26	0.17	0.17	0.30	0.38	0.61	0.74	0.77	0.84
0.12	0.75	0.54	0.21	0.14	0.13	0.26	0.32	0.55	0.68	0.71	0.79

Table F.48. REBS north: decision table for probabilities of satisfying the A2 criterion of $\leq 30\%$ decline over 1.5 generations (75 years) for selected projection years and for a range of **constant catch** *strategies. For reference, the average catch over the last 5 years (2015-2019) was 548 t.*

CC	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	0.25	0.34	0.45	0.57	0.68	0.91	0.96	>0.99	1	>0.99	>0.99
100	0.25	0.31	0.39	0.47	0.54	0.78	0.86	0.98	>0.99	>0.99	>0.99
200	0.25	0.29	0.34	0.39	0.43	0.65	0.72	0.91	0.99	0.99	>0.99
300	0.25	0.27	0.29	0.33	0.34	0.50	0.56	0.76	0.91	0.94	0.98
400	0.25	0.25	0.25	0.27	0.28	0.39	0.42	0.59	0.73	0.80	0.89
500	0.25	0.23	0.22	0.22	0.22	0.30	0.31	0.44	0.53	0.57	0.66
600	0.25	0.22	0.19	0.18	0.17	0.23	0.22	0.32	0.36	0.37	0.42
700	0.25	0.20	0.16	0.14	0.13	0.18	0.16	0.23	0.24	0.23	0.25
800	0.25	0.19	0.13	0.11	0.09	0.13	0.12	0.16	0.16	0.14	0.16
900	0.25	0.17	0.11	0.08	0.07	0.09	0.08	0.11	0.10	0.09	0.09
1000	0.25	0.16	0.09	0.06	0.05	0.07	0.06	0.08	0.06	0.05	0.05
1100	0.25	0.15	0.07	0.04	0.03	0.05	0.04	0.05	0.04	0.03	0.03
1200	0.25	0.14	0.05	0.03	0.02	0.03	0.03	0.03	0.02	0.02	0.02

Table F.49. REBS north: decision table for probabilities of satisfying the A2 criterion of $\leq 30\%$ decline over 1.5 generations (75 years) for selected projection years and for a range of **harvest rate** *strategies. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.023.*

HR	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	0.25	0.34	0.45	0.57	0.68	0.91	0.96	>0.99	1	>0.99	>0.99
0.01	0.25	0.30	0.37	0.44	0.51	0.79	0.87	0.98	>0.99	0.99	>0.99
0.02	0.25	0.27	0.29	0.33	0.36	0.62	0.72	0.93	0.98	0.97	0.99
0.03	0.25	0.24	0.22	0.24	0.25	0.44	0.54	0.82	0.93	0.93	0.96
0.04	0.25	0.21	0.16	0.16	0.16	0.31	0.38	0.69	0.85	0.86	0.91
0.05	0.25	0.18	0.10	0.09	0.10	0.22	0.27	0.55	0.74	0.78	0.85
0.06	0.25	0.15	0.06	0.05	0.06	0.15	0.20	0.43	0.62	0.68	0.78
0.07	0.25	0.12	0.03	0.03	0.04	0.10	0.14	0.33	0.52	0.59	0.70
0.08	0.25	0.10	0.01	0.01	0.03	0.07	0.11	0.25	0.42	0.50	0.61
0.09	0.25	0.07	0.01	0.01	0.02	0.05	0.08	0.19	0.34	0.42	0.54
0.1	0.25	0.05	<0.01	<0.01	0.01	0.04	0.06	0.15	0.28	0.36	0.47
0.11	0.25	0.03	<0.01	<0.01	0.01	0.03	0.05	0.11	0.22	0.30	0.41
0.12	0.25	0.02	<0.01	<0.01	0.01	0.03	0.04	0.09	0.18	0.25	0.36

Table F.50. *REBS north: decision table for reference criterion $0.5B_0$ for selected projection years over 1.5 generations (75 years) and for a range of* **constant catch** *strategies, such that valuTabes are P$(B_t > 0.5B_0)$. For reference, the average catch over the last 5 years (2015-2019) was 548 t.*

CC	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	0.74	0.82	0.90	0.96	0.99	>0.99	>0.99	>0.99	1	1	1
100	0.74	0.79	0.84	0.89	0.92	0.95	0.98	0.99	>0.99	>0.99	>0.99
200	0.74	0.77	0.78	0.79	0.81	0.83	0.88	0.93	0.95	0.97	0.98
300	0.74	0.74	0.71	0.69	0.67	0.67	0.72	0.77	0.82	0.85	0.87
400	0.74	0.71	0.65	0.58	0.54	0.53	0.55	0.59	0.64	0.66	0.67
500	0.74	0.69	0.58	0.49	0.44	0.42	0.42	0.45	0.47	0.48	0.48
600	0.74	0.66	0.52	0.41	0.36	0.34	0.33	0.33	0.34	0.34	0.34
700	0.74	0.63	0.46	0.35	0.30	0.27	0.25	0.25	0.24	0.24	0.23
800	0.74	0.61	0.41	0.30	0.25	0.21	0.19	0.18	0.18	0.17	0.16
900	0.74	0.58	0.36	0.26	0.20	0.17	0.14	0.13	0.12	0.11	0.11
1000	0.74	0.55	0.32	0.21	0.16	0.12	0.10	0.09	0.08	0.08	0.07
1100	0.74	0.53	0.29	0.18	0.12	0.08	0.07	0.06	0.05	0.05	0.04
1200	0.74	0.50	0.26	0.14	0.08	0.06	0.05	0.04	0.03	0.03	0.02

Table F.51. *REBS north: decision table for reference criterion $0.5B_0$ for selected projection years over 1.5 generations (75 years) and for a range of* **harvest rate** *strategies, such that values are P$(B_t > 0.5B_0)$. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.023.*

HR	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	0.74	0.82	0.90	0.96	0.99	>0.99	>0.99	>0.99	1	1	1
0.01	0.74	0.80	0.86	0.91	0.94	0.96	0.98	0.99	>0.99	>0.99	>0.99
0.02	0.74	0.78	0.80	0.83	0.85	0.87	0.92	0.95	0.97	0.98	0.98
0.03	0.74	0.75	0.74	0.72	0.69	0.71	0.79	0.86	0.90	0.92	0.93
0.04	0.74	0.73	0.67	0.57	0.53	0.53	0.63	0.73	0.77	0.80	0.81
0.05	0.74	0.70	0.58	0.44	0.40	0.40	0.49	0.58	0.63	0.65	0.66
0.06	0.74	0.67	0.49	0.34	0.29	0.30	0.37	0.45	0.49	0.52	0.52
0.07	0.74	0.65	0.41	0.26	0.22	0.23	0.28	0.34	0.38	0.40	0.40
0.08	0.74	0.62	0.33	0.19	0.16	0.17	0.22	0.26	0.28	0.30	0.31
0.09	0.74	0.59	0.27	0.14	0.11	0.13	0.17	0.20	0.22	0.23	0.24
0.1	0.74	0.56	0.21	0.09	0.08	0.10	0.13	0.15	0.17	0.18	0.18
0.11	0.74	0.53	0.15	0.07	0.06	0.08	0.11	0.11	0.13	0.14	0.14
0.12	0.74	0.49	0.11	0.05	0.05	0.06	0.09	0.09	0.10	0.11	0.11

Table F.52. REBS north: decision table for reference criterion $0.7B_0$ for selected projection years over 1.5 generations (75 years) and for a range of **constant catch** strategies, such that values are P$(B_t > 0.7B_0)$. For reference, the average catch over the last 5 years (2015-2019) was 548 t.

CC	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	0.24	0.29	0.34	0.39	0.45	0.53	0.70	0.84	0.92	0.95	0.97
100	0.24	0.27	0.29	0.31	0.34	0.38	0.50	0.63	0.74	0.81	0.86
200	0.24	0.25	0.25	0.25	0.26	0.28	0.35	0.44	0.53	0.60	0.64
300	0.24	0.23	0.21	0.19	0.19	0.20	0.24	0.30	0.36	0.40	0.43
400	0.24	0.21	0.17	0.14	0.14	0.14	0.17	0.20	0.23	0.26	0.27
500	0.24	0.19	0.14	0.10	0.09	0.09	0.11	0.13	0.15	0.16	0.17
600	0.24	0.18	0.11	0.07	0.05	0.06	0.07	0.08	0.10	0.10	0.11
700	0.24	0.16	0.08	0.04	0.04	0.04	0.05	0.05	0.06	0.06	0.06
800	0.24	0.15	0.06	0.02	0.02	0.02	0.03	0.03	0.04	0.04	0.04
900	0.24	0.14	0.05	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02
1000	0.24	0.13	0.03	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
1100	0.24	0.12	0.02	<0.01	<0.01	0.01	0.01	0.01	0.01	0.01	0.01
1200	0.24	0.10	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

Table F.53. REBS north: decision table for reference criterion $0.7B_0$ for selected projection years over 1.5 generations (75 years) and for a range of **harvest rate** strategies, such that values are P$(B_t > 0.7B_0)$. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.023.

HR	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	0.24	0.29	0.34	0.39	0.45	0.53	0.70	0.84	0.92	0.95	0.97
0.01	0.24	0.25	0.26	0.27	0.28	0.33	0.44	0.58	0.70	0.77	0.80
0.02	0.24	0.22	0.19	0.16	0.16	0.18	0.26	0.35	0.43	0.50	0.52
0.03	0.24	0.19	0.11	0.08	0.08	0.10	0.15	0.20	0.26	0.29	0.31
0.04	0.24	0.16	0.06	0.03	0.04	0.05	0.08	0.11	0.14	0.17	0.18
0.05	0.24	0.13	0.02	0.01	0.02	0.03	0.05	0.06	0.08	0.10	0.10
0.06	0.24	0.11	0.01	0.01	0.01	0.02	0.03	0.04	0.05	0.05	0.06
0.07	0.24	0.08	<0.01	<0.01	0.01	0.01	0.02	0.02	0.03	0.03	0.04
0.08	0.24	0.06	<0.01	<0.01	<0.01	0.01	0.01	0.01	0.02	0.02	0.02
0.09	0.24	0.04	<0.01	<0.01	<0.01	0.01	0.01	0.01	0.01	0.01	0.01
0.1	0.24	0.02	<0.01	<0.01	<0.01	<0.01	0.01	0.01	0.01	0.01	0.01
0.11	0.24	0.02	0	<0.01	<0.01	<0.01	0.01	<0.01	0.01	0.01	0.01
0.12	0.24	0.01	0	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	0.01	<0.01

F.2.4.4. Time to reach targets

Table F.54. REBS north: estimated time (years) for projected biomass B_t to exceed reference points and criteria with a probability of 50%, for for a range of **constant catch** *strategies. An estimated time of 0 means that the condition is satisfied and remains so over the 75-year projection; an estimated time of 75 means that the condition never becomes satisfied over the 1.5-generation projection. A further condition is that the probability of satisfying the condition must increase for two consecutive years. Columns respectively correspond to the provisional DFO reference points: LRP = $0.4B_{MSY}$, USR = $0.8B_{MSY}$; alternative reference points: B_{MSY}, B_{2021}, $0.2B_0$, $0.4B_0$; and COSEWIC reference criteria: 0.5$B_{t\text{-G}}$ = $\leq 50\%$ decline over 1.5 generations (G), 0.7$B_{t\text{-G}}$ = $\leq 30\%$ decline over 1.5G, $0.5B_0$, $0.7B_0$.*

	LRP	USR	B_{MSY}	B_{2021}	0.2B_0	0.4B_0	0.5$B_{t\text{-G}}$	0.7$B_{t\text{-G}}$	0.5B_0	0.7B_0
0	0	0	0	0	0	0	0	12	0	23
100	0	0	0	0	0	0	0	16	0	34
200	0	0	0	0	0	0	0	21	0	51
300	0	0	0	39	0	0	0	24	0	75
400	0	0	0	75	0	0	0	41	0	75
500	0	0	0	75	0	0	0	48	75	75
600	0	0	0	75	0	39	21	75	75	75
700	0	0	0	75	0	75	75	75	75	75
800	0	1	75	75	1	75	75	75	75	75
900	0	1	75	75	1	75	75	75	75	75
1000	0	1	75	75	1	75	75	75	75	75
1100	0	1	75	75	1	75	75	75	75	75
1200	0	1	75	75	1	75	75	75	75	75

Table F.55. REBS north: estimated time (years) for projected biomass B_t to exceed reference points and criteria with a probability of 50%, for for a range of **harvest rate** *strategies. See caption in Table F.54 for further details*

	LRP	USR	B_{MSY}	B_{2021}	0.2B_0	0.4B_0	0.5$B_{t\text{-G}}$	0.7$B_{t\text{-G}}$	0.5B_0	0.7B_0
0	0	0	0	0	0	0	0	12	0	23
0.01	0	0	0	0	0	0	0	18	0	39
0.02	0	0	0	1	0	0	0	21	0	66
0.03	0	0	0	39	0	0	0	33	0	75
0.04	0	0	0	75	0	0	0	40	0	75
0.05	0	0	0	75	0	0	0	43	36	75
0.06	0	0	0	75	0	0	0	47	58	75
0.07	0	0	0	75	0	0	21	51	75	75
0.08	0	0	0	75	0	0	23	64	75	75
0.09	0	0	0	75	0	32	33	71	75	75
0.1	0	0	0	75	0	43	39	75	75	75
0.11	0	0	0	75	0	75	41	75	75	75
0.12	0	0	0	75	0	75	43	75	75	75

Table F.56. REBS north: estimated time (years) for projected biomass B_t to exceed reference points and criteria with a probability of 65%, for for a range of **constant catch** strategies. See caption in Table F.54 for further details.

	LRP	USR	B_{MSY}	B_{2021}	0.2B_0	0.4B_0	0.5$B_{t\text{-G}}$	0.7$B_{t\text{-G}}$	0.5B_0	0.7B_0
0	0	0	0	0	0	0	0	17	0	32
100	0	0	0	0	0	0	0	21	0	46
200	0	0	0	31	0	0	0	28	0	75
300	0	0	0	59	0	0	0	41	0	75
400	0	0	0	75	0	0	0	47	59	75
500	0	0	0	75	0	41	23	73	75	75
600	0	0	0	75	0	75	67	75	75	75
700	0	1	2	75	1	75	75	75	75	75
800	0	1	75	75	1	75	75	75	75	75
900	0	1	75	75	1	75	75	75	75	75
1000	0	1	75	75	1	75	75	75	75	75
1100	1	1	75	75	1	75	75	75	75	75
1200	1	1	75	75	1	75	75	75	75	75

Table F.57. REBS north: estimated time (years) for projected biomass B_t to exceed reference points and criteria with a probability of 65%, for for a range of **harvest rate** strategies. See caption in Table F.54 for further details.

	LRP	USR	B_{MSY}	B_{2021}	0.2B_0	0.4B_0	0.5$B_{t\text{-G}}$	0.7$B_{t\text{-G}}$	0.5B_0	0.7B_0
0	0	0	0	0	0	0	0	17	0	32
0.01	0	0	0	0	0	0	0	21	0	50
0.02	0	0	0	39	0	0	0	32	0	75
0.03	0	0	0	75	0	0	0	40	0	75
0.04	0	0	0	75	0	0	0	43	36	75
0.05	0	0	0	75	0	0	20	47	59	75
0.06	0	0	0	75	0	0	22	56	75	75
0.07	0	0	0	75	0	28	33	70	75	75
0.08	0	0	0	75	0	39	39	75	75	75
0.09	0	0	0	75	0	75	41	75	75	75
0.1	0	0	0	75	0	75	43	75	75	75
0.11	0	0	0	75	0	75	46	75	75	75
0.12	0	0	0	75	0	75	48	75	75	75

Table F.58. REBS north: estimated time (years) for projected biomass B_t to exceed reference points and criteria with a probability of 80%, for for a range of **constant catch** *strategies. See caption in Table F.54 for further details.*

	LRP	USR	B_{MSY}	B_{2021}	0.2B_0	0.4B_0	0.5$B_{t\text{-G}}$	0.7$B_{t\text{-G}}$	0.5B_0	0.7B_0
0	0	0	0	0	0	0	2	21	3	41
100	0	0	0	1	0	0	3	28	5	61
200	0	0	0	52	0	0	5	40	17	75
300	0	0	0	75	0	0	20	46	50	75
400	0	0	0	75	0	35	39	65	75	75
500	0	0	0	75	0	75	48	75	75	75
600	0	1	2	75	1	75	75	75	75	75
700	0	1	2	75	1	75	75	75	75	75
800	1	1	75	75	1	75	75	75	75	75
900	1	1	75	75	1	75	75	75	75	75
1000	1	1	75	75	1	75	75	75	75	75
1100	1	1	75	75	1	75	75	75	75	75
1200	1	1	75	75	1	75	75	75	75	75

Table F.59. REBS north: estimated time (years) for projected biomass B_t to exceed reference points and criteria with a probability of 80%, for for a range of **harvest rate** *strategies. See caption in Table F.54 for further details.*

	LRP	USR	B_{MSY}	B_{2021}	0.2B_0	0.4B_0	0.5$B_{t\text{-G}}$	0.7$B_{t\text{-G}}$	0.5B_0	0.7B_0
0	0	0	0	0	0	0	2	21	3	41
0.01	0	0	0	37	0	0	3	32	4	73
0.02	0	0	0	75	0	0	4	40	8	75
0.03	0	0	0	75	0	0	6	43	36	75
0.04	0	0	0	75	0	0	20	48	60	75
0.05	0	0	0	75	0	0	23	68	75	75
0.06	0	0	0	75	0	1	37	75	75	75
0.07	0	0	0	75	0	57	41	75	75	75
0.08	0	0	0	75	0	75	43	75	75	75
0.09	0	0	0	75	0	75	47	75	75	75
0.1	0	0	0	75	0	75	55	75	75	75
0.11	0	0	0	75	0	75	70	75	75	75
0.12	0	0	0	75	0	75	75	75	75	75

Table F.60. REBS north: estimated time (years) for projected biomass B_t to exceed reference points and criteria with a probability of 95%, for for a range of **constant catch** *strategies. See caption in Table F.54 for further details.*

	LRP	USR	B_{MSY}	B_{2021}	0.2B_0	0.4B_0	0.5$B_{t\text{-G}}$	0.7$B_{t\text{-G}}$	0.5B_0	0.7B_0
0	0	0	0	48	0	0	10	33	14	63
100	0	0	0	75	0	0	16	41	25	75
200	0	0	0	75	0	0	22	47	53	75
300	0	0	0	75	0	1	41	66	75	75
400	0	0	0	75	0	75	53	75	75	75
500	0	1	2	75	1	75	75	75	75	75
600	1	1	2	75	1	75	75	75	75	75
700	1	1	2	75	1	75	75	75	75	75
800	1	1	75	75	1	75	75	75	75	75
900	1	1	75	75	1	75	75	75	75	75
1000	1	1	75	75	1	75	75	75	75	75
1100	1	1	75	75	1	75	75	75	75	75
1200	1	1	75	75	1	75	75	75	75	75

Table F.61. REBS north: estimated time (years) for projected biomass B_t to exceed reference points and criteria with a probability of 95%, for for a range of **harvest rate** *strategies. See caption in Table F.54 for further details.*

	LRP	USR	B_{MSY}	B_{2021}	0.2B_0	0.4B_0	0.5$B_{t\text{-G}}$	0.7$B_{t\text{-G}}$	0.5B_0	0.7B_0
0	0	0	0	48	0	0	10	33	14	63
0.01	0	0	0	75	0	0	13	41	21	75
0.02	0	0	0	75	0	0	20	46	44	75
0.03	0	0	0	75	0	0	22	71	75	75
0.04	0	0	0	75	0	1	39	75	75	75
0.05	0	0	0	75	0	1	42	75	75	75
0.06	0	0	0	75	0	1	47	75	75	75
0.07	0	0	0	75	0	75	69	75	75	75
0.08	0	0	0	75	0	75	75	75	75	75
0.09	0	0	0	75	0	75	75	75	75	75
0.1	0	0	0	75	0	75	75	75	75	75
0.11	0	0	1	75	0	75	75	75	75	75
0.12	0	0	1	75	0	75	75	75	75	75

F.2.5. REBS North – Sensitivity Runs

Eight sensitivity analyses were run (with full MCMC simulations) relative to the central run (Run28: M=0.045, CPUE c_p=0.2759) to test the sensitivity of the outputs to alternative model assumptions:

- **S01** (Run56) – estimated M using a normal prior: $\mathcal{N}(0.045, 0.009)$ (label: "estimate M");
- **S02** (Run57) – reduced commercial catch for 1965-1995 by 1/3 (label: "reduce catch");
- **S03** (Run58) – increased commercial catch for 1965-1995 by 50% (label: "increase catch");
- **S04** (Run59) – used wide ageing error (AE $\pm$5 ages), fixed M=0.045, and set CPUE c_p=0.10 (label: "AE5 M45 CV10");
- **S05** (Run60) – used wide AE, fixed M=0.045, and set CPUE c_p=0.2759 (label: "AE5 M45 CV28");
- **S06** (Run61) – used wide AE, fixed M=0.045, and set CPUE c_p=0.40 (label: "AE5 M45 CV40");
- **S07** (Run62) – used wide AE, fixed M=0.035, and set CPUE c_p=0.40 (label: "AE5 M35 CV40");
- **S08** (Run63) – used moderate AE but CV increasing by age (label: "AE3 varCV").

All sensitivity runs but one were reweighted once using the procedure of Francis (2011) for age frequencies; S02 (R42) was reweighted twice as the first reweight did not result in credible parameter fits. The abundance index CVs were adjusted on the first reweight only, using either that adopted in the central run (survey=0.25, CPUE=0.2759) or using specified process errors. 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 sensitivity runs, except for S01 (estimate M), were judged to have converged after 6 million iterations, sampling every 5000$^\mathrm{th}$ to give 1200 draws. The first 200 samples were discarded and the remaining 1000 samples were used for the MCMC analysis.

The differences among the sensitivity runs (including the central run) are summarised in tables of median parameter estimates (Table F.62) and median MSY-based quantities (Table F.63). Sensitivity plots appear in:

- Figure F.31 – trace plots for chains of R_0 MCMC samples;
- Figure F.32 – diagnostic split-chain plots for R_0 MCMC samples;
- Figure F.33 – diagnostic autocorrelation plots for R_0 MCMC sample;
- Figure F.34 – trajectories of median B_t/B_0;
- Figure F.35 – trajectories of median recruitment R_t (one-year old fish);
- Figure F.36 – trajectories of median exploitation rate u_t;
- Figure F.37 – quantile plots of selected parameters for the sensitivity runs;
- Figure F.38 – quantile plots of selected derived quantities for the sensitivity runs;
- Figure F.39 – stock status plots of B_{2021}/B_MSY.

The diagnostic plots (Figures F.31 to F.33) suggest that seven sensitivity runs exhibited good MCMC behaviour, and one was poor with little credibility:

- Good – no trend in traces, split-chains align, no autocorrelation
  - S02 (-33% 1965-1995 commercial catch)
  - S03 (+50% 1965-1995 commercial catch)
  - S04 (wide AE, M=0.045, CPUE c_p=0.1)

- S05 (wide AE, M=0.045, CPUE c_p=0.2759)
- S06 (wide AE, M=0.045, CPUE c_p=0.4)
- S07 (wide AE, M=0.035, CPUE c_p=0.4)
- S08 (AE with increasing CV, M=0.045, CPUE c_p=0.2759)

- Poor – trace trend fluctuates substantially or shows a persistent increase/decrease, split-chains differ from each other, substantial autocorrelation
  - S01 (estimate M)

The run that estimated M (S01) may not have converged and the marginal diagnostics suggested instability in the model. Additionally, the posterior for M_2 (males), 0.065 (0.059, 0.073), moved well above the prior ($\mathcal{N}(0.045, 0.009)$) and was deemed unrealistic given the long-lived nature of REBS north.

The trajectories of the B_t medians relative to B_0 (Figure F.34) indicate that estimating M (S01) resulted in the most optimistic scenario, while the most pessimistic run was the one using a wide AE matrix, the lowest M, and the widest CPUE c_p (S07). Only the sensitivity run that varied from the central run by using a wide AE (S05) tended to closely reflect the central run, indicating little sensitivity to this wider level of ageing error compared to more narrow ageing error used in the composite base case. The two catch sensitivity runs (S02, S03) departed from the central run during the reconstruction years but ended with similar spawning stock depletion (B_{2021}/B_0). The two sensitivity runs that differed by CPUE c_p ($\in \{0.1, 0.4\}$) (as well as the wide AE matrix) were considerably more optimistic and pessimistic, respectively. The trajectory using an AE with increasing CV by age (S08), followed the central run up until about 1990 and then mirrored the increased-catch scenario (S02) thereafter. The overall conclusion is that, other than being sensitive to values of M, the model outcome is also driven by how much weight is given to the CPUE data. If the model is informed that CPUE is important, the population trajectory is more optimistic, given the generally upward trend in CPUE; while the model which discounts the CPUE index, results in a more pessimistic trajectory. The need for CPUE as a stabilising influence was also found in the latest BC Bocaccio stock assessment (Starr and Haigh 2022), which featured a monotonic decline in population until a large recruitment event in 2016.

Parameter estimates varied little among sensitivity runs (Figure F.37), with the exception of S01. Derived quantities based on MSY (Figure F.38) exhibited suspiciously high values of u_MSY for a long-lived species (e.g., central run u_MSY=0.25/y, Table F.63). The lowest u_MSY (0.13/y) occurred in S08 (increasing CV in AE).

The stock status (B_{2021}/B_MSY) for the sensitivities (Figure F.39) all appear to be in the DFO Healthy Zone.

Table F.62. REBS north: median values of MCMC samples for the primary estimated parameters, comparing the central run to 8 sensitivity runs (1000 samples each). C =Central, R = Run, S = Sensitivity. Numeric subscripts other than those for R_0 and M indicate the following gear types g: 1 = WCHG Synoptic, 2 = commercial trawl CPUE/Trawl fishery, and 3 = Other fishery. Sensitivity runs: S01 = estimate M, S02 = reduce catch, S03 = increase catch, S04 = AE5 M45 CV10, S05 = AE5 M45 CV28, S06 = AE5 M45 CV40, S07 = AE5 M35 CV40, S08 = AE3 varCV

	C(R46)	S01(R56)	S02(R57)	S03(R58)	S04(R59)	S05(R60)	S06(R61)	S07(R62)	S08(R63)
R_0	1,617	5,620	1,305	2,038	1,811	1,621	1,538	893	1,487
M_1	—	0.0627	0.0450	0.0450	0.0450	0.0450	0.0450	0.0450	0.0450
M_2	—	0.0652	0.0450	0.0450	0.0450	0.0450	0.0450	0.0450	0.0450
q_1	0.326	0.147	0.383	0.280	0.279	0.322	0.358	0.444	0.401
q_2	0.0000823	0.0000400	0.0000916	0.0000737	0.0000587	0.0000790	0.0000947	0.000116	0.0000982
μ_1	42.0	39.5	42.7	40.9	44.9	42.6	41.6	41.9	43.0
μ_2	34.7	34.8	33.7	35.5	32.3	34.1	34.7	34.6	34.6
μ_3	46.4	—	49.4	45.2	48.8	46.0	45.3	50.0	42.2
Δ_1	-0.830	-1.08	-1.02	-0.811	0.0877	-0.891	-1.07	-1.23	-0.874
Δ_2	-1.10	-1.10	-1.09	-1.17	-0.893	-1.06	-1.12	-1.17	-1.06
Δ_3	-2.11	-0.534	-2.60	-2.43	-0.973	-2.27	-2.73	-2.21	-1.49
$\log v_{1L}$	5.29	4.96	5.35	5.18	5.47	5.35	5.26	5.36	5.33
$\log v_{2L}$	4.40	4.34	4.28	4.51	3.90	4.29	4.44	4.44	4.33
$\log v_{3L}$	5.42	—	5.54	5.36	5.56	5.38	5.35	5.64	5.87

Table F.63. REBS north: medians of MCMC-derived quantities from the central run and 8 sensitivity runs (1000 samples each) from their respective MCMC posteriors. Definitions are: B_0 – unfished equilibrium spawning biomass (mature females), V_0 – unfished equilibrium vulnerable biomass (males and females), B_{2021} – spawning biomass at the start of 2021, V_{2021} – vulnerable biomass in the middle of 2021, u_{2020} – exploitation rate (ratio of total catch to vulnerable biomass) in the middle of 2020, $u_{\max}$ – maximum exploitation rate (calculated for each sample as the maximum exploitation rate from 1935 - 2020), B_{MSY} – equilibrium spawning biomass at MSY (maximum sustainable yield), u_{MSY} – equilibrium exploitation rate at MSY, V_{MSY} – equilibrium vulnerable biomass at MSY. All biomass values (and MSY) are in tonnes. Sensitivity runs: S01 = estimate M, S02 = reduce catch, S03 = increase catch, S04 = AE5 M45 CV10, S05 = AE5 M45 CV28, S06 = AE5 M45 CV40, S07 = AE5 M35 CV40, S08 = AE3 varCV

	C(R46)	S01(R56)	S02(R57)	S03(R58)	S04(R59)	S05(R60)	S06(R61)	S07(R62)	S08(R63)
B_0	14,345	24,627	11,577	18,074	16,067	14,376	13,640	12,680	13,190
V_0 (Trawl)	24,759	36,722	20,254	30,658	28,035	24,892	23,565	22,979	22,406
V_0 (Other)	19,823	30,673	14,832	25,995	20,757	20,019	19,500	17,879	23,715
B_{2021}	8,000	20,931	6,229	10,076	10,956	8,159	6,865	4,640	6,760
V_{2021} (Trawl)	13,210	30,704	10,811	16,089	20,372	13,666	10,848	7,888	11,137
V_{2021} (Other)	9,161	24,592	6,140	12,173	12,946	9,495	7,788	4,546	11,808
B_{2021}/B_0	0.556	0.848	0.539	0.558	0.681	0.562	0.502	0.365	0.513
V_{2021}/V_0 (Trawl)	0.536	0.829	0.531	0.524	0.731	0.549	0.461	0.343	0.493
V_{2021}/V_0 (Other)	0.459	0.796	0.414	0.470	0.625	0.473	0.400	0.253	0.496
u_{2020} (Trawl)	0.0189	0.00821	0.0230	0.0156	0.0121	0.0183	0.0231	0.0312	0.0224
u_{2020} (Other)	0.0229	0.00858	0.0339	0.0173	0.0163	0.0220	0.0269	0.0459	0.0176
$u_{\max}$ (Trawl)	0.0692	0.0474	0.0609	0.0826	0.0628	0.0690	0.0725	0.0764	0.0771
$u_{\max}$ (Other)	0.0851	0.0394	0.103	0.105	0.0876	0.0832	0.0843	0.121	0.0620
MSY	627	1,499	508	790	701	631	598	428	552
B_{MSY}	3,856	6,531	3,113	4,869	4,249	3,850	3,677	3,381	3,624
$0.4B_{2021}$	1,542	2,612	1,245	1,948	1,700	1,540	1,471	1,352	1,449
$0.8B_{2021}$	3,085	5,225	2,491	3,895	3,399	3,080	2,942	2,705	2,899
B_{2021}/B_{MSY}	2.08	3.19	2.00	2.08	2.58	2.10	1.87	1.38	1.87
B_{MSY}/B_0	0.268	0.266	0.269	0.269	0.265	0.267	0.269	0.266	0.275
V_{MSY}	3,135	3,379	2,292	4,048	3,241	3,161	3,114	3,280	4,594
V_{MSY}/V_0 (Trawl)	0.127	0.0920	0.114	0.133	0.115	0.127	0.132	0.143	0.206
V_{MSY}/V_0 (Other)	0.158	0.109	0.154	0.156	0.156	0.158	0.160	0.184	0.194
u_{MSY}	0.202	0.442	0.220	0.194	0.218	0.198	0.192	0.130	0.120
u_{2020}/u_{MSY} (Trawl)	0.0954	0.0184	0.104	0.0798	0.0554	0.0916	0.121	0.240	0.189
u_{2020}/u_{MSY} (Other)	0.116	0.0192	0.153	0.0898	0.0760	0.110	0.142	0.353	0.147

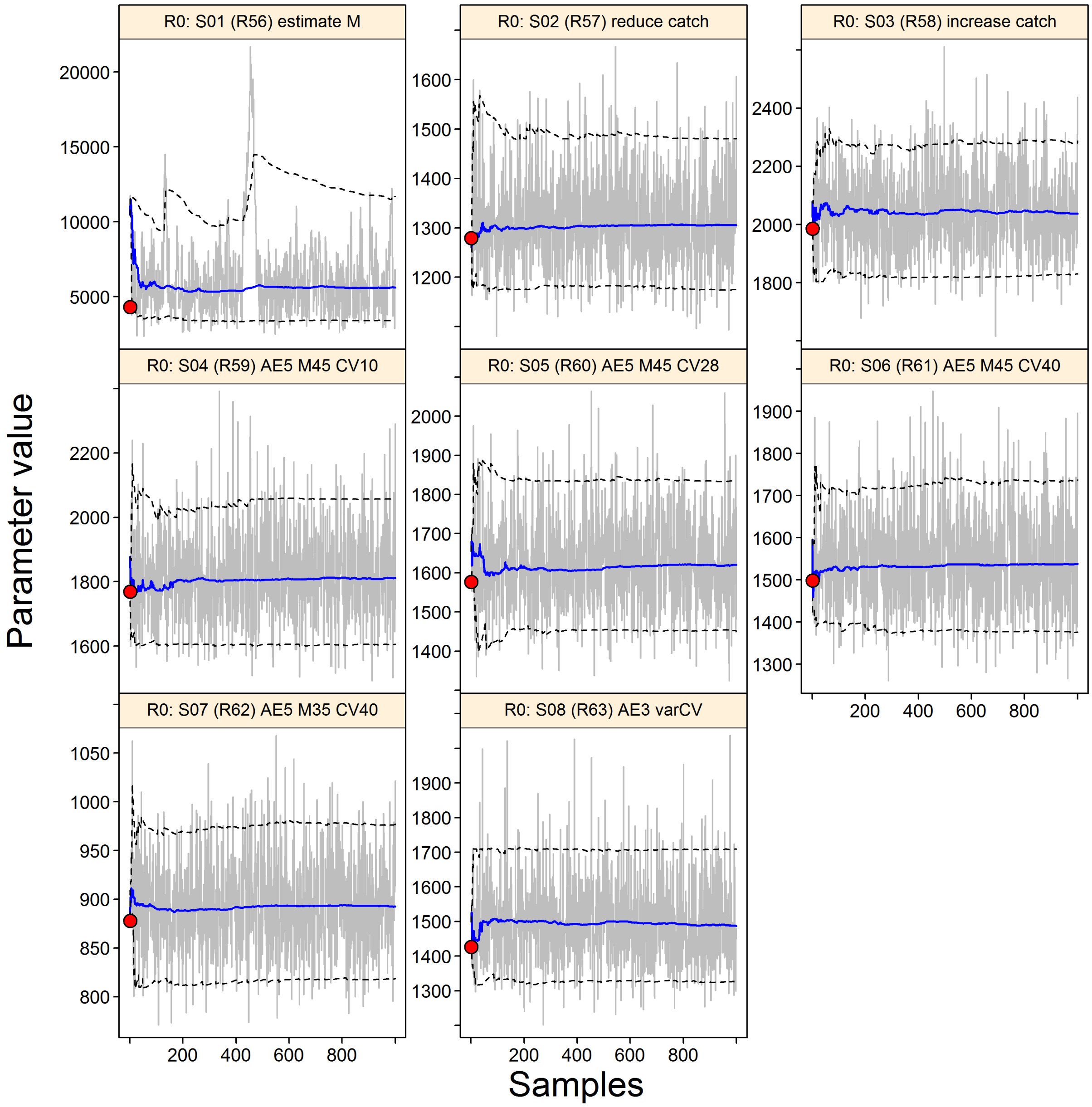


Figure F.31. REBS north sensitivity R_0: MCMC traces for the estimated parameters. Grey lines show the 1000 samples for each parameter, solid blue lines show the cumulative median (up to that sample), and dashed lines show the cumulative 0.05 and 0.95 quantiles. Red circles are the MPD estimates.

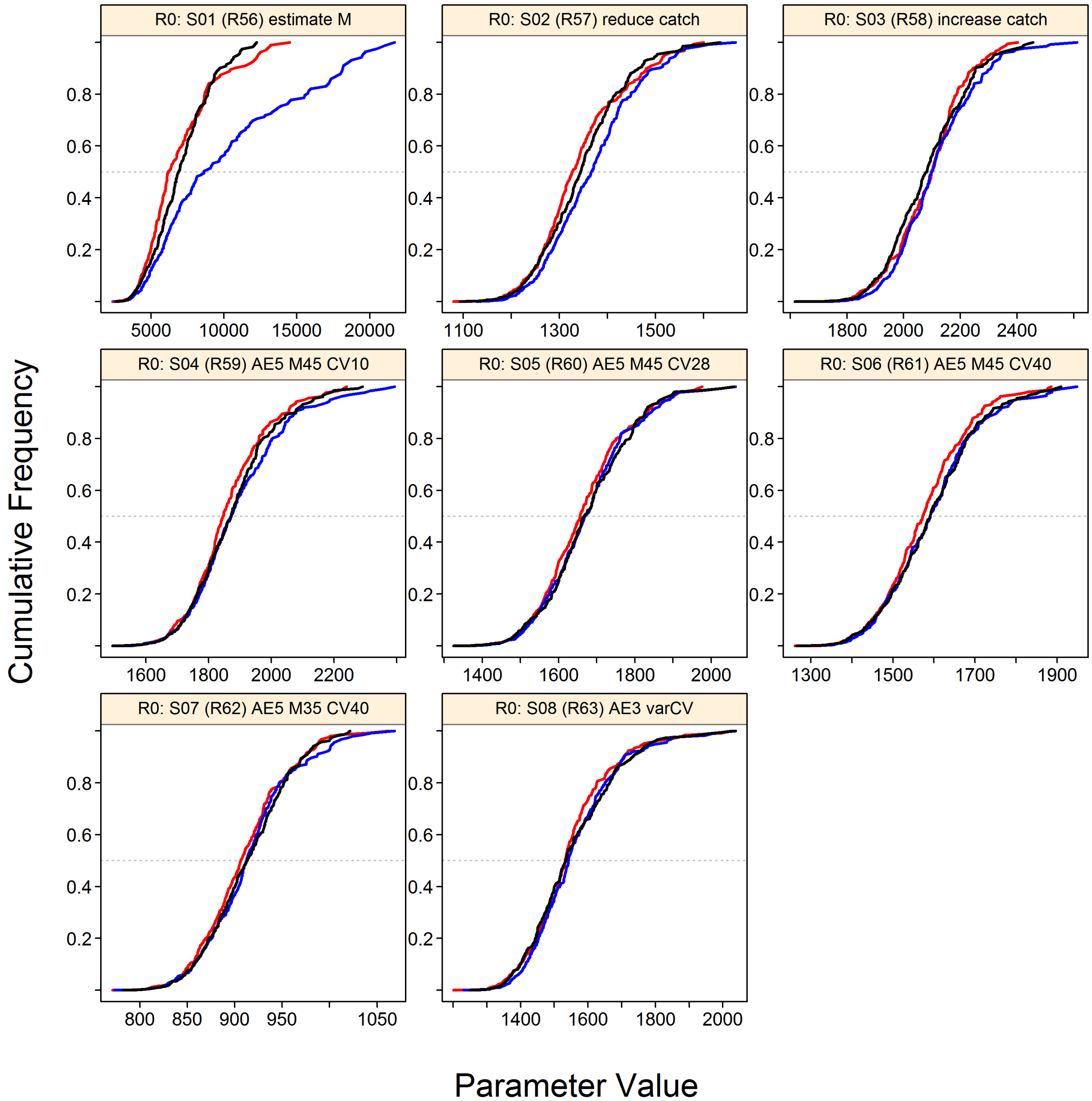


Figure F.32. REBS north sensitivity R_0: diagnostic plots obtained by dividing the MCMC chain of 1000 MCMC samples into three segments, and overplotting the cumulative distributions of the first segment (red), second segment (blue) and final segment (black).

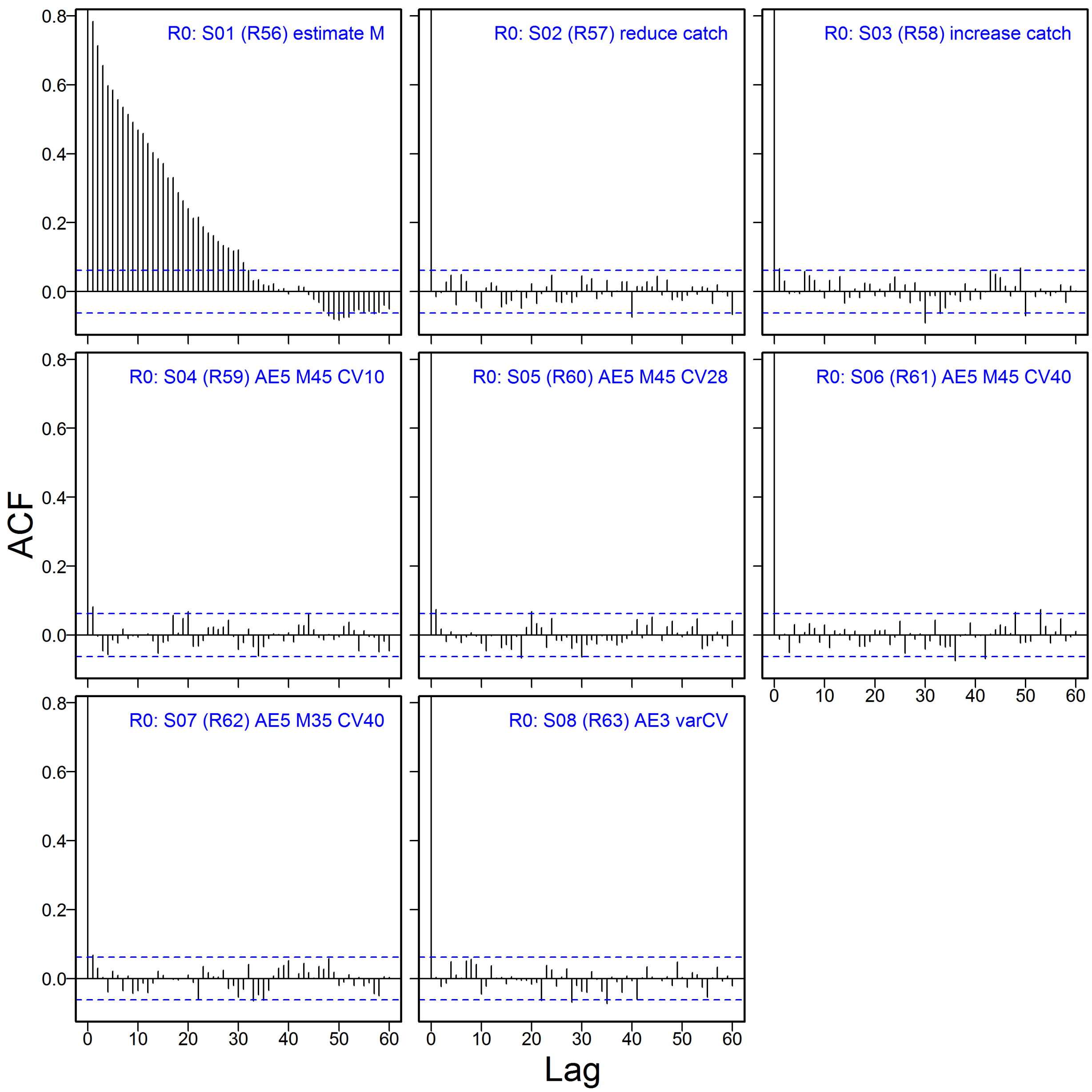


Figure F.33. REBS north sensitivity R_0: autocorrelation plots for the estimated parameters from the MCMC output. Horizontal dashed blue lines delimit the 95% confidence interval for each parameter's set of lagged correlations.

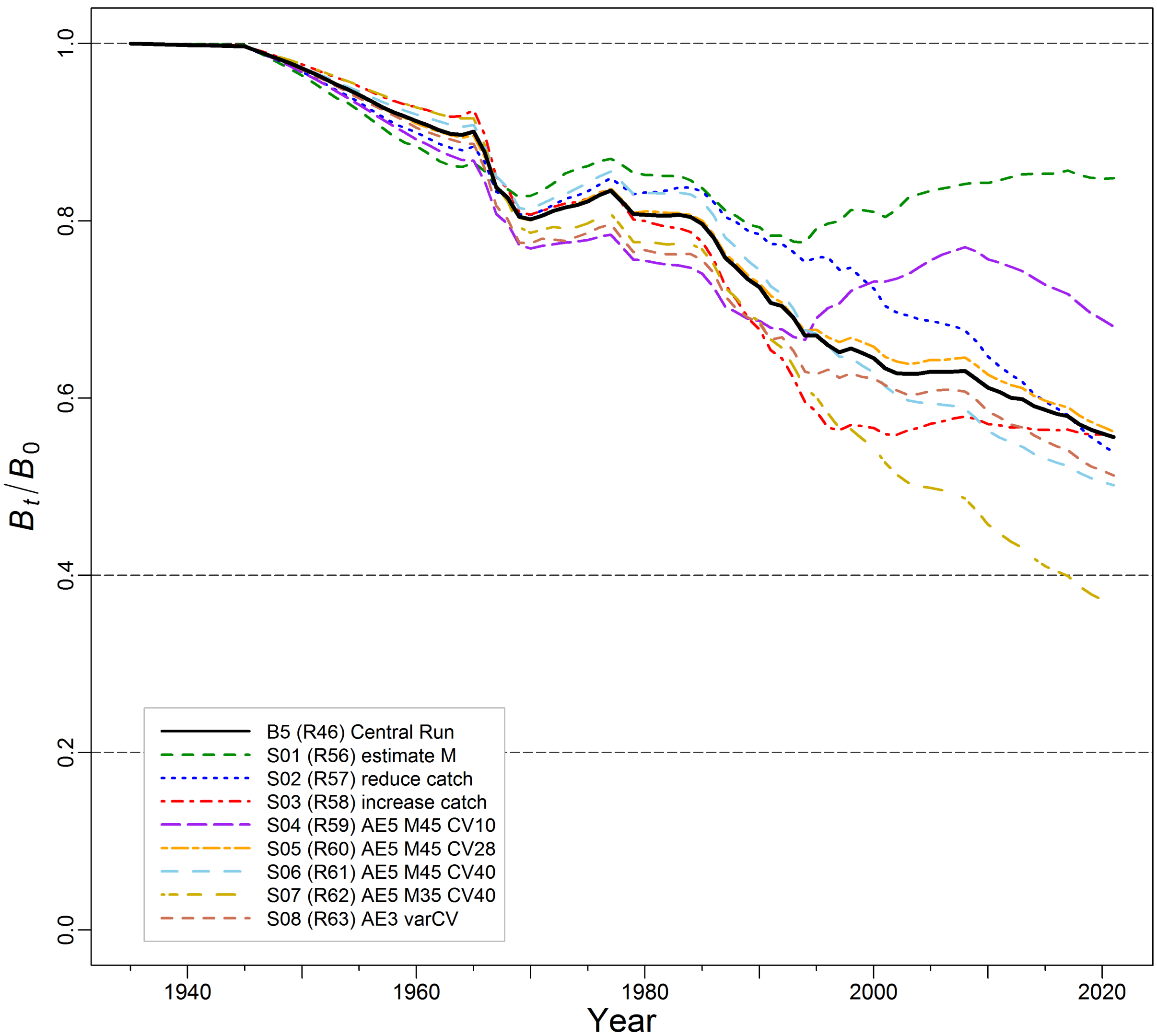


Figure F.34. REBS north sensitivity: model trajectories of median spawning biomass as a proportion of unfished equilibrium biomass (B_t/B_0) for the central run of the composite base case and 8 sensitivity runs (see legend lower left). Horizontal dashed lines show alternative reference points used by other jurisdictions: 0.2B_0 (~DFO's USR), 0.4B_0 (often a target level above B_{MSY}), and B_0 (equilibrium spawning biomass).

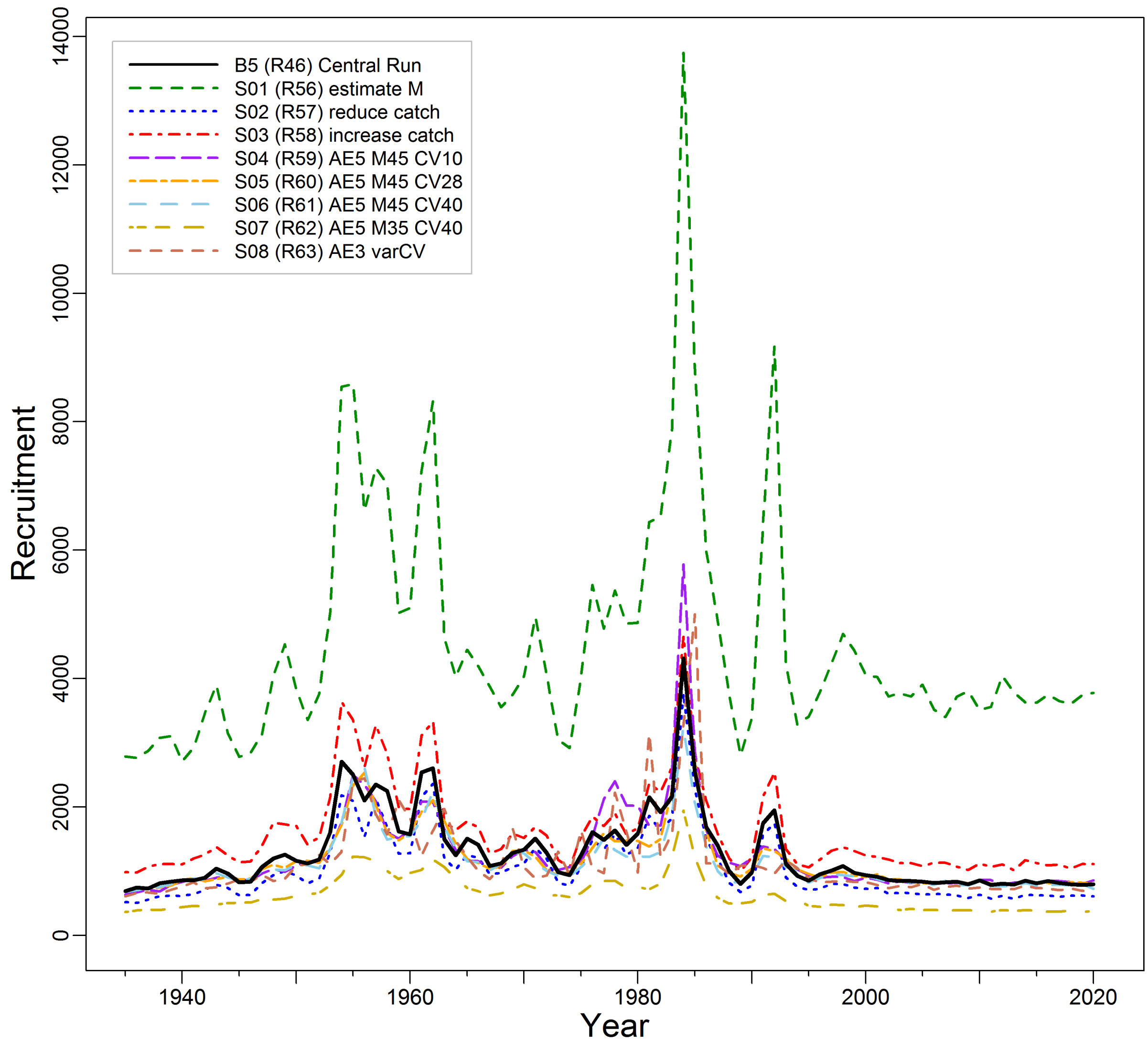


Figure F.35. REBS north sensitivity: model trajectories of median recruitment of one-year old fish (R_t, 1000s) for the central run of the composite base case and 8 sensitivity runs (see legend upper right).

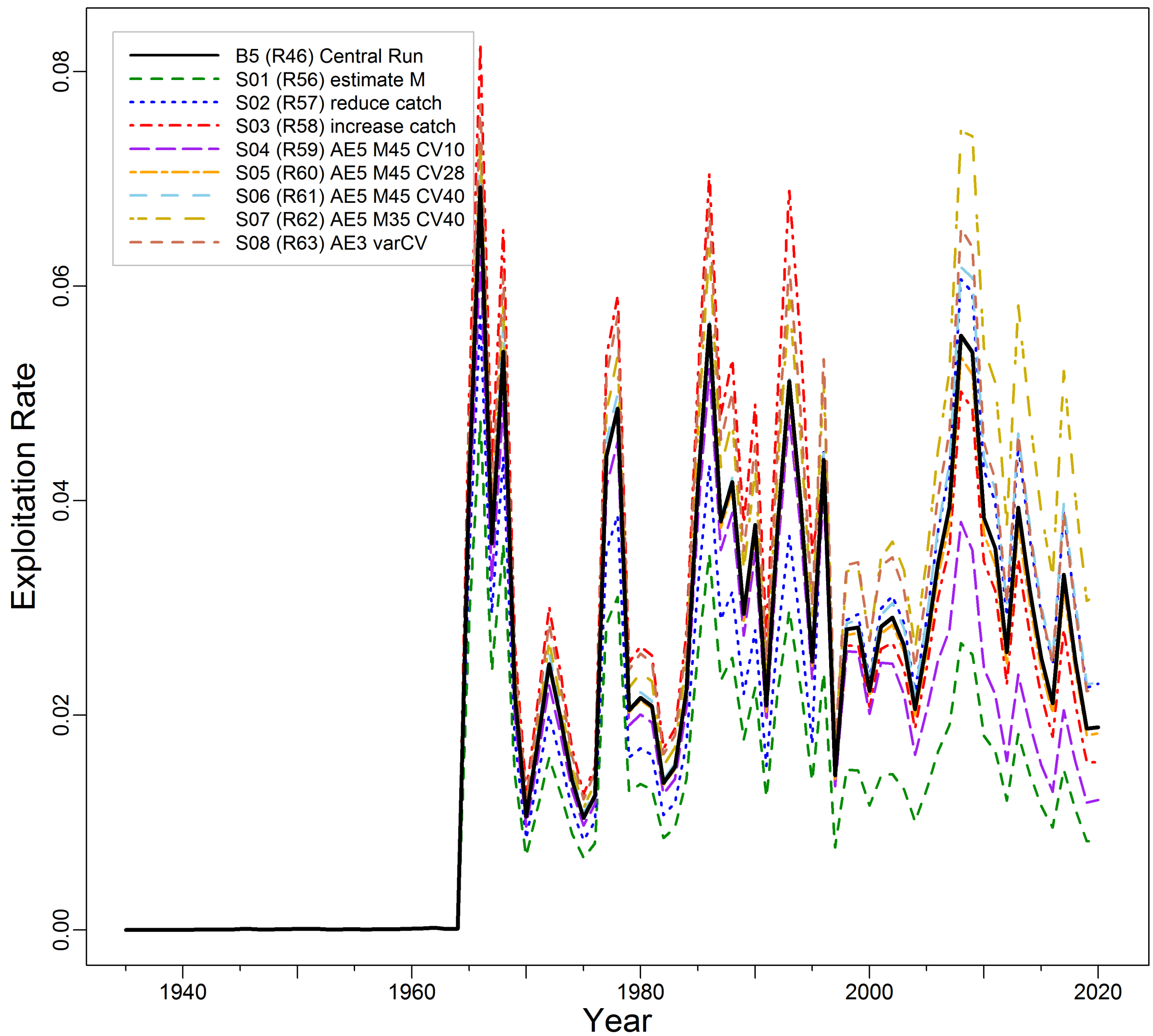


Figure F.36. REBS north sensitivity: model trajectories of median exploitation rate of vulnerable biomass (u_t) for the central run of the composite base case and 8 sensitivity runs (see legend upper left).

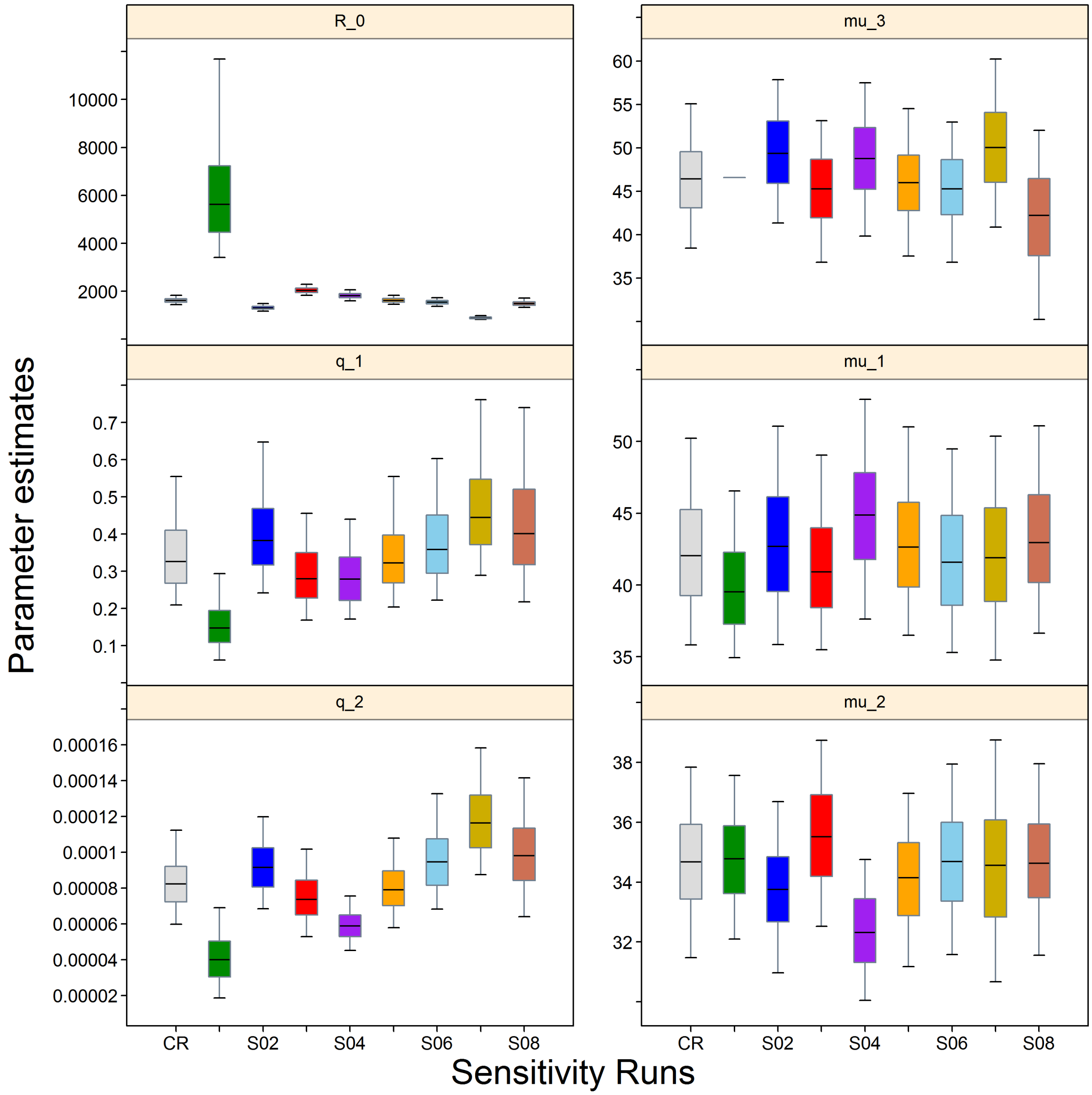


Figure F.37. REBS north sensitivity: quantile plots of selected parameter estimates (R_0, q_g, μ_g) comparing the central run with 8 sensitivity runs. Subscripts: g=1 corresponds to the WCHG synoptic survey, g=2 corresponds to the commercial Trawl fishery, and g=3 corresponds to the commercial Other fishery. See text on sensitivity numbers. The boxplots delimit the 0.05, 0.25, 0.5, 0.75, and 0.95 quantiles; outliers are excluded.

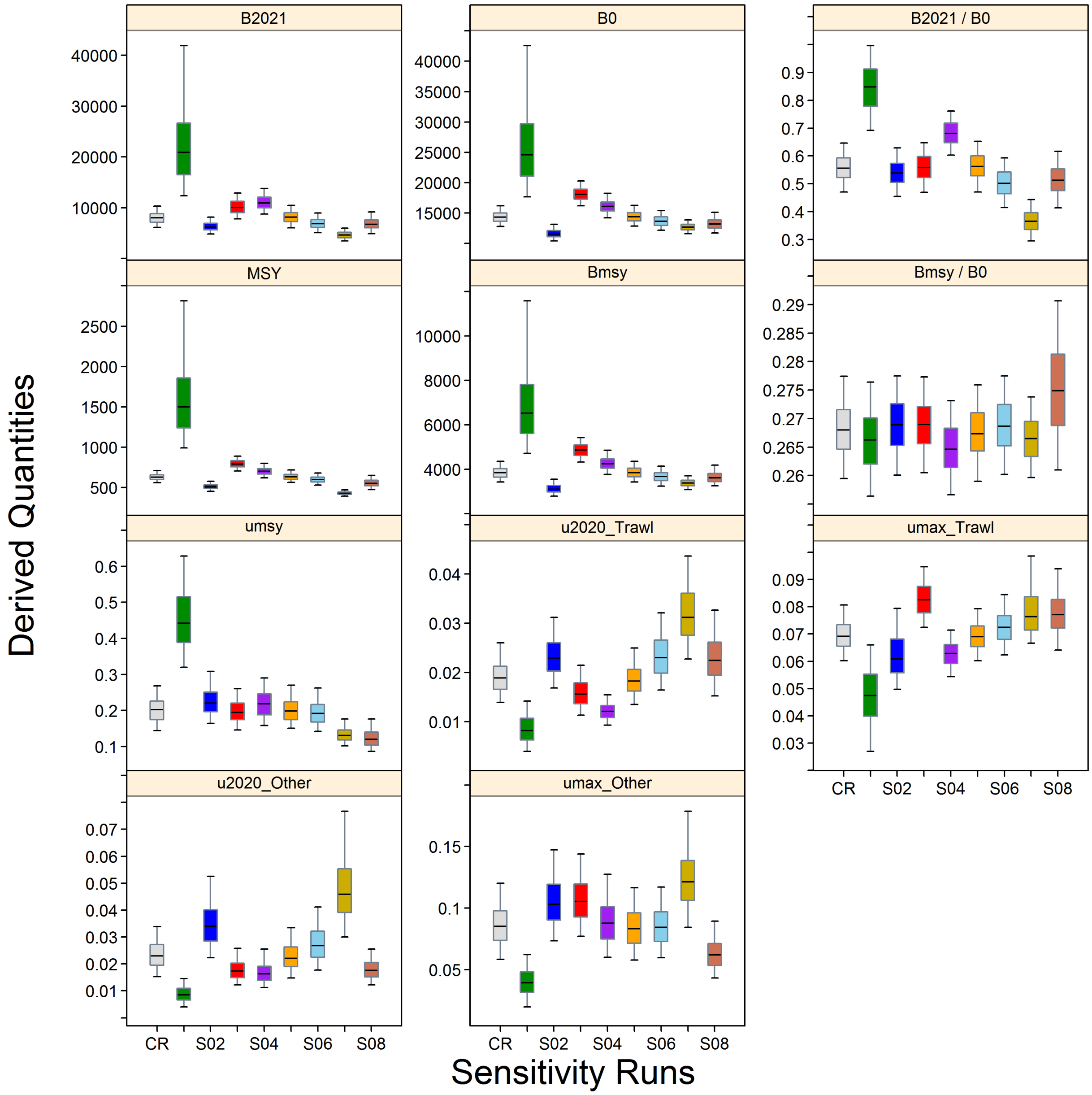


Figure F.38. REBS north sensitivity: quantile plots of selected derived quantities (B_{2021}, B_0, B_{2021}/B_0, MSY, B_{MSY}, B_{MSY}/B_0, u_{2020}, u_{MSY}, u_{max}) comparing the central run with 8 sensitivity runs. See text on sensitivity numbers. The boxplots delimit the 0.05, 0.25, 0.5, 0.75, and 0.95 quantiles; outliers are excluded.

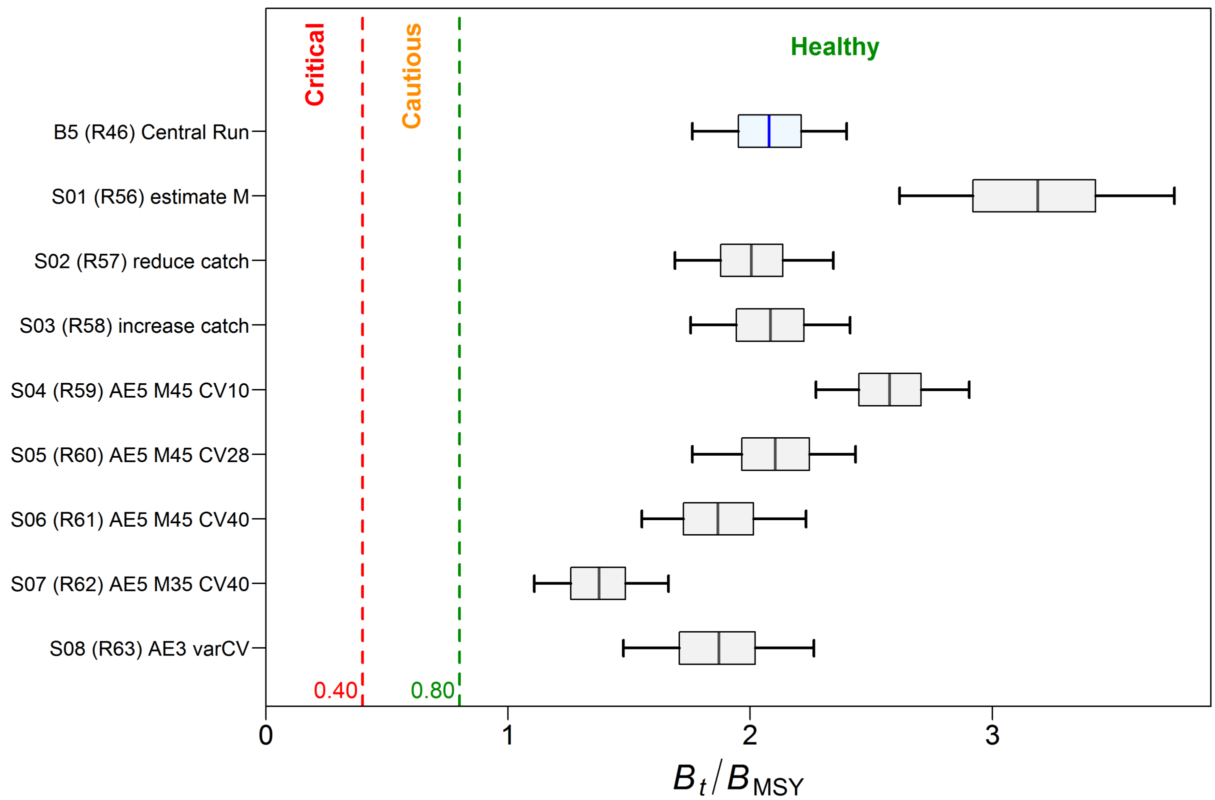


Figure F.39. REBS north sensitivity: stock status at beginning of 2021 relative to the DFO PA provisional reference points of 0.4B_{MSY} and 0.8B_{MSY} for the central run of the composite base case (Run46) and 8 sensitivity runs: S01 (R56) = estimated M using a normal prior: $\mathcal{N}(0.045, 0.009)$; S02 (R57) = reduced commercial catch for 1965-1995 by 33%; S03 (R58) = increased commercial catch for 1965-1995 by 50%; S04 (R59) = used wide ageing error (AE $\pm$5 ages), fixed M=0.045, and set CPUE c_{p}=0.10; S05 (R60) = used wide AE, fixed M=0.045, and set CPUE c_{p}=0.2759; S06 (R61) = used wide AE, fixed M=0.045, and set CPUE c_{p}=0.40; S07 (R62) = used wide AE, fixed M=0.035, and set CPUE c_{p}=0.40; ; S08 (R63) = used moderate AE with increasing CV, fixed M=0.045, and set CPUE c_{p}=0.2759. Boxplots show the 0.05, 0.25, 0.5, 0.75, and 0.95 quantiles from the MCMC posterior.

F.3. REBS SOUTH (3CD5AB)

The base case for REBS south was selected from model runs 11-19 and pooled. Important decisions made during the assessment of REBS south included:

- fixed natural mortality M to three levels: 0.035, 0.045, and 0.055, each with CPUE process error c_p of 0.1, 0.2539, and 0.4, for a total of nine reference models using two axes of uncertainty:
  - B1 (R18): M=0.035, CPUE c_p=0.1
  - B2 (R12): M=0.035, CPUE c_p=0.2529
  - B3 (R15): M=0.035, CPUE c_p=0.4
  - B4 (R17): M=0.045, CPUE c_p=0.1
  - B5 (R11): M=0.045, CPUE c_p=0.2529
  - B6 (R14): M=0.045, CPUE c_p=0.4
  - B7 (R19): M=0.055, CPUE c_p=0.1
  - B8 (R13): M=0.055, CPUE c_p=0.2529
  - B9 (R16): M=0.055, CPUE c_p=0.4
- set plus class A to 80 years;
- used three survey abundance index series (QCS Synoptic, WCVI Synoptic, and NMFS Triennial), two with age frequency (AF) data;
- used one commercial bottom trawl fishery abundance index series (bottom trawl CPUE index, 1996-2019);
- assumed two fisheries (1 = 'Trawl' – commercial bottom + midwater trawl; 2 = 'Other' – halibut longline, sablefish trap, lingcod longline, inshore longline, salmon troll), each with pooled catches and AF data);
- assumed two sexes (females, males);
- used normal priors for some commercial selectivity parameters: Trawl $\mu_4 \sim \mathcal{N}(33.6, 3.36)$, Other $\mu_5 \sim \mathcal{N}(56.5, 5.65)$, Other $v_{5\mathrm{L}} \sim \mathcal{N}(6, 1.2)$, and uniform priors on the remaining commercial selectivity parameters;
- fixed trawl selectivity parameters to MPD estimates for the QCS and WCVI synoptic surveys, and to arbitrary estimates for the NMFS triennial survey (μ_3=36, Δ_3=0, $v_{3\mathrm{L}}$=2.5);
- applied abundance reweighting: added CV process error to index CVs, c_p=0.25 for surveys and $c_\mathrm{p} \in \{0.1, 0.2529, 0.4\}$ for commercial CPUE series (see Appendix E);
- applied composition reweighting: adjusted AF effective sample sizes using the TA1.8 mean-age weighting method of Francis (2011);
- fixed standard deviation of recruitment residuals (σ_R) to 0.9;
- used 'moderate' ageing error matrix depicted as a normal distribution spanning three ages on either side of 'true age' (matrix diagonal), described in Appendix D, Section D.2.3 and plotted in Figure D.26 (left panel).

Three fixed M values and three CPUE c_p values produced nine separate model runs for potential use in a composite base case. During the peer review process, the participants agreed to use only six component runs because three of the nine runs had poor MCMC diagnostics (see Section F.3.3.). The posterior distributions of the six selected runs were pooled as a base case for advice to managers. The central run of the composite base case (Run11: M=0.045, c_p=0.2529) was used as an example reference case against which six sensitivity runs were compared.

All model runs were reweighted (i) one time for abundance, by adding process error c_p to the index CVs for the QCS Synoptic, WCVI Synoptic, NMFS Triennial, and commercial trawl CPUE series, and (ii) twice for composition (effective sample size for AF data) using the mean-age procedure of Francis (2011). Most of the runs needed two composition reweights to achieve stability; Run19 only required one reweight.

F.3.1. REBS South – Central Run MPD

The modelling procedure used here first determines the best fit (MPD) to the data by minimising the negative log likelihood. Because the RER composite base case examined nine models, only the central run (M=0.045, CPUE c_{p}=0.2529, moderate AE matrix) was used as an example (Tables F.64 and F.65). These MPD runs became the starting points for the MCMC simulations. The following plot references apply to the central run.

- Figure F.40 – survey index fits across all survey years;
- Figures F.41 to F.43 – individual survey fits and residuals;
- Figure F.44 – bottom trawl CPUE fit and its residuals;
- Figures F.45 to F.47 model fits to the female and male age frequency data for the commercial Trawl fishery and combined-sex residuals;
- Figures F.48 to F.49 model fits to the female and male age frequency data for the commercial Other fishery and combined-sex residuals;
- Figure F.50 to F.53 – model fits and residuals to the age data for the Queen Charlotte Sound (QCS) and West Coast Vancouver Island (WCVI) synoptic surveys;
- Figure F.54 – model estimates of mean age compared to the observed mean ages;
- Figure F.55 – the stock-recruitment relationship and recruitment time series;
- Figure F.56 – the recruitment deviations and auto-correlation of these deviations;
- Figure F.57 – estimated gear selectivities, together with the ogive for female maturity;
- Figure F.58 – exploitation rates and catches by gear type over time.

The model fits to the survey abundance indices were generally satisfactory (Figures F.40 to F.43), although the 2018 WCVI index point was poorly fit. The fit to the CPUE index series was much closer when using process error of 10%, causing the biomass to follow the CPUE signal more closely whereas higher CPUE c_{p}values discounted the series. The removal of the CPUE index series was not attempted for this stock because its equivalent removal for REBS north caused poor model behaviour. It was noted that for REBS south, like REBS north, a CPUE series had a stabilising influence on the model.

Fits to the commercial age frequency data for the Trawl fishery were generally fair (Figure F.45); however, the MPD fit often underestimated the observed age proportions. The fits to AFs for the Other fishery were very poor, but there was only one AF sample which may have been non-representative (Figure F.45).

Fits to the QCS survey AFs were fair but featured many negative residuals (Figure F.51). Fits to the WCVI survey AFs were a bit better than those for the QCS survey. Both surveys suffered from a lack of data because many of the surveyed years either did not have AF data or the data had not been aged.

Model estimates of mean age only partially matched the observed mean ages (Figure F.54). As in REBS north, the observed mean weights from Trawl's initial years did not match the model's estimates, with the model estimating far more older fish than were present in the age sample, indicating that these samples may not have been representative of the fishery. The recruitment estimates appeared to be typical of those in other rockfish assessments (Figure F.55), with several large recruitment events. There was obvious autocorrelation in the recruitment residuals, which attenuated after the first 20 lags. (Figure F.56).

The MPD estimate for the commercial Trawl fishery selectivity indicated that this fishery captured substantial amounts of immature fish whereas the Other fishery caught only mature fish (Figure F.57). The selectivity curves for the two synoptic surveys were well to the left of the maturity ogive, which confirmed that they also intercept fairly young fish. This was especially true for the QCS synoptic survey as the AF and length frequency data indicated that this survey captured much younger fish than did the WCVI synoptic survey.

F.3.1.1. Tables – REBS south CR MPD

Table F.64. REBS south CR.11.02: priors and MPD estimates for estimated parameters. Prior information – distributions: 0 = uniform, 1 = normal, 2 = lognormal, 5 = beta

Phase	Range	Type	(Mean,SD)	Initial	MPD
R_0 **(recruitment in virgin condition)**					
1	(1,10000000)	0	(0,0)	10000	708.727
M_s **(natural mortality by sex s, where $s = 1$ [female], 2 [male])**					
-3	(0.02,0.15)	1	(0.035,0.01)	0.045	0.045
-3	(0.02,0.15)	1	(0.035,0.01)	0.045	0.045
-3	(0.01,0.5)	0	(0,0)	0.12	0.12
h **(steepness of spawner-recruit curve)**					
-1	(0.01,5)	0	(0.7,0.6)	0.7	0.7
ϵ_t **(recruitment deviations)**					
2	(-15,15)	1	(0,0.9)	0	Fig F.56
ω **(initial recruitment)**					
-1	(0,2)	0	(1,0.1)	1	1

Table F.65. REBS south CR.11.02: priors and MPD estimates for index g (survey and commercial).

Index g	Phase	Range	Type	(Mean,SD)	Initial	MPD	exp (MPD)
CPUE catchability mode ($\log q_g$ where $g = 4, ...5$)							
4	1	(-15,15)	0	(0,0.1)	-1.60944	-8.878	0.00013942
Survey catchability mode ($\log q_g$, where $g = 1, ..., 3$)							
1	1	(-5,5)	0	(0,0.6)	-1.6	-2.6517	0.070533
2	1	(-5,5)	0	(0,0.6)	-1.6	-3.4818	0.03075
3	1	(-5,5)	0	(0,0.6)	-1.6	-3.083	0.045821
Commercial selectivity (μ_g, where $g = 4, 5$)							
4	3	(5,60)	1	(33.6,3.36)	33.6	25.294	
5	3	(5,70)	1	(56.5,5.65)	56.5	54.856	
Survey selectivity (μ_g, where $g = 1, ..., 3$)							
1	3	(5,70)	0	(36,7.2)	36	10.781	
2	3	(5,70)	0	(36,7.2)	36	25.135	
3	-3	(5,70)	1	(36,7.2)	36	36	
Variance (left) of commercial selectivity curve ($\log v_{gL}$, where $g = 4, 5$)							
4	4	(-15,15)	0	(2.5,2.5)	2.5	4.42	
5	4	(-15,15)	1	(6,0.6)	6	6.3914	
Variance (left) of survey selectivity curve ($\log v_{gL}$, where $g = 1, ..., 3$)							
1	4	(-15,15)	0	(2.5,2.5)	2.5	2.4153	
2	4	(-15,15)	0	(2.5,2.5)	2.5	4.3877	
3	-4	(-15,15)	0	(2.5,2.5)	2.5	2.5	
Shift in commercial selectivity for males (Δ_g, where $g = 4, 5$)							
4	4	(-8,10)	0	(0,1)	0	1.4292	
5	4	(-8,10)	1	(0.6,0.6)	0.6	0.64191	
Shift in survey selectivity for males (Δ_g, where $g = 1, ..., 3$)							
1	4	(-8,10)	0	(0,1)	0	-0.63292	
2	4	(-8,10)	0	(0,1)	0	1.6586	
3	-4	(-8,10)	0	(0,1)	0	0	

Table F.66. REBS south CR.11.02: 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 $g = 1...3$ refer to the trawl surveys and subscript $g = 4+$ refers to the commercial fishery.

Description	Negative log likelihood	Value
Survey 1	$\log \mathsf{L}_3 \left(\boldsymbol{\Theta} \middle\| \left\{\hat{I}_{t1}\right\}\right)$	1.36
Survey 2	$\log \mathsf{L}_3 \left(\boldsymbol{\Theta} \middle\| \left\{\hat{I}_{t2}\right\}\right)$	2.64
Survey 3	$\log \mathsf{L}_3 \left(\boldsymbol{\Theta} \middle\| \left\{\hat{I}_{t3}\right\}\right)$	0.45
CPUE 1	$\log \mathsf{L}_3 \left(\boldsymbol{\Theta} \middle\| \left\{\hat{I}_{t1}\right\}\right)$	-21.56
CAs 1	$\log \mathsf{L}_2 \left(\boldsymbol{\Theta} \| \{\hat{p}_{at1s}\}\right)$	-1315.96
CAs 2	$\log \mathsf{L}_2 \left(\boldsymbol{\Theta} \| \{\hat{p}_{at2s}\}\right)$	-1316.73
CAc 1	$\log \mathsf{L}_2 \left(\boldsymbol{\Theta} \| \{\hat{p}_{at4s}\}\right)$	-2277.25
CAc 2	$\log \mathsf{L}_2 \left(\boldsymbol{\Theta} \| \{\hat{p}_{at5s}\}\right)$	-477.39
Prior	$\log \mathsf{L}_1 \left(\boldsymbol{\Theta} \| \{\epsilon_t\}\right) - \log\left(\pi(\boldsymbol{\Theta})\right)$	10.06
	Objective function $f(\boldsymbol{\Theta})$	-5394.38

F.3.1.2. Figures – REBS south CR MPD

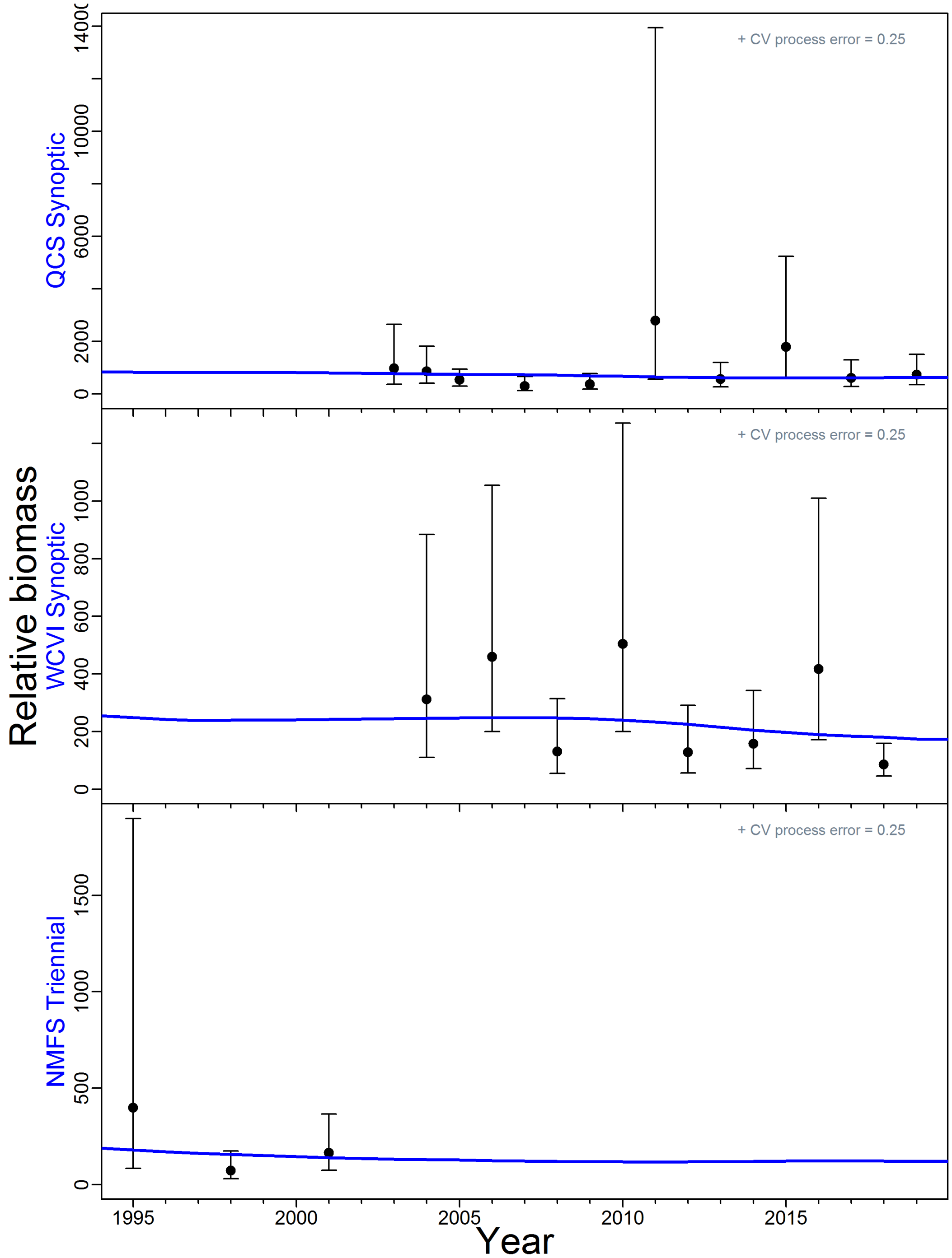


Figure F.40. REBS south CR.11.02: survey index values (points) with 95% confidence intervals (bars) and MPD model fits (curves) for the fishery-independent survey series.

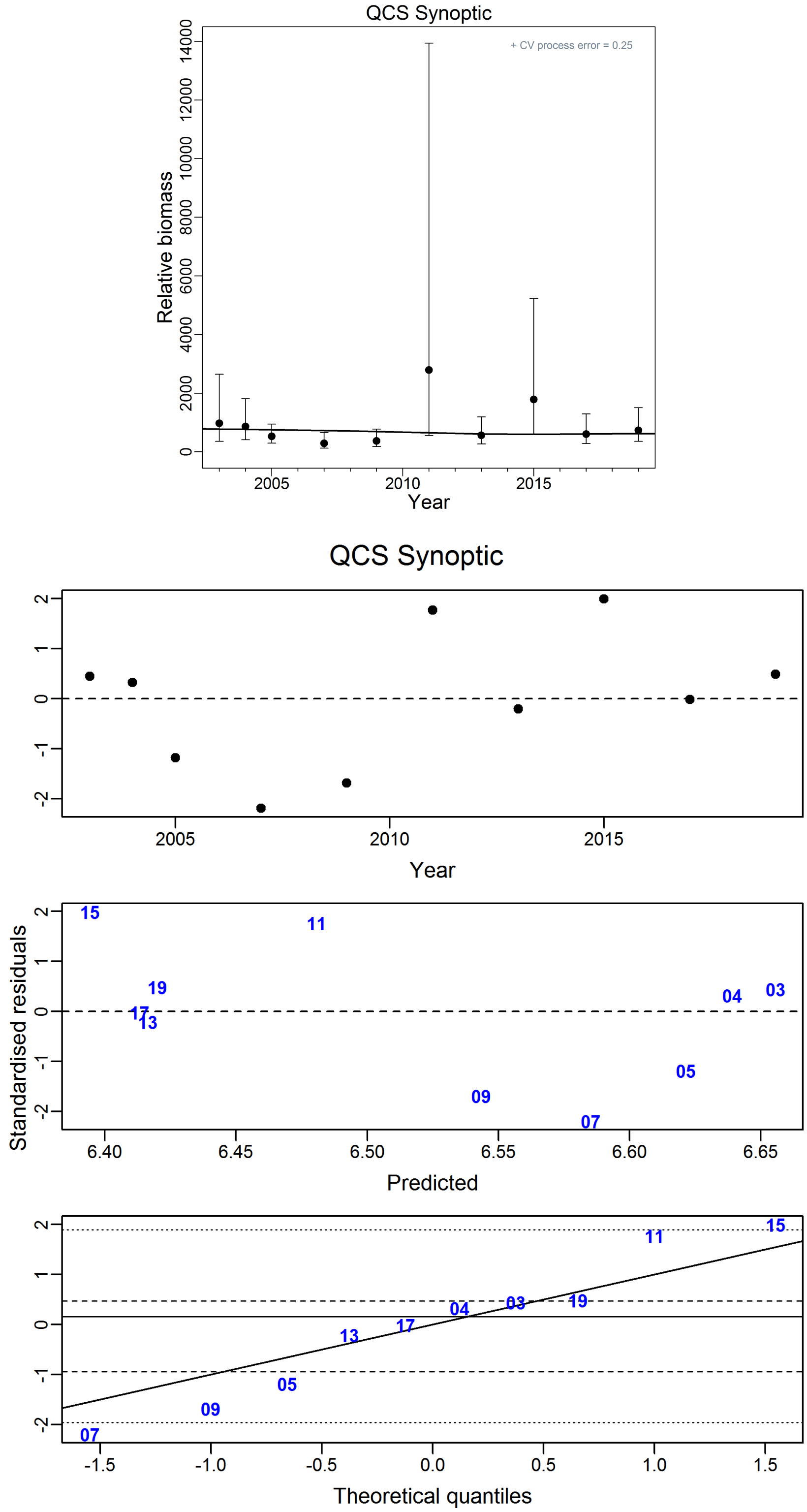


Figure F.41. REBS south CR.11.02: fit (top) and standardised residuals of fits (bottom) of model to QCS Synoptic survey series (MPD values). The three residuals plots show, respectively, residuals by year of index, residuals relative to predicted index, and normal quantile-quantile plot for residuals (horizontal lines give 5, 25, 50, 75 and 95 percentiles).

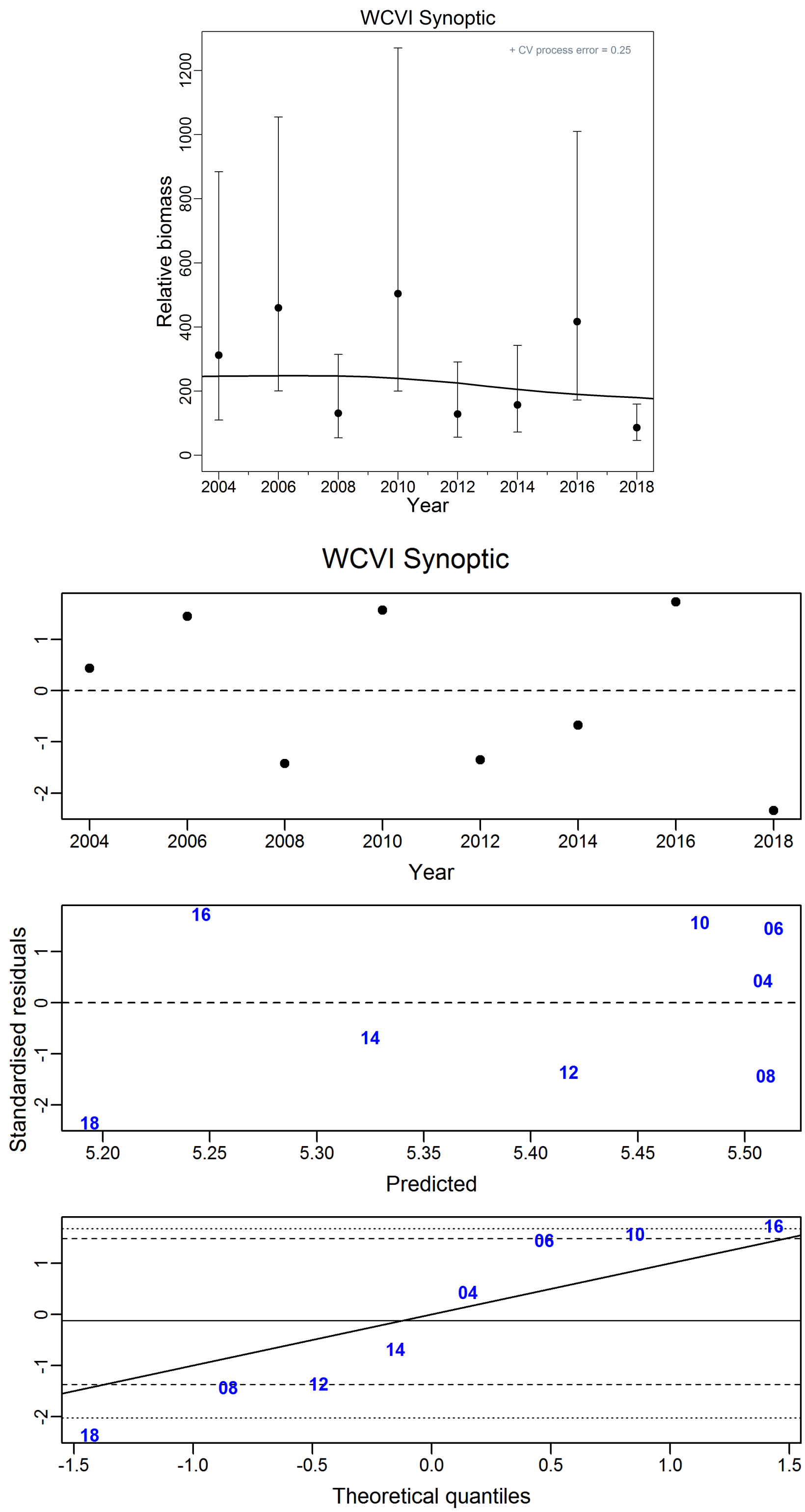


Figure F.42. REBS south CR.11.02: fit (top) and standardised residuals of fits (bottom) of model to WCVI Synoptic survey series (MPD values). The three residuals plots show, respectively, residuals by year of index, residuals relative to predicted index, and normal quantile-quantile plot for residuals (horizontal lines give 5, 25, 50, 75 and 95 percentiles).

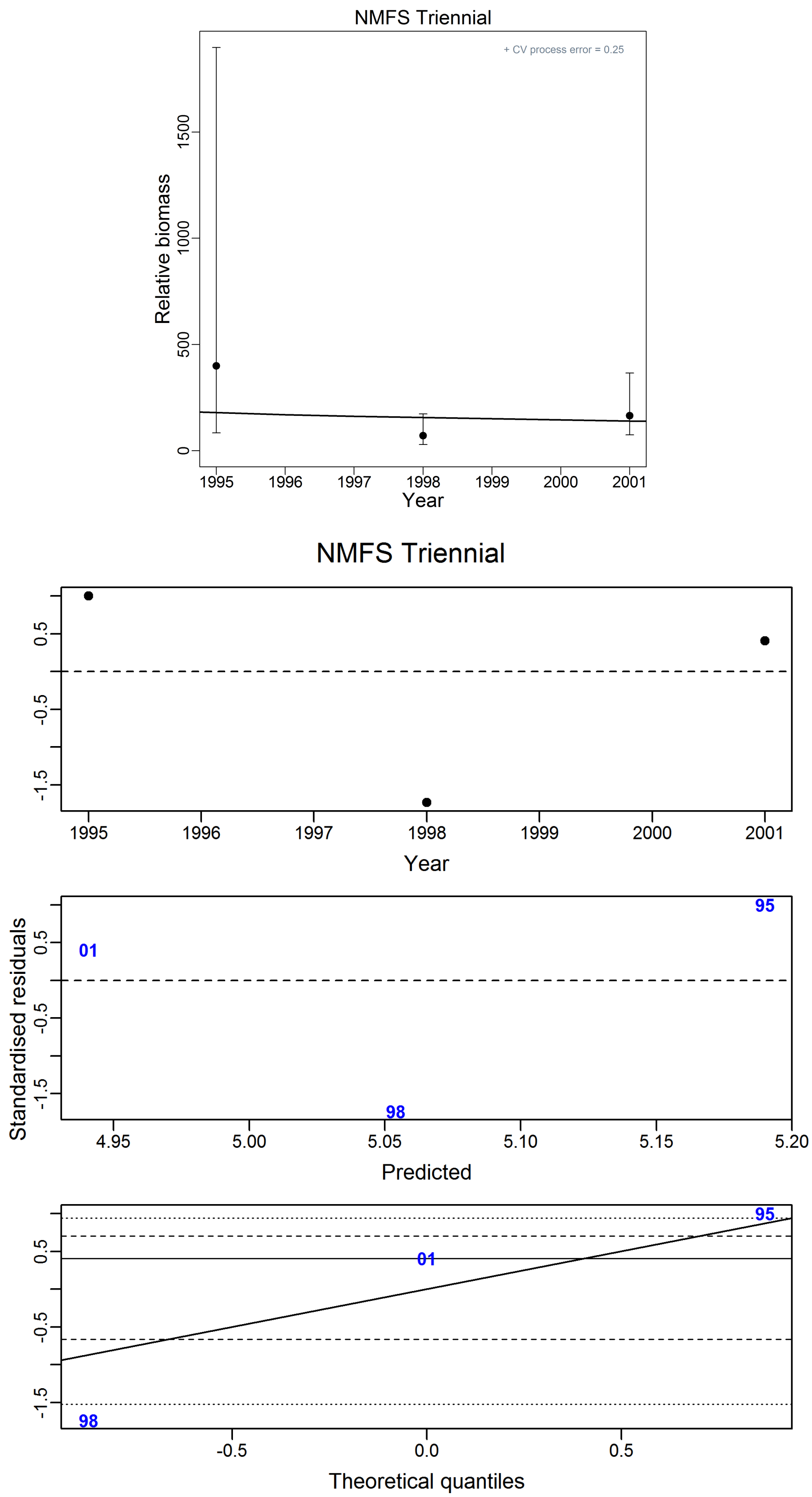


Figure F.43. REBS south CR.11.02: fit (top) and standardised residuals of fits (bottom) of model to NMFS Triennial survey series (MPD values). The three residuals plots show, respectively, residuals by year of index, residuals relative to predicted index, and normal quantile-quantile plot for residuals (horizontal lines give 5, 25, 50, 75 and 95 percentiles).

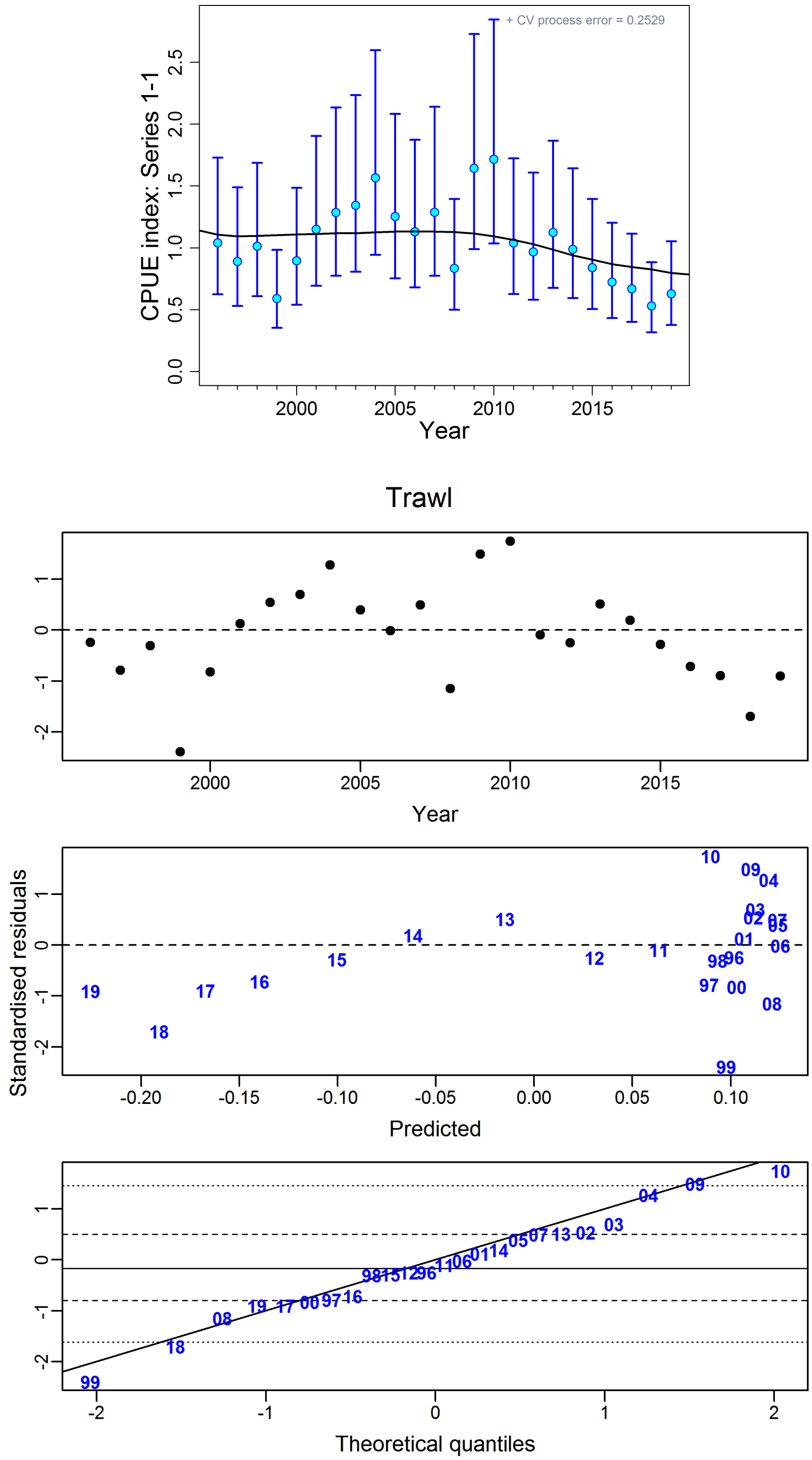


Figure F.44. REBS south CR.11.02: fit (top) and standardised residuals of fits (bottom) of model to Bottom Trawl CPUE series (MPD values). The three residuals plots show, respectively, residuals by year of index, residuals relative to predicted index, and normal quantile-quantile plot for residuals (horizontal lines give 5, 25, 50, 75 and 95 percentiles).

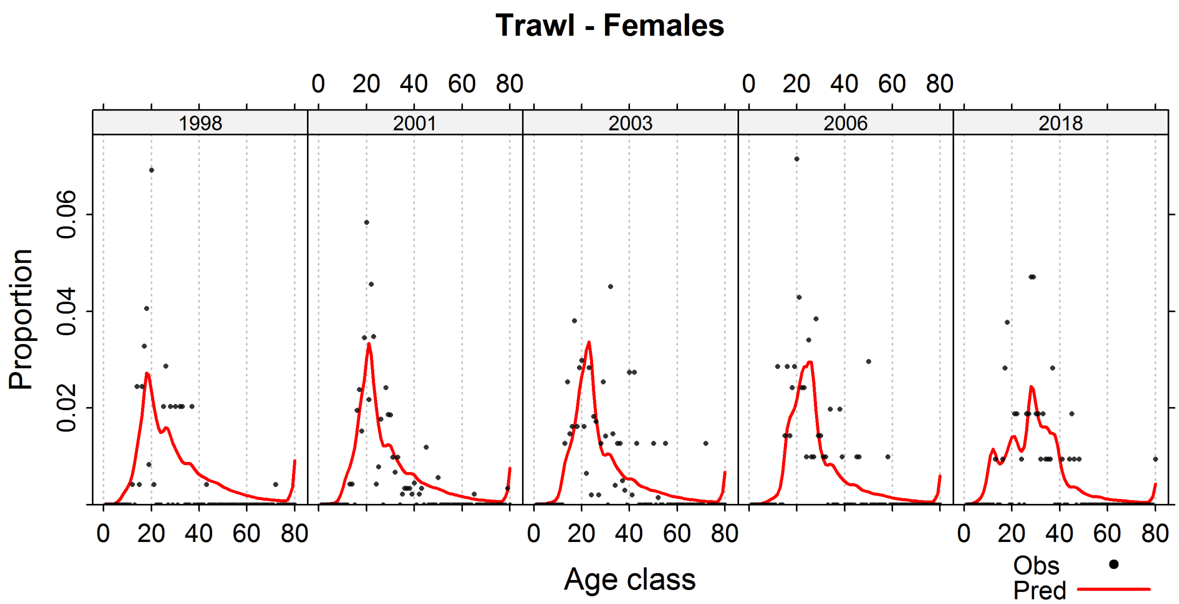


Figure F.45. REBS south CR.11.02: observed and predicted commercial (trawl) proportions-at-age for females. Note that years are not necessarily consecutive.

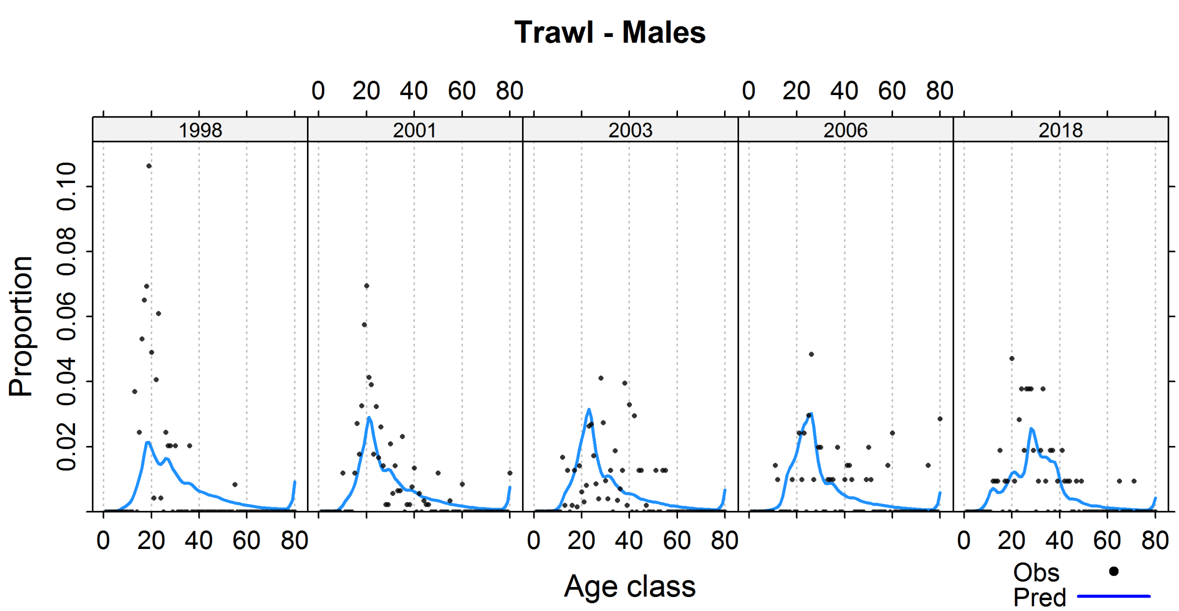


Figure F.46. REBS south CR.11.02: observed and predicted commercial (trawl) proportions-at-age for males. Note that years are not necessarily consecutive.

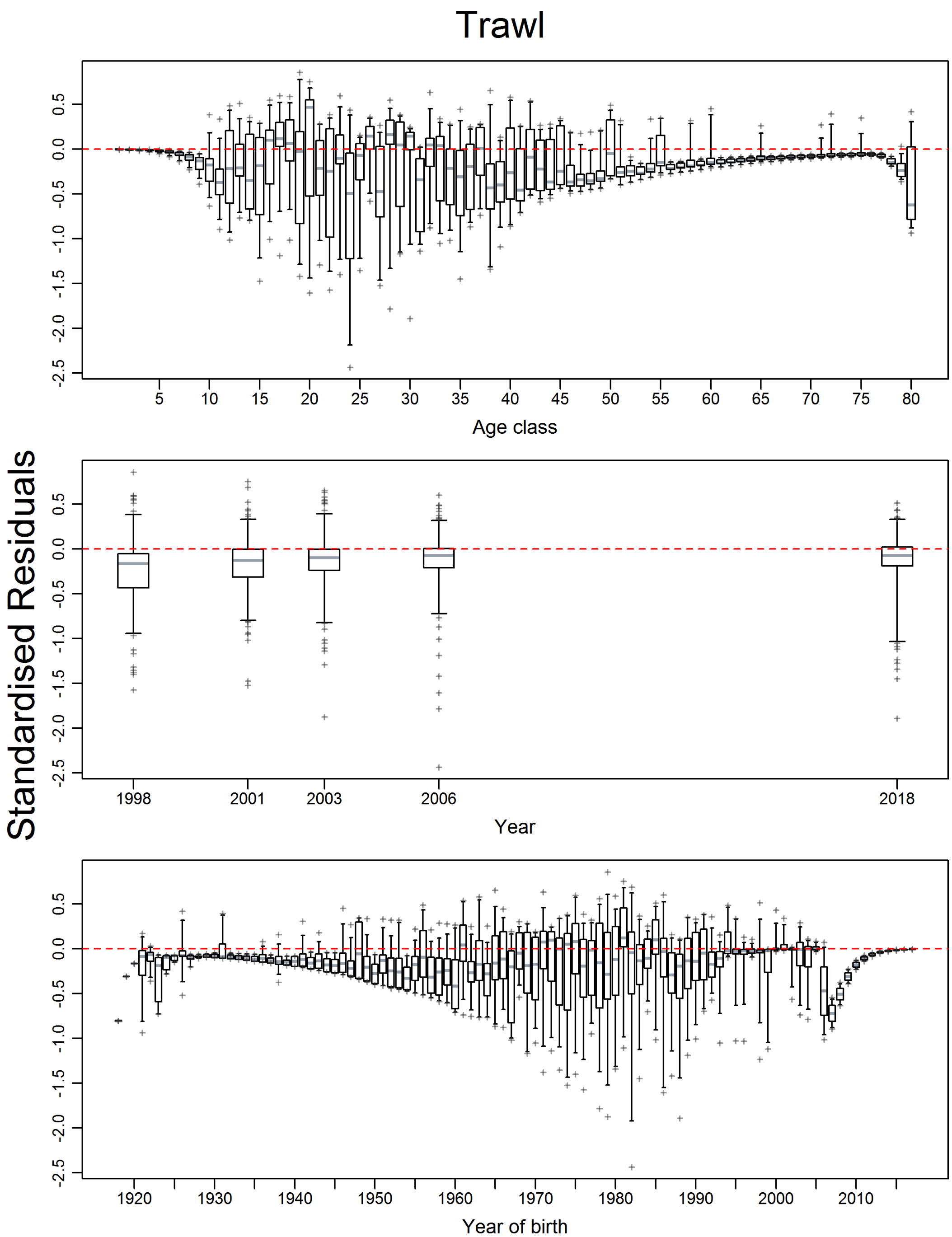
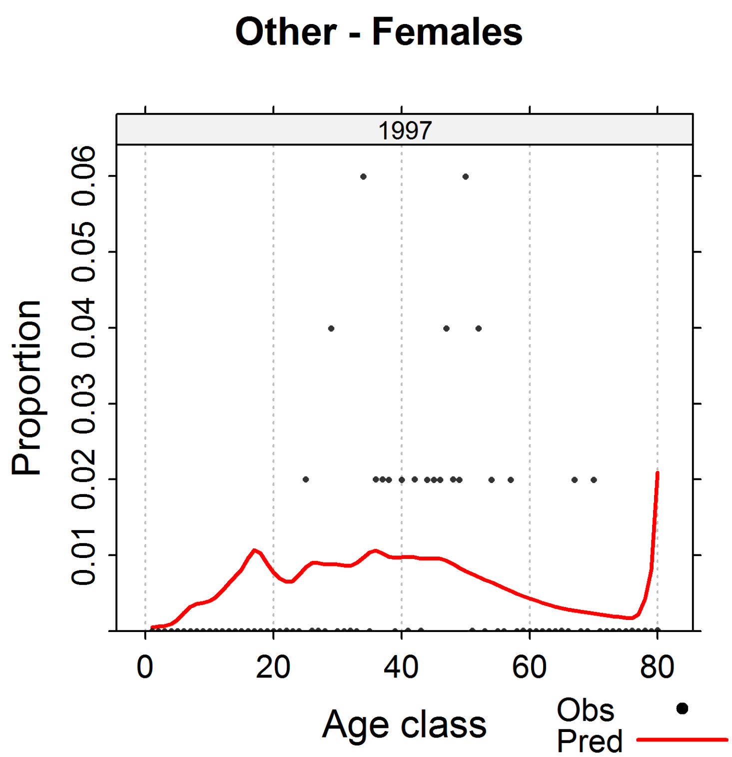


Figure F.47. REBS south CR.11.02: residuals (790 in total) of model fits to commercial proportion-at-age data (MPD values) for Trawl events. Vertical axes are standardised residuals. Boxplots show, respectively, residuals by age class, by year of data, and by year of birth (following a cohort through time). Boxes give quantile ranges (0.25-0.75) with horizontal lines at medians, vertical whiskers extend to the the 0.05 and 0.95 quantiles, and outliers appear as plus signs.



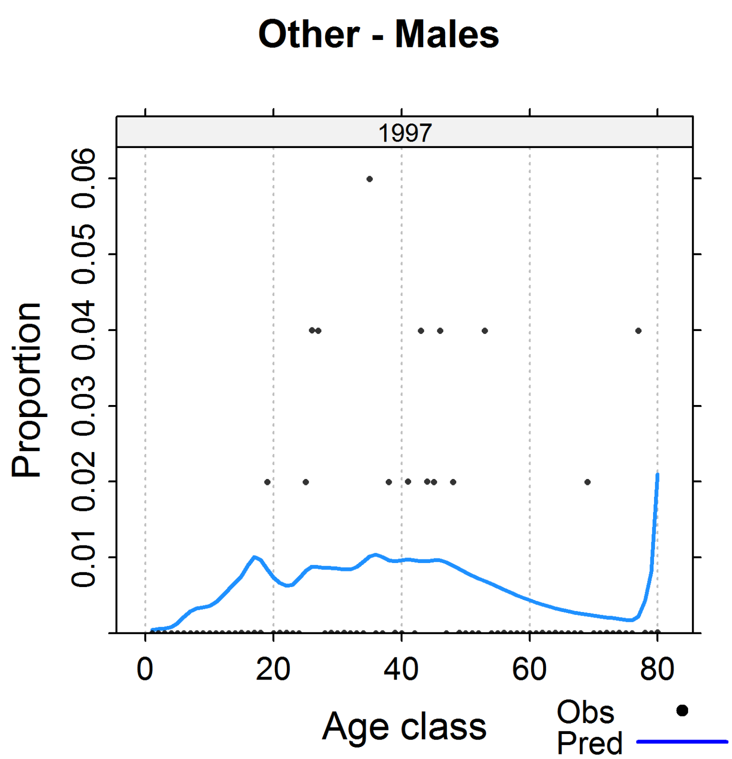


Figure F.48. REBS south CR.11.02: observed and predicted commercial (other) proportions-at-age for females (top) and males (bottom).

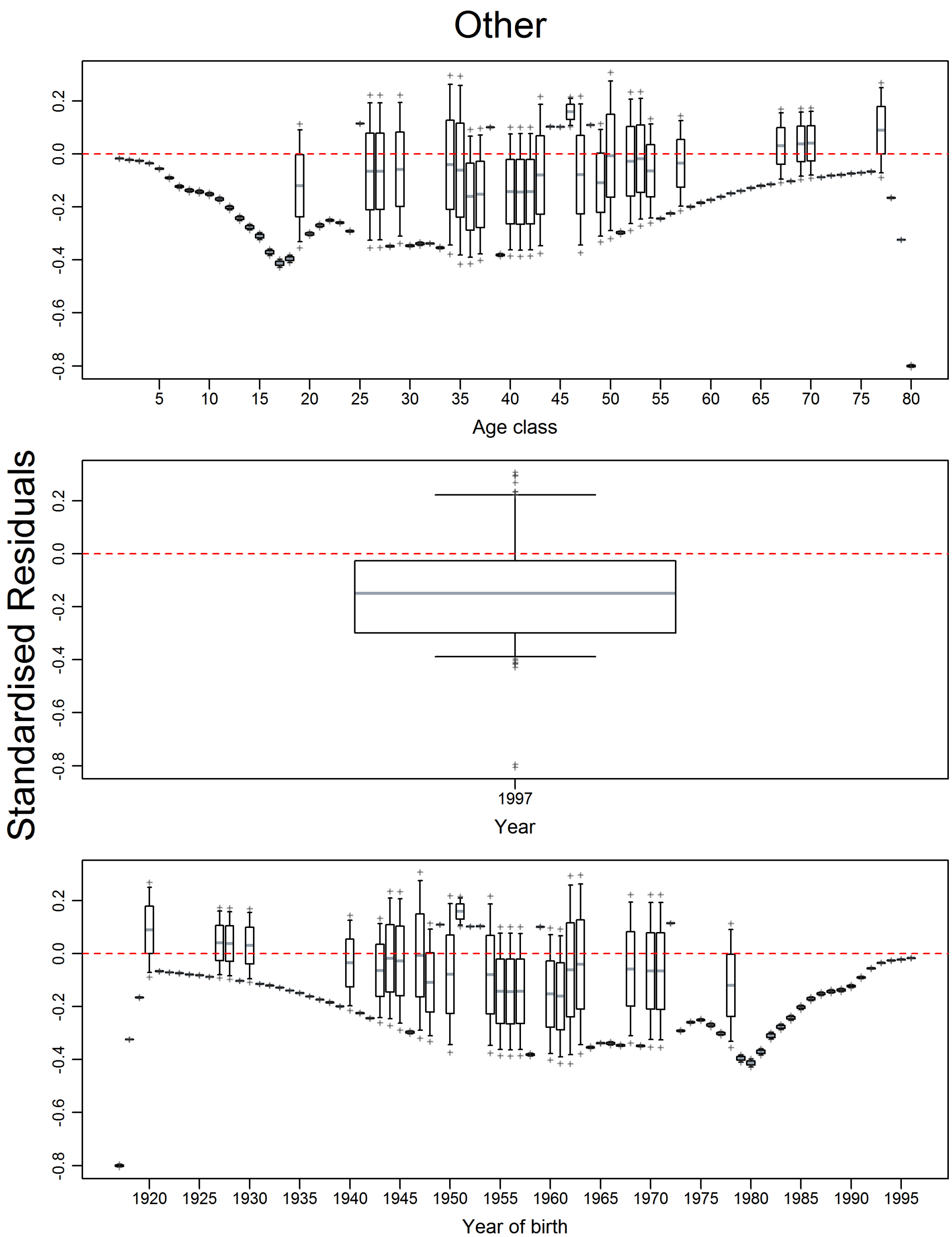


Figure F.49. REBS south CR.11.02: residuals (158 in total) of model fits to commercial proportion-at-age data (MPD values) for Other events. Vertical axes are standardised residuals. Boxplots show, respectively, residuals by age class, by year of data, and by year of birth (following a cohort through time). Boxes give quantile ranges (0.25-0.75) with horizontal lines at medians, vertical whiskers extend to the the 0.05 and 0.95 quantiles, and outliers appear as plus signs.

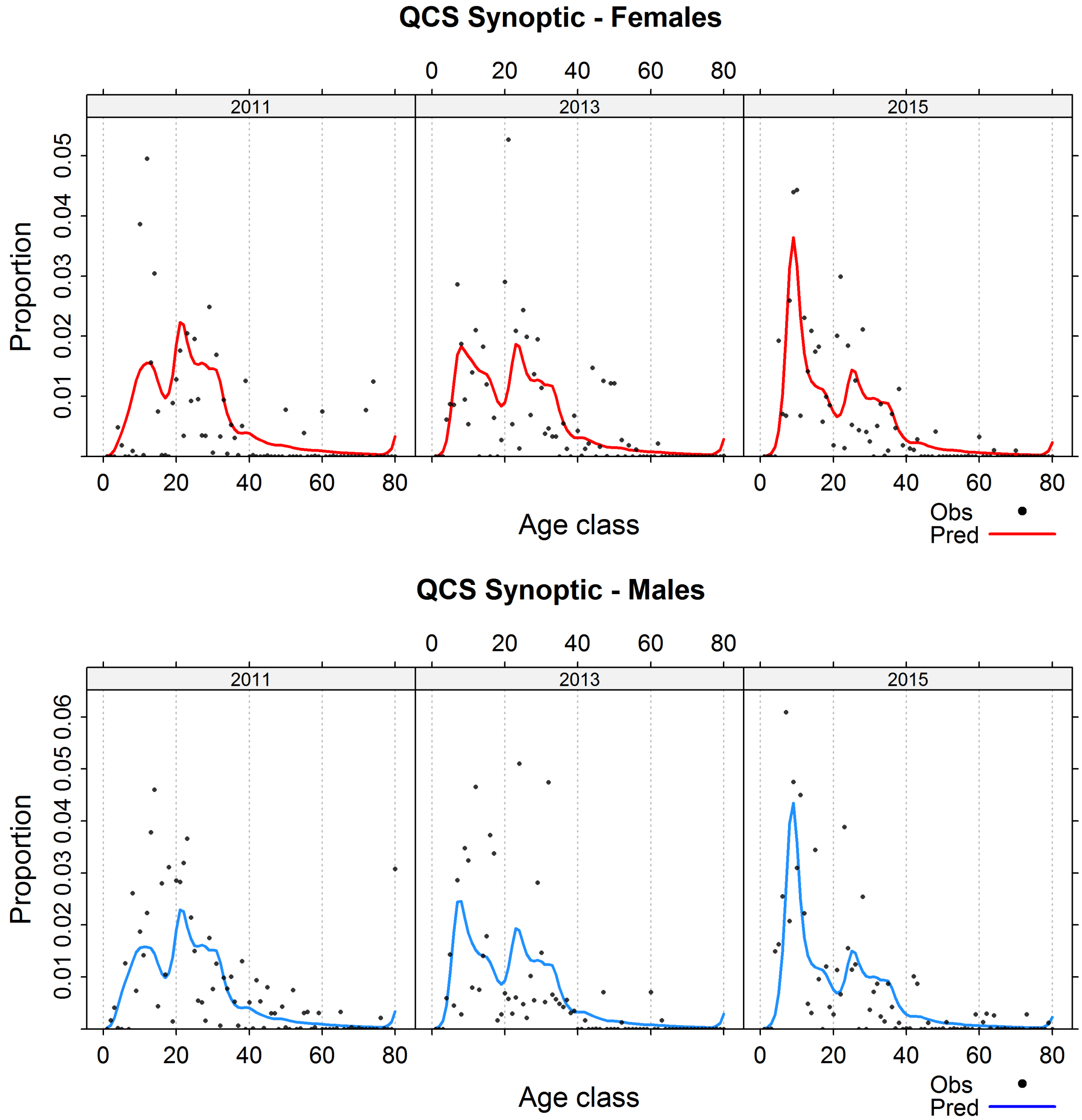


Figure F.50. REBS south CR.11.02: observed and predicted proportions-at-age for QCS Synoptic survey: females (top) and males (bottom).

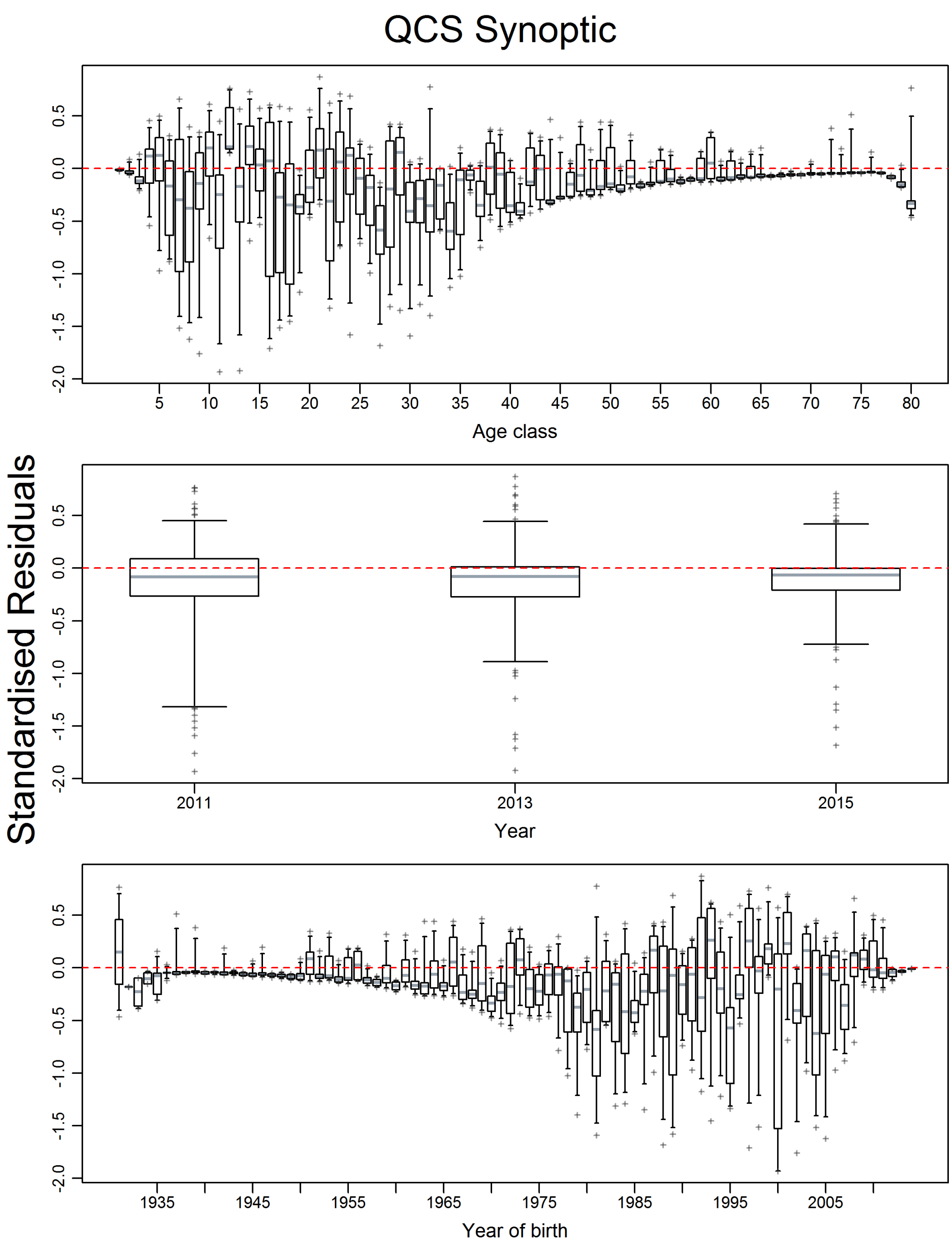
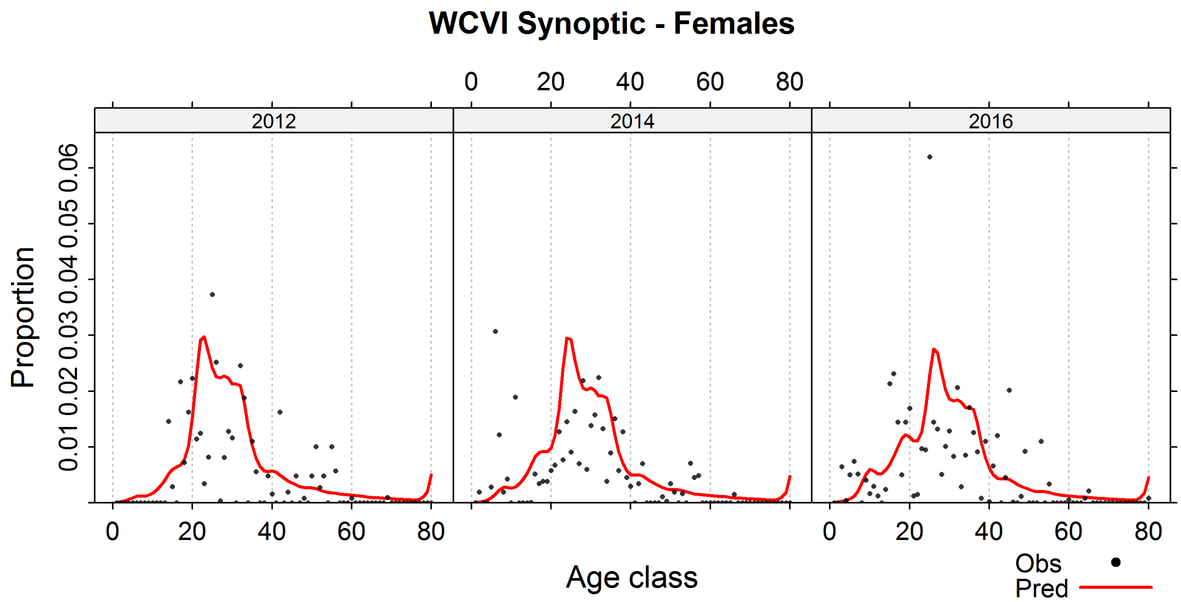


Figure F.51. REBS south CR.11.02: residuals of model fits to proportion-at-age data (MPD values) from the QCS Synoptic survey series. Details as for Figure F.47, for a total of 474 residuals.



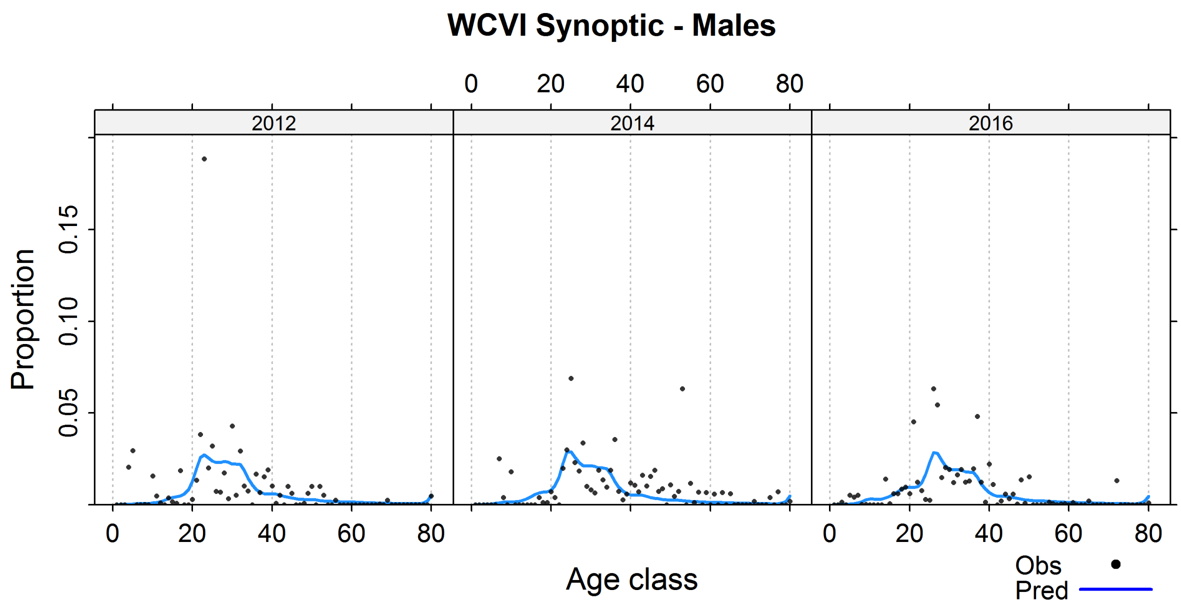


Figure F.52. REBS south CR.11.02: observed and predicted proportions-at-age for WCVI Synoptic survey: females (top) and males (bottom).

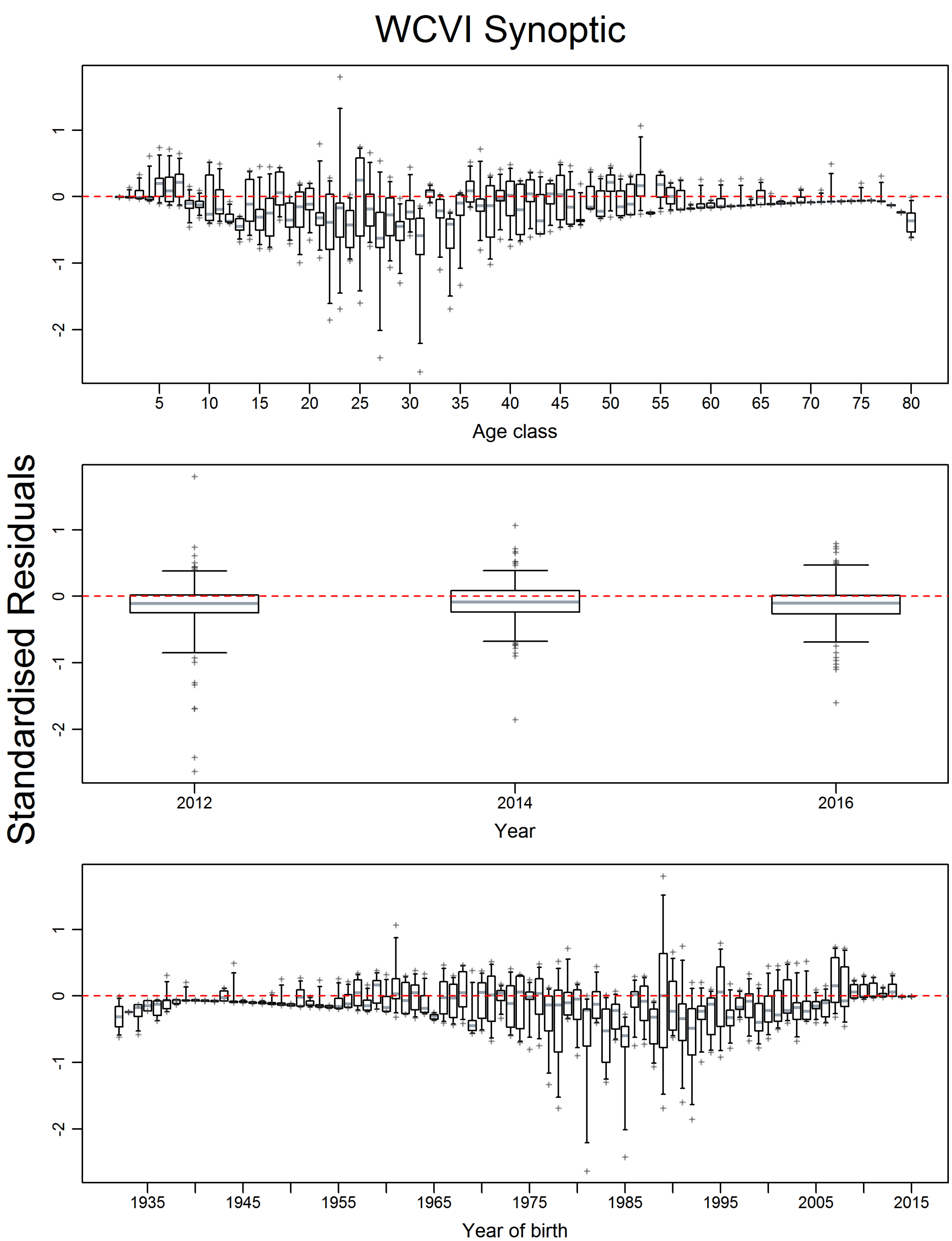


Figure F.53. REBS south CR.11.02: residuals of model fits to proportion-at-age data (MPD values) from the WCVI Synoptic survey series. Details as for Figure F.47, for a total of 474 residuals.

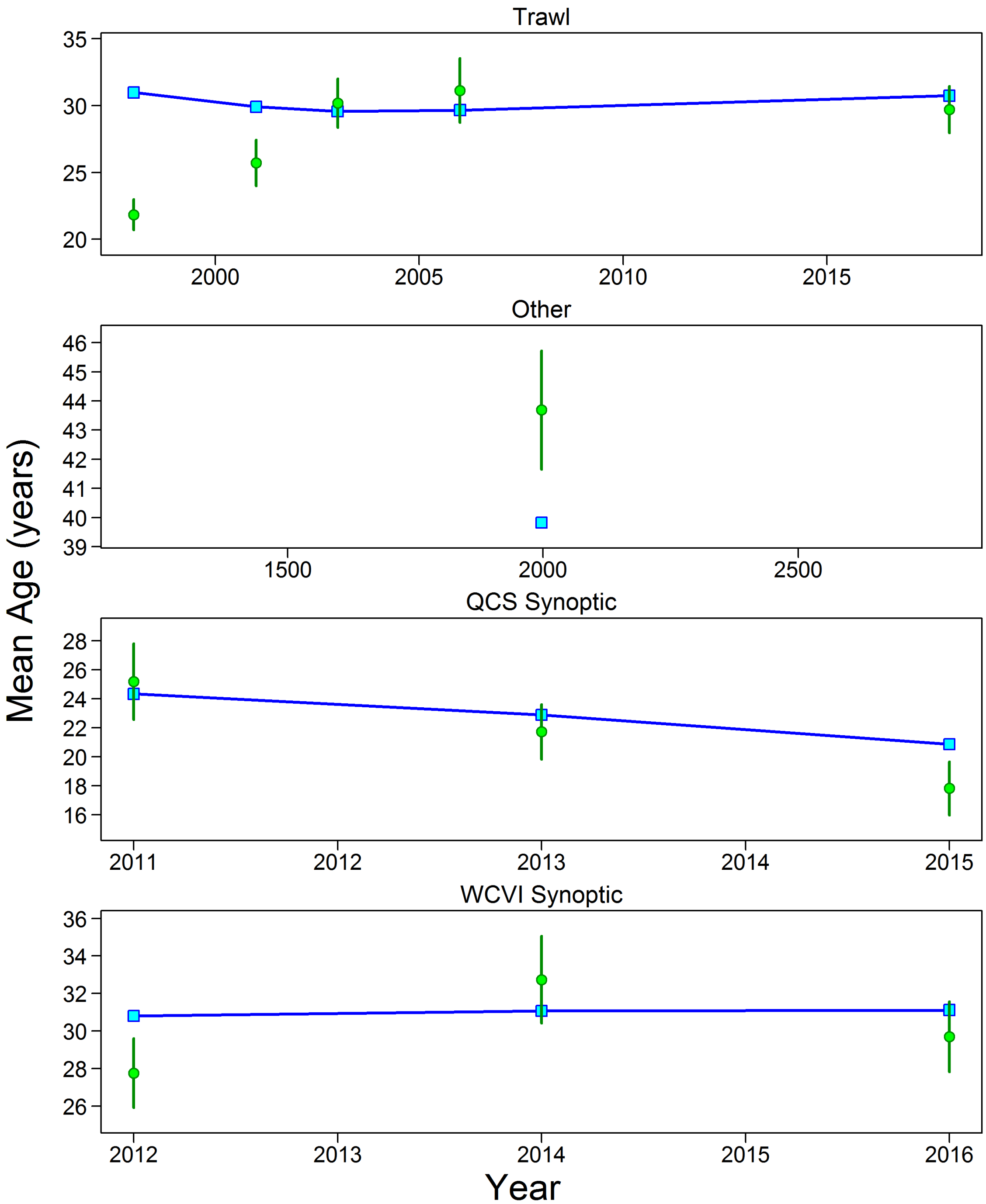


Figure F.54. REBS south CR.11.02: mean ages each year for the data (solid circles) with 95% confidence intervals and model estimates (joined open squares) for the commercial and survey age data.

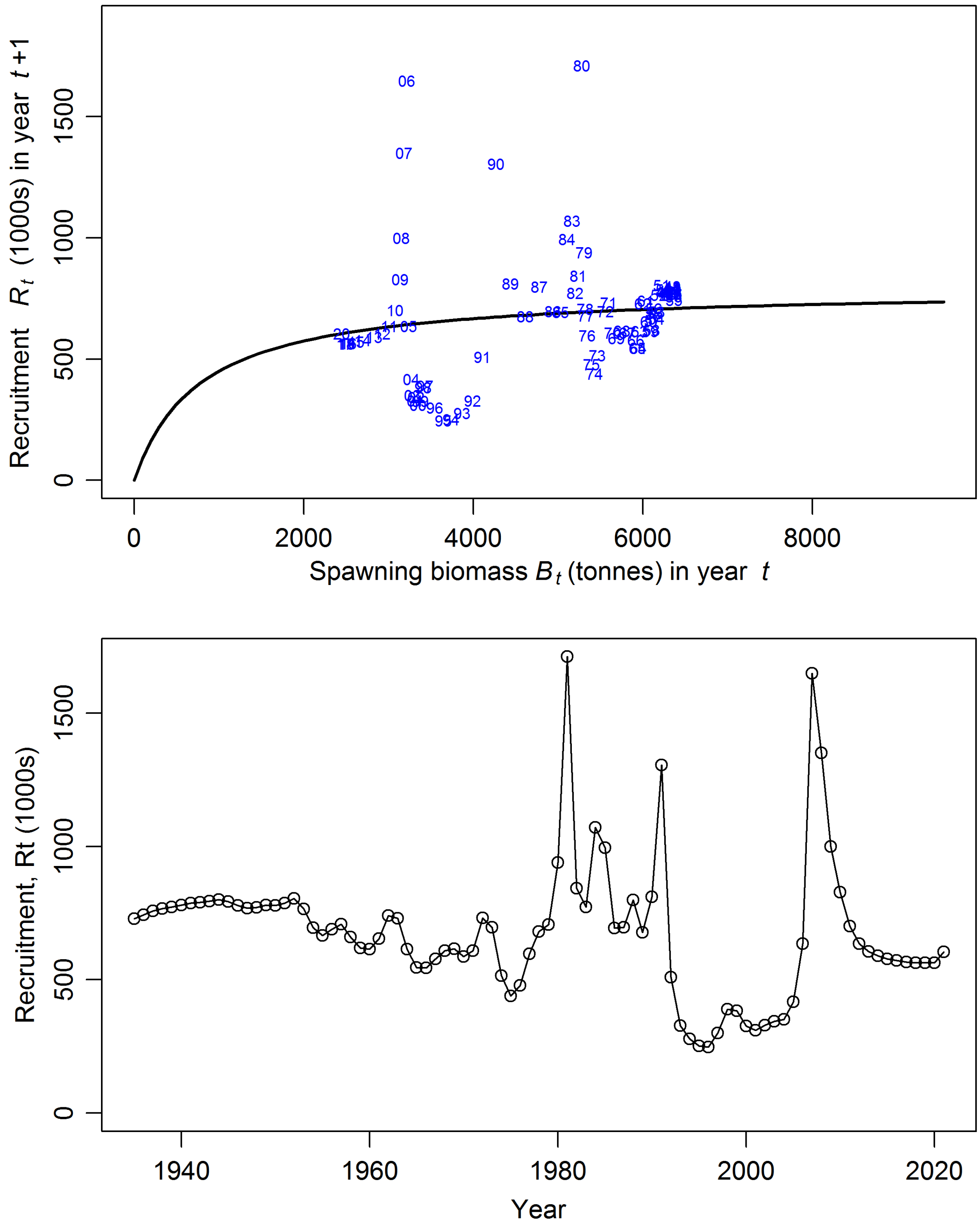


Figure F.55. REBS south CR.11.02: (top) deterministic stock-recruit relationship (black curve) and observed values (labelled by year of spawning) using MPD values; (bottom) recruitment (MPD values of age-1 individuals in year t) over time, in 1,000s of age-1 individuals, with a mean of 680.1.

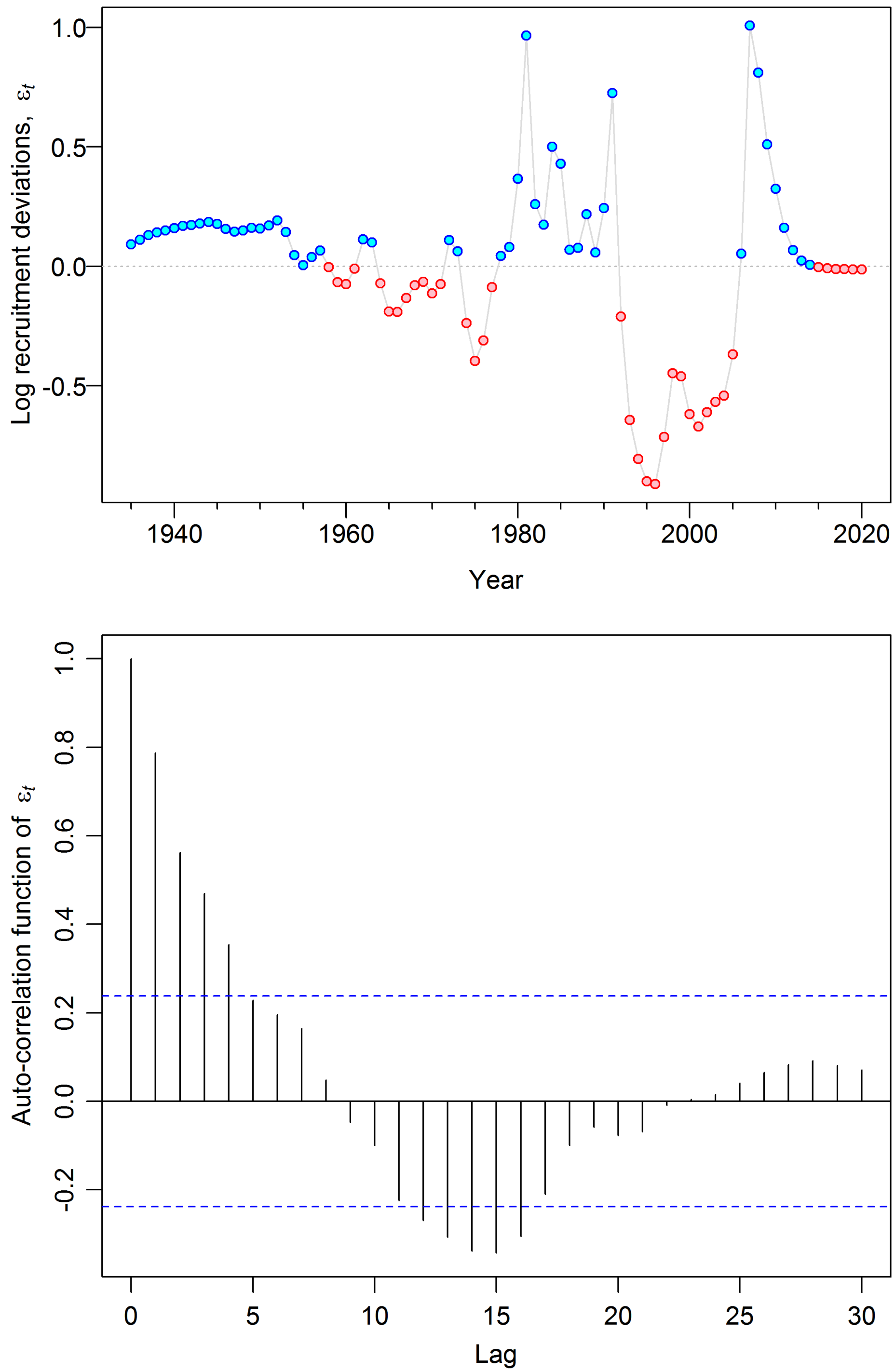


Figure F.56. REBS south CR.11.02: (top) log of the annual recruitment deviations, ϵ_t, where bias-corrected multiplicative deviation is e$^{\epsilon_t - \sigma_R^2/2}$ where $\epsilon_t \sim$ Normal$(0, \sigma_R^2)$; (bottom) autocorrelation function of the logged recruitment deviations (ϵ_t), for years 1935-2002. The start of this range is calculated as the first year of commercial age data (1997) minus the accumulator age class (A =80) plus the age for which commercial selectivity for females is 0.5 (namely 18); if the result is earlier than the model start year (1935), then the model start year is used. The end of the range is the final year that recruitments are calculated (2020) minus the age for which commercial selectivity for females is 0.5 (namely 18).

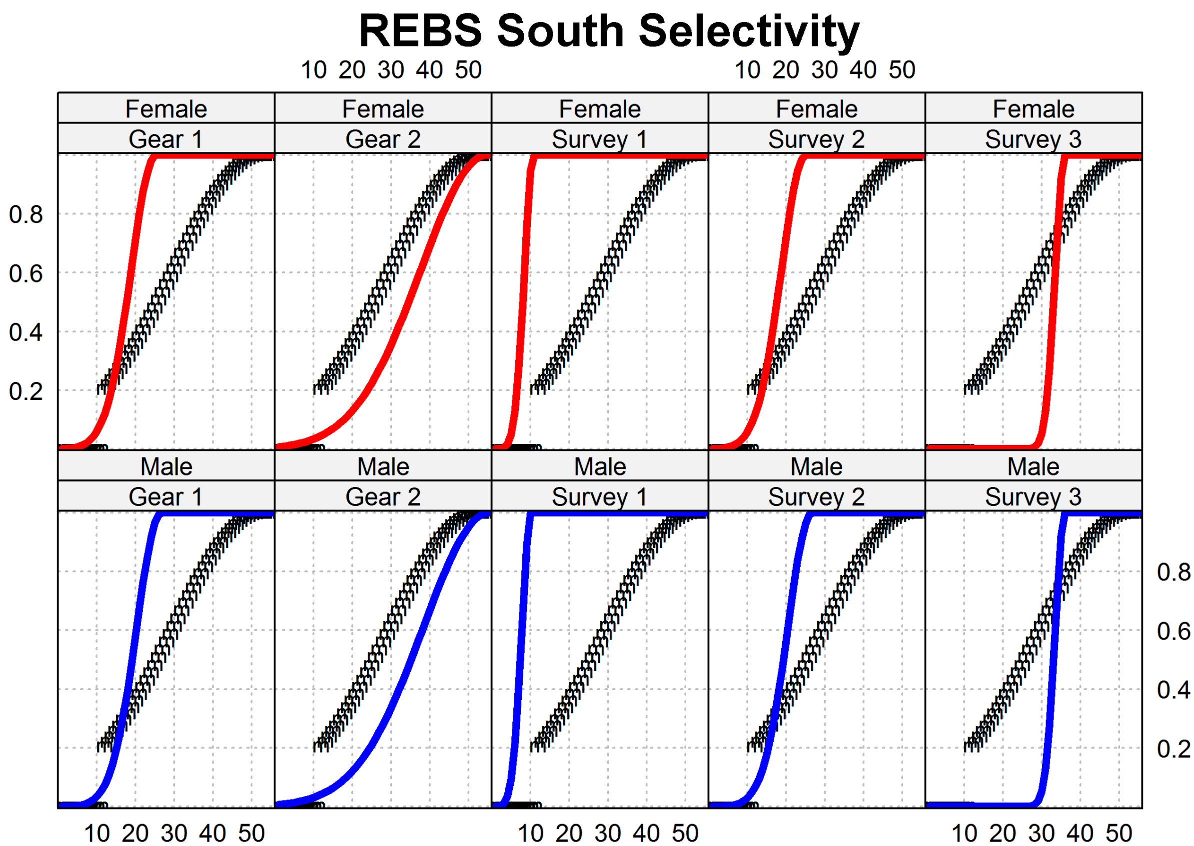
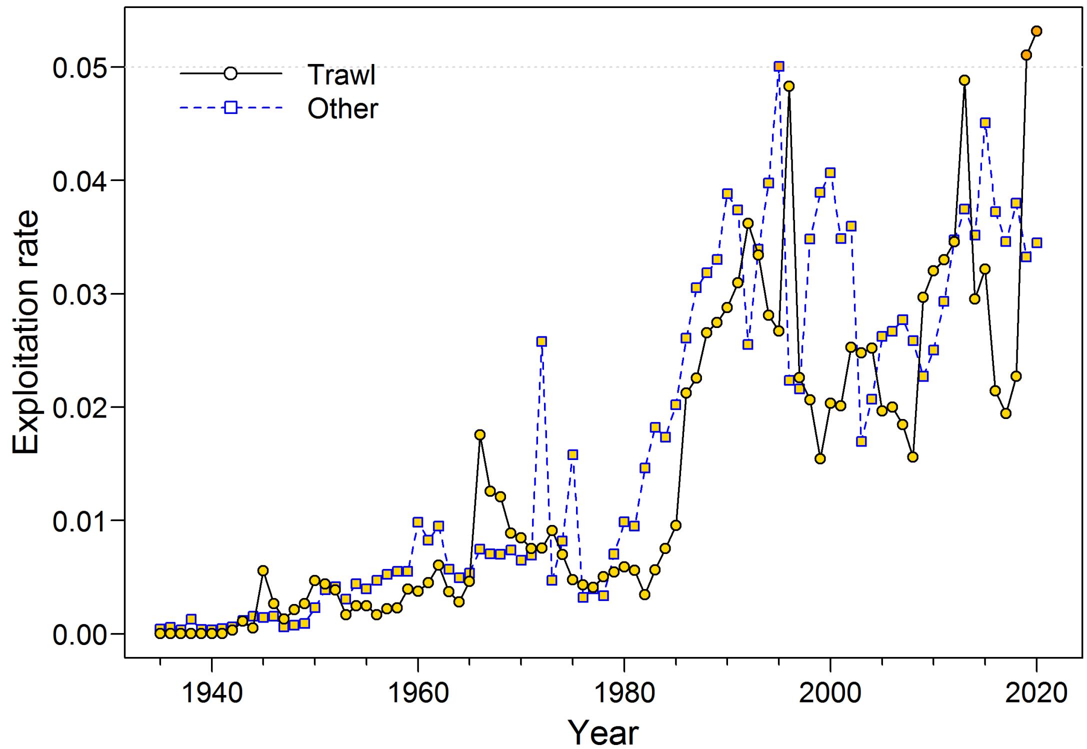


Figure F.57. REBS south CR.11.02: selectivities for commercial catch (Gear 1: Trawl, Gear 2: Other) and surveys (all MPD values), with maturity ogive for females indicated by 'm'.



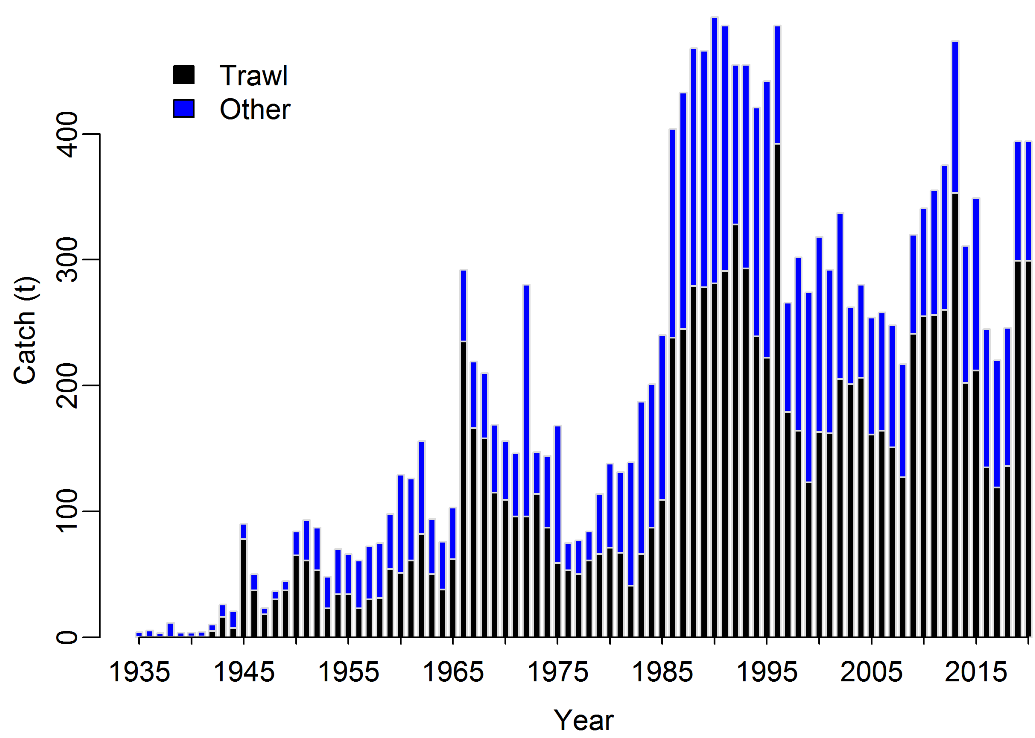


Figure F.58. REBS south CR.11.02: (top) exploitation rate (MPD) over time; (bottom) catch (t) by gear type.

F.3.2. REBS South – Central Run MCMC

The MCMC procedure performed 6 million iterations, sampling every 5000$^{\mathrm{th}}$ to give 1200 MCMC samples. The first 200 samples were discarded and the remaining 1000 samples were used for the MCMC analysis.

The MCMC plots show:

- Figure F.59 – traces for 1000 samples of the primary estimated parameters;
- Figure F.60 – split-chain diagnostic plots for the primary estimated parameters;
- Figure F.61 – auto-correlation diagnostic plots for the primary estimated parameters;
- Figure F.62 – marginal posterior densities for the primary parameters compared to their respective prior density functions.

MCMC traces showed acceptable convergence properties (no trend with increasing sample number) for the estimated parameters (Figure F.59), as did diagnostic analyses that split the posterior samples into three equal consecutive segments (Figure F.60) and checked for parameter autocorrelation out to 60 lags (Figure F.61). Most of the parameter medians did not move far from their initial MPD estimates (Figure F.62).

F.3.2.1. Figures – REBS south CR MCMC

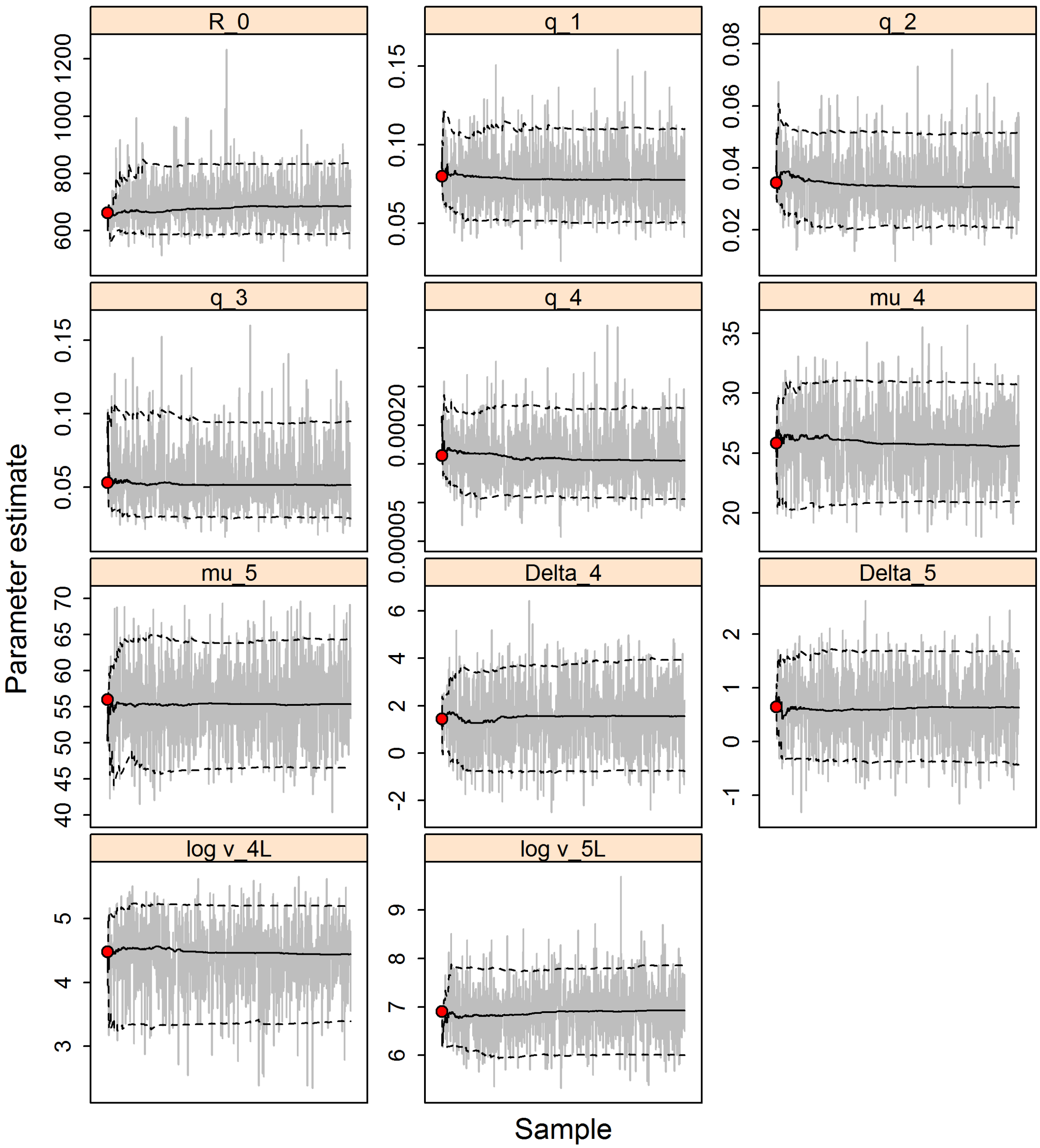


Figure F.59. REBS south CR.11.02: MCMC traces for the estimated parameters. Grey lines show the 1000 samples for each parameter, solid lines show the cumulative median (up to that sample), and dashed lines show the cumulative 0.05 and 0.95 quantiles. Red circles are the MPD estimates. For parameters other than M (if estimated), subscripts ≤ 3 correspond to fishery-independent surveys, and subscripts ≥ 4 denote the commercial fishery. Parameter notation is described in Appendix E.

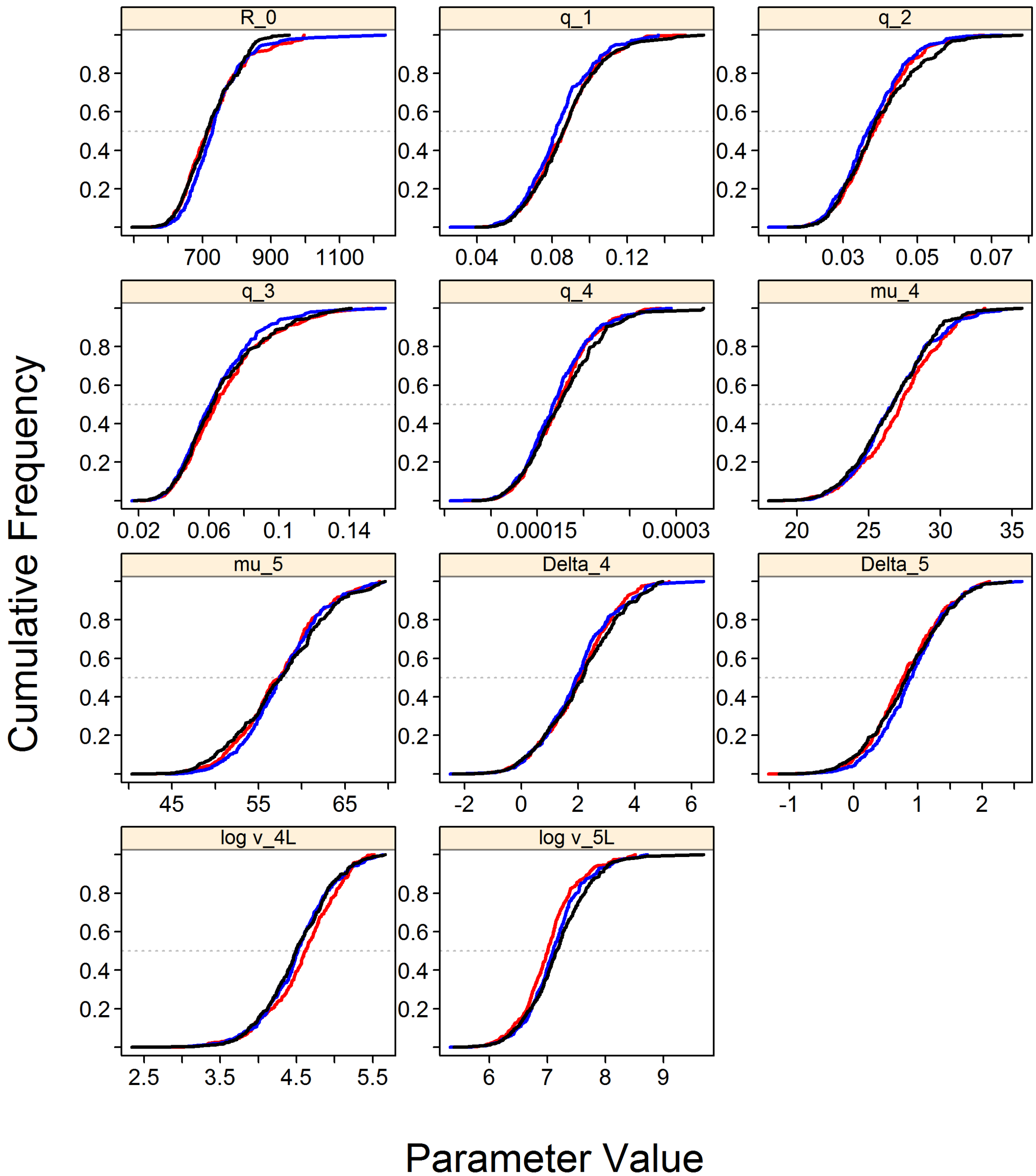


Figure F.60. REBS south CR.11.02: diagnostic plot obtained by dividing the MCMC chain of 1000 MCMC samples into three segments, and overplotting the cumulative distributions of the first segment (red), second segment (blue) and final segment (black).

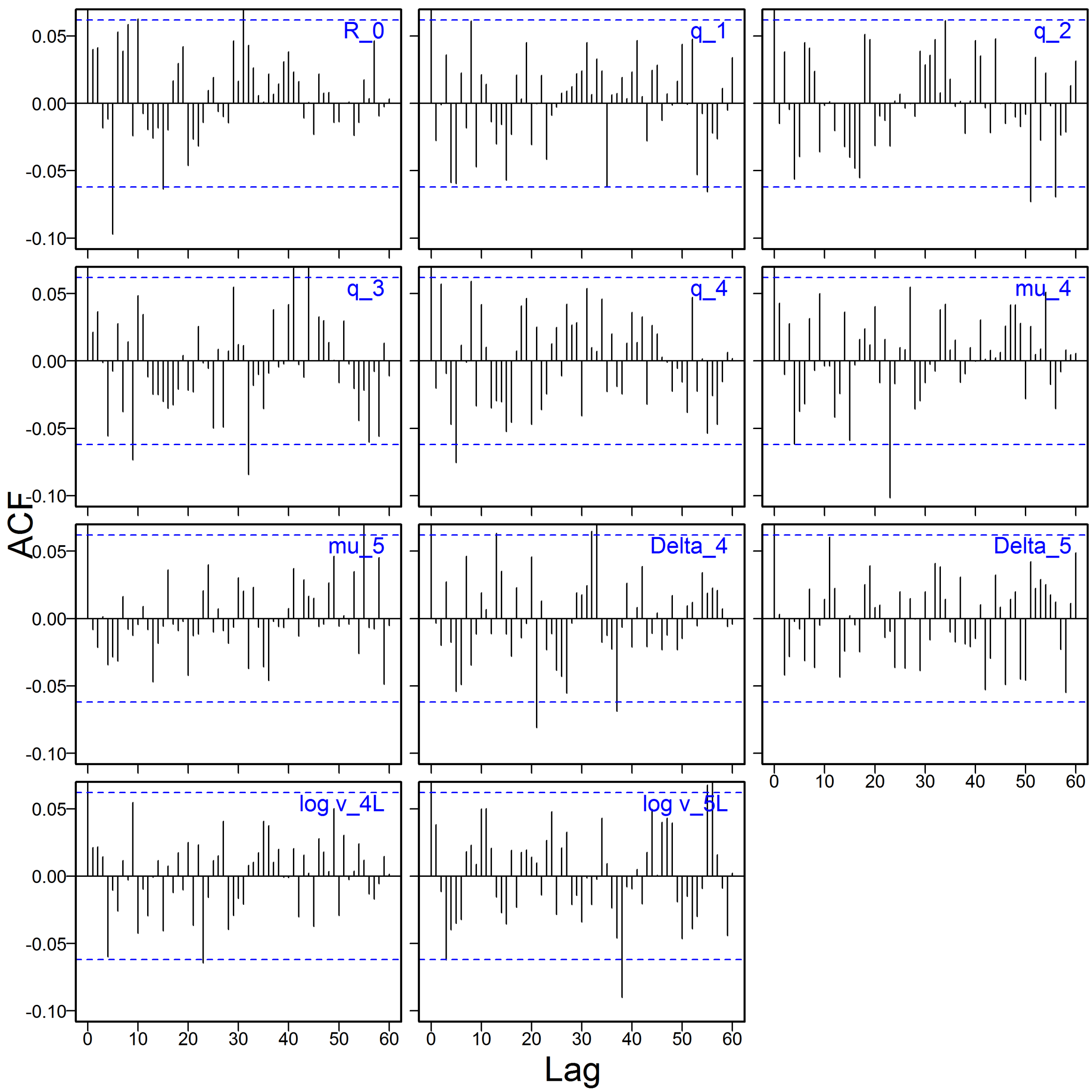


Figure F.61. REBS south CR.11.02: autocorrelation plots for the estimated parameters from the MCMC output. Horizontal dashed blue lines delimit the 95% confidence interval for each parameter's set of lagged correlations.

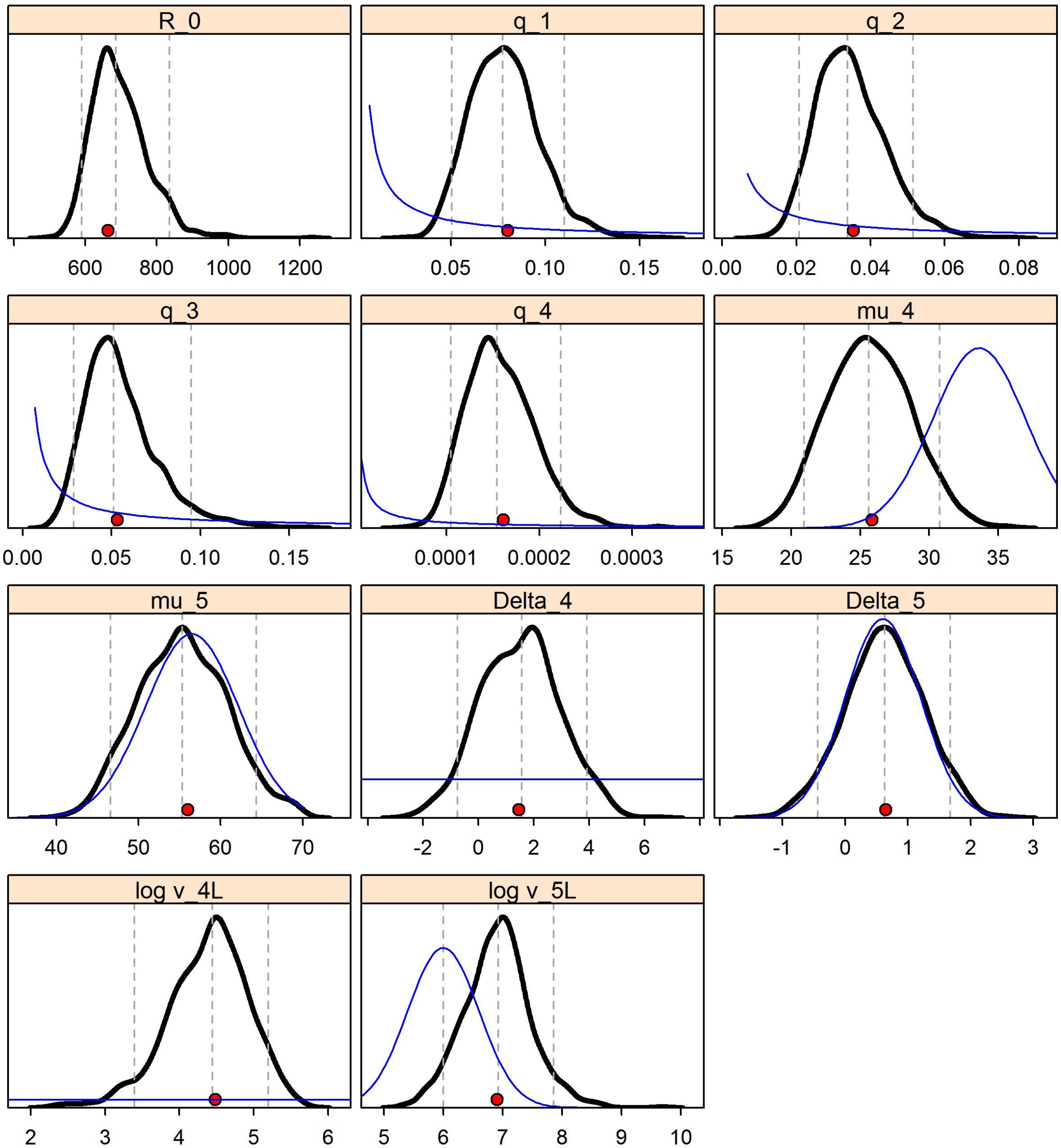


Figure F.62. REBS south CR.11.02: marginal posterior densities (thick black curves) and prior density functions (thin blue curves) for the estimated parameters. Vertical lines represent the 0.05, 0.5, and 0.95 quantiles, and red filled circles are the MPD estimates. For R_0 the prior is a uniform distribution on the range [1, 1e+07]. 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).

F.3.3. REBS South – Composite Base Case

The composite base case examined nine runs which spanned two axes of uncertainty (M and CPUE c_{p}) for this stock assessment:

- **B1*** (Run18) – fixed $M_{1,2} = 0.035$ and CPUE $c_p = 0.1$;
- **B2*** (Run12) – fixed $M_{1,2} = 0.035$ and CPUE $c_p = 0.2529$
- **B3*** (Run15) – fixed $M_{1,2} = 0.035$ and CPUE $c_p = 0.4$
- B4 (Run17) – fixed $M_{1,2} = 0.045$ and CPUE $c_p = 0.1$;
- **B5*** (Run11) – fixed $M_{1,2} = 0.045$ and CPUE $c_p = 0.2529$
- **B6*** (Run14) – fixed $M_{1,2} = 0.045$ and CPUE $c_p = 0.4$
- B7 (Run19) – fixed $M_{1,2} = 0.055$ and CPUE $c_p = 0.1$;
- B8 (Run13) – fixed $M_{1,2} = 0.055$ and CPUE $c_p = 0.2529$
- **B9*** (Run16) – fixed $M_{1,2} = 0.055$ and CPUE $c_p = 0.4$

During the peer review process, the participants agreed to use only six component runs (marked with an asterisk above) for the composite base case because three component runs had poor MCMC diagnostics. The 1000 MCMC samples from the six runs with acceptable MCMC diagnostics were pooled to create a composite posterior of 6000 samples, which was used to estimate population status and to provide advice to managers. Estimating M provided non-credible fits when assessing REBS north, so estimating M was not attempted for REBS south. Note that all of these runs required fixing both sets of the survey selectivity parameters to their MPD values in order to obtain acceptable MCMC diagnostics.

Composite base case median parameter estimates appear in Table F.67, and derived quantities at equilibrium and associated with maximum sustainable yield (MSY) appear in Table F.68. The differences among the component base runs are summarised by various figures:

- Figure F.63 – MCMC traces of R_0 for the 9 candidate base runs;
- Figure F.64 – three chain segments of R_0 MCMC chains;
- Figure F.65 – autocorrelation plots for R_0 MCMC output;
- Figure F.66 – quantile plots of parameter estimates from 6 component base runs;
- Figure F.67 – quantile plots of selected derived quantities from 6 component base runs.

In this assessement, projections extend to 2096 which equals 1.5 generations (75 years), where one generation was determined to be 50 years (see Appendix D). Various model trajectories and final stock status for the composite base case appear in the figures:

- Figure F.68 – estimates of spawning biomass B_t (tonnes) from pooled model posteriors spanning 1935-2096;
- Figure F.69 – estimates of vulnerable biomass V_t (tonnes) from pooled model posteriors;
- Figure F.70 – estimates of exploitation rate u_t from pooled model posteriors;
- Figure F.71 – estimates of reconstructed (1935-2021) and projected (2022-2096) recruitment R_t (1000s age-1 fish) from pooled model posteriors;
- Figure F.72 – phase plot through time of median B_t/B_{MSY} and u_{t-1}/u_{MSY} relative to DFO's Precautionary Approach (PA) provisional reference points;
- Figure F.73 – RER stock status at beginning of 2021.

Uncertainty in M, CPUE c_p, and width of the ageing error (AE) matrix were thought to be the most important components of uncertainty in this stock assessment. The first two categories were considered to be the most important and formed the two axes of uncertainty in the composite base case. The latter category was explored in sensitivity runs.

For each candidate component base run, 1000 MCMC samples were generated. Figures F.63 to F.65 show diagnostics for the R_0 parameter in each of the component runs The nine component runs converged with some poor MCMC diagnostics; five of the runs exhibited frayed chains (Figure F.64) and three of these showed undesirable autocorrelation (Figure F.65). Based on the diagnostics, a subjective ranking of the component runs would be:

- Good – no trend in traces, split-chains align, no autocorrelation
    - B2, B3, B5, and B9
- Marginal – trace trend temporarily interrupted, split-chains somewhat frayed, some autocorrelation
    - B1, B4, and B6
- Poor – trace trend fluctuates substantially or shows a persistent increase/decrease, split-chains differ from each other, substantial autocorrelation
    - B7 and B8

Component runs with poor diagnostics (B7 and B8) and one with marginal diagnostics (B4) were identified by the regional peer review participants to exclude from the candidate set of component runs for the composite base case. The chosen component runs (B1, B2, B3, B5, B6, B9) were pooled to provide an average stock trajectory for population status and advice to managers.

Figure F.66 shows box plots for the distribution of the estimated parameters for the chosen component runs. The selectivity parameters remained fairly constant across all component runs (overlapping distributions). The R_0 parameter increased in an exponential fashion from B1 through B9, with the latter two runs showing posterior distributions for R_0 that are much higher compared to the previous seven. The q parameters did not appear to vary by M, but were sensitive to differences in CPUE c_p, specifically between the low process error (c_p=0.1) and the model-based one (c_p=0.2529).

Similar to the parameter distributions, those for derived quantities (Figure F.67) varied by M and CPUE c_p; however, the difference in MSY was exaggerated by CPUE c_p for high M values.

The composite base case, comprising six pooled MCMC runs, was used to calculate a set of parameter estimates (Table F.67) and derived quantities at equilibrium and those associated with MSY (Table F.68). The composite base case population trajectory from 1935 to 2021 and projected biomass to 2096 (Figure F.68), assuming a constant catch policy of 300 t/y (and a harvest rate policy of u=0.06/y), indicated that the median stock biomass will eventually crash at the current amount of removals (5-year average catch of 291 t). The fixed harvest rate policy appears to offer a more sustainable catch policy, with median projected biomass remaining above the USR for the next 1.5 generations (75 years). We have little confidence in long-term projections which assume no active management intervention when stock size is reduced to low levels.

A phase plot of the time-evolution of spawning biomass and exploitation rate in the two modelled fisheries in MSY space (Figure F.72) suggests that the stock is in the Healthy Zone, with a current position at B_{2021}/B_MSY = 1.074 (0.582, 2.611), $u_{2020(\mathrm{trawl})}/u_\mathsf{MSY}$ = 1.172 (0.191, 2.588), and $u_{2020(\mathrm{other})}/u_\mathsf{MSY}$ = 0.721 (0.134, 1.766). The Trawl fishery's harvest rate is above that at u_MSY.

Table F.67. REBS south: the 0.05, 0.5, and 0.95 quantiles for pooled model parameters (defined in Appendix E) from MCMC estimation of 6 base model runs.

	5%	50%	95%
R_0	359	511	1,795
q_1	0.0289	0.0884	0.142
q_2	0.0128	0.0391	0.0672
q_3	0.0213	0.0567	0.138
q_4	0.0000673	0.000179	0.000295
μ_4	20.6	25.3	30.7
μ_5	47.2	56.1	65.4
Δ_4	-0.840	1.45	3.78
Δ_5	-0.510	0.669	1.83
$\log v_{4L}$	3.27	4.35	5.18
$\log v_{5L}$	5.81	6.51	7.28

Table F.68. *REBS south: the 0.05, 0.5, and 0.95 quantiles of MCMC-derived quantities from 6000 samples pooled from 6 MCMC posteriors. Definitions are: B_0 – unfished equilibrium spawning biomass (mature females), V_0 – unfished equilibrium vulnerable biomass (males and females), B_{2021} – spawning biomass at the start of 2021, V_{2021} – vulnerable biomass in the middle of 2021, u_{2020} – exploitation rate (ratio of total catch to vulnerable biomass) in the middle of 2020, $u_{\max}$ – maximum exploitation rate (calculated for each sample as the maximum exploitation rate from 1935-2020), 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 (2015-2019) was 291 t.*

	5%	50%	95%
B_0	5,187	6,045	10,574
V_0 (trawl)	10,927	13,136	23,704
V_0 (other)	6,813	8,643	13,292
B_{2021}	818	1,725	7,078
V_{2021} (trawl)	1,772	3,964	15,566
V_{2021} (other)	752	2,037	7,289
B_{2021}/B_0	0.155	0.286	0.680
V_{2021}/V_0 (trawl)	0.159	0.304	0.666
V_{2021}/V_0 (other)	0.104	0.239	0.572
u_{2020} (trawl)	0.0193	0.0716	0.150
u_{2020} (other)	0.0130	0.0442	0.112
$u_{\max}$ (trawl)	0.0259	0.0717	0.150
$u_{\max}$ (other)	0.0264	0.0592	0.125
MSY	152	193	495
B_{MSY}	1,380	1,611	2,739
$0.4B_{2021}$	552	644	1,095
$0.8B_{2021}$	1,104	1,289	2,191
$B_{2021}/B_{\mathrm{MSY}}$	0.582	1.07	2.61
B_{MSY}/B_0	0.258	0.265	0.272
V_{MSY}	2,418	3,213	5,130
V_{MSY}/V_0 (trawl)	0.184	0.239	0.289
V_{MSY}/V_0 (other)	0.326	0.369	0.426
u_{MSY}	0.0500	0.0620	0.106
$u_{2020}/u_{\mathrm{MSY}}$ (trawl)	0.191	1.17	2.59
$u_{2020}/u_{\mathrm{MSY}}$ (other)	0.134	0.721	1.77

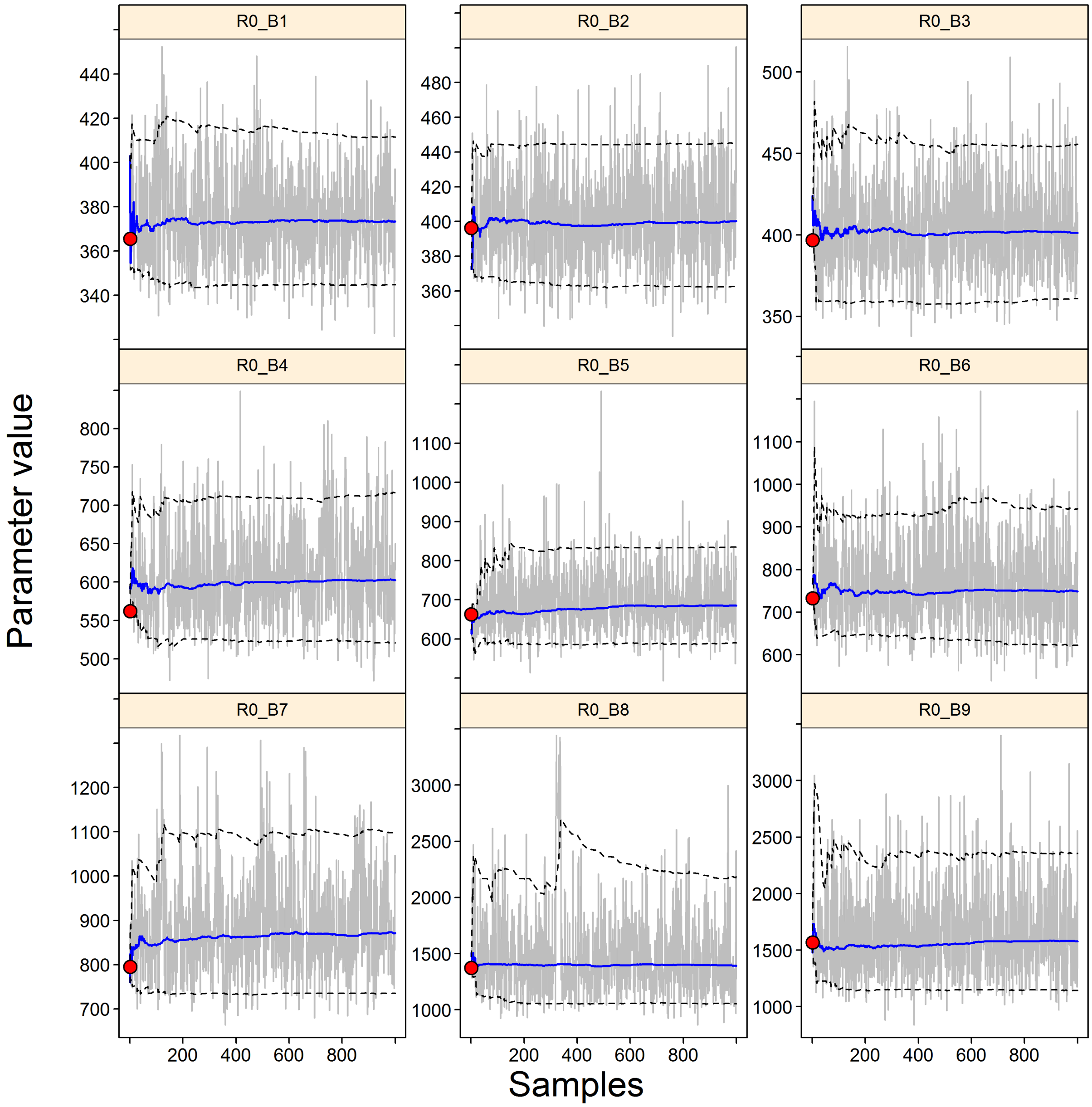


Figure F.63. REBS south base candidates: MCMC traces of R_0 for the 9 candidate base runs. Grey lines show the 1000 samples for the R_0 parameter, solid lines show the cumulative median (up to that sample), and dashed lines show the cumulative 0.05 and 0.95 quantiles. Red circles are the MPD estimates.

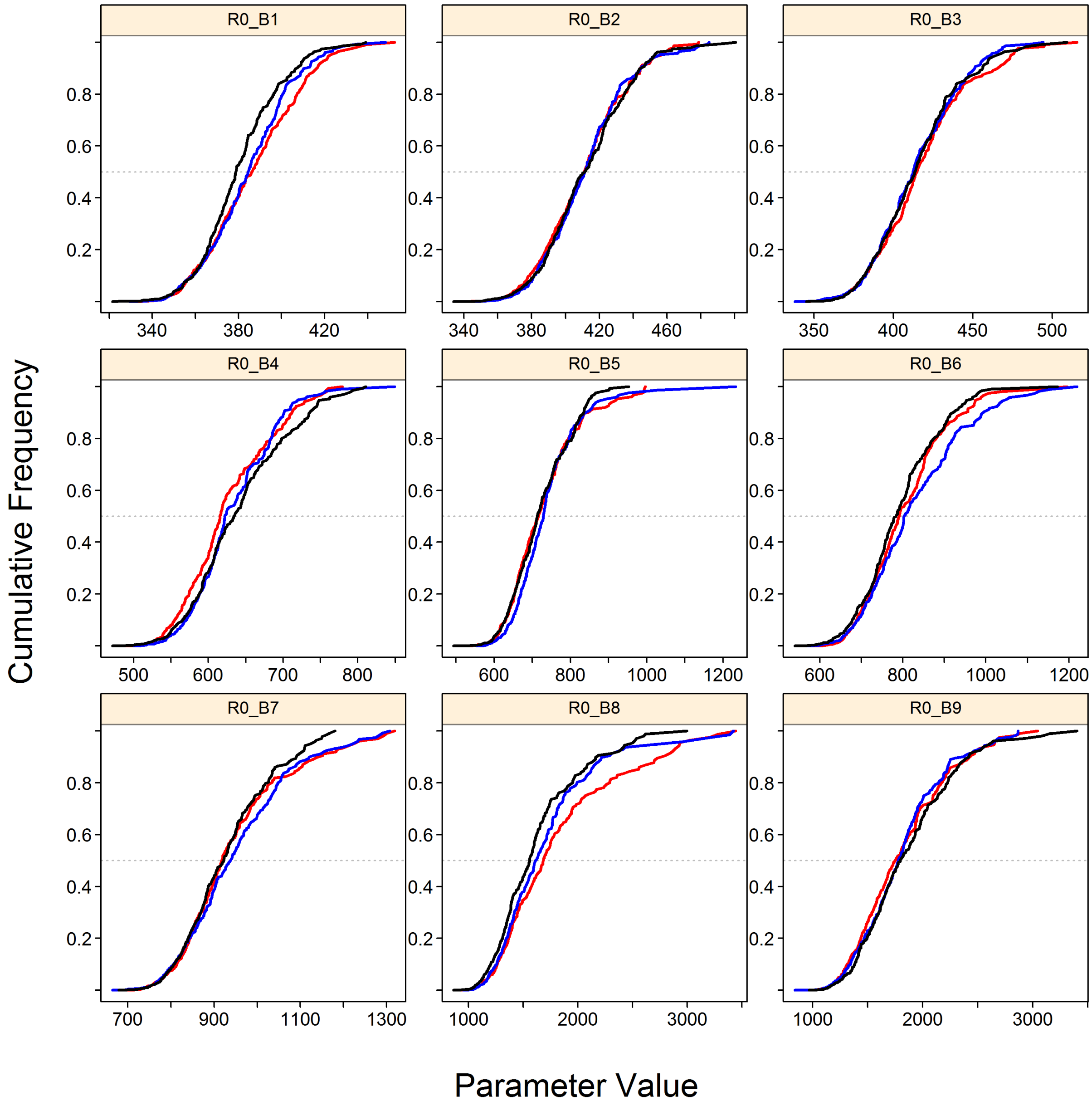


Figure F.64. REBS south base candidates: diagnostic plots obtained by dividing the R_0 MCMC chains of 1000 MCMC samples into three segments, and overplotting the cumulative distributions of the first segment (red), second segment (blue) and final segment (black).

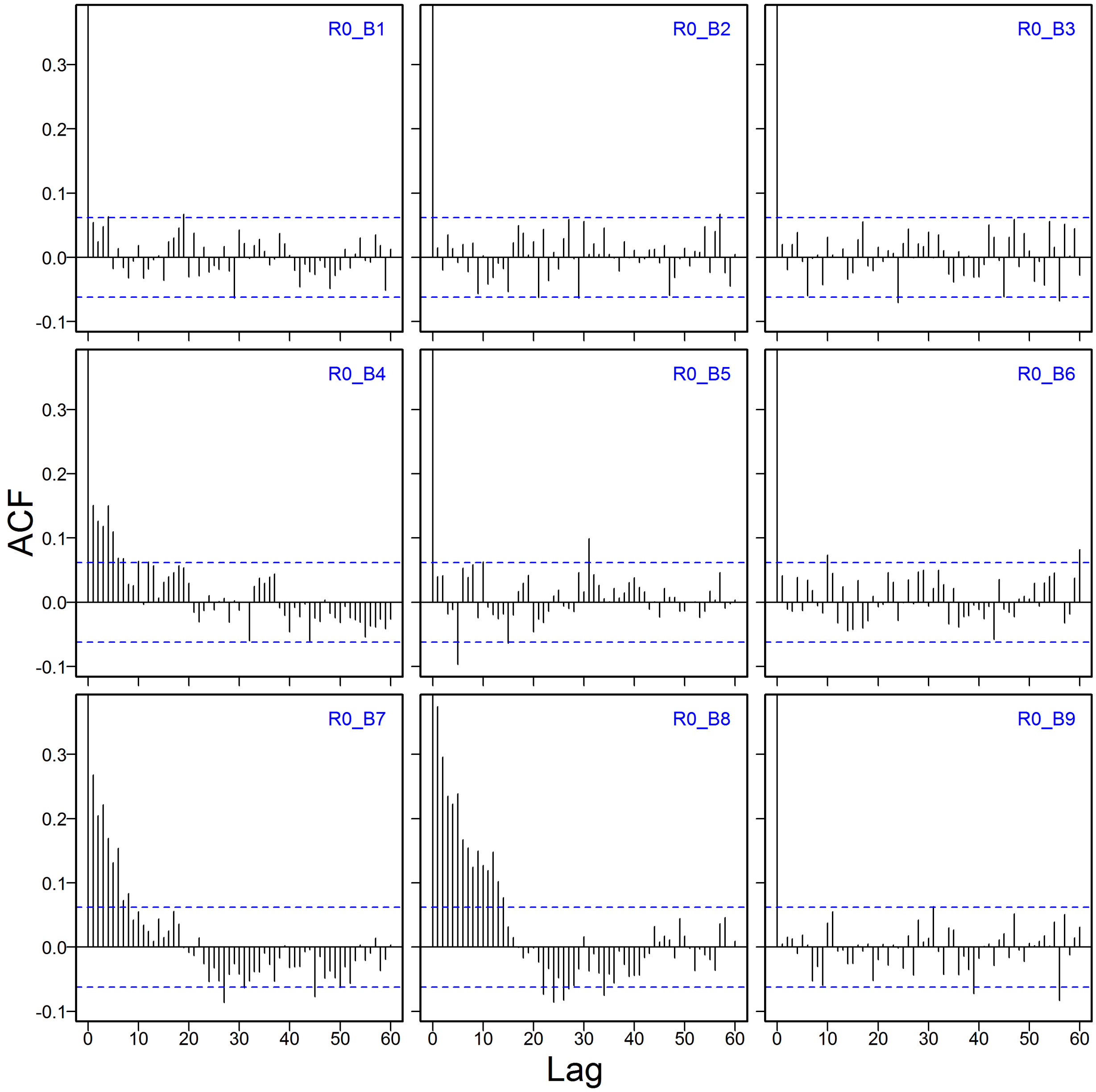


Figure F.65. REBS south base candidates: autocorrelation plots for the R_0 parameters from the MCMC output. Horizontal dashed blue lines delimit the 95% confidence interval for each parameter's set of lagged correlations.

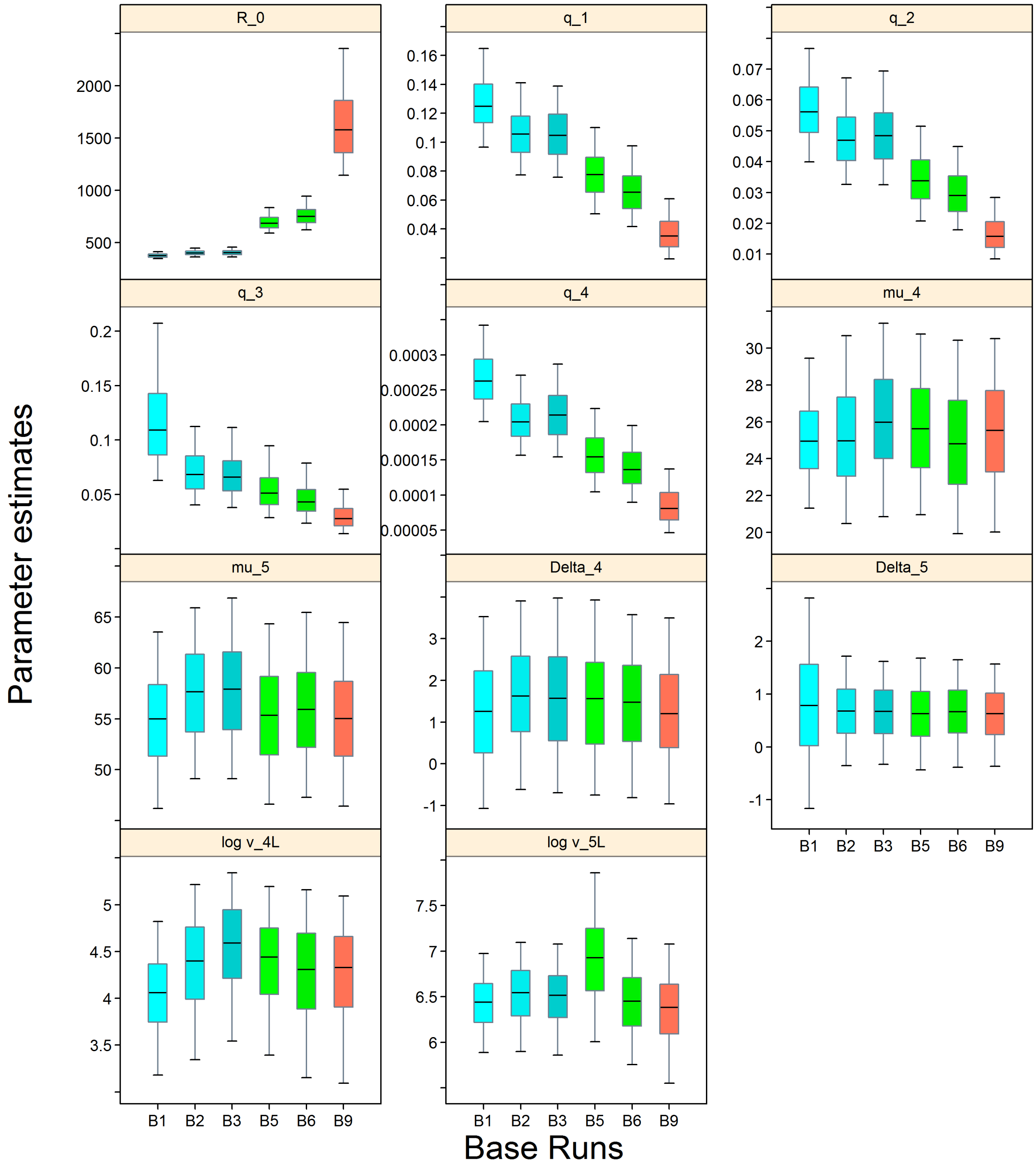


Figure F.66. REBS south base composite: quantile plots of the parameter estimates from 6 component runs of the base case, where blue boxes denote M=0.035, green boxes denote M=0.045, and red boxes denote M=0.055. The boxplots delimit the 0.05, 0.25, 0.5, 0.75, and 0.95 quantiles.

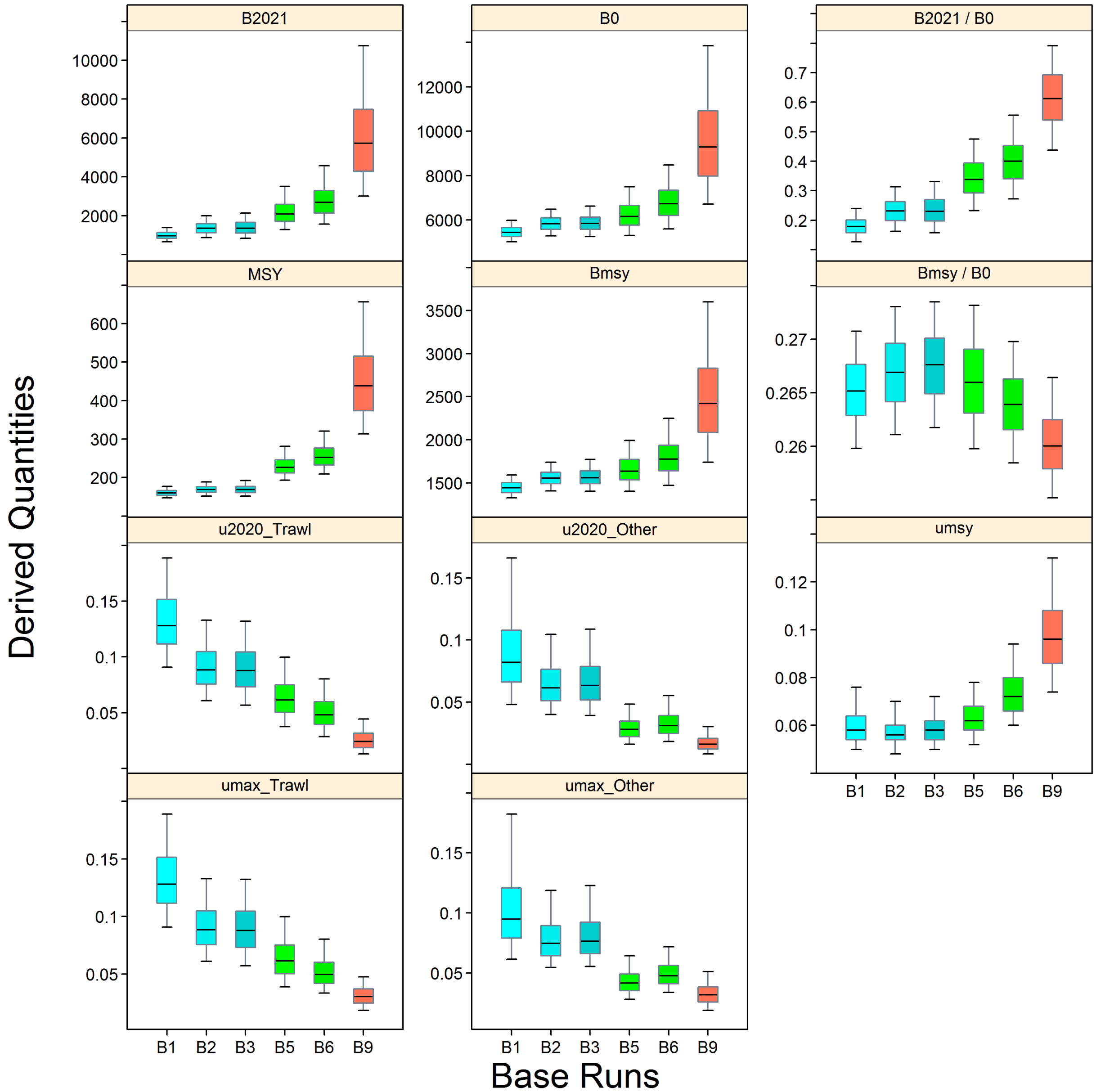


Figure F.67. REBS south base composite: quantile plots of selected derived quantities (B_{2021}, B_0, B_{2021}/B_0, MSY, B_{MSY}, B_{MSY}/B_0, u_{2020}, u_{MSY}, $u_{\max}$) from 6 component runs of the base case, where blue boxes denote M=0.035, green boxes denote M=0.045, and red boxes denote M=0.055. The boxplots delimit the 0.05, 0.25, 0.5, 0.75, and 0.95 quantiles.

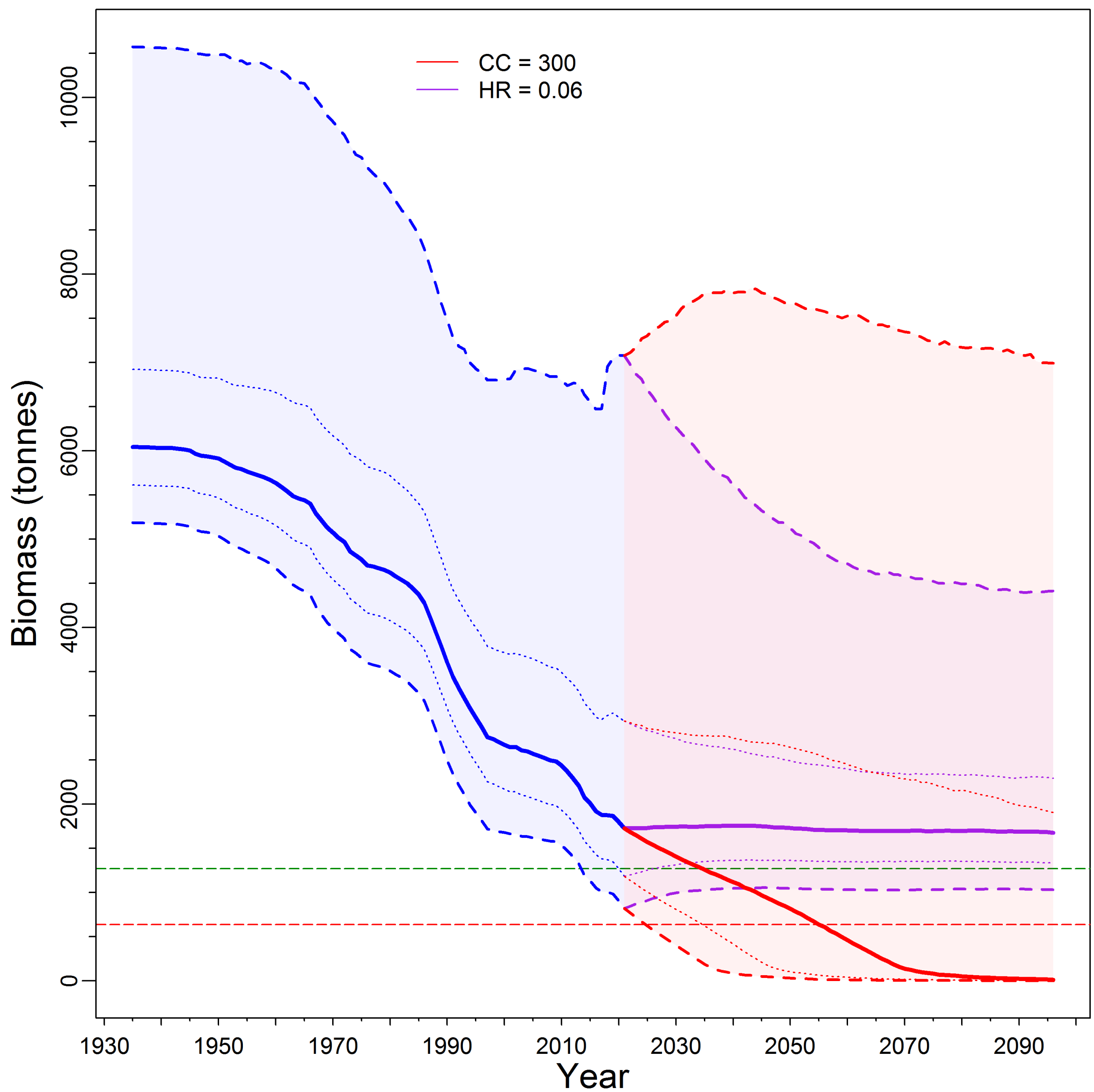


Figure F.68. REBS south base composite: estimates of spawning biomass B_t (tonnes) from pooled model posteriors. The median biomass trajectory appears as a solid curve surrounded by a 90% credibility envelope (quantiles: 0.05-0.95) in light blue and delimited by dashed lines for years t=1935:2021; projected biomass appears in light red for years t=2022:2096. Also delimited is the 50% credibility interval (quantiles: 0.25-0.75) delimited by dotted lines. The horizontal dashed lines show the median LRP and USR.

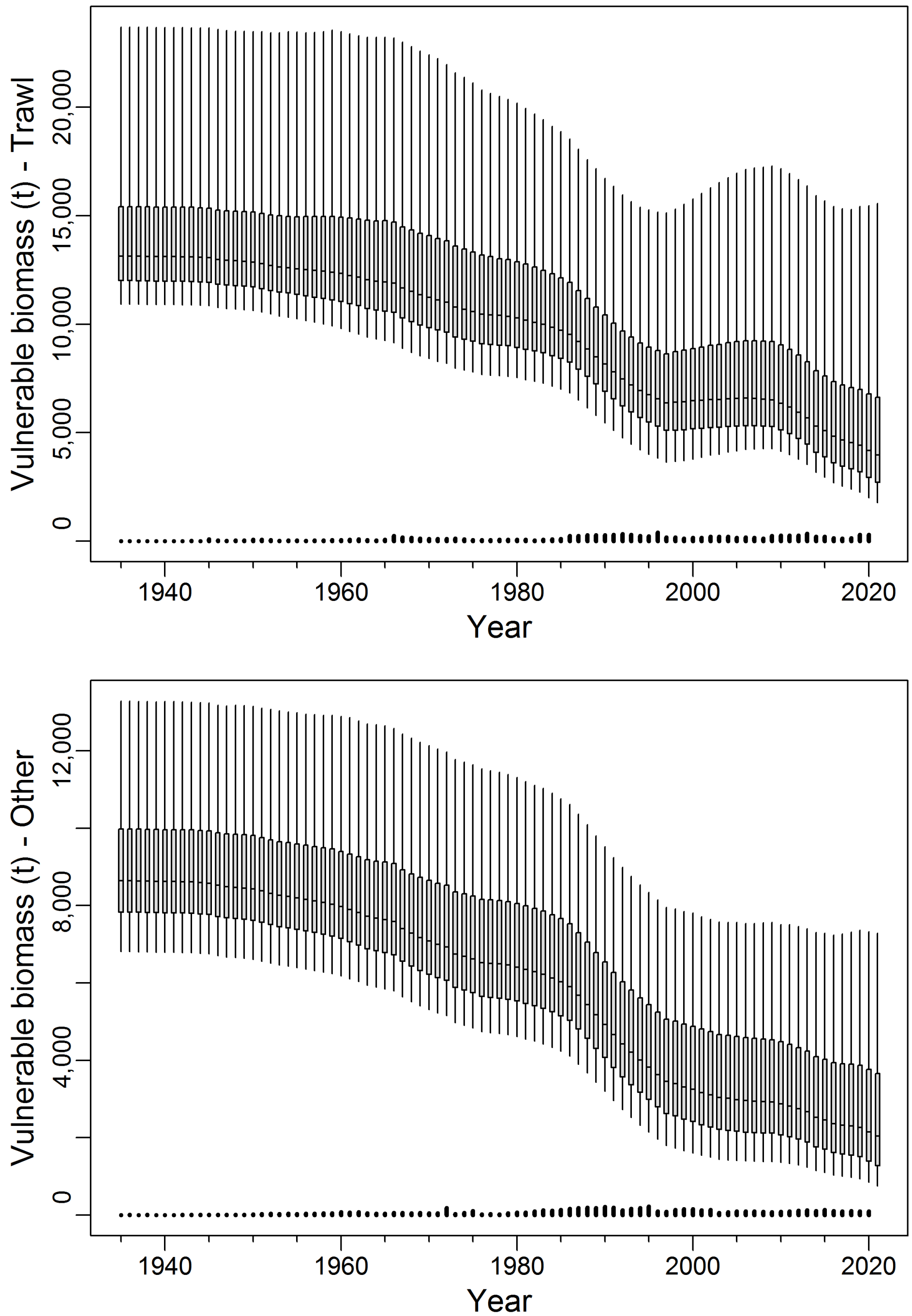
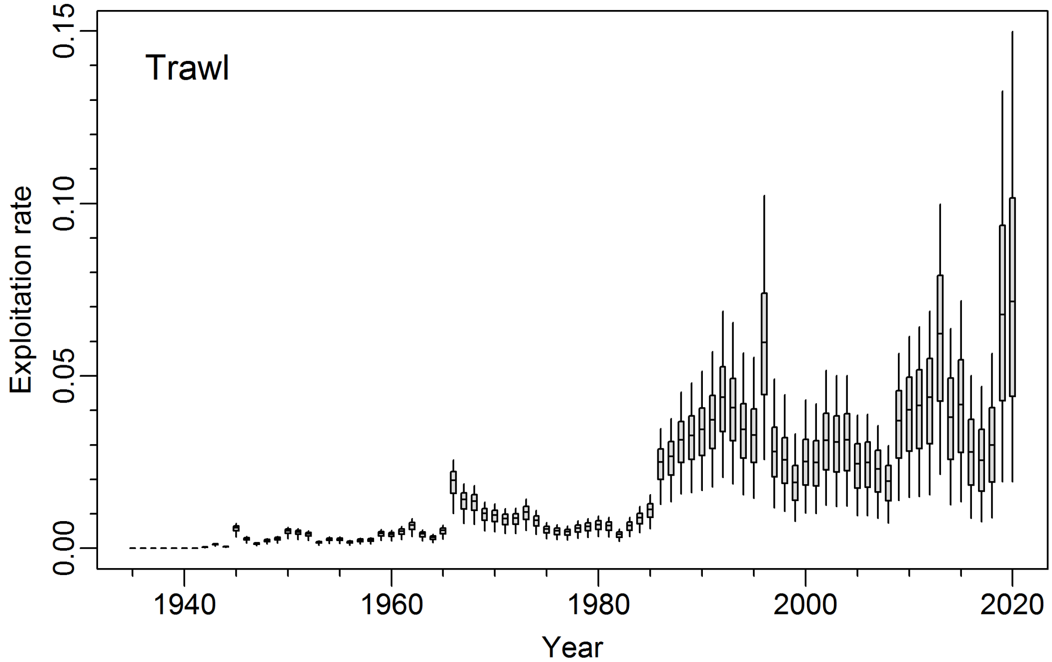


Figure F.69. REBS south base composite: estimated vulnerable biomass trajectory for two fisheries (boxplots) and commercial catch history (vertical bars), in tonnes. Boxplots show the 0.05, 0.25, 0.5, 0.75, and 0.95 quantiles from the MCMC results.



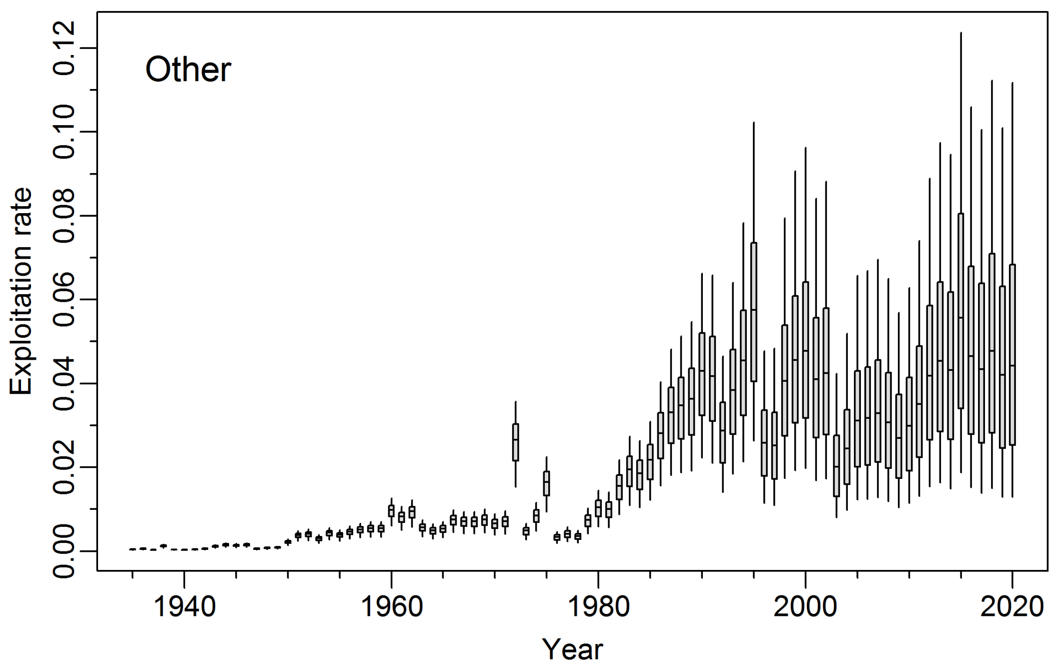


Figure F.70. REBS south base composite: marginal posterior distribution of exploitation rate trajectory for two fisheries. Boxplots show the 0.05, 0.25, 0.5, 0.75, and 0.95 quantiles from the MCMC results.

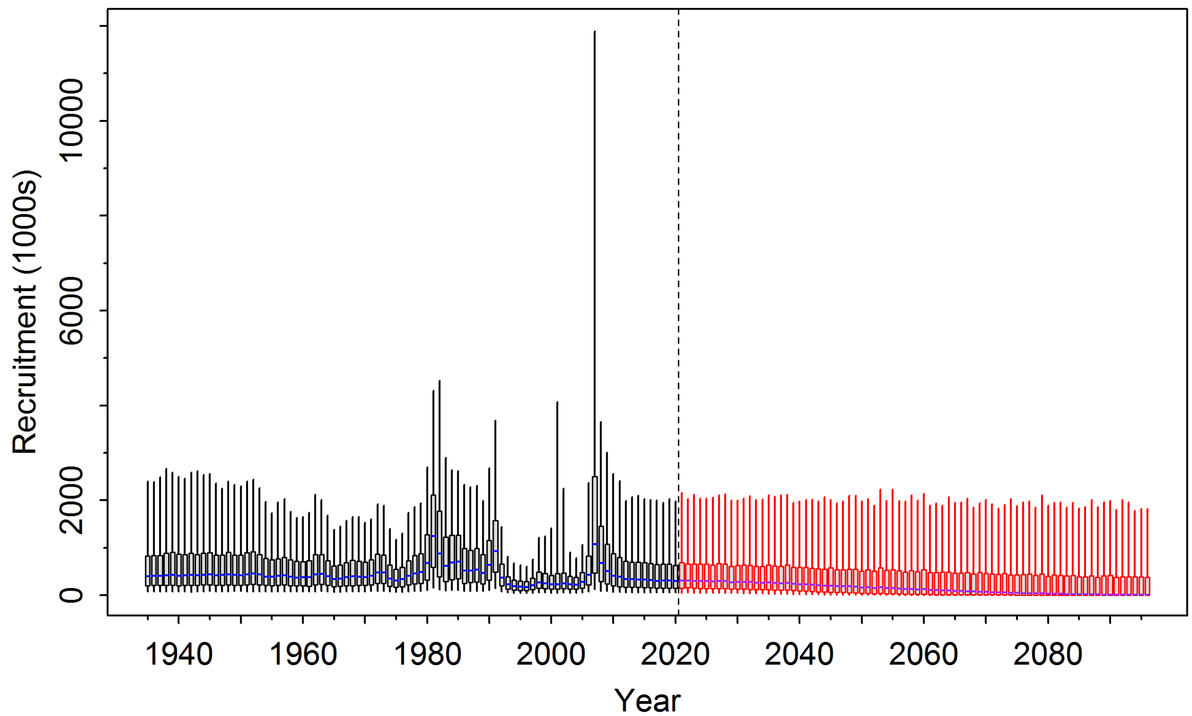


Figure F.71. REBS south base composite: marginal posterior distribution of recruitment trajectory (reconstructed: 1935-2021, projected: 2022-2096) in 1,000s of age-1 fish.

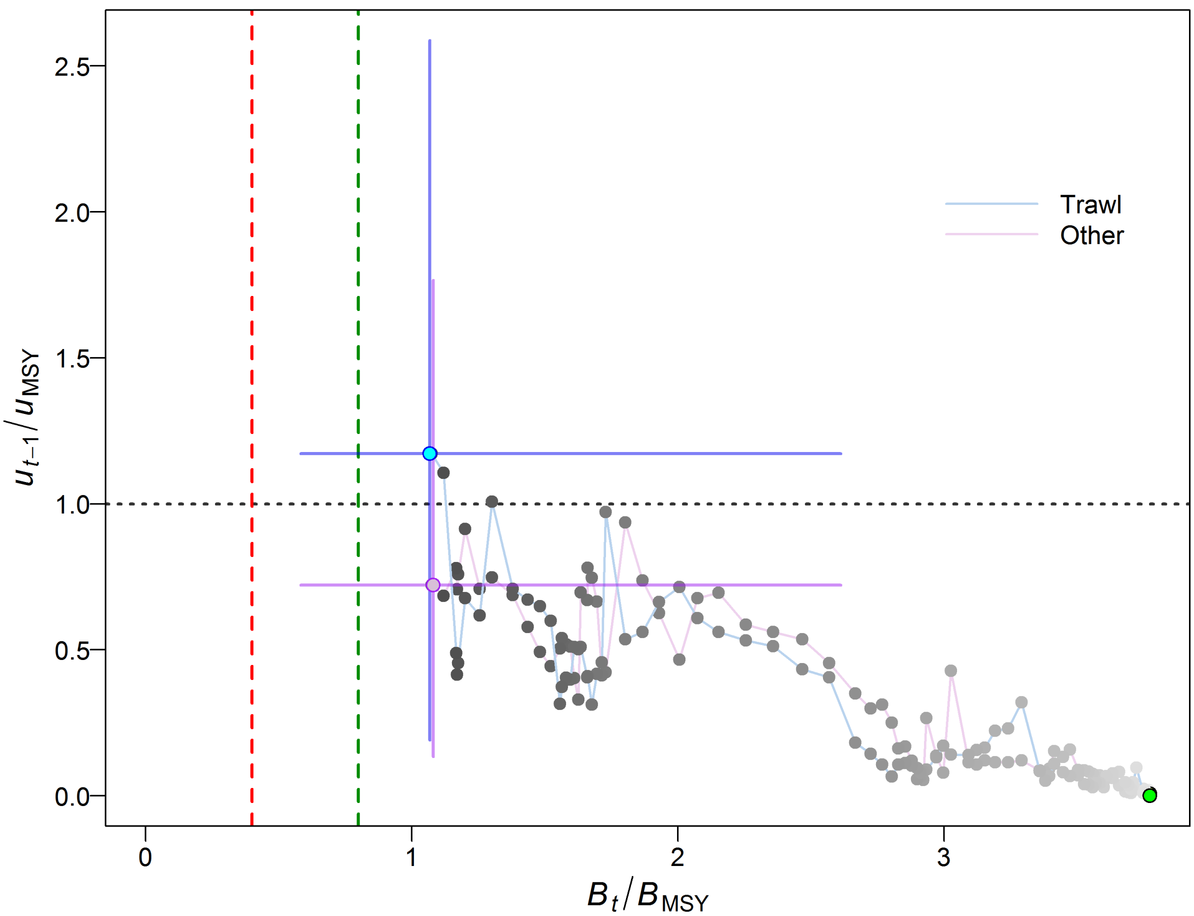


Figure F.72. REBS south base composite: phase plot through time of the medians of the ratios B_t/B_{MSY} (the spawning biomass in year t relative to B_{MSY}) and u_{t-1}/u_{MSY} (the exploitation rate in year $t-1$ relative to u_{MSY}) for two fisheries (trawl/other). The filled green circle is the starting year (1936). Years then proceed along lines gradually darkening from light grey/blue, with the final year (2021) as a filled cyan/purple circle, and the blue/purple cross lines represent the 0.05 and 0.95 quantiles of the posterior distributions for the final year. Red and green vertical dashed lines indicate the PA provisional limit and upper stock reference points (0.4, 0.8 B_{MSY}), and the horizontal grey dotted line indicates u at MSY.

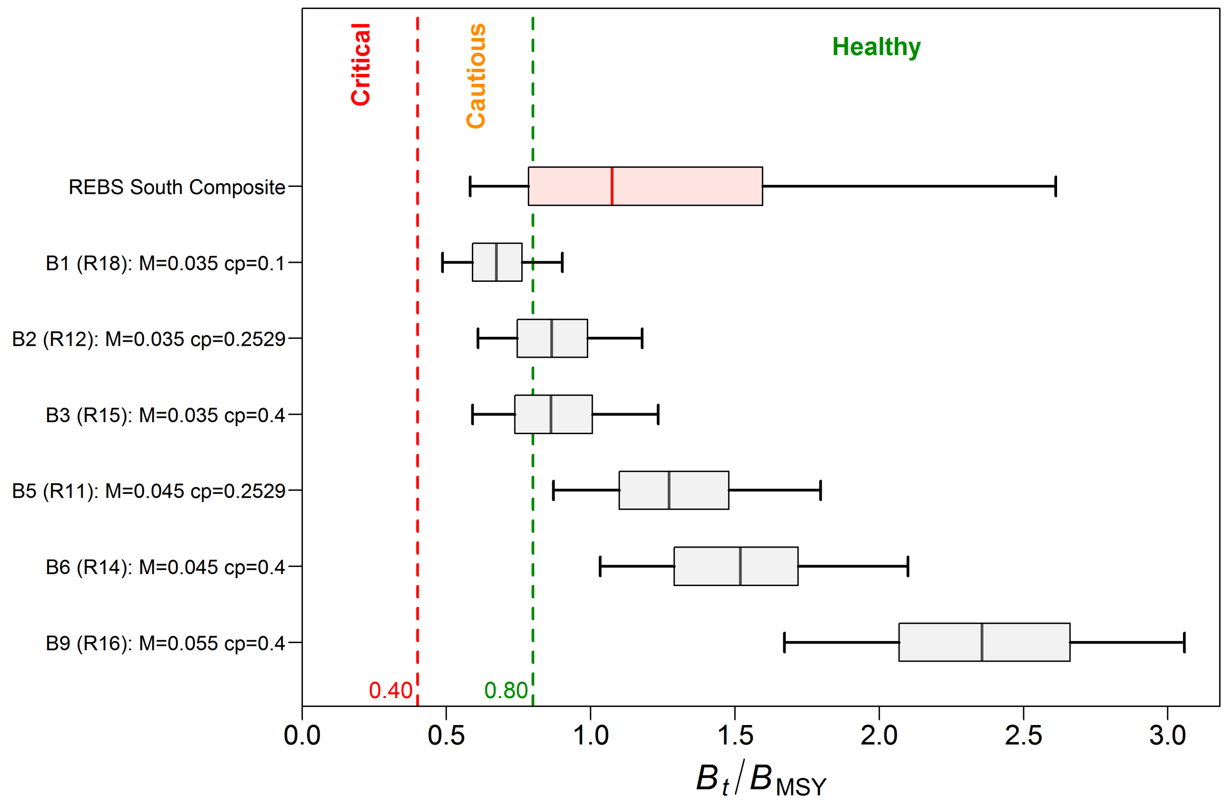


Figure F.73. REBS south base composite: stock status at beginning of 2021 relative to the PA provisional reference points of 0.4B_{MSY} and 0.8B_{MSY} for a base case comprising 6 model runs. The top quantile plot shows the composite distribution and below are the 6 contributing runs. Quantile plots show the 0.05, 0.25, 0.5, 0.75, and 0.95 quantiles from the MCMC posteriors.

F.3.4. REBS South – Decision Tables

F.3.4.1. GMU – Guidance for setting TACs

Decision tables for the composite base case provide advice to managers as probabilities that current and projected biomass B_t ($t = 2021, ..., 2031$) will exceed biomass-based reference points (or that projected exploitation rate u_t will fall below harvest-based reference points) under constant catch (CC) and harvest rate (HR) policies. Specifically:

- Tables F.69 & F.70 – probability of B_t exceeding the LRP, P$(B_t > 0.4B_{\text{MSY}})$, under CC and HR policies;
- Tables F.71 & F.72 – probability of B_t exceeding the USR, P$(B_t > 0.8B_{\text{MSY}})$, under CC and HR policies;
- Tables F.73 & F.74 – probability of B_t exceeding biomass at MSY, P$(B_t > B_{\text{MSY}})$, under CC and HR policies;
- Tables F.75 & F.76 – probability of u_t falling below harvest rate at MSY, P$(u_t < u_{\text{MSY}})$, under CC and HR policies;
- Tables F.77 & F.78 – probability of B_t exceeding current-year biomass, P$(B_t > B_{2021})$, under CC and HR policies;
- Tables F.79 & F.80 – probability of u_t falling below current-year harvest rate, P$(u_t < u_{2020})$, under CC and HR policies;
- Tables F.81 & F.82 – probability of B_t exceeding a non-DFO 'soft limit', P$(B_t > 0.2B_0)$, under CC and HR policies;
- Tables F.83 & F.84 – probability of B_t exceeding a non-DFO 'target' biomass, P$(B_t > 0.4B_0)$, under CC and HR policies.

MSY-based reference points estimated within a stock assessment model can be highly sensitive to model assumptions about natural mortality and stock recruitment dynamics (Forrest et al. 2018). As a result, other jurisdictions use reference points that are expressed in terms of B_0 rather than B_{MSY} (e.g., N.Z. Min. Fish. 2011), because B_{MSY} is often poorly estimated as it depends on estimated parameters and a consistent fishery (although B_0 shares several of these same problems). Therefore, the reference points of 0.2B_0 and 0.4B_0 are also presented here. These are default values used in New Zealand respectively as a 'soft limit', below which management action needs to be taken, and a 'target' biomass for low productivity stocks, a mean around which the biomass is expected to vary. The 'soft limit' is equivalent to the upper stock reference (USR, 0.8B_{MSY}) in the provisional DFO Sustainable Fisheries Framework while a 'target' biomass is not specified by the provisional DFO SFF. Additionally, results are provided comparing projected biomass to B_{MSY} and to current spawning biomass B_{2021}, and comparing projected harvest rate to current harvest rate u_{2020}.

Table F.69. REBS south: decision table for the limit reference point $0.4B_{MSY}$ for 1-10-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 6000 MCMC samples for which $B_t > 0.4B_{MSY}$. For reference, the average catch over the last 5 years (2015-2019) was 291 t.*

CC	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	>0.99	>0.99	>0.99	>0.99	1	1	1	1	1	1	1
50	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	1	1
100	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
150	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
200	>0.99	>0.99	>0.99	>0.99	>0.99	0.99	0.99	0.99	0.99	0.99	0.98
250	>0.99	>0.99	>0.99	0.99	0.99	0.98	0.98	0.96	0.95	0.94	0.93
300	>0.99	>0.99	0.99	0.98	0.97	0.96	0.94	0.91	0.89	0.88	0.85
350	>0.99	>0.99	0.99	0.97	0.94	0.91	0.89	0.85	0.82	0.79	0.76
400	>0.99	>0.99	0.98	0.95	0.91	0.87	0.82	0.78	0.74	0.70	0.66
450	>0.99	0.99	0.97	0.93	0.87	0.82	0.76	0.71	0.66	0.62	0.58
500	>0.99	0.99	0.96	0.90	0.83	0.76	0.70	0.64	0.59	0.56	0.52
550	>0.99	0.99	0.94	0.86	0.79	0.70	0.64	0.58	0.54	0.51	0.48
600	>0.99	0.98	0.92	0.83	0.74	0.66	0.59	0.54	0.50	0.47	0.44

Table F.70. REBS south: decision table for the limit reference point $0.4B_{MSY}$ for 1-10-year projections for a range of **harvest rate** *strategies. 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 6000 MCMC samples for which $B_t > 0.4B_{MSY}$. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.033.*

HR	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	>0.99	>0.99	>0.99	>0.99	1	1	1	1	1	1	1
0.01	>0.99	>0.99	>0.99	>0.99	1	1	1	1	1	1	1
0.02	>0.99	>0.99	>0.99	>0.99	>0.99	1	1	1	1	1	1
0.03	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	1	1	1	1	1
0.04	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	1	1	1	1
0.05	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	1	1
0.06	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	1	1
0.07	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
0.08	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
0.09	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
0.1	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
0.11	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
0.12	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99

Table F.71. *REBS south: decision table for the upper stock reference point $0.8B_{MSY}$ for 1-10-year projections for a range of* **constant catch** *strategies (in tonnes), such that values are P$(B_t > 0.8B_{MSY})$. For reference, the average catch over the last 5 years (2015-2019) was 291 t.*

CC	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	0.74	0.78	0.83	0.87	0.91	0.94	0.96	0.98	0.99	>0.99	>0.99
50	0.74	0.77	0.80	0.83	0.86	0.89	0.91	0.94	0.95	0.97	0.98
100	0.74	0.76	0.77	0.79	0.81	0.83	0.85	0.87	0.88	0.89	0.91
150	0.74	0.74	0.75	0.75	0.76	0.77	0.78	0.79	0.79	0.80	0.81
200	0.74	0.73	0.72	0.72	0.71	0.71	0.70	0.70	0.70	0.70	0.69
250	0.74	0.72	0.70	0.68	0.66	0.65	0.64	0.63	0.62	0.61	0.60
300	0.74	0.70	0.67	0.65	0.62	0.60	0.58	0.57	0.55	0.54	0.53
350	0.74	0.69	0.65	0.62	0.59	0.56	0.54	0.52	0.50	0.49	0.48
400	0.74	0.68	0.63	0.59	0.55	0.53	0.50	0.48	0.47	0.45	0.44
450	0.74	0.67	0.61	0.56	0.53	0.49	0.47	0.45	0.43	0.41	0.40
500	0.74	0.65	0.59	0.54	0.50	0.47	0.44	0.41	0.40	0.38	0.36
550	0.74	0.64	0.57	0.52	0.47	0.44	0.41	0.39	0.36	0.35	0.33
600	0.74	0.63	0.55	0.50	0.45	0.41	0.38	0.36	0.34	0.32	0.30

Table F.72. *REBS south: decision table for the upper stock reference point $0.8B_{MSY}$ for 1-10-year projections for a range of* **harvest rate** *strategies, such that values are P$(B_t > 0.8B_{MSY})$. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.033.*

HR	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	0.74	0.78	0.83	0.87	0.91	0.94	0.96	0.98	0.99	>0.99	>0.99
0.01	0.74	0.77	0.82	0.85	0.89	0.92	0.95	0.97	0.98	0.99	0.99
0.02	0.74	0.77	0.81	0.84	0.87	0.90	0.93	0.95	0.97	0.98	0.99
0.03	0.74	0.76	0.80	0.82	0.85	0.88	0.91	0.93	0.95	0.96	0.97
0.04	0.74	0.76	0.78	0.81	0.83	0.86	0.88	0.90	0.92	0.94	0.95
0.05	0.74	0.76	0.77	0.79	0.81	0.83	0.85	0.87	0.88	0.90	0.91
0.06	0.74	0.75	0.76	0.77	0.79	0.80	0.81	0.83	0.84	0.86	0.87
0.07	0.74	0.74	0.75	0.75	0.76	0.77	0.78	0.79	0.80	0.80	0.80
0.08	0.74	0.74	0.73	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.73
0.09	0.74	0.73	0.72	0.72	0.71	0.70	0.69	0.69	0.68	0.67	0.66
0.1	0.74	0.72	0.71	0.70	0.68	0.67	0.65	0.64	0.62	0.60	0.59
0.11	0.74	0.72	0.70	0.67	0.65	0.63	0.61	0.59	0.57	0.55	0.53
0.12	0.74	0.71	0.68	0.65	0.63	0.60	0.57	0.55	0.52	0.50	0.48

Table F.73. REBS south: decision table for the reference point B_{MSY} for 1-10-year projections-year projections for a range of **constant catch** *strategies (in tonnes), such that values are P($B_t > B_{MSY}$). For reference, the average catch over the last 5 years (2015-2019) was 291 t.*

CC	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	0.55	0.59	0.62	0.66	0.71	0.76	0.80	0.84	0.88	0.92	0.95
50	0.55	0.58	0.60	0.63	0.66	0.69	0.72	0.76	0.79	0.82	0.85
100	0.55	0.57	0.58	0.60	0.62	0.63	0.65	0.67	0.69	0.71	0.73
150	0.55	0.56	0.57	0.57	0.58	0.58	0.59	0.60	0.61	0.61	0.62
200	0.55	0.55	0.55	0.55	0.55	0.55	0.54	0.55	0.54	0.54	0.54
250	0.55	0.54	0.53	0.52	0.52	0.51	0.50	0.50	0.49	0.49	0.48
300	0.55	0.53	0.52	0.50	0.49	0.48	0.47	0.46	0.45	0.45	0.44
350	0.55	0.53	0.50	0.48	0.46	0.45	0.43	0.42	0.41	0.40	0.40
400	0.55	0.52	0.49	0.46	0.44	0.42	0.41	0.39	0.38	0.37	0.36
450	0.55	0.51	0.47	0.44	0.42	0.40	0.38	0.36	0.35	0.34	0.33
500	0.55	0.50	0.46	0.42	0.40	0.37	0.35	0.34	0.32	0.31	0.29
550	0.55	0.49	0.45	0.41	0.38	0.35	0.33	0.31	0.30	0.28	0.27
600	0.55	0.49	0.43	0.39	0.36	0.33	0.31	0.29	0.27	0.26	0.24

Table F.74. REBS south: decision table for the reference point B_{MSY} for 1-10-year projections-year projections for a range of **harvest rate** *strategies, such that values are P($B_t > B_{MSY}$). For reference, the average harvest rate over the last 5 years (2015-2019) was 0.033.*

HR	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	0.55	0.59	0.62	0.66	0.71	0.76	0.80	0.84	0.88	0.92	0.95
0.01	0.55	0.58	0.61	0.64	0.68	0.72	0.77	0.80	0.84	0.88	0.91
0.02	0.55	0.58	0.60	0.63	0.65	0.69	0.72	0.76	0.80	0.83	0.86
0.03	0.55	0.57	0.59	0.61	0.63	0.66	0.68	0.71	0.74	0.77	0.80
0.04	0.55	0.57	0.58	0.59	0.61	0.62	0.64	0.66	0.68	0.70	0.72
0.05	0.55	0.56	0.57	0.58	0.58	0.59	0.61	0.62	0.63	0.63	0.65
0.06	0.55	0.55	0.56	0.56	0.56	0.57	0.57	0.57	0.57	0.58	0.58
0.07	0.55	0.55	0.55	0.54	0.54	0.54	0.54	0.53	0.53	0.53	0.52
0.08	0.55	0.54	0.54	0.53	0.52	0.51	0.50	0.49	0.49	0.48	0.47
0.09	0.55	0.54	0.53	0.51	0.50	0.48	0.47	0.46	0.45	0.44	0.43
0.1	0.55	0.53	0.51	0.49	0.47	0.46	0.44	0.43	0.41	0.39	0.38
0.11	0.55	0.53	0.50	0.48	0.45	0.43	0.41	0.39	0.37	0.35	0.33
0.12	0.55	0.52	0.49	0.46	0.43	0.41	0.39	0.36	0.33	0.31	0.29

Table F.75. REBS south: decision table comparing the projected exploitation rate to that at MSY for a range of **constant catch** *strategies, such that values are P($u_t < u_{\mathrm{MSY}}$), i.e. the probability of the exploitation rate in the middle of year t being less than that at MSY. For reference, the average catch over the last 5 years (2015-2019) was 291 t.*

CC	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	1	1	1	1	1	1	1	1	1	1	1
50	>0.99	>0.99	>0.99	>0.99	1	1	1	1	1	1	1
100	0.87	0.88	0.89	0.91	0.93	0.94	0.96	0.97	0.98	0.98	0.98
150	0.63	0.63	0.63	0.64	0.65	0.67	0.68	0.70	0.72	0.73	0.74
200	0.49	0.49	0.49	0.49	0.50	0.50	0.51	0.51	0.52	0.52	0.52
250	0.40	0.40	0.40	0.40	0.40	0.41	0.41	0.42	0.42	0.42	0.43
300	0.34	0.33	0.33	0.33	0.33	0.33	0.34	0.34	0.34	0.34	0.34
350	0.28	0.27	0.27	0.27	0.27	0.27	0.27	0.28	0.28	0.28	0.27
400	0.24	0.23	0.23	0.22	0.22	0.22	0.23	0.23	0.23	0.23	0.22
450	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.19
500	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.17	0.17	0.17
550	0.17	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.15	0.15
600	0.16	0.15	0.15	0.15	0.15	0.14	0.14	0.14	0.14	0.14	0.14

Table F.76. REBS south: decision table comparing the projected exploitation rate to that at MSY for a range of **harvest rate** *strategies, such that values are P($u_t < u_{\mathrm{MSY}}$), i.e. the probability of the exploitation rate in the middle of year t being less than that at MSY. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.033.*

HR	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	1	1	1	1	1	1	1	1	1	1	1
0.01	1	1	1	1	1	1	1	1	1	1	1
0.02	1	1	1	1	1	1	1	1	1	1	1
0.03	1	1	1	1	1	1	1	1	1	1	1
0.04	1	1	1	1	1	1	1	1	1	1	1
0.05	0.96	0.95	0.95	0.96	0.95	0.95	0.95	0.95	0.95	0.95	0.95
0.06	0.60	0.60	0.60	0.60	0.60	0.59	0.59	0.60	0.60	0.59	0.60
0.07	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.32
0.08	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
0.09	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
0.1	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
0.11	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
0.12	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

Table F.77. REBS south: decision table (REBS south) comparing the projected biomass to current biomass for a range of **constant catch** *strategies, given by probabilities P$(B_t > B_{2021})$. For reference, the average catch over the last 5 years (2015-2019) was 291 t.*

CC	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	0	1	1	1	1	1	1	1	1	1	1
50	0	>0.99	1	1	1	1	1	1	1	1	1
100	0	0.98	0.99	0.99	0.99	0.99	>0.99	>0.99	>0.99	>0.99	>0.99
150	0	0.73	0.77	0.79	0.81	0.82	0.83	0.83	0.84	0.84	0.85
200	0	0.45	0.47	0.48	0.49	0.51	0.51	0.52	0.53	0.54	0.54
250	0	0.30	0.29	0.29	0.30	0.31	0.32	0.32	0.32	0.32	0.32
300	0	0.20	0.19	0.19	0.19	0.20	0.20	0.20	0.21	0.21	0.21
350	0	0.14	0.13	0.13	0.13	0.14	0.14	0.14	0.14	0.14	0.14
400	0	0.10	0.09	0.09	0.09	0.10	0.10	0.10	0.09	0.09	0.10
450	0	0.07	0.06	0.06	0.06	0.07	0.07	0.07	0.07	0.07	0.07
500	0	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.05	0.04	0.04
550	0	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
600	0	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

Table F.78. REBS south: decision table (REBS south) comparing the projected biomass to current biomass for a range of **harvest rate** *strategies, given by probabilities P$(B_t > B_{2021})$. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.033.*

HR	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	0	1	1	1	1	1	1	1	1	1	1
0.01	0	>0.99	>0.99	1	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
0.02	0	0.98	0.98	0.98	0.99	0.99	0.99	0.98	0.98	0.98	0.98
0.03	0	0.90	0.91	0.92	0.92	0.93	0.93	0.93	0.92	0.92	0.92
0.04	0	0.77	0.79	0.80	0.81	0.81	0.81	0.81	0.81	0.81	0.81
0.05	0	0.62	0.64	0.65	0.66	0.67	0.67	0.67	0.68	0.68	0.67
0.06	0	0.48	0.50	0.51	0.51	0.52	0.52	0.53	0.53	0.53	0.53
0.07	0	0.36	0.37	0.38	0.38	0.39	0.39	0.39	0.39	0.39	0.39
0.08	0	0.27	0.28	0.28	0.28	0.28	0.29	0.28	0.28	0.28	0.28
0.09	0	0.21	0.20	0.20	0.20	0.21	0.21	0.21	0.21	0.21	0.20
0.1	0	0.16	0.15	0.15	0.16	0.16	0.16	0.16	0.15	0.15	0.15
0.11	0	0.13	0.12	0.12	0.11	0.12	0.12	0.12	0.12	0.11	0.11
0.12	0	0.10	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.08	0.08

Table F.79. REBS south: decision table comparing the projected exploitation rate to that in 2020 for a range of **constant catch** *strategies, such that values are P*$(u_t < u_{2020})$. *For reference, the average catch over the last 5 years (2015-2019) was 291 t.*

CC	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	1	1	1	1	1	1	1	1	1	1	1
50	1	1	1	1	1	1	1	1	1	1	1
100	1	1	1	1	1	1	1	1	1	1	1
150	1	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
200	0.33	0.36	0.40	0.45	0.50	0.55	0.59	0.62	0.64	0.65	0.66
250	0	0	0	<0.01	0.01	0.02	0.05	0.07	0.10	0.12	0.13
300	0	0	0	0	0	<0.01	<0.01	<0.01	<0.01	0.01	0.01
350	0	0	0	0	0	0	0	<0.01	<0.01	<0.01	<0.01
400	0	0	0	0	0	0	0	0	<0.01	<0.01	<0.01
450	0	0	0	0	0	0	0	0	0	0	0
500	0	0	0	0	0	0	0	0	0	0	0
550	0	0	0	0	0	0	0	0	0	0	0
600	0	0	0	0	0	0	0	0	0	0	0

Table F.80. REBS south: decision table comparing the projected exploitation rate to that in 2020 for a range of **harvest rate** *strategies, such that values are P*$(u_t < u_{2020})$. *For reference, the average harvest rate over the last 5 years (2015-2019) was 0.033.*

HR	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	1	1	1	1	1	1	1	1	1	1	1
0.01	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
0.02	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
0.03	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
0.04	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72
0.05	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62
0.06	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
0.07	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41
0.08	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32
0.09	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
0.1	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
0.12	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08

Table F.81. *REBS south: decision table for the alternative limit reference point $0.2B_0$ for 1-10 year projections for a range of* **constant catch** *strategies, such that values are P$(B_t > 0.2B_0)$. For reference, the average catch over the last 5 years (2015-2019) was 291 t.*

CC	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	0.79	0.83	0.87	0.91	0.94	0.97	0.98	0.99	>0.99	>0.99	>0.99
50	0.79	0.82	0.85	0.88	0.91	0.93	0.95	0.96	0.97	0.98	0.99
100	0.79	0.81	0.82	0.84	0.86	0.88	0.89	0.90	0.92	0.93	0.94
150	0.79	0.79	0.80	0.81	0.81	0.82	0.82	0.83	0.84	0.84	0.85
200	0.79	0.78	0.77	0.77	0.76	0.76	0.75	0.75	0.74	0.74	0.74
250	0.79	0.77	0.75	0.73	0.71	0.70	0.69	0.67	0.66	0.64	0.64
300	0.79	0.75	0.72	0.69	0.67	0.64	0.62	0.60	0.59	0.57	0.56
350	0.79	0.74	0.70	0.66	0.62	0.60	0.57	0.55	0.53	0.51	0.50
400	0.79	0.73	0.68	0.63	0.59	0.56	0.53	0.51	0.49	0.47	0.46
450	0.79	0.72	0.65	0.60	0.56	0.52	0.49	0.47	0.45	0.43	0.41
500	0.79	0.70	0.63	0.57	0.53	0.49	0.46	0.43	0.41	0.39	0.38
550	0.79	0.69	0.61	0.55	0.50	0.46	0.43	0.40	0.38	0.36	0.34
600	0.79	0.68	0.59	0.53	0.48	0.43	0.40	0.38	0.35	0.33	0.31

Table F.82. *REBS south: decision table for the alternative limit reference point $0.2B_0$ for 1-10 year projections for a range of* **harvest rate** *strategies, such that values are P$(B_t > 0.2B_0)$. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.033.*

HR	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	0.79	0.83	0.87	0.91	0.94	0.97	0.98	0.99	>0.99	>0.99	>0.99
0.01	0.79	0.83	0.86	0.90	0.93	0.96	0.97	0.99	0.99	>0.99	>0.99
0.02	0.79	0.82	0.86	0.89	0.92	0.94	0.96	0.98	0.99	0.99	>0.99
0.03	0.79	0.82	0.84	0.88	0.90	0.93	0.95	0.96	0.97	0.98	0.99
0.04	0.79	0.81	0.84	0.86	0.89	0.91	0.93	0.94	0.96	0.97	0.98
0.05	0.79	0.81	0.83	0.85	0.87	0.89	0.90	0.92	0.93	0.94	0.95
0.06	0.79	0.80	0.82	0.83	0.85	0.86	0.88	0.89	0.90	0.91	0.92
0.07	0.79	0.80	0.81	0.81	0.82	0.83	0.84	0.86	0.86	0.87	0.87
0.08	0.79	0.79	0.80	0.80	0.80	0.80	0.81	0.82	0.82	0.82	0.82
0.09	0.79	0.79	0.78	0.78	0.78	0.78	0.78	0.77	0.76	0.75	0.75
0.1	0.79	0.78	0.77	0.76	0.75	0.74	0.73	0.72	0.70	0.69	0.67
0.11	0.79	0.77	0.76	0.74	0.73	0.71	0.69	0.67	0.65	0.62	0.60
0.12	0.79	0.77	0.74	0.72	0.70	0.67	0.65	0.62	0.59	0.57	0.54

Table F.83. REBS south: decision table for the alternative upper stock reference point $0.4B_0$ for 1-10 year projections for a range of **constant catch** *strategies, such that values are P$(B_t > 0.4B_0)$. For reference, the average catch over the last 5 years (2015-2019) was 291 t.*

CC	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	0.28	0.31	0.33	0.35	0.37	0.39	0.42	0.44	0.47	0.50	0.52
50	0.28	0.30	0.32	0.33	0.35	0.37	0.39	0.41	0.42	0.44	0.47
100	0.28	0.30	0.31	0.32	0.33	0.35	0.36	0.37	0.38	0.40	0.41
150	0.28	0.29	0.30	0.31	0.31	0.32	0.33	0.34	0.35	0.36	0.37
200	0.28	0.29	0.29	0.30	0.30	0.30	0.31	0.31	0.32	0.32	0.32
250	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.29
300	0.28	0.28	0.27	0.27	0.27	0.26	0.26	0.26	0.26	0.26	0.26
350	0.28	0.28	0.27	0.26	0.25	0.25	0.24	0.24	0.24	0.23	0.23
400	0.28	0.27	0.26	0.25	0.24	0.23	0.23	0.22	0.22	0.21	0.21
450	0.28	0.27	0.25	0.24	0.23	0.22	0.21	0.21	0.20	0.20	0.19
500	0.28	0.26	0.25	0.23	0.22	0.21	0.20	0.19	0.19	0.18	0.18
550	0.28	0.26	0.24	0.22	0.21	0.20	0.19	0.18	0.18	0.17	0.17
600	0.28	0.25	0.23	0.21	0.20	0.19	0.18	0.17	0.16	0.16	0.15

Table F.84. REBS south: decision table for the alternative upper stock reference point $0.4B_0$ for 1-10 year projections for a range of **harvest rate** *strategies, such that values are P$(B_t > 0.4B_0)$. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.033.*

HR	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	0.28	0.31	0.33	0.35	0.37	0.39	0.42	0.44	0.47	0.50	0.52
0.01	0.28	0.30	0.32	0.34	0.35	0.37	0.39	0.41	0.43	0.46	0.47
0.02	0.28	0.30	0.31	0.32	0.33	0.35	0.36	0.38	0.39	0.41	0.42
0.03	0.28	0.29	0.30	0.31	0.32	0.33	0.34	0.34	0.35	0.37	0.37
0.04	0.28	0.29	0.29	0.30	0.30	0.31	0.31	0.31	0.32	0.32	0.32
0.05	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
0.06	0.28	0.28	0.27	0.27	0.26	0.26	0.26	0.25	0.25	0.24	0.24
0.07	0.28	0.27	0.26	0.26	0.25	0.24	0.23	0.23	0.22	0.21	0.21
0.08	0.28	0.27	0.25	0.24	0.23	0.22	0.21	0.20	0.20	0.19	0.18
0.09	0.28	0.27	0.25	0.23	0.22	0.20	0.19	0.18	0.17	0.16	0.15
0.1	0.28	0.26	0.24	0.22	0.20	0.19	0.18	0.16	0.15	0.14	0.13
0.11	0.28	0.25	0.23	0.21	0.19	0.18	0.16	0.15	0.13	0.12	0.10
0.12	0.28	0.25	0.22	0.20	0.18	0.16	0.15	0.13	0.11	0.10	0.08

F.3.4.2. GMU – Long-term guidance

Table F.85. REBS south: decision table for the limit reference point $0.4B_{MSY}$ for selected projection years over 1.5 generations (75 years) and for a range of **constant catch** *strategies, such that values are P$(B_t > 0.4B_{MSY})$. For reference, the average catch over the last 5 years (2015-2019) was 291 t.*

CC	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	>0.99	1	1	1	1	1	1	1	1	1	1
50	>0.99	>0.99	1	1	1	1	1	1	1	1	1
100	>0.99	>0.99	>0.99	>0.99	>0.99	1	1	1	1	1	1
150	>0.99	>0.99	>0.99	>0.99	0.99	0.99	0.98	0.96	0.95	0.94	0.93
200	>0.99	>0.99	0.99	0.96	0.93	0.90	0.83	0.77	0.73	0.69	0.66
250	>0.99	0.99	0.94	0.88	0.81	0.73	0.63	0.57	0.52	0.49	0.47
300	>0.99	0.97	0.88	0.76	0.66	0.59	0.50	0.45	0.41	0.38	0.36
350	>0.99	0.94	0.79	0.64	0.55	0.49	0.41	0.36	0.32	0.29	0.26
400	>0.99	0.91	0.70	0.55	0.48	0.42	0.34	0.29	0.25	0.22	0.20
450	>0.99	0.87	0.62	0.49	0.42	0.36	0.28	0.23	0.20	0.18	0.17
500	>0.99	0.83	0.56	0.44	0.37	0.31	0.24	0.19	0.17	0.15	0.14
550	>0.99	0.79	0.51	0.40	0.32	0.27	0.20	0.17	0.14	0.13	0.11
600	>0.99	0.74	0.47	0.36	0.28	0.23	0.18	0.14	0.12	0.10	0.09

Table F.86. REBS south: decision table for the limit reference point $0.4B_{MSY}$ for selected projection years over 1.5 generations (75 years) and for a range of **harvest rate** *strategies, such that values are P$(B_t > 0.4B_{MSY})$. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.033.*

HR	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	>0.99	1	1	1	1	1	1	1	1	1	1
0.01	>0.99	1	1	1	1	1	1	1	1	1	1
0.02	>0.99	>0.99	1	1	1	1	1	1	1	1	1
0.03	>0.99	>0.99	1	1	1	1	1	1	1	1	1
0.04	>0.99	>0.99	1	1	1	1	1	1	1	1	1
0.05	>0.99	>0.99	1	1	1	1	1	1	1	1	1
0.06	>0.99	>0.99	1	1	1	1	1	1	1	1	1
0.07	>0.99	>0.99	>0.99	1	1	1	>0.99	>0.99	>0.99	>0.99	>0.99
0.08	>0.99	>0.99	>0.99	1	1	>0.99	>0.99	>0.99	>0.99	0.99	0.99
0.09	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	0.99	0.98	0.98	0.96	0.95
0.1	>0.99	>0.99	>0.99	>0.99	>0.99	0.99	0.97	0.94	0.91	0.90	0.87
0.11	>0.99	>0.99	>0.99	>0.99	0.99	0.97	0.92	0.87	0.83	0.78	0.75
0.12	>0.99	>0.99	>0.99	0.99	0.97	0.94	0.85	0.77	0.71	0.66	0.61

Table F.87. *REBS south: decision table for the upper stock reference $0.8B_{MSY}$ for selected projection years over 1.5 generations (75 years) and for a range of* **constant catch** *strategies, such that values are $P(B_t > 0.8B_{MSY})$. For reference, the average catch over the last 5 years (2015-2019) was 291 t.*

CC	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	0.74	0.91	>0.99	>0.99	1	1	1	1	1	1	1
50	0.74	0.86	0.97	0.99	>0.99	>0.99	1	1	1	1	1
100	0.74	0.81	0.89	0.94	0.97	0.98	0.98	0.99	0.99	0.99	>0.99
150	0.74	0.76	0.80	0.83	0.84	0.84	0.83	0.83	0.83	0.83	0.83
200	0.74	0.71	0.70	0.69	0.67	0.65	0.62	0.60	0.58	0.56	0.55
250	0.74	0.66	0.61	0.57	0.54	0.52	0.48	0.45	0.43	0.41	0.40
300	0.74	0.62	0.54	0.50	0.46	0.44	0.39	0.35	0.33	0.31	0.29
350	0.74	0.59	0.49	0.44	0.40	0.37	0.32	0.28	0.25	0.23	0.22
400	0.74	0.55	0.45	0.39	0.35	0.31	0.26	0.22	0.20	0.18	0.17
450	0.74	0.53	0.41	0.35	0.30	0.26	0.21	0.18	0.16	0.15	0.14
500	0.74	0.50	0.38	0.31	0.26	0.22	0.18	0.15	0.14	0.13	0.11
550	0.74	0.47	0.35	0.27	0.23	0.20	0.15	0.13	0.12	0.10	0.09
600	0.74	0.45	0.32	0.24	0.20	0.17	0.14	0.11	0.09	0.08	0.07

Table F.88. *REBS south: decision table for the upper stock reference $0.8B_{MSY}$ for selected projection years over 1.5 generations (75 years) and for a range of* **harvest rate** *strategies, such that values are $P(B_t > 0.8B_{MSY})$. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.033.*

HR	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	0.74	0.91	>0.99	>0.99	1	1	1	1	1	1	1
0.01	0.74	0.89	0.99	>0.99	1	1	1	1	1	1	1
0.02	0.74	0.87	0.98	>0.99	>0.99	1	1	1	1	1	1
0.03	0.74	0.85	0.96	0.99	>0.99	>0.99	>0.99	1	1	1	1
0.04	0.74	0.83	0.94	0.98	0.99	0.99	>0.99	>0.99	>0.99	>0.99	>0.99
0.05	0.74	0.81	0.90	0.94	0.96	0.97	0.96	0.96	0.96	0.97	0.97
0.06	0.74	0.79	0.86	0.89	0.90	0.89	0.87	0.85	0.86	0.85	0.84
0.07	0.74	0.76	0.80	0.81	0.80	0.77	0.73	0.69	0.68	0.67	0.64
0.08	0.74	0.74	0.74	0.71	0.67	0.63	0.57	0.53	0.51	0.48	0.46
0.09	0.74	0.71	0.67	0.61	0.57	0.52	0.44	0.39	0.36	0.34	0.32
0.1	0.74	0.68	0.60	0.53	0.47	0.42	0.33	0.28	0.26	0.24	0.22
0.11	0.74	0.65	0.55	0.46	0.39	0.34	0.25	0.20	0.19	0.17	0.15
0.12	0.74	0.63	0.50	0.40	0.33	0.27	0.20	0.15	0.14	0.12	0.11

Table F.89. REBS south: decision table for biomass at maximum sustainable yield B_{MSY} for selected projection years over 1.5 generations (75 years) and for a range of **constant catch** *strategies, such that values are P($B_t > B_{MSY}$). For reference, the average catch over the last 5 years (2015-2019) was 291 t.*

CC	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	0.55	0.71	0.92	0.99	>0.99	1	1	1	1	1	1
50	0.55	0.66	0.82	0.93	0.98	0.99	>0.99	>0.99	1	1	1
100	0.55	0.62	0.71	0.80	0.86	0.90	0.93	0.95	0.97	0.98	0.99
150	0.55	0.58	0.61	0.65	0.68	0.70	0.72	0.73	0.74	0.75	0.76
200	0.55	0.55	0.54	0.55	0.55	0.54	0.54	0.52	0.51	0.51	0.50
250	0.55	0.52	0.49	0.47	0.46	0.45	0.42	0.40	0.39	0.37	0.36
300	0.55	0.49	0.45	0.42	0.40	0.38	0.34	0.31	0.29	0.27	0.26
350	0.55	0.46	0.40	0.37	0.34	0.31	0.27	0.24	0.22	0.21	0.19
400	0.55	0.44	0.37	0.33	0.29	0.26	0.22	0.19	0.18	0.16	0.15
450	0.55	0.42	0.34	0.29	0.25	0.22	0.19	0.16	0.14	0.14	0.12
500	0.55	0.40	0.31	0.25	0.22	0.19	0.16	0.13	0.12	0.11	0.10
550	0.55	0.38	0.28	0.23	0.20	0.17	0.14	0.11	0.10	0.09	0.08
600	0.55	0.36	0.26	0.21	0.18	0.15	0.12	0.09	0.08	0.07	0.06

Table F.90. REBS south: decision table for biomass at maximum sustainable yield B_{MSY} for selected projection years over 1.5 generations (75 years) and for a range of **harvest rate** *strategies, such that values are P($B_t > B_{MSY}$). For reference, the average harvest rate over the last 5 years (2015-2019) was 0.033.*

HR	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	0.55	0.71	0.92	0.99	>0.99	1	1	1	1	1	1
0.01	0.55	0.68	0.88	0.98	>0.99	>0.99	1	1	1	1	1
0.02	0.55	0.65	0.83	0.95	0.99	>0.99	>0.99	>0.99	1	1	1
0.03	0.55	0.63	0.77	0.89	0.95	0.97	0.99	0.99	>0.99	>0.99	>0.99
0.04	0.55	0.61	0.70	0.80	0.86	0.90	0.92	0.93	0.94	0.96	0.96
0.05	0.55	0.58	0.63	0.70	0.74	0.76	0.77	0.78	0.79	0.80	0.79
0.06	0.55	0.56	0.58	0.60	0.61	0.61	0.59	0.58	0.58	0.58	0.56
0.07	0.55	0.54	0.53	0.51	0.50	0.48	0.44	0.40	0.39	0.38	0.37
0.08	0.55	0.52	0.48	0.44	0.41	0.38	0.32	0.27	0.26	0.24	0.24
0.09	0.55	0.50	0.44	0.38	0.33	0.29	0.23	0.19	0.17	0.16	0.15
0.1	0.55	0.47	0.39	0.32	0.27	0.22	0.17	0.13	0.12	0.10	0.10
0.11	0.55	0.45	0.35	0.27	0.22	0.18	0.12	0.09	0.08	0.07	0.06
0.12	0.55	0.43	0.31	0.23	0.18	0.14	0.08	0.06	0.05	0.05	0.04

Table F.91. REBS south: decision table for harvest rate at maximum sustainable yield u_{MSY} for selected projection years over 1.5 generations (75 years) and for a range of **constant catch** *strategies, such that values are P$(u_t < u_{MSY})$. For reference, the average catch over the last 5 years (2015-2019) was 291 t.*

CC	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	1	1	1	1	1	1	1	1	1	1	1
50	>0.99	1	1	1	1	1	1	1	1	1	1
100	0.87	0.93	0.98	0.99	0.99	0.99	0.99	0.99	>0.99	>0.99	>0.99
150	0.63	0.65	0.73	0.76	0.77	0.77	0.77	0.77	0.78	0.79	0.79
200	0.49	0.50	0.52	0.52	0.52	0.52	0.51	0.51	0.50	0.50	0.50
250	0.40	0.40	0.42	0.42	0.41	0.40	0.39	0.38	0.37	0.36	0.35
300	0.34	0.33	0.34	0.34	0.32	0.31	0.29	0.27	0.26	0.25	0.24
350	0.28	0.27	0.28	0.26	0.25	0.24	0.22	0.20	0.19	0.19	0.18
400	0.24	0.22	0.23	0.21	0.20	0.19	0.18	0.16	0.15	0.15	0.14
450	0.20	0.20	0.20	0.18	0.17	0.16	0.15	0.13	0.13	0.12	0.11
500	0.18	0.18	0.17	0.16	0.15	0.14	0.12	0.11	0.10	0.09	0.09
550	0.17	0.16	0.15	0.14	0.13	0.12	0.10	0.09	0.08	0.07	0.06
600	0.16	0.15	0.14	0.13	0.11	0.10	0.08	0.07	0.06	0.05	0.05

Table F.92. REBS south: decision table for harvest rate at maximum sustainable yield u_{MSY} for selected projection years over 1.5 generations (75 years) and for a range of **harvest rate** *strategies, such that values are P$(u_t < u_{MSY})$. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.033.*

HR	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	1	1	1	1	1	1	1	1	1	1	1
0.01	1	1	1	1	1	1	1	1	1	1	1
0.02	1	1	1	1	1	1	1	1	1	1	1
0.03	1	1	1	1	1	1	1	1	1	1	1
0.04	1	1	1	1	1	1	1	1	1	1	1
0.05	0.96	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.96	0.95	0.95
0.06	0.60	0.60	0.59	0.60	0.60	0.60	0.60	0.59	0.60	0.59	0.60
0.07	0.33	0.33	0.33	0.33	0.32	0.33	0.33	0.33	0.33	0.33	0.33
0.08	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
0.09	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
0.1	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
0.11	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
0.12	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

Table F.93. REBS south: decision table for comparing projected biomass to current biomass B_{2021} for selected projection years over 1.5 generations (75 years) and for a range of **constant catch** *strategies, such that values are P($B_t > B_{2021}$). For reference, the average catch over the last 5 years (2015-2019) was 291 t.*

CC	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	0	1	1	1	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
50	0	1	1	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	0.99
100	0	0.99	>0.99	>0.99	>0.99	0.99	0.99	0.99	0.99	0.99	0.99
150	0	0.81	0.84	0.86	0.85	0.84	0.82	0.80	0.79	0.80	0.80
200	0	0.49	0.54	0.54	0.54	0.52	0.47	0.44	0.43	0.42	0.40
250	0	0.30	0.32	0.33	0.32	0.30	0.26	0.24	0.22	0.21	0.20
300	0	0.19	0.21	0.21	0.20	0.18	0.15	0.12	0.12	0.11	0.10
350	0	0.13	0.14	0.13	0.12	0.11	0.08	0.07	0.06	0.06	0.05
400	0	0.09	0.09	0.09	0.08	0.07	0.05	0.04	0.03	0.03	0.03
450	0	0.06	0.07	0.06	0.06	0.05	0.03	0.02	0.02	0.01	0.01
500	0	0.04	0.04	0.04	0.04	0.03	0.02	0.01	0.01	0.01	0.01
550	0	0.03	0.03	0.03	0.03	0.02	0.01	0.01	0.01	<0.01	<0.01
600	0	0.02	0.02	0.02	0.02	0.01	0.01	0.01	<0.01	<0.01	<0.01

Table F.94. REBS south: decision table for comparing projected biomass to current biomass B_{2021} for selected projection years over 1.5 generations (75 years) and for a range of **harvest rate** *strategies, such that values are P($B_t > B_{2021}$). For reference, the average harvest rate over the last 5 years (2015-2019) was 0.033.*

HR	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	0	1	1	1	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
0.01	0	>0.99	>0.99	>0.99	>0.99	0.99	0.99	0.98	0.98	0.98	0.98
0.02	0	0.99	0.98	0.97	0.97	0.96	0.95	0.94	0.94	0.94	0.94
0.03	0	0.92	0.92	0.91	0.90	0.89	0.87	0.86	0.86	0.85	0.85
0.04	0	0.81	0.81	0.80	0.79	0.78	0.76	0.75	0.75	0.74	0.74
0.05	0	0.66	0.68	0.66	0.66	0.64	0.61	0.59	0.59	0.59	0.59
0.06	0	0.51	0.53	0.51	0.50	0.48	0.46	0.43	0.44	0.43	0.42
0.07	0	0.38	0.39	0.39	0.37	0.35	0.32	0.30	0.30	0.30	0.29
0.08	0	0.28	0.28	0.28	0.26	0.25	0.21	0.19	0.20	0.18	0.18
0.09	0	0.20	0.21	0.20	0.18	0.16	0.14	0.12	0.11	0.11	0.11
0.1	0	0.16	0.15	0.14	0.12	0.11	0.09	0.07	0.07	0.07	0.06
0.11	0	0.11	0.11	0.10	0.08	0.07	0.05	0.04	0.04	0.04	0.04
0.12	0	0.09	0.08	0.07	0.06	0.05	0.03	0.03	0.03	0.02	0.02

Table F.95. REBS south: decision table for comparing projected harvest rate to current harvest rate u_{2020} for selected projection years over 1.5 generations (75 years) and for a range of **constant catch** *strategies, such that values are P$(u_t < u_{2020})$. For reference, the average catch over the last 5 years (2015-2019) was 291 t.*

CC	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	1	1	1	1	1	1	1	1	1	1	1
50	1	1	1	1	1	1	1	1	1	1	1
100	1	1	1	1	1	1	1	1	1	1	1
150	1	>0.99	>0.99	0.99	0.99	0.97	0.95	0.93	0.92	0.91	0.90
200	0.33	0.50	0.65	0.64	0.60	0.57	0.52	0.48	0.48	0.46	0.45
250	0	0.01	0.12	0.15	0.16	0.16	0.15	0.14	0.13	0.13	0.13
300	0	0	0.01	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.02
350	0	0	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01
400	0	0	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
450	0	0	0	<0.01	0	<0.01	<0.01	<0.01	0	<0.01	<0.01
500	0	0	0	0	0	0	0	0	0	<0.01	<0.01
550	0	0	0	0	0	0	0	0	0	<0.01	0
600	0	0	0	0	0	0	0	0	0	0	0

Table F.96. REBS south: decision table for comparing projected harvest rate to current harvest rate u_{2020} for selected projection years over 1.5 generations (75 years) and for a range of **harvest rate** *strategies, such that values are P$(u_t < u_{2020})$. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.033.*

HR	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	1	1	1	1	1	1	1	1	1	1	1
0.01	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
0.02	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
0.03	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
0.04	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72
0.05	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62
0.06	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
0.07	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41
0.08	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32
0.09	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
0.1	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
0.12	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08

Table F.97. REBS south: decision table for alternative limit reference point $0.2B_0$ for selected projection years over 1.5 generations (75 years) and for a range of **constant catch** *strategies, such that values are P$(B_t > 0.2B_0)$. For reference, the average catch over the last 5 years (2015-2019) was 291 t.*

CC	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	0.79	0.94	>0.99	>0.99	1	1	1	1	1	1	1
50	0.79	0.91	0.98	>0.99	>0.99	1	1	1	1	1	1
100	0.79	0.86	0.93	0.96	0.98	0.98	0.99	0.99	0.99	>0.99	>0.99
150	0.79	0.81	0.84	0.87	0.87	0.87	0.86	0.85	0.85	0.85	0.84
200	0.79	0.76	0.74	0.73	0.70	0.68	0.64	0.61	0.60	0.58	0.56
250	0.79	0.71	0.64	0.60	0.57	0.54	0.50	0.46	0.44	0.42	0.41
300	0.79	0.67	0.57	0.52	0.48	0.45	0.40	0.36	0.34	0.32	0.30
350	0.79	0.62	0.51	0.46	0.42	0.38	0.33	0.29	0.26	0.24	0.22
400	0.79	0.59	0.47	0.41	0.36	0.32	0.27	0.23	0.20	0.19	0.17
450	0.79	0.56	0.43	0.36	0.31	0.27	0.22	0.19	0.17	0.15	0.14
500	0.79	0.53	0.39	0.32	0.27	0.23	0.19	0.16	0.14	0.13	0.11
550	0.79	0.50	0.36	0.29	0.23	0.20	0.16	0.13	0.12	0.10	0.09
600	0.79	0.48	0.33	0.25	0.21	0.18	0.14	0.11	0.10	0.08	0.07

Table F.98. REBS south: decision table for alternative limit reference point $0.2B_0$ for selected projection years over 1.5 generations (75 years) and for a range of **harvest rate** *strategies, such that values are P$(B_t > 0.2B_0)$. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.033.*

HR	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	0.79	0.94	>0.99	>0.99	1	1	1	1	1	1	1
0.01	0.79	0.93	>0.99	>0.99	1	1	1	1	1	1	1
0.02	0.79	0.92	0.99	>0.99	1	1	1	1	1	1	1
0.03	0.79	0.90	0.98	>0.99	>0.99	>0.99	1	1	1	1	1
0.04	0.79	0.89	0.97	0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99	>0.99
0.05	0.79	0.87	0.94	0.98	0.98	0.99	0.98	0.98	0.99	0.99	0.98
0.06	0.79	0.85	0.91	0.94	0.94	0.94	0.92	0.91	0.91	0.91	0.90
0.07	0.79	0.82	0.87	0.88	0.87	0.85	0.80	0.77	0.76	0.74	0.73
0.08	0.79	0.80	0.82	0.80	0.76	0.72	0.65	0.61	0.58	0.56	0.53
0.09	0.79	0.78	0.75	0.71	0.65	0.59	0.51	0.45	0.42	0.40	0.38
0.1	0.79	0.75	0.69	0.61	0.54	0.48	0.39	0.33	0.30	0.28	0.27
0.11	0.79	0.73	0.62	0.53	0.46	0.39	0.30	0.24	0.22	0.20	0.19
0.12	0.79	0.70	0.57	0.46	0.38	0.32	0.23	0.18	0.16	0.14	0.13

Table F.99. REBS south: decision table for alternative upper stock reference $0.4B_0$ for selected projection years over 1.5 generations (75 years) and for a range of **constant catch** *strategies, such that values are P$(B_t > 0.4B_0)$. For reference, the average catch over the last 5 years (2015-2019) was 291 t.*

CC	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	0.28	0.37	0.50	0.66	0.85	0.96	>0.99	1	1	1	1
50	0.28	0.35	0.44	0.53	0.65	0.76	0.91	0.96	0.98	>0.99	>0.99
100	0.28	0.33	0.40	0.46	0.51	0.57	0.66	0.72	0.79	0.84	0.87
150	0.28	0.31	0.36	0.39	0.43	0.45	0.48	0.50	0.52	0.55	0.56
200	0.28	0.30	0.32	0.34	0.36	0.36	0.37	0.37	0.37	0.38	0.37
250	0.28	0.28	0.28	0.29	0.29	0.29	0.28	0.28	0.27	0.26	0.26
300	0.28	0.27	0.26	0.25	0.25	0.24	0.22	0.21	0.19	0.19	0.19
350	0.28	0.25	0.23	0.22	0.21	0.20	0.18	0.16	0.15	0.15	0.14
400	0.28	0.24	0.21	0.20	0.19	0.17	0.15	0.13	0.12	0.12	0.10
450	0.28	0.23	0.20	0.18	0.16	0.15	0.12	0.11	0.10	0.09	0.08
500	0.28	0.22	0.18	0.16	0.14	0.12	0.10	0.09	0.08	0.06	0.06
550	0.28	0.21	0.17	0.15	0.13	0.11	0.09	0.07	0.06	0.05	0.04
600	0.28	0.20	0.16	0.13	0.11	0.10	0.07	0.05	0.04	0.04	0.03

Table F.100. REBS south: decision table for alternative upper stock reference $0.4B_0$ for selected projection years over 1.5 generations (75 years) and for a range of **harvest rate** *strategies, such that values are P$(B_t > 0.4B_0)$. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.033.*

HR	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	0.28	0.37	0.50	0.66	0.85	0.96	>0.99	1	1	1	1
0.01	0.28	0.35	0.46	0.56	0.71	0.85	0.96	0.99	>0.99	>0.99	1
0.02	0.28	0.33	0.41	0.48	0.57	0.66	0.81	0.89	0.93	0.96	0.97
0.03	0.28	0.32	0.37	0.41	0.46	0.50	0.59	0.64	0.70	0.74	0.75
0.04	0.28	0.30	0.32	0.34	0.36	0.38	0.39	0.40	0.42	0.44	0.44
0.05	0.28	0.28	0.28	0.28	0.28	0.27	0.25	0.23	0.23	0.23	0.23
0.06	0.28	0.26	0.24	0.23	0.21	0.19	0.15	0.13	0.13	0.12	0.11
0.07	0.28	0.25	0.21	0.18	0.15	0.13	0.09	0.07	0.07	0.06	0.06
0.08	0.28	0.23	0.19	0.15	0.11	0.08	0.05	0.04	0.04	0.03	0.03
0.09	0.28	0.22	0.16	0.11	0.08	0.05	0.03	0.02	0.02	0.01	0.01
0.1	0.28	0.20	0.14	0.08	0.05	0.03	0.02	0.01	0.01	0.01	0.01
0.11	0.28	0.19	0.12	0.06	0.03	0.02	0.01	<0.01	0.01	<0.01	<0.01
0.12	0.28	0.18	0.10	0.04	0.02	0.01	0.01	<0.01	<0.01	<0.01	<0.01

F.3.4.3. COSEWIC – Reference criteria

Table F.101. REBS south: decision table for probabilities of satisfying the A2 criterion of $\leq 50\%$ decline over 1.5 generations (75 years) for 10-year projections and for a range of **constant catch** *strategies. For reference, the average catch over the last 5 years (2015-2019) was 291 t.*

CC	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	0.17	0.18	0.20	0.21	0.23	0.25	0.28	0.30	0.33	0.35	0.37
50	0.17	0.18	0.20	0.21	0.22	0.24	0.25	0.27	0.29	0.31	0.33
100	0.17	0.18	0.19	0.20	0.21	0.22	0.23	0.25	0.26	0.27	0.28
150	0.17	0.18	0.19	0.19	0.20	0.21	0.22	0.23	0.23	0.24	0.25
200	0.17	0.17	0.18	0.18	0.19	0.20	0.20	0.21	0.21	0.22	0.22
250	0.17	0.17	0.18	0.18	0.18	0.18	0.19	0.19	0.20	0.20	0.20
300	0.17	0.17	0.17	0.17	0.17	0.17	0.18	0.18	0.18	0.18	0.18
350	0.17	0.17	0.17	0.16	0.16	0.17	0.17	0.17	0.17	0.17	0.17
400	0.17	0.17	0.16	0.16	0.16	0.16	0.16	0.16	0.15	0.15	0.15
450	0.17	0.16	0.16	0.16	0.15	0.15	0.15	0.14	0.14	0.14	0.14
500	0.17	0.16	0.16	0.15	0.15	0.14	0.14	0.13	0.13	0.13	0.12
550	0.17	0.16	0.15	0.15	0.14	0.13	0.13	0.13	0.12	0.12	0.12
600	0.17	0.16	0.15	0.14	0.13	0.13	0.12	0.12	0.11	0.11	0.11

Table F.102. REBS south: decision table for probabilities of satisfying the A2 criterion of $\leq 50\%$ decline over 1.5 generations (75 years) for 10-year projections and for a range of **harvest rate** *strategies. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.033.*

HR	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	0.17	0.18	0.20	0.21	0.23	0.25	0.28	0.30	0.33	0.35	0.37
0.01	0.17	0.18	0.19	0.20	0.22	0.23	0.25	0.27	0.29	0.30	0.32
0.02	0.17	0.18	0.19	0.20	0.20	0.21	0.23	0.24	0.25	0.26	0.27
0.03	0.17	0.17	0.18	0.19	0.19	0.20	0.21	0.21	0.22	0.22	0.23
0.04	0.17	0.17	0.17	0.18	0.18	0.18	0.19	0.19	0.19	0.19	0.20
0.05	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.16
0.06	0.17	0.16	0.16	0.16	0.16	0.15	0.15	0.15	0.14	0.14	0.13
0.07	0.17	0.16	0.16	0.15	0.14	0.14	0.13	0.13	0.12	0.11	0.11
0.08	0.17	0.16	0.15	0.14	0.13	0.12	0.11	0.11	0.10	0.09	0.08
0.09	0.17	0.16	0.15	0.13	0.12	0.11	0.10	0.09	0.08	0.07	0.06
0.1	0.17	0.16	0.14	0.12	0.11	0.10	0.09	0.08	0.06	0.05	0.04
0.11	0.17	0.15	0.13	0.12	0.10	0.09	0.07	0.06	0.05	0.04	0.03
0.12	0.17	0.15	0.13	0.11	0.09	0.08	0.06	0.05	0.03	0.02	0.02

Table F.103. REBS south: decision table for probabilities of satisfying the A2 criterion of $\leq 30\%$ decline over 1.5 generations (75 years) for 10-year projections and for a range of **constant catch** *strategies. For reference, the average catch over the last 5 years (2015-2019) was 291 t.*

CC	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.12	0.13	0.14
50	0.04	0.05	0.06	0.06	0.07	0.08	0.09	0.10	0.11	0.11	0.12
100	0.04	0.05	0.06	0.06	0.07	0.07	0.08	0.09	0.10	0.10	0.11
150	0.04	0.05	0.05	0.06	0.06	0.07	0.08	0.08	0.09	0.09	0.10
200	0.04	0.05	0.05	0.06	0.06	0.07	0.07	0.07	0.08	0.08	0.09
250	0.04	0.05	0.05	0.05	0.06	0.06	0.06	0.07	0.07	0.07	0.08
300	0.04	0.04	0.05	0.05	0.05	0.06	0.06	0.06	0.06	0.07	0.07
350	0.04	0.04	0.05	0.05	0.05	0.05	0.05	0.06	0.06	0.06	0.06
400	0.04	0.04	0.04	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.05
450	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.05	0.05	0.05	0.05
500	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
550	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03
600	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03

Table F.104. REBS south: decision table for probabilities of satisfying the A2 criterion of $\leq 30\%$ decline over 1.5 generations (75 years) for 10-year projections and for a range of **harvest rate** *strategies. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.033.*

HR	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.12	0.13	0.14
0.01	0.04	0.05	0.06	0.06	0.07	0.07	0.08	0.09	0.10	0.10	0.11
0.02	0.04	0.05	0.05	0.05	0.06	0.06	0.07	0.07	0.07	0.08	0.08
0.03	0.04	0.04	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.06
0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
0.05	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.02
0.06	0.04	0.04	0.03	0.03	0.02	0.02	0.02	0.01	0.01	0.01	0.01
0.07	0.04	0.04	0.03	0.02	0.02	0.01	0.01	0.01	0.01	<0.01	<0.01
0.08	0.04	0.03	0.02	0.02	0.01	0.01	0.01	<0.01	<0.01	<0.01	<0.01
0.09	0.04	0.03	0.02	0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
0.1	0.04	0.03	0.02	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
0.11	0.04	0.03	0.02	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0	0
0.12	0.04	0.02	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0	0	0

Table F.105. REBS south: decision table for reference criterion $0.5B_0$ for 10-year projections and for a range of **constant catch** *strategies, such that values are P($B_t > 0.5B_0$). For reference, the average catch over the last 5 years (2015-2019) was 291 t.*

CC	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	0.17	0.18	0.19	0.21	0.22	0.24	0.26	0.28	0.30	0.32	0.34
50	0.17	0.18	0.19	0.20	0.21	0.22	0.24	0.25	0.27	0.28	0.30
100	0.17	0.17	0.19	0.19	0.20	0.21	0.22	0.23	0.24	0.25	0.26
150	0.17	0.17	0.18	0.19	0.19	0.20	0.20	0.21	0.22	0.22	0.23
200	0.17	0.17	0.18	0.18	0.18	0.19	0.19	0.20	0.20	0.20	0.21
250	0.17	0.17	0.17	0.17	0.17	0.18	0.18	0.18	0.18	0.19	0.19
300	0.17	0.16	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
350	0.17	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
400	0.17	0.16	0.16	0.16	0.15	0.15	0.15	0.15	0.15	0.15	0.15
450	0.17	0.16	0.16	0.15	0.15	0.15	0.14	0.14	0.14	0.14	0.13
500	0.17	0.16	0.15	0.15	0.14	0.14	0.13	0.13	0.13	0.12	0.12
550	0.17	0.16	0.15	0.14	0.14	0.13	0.13	0.12	0.12	0.11	0.11
600	0.17	0.15	0.15	0.14	0.13	0.12	0.12	0.11	0.11	0.11	0.10

Table F.106. REBS south: decision table for reference criterion $0.5B_0$ for 10-year projections and for a range of **harvest rate** *strategies, such that values are P($B_t > 0.5B_0$). For reference, the average harvest rate over the last 5 years (2015-2019) was 0.033.*

HR	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	0.17	0.18	0.19	0.21	0.22	0.24	0.26	0.28	0.30	0.32	0.34
0.01	0.17	0.18	0.19	0.20	0.21	0.22	0.23	0.25	0.26	0.28	0.29
0.02	0.17	0.17	0.18	0.19	0.19	0.20	0.21	0.22	0.23	0.24	0.25
0.03	0.17	0.17	0.18	0.18	0.18	0.19	0.19	0.20	0.20	0.20	0.21
0.04	0.17	0.17	0.17	0.17	0.17	0.17	0.18	0.18	0.18	0.18	0.18
0.05	0.17	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.15	0.15
0.06	0.17	0.16	0.16	0.15	0.15	0.15	0.14	0.14	0.14	0.13	0.13
0.07	0.17	0.16	0.15	0.15	0.14	0.13	0.13	0.12	0.11	0.11	0.10
0.08	0.17	0.16	0.15	0.14	0.13	0.12	0.11	0.10	0.09	0.08	0.08
0.09	0.17	0.15	0.14	0.13	0.12	0.11	0.10	0.08	0.08	0.06	0.05
0.1	0.17	0.15	0.14	0.12	0.11	0.10	0.08	0.07	0.06	0.05	0.04
0.11	0.17	0.15	0.13	0.11	0.10	0.08	0.07	0.05	0.04	0.03	0.02
0.12	0.17	0.15	0.13	0.11	0.09	0.07	0.05	0.04	0.03	0.02	0.01

Table F.107. REBS south: decision table for reference criterion $0.7B_0$ for 10-year projections and for a range of **constant catch** strategies, such that values are P($B_t > 0.7B_0$). For reference, the average catch over the last 5 years (2015-2019) was 291 t.

CC	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	0.04	0.05	0.06	0.07	0.07	0.08	0.09	0.10	0.11	0.12	0.13
50	0.04	0.05	0.05	0.06	0.07	0.08	0.08	0.09	0.10	0.11	0.11
100	0.04	0.05	0.05	0.06	0.07	0.07	0.08	0.08	0.09	0.09	0.10
150	0.04	0.04	0.05	0.06	0.06	0.07	0.07	0.07	0.08	0.08	0.09
200	0.04	0.04	0.05	0.05	0.06	0.06	0.06	0.07	0.07	0.08	0.08
250	0.04	0.04	0.05	0.05	0.05	0.06	0.06	0.06	0.06	0.07	0.07
300	0.04	0.04	0.04	0.05	0.05	0.05	0.06	0.06	0.06	0.06	0.06
350	0.04	0.04	0.04	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.05
400	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.05	0.05	0.05	0.05
450	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
500	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03
550	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03
600	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.02

Table F.108. REBS south: decision table for reference criterion $0.7B_0$ for 10-year projections and for a range of **harvest rate** strategies, such that values are P($B_t > 0.7B_0$). For reference, the average harvest rate over the last 5 years (2015-2019) was 0.033.

HR	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0	0.04	0.05	0.06	0.07	0.07	0.08	0.09	0.10	0.11	0.12	0.13
0.01	0.04	0.04	0.05	0.06	0.06	0.07	0.07	0.08	0.09	0.09	0.10
0.02	0.04	0.04	0.05	0.05	0.05	0.06	0.06	0.06	0.07	0.07	0.07
0.03	0.04	0.04	0.04	0.04	0.04	0.05	0.05	0.05	0.05	0.05	0.05
0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03
0.05	0.04	0.04	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.01	0.01
0.06	0.04	0.03	0.03	0.02	0.02	0.02	0.01	0.01	0.01	<0.01	<0.01
0.07	0.04	0.03	0.02	0.02	0.01	0.01	0.01	<0.01	<0.01	<0.01	<0.01
0.08	0.04	0.03	0.02	0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
0.09	0.04	0.03	0.02	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
0.1	0.04	0.03	0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0	0
0.11	0.04	0.02	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0	0	0
0.12	0.04	0.02	0.01	<0.01	<0.01	<0.01	<0.01	0	0	0	0

Table F.109. REBS south: decision table for probabilities of satisfying the A2 criterion of $\leq 50\%$ decline over 1.5 generations (75 years) for selected projection years and for a range of **constant catch** strategies. For reference, the average catch over the last 5 years (2015-2019) was 291 t.

CC	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	0.17	0.23	0.35	0.49	0.73	0.94	>0.99	1	1	1	1
50	0.17	0.22	0.31	0.40	0.54	0.75	0.95	>0.99	1	1	1
100	0.17	0.21	0.27	0.34	0.42	0.54	0.74	0.95	>0.99	>0.99	1
150	0.17	0.20	0.24	0.29	0.34	0.40	0.52	0.71	0.87	0.89	0.93
200	0.17	0.19	0.22	0.25	0.28	0.32	0.37	0.48	0.58	0.59	0.64
250	0.17	0.18	0.20	0.21	0.23	0.26	0.28	0.35	0.40	0.40	0.42
300	0.17	0.17	0.18	0.19	0.19	0.21	0.22	0.26	0.29	0.28	0.29
350	0.17	0.16	0.17	0.16	0.16	0.17	0.17	0.20	0.22	0.21	0.21
400	0.17	0.16	0.15	0.14	0.14	0.14	0.14	0.16	0.17	0.16	0.15
450	0.17	0.15	0.14	0.13	0.12	0.12	0.11	0.13	0.13	0.13	0.11
500	0.17	0.15	0.13	0.11	0.10	0.10	0.09	0.10	0.11	0.10	0.08
550	0.17	0.14	0.12	0.10	0.09	0.09	0.08	0.08	0.08	0.07	0.06
600	0.17	0.13	0.11	0.09	0.08	0.08	0.06	0.07	0.06	0.05	0.04

Table F.110. REBS south: decision table for probabilities of satisfying the A2 criterion of $\leq 50\%$ decline over1.5 generations (75 years) for selected projection years and for a range of **harvest rate** strategies. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.033.

HR	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	0.17	0.23	0.35	0.49	0.73	0.94	>0.99	1	1	1	1
0.01	0.17	0.22	0.30	0.41	0.57	0.83	0.99	1	1	1	1
0.02	0.17	0.20	0.26	0.33	0.43	0.64	0.90	>0.99	1	1	1
0.03	0.17	0.19	0.22	0.26	0.32	0.45	0.70	0.98	1	1	>0.99
0.04	0.17	0.18	0.19	0.21	0.23	0.30	0.45	0.87	>0.99	>0.99	>0.99
0.05	0.17	0.17	0.17	0.16	0.16	0.19	0.26	0.66	0.96	0.97	0.99
0.06	0.17	0.16	0.14	0.12	0.11	0.11	0.14	0.43	0.83	0.89	0.95
0.07	0.17	0.14	0.11	0.09	0.07	0.07	0.08	0.25	0.63	0.73	0.89
0.08	0.17	0.13	0.09	0.06	0.04	0.04	0.05	0.14	0.43	0.52	0.78
0.09	0.17	0.12	0.07	0.04	0.03	0.02	0.03	0.07	0.27	0.34	0.64
0.1	0.17	0.11	0.05	0.02	0.01	0.02	0.01	0.04	0.17	0.21	0.50
0.11	0.17	0.10	0.04	0.01	0.01	0.01	0.01	0.02	0.10	0.12	0.37
0.12	0.17	0.09	0.02	0.01	<0.01	<0.01	<0.01	0.01	0.06	0.07	0.26

Table F.111. REBS south: decision table for probabilities of satisfying the A2 criterion of $\leq 30\%$ decline over 1.5 generations (75 years) for selected projection years and for a range of **constant catch** *strategies. For reference, the average catch over the last 5 years (2015-2019) was 291 t.*

CC	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	0.04	0.08	0.13	0.19	0.29	0.49	0.89	>0.99	1	1	1
50	0.04	0.07	0.11	0.16	0.22	0.33	0.62	0.97	1	1	1
100	0.04	0.07	0.10	0.13	0.18	0.25	0.40	0.75	0.97	0.99	1
150	0.04	0.06	0.09	0.11	0.14	0.18	0.27	0.48	0.72	0.79	0.90
200	0.04	0.06	0.08	0.10	0.12	0.15	0.19	0.32	0.45	0.48	0.56
250	0.04	0.06	0.07	0.09	0.10	0.12	0.14	0.22	0.30	0.31	0.36
300	0.04	0.05	0.07	0.07	0.08	0.09	0.11	0.16	0.21	0.21	0.23
350	0.04	0.05	0.06	0.06	0.07	0.08	0.08	0.12	0.15	0.15	0.15
400	0.04	0.05	0.05	0.06	0.06	0.06	0.07	0.10	0.11	0.11	0.10
450	0.04	0.04	0.05	0.05	0.05	0.05	0.05	0.08	0.09	0.08	0.06
500	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.06	0.06	0.05	0.04
550	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.03
600	0.04	0.04	0.03	0.03	0.02	0.02	0.02	0.03	0.03	0.02	0.02

Table F.112. REBS south: decision table for probabilities of satisfying the A2 criterion of $\leq 30\%$ decline over 1.5 generations (75 years) for selected projection years and for a range of **harvest rate** *strategies. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.033.*

HR	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	0.04	0.08	0.13	0.19	0.29	0.49	0.89	>0.99	1	1	1
0.01	0.04	0.07	0.10	0.14	0.19	0.30	0.64	0.99	1	1	1
0.02	0.04	0.06	0.08	0.10	0.12	0.18	0.36	0.88	>0.99	>0.99	>0.99
0.03	0.04	0.05	0.05	0.06	0.07	0.09	0.16	0.61	0.96	0.98	0.98
0.04	0.04	0.04	0.04	0.03	0.04	0.05	0.07	0.32	0.81	0.89	0.94
0.05	0.04	0.03	0.02	0.02	0.02	0.02	0.03	0.14	0.56	0.69	0.87
0.06	0.04	0.02	0.01	0.01	0.01	0.01	0.01	0.06	0.33	0.44	0.74
0.07	0.04	0.02	<0.01	<0.01	<0.01	<0.01	0.01	0.03	0.17	0.25	0.59
0.08	0.04	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	0.08	0.13	0.43
0.09	0.04	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.04	0.06	0.30
0.1	0.04	<0.01	<0.01	0	<0.01	<0.01	<0.01	<0.01	0.02	0.03	0.19
0.11	0.04	<0.01	0	0	<0.01	<0.01	<0.01	<0.01	0.01	0.02	0.12
0.12	0.04	<0.01	0	0	0	<0.01	<0.01	<0.01	0.01	0.01	0.07

Table F.113. REBS south: decision table for reference criterion $0.5B_0$ for selected projection years over 1.5 generations (75 years) and for a range of **constant catch** *strategies, such that valuTabes are P$(B_t > 0.5B_0)$. For reference, the average catch over the last 5 years (2015-2019) was 291 t.*

CC	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	0.17	0.22	0.32	0.43	0.55	0.70	0.93	0.99	>0.99	1	1
50	0.17	0.21	0.28	0.37	0.44	0.51	0.67	0.79	0.89	0.94	0.97
100	0.17	0.20	0.25	0.30	0.36	0.40	0.47	0.53	0.59	0.66	0.70
150	0.17	0.19	0.22	0.26	0.29	0.31	0.35	0.37	0.39	0.41	0.42
200	0.17	0.18	0.20	0.22	0.24	0.25	0.26	0.27	0.27	0.28	0.28
250	0.17	0.17	0.19	0.20	0.20	0.20	0.20	0.19	0.19	0.19	0.19
300	0.17	0.17	0.17	0.17	0.17	0.17	0.16	0.15	0.14	0.14	0.13
350	0.17	0.16	0.16	0.16	0.15	0.14	0.13	0.12	0.11	0.10	0.10
400	0.17	0.15	0.15	0.14	0.13	0.12	0.10	0.09	0.08	0.08	0.07
450	0.17	0.15	0.14	0.12	0.11	0.10	0.08	0.07	0.06	0.05	0.05
500	0.17	0.14	0.12	0.11	0.10	0.09	0.07	0.05	0.04	0.04	0.03
550	0.17	0.14	0.11	0.10	0.09	0.07	0.05	0.04	0.03	0.03	0.02
600	0.17	0.13	0.11	0.09	0.08	0.06	0.04	0.03	0.02	0.02	0.01

Table F.114. REBS south: decision table for reference criterion $0.5B_0$ for selected projection years over 1.5 generations (75 years) and for a range of **harvest rate** *strategies, such that values are P$(B_t > 0.5B_0)$. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.033.*

HR	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	0.17	0.22	0.32	0.43	0.55	0.70	0.93	0.99	>0.99	1	1
0.01	0.17	0.21	0.28	0.36	0.44	0.53	0.71	0.84	0.92	0.96	0.98
0.02	0.17	0.19	0.24	0.29	0.34	0.38	0.47	0.55	0.63	0.69	0.73
0.03	0.17	0.18	0.20	0.23	0.25	0.27	0.29	0.29	0.32	0.35	0.37
0.04	0.17	0.17	0.18	0.18	0.18	0.18	0.16	0.15	0.15	0.15	0.15
0.05	0.17	0.16	0.15	0.14	0.12	0.10	0.08	0.07	0.07	0.06	0.06
0.06	0.17	0.15	0.13	0.11	0.08	0.06	0.04	0.03	0.03	0.03	0.03
0.07	0.17	0.14	0.11	0.07	0.05	0.03	0.02	0.01	0.01	0.01	0.01
0.08	0.17	0.13	0.08	0.05	0.03	0.02	0.01	<0.01	0.01	0.01	<0.01
0.09	0.17	0.12	0.06	0.02	0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01
0.1	0.17	0.11	0.05	0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
0.11	0.17	0.10	0.03	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
0.12	0.17	0.09	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

Table F.115. REBS south: decision table for reference criterion $0.7B_0$ for selected projection years over 1.5 generations (75 years) and for a range of **constant catch** strategies, such that values are P$(B_t > 0.7B_0)$. For reference, the average catch over the last 5 years (2015-2019) was 291 t.

CC	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	0.04	0.07	0.12	0.17	0.22	0.29	0.44	0.59	0.76	0.87	0.93
50	0.04	0.07	0.11	0.14	0.18	0.22	0.30	0.36	0.45	0.54	0.61
100	0.04	0.07	0.09	0.12	0.15	0.17	0.21	0.23	0.27	0.30	0.33
150	0.04	0.06	0.08	0.10	0.12	0.13	0.14	0.15	0.17	0.18	0.19
200	0.04	0.06	0.08	0.09	0.10	0.10	0.11	0.11	0.11	0.11	0.11
250	0.04	0.05	0.07	0.08	0.08	0.08	0.08	0.08	0.08	0.07	0.08
300	0.04	0.05	0.06	0.07	0.07	0.07	0.06	0.05	0.05	0.05	0.04
350	0.04	0.05	0.05	0.06	0.06	0.05	0.04	0.03	0.03	0.03	0.03
400	0.04	0.04	0.05	0.05	0.04	0.04	0.03	0.02	0.02	0.02	0.02
450	0.04	0.04	0.04	0.04	0.03	0.03	0.02	0.02	0.01	0.01	0.01
500	0.04	0.04	0.04	0.03	0.03	0.02	0.02	0.01	0.01	0.01	0.01
550	0.04	0.03	0.03	0.02	0.02	0.02	0.01	0.01	0.01	<0.01	<0.01
600	0.04	0.03	0.02	0.02	0.01	0.01	0.01	<0.01	<0.01	<0.01	<0.01

Table F.116. REBS south: decision table for reference criterion $0.7B_0$ for selected projection years over 1.5 generations (75 years) and for a range of **harvest rate** strategies, such that values are P$(B_t > 0.7B_0)$. For reference, the average harvest rate over the last 5 years (2015-2019) was 0.033.

HR	2021	2025	2030	2035	2040	2045	2055	2065	2075	2085	2095
0	0.04	0.07	0.12	0.17	0.22	0.29	0.44	0.59	0.76	0.87	0.93
0.01	0.04	0.06	0.09	0.12	0.15	0.18	0.23	0.28	0.35	0.43	0.48
0.02	0.04	0.05	0.07	0.08	0.09	0.09	0.09	0.10	0.12	0.13	0.14
0.03	0.04	0.04	0.05	0.05	0.04	0.04	0.04	0.03	0.03	0.04	0.04
0.04	0.04	0.04	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01
0.05	0.04	0.03	0.01	0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
0.06	0.04	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
0.07	0.04	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
0.08	0.04	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
0.09	0.04	<0.01	<0.01	0	0	0	<0.01	<0.01	<0.01	<0.01	0
0.1	0.04	<0.01	0	0	0	0	<0.01	<0.01	<0.01	<0.01	0
0.11	0.04	<0.01	0	0	0	0	<0.01	<0.01	<0.01	<0.01	0
0.12	0.04	<0.01	0	0	0	0	0	0	<0.01	<0.01	0

F.3.4.4. Time to reach targets

Table F.117. REBS south: estimated time (years) for projected biomass B_t to exceed reference points and criteria with a probability of 50%, for for a range of **constant catch** *strategies. An estimated time of 0 means that the condition is satisfied and remains so over the 75-year projection; an estimated time of 75 means that the condition never becomes satisfied over the 1.5-generation projection. A further condition is that the probability of satisfying the condition must increase for two consecutive years. Columns respectively correspond to the provisional DFO reference points: LRP = $0.4B_{\mathrm{MSY}}$, USR = $0.8B_{\mathrm{MSY}}$; alternative reference points: B_{MSY}, B_{2021}, $0.2B_0$, $0.4B_0$; and COSEWIC reference criteria: 0.5$B_{t\text{-G}}$ = $\leq 50\%$ decline over 1.5 generations (G), 0.7$B_{t\text{-G}}$ = $\leq 30\%$ decline over 1.5G, $0.5B_0$, $0.7B_0$.*

	LRP	USR	B_{MSY}	B_{2021}	0.2B_0	0.4B_0	0.5$B_{t\text{-G}}$	0.7$B_{t\text{-G}}$	0.5B_0	0.7B_0
0	0	0	0	0	0	10	15	25	18	39
50	0	0	0	0	0	13	18	30	24	61
100	0	0	0	0	0	18	23	40	40	75
150	0	0	0	0	0	45	32	45	75	75
200	0	0	4	5	0	75	45	67	75	75
250	75	75	75	75	75	75	75	75	75	75
300	75	75	75	75	75	75	75	75	75	75
350	75	75	75	75	75	75	75	75	75	75
400	75	75	75	75	75	75	75	75	75	75
450	75	75	75	75	75	75	75	75	75	75
500	75	75	75	75	75	75	75	75	75	75
550	75	75	75	75	75	75	75	75	75	75
600	75	75	75	75	75	75	75	75	75	75

Table F.118. REBS south: estimated time (years) for projected biomass B_t to exceed reference points and criteria with a probability of 50%, for for a range of **harvest rate** *strategies. See caption in Table F.117 for further details*

	LRP	USR	B_{MSY}	B_{2021}	0.2B_0	0.4B_0	0.5$B_{t\text{-G}}$	0.7$B_{t\text{-G}}$	0.5B_0	0.7B_0
0	0	0	0	0	0	10	15	25	18	39
0.01	0	0	0	0	0	12	17	30	23	75
0.02	0	0	0	0	0	16	21	39	38	75
0.03	0	0	0	0	0	24	26	43	75	75
0.04	0	0	0	0	0	75	37	47	75	75
0.05	0	0	0	0	0	75	42	51	75	75
0.06	0	0	0	3	0	75	45	66	75	75
0.07	0	0	75	75	0	75	49	70	75	75
0.08	0	3	75	75	0	75	64	75	75	75
0.09	0	75	75	75	5	75	68	75	75	75
0.1	0	75	75	75	75	75	75	75	75	75
0.11	0	75	75	75	75	75	75	75	75	75
0.12	0	75	75	75	75	75	75	75	75	75

Table F.119. REBS south: estimated time (years) for projected biomass B_t to exceed reference points and criteria with a probability of 65%, for for a range of **constant catch** strategies. See caption in Table F.117 for further details.

	LRP	USR	B_{MSY}	B_{2021}	0.2B_0	0.4B_0	0.5$B_{t\text{-G}}$	0.7$B_{t\text{-G}}$	0.5B_0	0.7B_0
0	0	0	3	0	0	14	18	27	23	48
50	0	0	4	0	0	20	22	36	33	75
100	0	0	6	0	0	34	29	43	64	75
150	0	0	14	0	0	75	43	50	75	75
200	0	13	75	75	75	75	75	75	75	75
250	75	75	75	75	75	75	75	75	75	75
300	75	75	75	75	75	75	75	75	75	75
350	75	75	75	75	75	75	75	75	75	75
400	75	75	75	75	75	75	75	75	75	75
450	75	75	75	75	75	75	75	75	75	75
500	75	75	75	75	75	75	75	75	75	75
550	75	75	75	75	75	75	75	75	75	75
600	75	75	75	75	75	75	75	75	75	75

Table F.120. REBS south: estimated time (years) for projected biomass B_t to exceed reference points and criteria with a probability of 65%, for for a range of **harvest rate** strategies. See caption in Table F.117 for further details.

	LRP	USR	B_{MSY}	B_{2021}	0.2B_0	0.4B_0	0.5$B_{t\text{-G}}$	0.7$B_{t\text{-G}}$	0.5B_0	0.7B_0
0	0	0	3	0	0	14	18	27	23	48
0.01	0	0	4	0	0	18	21	35	31	75
0.02	0	0	4	0	0	24	25	41	57	75
0.03	0	0	5	0	0	46	31	45	75	75
0.04	0	0	7	0	0	75	41	49	75	75
0.05	0	0	11	3	0	75	44	62	75	75
0.06	0	0	75	75	0	75	48	68	75	75
0.07	0	1	75	75	0	75	57	75	75	75
0.08	0	3	75	75	1	75	68	75	75	75
0.09	0	75	75	75	5	75	75	75	75	75
0.1	0	75	75	75	75	75	75	75	75	75
0.11	0	75	75	75	75	75	75	75	75	75
0.12	1	75	75	75	75	75	75	75	75	75

Table F.121. *REBS south: estimated time (years) for projected biomass B_t to exceed reference points and criteria with a probability of 80%, for for a range of* **constant catch** *strategies. See caption in Table F.117 for further details.*

	LRP	USR	B_{MSY}	B_{2021}	0.2B_0	0.4B_0	0.5$B_{t\text{-G}}$	0.7$B_{t\text{-G}}$	0.5B_0	0.7B_0
0	0	2	6	0	1	18	21	31	28	57
50	0	2	9	0	1	26	26	40	46	75
100	0	4	14	0	1	57	39	45	75	75
150	0	9	75	4	2	75	48	66	75	75
200	1	75	75	75	75	75	75	75	75	75
250	75	75	75	75	75	75	75	75	75	75
300	75	75	75	75	75	75	75	75	75	75
350	75	75	75	75	75	75	75	75	75	75
400	75	75	75	75	75	75	75	75	75	75
450	75	75	75	75	75	75	75	75	75	75
500	75	75	75	75	75	75	75	75	75	75
550	75	75	75	75	75	75	75	75	75	75
600	75	75	75	75	75	75	75	75	75	75

Table F.122. *REBS south: estimated time (years) for projected biomass B_t to exceed reference points and criteria with a probability of 80%, for for a range of* **harvest rate** *strategies. See caption in Table F.117 for further details.*

	LRP	USR	B_{MSY}	B_{2021}	0.2B_0	0.4B_0	0.5$B_{t\text{-G}}$	0.7$B_{t\text{-G}}$	0.5B_0	0.7B_0
0	0	2	6	0	1	18	21	31	28	57
0.01	0	2	7	0	1	22	24	39	41	75
0.02	0	2	9	0	1	33	29	43	75	75
0.03	0	3	11	0	1	75	39	47	75	75
0.04	0	3	14	3	1	75	43	53	75	75
0.05	0	4	75	75	1	75	47	68	75	75
0.06	0	6	75	75	1	75	51	75	75	75
0.07	0	9	75	75	2	75	67	75	75	75
0.08	0	75	75	75	5	75	75	75	75	75
0.09	0	75	75	75	75	75	75	75	75	75
0.1	0	75	75	75	75	75	75	75	75	75
0.11	1	75	75	75	75	75	75	75	75	75
0.12	1	75	75	75	75	75	75	75	75	75

Table F.123. REBS south: estimated time (years) for projected biomass B_t to exceed reference points and criteria with a probability of 95%, for for a range of **constant catch** strategies. See caption in Table F.117 for further details.

	LRP	USR	B_{MSY}	B_{2021}	0.2B_0	0.4B_0	0.5$B_{t\text{-G}}$	0.7$B_{t\text{-G}}$	0.5B_0	0.7B_0
0	0	6	11	0	5	24	25	38	37	75
50	0	8	16	0	7	42	34	44	67	75
100	0	16	44	0	12	75	45	51	75	75
150	1	75	75	75	75	75	75	75	75	75
200	1	75	75	75	75	75	75	75	75	75
250	75	75	75	75	75	75	75	75	75	75
300	75	75	75	75	75	75	75	75	75	75
350	75	75	75	75	75	75	75	75	75	75
400	75	75	75	75	75	75	75	75	75	75
450	75	75	75	75	75	75	75	75	75	75
500	75	75	75	75	75	75	75	75	75	75
550	75	75	75	75	75	75	75	75	75	75
600	75	75	75	75	75	75	75	75	75	75

Table F.124. REBS south: estimated time (years) for projected biomass B_t to exceed reference points and criteria with a probability of 95%, for for a range of **harvest rate** strategies. See caption in Table F.117 for further details.

	LRP	USR	B_{MSY}	B_{2021}	0.2B_0	0.4B_0	0.5$B_{t\text{-G}}$	0.7$B_{t\text{-G}}$	0.5B_0	0.7B_0
0	0	6	11	0	5	24	25	38	37	75
0.01	0	7	12	0	5	32	29	43	61	75
0.02	0	7	15	1	6	59	39	46	75	75
0.03	0	9	20	75	7	75	43	52	75	75
0.04	0	11	59	75	8	75	47	69	75	75
0.05	0	16	75	75	10	75	53	75	75	75
0.06	0	75	75	75	75	75	68	75	75	75
0.07	0	75	75	75	75	75	75	75	75	75
0.08	0	75	75	75	75	75	75	75	75	75
0.09	1	75	75	75	75	75	75	75	75	75
0.1	1	75	75	75	75	75	75	75	75	75
0.11	1	75	75	75	75	75	75	75	75	75
0.12	1	75	75	75	75	75	75	75	75	75

F.3.5. REBS South – Sensitivity Runs

Six sensitivity analyses were run (with full MCMC simulations) relative to the central run (Run11: M=0.045, CPUE c_p=0.2529) to test the sensitivity of the outputs to alternative model assumptions:

- **S01** (R20) – reduced commercial catch for 1965-1995 by 33% (label: "reduce catch");
- **S02** (R21) – increased commercial catch for 1965-1995 by 50% (label: "increase catch");
- **S03** (R22) – used wide aging error (AE $\pm$5 ages), fixed M=0.035, and set CPUE c_p=0.2529 (label: "AE5 M35 CV25");
- **S04** (R23) – used wide AE matrix, fixed M=0.045, and set CPUE c_p=0.2529 (label: "AE5 M45 CV25");
- **S05** (R24) – used wide AE matrix, fixed M=0.055, and set CPUE c_p=0.2529 (label: "AE5 M55 CV25");
- **S06** (R25) – remove NMFS triennial survey (label: "remove NMFS").

All sensitivity runs but one were reweighted twice using the procedure of Francis (2011) for age frequencies; S04 (R23) was reweighted once as the second reweight did not provide credible parameter fits. The abundance index CVs were adjusted on the first reweight only, using that adopted in the central run (surveys=0.25, CPUE=0.2529). 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 sensitivity runs were judged to have converged after 6 million iterations, sampling every 5000$^{\mathrm{th}}$ to give 1200 draws. The first 200 samples were discarded and the remaining 1000 samples were used for the MCMC analysis.

The differences among the sensitivity runs (including the central run) are summarised in tables of median parameter estimates (Table F.125) and median MSY-based quantities (Table F.126). Sensitivity plots appear in:

- Figure F.74 – trace plots for chains of R_0 MCMC samples;
- Figure F.75 – diagnostic split-chain plots for R_0 MCMC samples;
- Figure F.76 – diagnostic autocorrelation plots for R_0 MCMC sample;
- Figure F.77 – trajectories of median B_t/B_0;
- Figure F.78 – trajectories of median recruitment R_t (one-year old fish);
- Figure F.79 – trajectories of median exploitation rate u_t;
- Figure F.80 – quantile plots of selected parameters for the sensitivity runs;
- Figure F.81 – quantile plots of selected derived quantities for the sensitivity runs;
- Figure F.82 – stock status plots of B_{2021}/B_MSY.

The diagnostic plots (Figures F.74 to F.76) suggest that four sensitivity runs exhibited good MCMC behaviour, and two were marginal but provisionally acceptable:

- Good – no trend in traces, split-chains align, no autocorrelation
    - S01 (-33% 1965-1995 commercial catch)
    - S03 (wide AE, M=0.035, CPUE c_p=0.2529)
    - S05 (wide AE, M=0.055, CPUE c_p=0.2529)
    - S06 (remove NMFS triennial survey)
- Marginal – trace trend temporarily interrupted, split-chains somewhat frayed, some autocorrelation

- S02 (+50% 1965-1995 commercial catch)
- S04 (wide AE, M=0.045, CPUE c_p=0.2529)

The trajectories of the B_t medians relative to B_0 (Figure F.77) indicate that using a wide AE matrix (S04) resulted in the most optimistic scenario, while the most pessimistic run was the one with the lowest M (S03). All sensitivity runs that adopted the same M (0.045) as the central run tended to closely reflect the central run. As with REBS north, the two catch sensitivity runs (S01, S02) departed from the central run somewhat but ended with similar spawning stock depletion (B_{2021}/B_0). Removing the NMFS triennial survey (S06) had little impact, likely because it provided only three index points and selectivity had been fixed. The overall conclusion is that the model outcome, given this limited set of sensitivities, is most sensitive to M and showed less sensitivity to the width of the AE matrix.

Parameter estimates varied little among sensitivity runs (Figure F.80), with the exception of S03 (M=0.035). Derived quantities based on MSY (Figure F.81) exhibited reasonable values of u_MSY (<0.10/year) for a long-lived species Table F.126).

The stock status (B_{2021}/B_MSY) for the sensitivities (Figure F.82) is clearly sensitive to M. All sensitivities with M=0.045 lie in the Healthy Zone, whereas, the sensitivity with M=0.035 lies in the Cautious Zone.

Table F.125. REBS south: median values of MCMC samples for the primary estimated parameters, comparing the central run to 6 sensitivity runs (1000 samples each). C =Central, R = Run, S = Sensitivity. Numeric subscripts other than those for R_0 and M indicate the following gear types g: 1 = QCS Synoptic, 2 = WCVI Synoptic, 3 = NMFS Triennial, 4 = commercial trawl CPUE/Trawl fishery, and 5 = Other fishery. Sensitivity runs: S01 = reduce catch, S02 = increase catch, S03 = AE5 M35 CV25, S04 = AE5 M45 CV25, S05 = AE5 M55 CV25, S06 = remove NMFS

	C(R11)	S01(R20)	S02(R21)	S03(R22)	S04(R23)	S05(R24)	S06(R25)
R_0	685	609	865	387	764	1,073	692
q_1	0.0775	0.0785	0.0649	0.134	0.0643	0.0677	0.0810
q_2	0.0338	0.0353	0.0285	0.200	0.0284	0.0464	0.0411
q_3	0.0512	0.0503	0.0463	0.101	0.0397	0.0532	—
q_4	0.000154	0.000153	0.000130	0.000337	0.000133	0.000165	0.000179
μ_4	25.6	24.4	23.2	27.0	27.6	26.5	26.7
μ_5	55.4	55.7	55.5	57.5	55.7	54.1	54.4
Δ_4	1.56	1.50	1.63	1.36	0.912	1.06	1.26
Δ_5	0.632	0.618	0.658	0.700	0.679	0.670	0.683
$\log v_{4L}$	4.44	4.23	3.98	4.38	4.70	4.35	4.51
$\log v_{5L}$	6.93	6.48	6.55	6.65	6.49	6.64	6.45

Table F.126. REBS south: medians of MCMC-derived quantities from the central run and 6 sensitivity runs (1000 samples each) from their respective MCMC posteriors. Definitions are: B_0 – unfished equilibrium spawning biomass (mature females), V_0 – unfished equilibrium vulnerable biomass (males and females), B_{2021} – spawning biomass at the start of 2021, V_{2021} – vulnerable biomass in the middle of 2021, u_{2020} – exploitation rate (ratio of total catch to vulnerable biomass) in the middle of 2020, $u_{\max}$ – maximum exploitation rate (calculated for each sample as the maximum exploitation rate from 1935 - 2020), B_{MSY} – equilibrium spawning biomass at MSY (maximum sustainable yield), u_{MSY} – equilibrium exploitation rate at MSY, V_{MSY} – equilibrium vulnerable biomass at MSY. All biomass values (and MSY) are in tonnes. Sensitivity runs: S01 = reduce catch, S02 = increase catch, S03 = AE5 M35 CV25, S04 = AE5 M45 CV25, S05 = AE5 M55 CV25, S06 = remove NMFS

	C(R11)	S01(R20)	S02(R21)	S03(R22)	S04(R23)	S05(R24)	S06(R25)
B_0	6,156	5,470	7,770	5,633	6,866	6,309	6,217
V_0 (Trawl)	13,476	12,143	17,437	11,660	14,880	13,755	13,416
V_0 (Other)	9,937	7,334	10,845	8,181	9,391	9,265	8,591
B_{2021}	2,088	1,997	2,737	944	2,708	2,476	2,064
V_{2021} (Trawl)	4,662	4,578	6,185	1,982	5,836	5,208	4,560
V_{2021} (Other)	3,273	2,239	3,260	925	3,125	3,200	2,243
B_{2021}/B_0	0.338	0.367	0.351	0.167	0.398	0.393	0.332
V_{2021}/V_0 (Trawl)	0.346	0.374	0.352	0.171	0.393	0.381	0.342
V_{2021}/V_0 (Other)	0.327	0.306	0.302	0.113	0.333	0.347	0.263
u_{2020} (Trawl)	0.0613	0.0626	0.0475	0.141	0.0500	0.0568	0.0644
u_{2020} (Other)	0.0280	0.0404	0.0284	0.0953	0.0295	0.0291	0.0409
$u_{\max}$ (Trawl)	0.0615	0.0626	0.0506	0.141	0.0504	0.0591	0.0654
$u_{\max}$ (Other)	0.0416	0.0512	0.0682	0.118	0.0437	0.0452	0.0573
MSY	227	205	291	165	258	296	234
B_{MSY}	1,637	1,440	2,046	1,500	1,819	1,649	1,639
$0.4B_{2021}$	655	576	819	600	728	660	656
$0.8B_{2021}$	1,309	1,152	1,637	1,200	1,455	1,320	1,312
B_{2021}/B_{MSY}	1.27	1.40	1.33	0.624	1.50	1.51	1.26
B_{MSY}/B_0	0.266	0.264	0.263	0.266	0.265	0.261	0.264
V_{MSY}	3,616	2,859	4,251	2,770	3,491	3,301	3,126
V_{MSY}/V_0 (Trawl)	0.270	0.235	0.245	0.239	0.236	0.241	0.235
V_{MSY}/V_0 (Other)	0.367	0.391	0.394	0.336	0.372	0.359	0.364
u_{MSY}	0.0620	0.0720	0.0680	0.0600	0.0740	0.0900	0.0740
u_{2020}/u_{MSY} (Trawl)	0.978	0.862	0.697	2.35	0.669	0.631	0.839
u_{2020}/u_{MSY} (Other)	0.447	0.564	0.416	1.60	0.394	0.328	0.548

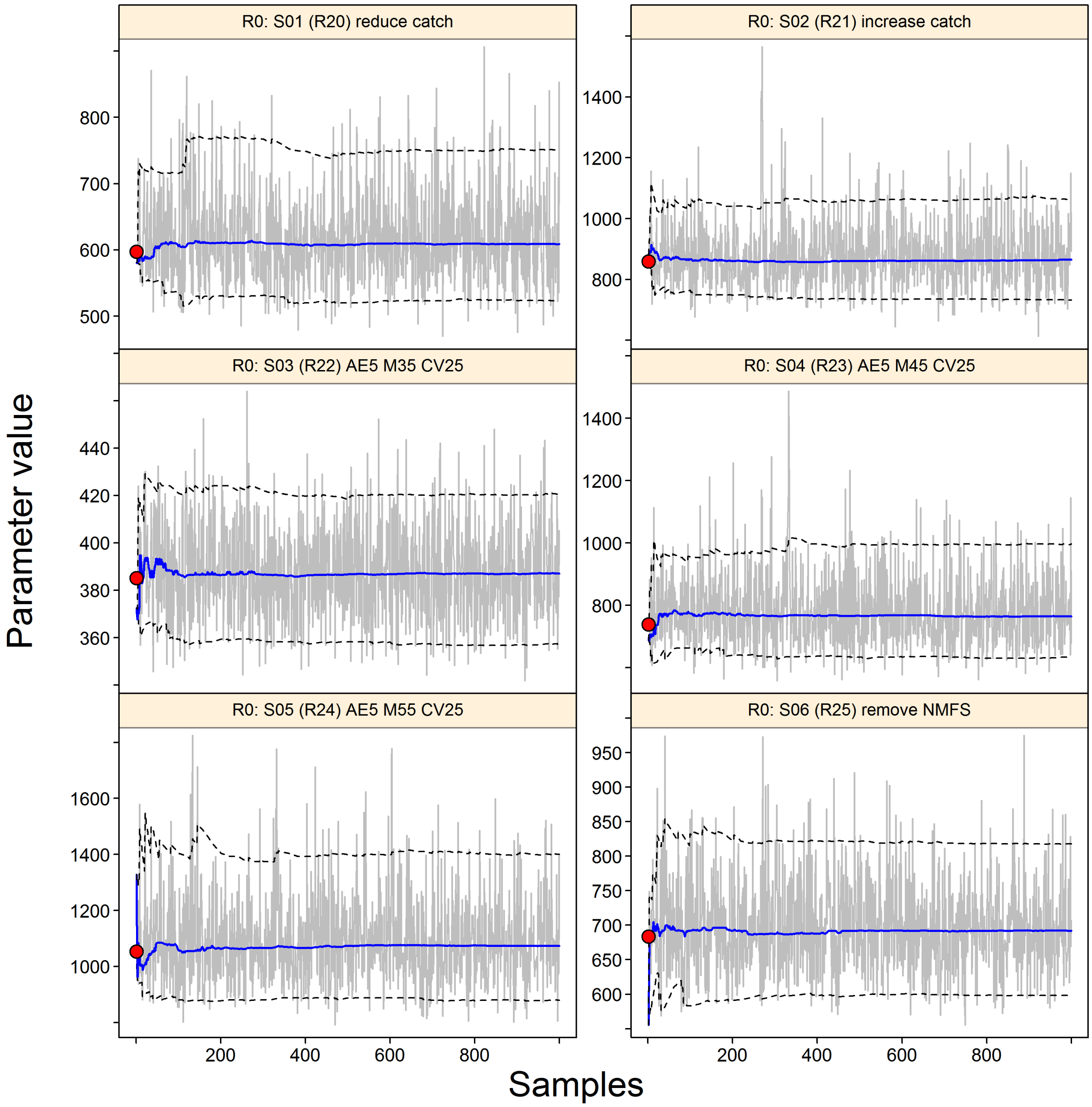


Figure F.74. REBS south sensitivity R_0: MCMC traces for the estimated parameters. Grey lines show the 1000 samples for each parameter, solid blue lines show the cumulative median (up to that sample), and dashed lines show the cumulative 0.05 and 0.95 quantiles. Red circles are the MPD estimates.

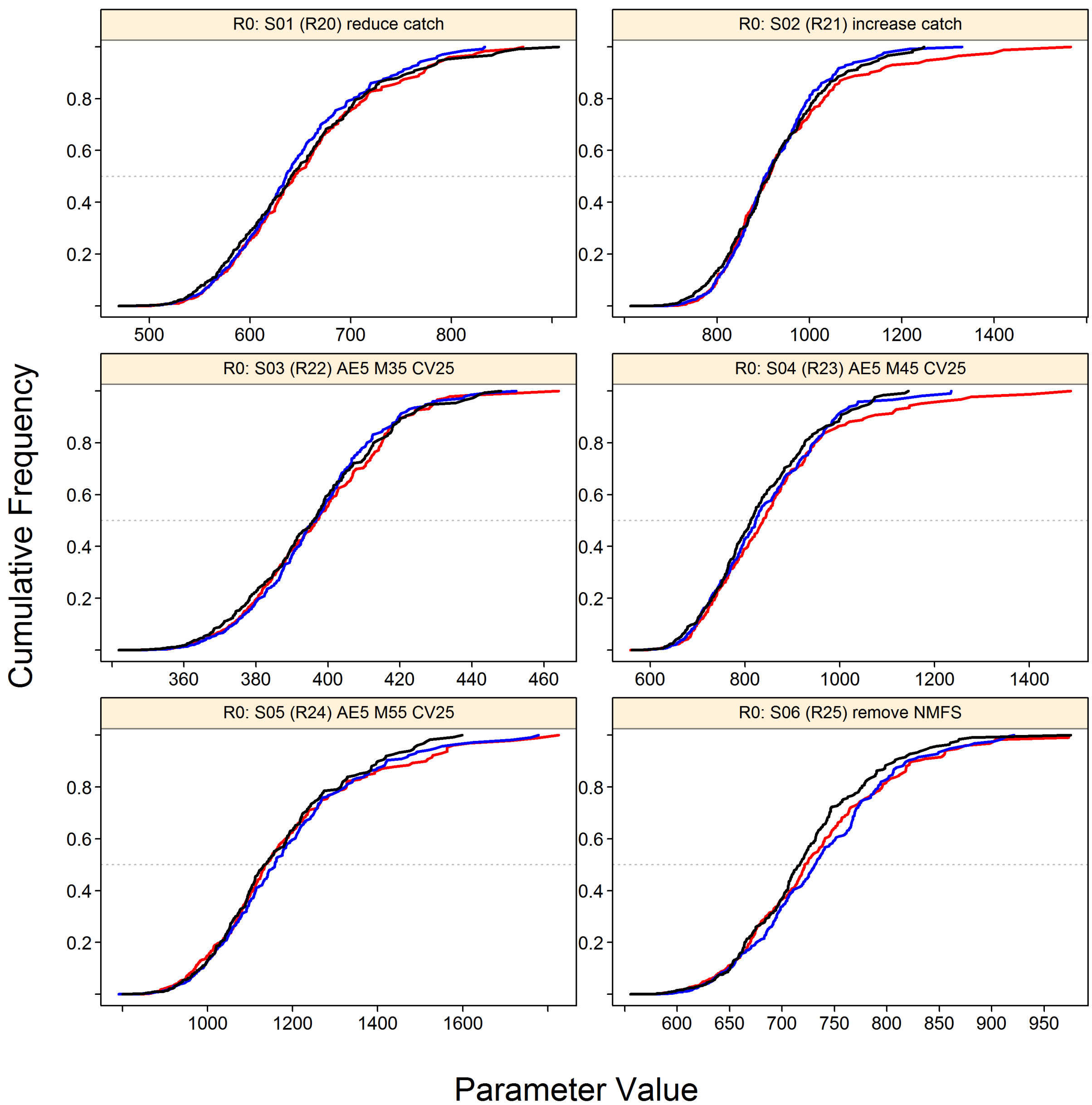


Figure F.75. REBS south sensitivity R_0: diagnostic plot obtained by dividing the MCMC chain of 1000 MCMC samples into three segments, and overplotting the cumulative distributions of the first segment (red), second segment (blue) and final segment (black).

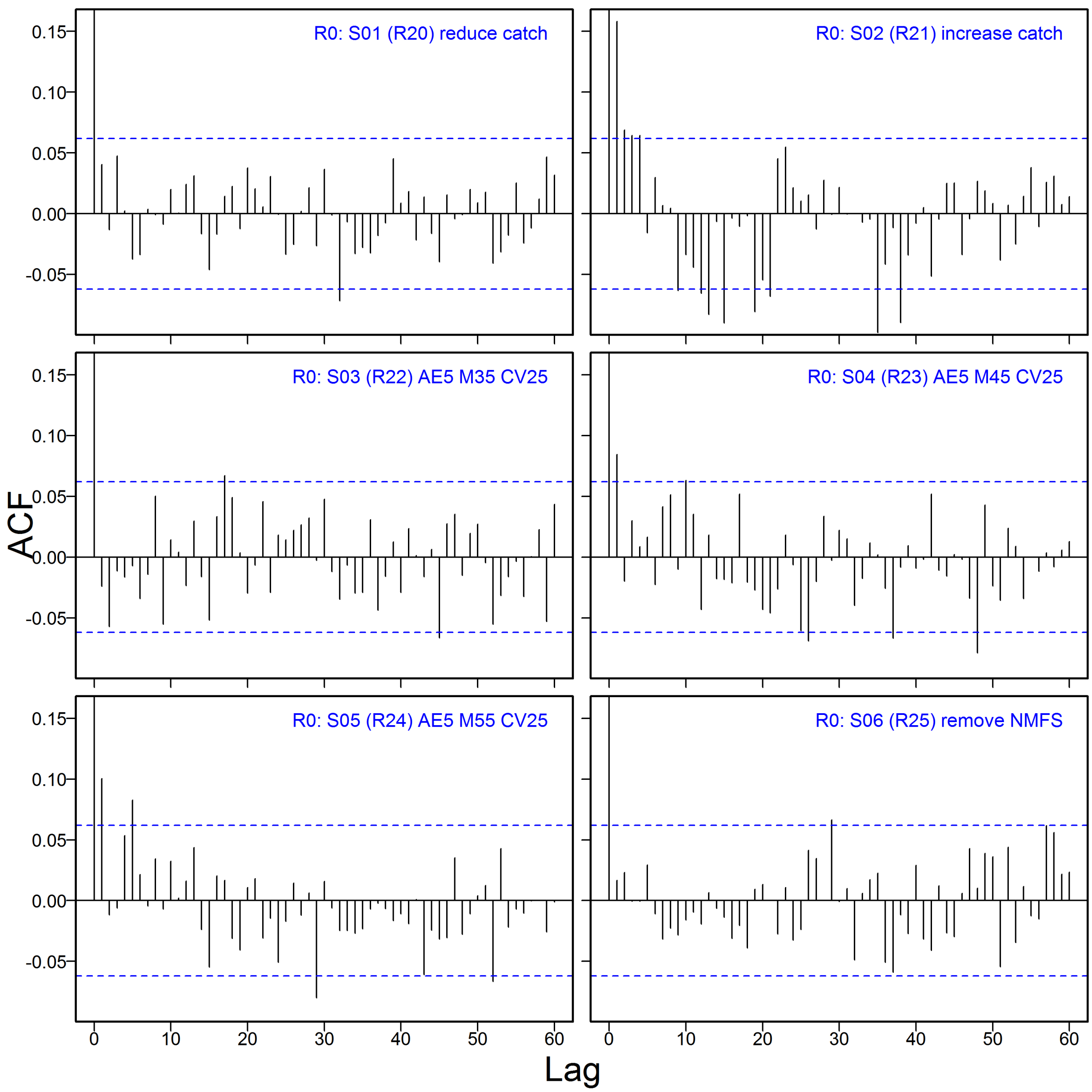


Figure F.76. REBS south sensitivity R_0: autocorrelation plots for the estimated parameters from the MCMC output. Horizontal dashed blue lines delimit the 95% confidence interval for each parameter's set of lagged correlations.

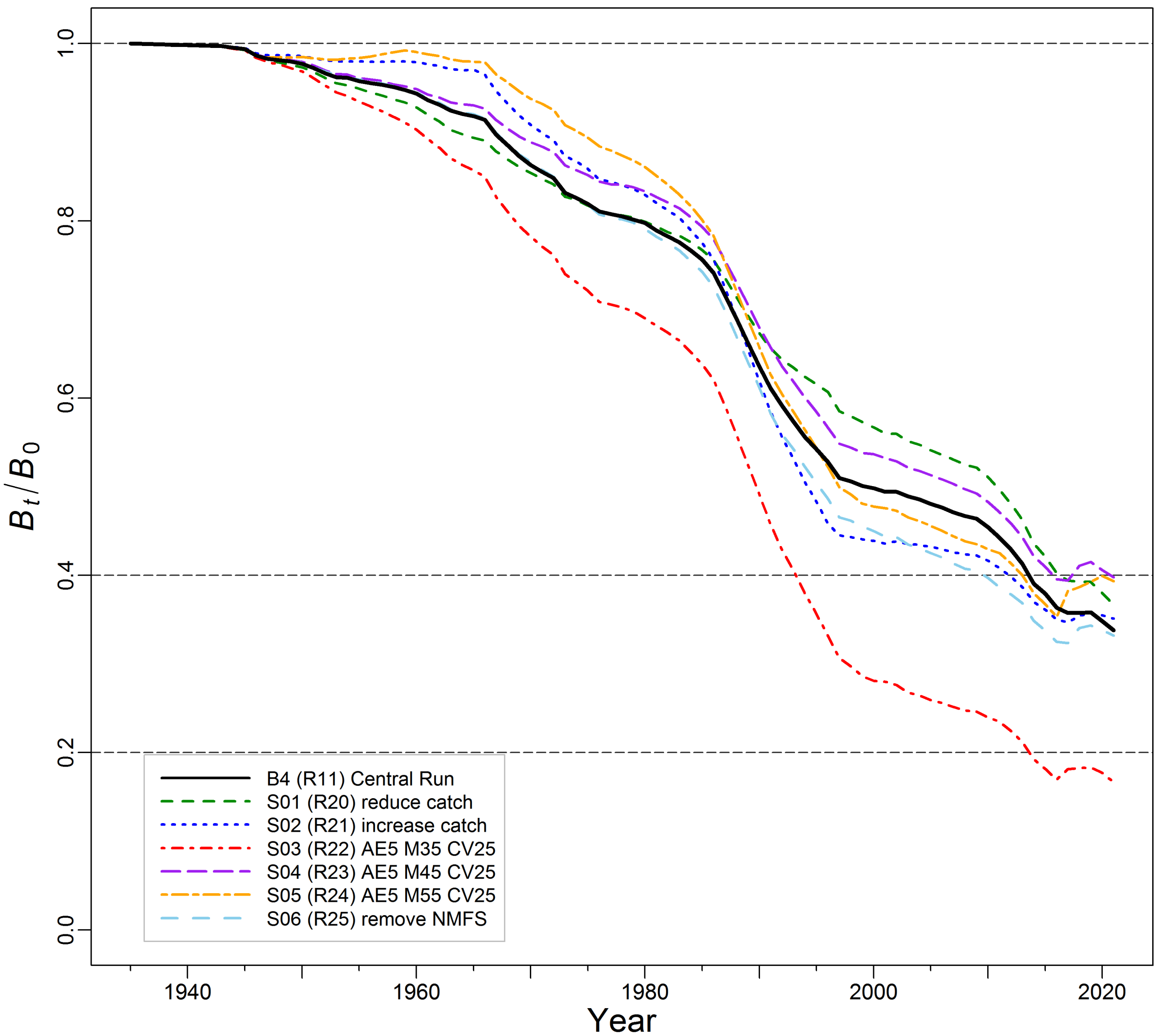


Figure F.77. REBS south sensitivity: model trajectories of median spawning biomass as a proportion of unfished equilibrium biomass (B_t/B_0) for the central run of the composite base case and 6 sensitivity runs (see legend lower left). Horizontal dashed lines show alternative reference points used by other jurisdictions: 0.2B_0 (∼DFO's USR), 0.4B_0 (often a target level above B_{MSY}), and B_0 (equilibrium spawning biomass).

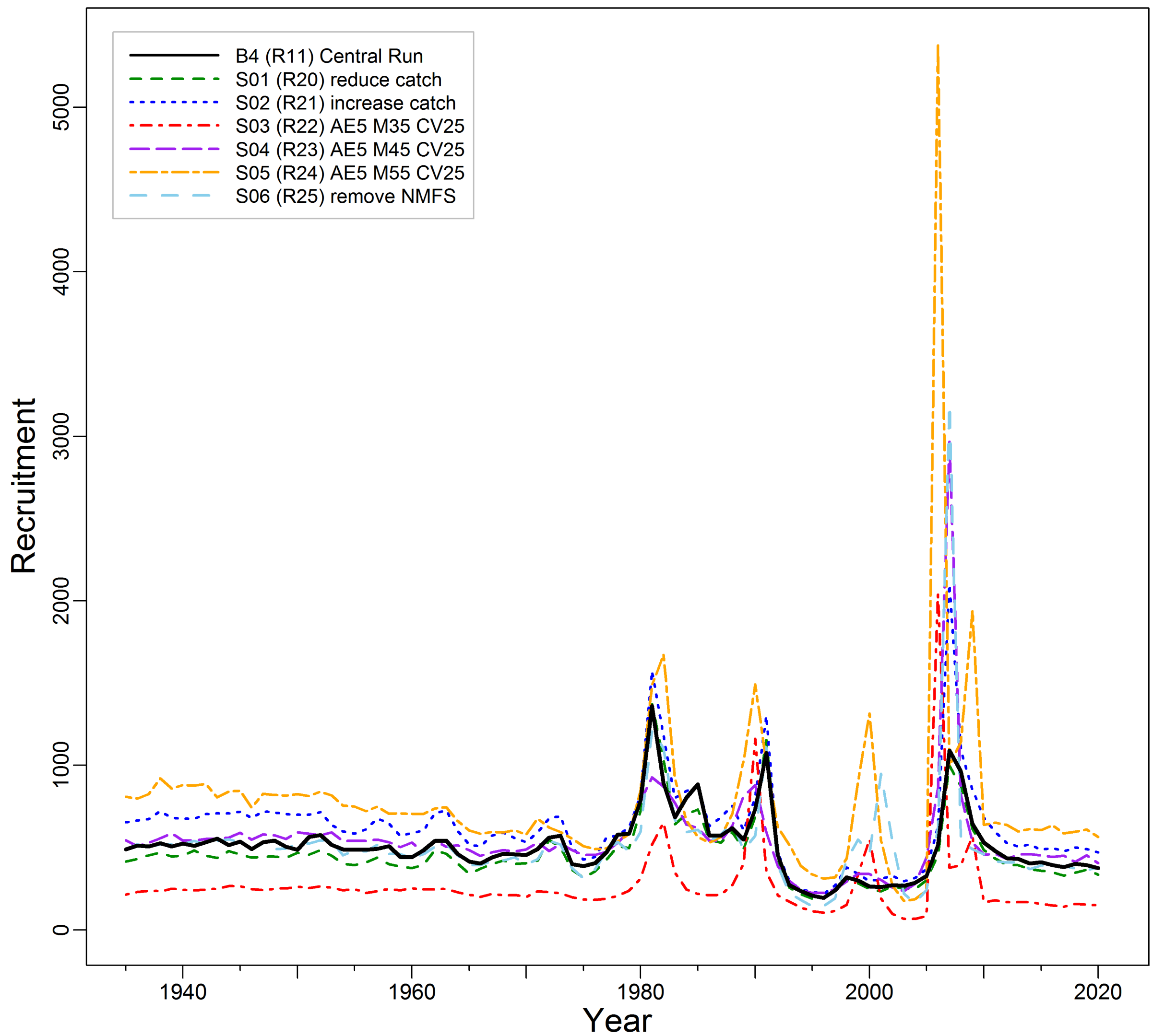


Figure F.78. REBS south sensitivity: model trajectories of median recruitment of one-year old fish (R_t, 1000s) for the central run of the composite base case and 6 sensitivity runs (see legend upper right).

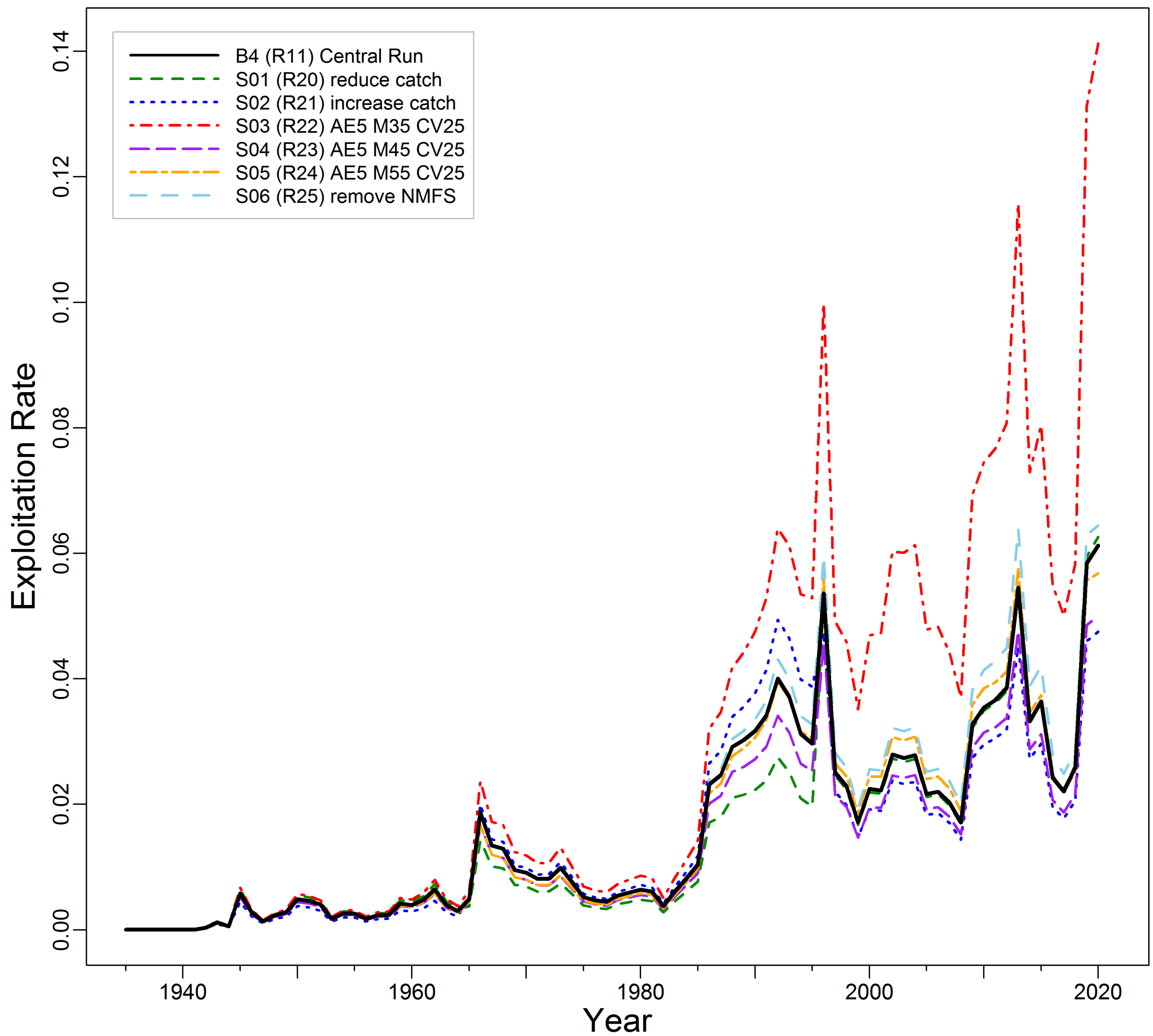


Figure F.79. REBS south sensitivity: model trajectories of median exploitation rate of vulnerable biomass (u_t) for the central run of the composite base case and 6 sensitivity runs (see legend upper left).

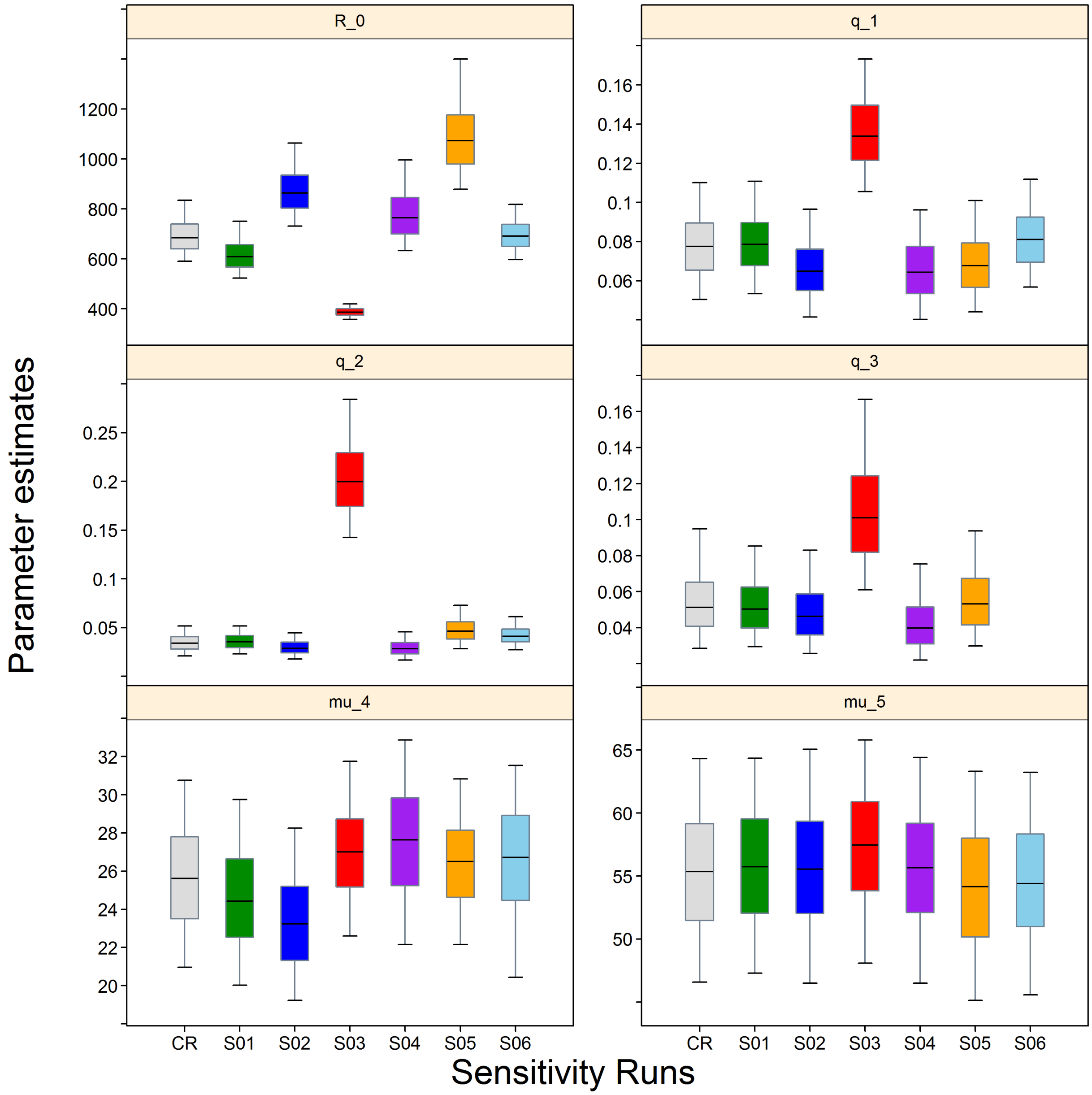


Figure F.80. REBS south sensitivity: quantile plots of selected parameter estimates (R_0, q_g, μ_g) comparing the central run with 6 sensitivity runs. Subscripts: g=1 corresponds to the QCS synoptic survey, g=2 corresponds to the WCVI synoptic survey, g=3 corresponds to the NMFS triennial survey, g=4 corresponds to the commercial Trawl fishery, and g=5 corresponds to the commercial Other fishery. See text on sensitivity numbers. The boxplots delimit the 0.05, 0.25, 0.5, 0.75, and 0.95 quantiles; outliers are excluded.

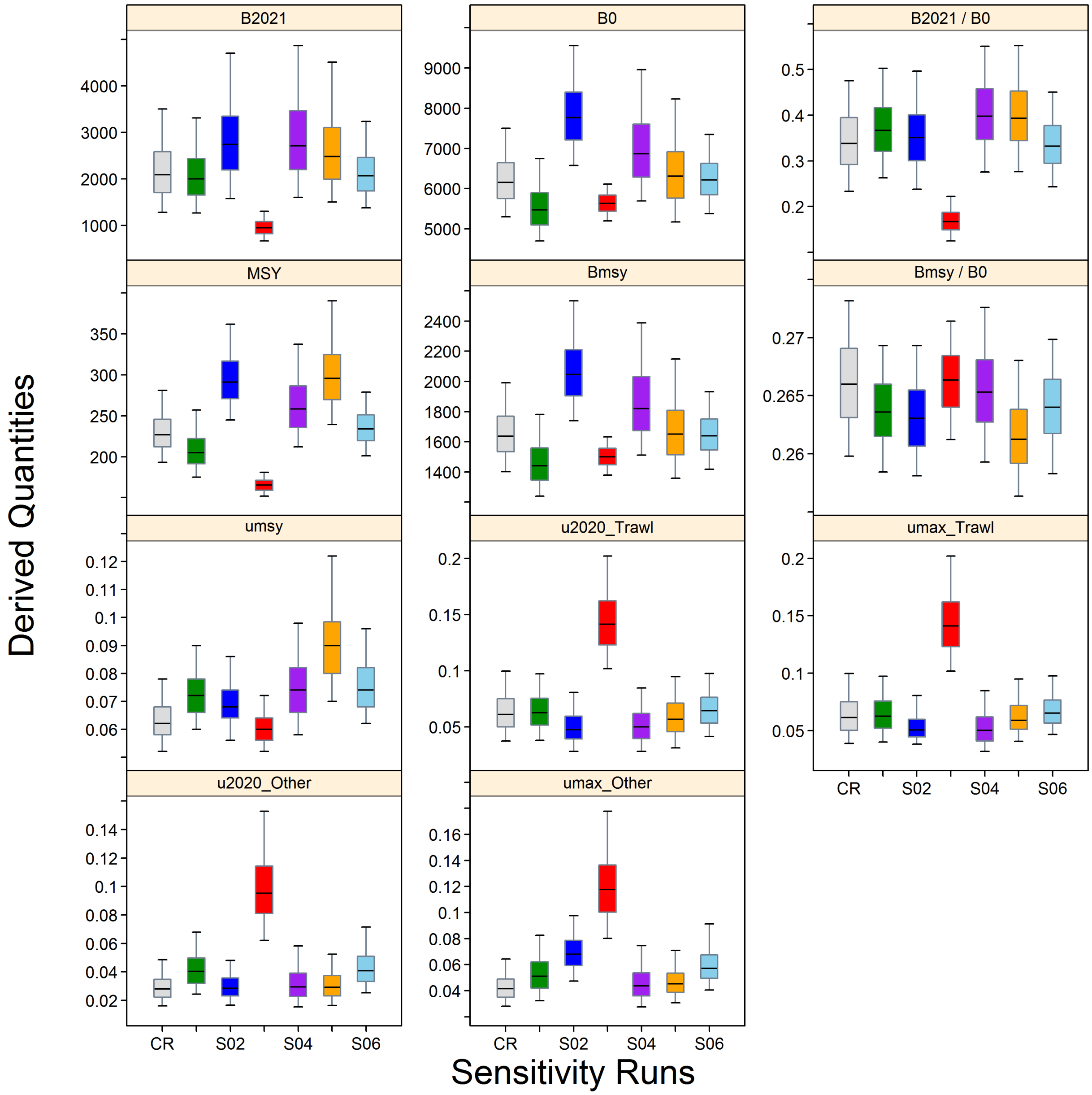


Figure F.81. REBS south sensitivity: quantile plots of selected derived quantities (B_{2021}, B_0, B_{2021}/B_0, MSY, B_{MSY}, B_{MSY}/B_0, u_{2020}, u_{MSY}, $u_{\max}$) comparing the central run with 6 sensitivity runs. See text on sensitivity numbers. The boxplots delimit the 0.05, 0.25, 0.5, 0.75, and 0.95 quantiles; outliers are excluded.

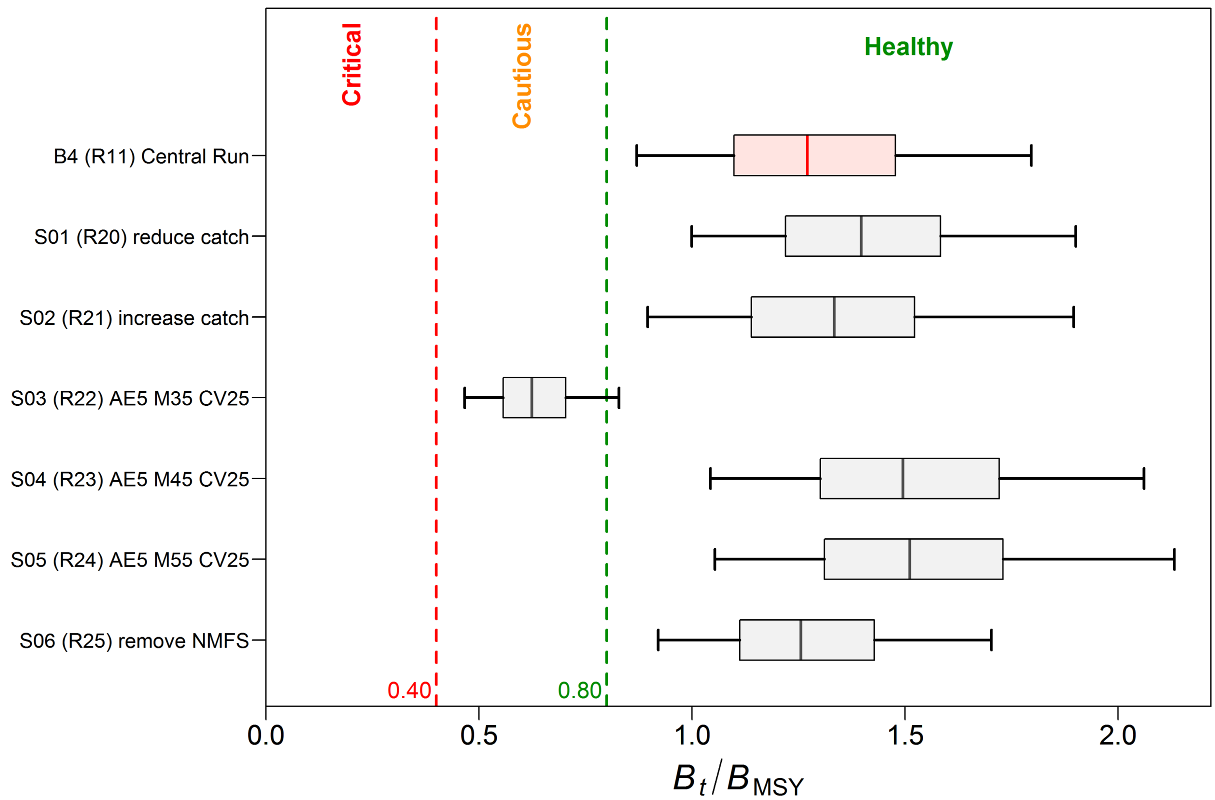


Figure F.82. REBS south sensitivity: stock status at beginning of 2021 relative to the DFO PA provisional reference points of 0.4B_{MSY} and 0.8B_{MSY} for the central run of the composite base case (Run11) and 6 sensitivity runs: S01 (R20) = reduced commercial catch for 1965-1995 by 33%; S02 (R21) = increased commercial catch for 1965-1995 by 50%; S03 (R22) = used wide aging error (AE $\pm$5 ages), fixed M=0.035, and set CPUE c_p=0.2529; S04 (R23) = used wide AE matrix, fixed M=0.045, and set CPUE c_p=0.2529; S05 (R24) = used wide AE matrix, fixed M=0.055, and set CPUE c_p=0.2529; S06 (R25) = removed the NMFS triennial survey. Boxplots show the 0.05, 0.25, 0.5, 0.75, and 0.95 quantiles from the MCMC posterior.

F.4. REFERENCES – MODEL RESULTS

Forrest, R.E., Holt, K.R. and Kronlund, A.R. 2018. Performance of alternative harvest control rules for two Pacific groundfish stocks with uncertain natural mortality: bias, robustness and trade-offs. Fish. Res. 206. 259–286.

Francis, R.I.C.C. 2011. Data weighting in statistical fisheries stock assessment models. Can. J. Fish. Aquat. Sci. 68(6). 1124–1138.

N.Z. Min. Fish. 2011. Operational Guidelines for New Zealand's Harvest Strategy Standard. Ministry of Fisheries, New Zealand.

Starr, P.J. and Haigh, R. 2022. Bocaccio (*Sebastes paucispinis*) stock assessment for British Columbia in 2019, including guidance for rebuilding plans. DFO Can. Sci. Advis. Sec. Res. Doc. *In press*.

APPENDIX G. ECOSYSTEM INFORMATION

This appendix describes ecosystem information relevant to Rougheye/Blackspotted Rockfish (REBS) along the British Columbia (BC) coast. Commercial catch data for REBS include Rougheye and Blackspotted Rockfish (RER and BSR), but both are identified using the GFBioSQL code '394' (so they all appear to be Rougheye Rockfish). The database administrators changed the code description tables so that '394' now refers to the REBS complex; however, **the appearance of 'RER' or 'Rougheye Rockfish' in figures should be interpreted to mean 'REBS'**. As in the main document, the two stocks are 'REBS north' comprising REBS in PMFC 5DE, and 'REBS south', comprising REBS in PMFC 3CD5AB. The information in this appendix is not used for the purposes of stock assessment but provides information that might be useful to other agencies and to support the interpretation of REBS spatial and biological information.

G.1. SPATIAL DISTRIBUTION

Data for spatial analyses of REBS were extracted from the SQL DFO databases 'PacHarvest' and 'GFFOS' on Feb 14, 2020. Some of the analyses below are designed to facilitate the reporting of findings to COSEWIC (Committee on the Status of Endangered Wildlife in Canada), regardless of its assessed status.

REBS is ubiquitous along the BC coast, with BSR more typical of the north and RER predominating in the south (Creamer 2016). Broadly, the 'extent of occurrence' (EO) for REBS covers 120,255 km^2 (on water and excluding seamounts data) using historical fishing events (1982-2020) to determine a convex hull envelope (Figure G.1). Of the bottom trawl tows capturing REBS, 99% of the tows have starting depths between 137 m and 845 m (Figure G.2). By stock, these boundaries are similar – REBS north: 131-834 m (Figure G.3), REBS south: 139-860 m (Figure G.4). Using the REBS bottom-tow depth range as a proxy for suitable REBS benthic habitat, a refined estimate of EO is 70,075 km^2 in BC's Exclusive Economic Zone (Figure G.5). To estimate the 'area of occupancy' (AO), the catch of REBS was located within a grid comprising 4 km^2 cells (2km × 2km), and the cells occupied by REBS were summed to estimate an AO of 23,784 km^2 along the BC coast spanning 24 years (Figure G.6). An alternative depiction of REBS catch is summarised by fishery in DFO fishing localities – Trawl (Figure G.7), Halibut (Figure G.8), Sablefish (Figure G.9), Dogfish/Lingcod (Figure G.10), and H&L Rockfish (Figure G.11).

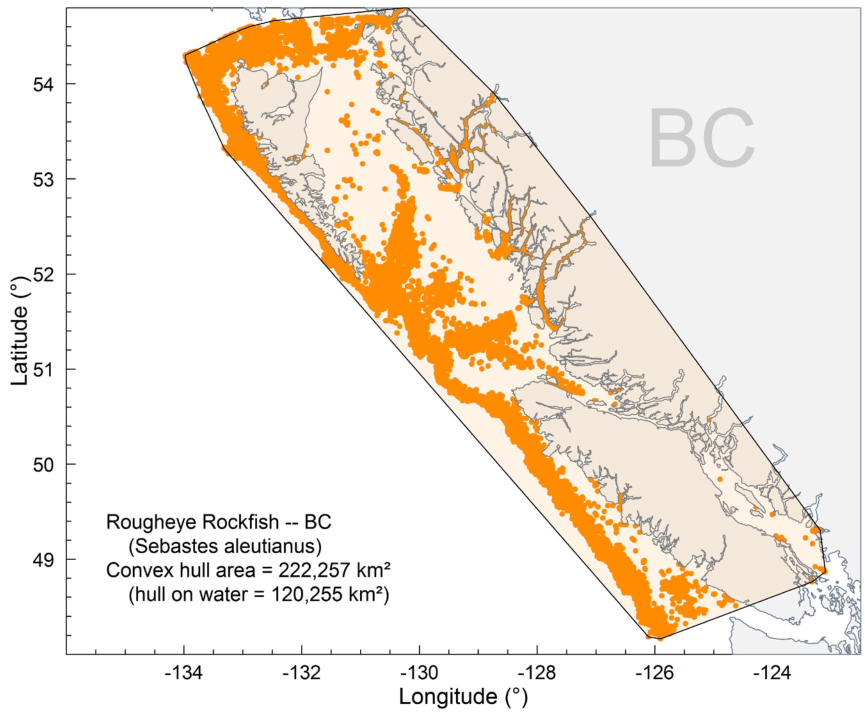


Figure G.1. REBS – Extent of Occurrence as a convex hull surrounding fishing events that caught REBS along the BC coast; the shading within the hull on water covers 120,255 km^2.

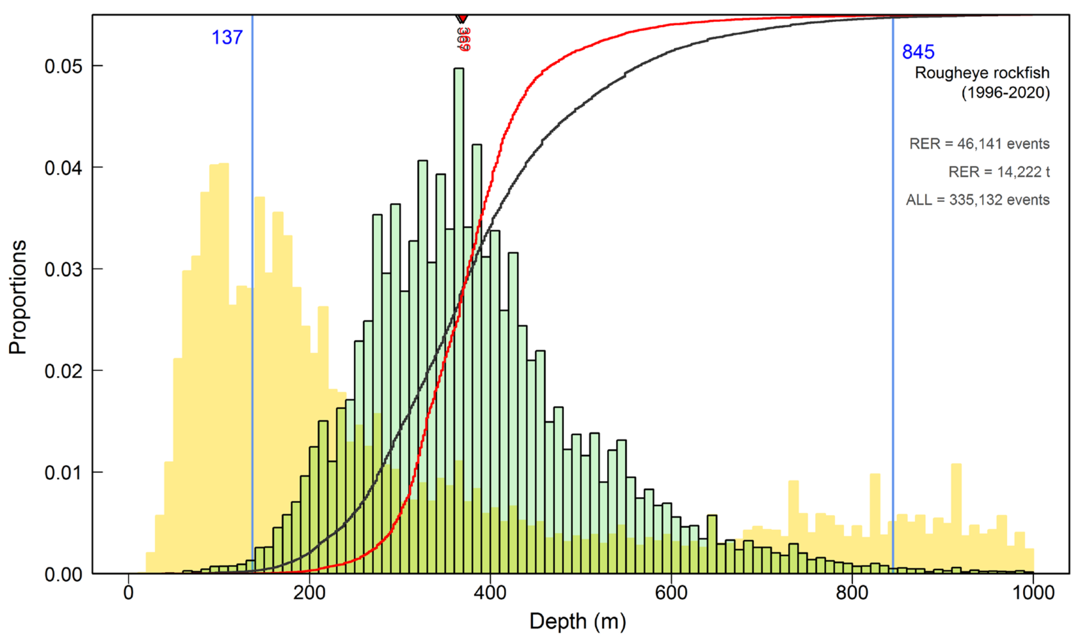


Figure G.2. REBS – Depth frequency of bottom trawl tows (green histogram) that captured REBS from commercial logs (1996-2020 in PacHarvest and GFFOS) in PMFC areas 3CD5ABCDE. The vertical solid lines denote the 0.005 and 0.995 quantiles. The black curve shows the cumulative frequency of tows that encounter REBS while the red curve shows the cumulative catch of REBS at depth (scaled from 0 to 1). The median depths of REBS encounters (inverted grey triangle) and of cumulative catch (inverted red triangle) are indicated along the upper axis. The yellow histogram in the background reports the relative trawl effort on all species offshore down to 1000 m.

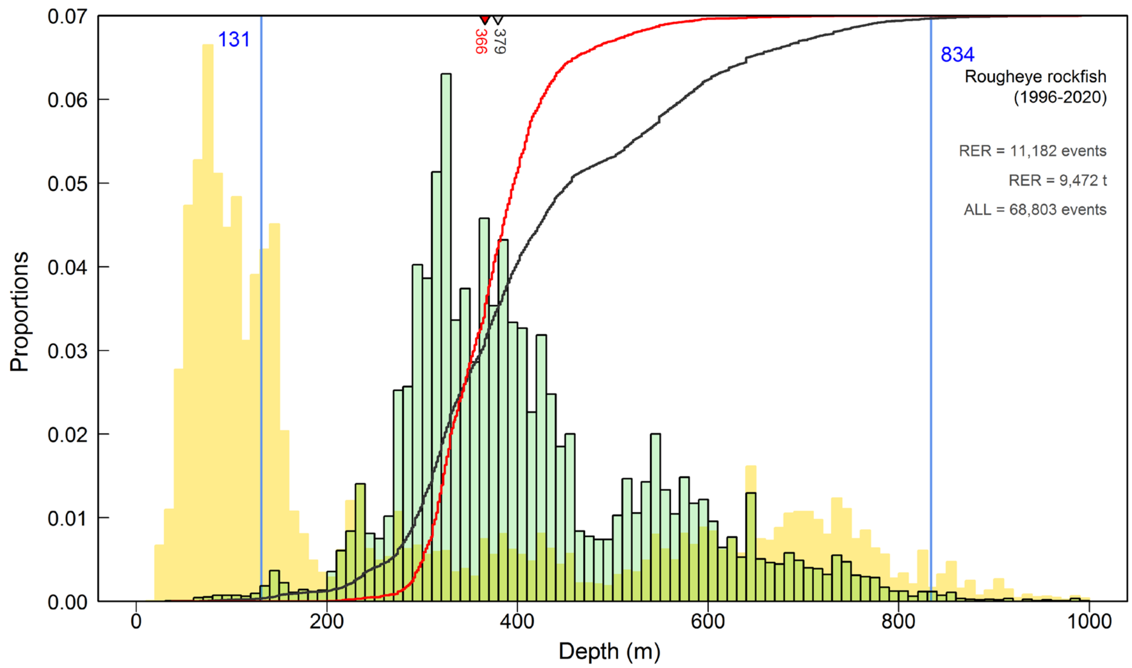


Figure G.3. REBS north – Depth frequency of bottom trawl tows (green histogram) that captured REBS from commercial logs (1996-2020 in PacHarvest and GFFOS) in PMFC areas 5DE. See Figure G.1 caption for additional details.

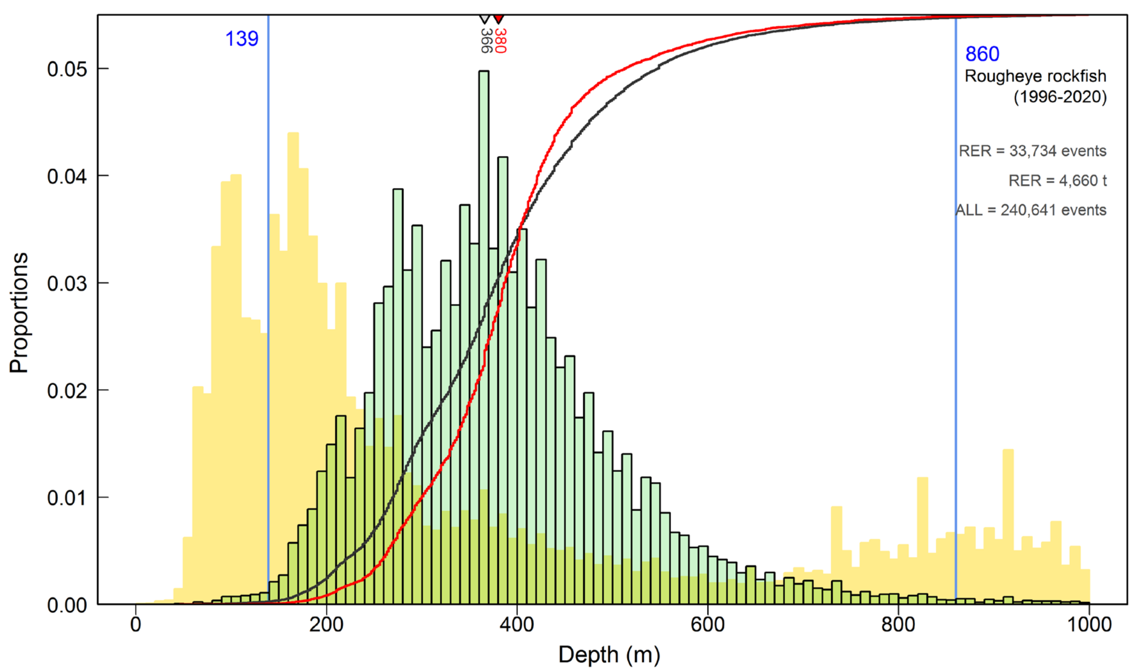


Figure G.4. REBS south – Depth frequency of bottom trawl tows (green histogram) that captured REBS from commercial logs (1996-2020 in PacHarvest and GFFOS) in PMFC areas 3CD5AB. See Figure G.1 caption for additional details.

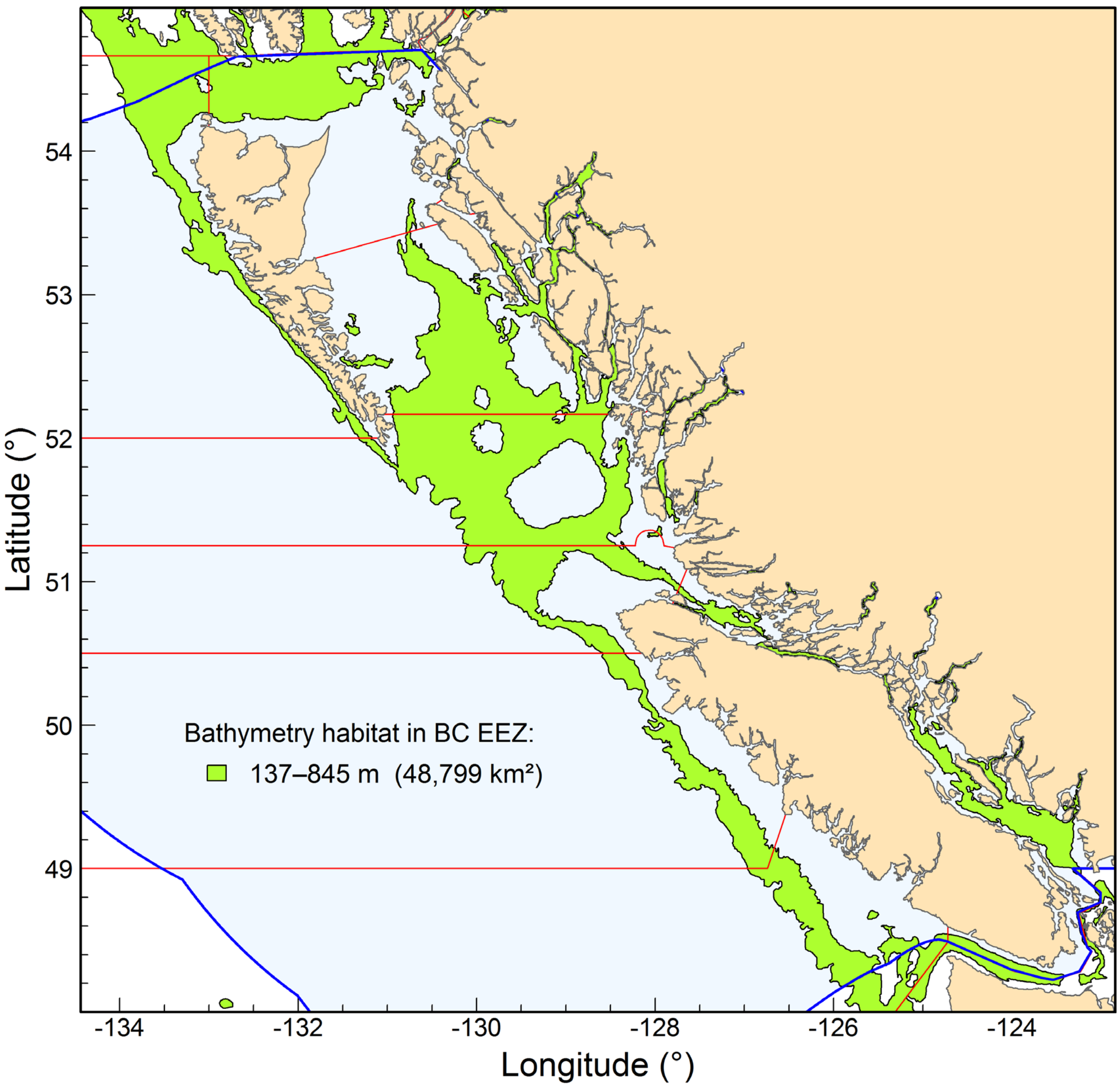


Figure G.5. REBS – Highlighted bathymetry (green) between 137 and 845 m serves as a proxy for benthic habitat along the BC coast. The green highlighted region within Canada's exclusive economic zone (EEZ, blue highlighted area) covers 48,799 km^2. The boundaries in red delimit PMFC areas.

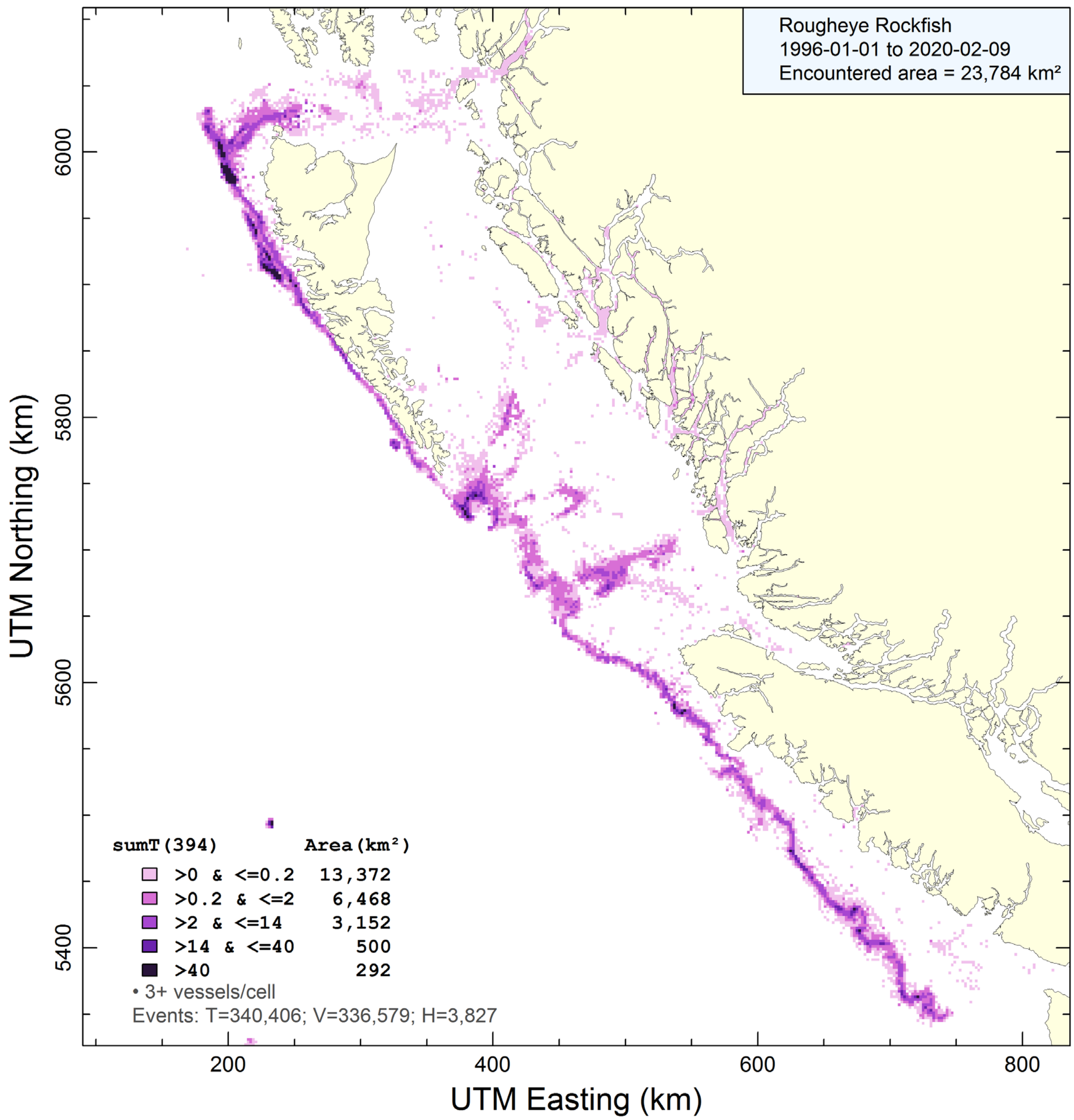


Figure G.6.REBS – Area of Occupancy (AO) determined by bottom trawl capture of REBS in grid cells 2km × 2km. Cells with fewer than three fishing vessels are excluded. The estimated AO is 23,784 km^2 along the BC coast.

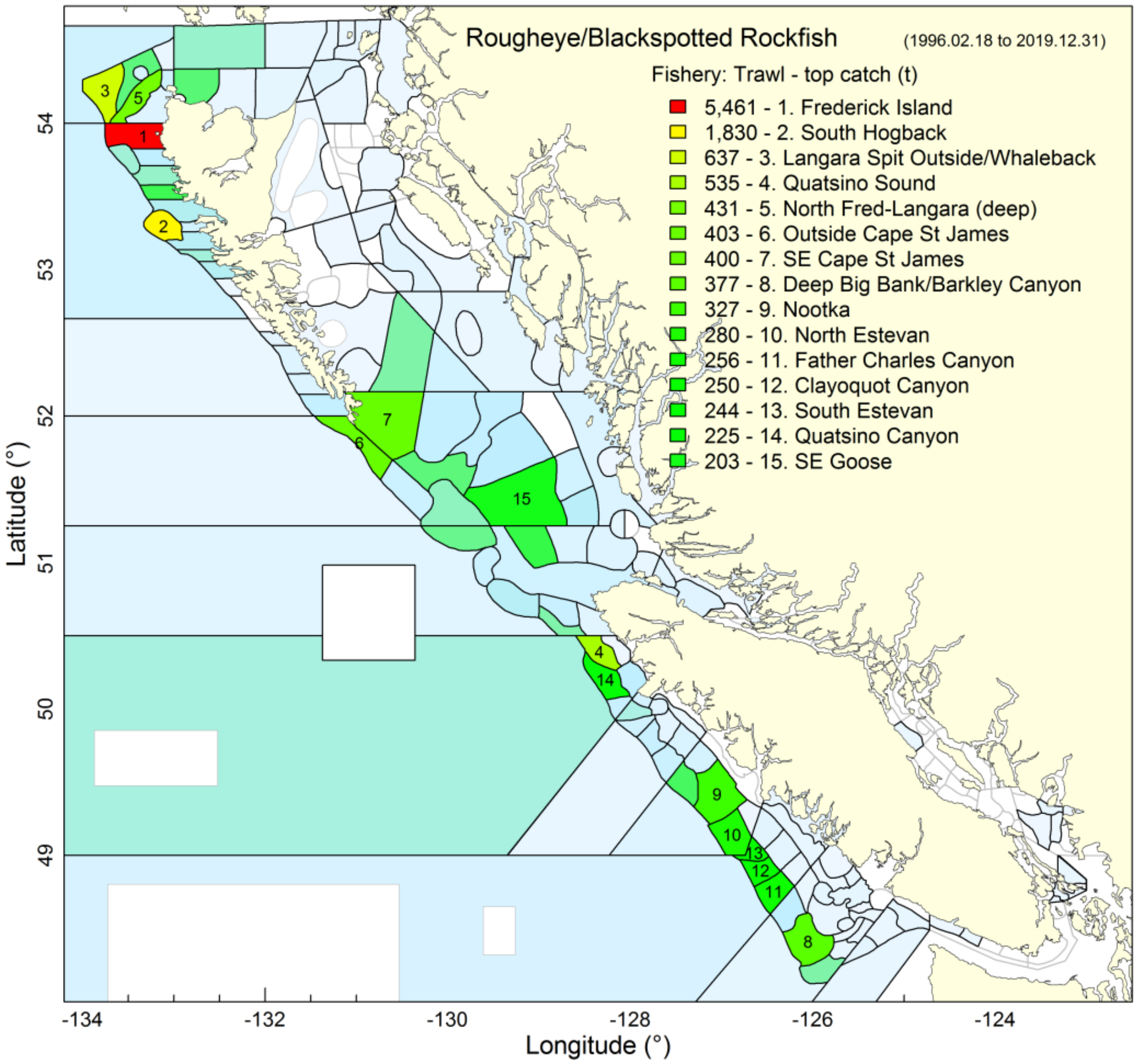


Figure G.7. REBS Trawl – Top 15 fishing localities by total catch (tonnes) where REBS was caught by the trawl fishery. All shaded localities indicate areas where REBS was encountered from 1996 to 2019, ranging from relatively low numbers in cool blue, through the spectrum, to relatively high catches in red. Seamount catches are excluded.

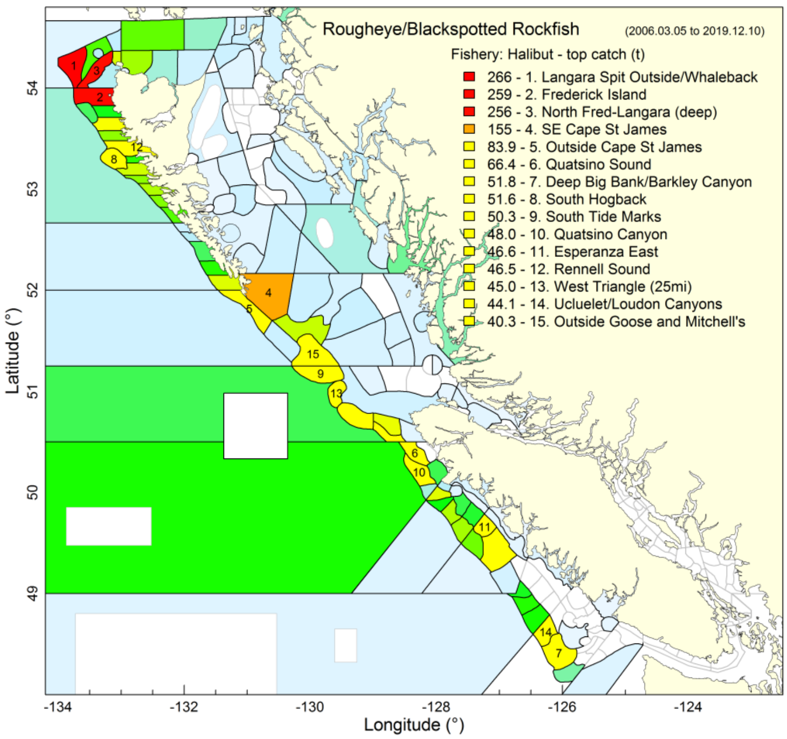


Figure G.8. REBS Halibut – Top 15 fishing localities by total catch (tonnes) where REBS was caught by the halibut fishery. See Figure G.7 caption for further details.

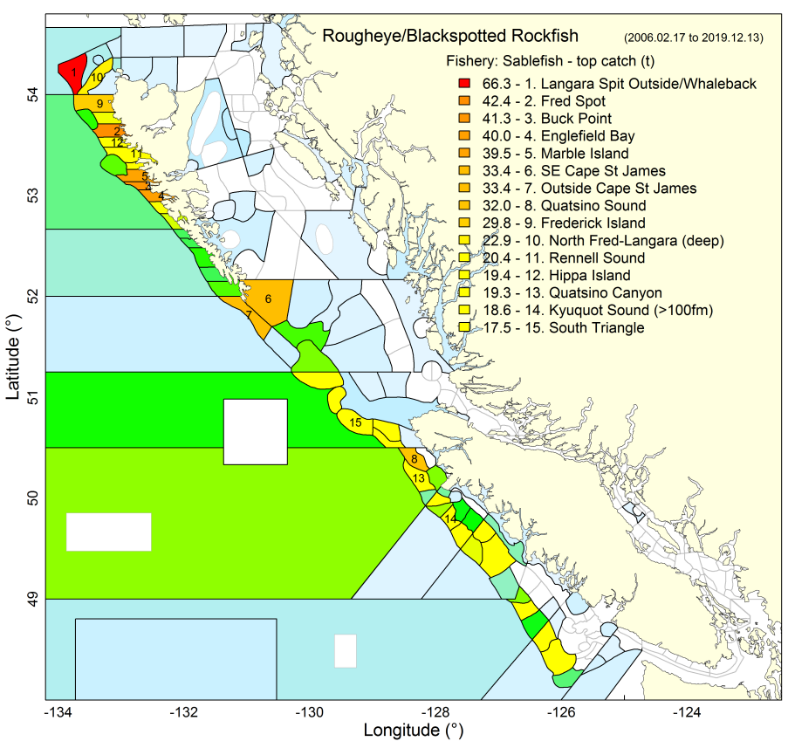


Figure G.9. REBS Sablefish – Top 15 fishing localities by total catch (tonnes) where REBS was caught by the sablefish fishery. See Figure G.7 caption for further details.

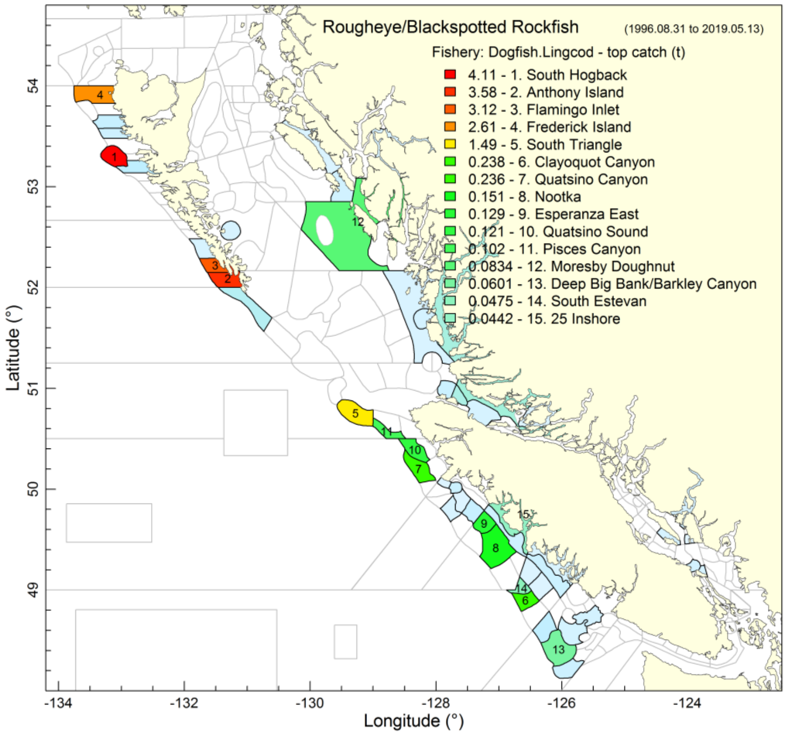


Figure G.10. REBS Dogfish/Lingcod – Top 15 fishing localities by total catch (tonnes) where REBS was caught by the dogfish/lingcod (Schedule II) fishery. See Figure G.7 caption for further details.

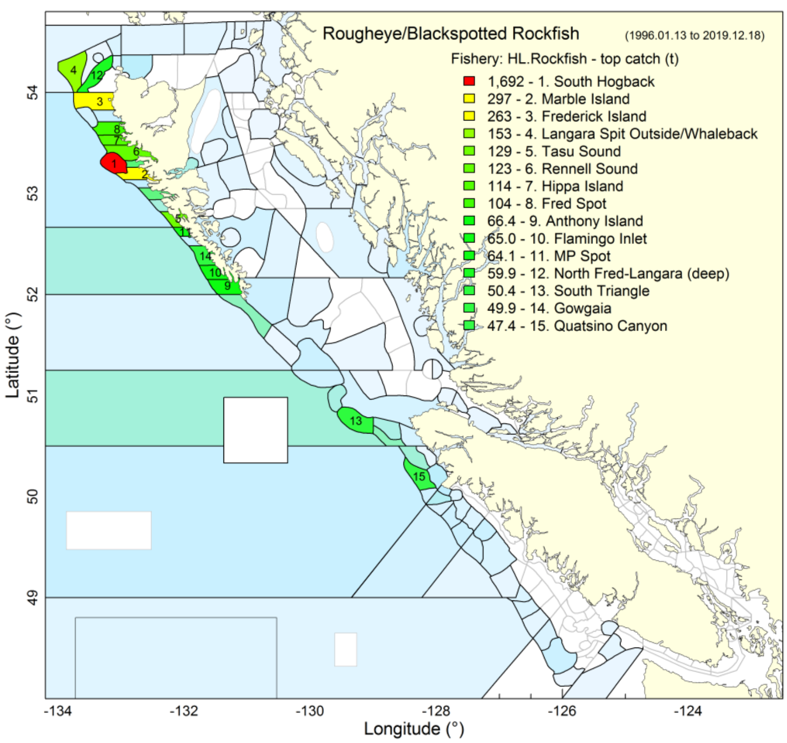


Figure G.11. REBS H&L Rockfish – Top 15 fishing localities by total catch (tonnes) where REBS was caught by the hook and line rockfish (ZN) fishery. See Figure G.7 caption for further details.

G.2. CONCURRENT SPECIES

Species caught concurrently in coastwide bottom trawl tows that capture at least one REBS specimen are dominated by Arrowtooth Flounder (27%), Pacific Ocean Perch (20%), Dover Sole (8%), and Yellowtail Rockfish (7%). REBS contributes only 2% by catch weight in coastwide REBS tows (Table G.16). A closer look by stock, however, shows that REBS in the north represents 9% of the catch weight in REBS tows (Table G.17) while assumed REBS in the south only makes up 1% of REBS tows (Table G.18). Clearly, the northern stock has a greater presence in the ecosystem accessible by trawl than does the southern one.

The other gear type that intercepts REBS significantly is hook and line (midwater trawl and trap gears catching REBS are dominated by hake [86%] and sablefish [96%]). Of the H&L fishing events capturing at least one REBS specimen, catches comprise Pacific Halibut (coast: 48%, 5DE: 53%, 3CD5AB: 44%), Sablefish (coast: 22%, 5DE: 17%, 3CD5AB: 27%), Spiny Dogfish (coast: 5%, 5DE: 1%, 3CD5AB: 7%), and REBS (coast: 7%, 5DE: 13%, 3CD5AB: 4%), amongst others (see Tables G.1-G.3).

To explore how REBS coastwide is associated with other rockfish in bottom trawl tows and hook and line events, the top 14 rockfish species caught by REBS fishing events were grouped by `clara` (clustering large applications) using R's package `cluster` (Maechler et al. 2018). The top rockfish used partially appear in Table G.16:

- Bottom trawl: Pacific Ocean Perch (POP 19.7%), Yellowtail Rockfish (YTR 7.3%), Yellowmouth Rockfish (YMR 5.3%), Silvergray Rockfish (SGR 4.7%), Redstripe Rockfish (RSR 2.8%), Canary Rockfish (CAR 2.5%), Rougheye/Blackspotted Rockfish (REBS 2.3%), Shortspine Thornyhead (SST 1.7%), Sharpchin Rockfish (SCR 1.3%), Widow Rockfish (WWR 0.88%), Redbanded Rockfish (RBR 0.85%), Splitnose Rockfish (SNR 0.59%), Longspine Thornyhead (LST 0.52%), Bocaccio (BOR 0.33%), Darkblotched Rockfish (DBR 0.25%).
- Hook and line: Rougheye/Blackspotted Rockfish (REBS 7.4%), Redbanded Rockfish (RBR 3.0%), Yelloweye Rockfish (YYR 1.5%), Shortraker Rockfish (SKR 1.4%), Shortspine Thornyhead (SST 0.85%), Silvergray Rockfish (SGR 0.80%), Canary Rockfish (CAR 0.21%), Yellowmouth Rockfish (YMR 0.15%), Bocaccio (BOR 0.089%), Quillback Rockfish (QBR 0.040%), Black Rockfish (BKR 0.029%), Copper Rockfish (CPR 0.028%), Yellowtail Rockfish (YTR 0.026%), Pacific Ocean Perch (POP 0.014%), Rosethorn Rockfish (RTR 0.013%).

The cluster analysis on commercial bottom trawl catch (Figure G.15) shows that the primary group featuring REBS (red) also includes the two thornyhead species (SST and LST) in deep-water areas off the west coast of Vancouver Island (WCVI), Queen Charlotte Sound (QCS), northwest Haida Gwaii. A secondary cluster (orange) represented by POP and YMR occurs in the three primary gullies of QCS – Moresby, Mitchell's, and Goose Island (from north to south). The remaining four groups are dominated by other rockfish species: group 3 (yellow) – SGR in the north, group 4 (light green) – YTR in shelf regions, group 5 (dark green) – RSR along the shelf-slope boundary, and group 6 (blue) – CAR scattered in shallow areas.

The cluster analysis on commercial hook and line catch (Figure G.16) shows that the primary group featuring REBS (red), including SST and SKR, lies along the entire coast of BC between the 200-m and 1000-m isobaths. A secondary cluster (orange) shows REBS with RBR and YYR at the mouths of the QCS gullies and in Dixon Entrance. The remaining four groups are dominated by inshore rockfish species that have low association with REBS: group 3 (yellow) – YYR along the shelf regions at depths less than 200 m, groups 4 (light green) and 5 (dark green) – QBR and YYR in shallow regions close to land, and group 6 (blue) – CPR located in numerous inlets of WCVI and in shallow sandy regions of Hecate Strait. The miscellaneous coloured pixels offshore (>1800 m) are likely records with incorrect geographic coordinates.

Table G.16. REBS – Top 10 species by catch weight (sum of landed + discarded 1996-2020) that co-occur in REBS fishing events by gear type in PMFC areas 3CD5ABCDE (Figure G.12). Rockfish species of interest to COSEWIC appear in red font, target species (occur in every tow) appear in blue font.

Code*	Species	Latin Name	Catch (tonnes)	Catch (%)	∑Catch (%)
Gear: Bottom Trawl					
602	Arrowtooth Flounder	*Atheresthes stomias*	155,294	26.7	26.7
396	Pacific Ocean Perch	*Sebastes alutus*	114,631	19.7	46.4
626	Dover Sole	*Microstomus pacificus*	47,287	8.12	54.5
418	Yellowtail Rockfish	*Sebastes flavidus*	42,720	7.34	61.8
440	Yellowmouth Rockfish	*Sebastes reedi*	31,128	5.35	67.2
405	Silvergray Rockfish	*Sebastes brevispinis*	27,545	4.73	71.9
439	Redstripe Rockfish	*Sebastes proriger*	16,114	2.77	74.7
437	Canary Rockfish	*Sebastes pinniger*	14,497	2.49	77.2
394	Rougheye/Blackspotted	*S. aleutianus/melanostictus*	13,322	2.29	79.5
467	Lingcod	*Ophiodon elongatus*	11,714	2.01	81.5
Gear: Hook and Line					
614	Pacific Halibut	*Hippoglossus stenolepis*	53,691	48.3	48.3
455	Sablefish	*Anoplopoma fimbria*	24,665	22.2	70.5
394	Rougheye/Blackspotted	*S. aleutianus/melanostictus*	8,226	7.40	77.9
044	Spiny Dogfish	*Squalus acanthias*	5,937	5.34	83.2
059	Longnose Skate	*Raja rhina*	4,321	3.89	87.1
401	Redbanded Rockfish	*Sebastes babcocki*	3,287	2.96	90.0
467	Lingcod	*Ophiodon elongatus*	2,772	2.49	92.5
442	Yelloweye Rockfish	*Sebastes ruberrimus*	1,613	1.45	94.0
403	Shortraker Rockfish	*Sebastes borealis*	1,605	1.44	95.4
451	Shortspine Thornyhead	*Sebastolobus alascanus*	944	0.85	96.3
Gear: Midwater Trawl**					
225	Pacific Hake	*Merluccius productus*	652,332	86.0	86.0
418	Yellowtail Rockfish	*Sebastes flavidus*	33,879	4.47	90.5
417	Widow Rockfish	*Sebastes entomelas*	30,008	3.96	94.4
228	Walleye Pollock	*Theragra chalcogramma*	14,658	1.93	96.4
396	Pacific Ocean Perch	*Sebastes alutus*	5,615	0.74	97.1
440	Yellowmouth Rockfish	*Sebastes reedi*	5,551	0.73	97.8
439	Redstripe Rockfish	*Sebastes proriger*	5,393	0.71	98.5
602	Arrowtooth Flounder	*Atheresthes stomias*	2,469	0.33	98.9
437	Canary Rockfish	*Sebastes pinniger*	1,600	0.21	99.1
044	Spiny Dogfish	*Squalus acanthias*	1,423	0.19	99.3
Gear: Trap					
455	Sablefish	*Anoplopoma fimbria*	45,080	96.1	96.1
602	Arrowtooth Flounder	*Atheresthes stomias*	713	1.52	97.6
614	Pacific Halibut	*Hippoglossus stenolepis*	585	1.25	98.8
394	Rougheye/Blackspotted	*S. aleutianus/melanostictus*	361	0.77	99.6
451	Shortspine Thornyhead	*Sebastolobus alascanus*	34	0.07	99.7
044	Spiny Dogfish	*Squalus acanthias*	29	0.06	99.7
403	Shortraker Rockfish	*Sebastes borealis*	24	0.05	99.8
401	Redbanded Rockfish	*Sebastes babcocki*	17	0.04	99.8
249	Grenadiers	*Macrouridae*	12	0.02	99.9
ZAD	Tanner crabs	*Chionoecetes*	11	0.02	99.9

*COSEWIC species in {"027","034","394","410","424","435","437","440","442","453"}
**REBS with 12th highest catch in REBS midwater tows, representing 0.1% by catch weight.

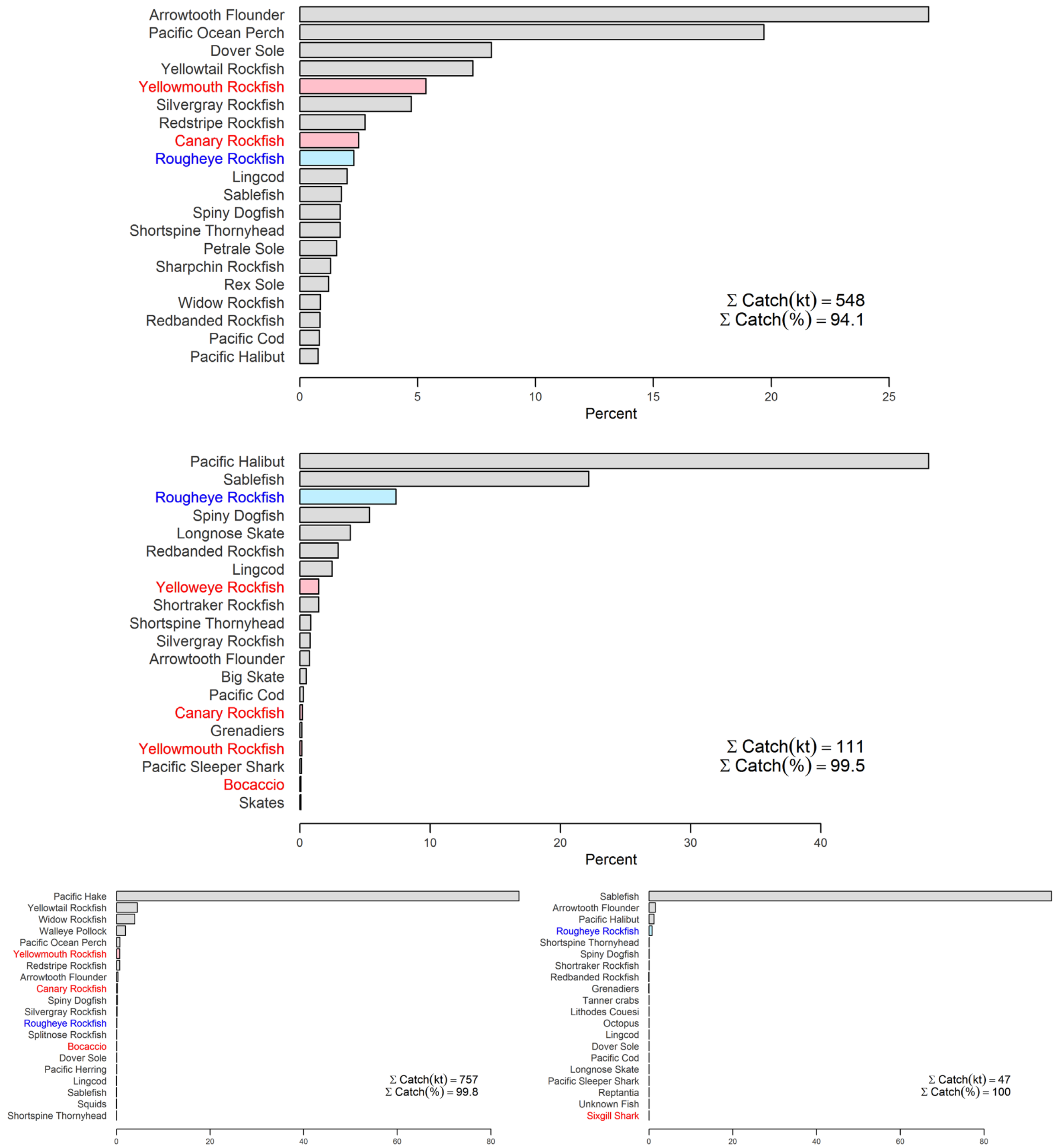


Figure G.12. REBS – Distribution of catch weights summed over the period Feb 1996 to Feb 2020 for important finfish species from fishing events in GFFOS that caught at least one REBS in PMFC areas 3CD5ABCDE. The four panels correspond to various gear types – bottom trawl (top), hook and line (middle), midwater trawl (bottom left), and trap (bottom right). Fishing events were selected over a depth range between 137 and 845 m (the 0.005 and 0.995 quantile range, see Figure G.2). Relative concurrence is expressed as a percentage by species relative to the total catch weight summed over all finfish species in the specified period. Assessment species appear in blue; COSEWIC species appear in red.

Table G.17. REBS north – Top 10 species by catch weight (sum of landed + discarded from 1996 to 2020) that co-occur in REBS fishing events by gear type in PMFC areas 5DE (Figure G.13). Rockfish species of interest to COSEWIC appear in red font, target species (which occur in every tow) appear in blue font.

Code*	Species	Latin Name	Catch (tonnes)	Catch (%)	∑Catch (%)
Gear: Bottom Trawl					
396	Pacific Ocean Perch	*Sebastes alutus*	25,157	24.9	24.9
602	Arrowtooth Flounder	*Atheresthes stomias*	16,504	16.3	41.3
626	Dover Sole	*Microstomus pacificus*	14,287	14.1	55.4
394	Rougheye/Blackspotted	*S. aleutianus/melanostictus*	9,417	9.33	64.7
405	Silvergray Rockfish	*Sebastes brevispinis*	6,096	6.04	70.8
440	Yellowmouth Rockfish	*Sebastes reedi*	4,338	4.30	75.1
451	Shortspine Thornyhead	*Sebastolobus alascanus*	3,889	3.85	78.9
439	Redstripe Rockfish	*Sebastes proriger*	3,328	3.30	82.2
610	Rex Sole	*Errex zachirus*	1,814	1.80	84.0
455	Sablefish	*Anoplopoma fimbria*	1,679	1.66	85.7
Gear: Hook and Line					
614	Pacific Halibut	*Hippoglossus stenolepis*	22,636	53.2	53.2
455	Sablefish	*Anoplopoma fimbria*	7,307	17.2	70.4
394	Rougheye/Blackspotted	*S. aleutianus/melanostictus*	5,672	13.3	83.7
059	Longnose Skate	*Raja rhina*	1,114	2.62	86.3
403	Shortraker Rockfish	*Sebastes borealis*	793	1.86	88.2
467	Lingcod	*Ophiodon elongatus*	787	1.85	90.0
401	Redbanded Rockfish	*Sebastes babcocki*	764	1.79	91.8
442	Yelloweye Rockfish	*Sebastes ruberrimus*	696	1.64	93.5
044	Spiny Dogfish	*Squalus acanthias*	594	1.40	94.9
405	Silvergray Rockfish	*Sebastes brevispinis*	478	1.12	96.0
Gear: Midwater Trawl					
225	Pacific Hake	*Merluccius productus*	7,991	40.0	40.0
228	Walleye Pollock	*Theragra chalcogramma*	7,706	38.6	78.5
417	Widow Rockfish	*Sebastes entomelas*	2,061	10.3	88.9
418	Yellowtail Rockfish	*Sebastes flavidus*	1,442	7.21	96.1
602	Arrowtooth Flounder	*Atheresthes stomias*	134	0.67	96.7
396	Pacific Ocean Perch	*Sebastes alutus*	134	0.67	97.4
439	Redstripe Rockfish	*Sebastes proriger*	94	0.47	97.9
626	Dover Sole	*Microstomus pacificus*	84	0.42	98.3
405	Silvergray Rockfish	*Sebastes brevispinis*	72	0.36	98.7
394	Rougheye/Blackspotted	*S. aleutianus/melanostictus*	47	0.24	98.9
Gear: Trap					
455	Sablefish	*Anoplopoma fimbria*	21,945	94.9	94.9
602	Arrowtooth Flounder	*Atheresthes stomias*	601	2.60	97.5
614	Pacific Halibut	*Hippoglossus stenolepis*	264	1.14	98.6
394	Rougheye/Blackspotted	*S. aleutianus/melanostictus*	245	1.06	99.7
451	Shortspine Thornyhead	*Sebastolobus alascanus*	18	0.08	99.7
403	Shortraker Rockfish	*Sebastes borealis*	13	0.05	99.8
ZAD	Tanner crabs	*Chionoecetes*	9	0.04	99.8
VMD	Lithodes Couesi	*Lithodes couesi*	8	0.04	99.9
249	Grenadiers	*Macrouridae*	7	0.03	99.9
626	Dover Sole	*Microstomus pacificus*	5	0.02	99.9

*COSEWIC species in {"027","034","394","410","424","435","437","440","442","453"}

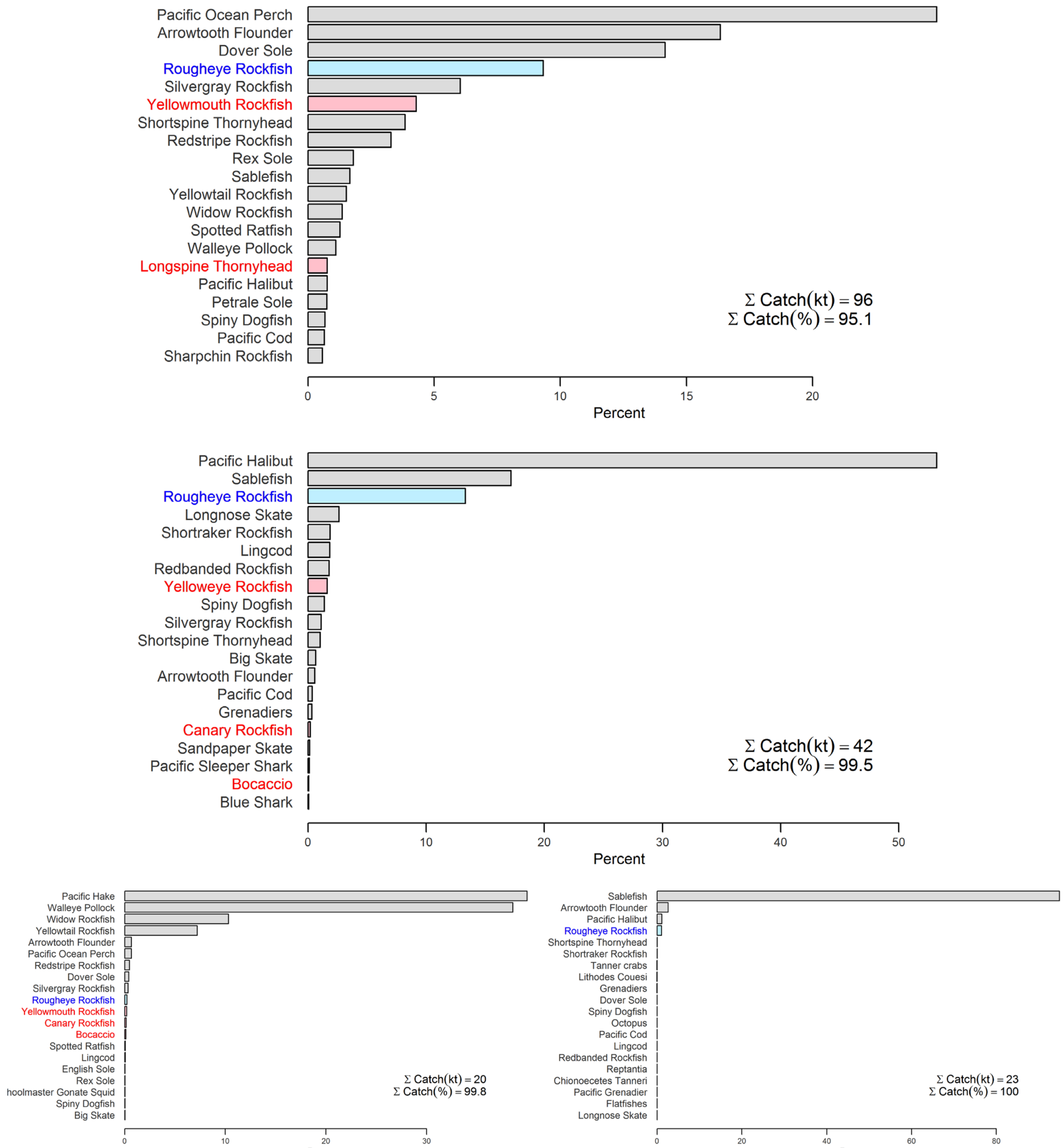


Figure G.13. REBS north – Distribution of catch weights summed over the period Feb 1996 to Feb 2020 for important finfish species from fishing events in GFFOS that caught at least one REBS in PMFC areas 5DE between 131 and 824 m for gears bottom trawl (top) , hook and line (middle), midwater trawl (bottom left), and trap (bottom right). See Figure G.12 caption for further details.

Table G.18. REBS south – Top 10 species by catch weight (sum of landed + discarded from 1996 to 2020) that co-occur in REBS fishing events by gear type in PMFC areas 3CD5AB (Figure G.14). Rockfish species of interest to COSEWIC appear in red font, target species (which occur in every tow) appear in blue font.

Code*	Species	Latin Name	Catch (tonnes)	Catch (%)	∑Catch (%)
Gear: Bottom Trawl**					
602	Arrowtooth Flounder	*Atheresthes stomias*	137,818	29.9	29.9
396	Pacific Ocean Perch	*Sebastes alutus*	85,419	18.5	48.4
418	Yellowtail Rockfish	*Sebastes flavidus*	38,282	8.29	56.7
626	Dover Sole	*Microstomus pacificus*	33,984	7.36	64.0
440	Yellowmouth Rockfish	*Sebastes reedi*	26,312	5.70	69.7
405	Silvergray Rockfish	*Sebastes brevispinis*	14,095	3.05	72.8
437	Canary Rockfish	*Sebastes pinniger*	13,190	2.86	75.6
439	Redstripe Rockfish	*Sebastes proriger*	11,944	2.59	78.2
467	Lingcod	*Ophiodon elongatus*	11,017	2.39	80.6
044	Spiny Dogfish	*Squalus acanthias*	8,943	1.94	82.5
Gear: Hook and Line					
614	Pacific Halibut	*Hippoglossus stenolepis*	27,525	43.9	43.9
455	Sablefish	*Anoplopoma fimbria*	17,112	27.3	71.2
044	Spiny Dogfish	*Squalus acanthias*	4,443	7.09	78.3
059	Longnose Skate	*Raja rhina*	2,849	4.54	82.8
394	Rougheye/Blackspotted	*S. aleutianus/melanostictus*	2,537	4.05	86.9
401	Redbanded Rockfish	*Sebastes babcocki*	2,355	3.76	90.6
467	Lingcod	*Ophiodon elongatus*	1,748	2.79	93.4
442	Yelloweye Rockfish	*Sebastes ruberrimus*	772	1.23	94.6
403	Shortraker Rockfish	*Sebastes borealis*	743	1.19	95.8
602	Arrowtooth Flounder	*Atheresthes stomias*	566	0.90	96.7
Gear: Midwater Trawl***					
225	Pacific Hake	*Merluccius productus*	629,448	87.7	87.7
418	Yellowtail Rockfish	*Sebastes flavidus*	30,277	4.22	91.9
417	Widow Rockfish	*Sebastes entomelas*	26,608	3.71	95.6
440	Yellowmouth Rockfish	*Sebastes reedi*	5,448	0.76	96.4
396	Pacific Ocean Perch	*Sebastes alutus*	5,422	0.76	97.1
228	Walleye Pollock	*Theragra chalcogramma*	5,376	0.75	97.9
439	Redstripe Rockfish	*Sebastes proriger*	5,086	0.71	98.6
602	Arrowtooth Flounder	*Atheresthes stomias*	2,329	0.32	98.9
437	Canary Rockfish	*Sebastes pinniger*	1,491	0.21	99.1
044	Spiny Dogfish	*Squalus acanthias*	1,362	0.19	99.3
Gear: Trap					
455	Sablefish	*Anoplopoma fimbria*	23,152	97.3	97.3
614	Pacific Halibut	*Hippoglossus stenolepis*	321	1.35	98.6
394	Rougheye/Blackspotted	*S. aleutianus/melanostictus*	116	0.49	99.1
602	Arrowtooth Flounder	*Atheresthes stomias*	113	0.47	99.6
044	Spiny Dogfish	*Squalus acanthias*	24	0.10	99.7
451	Shortspine Thornyhead	*Sebastolobus alascanus*	17	0.07	99.7
401	Redbanded Rockfish	*Sebastes babcocki*	16	0.07	99.8
403	Shortraker Rockfish	*Sebastes borealis*	12	0.05	99.9
467	Lingcod	*Ophiodon elongatus*	5	0.02	99.9
97A	Octopus	*Octopoda*	5	0.02	99.9

*COSEWIC species in {"027","034","394","410","424","435","437","440","442","453"}
**REBS with 19th highest catch in REBS bottom tows, representing 0.8% by catch weight.
***REBS with 12th highest catch in REBS midwater tows, representing 0.1% by catch weight.

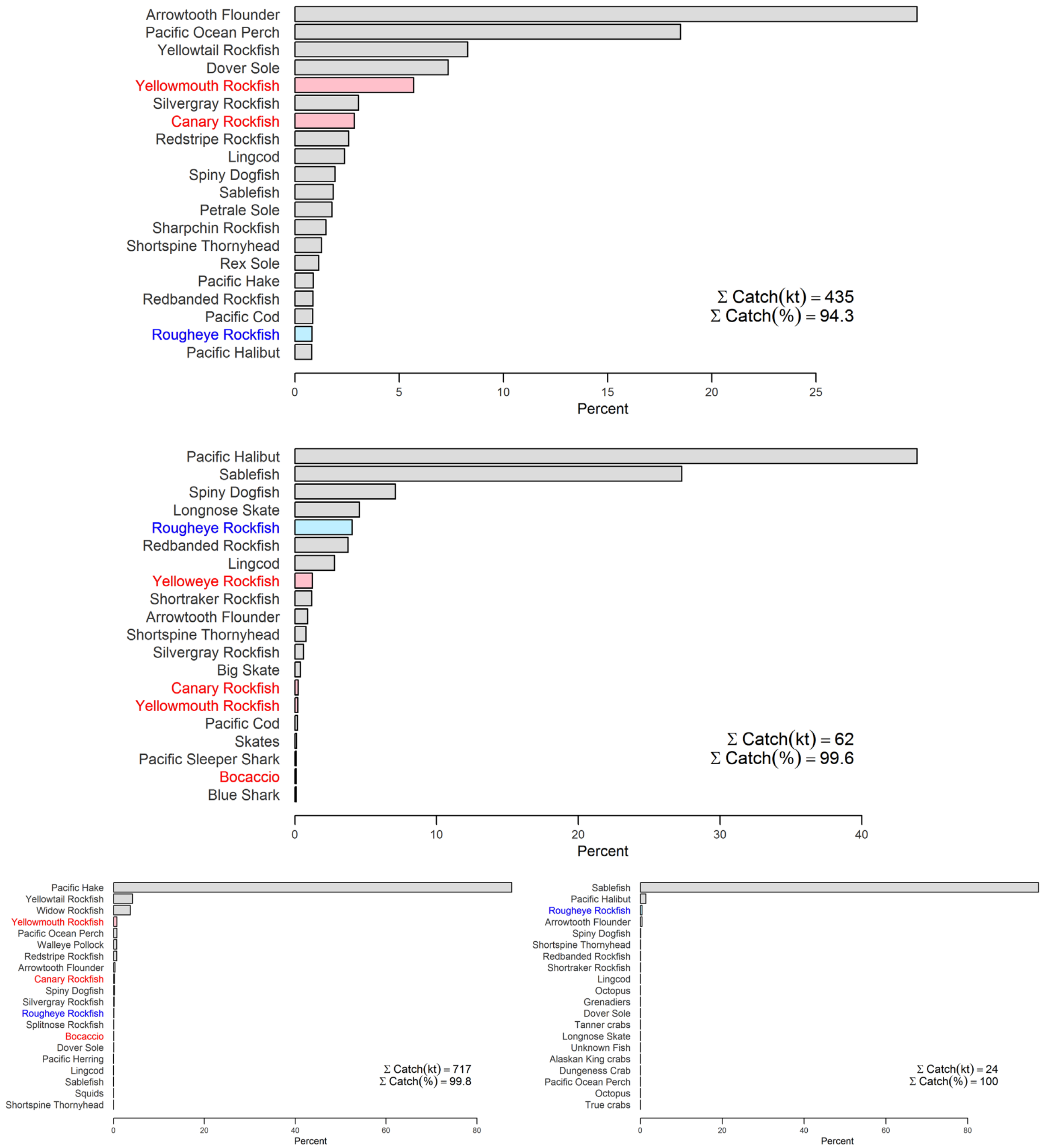


Figure G.14. REBS south – Distribution of catch weights summed over the period Feb 1996 to Feb 2020 for important finfish species from fishing events in GFFOS that caught at least one REBS south in PMFC areas 3CD5AB between 139 and 860 m for gears bottom trawl (top) , hook and line (middle), midwater trawl (bottom left), and trap (bottom right). See Figure G.12 caption for further details.

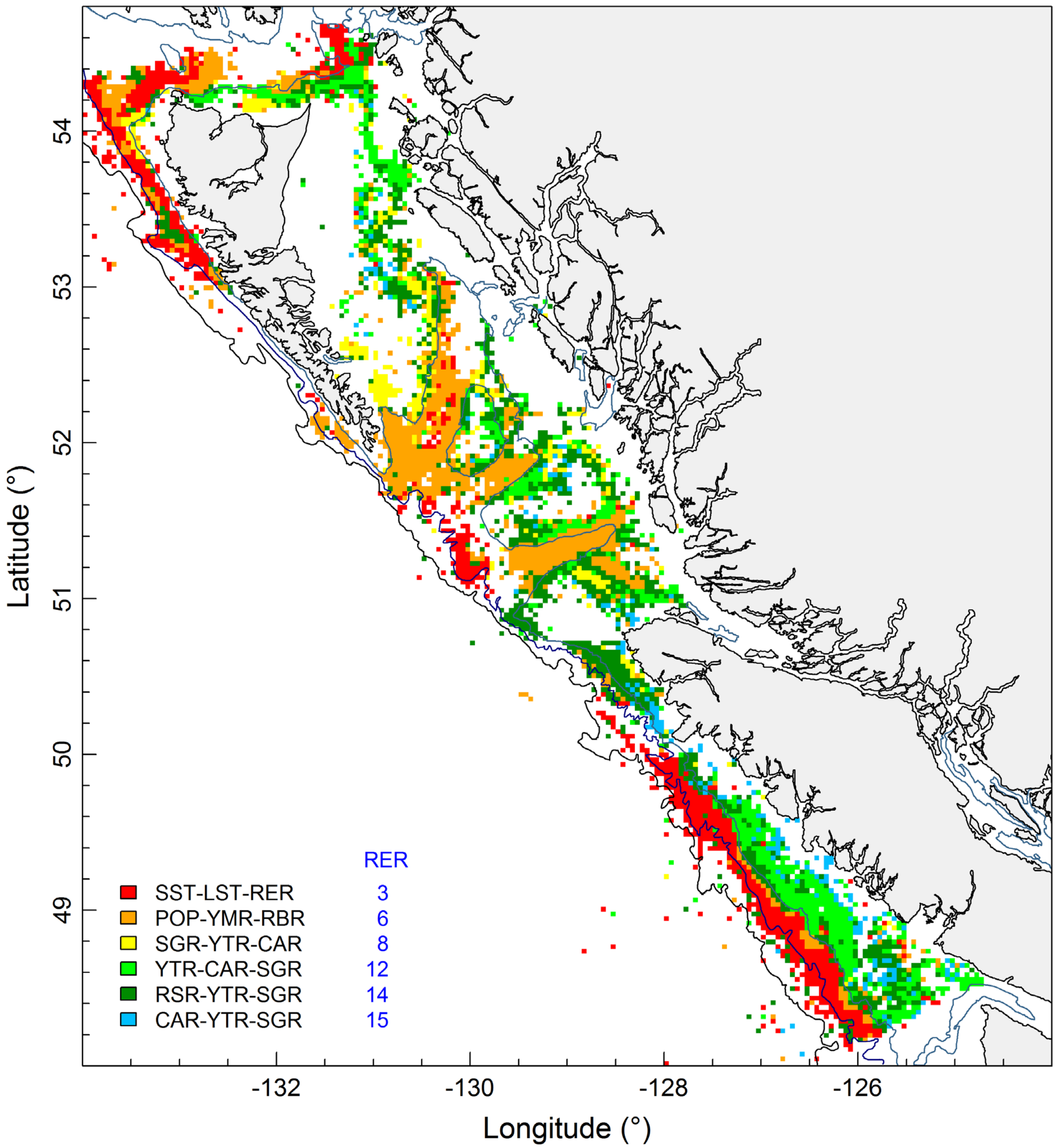


*Figure G.15. Groups of rockfish in **bottom trawl tows** (15 species from 1996-2020) identified by clara (clustering large applications) in R's package 'cluster' (Maechler et al. 2018). Isobaths trace the 200, 1000, and 1800 m depth contours. The legend identifies six clusters represented by the top three species comprising the medoids; the clusters are ordered by the contribution of Rougheye/Blackspotted Rockfish (REBS) to each medoid. Species codes: SST =Shortspine Thornyhead, LST =Longspine Thornyhead, POP =Pacific Ocean Perch, YMR = Yellowmouth Rockfish, RBR = Redbanded Rockfish, SGR Silvergray Rockfish, YTR =Yellowtail Rockfish, CAR = Canary Rockfish, and RSR = Redstripe Rockfish.*

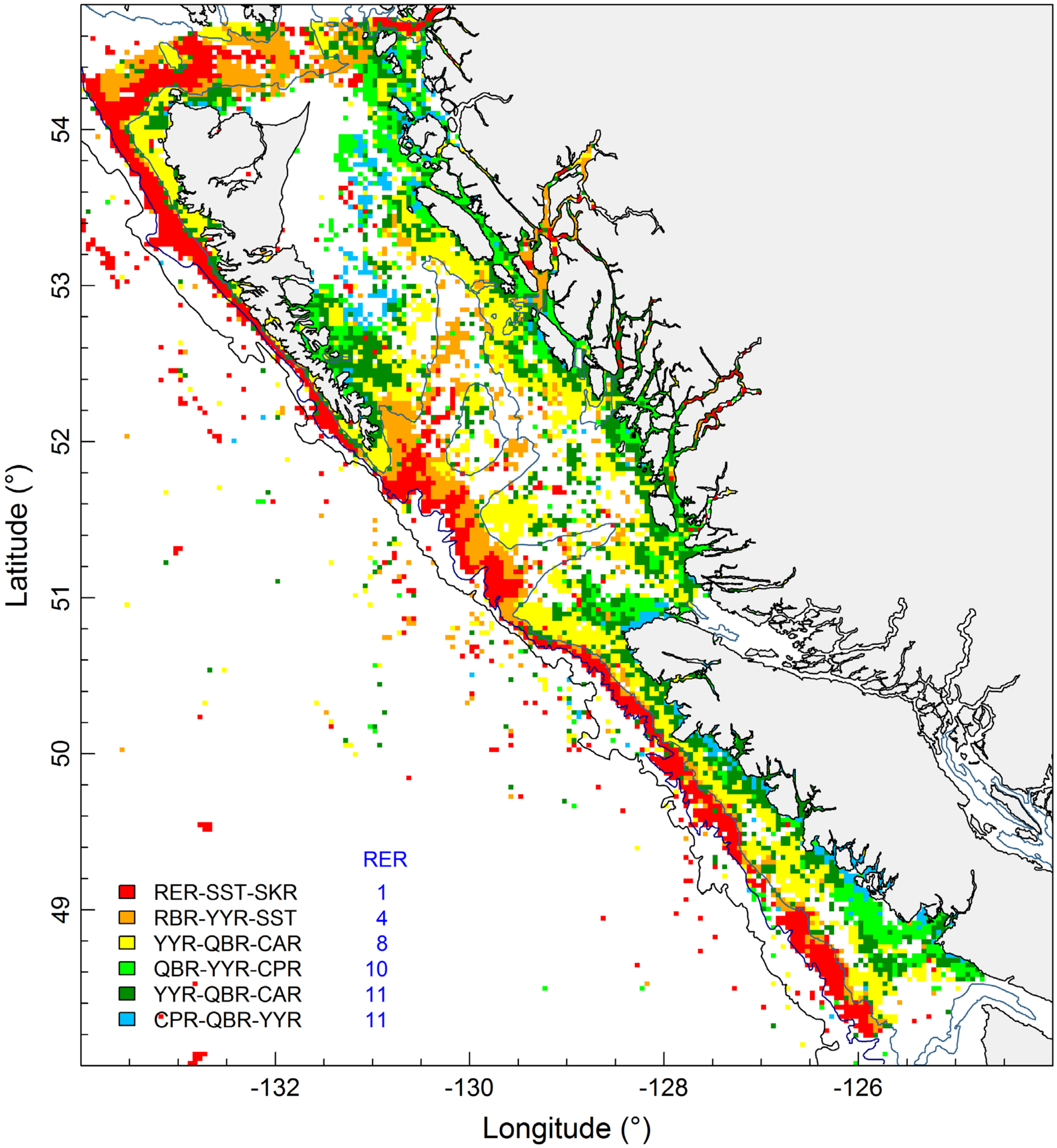


*Figure G.16. Groups of rockfish caught by **hook and line gear** (15 species from 1996-2020) identified by clara (clustering large applications) in R's package 'cluster' (Maechler et al. 2018). Isobaths trace the 200, 1000, and 1800 m depth contours. The legend identifies six clusters represented by the top three species comprising the medoids; the clusters are ordered by the contribution of Rougheye/Blackspotted Rockfish (REBS) to each medoid. Species codes: SST =Shortspine Thornyhead, SKR = Shortraker Rockfish, RBR = Redbanded Rockfish, YYR = Yelloweye Rockfish, QBR = Quillback Rockfish, CAR = Canary Rockfish, and CPR = Copper Rockfish.*

G.3. TROPHIC INTERACTIONS

Extract from DFO (2012):

> "In the Gulf of Alaska, individuals of the [REBS] complex have been reported to consume primarily shrimp (*Pandalus borealis*, *P. montagui tridens*, hyppolytids, and crangonids), composing roughly 45-60% by weight of total stomach contents (Yang and Nelson 2000). They also consume fish species, including Walleye Pollock (*Theragra chalcogramma*), Pacific Herring (*Clupea pallasi*), Eulachon (*Thaleichthys pacificus*), Pacific Sandlance (*Ammodytes hexapterus*), myctophids, zoarcids, cottids, snailfish, and flatfish. In the Gulf of Alaska, fish make up roughly 15-20% of total stomach contents (Yang and Nelson 2000). Additional food items include Tanner Crab (*Chionoecetes bairdi*), cephalopods, amphipods, mysids, euphausiids, cumaceans, isopods, and polychaetes. While all size-classes of [the REBS] complex primarily consume shrimp, fish less than 30 cm have a higher proportion of amphipods in their diet whereas fish larger than 30 cm consume more fish. Krieger and Ito (1999) note that individuals of the [REBS] complex will leave the bottom to capture various prey species.
>
> Predators likely include Pacific Halibut (*Hippoglossus stenolepis*), Pacific Cod (*Gadus macrocephalus*), and Sablefish (*Amoplopoma*[sic] *fimbria*) (Shotwell et al. 2009)."

G.4. ENVIRONMENTAL EFFECTS

There are few (if any) studies that directly tie the REBS complex to environmental effects. Soh et al. (2001) modelled the effects of harvest refugia size on projected biomass and fishing mortality for a complex of REBS and Shortraker Rockfish in Alaskan waters. Their findings suggested that thoughtful refugia design could mitigate discarding and serial overfishing without reducing overall catch by fisheries.

Stock assessments for REBS in Alaska and Washington note that little is known about the early life history, recruitment processes, or habitat requirements of this species complex (Shotwell and Hanselman 2019, Spencer et al. 2018, Hicks et al. 2014).

G.5. ADVICE FOR MANAGERS

There is potential for environmental series to be incorporated into stock assessment models. However, a previous attempt to link recruitment estimates for 5ABC Pacific Ocean Perch with a number of environmental indicators (Haigh et al. 2018) proved inconclusive. Similarly, early analyses that used sea level indicators to predict Pacific Cod recruitment have since broken down (Forrest et al. 2018). This type of oceanographic information falls outside the usual data sources in the stock assessment group, but collaboration with other DFO personnel or external colleagues may result in potentially useful hypotheses that could be incorporated into the stock assessment.

The modelling software Stock Synthesis has a rudimentary method for including environmental effects in the stock-recruitment function (Methot et al. 2018). However, the authors provide the following advice: "The preferred approach to including environmental effects on recruitment is not to use the environmental effect in the direct calculation of the expected level of recruitment. Instead, the environmental data would be used as if it was a survey observation of the recruitment deviation."

G.6. REFERENCES – ECOSYSTEM

Creamer, J.M. 2016. Using genetic species identification and environmental data to distinguish historical catches of cryptic Blackspotted Rockfish (*Sebastes melanostictus*) and Rougheye Rockfish (*Sebastes aleutianus*) in British Columbia. Master's thesis, Simon Fraser University, Burnaby, BC, 40 p.

DFO. 2012. Management plan for the Rougheye/Blackspotted Rockfish complex (*Sebastes aleutianus* and *S. melanostictus*) and Longspine Thornyhead (*Sebastolobus altivelis*) in Canada. Species at Risk Act Management Plan Series 412, Fisheries and Oceans Canada, Ottawa ON, vi + 49 p.

Forrest, R.E., Anderson, S.C., Grandin, C.J., and Starr, P.J. 2020. Assessment of Pacific Cod (*Gadus macrocephalus*) for Hecate Strait and Queen Charlotte Sound (Area 5ABCD), and West Coast Vancouver Island (Area 3CD) in 2018. DFO Can. Sci. Advis. Sec. Res. Doc. 2020/070. v + 215 p.

Haigh, R., Starr, P.J., Edwards, A.M., King, J.R. and Lecomte, J.B. 2018. Stock assessment for Pacific Ocean Perch (*Sebastes alutus*) in Queen Charlotte Sound, British Columbia in 2017. DFO Can. Sci. Advis. Sec. Res. Doc. 2018/038: v + 227 p.

Hicks, A.C., Wetzel, C. and Harms, J. 2014. The status of rougheye rockfish (*Sebastes aleutianus*) and blackspotted rockfish (*S. melanostictus*) as a complex along the U.S. West Coast in 2013. Stock Assessment and Fishery Evaluation (SAFE), NMFS, NOAA xvi + 250 p.

Krieger, K.J. and Ito, D.H. 1999. Distribution and abundance of shortraker rockfish, *Sebastes borealis*, and rougheye rockfish, *S. aleutianus*, determined from a manned submersible. Fish. Bull. 97(2): 264-272.

Maechler, M., Rousseeuw, P., Struyf, A., Hubert, M. and Hornik, K. 2018. cluster: Cluster Analysis Basics and Extensions. R package version 2.0.7-1.

Methot, R.D., Wetzel, C. and Taylor, I. 2018. Stock Synthesis: User Manual Version 3.30.10. Tech. rep., NOAA Fisheries, Seattle WA, USA.

Shotwell, S. K. Hanselman, D.H. and Clausen, D.M. 2009. Chapter 13: Assessment of Rougheye and Blackspotted Rockfish in the Gulf of Alaska. In Stock Assessment and Fishery Evaluation (SAFE) Report for the Groundfish Resources of the Gulf of Alaska, p. 993-1066. North Pacific Fishery Management Council (NPFMC).

Shotwell, S.K. and Hanselman, D.H. 2019. Chapter 13: Assessment of rougheye and blackspotted rockfish in the Gulf of Alaska. In Stock Assessment and Fishery Evaluation (SAFE) Report for the Groundfish Resources of the Gulf of Alaska, chap. 12, p. 1-115. North Pacific Fishery Management Council (NPFMC).

Soh, S., Gunderson, D.R. and Ito, D.H. 2001. The potential role of marine reserves in the management of shortraker rockfish (*Sebastes borealis*) and rougheye rockfish (*S. aleutianus*) in the Gulf of Alaska. Fish. Bull. 99(1): 168-179.

Spencer, P.D., Ianelli, J.N. and Palsson, W.A. 2018. Chapter 14. Assessment of Blackspotted and Rougheye Rockfish stock complex in the Bering Sea/Aleutian Islands. In NPFMC Bering Sea and Aleutian Islands SAFE, chap. 14, p. 1-88.

Yang, M.S. and Nelson, M.W. 2000. Food habits of the commercially important groundfishes in the Gulf of Alaska in 1990, 1993, and 1996. U.S. Dept. Comm., NOAA Technical Memorandum NMFS-AFSC-112.