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Redbanded Rockfish (*Sebastes babcocki*) stock assessment for the Pacific coast of Canada in 2014

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Foreword

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

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TABLE OF CONTENTS

ABSTRACT IV
RÉSUMÉ V
1. INTRODUCTION 1
1.1. BIOLOGICAL BACKGROUND 2
1.2. RANGE AND DISTRIBUTION 3
1.3. OVERVIEW OF FISHERY 3
2. CATCH DATA 5
3. FISHERIES MANAGEMENT 6
4. SURVEY DESCRIPTIONS 6
5. BIOLOGICAL INFORMATION 7
5.1. GROWTH 7
5.2. MATURITY AND FECUNDITY 8
5.3. AGE STRUCTURE 8
6. AGE-STRUCTURED MODEL 8
7. OTHER APPROACHES 12
8. REGRESSION FITS FOR REDBANDED ROCKFISH SURVEY DATA 12
9. ADVICE FOR MANAGERS 13
10. GENERAL COMMENTS 14
11. FUTURE RESEARCH AND DATA REQUIREMENTS 14
12. ACKNOWLEDGEMENTS 14
13. REFERENCES 15
APPENDIX A. CATCH HISTORY 27
APPENDIX B. TRAWL SURVEYS 38
APPENDIX C. IPHC SURVEY DATA 100
APPENDIX D. BIOLOGICAL DATA 124
APPENDIX E. RESULTS FROM CATCH-AT-AGE MODEL 144

ABSTRACT

Redbanded Rockfish (*Sebastes babcocki*) is found along the entire outer coast of British Columbia. It is caught by both the trawl and the hook-and-line commercial fisheries. The average annual commercial catch over the last 10 years (2004-2013) is 407 t, and over the last five years (2009-2013) is 342 t. Catches peaked at an estimated 1,360 t in 1992. The stock of Redbanded Rockfish along the Pacific coast of Canada has never been assessed using a population model.

We attempted to assess the status of the coastwide stock using an annual two-sex catch-at-age model, implemented in a Bayesian framework. The model was tuned to the following data: seven fishery-independent trawl survey series (including a novel series constructed from the annual International Pacific Halibut Commission longline survey), one fishery-independent hook-and-line survey series, annual estimates of commercial catch since 1940 from the trawl and hook-and-line fisheries, and age-composition data from the commercial fishery and surveys. The same modelling approach has been successfully used to assess stocks of other species of rockfish in Canadian Pacific waters.

However, for Redbanded Rockfish the data proved insufficient to yield reliable results from the model, despite numerous attempts using different assumptions and exclusion of various components of the data. In the simplest configurations we removed all of the age data, somewhat analogous to a surplus production model, but the Markov Chain Monte Carlo algorithm proved unstable.

We are therefore unable to provide specific quantitative advice to fisheries management, such as decision tables involving evaluation of current and future stock status relevant to reference points. We document all available data, including information on the species' biology, catch, fisheries management and our calculations of indices of abundance for the eight fishery-independent surveys. Catches have remained steady over the past eight years. We also present results of linear regressions on the survey indices. None of the regressions show a significant increasing or decreasing trend.

Évaluation du stock de sébaste à bandes rouges (*Sebastes babcocki*) le long de la côte canadienne du Pacifique en 2014

RÉSUMÉ

Le sébaste à bandes rouges (Sebastes babcocki) se trouve sur toute la longueur de la côte extérieure de la Colombie-Britannique. Ce poisson est visé par la pêche commerciale au chalut ainsi qu'à la ligne et à l'hameçon. Au total, la moyenne des captures commerciales s'élève à 407 tonnes pour les dix dernières années (2004-2013), et à 342 tonnes pour les cinq dernières années (2009-2013). C'est en 1992 que le plus grand volume de prises (estimation de 1 360 tonnes) a été enregistré. Le stock de sébaste à bandes rouges qui se trouve le long de la côte canadienne du Pacifique n'a jamais fait l'objet d'une évaluation au moyen d'un modèle de population.

Nous avons tenté d'évaluer l'état du stock de l'ensemble de la côte au moyen d'un modèle des deux sexes fondé sur les prises selon l'âge et utilisé dans un cadre d'évaluation bayésienne. Les données suivantes ont servi à ajuster le modèle : sept séries de relevés au chalut indépendants de la pêche (y compris une nouvelle série établie à l'aide du relevé annuel à la palangre réalisé par la Commission internationale du flétan du Pacifique), une série de relevés à la ligne et à l'hameçon indépendants de la pêche, les estimations annuelles des captures commerciales depuis 1940 dans le cadre des pêches au chalut ainsi qu'à la ligne et au hameçon, et les données sur la répartition selon l'âge obtenues des pêcheurs commerciaux et des relevés. Cette approche de modélisation avait déjà été utilisée avec succès pour évaluer les stocks d'autres espèces de sébastes dans les eaux canadiennes du Pacifique.

Toutefois, nous manquions de données sur le sébaste à bandes rouges pour que le modèle donne des résultats fiables, malgré de nombreuses tentatives selon différentes hypothèses et à partir de l'exclusion de certaines composantes des données. La configuration la plus simple excluait les données sur l'âge, un peu comme le modèle de production excédentaire, mais l'algorithme de Monte-Carlo par chaînes de Markov s'est avéré instable.

Nous sommes donc dans l'incapacité de fournir un avis quantitatif précis quant à la gestion des pêches, par exemple au moyen de tables de décision présentant une évaluation de l'état actuel et futur du stock par rapport à des points de références. Nous consignons toutes les données disponibles, notamment l'information sur la biologie de l'espèce, les prises et la gestion des pêches, ainsi que les résultats de nos calculs des indices d'abondance obtenus à l'aide des huit relevés indépendants des pêches. Les captures sont demeurées stables au cours des huit dernières années. Nous présentons également les résultats des régressions linéaires produites en fonctions des indices des relevés. Les régressions ne démontrent aucune tendance marquée à la hausse ou à la baisse.

1. INTRODUCTION

Redbanded Rockfish (*Sebastes babcocki*, abbreviated as 'RBR' in this document) derives its name from John Pease Babcock (1855-1936), a former administrator in California and British Columbia (Hart, 1973). Potential confusion with Flag Rockfish (*S. rubrivinctus*) exists historically; however, this latter species probably does not occur north of Heceta Bank, Oregon (Love et al., 2002). Redbanded Rockfish sports a distinctive colouration with a white or pale pink body and four vertical red/orange bands (Figure 1).

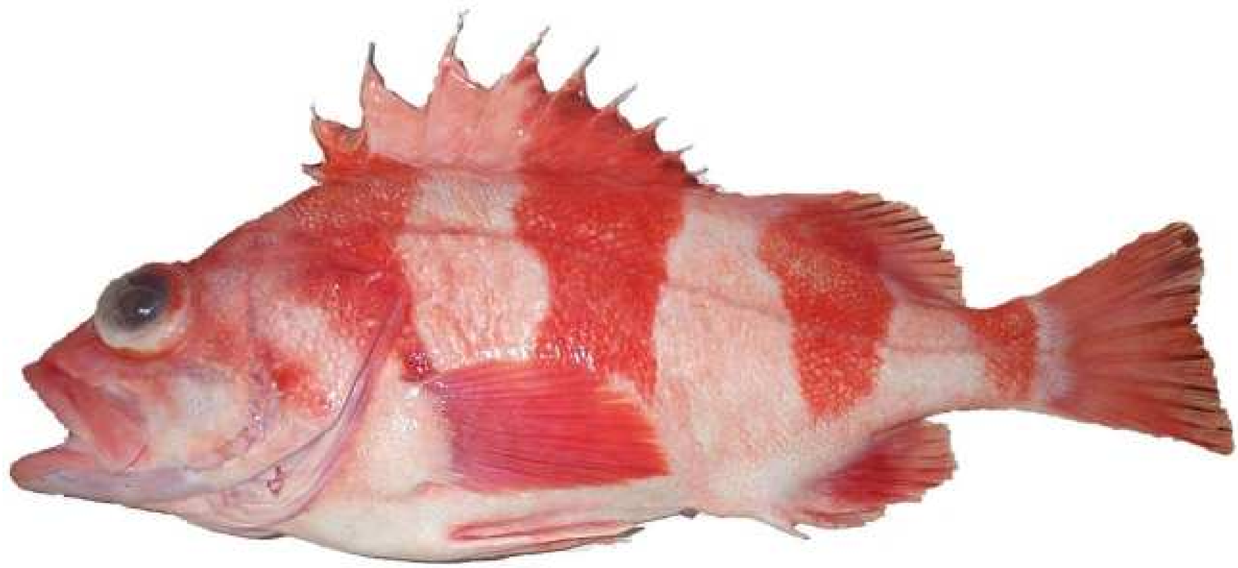

Figure 1. Redbanded Rockfish Sebastes babcocki*. Source: Fisheries and Oceans Canada.*

Fisheries managers have requested advice as to whether current harvests of RBR are sustainable, considering a coastwide stock in British Columbia (BC) waters. Previously, Haigh and Starr (2006) reviewed this species with respect to biology, distribution, and abundance trends; however, there were insufficient data at the time to determine whether catches of RBR were sustainable. Here we make the first attempt to use a modelling approach to estimate historical and present biomass of the stock. Specifically, we used a Bayesian catch-age model for a single stock that covers all regions on the outer BC coast – Pacific Marine Fisheries Commission (PMFC) major areas 3CD and 5ABCDE combined (Figure 2).

However, the model did not perform reliably, and we are unable to use it provide advice to managers. We document our investigations here, including assimilation of all available data. We also present results of a simple regression approach to look for trends in survey indices.

The following sections present background information on RBR, an overview of the fisheries, catch data, survey descriptions and summary results of the modelling. Further technical details are given in the relevant Appendices.

1.1 BIOLOGICAL BACKGROUND

Life history information on RBR remains limited. This species presumably shares many characteristics with all species in the genus *Sebastes*. Love et al. (2002) assume most, if not all, *Sebastes* are viviparous, though the extent of energy transfer directly from the mother varies

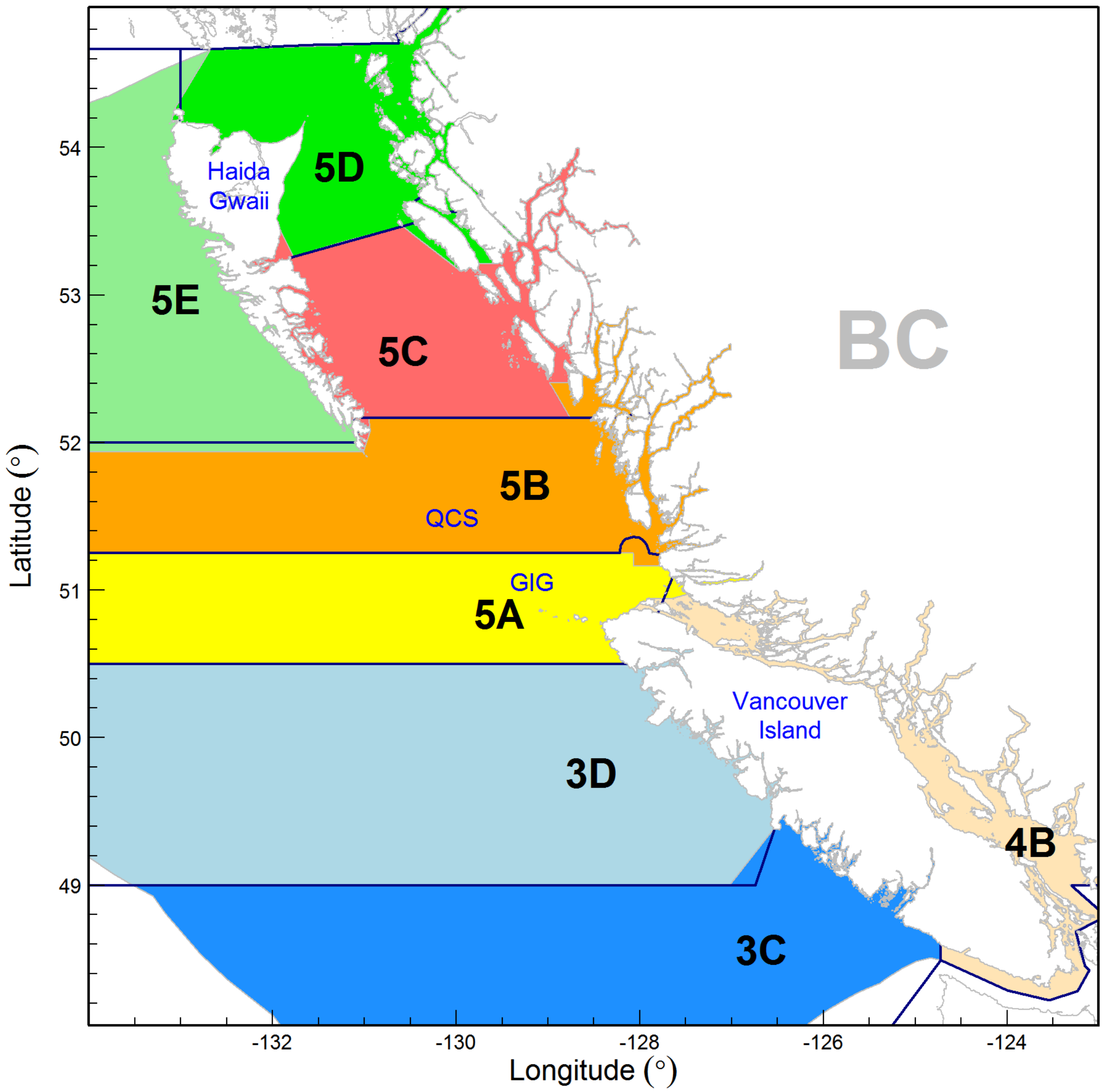

Figure 2. Pacific Marine Fisheries Commission (PMFC) major areas (outlined in dark blue) compared with Groundfish Management Unit areas for RBR (shaded). For reference, the map indicates Queen Charlotte Sound (QCS) and Goose Island Gully (GIG). This assessment is for PMFC areas 3CD and 5ABCDE combined (termed 'coastwide').

among species. *Sebastes* females release developed larvae (parturition) during the night to reduce mortality from predation and during the season of highest primary productivity (Apr-May in BC). As RBR can be classified as a deep shelf/slope species, the larvae and juveniles probably live in the epipelagic and upper mesopelagic zones before settling. Love (2011) notes that pelagic juveniles are observed under drifting kelp mats while older juveniles can be found on rocky reefs.

1.2 RANGE AND DISTRIBUTION

Redbanded Rockfish ranges from the Bering Sea and the Aleutian Islands (Alaska) to San Diego in southern California (Love et al., 2002; Love, 2011). Reported depth of habitation ranges from 31-1145 m, but they mostly occur at 150-450 m (Love, 2011). In BC, 95% of fishing events capture RBR between 134 and 425 m with a median depth of 230 m (DFO databases). These rockfish prefer hard bottoms where they shelter in crevices between boulders, but also occur over mixed substrata of mud, cobblestones, and pebbles. They can either form small groups or occur singly. The oldest recorded individual was captured in southern Alaska in 1986; the Alaska Department of Fish and Game determined its age at 106 years (Munk, 2001). The oldest RBR recorded in the Department of Fisheries and Oceans Canada (DFO) database GFBIO is 102 y for a male specimen caught in 1999 by a tow from the Queen Charlotte Sound Shrimp survey in PMFC 5B at a depth of 140 m.

The distribution of RBR spans the BC coast (Figures 3 and 4). Hotspots ($\geq$ the 0.95 quantile of catch per unit effort (CPUE) from trawl tows from 1996-2014) occur primarily at the heads of the three main canyons in Queen Charlotte Sound (QCS): Moresby Gully, Mitchell's Gully, and Goose Island Gully (Figure 3). Elsewhere, densities appear to be low for areas frequented by the trawl fleet. The density distribution seen by the hook and line fleets (primarily Halibut longline) appears very different – stretching along the outer shelf between the 200 and 1000 m isobaths (Figure 4). Although CPUE values are calculated in the same manner as for trawl (kg h^{-1}), the rates are not comparable to those of trawl. However, we use CPUE here only as a proxy for density and to visualise distributions spatially. The two CPUE figures together show that RBR is ubiquitous along the BC coast, and so we consider it to be one stock.

1.3 OVERVIEW OF FISHERY

Redbanded Rockfish became a quota species in 2011 when a coastwide TAC (total allowable catch) was set at 590 t to be split equally between the trawl and the hook and line (H&L) sectors (Table A.1). The H&L portion was further divided between the ZN H&L fishery (37.5% of the coastwide TAC) and the halibut fishery (12.5% of the coastwide TAC). In 2013, the Groundfish Hook and Line Sub Committee (GHLSC) agreed to set aside 5% of the ZN portion for research purposes.

Prior to implementation of a TAC, RBR was classified as a non-quota species. In 2000, formal discussions among the H&L rockfish (ZN), halibut, and trawl sectors were initiated to establish individual rockfish species allocations between the sectors to replace the previous 92/8 split between the trawl fishery and the H&L fishery. Allocation arrangements were agreed to for rockfish species that were not currently under TAC. The negotiated splits for non-quota rockfish (50/50 for RBR) are implemented when or if TACs are set for these species.

2. CATCH DATA

The preparation methods and the full catch reconstruction for this assessment are given in Appendix A. Catches were reconstructed back to 1940. Landings of Redbanded Rockfish prior to 1996 are poorly recorded and must be estimated, in this case from ratios of RBR to rockfish other than Pacific Ocean Perch (*Sebastes alutus*; POP) using reference years (1997-2005). The reconstructed landings include estimates from historical catches of rockfish (usually POP) by foreign fleets and reported minor catches from numerous research surveys. All available discards (reported and calculated) were added to the landed catches, with estimates of historical discards

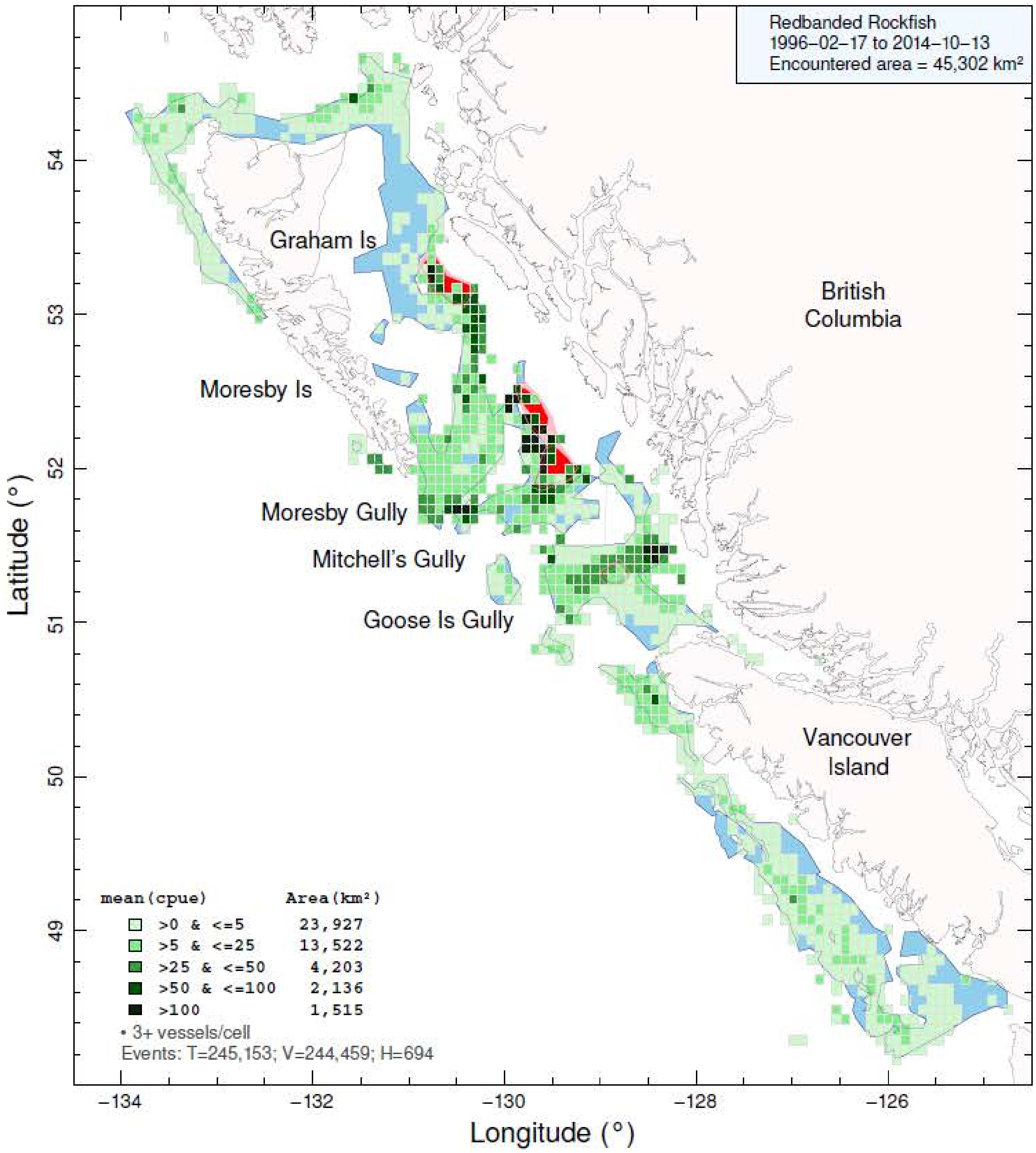

Figure 3. Mean catch per unit effort (CPUE, kg h^{-1}) of RBR in grid cells 0.09° longitude by 0.065° latitude (roughly 45 km^2 each). Shaded cells give an approximation of the area where RBR was encountered by fishing events from the groundfish trawl fishery from February 1996 to October 2014. Only cells that represent at least three fishing vessels are displayed; number of fishing events: T = total available, V = represented on map after vessel display restriction, H = hidden. Named gullies are to the northeast of their labels. The three areas comprising the Glass Sponge Reefs Area of Interest (a proposed Marine Protected Area) are shown in red (core protection zones) and pink (adaptive management zones); trawl fishing has been closed in these areas since 2006 (and in smaller areas since 2002). Blue areas show the trawl footprint to which the groundfish trawl fishery has been voluntarily constrained since 2012, a development made jointly between DFO, industry and environmental non-governmental organisations.

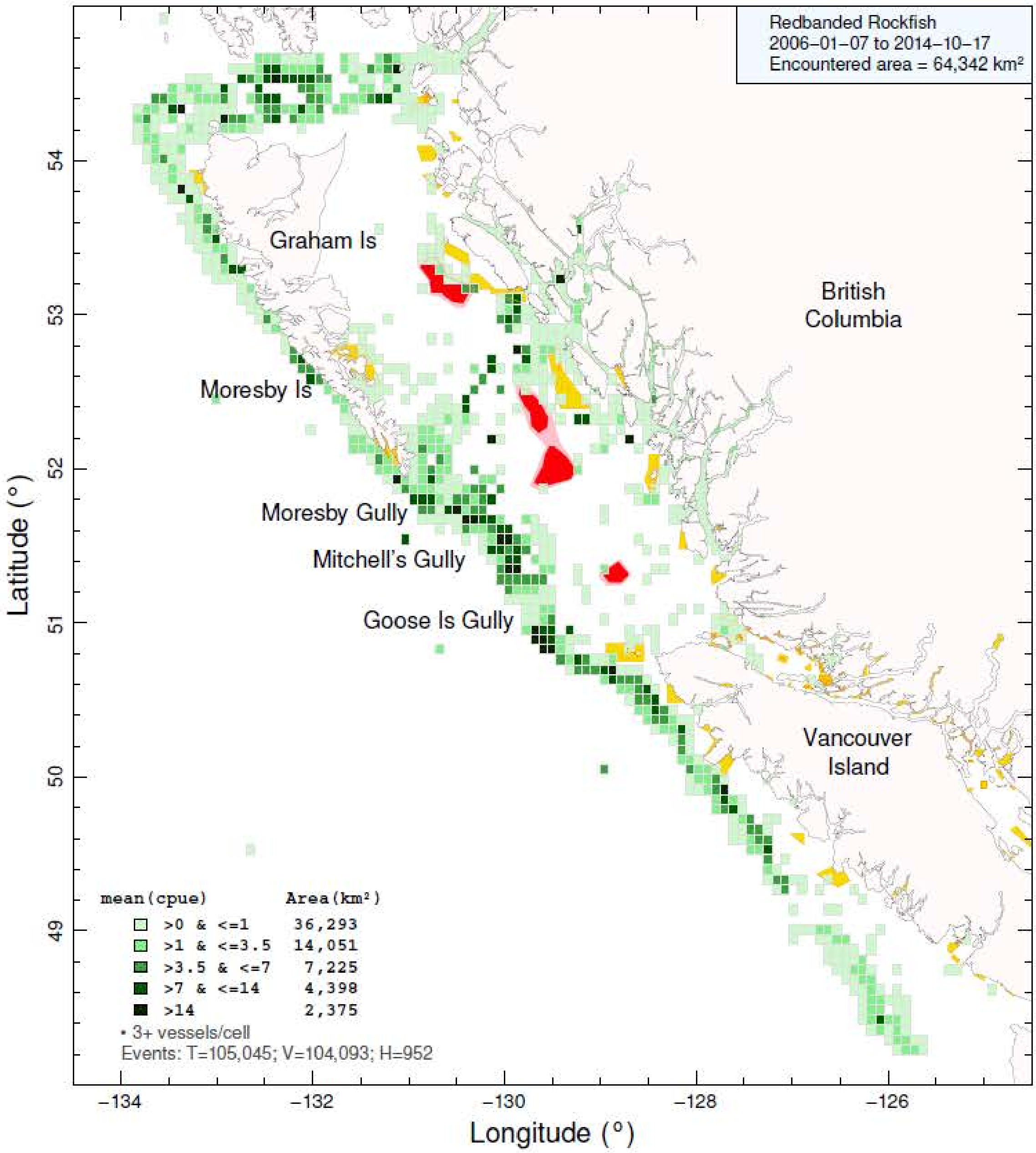

Figure 4. Mean catch per unit effort (CPUE, kg h^{-1}) of RBR encountered by fishing events from the hook and line fisheries from January 2006 to October 2014. Gold areas are Rockfish Conservation Areas. See Figure 3 for further details.

based on current observed levels. The resulting time series of catch data that is used as input for the catch-age model is shown in Figure A.1, and reaches a peak of 1,360 t in 1992 (during a period of intense fishing by the Canadian fleet). The recent (2009-2013) average commercial catch is 342 t (347 t when research survey catches are added), and the 10-yr average (2004-2013) is 407 t (412 t with survey catch). Catch data were only available for part of 2014, and so, for input to the model, the 2013 catch total was assumed to be the same as for 2014.

Table 1. Summary of the survey series analysed here. Mean CV (coefficient of variation) gives the mean of the CV's of the annual indices for that survey. Surveys are described in Appendices B and C. Abbreviations are: QCS – Queen Charlotte Sound, WCVI – West Coast Vancouver Island, WCHG – West Coast Haida Gwaii, HS – Hecate Strait, US – United States, IPHC – International Pacific Halibut Commission.

Series	Start year	End year	No. years	Mean CV
QCS Synoptic	2003	2013	7	0.18
WCVI Synoptic	2004	2014	6	0.27
QCS Shrimp	1999	2013	15	0.36
WCHG Synoptic	1997	2012	6	0.22
HS Synoptic	2005	2013	5	0.24
US Triennial	1980	2001	7	0.46
QCS Historic	1967	1994	8	0.23
IPHC Longline	1995	2012	18	0.20

There is uncertainty in the final catch time series, but it is hard to quantify. The major source of uncertainty is that the ratios of Redbanded Rockfish to rockfish other than POP derived from the modern fishery may not reflect the catch ratios during historical fishing by foreign fleets. However, applying these modern catch ratios remains the only practical method by which we can estimate the historical catches by species. Other historical issues include unreported discarding, shifting regulations and changing data storage technologies, although many of these problems have been resolved over recent years (Appendix A).

3. FISHERIES MANAGEMENT

Appendix A summarises all management actions taken for RBR (coastwide) since 1995 (Table A.2). In particular, there has been a 100% onboard observer program for the offshore trawl fleet since 1996, an Individual Vessel Quota for TAC trawl species in place since 1997, and a recent coastwide TAC implementation for RBR in 2011 that splits the 590 t TAC evenly between the trawl and non-trawl fleets (Table A.1).

4. SURVEY DESCRIPTIONS

Eight sets of fishery-independent survey indices were calculated in order to track changes in the biomass of the stock, primarily as input for the catch-age model. Summaries of the data for each survey series are given in Table 1 (with full details of the series in Appendix B for the trawl surveys and Appendix C for the hook-and-line series). Survey descriptions are as follows:

1. A synoptic survey located in Queen Charlotte Sound north of Vancouver Island and extending into the lower part of Hecate Strait, covering seven years from 2003-2013, referred to here as the 'QCS Synoptic survey series'.
2. A synoptic survey off the west coast of Vancouver Island, covering the six even years from 2004-2014, referred to here as the 'WCVI Synoptic survey series'.
3. A shrimp trawl survey located at the head of Goose Island Gully in Queen Charlotte Sound, covering every year from 1999-2013, referred to here as the 'QCS Shrimp survey series'.
4. A synoptic survey off the west coast of Graham Island (the northernmost of the two main Haida Gwaii islands) and the western end of Dixon Entrance, covering five years from

2006-2012. A sixth index in 1997 has been added to the series because of its similarity in design. This is referred to here as the ‘Haida Gwaii Synoptic survey series’.

5. A synoptic survey located in Hecate Strait and the eastern end of Dixon Entrance, covering five years from 2005-2013, referred to here as the ‘HS Synoptic survey series’.
6. The United States National Marine Fisheries Service (NMFS) Triennial survey series covering the lower half of the west coast of Vancouver Island, for seven years from 1980-2001, referred to here as the ‘US Triennnial survey series’.
7. A historical set of surveys operated in the Goose Island Gully of Queen Charlotte Sound, covering eight years from 1967-1994, referred to here as the ‘QCS Historic survey series’.
8. The annual International Pacific Halibut Commission (IPHC) stock assessment longline survey, for which catches of non-halibut species are enumerated in BC waters, every year from 1995-2012, referred to as the ‘IPHC Longline survey series’. For this survey we developed novel methods to account for the survey design changing over time (Appendix C).

The relative survey indices were used as data in the catch-age model, including the associated relative error (coefficient of variation, CV) for each index value.

5. BIOLOGICAL INFORMATION

5.1 GROWTH

A length-weight model was fit to the data for each sex, and the parameter estimates of the fitted models are very similar (Appendix D). The growth model used was a von Bertalanffy function, which determined that females grow larger than males (average length at maximum age of L_∞ of 56 cm vs 49 cm) and more slowly (von Bertalanffy growth rate coefficient k_s of 0.07 vs. 0.10).

5.2 MATURITY AND FECUNDITY

Stage of maturity was determined macroscopically, partitioning the samples into one of seven maturity stages (Stanley and Kronlund, 2000); see Figure D.5. This assessment used BC research samples (`ttype=2:3`) from February to July ($n = 1048$ qualified data points) to determine maturity. Using stage 3 and up to denote mature fish, we construct a maturity ogive (Figure D.6) using a double-normal model. The proportion of mature individuals is calculated (Table D.6, Figure D.6) and the age of 50% maturity is estimated at 17.8 y for females (16.1 y for males, not shown); Love (2011) reported 19 y for males and females. The catch-age model adopts the double-normal fitted values for ages 9 and up, but uses the empirical (raw) proportions-mature for ages 1 through 8 (except age 5 which is assigned $m_5 = 0$). This strategy follows previous assessments on BC rockfish where younger ages are not well sampled.

5.3 AGE STRUCTURE

Commercial catches of rockfish by trawl gear have been sampled for age proportions since the 1960s. However, only otoliths aged using the ‘break and burn’ method have been included in the age samples for this assessment because the earlier surface-ageing method is known to be biased (Beamish, 1979), especially with increasing age. Redbanded Rockfish is known to be a difficult species to age (Stephen Wischniowski, Pacific Biological Station, DFO, Nanaimo, BC, pers. comm.). There is a lot of structure in the otoliths which makes it difficult to interpret the annual age bands, and there is variable spacing between the bands. Future ageing will likely be done using thin sectioning rather than the break and burn method.

Commercial fishery age samples were summarised for each quarter, with samples combined within a trip and weighted by the RBR catch weight for the sampled trip. The quarterly samples were then scaled by the quarterly landed commercial catch weights of RBR to give annual proportions-at-age data (details in Appendix D).

The commercial age data for RBR are sparse, with only four years available for bottom trawl (2003-05, 2009, Figure D.7) and four years for longline sets (1995, 2004-05, 2009). The dearth of commercial hook and line age data and the fishery-like experimental PHMA surveys conducted in 1997 and 1998 in the north (Tasu and Anthony Island) and south (Triangle and Brooks) prompted the use of these age data in the commercial hook and line series. A large plus class (60+ y) was evident in most years except 2003 (Figure D.7). The ages from the 1997-98 PHMA survey were fairly well sampled (300-400 otoliths per sex per year) while all other samples were insufficient ($\sim$100 otoliths per sex per year) to properly represent population structure. It is not clear whether more otoliths aged would help elucidate cohort patterns for this species.

6. AGE-STRUCTURED MODEL

To use all available data and attempt to estimate reference points, we used a sex-specific, age-structured model in a Bayesian framework, as used for recent stock assessments of Pacific Ocean Perch (Edwards et al., 2012*b*, 2014*a*,*b*), Yellowmouth Rockfish (Edwards et al., 2012*a*) and Silvergray Rockfish (Starr et al., 2016) in Canadian Pacific waters. Appendix E gives details of the model, documentation of model runs, and example results. The model demonstrated sensitivity to minor assumptions and reweighting of the data, and, despite numerous attempts, we were unable to obtain reliable results.

One of the reasons seems to be the relatively small quantity of age data, both the number of years available and the number of samples available in each year. Furthermore, the age data appear to be very contradictory with no consistent cohort pattern. The observed sensitivity to reweighting of these age data is probably caused by variations in the relative importance of the component datasets. Such sensitivity did not occur in the aforementioned rockfish assessments that used the same catch-age modelling approach (Edwards et al., 2012*a*,*b*, 2014*a*,*b*).

Given the instability of the model fits, we do not consider any of the investigated catch-age models that included the age-composition data to be suitable for the provision of management advice.

We also ran the model with the age data excluded to see how well it performed when fitting to the survey indices alone (further details in Appendix E, Run 41-1). Such a model run should behave similarly to a surplus production model, with the main difference being the formulation of the productivity assumptions. Unlike a surplus production model where productivity is embodied in a single estimable parameter, this model formulation fixed natural mortality, steepness of the stock-recruitment function and all the selectivity parameters using the means of the informed priors for these parameters. The only exception was the mean of the selectivity prior for the hook-and-line fishery and the IPHC survey, which was fixed at age 18, a value favoured by the available age-composition data for some model runs that estimated it.

This model run is provided as an example of how such a model would behave and should not be

Table 2. Comparison of MCMC summary values for derived quantities of management interest obtained from two different chains (A and B) each of 25,000,000 iterations. Definitions are: B_0 – unfished equilibrium spawning biomass (mature females), V_0 – unfished equilibrium vulnerable biomass (males and females), B_{2015} – spawning biomass at the start of 2015, V_{2015} – vulnerable biomass in the middle of 2015, U_{2014} – exploitation rate (ratio of total catch to vulnerable biomass) in the middle of 2014, B_{MSY} – equilibrium spawning biomass at MSY (maximum sustainable yield), U_{MSY} – equilibrium exploitation rate at MSY. Values are the 5%, 50% and 95% quantiles from the empirical posterior distribution, and where applicable are given separately for the hook-and-line fishery and the trawl fishery.

	Chain A			Chain B		
	5%	50%	95%	5%	50%	95%
B_0	7,750	8,773	15,149	7,787	8,866	16,685
B_{2015}/B_0	0.146	0.258	0.586	0.151	0.266	0.625
V_{2015}/V_0 – hook and line	0.162	0.281	0.609	0.167	0.290	0.646
V_{2015}/V_0 – trawl	0.245	0.365	0.665	0.250	0.374	0.698
B_{MSY}/B_0	0.280	0.283	0.285	0.280	0.283	0.285
U_{2014} – hook and line	0.009	0.035	0.068	0.008	0.034	0.066
U_{2014} – trawl	0.009	0.027	0.046	0.008	0.026	0.044
$U_{2014}/U_{\mathrm{MSY}}$ – hook and line	0.177	0.638	1.222	0.151	0.612	1.180
$U_{2014}/U_{\mathrm{MSY}}$ – trawl	0.165	0.497	0.813	0.142	0.481	0.793

interpreted as a definitive assessment of the stock. The survey series are short, often with coefficients of variation $>$0.4 for individual years, and consequently cannot inform this model (or an equivalent surplus production model) very well. Also there are only two series available before the mid-1990s, which is the period when fishing was thought to be at its most intense and would have caused the greatest observable decline.

We ran a full MCMC simulation for Run 41-1, whereby we assumed deterministic recruitment with no annual deviations from the stock-recruitment function. A second version allowed the model to estimate annual recruitment deviations, but behaved very poorly when using the MCMC procedure and was consequently dropped.

Since Run 41-1 showed some MCMC instability, two very long chains (Chain A and Chain B) of 25,000,000 iterations were run using different random number seeds and different scaling step sizes to approximate the posterior distribution. Each of these were thinned to 1,000 draws by selecting every 25,000th iteration in the hope that this level of preparation would achieve convergence. Unfortunately, this process did not work, as can be seen in the diagnostic plots provided for each chain in Appendix E, with each chain exploring somewhat different regions of the parameter space.

This model run is further characterised by enormous uncertainty, particularly at the upper end of possible biomass levels (Figure 5). However, when only the medians of the biomass posterior are plotted, the effect of the relatively large catches in the late 1980s and early 1990s can be seen (Figure 6), although such a trajectory is conditioned on the assumption of constant recruitment.

Table 2 shows that the two chains differed mainly in the upper bounds (95% quantiles), with similar median and lower bound estimates. This outcome is not surprising, because there is little in the available data used in the model to constrain the upper levels of biomass, allowing the model to achieve satisfactory fits to the data at high biomass levels and thus admitting some probability to the existence of large levels of biomass. The only way to constrain this behaviour in

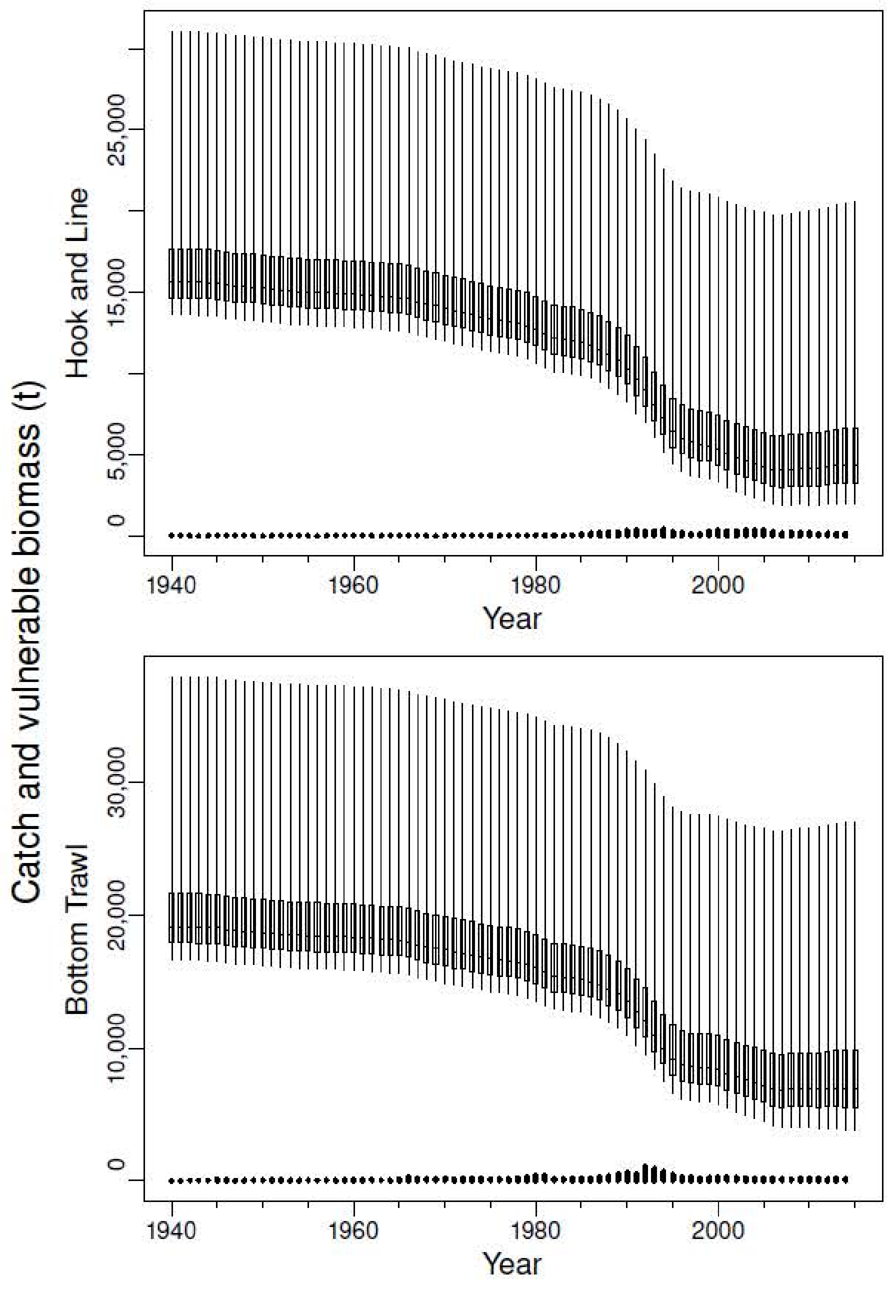

Figure 5. For Chain A of the model run with no age-composition data and deterministic recruitment (Run 41-1), estimated vulnerable biomass (boxplots) and commercial catch (vertical bars), in tonnes, over time for hook-and-line (top) and bottom trawl (bottom) fisheries. Boxplots show the 2.5, 25, 50, 75 and 97.5 percentiles of the marginal posterior distributions from the MCMC results. Catch is shown to compare its magnitude to the estimated vulnerable biomass, though it does not show up too clearly because of the large maximum values of estimated vulnerable biomass.

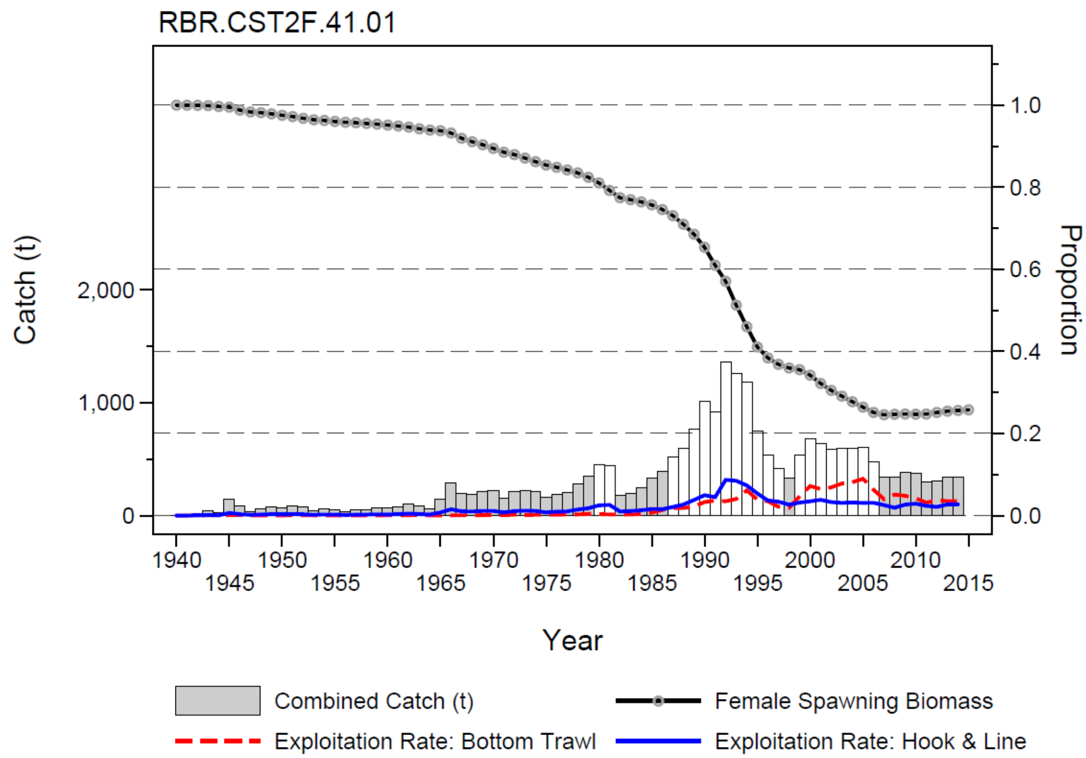

Figure 6. For Chain A, comparison of the median spawning biomass expressed as a proportion of the unfished equilibrium biomass (B_0), with median estimates of exploitation rate by fishery and the combined removals by year. Catches are scaled on the left-hand axis while median biomass and exploitation rates are scaled on the right-hand axis.

this type of model is to use informative priors which restrict the capacity of the model to explore these regions. However the construction of such priors is beyond the scope of the present study.

This model has been presented for illustrative purposes and would require considerable more work before being suitable for providing advice to management. We caution against over-interpreting these results, given the instability of the MCMC procedure and the lack of sensitivity exploration. Given the large uncertainty in the biomass trends and the need to generate strong informative priors to constrain the model, we suggest that it would be prudent to allow more survey biomass indices to accumulate before attempting to implement a surplus-production model or another similar low-information approach.

7. OTHER APPROACHES

For recent assessments of Big Skate (*Raja binoculata*) and Longnose Skate (*R. rhina*), King et al. (2015) explored several methods for quantitatively assessing the status of the stocks. A Bayesian surplus production model and a Depletion-Corrected Average Catch Analysis both produced unreliable results, and results of a Catch-MSY (maximum sustainable yield) approach were extremely sensitive to assumptions (and were not recommended as the sole basis of advice). Given the experience of King et al. (2015), and given the results above concerning the catch-age

Table 3. Summary of unweighted linear regression results of the estimate of the annual trend of each survey series. 'Trend' is the estimated annual trend (slope), with 95% confidence intervals given by 'Low' and 'High'. p is the p-value for the probability that the trend is significantly different to 0. If $p \geq 0.05$ then the trend can be considered not significantly different to 0. If $p < 0.05$ then a negative trend indicates a statistically significant decline in the index over its time period, and a positive trend indicates a statistically significant increase. Note that absolute values of trends cannot be compared between survey series as the series consist of relative indices. Full results for each series are shown after the References section.

Series	Low	Trend	High	p
QCS Synoptic	-55.46	6.17	67.80	0.81
WCVI Synoptic	-17.85	9.98	37.81	0.38
QCS Shrimp	-6.72	-0.25	6.22	0.94
WCHG Synoptic	-10.28	-4.85	0.58	0.07
HS Synoptic	-130.91	-12.70	105.51	0.75
US Triennial	-11.58	-2.10	7.38	0.59
QCS Historic	-73.16	-13.29	46.57	0.61
IPHC Longline	-0.09	-0.05	0.00	0.06

model with no age data, we did not investigate these approaches.

We undertook a trend analysis using the `trend` function in the R package `PBStools` package. The `trend` function uses the methods of Schnute et al. (2004) to produce bootstrapped estimates of trends in survey indices on a logarithmic scale. We tried this approach for the IPHC survey data (using the catch rates for each individual set each year). However, the use of a logarithmic scale required either eliminating catch rates of zero or adding a small number to the zero catch rates (so that they could be logged). The elimination option is not appropriate because the zeros represent true information, and the number of them varies from year to year. Adding small numbers to zeros is not really desirable; however, we tested it using values of 0.0001, 0.001, 0.01 and 0.1. Results were sensitive to these arbitrary values. Thus we did not consider this approach reliable for these data, and note that it does not currently permit the use of stratified data.

8. REGRESSION FITS FOR REDBANDED ROCKFISH SURVEY DATA

Given the above modelling issues, we investigated possible trends in the eight survey series. We fitted unweighted linear regressions to each survey series (each survey series independently) outlined in Table 1. Results are shown in Table 3; full results for each survey series are given in Figures 7-14 and Tables 4-11 at the end of this main text (after the References).

All of the fitted trends for all the surveys have $p > 0.05$ (Table 3). The smallest p-value is 0.06 for the IPHC survey. The 95% confidence intervals for the slopes all overlap 0 (Table 3), except for the IPHC longline survey where the upper bound equals 0. Thus, none of the fitted trends appear to be significantly different to 0 (at the 0.05 level). By definition, this analysis ignores any structure in the series; for example, the IPHC survey (Figure 14) shows an increase in the late 1990s followed by a drop to a lower level.

A weighted approach was also investigated, and gave the same conclusions of no significant trend for any survey index (results not shown). The weighted approach allows weights to be put on each survey value, by using the `weights` option of the `lm()` command in R (R Core Team, 2014). The `weights` are used to indicate that different observations have different variances, and their values are inversely proportional to the variances of each observed survey value.

9. ADVICE FOR MANAGERS

Given the modelling issues outlined above, we are unable to provide quantitative estimates of stock biomass, or calculate reference points and associated reference points, for Redbanded Rockfish along the Pacific coast of Canada.

The catch-age models that included the age-composition data were unreliable and are not suitable for providing advice to managers. We also investigated catch-age models which excluded the age-composition data, fitting only to the survey indices. Such models are similar to a surplus production model and may, with additional data and further investigation, be suitable for providing advice. However, the example results provided here are not reliable.

Linear regression fits to the eight survey series show no significant increase or decrease in relative abundance over the course of each survey. Catches have remained steady for the past eight years (Figures 6 and A.1).

10. GENERAL COMMENTS

Although the catch-age model could not be used to provide advice, we have still documented the currently available information concerning Redbanded Rockfish in BC waters. This includes data about biology, catch, fisheries management and survey series. In particular, the calculation of an index spanning 1995-2012 from the IPHC longline survey is a novel aspect of this work, that has resulted in methods and code that may prove useful for future assessments of other non-halibut species, such as Yelloweye Rockfish (*Sebastes ruberrimus*).

11. FUTURE RESEARCH AND DATA REQUIREMENTS

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

1. Continue the suite of fishery-independent trawl surveys that have been established along the BC coast. This includes obtaining age- and length-composition samples from tows with signficant catches of RBR, which will allow the estimation of survey-specific selectivity ogives. Further surveys would likely be needed to provide abundance indices that would improve the performance of the catch-age model.

2. Research how best to incorporate the uncertainty of ageing error into Canadian rockfish assessment models – the Sclerochronology Laboratory at the Pacific Biological Station currently records uncertainty for each aged otolith. Research into the quantification of such uncertainty could allow ageing error to be better incorporated into models as used in this assessment.

12. ACKNOWLEDGEMENTS

We thank the members of the RBR Technical Working Group (Lynne Yamanaka, Kendra Holt, Robert Tadey and Barry Ackerman, all DFO) for their valuable advice as this project progressed. We thank Jason Cope (NOAA) for his written review of this document, and acknowledge the other participants in the Regional Peer Review meeting for their contributions. We thank Eric Soderlund, Aaron Ranta and Claude Dykstra (IPHC) for timely help with understanding the IPHC data. Allan Hicks (NOAA) has kindly supported the Awatea version of the Coleraine stock assessment model used in this assessment, and we are thankful to Arni Magnusson and Ian

Stewart (NOAA) for producing their `plotMCMC` and `scape` R packages, which we have extensively incorporated into our `PBSawatea` package. We also thank the members of the Groundfish Section for ongoing data acquisition and data management, and thank Stephen Wischniowski, Darlene Gillespie and the members of the Sclerochronology Laboratory at the Pacific Biological Station for their processing of Redbanded Rockfish otoliths.

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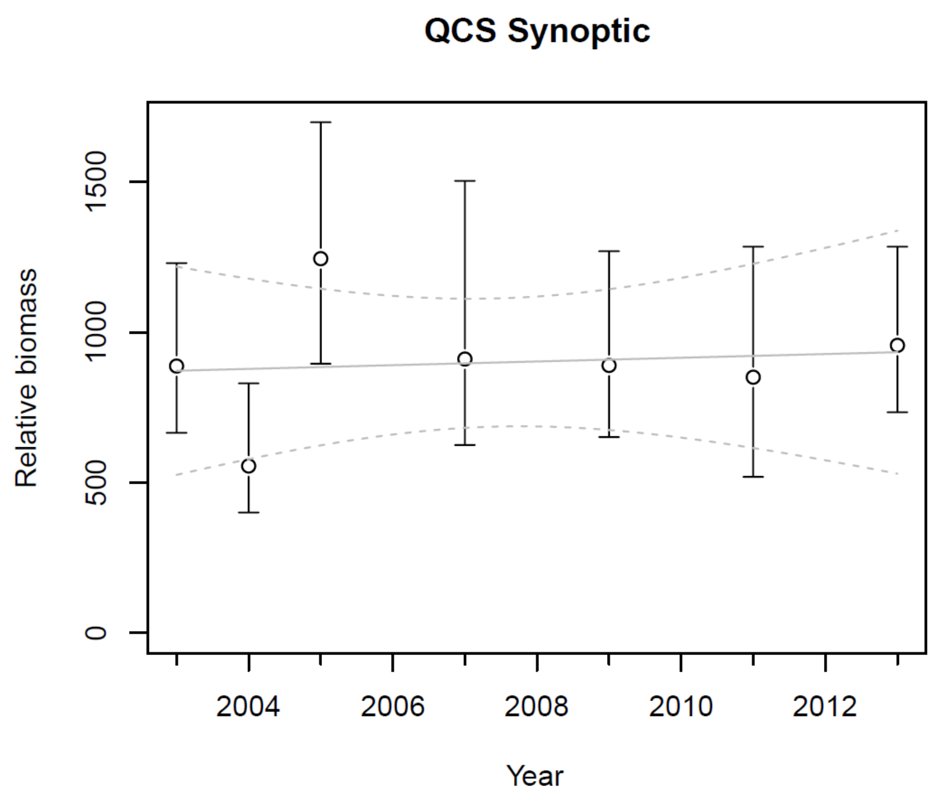


Figure 7. Relative biomass index for the QCS Synoptic series, shown as mean values (circles) and bootstrapped 95% confidence intervals (bars). Unweighted linear regression fit shown as solid lines (with 95% confidence intervals as dashed lines), but in light grey to indicate that the trend is not statistically significantly different from 0 ($p \geq 0.05$).

Table 4. Summary of unweighted linear regression fit for the QCS Synoptic series. The estimated value of the trend is 6.17 with the 95% confidence interval given below in parentheses, and below that the p value (with $p \geq 0.05$ indicating the trend can be considered not significantly different from 0). 'Intercept' indicates the intercept term of the regression (to three significant figures), and is given for completeness, though not really of biological interest. Further statistical results are also given.

	Value
Trend	6.17
	(−55.46, 67.80)
	p = 0.81
Intercept	−11,500
	(−105,800, 82,800)
	p = 0.83
Observations	7
R^2	0.01
Adjusted R^2	−0.18
Residual Std. Error	219.36 (df = 5)
F Statistic	0.07 (df = 1; 5)

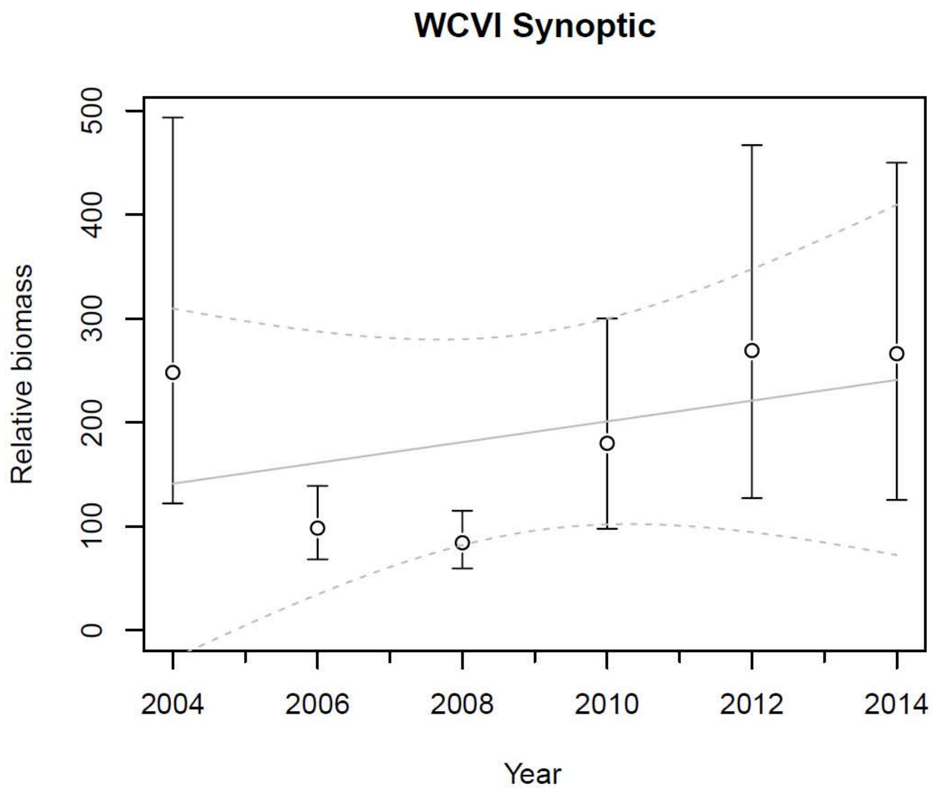


Figure 8. Relative biomass index for the WCVI Synoptic series, with results of unweighted linear regression. Details as in Figure 7.

Table 5. Summary of unweighted linear regression fit for the WCVI Synoptic series. Details as in Table 4.

	Value
Trend	9.98
	(−17.85, 37.81)
	p = 0.38
Intercept	−19,900
	(−59,300, 19,600)
	p = 0.38
Observations	6
R^2	0.20
Adjusted R^2	−0.002
Residual Std. Error	83.87 (df = 4)
F Statistic	0.99 (df = 1; 4)

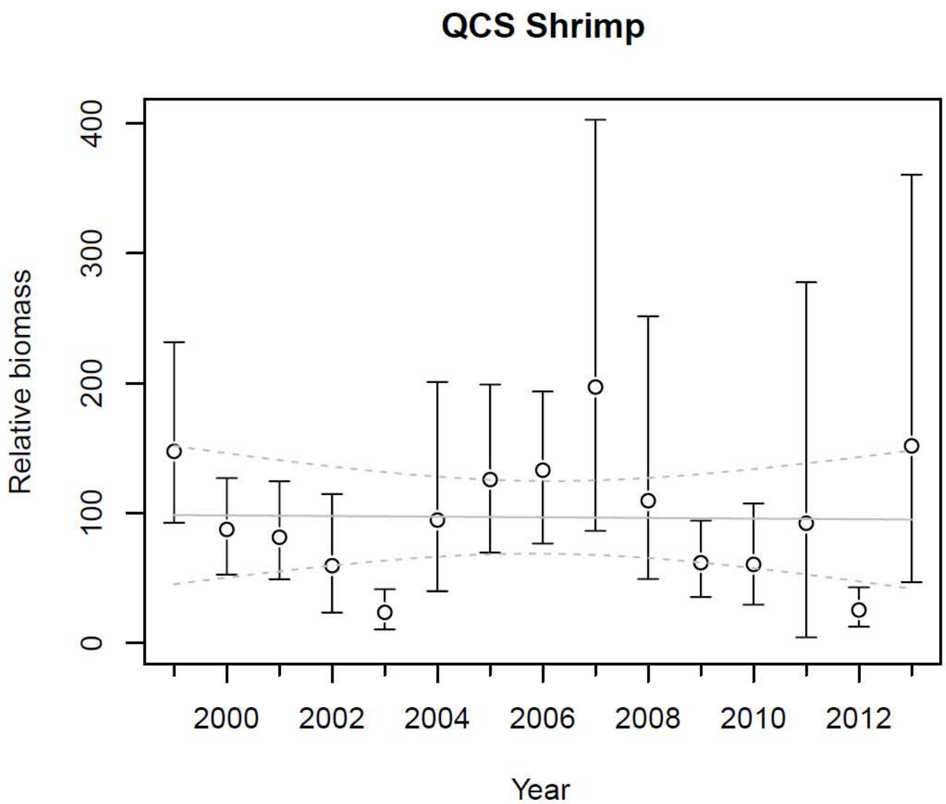


Figure 9. Relative biomass index for the QCS Shrimp series, with results of unweighted linear regression. Details as in Figure 7.

Table 6. Summary of unweighted linear regression fit for the QCS Shrimp series. Details as in Table 4.

	Value
Trend	−0.25
	(−6.72, 6.22)
	p = 0.94
Intercept	591
	(−11,186, 12,368)
	p = 0.93
Observations	15
R^2	0.001
Adjusted R^2	−0.08
Residual Std. Error	50.12 (df = 13)
F Statistic	0.01 (df = 1; 13)

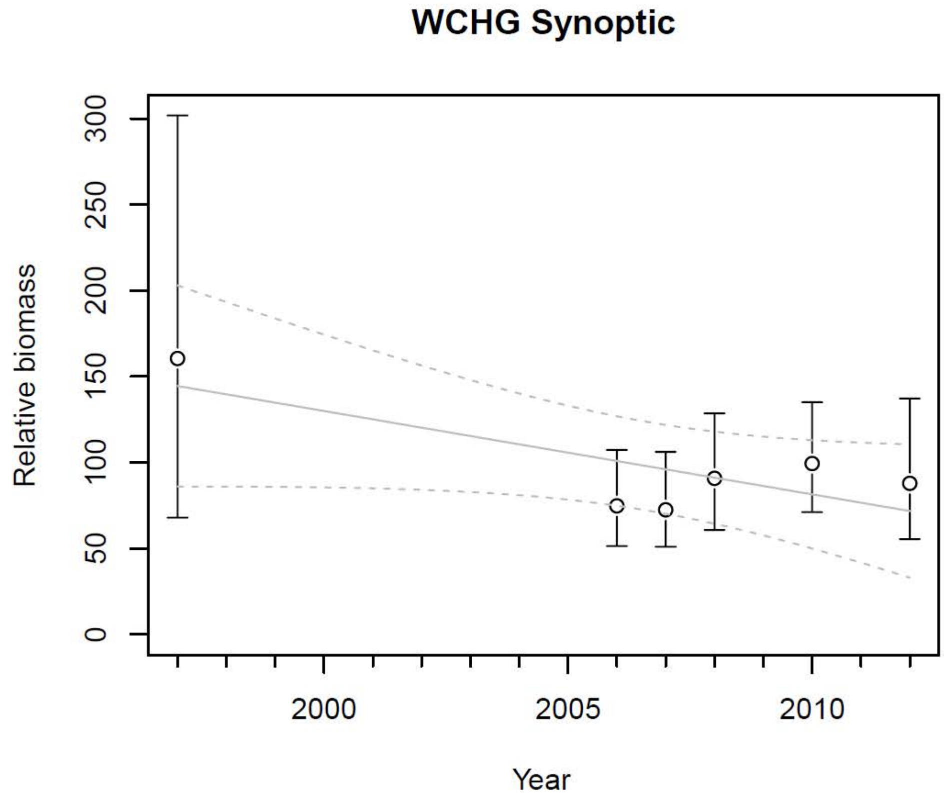


Figure 10. Relative biomass index for the WCHG Synoptic series, with results of unweighted linear regression. Details as in Figure 7.

Table 7. Summary of unweighted linear regression fit for the WCHG Synoptic series. Details as in Table 4.

	Value
Trend	−4.85
	(−10.28, 0.58)
	p = 0.07
Intercept	9,820
	(2,130, 17,520)
	p = 0.07
Observations	6
R^2	0.61
Adjusted R^2	0.51
Residual Std. Error	22.75 (df = 4)
F Statistic	6.14 (df = 1; 4)

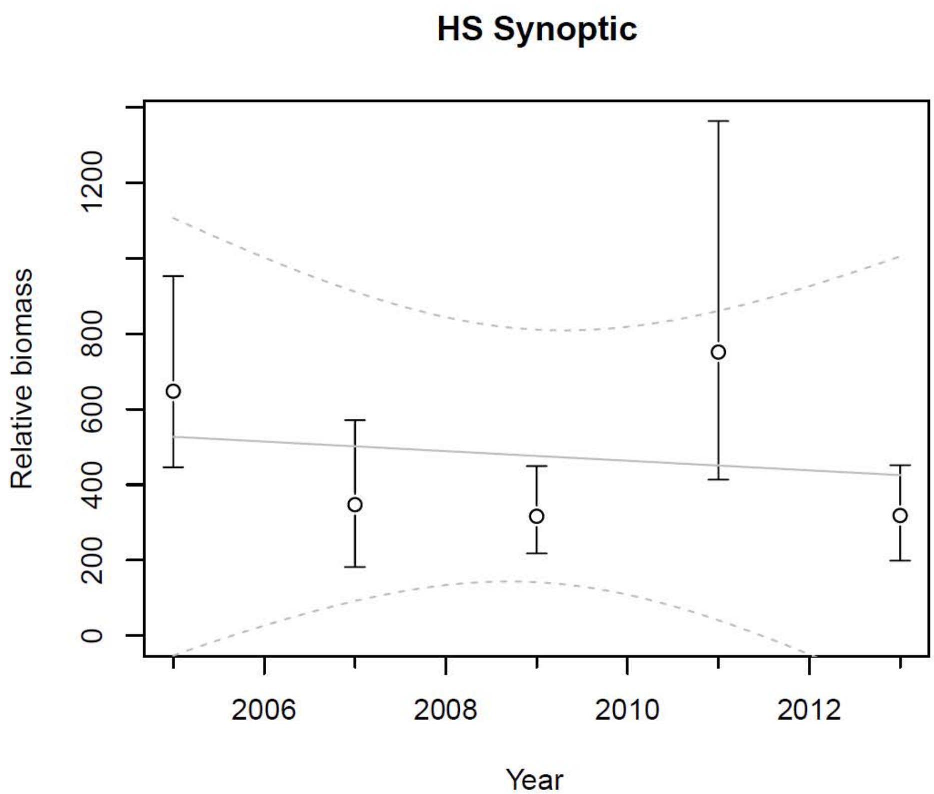


Figure 11. Relative biomass index for the HS Synoptic series, with results of unweighted linear regression. Details as in Figure 7.

Table 8. Summary of unweighted linear regression fit for the HS Synoptic series. Details as in Table 4.

	Value
Trend	−12.70
	(−130.91, 105.51)
	p = 0.76
Intercept	26,000
	(−120,300, 172,200)
	p = 0.76
Observations	5
R^2	0.04
Adjusted R^2	−0.28
Residual Std. Error	234.92 (df = 3)
F Statistic	0.12 (df = 1; 3)

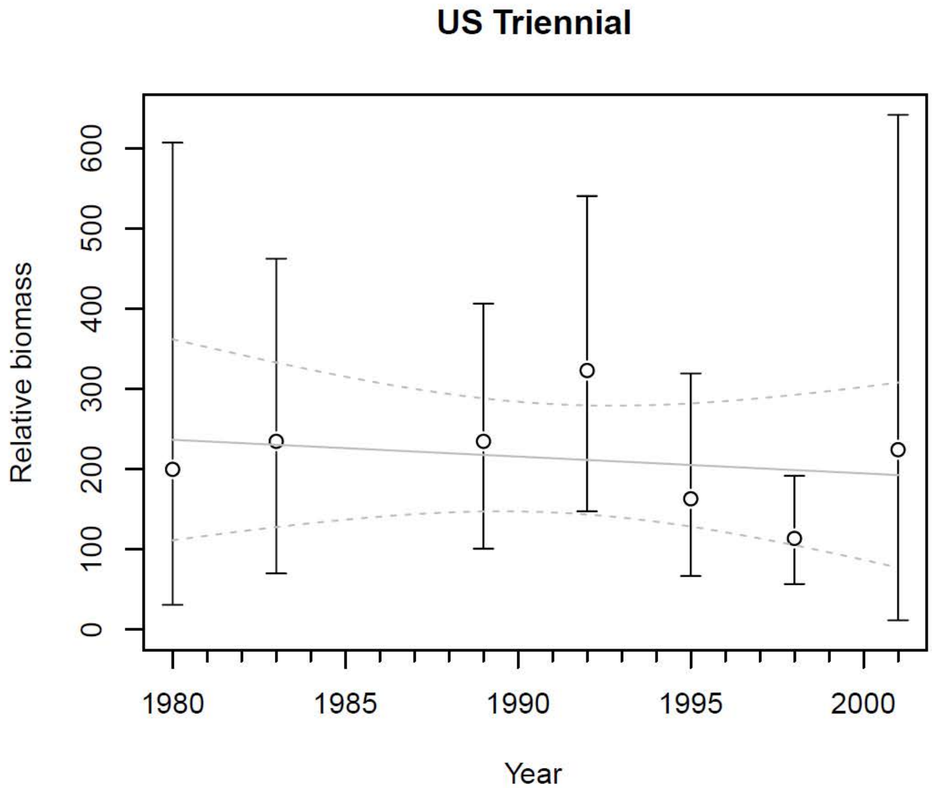


Figure 12. Relative biomass index for the US Triennial series, with results of unweighted linear regression. Details as in Figure 7.

Table 9. Summary of unweighted linear regression fit for the US Triennial series. Details as in Table 4.

	Value
Trend	−2.10
	(−11.58, 7.38)
	p = 0.60
Intercept	4,390
	(−10,010, 18,780)
	p = 0.58
Observations	7
R^2	0.06
Adjusted R^2	−0.13
Residual Std. Error	69.48 (df = 5)
F Statistic	0.32 (df = 1; 5)

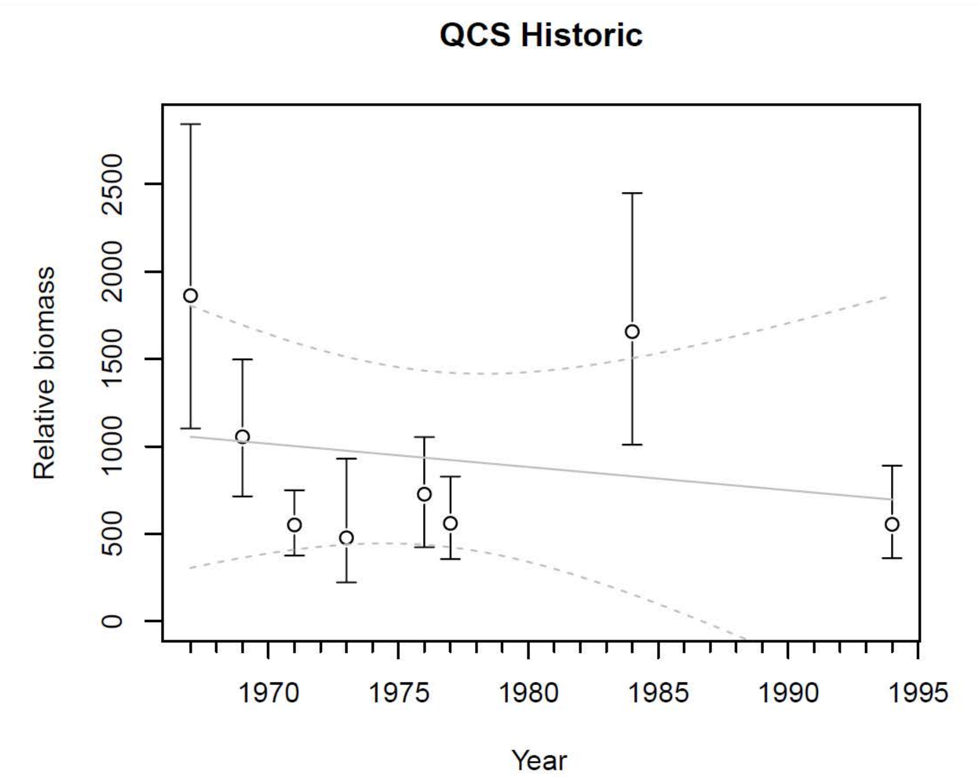


Figure 13. Relative biomass index for the QCS Historic series, with results of unweighted linear regression. Details as in Figure 7.

Table 10. Summary of unweighted linear regression fit for the QCS Historic series. Details as in Table 4.

	Value
Trend	−13.29
	(−73.16, 46.57)
	p = 0.61
Intercept	27,200
	(−67,600, 122,000)
	p = 0.60
Observations	8
R^2	0.05
Adjusted R^2	−0.11
Residual Std. Error	574.71 (df = 6)
F Statistic	0.30 (df = 1; 6)

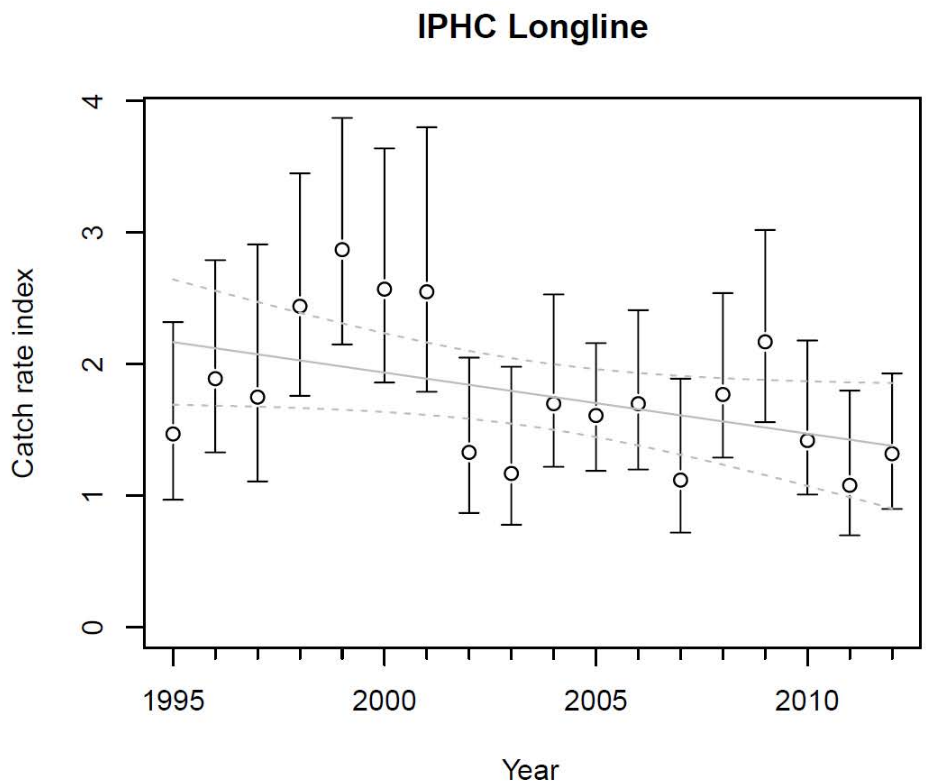


Figure 14. Relative catch rate index (numbers per effective skate) for the IPHC Longline series, with results of unweighted linear regression. Details as in Figure 7.

Table 11. Summary of unweighted linear regression fit for the IPHC Longline series. Details as in Table 4.

	Value
Trend	-0.05
	(-0.09, 0.00)
	p = 0.06
Intercept	94.6
	(6.0, 183.2)
	p = 0.06
Observations	18
R^2	0.21
Adjusted R^2	0.16
Residual Std. Error	0.50 (df = 16)
F Statistic	4.22 (df = 1; 16)

APPENDIX A. CATCH HISTORY

A.1 BRIEF HISTORY OF THE FISHERY

The early history of the British Columbia (BC) trawl fleet is discussed by Forrester and Smith (1972). A trawl fishery for slope rockfish has existed in BC since the 1940s. Aside from Canadian trawlers, foreign fleets targeted Pacific Ocean Perch (POP, *Sebastes alutus*) in BC waters for approximately two decades. These fleets were primarily from the US (1959–1980), the USSR (1965–1968), and Japan (1966–1976). The foreign vessels removed large amounts of rockfish biomass (presumably Redbanded Rockfish included), particularly in Queen Charlotte Sound (5ABC).

This assessment reconstructs catch back to 1940 (Figure A.1, Table A.6) when the fishery increased during World War II. From 1918 to 1939, removals were negligible compared to those that came after 1939. During the period 1950–1975, US vessels routinely caught more rockfish than did Canadian vessels. Additionally, from the mid-1960s to the mid-1970s, foreign fleets (Russian and Japanese) removed large amounts of rockfish, primarily POP. These large catches were first reported by various authors (Westrheim et al., 1972; Gunderson et al., 1977; Leaman and Stanley, 1993); however, Ketchen (1980*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. The catch of Redbanded Rockfish jumps in 1966, which reflects the foreign fleet targeting POP and the catch algorithm's calculations using catch ratios of RBR/ORF. Obviously, a caveat to this procedure is that ratios of Redbanded Rockfish to rockfish other than POP derived from the modern fishery will likely not reflect the catch ratios during the historical foreign fleet activity.

A.1.1 MANAGEMENT ACTIONS

Prior to 1977, no quotas were in effect for any slope rockfish species. Since then, the groundfish management unit (GMU) at the Department of Fisheries and Oceans (DFO) has imposed a combination of species/area quotas, area/time closures, and trip limits. In 1997, total allowable catches (TACs) were developed for the commercially valuable groundfish species, along with a 15,000 lb. per trip limit on all combined rockfish species not subject to TACs. For Redbanded Rockfish in particular, quotas were first introduced in 2011 coastwide (Table A.1), which followed sector allocation guidelines developed in 2000 (Table A.2) for future TAC implementations.

Table A.1. Annual trawl Total Allowable Catches (TACs) in tonnes for Redbanded Rockfish in Groundfish Management areas. Year can either be calendar year (1979-1996) or fishing year (1997 on). 't.l.' denotes trip limits on non-TAC rockfish. See Table A.2 for explanation of Notes column. Continued overleaf.

Year	Coast	Trawl	ZN	Halibut	Research	Notes
1995	—	—	—	—	—	m
1996	—	—	—	—	—	n,o
1997	t.l.	—	—	—	—	p,q
1998	t.l.	—	—	—	—	
1999	t.l.	—	—	—	—	
2000	t.l.	—	—	—	—	s,t,u
2001	t.l.	—	—	—	—	
2002	t.l.	—	—	—	—	x,y
2003	t.l.	—	—	—	—	

Year	Coast	Trawl	ZN	Halibut	Research	Notes
2004	t.l.	—	—	—	—	
2005	t.l.	—	—	—	—	
2006	t.l.	—	—	—	—	A,B,C
2007	t.l.	—	—	—	—	
2008	t.l.	—	—	—	—	
2009	t.l.	—	—	—	—	
2010	t.l.	—	—	—	—	
2011	590	295	221	73.8	—	E
2012	590	295	221	73.8	—	
2013	590	295	210	73.8	11.1	F
2014	590	295	210	73.8	11.1	

Table A.2. Codes to notes on management actions and quota adjustments that appear in Table A.1.

Code	Year	Management Actions
m	1995	Implemented catch limits (monthly) on rockfish aggregates for H&L.
n	1996	Started 100% onboard observer program for offshore Trawl fleet.
o	1996	Started DMP for H&L fleet.
p	1997	Started IVQ system for Trawl *Total Allowable Catch* (TAC) species (April 1, 2007)
q	1997	Implemented catch limits (15,000 lbs per trip) on combined non-TAC rockfish for the Trawl fleet.
s	2000	Implemented catch limits (20,000 lbs per trip) on rockfish aggregates for the Halibut option D fleet.
t	2000	Implemented formal allocation of rockfish species between Halibut and H&L sectors.
u	2000	Formal discussions between the hook and line rockfish (ZN), halibut and trawl sectors were initiated in 2000 to establish individual rockfish species allocations between the sectors to replace the 92/8 split. Allocation arrangements were agreed to for rockfish species that are not currently under TAC. The agreed to splits for these rockfish will be implemented in the future when or if TACs are set for those species.
x	2002	Established the inshore rockfish conservation strategy.
y	2002	Closed areas to preserve four hexactinellid (glassy) sponge reefs.
A	2006	Introduced an *Integrated Fisheries Management Plan* (IFMP) for most groundfish fisheries.
B	2006	Started 100% at-sea electronic monitoring for H&L.
C	2006	Implemented mandatory retention of rockfish for H&L.
E	2011	TAC implementation for RBR – 1,300,000 lbs has been set for Redbanded Rockfish coastwide (50% allocated to trawl, 37.5% allocated to rockfish outside and 12.5% allocated to halibut) and harvesters are now responsible for this mortality.
F	2013	To support rockfish research the Groundfish Hook and Line Sub Committee (GHLSC) has agreed to set aside 5% of the ZN allocations for research purposes.

A.2 CATCH RECONSTRUCTION

In this assessment we use calendar year for population models, and so catch estimates are made by calendar year. As with the previous rockfish assessments, we use "official" catch numbers whenever they have been prepared in the various modern catch databases. Essentially this means that DMP (dockside monitored) landings are treated as official, but the composition of each DMP landings is prorated to reflect the observer log records of catch by species and area, when they exist. These data comprise one set of inputs to the catch reconstruction.

The reconstruction uses historical data sources (the earliest extending back to 1918, Section A.2.3) and modern catch databases housed at various DFO facilities (Section A.2.4). The historical data comprise landings statistics for two broad categories of rockfish – Pacific Ocean Perch (POP) and rockfish other than POP (ORF). The sum of these two combine to form total rockfish (TRF) landings.

A detailed account of how we reconstruct rockfish catch on the BC coast can be found in Haigh and Yamanaka (2011). Since this report was written, the algorithm has undergone various changes. The following sections summarise the major features of the catch reconstruction algorithm to date.

A.2.1 CHALLENGES

The reconstruction of groundfish catch on the Canadian Pacific coast can present significant challenges for the period before:

- the implementation of the dockside monitoring program (DMP) in 1994;
- the inception of the at-sea observer program for the Option A trawl fleet in 1996; and
- for non-trawl sectors, the integrated groundfish catch-monitoring and at-sea observer program 2006.

The available catch data before 1994 present serious difficulties for use in a stock assessment model without some form of interpretation, both in terms of misreporting (i.e., reporting catches of one species as another) or misidentifying species and the possible existence of at-sea discarding due to catches exceeding what was permitted for retention. Although there were reports that fishermen misreported the location of catches, this issue is not a large problem for assessment of a coastwide stock. Finally, there was a significant foreign fishery for rockfishes in BC waters, primarily by the United States (US), the Soviet Union and Japan. These countries tended to report their catches in aggregate form, usually lumping rockfishes into a single category. These fisheries ceased after the declaration of the 200 nm limit by Canada in 1977.

A.2.2 CHANGES TO THE RECONSTRUCTION ALGORITHM

In a previous stock assessment for Pacific Ocean Perch, Edwards et al. (2014*b*) documented two departures from the catch reconstruction algorithm in Haigh and Yamanaka (2011). The first drops the use of data from the sales slip database PacHarv3 because catches are sometimes reported by large statistical areas that cannot be clearly mapped to PMFC areas. 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, we only use the GFCatch database for the trawl and trap records from 1954 to

1995, rather than trying to mesh GFCatch and PacHarv3. The second departure is the inclusion of an additional data source for Japanese rockfish catch reported in Ketchen (1980*a*).

For Redbanded Rockfish, catch and discards are known fully from 1996 on. Prior to this period, the reconstruction algorithm calculates landings and discards using ratios from reference years 1997–2005 when catch information was relatively well-recorded for all rockfish species, especially by the trawl fleet with its onboard observers. Composition ratios are used to disaggregate one of the broad rockfish categories (TRF, ORF, or POP) in the historical series. For Redbanded Rockfish, we use the ratio RBR/ORF. Historical discard rates are also estimated based on recent discard rates. The reconstruction provides catches (landings + discards) by calendar year, fishery sector (Trawl, Halibut, Sablefish, Dogfish-Lingcod, Hook & Line Rockfish), and Pacific Marine Fisheries Commission (PMFC) major areas in BC (4B, 3C, 3D, 5A, 5B, 5C, 5D, 5E). There are numerous decisions made during the reconstruction procedure that affect the final outcome, e.g., to allocate the annual catch A_t (for year t) from unknown areas to each PMFC area i using the proportions $C_{ti}/\Sigma_{i\in\mathtt{PMFC}}C_{ti}$ of known catch C_{ti} in PMFC area i. But decisions made include all identified removals whenever possible. This procedure includes currently available sources of commercial removals; research survey catches are also tallied and added to the table that summarises all catches.

A.2.3 ESTIMATE RBR LANDINGS BEFORE 1996 FROM ORF

Note: an asterisk '*' indicates a DFO database of groundfish catch from Canadian waters.

- Compile domestic ORF landings (CA=Canada, US=USA).
  - Start with CA rockfish catch records from the Dominion Bureau of Statistics (1918-1950) as a base.
  - Add the maximum CA + US landings by year, area, and fishery sector from:
    - Stewart (2009) US landings from BC waters (1930-1964);
    - GFCatch* table [B3_Catch_Pre54] of BC landings (1945-1953);
    - Ketchen (1976) CA + US landings from BC waters (1950-1975);
    - PacHarvHL* table [B22_Historic_Area_Catch] of sales slip data for red fish and rockfish compiled by S. Obradovich in 2000 (1951-1981);
    - GFCatch* logbook and landings data for trawl and trap only (1954-1995);
    - PacHarv3* sales slips – halibut, dogfish + lingcod, H&L rockfish (1982-1994);
- Add foreign ORF landings (JP=Japanese, UR=Russian) from:
  - Ketchen's (1980a) estimated UR catch from 3CD, 5AB, and 5E and estimated JP catch from 5AB (1965-1976)
  - Leaman's (1980) estimated JP catch from 3CD and 5E (1965-1977)
- Convert the ORF catch to RBR using PMFC area-specific ratios of RBR/ORF:
  - Five fishery sectors – calculated using verified modern landings from all localities during the reference years 1997-2005.

The mean RBR/ORF ratios γ are calculated from landings found in the modern databases (Section A.2.4) using reference years 1997-2005, which coincide with the start year of the trawl IVQ program to the year before catch data were being re-directed to GFFOS. The conversion ratios γ_{jk}, where j = major PMFC areas $(1,3,...,9)$ and k = fisheries $(1,...,5)$, are calculated as a mean of the following annual ratios:

$$\gamma_i = \frac{\sum_{h=1}^{N_i} \mathrm{RBR}_h}{\sum_{h=1}^{N_i} \mathrm{ORF}_h} \tag{A.1}$$

where, h = fishing events $(1...N_i)$ and i = years $(1997,...,2005)$.

A.2.4 COMPILE REPORTED RBR LANDINGS BASED ON POST-1996 DATABASES

- Domestic catch – use maximum reported landings of Redbanded Rockfish by year, PMFC area, and fishery sector from the following data sources:
  - PacHarvest* observer trawl – trawl;
  - PacHarvHL* halibut bycatch – halibut;
  - PacHarvSable* fisherlogs – sablefish;
  - PacHarvHL* validation records – halibut, dogfish+lingcod, H&L rockfish;
  - PacHarvHL* fisherlog records – dogfish+lingcod, H&L rockfish;
  - GFFOS* groundfish subset from Fishery Operations System – all fisheries.
- Add in foreign and domestic catches that don't appear in the harvest databases:
  - GFBioSQL* joint-venture hake bycatch by Canadian, Japanese, Polish, and Russian vessels (1982-2006) – trawl;
  - GFBioSQL* research survey catches – multiple gear types.

A.2.5 ESTIMATE/COMPILE DISCARDS AND ADD TO LANDINGS

Discards are only estimated during years that started with the introduction of catch limits and ended with effective catch monitoring. These periods vary by fishery sector (Table A.5) and usually have few, if any, discard records. Prior to catch limits, discarding is assumed to be negligible because the fishermen would keep what they caught. Once effective monitoring was in place (e.g., onboard observers), discards were fully reported and recorded.

Essentially, discard rates compare RBR discarded per Target landed. The mean discard ratios δ are calculated from discards and landings found in the PacHarvest database for the trawl fishery using reference years 1997-2006 and in the GFFOS database for the non-trawl fisheries using reference years 2007-2013. The discard ratios δ_{jk}, where j = major PMFC areas $(1,3,...,9)$ and k = fisheries $(1,...,5)$, are calculated as a mean of the following annual ratios:

$$\delta_i = \frac{\sum_{h=1}^{N_i} \mathrm{RBR}_h^{\mathrm{discards}}}{\sum_{h=1}^{N_i} \mathrm{Target}_h^{\mathrm{landings}}} \tag{A.2}$$

where, h = fishing events $(1...N_i)$ and i = years $(1997,...,2006)$ for trawl or $(2007,...,2013)$ for non-trawl.

The target landings (denominator) used in the discard equation above depend on the fishery sector (Table A.5), and the calculated discard rates δ_{jk} are only used during years that lie between regimes with no discarding and those that record and report discards completely (Table A.5). The latter regime (recording and reporting discards) is fairly certain for trawl which enjoys 100% onboard observer coverage. The other fisheries implemented electronic monitoring (EM) in July 2006; however, EM coverage is only 10%. By regulation, all non-trawl fisheries must record discards in fisherlogs and these are entered into GFFOS. DFO can perform a rough check on logbook compliance by comparing scaled-up EM records to fisherlog records, but this check is not robust to contagious distributions. However, in the absence of 100% monitoring, we assume that GFFOS reports discarding entirely.

A.2.6 CAVEATS

The accuracy and precision of reconstructed catch series inherently reflect the problems associated with the development of a commercial fishery: trips offloading catch with no area information, unreported discarding, recording catch of one species as another to avoid quota violations, developing expertise in monitoring systems, shifting regulations, changing data storage technologies, etc. Many of these problems have been solved through the introduction of onboard observer programs (started in 1996 for the offshore trawl fleet), dockside monitoring, and tradable individual vessel quotas (IVQs, 1997) that confer ownership of the resource to the fishing sector. Improvements in data storage and retrieval technologies are still ongoing.

A.2.7 KEY CATCH RECONSTRUCTION TABLES

The variable called γ in Haigh and Yamanaka (2011) describes a matrix of ratios of Redbanded Rockfish to rockfish other than POP by PMFC major area and fishery (Table A.3). The variable called δ in Haigh and Yamanaka (2011) describes a matrix of discard rates (Table A.4) that summarise the weight of Redbanded Rockfish discarded per target landed. The targets are specified in (Table A.5), as are the reference years specifying data periods to calculate δ and various discarding regimes. The discard rates in Table A.4 are only applied during the years labelled "Calculate Discards". The reconstructed annual catches for the trawl and non-trawl (halibut, sablefish, dogfish-lingcod, H&L rockfish) fishing sectors appear in Table A.6 and Figure A.1. Survey catches of Redbanded Rockfish appear in Table A.7. The total annual catches used in the model are those from the commercial catch (Table A.6).

Table A.3. Ratio γ = ratios of Redbanded Rockfish landed to rockfish other than Pacific Ocean Perch landed in PMFC area by fishery.

PMFC Major	Trawl	Halibut	Sablefish	Dog/Ling	H&L Rockfish
1	0.0057641	0.28618	—	0.00070714	0.0049971
3	0.0070948	0.13462	0.028900	0.022736	0.024263
4	0.0055284	0.19950	0.015226	0.090627	0.10718
5	0.0085301	0.18843	0.022080	0.12655	0.32767
6	0.047087	0.23814	0.029254	0.061000	0.28167
7	0.084517	0.20031	0.0055407	0.011330	0.017614
8	0.037252	0.24895	0.0036688	0.0010633	0.027156
9	0.0042054	0.15708	0.0014599	0.0077428	0.033203

Table A.4. Ratio δ = discard rates RBR / target landed of Redbanded Rockfish from observer logs in PacHarvest for the trawl fishery and fisherlogs in GFFOS for non-trawl fisheries.

PMFC Major	Trawl	Halibut	Sablefish	Dog/Ling	H&L Rockfish
1	—	0.0012500	—	0.00041907	0.0089352
3	0.042188	0.0010693	0.00017668	0.00035255	—
4	0.029245	0.0020697	0.00034542	0.00014124	0.0081905
5	0.011814	0.00054524	0.00010245	0.0012977	0.0039267
6	0.011390	0.00043126	9.6322	—	0.00025703
7	0.011856	0.0019733	—	9.4058	0.051731
8	0.0057436	0.00055926	—	—	0.037237
9	0.029223	0.00026438	0.0030710	—	0.0089112

Table A.5. Assumptions regarding the derivation of discard rates δ for the five fisheries.

Fishery	Target Landing	Log Source	Reference Years	No Discards	Calculate Discards	Reported Discards
Trawl	RBR	Observer	1997-2006	1940-1953	1954-1995	1996-2014
Halibut	PAH	Fisher	2007-2013	1940-1978	1979-2005	2006-2014
Sablefish	SBF	Fisher	2007-2013	1940-1985	1986-2005	2006-2014
Dogfish/Lingcod	DOG+LIN	Fisher	2007-2013	1940-1985	1986-2005	2006-2014
H&L Rockfish	RBR	Fisher	2007-2013	1940-1985	1986-2005	2006-2014

Table A.6. Catch reconstruction (landings + discards, tonnes) for Redbanded Rockfish in PMFC major areas 3CD, 5AB, 5CD, 5E, and Total (includes 4B) in the Trawl and Hook & Line (Halibut, Sablefish, Dogfish–Lingcod, H&L Rockfish) fisheries. Catch for 2014 remains incomplete (records accessed Nov 3, 2014). Continued overleaf.

Year	Trawl					Hook & Line				
	3CD	5AB	5CD	5E	Total	3CD	5AB	5CD	5E	Total
1940	0.141	1.07	0.104	0	1.31	0.232	0.224	0.148	0.0570	0.660
1941	0.0982	0.623	0.372	0	1.09	0.845	1.33	0.926	0.357	3.45
1942	1.04	7.61	0.651	0	9.30	2.11	1.34	0.811	0.313	4.58
1943	3.25	24.3	1.90	0	29.4	5.49	3.50	2.12	0.819	11.9
1944	1.65	10.7	1.56	0	13.9	7.22	4.71	2.87	1.11	15.9
1945	13	103	6.46	0	123	5.67	6.72	4.56	1.76	18.7
1946	6.69	53.5	4.90	0	65.1	4.98	9.27	6.57	2.54	23.4
1947	3.45	27.5	1.67	0	32.6	1.60	1.65	1.09	0.423	4.77
1948	5.58	44.4	2.66	0	52.7	2.44	2.50	1.66	0.641	7.23
1949	6.79	54	3.31	0	64.1	3.24	3.32	2.21	0.852	9.61
1950	6.90	52.6	4.48	0	63.9	1.39	1.42	0.945	0.365	4.12
1951	6.09	59.3	2.92	0	68.3	4.53	6.81	6.53	2.20	20.1
1952	6.73	52.1	2.87	0	61.7	3.23	6.76	3.03	1.47	14.5
1953	3.84	28.8	1.62	0	34.3	2.66	4.62	1.36	0.279	8.92
1954	5.23	41.5	2.22	0	48.9	3.25	3.43	1.62	0.509	8.81
1955	5.30	41.2	2.69	0	49.2	3.65	0.769	1	0.625	6.04
1956	4.51	22.7	1.61	0	28.8	3.69	1.54	0.232	0.170	5.64
1957	5.37	30.9	3.47	0	39.8	6.19	2.28	0.502	0.871	9.85
1958	4.94	39.5	2.07	0	46.5	5.40	0.562	0.112	0.0575	6.14
1959	9.93	44.6	2.82	0	57.4	6	0.969	0.0493	0.0822	7.10
1960	10.1	39.6	3.78	0	53.4	6.67	3.02	1.77	0.247	11.7
1961	12.1	47	4.32	0	63.4	8.49	3.25	0.616	0.279	12.6
1962	16.3	65.5	6.48	0	88.3	10.7	3.75	2.26	0.230	17
1963	9.28	53.1	2.81	0	65.2	6.91	10.6	1.72	1.14	20.3
1964	6.22	40.7	4.35	0	51.2	4.68	3.06	0.465	0.0931	8.29

Year	Trawl					Hook & Line				
	3CD	5AB	5CD	5E	Total	3CD	5AB	5CD	5E	Total
1965	7.87	104	5.37	19.8	137	3.88	1.43	1.24	0.734	7.29
1966	52.6	191	3.09	31.2	278	4.48	2.83	1.14	0.367	8.82
1967	37.8	132	2.05	15	186	6.23	2.15	3.38	0.425	12.2
1968	37	115	2.88	21.7	176	5.07	1.98	0.527	0.0575	7.64
1969	18.7	164	6.94	8.29	198	5.67	7.43	2.38	0.0247	15.5
1970	22.6	113	55.8	3.82	195	7.48	10.8	9.05	0.0219	27.4
1971	19.7	97	13	6.33	136	2.76	8.67	8.05	0.134	19.6
1972	15.4	143	18.8	8.85	186	10.9	10.2	7.44	0.252	28.8
1973	18.3	168	11	6.96	204	5.24	5.91	6.68	0.356	18.2
1974	10.8	161	13.5	4.83	190	7.96	4.34	13.9	0.0548	26.2
1975	7.42	107	11.1	3.63	129	6.47	8.43	16.7	0.548	32.2
1976	3.57	126	29.8	4.28	164	6.62	10.2	7.17	0.548	24.5
1977	4.66	103	44.9	15.8	168	7.92	19.3	9.42	0.438	37.1
1978	2.93	167	57.8	17.2	245	7.03	13	16.5	1.69	38.2
1979	18.3	164	105	6.70	294	14.1	18.5	15.9	3.14	51.7
1980	10.7	177	205	7.18	400	13.1	13.6	17.3	3.87	47.9
1981	5.28	142	252	11.2	410	9.95	10.5	12.4	2.57	35.4
1982	16	71.6	60.2	6.87	155	8.72	8.20	6.92	2.91	26.7
1983	27.3	75.8	51.3	13.9	168	11.3	8.98	8.16	2.45	30.9
1984	14.9	111	56.7	16.4	199	16.7	11.3	10.2	9.52	47.7
1985	18.9	95.1	116	13.5	243	22.4	26.6	27.7	8.05	84.8
1986	35.1	105	75.6	18.9	234	68.9	32.7	41.7	17.4	161
1987	29.4	183	87.7	11	311	70	65.6	57.9	17.8	211
1988	53.9	218	82.3	34.8	389	49.1	89.2	41.6	27.8	208
1989	137	266	113	18.4	534	60.1	98.8	45.6	28.8	233
1990	81.1	445	133	10	669	70.2	162	60.6	46.8	340
1991	88.4	376	84.4	21.4	570	73.4	171	62.3	45.6	352
1992	141	697	189	19.9	1,047	41.2	148	57.5	67.1	313
1993	162	584	156	28.4	929	102	90.9	67.7	66.1	327
1994	125	441	156	13.2	736	76.4	189	48.1	131	444
1995	72.4	245	160	15.4	493	44.1	121	4.76	83.5	253
1996	39.3	171	103	9.60	323	42.8	87.6	10.9	68.5	210
1997	26.9	195	62.7	5.55	290	27.2	37.7	10.5	50	125
1998	28.6	148	46.4	3.65	227	8.74	42.3	20.5	35.8	107
1999	35.4	165	68.1	2.71	271	95.5	101	27.4	37	261
2000	34.2	190	58.8	7.93	291	49.7	216	32	89.7	387
2001	35.4	133	135	6.73	310	41.1	183	26.1	77	327
2002	32.3	161	53	10.4	257	50.8	177	26.2	77.5	332
2003	42.3	143	44.9	5.39	236	43.3	227	24.3	67.9	362
2004	34.8	145	47.6	8.53	236	48.7	195	29.3	88.4	362
2005	36.7	128	53.5	4.01	222	47.5	224	29.3	82.8	383
2006	24.6	156	32.2	4.90	217	36.9	146	45	30.7	258
2007	24	127	21.1	3.58	176	21.4	80.2	40	20	161
2008	21	96.3	11.1	4.15	133	17.7	130	38.8	23.2	210
2009	25.2	138	16.6	6.32	186	14.6	120	35.9	29.1	200
2010	20.9	161	15.1	4.42	201	21.3	103	20.7	30	175
2011	26	128	5.65	3.56	164	30.5	66.2	11.3	23.8	132
2012	18.4	119	6.59	4.03	148	31.7	88.2	13.1	26.5	160
2013	36.6	138	12.7	3.94	191	34.8	75.2	20.2	22.7	153
2014	21.9	113	5.56	4.22	144	29.4	93.4	16.8	23.7	163

Table A.7. Total annual survey catch (t) of Redbanded Rockfish in PMFC areas. The final column contains the coastwide survey catch. Catch for 2014 may be incomplete (records accessed Nov 6, 2014). Continued overleaf.

Year	3C	3D	5A	5B	5C	5D	5E	Total
1963	0	0.169	0	1.87	0	0.0853	0	2.12
1964	0.0113	0.106	0	0.0127	0	0	0	0.130
1965	0.528	0.00544	0	0.613	0	0	0	1.15
1966	0.228	0.185	0.338	0.503	0.0136	0.286	0.00725	1.56
1967	5.54	0	1.17	1.33	0	0	0	8.04
1968	1.16	0	0	0	0	0.00136	0	1.16
1969	0.450	0	0.250	0.891	0	0	0	1.59
1970	0.212	0	0.0154	0.494	0	0	0.0222	0.743
1971	0	0	0.102	1.70	0	0	0.00363	1.81
1972	0.187	0	0	0.352	0	0	0	0.538
1973	0	0	0.135	0.947	2.37	0	0	3.45
1974	0	0	0.859	1.44	2.65	0	0	4.95
1975	0	0.00300	0	0	0	0	0	0.00300
1976	0.00272	0	0.317	2.32	0	0	0	2.64
1977	0.132	0.000250	0.658	1.35	0	0.0830	0	2.22
1978	0.0209	0.489	0.0493	0.611	1.72	0.0872	0.475	3.45
1979	1.27	1.57	0.322	1.24	0.0400	1.02	2	7.47
1980	0	0.00158	0.00362	0.00475	0.209	0.0445	0.153	0.416
1981	0.0730	0	0	0.115	1.88	0.0450	0.0749	2.19
1982	0	0	0	0.0441	1.28	0.00400	0	1.33
1983	0.000250	0.00100	0	0	0	0	0.0760	0.0772
1984	0.403	0.113	0.948	4.67	0.00800	0.0160	0	6.16
1985	0.824	0.555	0.0460	0.115	0.0660	0	0.0180	1.62
1986	0.101	1	0.0460	0	0.0780	0	0	1.23
1987	0.0900	0.0110	0	0	0.374	0	0	0.475
1988	0.0328	0	0.0650	0.190	0	0	0	0.288
1989	0.177	0.136	0.396	1.45	0.181	0.00200	0.484	2.83
1990	0	0.152	0.0410	0.0200	0	0	0	0.213
1991	0.00825	0	0	0	0.148	0	0	0.156
1992	0.00600	0.00700	0.00700	0.00700	0	0	0.0140	0.0410
1993	0.00525	0.0152	0	0	0	0	0.694	0.714
1994	0.00225	0.0350	0.374	0.896	0.00300	0	0.0230	1.33
1995	0.0300	0.230	0.768	1.24	0.0600	0	0.0230	2.35
1996	0.505	0.197	0.00700	0.00500	0.136	0.240	0.409	1.50
1997	0.0213	0.646	0.918	0.00500	0	0	2.40	3.99
1998	0.00360	0.579	6.02	2e-04	0	0	2.62	9.22
1999	1e-04	0.0110	0.0500	0.377	0	0	0.0330	0.471
2000	0.00150	0.00810	0.0200	0.174	0	0.00500	0.173	0.382
2001	0.000720	0.00120	0.0315	0.182	0	0.00750	0.00543	0.228
2002	0.00647	0.0144	0.229	0.127	0.00544	0.000450	0.337	0.720
2003	0.0695	0.100	0.464	1.54	1.52	0.0924	0.499	4.29
2004	0.108	0.621	0.255	2	1.31	0.0884	0.483	4.86
2005	0.0485	0.196	0.265	1.91	2.45	0.415	0.294	5.57
2006	0.163	0.258	0.153	1.18	1.19	0.636	1.93	5.51
2007	0.0578	0.545	1.02	1.72	1.38	0.283	0.674	5.68
2008	0.188	0.322	0.200	1.34	0.959	0.356	1.48	4.84
2009	0.0644	0.927	1.12	2.51	1.93	0.407	0.246	7.21
2010	0.187	0.388	0.299	0.862	1.53	0.426	1.49	5.19
2011	0.126	0.287	1.06	1.35	1.54	0.442	0.246	5.05
2012	0.459	0.415	0.209	1.04	0.894	0.506	1.19	4.71

Year	3C	3D	5A	5B	5C	5D	5E	Total
2013	0.0161	0.0607	0.136	0.985	0.762	0.210	0.0904	2.26
2014	0.131	1.02	0.00828	0	0	0	0	1.16

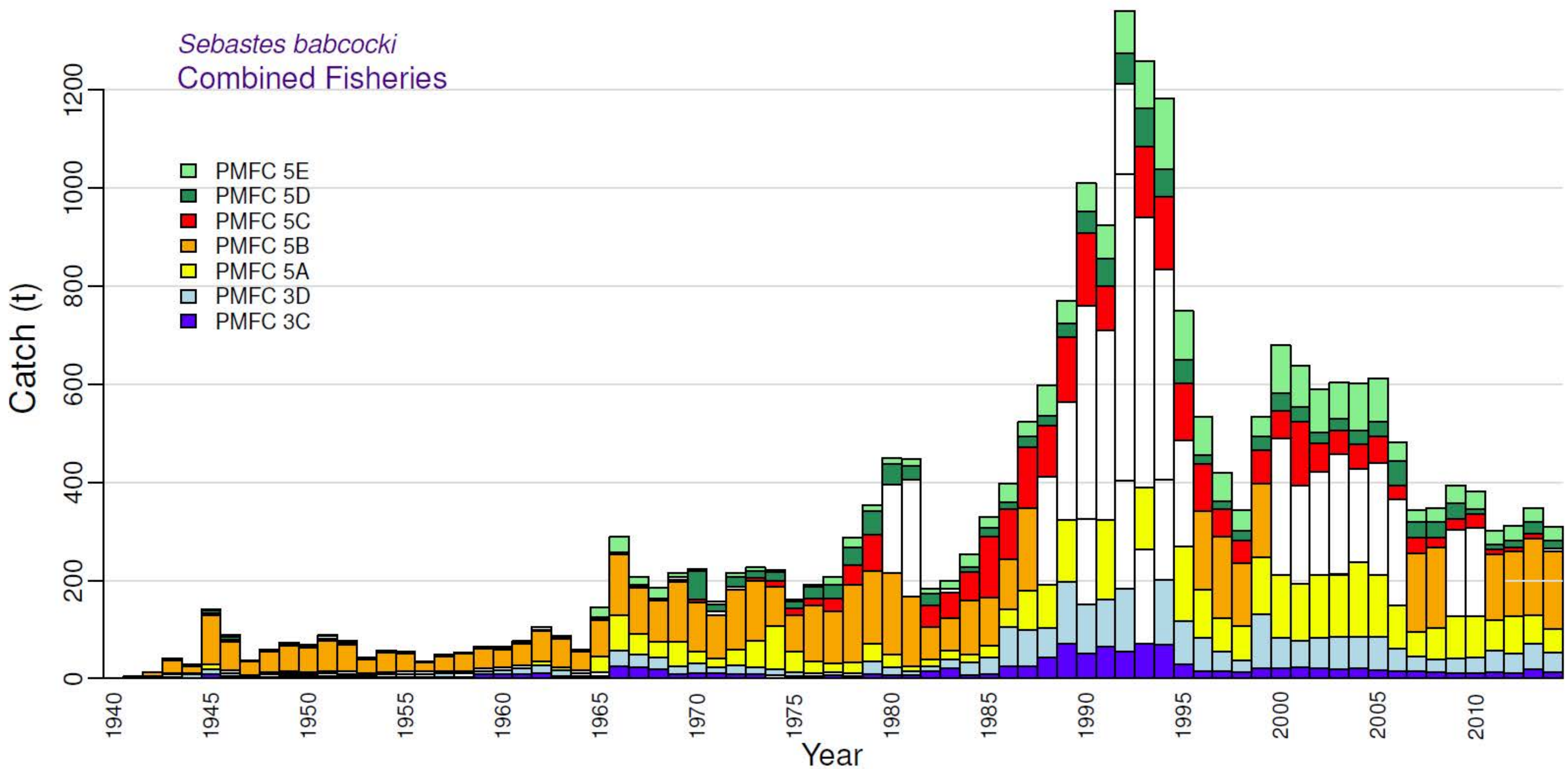


Figure A.1. Reconstructed total (landed + discarded) catch (t) for Redbanded Rockfish from all fisheries and surveys combined in all PMFC major areas along the BC coast.

APPENDIX B. TRAWL SURVEYS

B.1 INTRODUCTION

This appendix summarizes the derivation of relative Redbanded Rockfish (RBR) abundance indices from the following bottom trawl surveys:

- historical set of surveys operated in the Goose Island Gully of Queen Charlotte Sound (Section B.3);
- National Marine Fisheries Service (NMFS) Triennial survey operated off the lower half of Vancouver Island (Section B.4);
- Queen Charlotte Sound shrimp trawl survey (Section B.5);
- Hecate Strait synoptic survey (Section B.6);
- Queen Charlotte Sound synoptic survey (Section B.7);
- west coast Vancouver Island synoptic survey (Section B.8);
- west coast Haida Gwaii synoptic survey (Section B.9).

B.2 ANALYTICAL METHODS

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

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

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

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

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

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

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

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

w = average net width (km).

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

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

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

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

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

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

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

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

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

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

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

m = number of strata.

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

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

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

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

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

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

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

B.3.1 Data selection

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

The 1967 ([left panel]: Figure B.2) and 1969 ([left panel]: Figure B.3) surveys also performed tows on the west coast of Vancouver Island, the west coast of Haida Gwaii and SE Alaska, but both of these surveys had a reasonable number of tows in the GIG grounds (Table B.1). The 1971 survey ([left panel]: Figure B.4) was entirely confined to GIG while the 1973 ([left panel]: Figure B.5), 1976 ([left panel]: Figure B.6) and 1977 ([left panel]: Figure B.7) surveys covered both Goose Island and Mitchell Gullies in QCS.

A 1979 survey was conducted by a commercial fishing vessel (Southward Ho, Table B.1), with the distribution of tows being very different from the preceding and succeeding surveys (plot not provided; see Figure C.5 in Edwards et al. 2012*b*). As well, the distribution of tows by depth was also different from the other surveys (Table B.2). These observations imply a substantially different survey design and consequently this survey was not included in the time series used in the assessment.

The 1984 survey was conducted by two vessels: the GB Reed and the Eastward Ho. Part of the design of this survey was to compare the catch rates of the two vessels (one was a commercial fishing vessel and the other a government research vessel – Greg Workman, DFO, Nanaimo, B.C., pers. comm.), thus they both followed similar design specifications, including the configuration of the net. Unfortunately, the tows were not distributed similarly in all areas, with the GB Reed fishing mainly in the shallower portions of the GIG, while the Eastward Ho fished more in the deeper and seaward parts of the GIG ([left panel]: Figure B.8) although the two vessels fished more contiguously in Mitchell Gully (immediately to the north). When the depth-stratified catch rates for POP (the main target species of the surveys) of the two vessels were compared within the GIG only (using a simple ANOVA), the Eastward Ho catch rates were significantly higher (p=0.049) than those observed for the GB Reed. However, the difference in catch rates was no longer significant when tows from Mitchell's Gully were added to the analysis (p=0.12). Given the lack of significance when the full suite of available tows were compared, along with the uneven spatial distribution of tows among vessels within the GIG (although the ANOVA was depth-stratified, it is possible that the depth categories were too coarse), the most parsimonious conclusion was that there was no detectable difference between the two vessels. Consequently, all the GIG tows from both vessels were pooled for this survey year.

The 1994 survey, also conducted by a commercial vessel (the Ocean Selector, Table B.2) ([left panel]: Figure B.9), was modified by the removal of 19 tows which were part of an acoustic experiment and therefore were not considered appropriate for biomass estimation (they were tows used to estimate species composition for ensonified schools). Although this survey was designed to emulate as closely as possible the previous GB Reed surveys in terms of tow location selection (G. Workman, DFO, Nanaimo, B.C., pers. comm.), the timing of this survey was about two to three months earlier than the previous surveys (starting in mid-June rather than August or September, Table B.3). This survey was dropped it from the base case assessment data set for Silvergray Rockfish but has been provisionally kept for this assessment.

The 1995 survey, conducted by two commercial fishing vessels: the Ocean Selector and the Frosti (Table B.2), used a random stratified design with each vessel duplicating every tow ([left panel]: Figure B.10) (G. Workman, DFO, Nanaimo, B.C., pers. comm.). This type of design was entirely different from that used in the previous surveys. As well, the focus of this survey was entirely on Pacific Ocean Perch (POP), with tows optimised to capture this species. This survey was also dropped from the base case assessment data set for Silvergray and Yellowtail Rockfish.

Given that the only area that was consistently monitored by these surveys was the GIG grounds, tows lying between 50.9°N and 51.6°N latitude from the seven acceptable survey years, covering the period from 1967 to 1984, were used to index the RBR population (Table B.1).

Table B.1. Number of tows in GIG and in all other areas (Other) by survey year and vessel conducting the survey for the 12 historical (1965 to 1995) surveys. Survey years in grey(1965,1966, 1979, 1994, and 1995) were not used in the assessment

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

Table B.2. Total number of tows by 20 fathom depth interval (in metres) in GIG and in all other areas (Other) by survey year for the 12 historical (1965 to 1995) surveys. Survey years in grey(1965,1966, 1979, 1994, and 1995) were not used in the assessment. Some of the tows in the GIG portion of the table have usability codes other than 0,1,2, or 6.

Survey	20 fathom depth interval (m)									Total
year	66-146	147-183	184-219	220-256	257-292	293-329	330-366	367-402	440-549	Tows
Areas other than GIG										
1965	3	15	26	17	6	6	1	1	1	76
1966	3	11	18	8	2	1	3	2	1	49
1967	1	-	6	1	2	1	1	4	-	16
1969	-	1	-	1	-	1	-	-	-	3
1971	-	-	-	-	-	-	-	-	-	-
1973	-	-	4	3	2	2	2	-	-	13
1976	-	-	4	4	4	4	4	-	-	20
1977	-	-	3	2	2	3	2	-	-	12
1979	11	2	1	5	1	-	-	-	-	20
1984	-	-	4	10	7	7	6	-	-	34
1994	-	-	-	-	-	-	-	-	-	-
1995	-	-	-	-	-	-	-	-	-	-
GIG										
1965	-	2	4	1	1	-	-	-	-	8
1966	3	2	3	5	2	-	-	-	-	15
1967	1	6	11	6	10	-	-	-	-	34
1969	-	9	11	6	6	-	-	-	-	32
1971	-	5	15	9	10	-	-	-	-	39
1973	-	7	11	7	8	-	-	-	-	33
1976	-	7	15	8	6	-	-	-	-	36
1977	1	12	14	14	9	-	-	-	-	50
1979	23	12	18	6	-	-	-	-	-	59
1984	-	13	25	17	13	1	-	-	-	69
1994	-	15	18	20	18	-	-	-	-	71
1995	2	23	47	22	15	6	-	-	-	115

The original depth stratification of these surveys was in 20 fathom (36.1 m) intervals, with the important strata for RBR ranging from 70 fathoms (183 m) to 160 fathoms (300 m). For the GIG survey series, the shallowest tow capturing RBR was 121 m. Similarly, the deepest tow capturing RBR was 282 m. These depth strata were combined for analysis into three ranges:

70–100 fm, 100–120 fm and 120–160 fm, for a total of 282 tows from the seven accepted survey years (Table B.3).

Table B.3. Number of tows available by survey year and depth stratum for the analysis of the historical GIG trawl survey series. Survey years in grey(1994 and 1995) were not used in the base case data set.

Survey Year	Depth stratum: 120-183 m (70–100 fm)	184-218 m (100–120 fm)	219-300 m (120–160 fm)	Total	Start Date	End Date
1967	7	11	15	33	07-Sep-67	03-Oct-67
1969	9	11	12	32	14-Sep-69	24-Sep-69
1971	4	15	17	36	14-Oct-71	28-Oct-71
1973	7	11	15	33	07-Sep-73	24-Sep-73
1976	7	13	13	33	09-Sep-76	26-Sep-76
1977	13	14	20	47	24-Aug-77	07-Sep-77
1984	13	23	33	69	05-Aug-84	08-Sep-84
1994	10	16	24	50	21-Jun-94	06-Jul-94
1995	22	45	45	112	11-Sep-95	22-Sep-95

Table B.4. Biomass estimates for Redbanded Rockfish from the historical Goose Island Gully trawl surveys for the years 1967 to 1995. Biomass estimates are based on three depth strata (Table B.3), assuming that the survey tows were randomly selected within these areas. Bootstrap bias corrected confidence intervals and CVs are based on 1000 random draws with replacement.

Survey Year	Biomass (t)	Mean bootstrap biomass (t)	Lower bound biomass (t)	Upper bound biomass (t)	Bootstrap CV	Analytic CV (Eq. B.6)
1967	1,862.3	1,873.7	1,102.2	2,842.1	0.245	0.250
1969	1,055.2	1,056.7	714.6	1,497.0	0.186	0.192
1971	551.3	552.8	376.0	749.9	0.171	0.177
1973	477.5	476.9	222.1	929.8	0.365	0.369
1976	726.9	727.4	424.0	1,054.1	0.213	0.217
1977	560.3	561.6	355.9	827.9	0.209	0.211
1984	1,656.2	1,676.0	1,009.3	2,447.9	0.221	0.218
1994	554.5	551.0	361.0	889.6	0.234	0.237
1995	850.0	840.1	555.8	1,270.8	0.209	0.214

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

B.3.2 Results

Maps showing the locations where RBR were caught in the Goose Island Gully (GIG) indicate that this species is found throughout the GIG in all years (see Figure B.2 to Figure B.10). RBR was taken frequently in small amounts, with 373 of the 444 valid tows capturing RBR with a median catch weight of 18 kg. All but one of the 35 valid tows greater than 100 kg were less than 300 kg. The largest RBR tow in terms of catch weight was 461 kg in 1967. RBR were mainly taken at depths from 163 to 282 m (5% and 95% quantiles of the starting depth empirical distribution), with the minimum and maximum observed depths at 146 and 296 m respectively (Figure B.11).

Estimated biomass levels in the GIG for Redbanded Rockfish from the historical GIG trawl surveys were variable, with the maximum biomass recorded in 1967 (at 1860 t) and the minimum biomass in 1973 (at 477 t) (Figure B.12; Table B.4). The two GIG surveys which operated in the 1990s had similar RBR biomass indices in both 1994 and 1995 (Table B.4). Survey relative errors are moderate for this species in this survey, ranging from a low of 0.18 in 1971 to 0.37 in 1973 (Table B.4). The proportion of tows which caught RBR was relatively constant, generally ranging between 80% and 90% of the tows (Figure B.13). Overall, 373 tows from a total 444 valid tows (84%) contained RBR.

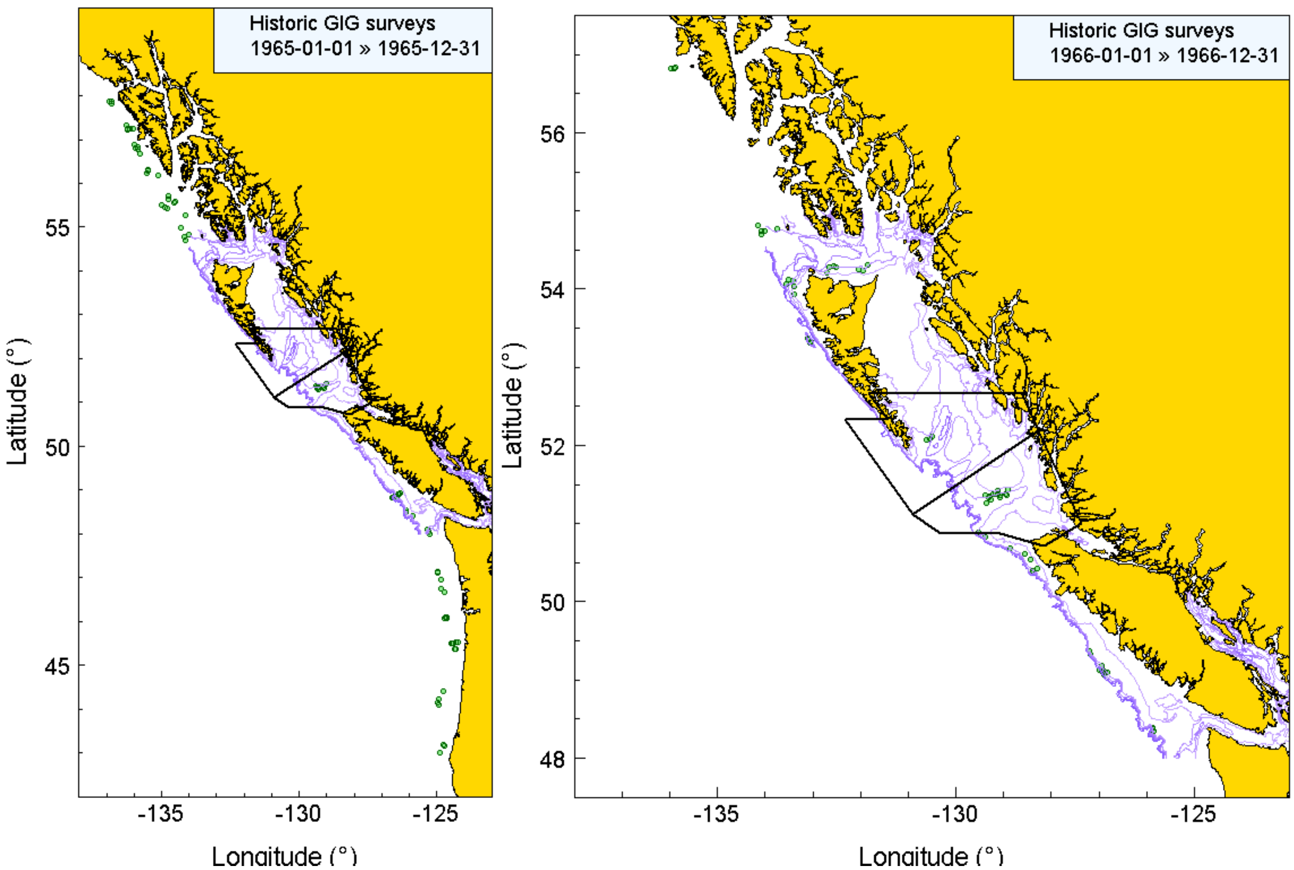


Figure B.1. Extent of the first two GB Reed surveys: [left panel] tow locations for the 1965 survey; [right panel] tow locations for the 1966 survey.

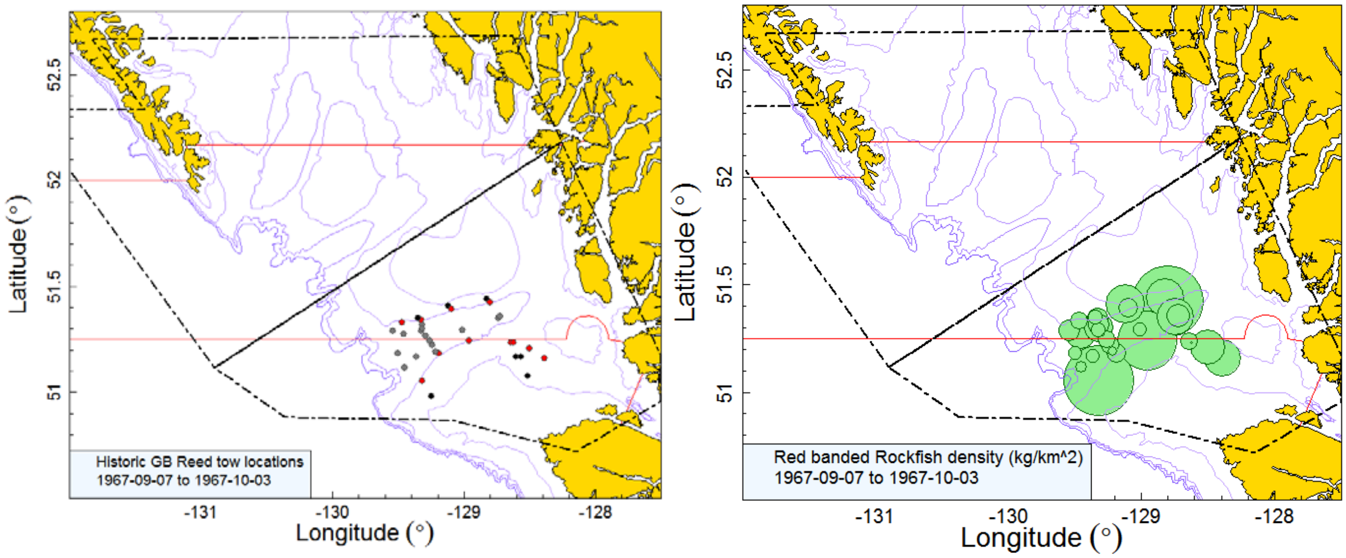


Figure B.2. Valid tow locations and density plots for the historic 1967 Goose Island Gully (GIG) survey. Tow locations are colour-coded by depth range: black=120–183m; red=184-218m; grey=219-300m. Circle sizes in the right-hand density plot scaled across all years (1967, 1969, 1971, 1973, 1976, 1977, 1984, 1994, and 1995), with the largest circle = 2539 kg/km^2 in 1967. Black boundary lines show the extent of the modern Queen Charlotte Sound synoptic survey and the red solid lines indicate the boundaries between PMFC areas 5A, 5B and 5C.

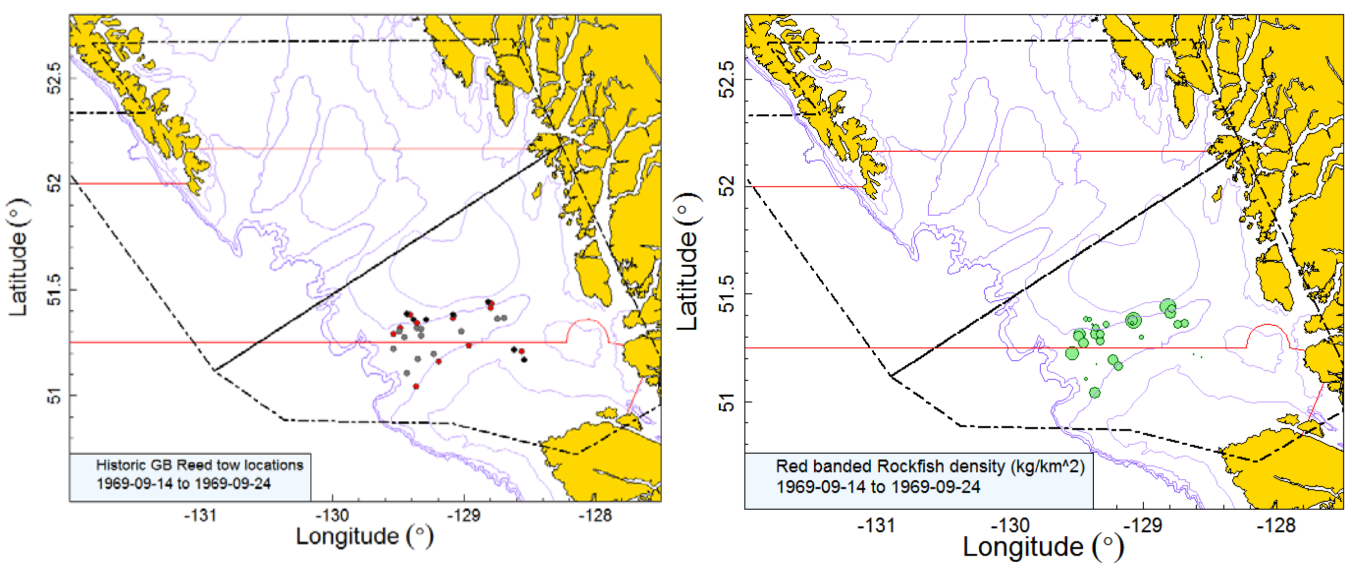


Figure B.3. Tow locations and density plots for the historic 1969 Goose Island Gully (GIG) survey (see Figure B.2 caption).

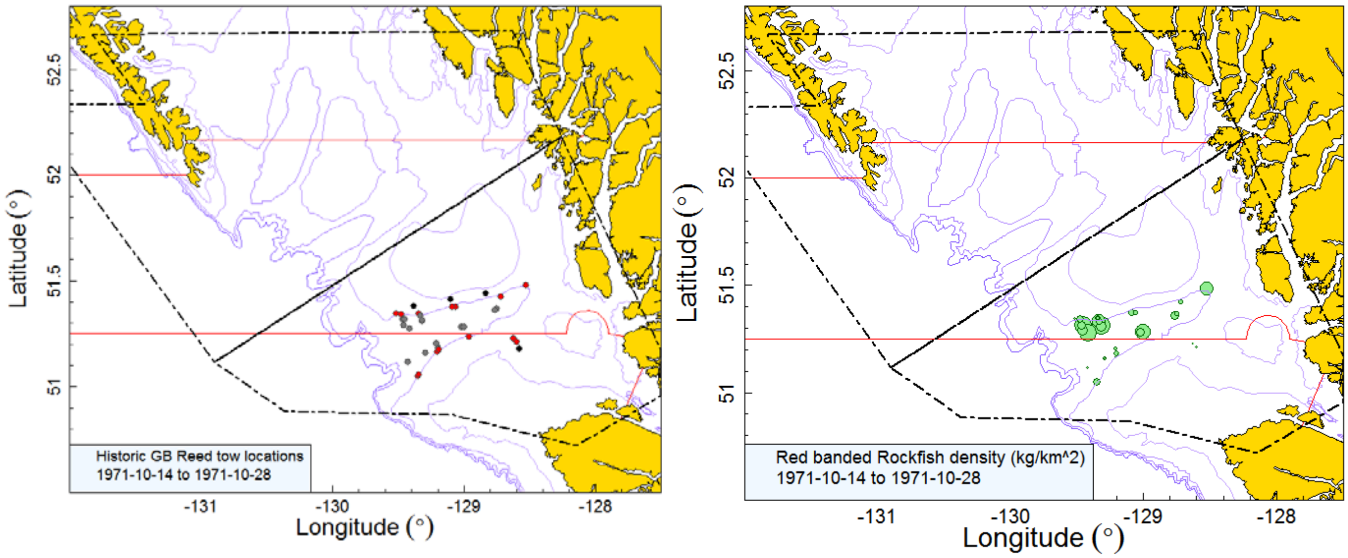


Figure B.4. Tow locations and density plots for the historic 1971 Goose Island Gully (GIG) survey (see Figure B.2 caption).

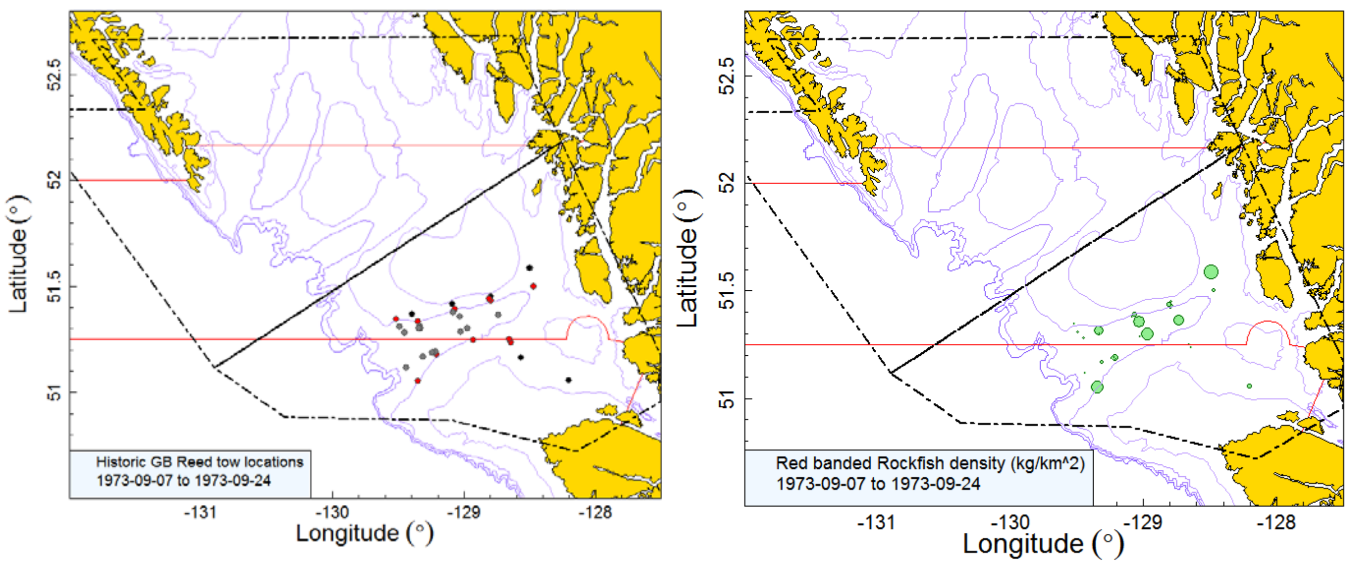


Figure B.5. Tow locations and density plots for the historic 1973 Goose Island Gully (GIG) survey (see Figure B.2 caption).

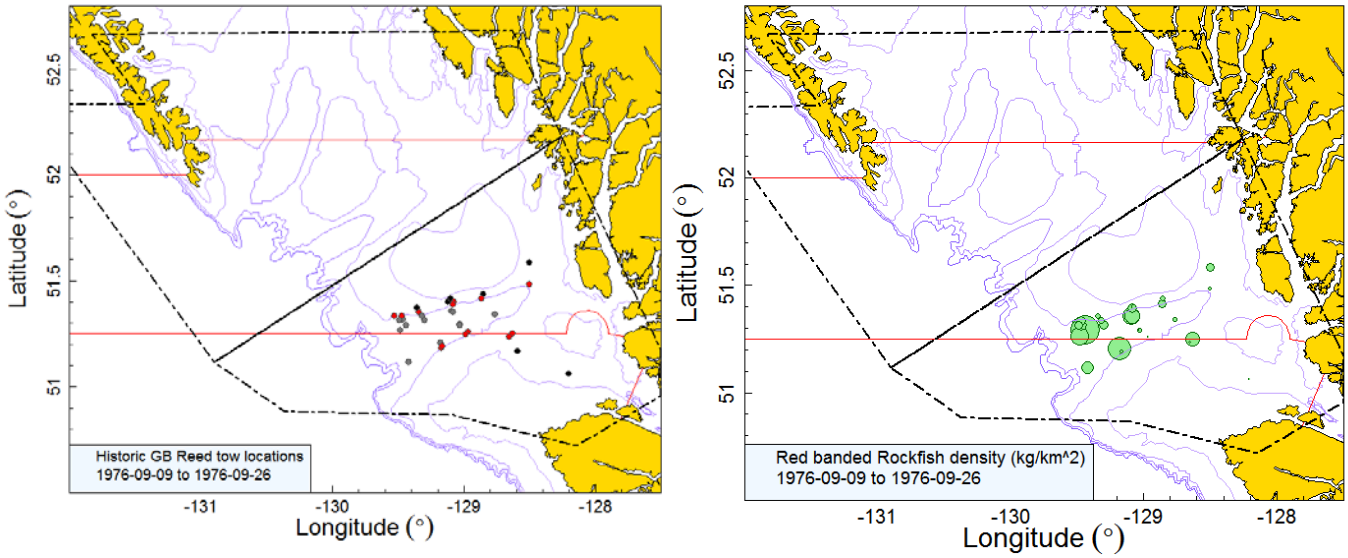


Figure B.6. Tow locations and density plots for the historic 1976 Goose Island Gully (GIG) survey (see Figure B.2 caption).

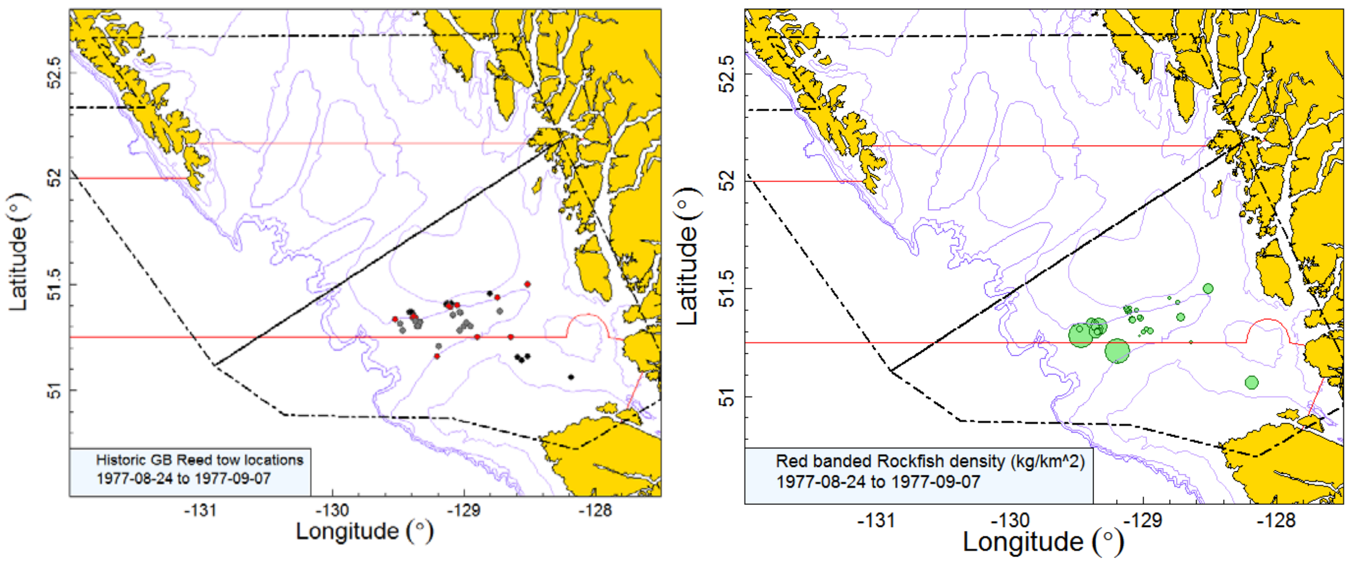


Figure B.7. Tow locations and density plots for the historic 1977 Goose Island Gully (GIG) survey (see Figure B.2 caption).

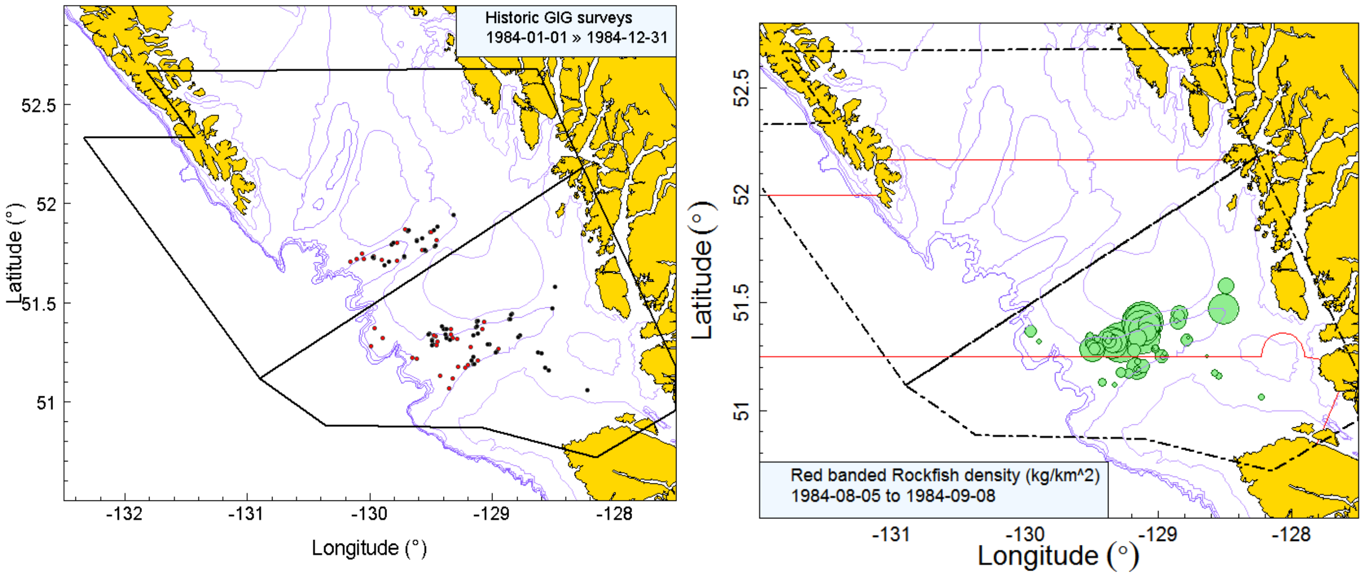


Figure B.8. [left panel]: Tow location colours indicate the vessel fishing rather than depth: black=GB Reed; red=Eastward Ho. Additional locations fished by vessel in Mitchell Gully are also shown; [right panel]: density plot for the historic 1984 Goose Island Gully (GIG) survey (see Figure B.2 caption).

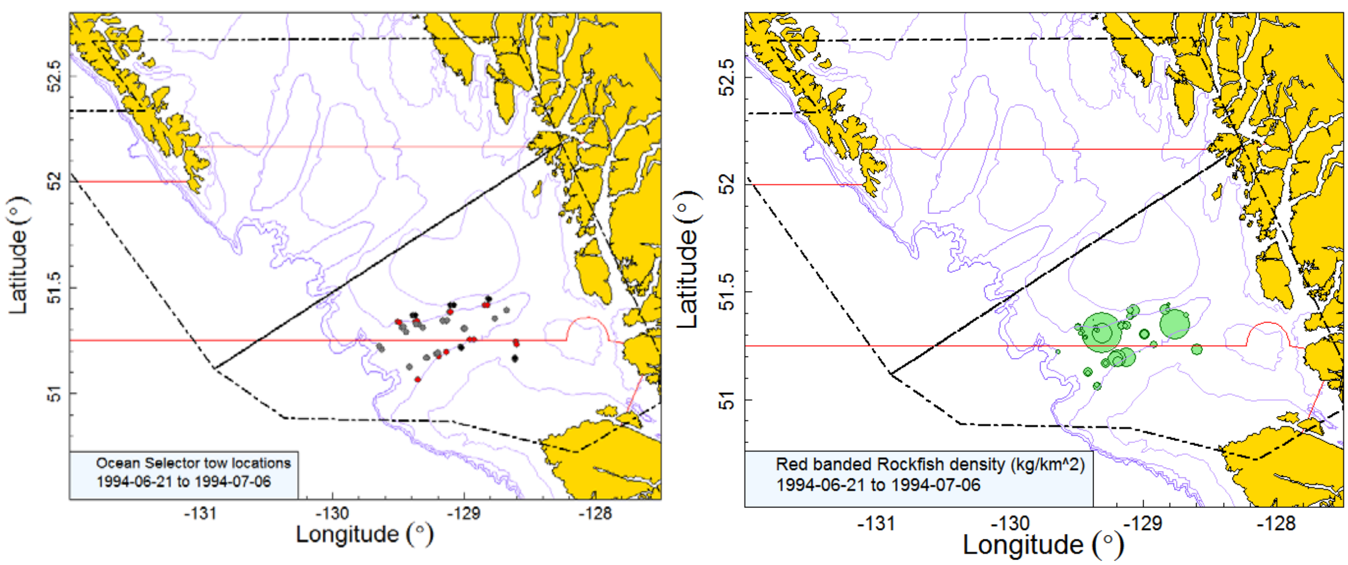


Figure B.9. Tow locations and density plots for the historic 1994 Goose Island Gully (GIG) survey (see Figure B.2 caption).

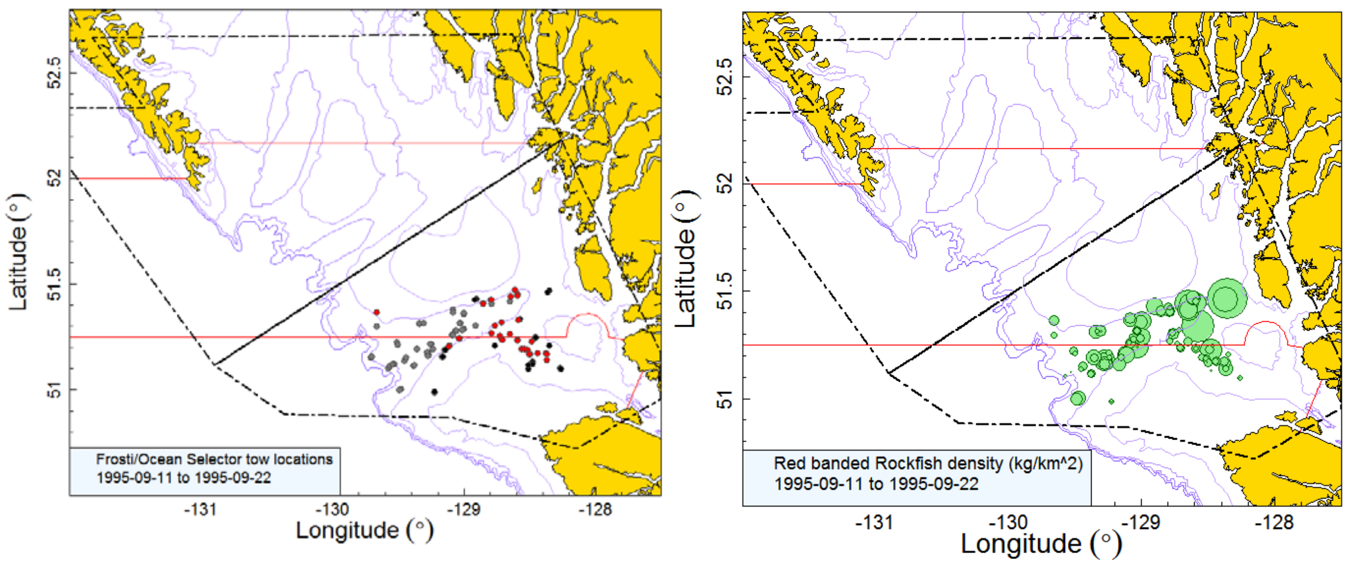


Figure B.10. Tow locations and density plots for the historic 1995 Goose Island Gully (GIG) survey(see Figure B.2 caption).

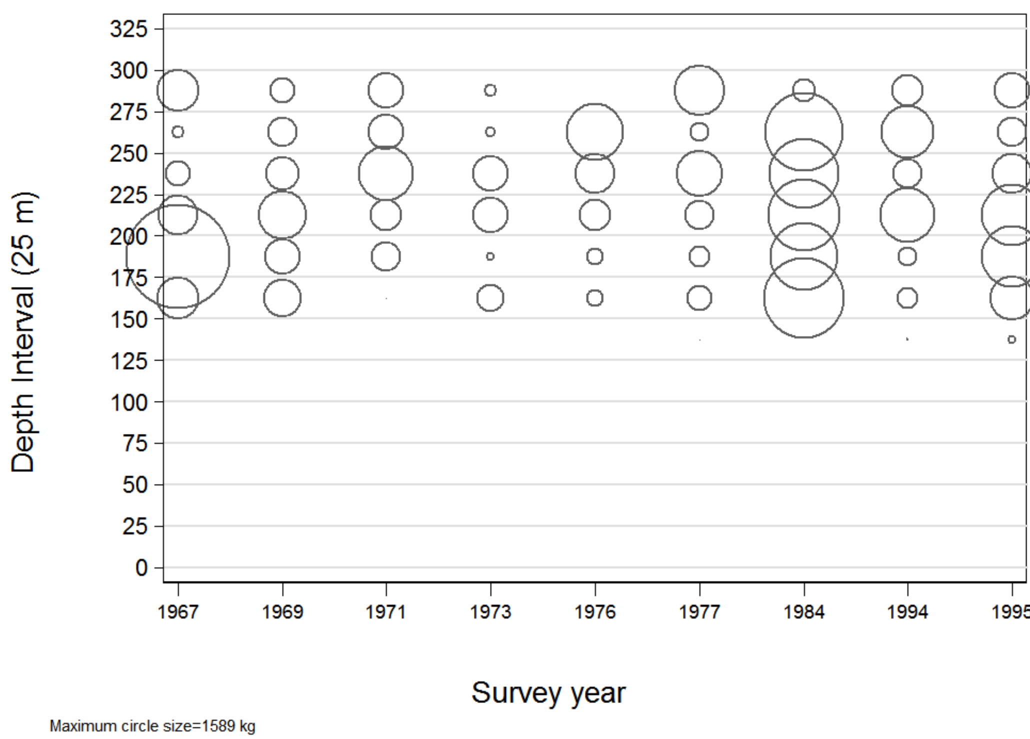


Figure B.11. Distribution of observed catch weights of Redbanded Rockfish (RBR) for the historic Goose Island Gully (GIG) surveys (Table B.3) by survey year and 25 m depth zone. Depth zones are indicated by the mid point of the depth interval and circles in the panel are scaled to the maximum value (1589 kg) in the 175–200 m interval in 1967. The 1% and 99% quantiles for the RBR empirical start of tow depth distribution= 154 m and 296 m respectively.

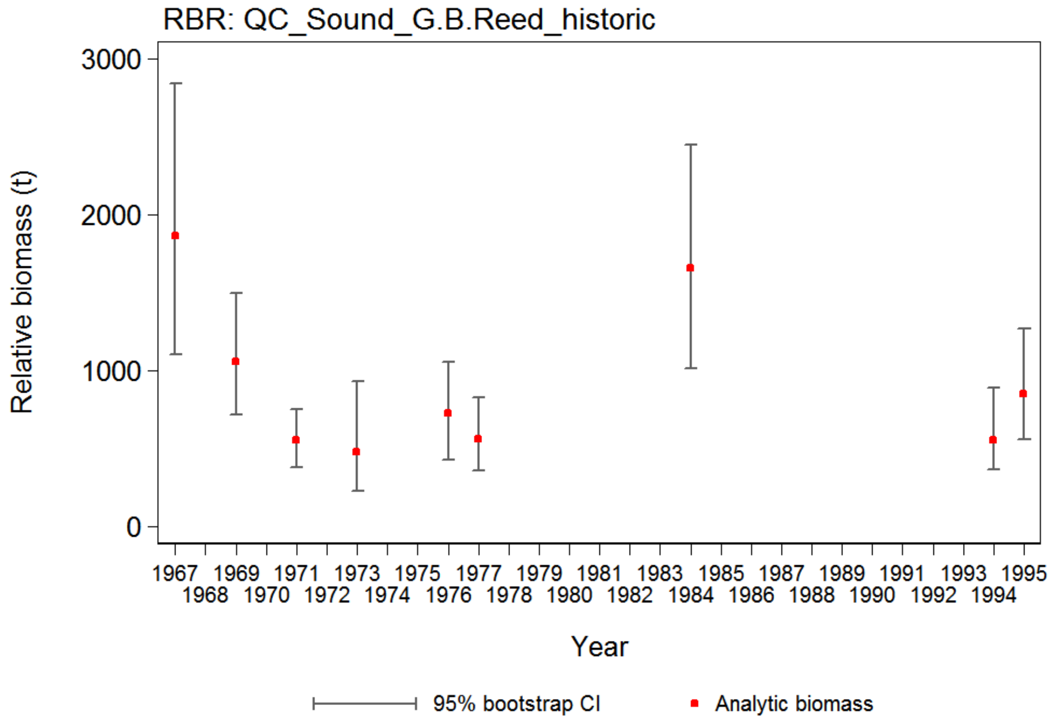


Figure B.12. Plot of biomass estimates for the RBR historic Goose Island Gully (GIG) surveys: 1967 to 1995 (values provided in Table B.4). Bias corrected 95% confidence intervals from 1000 bootstrap replicates are plotted.

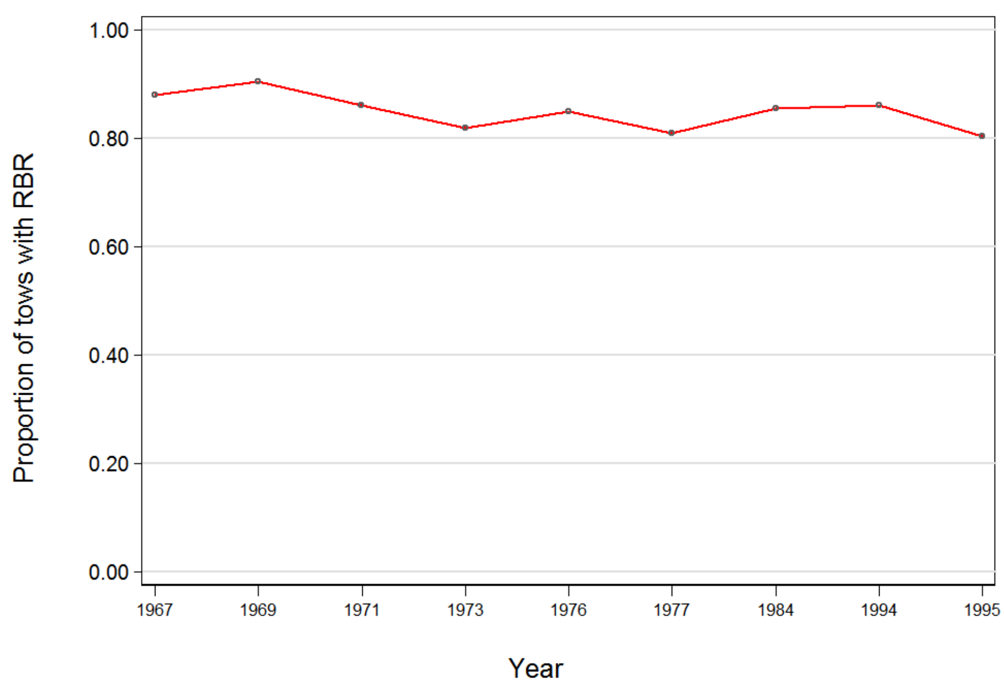


Figure B.13. Proportion of tows by year which contain RBR from the historic Goose Island Gully (GIG) surveys: 1967 to 1995.

B.4 NMFS TRIENNIAL TRAWL SURVEY

B.4.1 Data selection

Tow-by-tow data from the US National Marine Fisheries Service (NMFS) triennial survey covering the Vancouver INPFC (International North Pacific Fisheries Commission) region were provided by (Mark Wilkins, NMFS, Seattle, WA., pers. comm.) for the seven years that the survey worked in BC waters (Table B.5; 1980: Figure B.14; 1983: Figure B.15; 1989: Figure B.16; 1992: Figure B.17; 1995: Figure B.18; 1998: Figure B.19; 2001: Figure B.20). These tows were assigned to strata by the NMFS, but the size and definition of these strata have changed over the life of the survey (Table B.6). The NMFS survey database also identified in which country the tow was located. This information was plotted and checked against the accepted Canada/USA marine boundary: all tows appeared to be appropriately located with respect to country, based on the tow start position (Figure B.14 to Figure B.20). The NMFS designations were accepted for tows located near the marine border.

All usable tows had an associated median net width (with 1-99% quantiles) of 13.4 (11.3-15.7) m and median distance travelled of 2.8 (1.4-3.5) km, allowing for the calculation of the area swept by each tow. Biomass indices and the associated analytical CVs for Redbanded Rockfish were calculated for the total Vancouver INPFC region and for each of the Canadian- and US-Vancouver sub-regions, using appropriate area estimates for each stratum and year (Table B.6). Strata that were not surveyed consistently in all seven years of the survey were dropped from the analysis (Table B.5; Table B.6), allowing the remaining data to provide a comparable set of data for each year (Table B.7).

Table B.5. Number of tows by stratum and by survey year for the NFMS triennial survey. Strata coloured grey(17S, 18N, 27S, 28N,37N, 37S, 38N, 38S, and 39) have been excluded from the analysis due to incomplete coverage across the seven survey years or were from locations outside the Vancouver INPFC area (Table B.6).

Stratum No.	1980		1983		1989		1992		1995		1998		2001	
	CDN	US	CDN	US	CDN	US	CDN	US	CDN	US	CDN	US	CDN	US
10	-	17	-	7	-	-	-	-	-	-	-	-	-	-
11	48	-	-	39	-	-	-	-	-	-	-	-	-	-
12	-	-	38	-	-	-	-	-	-	-	-	-	-	-
17N	-	-	-	-	-	8	-	9	-	8	-	8	-	8
17S	-	-	-	-	-	27	-	27	-	25	-	26	-	25
18N	-	-	-	-	1	-	1	-	-	-	-	-	-	-
18S	-	-	-	-	-	32	-	23	-	12	-	20	-	14
19N	-	-	-	-	58	-	53	-	55	-	48	-	33	-
19S	-	-	-	-	-	4	-	6	-	3	-	3	-	3
27N	-	-	-	-	-	2	-	1	-	2	-	2	-	2
27S	-	-	-	-	-	5	-	2	-	3	-	4	-	5
28N	-	-	-	-	1	-	1	-	2	-	1	-	-	-
28S	-	-	-	-	-	6	-	9	-	7	-	6	-	7
29N	-	-	-	-	7		6	-	7	-	6	-	3	-
29S	-	-	-	-	-	3	-	2	-	3	-	3	-	3
30	-	4	-	2	-	-	-	-	-	-	-	-	-	-
31	7	-	-	11	-	-	-	-	-	-	-	-	-	-
32	-	-	5	-	-	-	-	-	-	-	-	-	-	-
37N	-	-	-	-	-	-	-	-	-	1	-	1	-	1
37S	-	-	-	-	-	-	-	-	-	2	-	1	-	1
38N	-	-	-	-	-	-	-	-	1	-	-	-	-	-
38S	-	-	-	-	-	-	-	-	-	2	-	-	-	3
39	-	-	-	-	-	-	-	-	6	-	4	-	2	-

Stratum No.	1980		1983		1989		1992		1995		1998		2001	
	CDN	US	CDN	US	CDN	US	CDN	US	CDN	US	CDN	US	CDN	US
50	-	5	-	1	-	-	-	-	-	-	-	-	-	-
51	4	-	-	10	-	-	-	-	-	-	-	-	-	-
52	-	-	4	-	-	-	-	-	-	-	-	-	-	-
Total	**59**	**26**	**47**	**70**	**67**	**87**	**61**	**79**	**71**	**68**	**59**	**74**	**38**	**72**

Table B.6. Stratum definitions by year used in the NMFS triennial survey to separate the survey results by country and by INPFC area. Stratum definitions in grey(17S, 18N, 27S, 28N,37N, 37S, 38N, and 38S) are those strata which have been excluded from the final analysis due to incomplete coverage across the seven survey years or because the locations were outside the Vancouver INPFC area.

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

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

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

Survey year	Number of tows			Area surveyed (km^2)		
	CDN waters	US waters	Total	CDN waters	US waters	Total
1995	62	35	97	9,166	4,699	13,865
1998	54	42	96	9,166	4,699	13,865
2001	36	37	73	9,166	4,699	13,865
Total	382	315	697	–	–	–

The stratum definitions used in the 1980 and 1983 surveys were different than those used in subsequent surveys, particularly in Canadian waters (Table B.7). Therefore, the 1980 and 1983 indices were scaled up by the ratio (9166 km^2 / 7399 km^2 = 1.24) of the total stratum areas relative to the 1989 and later surveys so that the coverage from the first two surveys would be comparable to the surveys conducted from 1989 onwards. The tow density was much higher in US waters although the overall number of tows was approximately the same for each country (Table B.7). This occurs because the size of the total area fished in the INPFC Vancouver area was about twice as large in Canadian waters than in US waters (Table B.7). Note that the northern extension of the survey has varied from year to year (Figure B.14 to Figure B.20), but this difference has been compensated for by using a constant survey area for all years and assuming that catch rates in the unsampled areas were the same as in the sampled area.

B.4.2 Methods

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

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

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

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

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

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

The biomass estimates Eq. B.4 and the associated standard errors were adjusted to a constant area covered using the ratios of area surveyed provided in Table B.7. This was required to adjust the Canadian biomass estimates for 1980 and 1983 to account for the smaller area surveyed in those years compared to the succeeding surveys. The 1980 and 1983 biomass estimates from Canadian waters were consequently multiplied by the ratio 1.24 (= 9166 km^2 / 7399 km^2) to make them equivalent to the coverage of the surveys from 1989 onwards.

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

B.4.3 Results

Redbanded Rockfish (RBR) are characterised by sporadic incidence in this survey in this region along with generally low catch tows. The relative large catches in some tows in some years result in relative large CVs for this survey compared to the more northerly surveys. Coverage by depth has been consistent for all seven years of the survey after the exclusion of the deep strata that were not covered in the earlier surveys (Figure B.21). The latter plot shows that this species was mainly found between 141 and 322 m (5 and 95% quantiles of [`bottom_depth`]), with few differences in preferred depth range between years.

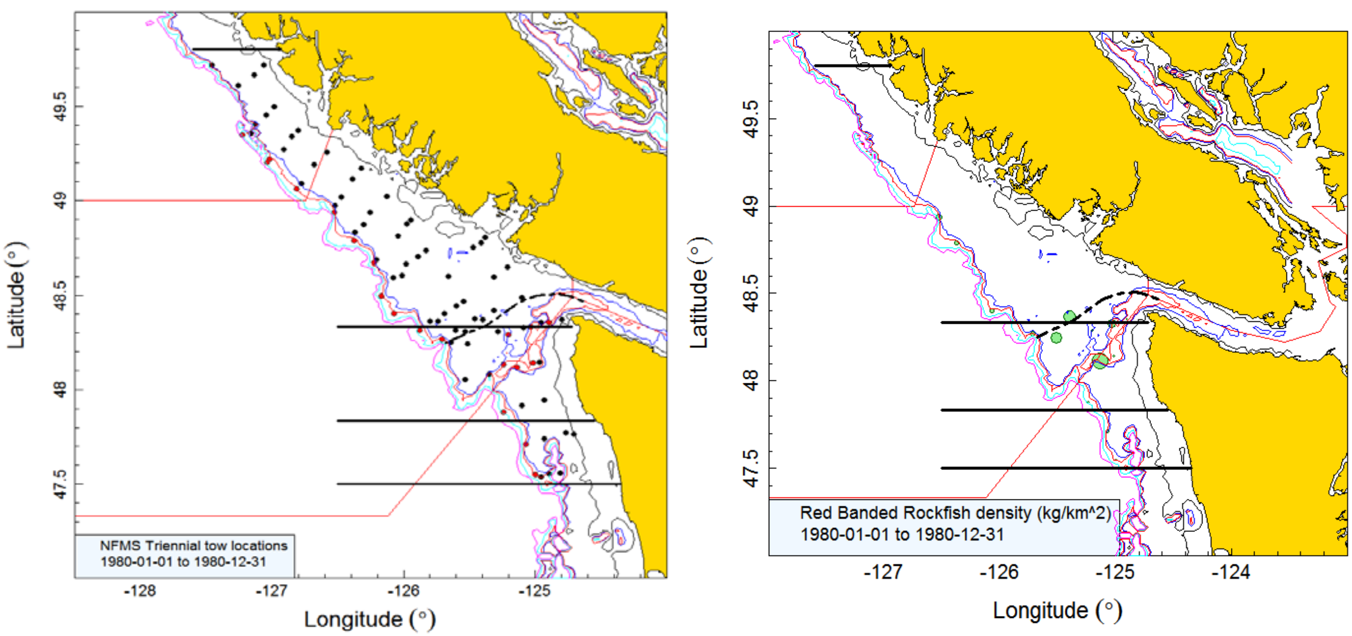


Figure B.14. [left panel]: plot of tow locations in the Vancouver INPFC region for the 1980 NMFS triennial survey in Canadian waters. Tow locations are colour-coded by depth range: black=55–183m; red=184-366m; grey=367-500m. Dashed line shows approximate position of the Canada/USA marine boundary. Horizontal lines are the stratum boundaries: 47°30', 47°50', 48°20' and 49°50'. Tows south of the 47°30' line were not included in the analysis. [right panel]: circle sizes in the density plot are scaled across all years (1980, 1983, 1989, 1992, 1995, 1998, and 2001), with the largest circle = 5354 kg/km^2 in 1983. The red solid lines indicate the boundaries between PMFC areas 3B, 3C and 3D.

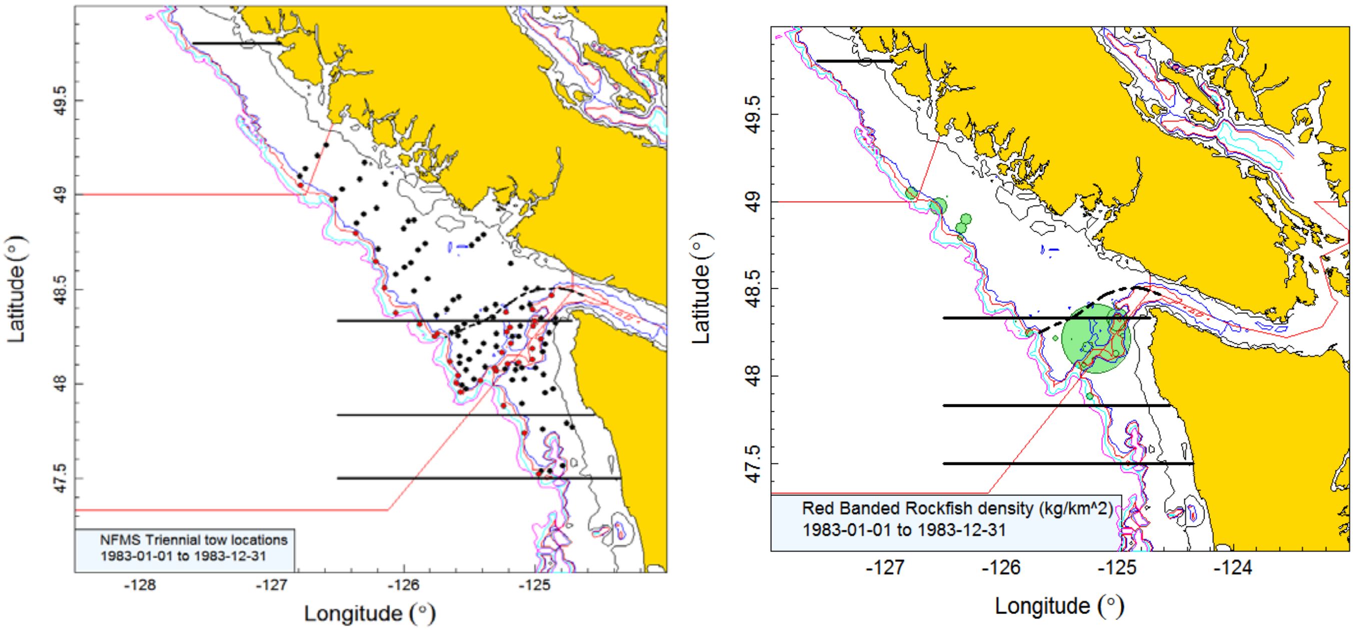


Figure B.15. Tow locations and density plots for the 1983 NMFS triennial survey in Canadian waters (see Figure B.14 caption).

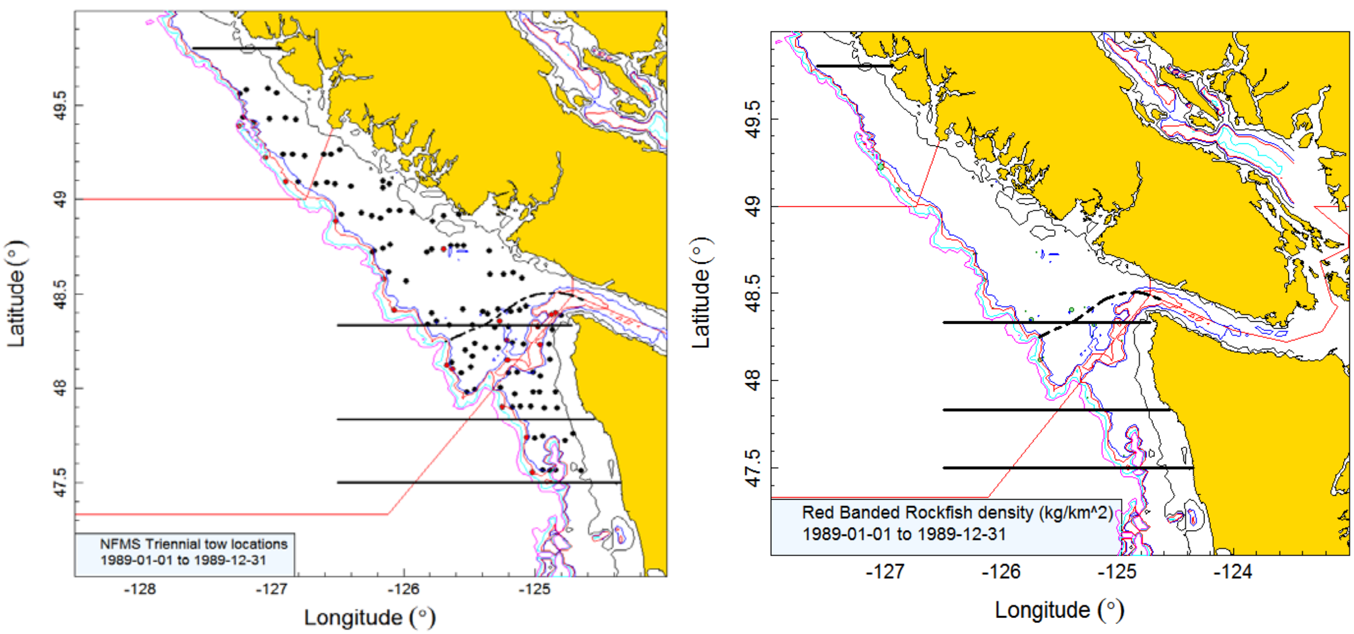


Figure B.16. Tow locations and density plots for the 1989 NMFS triennial survey in Canadian waters (see Figure B.14 caption).

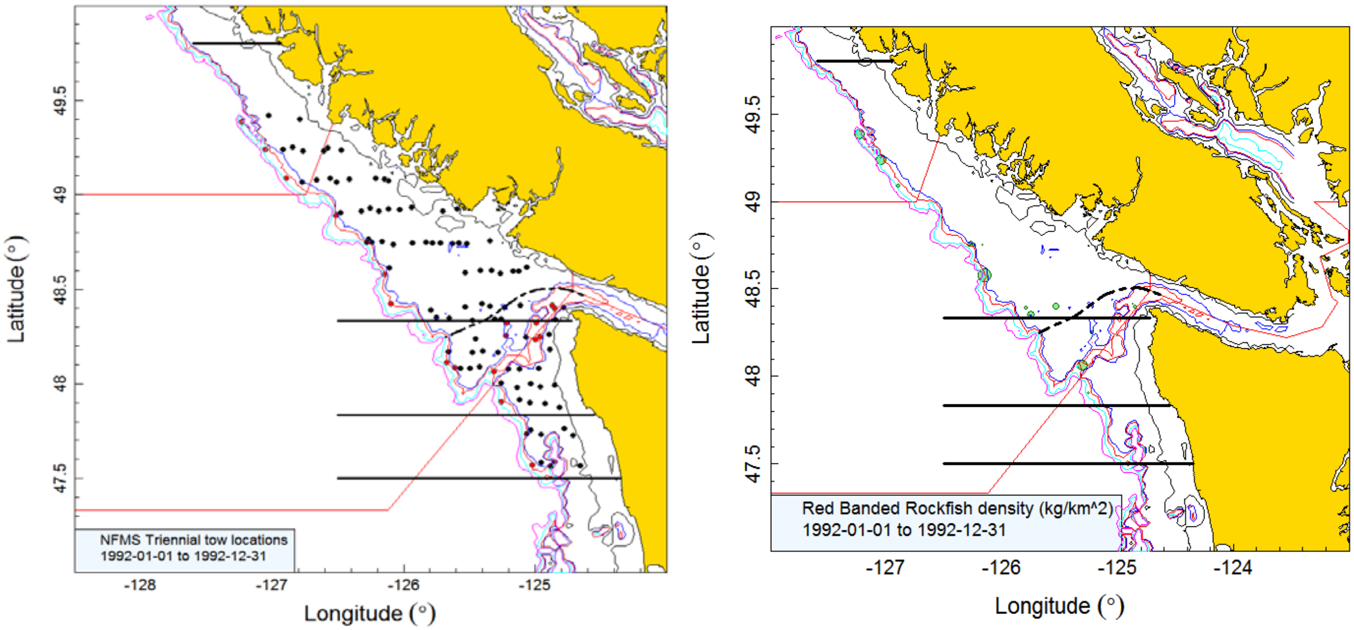


Figure B.17. Tow locations and density plots for the 1992 NMFS triennial survey in Canadian waters (see Figure B.14 caption).

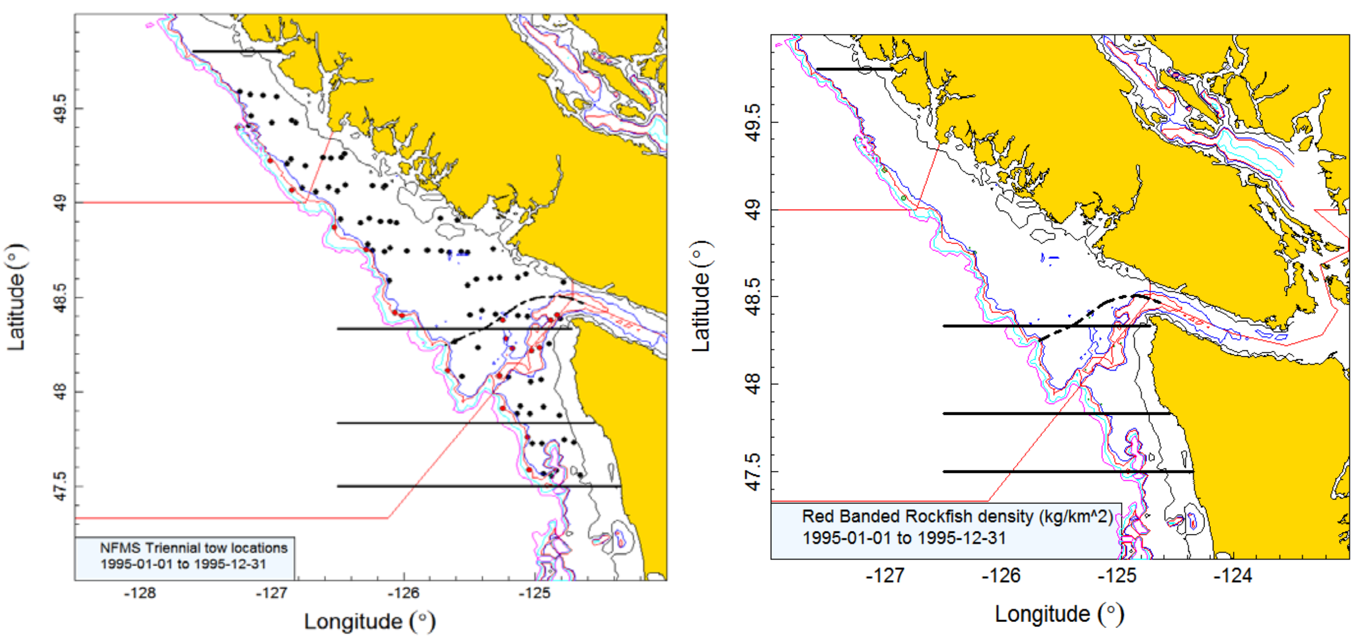


Figure B.18. Tow locations and density plots for the 1995 NMFS triennial survey in Canadian waters (see Figure B.14 caption).

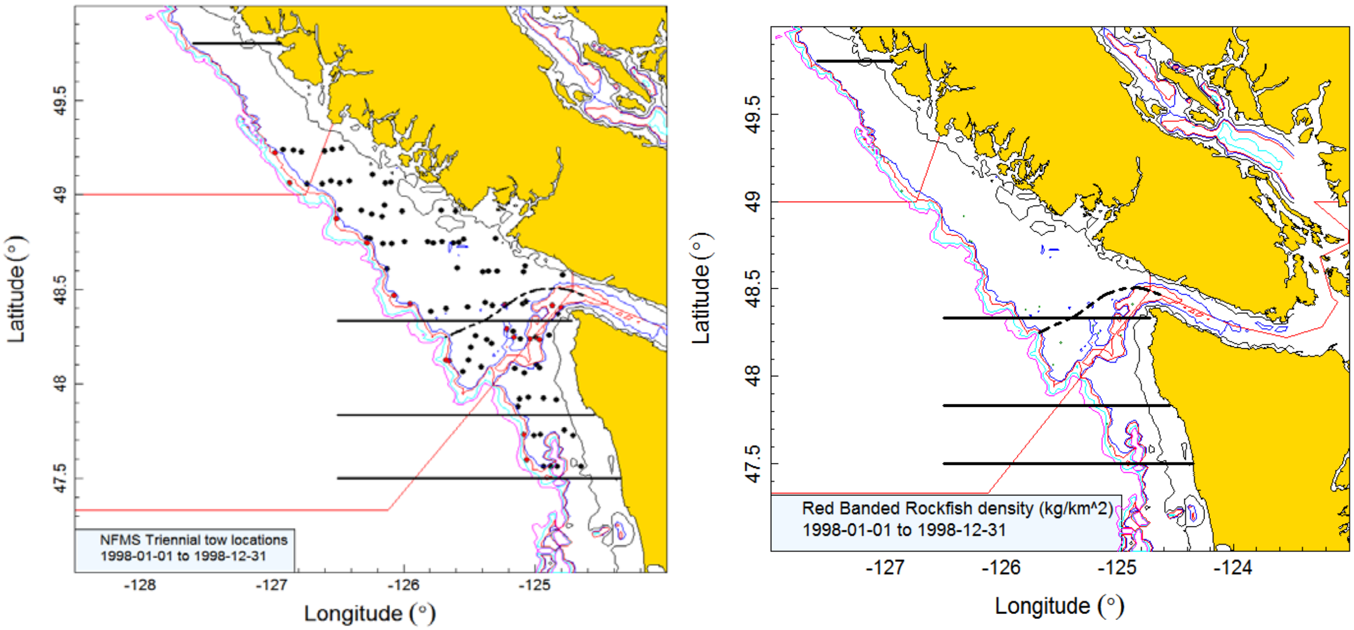


Figure B.19. Tow locations and density plots for the 1998 NMFS triennial survey in Canadian waters (see Figure B.14 caption).

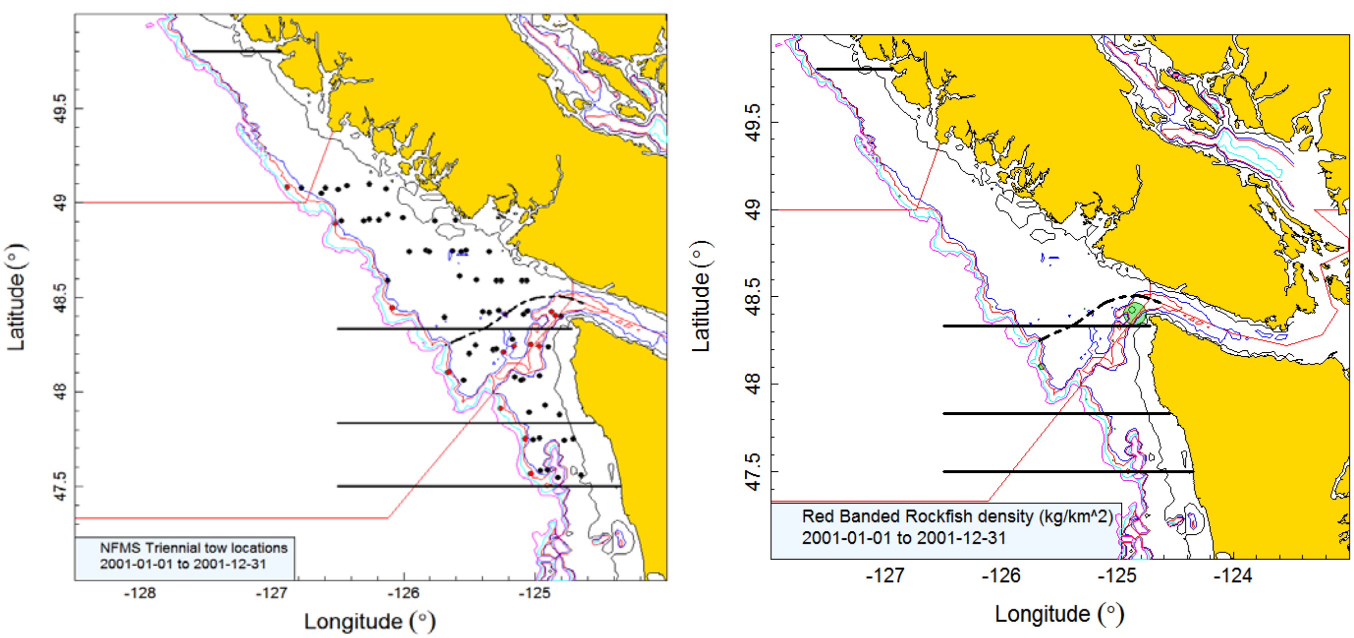


Figure B.20. Tow locations and density plots for the 2001 NMFS triennial survey in Canadian waters (see Figure B.14 caption).

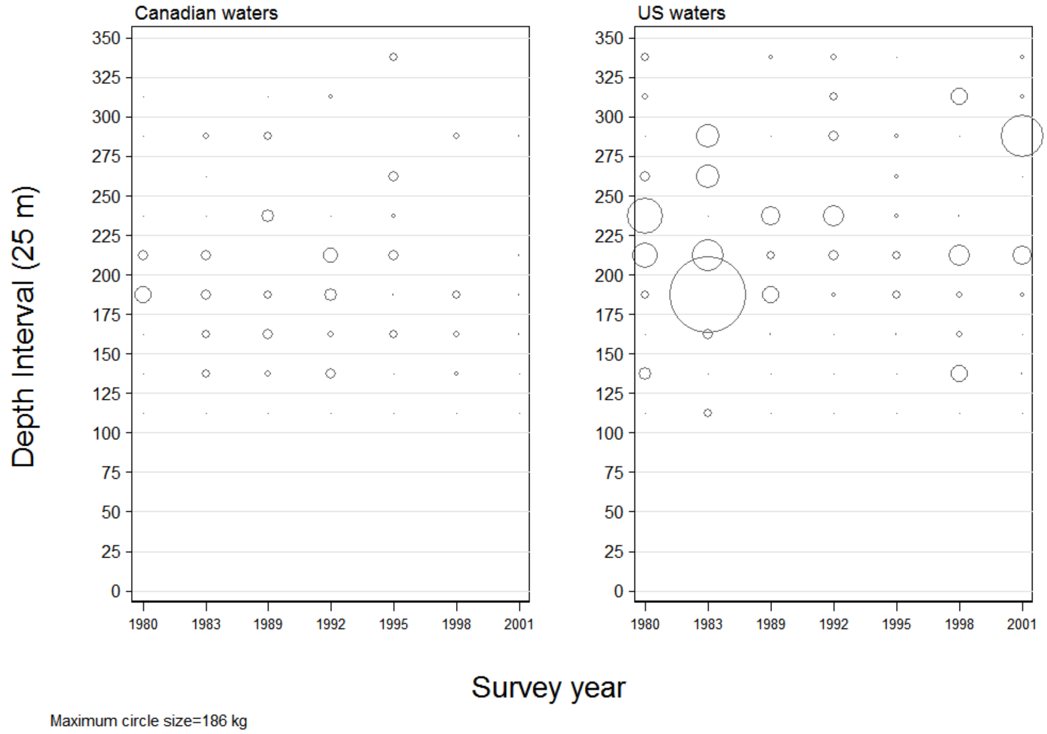


Figure B.21. Distribution of Redbanded Rockfish catch weights for each survey year summarised into 25 m depth intervals for all valid tows (Table B.6) in Canadian and US waters of the Vancouver INPFC area. Depth intervals are labelled with the mid-point of the interval.

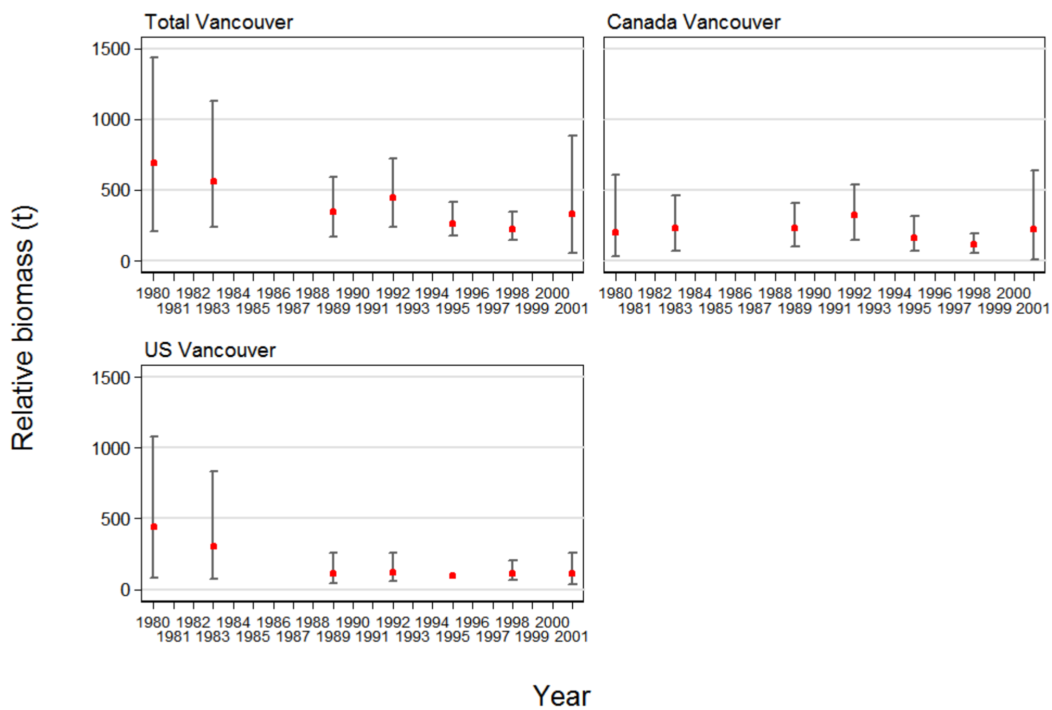


Figure B.22. Biomass estimates for three series of Redbanded Rockfish in the INPFC Vancouver region (total region, Canadian waters only, and US waters only) with 95% bias-corrected error bars estimated from 1000 bootstraps.

Table B.8. Biomass estimates for Redbanded Rockfish in the Vancouver INPFC region (total region, Canadian waters only, and US waters only) with 95% confidence bounds based on the bootstrap distribution of biomass.. Bootstrap estimates are based on 1000 random draws with replacement.

Estimate series	**Year**	**Biomass (**Eq. B.4**)**	**Mean bootstrap biomass**	**Lower bound biomass**	**Upper bound biomass**	**CV bootstrap**	**CV Analytic (**Eq. B.6**)**
Total Vancouver	1980	695.1	680.8	210.7	1,440.9	0.428	0.447
	1983	566.5	551.2	241.3	1,126.5	0.403	0.406
	1989	348.5	338.6	172.6	590.5	0.311	0.308
	1992	445.4	428.7	242.5	721.6	0.283	0.290
	1995	261.2	201.3	174.4	417.8	0.356	0.309
	1998	227.4	212.8	145.9	349.6	0.240	0.230
	2001	335.8	298.4	56.5	887.2	0.672	0.654
Canada Vancouver	1980	199.8	197.4	31.0	607.0	0.682	0.704
	1983	234.7	237.9	70.0	462.3	0.418	0.417
	1989	234.7	235.7	100.9	406.5	0.340	0.357
	1992	323.0	320.9	147.5	540.5	0.308	0.310
	1995	163.1	157.0	66.9	319.4	0.385	0.392
	1998	113.7	111.5	56.9	191.8	0.284	0.280
	2001	224.3	204.3	11.6	641.6	0.774	0.758
US Vancouver	1980	447.2	436.6	77.8	1,082.0	0.534	0.552
	1983	306.4	290.4	74.8	830.3	0.606	0.605
	1989	113.8	103.0	44.2	255.3	0.464	0.407
	1992	122.4	107.8	57.3	258.9	0.428	0.386
	1995	98.1	44.3	–	–	0.338	0.283
	1998	113.7	101.3	62.5	200.5	0.333	0.311
	2001	111.5	94.2	36.3	258.7	0.532	0.472

Redbanded Rockfish biomass estimates in both US waters were characterised by a declining trend from 1980 to 2001 while the indices from the Canadian waters tended to be flat (Figure B.22; Table B.8). The relative error estimates are moderate to large, with the lowest relative error occurring at 0.24 in 1998 for Total Vancouver and the greatest at 0.77 in 2001 for the Canada Vancouver (Table B.8). The relative error estimates for the sub-divided national strata tend to be higher that for Total Vancouver in the same years. Note that the bootstrap estimates of relative error do not include any uncertainty with respect to the ratio expansion required to make the 1980 and 1983 survey estimates comparable to the 1989 and later surveys. Therefore, it is likely that the true uncertainty for this series is even greater than estimated.

One hundred and twenty-five tows of the nearly 700 valid tows captured RBR (18%), with most tows under than 100 kg. The largest tow was 183 kg in 1983. The proportion of tows which contained Redbanded Rockfish is about the same in US waters as in Canadian waters, with the US proportions by year ranging from 12 to 35% (mean=21%) while the equivalent Canadian values are 11–20% and a mean value of 16% (Figure B.23). Neither region shows a variable or increasing trend in this statistic. The incidence of RBR in this survey is lower than for the synoptic survey operating in the 2000s off the west coast of Vancouver Island, with the latter survey having over 30% of the tows containing RBR.

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

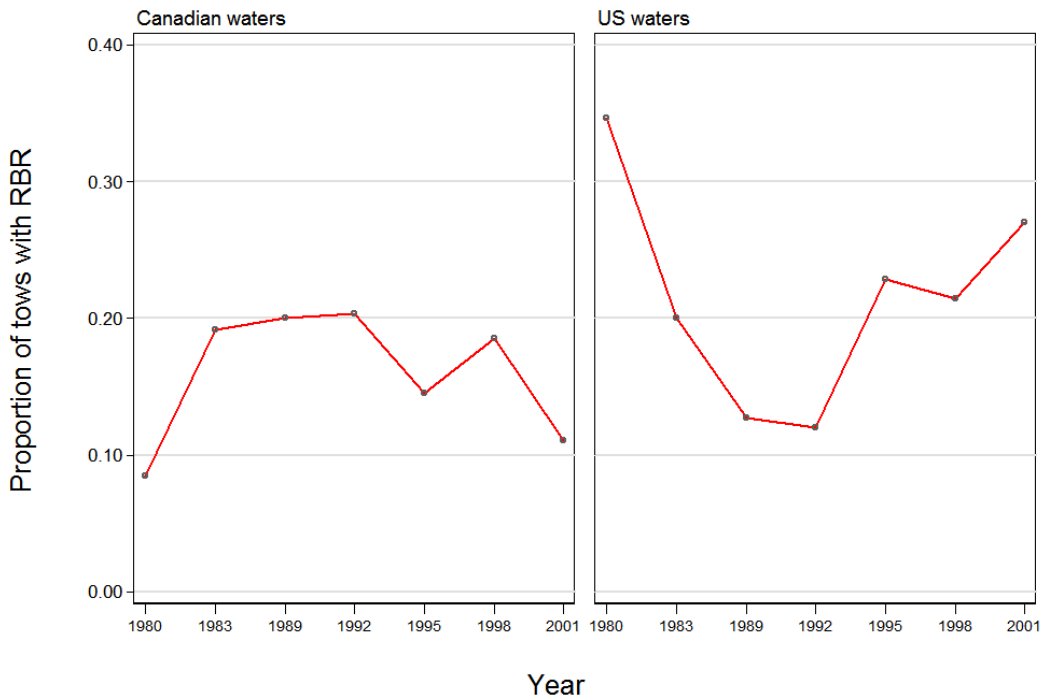


Figure B.23. Proportion of tows with Redbanded Rockfish by year for the Vancouver INPFC region (Canadian and US waters).

B.5 QUEEN CHARLOTTE SOUND SHRIMP TRAWL SURVEY

B.5.1 Data selection

This survey covers the SE corner of QCS extending westward from Calvert Island and Rivers Inlet into the Goose Island Gully. Figure B.24 to Figure B.38 provide the tow locations used in the analysis and the RBR relative density for each of the 15 survey years from 1999 to 2013. No survey was conducted in 2014. There are also tows providing coverage between Calvert Island and the mainland. Five vessels took part in the first year that the survey was conducted (1998) and the timing in that year was later than in subsequent years (July instead of May; Table B.9). It was decided to discard this initial survey year, given the apparent exploratory nature of the design and the potential for non-comparability among vessels in the same year and with subsequent surveys. After the initial year, the survey has been conducted routinely by the *W.E. Ricker* (except in 2005 when the *Frosti* was used) in May or early June. This assessment uses all years from1999 onwards.

The survey is divided into three areal strata: stratum 109 lying to the west of the outside islands and extending into Goose Island Gully; stratum 110 lying to the south of Calvert Island and stratum 111 lying between Calvert Island and the mainland (Figure B.24). Stratum 111 has been discarded as its location does not provide good habitat for rockfish species. The majority of tows occur in stratum 109 (the larger of the two remaining strata) while only a few are placed in Stratum 110 (Figure B.24). Only tows with usability codes of 1 (usable), 2 (fail, but all data usable), and 6 (gear torn, but all data usable) were included in the biomass estimate. Over 1000 usable tows have been conducted by this survey over the 15 available survey years (Table B.10).

These data were analysed using Eq. B.1 to Eq. B.6, which assume that tow locations were selected randomly within a stratum relative to the biomass of RBR, using the area stratification definition in Table B.10. One thousand bootstrap replicates with replacement were made on the survey data to estimate bias corrected 95% confidence regions for each survey year (Efron, 1982).

A doorspread density value (Eq. B.3) was generated for each tow based on the catch of RBR, an arbitrary doorspread (25 m) for the tow, and the distance travelled. The distance travelled was determined at the time of the tow, based on the bottom contact time (J. Boutillier, DFO, Nanaimo, B.C., pers. comm.). The few missing values for this field were filled in by multiplying the vessel speed and the tow time. All tows were used regardless of depth because this survey, unlike the west coast Vancouver Island shrimp survey, has consistently sampled depths up to about 240 m (Figure B.39), so there was no need to truncate the tows at depth to ensure comparability across survey years.

Table B.9. Number of sets made by each vessel involved in the QCS shrimp trawl by month and survey year. All sets north of 50°N are included, not just sets used in the analysis.

	Month			
Vessel and Year	**May**	**Jun**	**Jul**	**Total**
Frosti				
2005	54	-	-	54
Ocean Dancer				
1998	-	-	18	18
Pacific Rancher				
1998	-	-	18	18
Parr Four				
1998	-	-	17	17
W. E. Ricker				
1999	-	83	-	83
2000	84	-	-	84
2001	72	-	-	72
2002	72	-	-	72
2003	63	-	-	63
2004	65	-	-	65
2006	68	-	-	68
2007	65	-	-	65
2008	69	-	-	69
2009	66	-	-	66
2010	59	11	-	70
2011	67	-	-	67
2012	67	-	-	67
2013	67	-	-	67
Westerly Gail				
1998	-	-	21	21
Western Clipper				
1998	-	-	18	18

Table B.10. Stratum designations and number of useable tows, for the QCS shrimp survey from 1999 to 2013.

Survey year	Stratum 109	Stratum 110	Total
1999	72	10	82
2000	76	8	84
2001	65	7	72
2002	65	7	72
2003	57	6	63
2004	59	6	65
2005	41	6	47
2006	61	6	67
2007	60	5	65
2008	63	6	69
2009	57	7	64
2010	64	6	70
2011	61	6	67
2012	61	6	67
2013	61	6	67
Total	923	98	1,021
Area (km^2)	2,142	159	2,301

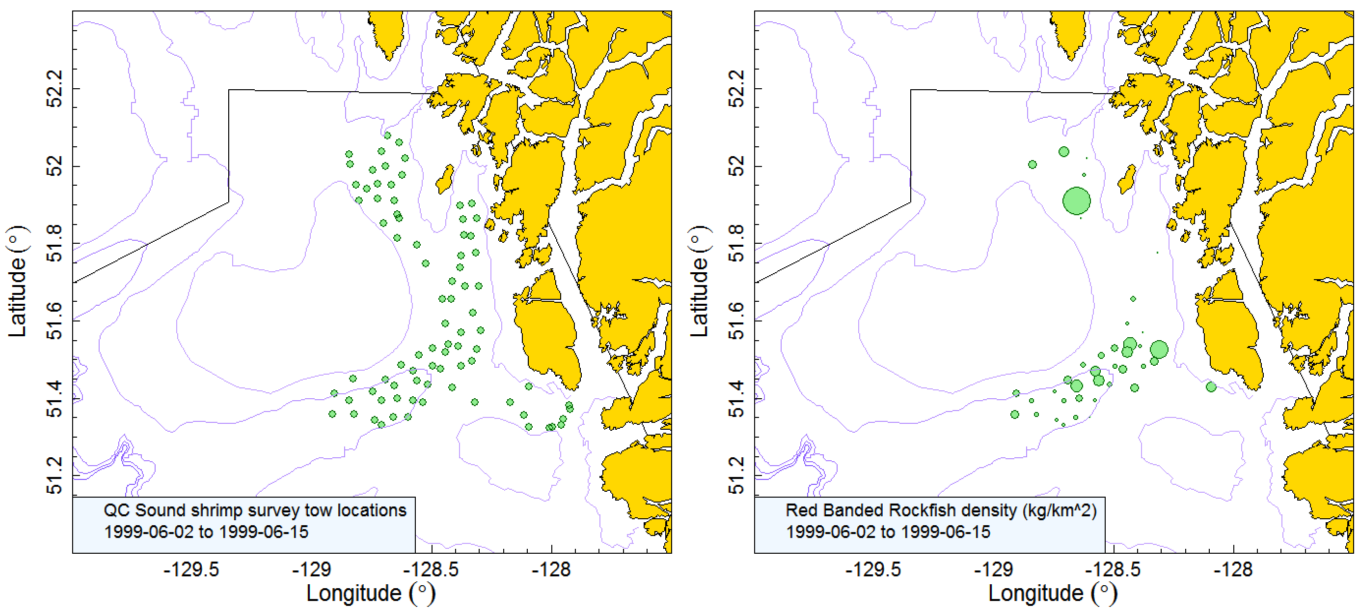


Figure B.24. Valid tow locations and density plots for the 1999 Queen Charlotte Sound shrimp trawl survey (stratum boundaries between 109 and 110 are not available). Circle sizes in the right-hand density plot scaled across all years (1999–2013), with the largest circle = 2395 kg/km^2 in 2011. The black solid line shows the boundary between the North and South strata of the Queen Charlotte Sound synoptic survey.

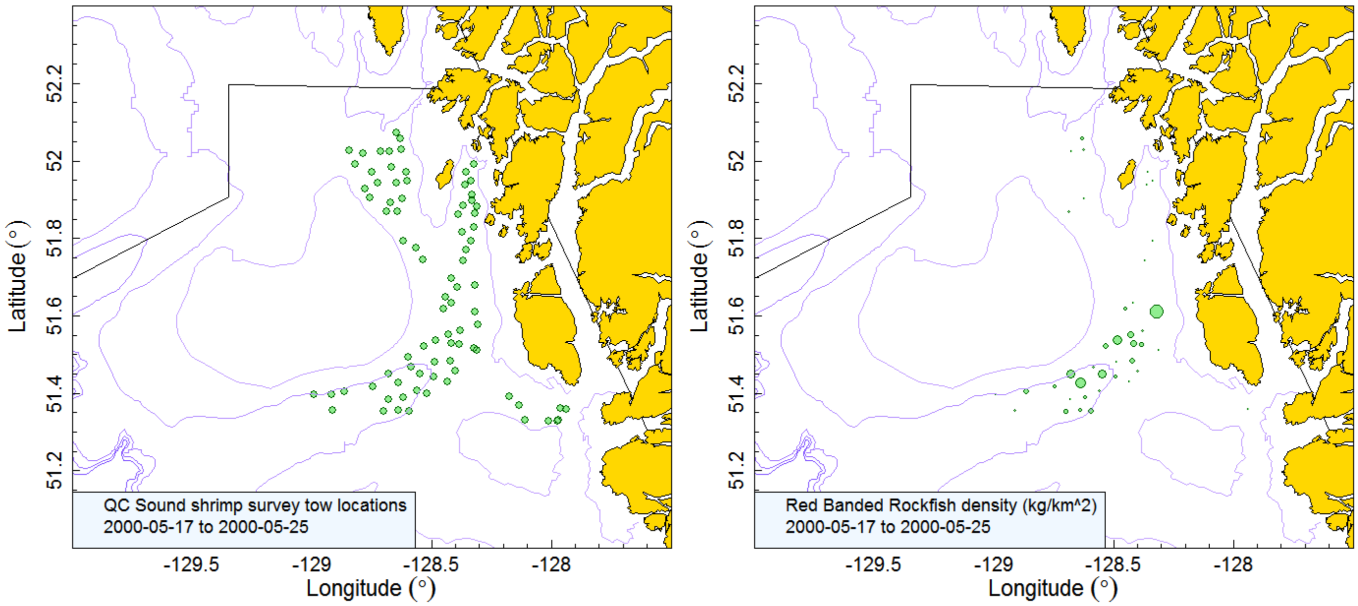


Figure B.25. Tow locations and density plots for the 2000 Queen Charlotte Sound shrimp trawl survey (see Figure B.24 caption).

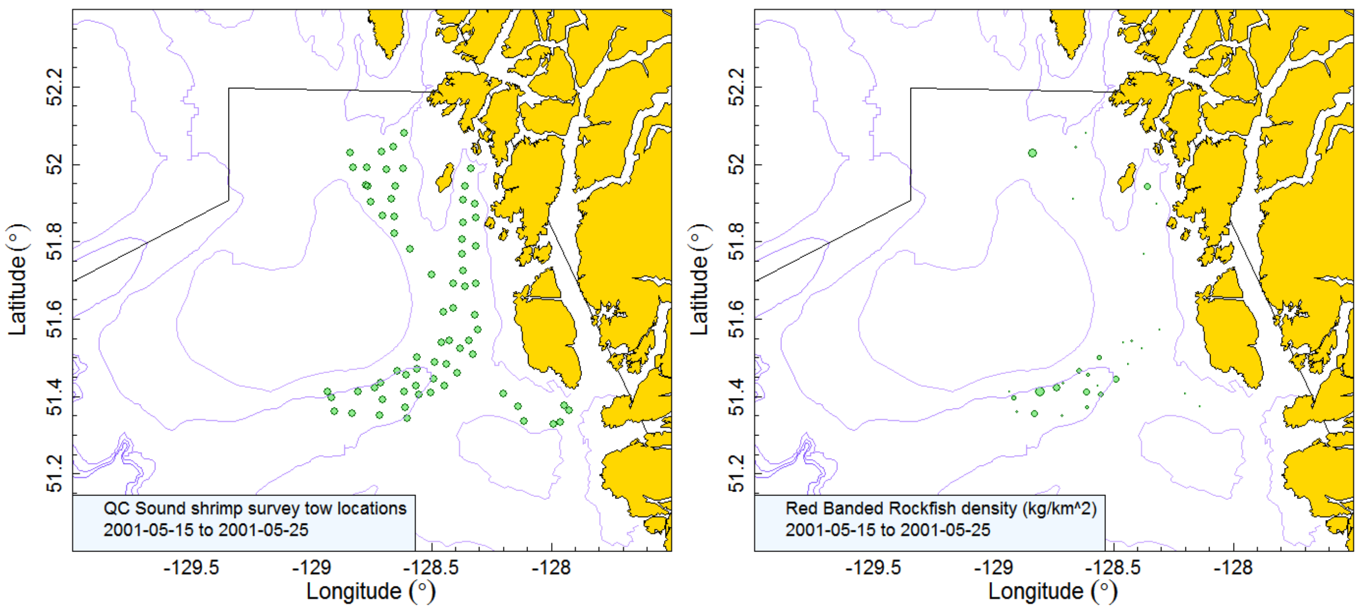


Figure B.26. Tow locations and density plots for the 2001 Queen Charlotte Sound shrimp trawl survey (see Figure B.24 caption).

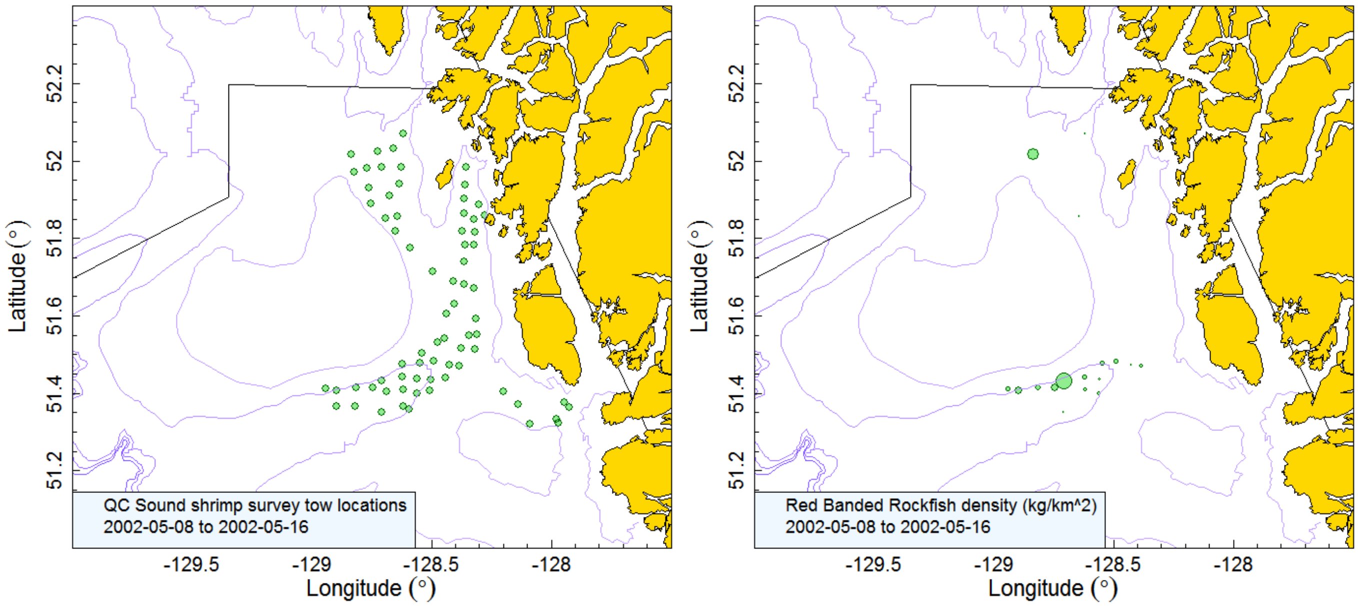


Figure B.27. Tow locations and density plots for the 2002 Queen Charlotte Sound shrimp trawl survey (see Figure B.24 caption).

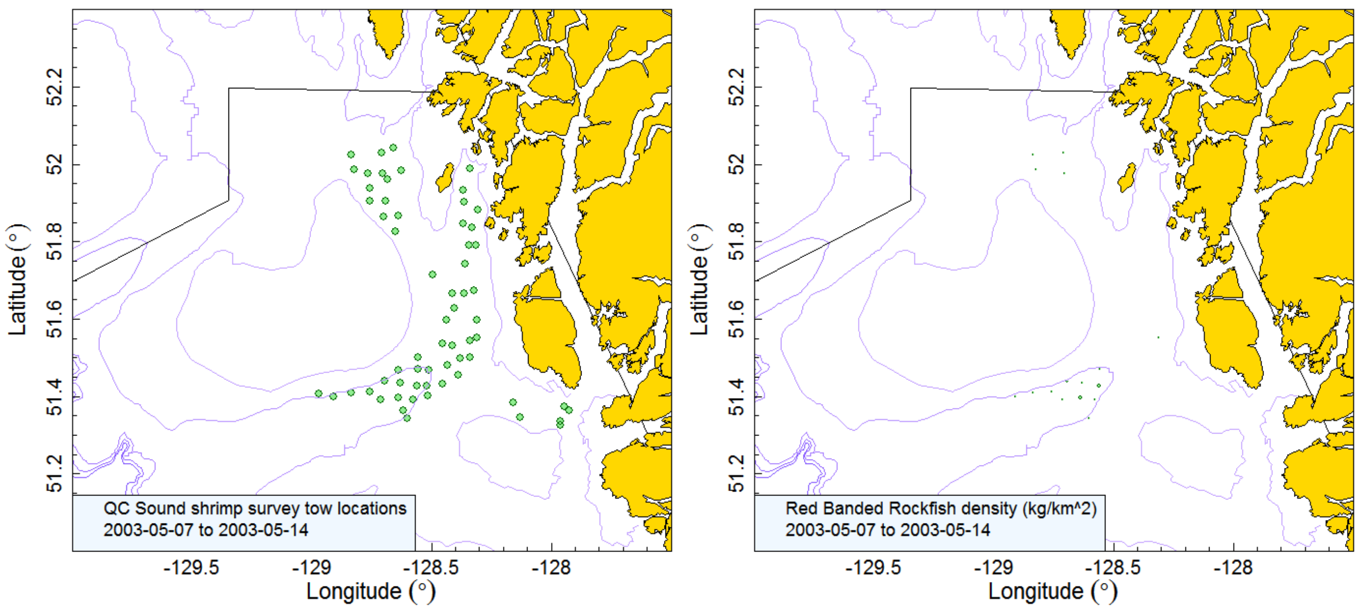


Figure B.28. Tow locations and density plots for the 2003 Queen Charlotte Sound shrimp trawl survey (see Figure B.24 caption).

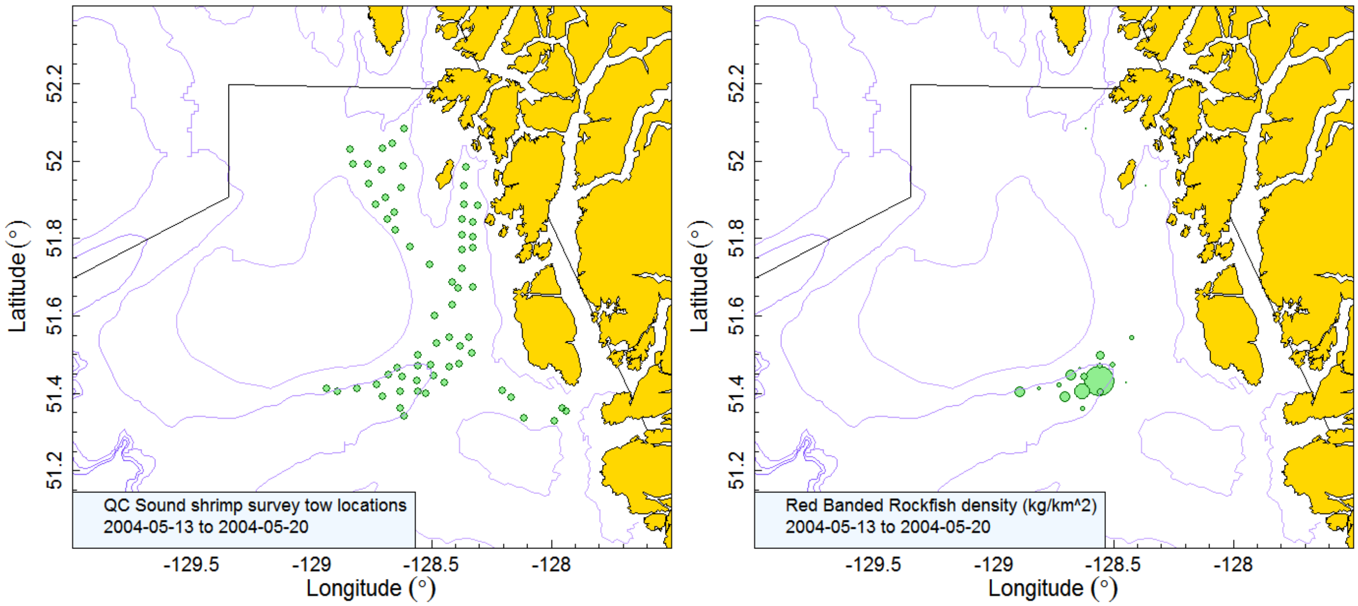


Figure B.29. Tow locations and density plots for the 2004 Queen Charlotte Sound shrimp trawl survey (see Figure B.24 caption).

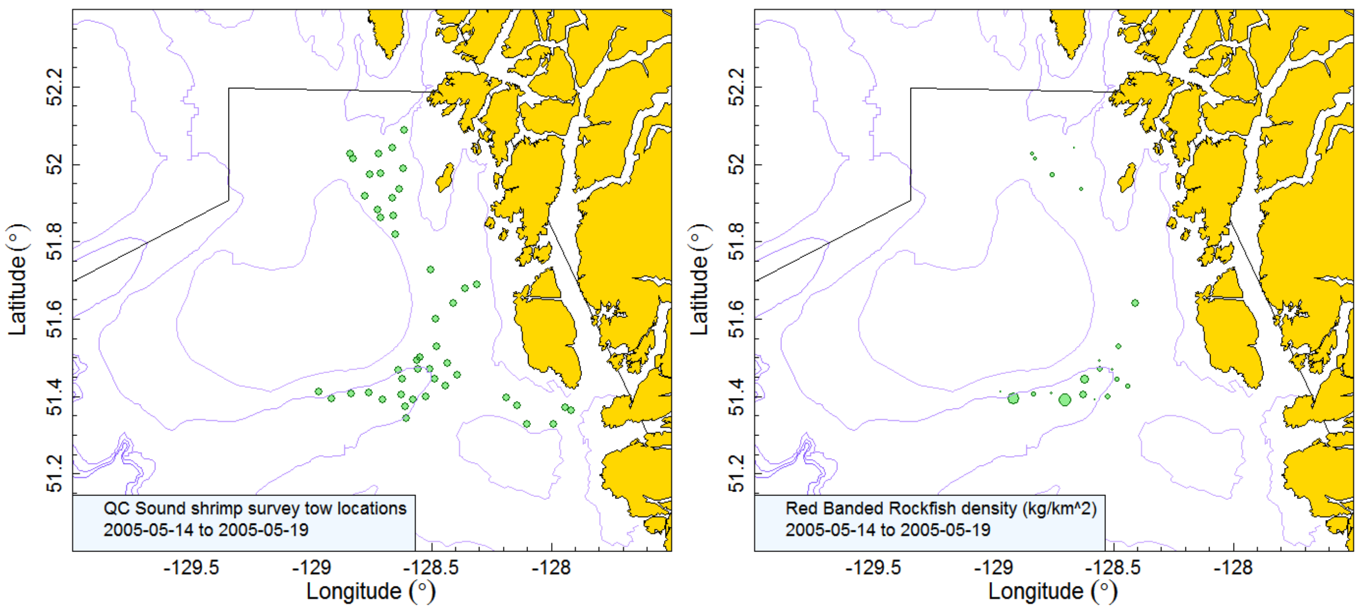


Figure B.30. Tow locations and density plots for the 2005 Queen Charlotte Sound shrimp trawl survey (see Figure B.24 caption).

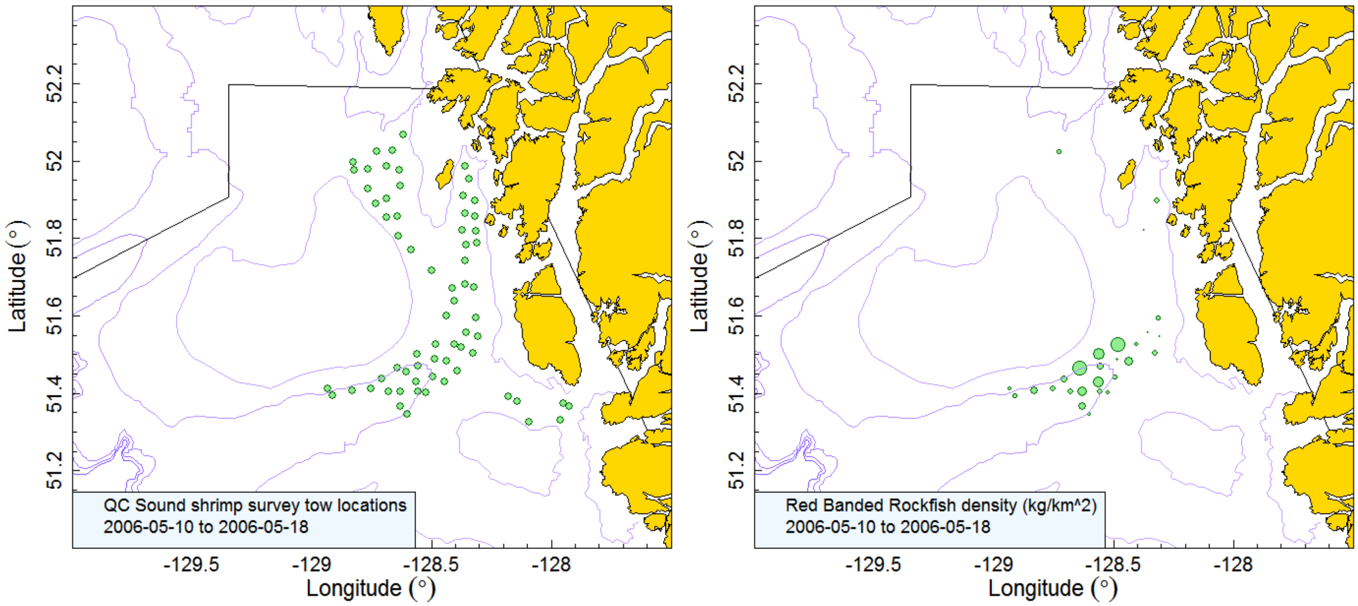


Figure B.31. Tow locations and density plots for the 2006 Queen Charlotte Sound shrimp trawl survey (see Figure B.24 caption).

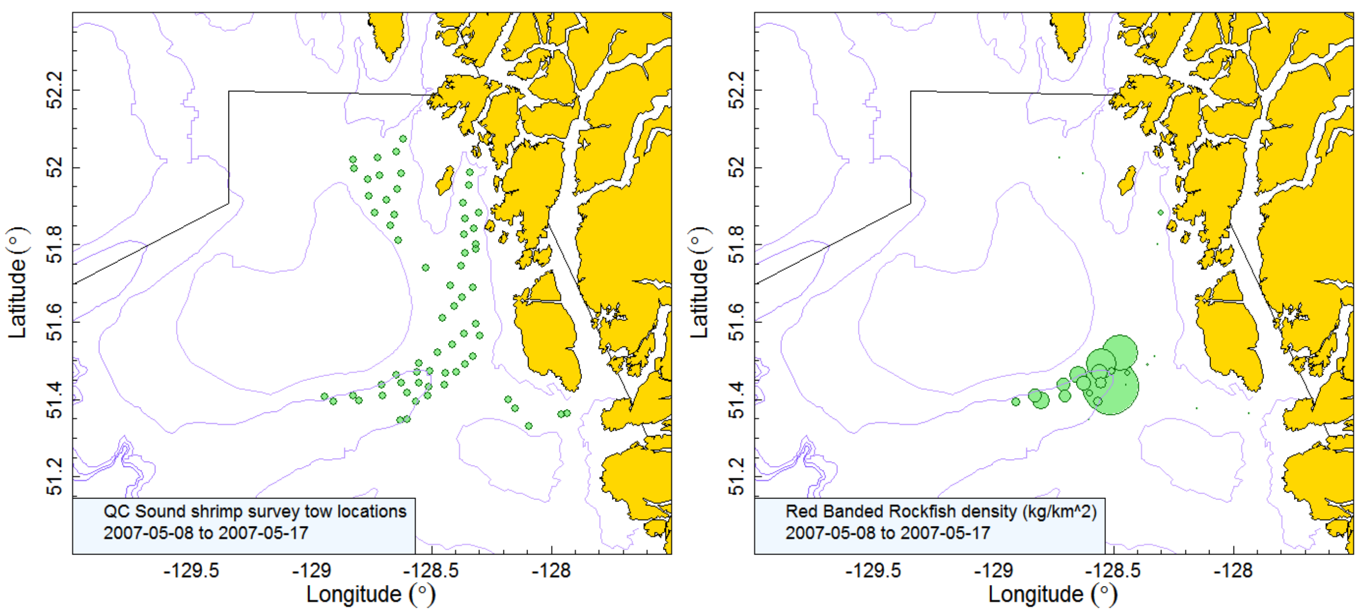


Figure B.32. Tow locations and density plots for the 2007 Queen Charlotte Sound shrimp trawl survey (see Figure B.24 caption).

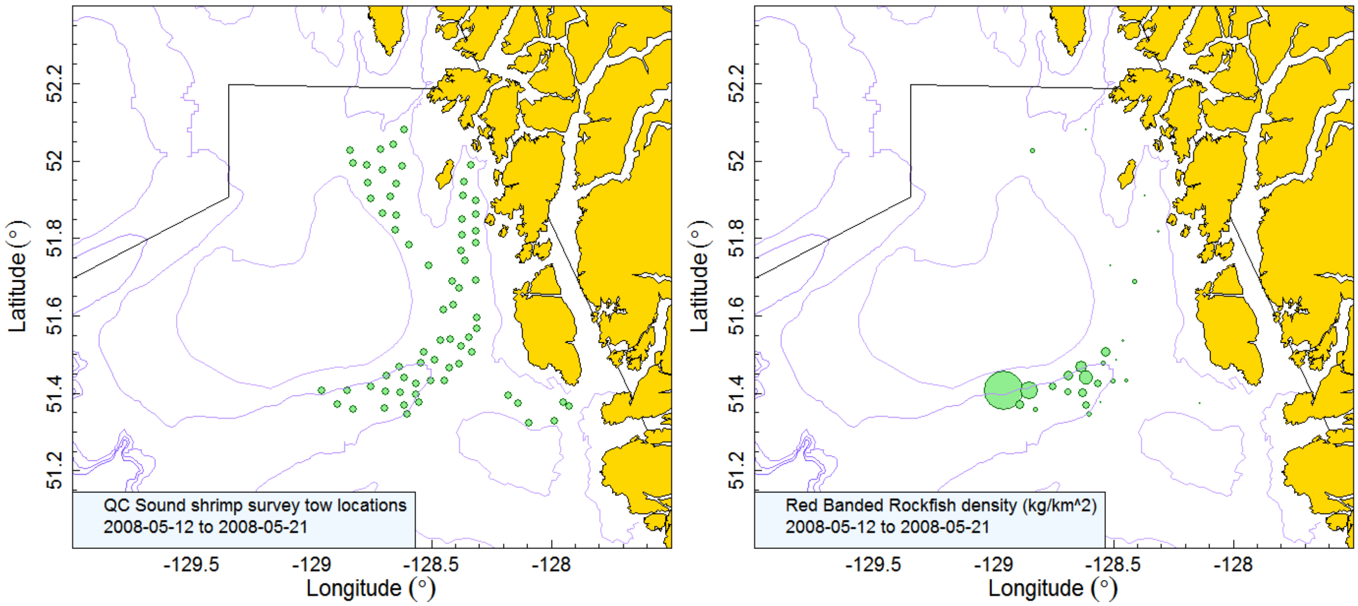


Figure B.33. Tow locations and density plots for the 2008 Queen Charlotte Sound shrimp trawl survey (see Figure B.24 caption).

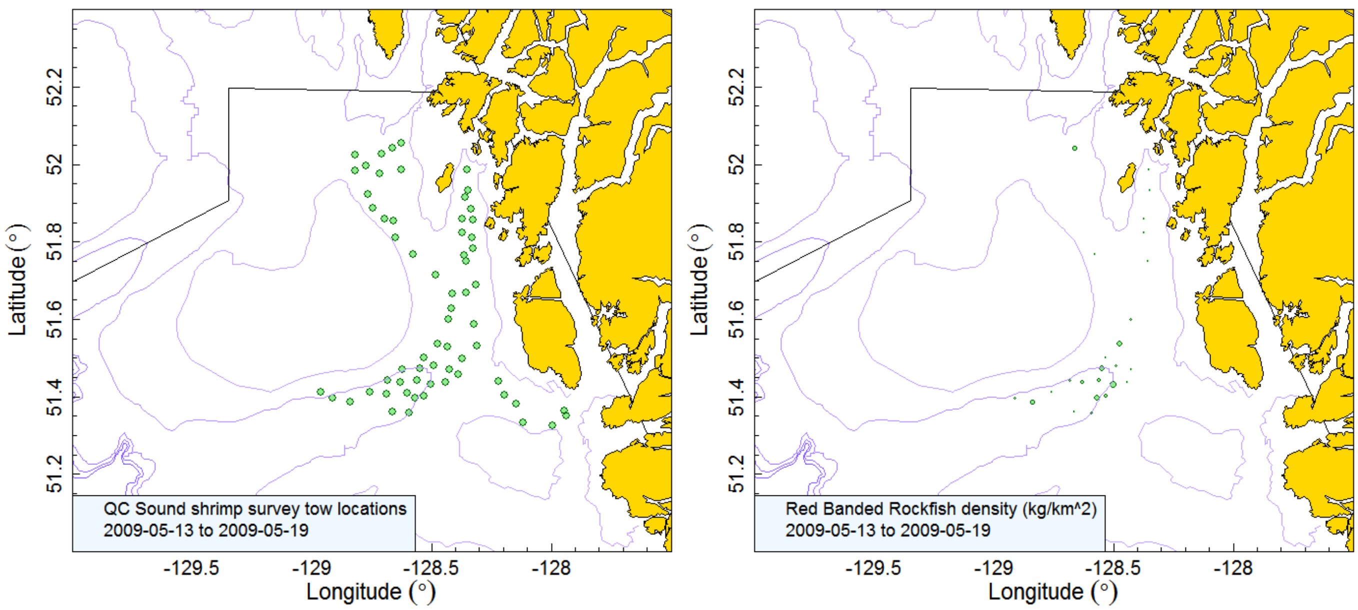


Figure B.34. Tow locations and density plots for the 2009 Queen Charlotte Sound shrimp trawl survey (see Figure B.24 caption).

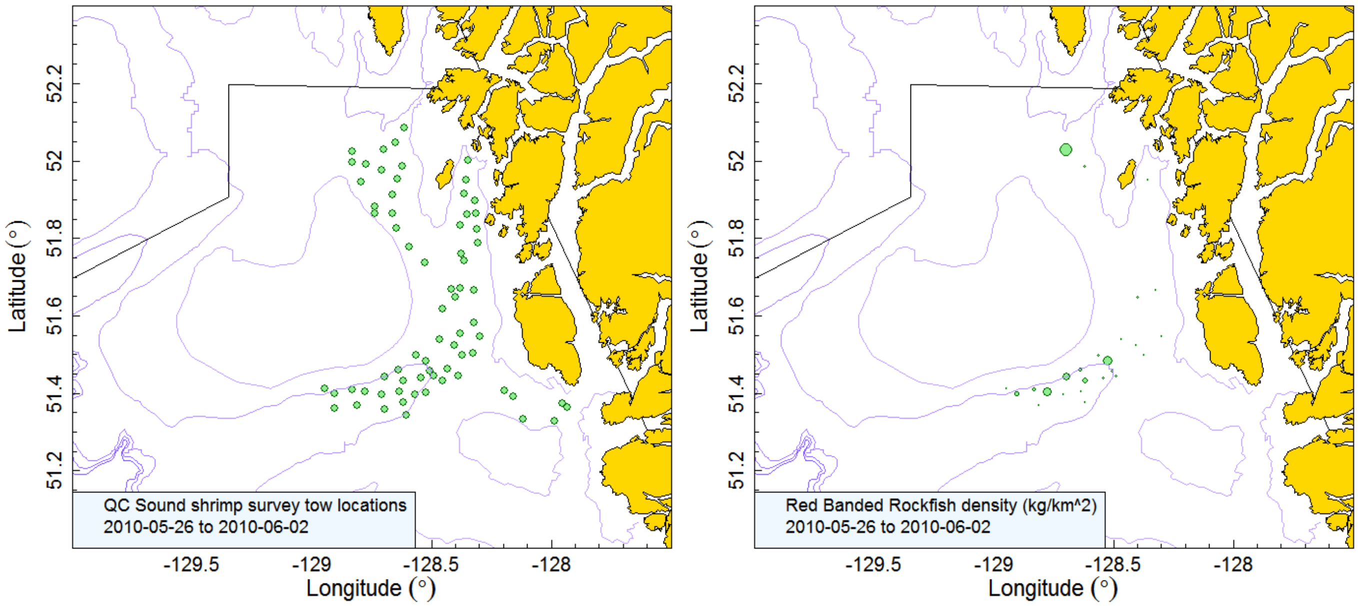


Figure B.35. Tow locations and density plots for the 2010 Queen Charlotte Sound shrimp trawl survey (see Figure B.24 caption).

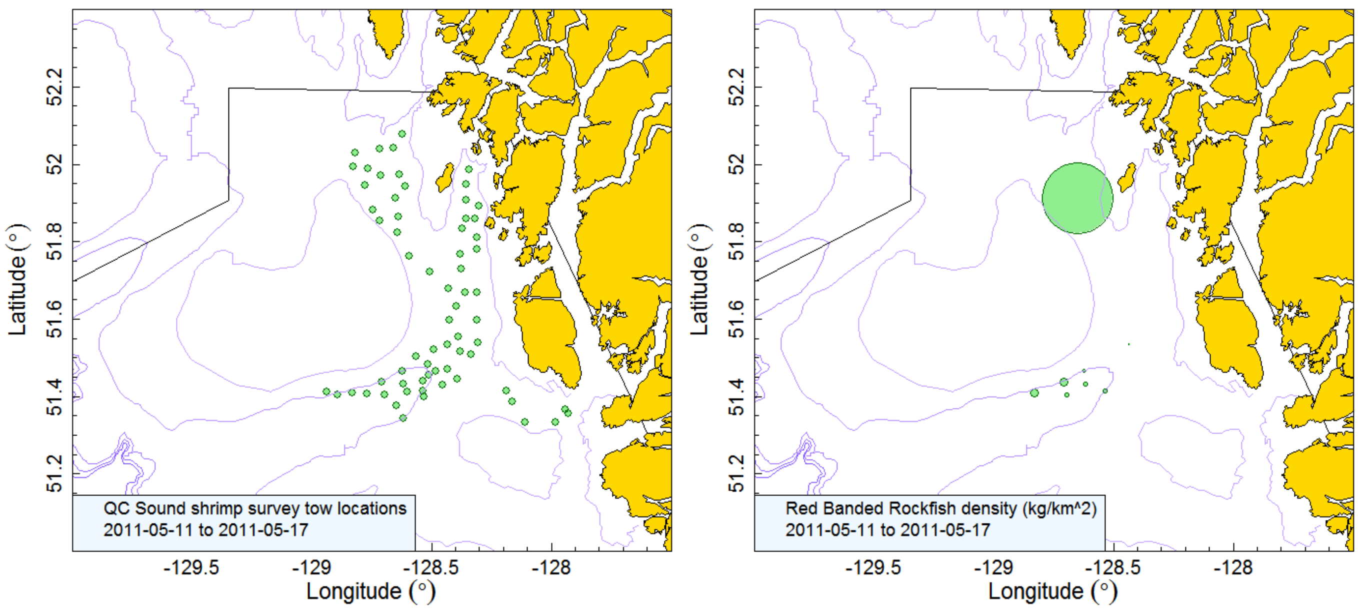


Figure B.36. Tow locations and density plots for the 2011 Queen Charlotte Sound shrimp trawl survey (see Figure B.24 caption).

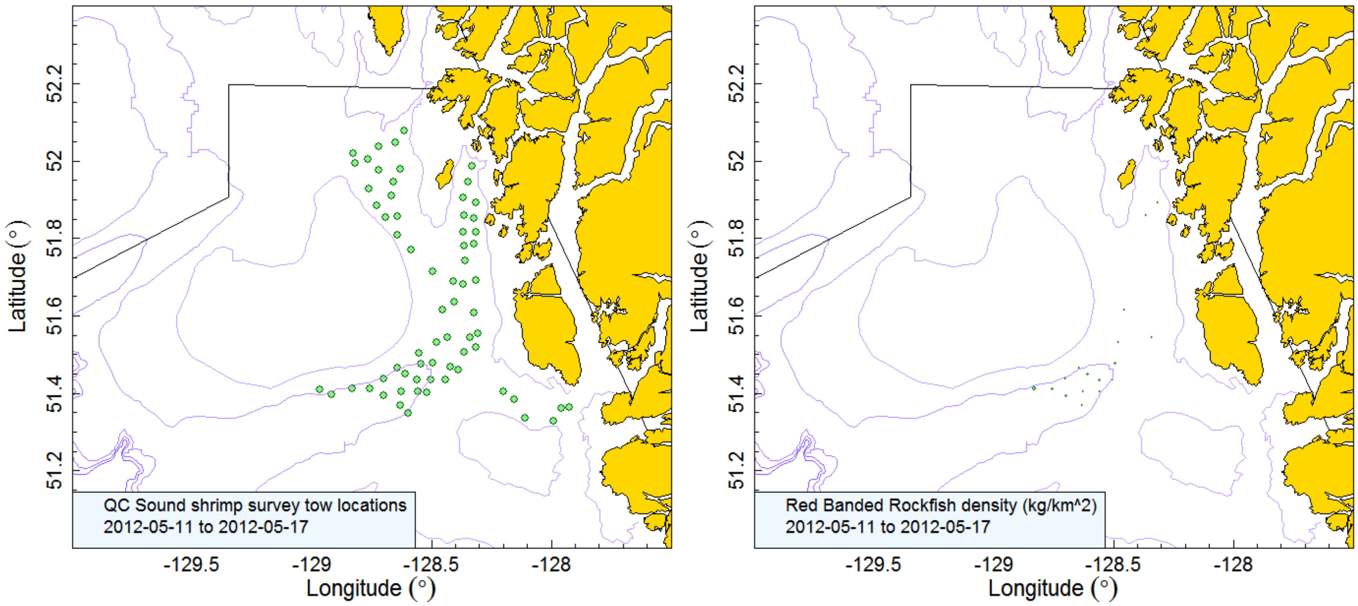


Figure B.37. Tow locations and density plots for the 2012 Queen Charlotte Sound shrimp trawl survey (see Figure B.24 caption).

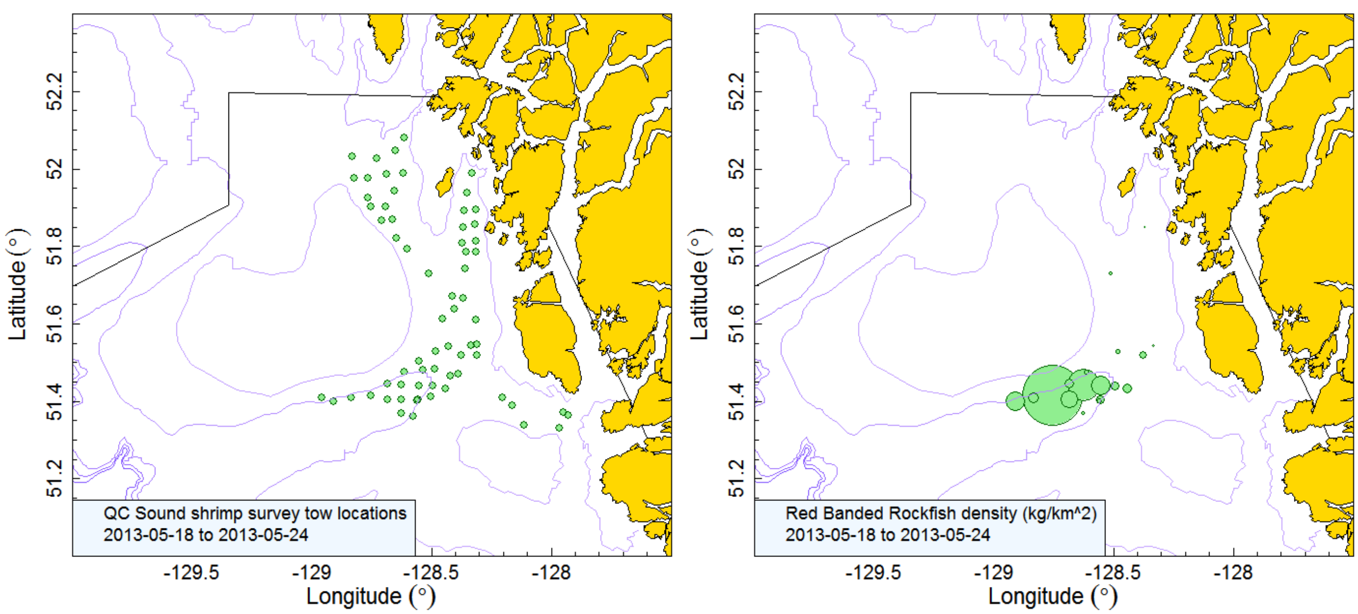


Figure B.38. Tow locations and density plots for the 2013 Queen Charlotte Sound shrimp trawl survey (see Figure B.24 caption).

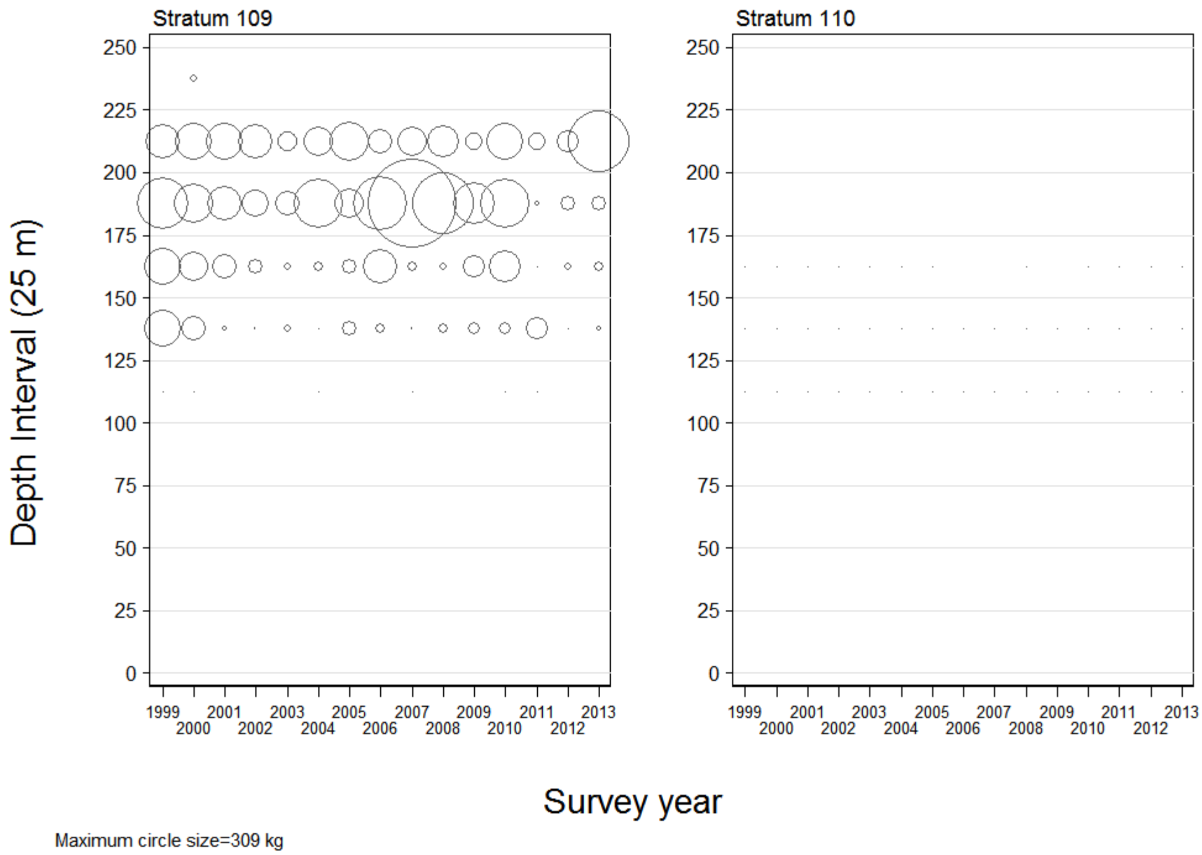


Figure B.39. Distribution of observed weights of Redbanded Rockfish by survey year and 25 m depth zone. Depth zones are indicated by the mid point of the depth interval and circles in the panel are scaled to the maximum value (309 kg) in the 175-200 m interval in 2007. The 1% and 99% quantiles for the RBR empirical start of tow depth distribution=128 m and 219 m respectively.

B.5.2 Results

Catches of RBR tend to be distributed along the trench of Goose Island Gully and along the shelf edge of the outside islands (see Figure B.24 to Figure B.38). Redbanded Rockfish were mainly taken at depths from 140-210 m (5–95% quantiles) and have been taken almost entirely in Stratum 109, with the maximum catch weight in Stratum 110 being 1.0 kg/tow (Figure B.39).

Estimated biomass levels for RBR from the QCS shrimp trawl survey show no trend across years, and with CVs ranging between 22% and 88% (Figure B.40; Table B.11). The proportion of tows with RBR is relatively high in Stratum 109, with the annual proportion varying from 0.13 to 0.54 (mean across years=35%; Figure B.41). These levels of RBR incidence are lower than those observed in the Queen Charlotte Sound synoptic survey (see Section B.7). There are usually between 5 and 10 tows per year in Stratum 110, with 6 in 2013 (Table B.10) and this stratum tended to sample the shallowest depths where RBR tend not to occur

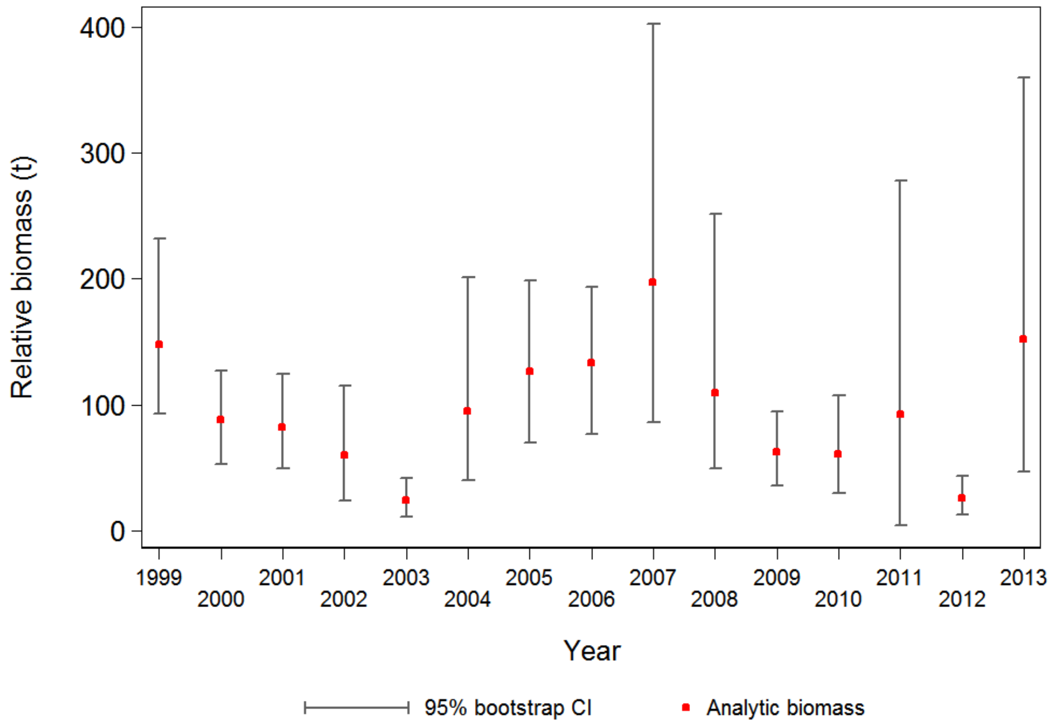


Figure B.40. Plot of biomass estimates for Redbanded Rockfish from the 2003 to 2013 Queen Charlotte Sound shrimp trawl surveys (Table B.11). Bias-corrected 95% confidence intervals from 1000 bootstrap replicates are plotted.

Table B.11. Biomass estimates for Redbanded Rockfish from the Queen Charlotte Sound shrimp trawl survey for the survey years 1999 to 2014.

Survey Year	Biomass (t)	Mean bootstrap biomass (t)	Lower bound biomass (t)	Upper bound biomass (t)	Bootstrap CV	Analytic CV (Eq. C.6)
1999	147.6	147.4	92.7	231.7	0.233	0.232
2000	87.5	87.2	52.7	127.0	0.221	0.225
2001	81.5	80.7	49.1	124.5	0.245	0.239
2002	59.6	60.2	23.6	114.8	0.374	0.374
2003	23.7	23.6	10.6	41.5	0.322	0.332
2004	94.7	94.0	40.0	200.9	0.405	0.418
2005	125.9	127.0	69.7	199.0	0.257	0.258
2006	133.1	133.7	76.7	193.6	0.231	0.229
2007	197.1	194.2	86.4	402.8	0.391	0.399
2008	109.6	109.1	49.3	251.6	0.430	0.427
2009	61.9	61.7	35.5	94.2	0.242	0.244
2010	60.6	60.0	29.6	107.5	0.312	0.325
2011	92.3	94.9	4.4	277.7	0.876	0.910
2012	25.5	25.5	12.6	42.9	0.302	0.299
2013	151.8	153.8	46.9	360.5	0.506	0.504

The 15 QC Sound shrimp trawl survey indices spanning the period 1999 to 2014 were used as abundance indices in the RBR stock assessment work.

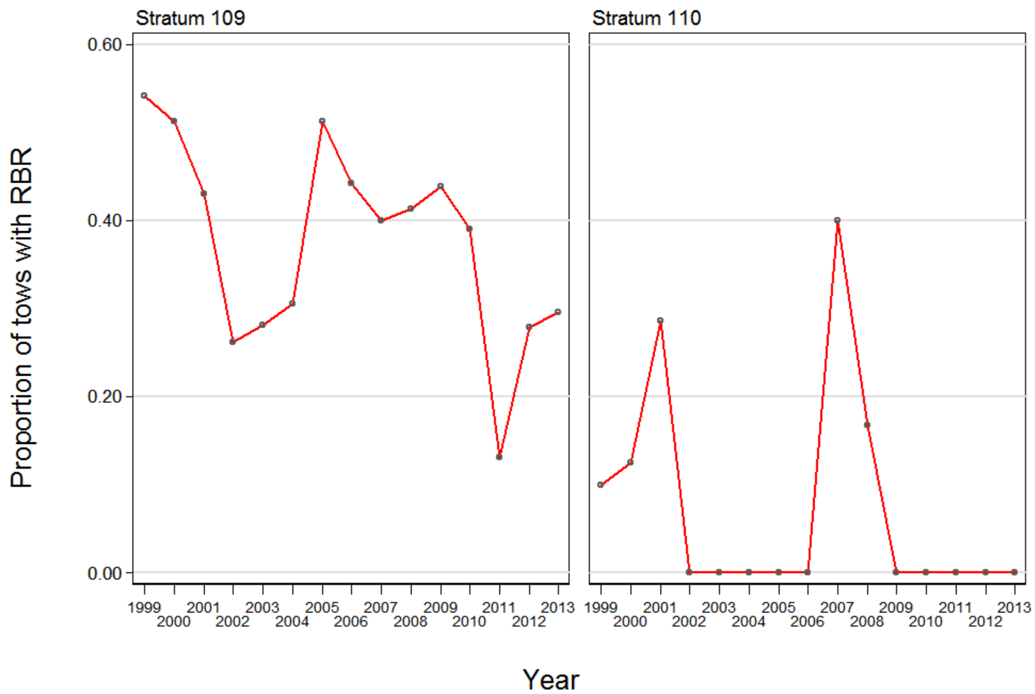


Figure B.41. Proportion of tows by stratum and year capturing Redbanded Rockfish in the Queen Charlotte Sound shrimp trawl surveys, 1999–2013.

B.6 HECATE STRAIT SYNOPTIC SURVEY

B.6.1 Data selection

This survey has been conducted in five alternating years over the period 2005 to 2013 in Hecate Strait (HS) between Moresby and Graham Islands and the mainland and in Dixon Entrance at the top of Graham Island (all valid tow starting positions by survey year are shown in Figure B.42 to Figure B.46). This survey treats the full spatial coverage as a single areal stratum divided into four depth strata: 10–70 m; 70–130 m; 130–220 m; and 220–500 m (Table B.12).

A doorspread density value (Eq. B.3) was generated for each tow based on the catch of Redbanded Rockfish (RBR) from the mean doorspread for the tow and the distance travelled. `[distance travelled]` is a database field which is calculated directly from the tow track. This field is used preferentially for the variable D_{yij} in Eq. B.3. A calculated value (`[vessel speed]` X `[tow duration]`) can be used for this variable if `[distance travelled]` is missing, but there were no instances of this occurring in the 5 trawl surveys. Missing values for the `[doorspread]` field were filled in with the mean doorspread for the survey year (217 values over all years: Table B.13).

Table B.12. Number of usable tows for biomass estimation by year and depth stratum for the Hecate Strait synoptic survey over the period 2005 to 2013. Also shown is the area of each depth stratum and the vessel conducting the survey by survey year.

		Depth stratum				Total
Year	Vessel	10-70	70-130	130-220	220-500	tows
2005	Frosti	80	88	26	9	203

Year	Vessel	Depth stratum				Total
		10-70	70-130	130-220	220-500	tows
2007	W.E. Ricker	48	43	36	7	134
2009	W.E. Ricker	53	43	48	12	156
2011	W.E. Ricker	71	51	50	14	186
2013	W.E. Ricker	74	42	43	16	175
Area (km^2)		5,958	3,011	2,432	1,858	13,259[1]

[1] total area for survey

Table B.13. Number of missing doorspread values by year for the Hecate Strait synoptic survey over the period 2005 to 2013 as well as showing the number of available doorspread observations and the mean doorspread value for the survey year.

Year	Number tows with missing doorspread [1]	Number tows with doorspread observations [2]	Mean doorspread (m) used for tows with missing values [2]
2005	7	217	64.4
2007	98	37	59.0
2009	93	70	54.0
2011	13	186	54.8
2013	6	176	51.7
Total	217	686	57.2

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

Table B.14. Biomass estimates for Redbanded Rockfish from the Hecate Strait synoptic trawl survey for the survey years 2005 to 2013. Bootstrap bias corrected confidence intervals and CVs are based on 1000 random draws with replacement.

Survey Year	Biomass (t)	Mean bootstrap biomass (t)	Lower bound biomass (t)	Upper bound biomass (t)	Bootstrap CV	Analytic CV (Eq. B.6)
2005	647.5	651.0	446.3	952.2	0.197	0.202
2007	347.2	349.4	182.1	570.8	0.281	0.270
2009	316.4	318.0	218.2	449.4	0.179	0.185
2011	751.2	746.0	413.4	1,362.8	0.314	0.314
2013	318.5	317.7	199.0	451.8	0.214	0.208

B.6.2 Results

Catches of RBR from this survey are seen in the waters north of Graham Island and in the eastern reaches of Dixon Entrance, as well as in the upper reaches of the Moresby Gully (Figure B.42 to Figure B.46). RBR were mainly taken at depths from 118 to 256 m (5–95% quantiles), but there were sporadic observations to depths just over 300 m and down to about 20 m (Figure B.47).

Estimated RBR doorspread biomass from this trawl survey showed no overall trend over the period 2005 to 2013, with the highest estimates recorded in 2011 and 2005 and low estimates in 2007, 2009 and 2013 (Table B.14; Figure B.48). The estimated relative errors were moderate, ranging from 18 to 31% (Table B.14). On average, 23% of the survey tows captured RBR (ranging from 0.15 to 0.27 by year) (Figure B.49). Overall, 192 of the 854 valid survey tows contained RBR with a low median catch weight for positive tows (around 8 kg/tow) and a maximum catch weight across all four surveys 143 kg (in 2011).

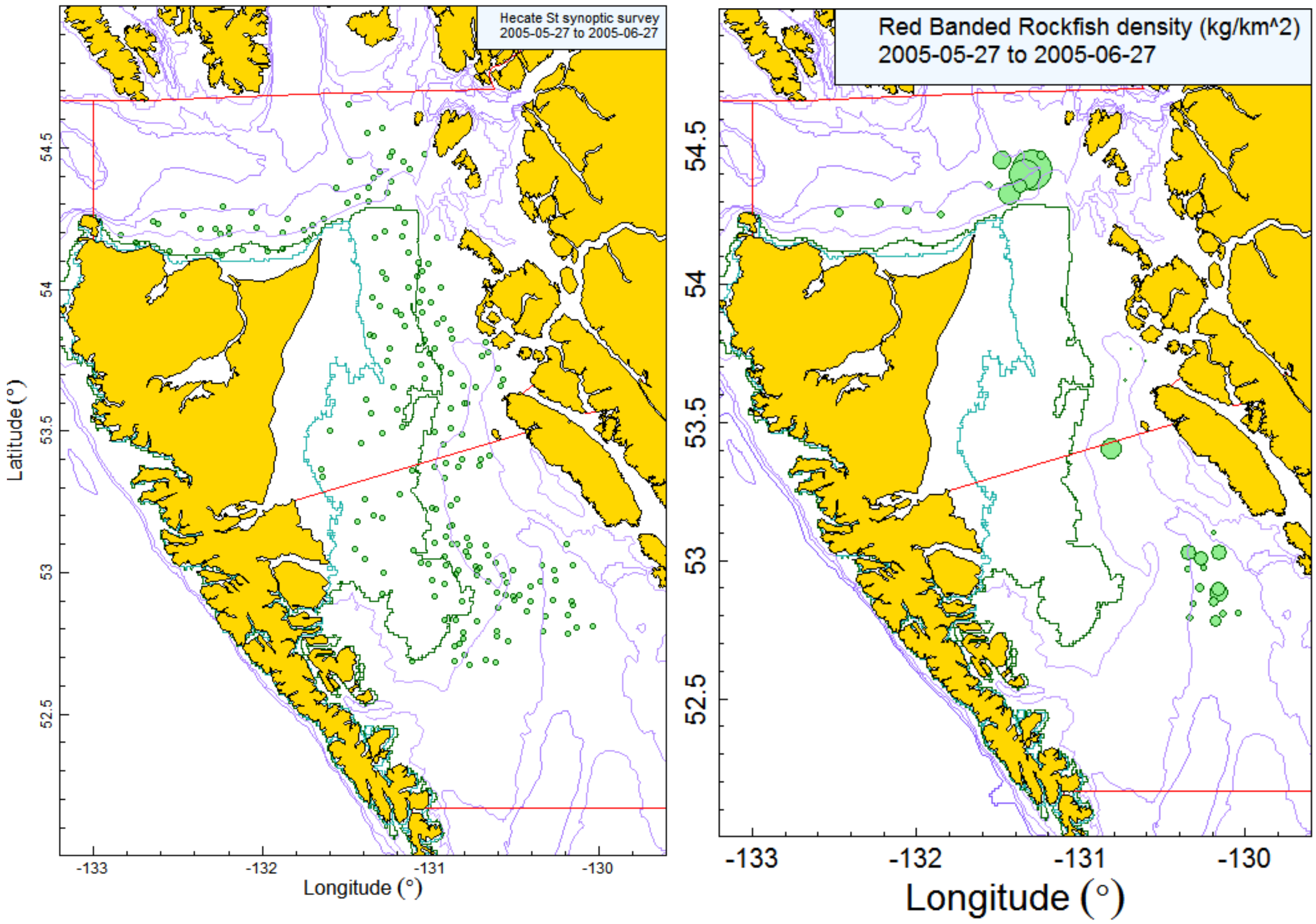
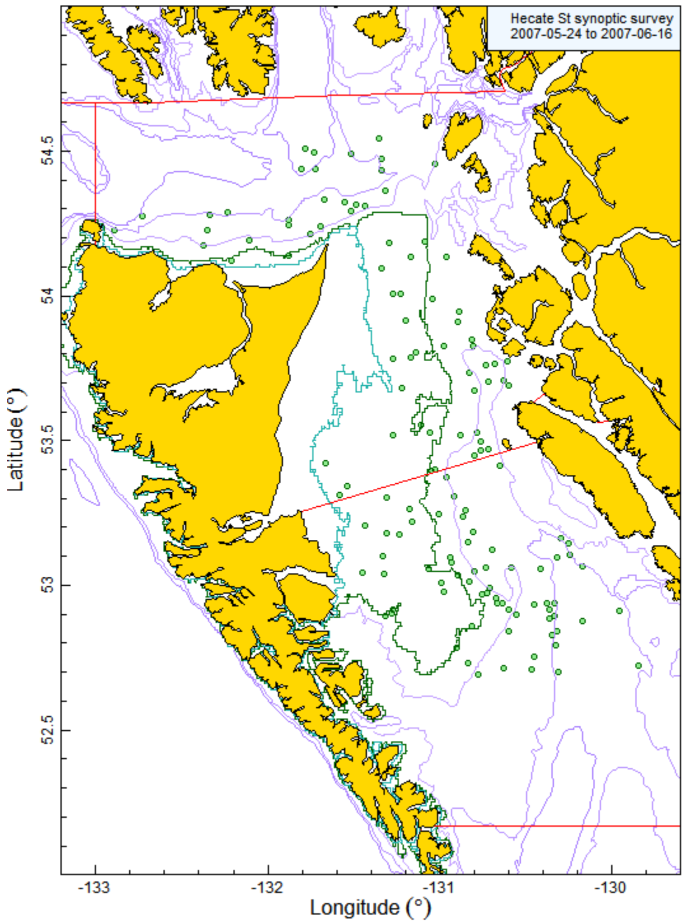


Figure B.42. Valid tow locations and density plots for the 2005 Hecate Strait synoptic survey. Circle sizes in the right-hand density plot scaled across all years (2005, 2007, 2009, 2011, 2013), with the largest circle = 1839 kg/km^2 in 2011. Red lines indicate boundaries for PMFC major statistical areas 5C, 5D and 5E.



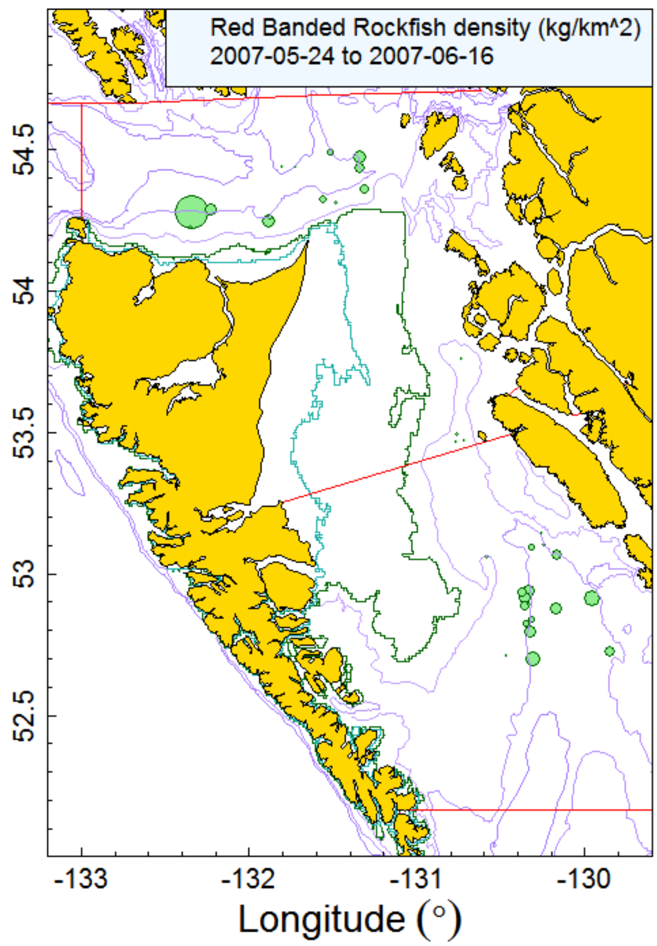


Figure B.43. Tow locations and density plots for the 2007 Hecate Strait synoptic survey (see Figure B.42 caption).

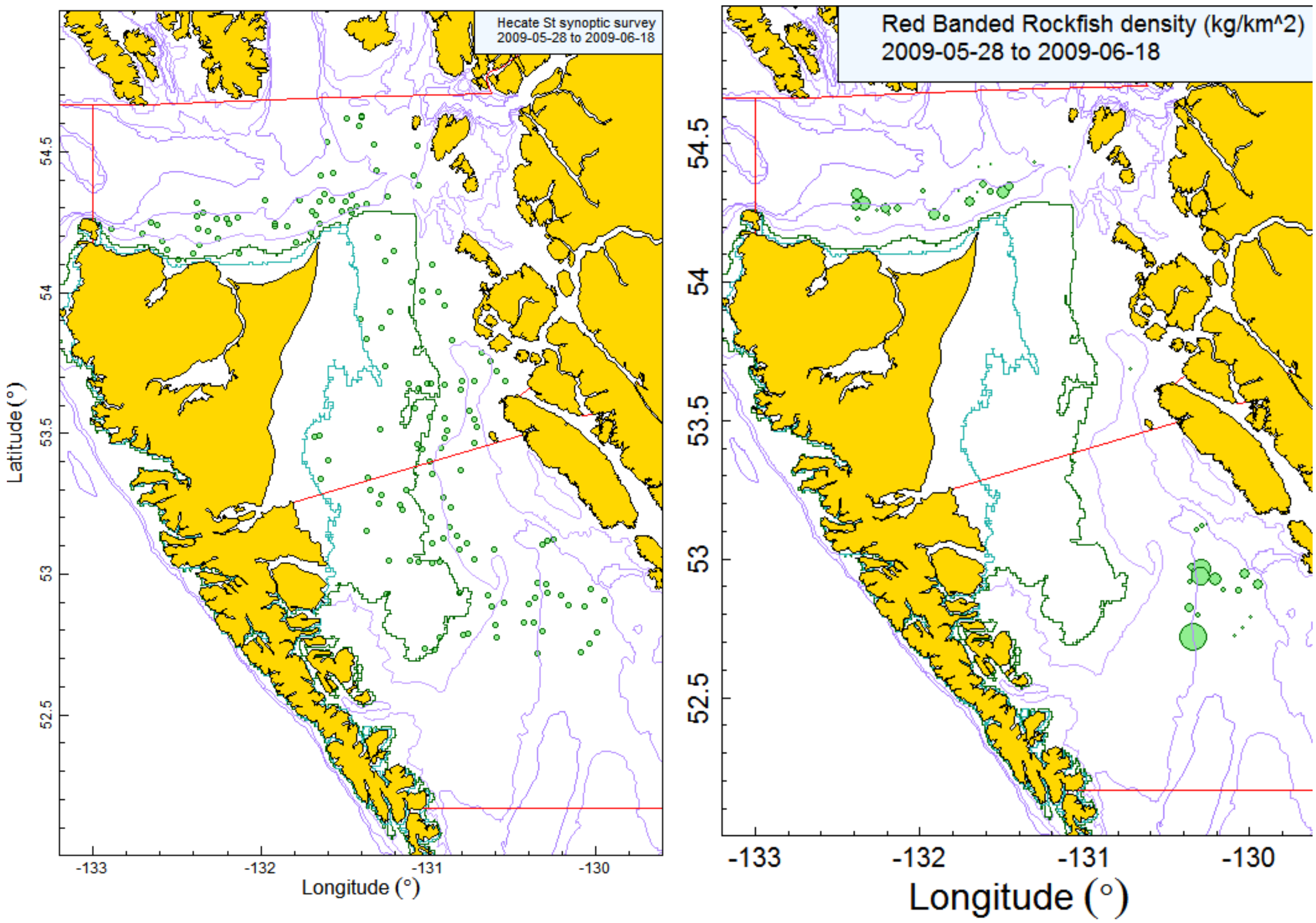


Figure B.44. Tow locations and density plots for the 2009 Hecate Strait synoptic survey (see Figure B.42 caption).

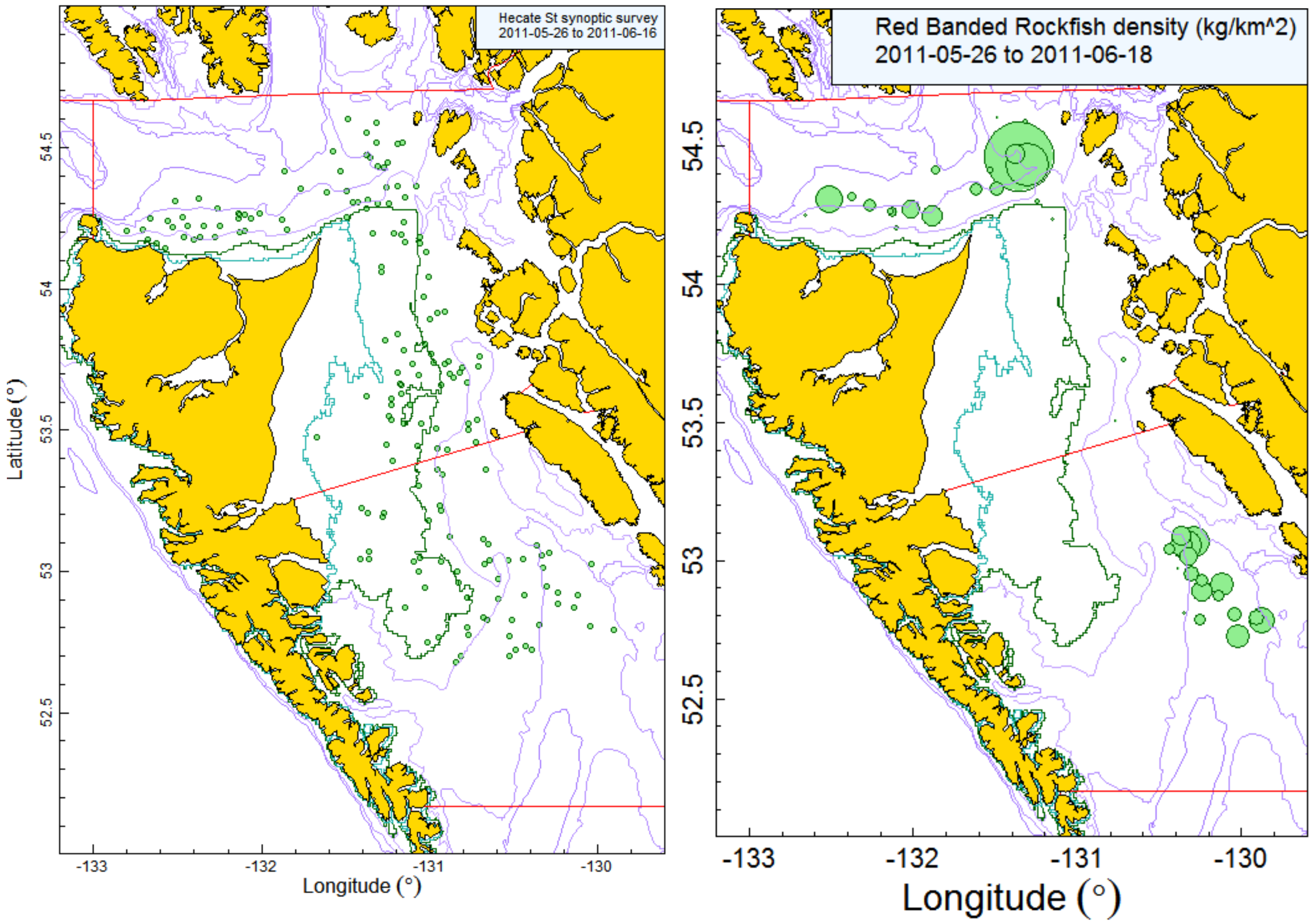


Figure B.45. Tow locations and density plots for the 2011 Hecate Strait synoptic survey (see Figure B.42 caption).

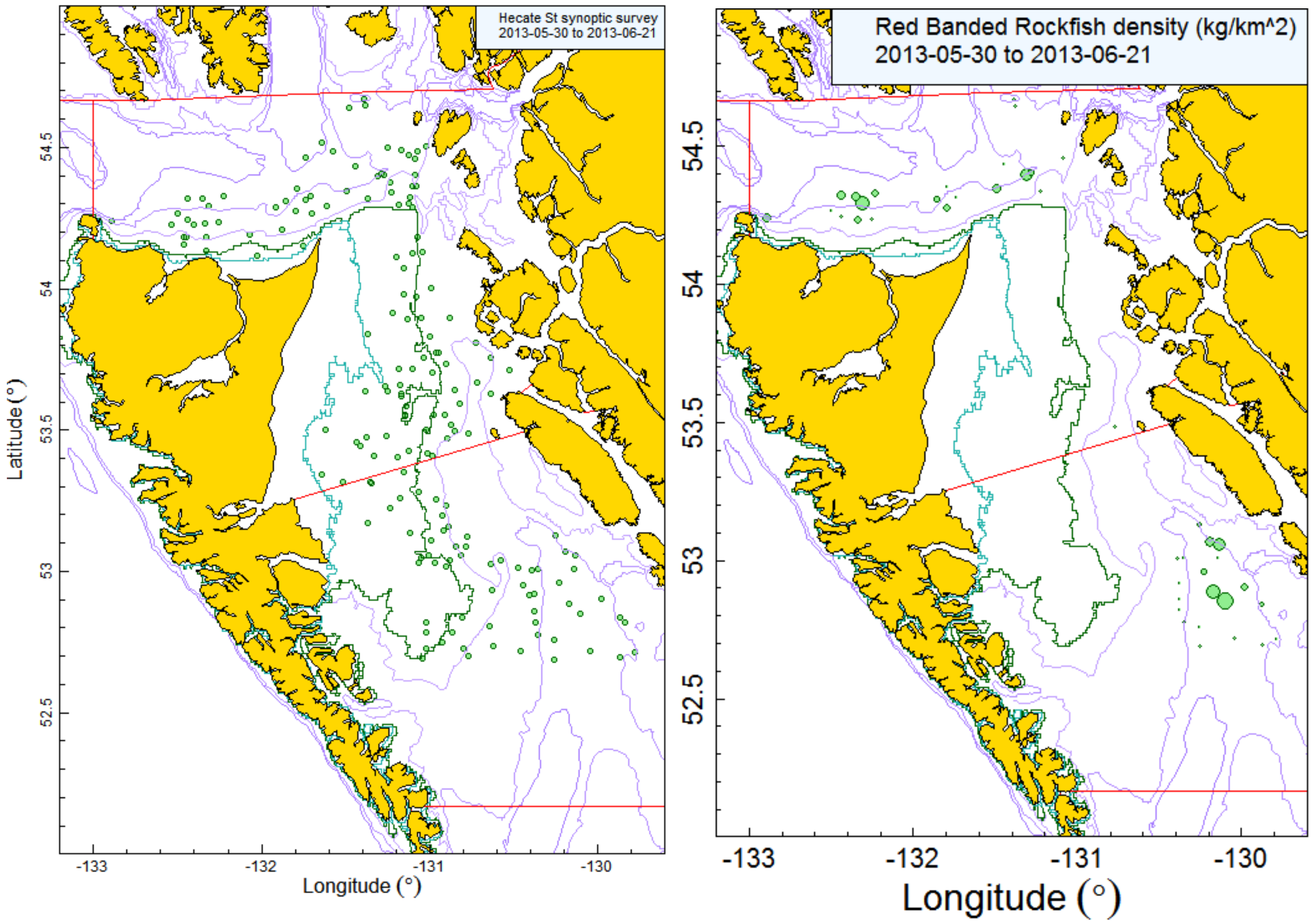


Figure B.46. Tow locations and density plots for the 2013 Hecate Strait synoptic survey (see Figure B.42 caption).

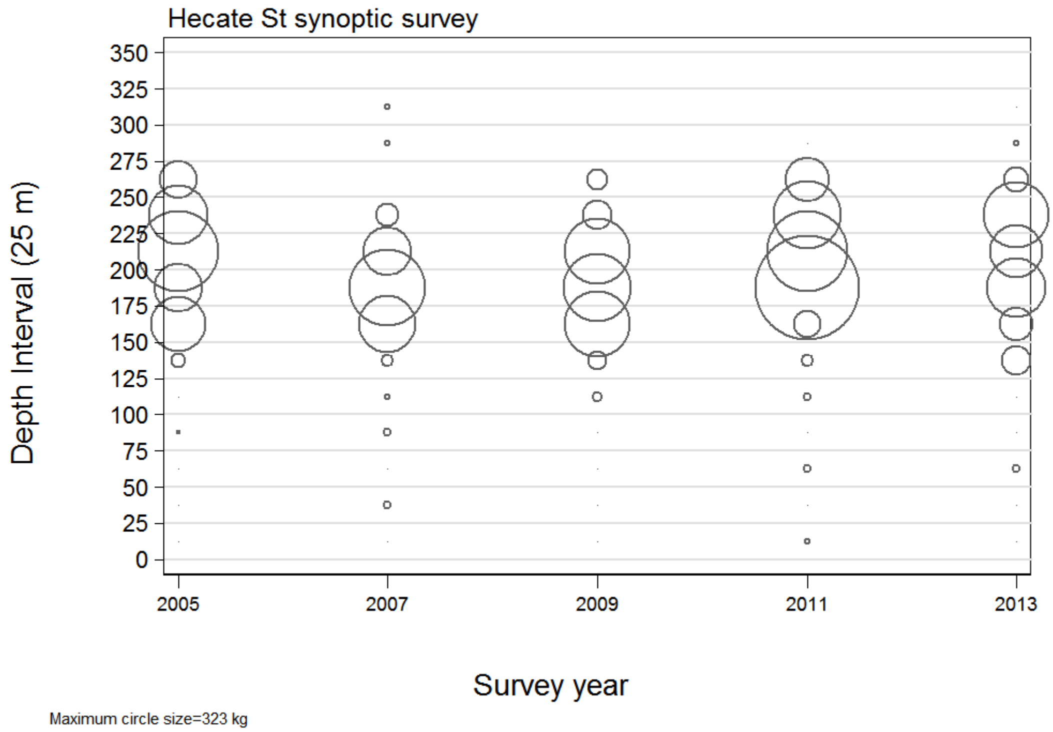


Figure B.47. Distribution of observed catch weights of Redbanded Rockfish for the Hecate Strait synoptic survey (Table B.12) by survey year and 25 m depth zone. Depth zones are indicated by the mid point of the depth interval and circles in the panel are scaled to the maximum value (323 kg) in the 175–200 m interval in 2011. The 1% and 99% quantiles for the RBR empirical start of tow depth distribution= 41 m and 289 m respectively.

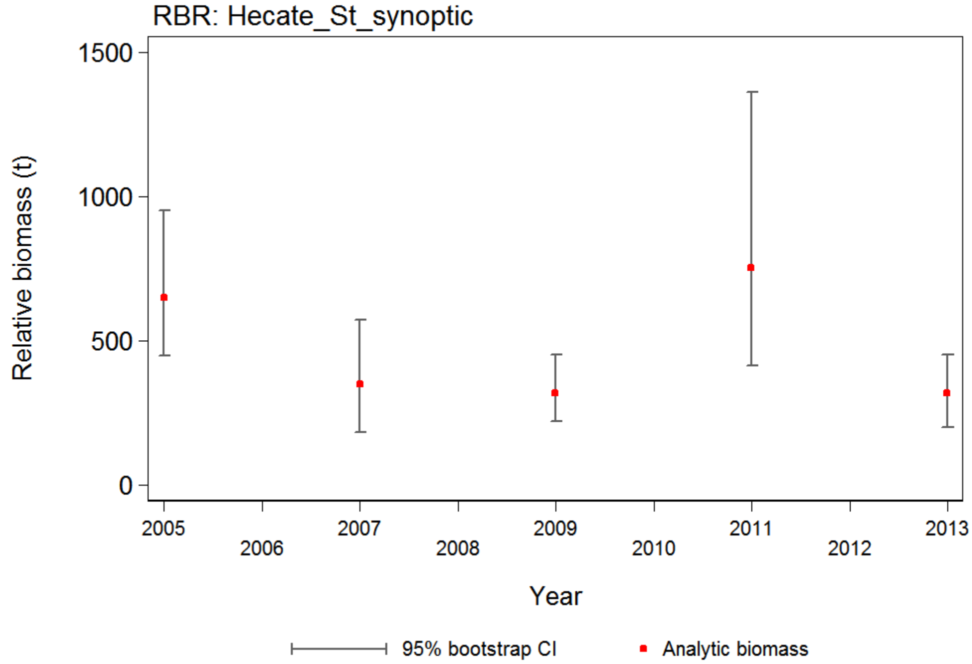


Figure B.48. Plot of biomass estimates for Redbanded Rockfish (values provided in Table B.14) from the Hecate Strait synoptic survey over the period 2005 to 2013 . Bias corrected 95% confidence intervals from 1000 bootstrap replicates are plotted.

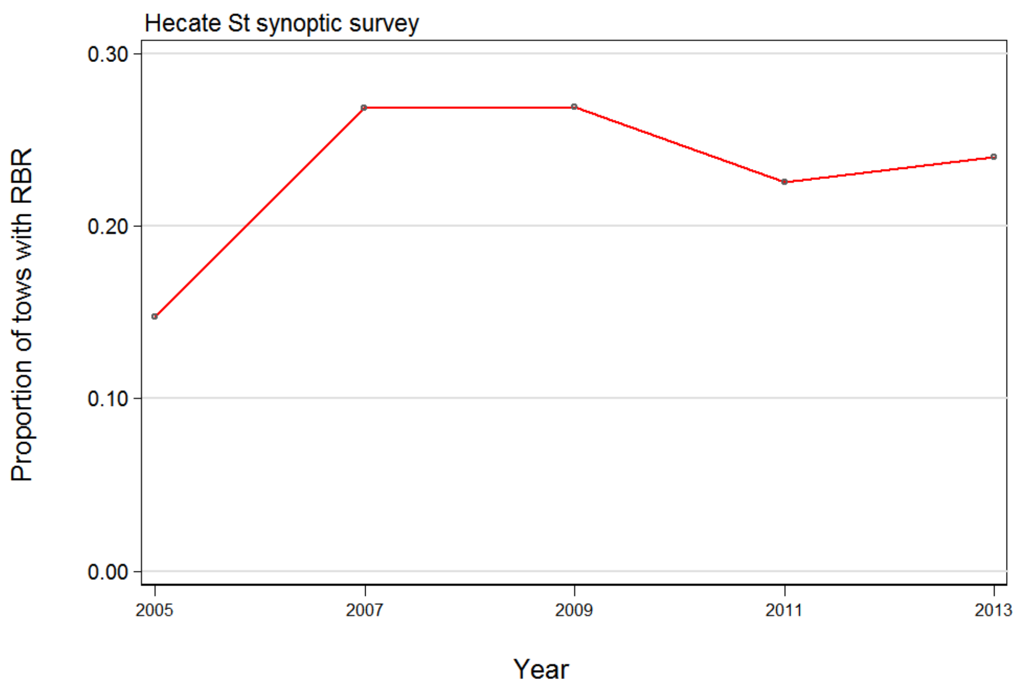


Figure B.49. Proportion of tows by year which contain Redbanded Rockfish from the Hecate Strait synoptic survey over the period 2005 to 2013.

B.7 QUEEN CHARLOTTE SOUND SYNOPTIC TRAWL SURVEY

B.7.1 Data selection

This survey has been conducted in seven years over the period 2003 to 2013 in Queen Charlotte Sound (QCS), which lies between the top of Vancouver Island and the southern portion of Moresby Island and extends into the lower part of Hecate Strait between Moresby Island and the mainland. The design divided the survey into two large areal strata which roughly correspond to the PMFC regions 5A and 5B while also incorporating part of 5C (all valid tow starting positions are shown by survey year in Figure B.50 to Figure B.56). Each of these two areas was divided into four depth strata: 50–125 m; 125–200 m; 200–330 m; and 330–500 m (Table B.15).

A doorspread density value (Eq. B.3) was generated for each tow based on the catch of Redbanded Rockfish (RBR) from the mean doorspread for the tow and the distance travelled. [`distance travelled`] is a database field which is calculated directly from the tow track. This field is used preferentially for the variable D_{yij} in Eq. B.3. A calculated value ([`vessel speed`] X [`tow duration`]) can be used for this variable if [`distance travelled`] is missing, but there were only two instances of this occurring in the 7 trawl surveys. Missing values for the [`doorspread`] field were filled in with the mean doorspread for the survey year (101 values over all years: Table B.16).

Table B.15. Number of usable tows for biomass estimation by year and depth stratum for the Queen Charlotte Sound synoptic survey over the period 2003 to 2013. Also shown is the area of each stratum and the vessel conducting the survey by survey year.

		South depth strata				North stratum				Total
Year	**Vessel**	**50-125**	**125-200**	**200-330**	**330-500**	**50-125**	**125-200**	**200-330**	**330-500**	**tows**
2003	Viking Storm	29	56	29	6	5	39	50	19	233
2004	Viking Storm	42	48	31	8	20	38	37	6	230
2005	Viking Storm	29	60	29	8	8	45	37	8	224
2007	Viking Storm	33	62	24	7	19	57	48	7	257
2009	Viking Storm	34	60	28	8	10	44	43	6	233
2011	Nordic Pearl	38	67	25	8	10	51	45	8	252
2013	Nordic Pearl	32	65	29	10	9	46	45	5	241
Area (km^2)		5,092	5,464	2,744	568	1,840	4,104	3,760	1,252	24,824

Table B.16. Number of missing doorspread values by year for the Queen Charlotte Sound synoptic survey over the period 2003 to 2013 as well as showing the number of available doorspread observations and the mean doorspread value for the survey year.

Year	Number tows with missing doorspread [1]	Number tows with doorspread observations [2]	Mean doorspread (m) used for tows with missing values [2]
2003	13	236	72.1
2004	8	267	72.8
2005	1	258	74.5
2007	5	262	71.8
2009	2	248	71.3
2011	30	242	67.0
2013	42	226	69.5
Total	101	1,739	71.3

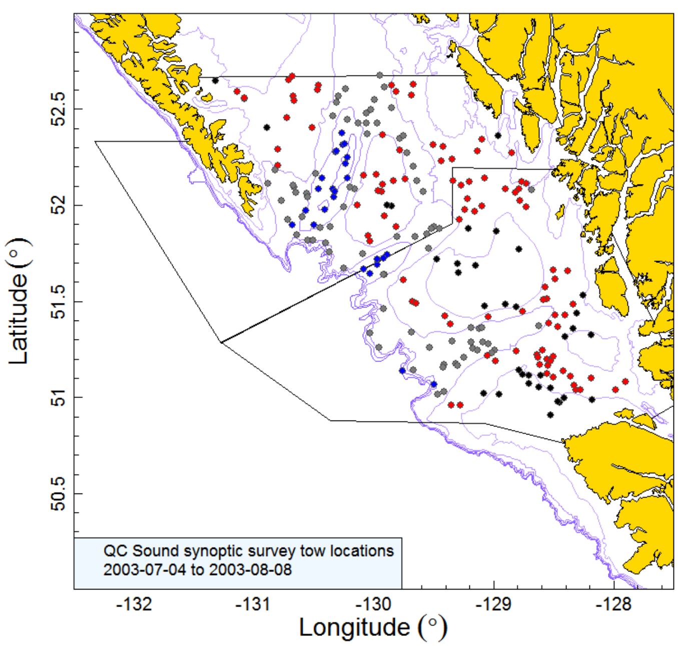
[1] valid biomass estimation tows only
[2] includes tows not used for biomass estimation

Table B.17. Biomass estimates for Redbanded Rockfish from the Queen Charlotte Sound synoptic trawl survey for the survey years 2003 to 2013. Bootstrap bias corrected confidence intervals and CVs are based on 1000 random draws with replacement.

Survey Year	Biomass (t)	Mean bootstrap biomass (t)	Lower bound biomass (t)	Upper bound biomass (t)	Bootstrap CV	Analytic CV (Eq. B.6)
2003	887.8	883.3	665.9	1,230.3	0.163	0.162
2004	555.4	550.9	400.9	830.0	0.189	0.192
2005	1,245.0	1,238.9	895.4	1,698.7	0.163	0.164
2007	911.1	906.1	625.1	1,503.7	0.228	0.232
2009	889.9	887.3	651.7	1,269.6	0.168	0.163
2011	850.7	860.4	519.1	1,284.9	0.234	0.243
2013	956.7	949.9	734.1	1,284.8	0.145	0.144

B.7.2 Results

Catch densities of RBR from this survey were similar in the two strata, with some high density tows recorded in both strata (Figure B.50 to Figure B.56). Based on the distribution of catch densities in these figures, it appears that RBR are taken almost anywhere in QC Sound. RBR were mainly taken at depths from 152 to 352 m (5–95% quantiles), but there were sporadic observations at depths up to 480 m and down to about 60 m (Figure B.57).



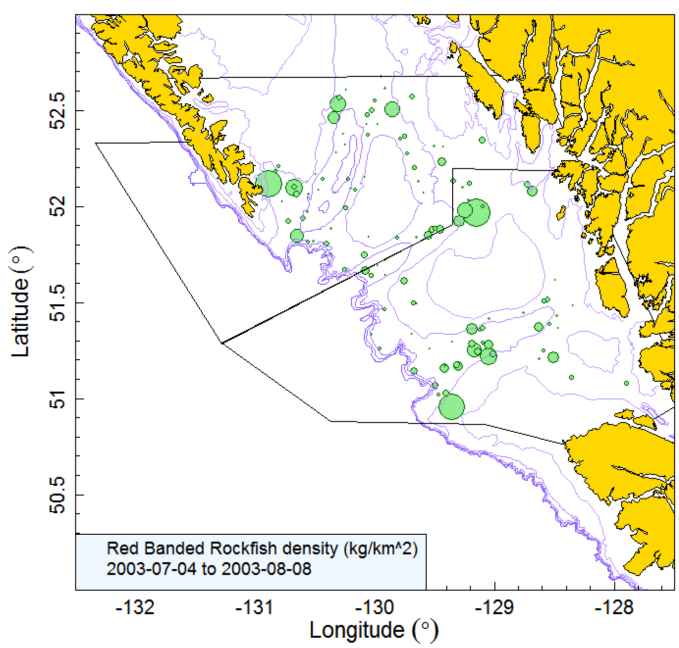


Figure B.50. Valid tow locations (50-125m stratum: black; 126-200m stratum: red; 201-330m stratum: grey; 331-500m stratum: blue) and density plots for the 2003 Queen Charlotte Sound synoptic survey. Circle sizes in the right-hand density plot scaled across all years (2003–2005, 2007, 2009, 2011, 2013), with the largest circle = 2207 kg/km^2 in 2007. Boundaries delineate the North and South areal strata.

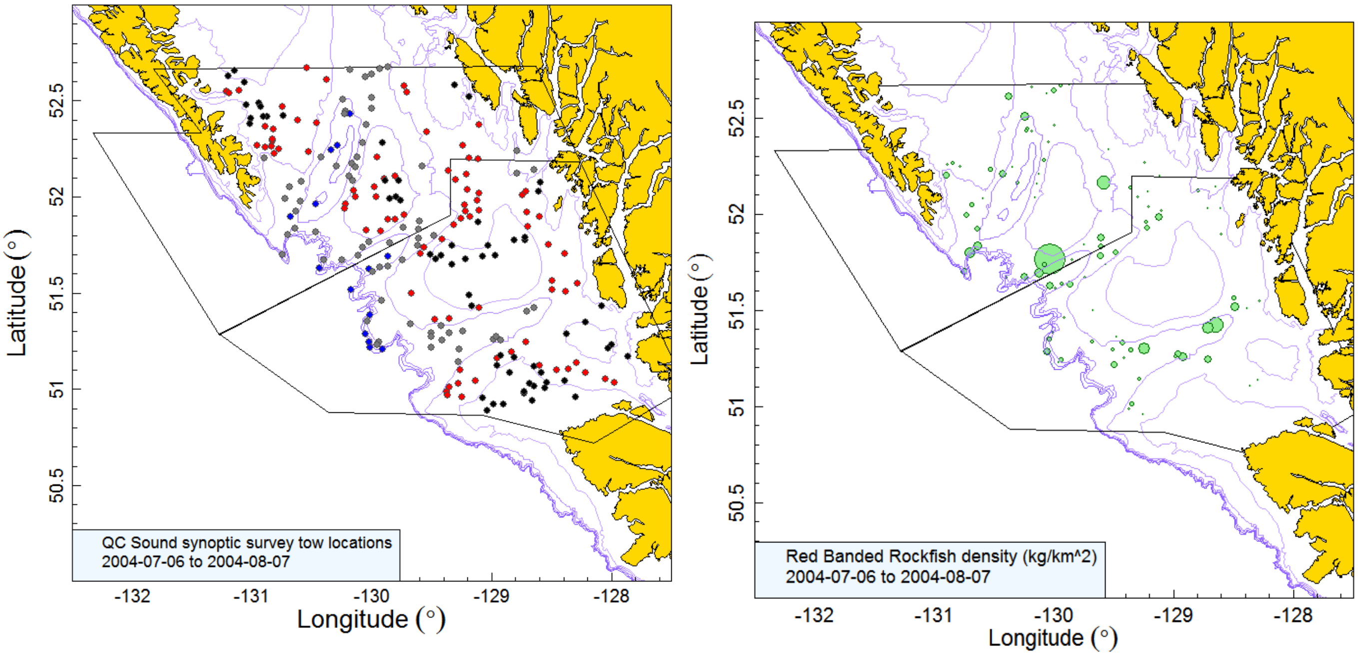


Figure B.51. Tow locations and density plots for the 2004 Queen Charlotte Sound synoptic survey (see Figure B.50 caption).

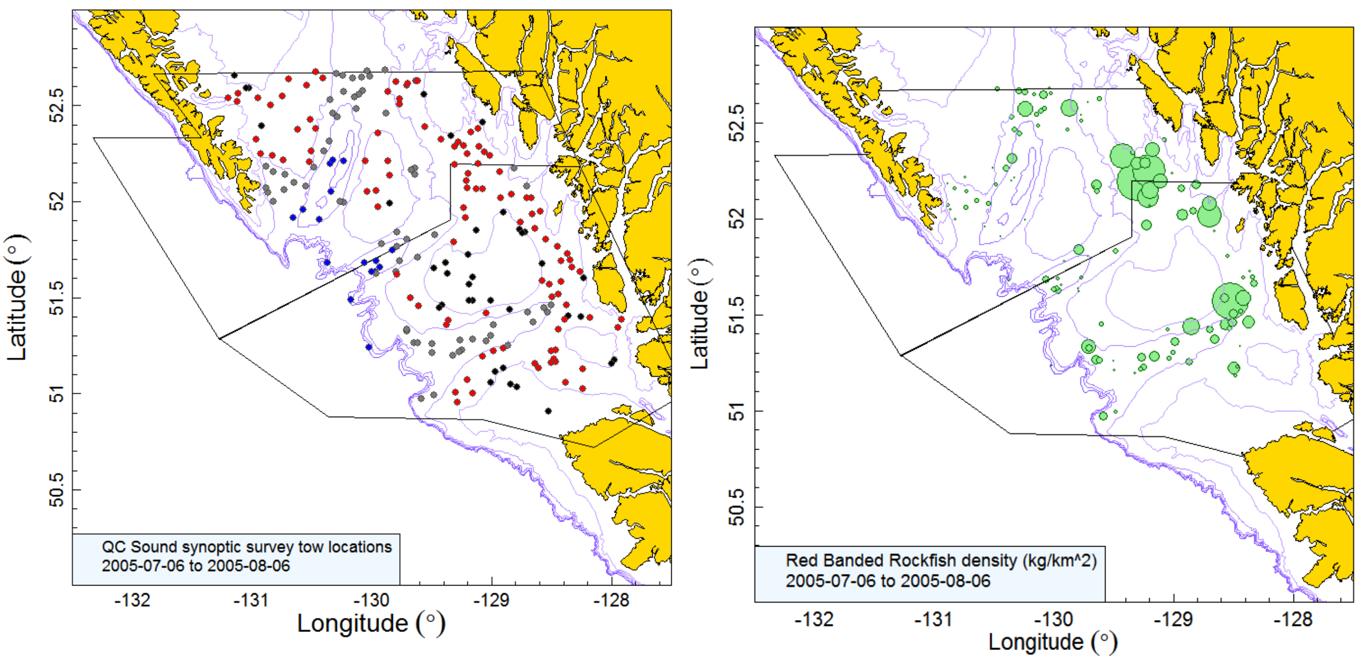


Figure B.52. Tow locations and density plots for the 2005 Queen Charlotte Sound synoptic survey (see Figure B.50 caption).

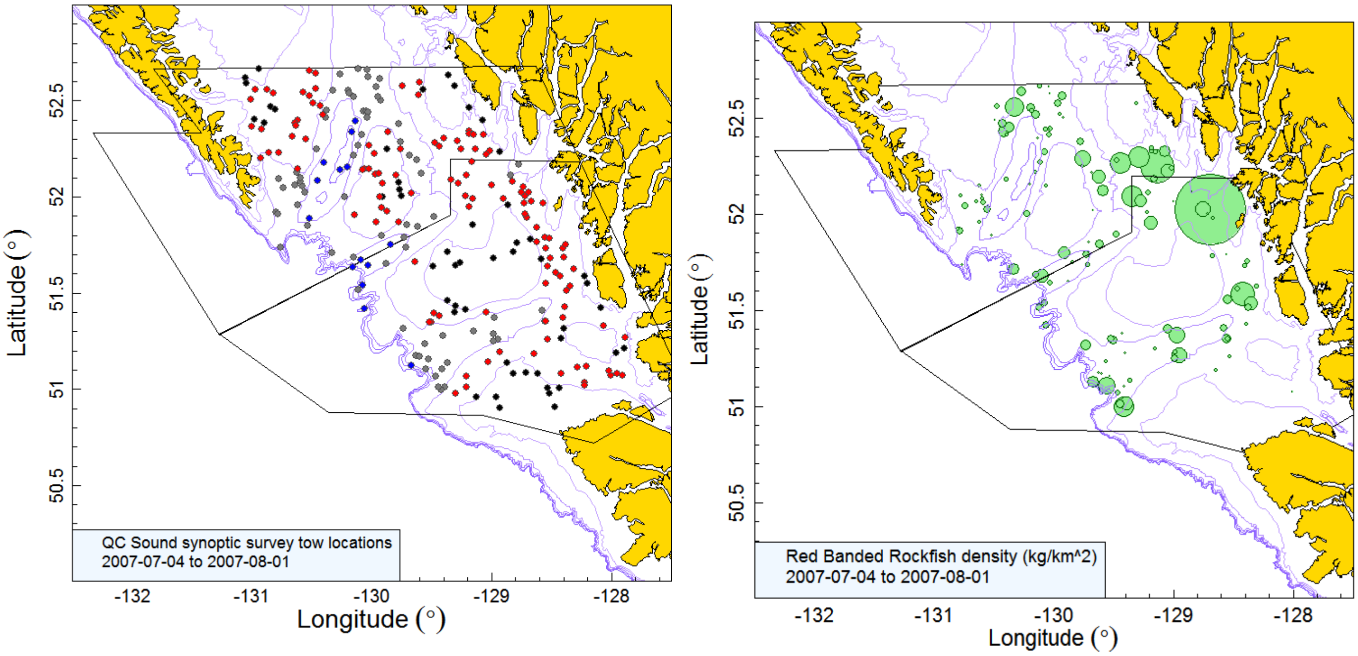


Figure B.53. Tow locations and density plots for the 2007 Queen Charlotte Sound synoptic survey (see Figure B.50 caption).

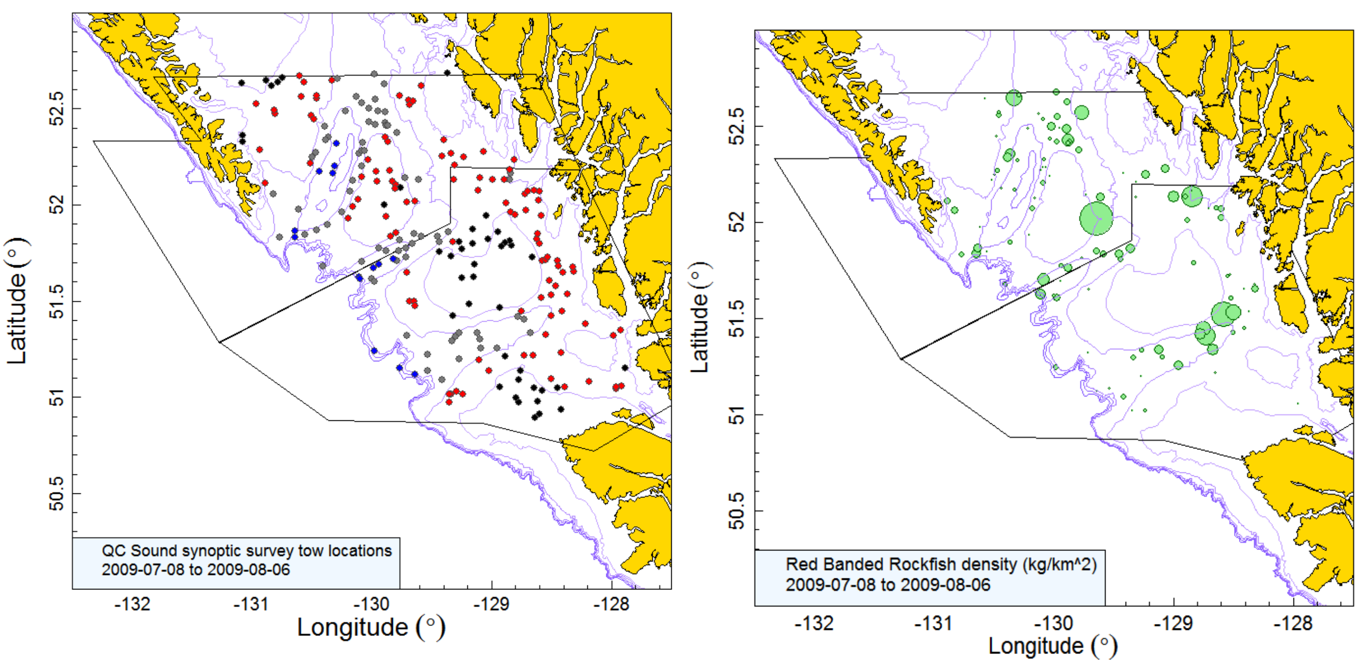


Figure B.54. Tow locations and density plots for the 2009 Queen Charlotte Sound synoptic survey (see Figure B.50 caption).

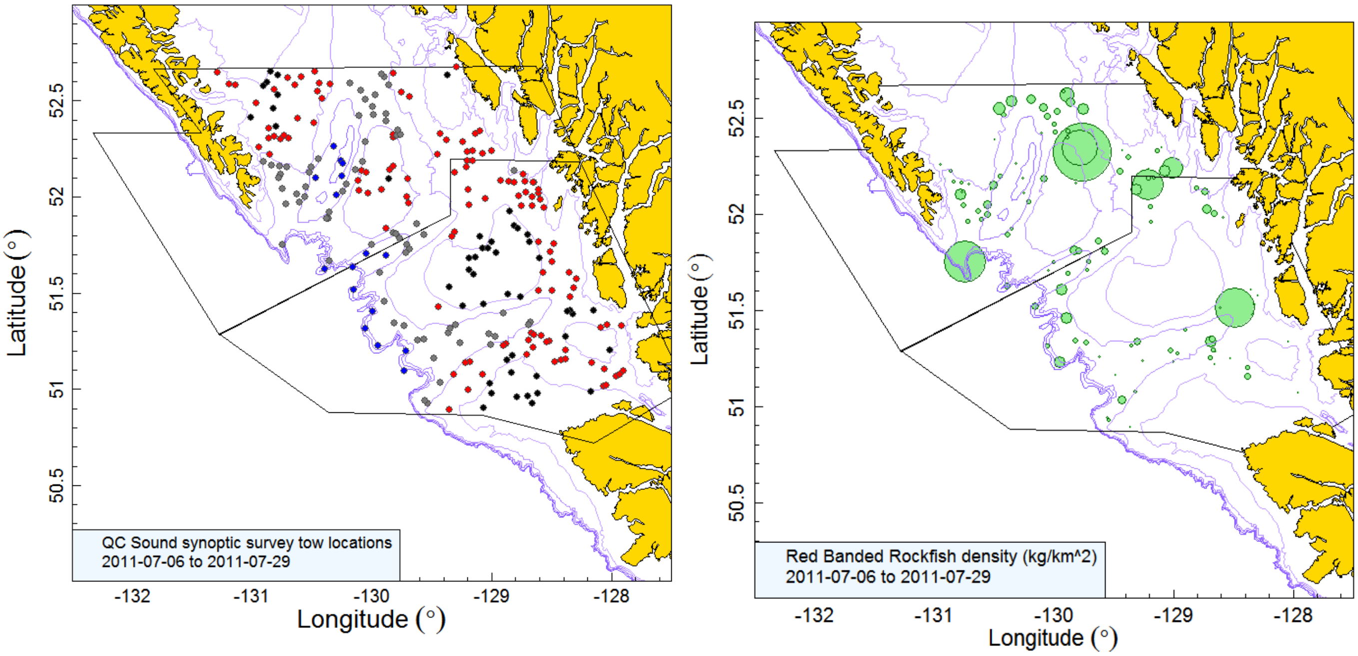


Figure B.55. Tow locations and density plots for the 2011 Queen Charlotte Sound synoptic survey (see Figure B.50 caption).

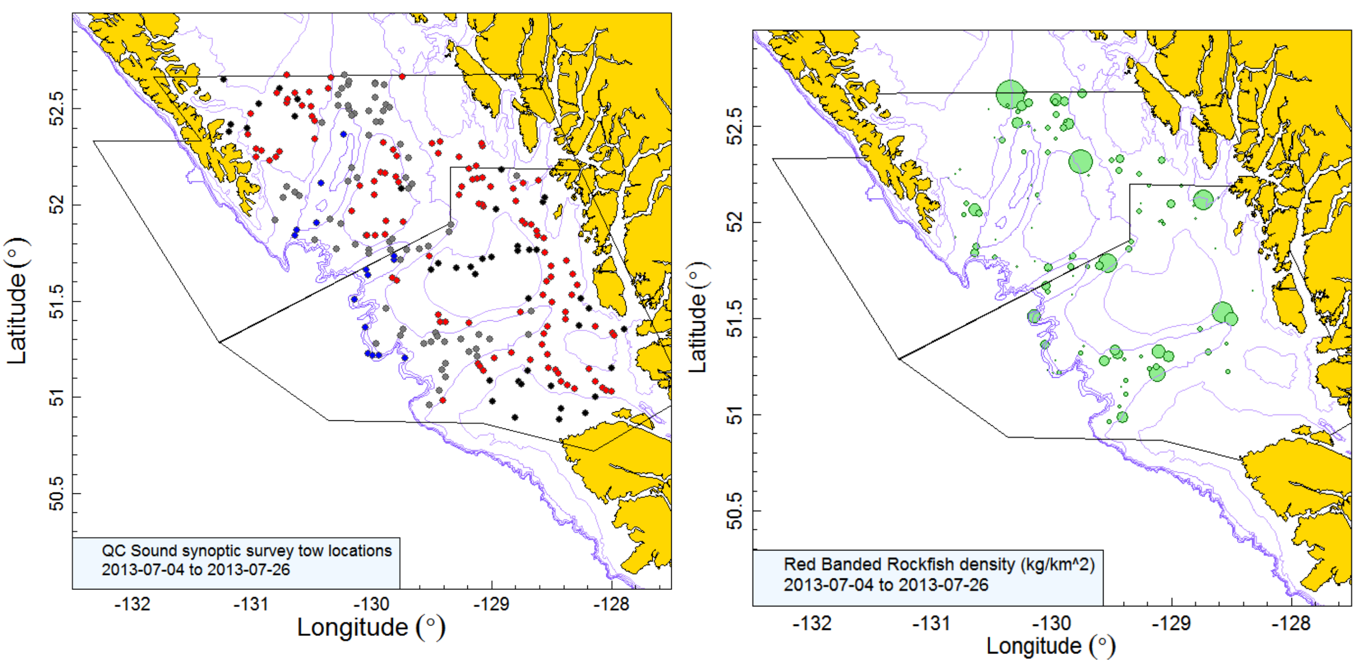


Figure B.56. Tow locations and density plots for the 2013 Queen Charlotte Sound synoptic survey (see Figure B.50 caption).

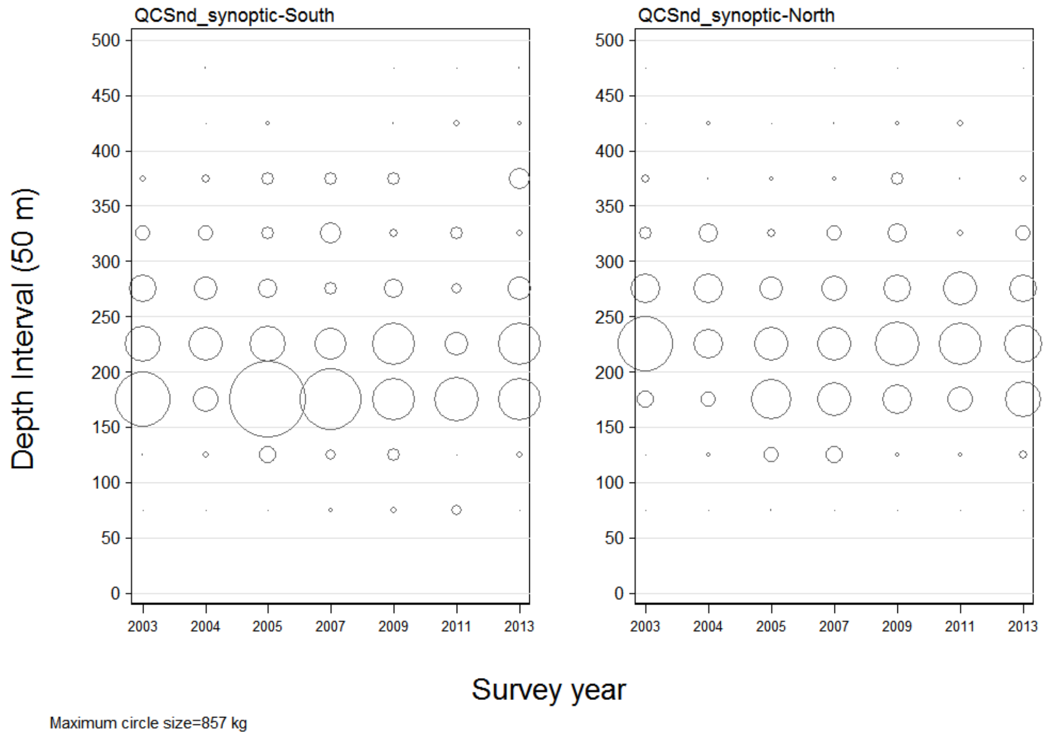


Figure B.57. Distribution of observed catch weights of Redbanded Rockfish for the two main Queen Charlotte Sound synoptic survey areal strata (Table B.15) by survey year and 50 m depth zone. Depth zones are indicated by the mid point of the depth interval and circles in the panel are scaled to the maximum value (857 kg) in the 150–200 m interval in 2005. The 1% and 99% quantiles for the RBR empirical start of tow depth distribution= 133 m and 412 m respectively.

Estimated RBR doorspread biomass from this trawl survey showed no overall trend from 2003 to 2013, with estimates varying between 550 and 1250 t (Table B.17; Figure B.58). The estimated relative errors were relatively low for this species, lying between 15 and 23% (Table B.17). Between 38 and 48% of the South stratum tows and 42 to 57% of the North stratum tows captured some RBR (Figure B.59). Overall, 806 of the 1670 valid survey tows (48%) contained RBR, with the North stratum having a 53% average proportion non-zero tows while the equivalent South stratum proportion was 44%. Although this species occurs frequently in this survey, catch weights tend to be low, with the median catch weight for positive tows around 5 kg/tow across all 7 surveys and the maximum catch weight just over 300 kg in the 2007 survey.

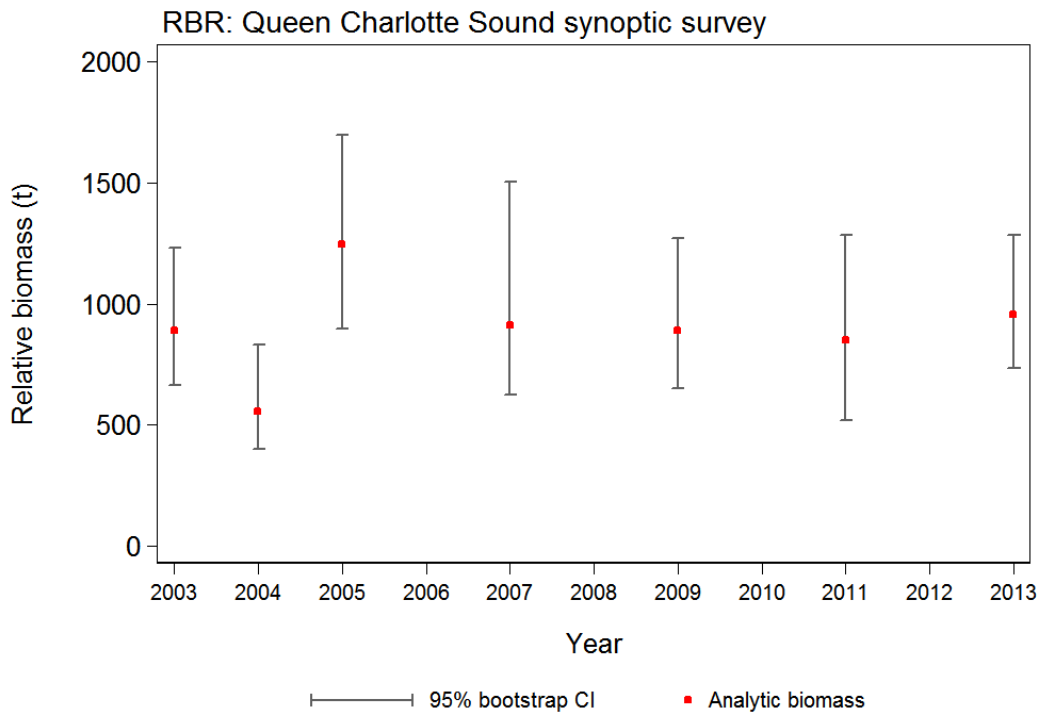


Figure B.58. Plot of biomass estimates for RBR (values provided in Table B.17) from the Queen Charlotte Sound synoptic survey over the period 2003 to 2013. Bias corrected 95% confidence intervals from 1000 bootstrap replicates are plotted.

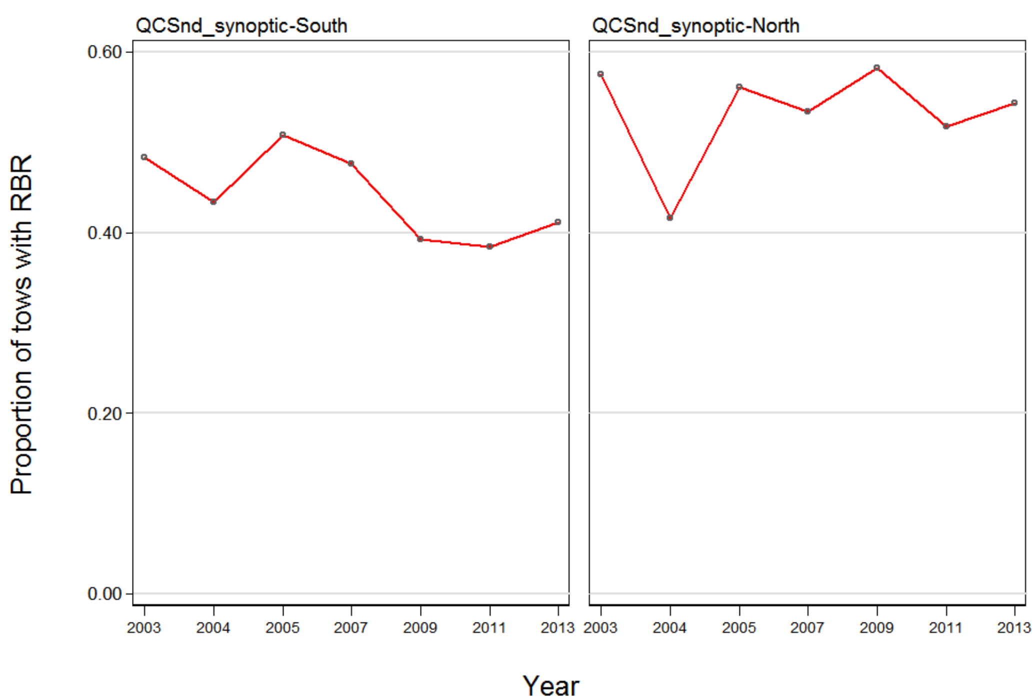


Figure B.59. Proportion of tows by stratum and year which contain RBR from the Queen Charlotte Sound synoptic survey over the period 2003 to 2013.

B.8 WEST COAST VANCOUVER ISLAND SYNOPTIC TRAWL SURVEY

B.8.1 Data selection

This survey has been conducted six times in the period 2004 to 2014 off the west coast of Vancouver Island by RV 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.18). Approximately 150 to 180 2-km^2 blocks are selected randomly among the four depth strata when conducting each survey (Olsen et. al. 2008).

Table B.18. Stratum designations, number of usable and unusable tows, for each year of the west coast Vancouver Island synoptic survey. Also shown is the area of each stratum and the start and end dates for each survey.

Survey year	Stratum depth zone				Total Tows[1]	Unusable tows	Start date	End date
	50-125 m	125-200 m	200-330 m	330-500 m				
2004	35	34	13	8	89	16	26-May-04	09-Jun-04
2006	62	63	28	13	164	10	24-May-06	18-Jun-06
2008	54	51	34	24	159	15	27-May-08	21-Jun-08
2010	58	47	22	10	136	7	08-Jun-10	28-Jun-10
2012	61	46	26	20	153	4	23-May-12	15-Jun-12
2014	55	49	29	14	147	6	29-May-14	20-Jun-14
Area (km^2)	5,872	3,844	720	624	11,060[2]	–	–	–

[1] GFBio usability codes=0,1,2,6
[2] Total area (km^2) for 2014 synoptic survey

A "doorspread density" value was generated for each tow based on the catch of Redbanded Rockfish, the mean doorspread for the tow and the distance travelled (Eq. B.3). The distance travelled was provided as a data field, determined directly from vessel track information collected during the tow. There were only two missing values in this field which were filled in by multiplying the vessel speed by the time that the net was towed. There were a large number of missing values for the doorspread field, which were filled in using the mean doorspread for the survey year or a default value of 64.4 m for the three years with no doorspread data (Table B.19). The default value is based on the mean of the observed doorspread from the net mensuration equipment.

Table B.19. 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.

	Number tows		
	Without doorspread	**With doorspread**	**Mean doorspread (m)**
2004	89	–	–
2006	96	69	64.3
2008	58	107	64.5
2010	136	–	–
2012	153	–	–
2014	14	139	64.3
All surveys	546	315	64.4

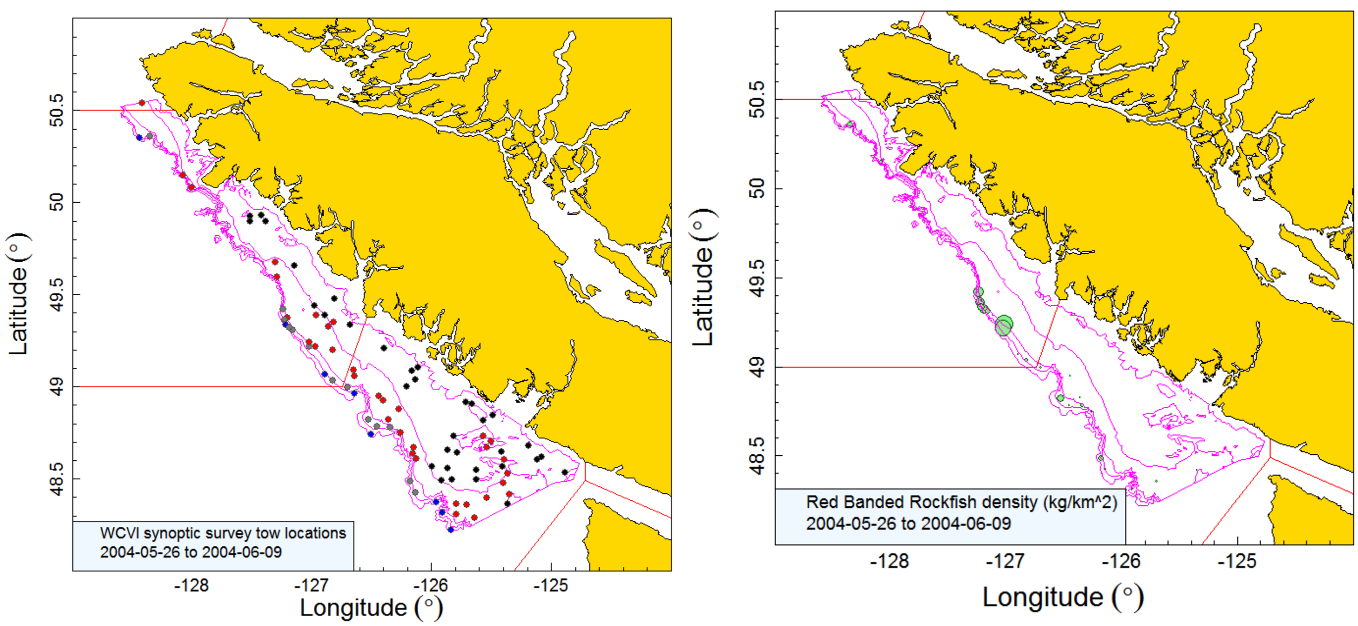


Figure B.60. Valid tow locations (50-125m stratum: black; 126-200m stratum: red; 201-330m stratum: grey; 331-500m stratum: blue) and density plots for the 2004 west coast Vancouver Island synoptic survey. Circle sizes in the right-hand density plot scaled across all years (2004, 2006, 2008, 2010, 2012, 2014), with the largest circle = 2821 kg/km^2 in 2014. The red solid lines indicate the boundaries for PMFC areas 3C, 3D and 5A.

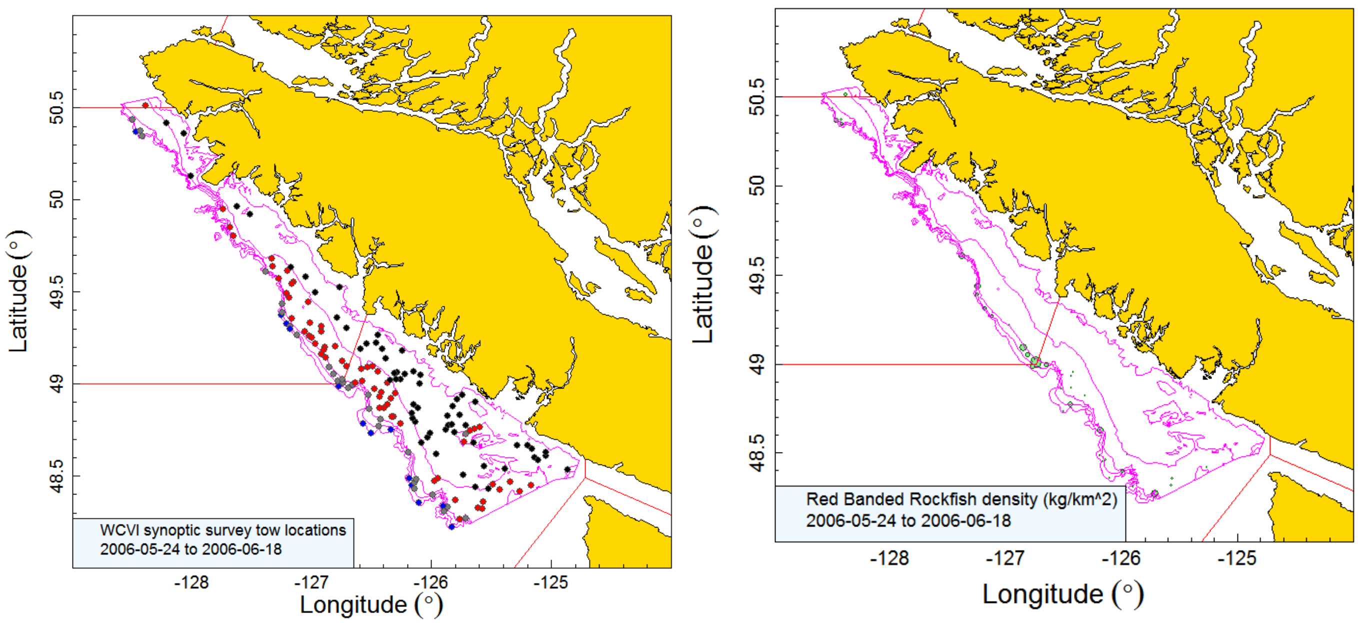


Figure B.61. Tow locations and density plots for the 2006 west coast Vancouver Island synoptic survey (see Figure B.60 caption).

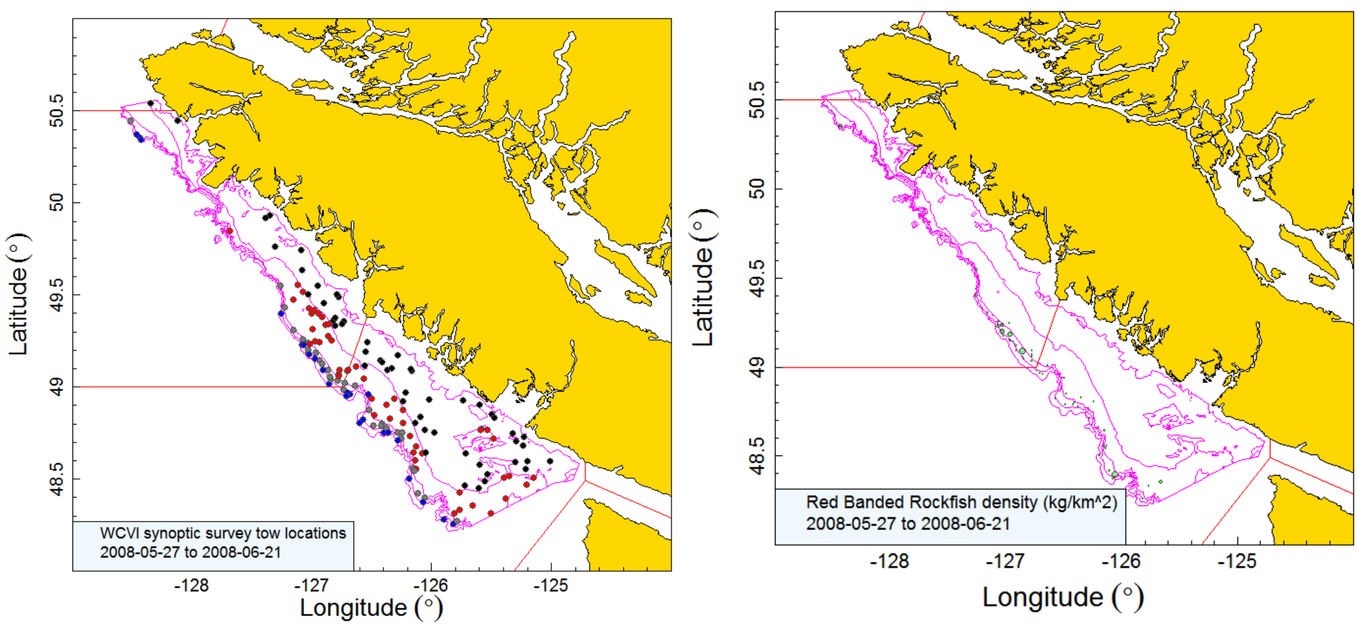


Figure B.62. Tow locations and density plots for the 2008 west coast Vancouver Island synoptic survey (see Figure B.60 caption).

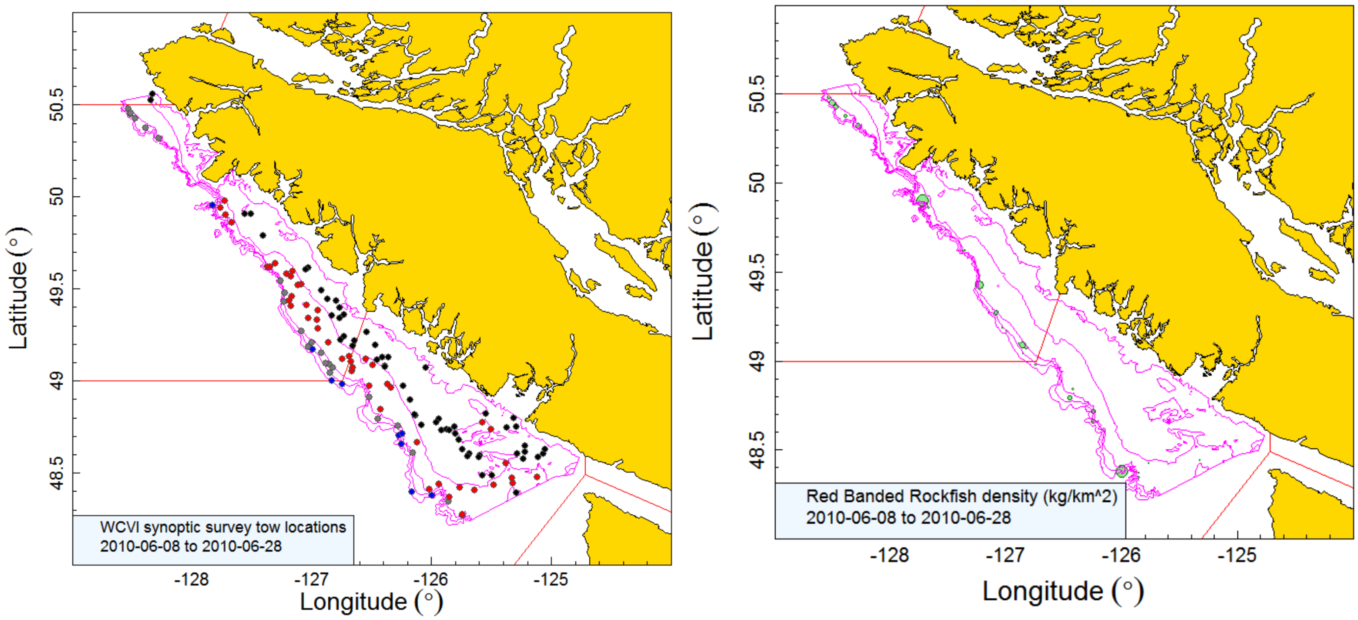


Figure B.63. Tow locations and density plots for the 2010 west coast Vancouver Island synoptic survey (see Figure B.60 caption).

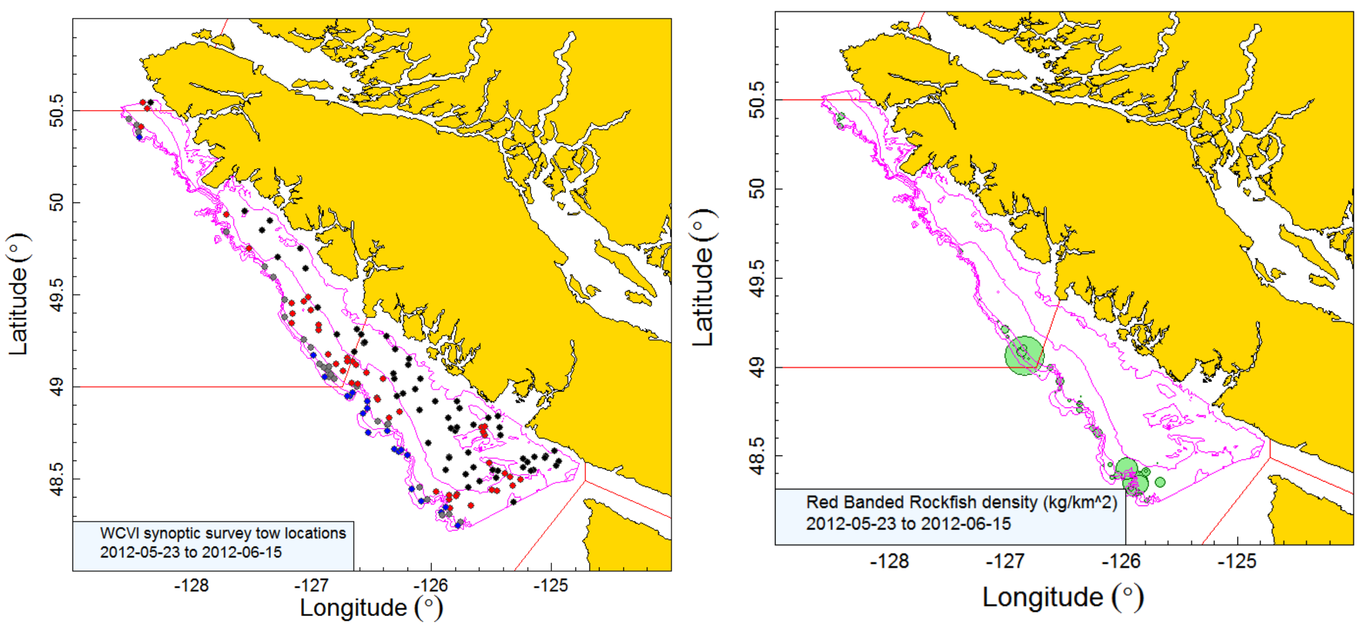


Figure B.64. Tow locations and density plots for the 2012 west coast Vancouver Island synoptic survey (see Figure B.60 caption).

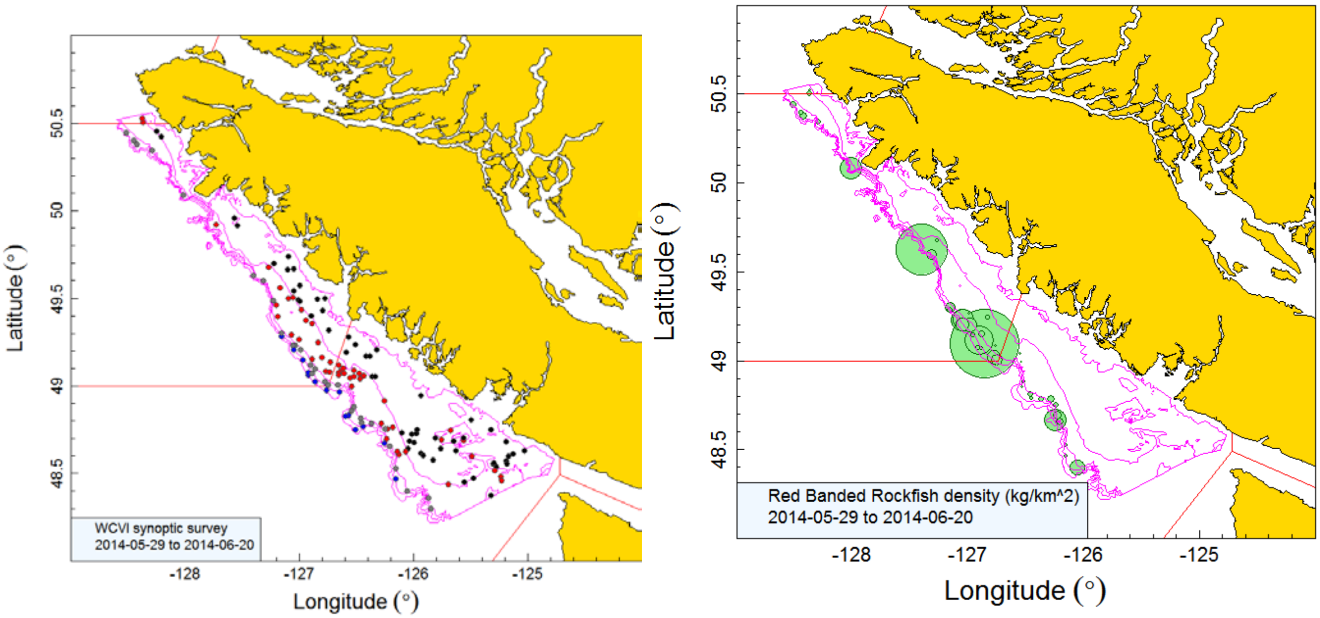


Figure B.65. Tow locations and density plots for the 2014 west coast Vancouver Island synoptic survey (see Figure B.60 caption).

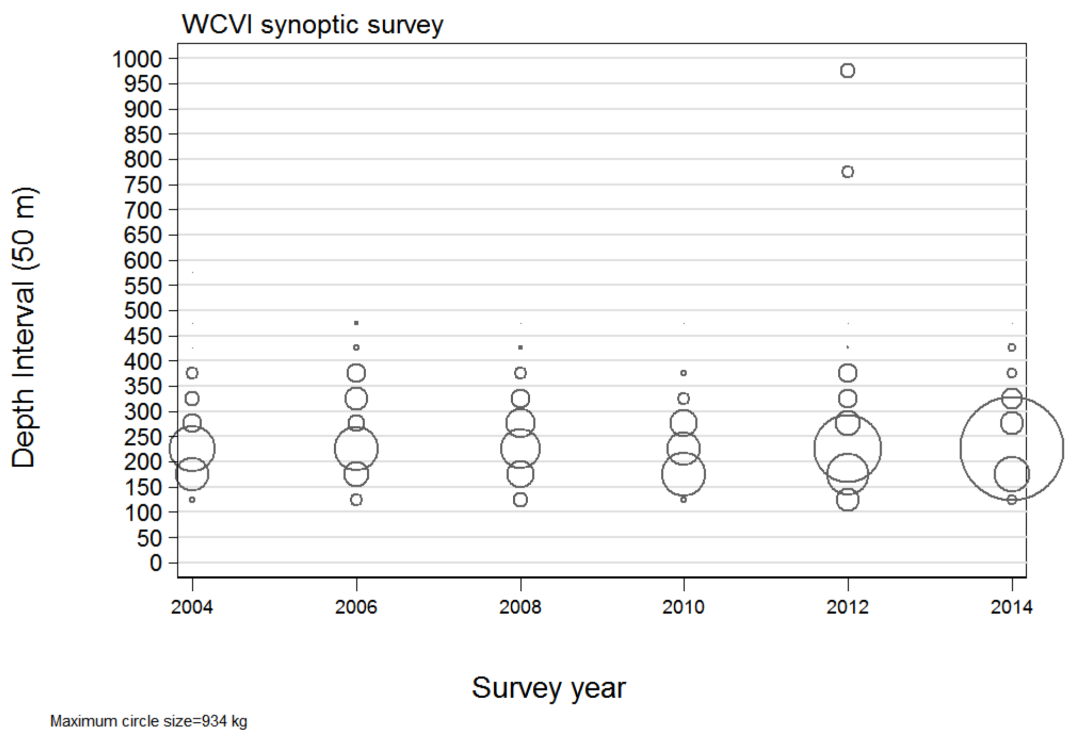


Figure B.66. Distribution of observed weights of Redbanded Rockfish by survey year and 50 m depth zone. Depth zones are indicated by the mid point of the depth interval and circles in the panel are scaled to the maximum value (934 kg) in the 200-250 m interval in 2014. The 1% and 99% quantiles for the RBR empirical start of tow depth distribution= 122 m and 470 m respectively.

B.8.2 Results

The distribution of RBR along the west coast of Vancouver Island does not seem to be as ubiquitous as seen in Queen Charlotte Sound. Figure B.61 to Figure B.65 show that RBR are caught at the edge of the shelf and can be taken anywhere. Redbanded Rockfish were mainly taken at depths from 144 to 375 m (5–95% quantiles), but there were sporadic observations at depths close to 500 m (observations at 764 and 988 m are likely errors; Figure B.66). Estimated biomass levels for Redbanded Rockfish from this trawl survey may be increasing from lows observed in 2006 and 2008, but the relative errors are large and there is no overall trend in the survey indices over the 11 year period of the survey (Figure B.67; Table B.20). The estimated relative errors ranged between 17% and 37% over all surveys, with the 2012 and 2014 surveys having relative error estimates of 32 and 31% respectively (Table B.20).

The proportion of tows capturing Redbanded Rockfish ranged between 29 and 36% for the six surveys, with a mean value of 31% (Figure B.68). Slightly less than a third of the tows from this survey contain RBR, but as in the QC Sound synoptic survey, the median catch weight for positive tows was low (around 5 kg/tow) and the maximum catch weight across all six surveys was 390 kg (in 2014).

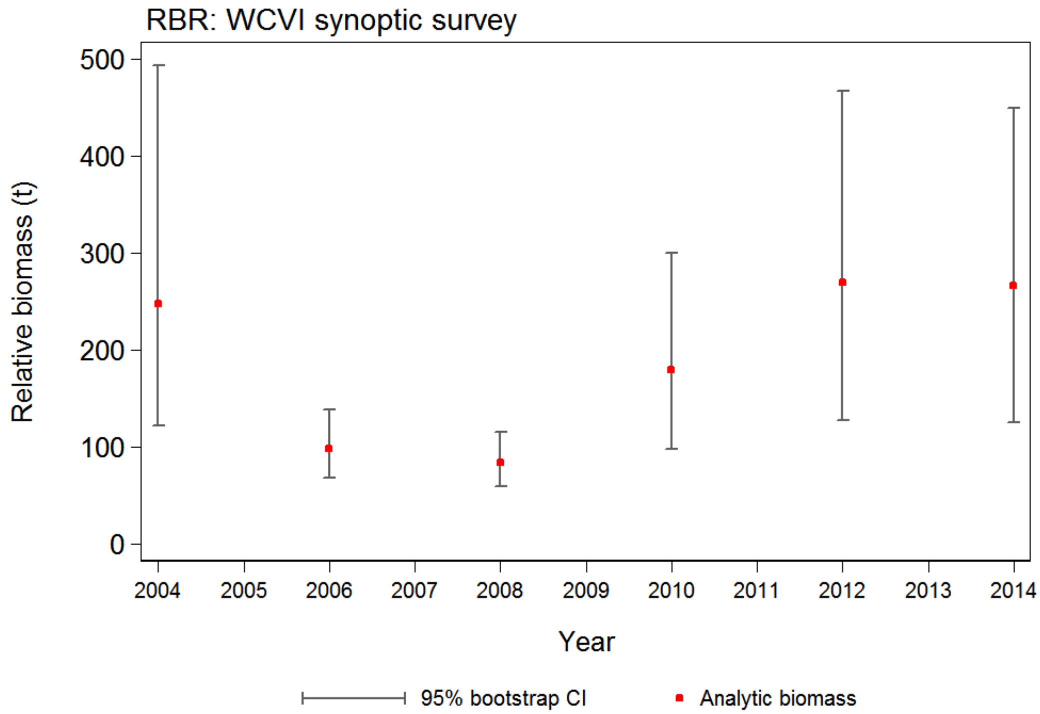


Figure B.67. Plot of biomass estimates for Redbanded Rockfish from the 2004 to 2014 west coast Vancouver Island synoptic trawl surveys (Table B.18). Bias-corrected 95% confidence intervals from 1000 bootstrap replicates are plotted.

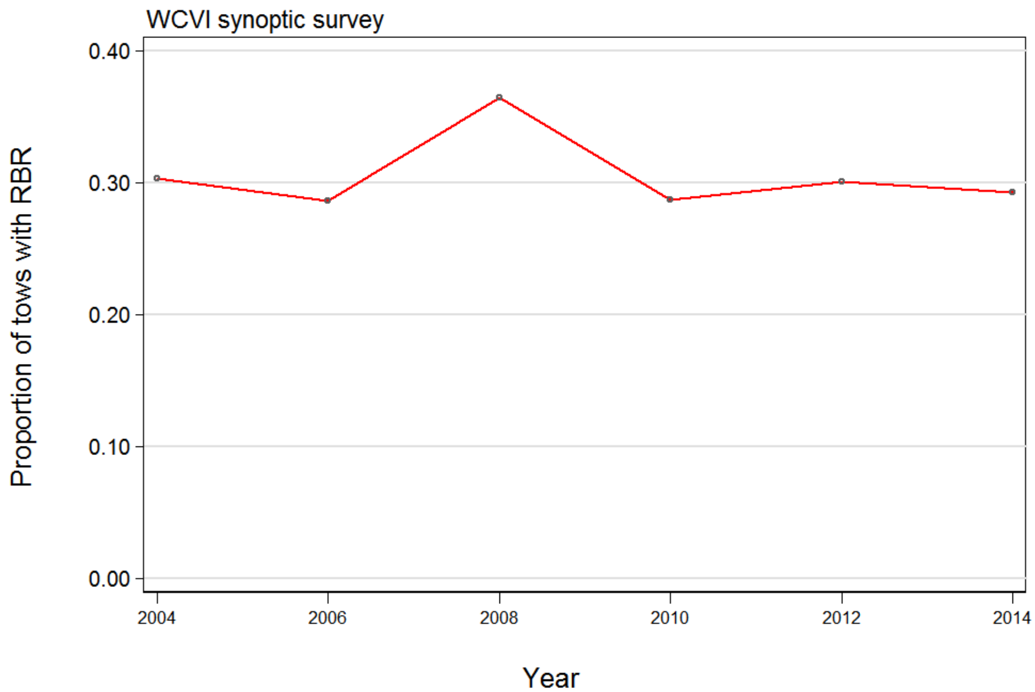


Figure B.68. Proportion of tows by stratum and year capturing Redbanded Rockfish in the WCVI synoptic trawl surveys, 2004–2014.

Table B.20. Biomass estimates for Redbanded Rockfish from the WCVI synoptic trawl survey for the survey years 2004 to 2014. The 1996 Caledonian survey areas by stratum were increased to match the equivalent 2012 WCVI synoptic strata (see Table B.18). Bootstrap bias-corrected confidence intervals and CVs are based on 1000 random draws with replacement.

Survey Year	**Biomass (t)**	**Mean bootstrap biomass (t)**	**Lower bound biomass (t)**	**Upper bound biomass (t)**	**Bootstrap CV**	**Analytic CV** (Eq. B.6)
2004	248.1	243.9	122.2	493.3	0.370	0.377
2006	98.4	97.3	68.4	139.0	0.178	0.174
2008	84.3	84.1	59.6	115.1	0.167	0.165
2010	180.0	178.8	97.8	300.1	0.293	0.299
2012	269.2	269.9	127.2	466.7	0.317	0.314
2014	266.2	270.9	125.4	450.0	0.310	0.312

The six WCVI synoptic survey indices spanning the period 2004 to 2014 were used as an abundance index series for use in the stock assessment model (described in Appendix E). A 1996 Caledonian survey index was not accepted into this series because of the substantial difference in timing for this survey (September) compared to the timing of the synoptic surveys (late spring). It was felt that this difference would lead to varying availability for this species between surveys and consequently there would be a difference in comparability between this survey and remaining six synoptic surveys.

B.9 THE WEST COAST HAIDA GWAII SYNOPTIC TRAWL SURVEY AND THE 1997 WEST COAST HAIDA GWAII OCEAN SELECTOR SURVEY

B.9.1 Data selection

The west coast Haida Gwaii (WCHG) survey has been conducted five times in the period 2006 to 2012 off the west coast of Haida Gwaii. It 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 2006 survey used a different depth stratification scheme compared to the later synoptic surveys: 150–200 m, 200–330 m, 330–500 m, 500–800 m, and 800–1300 m (Workman et al. 2007). All tows from this survey were re-stratified into the four depth strata used from 2007 onwards: 180–330 m; 330–500 m; 500–800 m; and 800–1300 m, based on the mean of the beginning and end depths of each tow (Table B.21). Plots of the locations of all valid tows by year and stratum are presented in Figure B.70 (2006), Figure B.71 (2007), Figure B.72 (2008), Figure B.73 (2010) and Figure B.74 (2012). Note that the depth stratum boundaries for this survey differ from those used for the Queen Charlotte Sound (Edwards et al., 2012*b*) and west coast Vancouver Island (Edwards et al., 2012*a*) synoptic surveys due to the considerable difference in the seabed topography of the area being surveyed. The deepest stratum (800–1300 m) was omitted from this analysis because of lack coverage in 2007.

A survey using the *Ocean Selector* was conducted in September 1997 (Workman et al. 1998), using a design that closely resembled that subsequently used for the WCHG synoptic survey, including the random selection of survey blocks and the use of Atlantic Western II box trawl net (Figure B.69, Table B.21). Tow times were set at 15 minutes, which was similar to the 20 minute target tow period used in the synoptic survey. Given the similarity in design, the familiarity of the skipper with this section of the coast and the use of three different vessels in the synoptic surveys (Table B.21), it seemed reasonable to link this survey with the four WCHG synoptic surveys conducted from 2006. Two tows conducted by this survey off the southern end of Moresby Island were dropped because the WCHG synoptic survey did not go south of 53°N latitude in 2007 and 2010, and none of the five synoptic surveys went as far south as the 1997 survey. The 1997 survey used a different depth stratification scheme compared to the later synoptic surveys: 180–275 m, 275–365 m, 365–460 m, 460–625 m, with the depth of all tows ranging from 166 m to 573 m (based on the mean of beginning and end depths). These tows were re-stratified to the WCHG stratum scheme used from 2007 onwards, taking the depth of the tow as the mean of the beginning and end depths of the tow (Table B.21).

A “doorspread density” value (Eq. B.4) was generated for each tow based on the catch of Redbanded Rockfish, the mean doorspread for the tow and the distance travelled for both the WCHG and the 1997 Selector survey. The distance travelled was determined directly by measuring the tow path for all six surveys. There were no missing values in the distance travelled field for these six surveys, but there were some missing doorspread values in valid tows from the five synoptic surveys, which had mean doorspread values that ranged from 69 m to 81 m (Table B.22). Missing doorspread values were replaced with the mean doorspread for the survey year. The 1997 Ocean Selector survey had no associated doorspread values for any of its tows because net mensuration instruments were not present at the time of the survey.

There were inconsistencies in the reported net dimensions for the 1997 survey in Workman et al. (1998), with Figure 3 of that document reporting 46 m as the combined length of the bridle plus sweeps, while the same dimension was reported as 55 m in the text of the document. Interviews with skippers who were active at the time, including Dave Clattenberg, the skipper of the 1997 Selector survey, indicated that the 55 m dimension was correct. Fifty-five metres was also the length of the bridle and sweeps used for the synoptic surveys. Consequently, the mean doorspread observed over the first four synoptic surveys (76.6 m) (Table B.22) was used to populate the missing doorspread field for the 1997 Ocean Selector survey. Stratum areas were held constant for all six surveys (Table B.21).

Table B.21. Stratum designations, vessel name, number of usable and unusable tows, for each year of the west coast Haida Gwaii synoptic survey as well as the 1997 Ocean Selector survey. Also shown are the area of each stratum and the dates of the first and last survey tow in each year.

		Depth stratum							
Survey year	**Vessel**	**180-330m**	**330-500m**	**500-800m**	**800-1300m**	**Total tows[1]**	**Unusable tows**	**Minimum date**	**Maximum date**
1997	Ocean Selector	39[2]	57	6	–	102[2]	5	07-Sep-97	21-Sep-97
2006	Viking Storm	54	27	18	11	110	13	30-Aug-06	22-Sep-06
2007	Nemesis	68	34	9	–	111	5	14-Sep-07	12-Oct-07
2008	Frosti	71	31	8	8	118	9	28-Aug-08	18-Sep-08
2010	Viking Storm	82	29	12	5	128	3	28-Aug-10	16-Sep-10
2012	Nordic Pearl	75	29	10	15	129	12	27-Aug-12	16-Sep-12
Area (km^2)		1104	1028	956	2248	5336[3]	–	–	–

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

Table B.22. Number of valid tows with doorspread measurements, the mean doorspread values (in m) from these tows for each survey year and the number of valid tows without doorspread measurements.

Year	**Tows with doorspread**	**Tows missing doorspread**	**Mean doorspread (m)**
2006	93	30	77.7
2007	113	3	68.5
2008	123	4	80.7
2010	129	2	79.1
2012	92	49	73.8
Total/Average	550	88	76.6[1]

[1] average 2006–2010: all observations

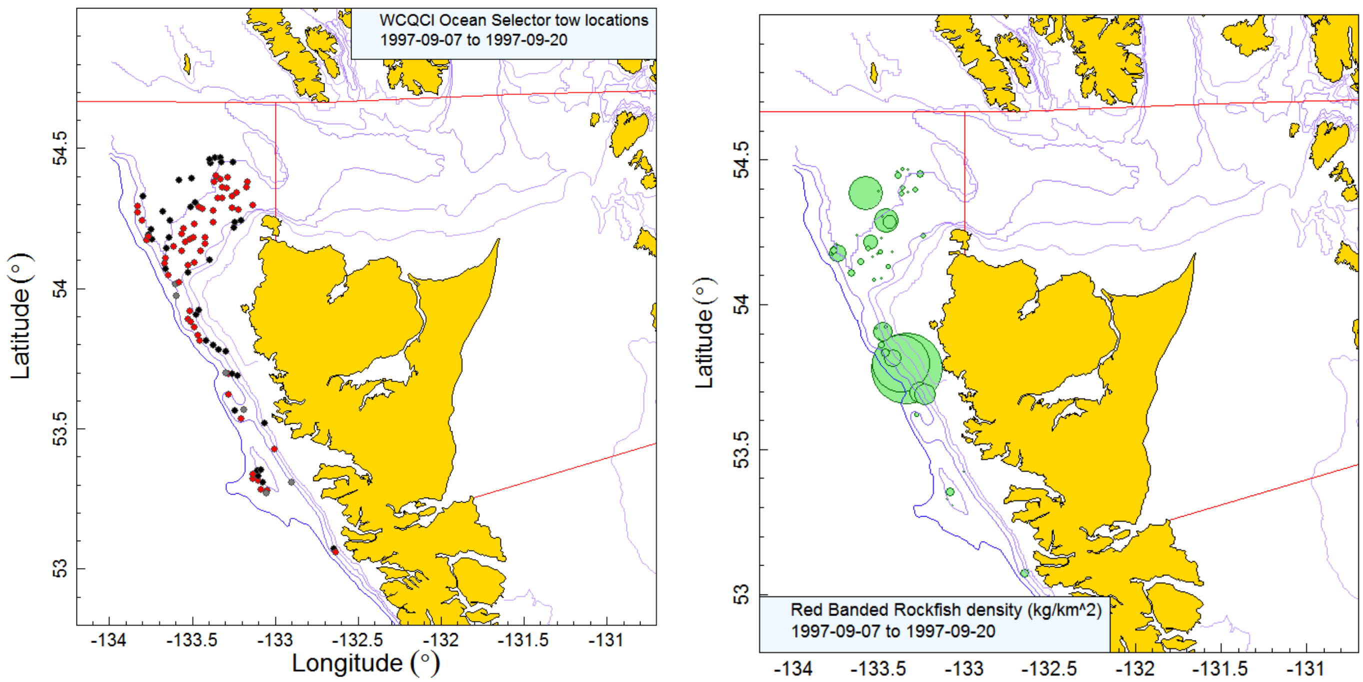


Figure B.69. Valid tow locations (180-330m stratum: black; 330-500m stratum: red; 500-800m stratum: grey) and density plots for the 1997 Ocean Selector random survey. Circle sizes in the right-hand density plot scaled across all years (1997, 2006–2012), with the largest circle = 1778 kg/km^2 in 1997. The red lines show the Pacific Marine Fisheries Commission 5E and 5D major area boundaries.

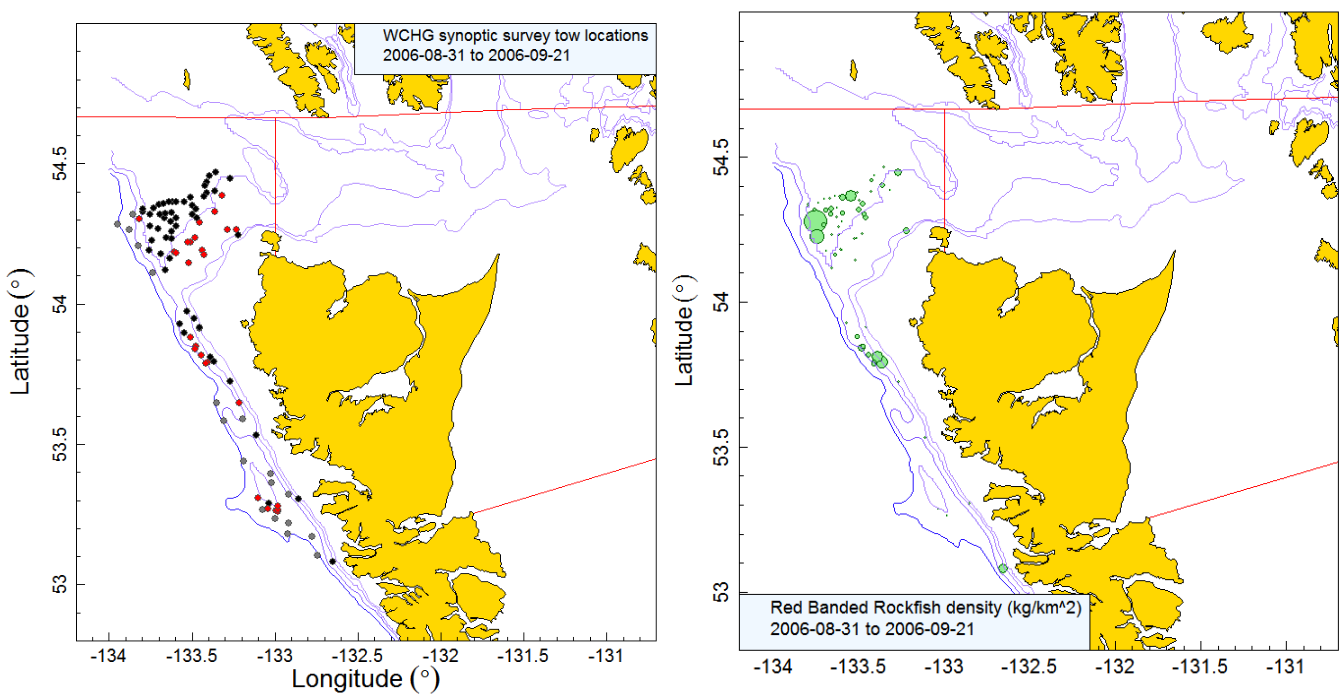


Figure B.70. Tow locations and density plots for the 2006 Viking Storm synoptic survey (see Figure B.69 caption).

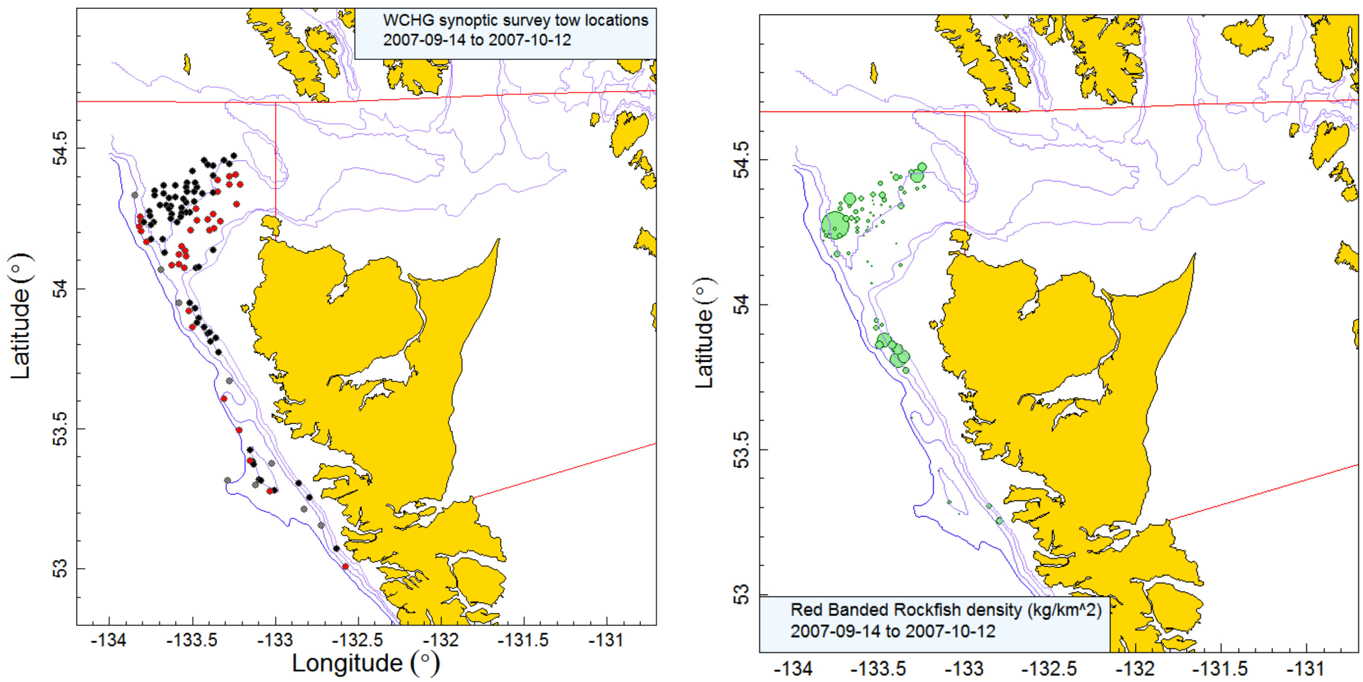


Figure B.71. Tow locations and density plots for the 2007 Nemesis synoptic survey (see Figure B.69 caption).

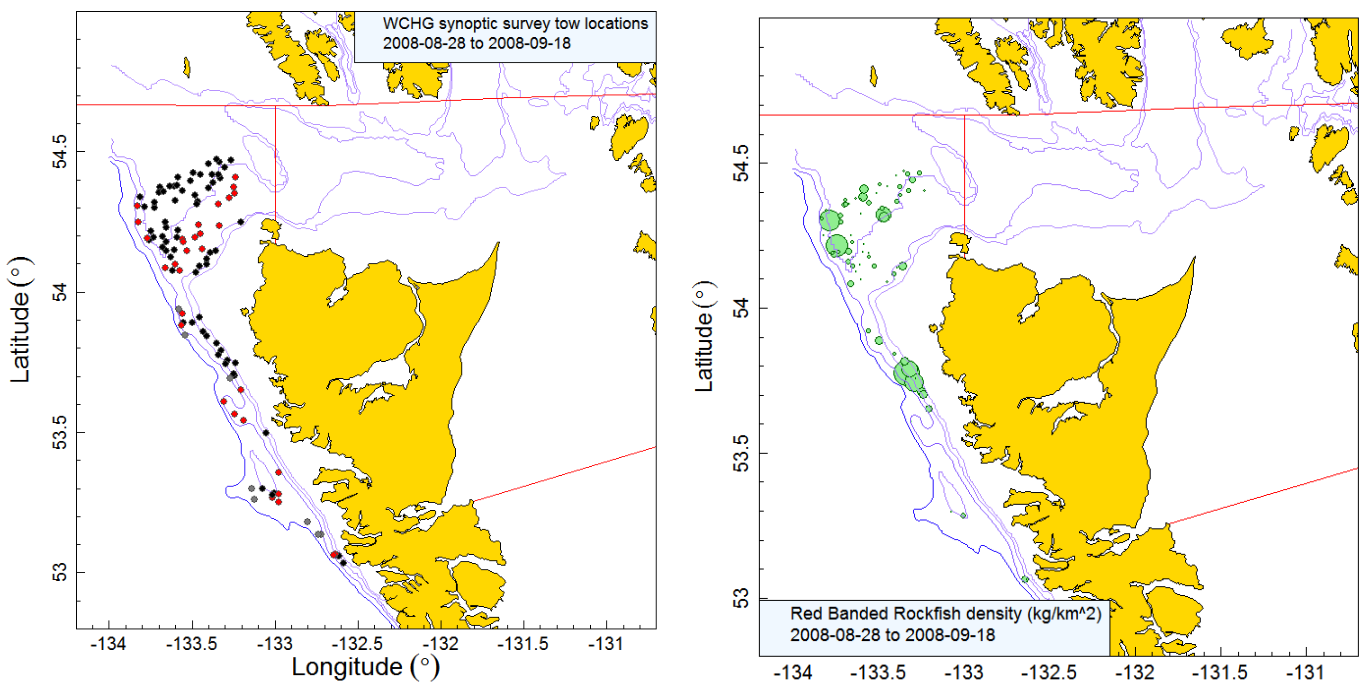


Figure B.72. Tow locations and density plots for the 2008 Frosti synoptic survey (see Figure B.69 caption).

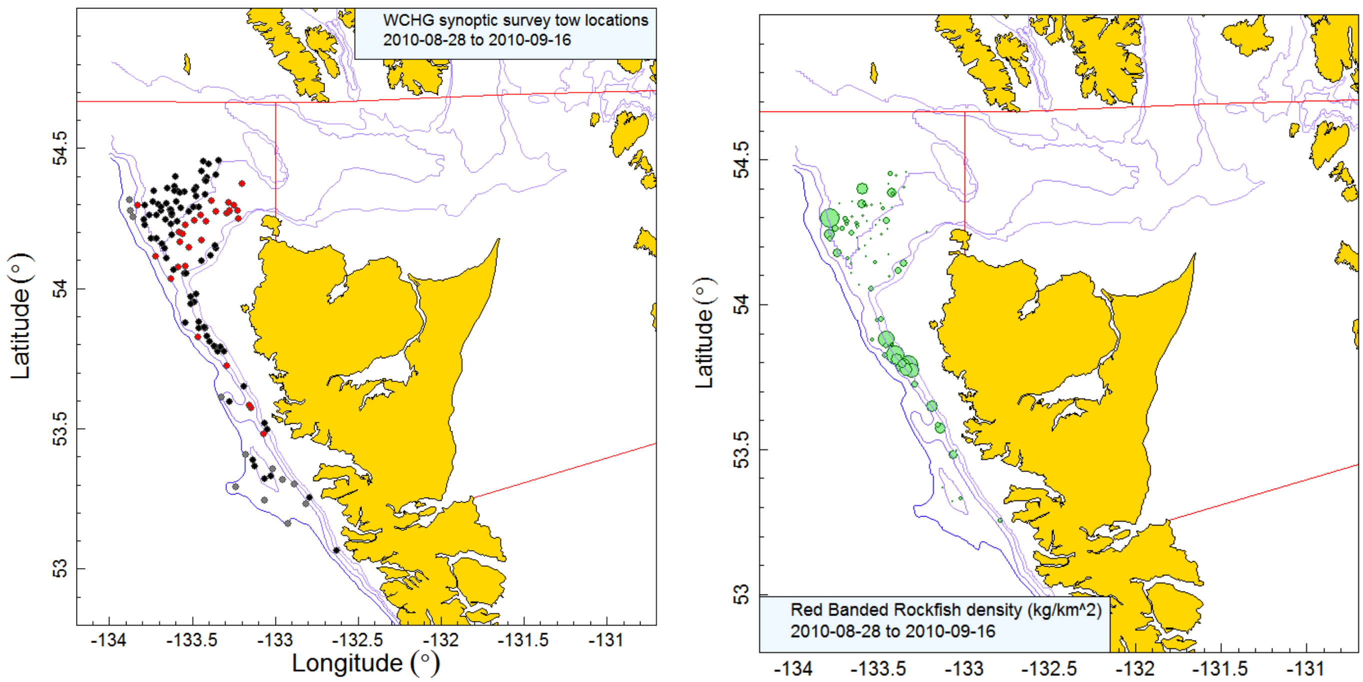


Figure B.73. Tow locations and density plots for the 2010 Viking Storm synoptic survey (see Figure B.69 caption).

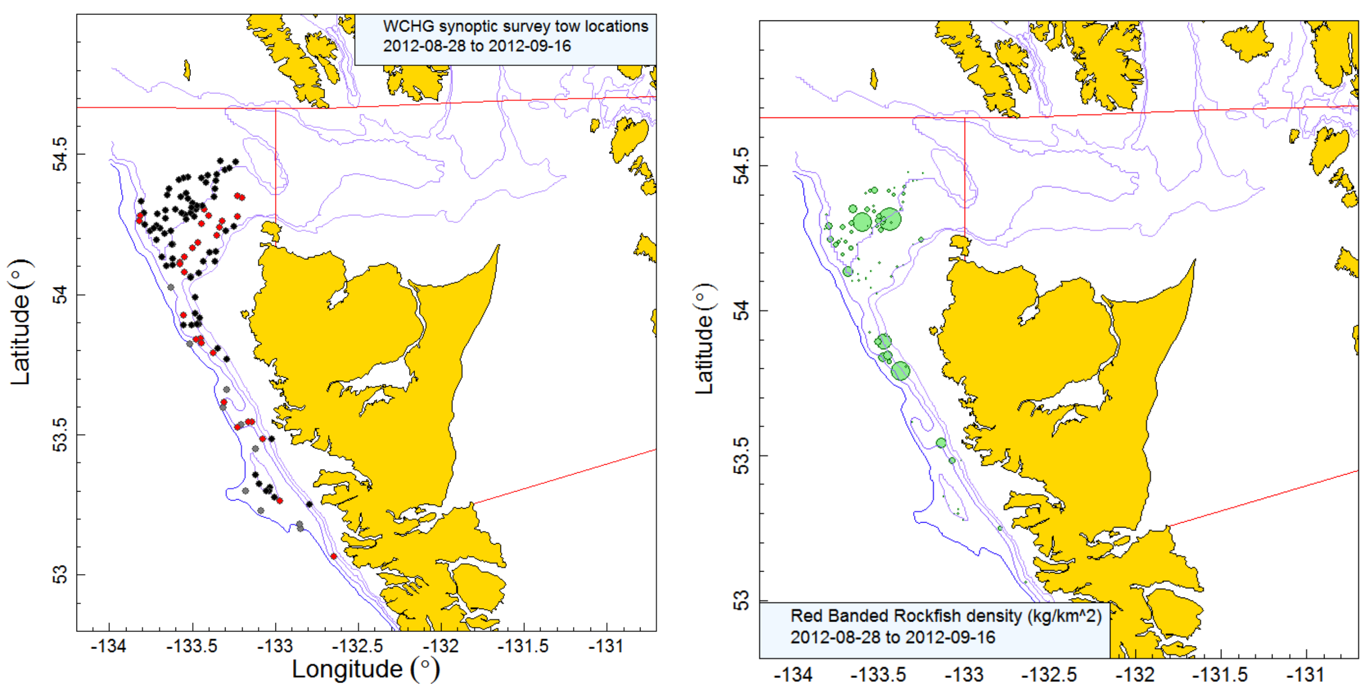


Figure B.74. Tow locations and density plots for the 2012 Viking Storm synoptic survey (see Figure B.69 caption).

B.9.2 Results

Catch densities of Redbanded Rockfish from this survey series were common, distributed along the northwest shelf and into the western part of Dixon Entrance [Figure B.69 (1997), Figure B.70 (2006), Figure B.71 (2007), Figure B.72 (2008), and Figure B.73 (2010)]. Redbanded Rockfish were mainly taken at depths from 217 to 392 m (5 to 95% quantiles), with few observations below 400 m (Figure B.75).

Table B.23. Biomass estimates for Redbanded Rockfish from the five west coast Haida Gwaii synoptic surveys and the 1997 Ocean Selector random survey. Bootstrap bias-corrected confidence intervals and coefficients of variation (CVs) are based on 1000 random draws with replacement.

Survey Year	**Biomass (t)**	**Mean bootstrap biomass (t)**	**Lower bound biomass (t)**	**Upper bound biomass (t)**	**Bootstrap CV**	**Analytic CV (**Eq. B.6**)**
1997	160.5	160.4	68.0	301.8	0.371	0.392
2006	74.8	74.8	51.4	107.3	0.191	0.198
2007	72.5	72.8	51.0	106.2	0.187	0.187
2008	90.8	91.9	60.8	128.6	0.190	0.187
2010	99.4	99.9	71.1	135.1	0.160	0.160
2012	87.9	88.4	55.4	137.2	0.235	0.229

Estimated biomass levels for Redbanded Rockfish from these trawl surveys were low but consistent (ranging from 160 t in 1997 to 73 t in 2007) with no trend in the five synoptic surveys, but the 1997 Ocean Selector survey index was nearly twice the mean of the five synoptic indices, although with a high relative error (Figure B.76; Table B.23). The estimated relative errors for these surveys were moderate, ranging from 16 to 37% (Table B.23). The proportion of tows that captured Redbanded Rockfish ranged from 64 to 73% of the valid tows over the five synoptic survey years, while being about 50% for the 1997 Ocean Selector survey (Figure B.77). RBR occur frequently in this survey (as seen in the other synoptic surveys), but the median catch weight for positive tows is low (around 5 kg/tow) and the maximum catch weight across all six surveys is 207 kg (in 1997).

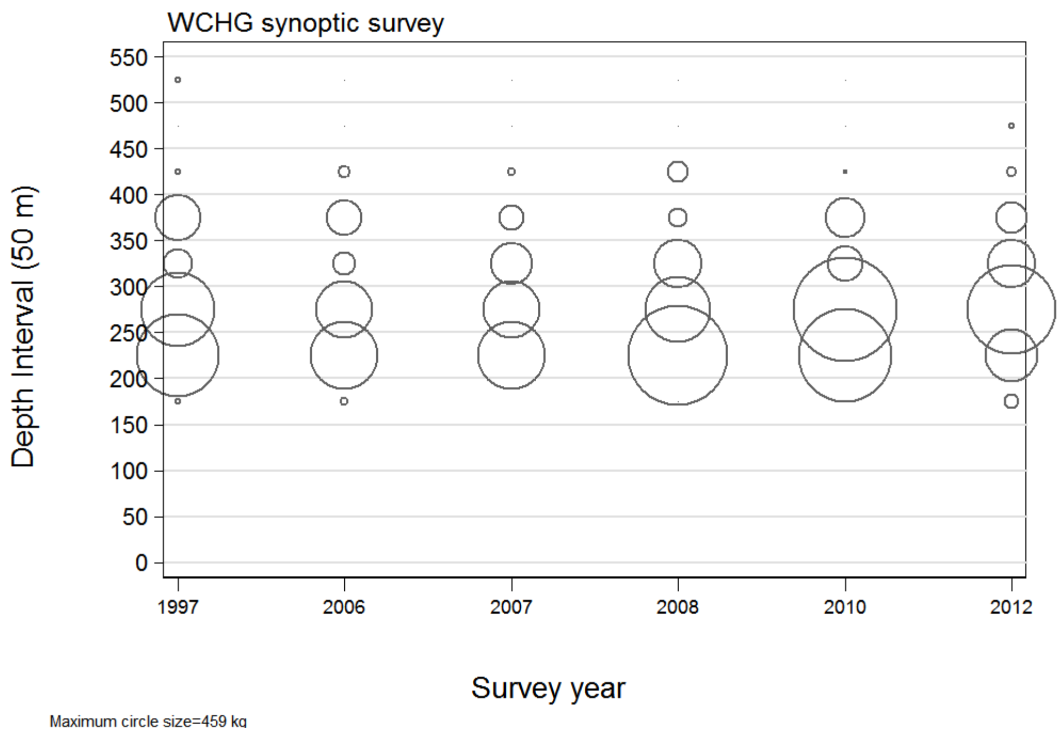


Figure B.75. Distribution of observed weights of Redbanded Rockfish by survey year and 50 m depth zone intervals. Depth zones are indicated by the mid point of the depth interval and circles in the each panel are scaled to the maximum value (126 kg – 250-300 m interval in 2010). Minimum and maximum depths observed for RBR: 201 m and 432 m, respectively. Depth is taken at the start position for each tow.

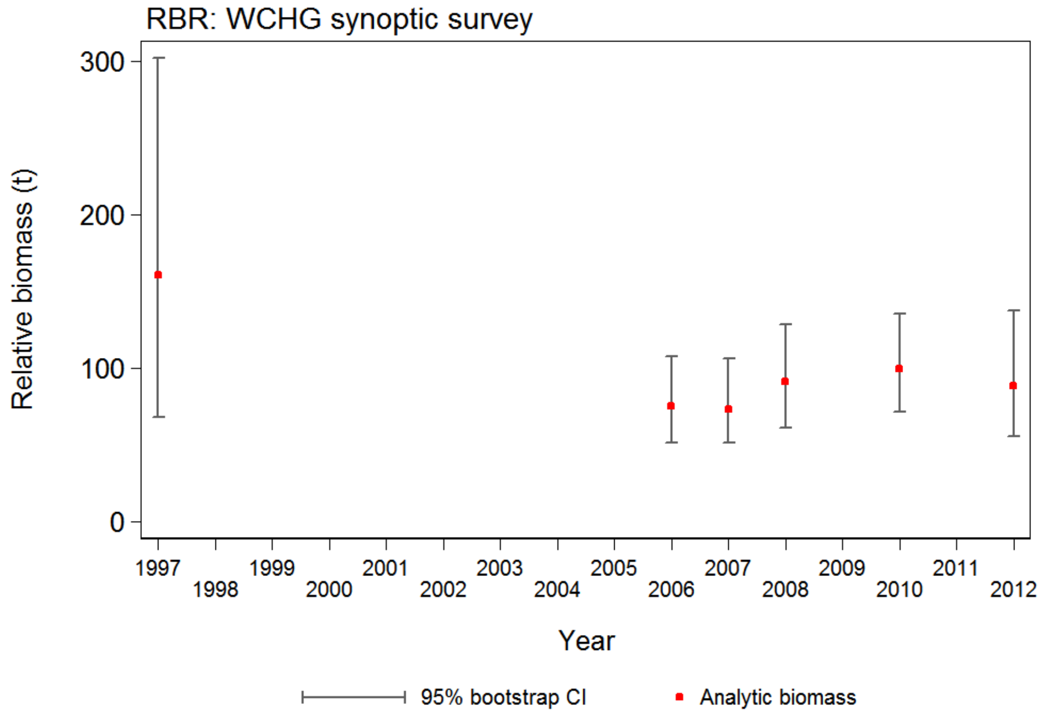


Figure B.76. Biomass estimates for Redbanded Rockfish from the five west coast Haida Gwaii synoptic surveys and the 1997 Ocean Selector random survey (Table B.23). Bias-corrected 95% confidence intervals from 1000 bootstrap replicates are plotted.

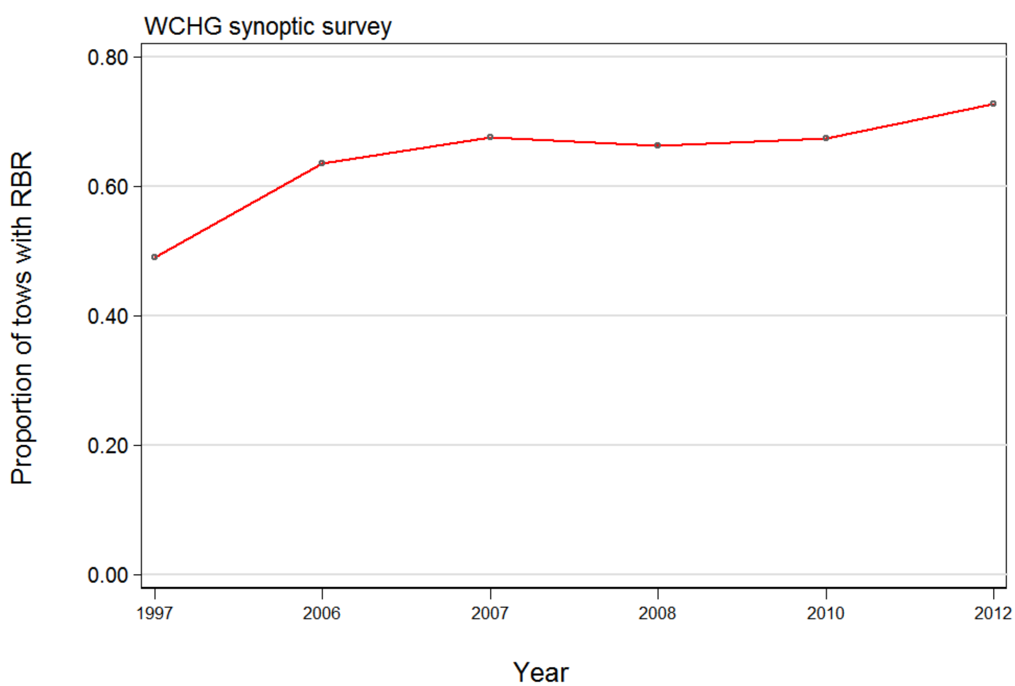


Figure B.77. Proportion of tows by year that contain Redbanded Rockfish for the five west coast Haida Gwaii synoptic surveys and the 1997 Ocean Selector random survey.

APPENDIX C. IPHC SURVEY DATA

C.1 INTRODUCTION

The International Pacific Halibut Commission (IPHC) conducts an annual stock assessment longline survey in waters from California to Alaska, including British Columbia waters (e.g. Flemming et al. 2012). The survey's main purpose is to provide data on Pacific Halibut (*Hippoglosus stenolepis*) for stock assessment purposes.

At each station, the fishing gear consists of a set of skates each of about 100 hooks. Up to eight skates are on each set, with the number of skates per set varying between years. For each set the IPHC calculates an 'effective skate number', which we use here to scale the count of Redbanded Rockfish to obtain a catch rate for each set (described below). The effective skate number "standardizes survey data in years when the number of hooks, hook spacing, or hook type varied" (Yamanaka et al., 2008). An effective skate of one represents a skate of 100 circle hooks with 18-foot spacing (Yamanaka et al., 2008).

The index series constructed here from the IPHC surveys for Redbanded Rockfish consists of the mean catch rate for each year. The mean for a year is the mean of the catch rates of all sets within that year. The catch rate of a set has units of 'number of Redbanded Rockfish caught per effective skate'. The catch rates within a year are bootstrapped, to give bootstrapped means, bias-corrected and adjusted (BCa) bootstrapped 95% confidence intervals, and bootstrapped coefficients of variation (CV). The bootstrapped means and CVs are used as input for the statistical catch-at-age model (Appendix E) and the regression analyses reported in the main text.

C.2 DATA

In British Columbia waters (IPHC area 2B), since 2003 a third observer has been deployed on the IPHC survey to identify all catch to the species level on a hook-by-hook basis and to conduct biological sampling (Flemming et al., 2012), although in 2013 there was no such observer (and 2014 data are not yet available). Prior to 2003 observers were also deployed, though data are not available in such detail, as summarised in Table C.1.

Three issues are apparent:

1. From 1997-2002 only the first 20 hooks of each skate were enumerated, whereas for all

Table C.1. Summary of available data from the IPHC stock assessment longline surveys. [1] For 1995, the biological data were in the file "1995 IPHC SSA Rockfish catch from Kelly Ames.xls" on DFO's Inshore Rockfish shared drive, and effective skates were obtained from Aaron Ranta (IPHC) in the file "1995EffSktValues by Station.xlsx". [2]For 1996-2002, the data were in the file "2B AllSpecies 96-02 roundIII.xls", which originally came from the IPHC. 'Data resolution' indicates at what level the data are available.

Year	Hooks enumerated	Data resolution	Location of data	Other details
1995	All	Set-by-set	Spreadsheets[1]	
1996	All	Set-by-set	Spreadsheet[2]	
1997-2002	First 20 of each skate	Set-by-set	Spreadsheet[2]	
2003-2011	All	Hook-by-hook	DFO database `GFBio`	
2012	All	Hook-by-hook	DFO database `GFBio`	Bait experiment

other years all hooks were enumerated. Thus, the data from each year cannot simply be considered as comparable and analysed as one consecutive time series.

2. For the datasets from 1995, 1996 and 1997-2002, data are only available at the set-by-set level, in terms of numbers of a given species per effective skate. Which species was caught on each hook is not available, unlike for 2003-2012. Thus, for 1995 and 1996 we cannot simply calculate catch rates based on the first 20 hooks, whereas we can for 2003-2012 and that's the only information we have for 1997-2002.
3. In 2012 a bait experiment was conducted such that data from all skates could not be used; see Section C.4.

To address 1 and 2 we therefore considered two time series:

Series A – 1997-2002 and 2003-2012 stations, with catch rates based on first 20 hooks only (which is all we have for 1997-2002).

Series B – 1995, 1996 and 2003-2012 stations, with catch rates based on all hooks (which is all we have for 1995 and 1996).

We investigated how to combine the 1995 and 1996 values from Series B, based on all hooks, with the 1997-2012 values from Series A that are based on first 20 hooks only. We obtained a single combined series, as described in Section C.6.

C.3 SPATIAL LOCATIONS OF STATIONS

First, we show the locations of the stations for each year, and justify why we only considered station north of the northernmost tip of Vancouver Island.

For Series A, the locations of the stations for each year from 1997 to 2002 are shown in Figures C.1-C.6. Stations were not fixed between years, with the main difference being whether or not the waters off the west coast of Vancouver Island were surveyed. From 2003 onwards, the survey was conducted at 170 regular fixed (non-random) stations positioned on a 10 nautical mile square grid (Flemming et al., 2012), as shown in Figure C.7.

Given the difference in coverage between years, we excluded those stations south of 50.87° latitude, which is the northern tip of Vancouver Island, as shown in Figure C.1. The black crosses in Figures C.1-C.7 indicate which stations were excluded. Since for Series A we only consider the first 20 hooks from each skate (but for 2003 onwards we have data for all hooks), in Figure C.8 we illustrate the stations where a Redbanded Rockfish was ever caught in the first 20 hooks of each skate, those that caught Redbanded Rockfish on some hooks but never in the first 20, and those that never caught Redbanded Rockfish.

For Series B, the stations used in 1995 and 1996 are almost identical in location (Figures C.9 and C.11), and similarly to 1997, 1998 and 2000, do not sample off the west coast of Vancouver Island. North of Vancouver Island, the 1995 and 1996 stations show good overlap with the 2003+ stations (Figure C.12), such that only considering stations north of Vancouver Island (Figure C.13) gives similar coverage for Series B and Series A.

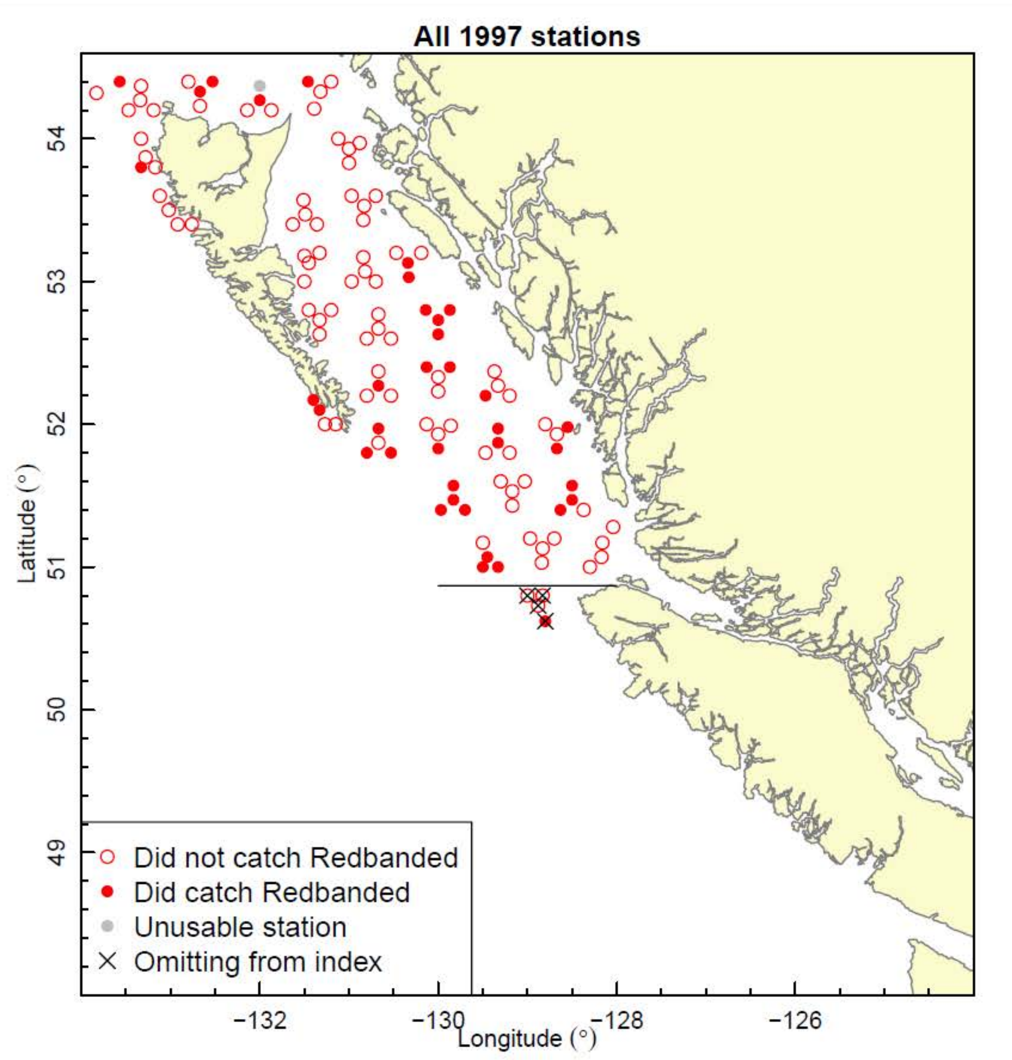


Figure C.1. Locations of the 122 stations in 1997, of which 84 did not catch Redbanded Rockfish (red open circles), 37 stations did catch it (red closed circles), and 1 were deemed unusable by the IPHC (grey closed circles) and so are not considered further. Black crosses indicate the 4 stations being excluded from the analyses. The black line indicates the latitude of the northern tip of Vancouver Island, below which stations are being excluded.

C.4 CHUM SALMON BAIT EXPERIMENT

Prior to 2012, Chum Salmon (*Oncorhynchus keta*) was used for bait. But in 2012, a bait experiment was conducted (Henry et al., 2013). At each station three different bait types were used on the same set: a consecutive four-skate Chum Salmon treatment, a one-skate Pink Salmon (*Oncorhynchus gorbuscha*) treatment, and a one-skate Walleye Pollock (*Theragra chalcogramma*) treatment. The location of the three treatments on each set was randomized throughout the survey, and each treatment was separated by one skate (1800 ft) of hookless groundline. For consistency with previous years, we only considered the four skates that used Chum Salmon as bait.

The effective skate number provided by the IPHC is for all skates used, which in 2012 will include skates that were not baited with Chum Salmon (Eric Soderlund, IPHC, Seattle, WA, USA,

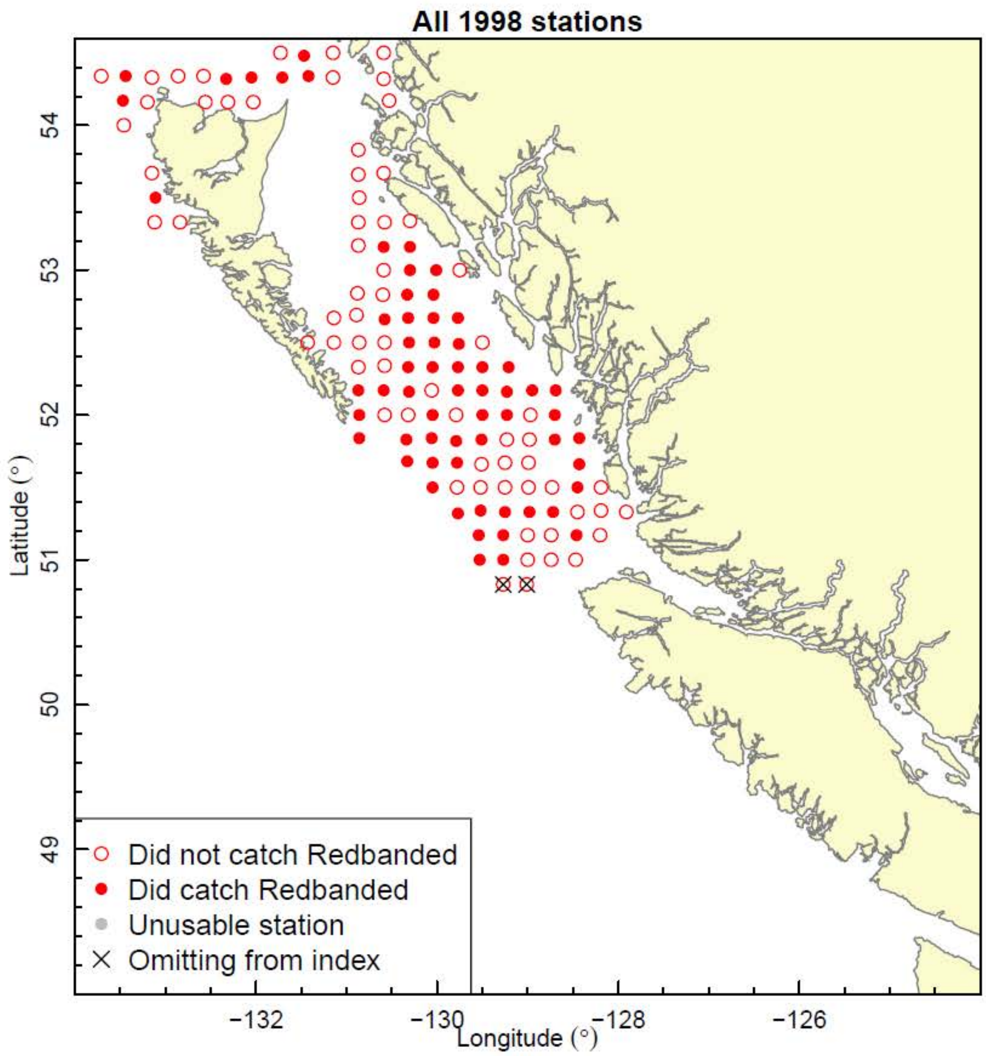


Figure C.2. Locations of the 128 stations in 1998, of which 66 did not catch Redbanded Rockfish (red open circles), 62 stations did catch it (red closed circles), and 0 were deemed unusable by the IPHC (grey closed circles) and so are not considered further. Black crosses indicate the 2 stations being excluded from the analyses.

pers. comm.). But we wish to only include the Chum Salmon baited skates, and so we needed to modify the effective skate number (see below). The effective skate number depends on the number of observed hooks (Eric Soderlund, IPHC, Seattle, WA, USA, pers. comm.), rather than the number of hooks that were deployed.

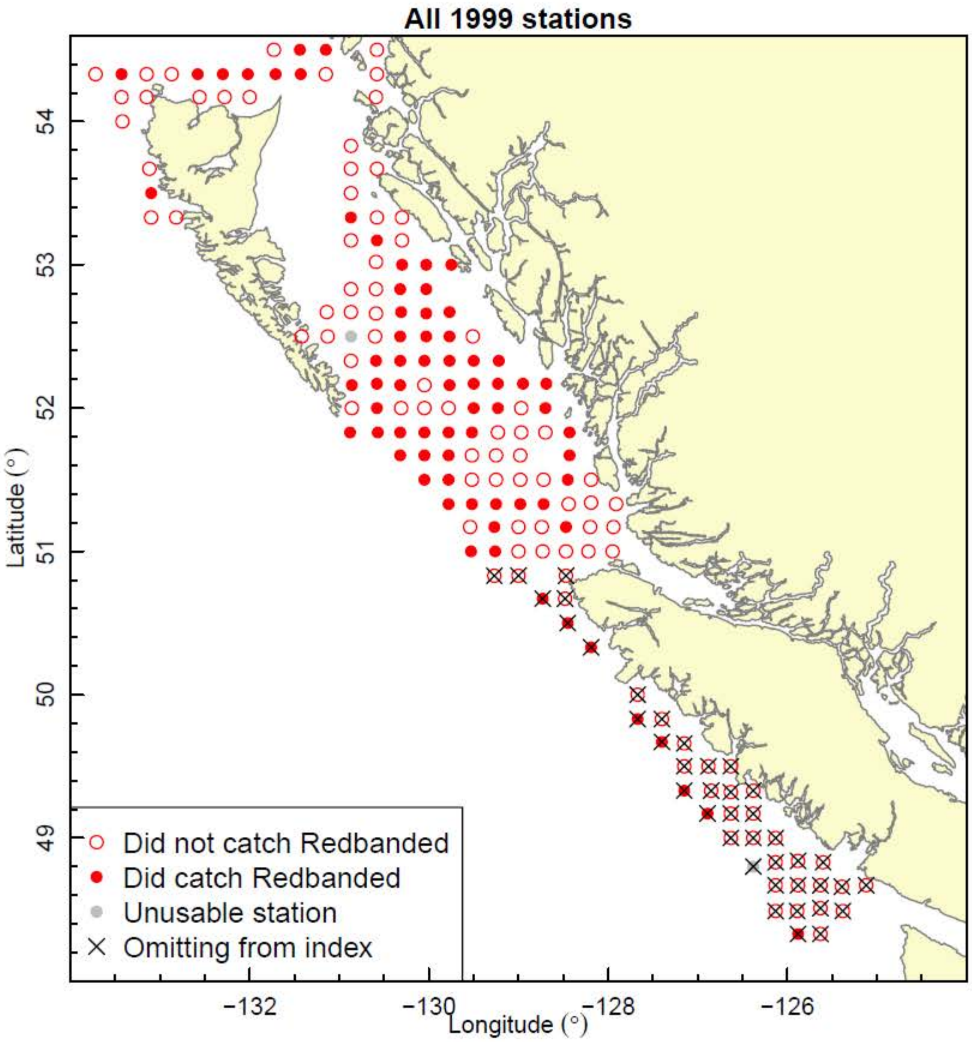


Figure C.3. Locations of the 170 stations in 1999, of which 97 did not catch Redbanded Rockfish (red open circles), 71 stations did catch it (red closed circles), and 2 were deemed unusable by the IPHC (grey closed circles) and so are not considered further. Black crosses indicate the 40 stations being excluded from the analyses.

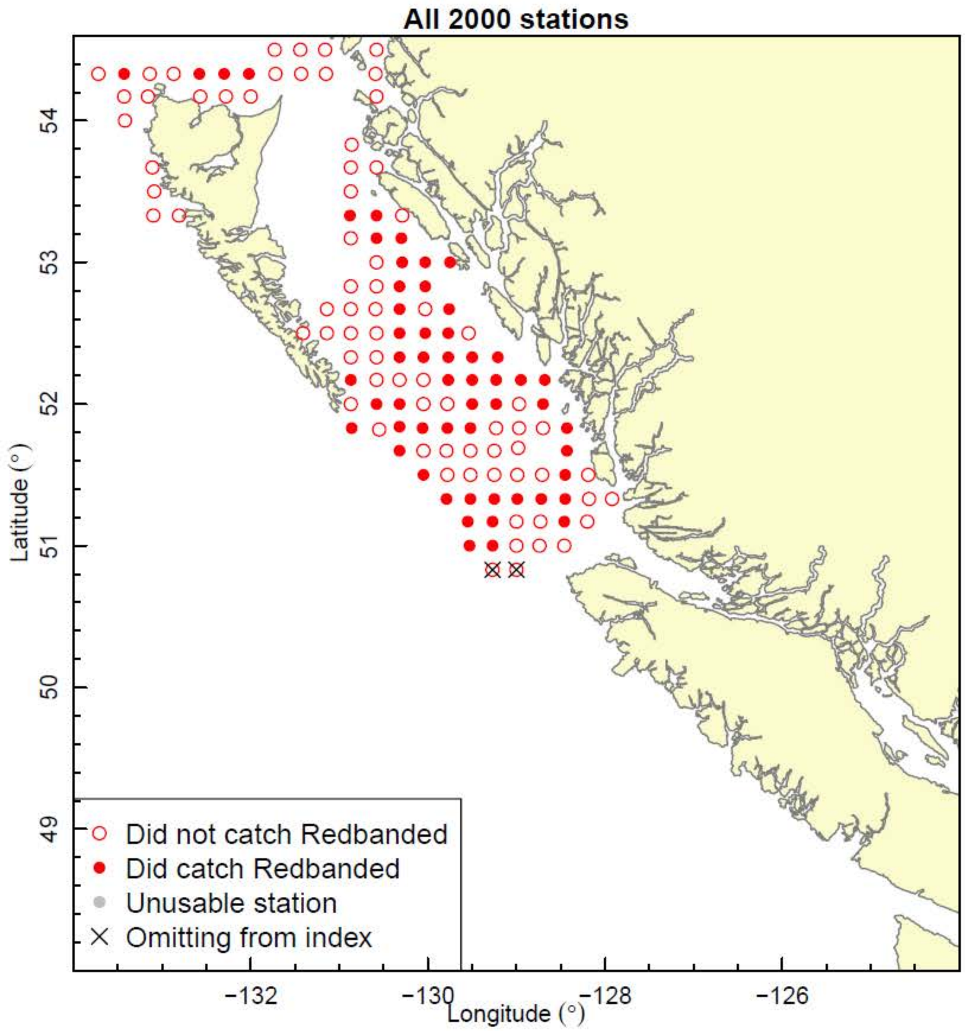


Figure C.4. Locations of the 129 stations in 2000, of which 74 did not catch Redbanded Rockfish (red open circles), 55 stations did catch it (red closed circles), and 0 were deemed unusable by the IPHC (grey closed circles) and so are not considered further. Black crosses indicate the 2 stations being excluded from the analyses.

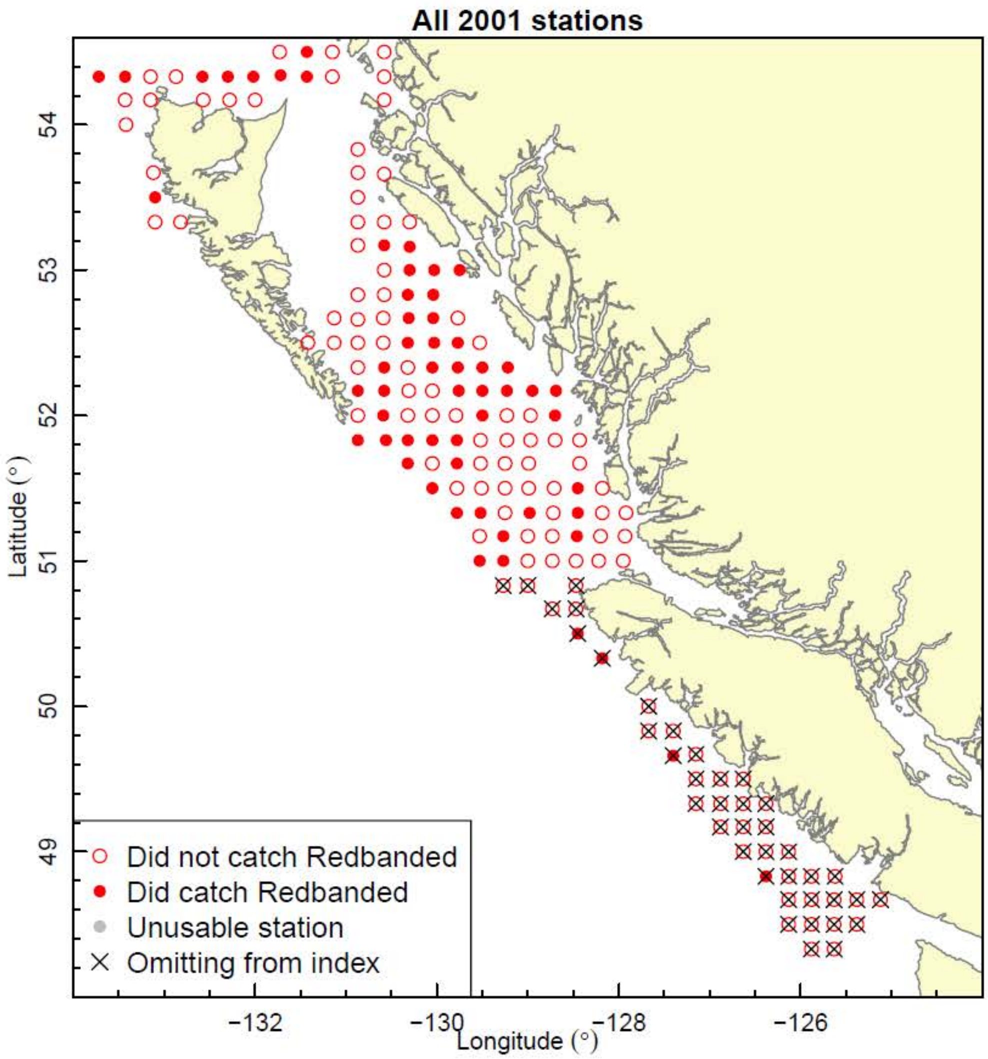


Figure C.5. Locations of the 170 stations in 2001, of which 113 did not catch Redbanded Rockfish (red open circles), 57 stations did catch it (red closed circles), and 0 were deemed unusable by the IPHC (grey closed circles) and so are not considered further. Black crosses indicate the 40 stations being excluded from the analyses.

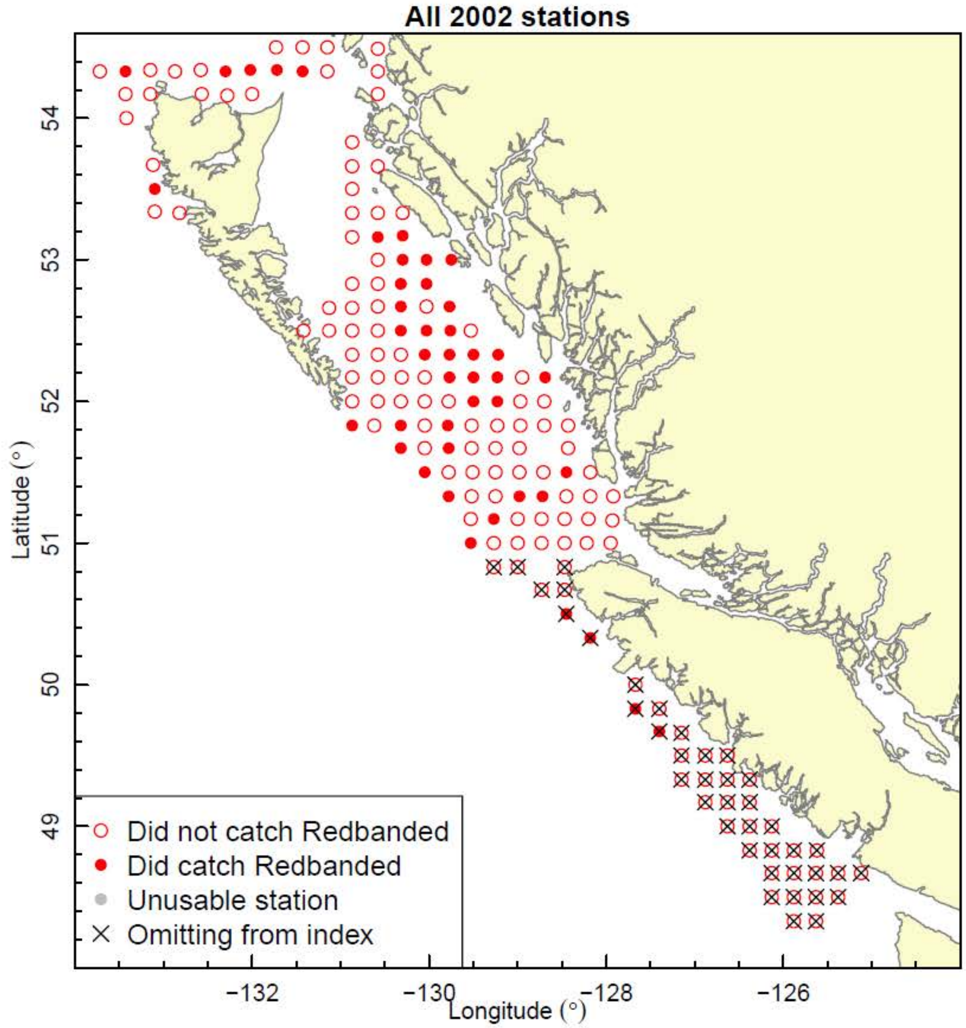


Figure C.6. Locations of the 170 stations in 2002, of which 126 did not catch Redbanded Rockfish (red open circles), 44 stations did catch it (red closed circles), and 0 were deemed unusable by the IPHC (grey closed circles) and so are not considered further. Black crosses indicate the 40 stations being excluded from the analyses.

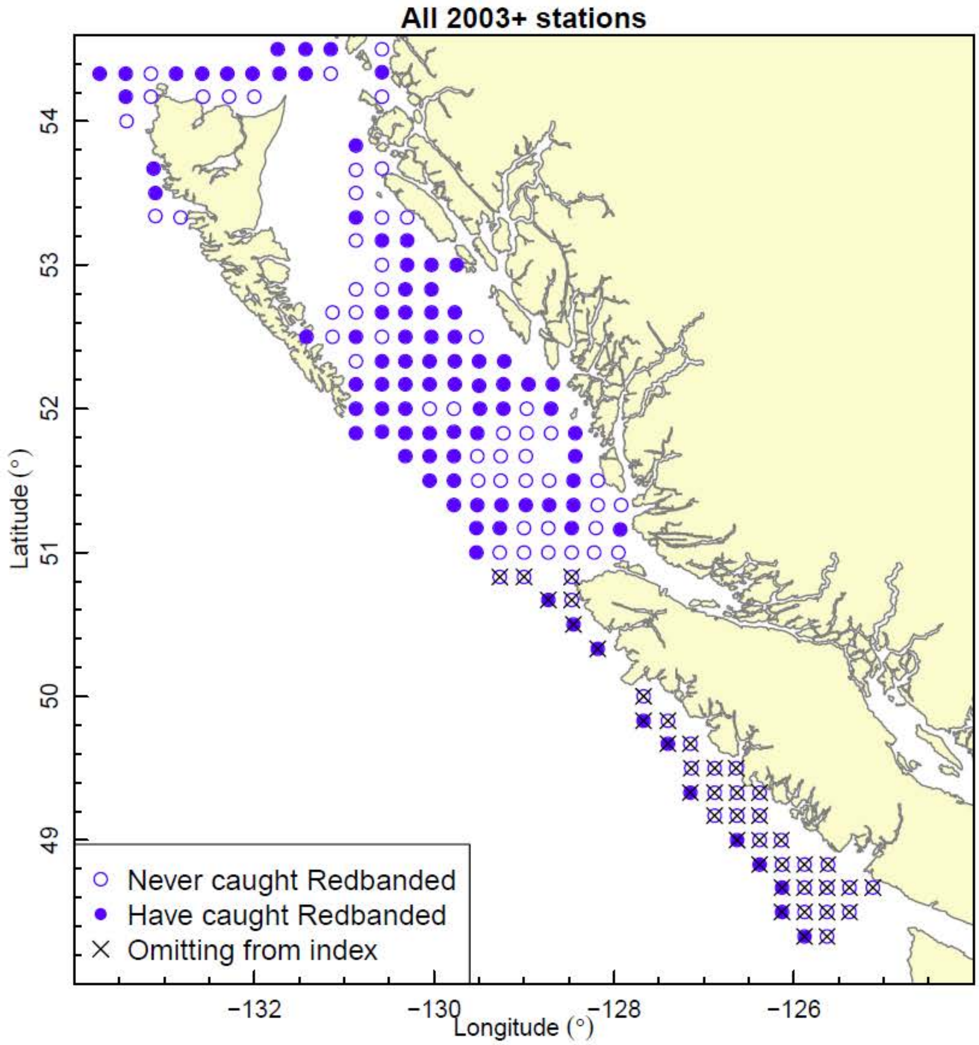


Figure C.7. Locations of all 170 stations for the IPHC survey for 2003 onwards. There are 80 stations that never caught Redbanded Rockfish (blue open circles), and 90 stations that did catch it at least once. Black crosses indicate the 40 stations being excluded from the analyses.

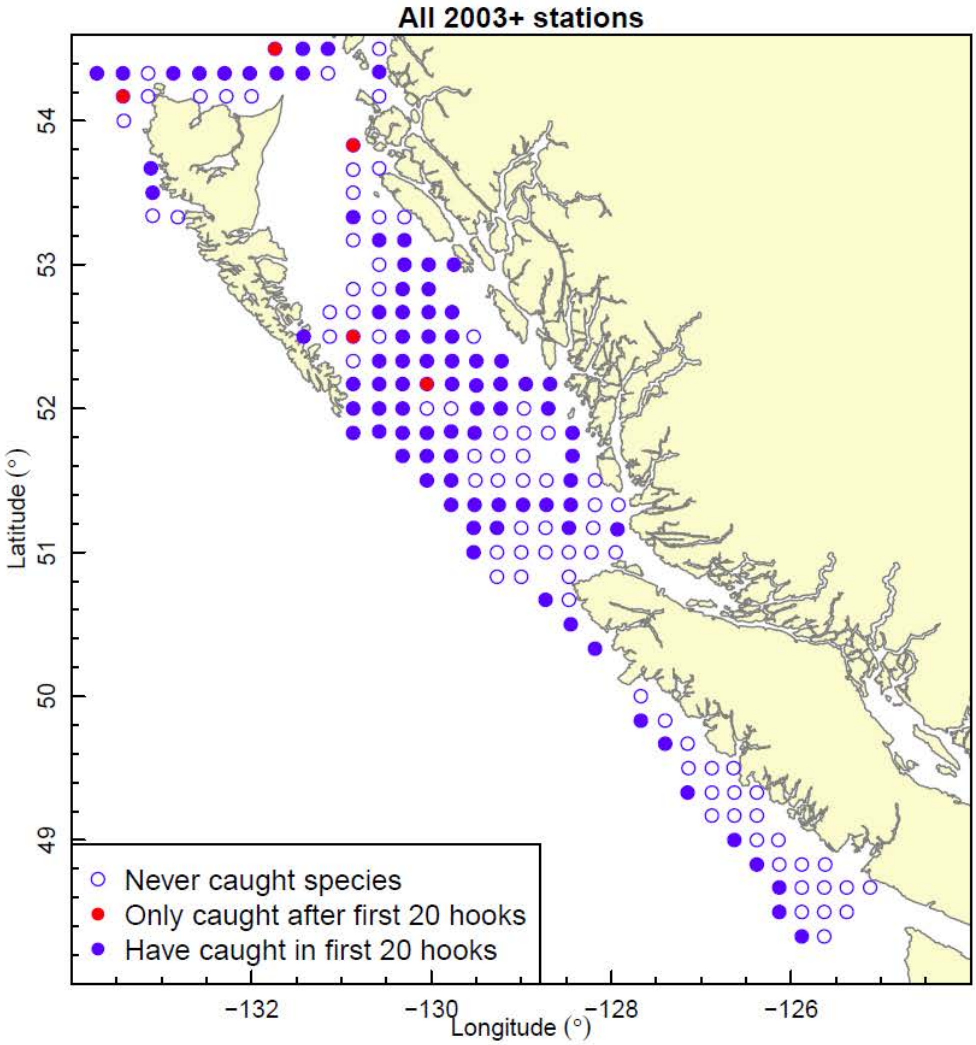


Figure C.8. Locations of all 170 stations for the IPHC survey for 2003 onwards. There are 80 stations that never caught Redbanded Rockfish (blue open circles), 5 stations that caught Redbanded Rockfish but never in the first 20 hooks (red closed circles), and 85 that caught Redbanded Rockfish within the first 20 hooks (blue closed circles).

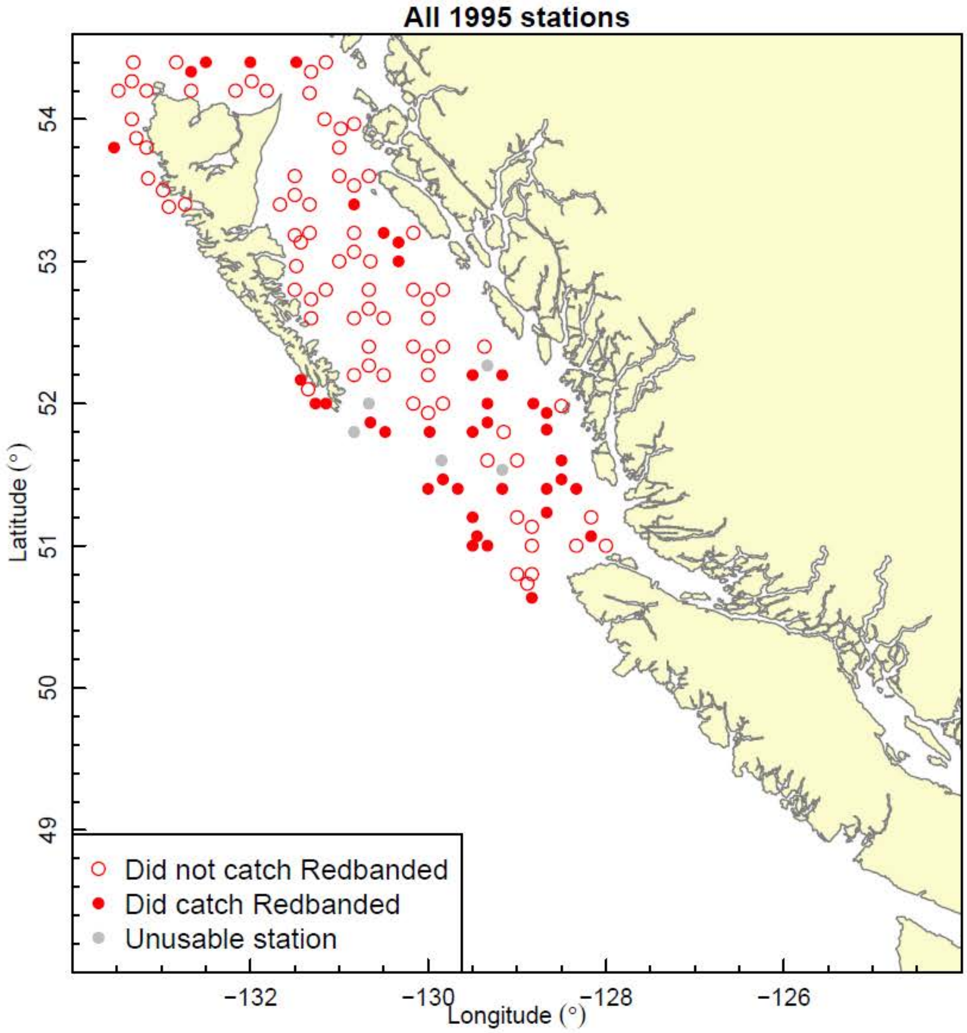


Figure C.9. Locations of the 120 stations in 1995, of which 77 did not catch Redbanded Rockfish (red open circles), 38 stations did catch it (red closed circles), and 5 were deemed unusable by the IPHC (grey closed circles) and so are not considered further.

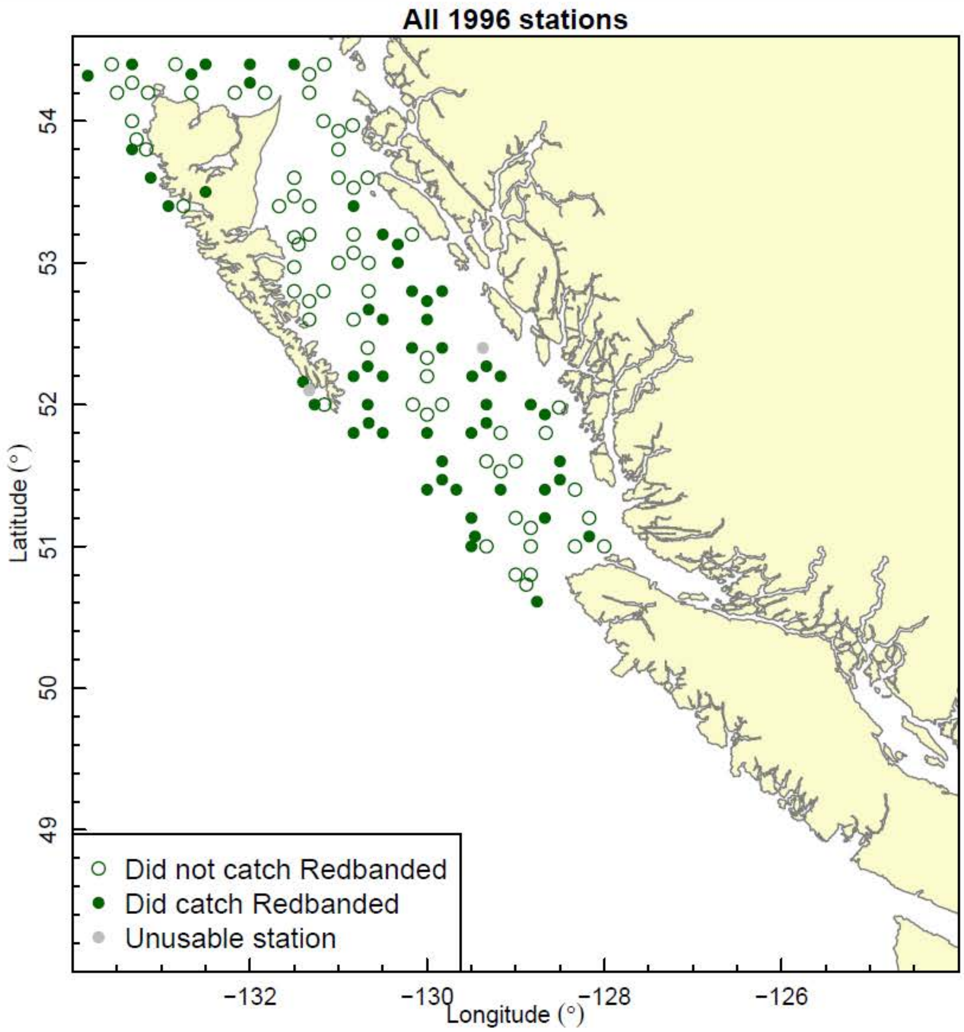


Figure C.10. Locations of the 122 stations in 1996, of which 65 did not catch Redbanded Rockfish (dark green open circles), 55 stations did catch it (dark green closed circles), and 2 were deemed unusable by the IPHC (grey closed circles) and so are not considered further.

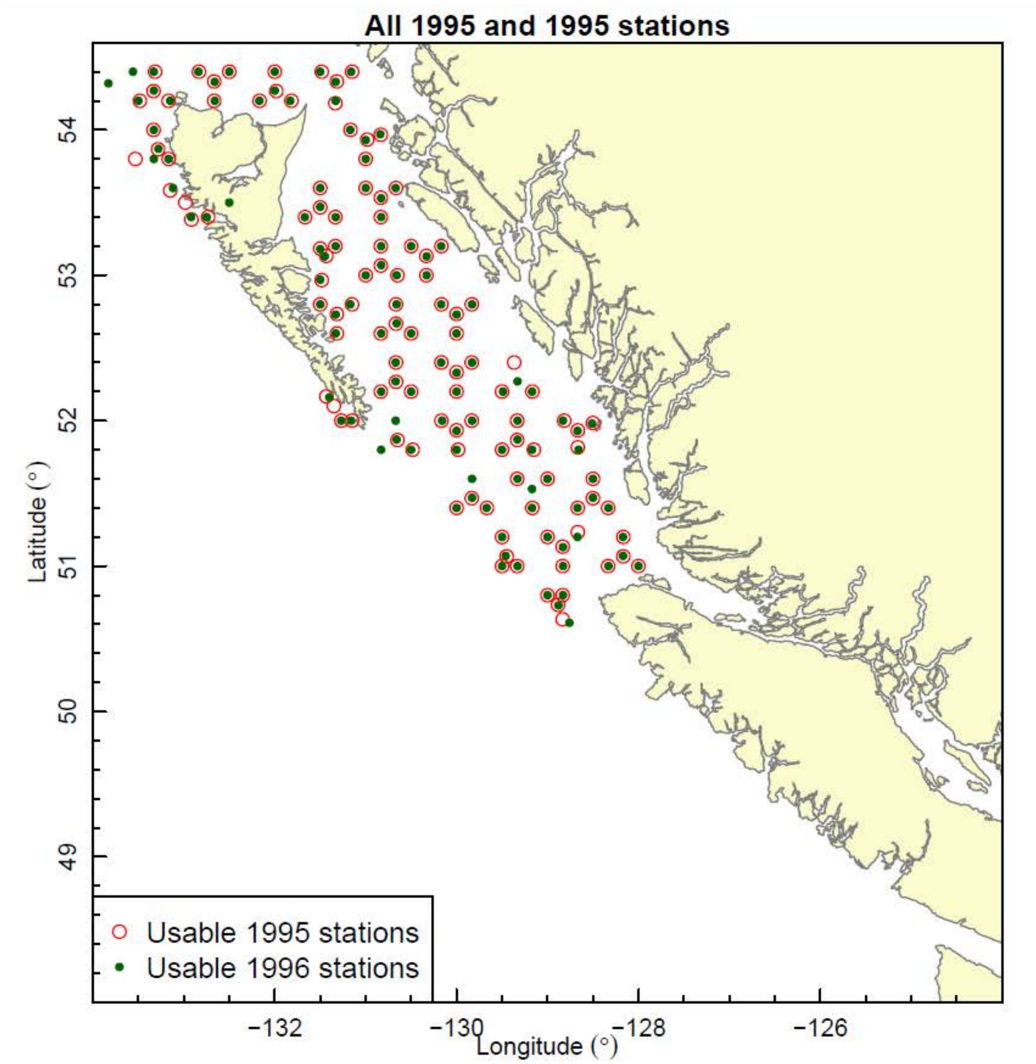


Figure C.11. Locations of all 115 usable stations in 1995 (red open circles) and all 120 usable stations in 1996 (closed dark green circles).

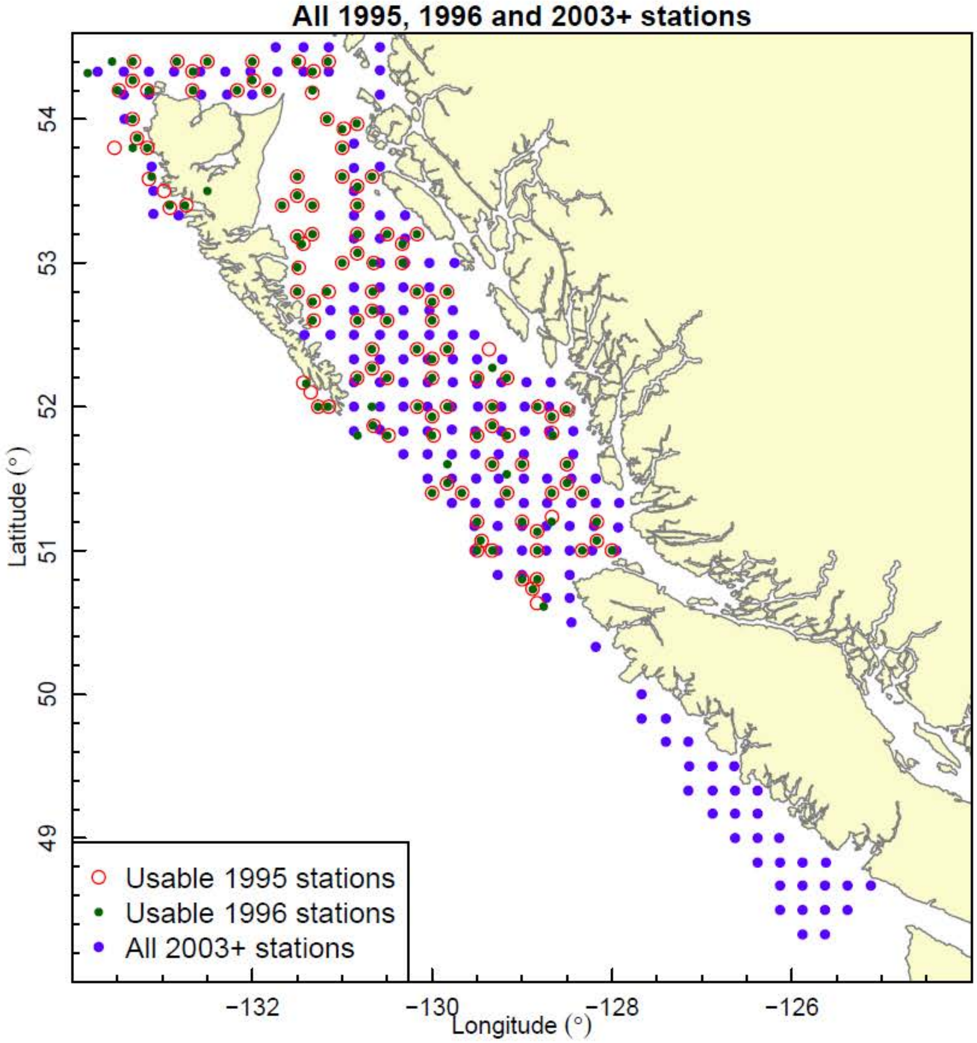


Figure C.12. Locations of all 115 usable stations in 1995 (red open circles), all 120 usable stations in 1996 (dark green closed circles) and all 170 stations for 2003 onwards (closed blue circles).

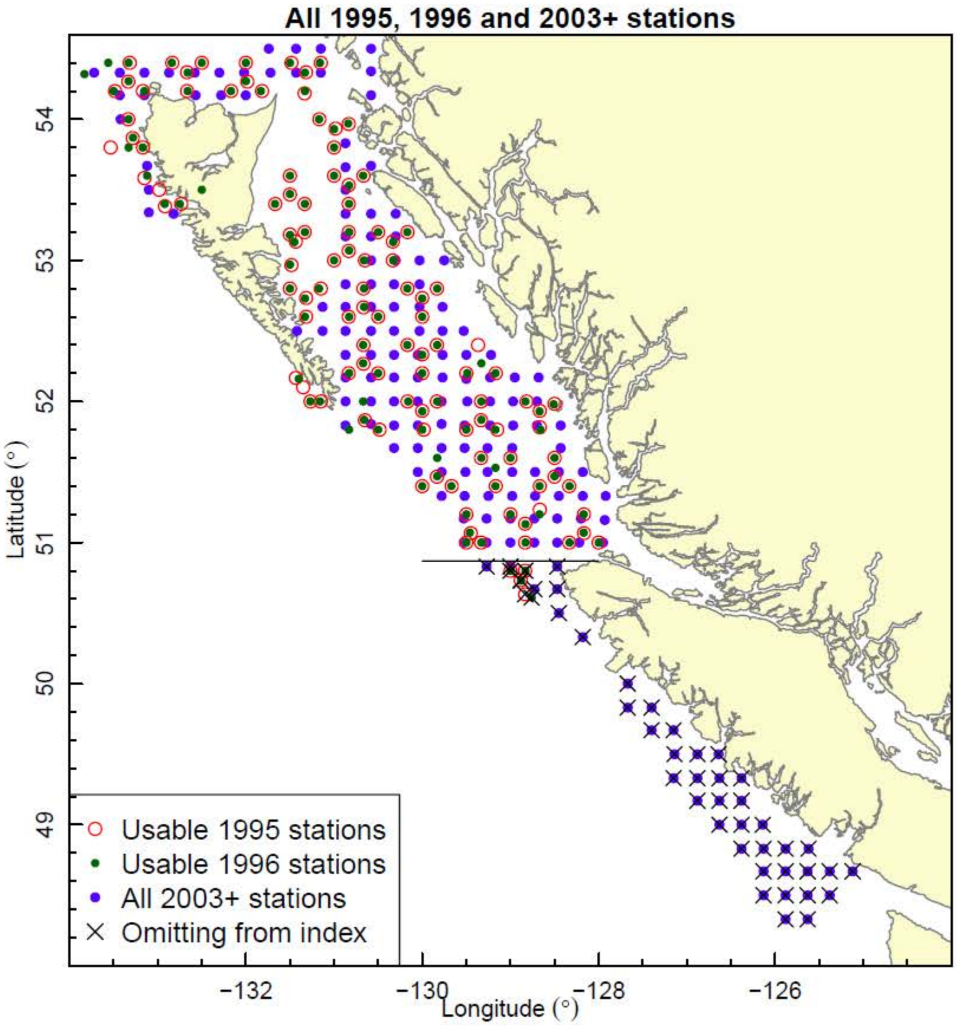


Figure C.13. All stations, with those being omitted in the analyses indicated by black crosses, namely 4 stations for 1995, 4 stations for 1996 and 40 for 2003+. The black line indicates the latitude of the northern tip of Vancouver Island, below which stations are being excluded.

C.5 CATCH RATE EQUATIONS

C.5.1 CATCH RATE BASED ON ALL CHUM-BAIT HOOKS

We wish to obtain a catch rate index, which, for each year, will be the mean catch rate across all sets that year. The units will be numbers of Redbanded Rockfish caught per effective skate. We only want to consider hooks that used Chum Salmon as bait (hereafter 'chum-bait hooks'), because we have no information as to how catch rates of Redbanded Rockfish may change depending on the bait used. For our data, 2012 was the only year that hooks were not exclusively chum-bait hooks.

Define:

H_{it} – number of observed chum-bait hooks in set i in year t,

H^*_{it} – number of observed hooks for all bait types ($H_{it} \neq H^*_{it}$ only for 2012),

E_{it} – effective skate number of set i in year t, which needs to be based on observed chum-bait hooks,

E'_{it} – effective skate number from IPHC, which is based on all observed hooks (regardless of bait).

Thus, E_{it} is

$$E_{it} = \frac{H_{it}}{H^*_{it}} E'_{it}. \tag{C.1}$$

Adapting equations on page 3 of (Yamanaka et al., 2008), define:

N_{it} – the number of fish of a given species caught on set $i = 1, 2, ..., n_t$ in year t, based on observed chum-bait hooks,

n_t – the number of sets in year t,

C_{it} – catch rate (with units of numbers per effective skate) of Redbanded Rockfish for set i in year t, based on observed chum-bait hooks, given by

$$C_{it} = \frac{N_{it}}{E_{it}}. \tag{C.2}$$

The catch rate index for year t, I_t (numbers per effective skate), is then the mean catch rate across all sets:

$$I_t = \frac{1}{n_t} \sum_{i=1}^{n_t} C_{it} = \frac{1}{n_t} \sum_{i=1}^{n_t} \frac{N_{it}}{E_{it}}. \tag{C.3}$$

C.5.2 CATCH RATE BASED THE FIRST 20 CHUM-BAIT HOOKS OF EACH SKATE

Let $\tilde{X}$ indicate a calculation of value X made only based on the first 20 hooks of each skate. These are the first 20 *numbered* hooks, not the first 20 *observed* hooks (so not all of the numbered hooks may have been observed). Thus we have:

$\tilde{H}_{it}$ – number of observed chum-bait hooks in the first 20 hooks of all skates in set i in year t,

$\tilde{E}_{it}$ – effective skate number of set i in year t based on the first 20 chum-bait hooks that were sent out on each skate,

Since effective skate number is a linear function of the number of hooks in a set (Yamanaka et al., 2008), we have

$$\tilde{E}_{it} = \frac{\tilde{H}_{it}}{H_{it}} E_{it} \left(= \frac{\tilde{H}_{it}}{H^*_{it}} E'_{it} \right). \tag{C.4}$$

The resulting notation for the index will be:

$\tilde{I}_t$ – catch rate index for year t (in numbers of Redbanded Rockfish per effective skate) based on only the first 20 hooks sent out for each skate,

$\tilde{N}_{it}$ – the number of Redbanded Rockfish caught on set $i = 1, 2, ..., n_t$ in year t, based on observed chum-bait hooks and only the first 20 hooks sent out for each skate,

$\tilde{C}_{it}$ – catch rate (with units of numbers per effective skate) for set i in year t, based only on the first 20 hooks of each skate (and only skates with chum as bait), such that

$$\tilde{C}_{it} = \frac{\tilde{N}_{it}}{\tilde{E}_{it}}. \tag{C.5}$$

The catch rate index for year t, $\tilde{I}_t$ (in units of numbers per effective skate), based on only the first 20 hooks of each skate, is then the mean catch rate across all sets:

$$\tilde{I}_t = \frac{1}{\tilde{n}_t} \sum_{i=1}^{\tilde{n}_t} \tilde{C}_{it} = \frac{1}{\tilde{n}_t} \sum_{i=1}^{\tilde{n}_t} \frac{\tilde{N}_{it}}{\tilde{E}_{it}}. \tag{C.6}$$

C.5.3 EQUIVALENCY OF CATCH RATES BASED ON ALL HOOKS AND ON JUST THE FIRST 20 HOOKS

Equation (C.5) can be written as

$$\tilde{C}_{it} = \frac{\tilde{N}_{it}}{\tilde{E}_{it}} = \frac{H_{it}}{\tilde{H}_{it}} \frac{\tilde{N}_{it}}{E_{it}}. \tag{C.7}$$

If all hooks are equally likely to catch a Redbanded Rockfish, then the catch rates based on the first 20 hooks of each skate should be an unbiased sample of the catch rates based on all the hooks. The ratio of fish caught, $\tilde{N}_{it}/N_{it}$, should equal (on average) the ratio of hook numbers, $\tilde{H}_{it}/H_{it}$, because a proportionally reduced number of fish are caught on the proportionally fewer hooks. Thus

$$\frac{\tilde{H}_{it}}{H_{it}} = \frac{\tilde{N}_{it}}{N_{it}} \tag{C.8}$$

such that

$$\tilde{C}_{it} = \frac{N_{it}}{\tilde{N}_{it}} \frac{\tilde{N}_{it}}{E_{it}} = \frac{N_{it}}{E_{it}} = C_{it}. \tag{C.9}$$

If the catch rates are greatly different, then this suggests that the catch rates from the first 20 hooks are not equivalent to the catch rates based on all the hooks.

C.6 RESULTS

Tables C.2 and C.3 show the effective skate numbers for Series A and B. The values are lower for Series A because they are only based on 20 hooks per skate, compared to all skates for Series B (see equation C.4).

For the overlapping years 2003-2012, the mean effective skate numbers for series A are slightly over 20% of those for series B. This is because skates had a mean of just under 100 observed hooks, and so the first 20 hooks in each skate comprise just over 20% of the observed hooks. Thus the scaling ratio $\tilde{H}_{it}/H_{it}$ in (C.4) is just over 0.2. The lowest value, for 2012, is due to only four skates (those with Chum Salmon as bait) being usable for this analysis.

The resulting bootstrapped catch rate indices for the two Series are shown in Figure C.14. For Series A there is an increase in catch rates in the early years (1997-1999), followed later by a decline in 2002 to a lower level. The increase and decline is not seen for Series B because it does not contain data for that time period (1997-2002).

Table C.2. For series A, summary of effective skate numbers, E_{it}, for each year. Lower and Higher are the 2.5% and 97.5% quantiles, respectively.

Year	Lower	Mean	Higher
1997	1.00	1.20	1.21
1998	1.51	1.60	1.62
1999	1.59	1.60	1.61
2000	1.35	1.40	1.42
2001	0.96	1.00	1.02
2002	0.96	1.00	1.01
2003	1.60	1.61	1.64
2004	1.60	1.60	1.65
2005	1.40	1.41	1.43
2006	1.19	1.21	1.24
2007	0.98	1.01	1.03
2008	0.99	1.01	1.03
2009	1.38	1.40	1.43
2010	1.59	1.61	1.63
2011	1.18	1.20	1.24
2012	0.79	0.80	0.83

Table C.3. For series B, summary of effective skate numbers, E_{it}, for each year. Lower and Higher are the 2.5% and 97.5% quantiles, respectively.

Year	Lower	Mean	Higher
1995	4.76	4.99	5.08
1996	4.82	4.93	5.00
2003	7.95	8.01	8.11
2004	7.89	7.90	8.03
2005	6.96	7.00	7.03
2006	5.84	5.96	6.08
2007	4.87	4.98	5.02
2008	4.92	4.98	5.02
2009	6.89	6.98	7.10
2010	7.95	8.01	8.11
2011	5.90	5.93	6.02
2012	3.88	4.01	4.10

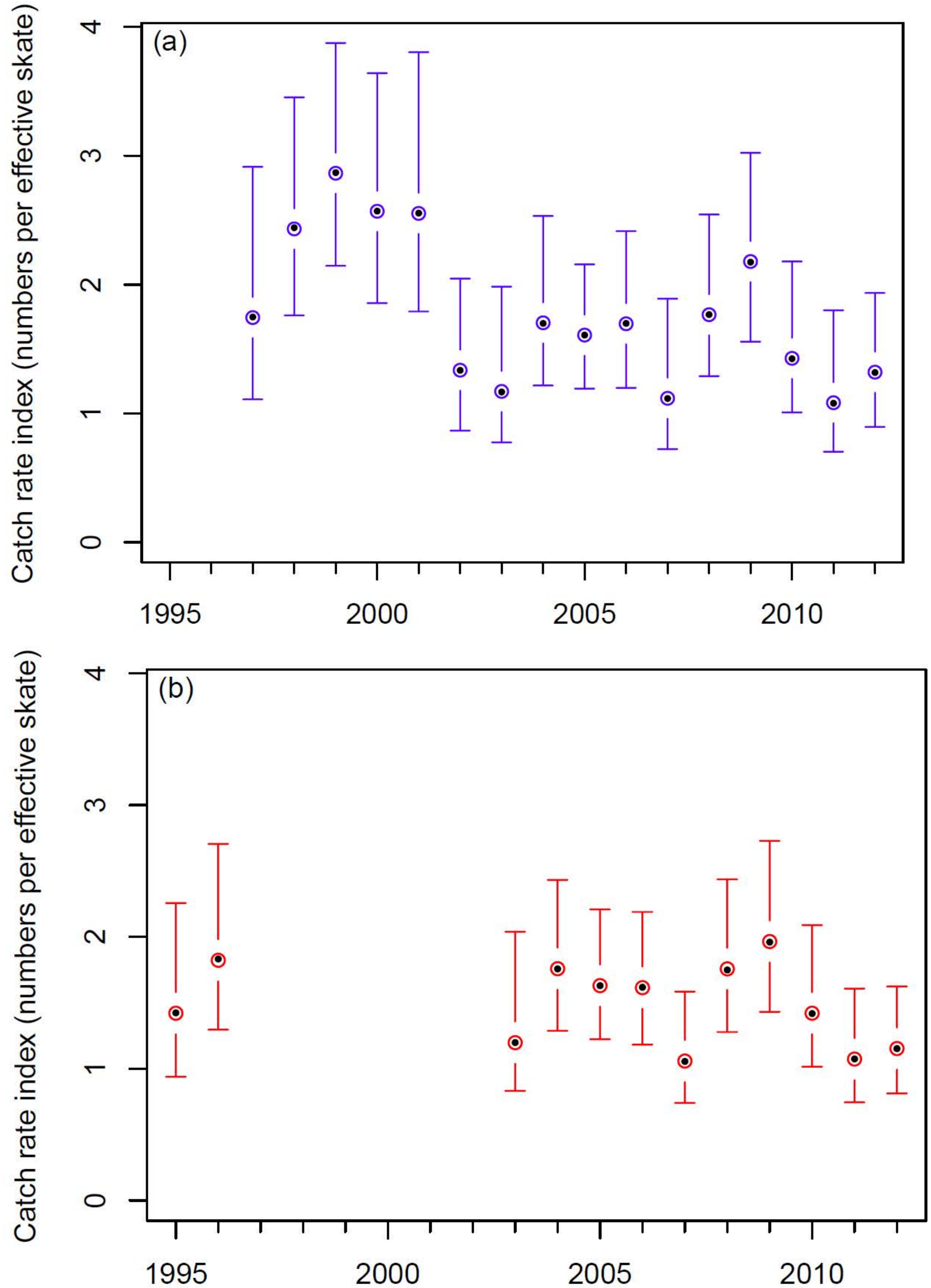


Figure C.14. Catch rate index (number of individual Redbanded Rockfish caught per skate) for (a) Series A and (b) Series B. For a given year, the catch rate for each set is calculated from (C.2) or (C.5) as appropriate. These catch rates are then resampled for 10000 bootstrap values, from which a bootstrapped mean (open circles) and 95% bias-corrected and adjusted confidence intervals (bars) are calculated. Small black closed circles are sample means (not bootstrapped), and essentially equal the bootstrapped means.

Table C.4. Catch rates by year for Series A. 'Sample $\bar{I}_t$' is the sample mean. B'ed means bootstrapped value. 'No RBR' is the proportion of sets that did not catch Redbanded Rockfish that year. Lower and higher are the lower and upper bounds of the 95% bias-corrected and adjusted (BCa) confidence intervals.

Year	Sets, n_t	No RBR	Sample $\bar{I}_t$	B'ed I_t	B'ed I_t lower	B'ed I_t higher	B'ed I_t CV
1997	117	0.69	1.75	1.74	1.11	2.91	0.24
1998	126	0.51	2.44	2.43	1.76	3.45	0.17
1999	129	0.51	2.87	2.86	2.15	3.87	0.15
2000	127	0.57	2.57	2.57	1.86	3.64	0.17
2001	130	0.59	2.55	2.55	1.79	3.80	0.19
2002	130	0.69	1.33	1.34	0.87	2.05	0.22
2003	130	0.62	1.17	1.17	0.78	1.98	0.24
2004	130	0.61	1.70	1.70	1.22	2.53	0.18
2005	130	0.58	1.61	1.61	1.19	2.16	0.15
2006	130	0.61	1.70	1.70	1.20	2.41	0.18
2007	130	0.71	1.12	1.12	0.72	1.89	0.24
2008	129	0.60	1.77	1.77	1.29	2.54	0.17
2009	130	0.58	2.17	2.18	1.56	3.02	0.17
2010	130	0.58	1.42	1.43	1.01	2.18	0.20
2011	130	0.69	1.08	1.08	0.70	1.80	0.24
2012	130	0.70	1.32	1.32	0.90	1.93	0.19

Table C.5. Catch rates by year for Series B. 'Sample $\bar{I}_t$' is the sample mean. B'ed means bootstrapped value. 'No RBR' is the proportion of sets that did not catch Redbanded Rockfish that year. Lower and higher are the lower and upper bounds of the 95% bias-corrected and adjusted (BCa) confidence intervals.

Year	Sets, n_t	No RBR	Sample $\bar{I}_t$	B'ed I_t	B'ed I_t lower	B'ed I_t higher	B'ed I_t CV
1995	111	0.67	1.42	1.42	0.94	2.26	0.22
1996	116	0.53	1.83	1.82	1.30	2.71	0.19
2003	130	0.52	1.20	1.20	0.83	2.04	0.22
2004	130	0.51	1.76	1.76	1.29	2.43	0.16
2005	130	0.48	1.63	1.63	1.22	2.21	0.15
2006	130	0.50	1.62	1.61	1.18	2.19	0.16
2007	130	0.55	1.05	1.06	0.74	1.58	0.19
2008	129	0.50	1.75	1.76	1.28	2.44	0.16
2009	130	0.50	1.96	1.96	1.43	2.73	0.16
2010	130	0.49	1.42	1.42	1.02	2.09	0.18
2011	130	0.52	1.07	1.07	0.74	1.61	0.19
2012	130	0.57	1.15	1.15	0.81	1.62	0.18

Values for the indices for Series A and Series B are given in Tables C.4 and C.5, respectively, as well as the number of sets each year and the proportion of sets in each year that did not catch Redbanded Rockfish. The early years have slightly fewer sets than the 130 that occurred from 2001 onwards. Year 2008 has only 129 sets because for station number 2113 the hook-tally sheet was lost overboard (Yamanaka et al., 2011).

For Series A, define G_A to be the geometric mean of the bootstrapped annual means, with the geometric mean based only on the overlapping years (2003-2012). Define G_B similarly for Series B. By dividing the bootstrapped values for each series by their respective geometric means, we obtain Figure C.15(a). This shows that Series A and Series B are very similar for the overlapping years. Thus, on this scale, the 1995 and 1996 values from Series B can be compared to the full Series A data.

We can therefore append the 1995 and 1996 values from Series B in Figure C.15(a) to the original Series A values (Figure C.14(a)) by multiplying them by G_A, to yield the index series in Figure C.15(b) that has units of 'numbers per effective skate'. Equivalently, the original 1995 and 1996 values from Figure C.14(b) have thus been multiplied by G_A/G_B to give those in Figure C.15(b). The resulting values for the merged series are shown in Table C.6, and were used in the catch-age models and for the regression analysis.

C.7 DISCUSSION

The method used here does not explicitly account for the increased number of sets with zero catches in 2012 compared to the earlier years (recall that the bait experiment in 2012 meant that only four skates could be used from each set). However, 2012 does not look anomalous (Figure C.15), and so this approach appears to be suitable.

A more detailed approach, such as the delta-gamma method (e.g. Lecomte et al. 2013) may be warranted for similar analyses in future years because the bait experiment is continuing (for 2014 at least), which will consequently produce more sets with zero catch of a given species. Also, for rarer species that are caught less frequently than Redbanded Rockfish, explicit consideration of the zero catches may be necessary. For the Redbanded Rockfish data, it is not clear whether or not the delta-gamma method would lead to reduced coefficients of variation (Jean-Baptiste Lecomte, Pacific Biological Station, DFO, Nanaimo, BC, pers. comm.).

If the IPHC switches its bait to exclusively Chum Salmon in the future, then future catch rates will need to be adjusted to account for the bait, based on analyses of data collected during the bait experiments. This could potentially be problematic for rockfish species because of low catch rates relative to Pacific Halibut, the species that is the main focus of the survey.

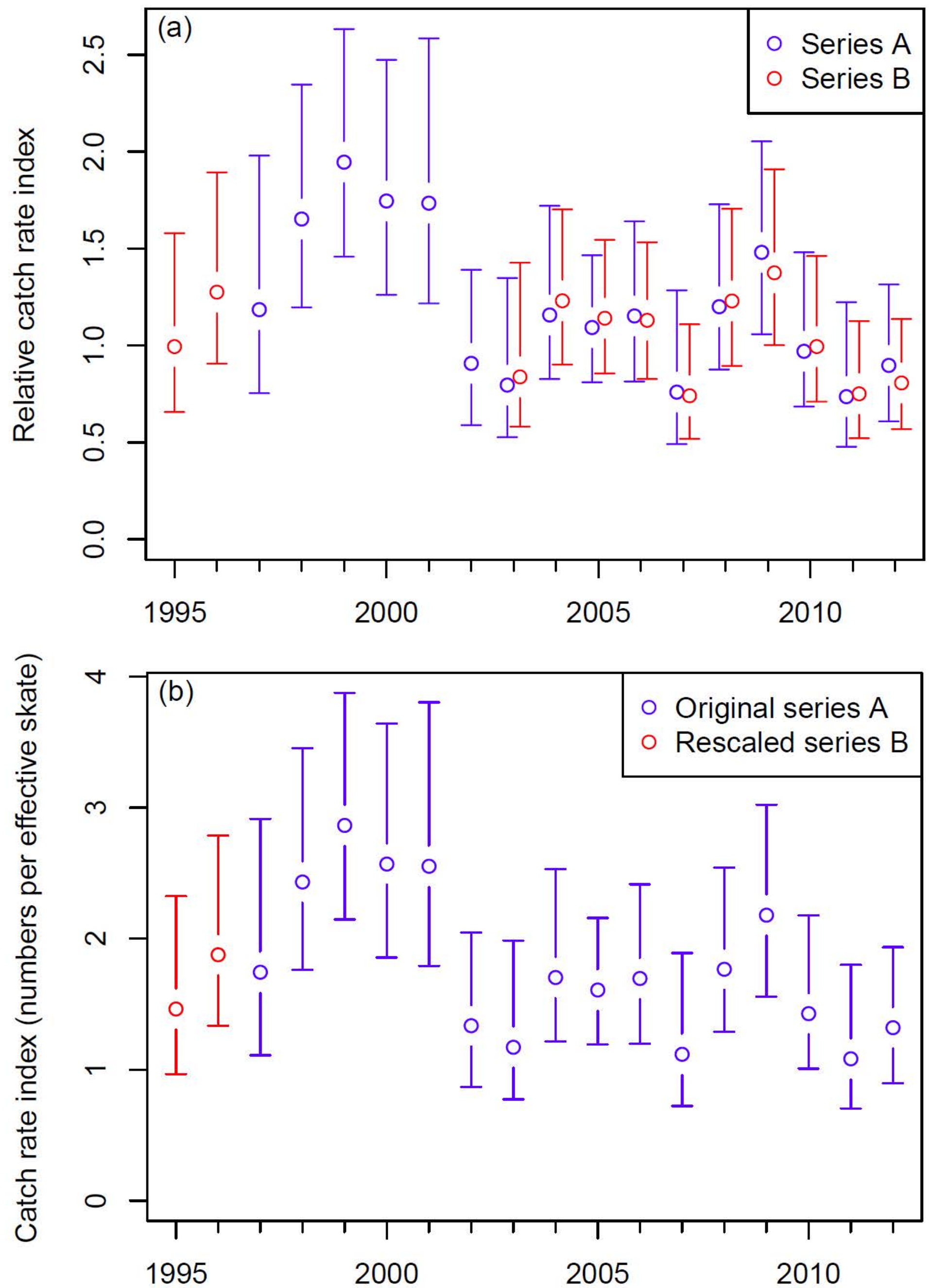


Figure C.15. (a) Each of the two catch rate series from Figure C.14 is divided by the geometric mean of its bootstrapped annual means (with the geometric mean based on the overlapping years (2003-2012) only). (b) The catch rate index to be used as a model input. The original Series A is extended by incorporating the suitably scaled 1995 and 1996 values from Series B (see text).

Table C.6. Catch rates by year from combining 1995 and 1996 data from Series B with the full data for Series A. The 1995 and 1996 values were rescaled by multiplying them by the ratio of the geometric means of the bootstrapped means for the two series for the overlapping years, G_A/G_B. Values are $G_A =$ 1.47 and G_B= 1.43 such that $G_A/G_B =$ 1.03 'Sample $\bar{I}_t$' is the sample mean. B'ed means bootstrapped value. 'No RBR' is the proportion of sets that did not catch Redbanded Rockfish that year. Lower and higher are the lower and upper bounds of the 95% bias-corrected and adjusted (BCa) confidence intervals.

Year	Sets, n_t	No RBR	Sample $\bar{I}_t$	B'ed I_t	B'ed I_t lower	B'ed I_t higher	B'ed I_t CV
1995	111	0.67	1.47	1.46	0.97	2.32	0.22
1996	116	0.53	1.89	1.88	1.33	2.79	0.19
1997	117	0.69	1.75	1.74	1.11	2.91	0.24
1998	126	0.51	2.44	2.43	1.76	3.45	0.17
1999	129	0.51	2.87	2.86	2.15	3.87	0.15
2000	127	0.57	2.57	2.57	1.86	3.64	0.17
2001	130	0.59	2.55	2.55	1.79	3.80	0.19
2002	130	0.69	1.33	1.34	0.87	2.05	0.22
2003	130	0.62	1.17	1.17	0.78	1.98	0.24
2004	130	0.61	1.70	1.70	1.22	2.53	0.18
2005	130	0.58	1.61	1.61	1.19	2.16	0.15
2006	130	0.61	1.70	1.70	1.20	2.41	0.18
2007	130	0.71	1.12	1.12	0.72	1.89	0.24
2008	129	0.60	1.77	1.77	1.29	2.54	0.17
2009	130	0.58	2.17	2.18	1.56	3.02	0.17
2010	130	0.58	1.42	1.43	1.01	2.18	0.20
2011	130	0.69	1.08	1.08	0.70	1.80	0.24
2012	130	0.70	1.32	1.32	0.90	1.93	0.19

APPENDIX D. BIOLOGICAL DATA

D.1 GROWTH AND MATURITY

D.1.1 LENGTH DATA

The availability of length data for Redbanded Rockfish is summarized in Tables D.1 and D.2. Tows with randomly sampled length data are sparse for the commercial trawl fishery (Figure D.1), which apparently does not catch or retain any Redbanded Rockfish <23 cm. The research survey trawls, on the other hand, catch fish as small as 7 cm (Figure D.2), and the estimates of mean length tend to be smaller (by ∼5 cm) than those from the commercial fishery.

Table D.1. Frequency of length data by calendar year and various code types – T.1 = non-observed commecial trips, T.2 = research trips, T.3 = charter vessel trips, T.4 = observer-vessel trips, S.0 = unknown sample type, S.1 = total catch sample, S.2 = random sample, S.4 = selected sample, S.6 = random sample from randomly assigned set, C.0 = unknown species collection method, C.1 = unsorted collection, C.3 = keepers (sorted), C.4 = discarded (sorted). Continued overleaf.

Year	T.1	T.2	T.3	T.4	S.0	S.1	S.2	S.4	S.6	C.0	C.1	C.3	C.4
1966	—	120	—	—	—	—	120	—	—	—	120	—	—
1967	—	1944	—	—	473	941	530	—	—	—	1944	—	—
1968	—	822	—	—	—	628	194	—	—	—	822	—	—
1969	204	325	—	—	325	—	204	—	—	—	325	204	—
1970	—	230	—	—	—	230	—	—	—	—	230	—	—
1971	—	4	—	—	—	4	—	—	—	—	4	—	—
1973	227	98	—	—	—	98	227	—	—	—	98	227	—
1976	—	510	—	—	—	388	122	—	—	—	510	—	—
1977	—	—	36	—	—	36	—	—	—	—	36	—	—
1978	901	215	66	—	—	229	953	—	—	—	281	901	—
1979	205	—	273	—	—	173	305	—	—	—	273	205	—
1980	234	—	52	—	—	52	234	—	—	—	52	234	—
1984	—	1	1	—	—	2	—	—	—	—	2	—	—
1986	—	57	—	—	—	57	—	—	—	—	57	—	—
1987	—	—	209	—	—	209	—	—	—	—	209	—	—
1989	—	—	362	—	—	362	—	—	—	—	362	—	—
1991	—	54	—	—	—	54	—	—	—	—	54	—	—
1994	1	—	169	—	—	1	169	—	—	1	169	—	—
1995	80	—	302	252	—	465	169	—	—	80	302	252	—
1996	104	—	45	—	—	17	132	—	—	104	45	—	—
1997	99	—	1153	—	—	797	455	—	—	—	44	1207	1
1998	—	—	1880	413	—	1370	923	—	—	—	55	2238	—
1999	6	231	—	226	6	231	226	—	—	6	231	226	—
2000	—	—	106	725	106	239	486	—	—	—	597	234	—
2001	—	—	—	263	—	—	108	—	155	—	155	108	—
2002	145	—	280	—	—	425	—	—	—	—	280	145	—
2003	—	15	1930	225	—	1663	391	—	116	—	1195	975	—
2004	187	317	636	231	—	789	485	—	97	—	1084	287	—
2005	98	—	1654	91	—	1470	328	—	45	—	1699	144	—
2006	50	370	839	102	—	960	401	—	—	—	1209	152	—
2007	—	307	1842	62	—	1915	293	3	—	—	2149	62	—
2008	—	449	1211	45	—	1524	179	2	—	—	1660	45	—
2009	107	298	3463	169	—	3376	635	26	—	—	3825	212	—
2010	—	403	2887	54	—	2973	371	—	—	—	3344	—	—
2011	—	460	2006	50	—	2157	309	—	50	—	2516	—	—

Year	T.1	T.2	T.3	T.4	S.0	S.1	S.2	S.4	S.6	C.0	C.1	C.3	C.4
2012	—	432	2244	65	—	2134	530	12	65	—	2741	—	—
2013	—	272	1015	29	—	1134	153	—	29	—	1316	—	—
2014	—	439	—	—	—	282	157	—	—	—	439	—	—

Table D.2. Frequency of length data by calendar year and PMFC (Pacific Marine Fisheries Commission) area.

Year	4B	3C	3D	5A	5B	5C	5D	5E
1966	—	—	—	120	—	—	—	—
1967	—	1471	—	185	288	—	—	—
1968	—	822	—	—	—	—	—	—
1969	—	52	—	87	390	—	—	—
1970	—	8	—	—	199	—	—	23
1971	—	—	—	—	4	—	—	—
1973	—	—	—	—	—	98	227	—
1976	—	—	—	108	402	—	—	—
1977	—	—	—	—	—	—	36	—
1978	—	—	52	—	603	513	14	—
1979	—	—	—	—	200	105	173	—
1980	—	—	—	—	234	10	—	42
1984	—	—	—	—	—	2	—	—
1986	—	—	—	—	—	57	—	—
1987	—	—	—	—	—	209	—	—
1989	—	—	57	250	—	54	1	—
1991	—	1	—	—	—	53	—	—
1994	1	—	—	23	146	—	—	—
1995	—	—	—	11	341	30	—	252
1996	1	20	75	2	—	—	—	51
1997	—	—	316	264	99	—	—	573
1998	—	—	324	731	358	55	—	825
1999	—	110	6	15	279	53	—	—
2000	—	—	—	—	424	—	301	106
2001	—	—	—	—	—	263	—	—
2002	—	—	—	110	—	—	—	315
2003	—	20	96	339	870	653	26	166
2004	—	90	218	32	621	136	134	140
2005	—	—	26	62	658	852	166	79
2006	—	140	233	11	152	63	119	643
2007	—	30	127	378	634	452	140	450
2008	—	200	298	42	251	120	92	702
2009	—	40	515	350	1402	1194	385	151
2010	—	158	268	186	547	994	248	943
2011	—	74	146	332	833	769	217	145
2012	—	262	194	134	591	503	282	775
2013	—	14	30	117	560	420	139	36
2014	—	83	351	5	—	—	—	—

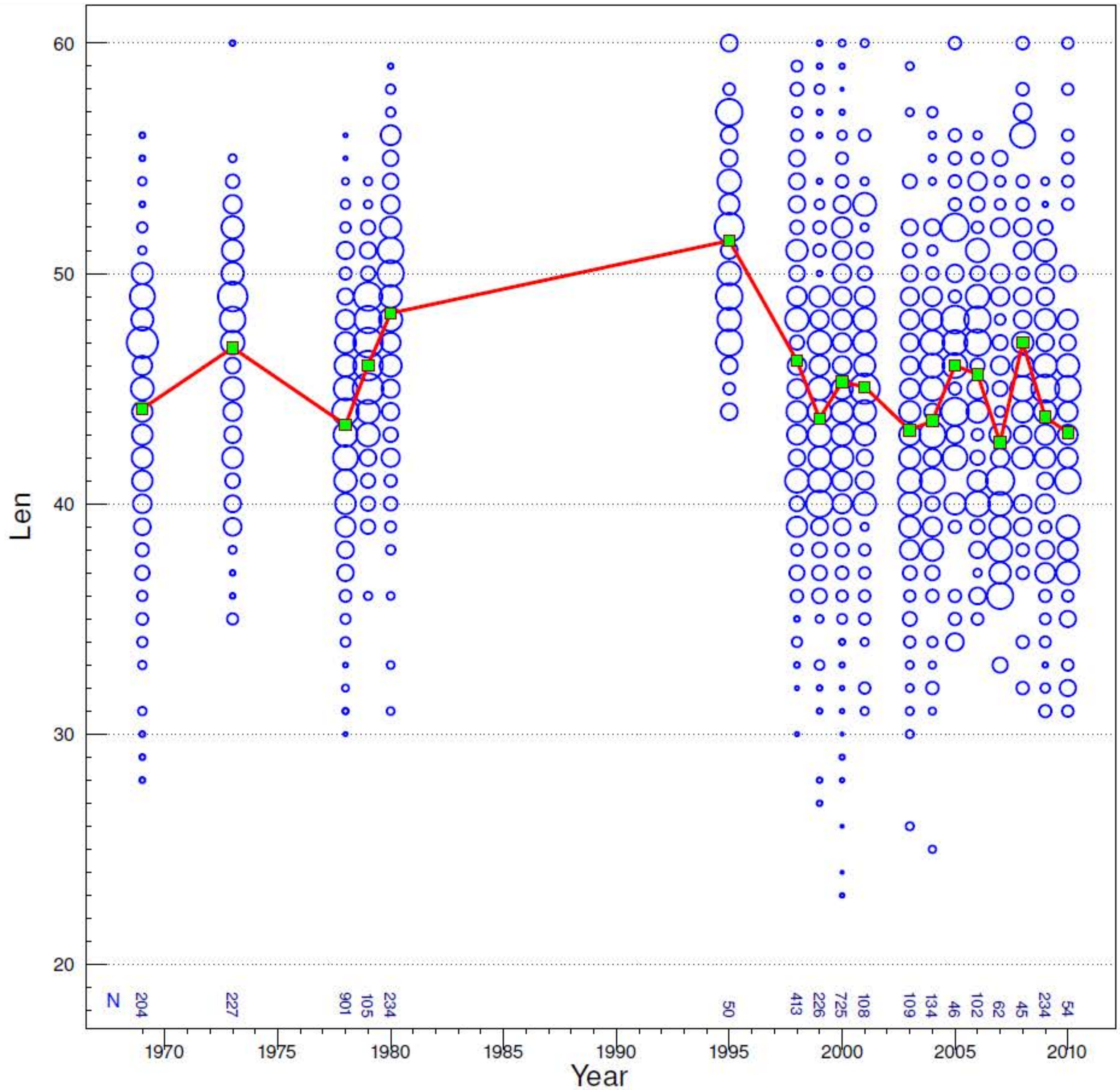


Figure D.1. Frequency distribution of Redbanded Rockfish lengths (cm), proportional to bubble area, from randomly-collected commercial trawl samples. The mean length is plotted as green square symbols connected by a solid red line. The number of specimens appear along the bottom as annual totals.

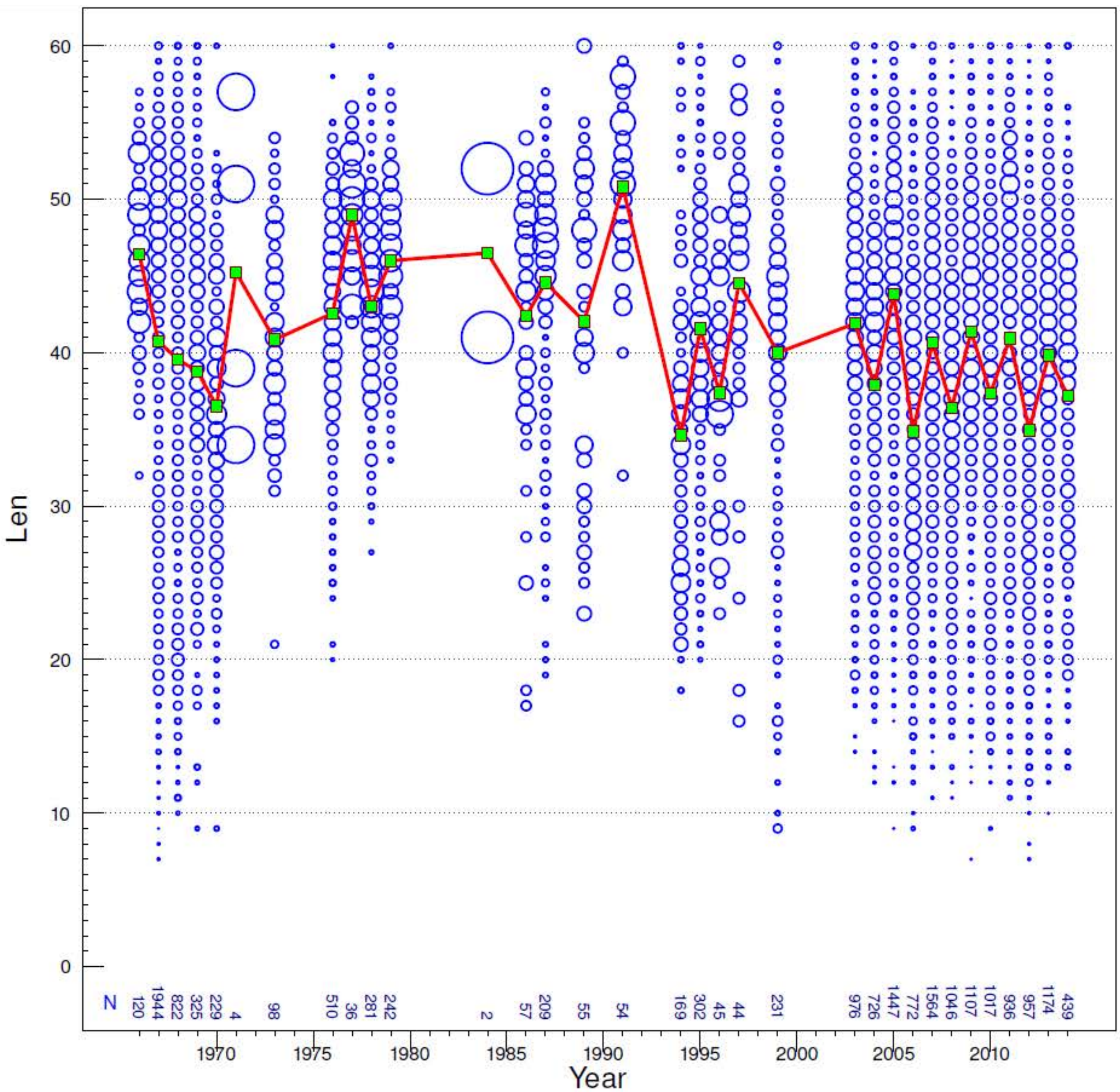


Figure D.2. Frequency distribution of Redbanded Rockfish lengths (cm), proportional to bubble area, from randomly-collected research and/or survey trawl samples. The mean length is plotted as green square symbols connected by a solid red line. The number of specimens appear along the bottom as annual totals.

D.1.2 LENGTH-WEIGHT

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

$$W_{si} = \alpha_s (L_{si})^{\beta_s} \tag{D.1}$$

where W_{si} = observed weight (kg) of individual i with sex s,
L_{si} = observed length (cm) of individual i with sex s,
α_s = growth rate scalar for sex s,
β_s = growth rate exponent for sex s.

The above model was fit as a linear regression to the logged length-weight pairs that satisfied the following conditions:

- occurred in at least one of the PMFC major ares 3C, 3D, 5A, 5B, 5C, 5D, or 5E;
- originated from a research and/or survey trip (`ttype=2:3`);
- included all available sample types (in this case, `c(0,1,2,6)`);
- excluded length-weight pairs with Studentised residuals $\geq$ 3.0 (the final fit was run after these data were removed).

The resulting estimates for log(α_s) were exponentiated to provide the α_s parameters used in the stock assessments (Table D.3 and Figure D.3).

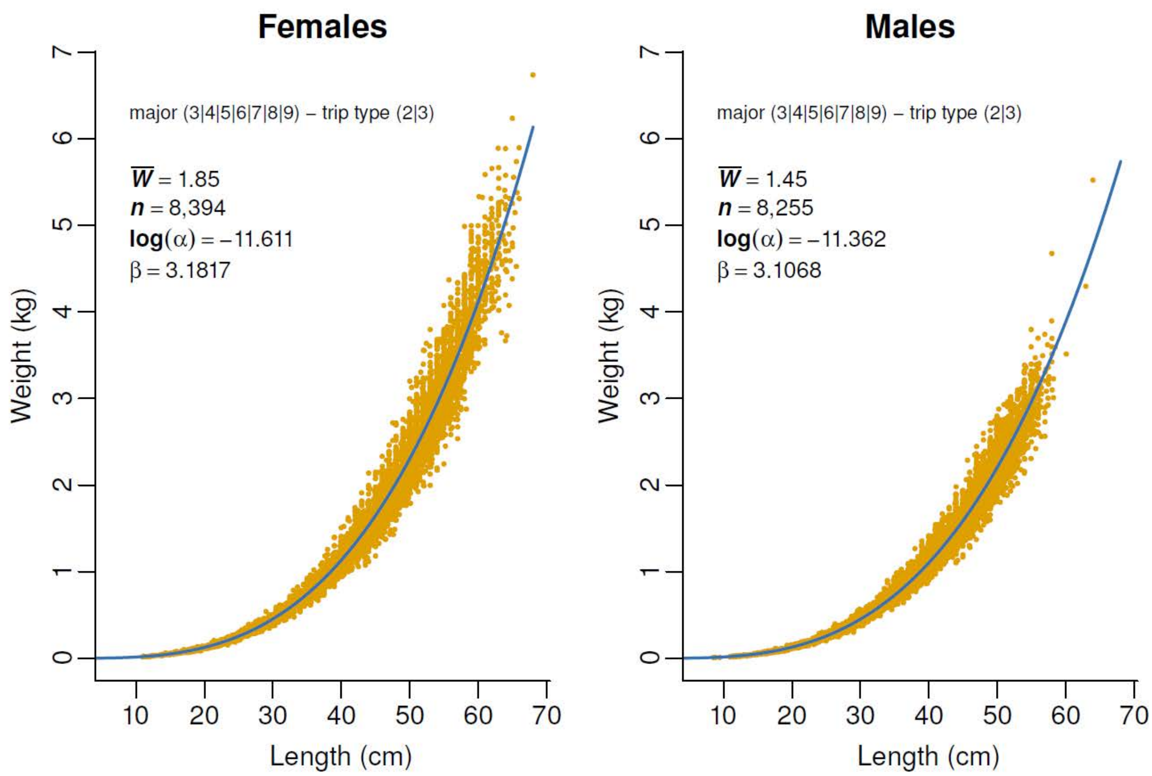


Figure D.3. Regression analyses showing the fitted model and length-weight pairs, given constraints outlined in the text, used to estimate α_s and β_s.

Table D.3. *Length-weight relationships for Redbanded Rockfish collected by research/survey trips, where s = sex, n_s = number of specimens by sex, and α_s = log(α_s).*

s	n_s	α_s	SE$_\alpha$	β_s	SE$_\beta$
Females	8394	-11.611	0.012537	3.1817	0.0033340
Males	8255	-11.362	0.013043	3.1068	0.0035121

Table D.4. *Growth parameters ($L_{\infty,s}$, k_s, $t_{0,s}$) for Redbanded Rockfish using the von Bertalanffy model, where s = sex, n_s = number of specimens by sex.*

s	n_s	$L_{\infty,s}$	k_s	$t_{0,s}$
Females	1964	56.003	0.067880	-3.1394
Males	1655	49.219	0.10082	-0.93642
Both	3626	52.720	0.080123	-2.2158

D.1.3 VON BERTALANFFY GROWTH

The parameterisation of the von Bertalanffy growth model is:

$$L_{as} = L_{\infty,s}\left(1 - \mathrm{e}^{-k_s(a-t_{0,s})}\right) \tag{D.2}$$

where L_{as} = average length (cm) of an individual with sex s at age a,
$L_{\infty,s}$ = average length (cm) of an individual with sex s at maximum age,
k_s = growth rate coefficient for sex s,
$t_{0,s}$ = age at which the average length is 0 for sex s.

The above model was fit using non-linear minimisation on Redbanded Rockfish age-length pairs that satisfied the following conditions:

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

Non-linear von Bertalanffy models were fit to age-length pairs, with data from 1980-02-15 to 2012-06-14 coastwide for female, male and both combined (Table D.4 and Figure D.4). Generally, females attain larger sizes than do males, with L_∞ for females being $\sim$7 cm larger than that for males.

D.1.4 MATURITY

A bubble plot of frequency data (maturity vs. month), extracted from the SPECIMEN table in the GFBioSQL database for Redbanded Rockfish, appears in Figure D.5. The maturity data selected satisfy the following conditions:

- occurred in at least one of the PMFC major ares 3C, 3D, 5A, 5B, 5C, 5D, or 5E;

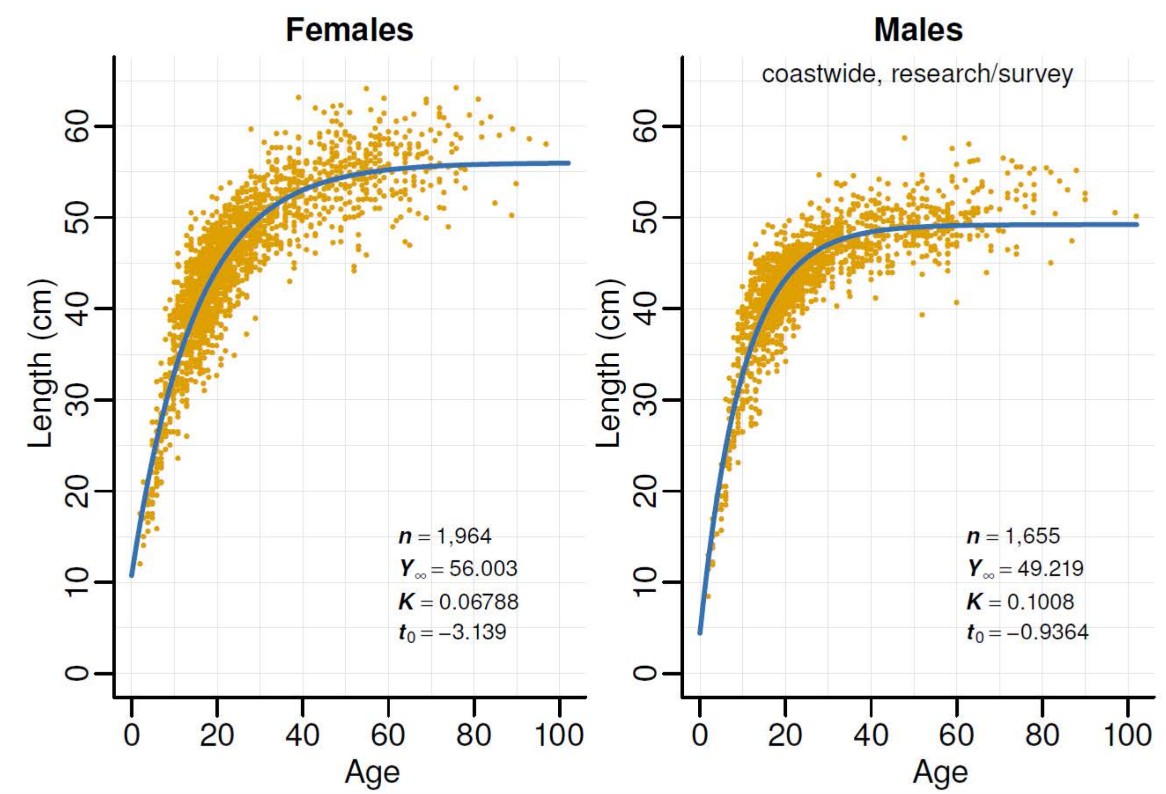


Figure D.4. Age-length relationships using the von Bertalanffy growth model (D.2) for Redbanded Rockfish specimens that satisfy the conditions listed in the text. n *= number of specimens;* Y_∞ *=* $L_{\infty,s}$*.*

- originated from a either a commercial trip (`ttype=c(1,4)`) or a research survey trip (`ttype=2:3`);
- included only sample types `c(1,2,6,7)` (total catch, random, random from randomly assigned set, or random from set after randomly assigned set, respectively);
- included definitely identified maturity codes (`mats=1:7`).

Ideally, lengths- and ages-at-maturity are calculated at times of peak development stages (males: insemination season, females: parturition season; Westrheim 1975). On the other hand, to see changes in maturity it is sometimes best to use data from time periods that ensure a clear delineation between immature and mature fish. Judging from Figure D.5, female spawning – fertilization (stage 4) and embryo production (stage 5) – occurs predominantly during the first half of the year (as there is a lack of spawning observations after mid-year). Spent females (stage 6) seem to persist for some time (Apr-Oct). Observations from November to January are very poorly determined. Based on these patterns, the period February to July or August is likely suitable for determining a maturity ogive.

Regardless of month, qualified female data for Redbanded Rockfish are available from the commercial fishery ($n = 99$), three trawl surveys – QCS Synoptic ($n = 265$), WCVI Synoptic ($n = 117$), QCS Shrimp ($n = 84$), and two longline surveys – PHMA Rockfish Longline North ($n = 527$) and PHMA Rockfish Longline South ($n = 485$). From the discussion above, Figure D.5, and various trials (not shown), we use BC research samples (`ttype=2:3`) from February to July

($n = 1048$ qualified data points). The narrower month span meant excluding a large number of September specimens from the PHMA longline surveys (N = 275, S = 270), as well as 24 specimens from the QCS Synoptic survey, but gaining 61 specimens from one-off surveys. Using stage 3 and up to denote mature fish, we construct a maturity ogive (Figure D.6) using a double-normal model:

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

where m_{as} = maturity at age a for sex s,
ν_s = age of full maturity for sex s,
ρ_s = variance for the left limb of the maturity curve for sex s.

The proportion of mature individuals is calculated (Table D.6, Figure D.6) and the age of 50% maturity is estimated at 17.8 y for females (16.1 y for males, not shown). The binomial logit fit is included in Table D.6 for comparison purposes; it mirrors the double-normal model (D.3) closely. The maturity ogive used in this assessment appears as the last column in Table D.6. It adopts the double-normal fitted values for ages 9 and up, but uses the empirical (raw) proportions-mature for ages 1 through 8 (except age 5 which is assigned $m_5 = 0$). This strategy follows previous assessments on BC rockfish where younger ages are not well sampled.

Table D.5. Frequency of maturity codes (columns) by month (rows) for each of the trip types. All data were used to derive Figure D.5.

	Month/Maturity	1	2	3	4	5	6	7
Comm – Non-observed	4	3	7	7	9	1	3	2
	6	3	8	4	—	3	45	44
	7	7	35	37	2	5	1	4
	9	2	20	18	—	—	—	84
	10	2	93	3	—	—	17	82
Survey – Research	2	96	32	68	3	1	1	4
	3	110	10	34	3	—	—	5
	4	124	12	11	118	277	92	25
	5	137	127	16	5	21	30	80
	6	384	358	21	6	64	110	395
Survey – Charter	3	1	—	1	1	—	—	—
	5	123	167	61	30	111	289	131
	6	15	120	471	25	77	781	656
	7	186	730	771	28	26	1617	1875
	8	77	433	250	77	42	673	1107
	9	153	541	255	140	25	299	349
	10	2	34	39	1	—	15	7
	11	—	1	8	—	—	—	—
Comm – Observed	1	—	3	48	—	—	—	—
	2	1	3	24	6	1	—	—
	3	—	4	30	19	1	—	—
	4	—	4	—	5	4	2	2
	5	1	3	—	11	26	4	1
	6	2	12	3	—	—	25	24
	7	1	18	3	—	—	5	29
	8	—	8	—	—	—	—	15
	9	2	6	—	1	—	2	34
	10	—	3	9	—	—	—	5

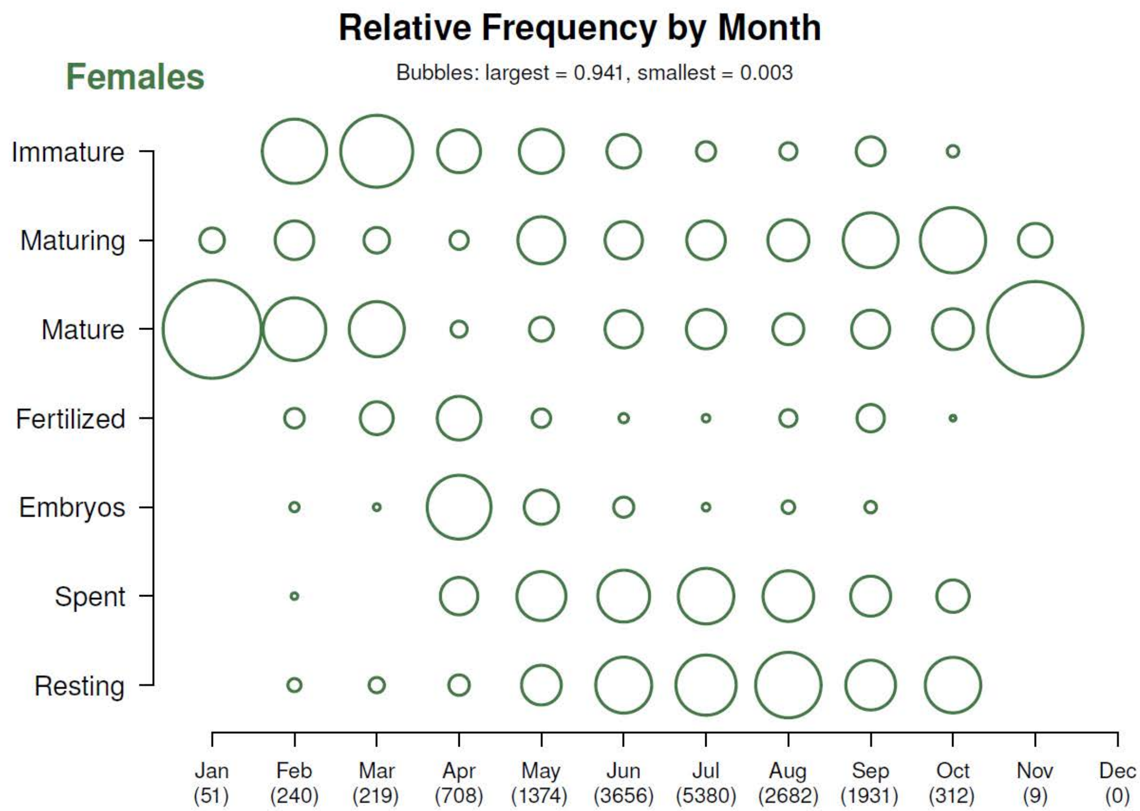


Figure D.5. Relative frequency of maturity codes by month for Redbanded Rockfish females (data stored in DFO's GFBioSQL database). Data include maturities from commercial and research specimens. Frequencies are calculated among each maturity category for every month.

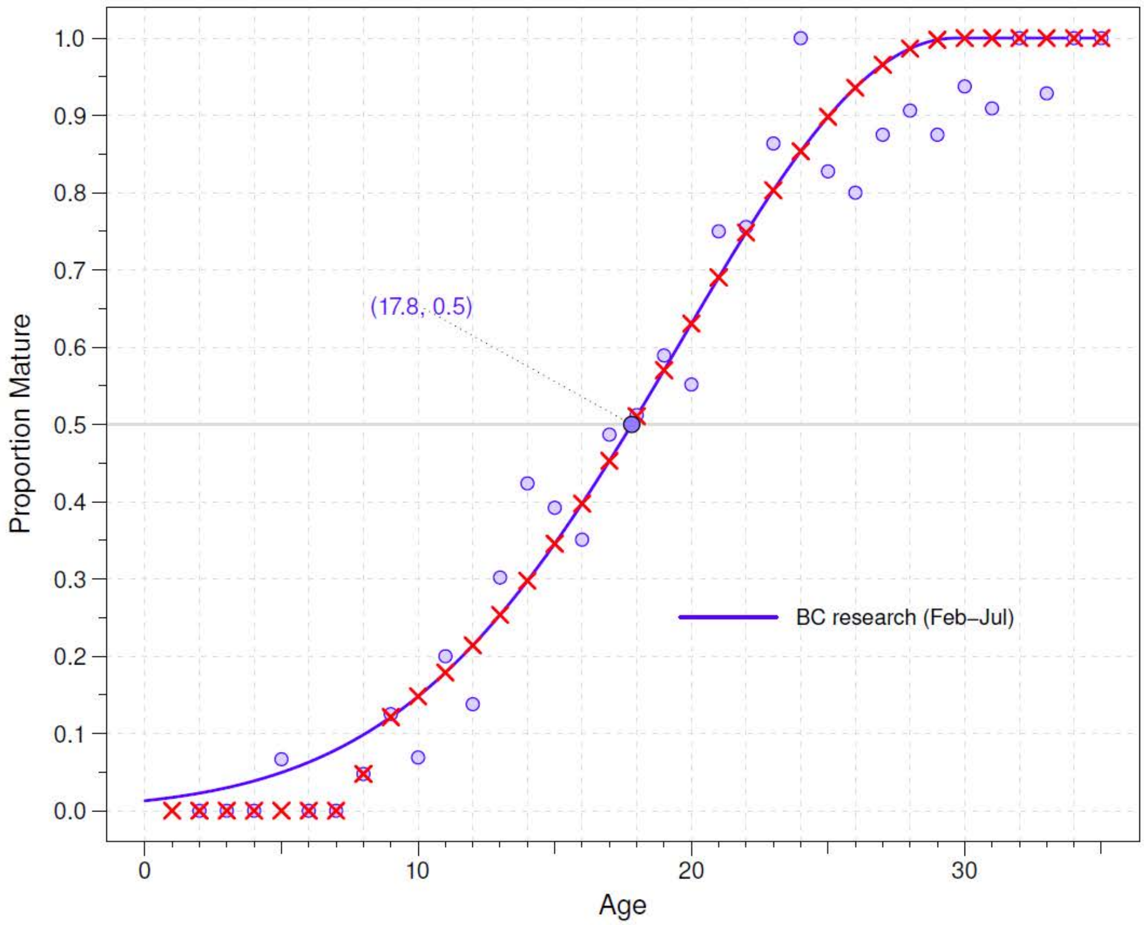


Figure D.6. Maturity ogives for BC Redbanded Rockfish females (data stored in DFO's GFBioSQL database). Solid line shows the double-normal curve fit; circles denote input proportions-mature; crosses indicate values used in the model. Age at 50% maturity is indicated along the median line.

Table D.6. Proportion of Redbanded Rockfish females mature by age used in the catch-age model (final column). Maturity stages 1 and 2 were assumed to be immature fish and all other staged fish (stages 3 to 7) were assumed to be mature. Only BC specimens caught by research surveys from February to July were used in the calculation of observed proportion mature.

Age	# Fish	Obs. m_a	Logit Fit m_a	(D.3) Fit m_a	Model m_a
1	—	—	0.01750	0.01725	0
2	2	0	0.02223	0.02279	0
3	4	0	0.02821	0.02981	0
4	8	0	0.03573	0.03861	0
5	15	0.06667	0.04516	0.04951	0
6	19	0	0.05694	0.06286	0
7	24	0	0.07156	0.07904	0
8	21	0.04762	0.08957	0.09839	0.04762
9	16	0.1250	0.1116	0.1213	0.1213
10	29	0.06897	0.1382	0.1480	0.1480
11	25	0.2000	0.1699	0.1789	0.1789
12	29	0.1379	0.2071	0.2141	0.2141
13	53	0.3019	0.2501	0.2536	0.2536
14	59	0.4237	0.2986	0.2976	0.2976
15	51	0.3922	0.3521	0.3457	0.3457
16	57	0.3509	0.4096	0.3976	0.3976
17	76	0.4868	0.4696	0.4529	0.4529
18	82	0.5122	0.5306	0.5107	0.5107
19	56	0.5893	0.5906	0.5703	0.5703
20	58	0.5517	0.6481	0.6305	0.6305
21	52	0.7500	0.7016	0.6903	0.6903
22	45	0.7556	0.7501	0.7482	0.7482
23	44	0.8636	0.7930	0.8031	0.8031
24	25	1	0.8302	0.8535	0.8535
25	29	0.8276	0.8619	0.8982	0.8982
26	20	0.8000	0.8885	0.9359	0.9359
27	24	0.8750	0.9105	0.9656	0.9656
28	32	0.9062	0.9285	0.9865	0.9865
29	16	0.8750	0.9431	0.9978	0.9978
30	16	0.9375	0.9549	1	1
31	11	0.9091	0.9643	1	1
32	14	1	0.9718	1	1
33	14	0.9286	0.9778	1	1
34	16	1	0.9825	1	1
35	6	1	0.9862	1	1

D.2 WEIGHTED AGE PROPORTIONS

This appendix summarizes a method for representing commercial and survey age structures for a given species through weighting observed age frequencies x_a or proportions x'_a by catch$\|$density in defined strata. (Throughout this section, we use the symbol '$\|$' to delimit parallel values for commercial and survey analyses, respectively, as the mechanics of the weighting procedure are similar for both.) For commercial samples, these strata comprise quarterly periods within a year, while for survey samples, the strata are defined by longitude, latitude, and depth. Within each stratum, commercial ages are weighted by the catch weight (kg) of the species in tows that were sampled, and survey ages are weighted by the catch density (kg/km^2) of the species in sampled tows. A second weighting is then applied: quarterly commercial ages are weighted by the commercial catch weight of the species from all tows within each quarter; stratum survey ages are weighted by stratum areas (km^2) in the survey.

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

For simplicity herein, we illustrate the weighting of age frequencies x_a, unless otherwise specified. The weighting occurs at two levels: h (quarters for commercial ages, strata for survey ages) and i (years if commercial, surveys in series if survey). Notation is summarised in Table D.7.

*Table D.7. Equations for weighting age frequencies or proportions for Redbanded Rockfish. (**c**) = commercial, (**s**) = survey*

Symbol	Description
	Indices
a	age class (1 to A, where A is an accumulator age-class)
d	(**c**) trip IDs as sample units
	(**s**) sample IDs as sample units
h	(**c**) quarters (1 to 4), 91.5 days each
	(**s**) strata (area-depth combinations)
i	(**c**) calendar years (1977 to present)
	(**s**) survey IDs in survey series (e.g., QCS Synoptic)
	Data
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 (kg) of a given species for sample unit d in quarter h of year i
	(**s**) density (kg/km^2) of a given species 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 (kg) of species in quarter h of year i
	(**s**) stratum area (km^2) of stratum h in survey i
K'_{hi}	K_{hi} as a proportion of total catch$\|$area $K_i = \sum_h K_{hi}$
p_{ai}	weighted frequencies at age a in year$\|$survey i
p'_{ai}	weighted proportions at age a in year$\|$survey i

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

$$C'_{dhi} = \frac{C_{dhi}}{\sum_d C_{dhi}} \; . \tag{D.4}$$

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

$$y_{ahi} = \textstyle\sum_d \big(C'_{dhi} x_{adhi} \big) \; . \tag{D.5}$$

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

$$\frac{\sum_a x_{ahi}}{\sum_a y_{ahi}} \tag{D.6}$$

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

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

$$K'_{hi} = \frac{K_{hi}}{\sum_h K_{hi}} \tag{D.7}$$

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

$$p_{ai} = \textstyle\sum_h \big(K'_{hi} y_{ahi} \big) \; . \tag{D.8}$$

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

$$\frac{\sum_a y_{ai}}{\sum_a p_{ai}} \; . \tag{D.9}$$

to retain the original number of observations.

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

$$p'_{ai} = \frac{p_{ai}}{\sum_a p_{ai}} \; . \tag{D.10}$$

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

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

D.2.1 COMMERCIAL AGES

The commercial age data for Redbanded Rockfish are sparse, with only four years available for bottom trawl (2003-05, 2009, Figure D.7) and four years for longline sets (1995, 2004-05, 2009). Further, the number of trips sampled per year only exceeded our criteria for using commercial age data ($\geq$4 trips) in 2003-04 and 2009 for bottom trawl tows (Table D.8) and in 1995 and 2004 for longline sets (Table D.9). A large plus class (60+ y) was evident in most years except 2003 (Figure D.7). Note that all bubble plots for proportions-at-age are scaled to the largest proportion across sex and year, *not* within each year.

The dearth of commercial hook and line age data and the fishery-like experimental PHMA surveys conducted in 1997 and 1998 in the north (Tasu and Anthony Is) and south (Triangle and Brooks) prompted the use of these age data in the commercial hook and line series.

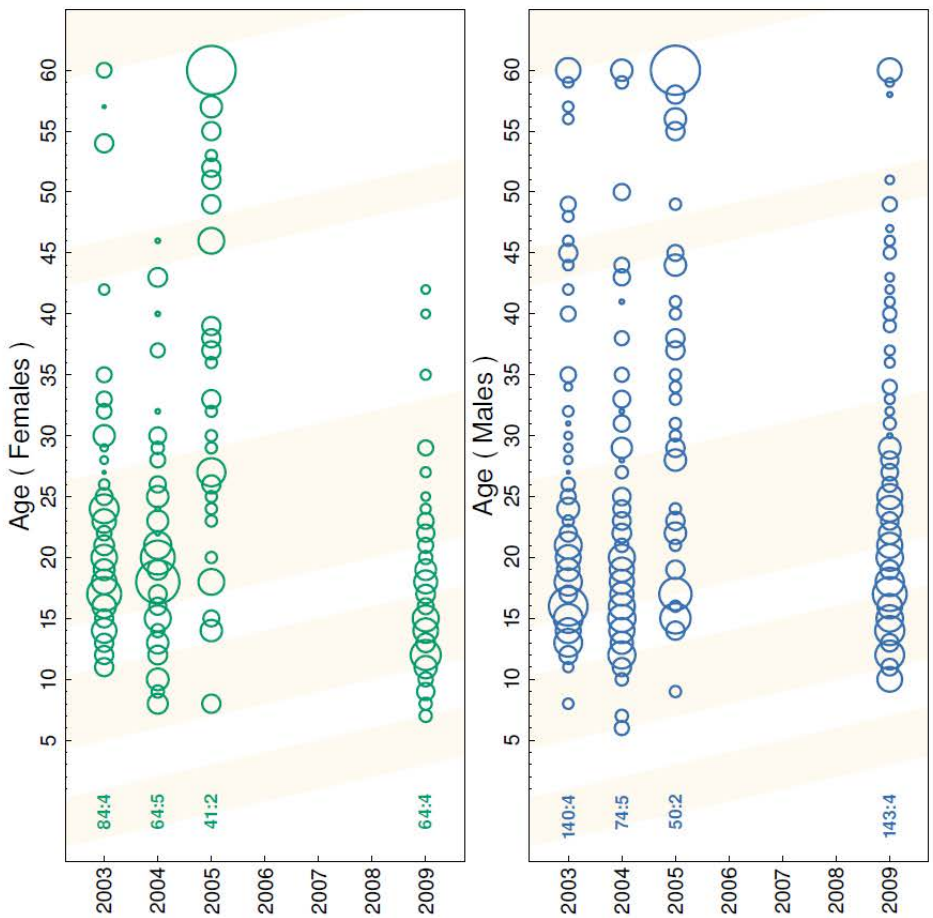


Figure D.7. Proportions-at-age for Redbanded Rockfish caught by commercial bottom trawl, calculated as age frequencies weighted by trip catch within quarters and commercial catch within years. Diagonal shaded bands indicate cohorts that were born when the mean Pacific Decadal Oscillation was positive. Numbers displayed along the bottom axis indicate number of fish aged and number of samples (colon delimited) by year.

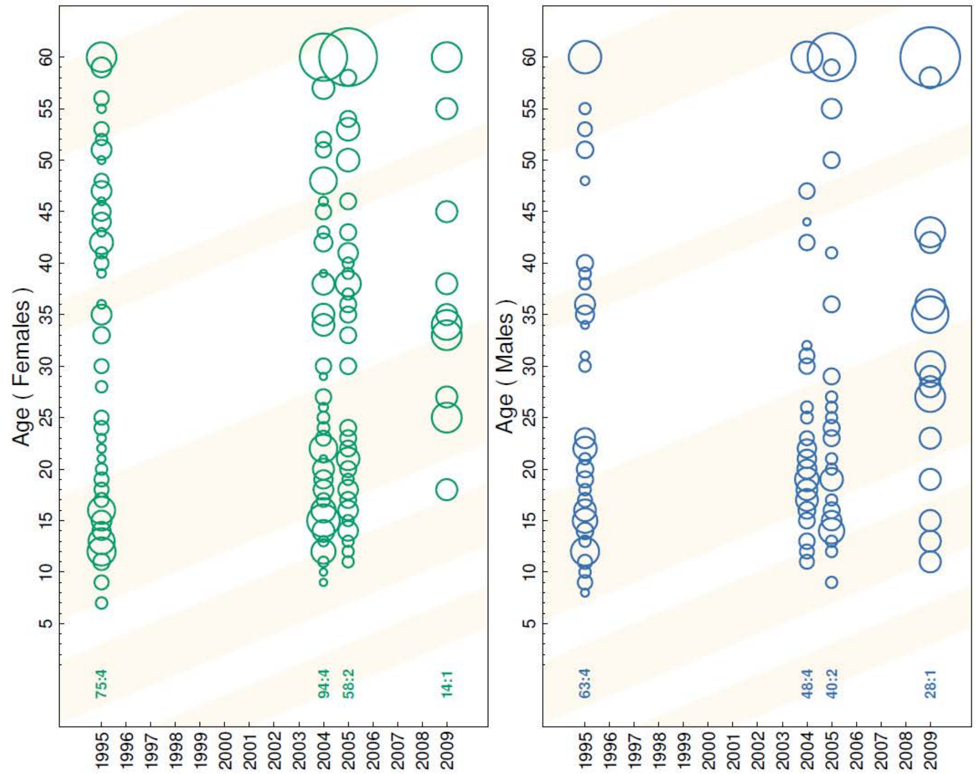


Figure D.8. Proportions-at-age for Redbanded Rockfish caught by commercial longline., Figure details as above. See Figure D.7 for details on diagonal shaded bands and displayed numbers.

Table D.8. Commercial trips (bottom trawl): number of sampled trips, Redbanded Rockfish catch (t) by trip and per quarter.

Year	# Trips				Trip catch (t)				Commercial catch (t)			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
2003	3	1	0	0	7.48	1.13	0	0	47.4	59	75.9	32.1
2004	0	1	4	0	0	0.268	6.56	0	27.5	69.2	77.2	36.4
2005	0	1	0	1	0	0.151	0	3.40	37.1	71.9	67.4	27.3
2009	2	1	1	0	3.63	0.118	3.54	0	52.2	133	90.3	53.2

Table D.9. Commercial trips (longline): number of sampled trips, Redbanded Rockfish catch (t) by trip and per quarter.

Year	# Trips				Trip catch (t)				Commercial catch (t)			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1995	0	1	3	0	0	1.18	0.210	0	15.4	106	53.7	0.0195
2004	1	2	0	1	0.336	0.732	0	0.318	17.2	22.7	9.58	6.50
2005	0	1	1	0	0	0.363	0.181	0	4.01	13.3	26.7	13.2
2009	0	1	0	0	0	3.27	0	0	11.2	27.4	32.3	14.2

D.2.2 SURVEY AGES

The Queen Charlotte Sound Synoptic survey (survey series ID (SSID) 1, Figure D.9, Table D.10) has three years of age data with minimal numbers of otoliths aged. All years show substantial plus class representation. Clear signals of single-year high recruitment are not evident, suggesting that either age determination is not precise or recruitment autocorrelation (e.g., good years for recruitment are grouped together). Tracking of large cohorts through time is poorly demonstrated.

The West Coast Vancouver Island Synoptic survey (SSID 4, Figure D.10, Table D.11) is only represented by one year of age data (2012). Ages above 40 are conspicuously rare. Otoliths aged are minimal, and age proportions for females and males differ in that females appear to be younger (on average).

The Queen Charlotte Sound Shrimp survey (SSID 6, Figure D.10, Table D.12) also has only one year of data. The plus class for males is huge, but otoliths aged are minimal and so the age distribution may be skewed by chance. Below age 30, there appears to be no particular cohort that dominates.

In 1997 and 1998, a collaborative project between DFO and the hook and line industry identified areas of ‘light’ and ‘heavy’ exploitation along the northern and southern regions of the BC coast. The details of this project appear in Kronlund and Yamanaka (2001), and analyses therein pertain to Yelloweye Rockfish *Sebastes ruberrimus*. Chartered fisherfolk also sampled Redbanded Rockfish in three of the documented survey areas – Tasu (north: light exploitation) and Flamingo (north: heavy) along the SW coast of the Queen Charlotte Islands, and Triangle (south: light) along the NW coast of Vancouver Island. They also sampled Redbanded Rockfish in a fourth area – Brooks (south: heavy) just north of Brooks Peninsula. A mortality summary for Redbanded Rockfish in the four areas of exploitation appears in Haigh and Starr (2006).

These surveys are stored in the GFBIO database as the Pacific Halibut Management Association (PHMA) Rockfish Longline surveys North (SSID 22, Figure D.11, Table D.14) and South (SSID 36, Figure D.11, Table D.14). The 1997/98 PHMA surveys are well-sampled; however, large cohorts are not consistently represented between the two years. For instance, the largest female cohort (born in 1971) from the 1997 PHMA North survey does not register in the 1998 survey. In fact, the 1997 and 1998 surveys appear to represent two different populations. According to Kronlund and Yamanaka (2001), the 1997 longline sets occurred in September while the 1998 sets occurred in May. Their results showed that females (Yelloweye Rockfish) dominated all sites in the fall of 1997 and that fish were generally older in the fall 1997 samples than in the May 1998 samples. These trends also seem to hold for Redbanded Rockfish.

Redbanded Rockfish is known to be a difficult species to age (Stephen Wischniowski, Pacific Biological Station, DFO, Nanaimo, BC, pers. comm.). There is a lot of structure in the otoliths which makes it difficult to interpret the annual age bands, and there is variable spacing between the bands. Future ageing will likely be done using thin sectioning rather than the break and burn method.

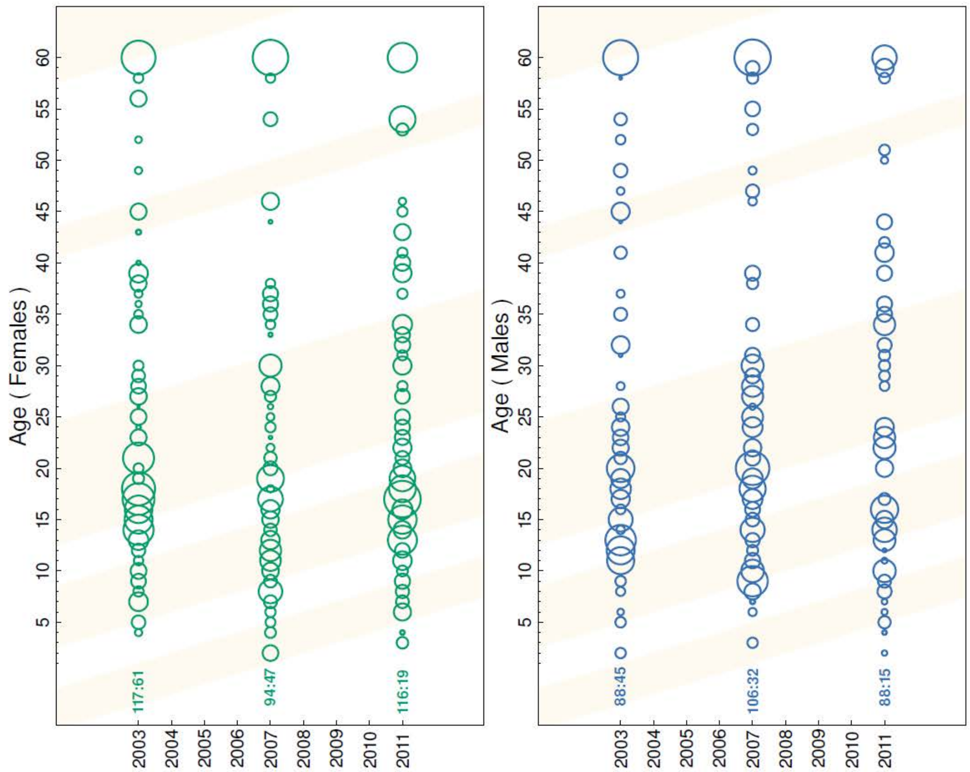


Figure D.9. Queen Charlotte Sound Synoptic survey – Redbanded Rockfish proportions-at-age based on age frequencies weighted by mean fish density within strata and by total stratum area within survey. See Figure D.7 for details on diagonal shaded bands and displayed numbers.

Table D.10. Queen Charlotte Sound Synoptic survey: number of sampled tows and Redbanded Rockfish density per stratum (kg/km^2). Stratum areas: 019= 5464 km^2; 020= 2744 km^2; 021= 568 km^2; 023= 4104 km^2; 024= 3760 km^2; 025= 1252 km^2

Year	# Samples						Mean density (kg/km^2)					
	019	020	021	023	024	025	019	020	021	023	024	025
2003	14	18	3	6	35	8	205	109	84.5	60.8	154	17.6
2007	9	7	2	7	27	0	379	167	123	261	72.6	0
2011	3	4	1	3	8	0	553	116	126	200	540	0

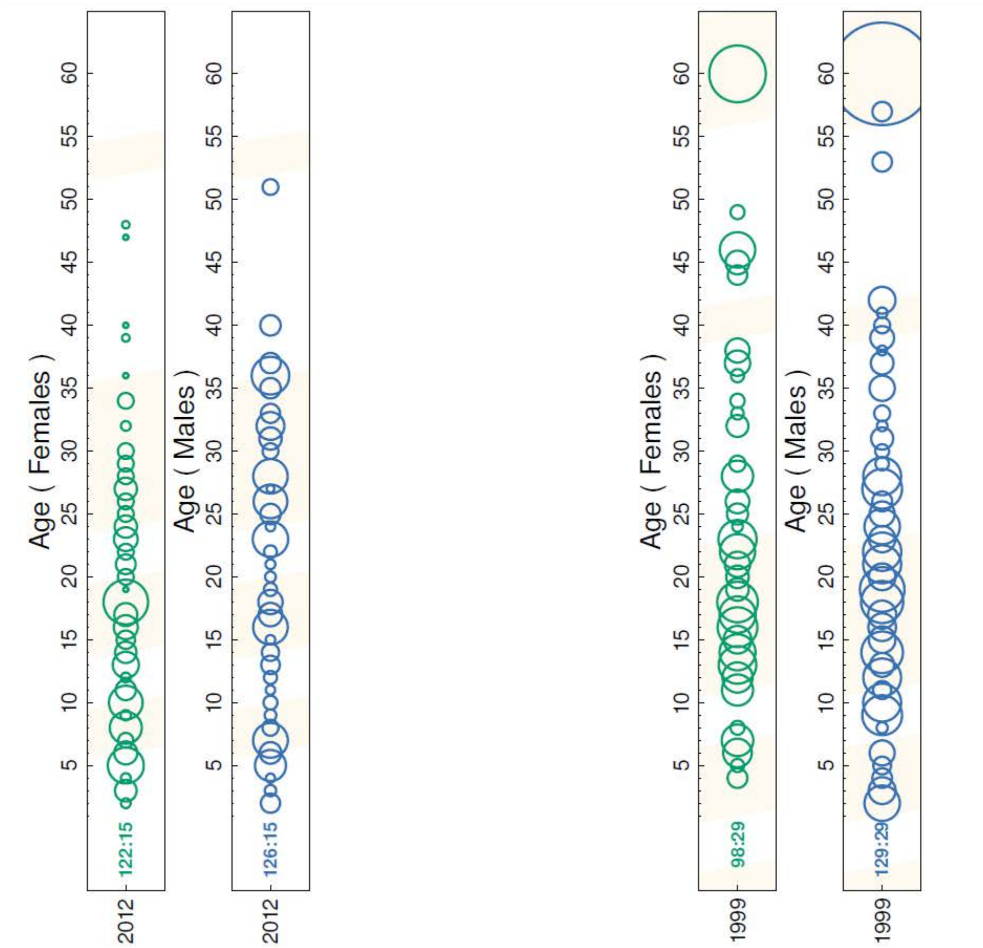


Figure D.10. West Coast Vancouver Island Synoptic survey (left) and Queen Charlotte Sound Shrimp survey (right) – Redbanded Rockfish proportions-at-age based on age frequencies weighted by mean fish density within strata and by total stratum area within survey. See Figure D.7 for details on diagonal shaded bands and displayed numbers.

Table D.11. West Coast Vancouver Island Synoptic survey: number of sampled tows and Redbanded Rockfish density per stratum (kg/km^2). Stratum areas: 066= 3844 km^2; 067= 720 km^2; 068= 624 km^2

Year	# Samples			Mean density (kg/km^2)		
	066	067	068	066	067	068
2012	3	7	5	149	347	106

Table D.12. Queen Charlotte Sound Shrimp survey: number of sampled tows and Redbanded Rockfish density per stratum (kg/km^2). Stratum areas: 000= 3926 km^2; 109= 2142 km^2

Year	# Samples		Mean density (kg/km^2)	
	000	109	000	109
1999	8	23	134	62.6

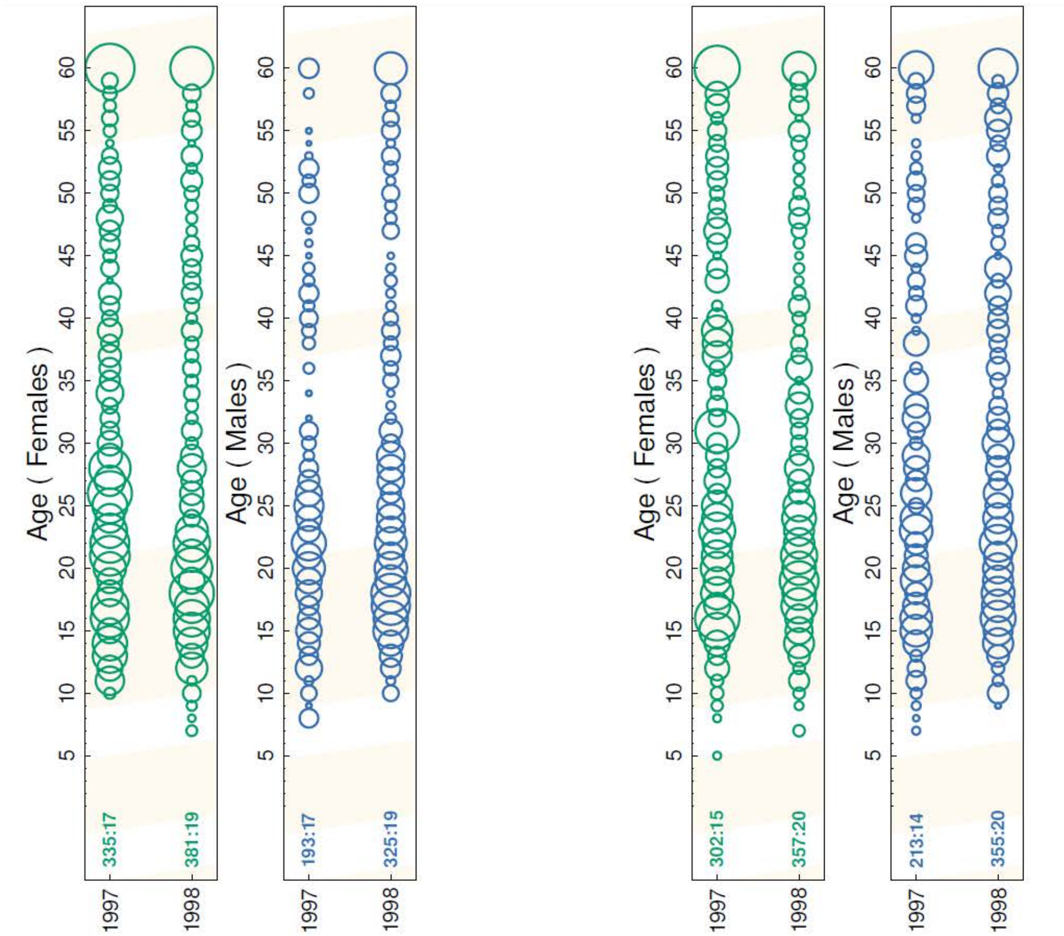


Figure D.11. Pacific Halibut Management Association (PHMA) Rockfish Longline North survey (left) and South survey (right) – Redbanded Rockfish proportions-at-age based on age frequencies weighted by mean fish density within strata and by total stratum area within survey. See Figure D.7 for details on diagonal shaded bands and displayed numbers.

Table D.13. PHMA Rockfish Longline North survey: number of sampled tows and Redbanded Rockfish density per stratum (kg/km^2). Stratum areas: 322= 5485 km^2; 323= 3705 km^2

Year	# Samples		Mean density (kg/km^2)	
	322	323	322	323
1997	0	17	0	881
1998	1	18	757	720

Table D.14. PHMA Rockfish Longline South survey: number of sampled tows and Redbanded Rockfish density per stratum (kg/km^2). Stratum areas: 325= 5499 km^2; 326= 1957 km^2

Year	# Samples		Mean density (kg/km^2)	
	325	326	325	326
1997	3	12	179	861
1998	2	18	52.4	636

APPENDIX E. RESULTS FROM CATCH-AT-AGE MODEL

E.1 INTRODUCTION

To use all available data and attempt to estimate past, present and projected stock status relative to reference points, we used a sex-specific, age-structured model in a Bayesian framework. In particular, the model can simultaneously estimate the steepness of the stock-recruitment function and separate mortalities for males and females (or it can fix them). This approach follows that used in our recent stock assessments of Pacific Ocean Perch (Edwards et al., 2012*b*, 2014*a*,*b*), Yellowmouth Rockfish (Edwards et al., 2012*a*) and Silvergray Rockfish (Starr et al., 2016) in Canadian Pacific waters.

Implementation was done using a modified version of the Coleraine statistical catch-at-age software (Hilborn et al., 2003) called Awatea (Allan Hicks, International Pacific Halibut Commission, Seattle, WA, USA, pers. comm.). Awatea is a platform for implementing the AD (Automatic Differentiation) Model Builder software (Otter Research Limited, 1999), which provides (a) maximum posterior density estimates using a function minimiser and automatic differentiation, and (b) an approximation of the posterior distribution of the parameters using the Markov Chain Monte Carlo (MCMC) method, specifically using the Hastings-Metropolis algorithm (Gelman et al., 2004).

Running of Awatea was streamlined using code written in R (R Core Team, 2014). Figures and tables of output were automatically produced through R using code adapted from the R packages `scape` (Magnusson, 2009) and `scapeMCMC` (Magnusson and Stewart, 2007). We used the R software `Sweave` (Leisch, 2002) to automatically collate, via LaTeX, the large amount of figures and tables into a single pdf file for each model run. We have incorporated our code for this into our R package `PBSawatea`, which required updating for this assessment.

The statistical catch-age model demonstrated sensitivity to minor assumptions and reweighting of the data. Despite numerous attempts, we were unable to obtain acceptable behaviour. Given the instability of the model fits, we do not consider any catch-age model results for the provision of management advice. We present some example model configurations here to give an indication of the behaviour of the model. One of the reasons seems to be the relatively small quantity of age data, both the number of years available and the number of samples available in each year, compared to other rockfish assessments that have used the same catch-age modelling approach (Edwards et al., 2012*b*,*a*, 2014*a*,*b*; Starr et al., 2016).

E.2 BRIEF DESCRIPTION OF THE CATCH-AGE MODEL

Equations for the catch-age model are given in full in Edwards et al. (2012*a*,*b*, 2014*a*,*b*), and are not repeated here. The differences to previous assessments are the input data and the prior distributions for parameters. Modifications to the previous equations include logical extensions to account for two fisheries, and consideration that the International Pacific Halibut Commission (IPHC) hook-and-line survey indexes numbers of fish rather than biomass.

We modelled two sexes and two fisheries, started the model at an assumed unfished equilibrium state in 1940 and ended it at the start of 2015. We used age classes from 1 to 60+, with 60+ consisting of fish 60 years and older.

The main assumptions of the model are:

1. The stock is treated as a single coastwide stock.
2. Catches are taken by two fisheries (commercial and hook-and-line), are known without error and occur in the middle of the year.
3. Recruitment is modelled using a time-invariant Beverton-Holt stock-recruitment relationship with log-normal error structure. We tried various values of the standard deviation parameter of the error structure.
4. Selectivity differs between sexes and between the commercial fisheries and the surveys, and remains invariant over time. It is modelled by a half-Gaussian formulation, permitting an increase in selectivity up to the age of full selectivity (above which fish are assumed fully selected). Selectivity parameters are estimated when ageing data are available.
5. Natural mortality is held invariant over time, and estimated independently for females and males.
6. Growth parameters are fixed and assumed to be invariant over time. See Appendix D for details.
7. Maturity-at-age parameters for females are fixed and assumed to be invariant over time; see Appendix appBiology for details. Male maturity is not considered because it is assumed that there are always sufficient mature males.
8. Recruitment at age 1 comprises 50% females and 50% males.
9. Fish ages determined using the surface ageing methods (prior to 1977) are too biased to use (Beamish, 1979). Ages determined using the otolith break-and-burn methodology (MacLellan, 1997) are aged without error.
10. Relative abundance indices are proportional to the vulnerable biomass in the middle of the year, after half the catch and half the natural mortality are accounted for.
11. The age composition samples come from the middle of the year after half the catch and half the natural mortality are accounted for.

Data from eight survey series were used, as described in detail in Appendices B and C. As described in Appendix A, the commercial catch has been reconstructed back to 1918; given the negligible catches in the early years, the model was started in 1940, and catches prior to 1940 were not considered.

A Beverton-Holt recruitment function was 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). A log-normal process error was assumed, giving

$$R_t = \frac{4hR_0B_{t-1}}{(1-h)B_0 + (5h-1)B_{t-1}} e^{\epsilon_t - \sigma_R^2/2} \tag{E.1}$$

where R_t is the recruitment in year t, R_0 is the virgin recruitment, B_{t-1} is the spawning biomass at the start of year $t-1$, B_0 is the virgin spawning biomass, $\epsilon_t \sim$ Normal$(0, \sigma_R^2)$ is the recruitment deviation with standard deviation σ_R. The value of σ_R was fixed at either 0.4, 0.6 or 0.9 in various model runs.

E.3 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 which is the negative of the sum of the total log-likelihood function and the logarithm of the joint prior distribution.

The procedure for the Bayesian computations is as follows.

1. Minimise the objective function to give estimates of the mode of the posterior density (MPD) for each parameter:
    - the estimation of parameters is introduced in phases;
    - the total error for the survey indices are adjusted by adding process error;
    - an iterative reweighting procedure is performed on the age-composition data.
2. Generate samples from the joint posterior distributions of the parameters using the Monte Carlo Markov Chain (MCMC) procedure, starting the chains from the MPD estimates.

For the survey indices, as for our recent rockfish assessments (Edwards et al., 2012*a*, 2014*a*,*b*) we adjusted the observed coefficients of variation of the survey indices by adding a process error component, as recommended by Francis (2011). For some model runs we fixed it at 0.2 for all surveys (the value recommended by Francis 2011), and for others we adjusted the value for each survey series to try and obtain standard deviations of normal residuals of these data sets that were approximately 1.

For the age data, we used the Francis (2011) iterative reweighting procedure to change the effective sample size of each age-composition data set, as we did for recent rockfish assessments (Edwards et al., 2012*a*, 2014*a*,*b*). However, we found that for Redbanded Rockfish the reweighting would not settle down – we give an example below. Model runs are denoted by, for example, Run 45-4, where the 45 represents a particular model configuration (inclusion or exclusion of certain data sets, fixing or estimation of certain parameters, particular prior distributions etc.), and the 4 represents the iterative reweighting number.

For illustration, we describe the inputs and some of the results from Run 45-4. In particular, this model run used all the available proportions-at-age data, and attempted to estimate the steepness (h) of the Beverton-Holt stock-recruitment function, and natural mortalities for females (M_1) and males (M_2).

E.4 PRIOR DISTRIBUTIONS

Details of the prior distributions for the estimated parameters for Run 45-4 are given in Tables E.1 and E.2. Prior distributions were those used for the recent assessment of Silvergray Rockfish along the Pacific coast of Canada (Starr et al., 2016), which in turn were based on priors and posteriors from previous Pacific Ocean Perch assessments (Edwards et al., 2012*b*, 2014*a*,*b*). Priors for the selectivity parameters for the hook-and-line fishery were set to those for the trawl fishery, and similarly those for the hook-and-line IPHC survey equalled those for the QCS Shrimp trawl survey.

For Run 45-4, the aforementioned adjustment procedure resulted in adding process errors of

Table E.1. For Run 45-4, 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 final column gives the resulting MPD value or the fixed value if the parameter is fixed. For the recruitment deviations ϵ_t there is one estimated value for each year; σ_R sets the standard deviation of the deviations. Not all parameters given here are fully described in the text (but notation is consistent with that of our previous rockfish assessments, e.g. Edwards et al. 2014a*). Surveys are numbered in the order that they appear in Table 1. Catchability parameters are given in Table E.1.*

Parameter	Prior distribution	Mean, standard deviation	Bounds	Initial value	MPD or fixed value
Unfished equilibrium recruitment, R_0	uniform	–	[1, 100,000]	10,000	801
Natural mortality for females, M_1	normal	0.06, 0.006	[0.01, 0.20]	0.06	0.0466
Natural mortality for males, M_2	normal	0.06, 0.006	[0.01, 0.20]	0.06	0.0485
Steepness, h	beta	0.674, 0.168	[0.2, 0.999]	0.674	0.809
Recruitment deviations, ϵ_t	normal	0, σ_R =0.4	[-15, 15]	0	–
Age of full selectivity for females, μ_g:					
Commercial trawl	uniform	–	[5, 30]	10.5	14.9
Hook-and-line trawl	uniform	–	[5, 30]	10.5	20.7
Survey 1	normal	13.3, 4	[5, 30]	13.3	16.8
Survey 2	normal	15.4, 4.62	[5, 30]	15.4	18.0
Survey 3	normal	10.8, 3.24	[5,30]	10.8	14.9
Survey 4	fixed	–	–	–	10.8
Survey 5	fixed	–	–	–	10.8
Survey 6	fixed	–	–	–	15.4
Survey 7	fixed	–	–	–	12.4
Survey 8	fixed	–	–	–	10.8
Log of variance parameter for left-limb of selectivity curve, $\log v_{gL}$					
Commercial trawl	uniform	–	[-15, 15]	1.52	2.60
Hook-and-line trawl	uniform	–	[-15, 15]	1.52	3.71
Survey 1	normal	3.3, 1	[-15, 15]	3.3	3.78
Survey 2	normal	3.44, 1.03	[-15, 15]	3.44	4.67
Survey 3	normal	2.08, 0.62	[-15, 15]	2.08	2.19
Survey 4	fixed	–	–	–	2.08
Survey 5	fixed	–	–	–	2.08
Survey 6	fixed	–	–	–	3.44
Survey 7	fixed	–	–	–	3.52
Survey 8	fixed	–	–	–	2.08
Shift in commercial selectivity for males, Δ_g:					
Commercial trawl	uniform	–	[-6, 6]	0	0.21
Hook-and-line trawl	uniform	–	[-6, 6]	0	1.24
Survey 1	normal	0.22, 0.066	[-6, 6]	0.22	0.22
Survey 2	normal	0.22, 0.066	[-6, 6]	0.22	0.22
Survey 3	normal	0.22, 0.066	[-6, 6]	0.22	0.22
Survey 4	fixed	–	–	–	0.22
Survey 5	fixed	–	–	–	0.22
Survey 6	fixed	–	–	–	0.22
Survey 7	fixed	–	–	–	0.39
Survey 8	fixed	–	–	–	0.22

Table E.2. For Run 45-4, priors and MPD values for the survey catchability parameters, $q_1, q_2, q_3, ..., q_8$. Details as for Table E.1.

Parameter	Prior distribution	Mean, standard deviation	Bounds	Initial value	MPD or fixed value
Log of survey catchability parameter, $\log q_g$					
Survey 1	uniform	–	[-10, 5]	0	-1.74
Survey 2	uniform	–	[-10, 5]	0	-3.39
Survey 3	uniform	–	[-10, 5]	0	-3.98
Survey 4	uniform	–	[-10, 5]	0	-4.16
Survey 5	uniform	–	[-10, 5]	0	-2.48
Survey 6	uniform	–	[-10, 5]	0	-3.83
Survey 7	uniform	–	[-10, 5]	0	-2.89
Survey 8	uniform	–	[-10, 5]	0	-7.97

0.20, 0.45, 0.50, 0.05, 0.40, 0.05, 0.40 and 0.25 to the eight survey indices, respectively.

E.5 MPD (MAXIMUM OF THE POSTERIOR DENSITY) RESULTS FOR RUN 45-4.

We present some results from Run 45-4 which was described above. The model is able to fit the survey indices fairly well for Run 45-4 (Figure E.1); similarly good fits were typical for all model runs (not shown). The age composition data and fits for Run 45-4 (Figures E.2-E.8) are not good, with the data generally suggesting higher proportions of older fish than could be fit by the model. The mean age for each data set was generally underestimated (Figure E.9).

The residuals of the fits to the age data (Figures E.10-E.18) demonstrate unsatisfactory fits to the age data. For example, the top panel of Figure E.10 shows negative residuals for long sequences of consecutive ages, punctuated by relative few positive residuals. Fits for recent Canadian rockfish assessments (e.g. Edwards et al. 2014*b*; Starr et al. 2016) were much better.

The estimated spawning biomass and recruitment for each year is presented for interest in Figure E.19, but is not a robust output of the model, as is now shown.

E.6 SENSITIVITY TO REWEIGHTING OF AGE DATA: MPD RESULTS FOR RUN 46

As an example of sensitivity to successive reweightings, we present recruitment results for Runs 46-1, 46-2, 46-3 and 46-4 (Figures E.20-E.23). These runs differ from each other in the reweighting of the age data, and differ from Run 45-4 in the following ways:

1. the standard deviation of the normal priors for sex-specific natural mortality increased from 0.006 to 0.02;
2. σ_R increased from 0.4 to 0.9;
3. removal of the single year of age data from the QCS shrimp survey data (as we did for our QCS POP assessment, Edwards et al. 2012*b*);
4. fixing of the selectivity parameters for the QCS shrimp survey at the means of the priors given in Table E.1 (survey 3);
5. incorporating ageing error;

6. fixing the additional survey index process error to 0.2 for all surveys.

Note, that, in practice we tried incremental changes in the model inputs (we did not jump straight from Run 45 to Run 46), but none of them were able to stabilise the behaviour of the model.

The ageing error was introduced in the same way as for the sensitivity run for our Yellowmouth Rockfish assessment (Edwards et al., 2012*a*). We used a simple ageing error matrix, whereby the observed age was accurately determined 80% of the time. The remaining error was assumed to be plus one year 10% of the time and minus one year 10% of the time, creating an error matrix with $(0.1, 0.8, 0.1)$ along the tridiagonal. Ages 1 and 60$+$ (the youngest and oldest age classes in the model) were assumed to be aged accurately 90% of the time, and thus their respective rows in the ageing error matrix were $(0.9, 0.1, 0, 0, ..., 0)$ and $(0, 0, ..., 0, 0.1, 0.9)$.

Although the only difference between the four model runs 46-1 to 46-4 is the reweighting of the age data, the estimated patterns of recruitments are different between them (Figures E.20-E.23); the recruitment plots are shown as an example output to demonstrate the issues. Run 46-1 (Figure E.20) estimates a pronounced 1987 (age-0) recruitment event, over four times the size of recruitment in all other years. However, Run 46-2 (Figure E.21) estimates the largest recruitment event to be in 2007, only slightly larger than for a few years in the 1980s. Run 46-3 (Figure E.22) estimates the largest recruitment of age-0's to occur in 1940, the first year of the model. Whereas Run 46-4 (Figure E.23) estimates it to occur in 1987 again, with a similar pattern to Run 46-1, suggesting there may be some cyclical behaviour in the iterative reweightings, without settling down or approaching particular values. Also, all of these recruitment patterns differ from that shown in Figure E.19 for Run 45-4.

Thus, the model is sensitive to the reweighting of the age data, with the iterative procedure not approaching constant values and unable to settle on an effective sample size for each set of age-composition data.

E.7 OTHER MODEL RUNS

Numerous attempts were made to eliminate such spurious behaviour, such as incrementally removing sets of ageing data, adjusting the standard deviation for the recruitment process error σ_R (using values of 0.4, 0.6 and 0.9), and introducing ageing uncertainty as just discussed. But these were also unsuccessful.

Table E.3 documents various runs. For some of these Table E.4 gives the estimated current spawning biomass at the start of 2015 (B_t with t=2015), the estimated unexploited spawning biomass (B_0) at the start of 1940, and the ratio B_t/B_0.

Table E.3. Documentation (authors' notes) of various model runs attempted by the authors during the assessment process. For each model run and reweighting, a .pdf file is available from the lead author showing equivalent results to those shown in Figures E.1 to E.19 for model run 45-4. Continued over next two pages.

Model	Description
Run01	Natural mortality (M) & steepness (h) fixed, σ_R=0.4, $N_{\rm surv}$= 8 (QCS Synoptic, WCVI Synoptic, QCS Shrimp, WCHG Synoptic, HS Synoptic, US Triennial, Historic GB Reed, IPHC Longline), first 3 surveys with ages, $N_{\rm gear}$= 2 (bottom trawl, hook & line), $N_{\rm cpue}$= 0, $N_{\rm sex}$= 2, Francis (2011) reweighting using mean ages and increasing abundance index error by adding process error (c_p) = c(0.2, 0.3, 0.2, 0.2, 0.2, 0.2, 0.2, 0.2).
Run02	Same as Run01 but set c_p = c(0.2, 0.4, 0.4, 0.1, 0.3, 0.1, 0.4, 0.2).
Run03	Same as Run01 but set c_p = c(0.2, 0.45, 0.5, 0.05, 0.4, 0.05, 0.4, 0.25).
Run04	Same as Run03 but estimate M (CV=0.4) and h.
Run05	Same as Run04 but estimate M (CV=0.1).
Run06	Same as Run05 but set c_p = c(0.2, 0.45, 0.55, 0.03, 0.35, 0.03, 0.5, 0.1).
Run07	Same as Run06 but estimate M (lognormal CV=0.006), set c_p = c(0.19, 0.48, 0.59, 0.02, 0.36, 0.03, 0.5, 0.12).
Run08	Same as Run06 but fix M at 0.06.
Run09	Same as Run06 but remove 1995 commercial H&L age data, set c_p=0. Used reweight 2 for MPD – SDNR surveys = c(0.99612, 1.00179, 1.04011, 1.22701, 0.97572, 1.04647, 1.11258, 1.0855). Fits to age data still poor.
Run10	Same as Run09 but set σ_R=0.9. Used reweight 2 for MPD – SDNR surveys = c(0.97123, 0.91685, 1.07242, 1.19304, 0.98314, 1.06872, 1.11442, 1.12102). Fits to age data somewhat better.
Run11	Same as Run10 but set survey μ (S full) to commercial MPD μ values. Used reweight 2 for MPD – SDNR surveys = c(0.92614, 1.02541, 1.10103, 1.07833, 1.36828, 1.04905, 1.13059, 1.36108). Fits to age not as good as in Run10.
Run12	Same as Run11 but remove the 2004 commercial H&L age data . Used reweight 2 for MPD – SDNR surveys = c(0.92761, 0.9418, , 1.08277, 0.88962, 1.49028, 1.07673, 1.14837, 1.26589). The commercial H&L selectivity is very badly estimated at reweight 2 (μ=9.2 vs μ=21.8 in Run11) and the fit to the age data is terrible. Reweights have B_t/B_0 as: reweight 1 (0.19), reweight 2 (0.39) reweight 3 (0.21), reweight 4 (0.33) so clearly bouncing around. RH sent co-authors RBRrun12-1.pdf which is the first reweight. Model estimates a large 1993 recruitment event, which (looking at the residual figures for the age data plus the fitted age distributions) only seems to be supported (albeit weakly) by the QCS Shrimp age data. In those data there seem to be 4-5 year-olds caught. However, the selectivity MPD is μ_3=14.7, above it's mean prior value (i.e. the model hasn't ramped down the selectivity, so has to compensate by introducing a large 1993 recruitment event). For QCS POP this was the dataset we removed.
Run13	Same as Run12 but set σ_R=0.6. Also have to set the standard deviation for deviates of initial age structure to 0.6 (PBSawatea gives an error otherwise). Results from different reweights still bounce around, giving or not giving the big 1993 recruitment event.

Model	Description
Run14	Same as Run13 but removing the QCS Shrimp age data, keep σ_R=0.6. Reweight 1 – fits age data better, except still has big 1993 recruitment. Reweight 2 – higher B_t/B_0, age data fits good, big 1994 recruitment. Reweight 3 – age data fits possibly not quite as good, but no big 1993/1994 recruitment; for part of the 1960s, $B_t > B_0$. Reweight 4 – big 1994 recruitment, all hook-and-line age data poorly fit (commercial μ_{10}=7.6, for reweight 3 was 24, and for reweight 2 was 11). Note that WCVI age data 2012 has spike in 18-year old females (easily the largest age class, but for males 18-y old are about 9th highest) and QCS 2011 has spike in 17-y old females (but very low males), which seem to influence the big 1994 recruitment (but it still gets over-estimated). Seems that some of the male and female age data are themselves conflicting.
Run15	Same as Run14 but σ_R up to 0.9 again, which is what we had for the POP assessments. For reweight 2, SDNRs are c(0.97522, 1.243, 1.03071, 0.85363, 0.97994, 0.86982, 0.94853, 0.83618, 1.55069, 0.39953). Reweight 2 has big 1994 class, reweight 3 does not, reweight 4 does.
Run16	Same as Run15 but removing the WCVI Synoptic age data, since only one year and males and females are somewhat different (see above). Reweight 1 – big 1993 recruitment; reweight 2 – big 1994 recruitment (!); reweight 3 – no 1993/1994 big recruitment, above average for 1940s and most of 1950s; reweight 4 – big 1994 recruitment again, but still way higher than for the data in any year. For reweight 2, SDNRs are c(0.97762, 1.05432, 1.03696, 0.87425, 1.01993, 0.85141, 0.92543, 0.80036, 1.56945, 0.41017).
Run17	Same as Run16 but removing the 2011 QC Sound Synoptic age data, since has particularly high proportion of 17-year old females but particularly low proportion of 17-year old males. Reweight 2 – big 1993 recruitment (but can't see what's driving that – feels like a ghost from Run16!). Reweight 3 – a few early large recuitments (1945, though it keeps plotting something funny on the stock-recruit curve plots regarding the years), and 97, 98, and 99 are larger than 1960+ but not extreme, good fits to hook-and-line commercial age data. Reweight 4 – no big 1993 (so no longer oscillating between two states, like earlier runs had), somewhat like reweight 3 but fits to hook-and-line commercial age data not so good. SDNR for reweight 2 = c(1.03104, 1.1024, 1.04456, 1.08873, 1.09265, 0.95503, 0.97775, 1.02304, 1.50975, 1.61854) [look at first 8 only?] – getting much closer to 1 across the board compared to earlier runs.
Run18	Same as Run16 but removing the remaining QC Sound Synoptic age data. Still oscillating between reweights.
Run19	Same as Run17 but removing the commercial trawl age data. Doesn't run, but fixed in Run20.
Run20	Same as Run19 but switching order of the two commerical data sets, since think you can't have dataset 2 with age data and dataset 1 without. SDNR for reweight 2 = c(0.97624, 1.08547, 1.03603, 1.13536, 1.01906, 0.97896, 0.95254, 0.96658, 2.07592, 0.54408). Reweight 3 looks good, though autocorrelation in recruitment residuals. Reweight 4 introduces spurious year classes though, so still not settling down.
Run21	Same as Run20 but setting survey abundance units to be numbers not catch for IPHC survey. SDNR for reweight 2 have changed quite a bit from previous run: c(1.02776, 1.04222, 1.03743, 0.84092, 1.01354, 1.0414, 1.08966, 1.05121, 1.00497, 0.54408). Reweights 3 and 4 still different (haven't looked closely). So correcting the abundance units does have an influence. Also the penultimate SDNR (which thought wasn't really meant to look at) is now 1 not 2. Final one is the same. But then penultimate is 2.2 then 1.6 for reweights 3 and 4. So still very unstable. Reweights 3 and 4 look okay, reweight 4 has closer mean ages, but 3 has no autocorrelation. Reweight 3 $B_t/B0$=0.35, reweight 4 =0.46, so still significant difference in results. Commercial hook and line selectivity is (reweights 3 and 4, respectively) μ_9=12.2 and μ_9=12.5.

Model	Description
Run22	Same as Run21 but setting c_p=0.2, (as used for POP I think). In Run01 it was 0.2 for all except 0.3 for second value. So input file doesn't change. SDNRs are kind of spiralling in to values that aren't as close to 1 as for Run21, and penultimate value is changing somewhat, but they're not oscillating back and forth like they have been. SDNR for reweight 2 is c(0.93931, 1.61866, 1.67156, 0.5338, 1.33602, 0.79816, 1.8257, 0.93474, 1.34095, 0.54408). Reweight 3 has big 1983 year class, reweight 4 doesn't (just large-ish early ones, which seems common). M_s and h close for both. For reweights 3 and 4, have: B_t/B_0=0.40, 0.24 μ_9=15.3, 23.6, so changing dramatically again (unlike Run21).
Run23	Same as Run22 but σ_R=0.6 instead of 0.9, as we tried earlier. Between reweights 3 and 4, female M_s is 0.63, 0.57, but males 0.62, 0.61; B_t/B_0=0.25, 0.31, h=0.84, 0.80, μ_9=8.8 (!, and knife-edged), 20.1. That 8.8 is way lower than seen before I think. Reweight 3 puts in big recruitment in '53 and '89, wherease reweight 4 has higher typical recruitment, with no outstanding years. Big '89 is not supported by age composition data, so reweight 4 looks more consistent with the data. Reweight 3 has no autocorrelation (because it just does the occasional big year) whereas 4 does because years are more similar.
Run24	Same as Run23 but removing the 1997 hook & line age composition data, because in that year the females may have been aggregating. So only age data is 1998 hook & line. Fits look good, B_t/B_0=0.33, autocorrelation in recruitments (since there kind of has to be, and no big recruitment years). Reweights are the same after number 1, since w_j=1 (think something to do with only one set of age data).
Run25	Same as Run24 but σ_R back to 0.9. Results very similar, which is good – model not super-sensitive to σ_R.
Run26	Same as Run25 but survey selectivity μ (S full) back to those in Runs 1-10, fixed to the priors that Paul determined for Silvergray.
Run27	Same as Run26 but removed all catch-at-age. Selectivity for commercial hook and line fixed at 18 (prior had mean of 10.5); fixed IPHC μ to 18 also. Run not correct. Likelihood should have been switched off.
Run28	Same as Run26 but changed IPHC survey μ to 18. Doing MCMC on reweight 1. Run not correct.
Run36	Using PJS' new Run06 – M & h estimated, ageing error (0.8 along diagonal), σ_R = 0.9.
Run37	Same as Run 36, correcting IPHC survey to be numbers. Not changing c_p.
Run38	Same as Run37 except removing the QCS Shrimp age data – use Run39.
Run39	Same as Run38 except correctly setting all the QCS Shrimp selectivity parameters to be fixed. Same c_p. First reweighting very similar to Run38, but by reweight 4 commercial trawl selectivity in particular (and probably more) change – big recruitment in 1994 for reweight 4, not for Run38. c_p were set a few runs ago, so maybe set them all to 0.2.
Run40	Same as Run28 (no catch-age data). Fix hook-and-line selectivity at μ=18, corrected commercial likelihood switch, fix M & h, and set c_p=0. Like surplus production model, in a sense.
Run41	Run40 but fixing recruitment deviations to 0. Only estimating R_0 and q values. Did MCMC 25,000,000 with two slight differences [as reported elsewhere in this Research Document]. Folders are MCMC.41.01A – (25,000,000, thinning to 1,000) and MCMC.41.01B (same, but different seed and a rescaled step size to give a higher acceptance rate).
Run45	Run05 again, just correcting input file to have IPHC survey abundance type as numbers not catch. And turning off the debugger. Comparing results for 45-02 with 05-02.
Run46	Same as Run39 except setting all c_p=0.2, since they'd been adjusted a few runs earlier.

Table E.4. Estimated spawning biomass at the start of 2016 (B_t), unexploited equilibrium biomass at the start of 1940 (B_0), and ratio B_t/B_0 for some of the model runs outined in Table E.3. These MPD results are reported for the unweighted data (rwt=0) and for various reweightings (rwt=1,...,4) of abundance index precision and mean ages in the fisheries and surveys. Run 41-1 approximates a surplus production model that yields population trajectories displayed in Figure E.28. Continued overleaf.

Model	B_t	B_0	B_t/B_0	Model	B_t	B_0	B_t/B_0
Run 01 (rwt 0)	6,158	14,503	0.425	Run 24 (rwt 0)	3,129	9,567	0.327
(rwt 1)	5,511	12,046	0.458	(rwt 1)	3,205	9,724	0.330
Run 02 (rwt 0)	6,208	13,449	0.462	(rwt 2)	3,205	9,724	0.330
(rwt 1)	3,900	11,598	0.336	(rwt 3)	3,205	9,724	0.330
(rwt 2)	3,432	11,020	0.311	(rwt 4)	3,205	9,724	0.330
(rwt 3)	3,514	11,039	0.318	Run 25 (rwt 0)	3,038	9,338	0.325
(rwt 4)	3,518	11,023	0.319	(rwt 1)	3,320	9,827	0.338
Run 09 (rwt 0)	3,230	10,769	0.300	(rwt 2)	3,320	9,827	0.338
(rwt 1)	1,310	9,513	0.138	(rwt 3)	3,320	9,827	0.338
(rwt 2)	1,985	7,940	0.250	(rwt 4)	3,320	9,827	0.338
(rwt 3)	1,428	10,173	0.140	Run 26 (rwt 0)	1,087	7,161	0.152
(rwt 4)	1,863	7,642	0.244	(rwt 1)	1,526	7,926	0.192
Run 10 (rwt 0)	3,128	11,056	0.283	Run 27 (rwt 0)	1,461	7,212	0.203
(rwt 1)	1,255	9,216	0.136	(rwt 1)	1,962	8,096	0.242
(rwt 2)	1,377	7,277	0.189	Run 28 (rwt 0)	1,962	8,170	0.240
(rwt 3)	1,537	8,937	0.172	(rwt 1)	2,258	8,704	0.259
Run 11 (rwt 0)	3,141	10,976	0.286	Run 36 (rwt 0)	2,484	10,851	0.229
(rwt 1)	2,031	9,406	0.216	(rwt 1)	1,763	9,398	0.188
(rwt 2)	2,525	9,001	0.281	(rwt 2)	2,661	9,846	0.270
(rwt 3)	2,085	9,886	0.211	Run 38 (rwt 0)	2,962	11,486	0.258
Run 12 (rwt 0)	3,124	10,853	0.288	(rwt 1)	1,423	9,273	0.153
(rwt 1)	1,896	9,767	0.194	(rwt 2)	1,858	8,723	0.213
(rwt 2)	2,230	8,153	0.274	(rwt 3)	1,577	9,171	0.172
(rwt 3)	2,333	10,423	0.224	(rwt 4)	1,507	7,965	0.189
(rwt 4)	2,334	12,805	0.182	Run 40 (rwt 0)	1,792	8,079	0.222
Run 15 (rwt 0)	3,602	11,570	0.311	(rwt 1)	1,550	8,020	0.193
(rwt 1)	1,784	9,398	0.190	Run 41 (rwt 0)	1,707	8,267	0.207
(rwt 2)	2,540	9,990	0.254	(rwt 1)	1,612	8,180	0.197
(rwt 3)	3,552	10,528	0.337	Run 45 (rwt 0)	2,958	10,443	0.283
(rwt 4)	2,594	10,554	0.246	(rwt 1)	2,273	10,235	0.222
Run 16 (rwt 0)	3,525	11,264	0.313	(rwt 2)	1,285	9,080	0.142
(rwt 1)	1,858	9,892	0.188	(rwt 3)	1,851	8,732	0.212
(rwt 2)	3,544	10,750	0.330	(rwt 4)	1,905	9,833	0.194
(rwt 3)	2,387	9,358	0.255	Run 46 (rwt 0)	2,964	11,487	0.258
(rwt 4)	3,689	11,087	0.333	(rwt 1)	3,119	10,113	0.308
Run 18 (rwt 0)	2,283	8,696	0.263	(rwt 2)	2,632	9,336	0.282
(rwt 1)	3,052	10,525	0.290	(rwt 3)	1,648	9,888	0.167
(rwt 2)	1,511	9,026	0.167	(rwt 4)	2,764	9,461	0.292
(rwt 3)	3,863	11,059	0.349				
(rwt 4)	4,921	12,553	0.392				
Run 23 (rwt 0)	3,128	10,236	0.306				
(rwt 1)	2,418	10,532	0.230				
(rwt 2)	51,754	63,661	0.813				
(rwt 3)	3,311	11,308	0.293				
(rwt 4)	20,347	29,989	0.678				

E.7.1 MCMC RESULTS FOR RUN 41-1

We also tried removing all the age data (Run 41-1). All parameters were fixed to the means of their priors, except for:

1. the unfished equilibrium recruitment (R_0) and survey catchabilities whose priors were kept at those in Tables E.1 and E.2;
2. recruitment deviations which were all set to zero;
3. age of full selectivity for females was set to 18 for the hook-and-line commercial catch and IPHC survey, which is closer to the values suggested by model runs (e.g. Run 45-4, Table E.1).

We present some MCMC results from this model run.

For Run 41-1 that we just described, we ran two MCMC chains (Chain A and Chain B), both starting from the MPD values. 25,000,000 iterations were performed, sampling every 25,000th to give 1,000 samples, which were used with no burn-in period (because the MCMC searches started from the MPD values). The difference between the two MCMC chains is that Chain B started from a different seed for the random number generator and used a rescaled step size to give a higher acceptance rate for the MCMC algorithm. For a well-behaved model, these differences should not materially affect the results.

For Chain A, Figure E.24 shows that the MCMC algorithm has still not fully converged. The cumulative 97.5 quantiles for R_0 gradually drift higher, and do not settle down as they would under satisfactory convergence. Figure E.25 shows that the distribution of R_0 is shifted much higher for the final third of the chain compared to the first two thirds. Such behaviour means that the results are not credible, although, as shown in Figure 5, there is a huge range in the estimated vulnerable biomass.

For Chain B, which under convergence would give the same results as a well-converged Chain A, Figures E.26-E.28 also show poor convergence. As an example of the consequences of such poor convergence, note the differing estimates of the 97.5 percentiles of vulnerable biomass in 1940 between the two chains.

Thus, neither Chain A or Chain B converge and they give different results. These MCMC results are therefore not credible, and cannot be used to form the basis of advice to management.

Finally, we also tried allowing the model to estimate recruitment deviations (rather than setting them to zero), with everything else as for Run 41-1, but the MCMC behaviour was also unsatisfactory.

For the maximum sustainable yield (MSY) calculations reported as examples in the main text, based on Run 41-1, the model was projected forward across a range of constant harvest rates, apportioned to each fishery in the same proportion as for the last year of data, until equilibrium was reached. The MSY for each fishery is the largest of the equilibrium yields, with an associated exploitation rate and spawning biomass. This calculation was done for each of the 1,000 MCMC samples.

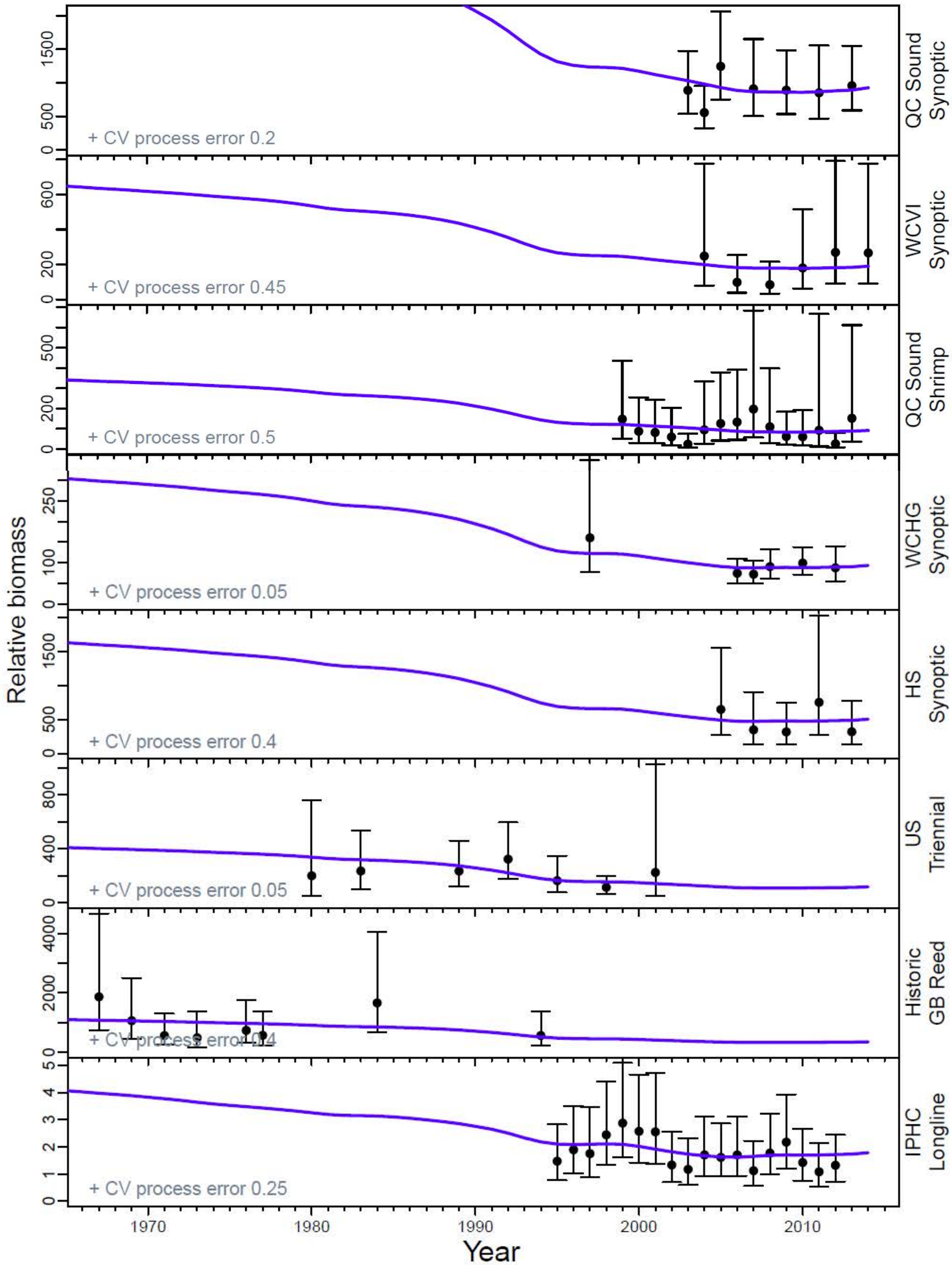


Figure E.1. Survey index values (points) with 95% confidence intervals (bars) and MPD model fits (curves) for the fishery-independent survey series for Run 45-4. Under various configurations the model could fit the survey data similarly to the fit shown here.

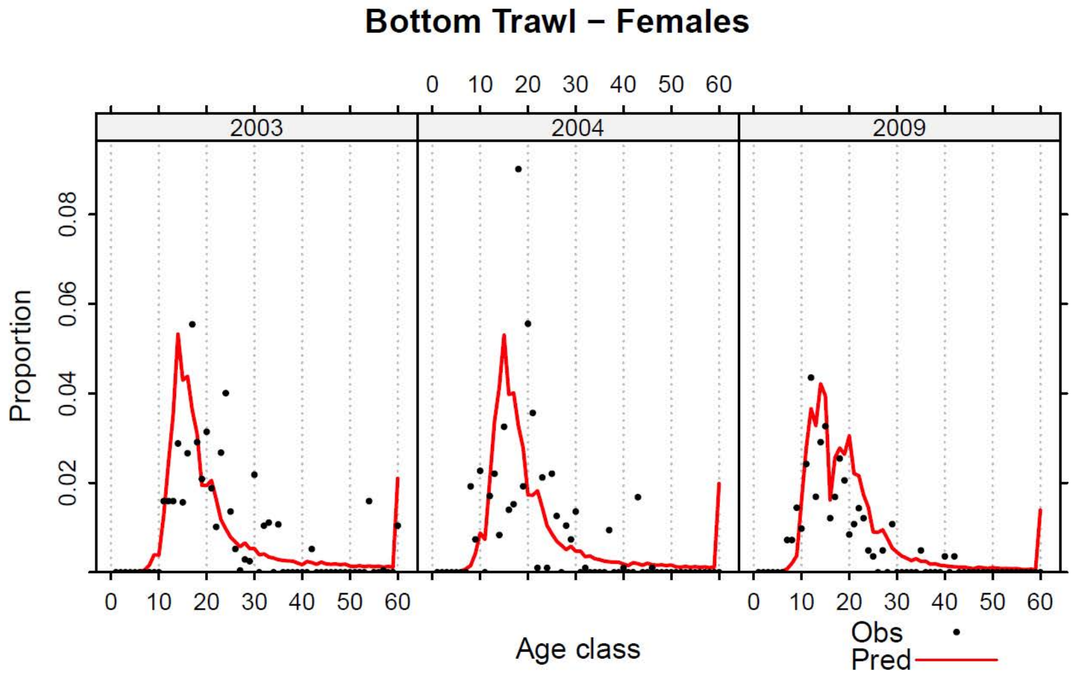


Figure E.2. Observed and predicted commercial (bottom trawl) proportions-at-age for females for Run 45-4. Note that years are not consecutive.

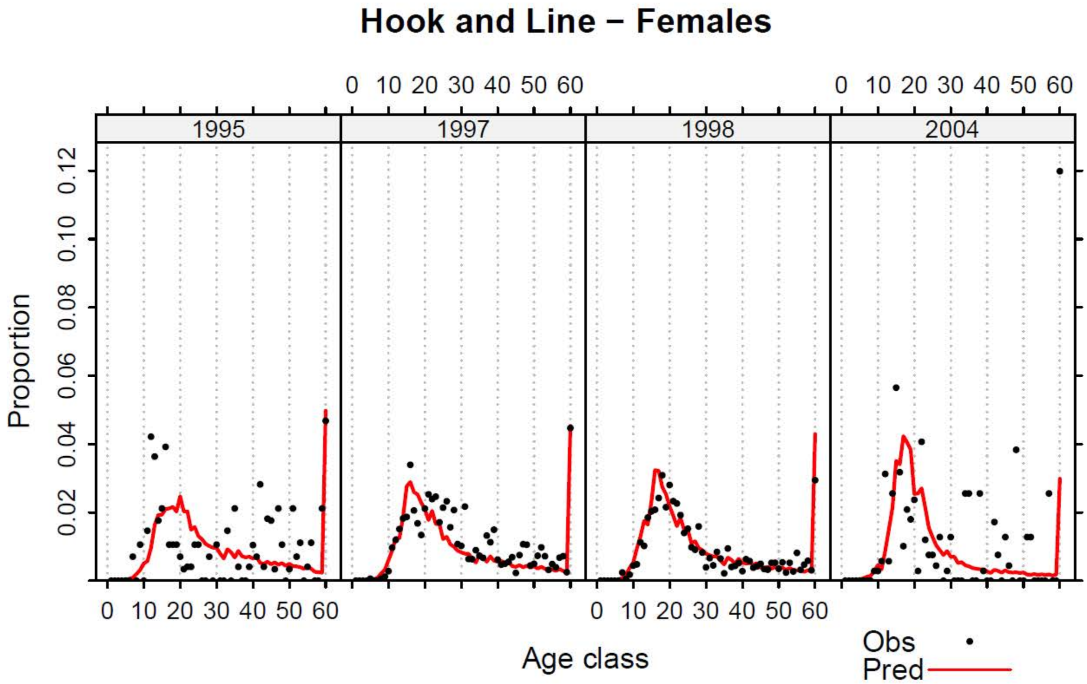


Figure E.3. Observed and predicted commercial (hook and line) proportions-at-age for females for Run 45-4. Note that years are not consecutive.

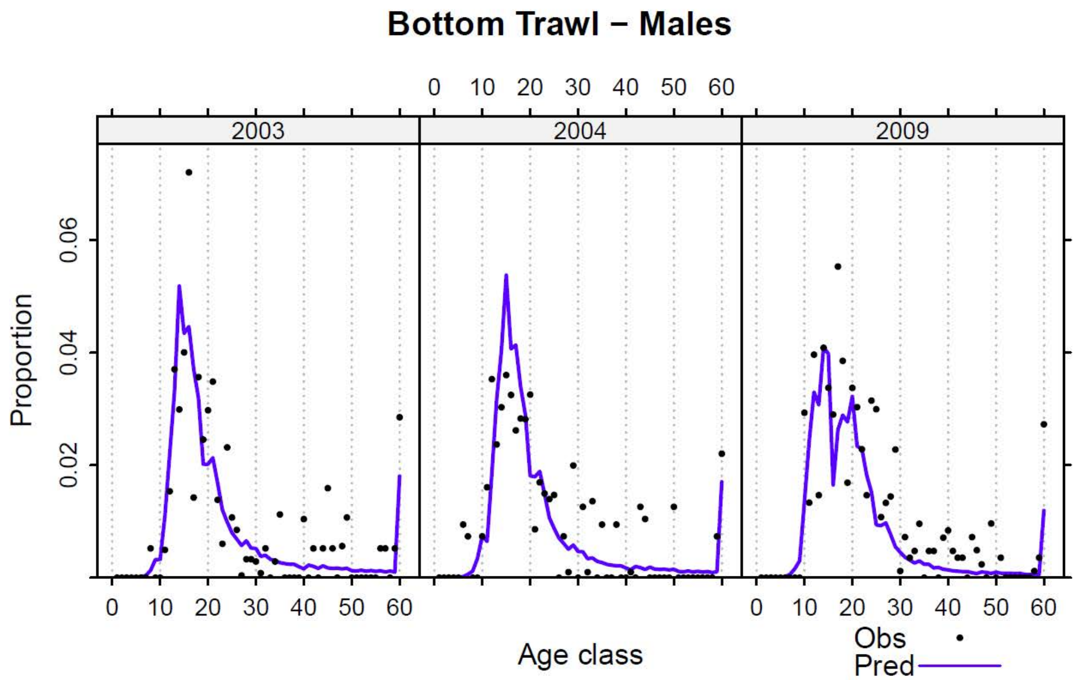


Figure E.4. Observed and predicted commercial (bottom trawl) proportions-at-age for males for Run 45-4. Note that years are not consecutive.

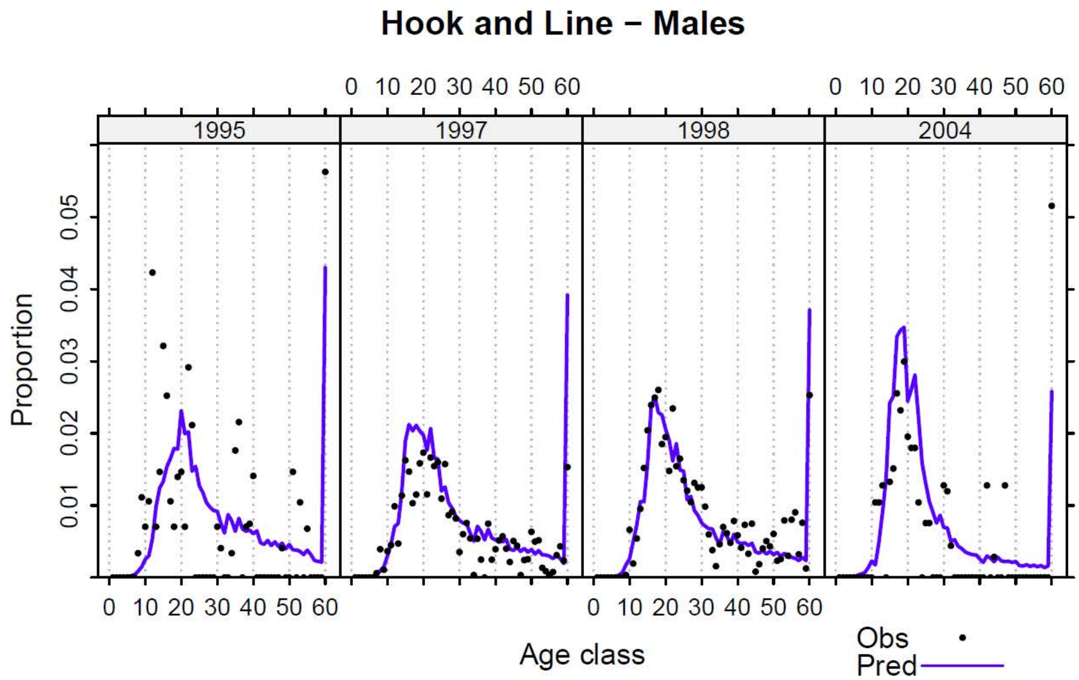


Figure E.5. Observed and predicted commercial (hook and line) proportions-at-age for males for Run 45-4. Note that years are not consecutive.

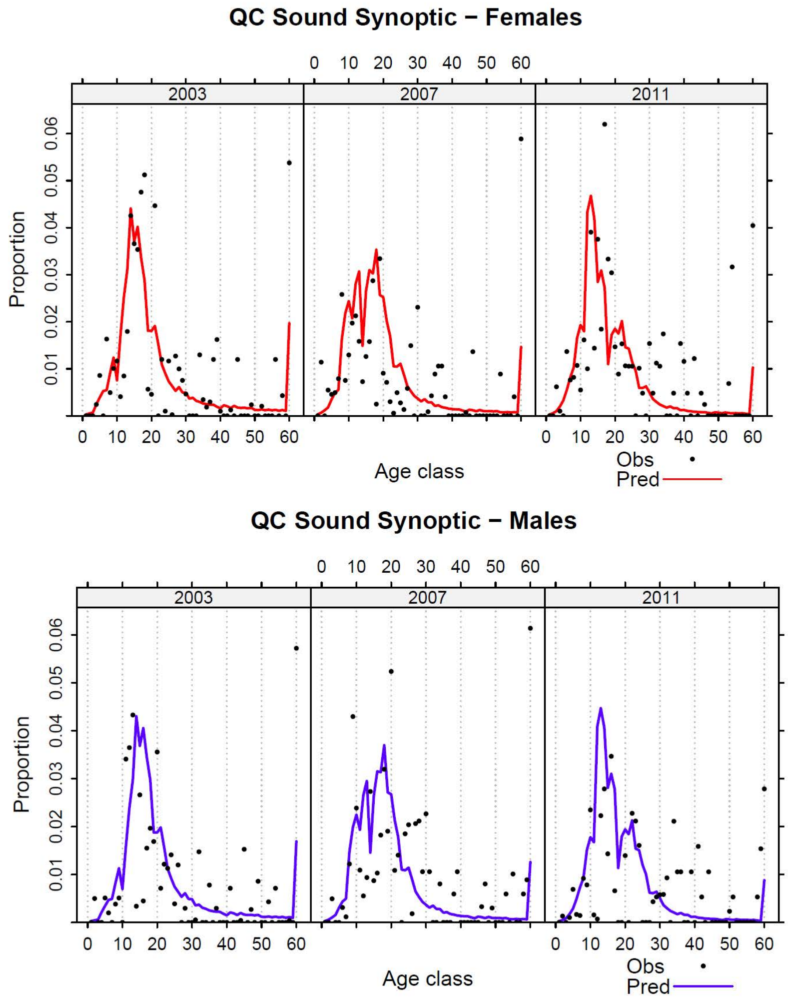
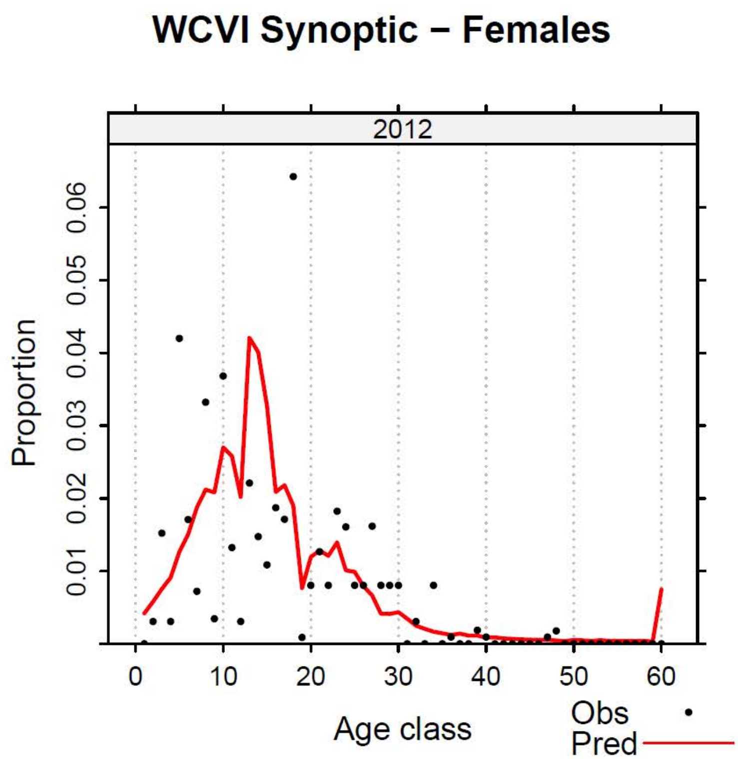


Figure E.6. Observed and predicted proportions-at-age for QC Sound Synoptic survey for Run 45-4.



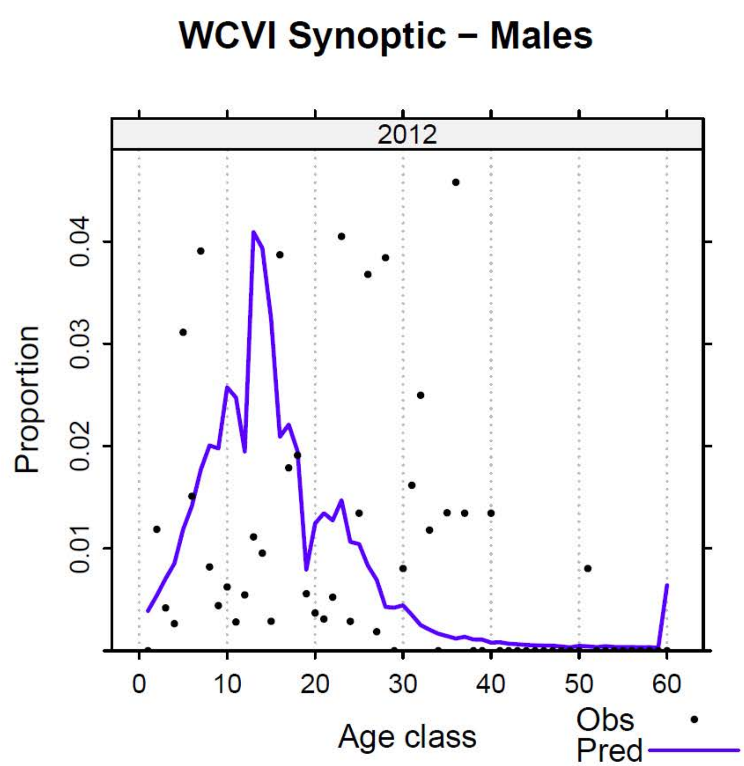


Figure E.7. Observed and predicted proportions-at-age for WCVI Synoptic survey for Run 45-4.

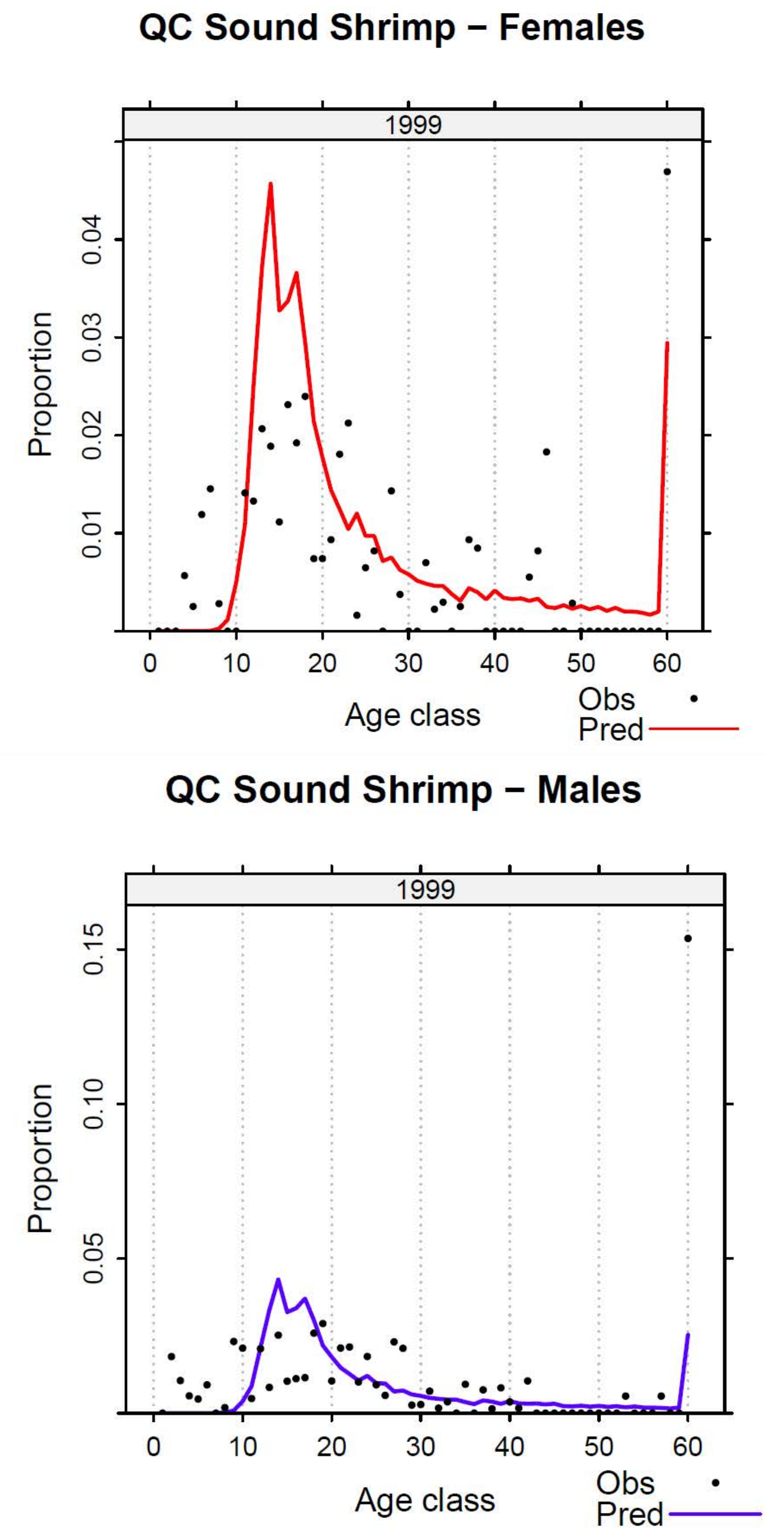


Figure E.8. Observed and predicted proportions-at-age for QC Sound Shrimp survey for Run 45-4.

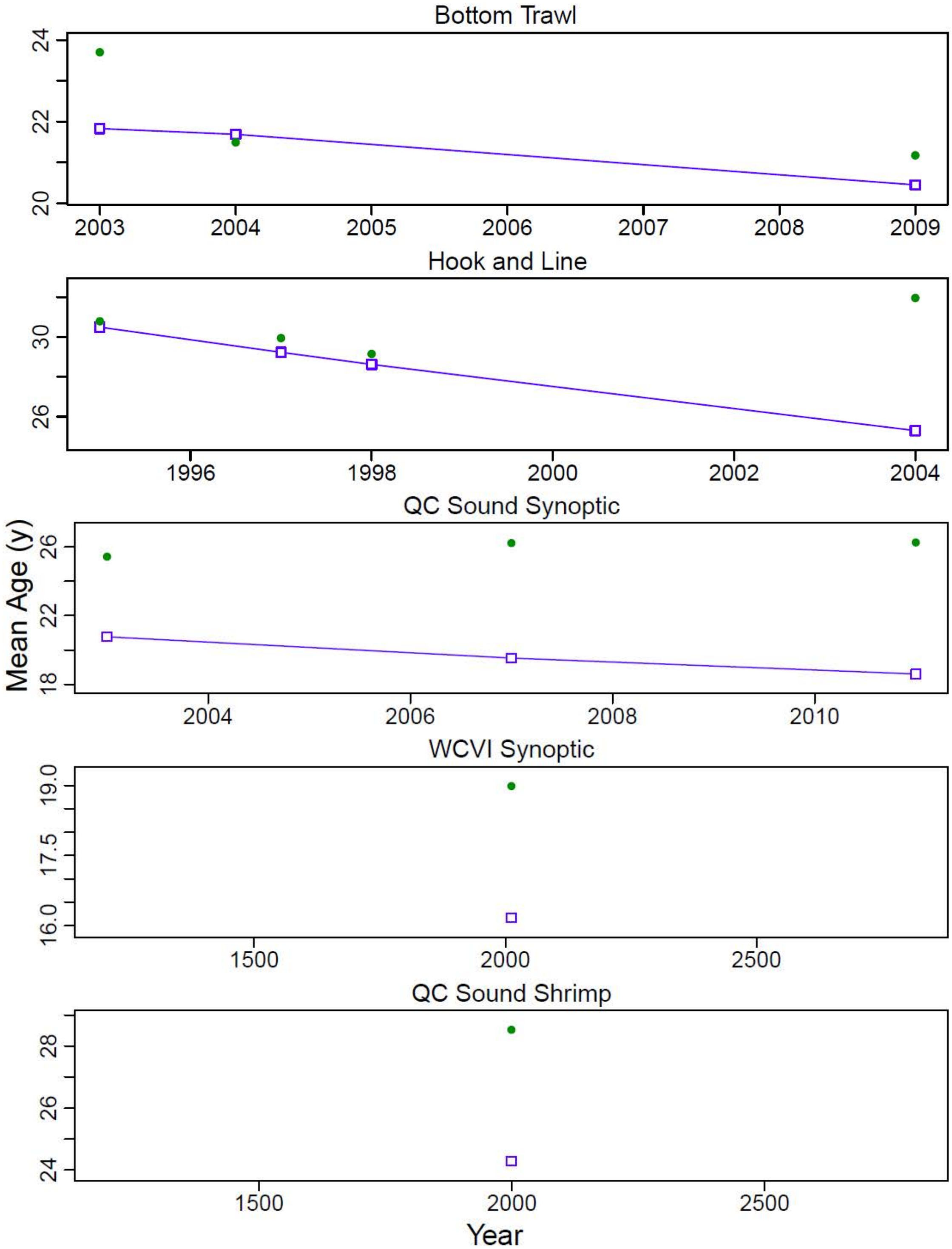


Figure E.9. Mean ages each year for the data (solid circles) and model estimates (joined open squares) for the commercial and survey age data for Run 45-4.

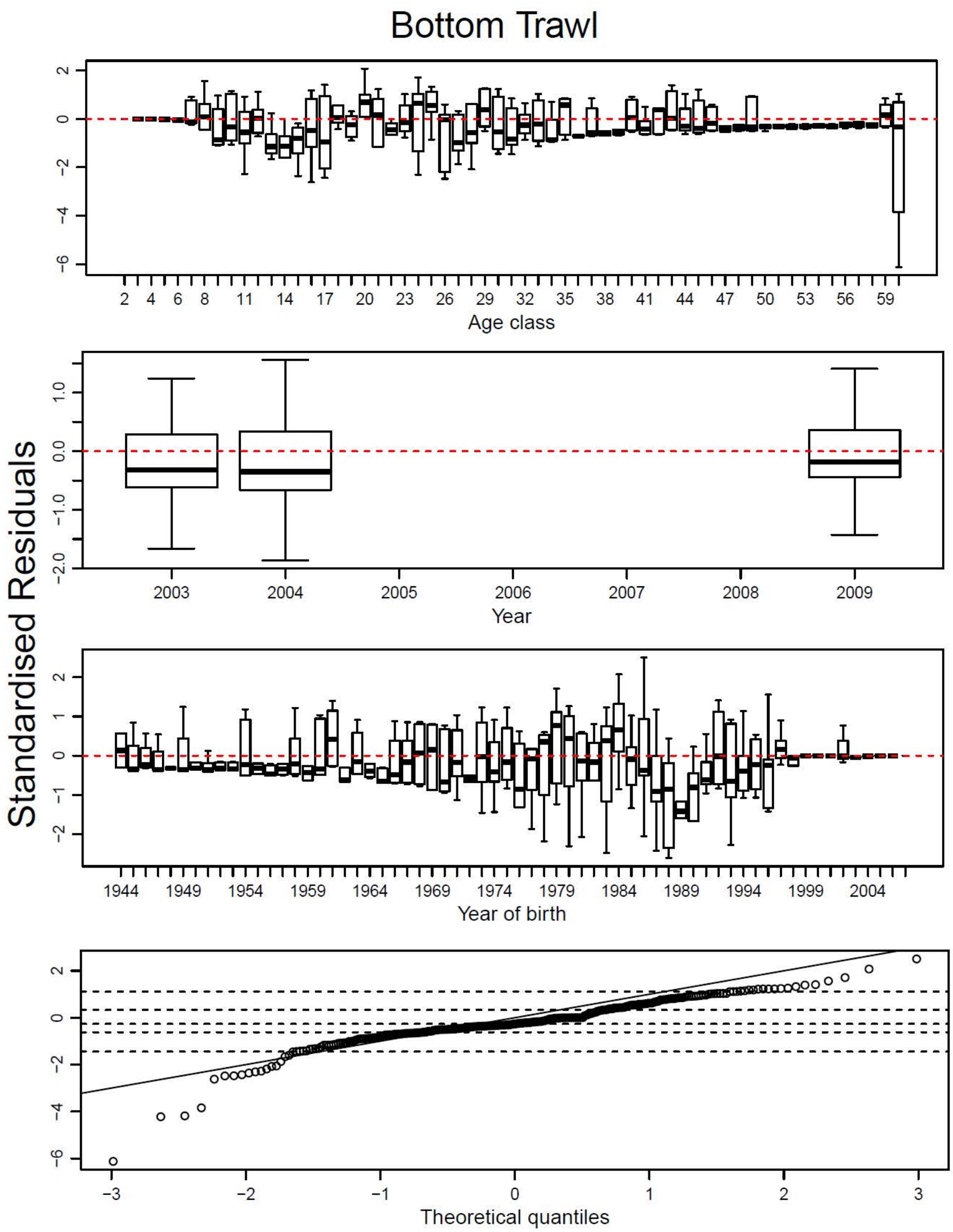


Figure E.10. Residual of fits of model to commercial proportions-at-age data (MPD values) for Bottom Trawl events for Run 45-4. Vertical axes are standardised residuals. Boxplots show, respectively, residuals by age class, by year of data, and by year of birth (following a cohort through time). Boxes give interquartile ranges, with bold lines representing medians and whiskers extending to the most extreme data point that is <1.5 times the interquartile range from the box. Bottom panel is the normal quantile-quantile plot for residuals, with the 1:1 line, though residuals are not expected to be normally distributed because of the likelihood function used; horizontal lines give the 5, 25, 50, 75, and 95 percentiles (for a total of 354 residuals).

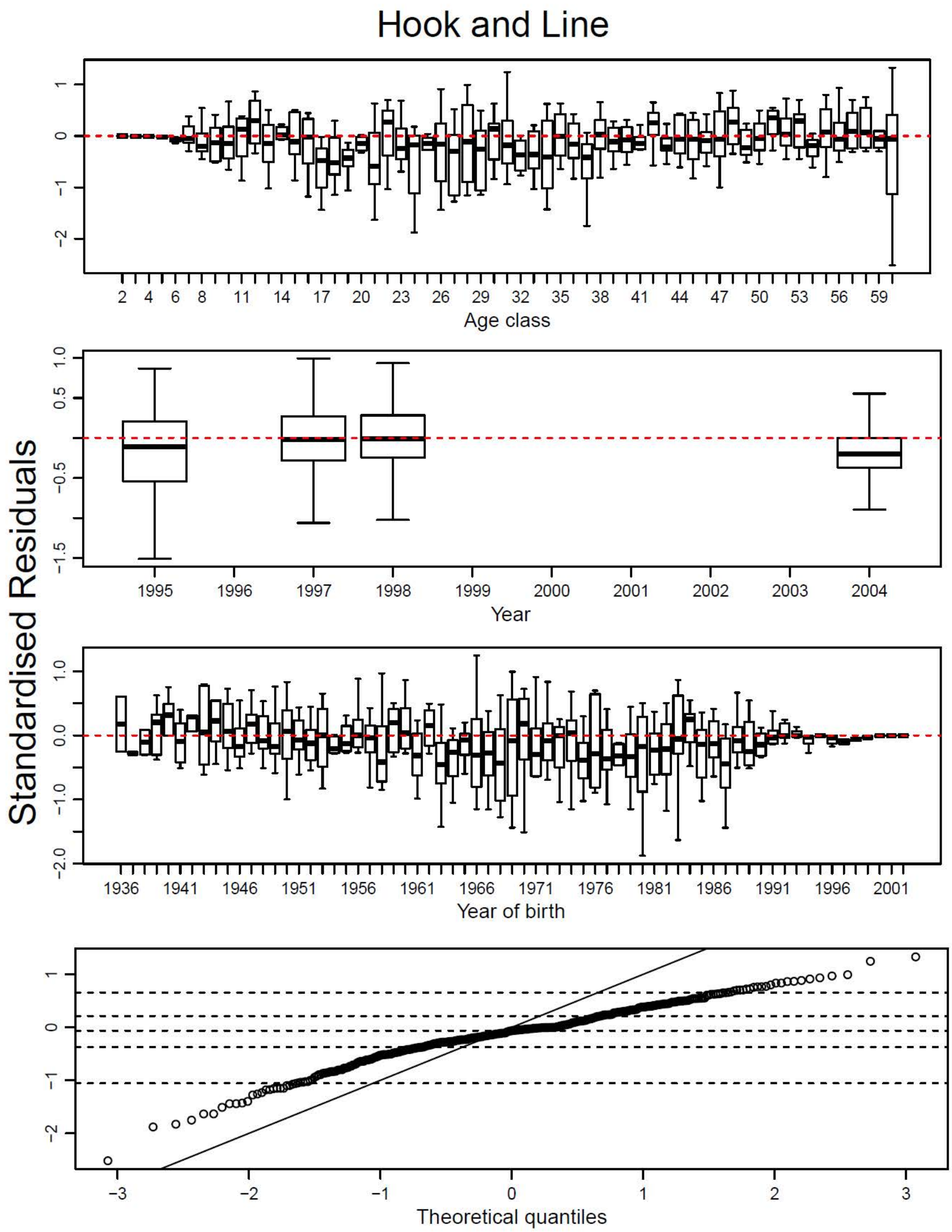


Figure E.11. Residual of fits of model to commercial proportions-at-age data (MPD values) for Hook and Line events for Run 45-4. Details as for Figure E.10, for a total of 472 residuals.

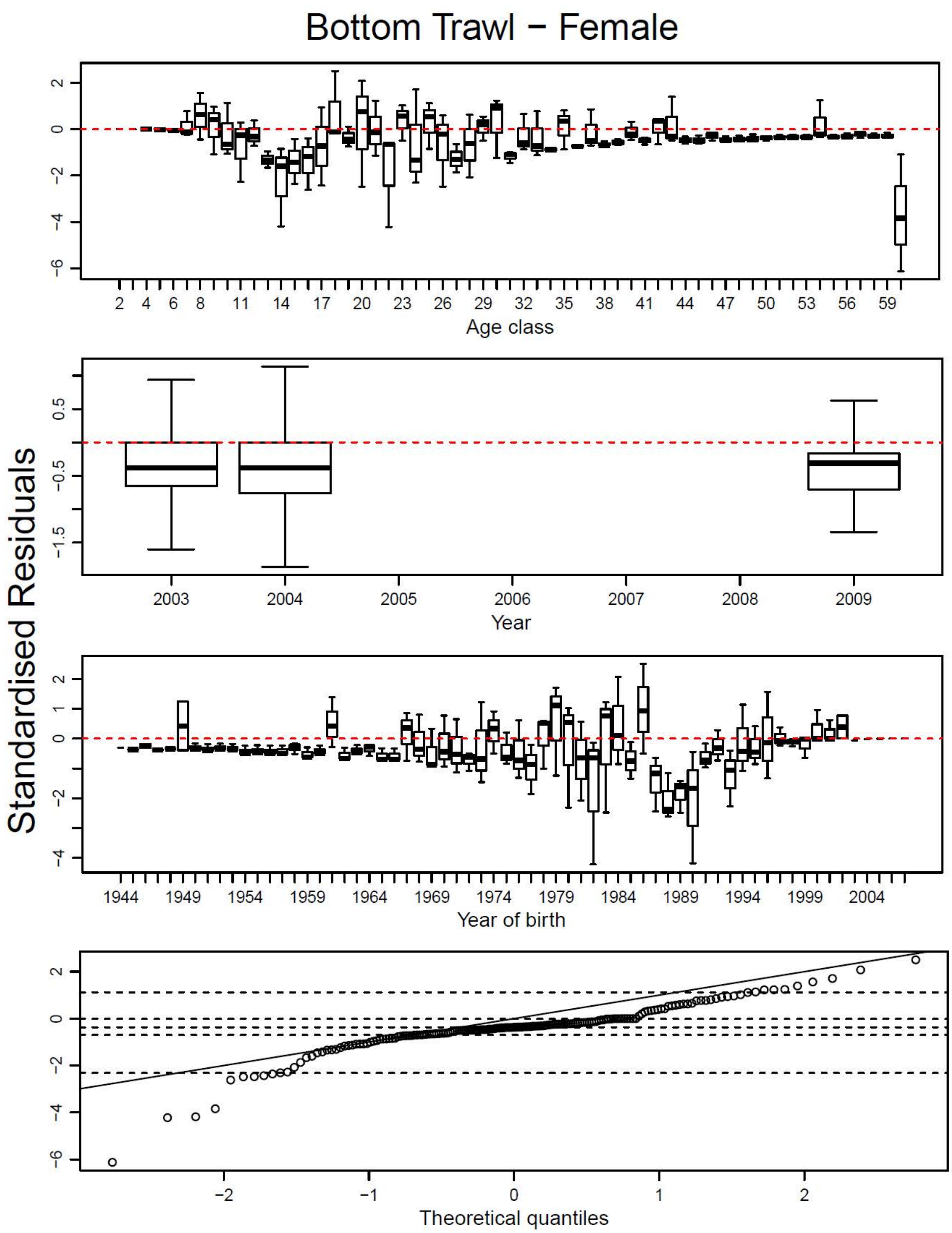


Figure E.12. Residual of fits of model to commercial proportions-at-age data (MPD values) for females (Bottom Trawl) for Run 45-4. Details as for Figure E.10, for a total of 177 residuals.

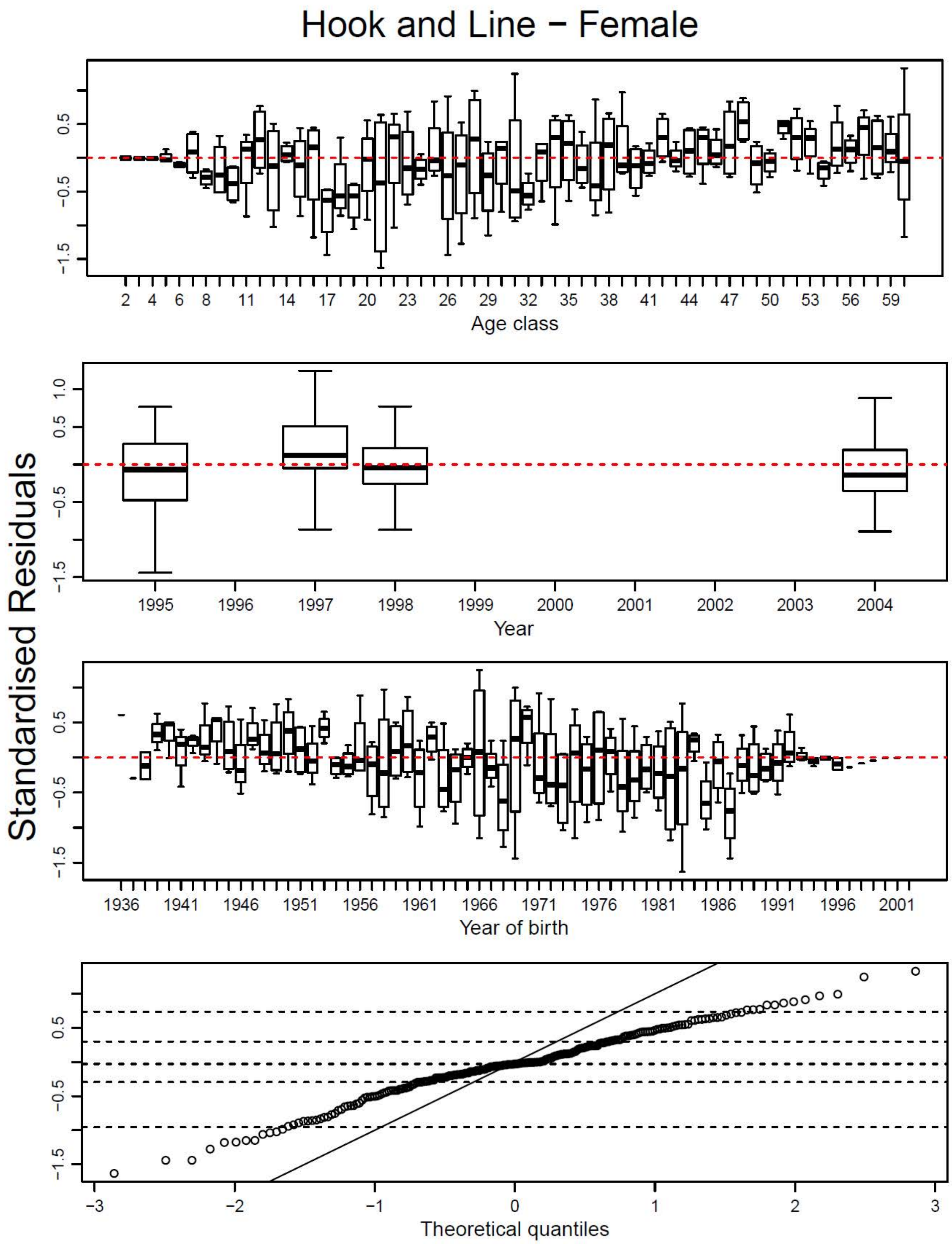


Figure E.13. Residual of fits of model to commercial proportions-at-age data (MPD values) for females (Hook and Line) for Run 45-4. Details as for Figure E.10, for a total of 236 residuals.

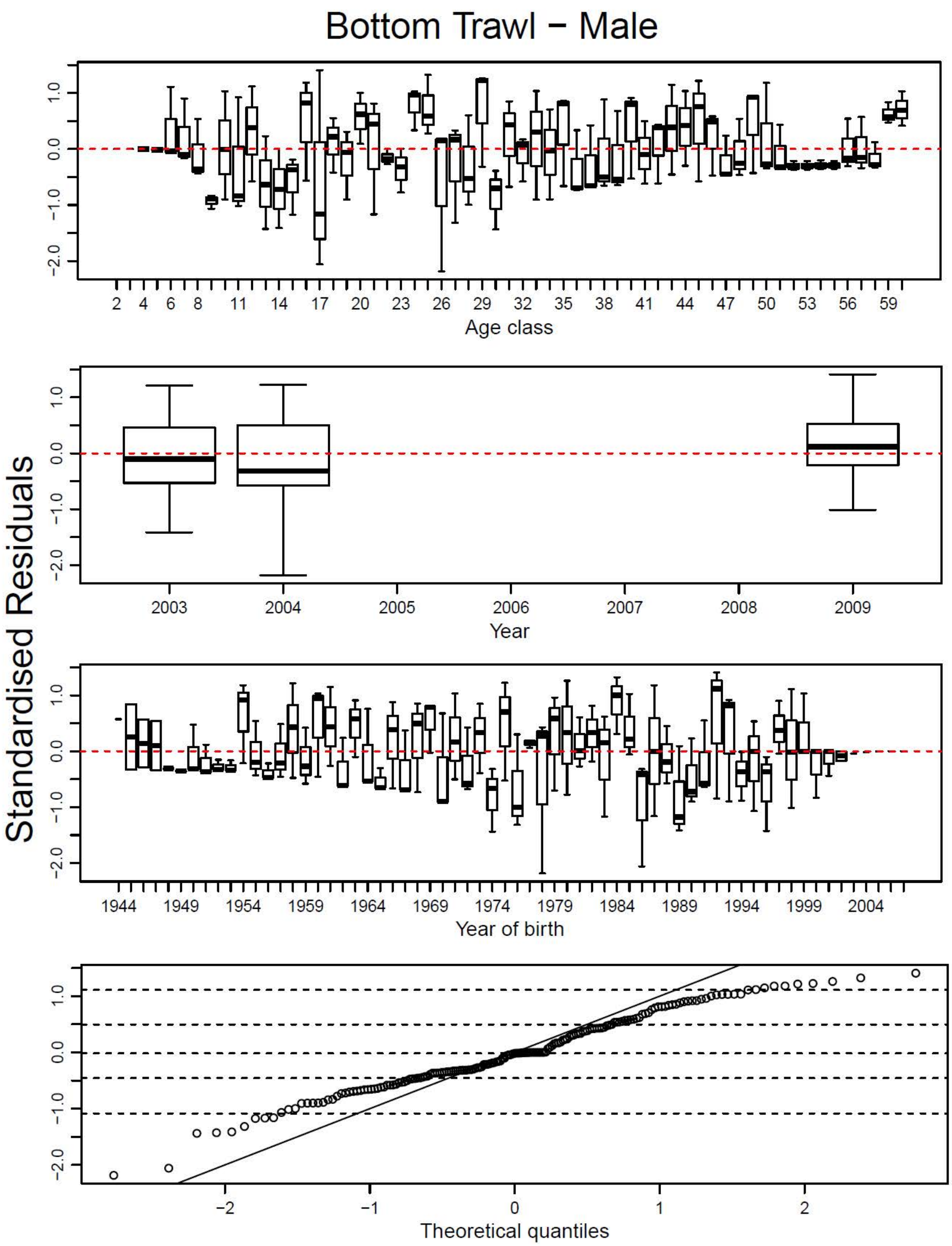


Figure E.14. Residual of fits of model to commercial proportions-at-age data (MPD values) for males (Bottom Trawl) for Run 45-4. Details as for Figure E.10, for a total of 177 residuals.

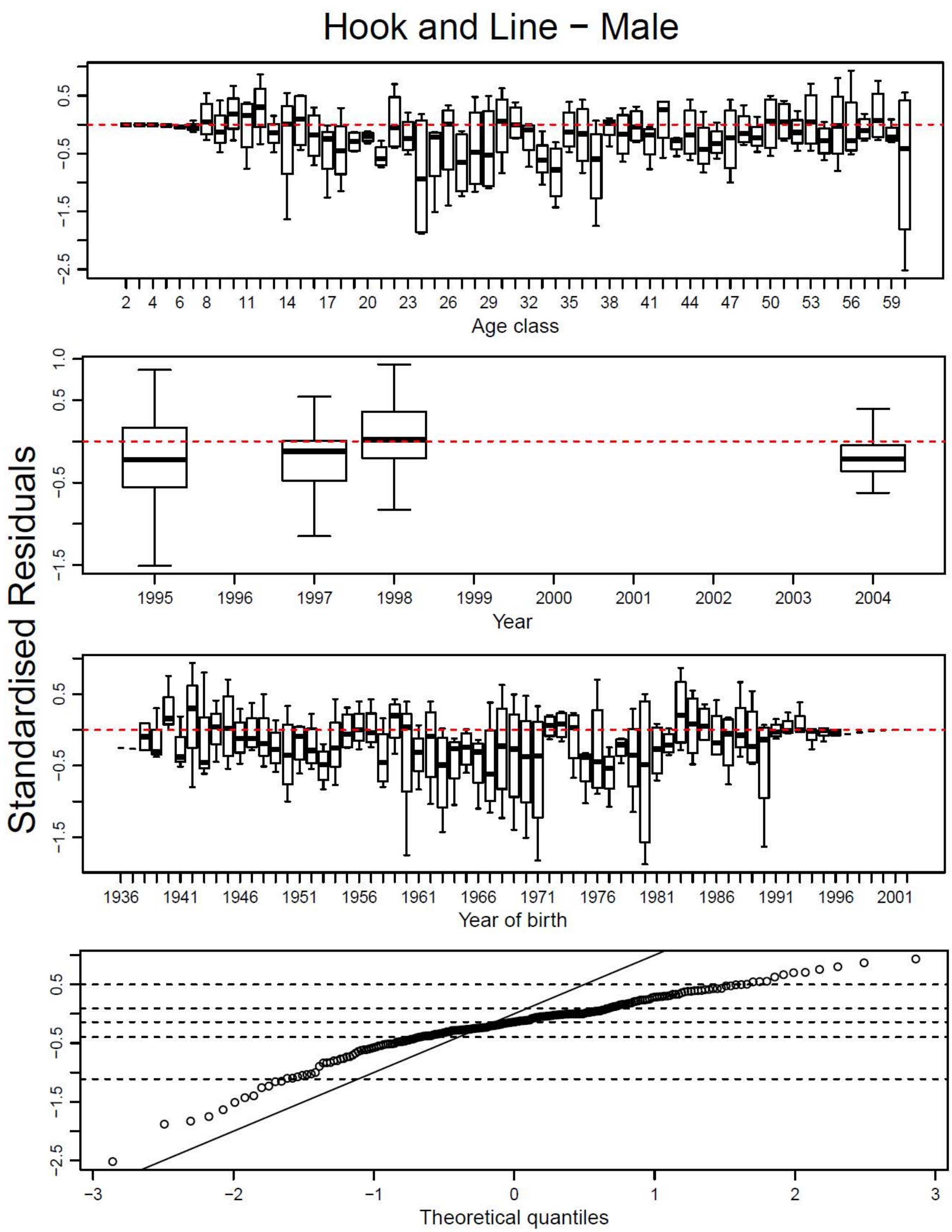


Figure E.15. Residual of fits of model to commercial proportions-at-age data (MPD values) for males (Hook and Line) for Run 45-4. Details as for Figure E.10, for a total of 236 residuals.

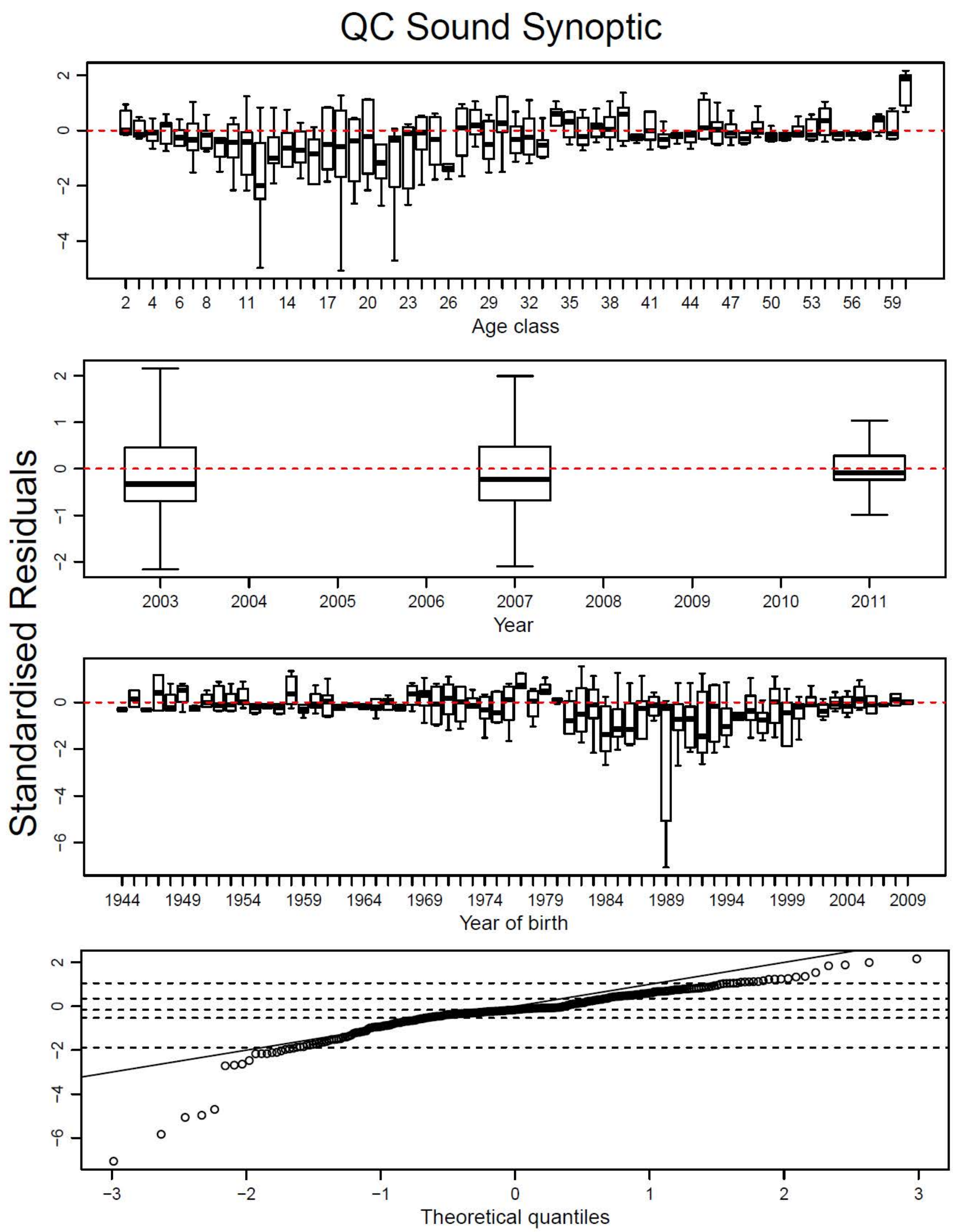


Figure E.16. Residuals of fits of model to proportions-at-age data (MPD values) from the QC Sound Synoptic survey series for Run 45-4. Details as for Figure E.10, for a total of 354 residuals.

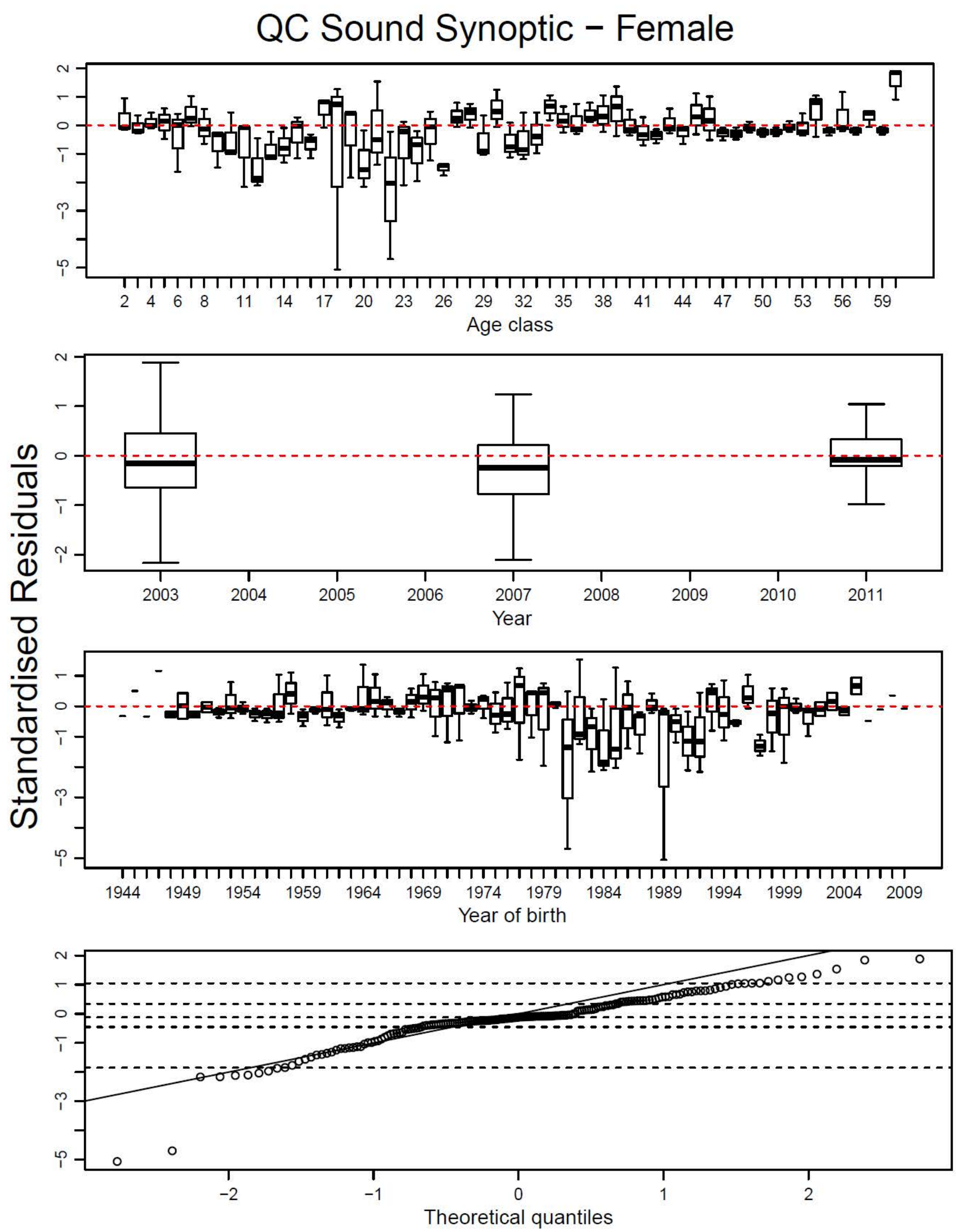


Figure E.17. Residuals of fits of model to proportions-at-age data (MPD values) for females from QC Sound Synoptic survey series for Run 45-4. Details as for Figure E.10, for a total of 177 residuals.

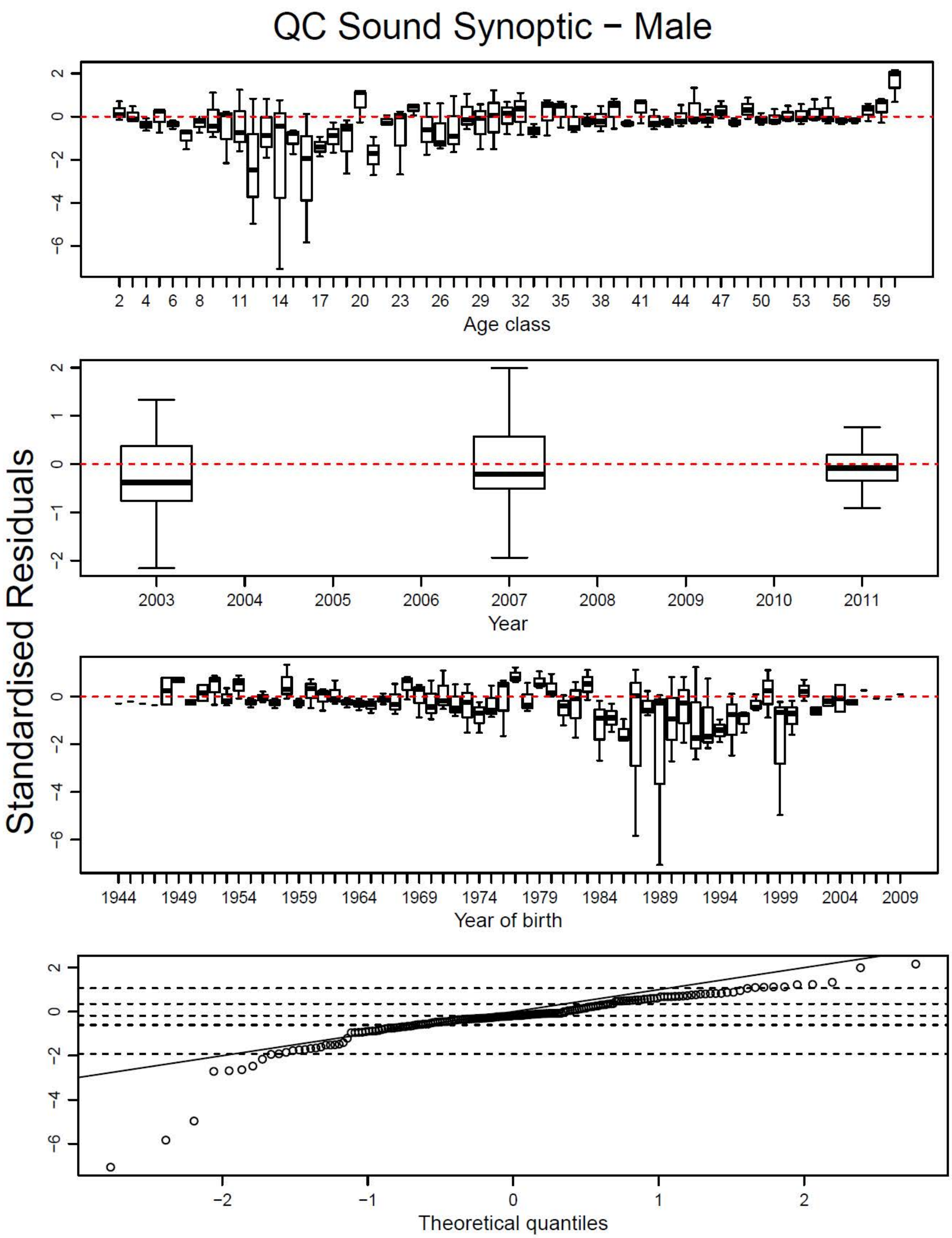


Figure E.18. Residuals of fits of model to proportions-at-age data (MPD values) for males from QC Sound Synoptic survey series for Run 45-4. Details as for Figure E.10, for a total of 177 residuals.

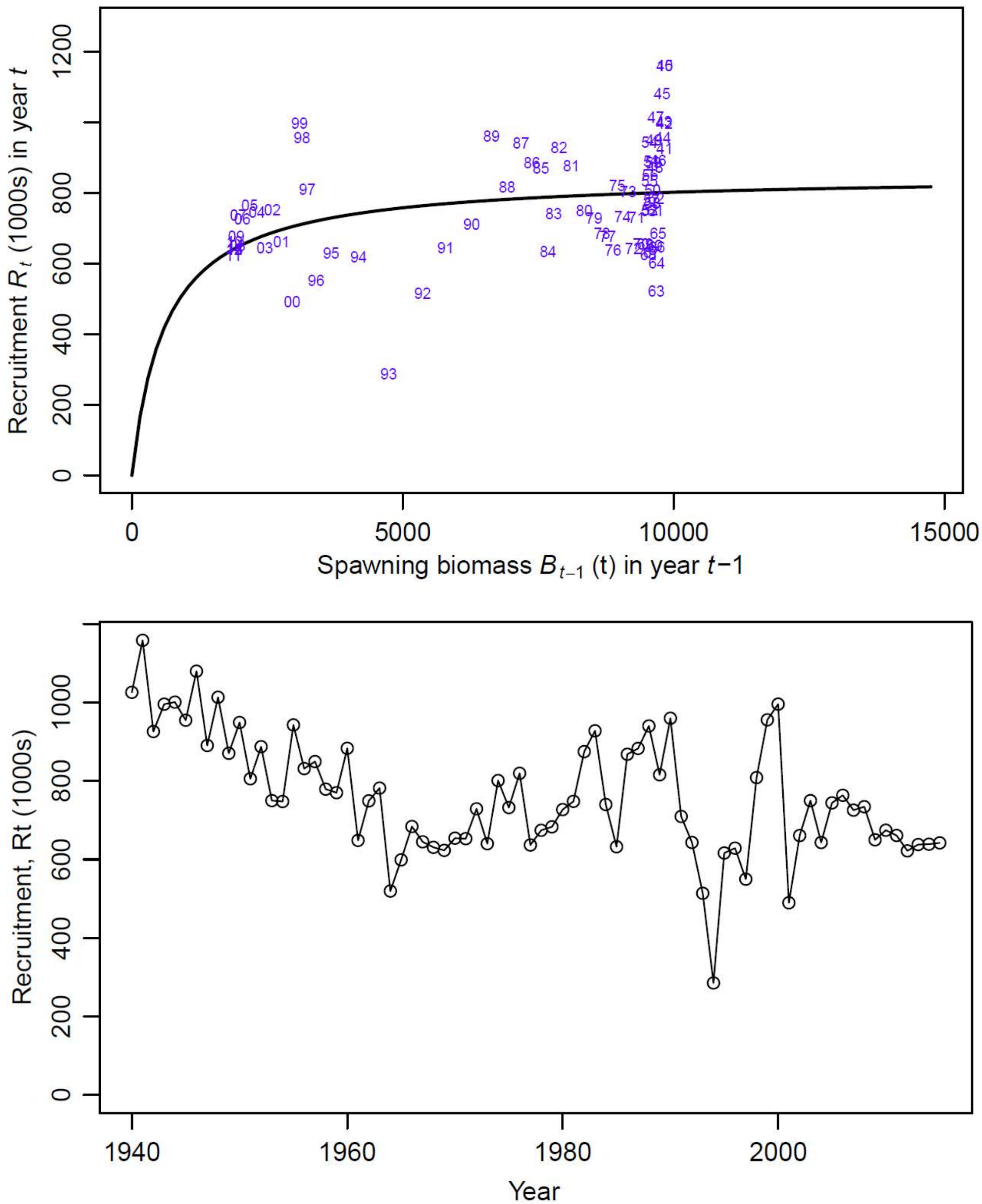


Figure E.19. Top: For Run 45-4, the deterministic stock-recruit relationship (black curve) and observed values (labelled by year of spawning) using MPD values. Bottom: Recruitment (MPD values of age-1 individuals in year t) over time, in 1,000s of age-1 individuals.

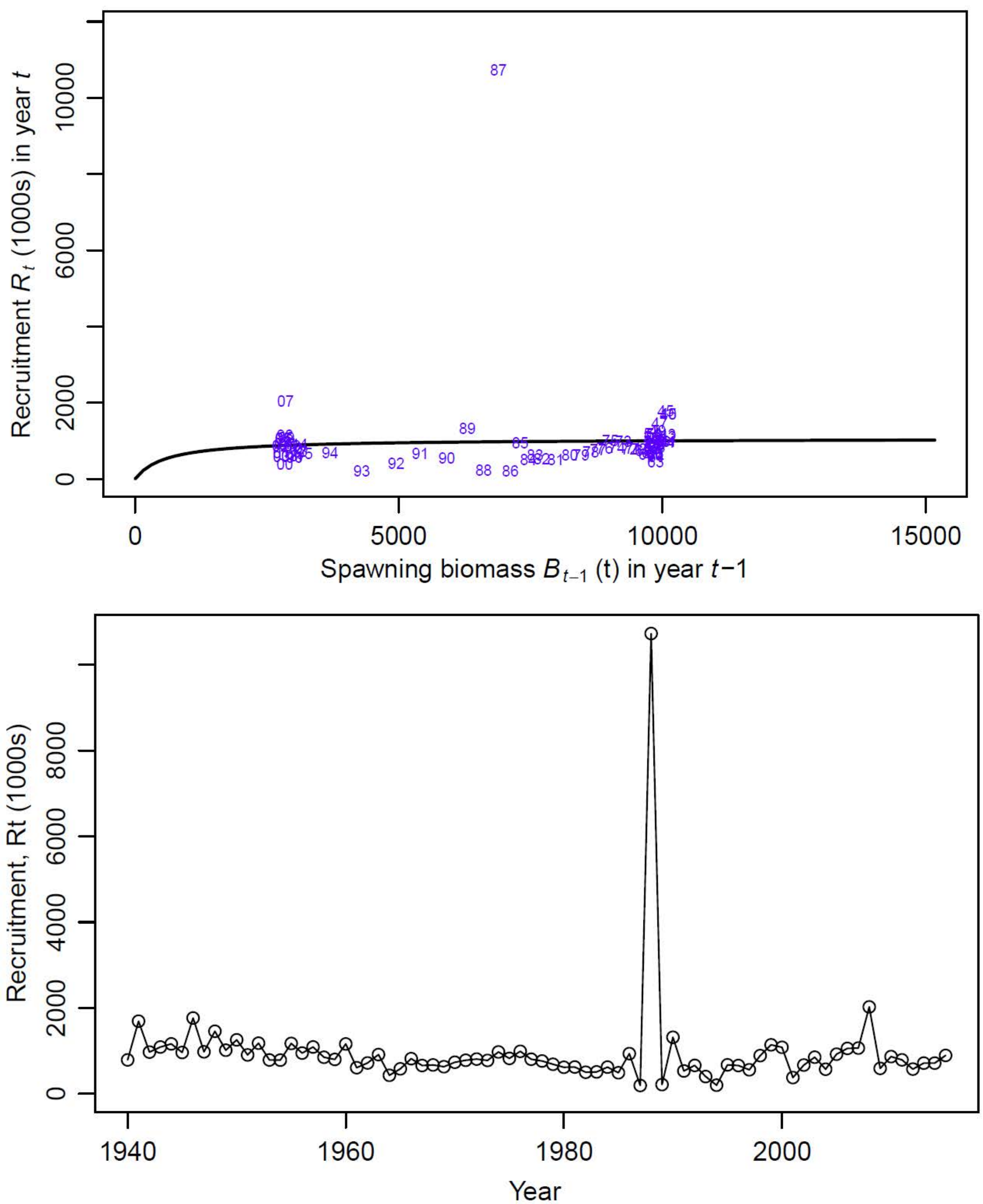


Figure E.20. Top: For Run 46-1, the deterministic stock-recruit relationship (black curve) and observed values (labelled by year of spawning) using MPD values. Bottom: Recruitment (MPD values of age-1 individuals in year t) over time, in 1,000s of age-1 individuals.

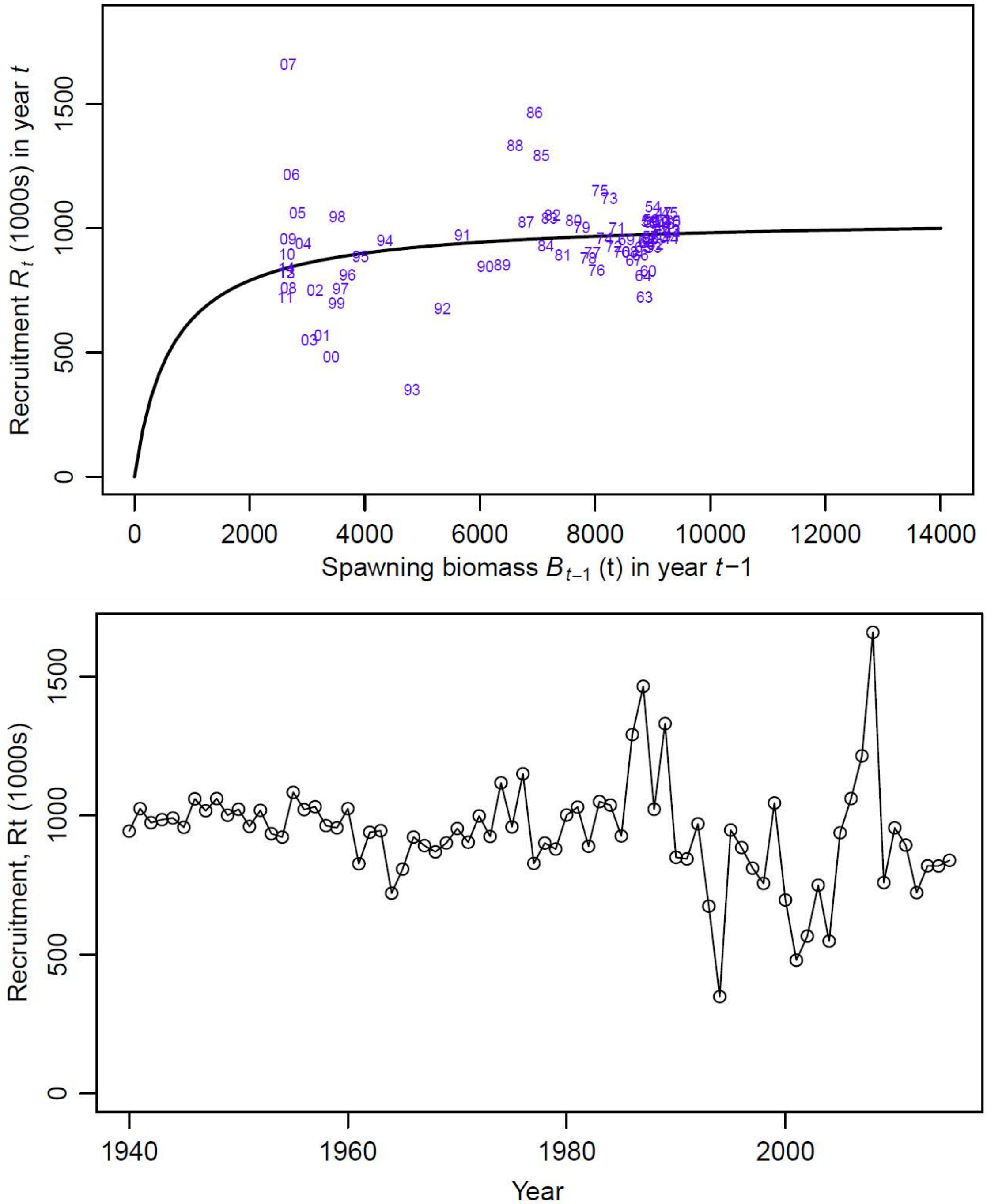


Figure E.21. Top: For Run 46-2, the deterministic stock-recruit relationship (black curve) and observed values (labelled by year of spawning) using MPD values. Bottom: Recruitment (MPD values of age-1 individuals in year t) over time, in 1,000s of age-1 individuals.

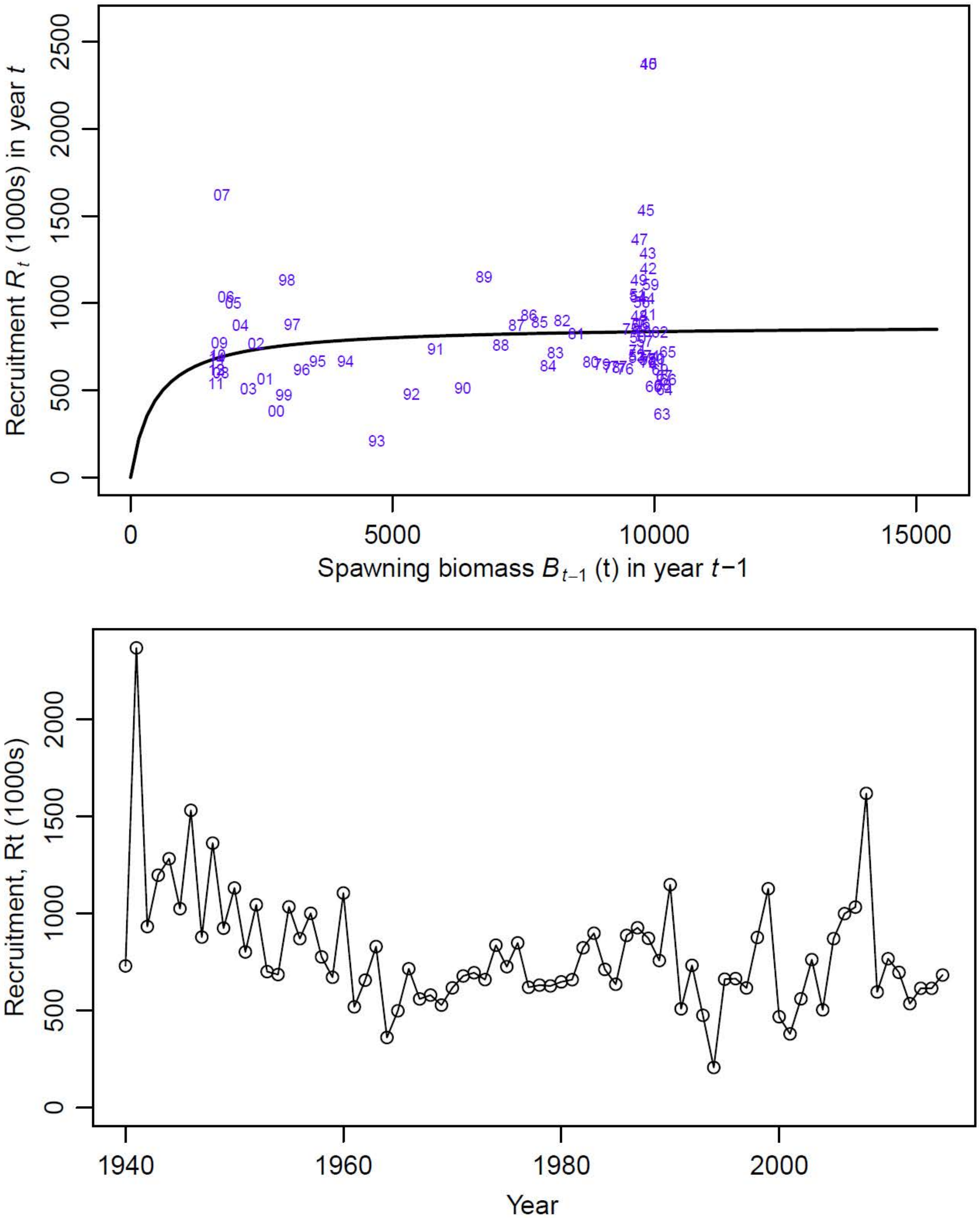
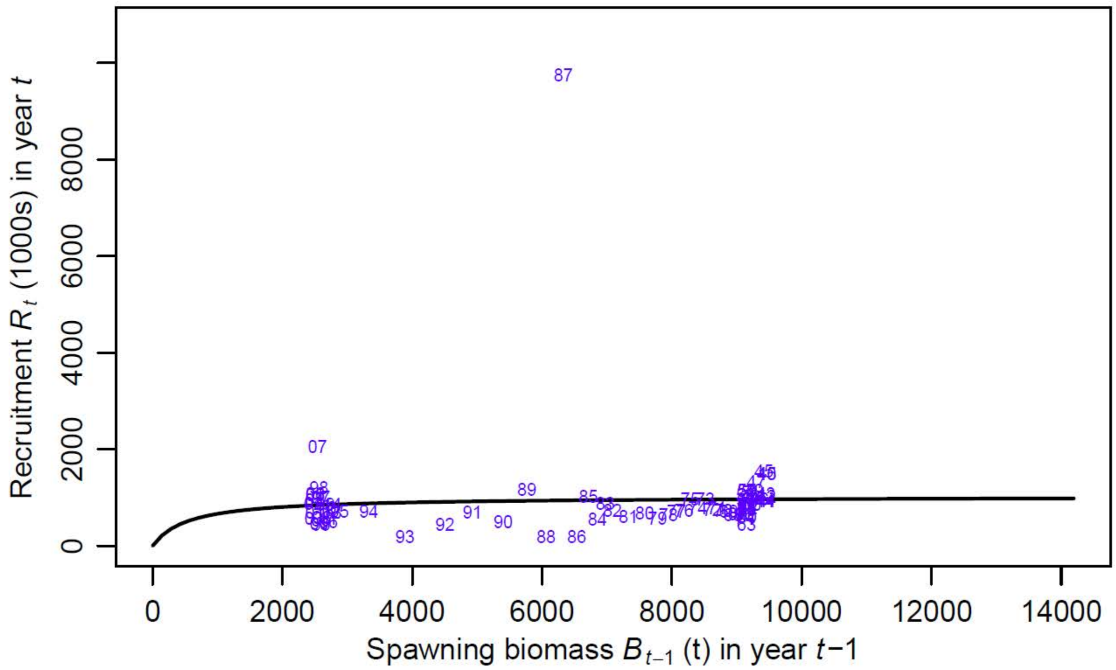


Figure E.22. Top: For Run 46-3, the deterministic stock-recruit relationship (black curve) and observed values (labelled by year of spawning) using MPD values. Bottom: Recruitment (MPD values of age-1 individuals in year t) over time, in 1,000s of age-1 individuals.



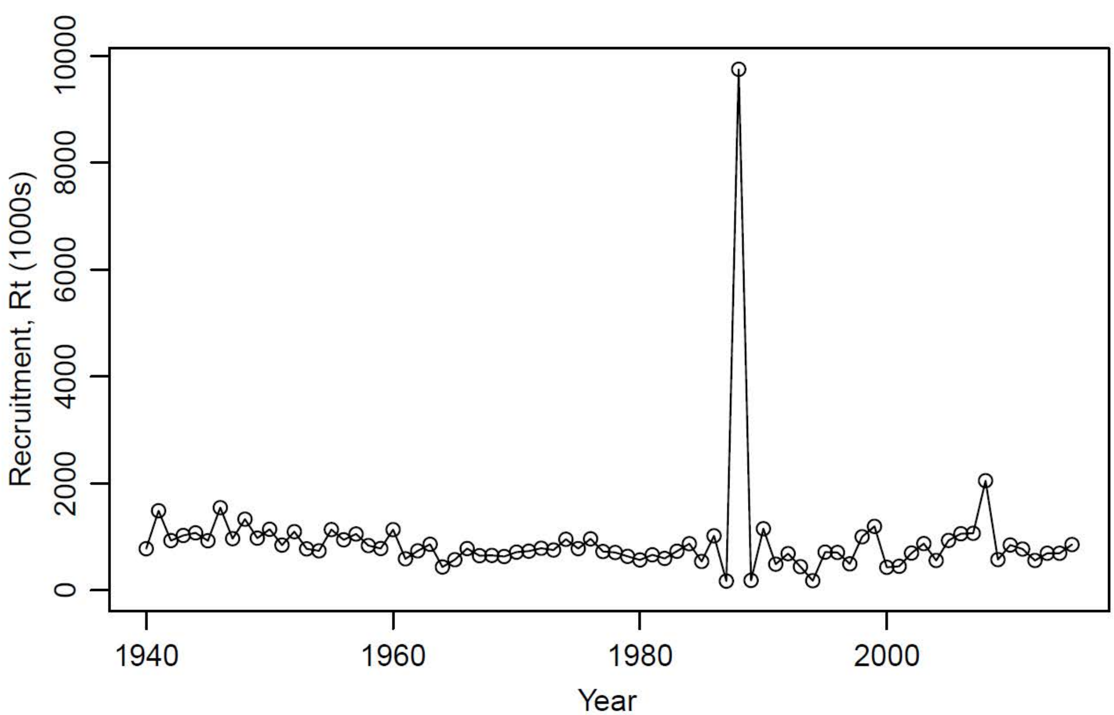


Figure E.23. Top: For Run 46-4, the deterministic stock-recruit relationship (black curve) and observed values (labelled by year of spawning) using MPD values. Bottom: Recruitment (MPD values of age-1 individuals in year t) over time, in 1,000s of age-1 individuals.

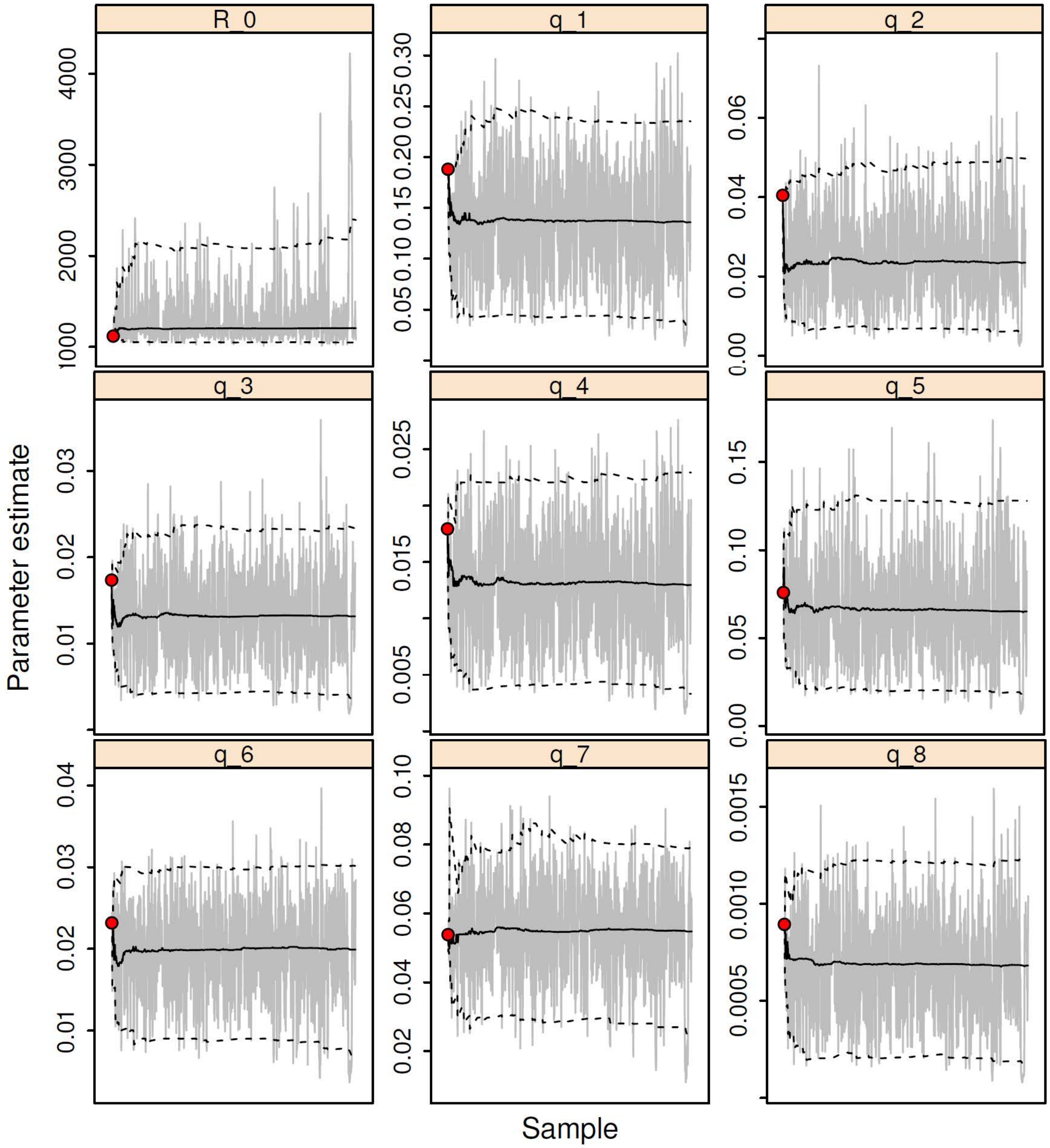


Figure E.24. For Chain A of Run 41-1, the MCMC traces for the estimated parameters are shown. Grey lines show the 1,000 samples for each parameter (thinned from the 25,000,000 samples run), solid lines show the cumulative median (up to that sample), and dashed lines show the cumulative 2.5 and 97.5 quantiles. Red circles are the MPD estimates. The only estimated parameters are the unfished equilibrium recruitment (R_0) and survey catchabilities ($q_1, q_2, ..., q_8$).

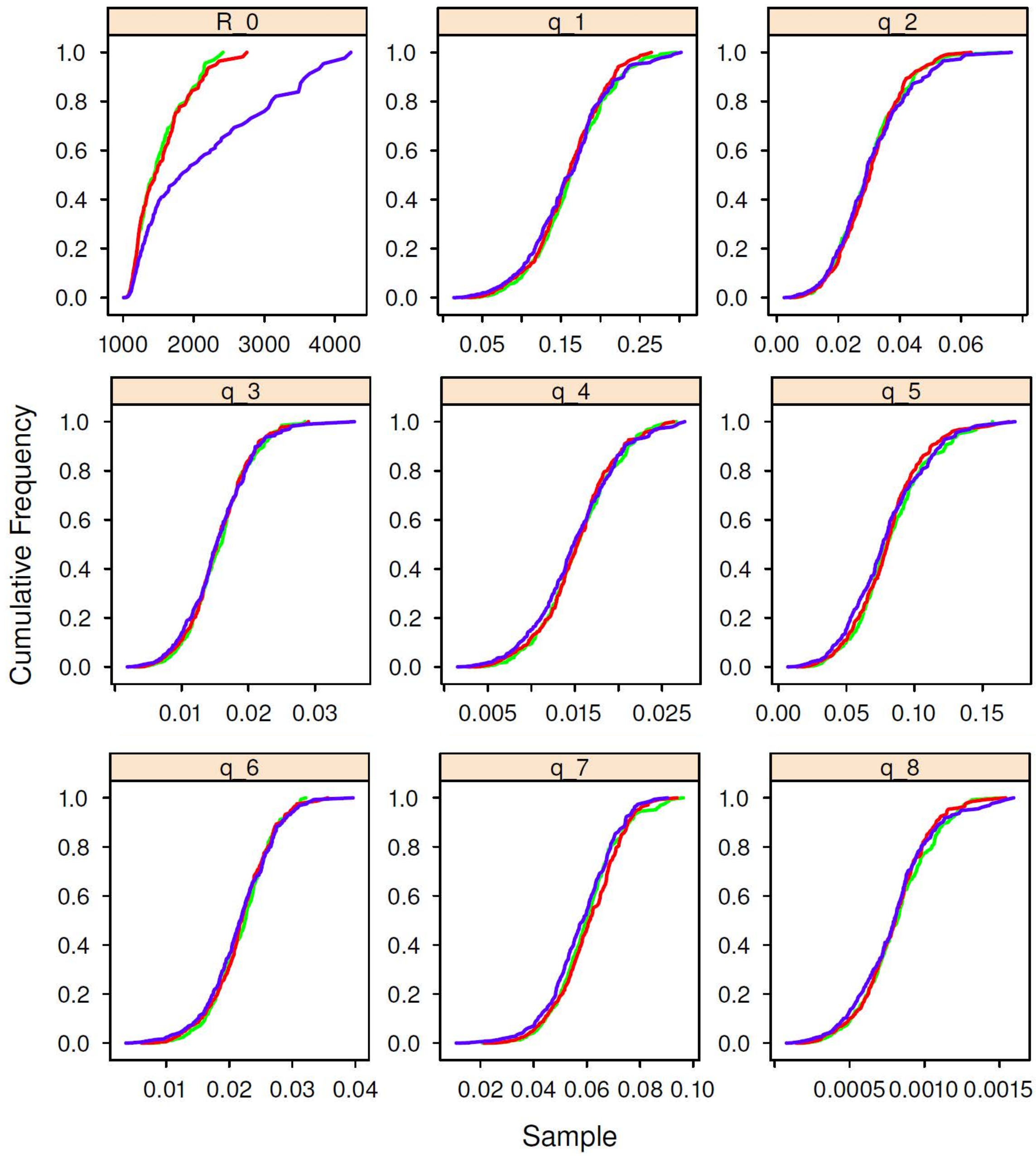


Figure E.25. For Chain A of Run 41-1, a diagnostic plot obtained by dividing the MCMC chain of 1,000 MCMC samples into three segments, and overplotting the cumulative distributions of the first segment (green), second segment (red) and final segment (blue).

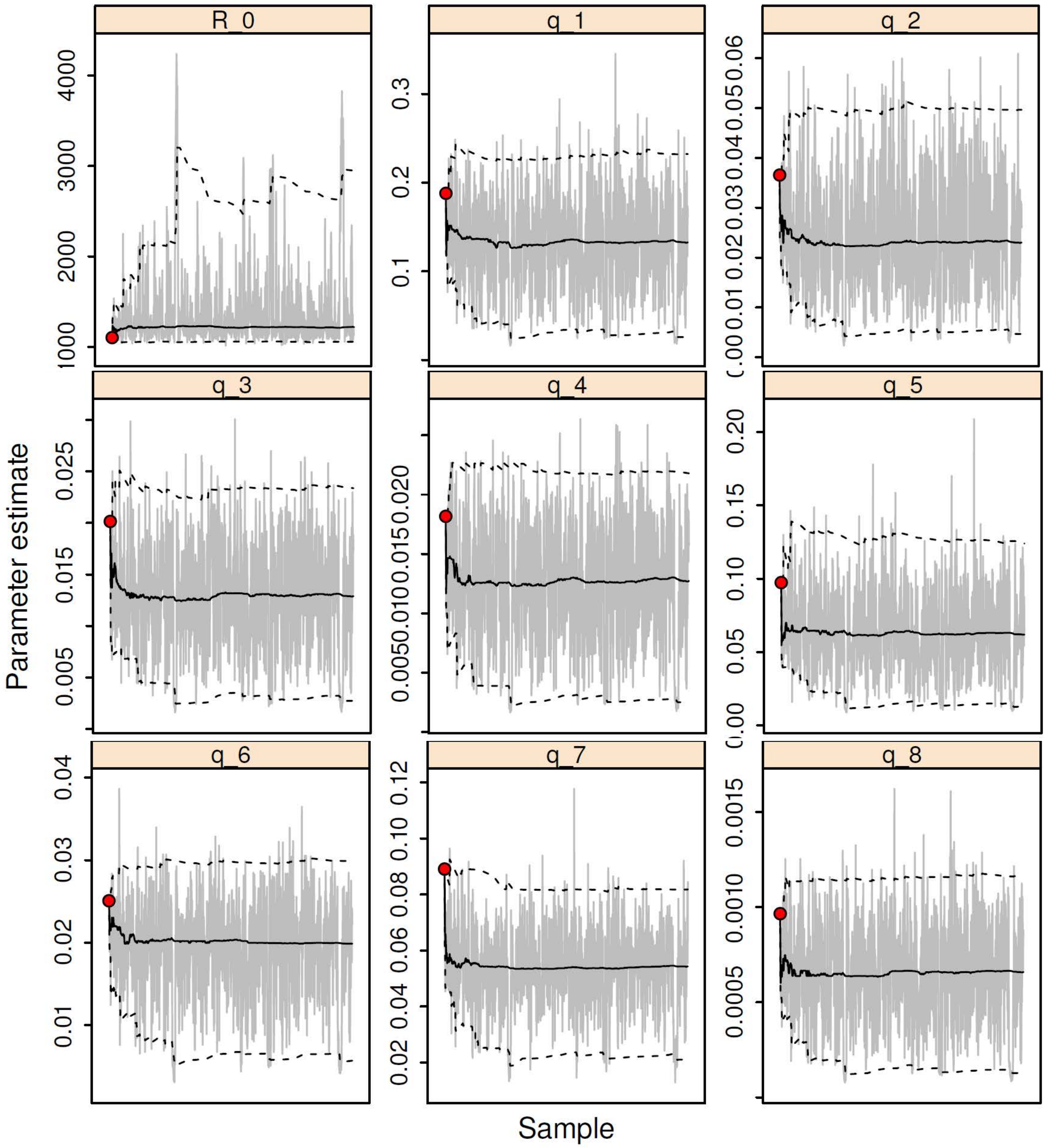


Figure E.26. For Chain B of Run 41-1, the MCMC traces for the estimated parameters are shown. Grey lines show the 1,000 samples for each parameter (thinned from the 25,000,000 samples run), solid lines show the cumulative median (up to that sample), and dashed lines show the cumulative 2.5 and 97.5 quantiles. Red circles are the MPD estimates. The only estimated parameters are the unfished equilibrium recruitment (R_0) and survey catchabilities ($q_1, q_2, ..., q_8$).

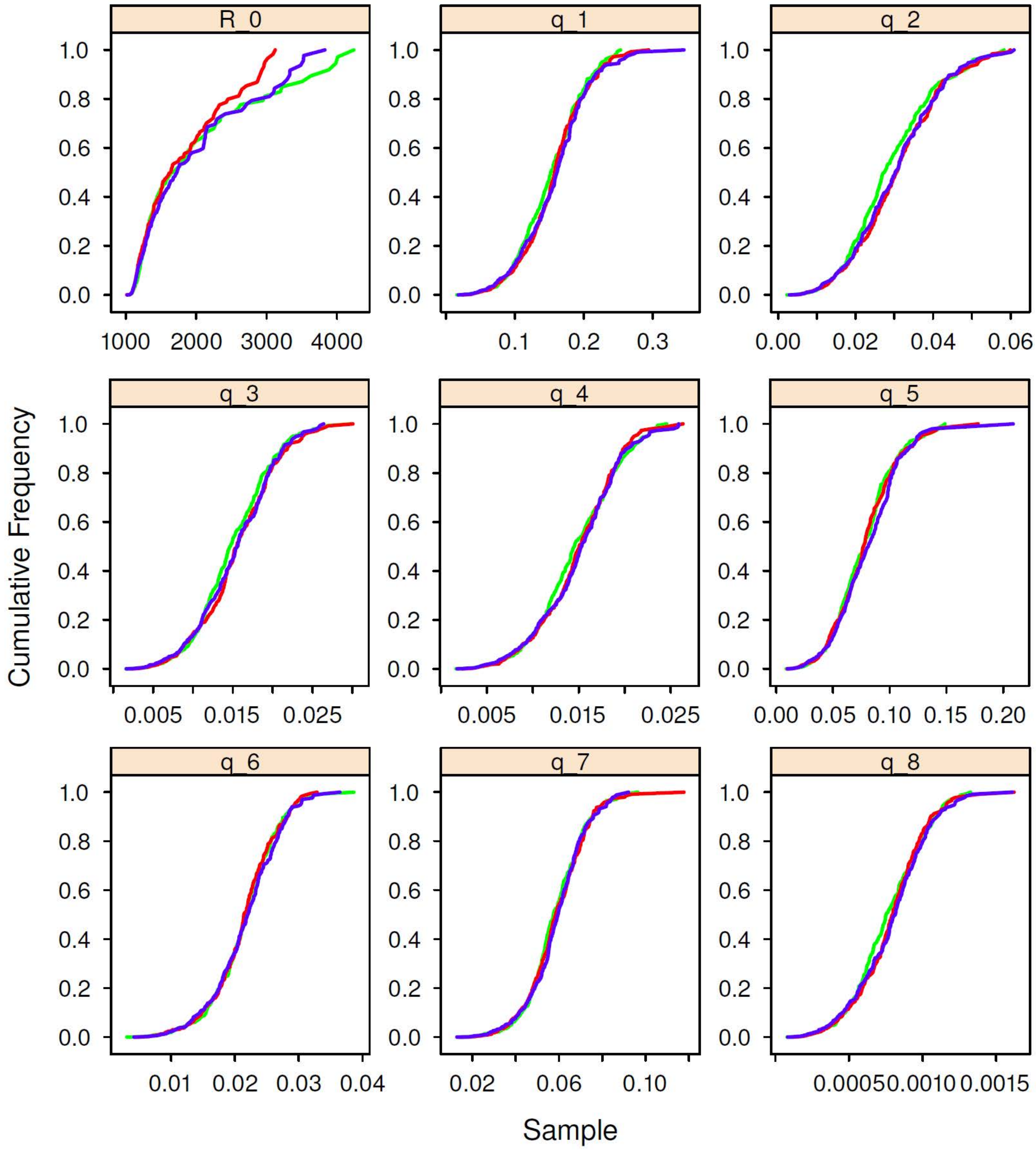


Figure E.27. For Chain B of Run 41-1, a diagnostic plot obtained by dividing the MCMC chain of 1,000 MCMC samples into three segments, and overplotting the cumulative distributions of the first segment (green), second segment (red) and final segment (blue).

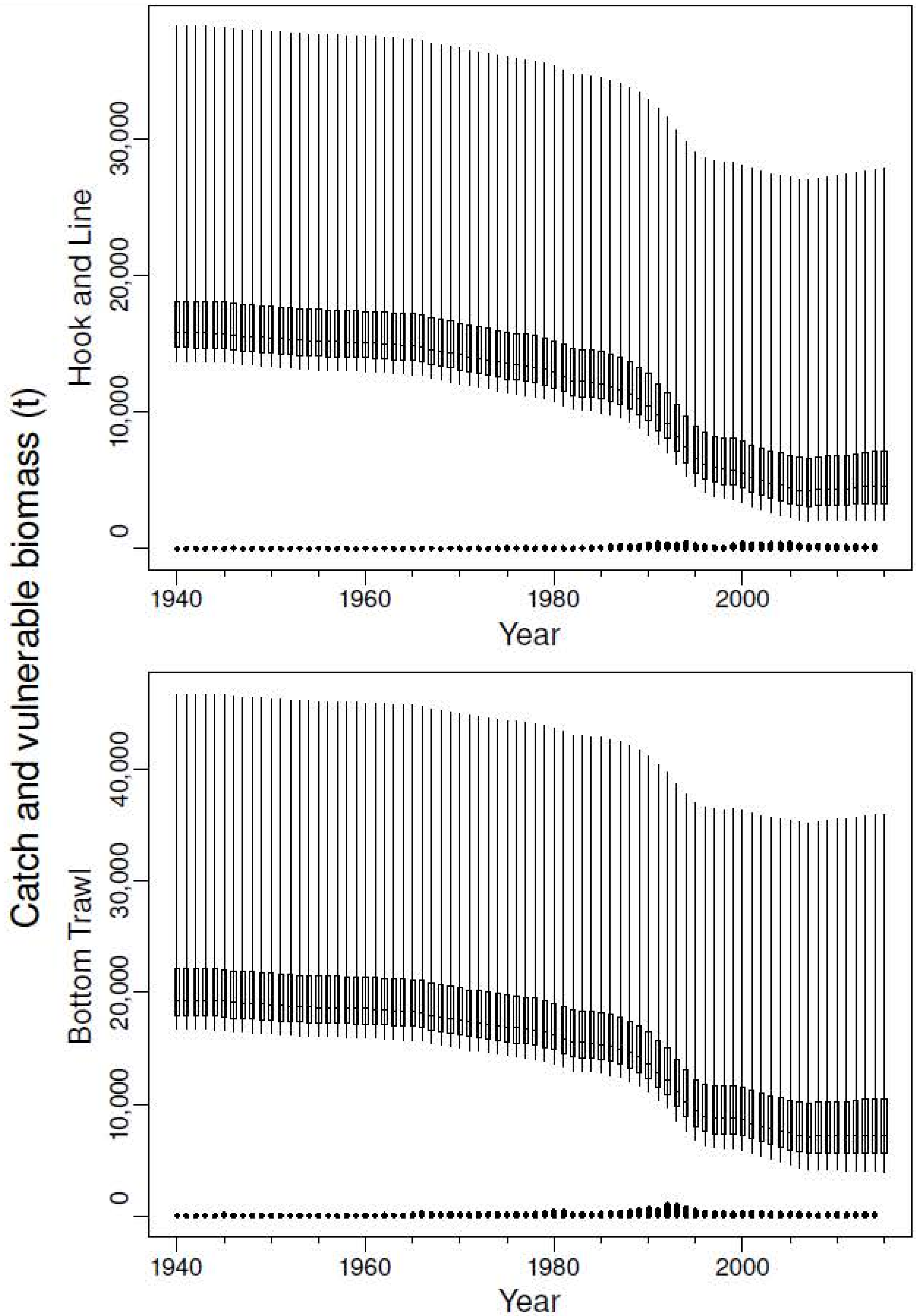


Figure E.28. For Chain B of Run 41-1, estimated vulnerable biomass (boxplots) and commercial catch (vertical bars), in tonnes, over time for hook-and-line (top) and bottom trawl (bottom) fisheries. Boxplots show the 2.5, 25, 50, 75 and 97.5 percentiles from the MCMC results. Catch is shown to compare its magnitude to the estimated vulnerable biomass, though it does not show up too clearly because of the large maximum values of estimated vulnerable biomass. The equivalent figure for Chain A is shown in Figure 5.