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Pacific Ocean Perch (*Sebastes alutus*) stock assessment for the west coast of Vancouver Island, British Columbia

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Canada

Foreword

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

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ABSTRACT

Pacific Ocean Perch (*Sebastes alutus*, POP) is a commercially important species of rockfish that inhabits the marine canyons along the coast of British Columbia. The status of POP off the west coast of Vancouver Island, British Columbia, is assessed here under the assumption that it is a single stock harvested entirely in Pacific Marine Fisheries Commission (PMFC) major areas 3C and 3D. This is the first time that a population model has been used to assess this stock.

We used an annual two-sex catch-at-age model tuned to: three fishery-independent trawl survey series, annual estimates of commercial catch since 1940, and age composition data from the commercial fishery (15 years of data) and from one of the survey series (four years of data). The model starts from an assumed unfished equilibrium state in 1940, and the survey data cover the period 1967 to 2012 (although not all years are represented). The model was implemented in a Bayesian framework (using the Markov Chain Monte Carlo procedure) to quantify uncertainty of estimated quantities.

Estimated exploitation rates were calculated as the ratio of total catch to the vulnerable biomass in the middle of each year. Rates peaked in the mid-1960s due to large catches by foreign fleets, and peaked again (though not as high) in the early 1990s. Exploitation rates have remained low since the mid-1990s, with the exploitation rate for 2012 estimated as 0.035 (0.018-0.077), denoting median and 5th and 95th quantiles of the Bayesian posterior distribution.

The spawning biomass (mature females only) at the beginning of 2013 is estimated to be 0.41 (0.19-0.68) of unfished spawning biomass. It is estimated to be 1.53 (0.55-3.32) of B_{MSY}, where B_{MSY} is the equilibrium spawning biomass that would support the maximum sustainable yield (MSY).

Advice to managers is presented as a set of decision tables that provide probabilities of exceeding limit and upper stock reference points for ten-year projections across a range of constant catch scenarios. The primary reference points used are a limit reference point of $0.4B_{\text{MSY}}$ and an upper stock reference point of $0.8B_{\text{MSY}}$, which are the Fisheries and Oceans Canada Precautionary Approach provisional reference points. Decision tables are also presented with respect to alternative reference points based on proportions of unfished equilibrium biomass, on current biomass and on the exploitation rate at MSY.

The estimated spawning biomass at the beginning of 2013 has a 0.99 probability of being above the limit reference point of $0.4B_{\text{MSY}}$, and a 0.87 probability of being above the upper stock reference point of $0.8B_{\text{MSY}}$.

The estimated median MSY (tonnes) is 1,048 (700-1,509), compared to the recent mean catch (from 2007-2011) of 547 t. The probability that the exploitation rate in 2012 is below that associated with MSY is 0.89.

Ten-year projections, for constant catches of 600 t, indicate essentially no change in the aforementioned probabilities of the spawning biomass being above the reference points, and indicate a projected increase in the median spawning biomass.

Évaluation des stocks de sébaste à longue mâchoire (*Sebastes alutus*) sur la côte ouest de l'île de Vancouver, en Colombie-Britannique

RÉSUMÉ

Le sébaste à longue mâchoire (*Sebastes alutus*) est une espèce commerciale de sébaste importante qui fréquente les canyons marins le long de la côte de la Colombie-Britannique. On a évalué l'état des stocks de sébaste à longue mâchoire au large de la côte ouest de l'île de Vancouver, en Colombie-Britannique, en présupposant l'existence d'un seul stock exploité entièrement dans les zones principales 3C et 3D de la Commission des pêches maritimes du Pacifique (CPMP). C'est la première fois qu'un modèle de population est utilisé pour évaluer ce stock.

Nous avons utilisé un modèle de prises annuelles selon l'âge et le sexe tenant compte des données de trois séries de relevés au chalut indépendants de la pêche; des estimations annuelles des prises commerciales depuis 1940; des données sur la composition selon l'âge de la pêche commerciale (données obtenues sur une période de 15 ans) et d'une des séries de relevés (données obtenues sur une période de 4 ans). Le modèle se fonde sur l'hypothèse d'un état à l'équilibre non exploité en 1940; les données des relevés couvrent la période de 1967 à 2012 (tous les ans ne sont cependant pas représentés). Ce modèle a été utilisé dans un cadre d'évaluation bayésienne (à l'aide de la méthode de Monte-Carlo par chaîne de Markov) pour quantifier les incertitudes entourant les quantités estimées.

Les taux d'exploitation estimés ont été calculés en divisant les prises totales par la biomasse vulnérable au milieu de l'année. Les taux d'exploitation ont atteint un pic au milieu des années 1960 en raison du nombre considérable de prises effectuées par les flottes étrangères et un autre pic, moins important, au début des années 1990. Les taux d'exploitation demeurent faibles depuis le milieu des années 1990; le taux d'exploitation pour 2012 s'élevait à 0,035 (0,018-0,077), ces chiffres indiquent respectivement la valeur médiane ainsi que les 5^{e} et 95^{e} centiles de la distribution bayésienne a posteriori.

On estime la biomasse reproductrice (femelles adultes uniquement) au début de 2013 à 0,41 (0,19-0,68) de la biomasse reproductrice non exploitée. Sa valeur estimée est de 1,53 (0,55-3,32) de B_{PMS}, où B_{PMS} représente la biomasse reproductrice à l'équilibre qui soutiendrait la production maximale soutenable (PMS).

Les avis à l'intention des gestionnaires sont présentés sous la forme de tables de décision qui indiquent les probabilités de dépasser le niveau de référence limite et le niveau de référence supérieur du stock pour des projections décennales réalisées à partir d'un éventail de scénarios de prises constantes. Les principaux niveaux de référence utilisés sont un niveau de référence limite de $0{,}4B_{\text{PMS}}$ et un niveau de référence supérieur de $0{,}8B_{\text{PMS}}$, qui constituent les niveaux de référence provisoires de l'approche de précaution de Pêches et Océans Canada. On présente aussi des tables de décision avec d'autres niveaux de référence fondés sur des proportions de la biomasse à l'équilibre non exploitée, la biomasse actuelle et le taux d'exploitation en fonction de la PMS.

La biomasse reproductrice estimée au début de 2013 a une probabilité de 0,99 de dépasser le niveau de référence limite de $0{,}4B_{\text{PMS}}$ et une probabilité de 0,87 de dépasser le niveau de référence supérieur de $0{,}8B_{\text{PMS}}$.

La médiane de la PMS estimée est de 1 048 tonnes (700 t-1509 t) tandis que les prises moyennes récentes (de 2007 à 2011) s'élevaient à 547 t. La probabilité pour que le taux d'exploitation en 2012 soit inférieur à celui qui est associé à la PMS s'établit à 0,89.

Les projections décennales pour des prises constantes de 600 t indiquent que les probabilités pour que la biomasse reproductrice se situe au-dessus des niveaux de référence sont fondamentalement les mêmes que celles mentionnées ci-dessus; les projections prévoient également une augmentation de la biomasse reproductrice médiane.

1 INTRODUCTION

This stock assessment is for Pacific Ocean Perch in combined Pacific Marine Fisheries Commission (PMFC) major areas 3C and 3D, off the west coast of Vancouver Island, British Columbia (Figure 1). A concurrent stock assessment for Pacific Ocean Perch in PMFC major areas 5D and 5E, off the coast of Haida Gwaii, is documented in Edwards et al. (2013). The same modelling approach is used for both stocks. Given that almost all the input data and all the results are different for the two stocks, it was deemed preferable to produce two independent stand-alone documents rather than one larger one, although there will inevitably be some overlap between the two documents. Some background information is taken from Edwards et al. (2012*b*).

This main section presents background information, an overview of the assessment model and input data, the main model results and the advice to managers. Further technical details are given in the relevant Appendices.

1.1 BIOLOGICAL BACKGROUND

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

The life history of POP follows similar patterns to other *Sebastes* species, with release of larvae that spend periods ranging from about three to twelve months as free-swimming pelagic larvae before settling to the bottom as juveniles. Reproduction appears to follow onshore-offshore migration patterns where females move onshore for insemination and then migrate deeper to the entrances of submarine gullies where they release larvae from February to May (Love et al., 2002). The larvae depend on vertical upwelling to bring them into the upper pelagic zone to facilitate growth and dispersal. The larvae can spend up to a year in the water column before settling on benthic habitat (Kendall Jr. and Lenarz, 1986). Juvenile benthic habitat is shallow (100-200 m), compared to the depths occupied by adult POP, and comprises either rough rocky bottoms or high relief features such as boulders, anemones, sponges, and corals Carlson and Straty (1981); Rooper et al. (2007). The maximum known age appears to be 103 y for a female specimen from Moresby Gully at 364 m in 2002, from the Department of Fisheries and Oceans Canada (DFO) Groundfish database GFBio (Edwards et al., 2012*b*).

1.2 RANGE AND DISTRIBUTION

Pacific Ocean Perch occur along the North Pacific rim, ranging from Honshu (Japan), through the Bering Sea, along the Aleutian Islands (Alaska), then southward through BC down to central Baja California (Love et al., 2002). They appear to be most abundant north of 50° N (Allen and Smith, 1988). In BC (Figure 2), hotspots ($\geq$ the 0.95 quantile of catch per unit effort (CPUE) from trawl tows from 1996-2012) occur southeast of Moresby Island (Moresby Gully), southwest of Moresby

Island (Anthony Island), northwest of Graham Island (Langara Spit), and in Dixon Entrance north of Graham Island; catch rates are relatively low in PMFC areas 3C and 3D, off the west coast of Vancouver Island. Pacific Ocean Perch has been encountered by the BC trawl fleet over an estimated 46,240 km^2 (Figure 2). For PMFC areas 3C and 3D, 98% of the commercial captures of POP lie between depths 128 m and 581 m (Appendix H).

1.3 OVERVIEW OF FISHERY

Pacific Ocean Perch supports the largest rockfish fishery in British Columbia (BC) with an annual coastwide TAC (total allowable catch) of 5,448 t in 2010, which is being progressively reduced to 5,189 t over three years (see Appendix B). The mean annual coastwide catch was about 5,000 t from 2006-2010 and the mean coastwide landed value of the POP catch for 2007-2010 was $4.4 million (landed value data from D. Lau, DFO Economics Sector). The trawl fishery accounts for 99.98% of the coastwide TAC, with the rest allocated to the hook and line fishery. A detailed history of the POP fishery prior to the inception of the observer trawl program in 1996 can be found in Richards and Olsen (1996).

2 ASSESSMENT BOUNDARIES AND BACKGROUND

For this assessment, we use PMFC major areas 3C and 3D (herein referred to as area 3CD), covering most of the west coast of Vancouver Island (Figure 1). The PMFC areas are similar but not identical to the groundfish management areas (GMAs) used by the DFO Groundfish Management Unit (GMU); those areas (Figure 1) are more attuned to the pattern of fishing for a range of demersal species. We have not used the GMAs because reporting from these areas has only been available since 1996 and there is no procedure to alter historical landings to conform to current boundaries. The TAC for GMA 3CD has been 530 t since 1998. The mean catch from 2007-2011 in PMFC area 3CD was 547 t.

This is the first quantitative stock assessment for the stock of POP in area 3CD. The most recent POP assessment for BC waters considered only Queen Charlotte Sound (QCS, combined PMFC area 5ABC, Edwards et al. 2012*b*), the primary fishing grounds for POP. Previous population modelling for POP (Schnute and Richards, 1995; Richards and Schnute, 1998; Schnute et al., 2001) focused on Goose Island Gully, one of the three main gullies in QCS. Schnute et al. (2001) extended their results to the rest of the BC coast.

We follow several recent west coast Canadian rockfish assessments (Stanley et al., 2009; Edwards et al., 2012*a*,*b*), in using a modified version of the Coleraine statistical catch-at-age software (Hilborn et al., 2003), called Awatea, to implement the model (Appendix F). The model is an annual two-sex catch-at-age model tuned to: three fishery-independent trawl survey series, annual estimates of commercial catch since 1940, and age composition data from the commercial fishery (15 years of data) and from one survey series (four years of data).

The model estimates parameters from the stock-recruitment function, natural mortality (independently for females and males), catchability coefficients for the three survey series, and selectivity parameters for the commercial fishery and the one survey series for which age data are available.

The model is used to estimate the past and present vulnerable biomass (the biomass that is vulnerable to capture by the fishery, taking into account selectivity), spawning stock biomass (mature females only) and population age structure. Estimated parameters are then used to calculate maximum sustainable yield (MSY) and reference points. Projections are performed to estimate future probabilities of the spawning biomass being greater than the reference points under a range of constant catch scenarios. All of these calculations are made in a Bayesian context to capture the uncertainty associated with parameter estimation. Uncertainty relative to some data sets is explored through sensitivity runs (Appendix I).

Advice for managers was requested (see Appendix A) to be guided by the DFO Sustainable Fisheries Framework, particularly the Fishery Decision-making Framework Incorporating the Precautionary Approach (DFO, 2009). Consequently, advice to managers is presented as a set of decision tables that provide probabilities of exceeding reference points for various years of projections across a range of constant catch scenarios.

A DFO Technical Working Group provided valuable guidance with respect to many of the decisions that were made in the course of this work.

3 CATCH DATA

The preparation methods and the full catch history for this assessment are given in Appendix B. Catches were estimated back to 1940. Poorly reported historical catches by foreign fleets were reconstructed based on sparse historical sampling data, and minor catches from other capture methods have been added to the totals. All available discard estimates were added to the catches, with estimates of historical discards based on current observed levels. The resulting time series of catch data that is used as model input is shown in Figure B.2, and reaches a peak of 7,753 t in 1966 (during a period of intense fishing by foreign fleets) and a recent (2007-2011) average catch of 547 t. Catch data were only available for part of 2012, and so, for input to the model, the 2012 catch total was assumed to be the same as for 2011. Information about other species caught concurrently with POP commercial catches is presented in Appendix H.

4 FISHERIES MANAGEMENT

Appendix B summarises all management actions taken for POP (coastwide) since 1979. 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 reduction in the combined GMA 5ABCD total allowable catch (from 4,188 t to 3,413 t, implemented progressively over three years).

5 OVER-HARVESTING EXPERIMENT

In the 1980s, experimental over-harvesting of POP stocks was attempted in two regions along the BC coast (Leaman and Stanley, 1993; Leaman, 1998). The objectives of the experiments included (i) ground-truthing trawl survey biomass estimates, (ii) estimating fishing mortality, (iii) validating ageing techniques by introducing a large negative anomaly in the age composition, (iv) exploring stock-recruitment relationships, and (v) involving industry in research and management.

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

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

6 SURVEY DESCRIPTIONS

Three sets of fishery independent survey indices were used to track changes in the biomass of the 3CD stock (Appendix C):

1. the west coast Vancouver Island (WCVI) synoptic survey series, from 2004-2012 (even years only), referred to here as the ‘WCVI synoptic survey series’;

2. the United States National Marine Fisheries Service (NMFS) Triennial survey series, covering seven years from 1980-2011, referred to here as the ‘NMFS Triennnial survey series’;

3. a set of historic Research Vessel GB Reed surveys off the WCVI, for the four years 1967-1970, referred to here as the ‘GB Reed survey series’.

The relative biomass survey indices are used as data in the model along with the associated relative error for each index value. See Appendix C for justification of inclusion or exclusion of survey data.

Pre-1996 commercial catch and effort data were also investigated with the intent of creating CPUE-based abundance indices for use in the stock assessment model. This approach was abandoned because it was felt that there were problems with the reliability of the data as well as questions as to the representative nature of the resulting indices, given the schooling behaviour of the species and the capacity of fishers to target these schools. Given the concern that the resulting indices would be hyperstable, they were not used in this assessment.

7 BIOLOGICAL INFORMATION

7.1 BIOLOGICAL SAMPLES

Commercial catches of rockfish by trawl gear have been sampled for age proportions since the 1960s. However, only POP 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. Practically, this means that no usable age data were available for this assessment prior to 1982. Commercial fishery age samples were summarised for each quarter, with samples combined within a trip and weighted by the POP catch weight for the sampled trip. The quarterly samples were then scaled by the quarterly landed commercial catch weights to give annual proportions-at-age data (details are in Appendix E; Table F.1 gives the years of data).

Survey age samples were only available from the WCVI synoptic survey series for even years from 2004 to 2010 (the 2012 samples have not yet been aged). These samples were scaled to represent the total survey in a manner similar to that used for the commercial samples (see Appendix E).

7.2 GROWTH PARAMETERS

Growth parameters for both sexes were taken from the POP QCS assessment (Edwards et al., 2012*b*), which estimated parameters from biological samples collected from 1978 to 2009 by research surveys and from the commercial fishery (Appendix D). Estimates of growth parameters were compared across the major assessment areas (3CD, 5ABC and 5DE) and across sample origins (research and commercial), and found to be consistent in all comparisons (Edwards et al., 2012*b*). Consequently, the same sex-specific growth parameters have been used for all three assessment areas, with sex-specific growth specified as a three-parameter von Bertalanffy model that estimates length-at-age. Weights-at-age, used to convert population numbers to biomass, were given by an allometric length-weight relationship. See Appendix D for details.

7.3 MATURITY AND FECUNDITY

The maturity ogive was also taken from Edwards et al. (2012*b*). Stage of maturity was determined macroscopically, partitioning the samples into one of seven maturity stages (Stanley and Kronlund, 2000) during the months of January to June. The analysis was restricted to this period because it is the period of maximum expected maturity (Edwards et al., 2012*b*). Fish assigned to stages 1 or 2 were considered immature while those assigned to stages 3-7 were considered mature. Data representing staged and aged females (using the break and burn method) were pooled from all sampling sources and the observed proportion mature at each age was calculated, and a model fitted (see Appendix D). Fecundity was assumed to be proportional to the female body weight.

7.4 NATURAL MORTALITY

Male and female natural mortalities were estimated as parameters of the model (see Appendix F), using an informed prior based on the marginal posterior distributions from the QCS POP assessment (Edwards et al., 2012*b*), specifically a normal prior with mean 0.07 and standard deviation 0.007 for both sexes (see Appendix F). The QCS assessment used a prior based on a POP assessment for the Gulf of Alaska (Hanselman et al., 2009), with mean 0.06 and standard deviation 0.006.

In recent assessments (Edwards et al., 2012*a*,*b*), model runs that fixed natural mortality were also used to provide the final advice to managers. However, because we were able to develop a prior based on Canadian POP data, and since the resulting Bayesian estimates of natural mortality and steepness (defined below) are uncorrelated (Appendix G), only runs that estimate natural mortality are used in this assessment (as agreed upon by the Technical Working Group). Prior distributions for all estimated parameters are given in Table F.4.

7.5 STEEPNESS

A Beverton-Holt stock-recruitment function was used to generate average recruitment estimates in each year, based on the biomass of female spawners (Appendix F). Recruitments, defined as numbers of age-1 fish, were allowed to deviate from this average in order to improve the fit of the model to the data, constrained by an assumed recruitment standard deviation. The Beverton-Holt function was parameterised using a steepness parameter, h, which specified the proportion of the maximum recruitment that was available at $0.2B_0$, where B_0 is the unexploited equilibrium spawning biomass (mature females). The parameter h was estimated in all model runs, constrained by a prior developed for west coast rockfish by Forrest et al. (2010), after removing all information for QCS POP (R. Forrest, DFO, pers. comm.). This prior took the form of a beta distribution with mean 0.674 and standard deviation 0.168. This approach is the same as that in our previous rockfish assessments (Edwards et al., 2012*a*,*b*).

8 AGE-STRUCTURED MODEL

A two-sex, age-structured stochastic model was used to reconstruct the population trajectory of POP in area 3CD from 1940 to the beginning of 2013. Ages were tracked from 1 to 30, with 30 being an accumulator age class. Although an accumulator age class of 60 was used in the QCS assessment (Edwards et al., 2012*b*), initial exploration runs for this assessment did not perform well using 60 for the accumulator age class. Better model performance was obtained using age 30, which is consistent with the earlier Goose Island Gully POP assessment by Schnute et al. (2001).

The population at the beginning of the reconstruction was assumed to be in equilibrium with average recruitment and no fishing. Selectivities by sex for one of the surveys and the commercial fishery were estimated using three parameters describing a half-Gaussian function (that is set to 1 above a certain age). The model equations and implementation are described in Appendix F.

The model was fit to the available data (three sets of survey indices, 15 annual proportions-at-age samples from the commercial fishery and four proportions-at-age samples from the WCVI synoptic survey series) by minimising a function which summed the negative log-likelihoods arising from each data set, the deviations from mean recruitment and the penalties stemming from the Bayesian priors. The minimised MPD (mode of the posterior distribution) 'best fit' was used as the starting point for the Bayesian search across the joint posterior distributions of the parameters using the Monte Carlo Markov Chain (MCMC) procedure.

The MCMC procedure was run for 10,000,000 iterations, sampling every 10,000th, to give 1,000 samples. These samples were used to estimate parameters and quantities of interest, including stock sizes and the probabilities of being above reference points.

Initial model fits to the data gave sensible and consistent results. Numerous sensitivity runs that systematically explored the effect of different components of the data on model results did not seem justified, given the small amount of available data when spread over the long period of stock reconstruction (particularly for the early years). Two sensitivity runs are presented in Appendix I, one exploring possible systematic catch mis-reporting from 1987-1995 and the other dropping the early (1967-1970) GB Reed survey series. We did not explore ageing error. Such a sensitivity run was conducted for the Yellowmouth Rockfish assessment (Edwards et al., 2012*a*), with the conclusion that a full investigation of ageing error would require an independent dedicated analysis, which was beyond the capacity of the current assessment.

9 RESULTS

The base case model run had credible fits to the data, as demonstrated by visual examination of the MPD fits and the patterns of residuals (results in Appendix G). The MCMC results showed satisfactory convergence of the MCMC search process (Appendix G). Priors and marginal posteriors of the estimated parameters are also given in Appendix G, along with the values of the estimated parameters (Table G.2). For example, natural mortality is estimated as having median (and 5-95% credible interval) of 0.069 (0.060-0.079) for females and 0.072 (0.063-0.082) for males. Steepness is estimated to be 0.70 (0.48-0.91). The remaining MCMC results, of more general interest, are given here.

Figure 3 shows the MCMC results for the estimated vulnerable biomass, together with the reconstructed historical catches, and Figure 4 shows the estimated medians of vulnerable and spawning (mature females only) biomass relative to their unfished values. (The full MCMC results for spawning biomass are included later in Figure 9 regarding projections). These demonstrate a slight decline in biomass from 1940 to 1960 with the onset of fishing, followed by a very sharp decline in the 1960s due to heavy fishing (primarily by foreign fleets). After the cessation of foreign fishing, the biomass increased through the remainder of the 1970s. The biomass then declined through the 1980s until the mid-1990s, and has since increased, with median values of relative biomass now above the 1980 values.

Estimates of various quantities of interest are given in Table 1. In particular, the median (and 5-95% credible interval) for B_{2013}/B_0, the ratio of current spawning biomass (B_{2013}) to the unfished equilibrium level (B_0), is 0.41 (0.19-0.68); thus 0.41 is the value for the final circle in Figure 4.

The estimated recruitments (age-1 fish, Figure 5) in part further explain the aforementioned stock trajectory. There was lower-than-average recruitment in the early 1970s, which may, together with increased catches, explain why the vulnerable biomass declined through the 1980s (note the approximate ten-year lag from recruitment to fish becoming fully selected by the commercial fishery). There are a number of year classes with approximately double the long-term average recruitment. This is unlike the patterns observed for the QCS area 5ABC stock (Figure 5 of Edwards et al. 2012*b*) and the companion assessment for area 5DE (Edwards et al., 2013), which both exhibited a dominant 1976 year class (age-1 recruits in 1977) that was approximately five times larger than the long-term average recruitment.

Figure 6 shows the estimated exploitation rates (ratio of total catch to the vulnerable biomass in the middle of the year), which peaked in the mid-1960s due to the large foreign catches, and then peaked again (although not as high) in the early 1990s due to increased domestic exploitation. Exploitation rates have remained low since the mid-1990s, with u_{2012}, the exploitation rate for 2012, estimated to be 0.035 (0.018-0.077).

Estimates of further quantities of interest, such as absolute values of biomass (rather than relative values), are also given in Table 1, as well as quantities based on MSY, discussed below.

10 ADVICE FOR MANAGERS

10.1 CURRENT STOCK LEVEL

The estimated median MSY (with 5-95% credible interval, tonnes) is 1,048 (700-1,509), compared to the mean catch over the last 5 years (2007-2011) of 547 t. The MSY is calculated as an equilibrium yield under constant average recruitment.

The estimated ratio $B_{2013}/B_{\mathrm{MSY}}$ of spawning biomass (mature females only) at the start of 2013 (B_{2013}) to the equilibrium spawning biomass that will support the maximum sustainable yield (B_{MSY}), is 1.53 (0.55-3.32).

As noted above, B_{2013}/B_0, the ratio of current spawning biomass to the unfished equilibrium level, is 0.41 (0.19-0.68). The estimate of the ratio B_{MSY}/B_0 is 0.27 (0.18-0.36).

10.2 REFERENCE POINTS

Decision tables are presented with respect to two sets of reference points as determined from consultation with N. Davis (DFO Groundfish Management Unit, pers. comm.); see below for rationale for the reference points. Each set is based on either B_{MSY} or B_0. Decision tables are also given with respect to additional reference points based on current biomass and u_{MSY}. All reference points and the associated probabilities were derived from the posterior distributions of Bayesian output from the model.

As part of the Sustainable Fisheries Framework, DFO (2009) suggested provisional reference points to guide management and to assess harvest in relation to sustainability. Because alternative reference points for Canadian west coast groundfish species have not been specified by policy, the suggested provisional DFO limit and upper stock reference points of $0.4B_{\mathrm{MSY}}$ and $0.8B_{\mathrm{MSY}}$ have been adopted here. These were the reference points used for the POP stock in QCS (Edwards et al., 2012*b*). Note that no modelling has been carried out to determine the suitability of these reference points for these stocks, nor have acceptable levels of risk been specified.

The zone below the limit reference point ($0.4B_{\mathrm{MSY}}$) is termed the “critical zone” while the zone lying between the two reference points is termed the “cautious zone”. The region above the upper stock reference point ($0.8B_{\mathrm{MSY}}$) is termed the “healthy zone”. B_{MSY} is also reported here as an additional reference point because it “provides a useful basis for comparing stocks” (Ricard et al., 2011) when conducting meta-analyses of assessment results.

Figure 7 shows the distribution of $B_{2013}/B_{\mathrm{MSY}}$ relative to the DFO Precautionary Approach provisional reference points of $0.4B_{\mathrm{MSY}}$ and $0.8B_{\mathrm{MSY}}$. The stock is estimated to be currently above the critical zone with probability P$(B_{2013} > 0.4B_{\mathrm{MSY}}) = 0.99$, and in the healthy zone with probability P$(B_{2013} > 0.8B_{\mathrm{MSY}}) = 0.87$. For comparison, Figure 7 also shows the estimated status of the other two POP stocks, where the status for the 5ABC stock is based on a different year.

A second component of the provisional harvest rule of DFO (2009) concerns the relationship of the exploitation rate relative to that associated with MSY under equilibrium conditions (u_{MSY}). The rule specifies that the exploitation rate should be at or below u_{MSY} when the stock is in the healthy zone, it should be ramped down when in the cautious zone, and it should be kept to an absolute minimum when in the critical zone. Figure 8 shows the exploitation rate in 2012 relative to that at u_{MSY} (red dot and vertical red line). The estimated ratio of $u_{2012}/u_{\mathrm{MSY}}$ is $0.38\ (0.13 - 1.43)$. The probability that the current exploitation rate is below that associated with MSY is P$(u_{2012} < u_{\mathrm{MSY}}) = 0.89$.

The blue and grey circles in Figure 8 show that, based on medians, the stock is estimated to have been in the healthy zone since the start of fishing. The median exploitation rate has been $> u_{\mathrm{MSY}}$ for a total of 18 years, the most recent being 1995.

Other agencies and jurisdictions often use ‘proxy’ reference points that are expressed in terms of B_0 rather than B_{MSY} (e.g. New Zealand Ministry of Fisheries 2007, 2011), because B_{MSY} is often poorly estimated as it is dependent on a consistent fishery. Therefore, the reference points of $0.2B_0$ and $0.4B_0$ are also presented here (see decision tables described below), as for the Yellowmouth Rockfish assessment (Edwards et al., 2012*a*). These reference points are the respective default values used in New Zealand as a ‘soft’ limit (below which management action needs to be taken) and a ‘target’ biomass for low productivity stocks (a mean around which the biomass is expected to vary).

10.3 PROJECTION RESULTS AND DECISION TABLES

Projections were made to evaluate the future behaviour of the population under different levels of constant catch, given the model assumptions. The projections, starting with the biomass at the beginning of 2013, were made over a range of constant catch strategies (0-2,000 t in 200 t steps) for each of the 1,000 MCMC samples in the posterior. Future recruitments were generated through the stock-recruitment function using recruitment deviations drawn randomly from a lognormal distribution with zero mean and constant standard deviation (see Appendix F for full details). Projections were made for 10 years, as agreed upon with N. Davis (pers. comm.). This time frame was considered as long enough to satisfy the 'long-term' requirement of the Request for Science Information and Advice (Appendix A), yet short enough for the projected recruitments to be mainly based on individuals spawned before 2013 (and hence already estimated by the model).

Resulting projections of spawning biomass are shown for selected catch strategies (Figure 9). These suggest, for example, that the median spawning biomass is projected to increase for a constant catch of 600 t, which is larger than the recent average catch.

Decision tables give the probabilities of the spawning biomass exceeding the reference points in specified years, for various constant catch strategies, calculated as the proportion of MCMC samples for which the biomass exceeded the given reference point. Note that catches are held constant, without feedback control simulation. Consequently, there is no ramping down of fishing mortality if the stock reaches the cautious or critical zones.

Results for the three B_{MSY}-based reference points are presented in Tables 2-4. As an example of how to read the tables, the estimated probability that the stock is in the provisional healthy zone in 2017 under a constant catch strategy of 1,000 t is P$(B_{2017} > 0.8B_{\mathrm{MSY}}) = 0.82$ ('1000' row and '2017' column of Table 3). Results for the two B_0-based reference points are given in Tables 5 and 6.

For a constant catch of 600 t, above the average recent catch of 547 t, the probabilities of the stock remaining above the critical zone, P$(B_t > 0.4B_{\mathrm{MSY}})$, or in the healthy zone, P$(B_t > 0.8B_{\mathrm{MSY}})$, essentially remain constant over the ten-year projections ('600' rows in Tables 2 and 3). However, note that the median of spawning biomass, B_t, is estimated to increase over this time (600 t catch strategy in Figure 9).

The probabilities over time also essentially remain constant (for a catch of 600 t) for the reference point $0.2B_0$, as shown by P$(B_t > 0.2B_0)$ in Table 5. However, for $0.4B_0$, the probabilities increase over the 10 years from P$(B_{2013} > 0.4B_0) = 0.52$ to P$(B_{2023} > 0.4B_0) = 0.67$, Table 6.

Also given are two further tables of potential interest to management. Table 7 gives probabilities P$(B_t > B_{2013})$ for the projected spawning biomass to exceed the current spawning biomass. Table 8 gives probabilities P$(u_t > u_{\mathrm{MSY}})$ for the projected exploitation rate to exceed that at MSY.

The choice of which decision table to use depends on the current status of the stock, since the status will determine the objectives, which may be based on conservation, stock growth or fisheries catch.

11 GENERAL COMMENTS

The picture presented from this assessment is of a slow-growing, low productivity stock that was depleted to less than B_{MSY} due to commercial fishing by foreign fleets from 1965 to 1976 (Figures 4 and 8). The heavy exploitation during this period was followed by reduced recruitment (Figure 5). Since then there have been a number of recruitment events that were approximately double the long-term mean, the highest occurring in 1990 and 2000. The biomass appears to have increased since 1996-1997 (Figure 4), coinciding with the commencement of the observer and Individual Vessel Quota programs.

Annual exploitation rates increased during the 1960s and peaked in 1966, but decreased steadily thereafter to a low point in 1977 (Figure 6). After this, the Canadian fishery steadily ramped up exploitation until 1994, and then, once the observer and Individual Vessel Quota programs were initiated, the exploitation rates quickly settled down to reach a mean of 0.039 (mean of the 1997-2012 medians), with a current median of 0.035. This is around half the estimated median natural mortality rates of 0.069 (females) and 0.072 (males).

The spawning biomass (mature females only) at the beginning of 2013 is estimated to be 0.41 (0.19-0.68) of B_0 and 1.53 (0.55-3.32) of B_{MSY}. Using the DFO Precautionary Approach provisional reference points of $0.4B_{\mathrm{MSY}}$ and $0.8B_{\mathrm{MSY}}$ to define zones, the stock is estimated to be currently above the critical zone with probability P$(B_{2013} > 0.4B_{\mathrm{MSY}}) = 0.99$, and in the healthy zone with probability P$(B_{2013} > 0.8B_{\mathrm{MSY}}) = 0.87$ (and thus in the intermediate cautious zone with probability 0.12).

The decision tables provide guidance on the selection of short-term TAC recommendations and describe the range of possible future outcomes over the projection period at fixed levels of annual catch. The accuracy of the projections is predicated on the model being correct and assumes no management intervention in the time period covered by the tables.

Uncertainty in the estimated parameters and quantities is explicitly addressed using a Bayesian approach, but reflects only the specified model and weights assigned to the various data components. Sensitivity runs provide some insight into model uncertainty. However, the sensitivity runs presented here do not differ greatly from the base run.

We expect that the results from the several surveys initiated in the previous decade will continue to provide monitoring capability for POP. Catches in the commercial groundfish fisheries are very well recorded. These ongoing initiatives give confidence that this stock is currently well monitored and that corrective action can be taken if required.

12 FUTURE RESEARCH AND DATA REQUIREMENTS

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

1. Continue the suite of fishery-independent trawl surveys that have been established along the BC coast. This includes obtaining age and length composition samples, which will allow the estimation of survey-specific selectivity ogives.

2. Review and potentially improve the commercial sampling program for POP age composition with the goal of continuing the representative sampling of all fisheries that take significant amounts of POP.

3. 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.

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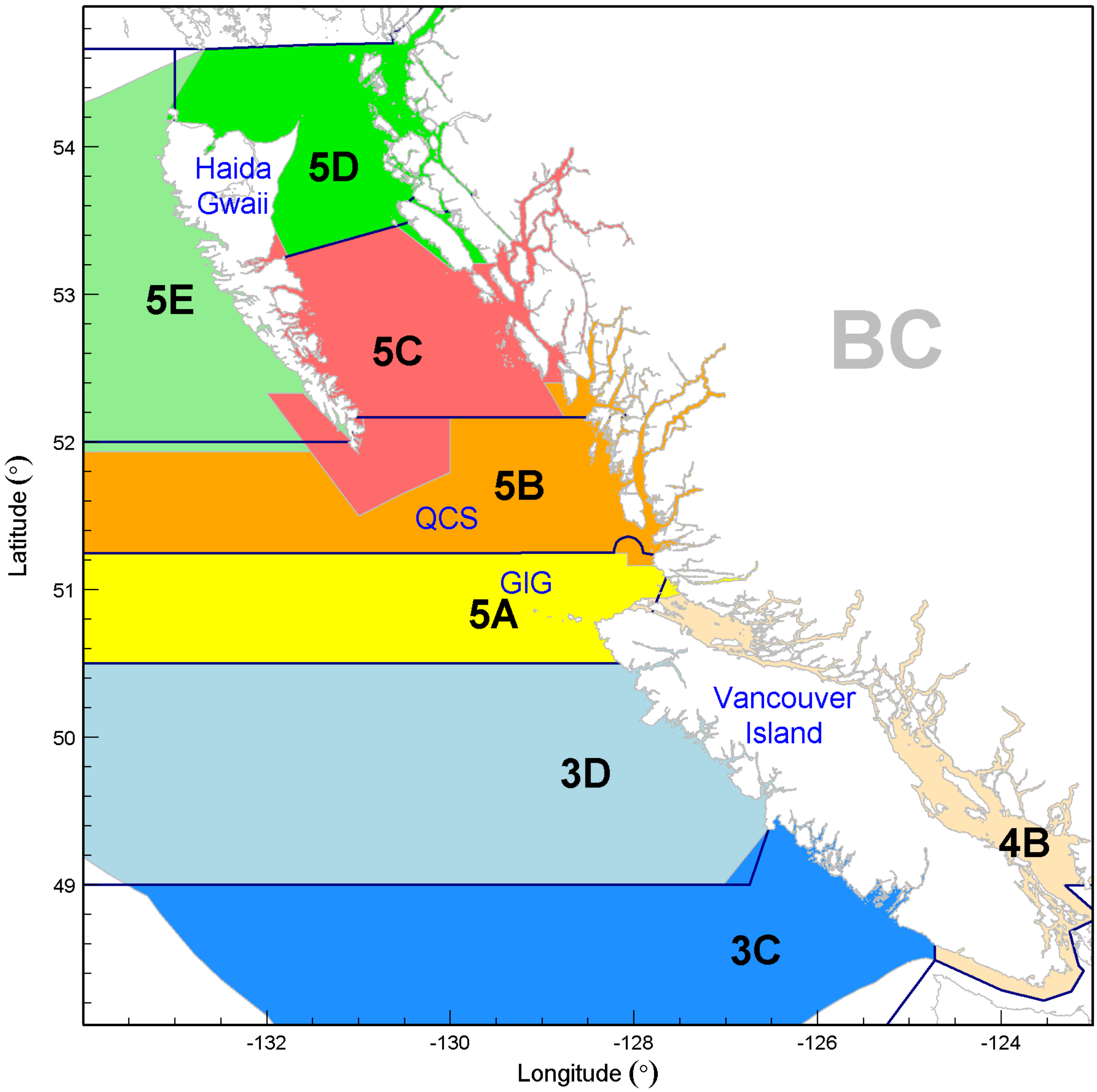

Figure 1. Pacific Marine Fisheries Commission (PMFC) major areas (outlined in dark blue) compared with Groundfish Management Unit areas for POP (shaded). For reference, map indicates Queen Charlotte Sound (QCS) and Goose Island Gully (GIG). This assessment is for the stock in PMFC areas 3C and 3D (termed area 3CD).

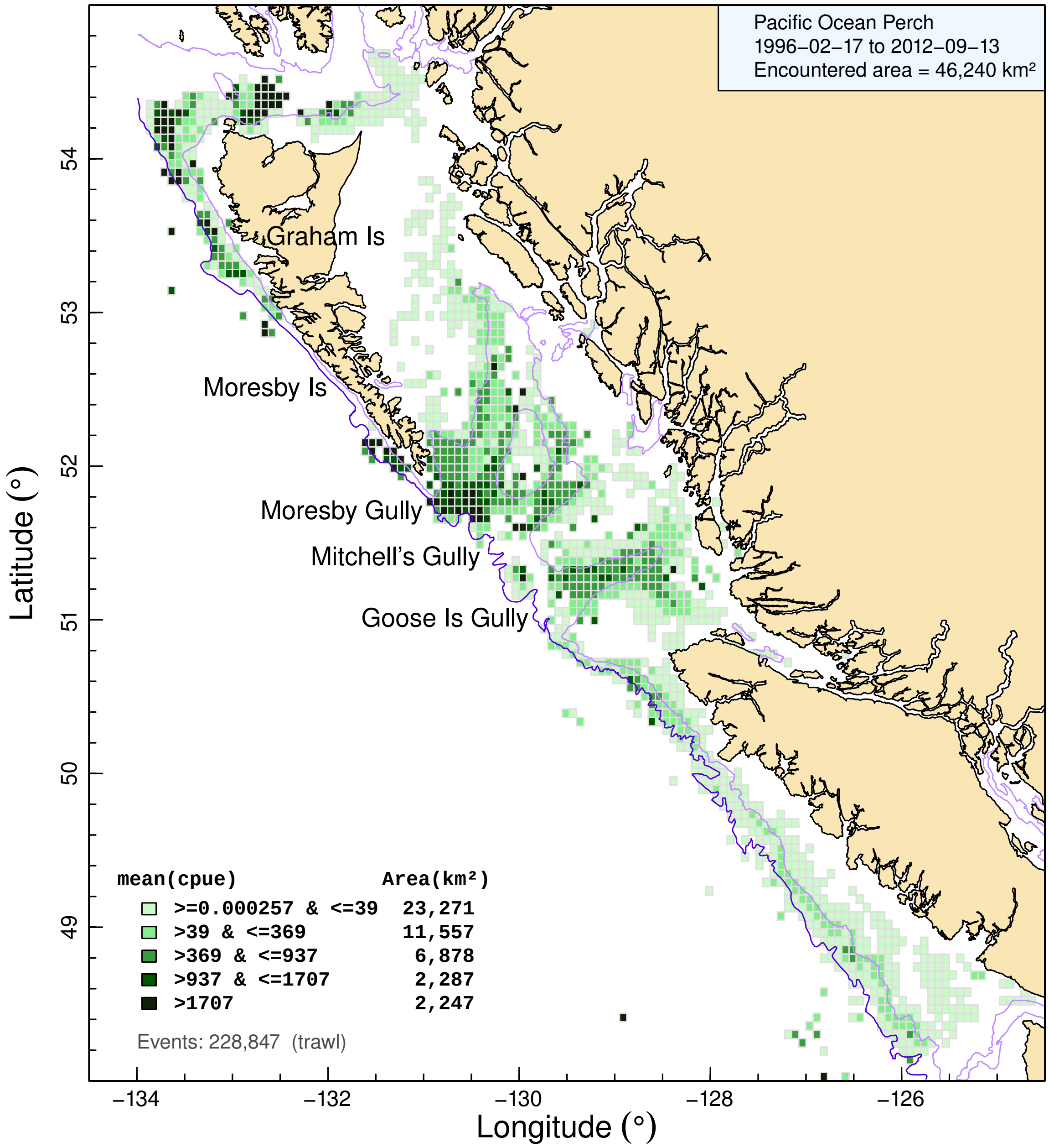

Figure 2. Mean catch-per-unit-effort (CPUE, kg/h) of POP in grid cells 0.075° longitude by 0.055° latitude (roughly 32 km^2). The shaded cells give an approximation of the area where POP was encountered by fishing events from the groundfish trawl fishery from February 1996 to September 2012. Named gullies are to the northeast of their labels. Contours are 200 m and 1000 m isobaths.

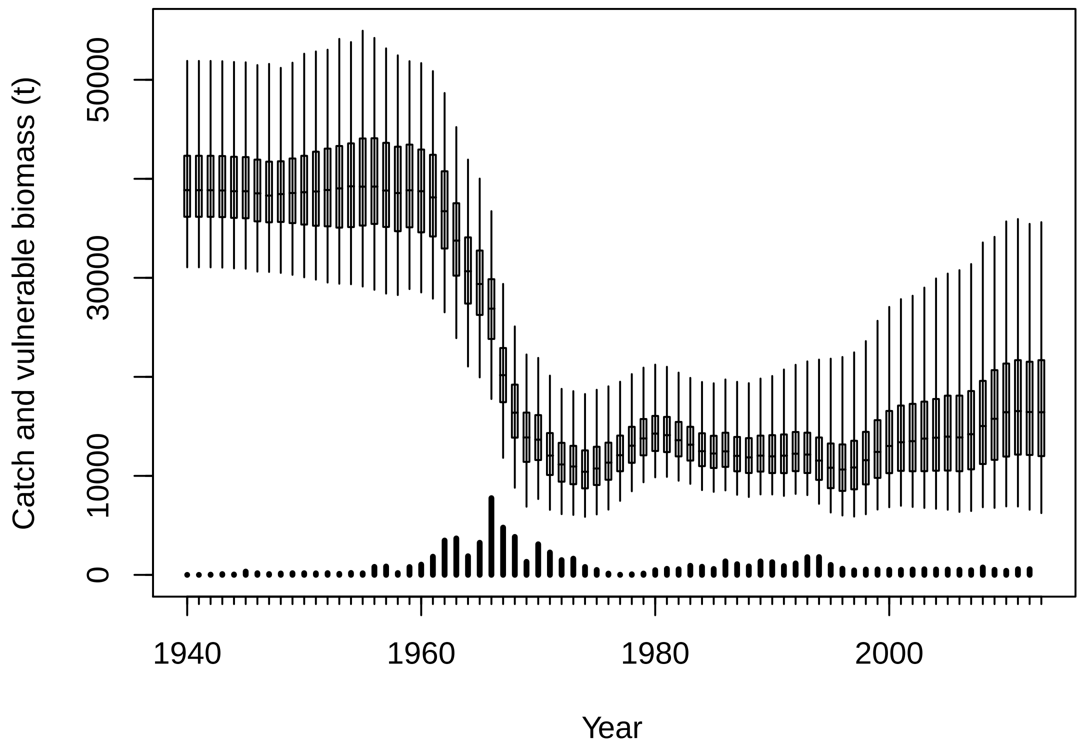

Figure 3. Estimated vulnerable biomass (boxplots) and commercial catch (vertical bars), in tonnes, over time. Boxplots show the 2.5, 25, 50, 75 and 97.5 percentiles from the MCMC results. Catch is shown to compare its magnitude to the estimated vulnerable biomass.

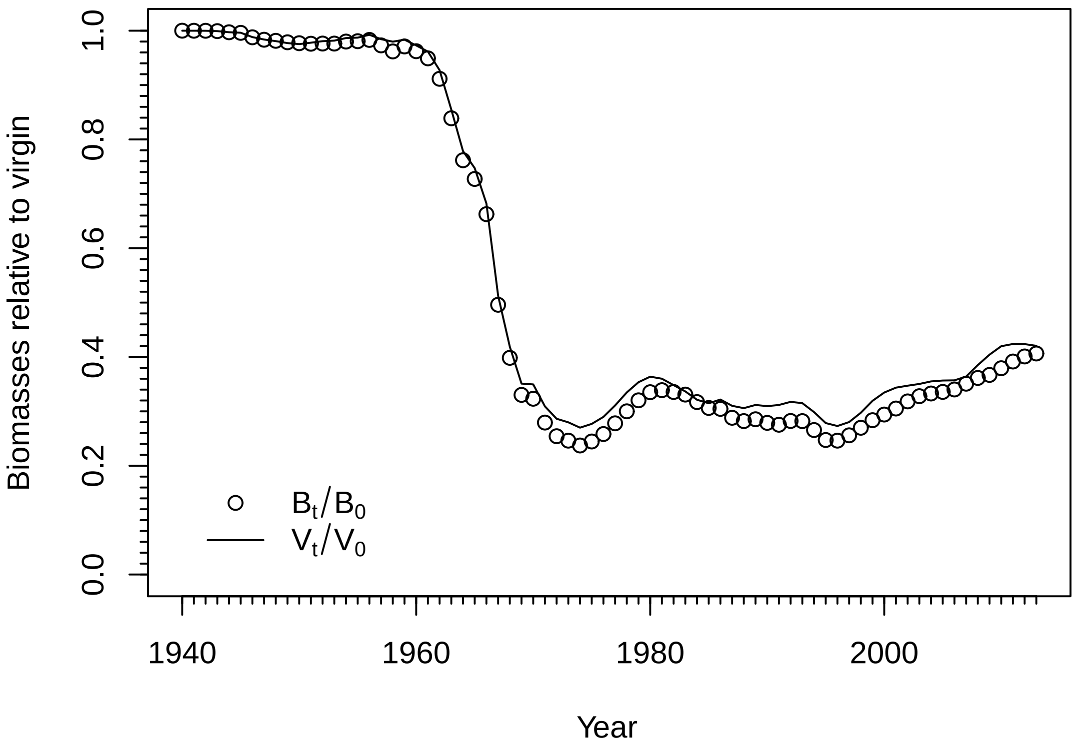

Figure 4. Changes in B_t/B_0 and V_t/V_0 (spawning and vulnerable biomass relative to unfished equilibrium levels) over time, shown as the medians of the MCMC posteriors.

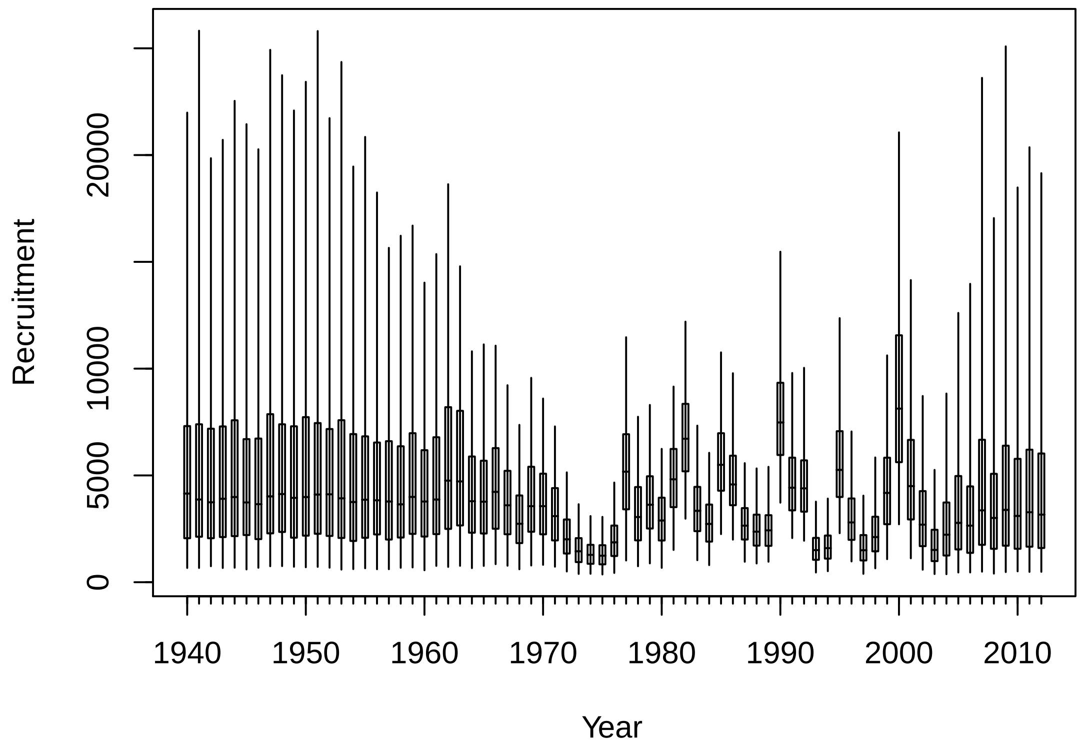

Figure 5. Marginal posterior distribution of recruitment in 1,000's of age-1 fish plotted over time. Boxplots show the 2.5, 25, 50, 75 and 97.5 percentiles from the MCMC results. Note that the first year for which there are age data is 1982, and the plus-age class is 30, such that there are no direct data concerning age-1 fish before 1953. Also, the final few years have no direct age data from which to estimate recruitment, because fish are not fully selected until age 11 by the commercial vessels or age 15 by the WCVI synoptic survey (using the MCMC median ages of full selectivity for commercial catch, μ_4, and WCVI survey μ_1, Table G.2).

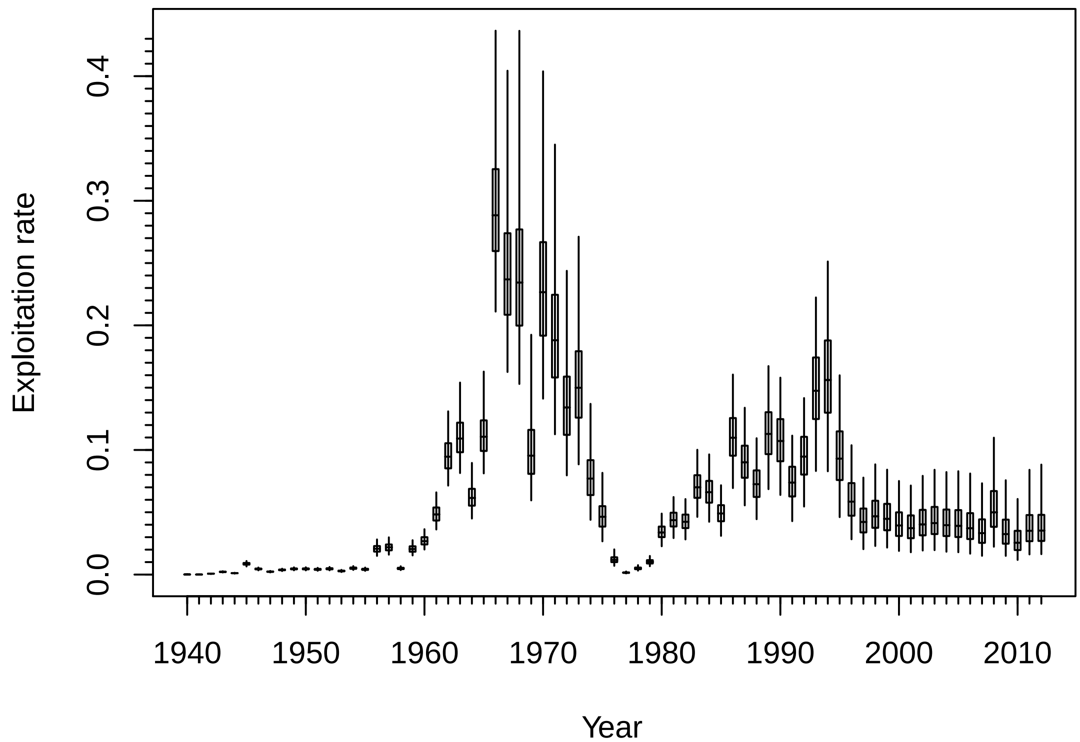

Figure 6. Marginal posterior distribution of exploitation rate plotted over time. Boxplots show the 2.5, 25, 50, 75 and 97.5 percentiles from the MCMC results.

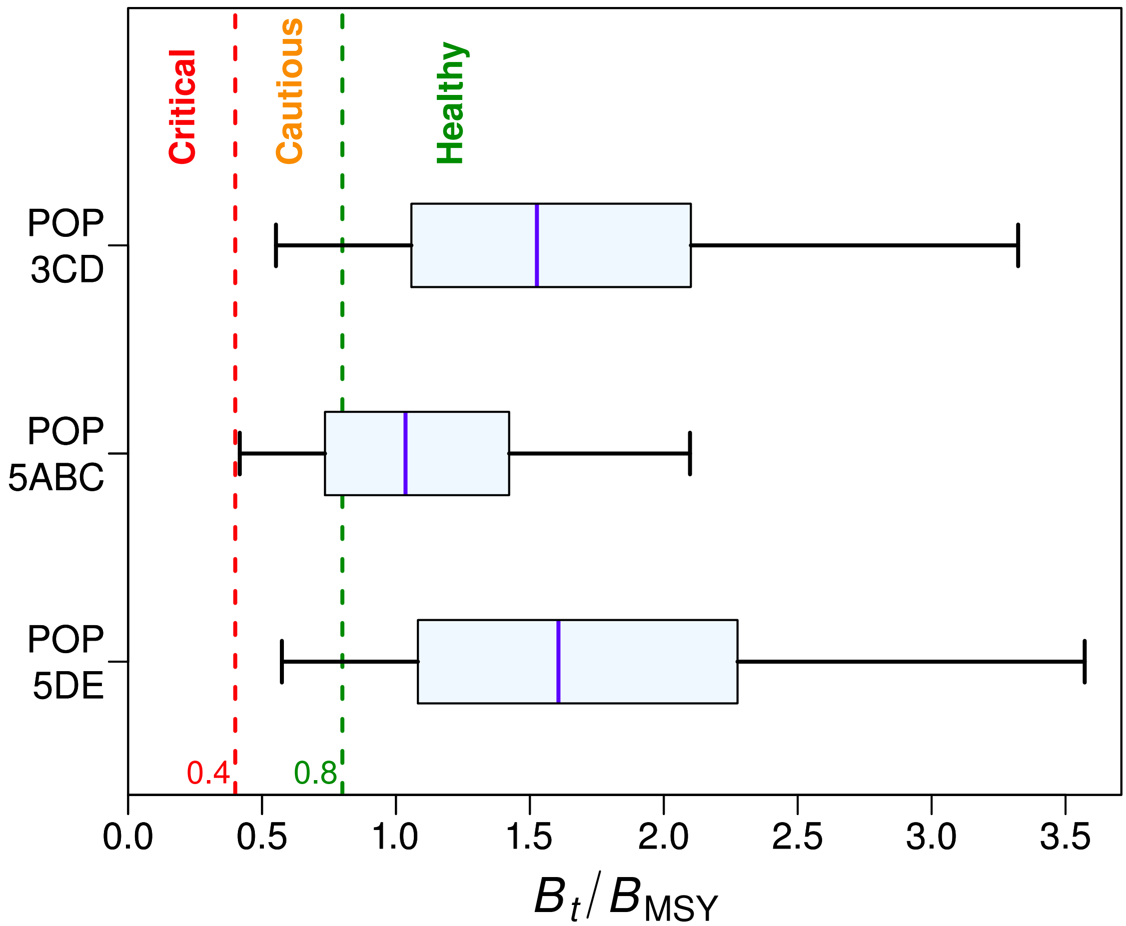

Figure 7. Current status of the three Canadian POP stocks relative to the DFO Precautionary Approach provisional reference points of $0.4B_{\mathrm{MSY}}$ and $0.8B_{\mathrm{MSY}}$. The value of B_t/B_{MSY} is for $t = 2013$ for 3CD (this assessment) and 5DE (Edwards et al., 2013), and for $t = 2011$ for area 5ABC (run 'Estimate $M\&h$' from Edwards et al. 2012b). Boxplots show the 5, 25, 50, 75 and 95 percentiles from the MCMC results.

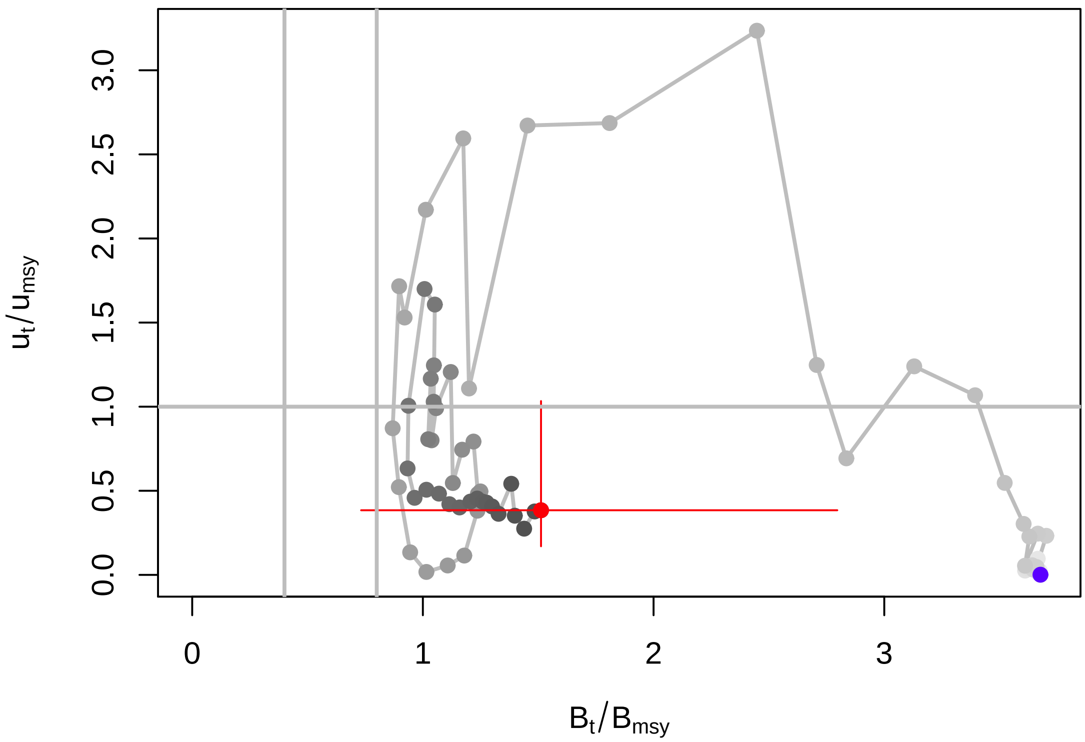

Figure 8. Phase plot through time of the medians of the ratios B_t/B_{MSY} (the spawning biomass in year t relative to B_{MSY}) and u_t/u_{MSY} (the exploitation rate in year t relative to u_{MSY}). Blue filled circle is the starting year (1940). Years then proceed from light grey through to dark grey with the final year (2012) as a filled red circle, and the red lines represent the 10% and 90% percentiles of the posterior distributions for the final year. Vertical grey lines indicate the Precautionary Approach provisional limit and upper stock reference points of 0.4B_{MSY} and 0.8B_{MSY}, and horizontal grey line indicates u_{MSY}.

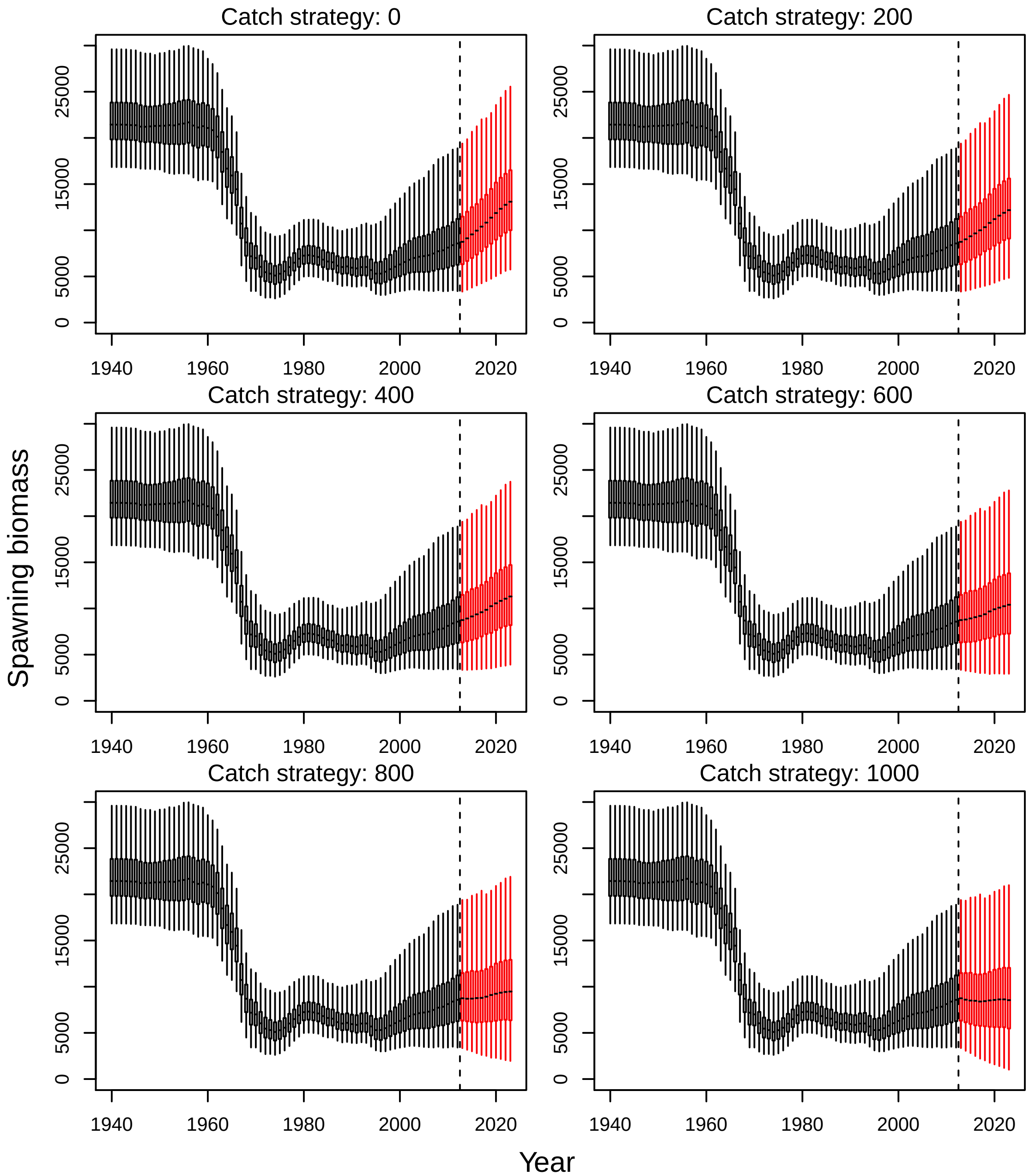

Figure 9. Projected biomass (t) under different constant catch strategies (t); boxplots show the 2.5, 25, 50, 75 and 97.5 percentiles from the MCMC results. For each of the 1,000 samples from the MCMC posterior, the model was run forward in time (red, with medians in black) with a constant catch, and recruitment was simulated from the stock-recruitment function with lognormal error (see equation F.24). For reference, the average catch over the last 5 years (2007-2011) is 547 t.

Table 1. The 5th, 50th and 95th percentiles of MCMC-derived quantities from the 1,000 samples of the MCMC posterior. Definitions are: B_0 – unfished equilibrium spawning biomass (mature females), V_0 – unfished equilibrium vulnerable biomass (males and females), B_{2013} – spawning biomass at the start of 2013, V_{2013} – vulnerable biomass in the middle of 2013, u_{2012} – exploitation rate (ratio of total catch to vulnerable biomass) in the middle of 2012, $u_{\max}$ – maximum exploitation rate (calculated for each sample as the maximum exploitation rate from 1940-2012), B_{MSY} – equilibrium spawning biomass at MSY (maximum sustainable yield), u_{MSY} – equilibrium exploitation rate at MSY, V_{MSY} – equilibrium vulnerable biomass at MSY. All biomass values (and MSY) are in tonnes. For reference, the average catch over the last 5 years (2007-2011) is 547 t.

Value	Percentile		
	5%	50%	95%
	From model output		
B_0	17,562	21,442	27,877
V_0	32,687	38,855	49,469
B_{2013}	3,888	8,745	17,269
V_{2013}	7,360	16,427	32,072
B_{2013}/B_0	0.189	0.406	0.684
V_{2013}/V_0	0.199	0.420	0.708
u_{2012}	0.018	0.035	0.077
$u_{\max}$	0.221	0.288	0.418
	MSY-based quantities		
$0.4B_{\mathrm{MSY}}$	1,433	2,324	3,592
$0.8B_{\mathrm{MSY}}$	2,866	4,647	7,183
B_{MSY}	3,583	5,809	8,979
B_{MSY}/B_0	0.178	0.272	0.357
$B_{2013}/B_{\mathrm{MSY}}$	0.552	1.526	3.323
MSY	700	1,048	1,509
u_{MSY}	0.045	0.091	0.174
$u_{2012}/u_{\mathrm{MSY}}$	0.134	0.384	1.434
V_{MSY}	7,586	11,729	17,112
V_{MSY}/V_0	0.213	0.301	0.379

Table 2. Decision table concerning the limit reference point $0.4B_{\mathrm{MSY}}$ for 1-10 year projections for a range of constant catch strategies (in tonnes). Values are P($B_t > 0.4B_{\mathrm{MSY}}$), i.e. the probability of the spawning biomass (mature females) at the start of year t being greater than the limit reference point. The probabilities are the proportion (to two decimal places) of the 1000 MCMC samples for which $B_t > 0.4B_{\mathrm{MSY}}$. For reference, the average catch over the last 5 years (2007-2011) is 547 t.

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

Annual catch	Projection year										
strategy	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
0	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	1.00	1.00	1.00
200	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
400	0.99	0.99	0.98	0.98	0.98	0.98	0.99	0.99	0.99	0.99	0.99
600	0.99	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.97	0.97	0.97
800	0.99	0.98	0.98	0.97	0.97	0.96	0.96	0.96	0.95	0.95	0.95
1000	0.99	0.98	0.97	0.96	0.95	0.95	0.94	0.94	0.93	0.93	0.92
1200	0.99	0.98	0.97	0.95	0.94	0.93	0.92	0.92	0.90	0.90	0.89
1400	0.99	0.98	0.95	0.94	0.92	0.92	0.90	0.88	0.87	0.84	0.83
1600	0.99	0.97	0.95	0.93	0.91	0.89	0.86	0.83	0.81	0.79	0.77
1800	0.99	0.97	0.94	0.92	0.89	0.85	0.82	0.79	0.76	0.74	0.72
2000	0.99	0.96	0.94	0.90	0.86	0.81	0.78	0.75	0.72	0.69	0.65

Table 3. Decision table for the upper reference point $0.8B_{\mathrm{MSY}}$ for 1-10 year projections, such that values are P($B_t > 0.8B_{\mathrm{MSY}}$). For reference, the average catch over the last 5 years (2007-2011) is 547 t.

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

Annual catch	Projection year										
strategy	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
0	0.87	0.88	0.90	0.92	0.93	0.94	0.94	0.95	0.96	0.96	0.97
200	0.87	0.88	0.89	0.90	0.91	0.92	0.93	0.93	0.94	0.95	0.95
400	0.87	0.87	0.88	0.88	0.89	0.90	0.91	0.91	0.92	0.92	0.93
600	0.87	0.86	0.86	0.86	0.87	0.87	0.88	0.88	0.88	0.88	0.89
800	0.87	0.86	0.85	0.84	0.85	0.85	0.85	0.84	0.85	0.85	0.85
1000	0.87	0.85	0.83	0.83	0.82	0.81	0.81	0.81	0.80	0.80	0.79
1200	0.87	0.84	0.82	0.81	0.79	0.78	0.77	0.76	0.75	0.74	0.72
1400	0.87	0.84	0.81	0.79	0.76	0.75	0.73	0.72	0.70	0.69	0.67
1600	0.87	0.83	0.80	0.76	0.74	0.71	0.69	0.67	0.65	0.63	0.61
1800	0.87	0.83	0.78	0.74	0.71	0.68	0.64	0.61	0.59	0.57	0.53
2000	0.87	0.82	0.77	0.72	0.68	0.63	0.60	0.57	0.53	0.49	0.46

Table 4. Decision table for the reference point B_{MSY} for 1-10 year projections, such that values are P$(B_t > B_{\mathrm{MSY}})$. For reference, the average catch over the last 5 years (2007-2011) is 547 t.

P$(B_t > B_{\mathrm{MSY}})$

Annual catch	Projection year										
strategy	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
0	0.78	0.80	0.82	0.84	0.86	0.88	0.90	0.91	0.92	0.93	0.94
200	0.78	0.80	0.81	0.82	0.84	0.85	0.87	0.88	0.89	0.90	0.91
400	0.78	0.79	0.80	0.80	0.81	0.82	0.84	0.85	0.85	0.86	0.87
600	0.78	0.78	0.79	0.78	0.79	0.79	0.80	0.81	0.82	0.82	0.83
800	0.78	0.77	0.77	0.76	0.76	0.76	0.76	0.77	0.77	0.77	0.77
1000	0.78	0.77	0.75	0.74	0.73	0.73	0.73	0.72	0.72	0.71	0.72
1200	0.78	0.76	0.74	0.71	0.70	0.69	0.68	0.68	0.67	0.67	0.66
1400	0.78	0.75	0.71	0.70	0.67	0.66	0.64	0.63	0.62	0.61	0.58
1600	0.78	0.74	0.70	0.66	0.64	0.61	0.60	0.58	0.56	0.54	0.52
1800	0.78	0.73	0.69	0.64	0.60	0.57	0.54	0.52	0.49	0.47	0.44
2000	0.78	0.72	0.66	0.61	0.56	0.53	0.49	0.46	0.44	0.40	0.37

Table 5. Decision table for the alternative reference point $0.2B_0$ for 1-10 year projections, such that values are P$(B_t > 0.2B_0)$. For reference, the average catch over the last 5 years (2007-2011) is 547 t.

P$(B_t > 0.2B_0)$

Annual catch	Projection year										
strategy	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
0	0.94	0.95	0.96	0.97	0.97	0.98	0.98	0.99	0.99	0.99	0.99
200	0.94	0.94	0.95	0.96	0.96	0.97	0.97	0.98	0.98	0.98	0.98
400	0.94	0.94	0.94	0.95	0.95	0.95	0.96	0.96	0.96	0.96	0.96
600	0.94	0.94	0.94	0.93	0.93	0.93	0.93	0.94	0.94	0.94	0.94
800	0.94	0.94	0.93	0.91	0.91	0.90	0.91	0.90	0.90	0.90	0.89
1000	0.94	0.93	0.91	0.89	0.89	0.88	0.87	0.86	0.86	0.85	0.84
1200	0.94	0.92	0.90	0.88	0.85	0.84	0.83	0.81	0.80	0.79	0.78
1400	0.94	0.91	0.88	0.85	0.82	0.79	0.78	0.76	0.74	0.73	0.72
1600	0.94	0.90	0.86	0.82	0.78	0.75	0.74	0.72	0.69	0.66	0.64
1800	0.94	0.90	0.84	0.79	0.76	0.72	0.69	0.65	0.62	0.59	0.57
2000	0.94	0.89	0.82	0.77	0.72	0.68	0.64	0.59	0.57	0.52	0.48

Table 6. Decision table for the alternative reference point $0.4B_0$ for 1-10 year projections, such that values are P$(B_t > 0.4B_0)$. For reference, the average catch over the last 5 years (2007-2011) is 547 t.

P$(B_t > 0.4B_0)$

Annual catch	Projection year										
strategy	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
0	0.52	0.57	0.62	0.67	0.70	0.74	0.78	0.81	0.84	0.86	0.87
200	0.52	0.56	0.59	0.64	0.67	0.70	0.73	0.75	0.77	0.80	0.81
400	0.52	0.54	0.56	0.59	0.62	0.66	0.68	0.70	0.71	0.73	0.75
600	0.52	0.52	0.53	0.55	0.58	0.60	0.63	0.64	0.65	0.66	0.67
800	0.52	0.51	0.51	0.51	0.52	0.55	0.56	0.57	0.59	0.59	0.60
1000	0.52	0.50	0.49	0.48	0.48	0.49	0.50	0.51	0.52	0.51	0.51
1200	0.52	0.49	0.46	0.44	0.44	0.44	0.45	0.44	0.44	0.43	0.42
1400	0.52	0.48	0.44	0.42	0.40	0.38	0.38	0.38	0.37	0.35	0.33
1600	0.52	0.47	0.42	0.40	0.36	0.35	0.32	0.31	0.30	0.28	0.27
1800	0.52	0.46	0.40	0.36	0.33	0.30	0.28	0.26	0.25	0.24	0.22
2000	0.52	0.44	0.38	0.34	0.29	0.27	0.23	0.21	0.20	0.18	0.16

Table 7. Decision table for comparing the projected biomass to the current biomass, given by probabilities P$(B_t > B_{2013})$. For reference, the average catch over the last 5 years (2007-2011) is 547 t.

P$(B_t > B_{2013})$

	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
0	-	0.99	0.99	0.99	0.99	0.98	0.98	0.99	0.99	0.99	0.99
200	-	0.95	0.93	0.93	0.93	0.93	0.93	0.94	0.94	0.94	0.94
400	-	0.80	0.76	0.76	0.77	0.79	0.81	0.82	0.83	0.85	0.85
600	-	0.58	0.54	0.56	0.57	0.60	0.63	0.66	0.67	0.68	0.70
800	-	0.39	0.37	0.38	0.42	0.44	0.47	0.50	0.52	0.53	0.53
1000	-	0.24	0.24	0.26	0.29	0.32	0.34	0.36	0.38	0.38	0.38
1200	-	0.16	0.16	0.17	0.20	0.22	0.25	0.26	0.26	0.27	0.27
1400	-	0.10	0.10	0.12	0.14	0.16	0.17	0.18	0.19	0.19	0.19
1600	-	0.06	0.07	0.08	0.10	0.11	0.12	0.12	0.13	0.13	0.13
1800	-	0.04	0.04	0.06	0.07	0.08	0.09	0.09	0.09	0.09	0.09
2000	-	0.03	0.03	0.03	0.04	0.05	0.06	0.07	0.07	0.07	0.06

Table 8. Decision table for comparing the projected exploitation rate to that at MSY, such that values are P$(u_t > u_{\mathrm{MSY}})$, i.e. the probability of the exploitation rate in the middle of year t being greater than that at MSY. For reference, the average catch over the last 5 years (2007-2011) is 547 t.

P$(u_t > u_{\mathrm{MSY}})$

	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
200	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00
400	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04
600	0.12	0.12	0.12	0.12	0.11	0.11	0.10	0.10	0.10	0.11	0.11
800	0.20	0.20	0.20	0.21	0.21	0.20	0.20	0.20	0.20	0.20	0.20
1000	0.28	0.29	0.30	0.31	0.31	0.31	0.30	0.30	0.31	0.31	0.31
1200	0.38	0.40	0.40	0.41	0.40	0.40	0.41	0.41	0.41	0.42	0.43
1400	0.46	0.48	0.49	0.51	0.52	0.52	0.52	0.53	0.54	0.55	0.57
1600	0.54	0.56	0.58	0.60	0.61	0.61	0.62	0.63	0.65	0.65	0.67
1800	0.60	0.63	0.65	0.67	0.68	0.70	0.70	0.72	0.72	0.74	0.75
2000	0.66	0.70	0.73	0.75	0.75	0.77	0.78	0.79	0.80	0.81	0.82

A REQUEST FOR SCIENCE INFORMATION AND ADVICE

Data / Données

Fisheries and Oceans Canada | Pêches et Océans Canada

REQUEST FOR PEER REVIEWED SCIENCE INFORMATION AND/OR ADVICE

Title of Request	ID# (for internal use only)
Request for CSAP review: Pacific Ocean Perch (3CD, 5DE) (PMFC areas)	

Branch Contact

Name Tamee Karim	Title Regional Manager, Groundfish
Telephone Number (604) 666-9033	Email tameezan.karim@dfo-mpo.gc.ca
Region Pacific	Sector Groundfish Management Unit
Directorate	Branch Fisheries Management

Request Details

Issue requiring science information and/or advice (i.e., "the question" or "the need"). Posed as a question to be answered by Science.

What is the current status of the POP (3CD, 5DE) stocks relative to the DFO Precautionary Approach reference points for areas 3CD and 5DE? Please include a pictorial of the status of POP relative to the PA policy graph.

Is it appropriate to recommend alternative Limit Reference Points (LRP), Upper Stock Reference Points (USR) and Target Reference Points (TRP) for POP (3CD/5DE)? If so what would the alternative points be (include biological considerations and rationale used to form them)?

Include decision tables which forecast the impact/risk of varying total fishing mortality levels on future population trends. Please also include long-term trajectory graphs.

This request is consistent with the work on the groundfish strategic assessment plan with respect to prioritizing of species assessments.

Rationale or context for the request: What will the information/advice be used for? Who will be the end user(s)? Will it impact other DFO programs or regions?

This species accounts for the largest single species proportion of quotas making up the annual rockfish TAC for west coast of Canada. POP accounts for 25% of the total weight of rockfish landed by bottom trawl gear. A detailed stock assessment has never been done for these stocks. Updated harvest advice is required to determine if current harvest levels are sustainable and compliant with the PA.

Once an accepted assessment is completed, the fishery checklist for this species can be created (if it falls within the decision tree that indicates it is a species that requires a checklist). The management portion for this species has been completed and requires the science portion to be updated.

Additional Information (please be as concise as possible)

What is the expected course of action if science advice is not provided? Could this negatively affect species, habitat(s) or ecosystem(s) of concern?

In the absence of updated science information, the GMU has been making management decisions based on dated information and will continue to do so until new information is provided.

Canada

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Will this request help DFO move towards an ecosystem approach to management? For example, does this request relate to overarching national objectives of conserving biodiversity, productivity or habitat, or more specific bioregional ecosystem objectives (if they exist)? Are there specific ecosystem considerations that should be taken into account?	
(●) Yes ( ) No	If yes, please elaborate. While this not an ecosystem (based) assessment it is critical to know the relative abundance of various ecosystem components before one can move towards ecosystem based fisheries management. This assessment will provide a time series of biomass estimates for the target species that can be used in the future to inform an ecosystem based approach.
Is the provision of this information/advice required to meet a legal or regulatory requirement?	
( ) Yes (●) No	If yes, please elaborate.
Does this issue have public, media and/or government (outside DFO) interest or involvement at the local, regional, national or international level?	
(●) Yes ( ) No	If yes, please elaborate. Fishing industry and environmental organizations will be interested. These stocks border the United States waters, and so there may be international interest.
Is the provision of this information/advice required to support a departmental priority?	
(●) Yes ( ) No	If yes, describe which priority and provide a short rationale. This work contributes to the implementation of the policies within the Sustainable Fisheries Framework.
Is the provision of this information/advice required to respond to or meet an international commitment?	
( ) Yes (●) No	If yes, which commitment?

Administrative Details

Deadline

Latest Possible Date to Receive Science Advice November 2012
Rationale Updated advice from this assessment is requested for inclusion in the 2013 Groundfish Integrated Fisheries Management Plan.

Funding

Do you have funds to cover any extra costs associated with this request (i.e.: special analysis, meeting costs, translation)?	
( ) Yes (●) No	If yes, please elaborate.

Branch Approval

Canada

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Data / Données

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Approval Date	Name of Director (or Delegated Authority)	Submission Date

Approved request forms are to be submitted to the CSA/CSAS Coordinator in your region.

Canada

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B CATCH DATA

B.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 POP biomass, particularly in Queen Charlotte Sound. Canadian effort escalated in 1965 but the catch never reached the levels of those by the combined foreign vessels.

Prior to 1977, no quotas were in effect for any slope rockfish species. Since then, the groundfish management unit (GMU) at the Department of Fisheries and Oceans (DFO) has imposed a combination of species/area quotas, area/time closures, and trip limits on the major species. Quotas were first introduced for POP (and Yellowmouth Rockfish *S. reedi*) in 1979 for GMU area 3C (Tables B.1 and B.2); areas are defined in Figure 1. The west coast of Vancouver Island (WCVI, 3CD) has not historically shown high densities of POP compared to other regions along the BC coast.

Table B.1. Annual trawl Total Allowable Catches (TACs) in tonnes for Pacific Ocean Perch in Groundfish Management Unit areas. Year can either be calendar year (1979-1996) or fishing year (1997 on). See Table B.2 for explanation of Notes column.

Year	3C	3D	5AB	5CD	5E	Coast	Notes
1979	50		2000		600	2650	a
1980	600		2200		800	3600	b
1981	500		1500	1800	800	4600	c
1982	500	250	1000	2000	800	4550	
1983	500	250	1000	2000		3750	d
1984	500	250	800	2000		3550	e
1985	300	350	850	2000		3500	
1986	100	350	500	2000		2950	
1987	100	350	500	2000		2950	
1988	100	350	700	3000		4150	
1989	150	400	850	3000	400	4800	
1990	150	400	850	2450	400	4250	f
1991	0	400	850	2150	400	3800	g,h
1992	0	400	850	2400	400	4050	i
1993	150	400	850	2400	400	4200	j,k
1994	1173	207	2177	1107	253	4917	l
1995	548	72	1892	1178	544	4234	m
1996	491	164	1500	4003	726	6884	n,o
1997	431	230	2358	2818	644	6481	+,p,q
1998	300	230	2070	2817	730	6147	+
1999	300	230	2070	2817	730	6147	+
2000	300	230	2070	2818	730	6148	+,r,s
2001	300	230	2070	2818	730	6148	+
2002	300	230	2070	2518	730	5848	+,t,u,v
2003	300	230	2070	2818	730	6148	+
2004	300	230	2070	2818	730	6148	+
2005	300	230	2070	2818	730	6148	+
2006	300	230	2070	2118	730	5448	+,w,x,y,z
2007	300	230	2070	2118	730	5448	+
2008	300	230	2070	2118	730	5448	+
2009	300	230	2070	2118	730	5448	+
2010	300	230	2070	2118	730	5448	+
2011	300	230	1942	1987	730	5189	+,A
2012	300	230	1814	1856	730	5189	+,A

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

Code	Management Actions
a	Started limited vessel entry for Halibut fleet.
b	Started experimental over-harvesting of SW Vancouver Island POP stock.
c	Started limited vessel entry for Sablefish fleet.
d	Started experimental unlimited harvesting of Langara Spit POP stock (5EN).
e	Ended experimental over-harvesting of SW Vancouver Island POP stock.
f	Started *Individual Vessel Quotas* (IVQ) systems for Halibut and Sablefish.
g	Started *Dockside Monitoring Program* (DMP) for the Halibut fleet.
h	Started limited vessel entry for *Hook and Line* (H&L) fleet inside.
i	Started limited vessel entry for H&L fleet outside.
j	Stopped experimental fishing of Langara Spit POP stock.
k	Closed POP fishery in PMFC area 5EN (Langara Spit).
l	Started DMP for Trawl fleet.
m	Implemented catch limits (monthly) on rockfish aggregates for H&L.
n	Started 100% onboard observer program for offshore Trawl fleet.
o	Started DMP for H&L fleet.
p	Started IVQ system for Trawl *Total Allowable Catch* (TAC) species (April 1, 2007)
q	Implemented catch limits (15,000 lbs per trip) on combined non-TAC rockfish for the Trawl fleet.
r	Implemented catch limits (20,000 lbs per trip) on rockfish aggregates for the Halibut option D fleet.
s	Implemented formal allocation of rockfish species between Halibut and H&L sectors.
t	*Department of Fisheries and Oceans* (DFO) reduced the 5CD POP TAC by 300 tonnes for research use as payment for the Hecate Strait Pacific Cod charter for each of the next three fishing seasons.
u	Established the inshore rockfish conservation strategy.
v	Closed areas to preserve four hexactinellid (glassy) sponge reefs.
w	DFO reduced the 5CD POP TAC by 700 tonnes for use in possible research programs.
x	Introduced an *Integrated Fisheries Management Plan* (IFMP) for most groundfish fisheries.
y	Started 100% at-sea electronic monitoring for H&L.
z	Implemented mandatory retention of rockfish for H&L.
+	Pacific Ocean Perch and Yellowmouth Rockfish caught within Subarea 102-3 and those portions of Subareas 142-1, 130-3 and 130-2 found southerly and easterly of a straight line commencing at $52°20'00''$N $131°36'00''$W thence to $52°20'00''$N $132°00'00''$W thence to $51°30'00''$N $131°00'00''$W and easterly and northerly of a straight line commencing at $51°30'00''$N $131°00'00''$W thence to $51°39'20''$N $130°30'30''$W will be deducted from the vessel's 5CD IVQ for those two species.
A	POP combined 5ABCD TAC reduction to 3413 t will be achieved over a three year period (from 2010) through an annual reduction of 258 t. The expected catch level will be 68% of TAC. TAC is subject to annual review.

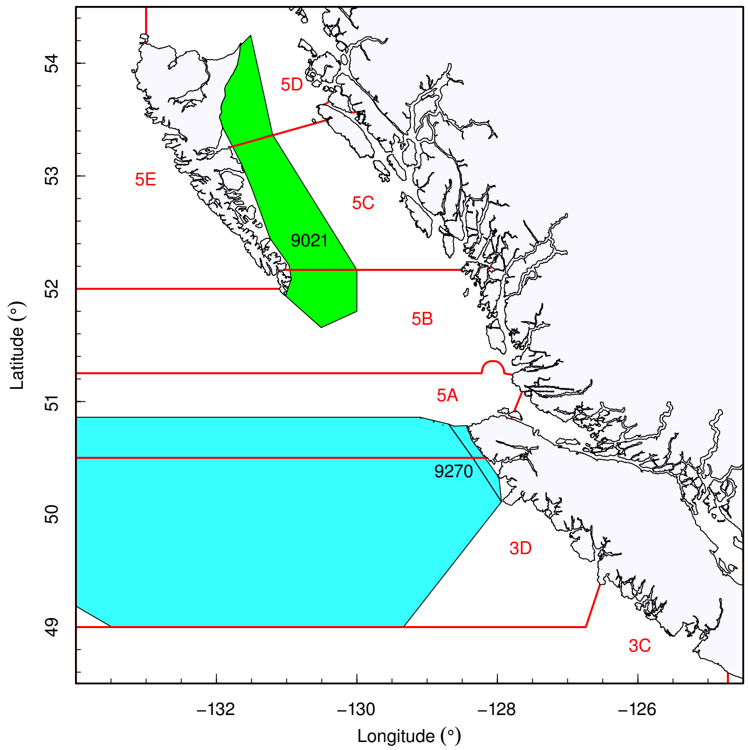

Figure B.1. Problematic statistical areas in the PacHarv3 database that span multiple PMFC areas – 9021 (shaded) in the figure shows DFO statistical area 102 and 9270 (shaded) shows statistical area 127, where the inshore areas 2E and 27, respectively, are excluded.

B.2 POP CATCH RECONSTRUCTION

A detailed account of how we reconstruct Pacific Ocean Perch catch on the BC coast can be found in Haigh and Yamanaka (2011). The algorithm uses eight historical data sources (the earliest extending back to 1918) and five modern catch databases housed at various DFO facilities. 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.

For the first time here, we document a significant departure from previous reconstructions in that for the trawl and trap fisheries from 1954 to 1995 we use only the database GFCatch (Rutherford, 1999). In previous reconstructions, we used both GFCatch (logbook records) and PacHarv3 (sales slips) because they should be recording the same landings. Assuming this, landings from the two sources can be compared by year and area, and the maximum values used. Unfortunately, sales slips used large statistical areas while logbooks used PMFC areas and subareas. Conversion from the former to the latter can be performed reasonably well, but two large statistical areas in particular straddle PMFC boundaries with no easy way to assign the catch (Figure B.1). The first area, coded 9021, comprises statistical areas 2E and 102, which cover large portions of PMFC 5B, 5C, and 5D. For POP in particular, area 9021 includes Moresby Gully in PMFC areas 5B and 5C. The second area, coded 9270, comprises statistical areas 27 and 127 which include a POP agglomeration in PMFC areas 3D and 5A off the NW tip of

Vancouver Island. The problem occurs, for example, when GFCatch reports POP landings from 3D and 5A in the 9270 region while the POP landings reported by PacHarv3 are assigned to 3D or 5A only, neither of which matches the GFCatch landings. At this time, we have no method for splitting the PacHarv3 catch from these two statistical areas.

Another departure from Haigh and Yamanaka (2011) is the addition of a previously unused source of foreign catch numbers (Ketchen, 1980*a*). In the earlier POP assessment for 5ABC (Edwards et al., 2012*b*), Russian and Japanese catch were estimated by Ketchen (1980*b*) for the Queen Charlotte Sound (QCS) area; however, he only supplied a one-page Appendix for estimates of Russian rockfish catch for the west coast of Vancouver Island (WCVI) and the west coast of Haida Gwaii (WCHG). Japanese catch numbers were not supplied for WCVI and WCHG in his QCS reconstruction. Fortunately, Ketchen (1980*a*) reported landings estimates of “Pacific Ocean Perch”, a term most likely including all rockfish, by the Japanese fleet. Therefore, in this document we use the Russian catch in Ketchen (1980*b*) and the Japanese catch in Ketchen (1980*a*).

Composition ratios of specific rockfish species (herein POP/TRF), derived from modern landings data, are used to disaggregate the two broad rockfish categories in the historical series. Historical discard rates are also estimated based on recent discard rates. The reconstruction yields catches (landings + discards) by calendar year, fishery (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 U_t (for year t) from unknown areas to each PMFC area i using the proportions $C_{ti}/\sum_{i\in\mathtt{PMFC}} C_{ti}$ of known catch C_{ti} in PMFC area i. But decisions made include all identified removals whenever possible. Some data sources are not incorporated here (e.g., research survey catch), but this procedure includes currently available sources of commercial removals.

Catch of rockfish species is known with ‘certainty’ from 1996 on; however, because POP supports a major fishery, catches of this species are fairly well-known back to 1956 (Ketchen, 1976). During the period 1950–1975, US vessels routinely caught more POP than did Canadian vessels. Additionally, from the mid-1960s to the mid-1970s, foreign fleets (Russian and Japanese) removed large amounts of POP. These large catches were first reported by Westrheim et al. (1972) then Gunderson et al. (1977) for the period 1956-74, which subsequent researchers such as Leaman and Stanley (1993) used for the WCVI region. 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. Additionally, the region labelled ‘Vancouver Island’ by some researchers was in fact the INPFC (International North Pacific Fisheries Commission) region ‘Vancouver’, which extends from 50°30′N (the northern boundary of PMFC 3D) to 47°30′N (north of Cape Elizabeth, WA). Therefore, the original data series in Gunderson et al. (1977) not only reports total rockfish catch, it also includes removals from Washington state.

This assessment reconstructs catch back to 1940 (Figure B.2, Table B.3) when the fishery increased during World War II. From 1918 to 1939, removals were negligible compared to those that came after 1939. The over-harvesting experiment initiated in 1980 (Leaman and Stanley, 1993) appears to have had little more effect than to increase catch far above the TAC until the IVQ system was implemented in 1997.

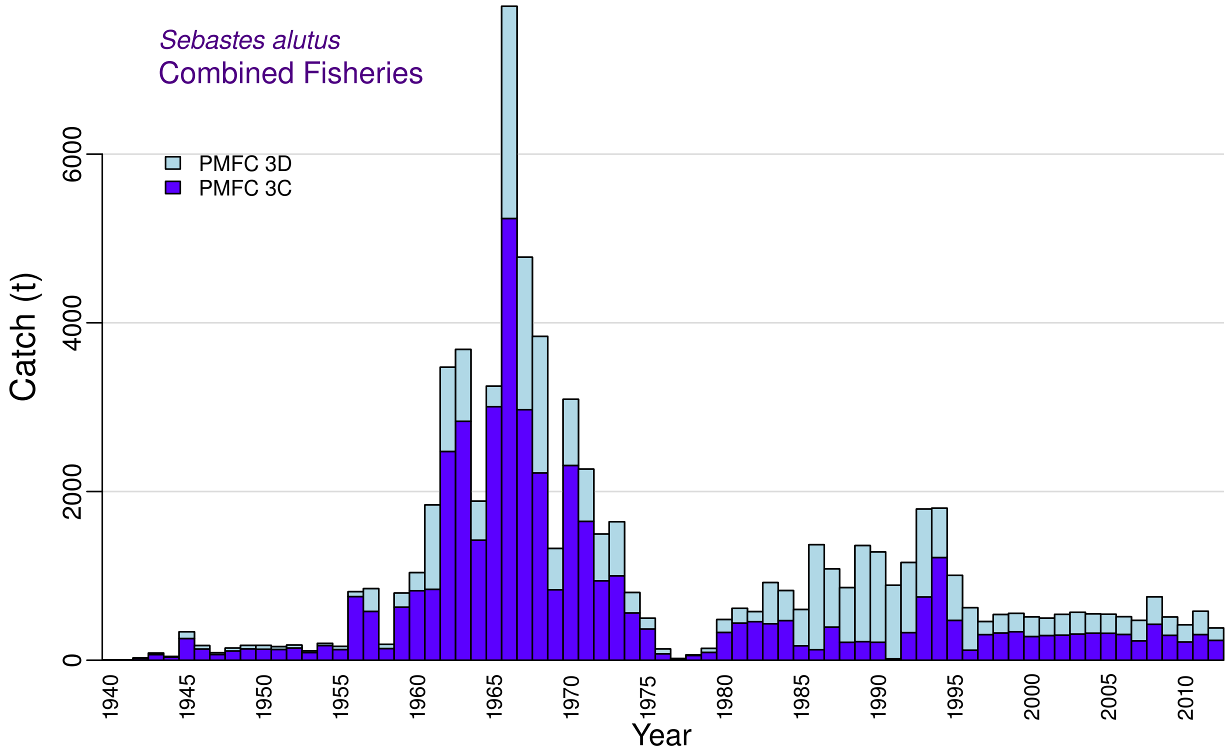

Figure B.2. Reconstructed total (landed + discarded) catch (t) for Pacific Ocean Perch from all fisheries combined in PMFC major areas 3C and 3D.

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). Improvements in data storage and retrieval technologies are still ongoing.

Table B.3. Catch reconstruction (landings + discards, tonnes) for Pacific Ocean Perch in PMFC major areas 3C & 3D, where k denotes fishery ID: 1=Trawl, 2=Halibut, 3=Sablefish, 4=Dogfish–Lingcod, and 5=H&L Rockfish. The final three columns give the totals across all fisheries. Values $<$ 1000 are reported to three significant figures. *2012 data remain incomplete (up to September 2012), and so the 2011 catch was used as model input for 2012.

Year	$3C_{k=1}$	$3D_{k=1}$	$3CD_{k=1}$	$3C_{k\in(2:5)}$	$3D_{k\in(2:5)}$	$3CD_{k\in(2:5)}$	3C	3D	3CD
1940	2.80	0.785	3.59	0.000191	0.00221	0.00240	2.80	0.787	3.59
1941	2.32	0.340	2.66	0.000702	0.00812	0.00882	2.32	0.348	2.66
1942	21.1	5.74	26.9	0.00177	0.0204	0.0222	21.2	5.76	26.9
1943	66.2	18.5	84.6	0.00462	0.0535	0.0581	66.2	18.5	84.7
1944	35.8	7.97	43.8	0.00609	0.0704	0.0765	35.8	8.04	43.9
1945	257	79.3	337	0.00477	0.0552	0.0600	257	79.4	337
1946	133	40.1	173	0.00419	0.0484	0.0526	133	40.2	173
1947	67.9	20.9	88.8	0.00134	0.0155	0.0168	68.0	20.9	88.8
1948	110	33.9	144	0.00204	0.0236	0.0256	110	33.9	144

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Table B.3 – continued from previous page

Year	$3C_{k=1}$	$3D_{k=1}$	$3CD_{k=1}$	$3C_{k\in(2:5)}$	$3D_{k\in(2:5)}$	$3CD_{k\in(2:5)}$	3C	3D	3CD
1949	134	41.2	176	0.00271	0.0314	0.0341	134	41.3	176
1950	131	45.3	176	0.00116	0.0134	0.0145	131	45.3	176
1951	128	33.0	161	0.00460	0.0434	0.0480	128	33.0	161
1952	145	34.4	180	0.00175	0.0320	0.0337	145	34.4	180
1953	91.3	19.8	111	0.00185	0.0161	0.0180	91.3	19.8	111
1954	174	25.1	199	0.00200	0.0199	0.0219	174	25.1	199
1955	127	37.4	164	0.00108	0.0232	0.0243	127	37.4	164
1956	755	57.9	812	0.00331	0.0219	0.0252	755	57.9	812
1957	579	270	849	0.00977	0.0337	0.0435	579	270	849
1958	138	50.2	189	0.00316	0.0332	0.0364	138	50.2	189
1959	630	166	796	0.00509	0.0358	0.0409	630	166	796
1960	824	215	1,038	0.00528	0.0400	0.0453	824	215	1,039
1961	841	1,000	1,840	0.00532	0.0520	0.0573	841	1,000	1,840
1962	2,475	999	3,474	0.0141	0.0604	0.0745	2,475	999	3,474
1963	2,833	852	3,684	0.00931	0.0387	0.0480	2,833	852	3,685
1964	1,424	462	1,886	0.00401	0.0279	0.0319	1,424	462	1,886
1965	3,005	244	3,249	0.00331	0.0232	0.0265	3,005	244	3,249
1966	5,237	2,516	7,753	0.00239	0.0277	0.0301	5,237	2,516	7,753
1967	2,970	1,808	4,778	0.00516	0.0373	0.0424	2,970	1,809	4,778
1968	2,221	1,618	3,839	0.00406	0.0304	0.0345	2,221	1,618	3,839
1969	835	490	1,325	0.00877	0.0310	0.0397	835	490	1,325
1970	2,309	785	3,094	0.0173	0.0368	0.0541	2,309	785	3,094
1971	1,646	619	2,266	0.0108	0.0104	0.0212	1,646	619	2,266
1972	941	554	1,495	0.0199	0.0574	0.0774	941	554	1,496
1973	1,000	641	1,641	0.0141	0.0243	0.0384	1,000	641	1,641
1974	561	242	802	0.0324	0.0291	0.0615	561	242	802
1975	371	128	498	0.0250	0.0246	0.0496	371	128	498
1976	75.7	57.4	133	0.0233	0.0268	0.0502	75.8	57.5	133
1977	17.3	1.19	18.5	0.0295	0.0309	0.0604	17.4	1.22	18.6
1978	56.5	7.44	63.9	0.0246	0.0286	0.0532	56.5	7.46	64.0
1979	93.1	46.6	140	0.0450	0.0602	0.105	93.2	46.7	140
1980	330	152	482	0.0386	0.0582	0.0968	330	152	482
1981	441	175	616	0.0350	0.0403	0.0753	441	175	616
1982	457	119	576	0.403	0.0420	0.445	457	119	576
1983	432	488	920	0.119	0.0440	0.163	432	488	921
1984	470	356	825	0.0522	0.0740	0.126	470	356	826
1985	171	430	601	0.0515	0.0999	0.151	171	430	601
1986	124	1,244	1,369	0.235	0.587	0.822	125	1,245	1,370
1987	393	688	1,081	0.322	1.18	1.51	393	689	1,082
1988	212	647	860	0.295	0.550	0.845	212	648	860
1989	220	1,138	1,358	0.230	1.38	1.61	220	1,139	1,359
1990	212	1,069	1,281	0.929	1.38	2.30	213	1,070	1,283
1991	12.3	863	875	5.19	8.79	14.0	17.5	872	889
1992	324	831	1,154	3.21	0.560	3.77	327	831	1,158
1993	750	1,041	1,791	0.0814	0.872	0.954	750	1,042	1,792
1994	1,217	583	1,800	0.0444	2.14	2.18	1,217	585	1,803
1995	473	534	1,006	0.0366	0.687	0.723	473	534	1,007
1996	119	502	622	0.0449	0.784	0.828	119	503	623
1997	304	154	457	0.0768	0.955	1.03	304	154	458
1998	323	218	541	0.140	0.619	0.758	323	218	541
1999	337	217	554	0.108	0.944	1.05	337	218	555

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Table B.3 – continued from previous page

Year	$3C_{k=1}$	$3D_{k=1}$	$3CD_{k=1}$	$3C_{k\in(2:5)}$	$3D_{k\in(2:5)}$	$3CD_{k\in(2:5)}$	3C	3D	3CD
2000	281	231	512	0.0682	0.486	0.554	281	232	513
2001	293	205	498	0.0762	0.558	0.634	293	206	499
2002	298	245	543	0.0686	0.515	0.584	298	246	544
2003	311	257	568	0.0475	0.397	0.444	311	258	569
2004	321	227	548	0.0494	0.605	0.654	321	228	549
2005	320	224	544	0.138	1.13	1.27	320	226	545
2006	306	210	516	0.164	0.197	0.361	306	210	516
2007	229	243	472	0.149	0.279	0.428	229	243	472
2008	426	324	750	0.0654	0.186	0.252	426	324	751
2009	295	217	512	0.00506	0.0677	0.0728	295	217	512
2010	217	202	418	0.0779	0.880	0.958	217	202	419
2011	304	276	580	0.0792	0.185	0.264	304	276	581
2012*	236	146	382	0.00839	0.267	0.276	236	146	382

APPENDIX C. TRAWL SURVEYS

C.1. INTRODUCTION

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

- US NMFS Triennial survey (Section C.3)
- west coast Vancouver Island (WCVI) synoptic survey plus an additional 1996 lower WCVI survey by FV Caledonian (Section C.4)
- historic RV G.B. Reed surveys off the west coast Vancouver Island (WCVI) (Section C.5)

All three sets of indices were used as indices of abundance in the 3CD stock assessment model, with the exception of the 1996 Caledonian survey index (Appendix F).

C.2. ANALYTICAL METHODS

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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:

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

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 CV of the annual biomass estimates is

$$CV_y = \frac{\sqrt{V_y}}{B_y} \, . \tag{C.6}$$

C.3. NMFS TRIENNIAL TRAWL SURVEY

C.3.1. DATA SELECTION

Tow-by-tow data from the US National Marine Fisheries Service (NMFS) triennial survey covering the Vancouver INPFC (International North Pacific Fisheries Commission) region were provided by (Mark Wilkins, NMFS, pers. comm.) for the seven years that the survey worked in BC waters (Figure C.1, Table C.1). 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 C.2). The NMFS survey database also identified in which country the tow was located. This information was plotted and checked against the accepted Canada/USA marine boundary: all tows appeared to be appropriately located with respect to country, based on the tow start position (Figure C.1). The NMFS designations were accepted for tows located near the marine border.

All usable tows have 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 Pacific Ocean Perch 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 C.2). Strata that were not surveyed consistently in all seven years of the survey were dropped from the analysis (Table C.1; Table C.2), allowing the remaining data to provide a comparable set of data for each year (Table C.3).

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

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	
50		5		1										
51	4			10										
52			4											
Total	**59**	**26**	**47**	**70**	**67**	**87**	**61**	**79**	**71**	**68**	**59**	**74**	**38**	**72**

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

Year	Stratum No.	Area (km²)	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 C.3. 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 C.2) 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 C.2) were also dropped.

	Number of tows			Area surveyed (km²)		
Survey year	CDN waters	US waters	Total	CDN waters	US waters	Total
1980	59	26	85	7,399	4,738	12,137
1983	47	70	117	7,399	4,738	12,137
1989	65	55	120	9,166	4,699	13,865
1992	59	50	109	9,166	4,699	13,865
1995	62	35	97	9,166	4,699	13,865
1998	54	42	96	9,166	4,699	13,865
2001	36	37	73	9,166	4,699	13,865
Total	382	315	697	–	–	–

The stratum definitions used in the 1980 and 1983 surveys were considerably different than those used in subsequent surveys, particularly in Canadian waters (Table C.3). Therefore, the 1980 and 1983 indices were scaled up by the ratio (9169 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 C.3). This occurs because the size of the total area fished was about twice as large in Canadian waters than in US waters (Table C.3).

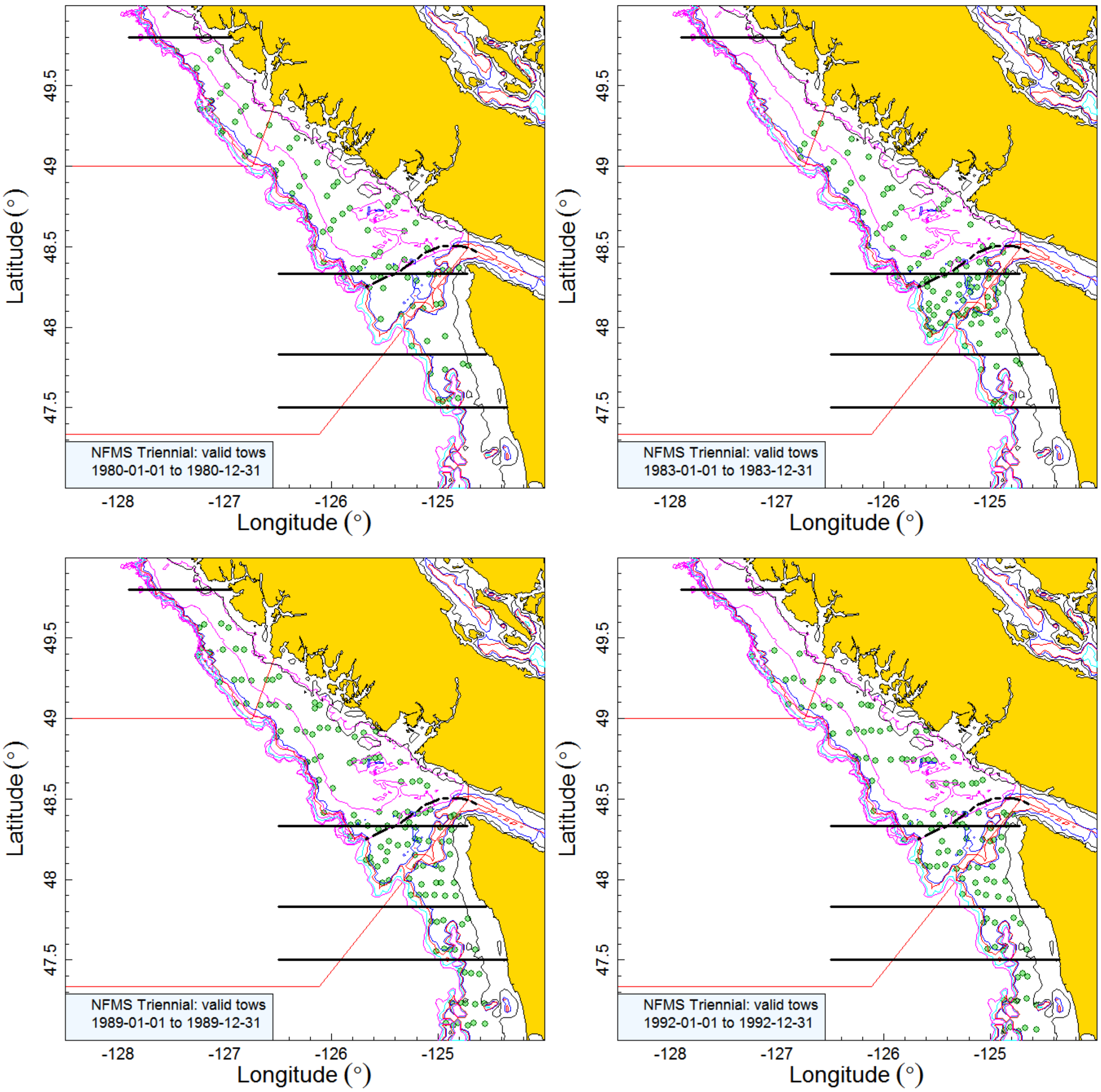


Figure C.1. Plot of tow locations (green dots) in the Vancouver INPFC region for the 1980, 1983, 1989 and 1992 NMFS triennial surveys in Canadian waters. Dashed line shows approximate position of the Canada/USA marine boundary. Horizontal lines are the stratum boundaries: 47°30', 47°50', 48°20' and 49°50'. Tows south of the 47°30' line were not included in the analysis. Isobaths act as stratum boundaries at 55, 183, 220, 366, and 500 m.

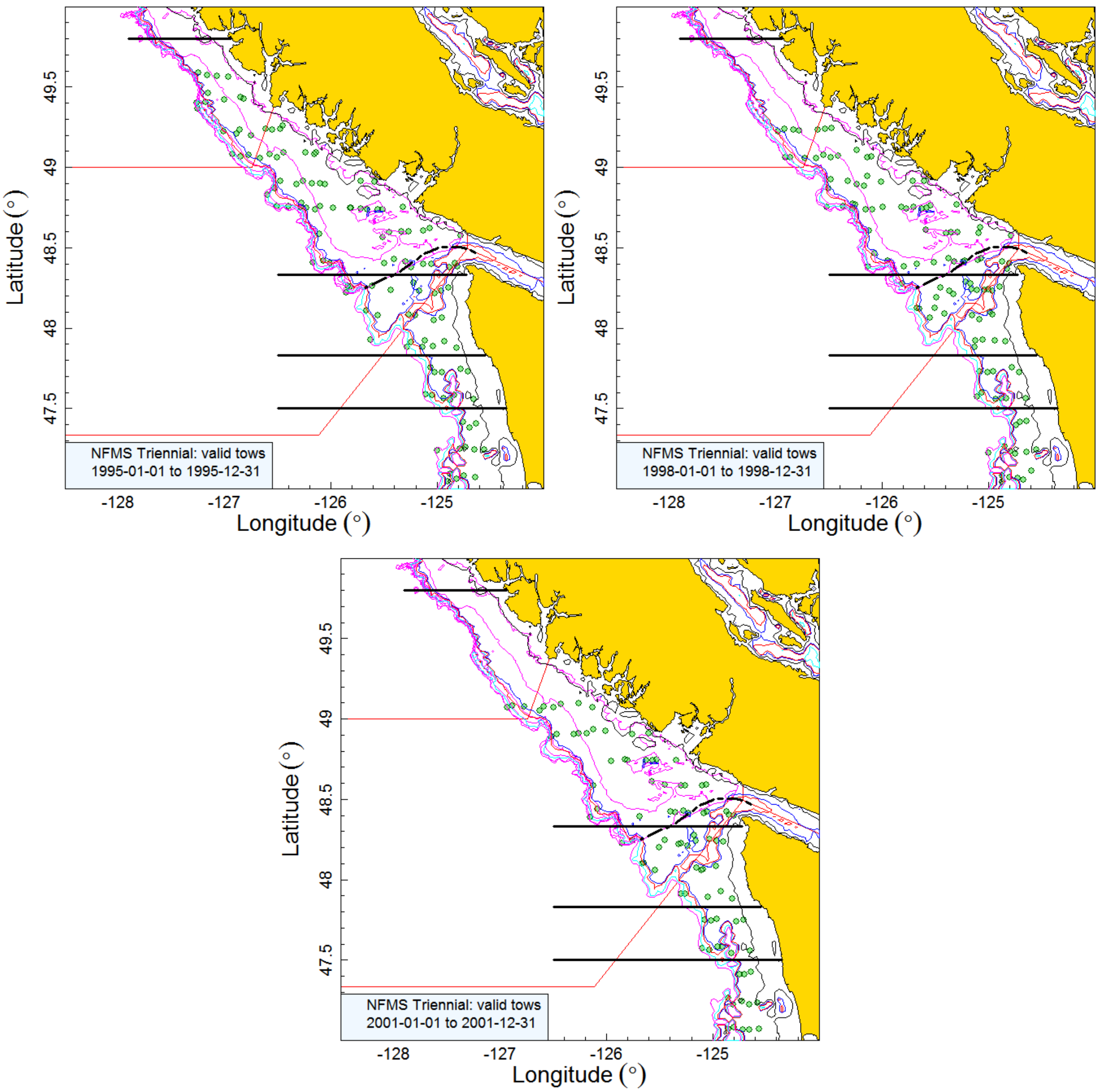


Figure C.1. (cont.). Plot of tow locations (green dots) in the Vancouver INPFC region for the 1995, 1998 and 2001 triennial surveys in Canadian waters.

C.3.2. METHODS

The data were analysed using the equations in Section C.1. When calculating the variance for this survey, it was assumed that the variance and CPUE within any stratum was constant, 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 $\left(B_{y_{ic}}\right)$ by the ratio of the relative area within each country:

$$B_{y_{i_c}} = B_{y_i} \frac{A_{y_{i_c}}}{A_{y_i}}, \quad \text{(C.7)}$$

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:

$$V_{y_{i_c}} = V_{y_i} \frac{A^2_{y_{i_c}}}{A^2_{y_i}}. \quad \text{(C.8)}$$

The partial variance $V_{y_{i_c}}$ for country *c* was used in (C.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 (C.6).

The biomass estimates (C.4) and the associated standard errors were adjusted to a constant area covered using the ratios of area surveyed provided in Table C.3. 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.

C.3.3. RESULTS

Pacific Ocean Perch were reasonably frequent in both US and Canadian waters along the shelf edge, with a great deal of between-year variability (Figure C.2). Note that the northern extension of the survey has varied from year to year (Figure C.2), but this difference has been compensated for by using a constant survey area for all years and assuming that the CPUE in the unsampled area was the same as that in the sampled stratum area. 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 C.3). The latter plot shows that this species was mainly found between 180 and 300 m, with few differences in preferred depth range between years.

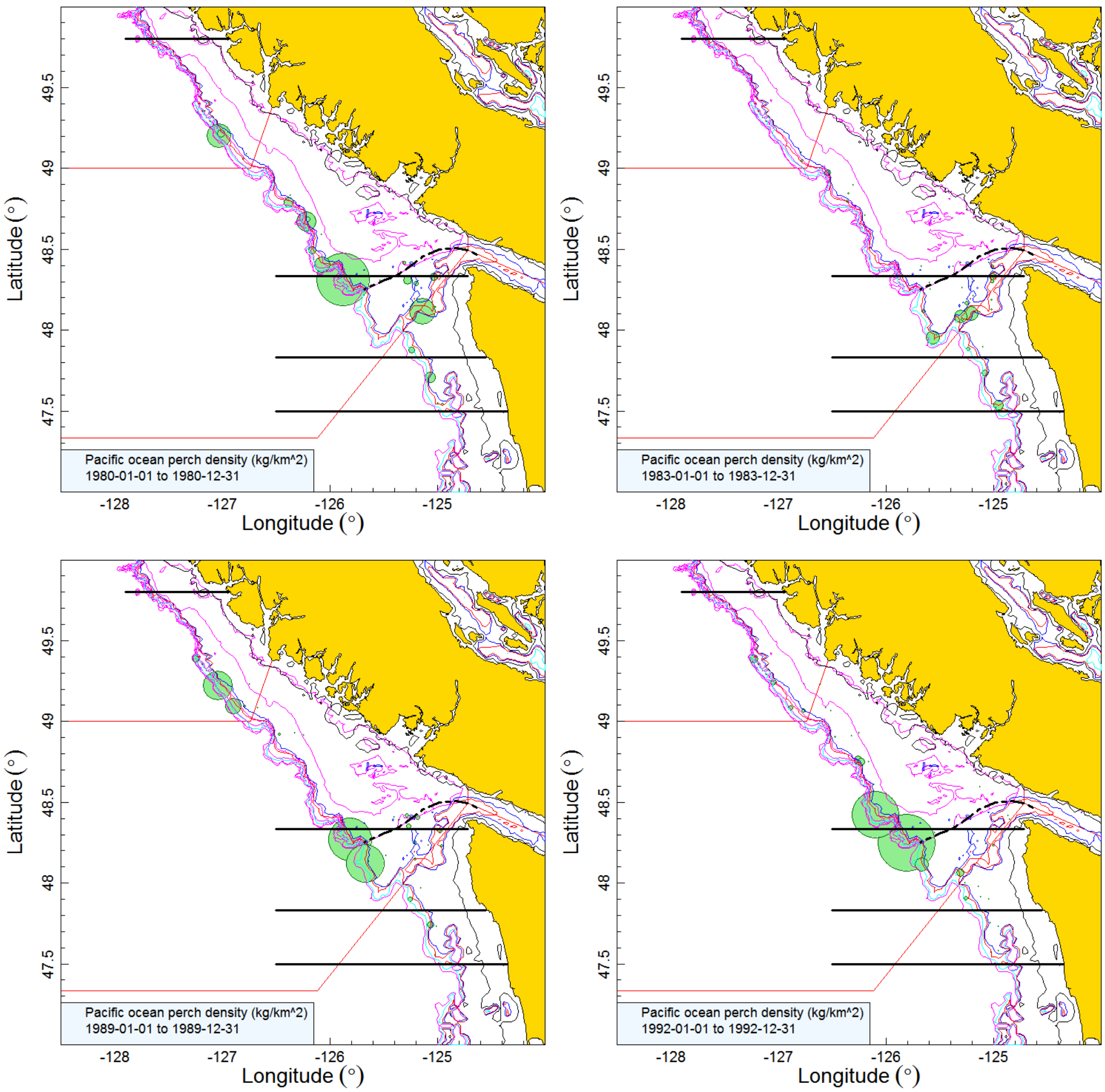


Figure C.2. Plot of valid tows, weighted by the density of Pacific Ocean Perch, in the Vancouver INPFC region for the 1980, 1983, 1989 and 1992 triennial surveys in Canadian waters. Catches in each year are scaled to the weight of the largest density of Pacific Ocean Perch (43,052 kg/km^2 in 1992). The approximate position of the Canada/USA marine boundary is shown (dashed line). The horizontal lines are the stratum boundaries: 47°30', 47°50', 48°20' and 49°50'.

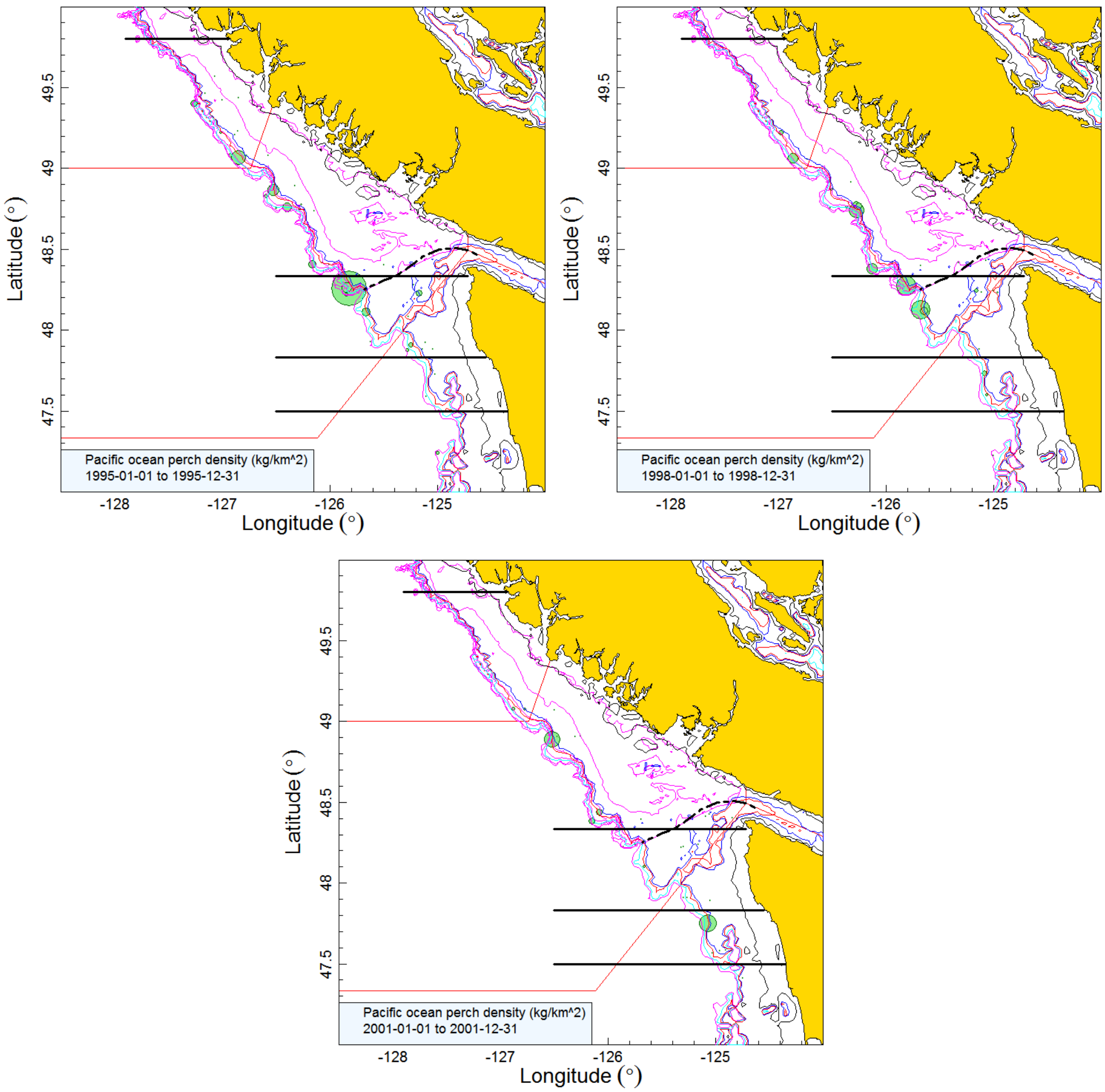


Figure C.2. (cont.). Plot of valid tows, weighted by the density of Pacific Ocean Perch, in the Vancouver INPFC region for the 1995, 1998 and 2001 triennial surveys in Canadian waters.

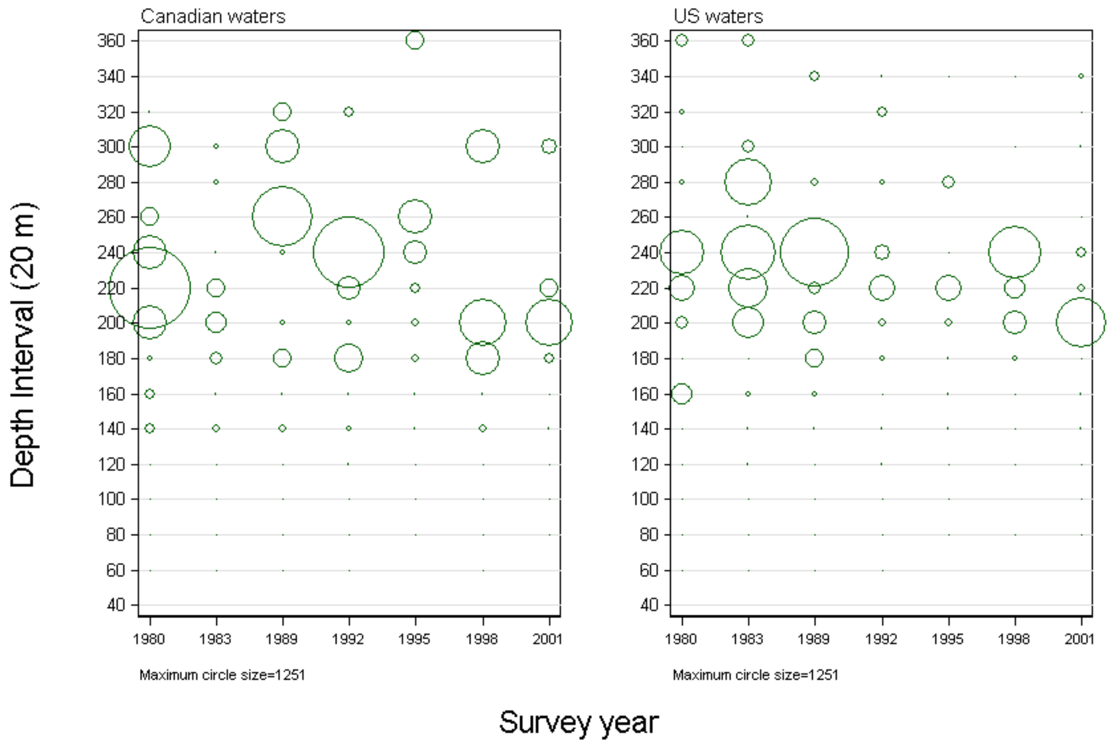


Figure C.3. Distribution of Pacific Ocean Perch catch weights for each survey year summarised into 20-m depth intervals for all valid tows (Table C.2) in Canadian and US waters of the Vancouver INPFC area. Depth intervals are labelled with the mid-point of the interval.

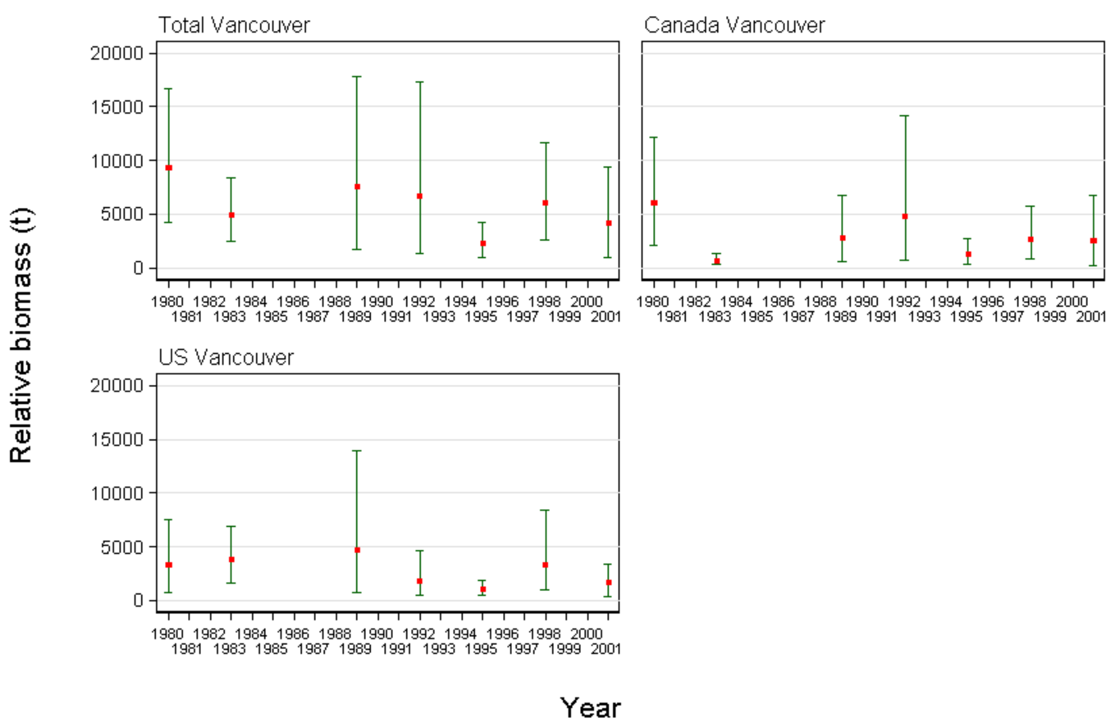


Figure C.4. Biomass estimates for three series of Pacific Ocean Perch in the INPFC Vancouver region (total region, Canadian waters only, and US waters only) with 95% bias-corrected error bars estimated from 1000 bootstraps.

Table C.4. Biomass estimates for Pacific Ocean Perch 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** (C.4)	**Mean bootstrap biomass**	**Lower bound biomass**	**Upper bound biomass**	**CV bootstrap**	**CV Analytic** (C.6)
Total Vancouver	1980	9,307	9,365	4,292	16,677	0.327	0.356
	1983	4,951	4,870	2,436	8,372	0.315	0.331
	1989	7,544	7,424	1,716	17,821	0.544	0.532
	1992	6,667	6,302	1,350	17,344	0.686	0.698
	1995	2,321	2,268	954	4,249	0.375	0.384
	1998	6,022	5,927	2,569	11,633	0.376	0.387
	2001	4,122	4,002	991	9,331	0.534	0.567
Canada Vancouver	1980	6,055	6,140	2,045	12,154	0.416	0.441
	1983	693	702	296	1,346	0.360	0.357
	1989	2,822	2,782	565	6,759	0.564	0.570
	1992	4,836	4,715	727	14,193	0.740	0.747
	1995	1,305	1,278	283	2,736	0.494	0.498
	1998	2,719	2,733	867	5,757	0.447	0.444
	2001	2,484	2,505	215	6,714	0.666	0.685
US Vancouver	1980	3,260	3,241	788	7,477	0.548	0.596
	1983	3,775	3,696	1,626	6,913	0.361	0.376
	1989	4,722	4,642	708	13,976	0.745	0.735
	1992	1,831	1,587	431	4,656	0.653	0.594
	1995	1,016	990	428	1,835	0.360	0.360
	1998	3,303	3,194	953	8,406	0.543	0.550
	2001	1,638	1,497	320	3,386	0.519	0.584

The biomass estimates and the associated annual CVs obtained from the above methods show no strong trend for the total region or the two sub-regions (Figure C.4). A few large tows in each survey year increased the overall variability of the survey for this species. All surveys have imprecise biomass estimates, with CVs ranging from a minimum 32% in 1983 to 69% for the 1992 "Total Vancouver" stratum (Table C.4). CVs for the sub-divided national strata tend to be higher for the same years. Note that the bootstrap estimates of CV 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.

Two hundred thirty-five of the 697 tows in this data set caught Pacific Ocean Perch over the entire history of the survey. The proportion of tows which contained Pacific Ocean Perch has been relatively consistent between 30 and 40%, with the last two surveys in Canadian waters below 30% while several of the surveys in US waters exceeded 40% (Figure C.5). Neither region appears to show a trend in this statistic.

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

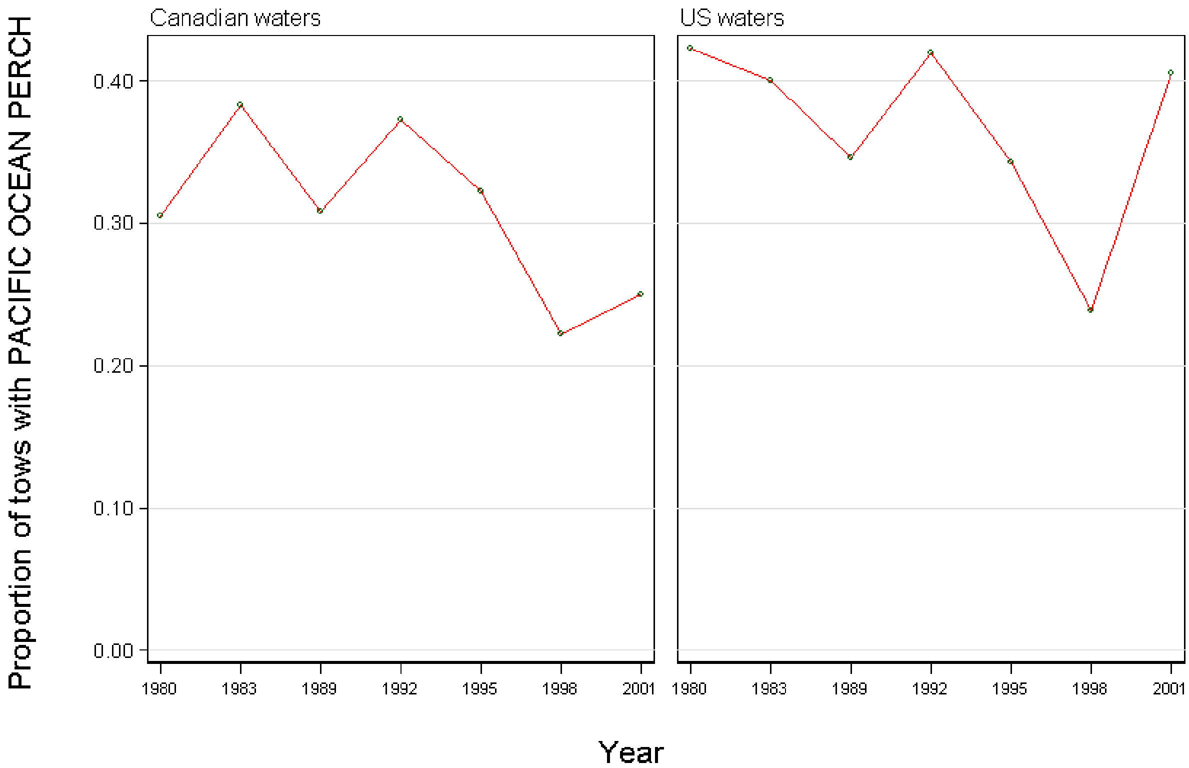


Figure C.5. Proportion of tows with Pacific Ocean Perch by year for the Vancouver INPFC region (Canadian and US waters).

C.4. WEST COAST VANCOUVER ISLAND SYNOPTIC TRAWL SURVEY AND 1996 CALEDONIAN SURVEY

C.4.1. DATA SELECTION

This survey has been conducted five times in the period 2004 to 2012 off the west coast of Vancouver Island by the 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 C.5; Figure C.6). Approximately 150-180 2-km^2 blocks are selected randomly among the four depth strata when conducting each survey (Olsen et. al. 2009). A random stratified survey was conducted in September 1996 by the FV Caledonian (Olsen et al. 1997), which was investigated for its potential to extend the WCVI synoptic series backwards by assuming that it represented the same proportionality constant (q) as the later surveys. This survey used the same net configuration as the synoptic surveys and a similar random selection of grid blocks, although it only covered the lower half of the west coast of Vancouver Island (Figure C.6) and the tows spanned a beginning tow depth of 150 m to 787 m (only three tows with starting depths deeper than 500 m, Table C.5). Tows in this survey were allocated to the same depth strata as those used for the WCVI synoptic survey. Net mensuration equipment was not used on this survey as it was not commonly available at the time. Consequently, because there are no *in situ* doorspread data, a value of 61.6 m (Yamanaka et al. 1996) was used to populate this field.

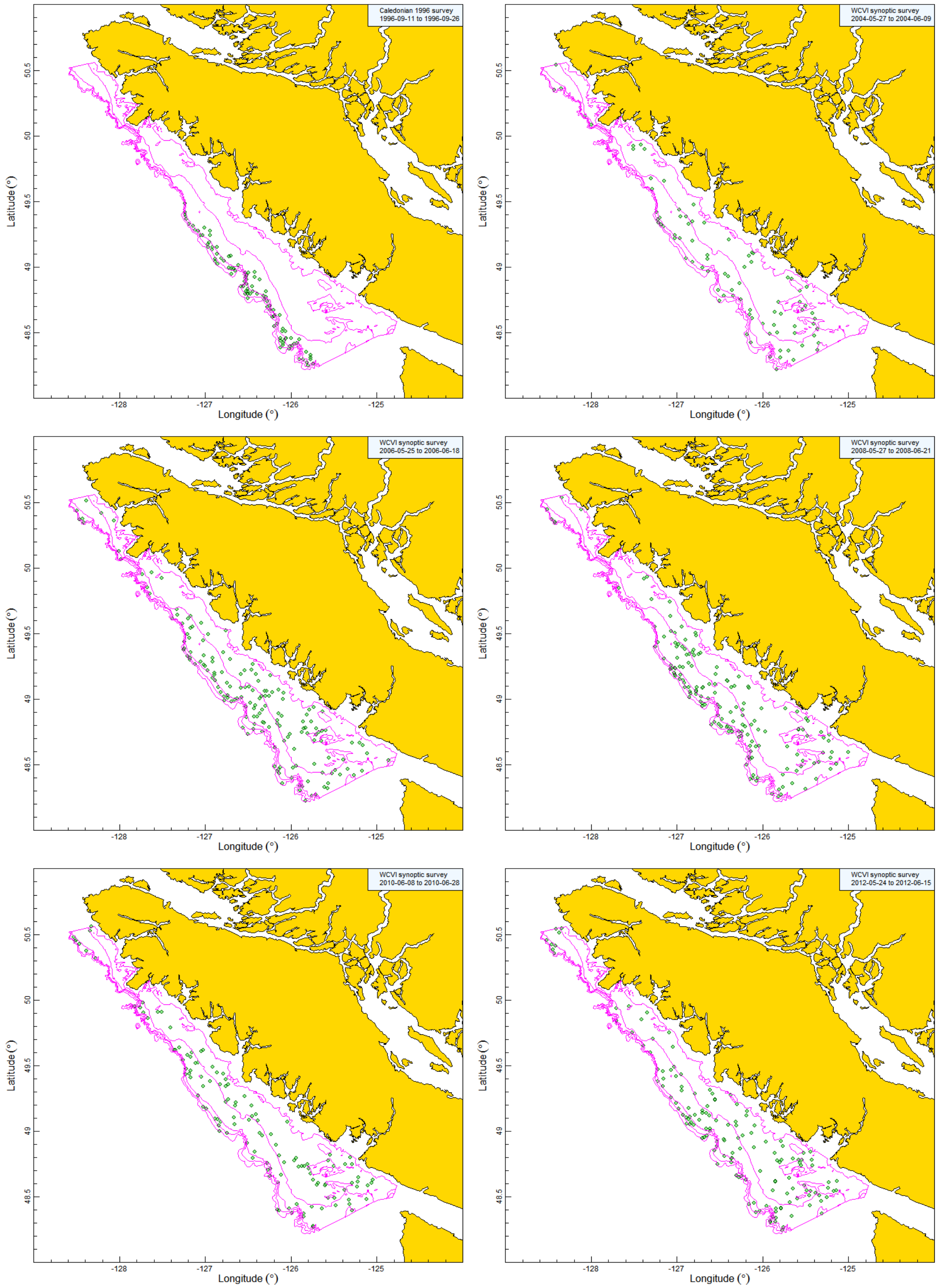


Figure C.6. Location of valid tows (green dots) conducted by the 1996 Caledonian survey (upper left) and the west coast Vancouver Island synoptic trawl survey (period 2004 to 2012).

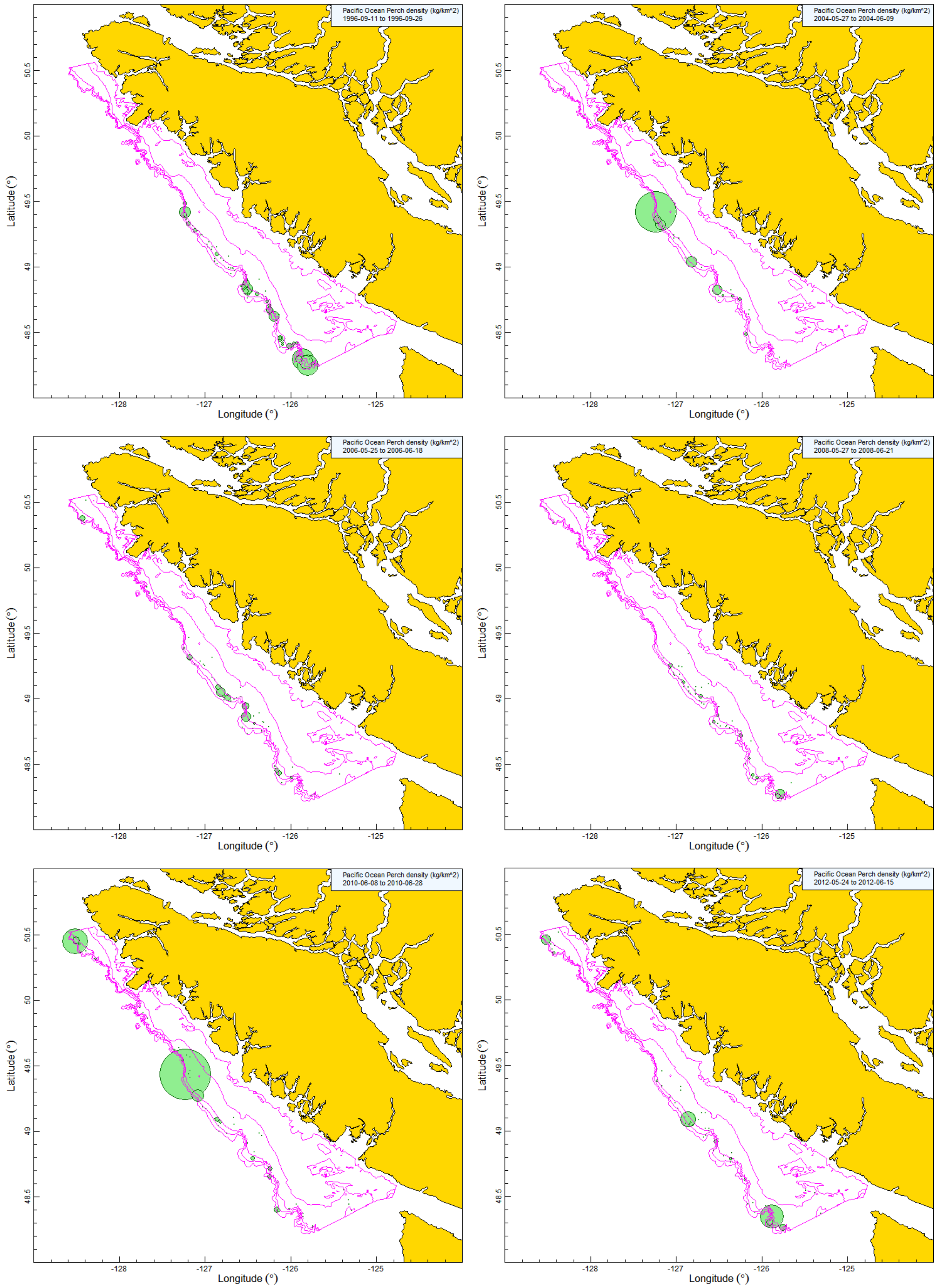


Figure C.7. Location of trawls capturing POP from the 1996 Caledonian survey (upper left) and the west coast Vancouver Island synoptic trawl surveys (2004, 2006, 2008, 2010 and 2012). Circles are proportional to catch density (largest circle = 42,560 kg/km^2 in 2010 WCVI survey).

Table C.5. Stratum designations and numbers of total and unusable tows for each year of the west coast Vancouver Island synoptic survey plus the 1996 Caledonian survey. Also shown is the area of each stratum and the start and end dates for each survey.

Survey year	Stratum depth zone 50-125 m	125-200 m	200-330 m	330-500 m	Total Tows[1]	Unusable tows	Start date	End date
1996	0	34	50	16	100	0	11-Sep-96	26-Sep-96
2004	35	34	13	8	106	16	26-May-04	09-Jun-04
2006	62	63	28	13	176	10	24-May-06	18-Jun-06
2008	54	51	34	24	178	15	27-May-08	21-Jun-08
2010	58	47	22	10	144	7	08-Jun-10	28-Jun-10
2012	61	46	26	20	157	4	23-May-12	15-Jun-12
Area (km^2)	6,180	3,936	752	688	11,556[2]	–	–	–

[1] GFBio usability codes=0,1,2,6
[2] Total area (km^2) for 2012 synoptic survey

A “doorspread density” value was generated for each tow based on the catch of Pacific Ocean Perch, the mean doorspread for the tow and the distance travelled (C.4). 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 61.6 m for the three years with no doorspread data (Table C.6). The default value is based on the mean of the observed doorspreads from the net mensuration equipment. Comparable density (kg/km^2) values were generated for each survey. These are plotted and show a wide variation between tows and between years (Figure C.7).

Table C.6. 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	90	–	–
2006	98	69	64.3
2008	60	107	64.5
2010	137	–	–
2012	153	–	–
All surveys	538	176	64.4

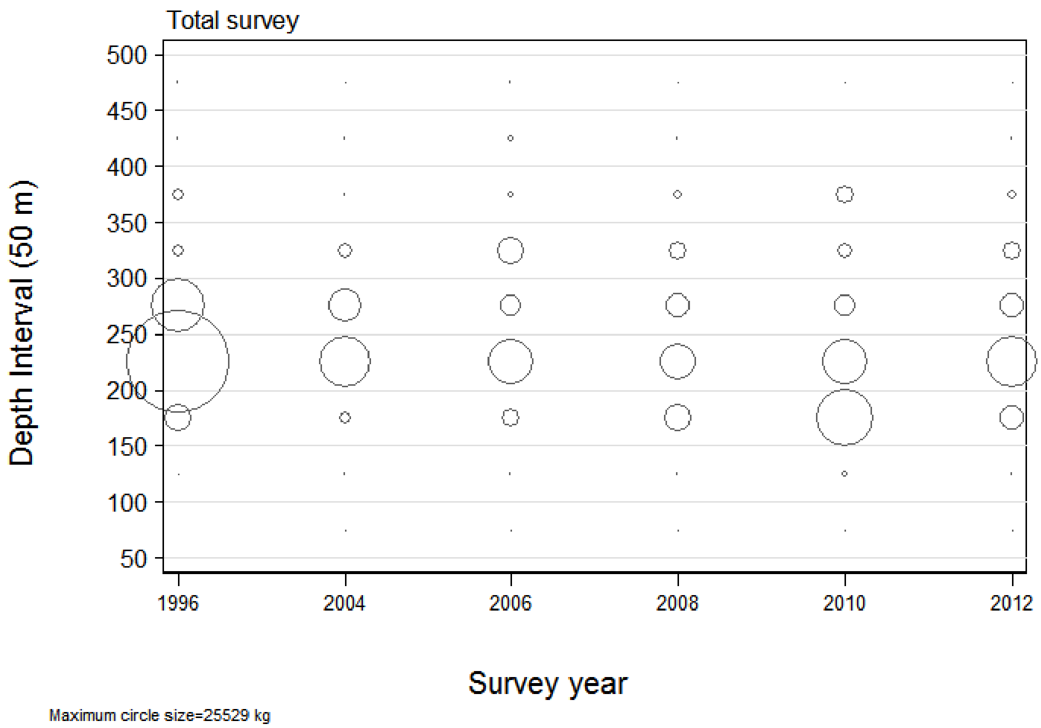


Figure C.8. Distribution of observed weights of Pacific Ocean Perch by survey year and 50-m depth zone. Depth zones are indicated by the start point of the depth interval. Minimum and maximum depths observed for POP: 91 m and 988 m, respectively. Depth is taken at the start position for each tow.

C.4.2. RESULTS

Pacific Ocean Perch were mainly taken at depths from 150 to 350 m, but there were sporadic observations at depths up to about 450 m (Figure C.8). Estimated biomass levels for Pacific Ocean Perch from this trawl survey declined from the initial 2004 survey, but then rose in 2010 to the highest level in the series (Figure C.9; Table C.7). The 2012 biomass index dropped to just below the average of the preceding four survey years. The estimated CV was high (36%) for the 2004 survey, while the two following surveys had CVs which were less than 20%, followed by an increase to near 30% in both 2010 and 2012 (Table C.7). The CV for the 1996 Caledonian survey (16%) is the lowest of the six surveys.

The proportion of tows capturing Pacific Ocean Perch ranged consistently between 34 and 44% for the five synoptic surveys when all four depth strata were included (Figure C.10). The proportion of tows capturing POP increased considerably when the most shallow stratum (5-125 m) was dropped, with the range increasing from 54% in 2004 to 79% in 1996. This second comparison was made to parallel the 1996 Caledonian survey, which did not fish in the shallow stratum.

It is unclear whether the 1996 Caledonian survey should be included with the synoptic series, which began in 2004. The survey cruise report (Olsen et al. 1997) states that the Caledonian survey was primarily directed at POP, which meant that the skipper would be favouring habitat and locations known to contain POP, within the range of behaviour allowed. This is in contrast to the design of the “synoptic” survey which is directed at a wider range of species (Olsen et al. 2008). The proportion of tows capturing POP in the 1996 survey relative to the succeeding five surveys is comparable when an equivalent depth range is summarised, and the biomass estimate exhibits a similar range as those from the synoptic surveys. After the available information was reviewed, it was decided that the 1996 Caledonian survey should not be linked with the subsequent synoptic surveys because the synoptic surveys were conducted in late spring (May and June) while the 1996 Caledonian survey was conducted in September, a period when POP are thought to leave the area (see final two columns in Table C.5).

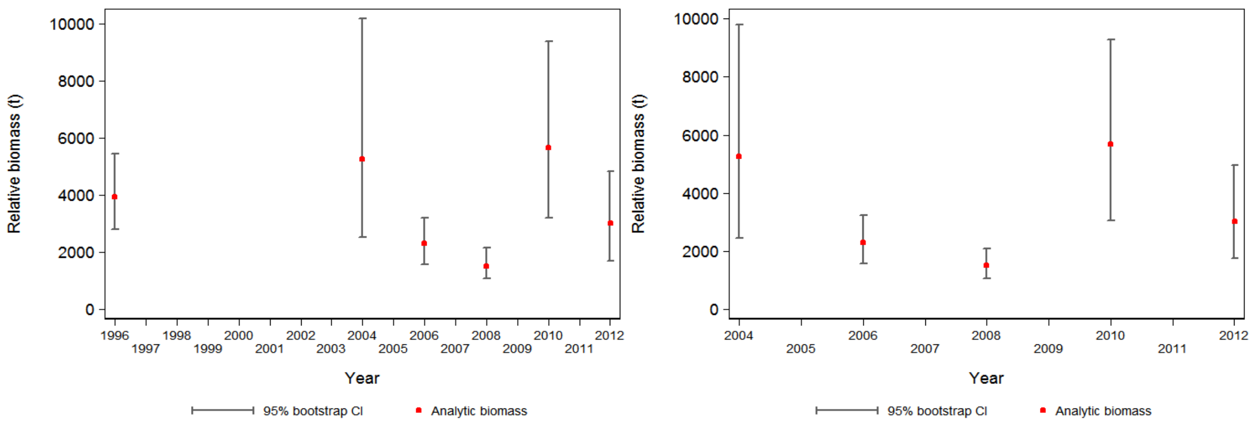


Figure C.9. [left panel] Biomass estimates for Pacific Ocean Perch from the 1996 Caledonian survey and the 2004 to 2012 west coast Vancouver Island synoptic trawl surveys with stratum 1 (50–125 m) omitted for the five WCVI synoptic surveys and with the 1996 Caledonian stratum areas matching the WCVI synoptic stratum areas (Table C.5); [right panel] plot of biomass estimates for Pacific Ocean Perch from the 2004 to 2012 west coast Vancouver Island synoptic trawl surveys with all strata included. Bias-corrected 95% confidence intervals from 1000 bootstrap replicates are plotted.

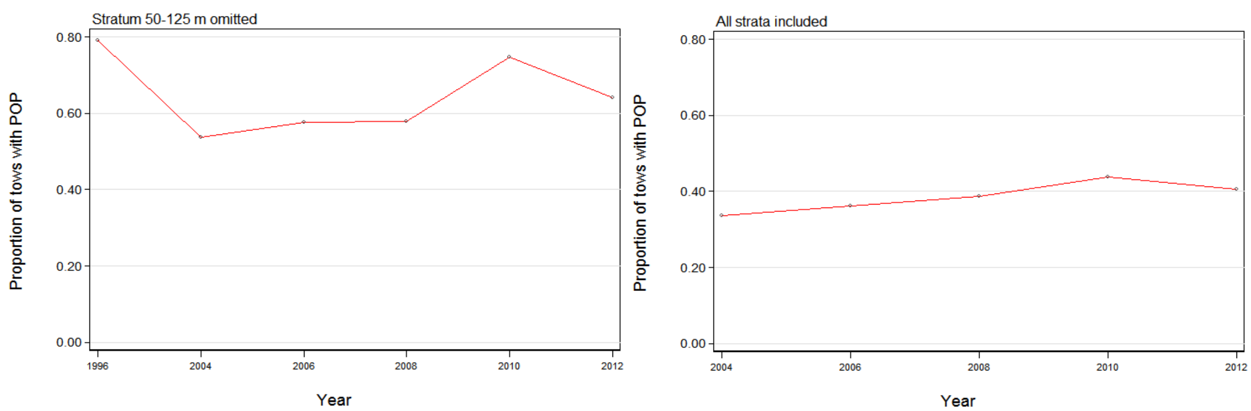


Figure C.10. Proportion of tows by stratum and year capturing Pacific Ocean Perch in the WCVI synoptic trawl survey: [left panel] omit Stratum 1 (50–125m) and include 1996 Caledonian survey; [right panel] include Stratum 1 (50–125m) and exclude 1996 Caledonian survey.

Table C.7. Biomass estimates for Pacific Ocean Perch from the WCVI synoptic trawl survey for the survey years 1996 (Caledonian), 2004 to 2012. The 1996 Caledonian survey areas by stratum were increased to match the equivalent 2012 WCVI synoptic strata (see Table C.5). 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** (C.6)
Exclude Stratum 1 (50–125 m)						
1996	3,946	3,942	2,801	5,451	0.167	0.164
2004	5,270	5,310	2,514	10,186	0.359	0.367
2006	2,307	2,314	1,548	3,183	0.184	0.183
2008	1,517	1,511	1,059	2,135	0.181	0.180
2010	5,675	5,631	3,200	9,403	0.278	0.284
2012	3,010	3,027	1,679	4,840	0.263	0.274
Include Stratum 1 (50–125 m)						
2004	5,273	5,333	2,454	9,814	0.360	0.367
2006	2,307	2,299	1,574	3,237	0.181	0.183
2008	1,517	1,519	1,043	2,089	0.179	0.180
2010	5,676	5,665	3,057	9,273	0.281	0.284
2012	3,010	3,054	1,733	4,961	0.269	0.274

The five WCVI synoptic survey indices spanning the period 2004 to 2012 were accepted as a linked series of abundance indices for use in the stock assessment model (described in Appendix F). The 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 five synoptic surveys.

C.5. HISTORIC WEST COAST VANCOUVER ISLAND GB REED TRAWL SURVEYS

C.5.1. DATA SELECTION

A number of deepwater surveys capable of capturing POP were conducted by RV G.B. Reed off the west coast of Vancouver Island over the period 1965 to 1972 (Table C.8; Figure C.11). Several of these surveys, particularly the 1965 and 1966 surveys, were conducted over large exploratory areas where only a fraction of the tows were conducted off WCVI (Westrheim 1967). The remaining five surveys were concentrated in the southern half of WCVI known as PMFC Area 3C (Figure C.11). These surveys had inconsistent designs, and it is not known if the tow locations were selected in a random manner (1967: Westrheim et al. 1968; 1968: report not available; 1969: Harling et al. 1969; 1970: Harling et al. 1970; 1972: report not available).

These surveys were examined for areas of consistent coverage: this occurred almost entirely on La Perouse Bank (DFO localities known as Deep Big Bank and Fingers). There were tows in some years in other parts of 3C and some in 3D, but these two localities were the only ones fished consistently by all five surveys from 1967 to 1972. Tows outside these two areas were dropped (although a few nearby tows were accepted). Plots of the accepted tow locations are shown in Figure C.12, after dropping all tows east of –125.8°W and those shallower than 125 m. A plot showing the density values for POP indicates that most of the tows that captured POP in these surveys were located in parts of La Perouse Bank (Figure C.13). Tows in these areas were allocated to the same depth strata as those used for the WCVI synoptic survey (Table C.8), and the swept areas used were consistent for 3C within the indicated depth ranges.

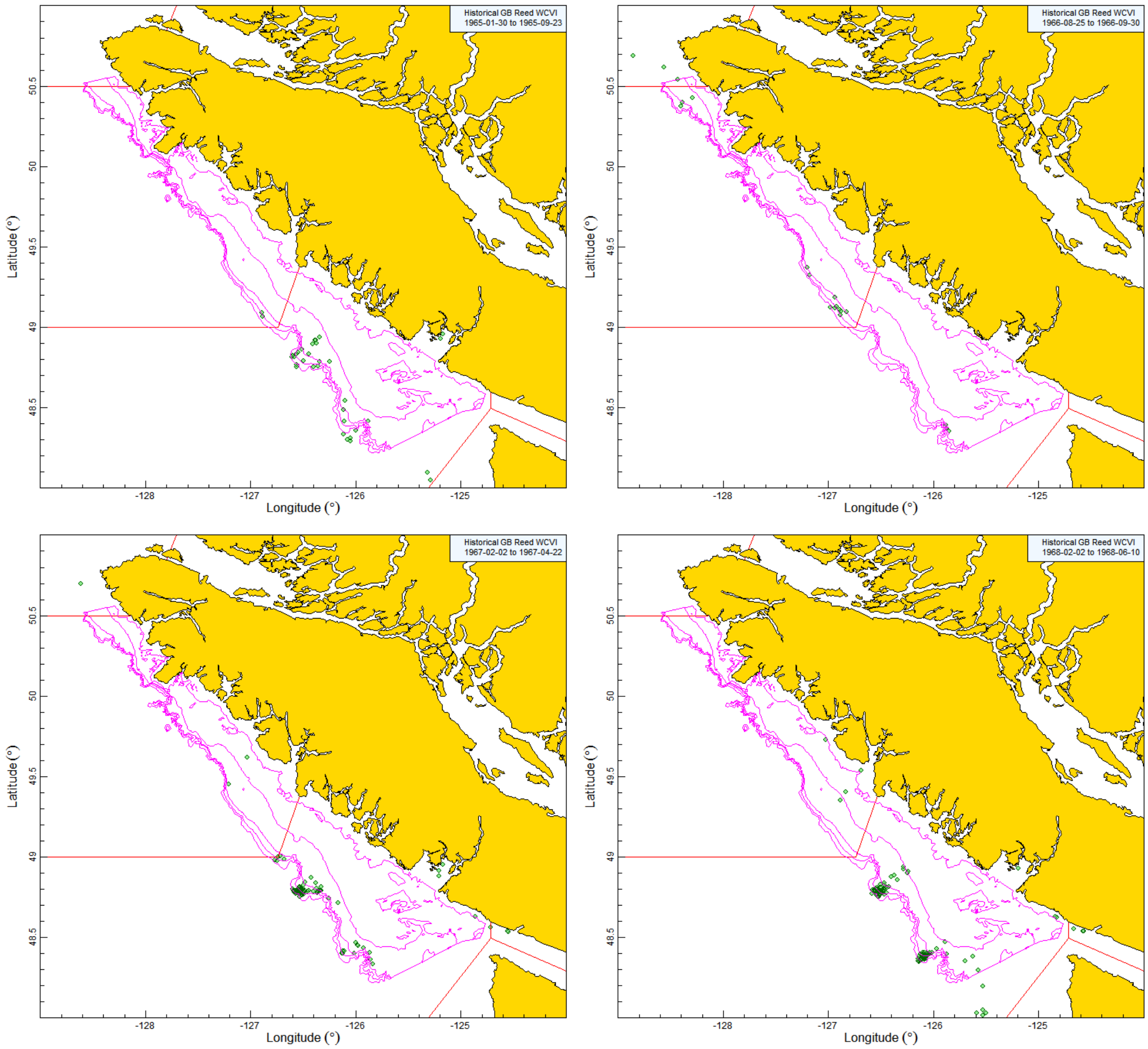


Figure C.11. Location of tows (green dots) conducted off the west coast of Vancouver Island by the GB Reed over the period 1965, 1966, 1967 and 1968.

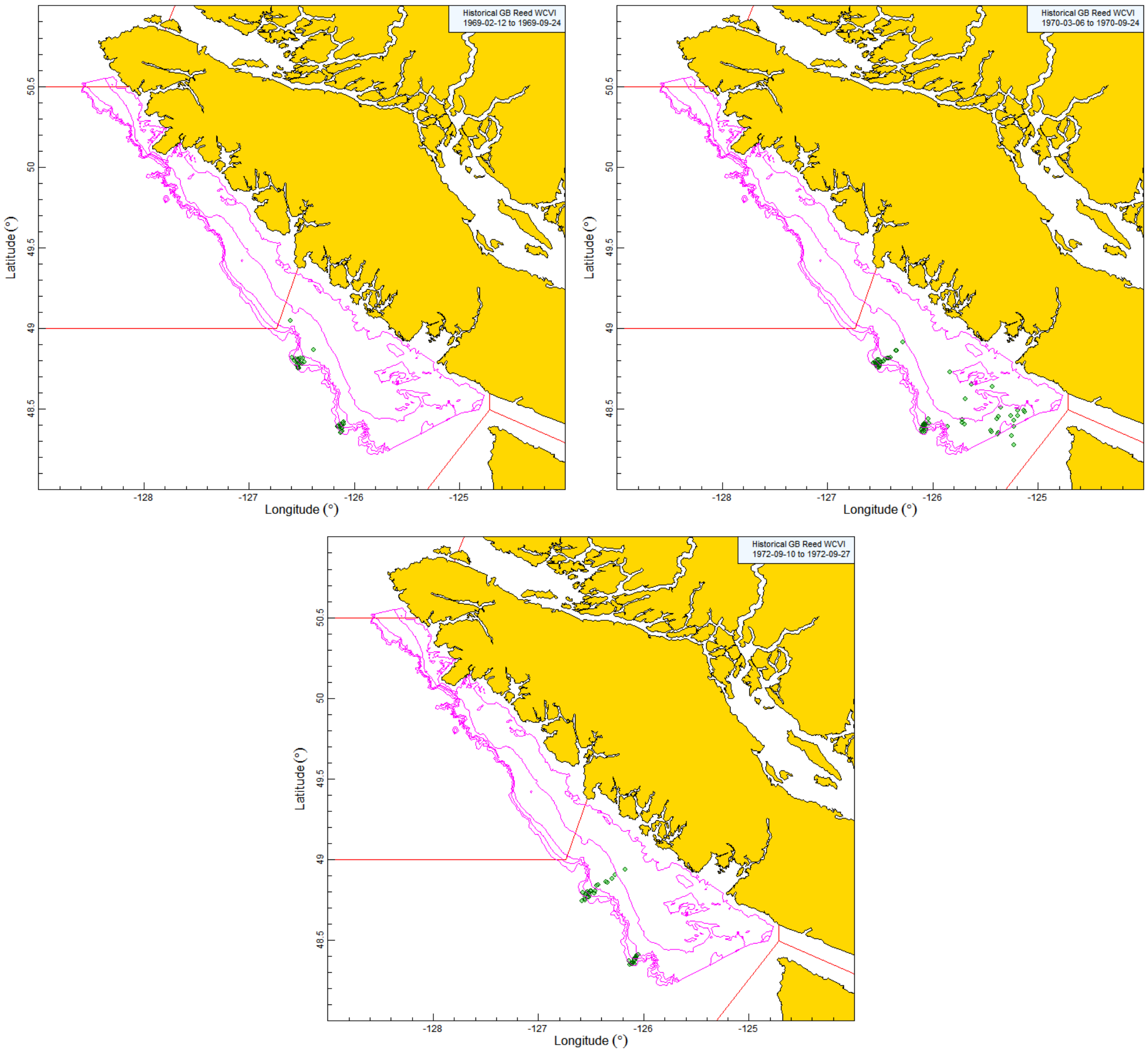


Figure C.11 (cont.) Locations of tows (green dots) conducted off the west coast of Vancouver Island by the GB Reed in 1969, 1970 and 1972.

Table C.8. Stratum designations, number of usable and unusable tows, for each of the seven years of the historic GB Reed Vancouver Island synoptic survey. Also shown is the area of each stratum.

Survey year	Stratum depth zone 125-200m	200-330m	330-500m	Total tows[1]	Unusable tows	Start date	End date	Ave. speed[3]	N rec-ords	N missing speed
1965	9	8	8	25	106	30-Jan-65	23-Sep-65	6.14	131	87
1966	1	0	0	1	63	25-Aug-66	30-Sep-66	6.37	64	0
1967	12	28	25	65	33	02-Feb-67	22-Apr-67	6.13	98	2
1968	8	34	43	85	83	02-Feb-68	10-Jun-68	6.20	168	3
1969	2	14	19	35	39	12-Feb-69	24-Sep-69	6.50	74	35
1970	6	18	24	48	129	06-Mar-70	24-Sep-70	6.33	177	53
1972	6	17	17	40	2	10-Sep-72	27-Sep-72	3.45	42	0
Area (km^2)	1082	499	587	2,168[2]	–	–	–	6.05	754	180

[1] GFBio usability codes=0,1,2,6 and in PMFC Major 3C west of –125.8°W
[2] Total area (km^2): Area 3C only within the indicated depth range
[3] km/h, except for 1972, which appears to be nautical miles/h

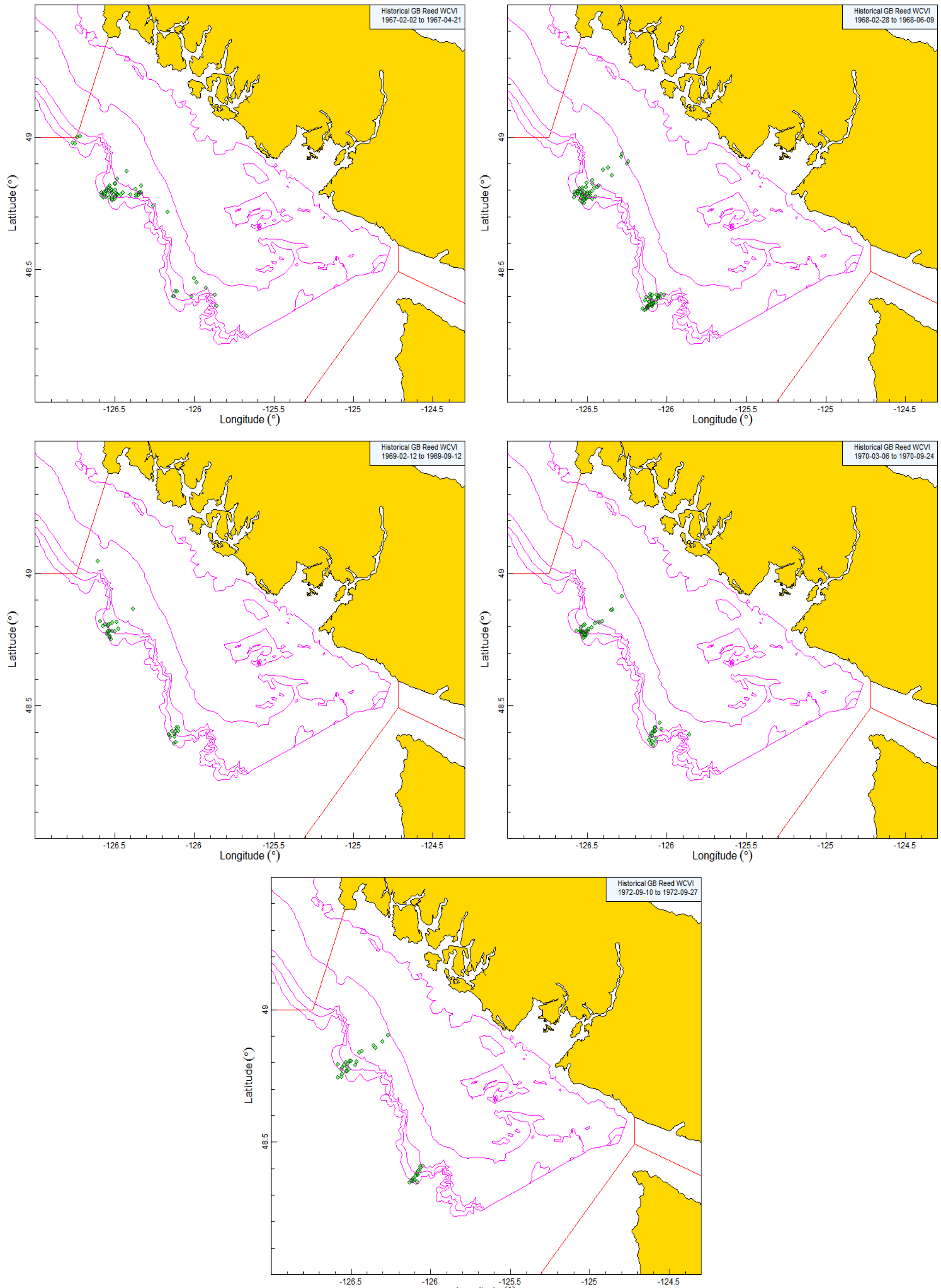


Figure C.12. Locations of tows (green dots) conducted off the west coast of Vancouver Island by the GB Reed, constrained to a relatively uniform set of tows, over the period 1967 to 1972. Predominant months for these surveys: 1967 (April); 1968 (April); 1969 (February); 1970 (April); 1972(September).

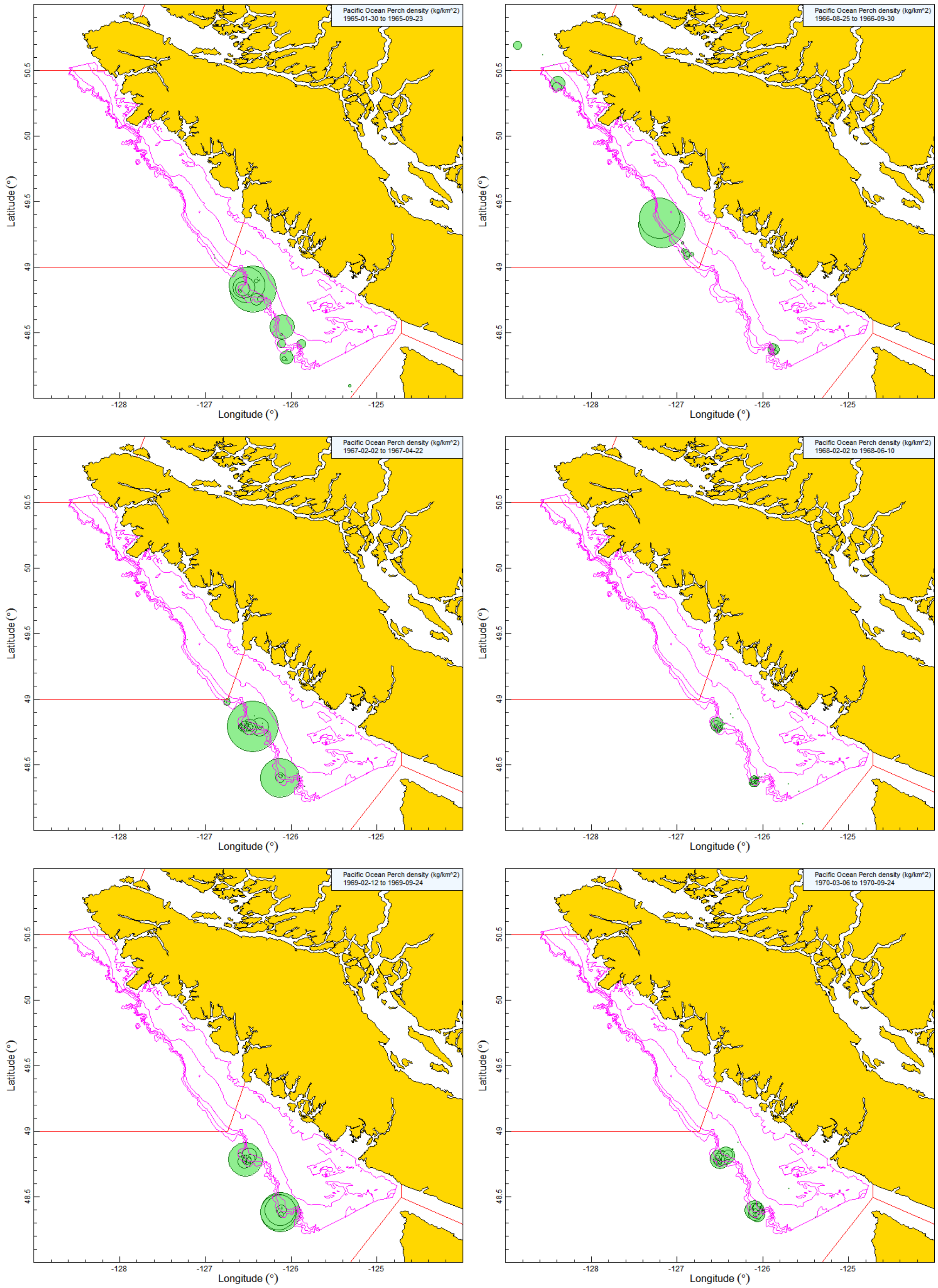


Figure C.13. Relative density of POP for tows conducted off the west coast of Vancouver Island by the GB Reed over the period 1965 to 1970. Circles are proportional to catch density (largest circle = 30,435 kg/km^2 in 1967).

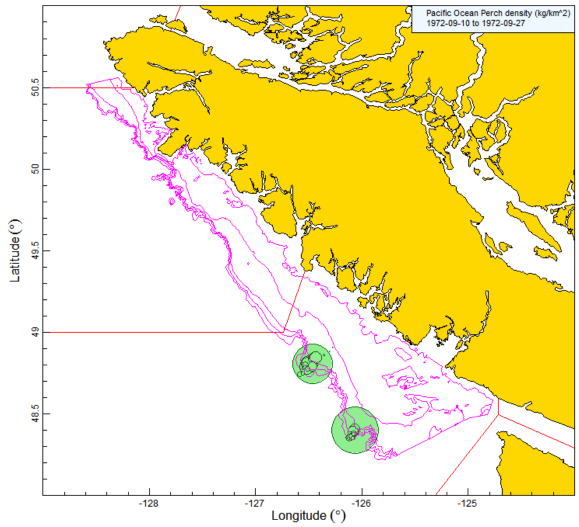


Figure C.13 (cont). Relative density of POP for tows conducted off the west coast of Vancouver Island by the GB Reed in 1972 (largest circle = 30,435 kg/km^2 in 1967).

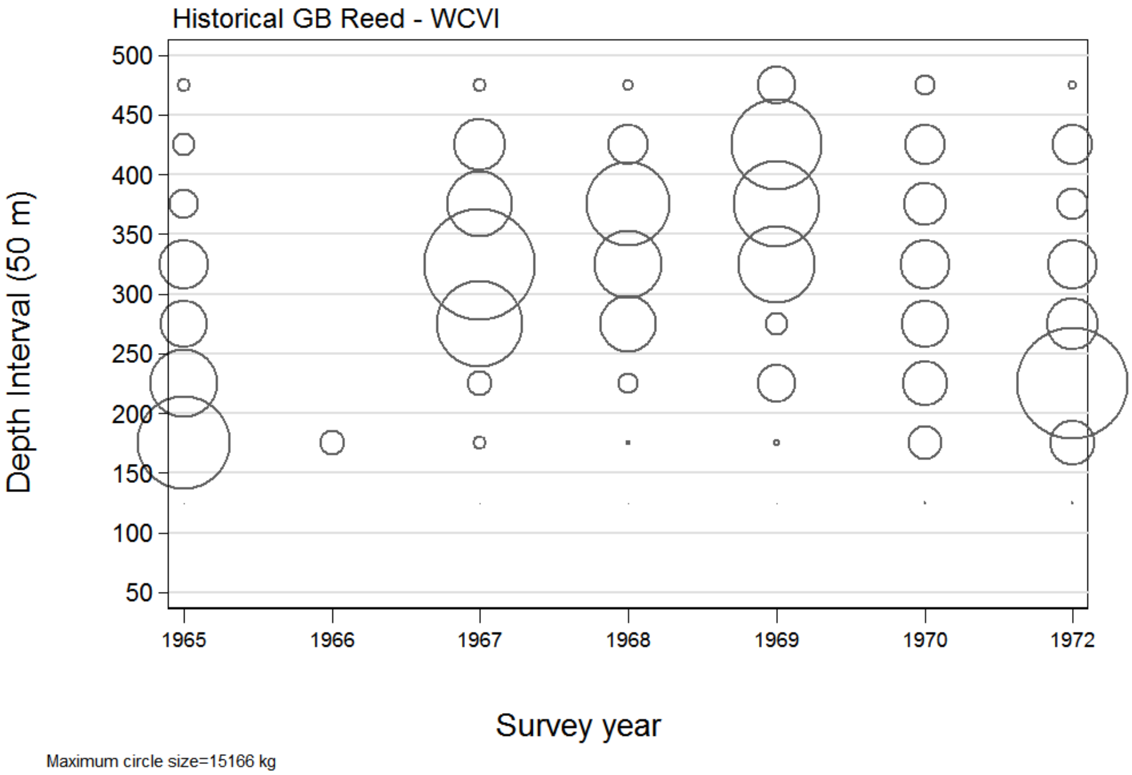


Figure C.14. Distribution of observed weights of Pacific Ocean Perch by survey year and 50-m depth zone. Depth zones are indicated by the start point of the depth interval. Minimum and maximum depths observed for POP: 128 m and 503 m, respectively. Depth is taken at the start position for each tow.

Tows from the surveys conducted in 1965 and 1966 were not accepted in this group. Previously it was determined that these two surveys, with their wide-ranging design and exploratory nature, were not suitable for biomass index estimation (Edwards et al. 2012*b*). The surveys conducted in 1967, 1968, 1969 and 1970 all took place from late winter and spring to mid-summer, although both the 1968 and 1969 surveys extended into September (Table C.8). The 1972 survey was conducted entirely in September. On the basis of the available dates, a decision was made to exclude the 1972 survey because of its late timing (to be consistent with the decision made for the 1996 Caledonian survey (see Paragraph C.4.2). Although the remaining surveys were not completely consistent with regard to dates, the overlap in timing appeared acceptable and these surveys were treated as a single comparable series (Table C.8).

A doorspread density value was generated for each tow based on the catch of Pacific Ocean Perch, using a calculated doorspread appropriate for these G.B. Reed surveys (61.6 m, see Table 9 in Yamanaka et al. 1996) and the distance travelled for the tow. Such an assumption was required because no doorspread values were provided in the raw survey data due to the absence of net mensuration equipment at the time when these surveys were conducted. The distance travelled was missing for almost every tow in these five surveys, with the few that were provided being inconsistent with a value calculated from the speed and duration of the tow. Consequently, all travel distance measurements were calculated from the time towed multiplied by the recorded speed of the tow, including those tows with populated distance travelled fields. Missing tow speed values were filled in from the mean for the survey year. There is relatively little variability in the available speed travelled field (CV=0.08), because 80% of the tows only varied between 5.6 and 6.5 km/h while 98% of the tows ranged from 4.6 to 7.4 km/h (median speed = 6.5 km/h). This procedure resulted in the generation of comparable density (kg/km^2) values for each survey (Figure C.13).

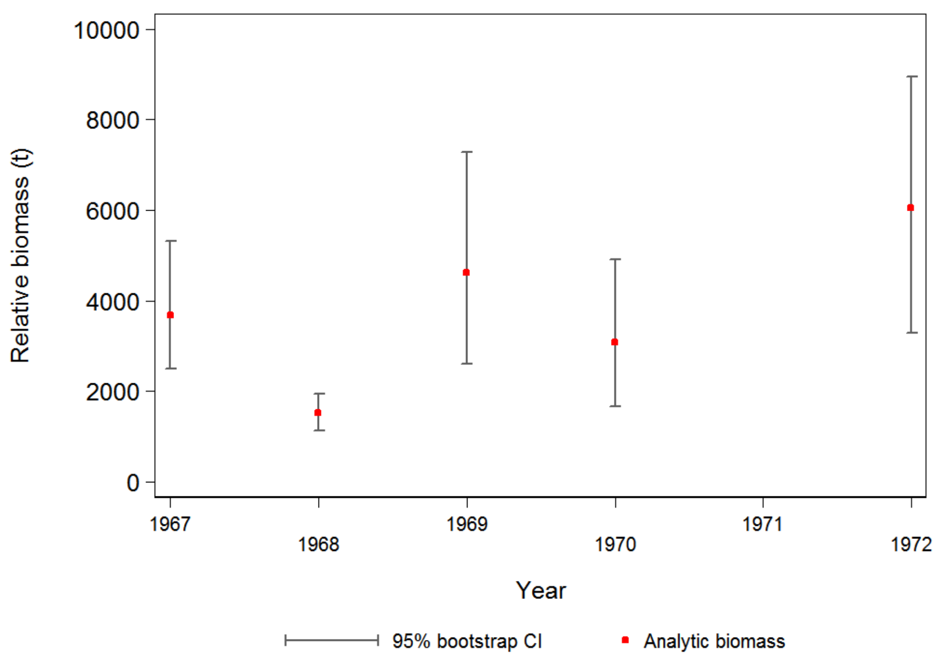


Figure C.15. Plot of biomass estimates for Pacific Ocean Perch from the 1967 to 1972 historic GB Reed west coast Vancouver Island trawl surveys using the strata shown in Table C.8. The 1965 and 1966 surveys were omitted for reasons provided in the text. Bias-corrected 95% confidence intervals from 1000 bootstrap replicates are plotted.

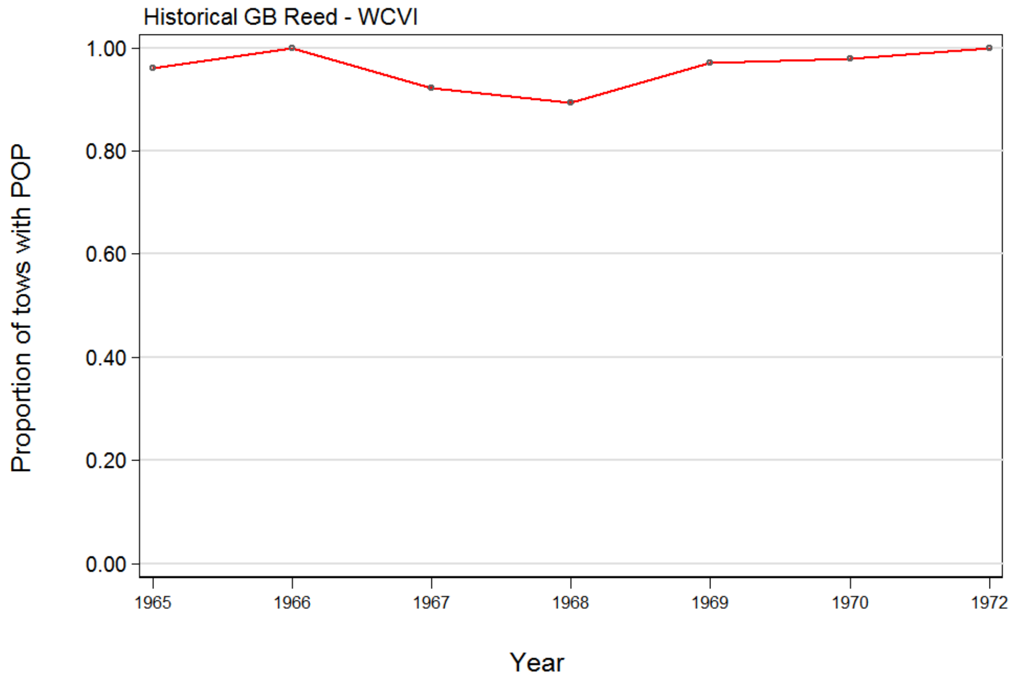


Figure C.16. Proportion of tows by stratum and year which contain Pacific Ocean Perch for the historic GB Reed WCVI surveys (valid WCVI tows only).

C.6. RESULTS

Pacific Ocean Perch was chiefly captured at depths from 150 to 400 m, but there were sporadic observations at depths up to ~500 m (Figure C.14). Estimated biomass for Pacific Ocean Perch from these trawl surveys showed little contrast, with the 1972 survey showing the highest biomass (Figure C.15; Table C.9). The estimated CVs are low (14–28%), but this may reflect a non-random tow selection, which would tend to reduce the variability among tows (Table C.9).

The proportion of WCVI tows that captured Pacific Ocean Perch varied between 90 and 100% among all seven surveys (Figure C.10). This proportion of tows with POP seems high compared to data previously presented for the WCVI synoptic surveys (see Figure C.10) and may reflect the non-random nature of tow selection.

Table C.9. Biomass estimates for Pacific Ocean Perch from five GB Reed WCVI surveys (see Table C.8 survey configuration details). 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 (C.6)
1967	3,688	3,668	2,498	5,325	0.195	0.195
1968	1,526	1,535	1,133	1,950	0.135	0.140
1969	4,619	4,559	2,598	7,288	0.260	0.256
1970	3,076	3,116	1,660	4,916	0.281	0.277
1972	6,051	6,097	3,283	8,939	0.242	0.233

The 1965 and 1966 GB Reed surveys were not considered to be comparable to the remaining GB Reed series because of the exploratory nature of these two surveys (and the lack of WCVI tows by the 1966 survey). Of the remaining five surveys investigated, the four surveys spanning the period 1967–1970 were considered to be comparable, given that they were conducted in the same area by the same vessel over reasonably comparable time periods. The fifth survey, conducted in September 1972, was not considered comparable for the reason given for the 1996 Caledonian survey: the timing of the survey coincided with a period when it is thought that POP are moving away from the area. Therefore, only the four WCVI GB Reed survey indices spanning the period 1967 to 1970 were accepted as a linked series of abundance indices for use in the stock assessment model (described in Appendix F).

D BIOLOGICAL DATA

Here we present the parameterisation of the weights-at-age and female maturity. These are taken from our Pacific Ocean Perch assessment for Queen Charlotte Sound (Edwards et al., 2012*b*); the same values are used for the companion assessment (Edwards et al., 2013) for area 5DE.

D.1 PARAMETERISATION OF WEIGHTS-AT-AGE

The estimates of weights-at-age are the same as those used in Edwards et al. (2012*b*). The average weight of an individual of age-class a of sex s is denoted w_{as} (kg), and is given by

$$w_{as} = \alpha_s L_{as}^{\beta_s}, \tag{D.1}$$

where (for each sex, s) α_s is the growth rate scalar, L_{as} is the length (cm) of an individual of age a, and β_s is the growth rate exponent. Sex $s = 1, 2$ for females and males, respectively.

The lengths L_{as} are given by the von-Bertalanffy model

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

where (for each sex, s) $L_{\infty,s}$ is the average length at maximum age of an individual, k_s is the growth rate coefficient, and $t_{0,s}$ is the age at which the average size is zero.

In Edwards et al. (2012*b*) data came from Queen Charlotte Sound and the west coasts of Vancouver Island and Haida Gwaii. The differences between areas were found to be relatively small and probably a result of data issues rather than reflecting actual differences in growth rates among the five areas. There was also little sensitivity to combining length-age pairs from research and commercial sources or using each source separately. The parameters were calculated from combining data from areas 5A, 5B, 5C and 5E. Given the similarities between areas, here we use the same estimated parameters as in Edwards et al. (2012*b*). The values are given in Table D.1, and were used as fixed inputs to the stock assessment model (to calculate w_{as} for each a and s). Figure D.1 shows the resulting mean lengths-at-age and mean weights-at-age.

Table D.1. Fixed allometric growth parameters for females and males, used as inputs for the stock assessment model. See text for parameter definitions.

Parameter	Females	Males
$L_{\infty,s}$	45.11	41.62
k_s	0.1404	0.1675
$t_{0,s}$	-1.303	-1.021
α_s	9.258×10^{-6}	8.126×10^{-6}
β_s	3.116	3.155

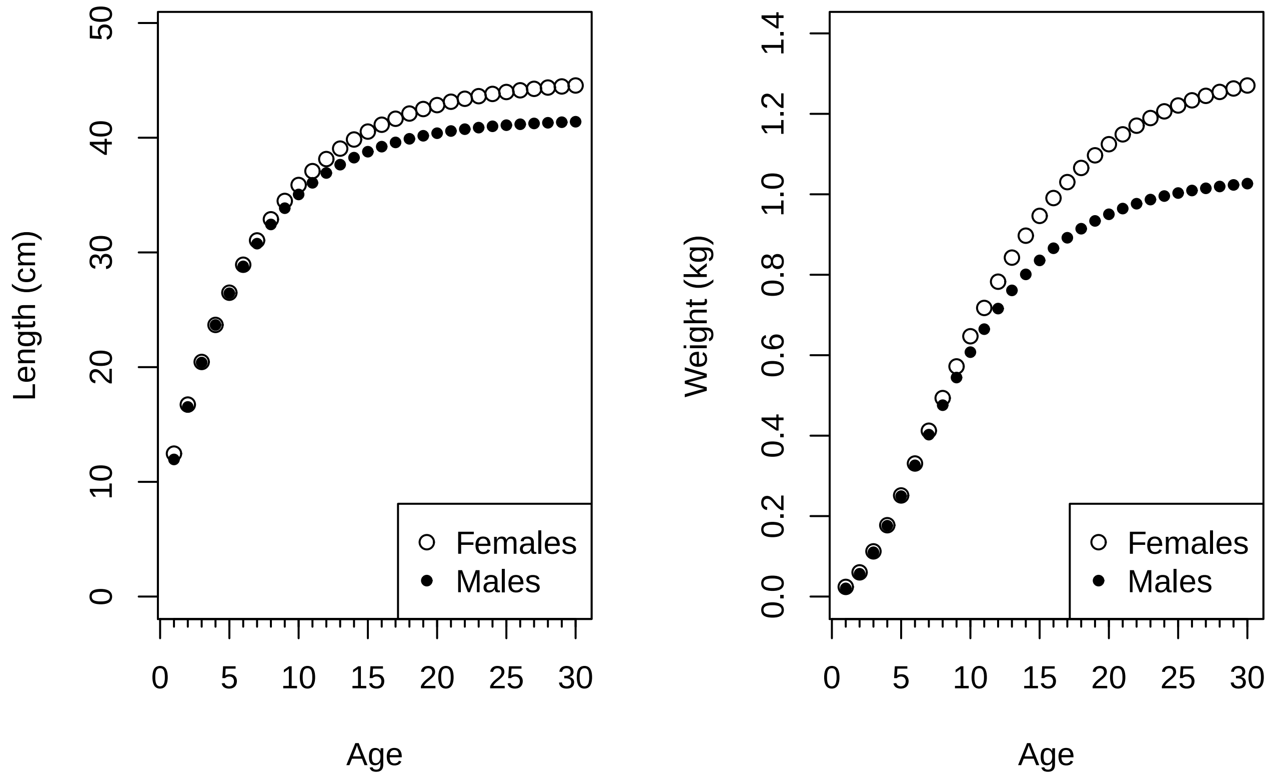


Figure D.1. Mean lengths-at-age and mean weights-at-age for each sex, as given by (D.2) and (D.1) with parameter values from Table D.1.

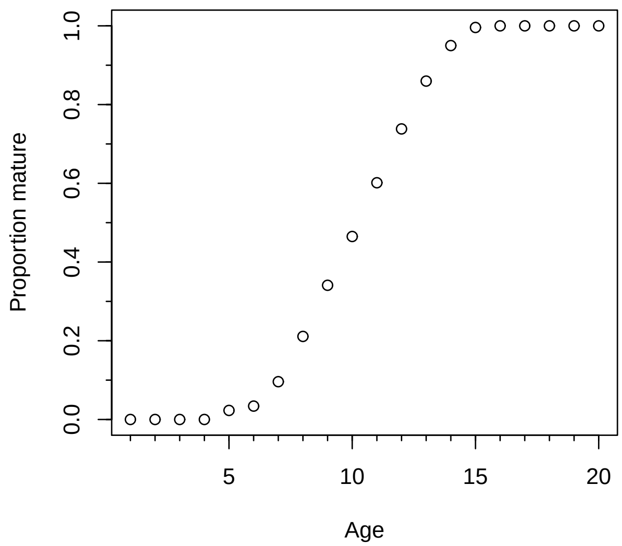


Figure D.2. Maturity ogive for females used in the stock assessment model. Values are given in Table D.2.

D.2 PARAMETERISATION OF FEMALE MATURITY

The proportion of age-class a females that are mature, m_a, was also taken from Edwards et al. (2012*b*). The resulting ogive is given in Figure D.2 and Table D.2, and was based on 21,000 observations from PMFC areas 5ABCE. It was calculated by fitting a double-normal function to the observed proportions that were mature at each age, and then, as for Stanley et al. (2009) for Canary Rockfish, using the observed proportions for ages < 9 because the fitted function appeared to overestimate the proportion of mature females.

Table D.2. Maturity ogive for females used in the stock assessment model, as plotted in Figure D.2.

Age	Proportion mature	Age	Proportion mature
1	0.000	11	0.601
2	0.000	12	0.738
3	0.000	13	0.860
4	0.000	14	0.950
5	0.023	15	0.996
6	0.034	16	1.000
7	0.096	17	1.000
8	0.211	18	1.000
9	0.341	19	1.000
10	0.465	20	1.000

E WEIGHTED AGE FREQUENCIES/PROPORTIONS

We summarize a method for representing commercial and survey age structures for a given species through weighting age frequencies n_a or proportions n'_a by catch$\|$density in defined strata. (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 POP in tows that were sampled, and survey ages are weighted by the catch density (kg/km^2) of POP in sampled tows. A second weighting is then applied: quarterly commercial ages are weighted by the commercial catch weight of POP 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 POP 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 n_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 E.1.

Table E.1. Equations for weighting age frequencies or proportions for a given species.
*(**c**) = commercial, (**s**) = survey*

Symbol	Description
	Indices
a	age class (1 to 30, where 30 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 2012)
	(**s**) survey IDs in survey series (e.g., WCVI Synoptic)
	Data
n_{adhi}	frequency-at-age a for sample unit d in quarter$\|$stratum h of year$\|$survey i
n'_{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 $C_{hi} = \sum_d C_{dhi}$
m_{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 n_{ad} by sample unit catch||density of a given 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:

$$C'_{dhi} = \frac{C_{dhi}}{\sum_d C_{dhi}} \; . \tag{E.1}$$

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

$$m_{ahi} = \sum_d \left(C'_{dhi} n_{adhi} \right) \; . \tag{E.2}$$

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

$$\frac{\sum_a n_{ahi}}{\sum_a m_{ahi}} \tag{E.3}$$

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

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

$$K'_{hi} = \frac{K_{hi}}{\sum_h K_{hi}} \tag{E.4}$$

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

$$p_{ai} = \sum_h \left(K'_{hi} m_{ahi} \right) \; . \tag{E.5}$$

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

$$\frac{\sum_a m_{ai}}{\sum_a p_{ai}} \; . \tag{E.6}$$

to retain the original number of observations.

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

$$p'_{ai} = \frac{p_{ai}}{\sum_a p_{ai}} \; . \tag{E.7}$$

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

The choice of data input (frequencies n *vs*. proportions n') does matter: the numeric outcome can be very different, especially if the input samples comprise few observations. Theoretically,

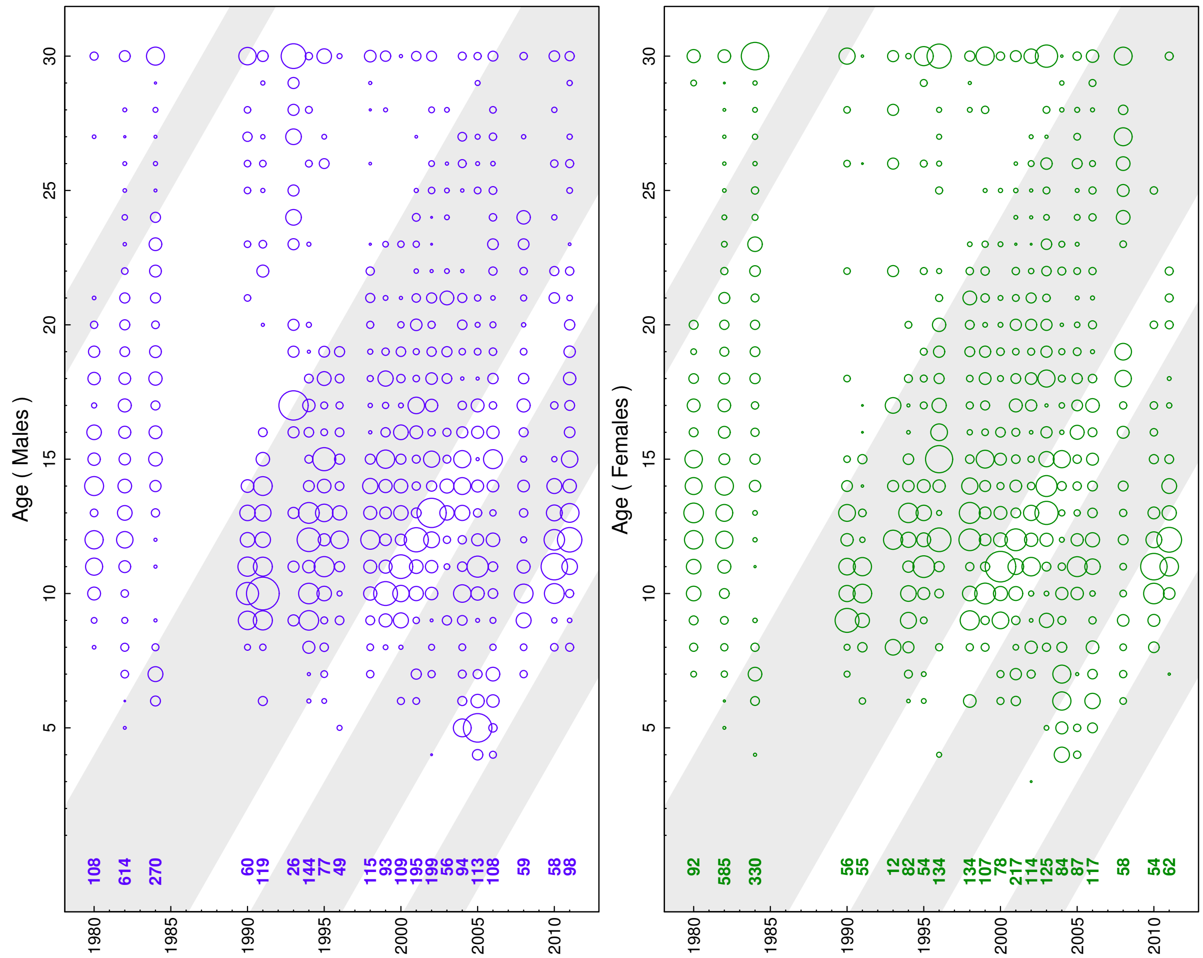


Figure E.1. Commercial POP proportions-at-age in PMFC 3CD based on age frequencies weighted by trip catch within quarters and commercial catch within years. Diagonal shaded bands indicate cohorts that were born when the Pacific Decadal Oscillation was positive, potentially creating conditions in pelagic waters that foster productivity. Number of specimens aged are displayed along the bottom axis.

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 n.

The commercial age data (Figure E.1) show no clear cohort patterns, except perhaps for 1989. The strong 1976 year-class seen in Queen Charlotte Sound POP (Edwards et al., 2012*b*) is not evident here. Young ages are under-represented due to the usual gear selectivity issues, and the annual 30-y plus classes exhibit an episodic pattern. For the model analysis, years with fewer than three sampled trips were excluded: 1980, 1990, 1993, 1995, 1996, and 2010 (Table E.2).

The survey age data (Figure E.2), which are weighted by POP density and stratum area, suggest a better-than average recruitment for the years 1989-1991. Additionally, pulses of young fish appear in 2004 from the 1999 year class and in 2010 from the 2008 year class. The 2010 survey conducted a much larger number of samples than in previous survey years (Table E.3).

Table E.2. Quarterly data for commercial trips: number of sampled trips N_h, POP catch(t) by sampled trip C_h and by quarter K_h.

Year	$N_{h=1}$	$N_{h=2}$	$N_{h=3}$	$N_{h=4}$	$C_{h=1}$	$C_{h=2}$	$C_{h=3}$	$C_{h=4}$	$K_{h=1}$	$K_{h=2}$	$K_{h=3}$	$K_{h=4}$
1980	2	0	0	0	77.4	0.0	0.0	0.0	240	77	4	109
1982	4	0	0	2	78.1	0.0	0.0	93.9	141	88	10	269
1984	0	1	0	2	0.0	13.8	0.0	105.0	29	322	172	221
1990	2	0	0	0	23.4	0.0	0.0	0.0	394	517	199	89
1991	2	2	0	1	12.9	13.5	0.0	1.9	375	401	45	35
1993	0	1	0	0	0.0	4.6	0.0	0.0	309	524	265	563
1994	2	0	0	2	6.3	0.0	0.0	20.2	288	354	361	642
1995	1	1	0	0	5.2	1.5	0.0	0.0	188	402	334	7
1996	0	0	1	0	0.0	0.0	6.8	0.0	81	206	204	129
1998	3	3	3	2	1.9	4.4	9.0	9.9	267	144	38	93
1999	1	1	1	1	2.4	1.8	0.5	2.7	190	133	96	138
2000	2	1	0	1	4.6	3.0	0.0	5.0	190	153	57	114
2001	2	5	0	0	3.7	19.9	0.0	0.0	205	112	122	105
2002	2	1	1	3	1.2	0.6	0.7	10.5	214	117	77	135
2003	1	2	1	0	0.7	13.0	0.3	0.0	236	123	51	157
2004	1	4	0	0	0.2	3.8	0.0	0.0	192	113	83	159
2005	1	3	0	1	0.0	2.5	0.0	0.1	184	180	78	104
2006	2	2	1	1	4.4	1.7	2.2	2.3	144	142	98	120
2008	0	2	2	0	0.0	8.3	13.6	0.0	186	143	185	208
2010	1	0	0	1	5.2	0.0	0.0	14.3	177	96	52	90
2011	5	0	0	0	19.3	0.0	0.0	0.0	252	145	32	144

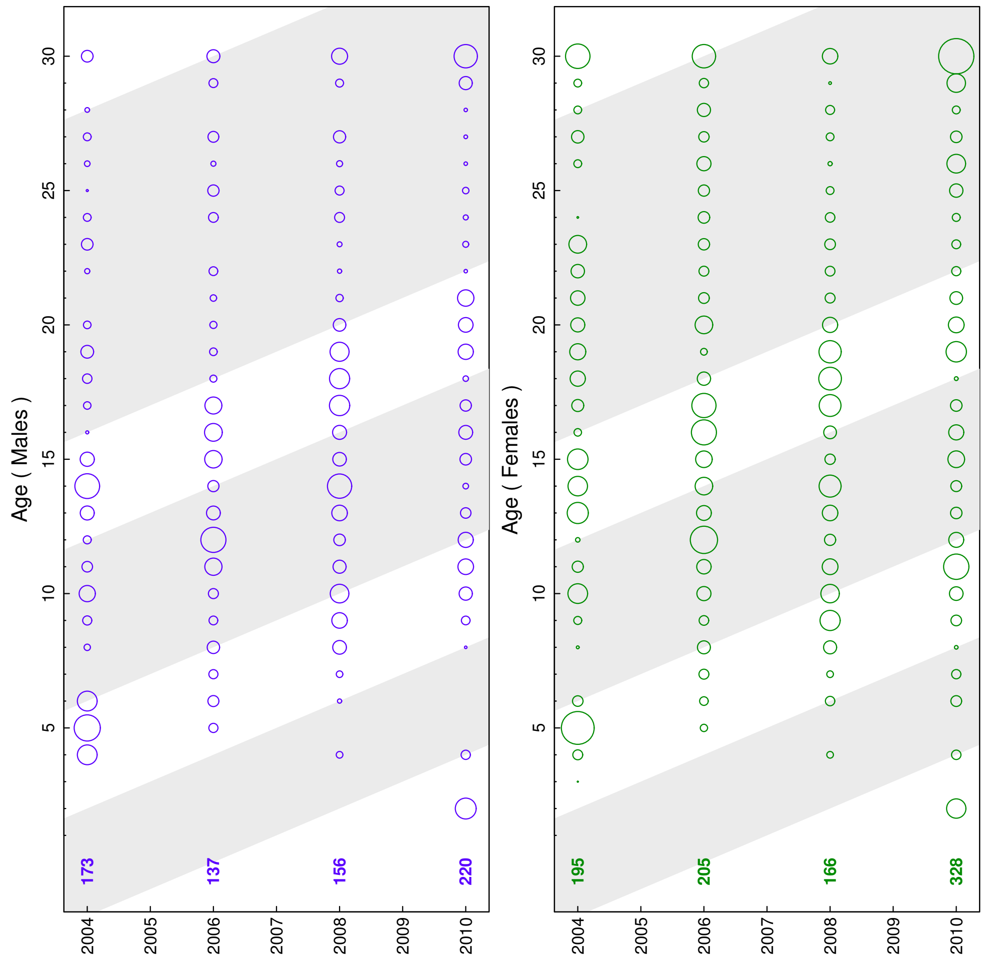


Figure E.2. WCVI Synoptic survey POP proportions-at-age based on age frequencies weighted by POP density (kg/km^2) within strata and stratum area (km^2) within survey. See Figure E.1 for details on diagonal shaded bands. Number of specimens aged are displayed along the bottom axis.

Table E.3. WCVI Synoptic survey: number of sampled tows N_h, POP density (kg/km^2) C_h from stratum samples, and stratum area (km^2) K_h.

	year	h=066	h=067	h=068
N_h	2004	1	8	1
	2006	0	7	1
	2008	0	5	3
	2010	4	18	7
C_h	2004	3266	7593	540
	2006	0	4824	4111
	2008	0	2140	1362
	2010	1261	5966	2803
K_h	2004	3880	728	668
	2006	3880	728	668
	2008	3880	728	668
	2010	3880	728	668

F DESCRIPTION OF CATCH-AT-AGE MODEL

F.1 INTRODUCTION

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

The model structure is the same as that used previously, and, as for the Yellowmouth Rockfish assessment, we used the weighting scheme of Francis (2011) described below. The same methodology is used in the companion POP assessment for area 5DE (Edwards et al., 2013), but with different input data for commercial catch, survey indices and age compositions.

Implementation was done using a modified version of the Coleraine statistical catch-at-age software (Hilborn et al., 2003) called Awatea (A. Hicks, NOAA, pers. comm.). Awatea is a platform for implementing the AD (Automatic Differentiation) Model Builder software (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 Development Core Team, 2012), rather than the original Excel implementation. 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 new R package `PBSawatea`.

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

F.2 MODEL ASSUMPTIONS

The assumptions of the model are:

1. The stock in area 3CD is treated as a single stock.

2. Catches are taken by a single fishery, 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.

4. Selectivity differs between sexes and surveys and remains invariant over time. 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.

7. Maturity-at-age parameters for females are fixed and assumed to be invariant over time. 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. Commercial samples of catch-at-age in a given year are representative of the fishery when $\geq$3 samples are available.

11. 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.

12. The age composition samples come from the middle of the year after half the catch and half the natural mortality are accounted for.

F.3 MODEL NOTATION AND EQUATIONS

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

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

As known fixed values are not available for all parameters, we need to estimate many of them, and add stochasticity to recruitment. This is accomplished by the stochastic components given in Table F.3.

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

Table F.1 (continued overleaf). Notation for the catch-at-age model.

Symbol	Description and units
	Indices (all subscripts)
a	age class, where $a = 1, 2, 3, ...A$, and $A = 30$ is the accumulator age class
t	model year, where $t = 1, 2, 3, ...T$, corresponds to actual years 1940, 1941, 1942, ..., 2013, and $t = 0$ represents unfished equilibrium conditions
g	index for certain data: 1 - West Coast Vancouver Island synoptic survey series 2 - National Marine Fisheries Service Triennial survey series 3 - GB Reed historical survey series 4 - commercial trawl data
s	sex, $1 =$ females, $2 =$ males
	Index ranges
A	accumulator age-class, $A = 30$
T	number of model years, $T = 74$
$\mathbf{T}_g$	sets of model years for survey abundance indices from series g, $g = 1, 2, 3$, listed here for clarity as actual years (subtract 1939 to give model year t): $\mathbf{T}_1 = \{$2004, 2006, 2008, 2010, 2012$\}$ $\mathbf{T}_2 = \{$1980, 1983, 1989, 1992, 1995, 1998, 2001$\}$ $\mathbf{T}_3 = \{$1967, 1968, 1969, 1970$\}$
$\mathbf{U}_g$	sets of model years with proportion-at-age data, $g = 1, 4$ (listed here as actual years): $\mathbf{U}_1 = \{$2004, 2006, 2008, 2010$\}$ $\mathbf{U}_4 = \{$1982, 1984, 1991, 1994, 1998, 1999, ..., 2006, 2008, 2011$\}$
	Data and fixed parameters
p_{atgs}	observed weighted proportion of fish from series g in each year $t \in \mathbf{U}_g$ that are age-class a and sex s; so $\Sigma_{a=1}^{A} \Sigma_{s=1}^{2} p_{atgs} = 1$ for each $t \in \mathbf{U}_g$, $g = 1, 4$
n_{tg}	assumed sample size that yields corresponding p_{atgs}
C_t	observed catch biomass in year $t = 1, 2, ..., T-1$, tonnes
w_{as}	average weight of individual of age-class a of sex s from fixed parameters, kg
m_a	proportion of age-class a females that are mature, fixed from data
I_{tg}	biomass estimates from surveys $g = 1, 2, 3$, for year $t \in \mathbf{T}_g$, tonnes
κ_{tg}	standard deviation of I_{tg}
σ_R	standard deviation parameter for recruitment process error, $\sigma_R = 0.9$

Table F.1 (cont.). Notation for the catch-at-age model.

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

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

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

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

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

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

Initial conditions ($t = 1$)

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

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

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

Selectivities ($g = 1, 2, 3, 4$)

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

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

Table F.2 (cont.)

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

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

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

$$V_t = \sum_{s=1}^{2} \sum_{a=1}^{A} e^{-M_s/2} \, w_{as} \, s_{a4s} \, N_{ats} \tag{F.11}$$

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

$$u_{ats} = s_{a4s} \, u_t \, ; \quad 1 \leq a \leq A, \; s = 1, 2 \tag{F.13}$$

Estimated observations

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

$$\widehat{p}_{atgs} = \frac{e^{-M_s/2} (1 - u_{ats}/2) s_{ags} N_{ats}}{\sum_{s=1}^{2} \sum_{a=1}^{A} e^{-M_s/2} (1 - u_{ats}/2) s_{ags} N_{ats}} ; \quad 1 \leq a \leq A, \; t \in \mathbf{U}_g, \; g = 1, 4, \; s = 1, 2 \tag{F.15}$$

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

Estimated parameters

$$\mathbf{\Theta} = \{R_0, M_1, M_2, h, q_1, q_2, q_3, \mu_1, \mu_4, \Delta_1, \Delta_4, v_{1L}, v_{4L}\} \tag{F.16}$$

Recruitment deviations

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

Log-likelihood functions

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

$$\begin{aligned}\log L_2(\mathbf{\Theta}|\{\widehat{p}_{atgs}\}) = {} & -\frac{1}{2}\sum_{g=1,4}\sum_{a=1}^{A}\sum_{t\in\mathbf{U}_g}\sum_{s=1}^{2}\log\left[p_{atgs}(1-p_{atgs}) + \frac{1}{10A}\right] \\ & + \sum_{g=1,4}\sum_{a=1}^{A}\sum_{t\in\mathbf{U}_g}\sum_{s=1}^{2}\log\left[\exp\left\{\frac{-(p_{atgs}-\widehat{p}_{atgs})^2\; n_{tg}}{2\left(p_{atgs}(1-p_{atgs}) + \frac{1}{10A}\right)}\right\} + \frac{1}{100}\right]\end{aligned} \tag{F.19}$$

$$\log L_3(\mathbf{\Theta}|\{\widehat{I}_{tg}\}) = \sum_{g=1}^{3}\sum_{t\in\mathbf{T}_g}\left[-\frac{1}{2}\log 2\pi - \log\kappa_{tg} - \frac{(\log I_{tg} - \log\widehat{I}_{tg})^2}{2\kappa_{tg}^2}\right] \tag{F.20}$$

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

Joint prior distribution and objective function

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

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

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

Parameter	Prior distribution	Mean, standard deviation	Bounds	Initial value
R_0	uniform	–	[1, 100,000]	4,000
M_1, M_2	normal	0.07, 0.007	[0.01, 0.12]	0.07
h	beta	0.674, 0.168	[0.2, 0.999]	0.674
$\log q_g, g = 1, 2, 3$	uniform	–	[-12, 5]	0
μ_1	normal	13.3, 4	[5, 40]	13.3
μ_4	normal	10.5, 3.15	[5, 40]	10.5
$\log v_{1L}$	normal	3.3, 1	[-15, 15]	3.3
$\log v_{4L}$	normal	1.52, 0.456	[-15, 15]	1.52
Δ_1	normal	0.22, 0.066	[-8, 10]	0.22
Δ_4	normal	0, 0.3	[-8, 10]	0

F.4 DESCRIPTION OF DETERMINISTIC COMPONENTS

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

F.4.1 AGE CLASSES

Index (subscript) a represents age classes, going from 1 to the accumulator age class, A, of 30. Age class $a = 5$, for example, represents fish aged 4-5 years (which is the usual, though not universal, convention, Caswell 2001), and so an age-class 1 fish was born the previous year. The variable N_{ats} is the number of age-class a fish of sex s at the *start* of year t, so the model is run to year T which corresponds to 2013.

In Edwards et al. (2012*a*,*b*) an accumulator age class of 60 was used, but this did not perform well in preliminary model runs for area 3CD, and so, in consultation with the Technical Working Group, the accumulator age class was set to 30.

F.4.2 YEARS

Index t represents model years, going from 1 to $T = 74$, and $t = 0$ represents unfished equilibrium conditions. The actual year corresponding to $t = 1$ is 1940, and so model year $T = 74$ corresponds to 2013. The model was run to the start of 2013 to incorporate the 2012 index from the West Coast Vancouver Island synoptic survey. Catch data for the whole of 2012 are not available (since the assessment model is being run in September 2012), and so the catch for 2012 was set to that for 2011.

F.4.3 SURVEY DATA

Data from three survey series were used, as described in detail in Appendix C. Here, subscript $g = 1$ corresponds to the West Coast Vancouver Island synoptic survey series, $g = 2$ to the United States National Marine Fisheries Service Triennial survey series, and $g = 3$ to the GB Reed historical survey series. The years for which data are available for each survey are given in Table F.1; $\mathbf{T}_g$ corresponds to years for the survey biomass estimates I_{tg} (and corresponding standard deviations κ_{tg}), and $\mathbf{U}_g$ corresponds to years for proportion-at-age data p_{atgs} (with assumed sample sizes n_{tg}). Note that there are no $\mathbf{U_2}$ or $\mathbf{U_3}$ because there are no age data for those surveys.

F.4.4 COMMERCIAL DATA

As described in Appendix B, the commercial catch has been reconstructed back to 1918. Given the negligible catches in the early years, the model was started in 1940, and catches prior to 1940 were not considered. The time series for catches is denoted C_t. The set $\mathbf{U}_4$ (Table F.1) gives the years of available ageing data from the commercial fishery. The proportions-at-age values are given by p_{atgs} with assumed sample size n_{tg}, where $g = 4$ (to correspond to the commercial data). These proportions are the weighted proportions calculated using the stratified weighting scheme described in Appendix E, that adjusts for unequal sampling effort across temporal and spatial strata.

F.4.5 SEX

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

F.4.6 WEIGHTS-AT-AGE

The weights-at-age w_{as} are assumed fixed over time and based on the biological data; see Appendix D for details.

F.4.7 MATURITY OF FEMALES

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

F.4.8 STATE DYNAMICS

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

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

F.4.9 INITIAL CONDITIONS

An unfished equilibrium situation at the beginning of the reconstruction is assumed, because there is no evidence of significant removals prior to 1940, and 1940 predates significant removals by about 15 years (Appendix B). The initial conditions (F.4) and (F.5) are obtained by setting $R_t = R_0$ (virgin recruitment), $N_{ats} = N_{a1s}$ (equilibrium condition) and $u_{ats} = 0$ (no fishing) into (F.1)-(F.3). The virgin spawning biomass B_0 is then obtained from (F.9).

F.4.10 SELECTIVITIES

Separate selectivities were modelled for the commercial catch data and for each survey series. A half-Gaussian formulation was used, as given in (F.7) and (F.8), to give selectivities s_{ags} (note that the subscript $\cdot_s$ always represents the index for sex, whereas the variable $s_{\dots}$ always represents selectivity). This permits an increase in selectivity up to the age of full selection (μ_g for females). Given there was no evidence to suggest a dome-shaped function, it was assumed that fish older than μ_g remain fully selected. The rate of ascent of the left limb is controlled by the parameter v_{gL} for females. For males, the same function is used except that the age of full selection is shifted by an amount Δ_g, see (F.8).

F.4.11 DERIVED STATES

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

Equation (F.13) calculates, for year t, the proportion u_{ats} of age-class a and sex s fish that are caught. This requires the commercial selectivities s_{a4s} and the ratio u_t, which equation (F.12) shows is the ratio of total catch to vulnerable biomass in the middle of the year, V_t, given by equation (F.11). So (F.12) calculates the proportion of the vulnerable biomass that is caught, and (F.13) partitions this out by sex and age.

F.4.12 STOCK-RECRUITMENT FUNCTION

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

F.4.13 ESTIMATES OF OBSERVED DATA

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

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

F.5 DESCRIPTION OF STOCHASTIC COMPONENTS

F.5.1 PARAMETERS

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

F.5.2 RECRUITMENT DEVIATIONS

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

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

where $\epsilon_t \sim \text{Normal}(0, \sigma_R^2)$, and the bias-correction term $-\sigma_R^2/2$ term in (F.24) ensures that the mean of the recruitment deviations equals 0. This then gives the recruitment deviation equation

(F.17) and log-likelihood function (F.18). The value of σ_R was fixed at 0.9, which was the value used in the Queen Charlotte Sound (QCS) POP assessment (Edwards et al., 2012*b*), where the value was determined empirically from model fits.

F.5.3 LOG-LIKELIHOOD FUNCTIONS

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

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

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

F.6 BAYESIAN COMPUTATIONS

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

The procedure for the Bayesian computations is as follows:

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

The details for these steps are now given.

F.6.1 PHASES

Simultaneously estimating all the estimable parameters straight away for complex nonlinear models is ill advised, and so ADMB allows some of the estimable parameters to be kept fixed during the initial part of the optimisation process (Otter Research Limited, 1999). Some parameters are estimated in phase 1, then some further ones in phase 2, and so on. The order used here was:

phase 1: virgin recruitment R_0 and survey catchabilities q_1, q_2, q_3

phase 2: recruitment deviations ϵ_t (held at 0 in phase 1)

phase 3: age of full selectivity for females, μ_1, μ_4

phase 4: selectivity parameters Δ_g, v_{gL} for $g = 1, 4$, and mortalities M_1, M_2

phase 5: steepness h.

F.6.2 REWEIGHTING

Given that sample sizes are not comparable between different types of data, a procedure that adjusts the relative weights between data sources is required. For the QCS POP assessment (Edwards et al., 2012*b*) we used an iterative reweighting scheme based on adjusting the standard deviation of normal residuals of data sets until these standard deviations were approximately 1. This procedure did not perform well for the Yellowmouth Rockfish assessment (Edwards et al., 2012*a*), leading to spurious cohorts, and so for that assessment we used the reweighting scheme proposed by Francis (2011).

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

$$c_1 = \sqrt{c_0^2 + c_p^2}\,. \tag{F.25}$$

For each survey index, I_{tg} ($g = 1, 2, 3; t \in \mathbf{T}_g$), the associated standard deviation is κ_{tg}. The associated coefficient of variation is therefore κ_{tg}/I_{tg}, which is used in (F.25) to determine the reweighted coefficient of variation associated with κ_{tg}. This reweighted coefficient of variation is then converted back to a standard deviation, which is used as the reweighted standard deviation κ_{tg} in the likelihood function (F.20).

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

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

where $r = 1, 2, 3, ..., 6$ represents the reweighting iteration, $n_{tg}^{(r)}$ is the effective sample size for reweighting r, $W_g^{(r)}$ is the weight applied to obtain reweighting r, and $n_{tg}^{(0)} = n_{tg}$. So a single weight $W_g^{(r)}$ is calculated for each series $g = 1, 4$ for reweighting r.

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

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

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

$$\bar{O}_{gt} = \sum_{a=1}^{A} \sum_{s=1}^{2} a p_{atgs} \tag{F.28}$$

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

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

and Var_t is the usual finite-sample variance function applied over the index t. For the Yellowmouth Rockfish assessment (Edwards et al., 2012*a*) we used this approach iteratively with $r = 1, 2, ..., 6$, but found that reweightings after the first ($r = 1$) had little effect, and so the reported results were based on the first reweighting. Therefore, for the current assessment we used just one reweighting.

F.6.3 PRIOR DISTRIBUTIONS

Descriptions of the prior distributions for the 18 estimated parameters are given in Table F.4. The resulting probability density functions give the $\pi_j(\mathbf{\Theta})$, whose logarithms are then summed in (F.22) to give the joint prior distribution $\pi(\mathbf{\Theta})$. Since uniform priors are, by definition, constant across their bounded range (and zero outside), their contributions to the objective function can be ignored. Thus, in the calculation (F.22) of the joint prior distribution $\pi(\mathbf{\Theta})$, only those priors that are not uniform need to be considered in the summation.

A uniform prior over a large range was used for R_0. The priors for female and male natural mortality, M_1 and M_2 respectively, were based on the results of the QCS POP assessment (Edwards et al., 2012*b*). We first fit normal distributions, using maximum likelihood, to the posteriors from the ‘Estimate M and h’ model run of Edwards et al. (2012*b*), yielding N(0.0668, 0.00293) [indicating a normal distribution with mean 0.0668 and standard deviation 0.00293] for females, and N(0.0727, 0.00314) for males. For the QCS POP assessment we had taken priors from the posterior distributions of the Gulf of Alaska assessment of POP (Hanselman et al., 2007, 2009), namely N(0.06, 0.006) [rounding the mean to one decimal place] for both females and males. To avoid the overly tight priors based on our likelihood analysis, we set the coefficient of variation here to 0.1 (the same as the Gulf of Alaska value). Given the closeness of the resulting female and male distributions, with an overall mean of 0.0697, for the current assessment we used a single prior for females and males of N(0.07, 0.007).

For steepness, h, the same prior was used as for the QCS POP assessment (Edwards et al., 2012*b*) – a beta distribution with values fitted to the posterior distribution for rockfish calculated by

Forrest et al. (2010), with the Pacific Ocean Perch data removed (R. Forrest, DFO, pers. comm., though removing those data made little difference to the distribution). Uniform priors on a logarithmic scale were used for the catchability parameters q_g.

Selectivity was estimated for the West Coast Vancouver Island synoptic survey series ($g = 1$), because age data were available. Priors for the three selectivity parameters, μ_1, Δ_1, and v_{1L} were based on the results from the QCS POP assessment (Edwards et al., 2012*b*). Normal distributions were used for the priors, with means taken from the median values of the posteriors for the QCS synoptic survey series for the ‘Estimate M and h’ model run, given as $\mu_2 = 13.3, \log v_{2L} = 3.30$ and $\Delta_2 = 0.22$ in Table G3 (p156) of Edwards et al. (2012*b*). To give broad priors here, the standard deviations of the priors were set to give coefficients of variation of 0.3.

For the other two survey series, the National Marine Fisheries Service triennial survey series and the GB Reed historical survey series, no age data were available, and so the selectivity parameters were held fixed rather than estimated. The aforementioned median values were used for the fixed values.

For the commercial selectivity ($g = 4$), age data were available and so selectivity was estimated. Again, the priors for the three parameters were normal distributions with means based on the median values of the posteriors for the ‘Estimate M and h’ model run of the QCS assessment, given in Table G3 (p156) of Edwards et al. (2012*b*) as $\mu_4 = 10.5, \log v_{4L} = 1.52$ and $\Delta_4 = 0.00$. To give broad priors, the standard deviations of the priors were set to give coefficients of variation of 0.3 (except for Δ_4 for which the standard deviation was set to 0.3, because its mean was 0).

F.6.4 MCMC PROPERTIES

The MCMC searches started from the MPD values. 10,000,000 iterations were performed, sampling every 10,000th for 1,000 samples, which were used with no burn-in period (because the MCMC searches started from the MPD values).

F.7 REFERENCE POINTS, PROJECTIONS AND ADVICE TO MANAGERS

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

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

The probability P$(B_{2013} > 0.8 B_{\mathrm{MSY}})$ is then calculated as the proportion of the 1,000 MCMC samples for which $B_{2013} > 0.8 B_{\mathrm{MSY}}$ (and similarly for the other reference points).

Projections were made for 10 years (as agreed upon with N. Davis, DFO Groundfish Management Unit, pers. comm.), starting with the biomass and age structure calculated for the start of 2013. A range of constant catch strategies were used, from 0-2,000 t (the average catch from 2007-2011 was 547 t). For each strategy, projections were performed for each of the 1,000 MCMC samples (resulting in posterior distributions of future spawning biomass). Recruitments were randomly calculated using (F.24) (i.e. based on lognormal recruitment deviations from the estimated stock-recruitment curve), using randomly generated values of $\epsilon_t \sim$ Normal$(0, \sigma_R^2)$. For each of the 1,000 MCMC samples a time series of $\{\epsilon_t\}$ was generated. For each MCMC sample, the same time series of $\{\epsilon_t\}$ was used for each catch strategy (so that, for a given MCMC sample, all catch strategies experience the same recruitment stochasticity).

G RESULTS

G.1 INTRODUCTION

This Appendix describes the results from the mode of the posterior distribution (MPD) (to compare model estimates to observations), diagnostics of the Markov chain Monte Carlo (MCMC) results, and the MCMC results for the estimated parameters. The final advice and major outputs are obtained from the MCMC results. Estimates of major quantities and advice to management (such as decision tables) are presented in the main text.

G.2 MODE OF THE POSTERIOR DISTRIBUTION (MPD) RESULTS

Awatea first determines the MPD for each estimated parameter. These are then used as the starting points for the MCMC simulations. The MPD fits are shown for the survey indices (Figure G.1), the commercial catch-at-age data (as bubble plots in Figures G.2-G.5 and as overlaid age structures in Figures G.6 and G.7), and the West Coast Vancouver Island (WCVI) survey series age data (Figure G.8). The results are sensible and are able to capture the main features of the data sets fairly well. There appears to be relative consistency between the available data sources.

Residuals to the MPD model fits are provided for the three survey indices (Figures G.9 to G.11), and the two sets of age data (Figures G.12 and G.13). These further suggest that the model fits are consistent with the data, as do the mean ages for the two sets of age data (Figure G.14).

Figure G.15 shows the resulting stock-recruitment function and the MPD values of recruitment over time (though see Figure 5 for the MCMC values of recruitment). Figure G.16 shows that the recruitment deviations display no trend over time, and that the auto-correlation function of the deviations appears satisfactory. Figure G.17 gives the MPD fits for the selectivities, together with ogive for female maturity. The values of the log-likelihood and objective functions for the MPD fits are given in Table G.1.

G.3 BAYESIAN MCMC RESULTS

The MCMC procedure performed 10,000,000 iterations, sampling every 10,000th to give 1,000 MCMC samples. The 1,000 samples were used with no burn-in period (because the MCMC searches started from the MPD values). MCMC traces show good convergence properties (no trend with increasing sample number) for the estimated parameters (Figure G.18), as does a diagnostic analysis that splits the samples into three segments (Figure G.19). Pairs plots of the estimated parameters (Figures G.20-G.22) show no undesirable correlations between parameters. In particular, steepness, h, shows little correlation with the two natural mortality parameters, M_1 and M_2, suggesting there are sufficient data to simultaneously estimate steepness and natural mortality. Trace plots of the derived spawning biomass (Figure G.23) and recruitment (Figure G.24) also show good convergence properties. Thus, the MCMC computations seem satisfactory.

Marginal posterior distributions and corresponding priors for the estimated parameters are shown in Figure G.25. For most parameters, it appears that there is enough information in the data to move the posterior distribution away from the prior. The estimates of natural mortality, M_1 and M_2, did not move too far from their priors, which were based on our previous Queen Charlotte Sound POP assessment (Edwards et al., 2012*b*); see Appendix F. Corresponding summary statistics for the estimated parameters are given in Table G.2.

Plots of marginal posterior distributions of vulnerable biomass, spawning biomass, annual recruitment and exploitation rate are presented in the main text, because of their interest to management. Phase plots showing the time-evolution of spawning biomass and exploitation rate relative to reference points are also shown in the main text, together with projections and resulting decision tables.

For the maximum sustainable yield (MSY) calculations, projections were run for 301 values of constant exploitation rate u_t between 0 and 0.3, until an equilibrium yield was reached within a tolerance of 0.01 t (or until 15,000 years had been reached). This was done for each of the 1,000 samples.

The lower bound of u_t was not reached for any of the MCMC samples, and the upper bound reached for two of the MCMC samples. All of the total of 301,000 projection calculations had converged by the 15,000-year maximum.

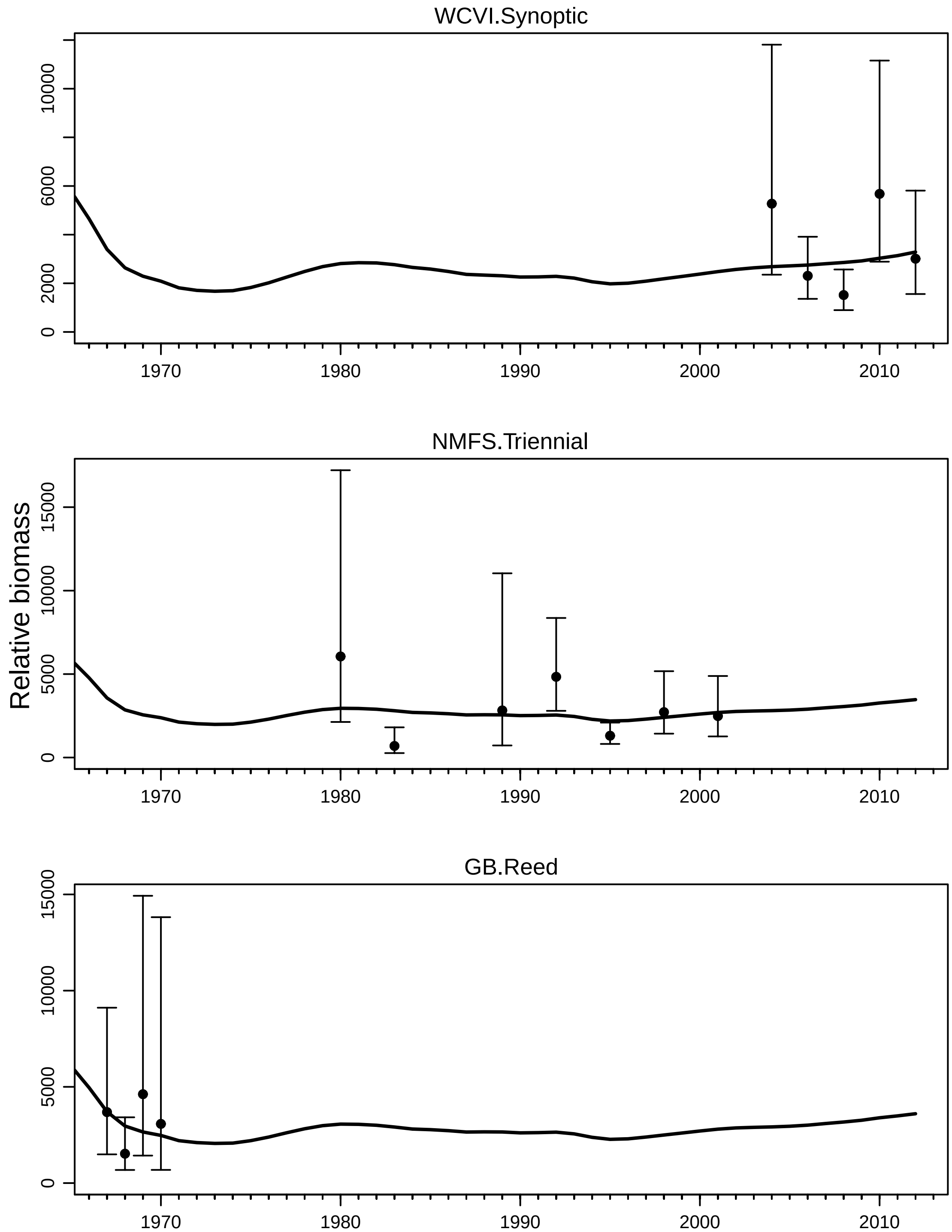


Figure G.1. Survey index values (points) with 95% confidence intervals (bars) and MPD model fits (curves) for the fishery-independent survey series.

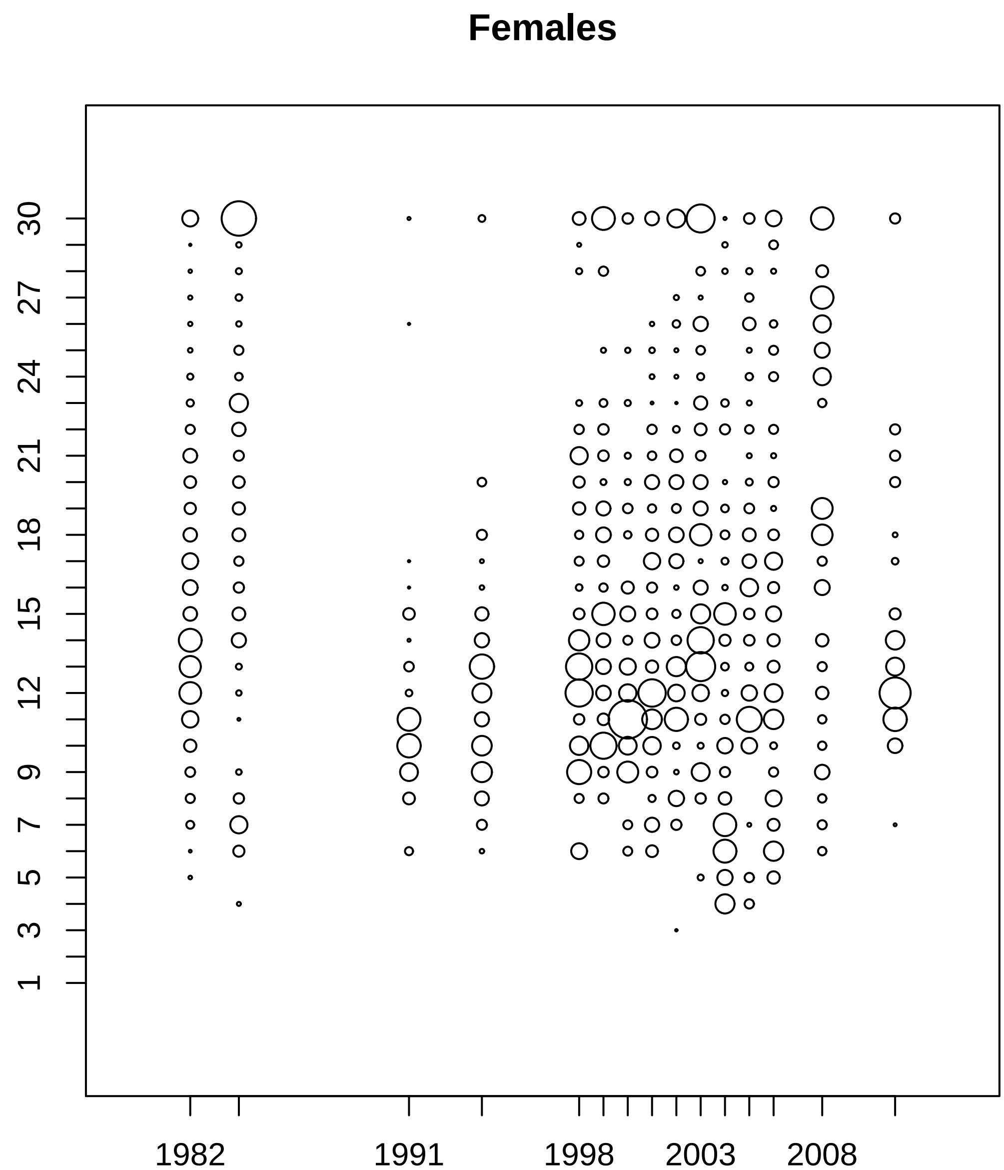


Figure G.2. Commercial catch-at-age data for females. Bubbles are, for each year, the proportions assigned to each age class, based on the weighted age calculations described in Appendix E. Bubble areas are proportional to the respective proportions.

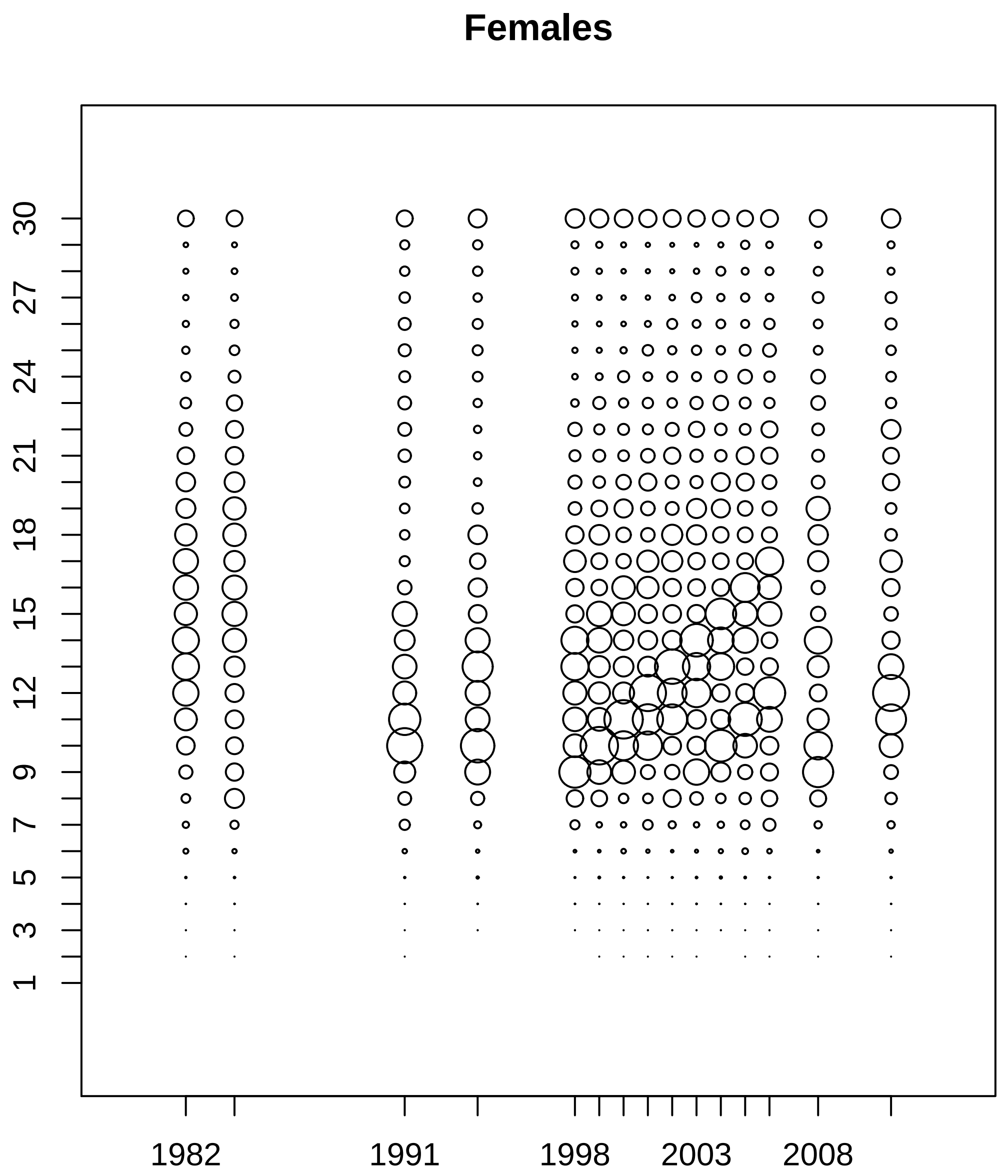


Figure G.3. Estimated proportions-at-age of females that are vulnerable to the fishery. Only years for which commercial data are used in the model are shown. Details as for Figure G.2.

Males

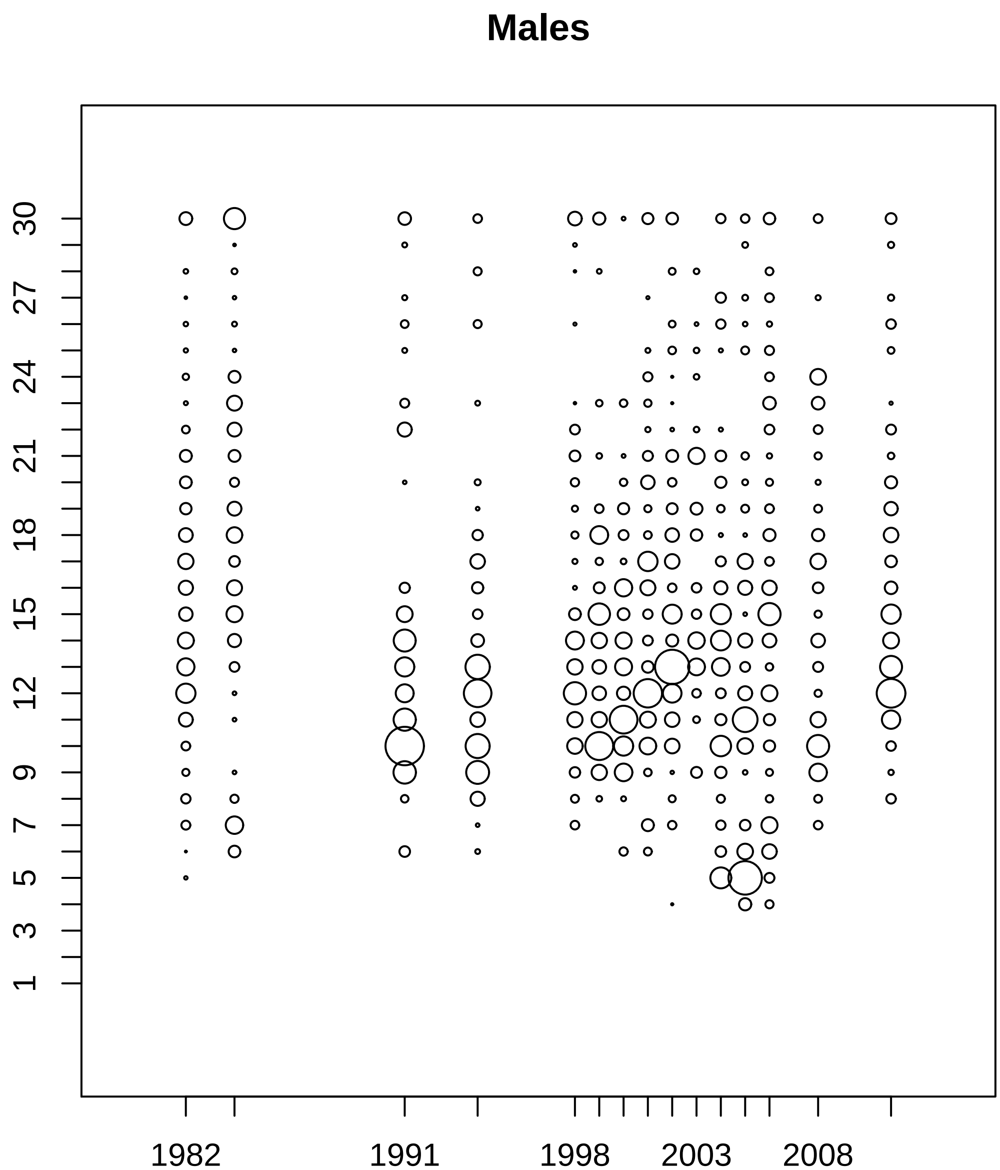


Figure G.4. Commercial catch-at-age data for males, details as for Figure G.2.

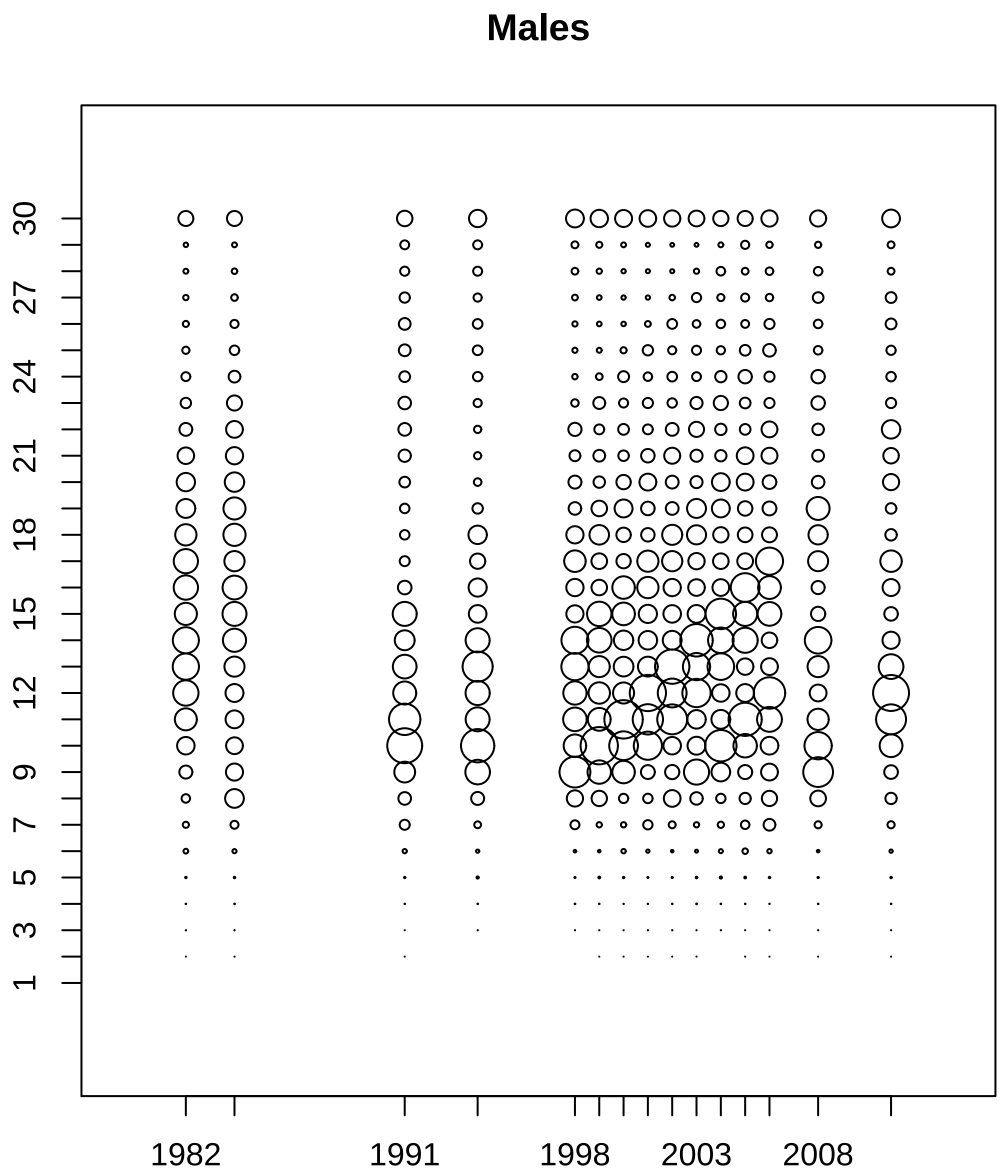


Figure G.5. Estimated proportions-at-age of males that are vulnerable to the fishery. Only years for which commercial data are used in the model are shown. Details as for Figure G.2.

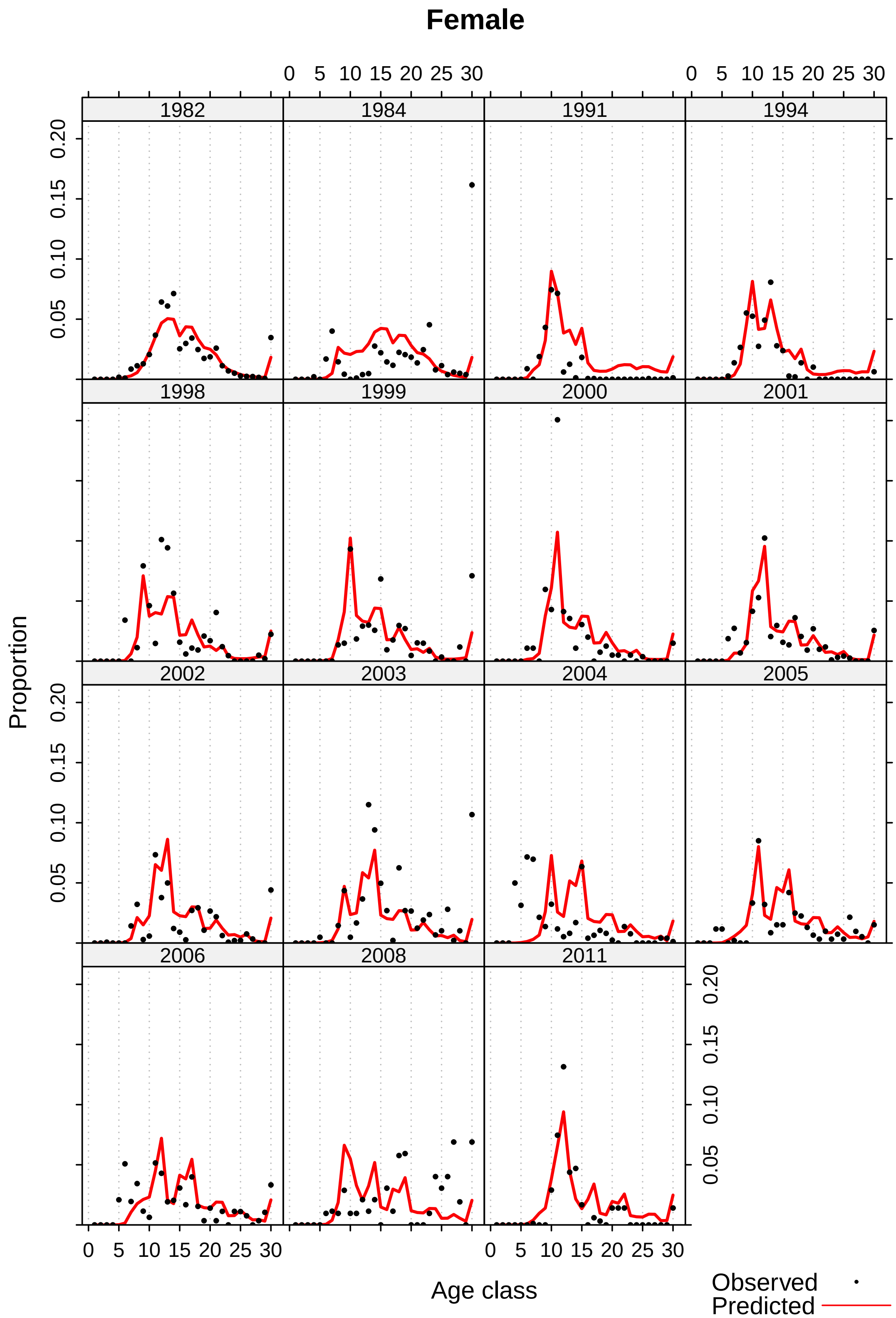


Figure G.6. Observed and predicted commercial proportions-at-age for females. Note that years are not consecutive.

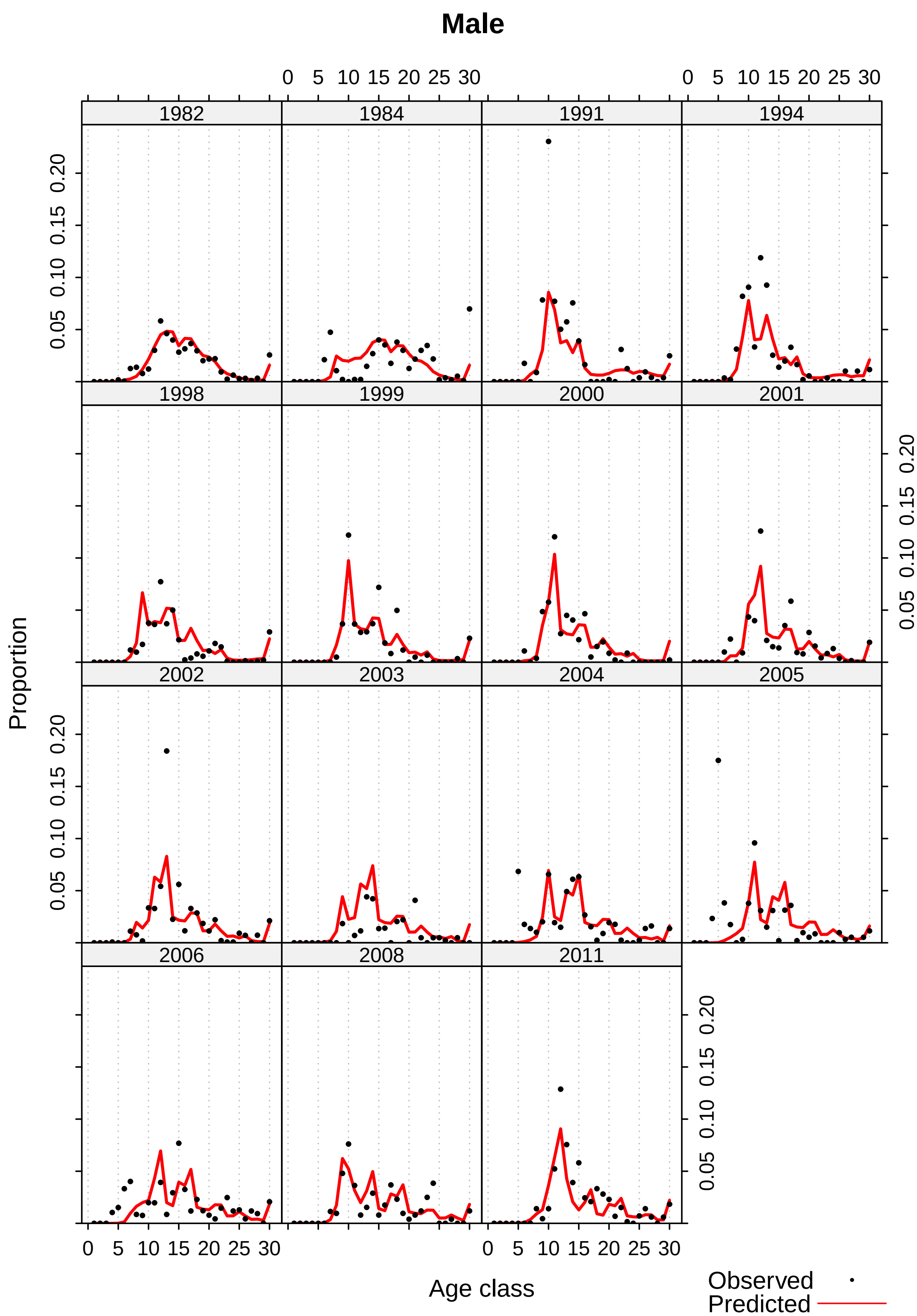
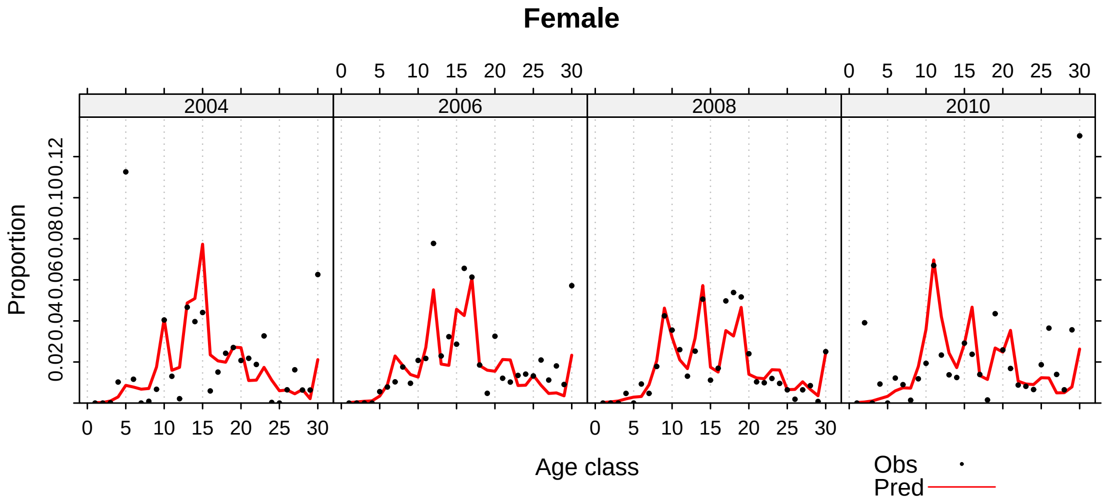


Figure G.7. Observed and predicted commercial proportions-at-age for males. Note that years are not consecutive.



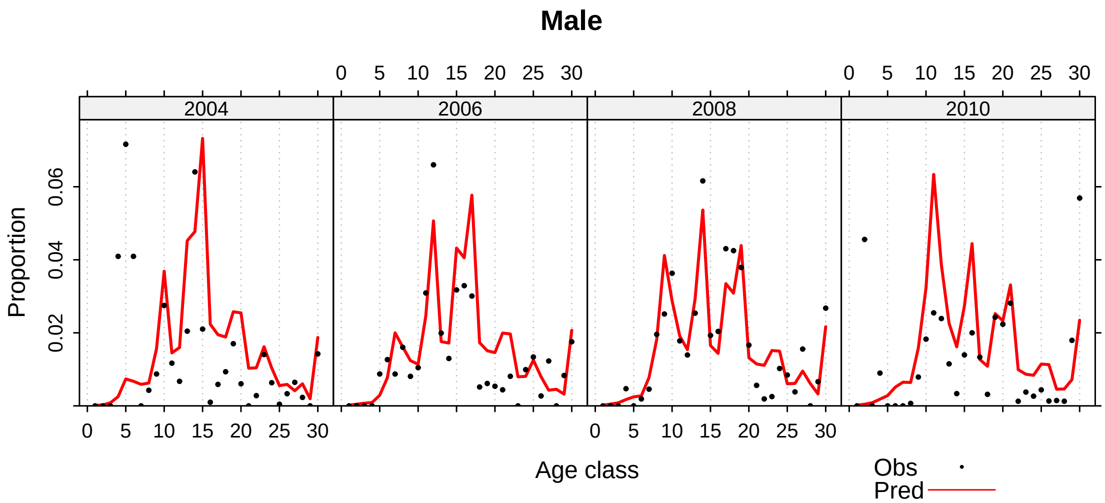


Figure G.8. Observed and predicted proportions-at-age for the WCVI synoptic survey series.

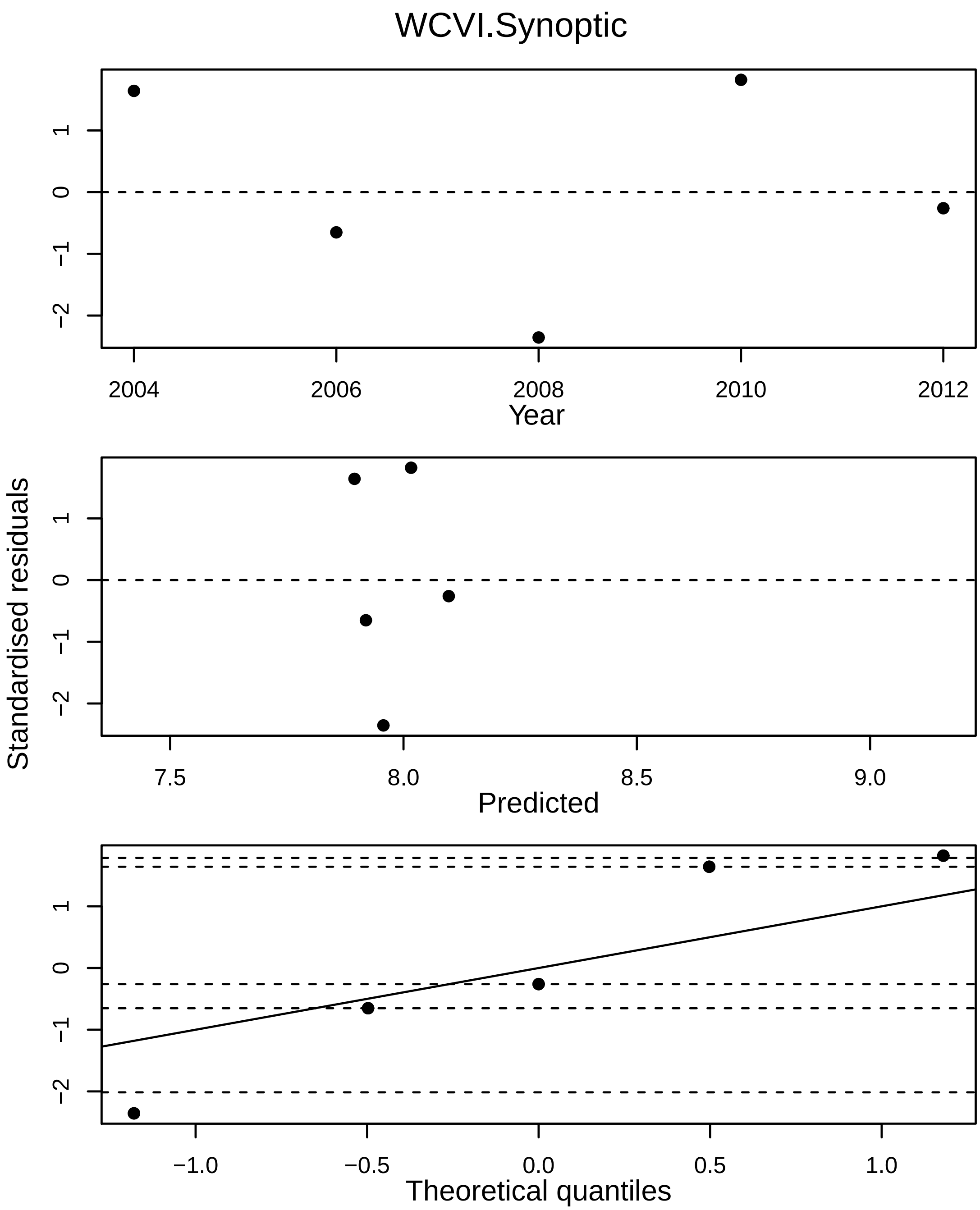


Figure G.9. Residuals of fits of model to the WCVI synoptic survey series (MPD values). Vertical axes are standardised residuals. The three plots show, respectively, residuals by year of index, residuals relative to predicted index, and normal quantile-quantile plot for residuals (horizontal lines give 5, 25, 50, 75 and 95 percentiles).

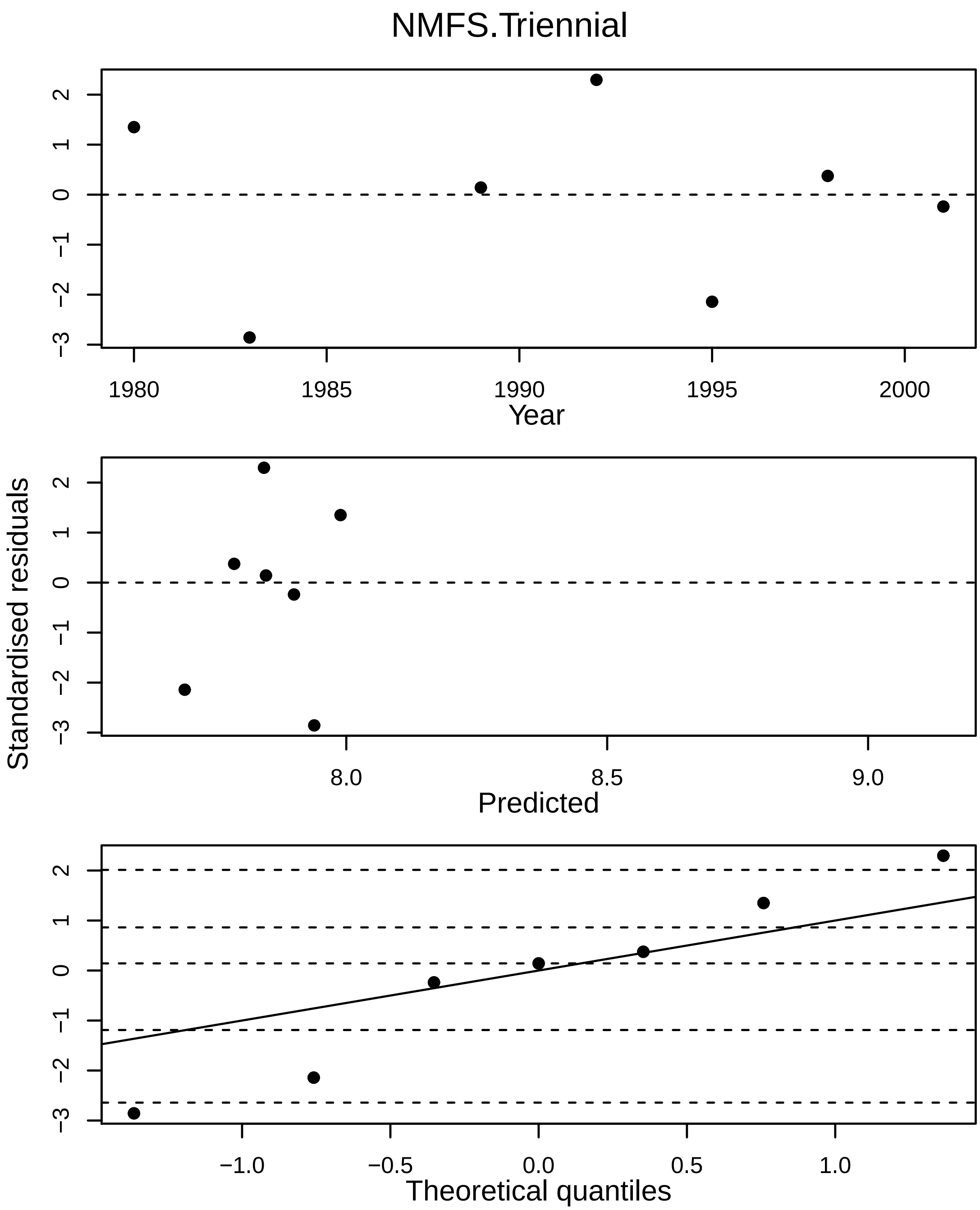


Figure G.10. Residuals of fits of model to the NMFS Triennial survey series (MPD values). Vertical axes are standardised residuals. The three plots show, respectively, residuals by year of index, residuals relative to predicted index, and normal quantile-quantile plot for residuals (horizontal lines give 5, 25, 50, 75 and 95 percentiles).

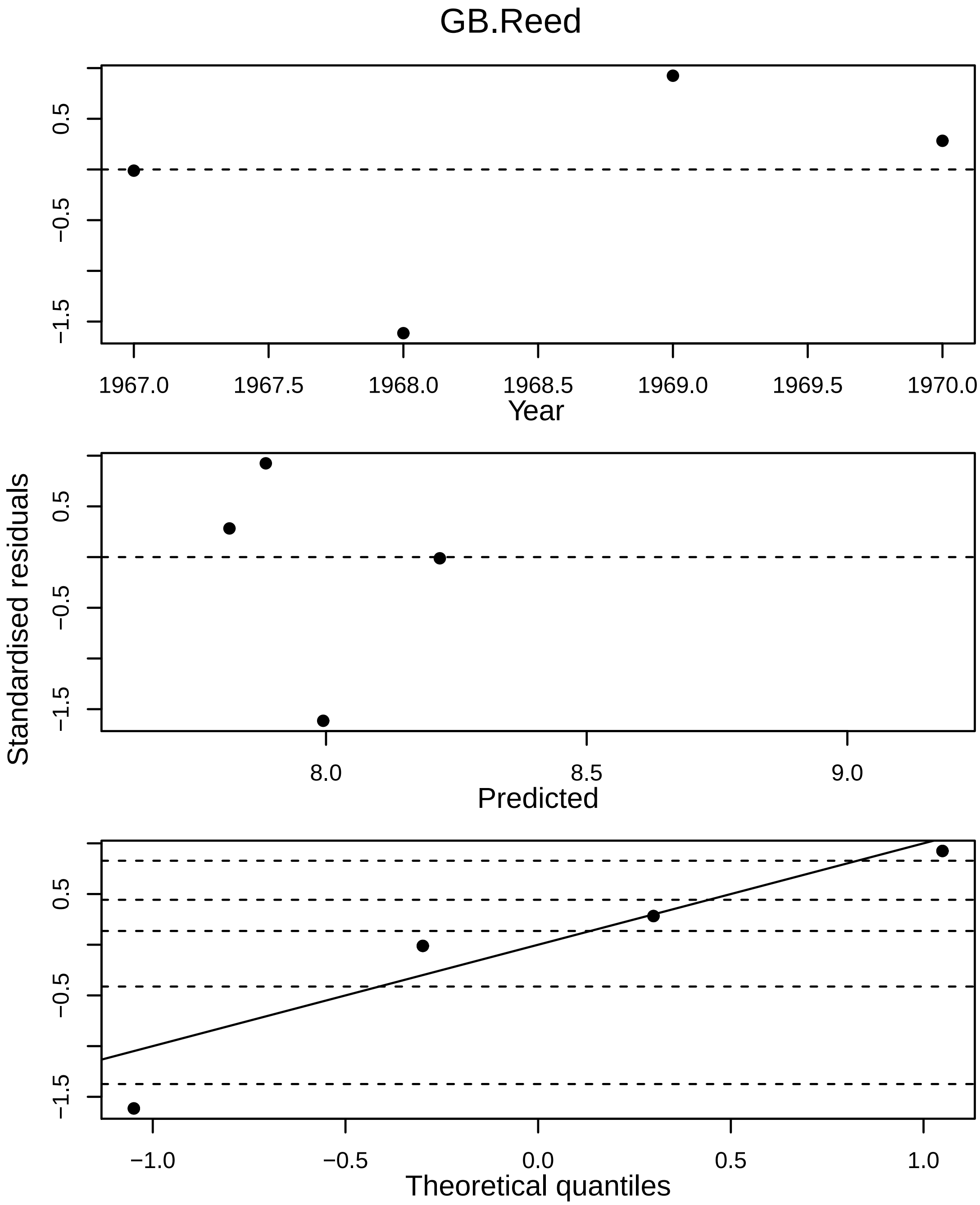


Figure G.11. Residuals of fits of model to the GB Reed survey series (MPD values). Vertical axes are standardised residuals. The three plots show, respectively, residuals by year of index, residuals relative to predicted index, and normal quantile-quantile plot for residuals (horizontal lines give 5, 25, 50, 75 and 95 percentiles).

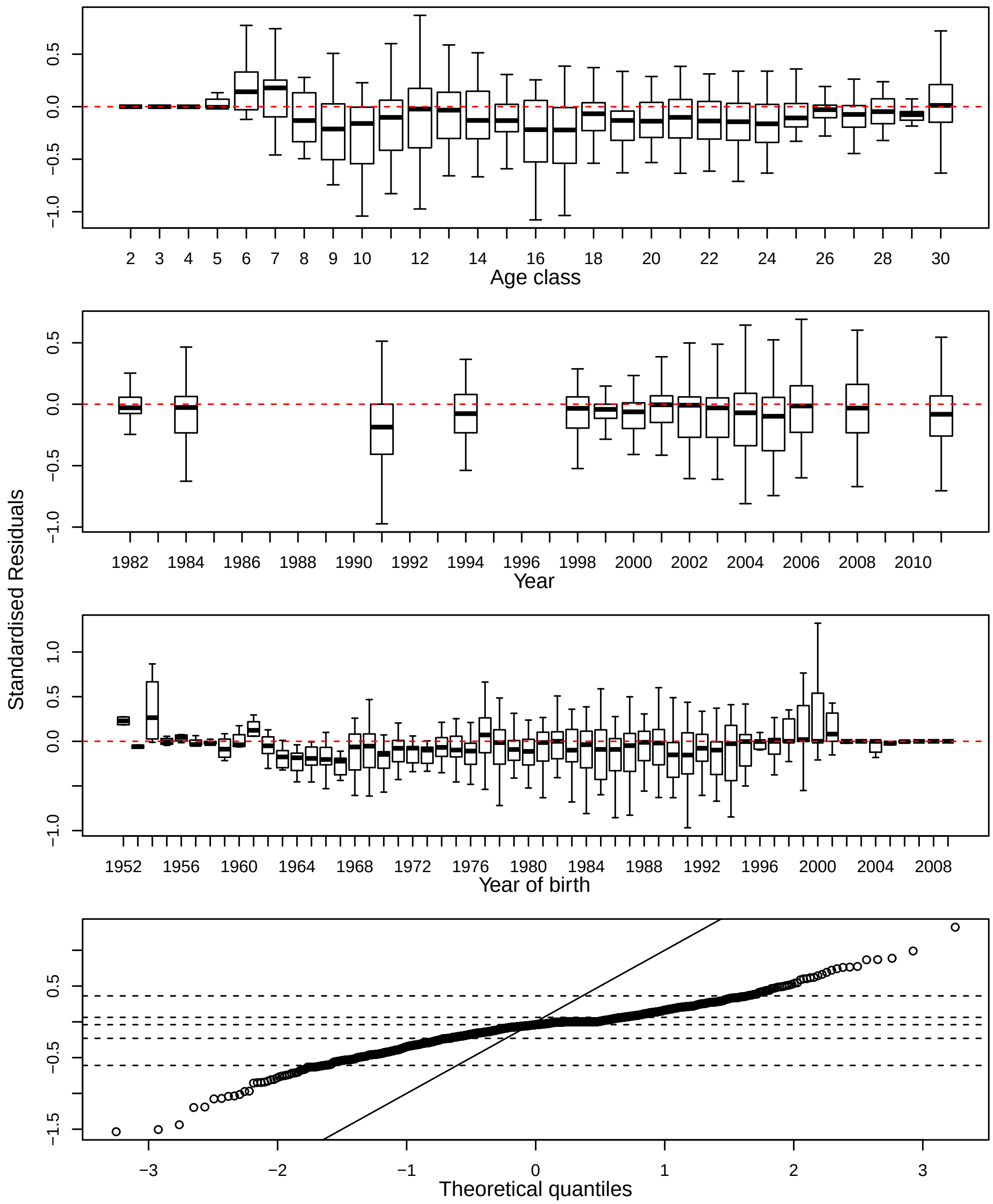


Figure G.12. Residual of fits of model to commercial proportions-at-age data (MPD values). Vertical axes are standardised residuals. Boxplots show, respectively, residuals by age class, by year of data, and by year of birth (following a cohort through time). Boxes give interquartile ranges, with bold 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 the total of 870 residuals).

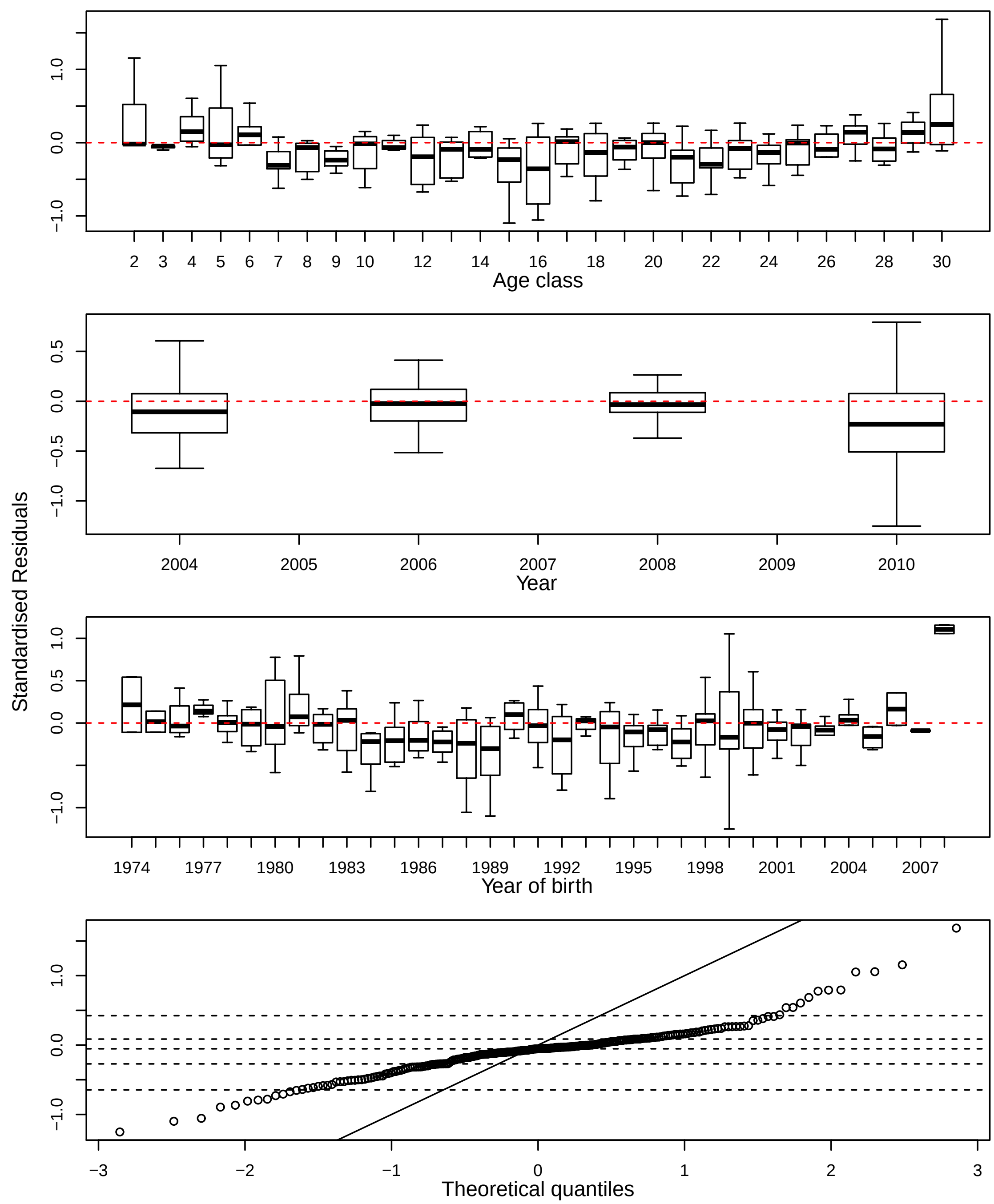


Figure G.13. Residuals of fits of model to proportions-at-age data (MPD values) from the WCVI synoptic survey series. Details as for Figure G.12, for a total of 232 residuals.

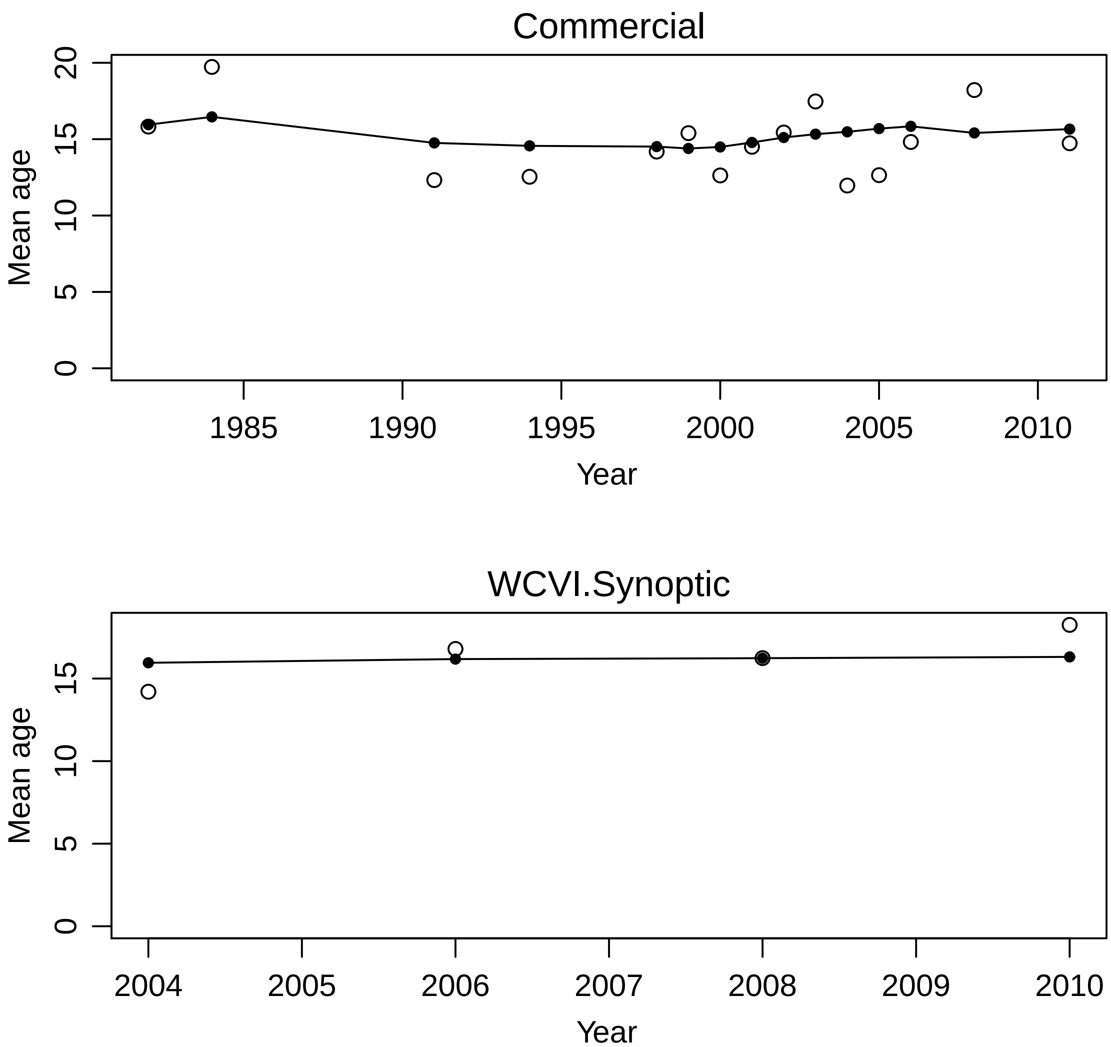


Figure G.14. Mean ages each year for the data (open circles) and model estimates (joined filled circles) for the commercial and survey age data.

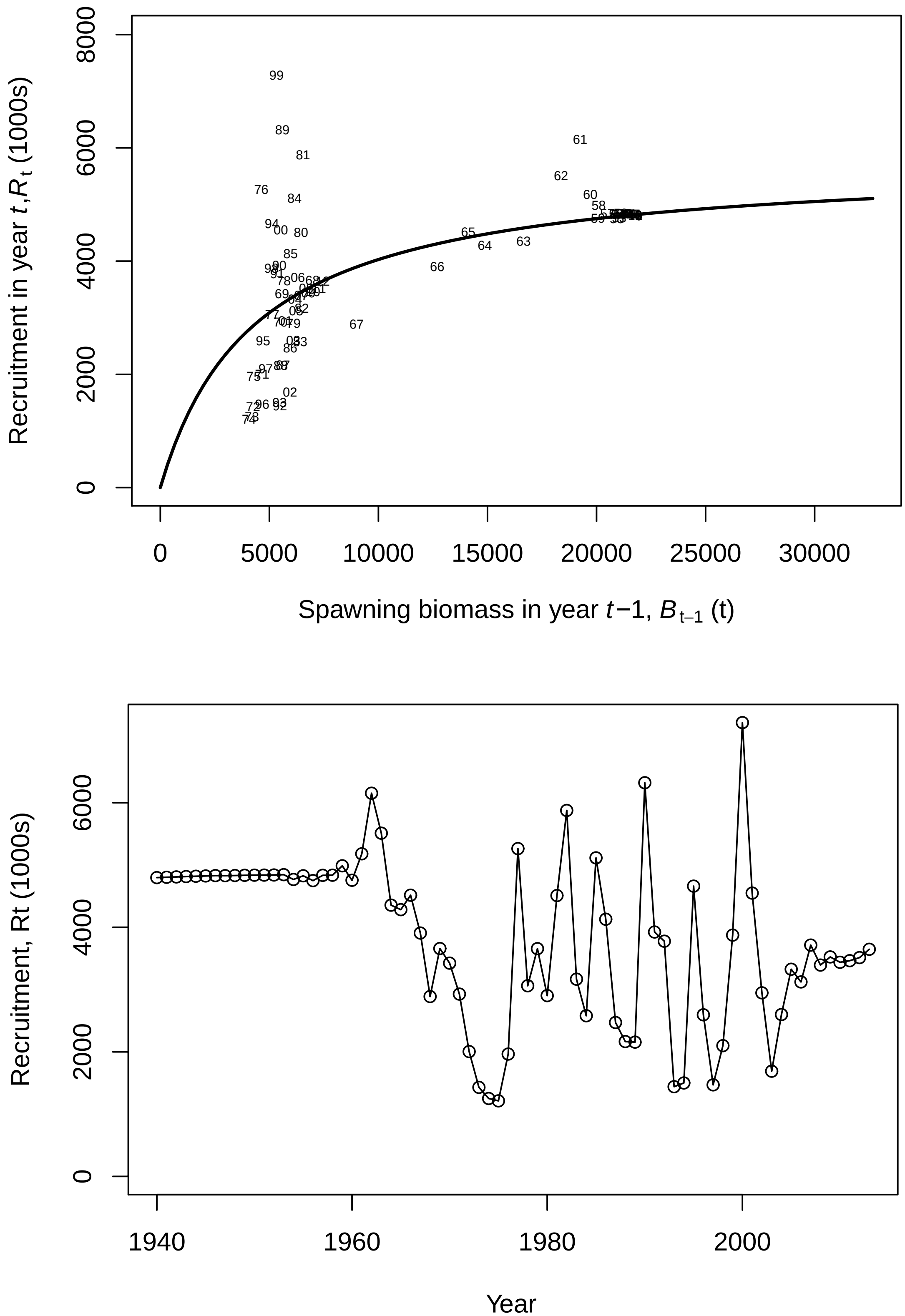


Figure G.15. Top: Deterministic stock-recruit relationship (black curve) and observed values (labelled by year of spawning) using MPD values. Bottom: Recruitment (MPD values of age-1 individuals in year t) over time, in 1,000s of age-1 individuals, with a mean of 3,850.

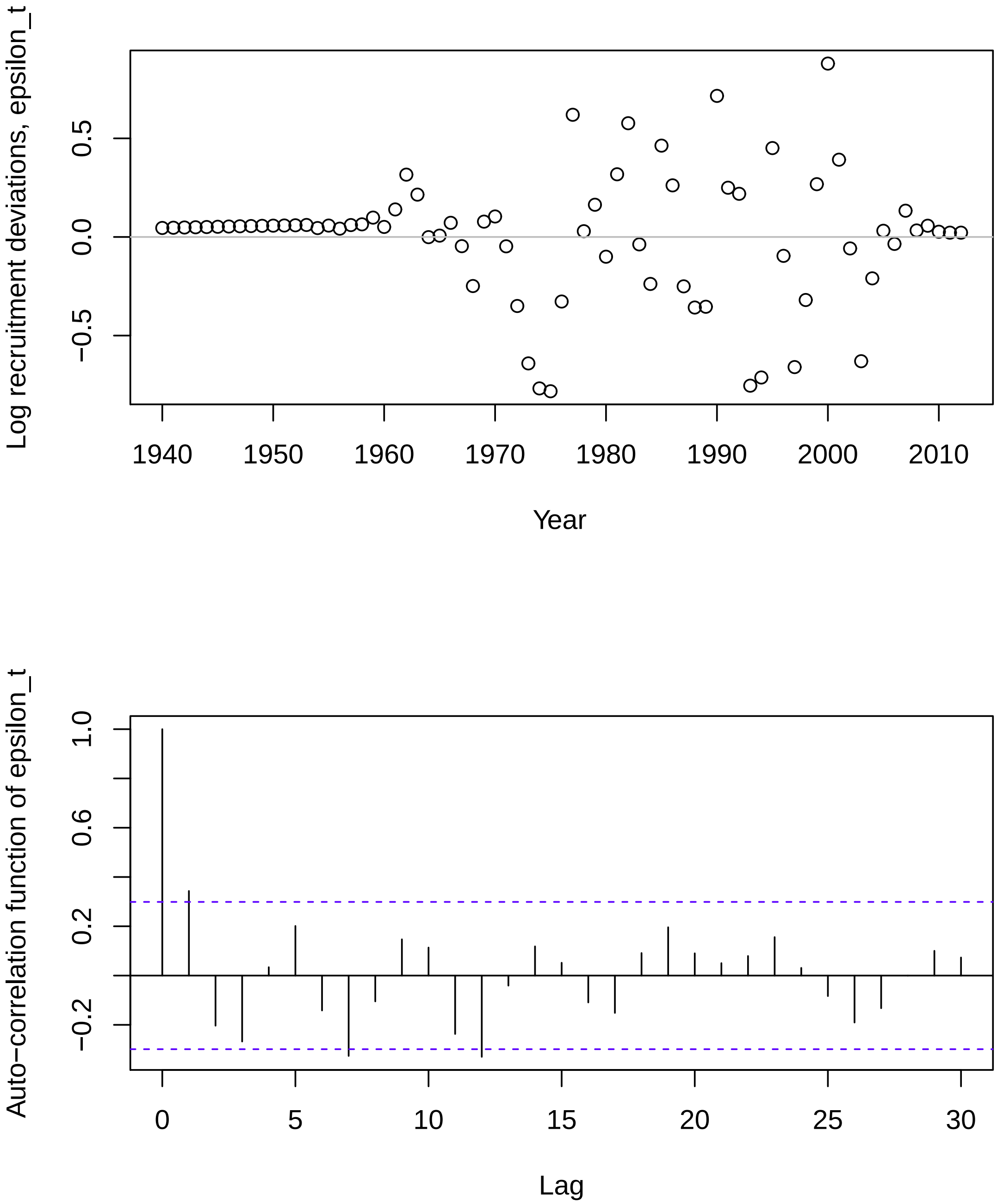


Figure G.16. Top: log of the annual recruitment deviations, ϵ_t, where bias-corrected multiplicative deviation is e$^{\epsilon_t - \sigma_R^2/2}$ where $\epsilon_t \sim$ Normal$(0, \sigma_R^2)$. Bottom: Auto-correlation function of the logged recruitment deviations (ϵ_t), for years 1961-2003 (determined as the first year of commercial age data minus the accumulator age class plus the age for which commercial selectivity for females is 0.5, to the final year that recruitments are calculated minus the age for which commercial selectivity for females is 0.5).

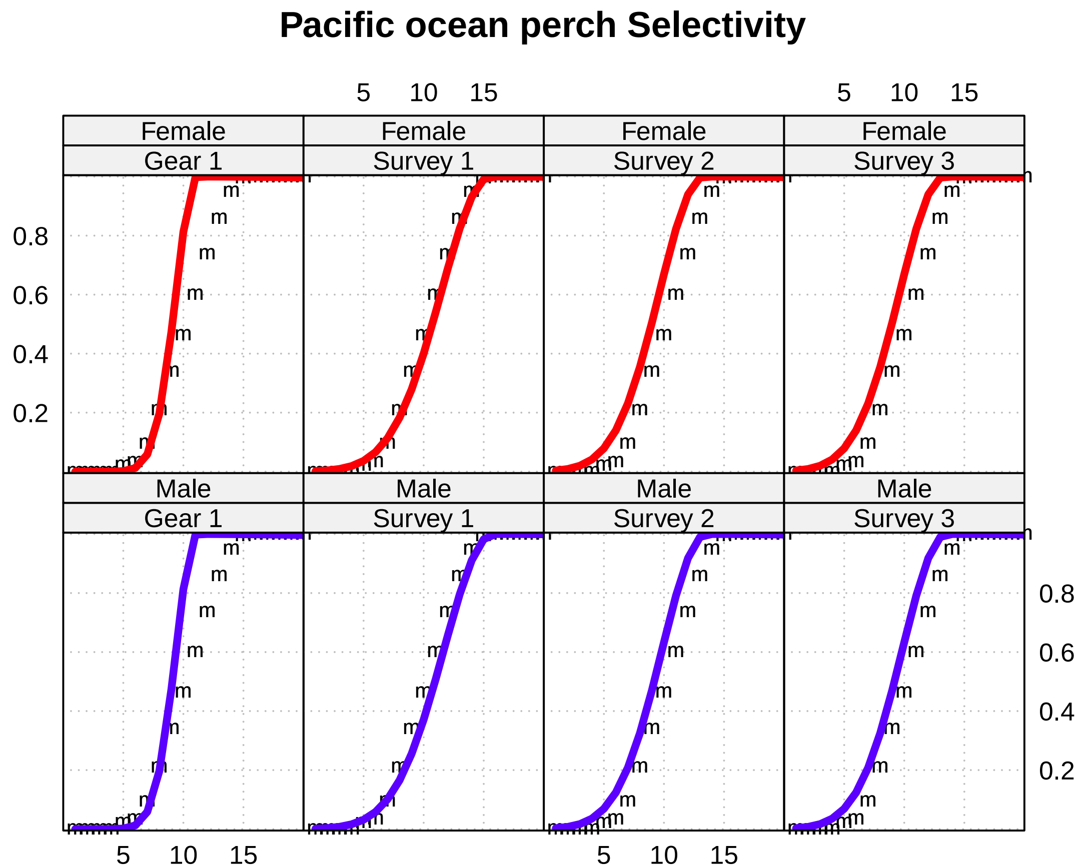


Figure G.17. Selectivities for commercial catch (labelled 'Gear 1' here) and surveys (all MPD values), with maturity ogive for females indicated by 'm'. Selectivities are fixed for surveys 2 and 3 (NMFS Triennial and GB Reed).

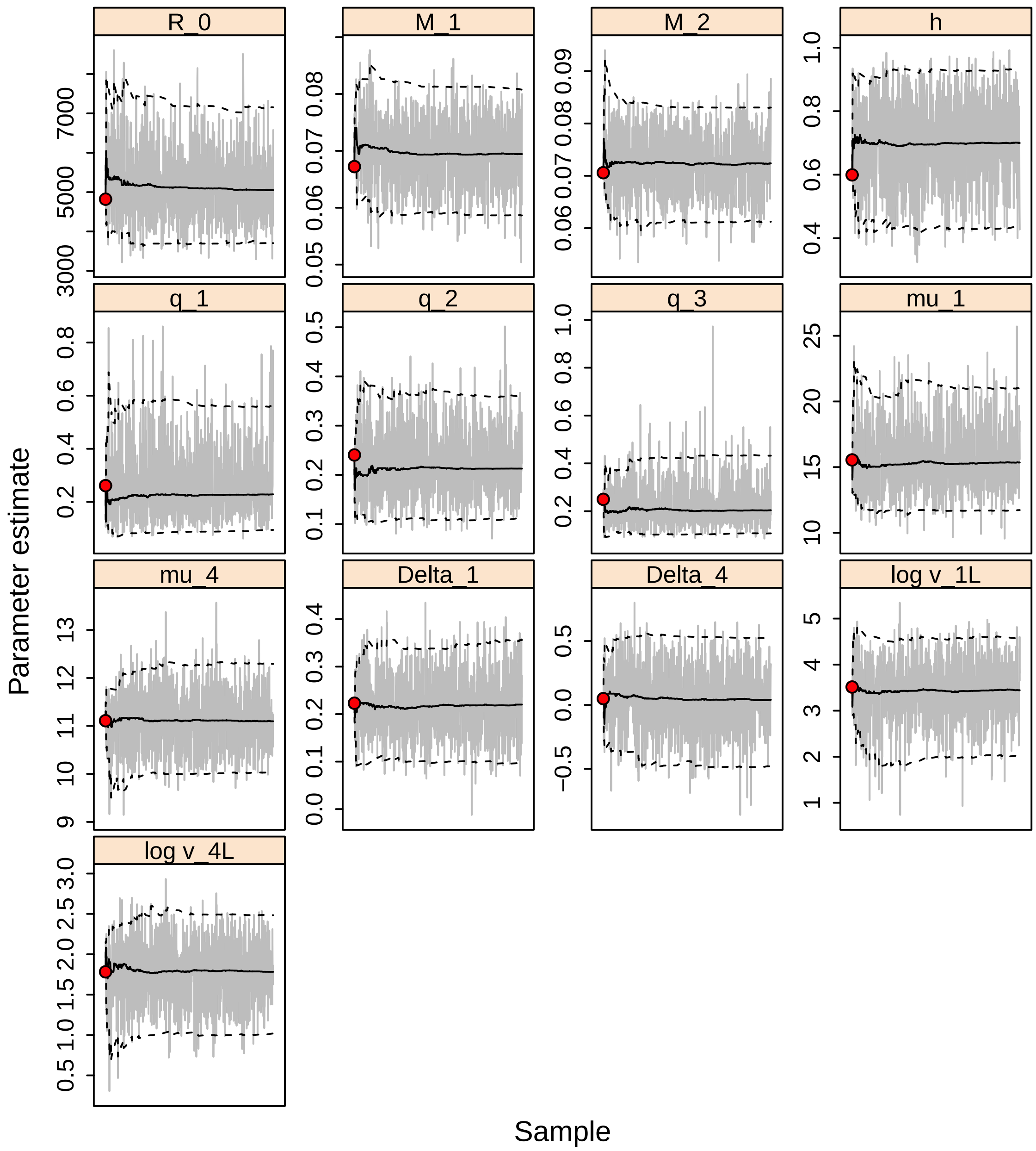


Figure G.18. MCMC traces for the estimated parameters. Grey lines show the 1,000 samples for each parameter, solid lines show the cumulative median (up to that sample), and dashed lines show the cumulative 2.5 and 97.5 quantiles. Red circles are the MPD estimates. Except for M_1 and M_2, subscripts 1 to 3 correspond to the fishery-independent surveys, and subscript 4 to the commercial fishery.

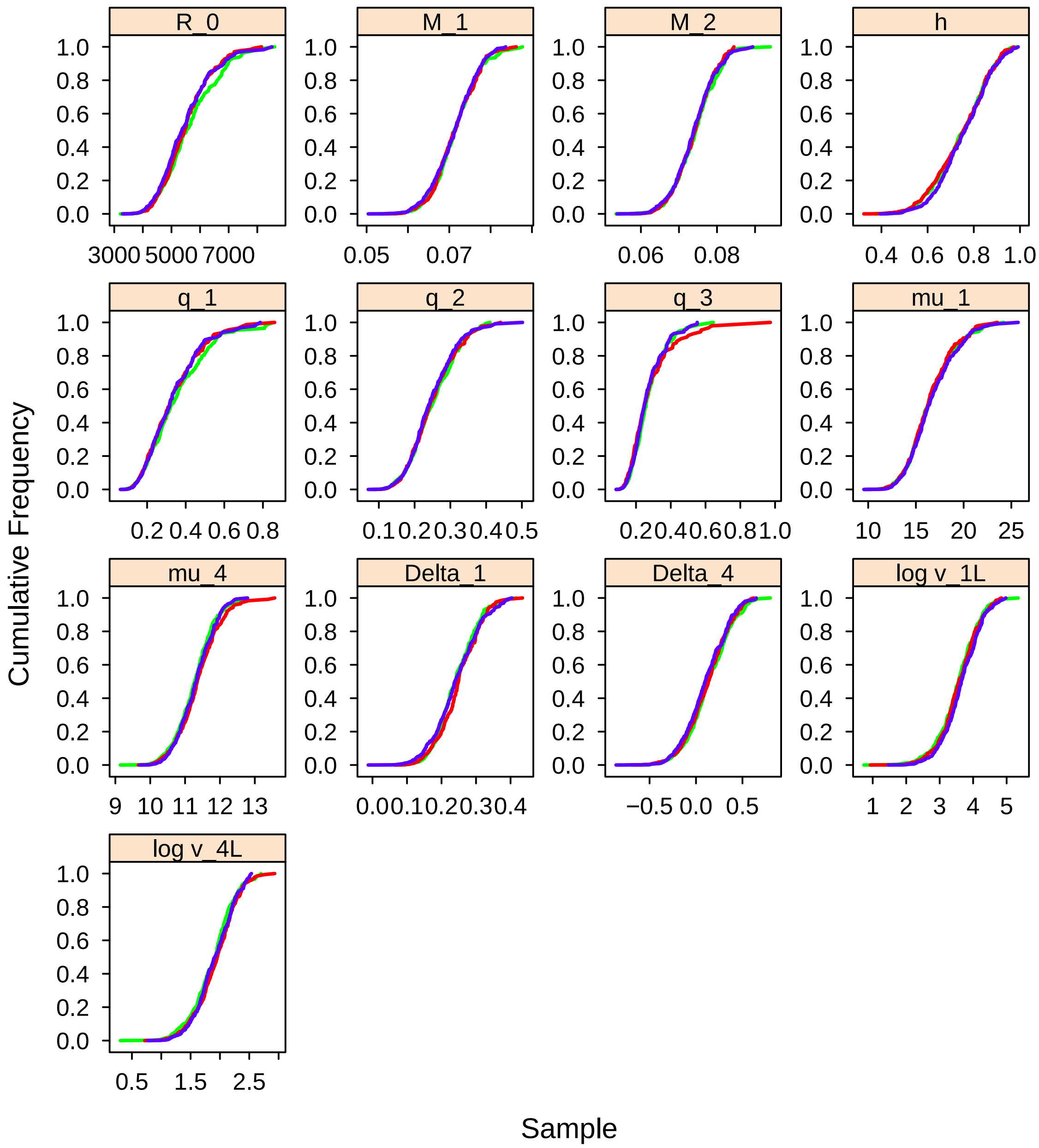


Figure G.19. Diagnostic plot obtained by dividing the MCMC chain of 1,000 MCMC samples into three segments, and overplotting the cumulative distributions of the first segment (green), second segment (red) and final segment (blue).

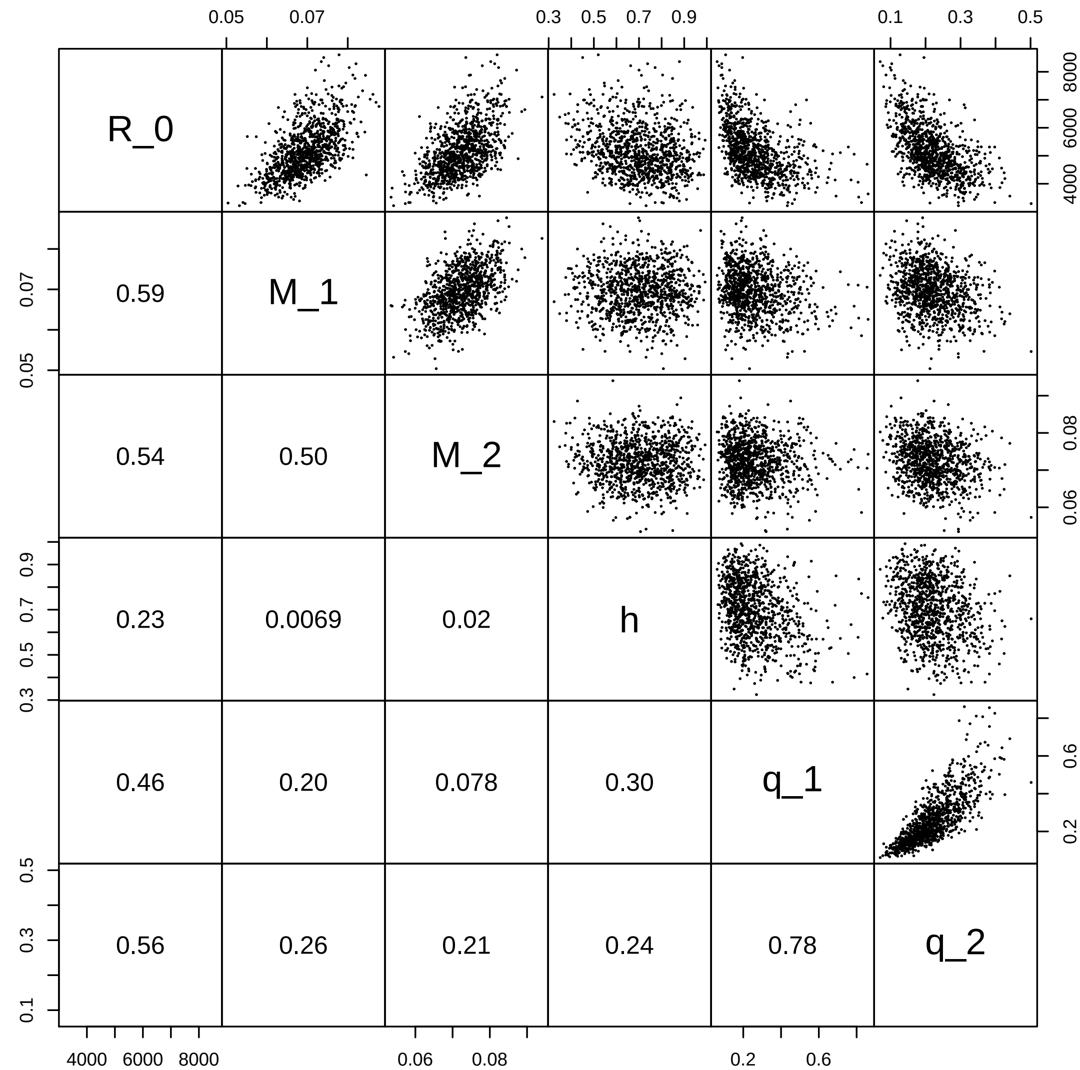


Figure G.20. Pairs plot of 1,000 MCMC samples for 1st six parameters. Numbers are the absolute values of the correlation coefficients.

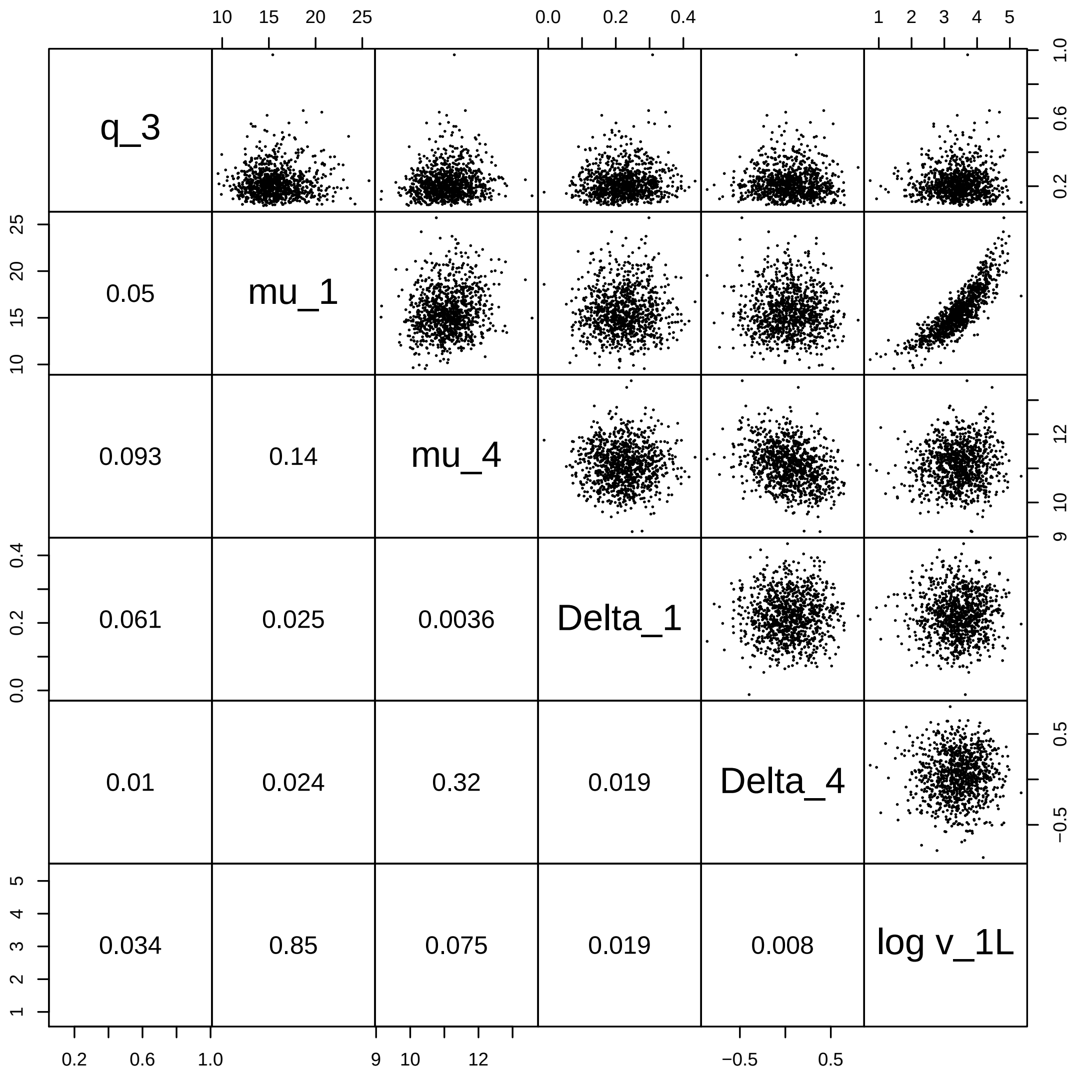


Figure G.21. Pairs plot of 1,000 MCMC samples for 2nd six parameters. Numbers are the absolute values of the correlation coefficients.

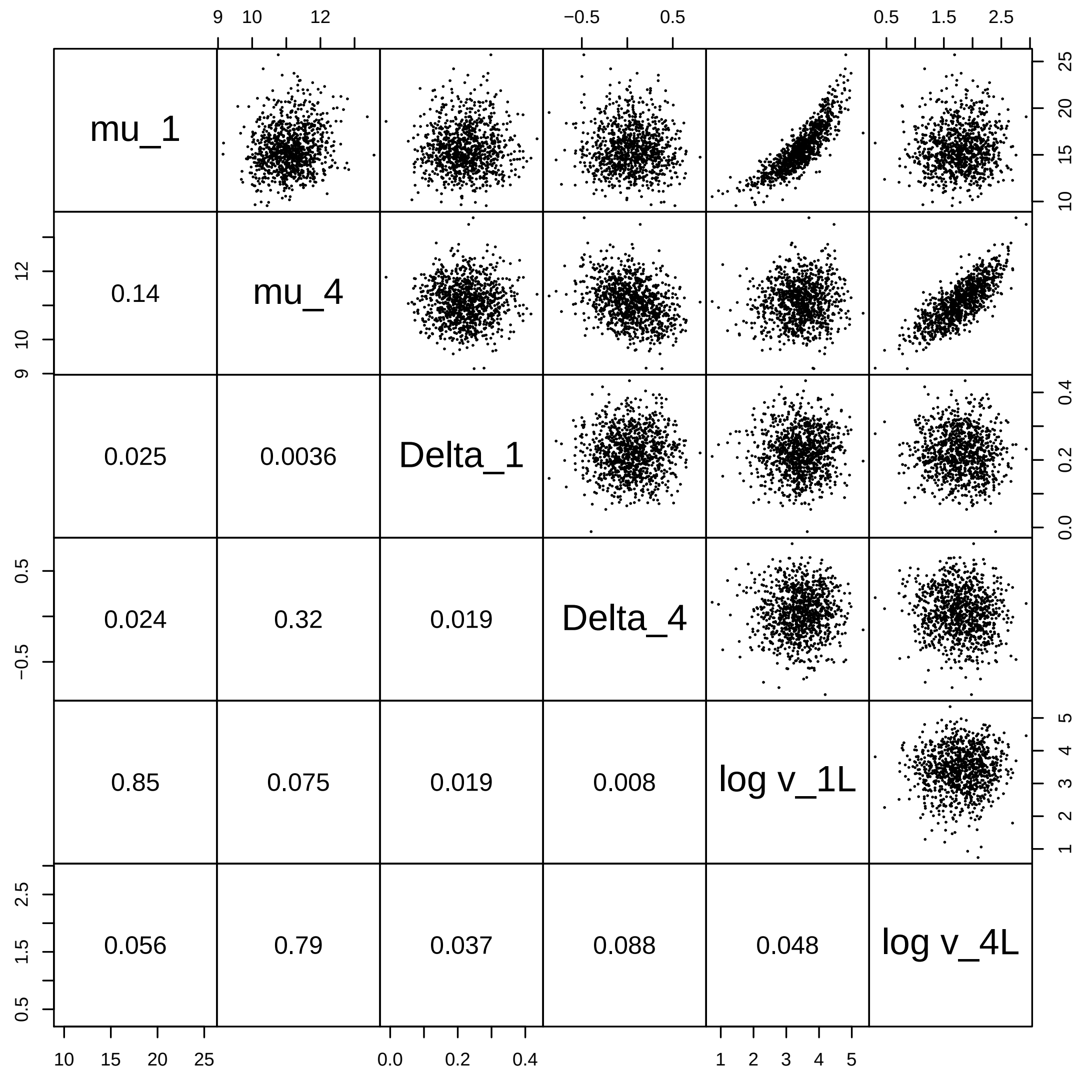


Figure G.22. Pairs plot of 1,000 MCMC samples for 3rd six parameters. Numbers are the absolute values of the correlation coefficients.

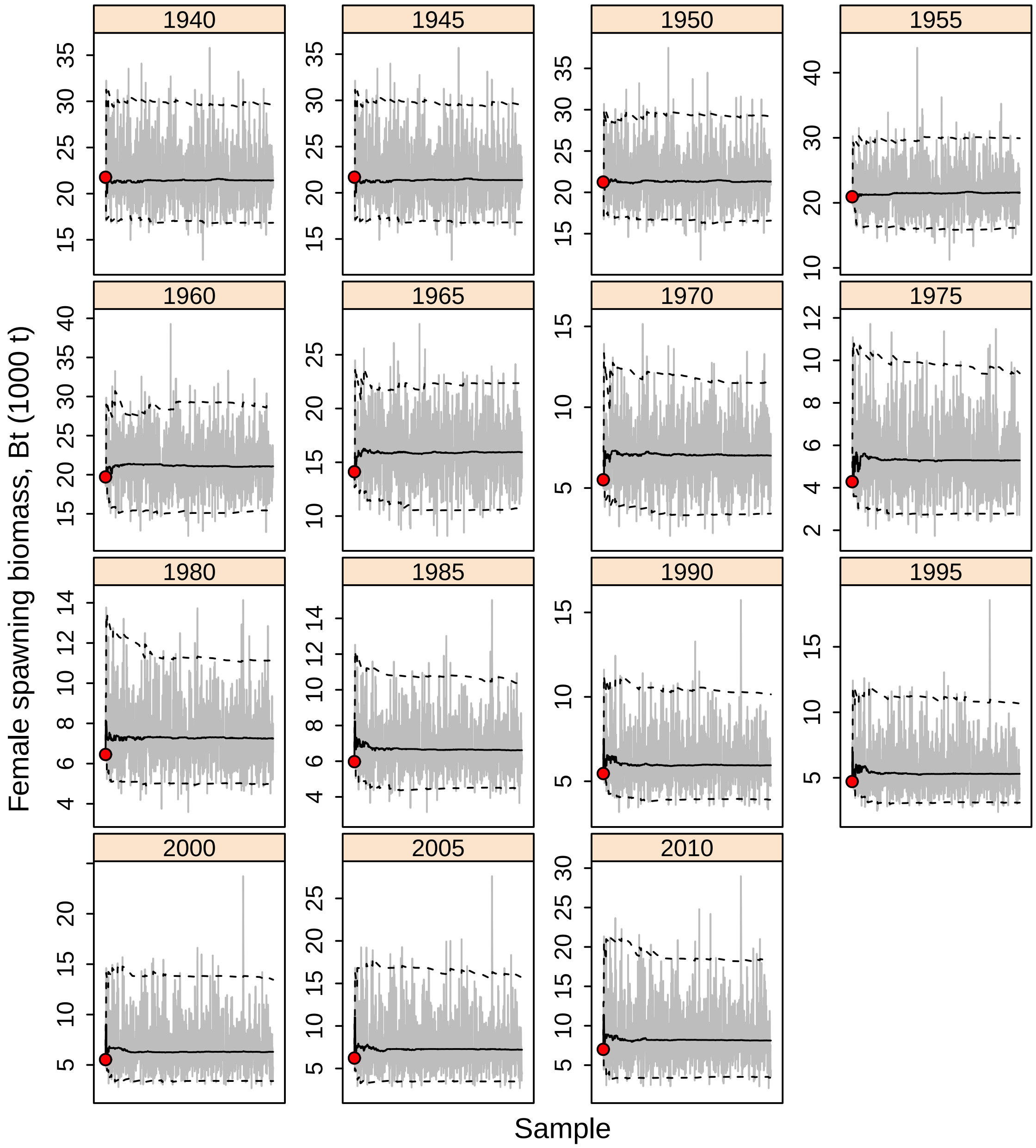


Figure G.23. MCMC traces for female spawning biomass estimates at five-year intervals. Note that vertical scales are different for each plot (to show convergence of the MCMC chain, rather than absolute differences in annual values). Grey lines show the 1,000 samples for each parameter, solid lines show the cumulative median (up to that sample), and dashed lines show the cumulative 2.5 and 97.5 quantiles. Red circles are the MPD estimates.

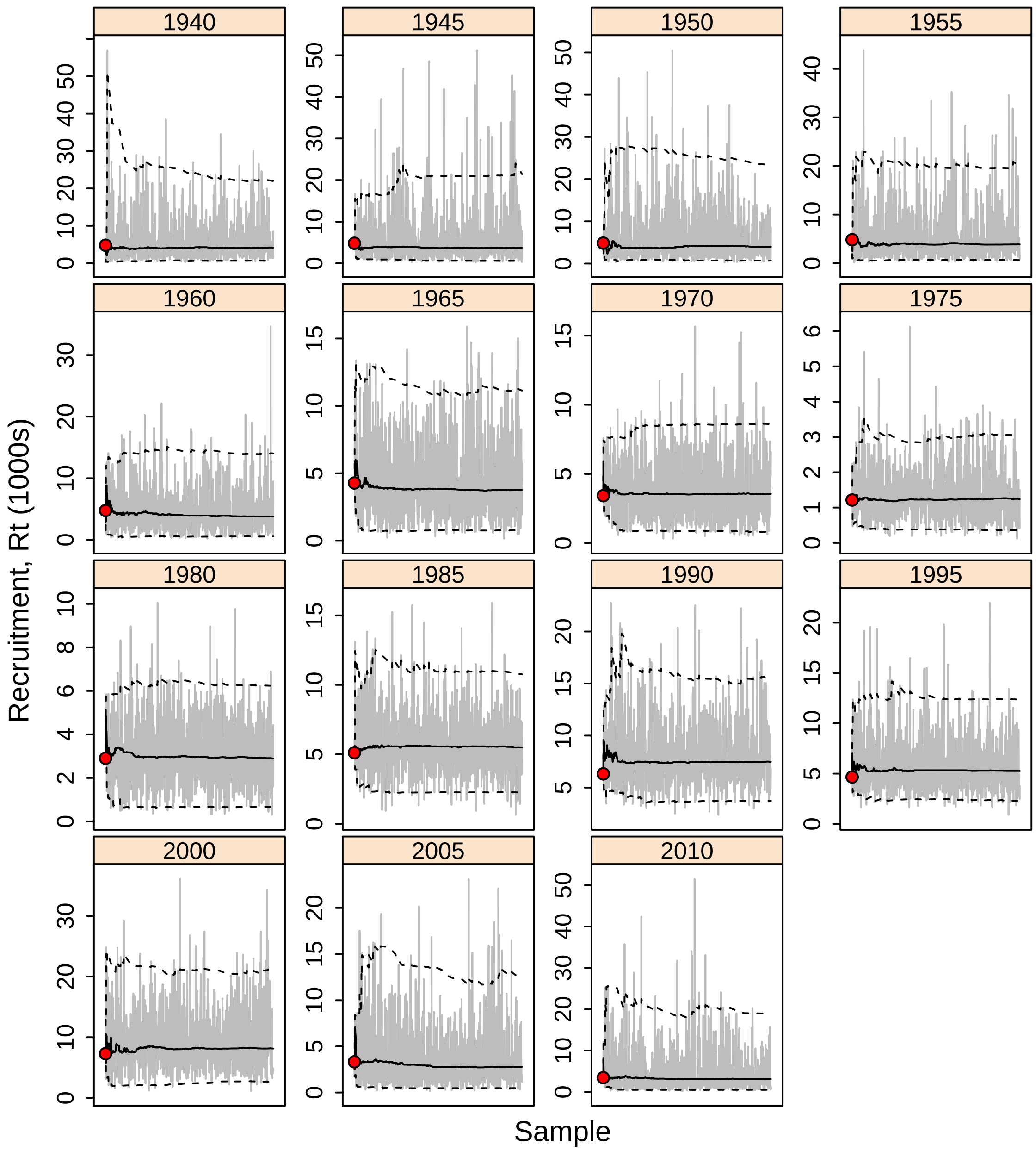


Figure G.24. MCMC traces for recruitment estimates at five-year intervals. Note that vertical scales are different for each plot (to show convergence of the MCMC chain, rather than absolute differences in annual recruitment). Grey lines show the 1,000 samples for each parameter, solid lines show the cumulative median (up to that sample), and dashed lines show the cumulative 2.5 and 97.5 quantiles. Red circles are the MPD estimates.

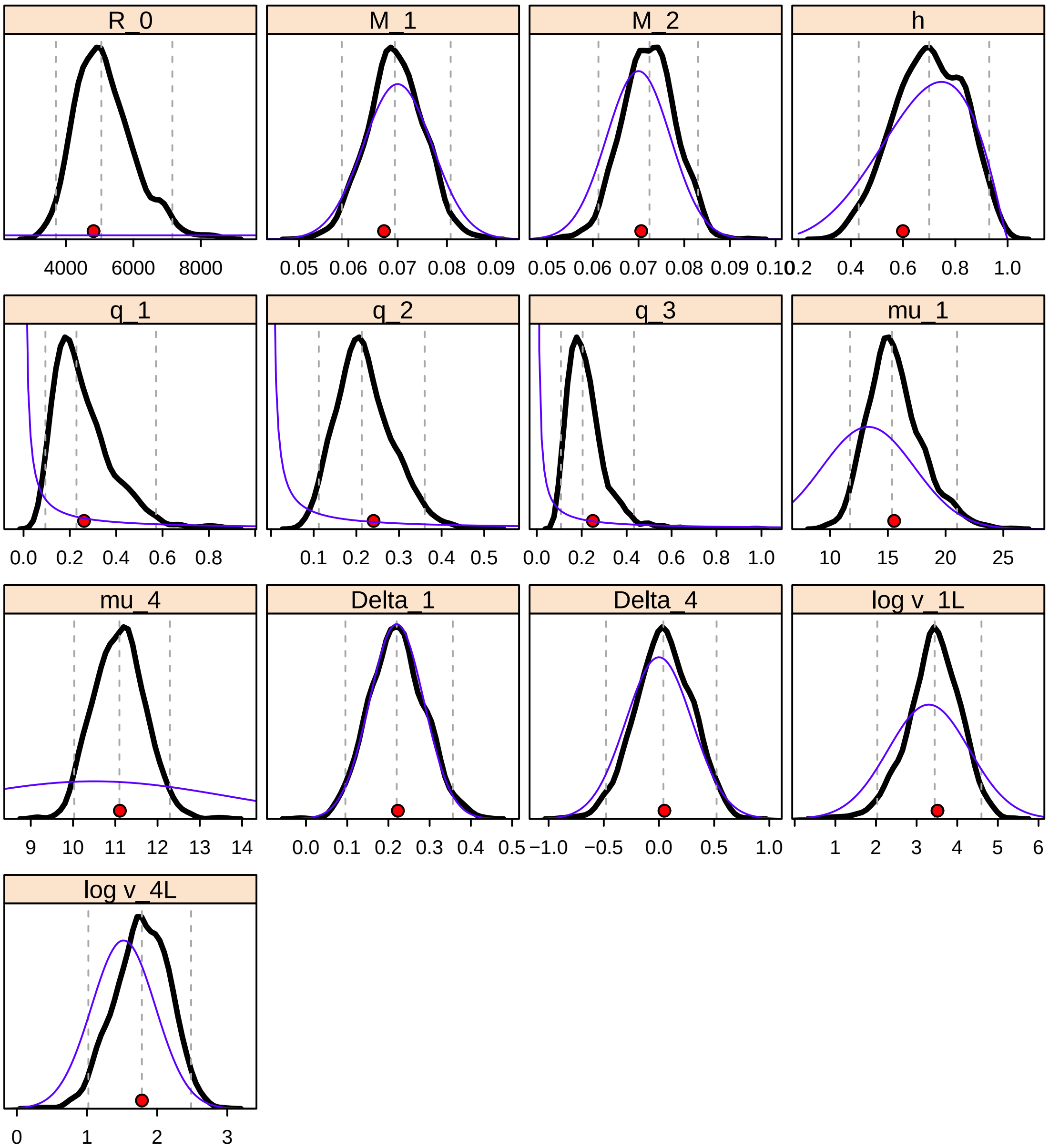


Figure G.25. Marginal posterior densities (thick black curves) and prior density functions (thin blue curves) for the estimated parameters. Vertical lines represent the 2.5, 50 and 97.5 percentiles, and red filled circles are the MPD estimates. For R_0 the prior is a uniform distribution on the range [1, 100000], and is at too low a value to show up on the graph. The priors for q_g are uniform on a log-scale, and so the probability density function is $1/(x(b-a))$ on a linear scale (where a and b are the bounds on the log scale).

Table G.1. Negative log-likelihoods and objective function from the MPD results. Parameters and likelihood symbols are defined in Appendix F. For indices ($\hat{I}_{tg}$) and proportions-at-age ($\hat{p}_{atgs}$), subscripts $g = 1$-3 refer to the survey series and subscript $g = 4$ refers to the commercial fishery.

Negative log likelihood component	Value
$\log \mathsf{L}_3 \left(\mathbf{\Theta} \middle\vert \left\{\hat{I}_{t1}\right\}\right)$	0.81
$\log \mathsf{L}_3 \left(\mathbf{\Theta} \middle\vert \left\{\hat{I}_{t2}\right\}\right)$	3.85
$\log \mathsf{L}_3 \left(\mathbf{\Theta} \middle\vert \left\{\hat{I}_{t3}\right\}\right)$	-0.58
$\log \mathsf{L}_2 \left(\mathbf{\Theta} \vert \left\{\hat{p}_{at1s}\right\}\right)$	-505.91
$\log \mathsf{L}_2 \left(\mathbf{\Theta} \vert \left\{\hat{p}_{at4s}\right\}\right)$	-1998.41
$\log \mathsf{L}_1 \left(\mathbf{\Theta} \vert \left\{\epsilon_t\right\}\right) - \log\left(\pi(\mathbf{\Theta})\right)$	9.54
Objective function $f(\mathbf{\Theta})$	-2490.68

Table G.2. Summary statistics of MCMC results for estimated parameters (defined in Appendix F). Except for M_1 and M_2, subscripts 1 to 3 correspond to the fishery-independent surveys, and subscript 4 to the commercial fishery.

Parameter	Percentile		
	5%	50%	95%
R_0	3,941	5,052	6,831
M_1	0.0601	0.0694	0.0786
M_2	0.0629	0.0724	0.0820
h	0.476	0.700	0.909
q_1	0.1091	0.2284	0.5011
q_2	0.1246	0.2127	0.3400
q_3	0.1166	0.2041	0.3786
μ_1	12.2	15.4	20.2
μ_4	10.2	11.1	12.1
Δ_1	0.11	0.22	0.33
Δ_4	-0.37	0.04	0.45
$\log v_{1L}$	2.31	3.44	4.40
$\log v_{4L}$	1.13	1.78	2.38

H HABITAT AND CONCURRENT SPECIES

The depth distribution of bottom trawl tows that captured Pacific Ocean Perch (POP, *Sebastes alutus*) along the WCVI Pacific Marine Fisheries Commission (PMFC) areas 3C and 3D shows that 98% of the encounters lie between 128 and 581 m, with a depth-of-median-catch at 269 m (Figure H.1); data extracted from the PacHarvest and GFFOS databases. Hereafter, we refer to the WCVI bottom tows between 128 and 581 m as “POP bottom tows” even though POP is not necessarily the predominant species in all tows. The distribution of POP bottom tows differs from the effort of the trawl fishery (shaded background histogram) due to a large flatfish fishery off WCVI and deepwater Thornyhead/Sablefish fisheries (shaded bars occur deeper than the depths shown).

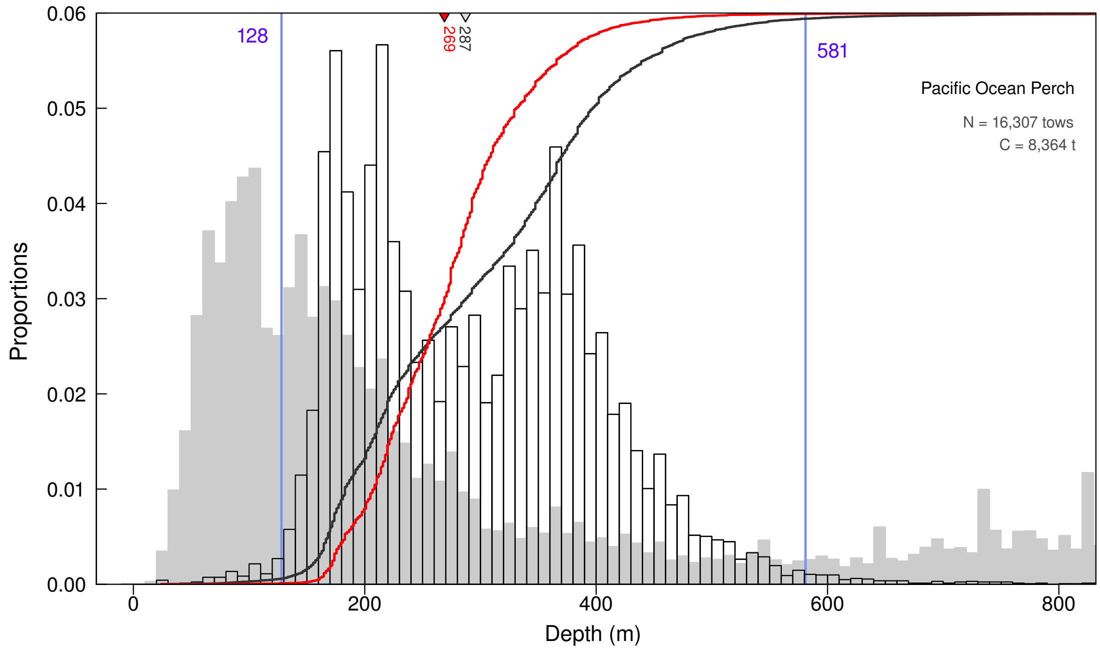


Figure H.1. Depth frequency of bottom tows that capture POP from commercial trawl logs (1996–2007 in PacHarvest, 2007–2012 in GFFOS, where 2012 records are incomplete) in PMFC major areas 3CD. The vertical solid lines denote the 1% and 99% quantiles. The black curve shows the cumulative frequency of tows that encounter POP while the red curve shows the cumulative catch of POP at depth (scaled from 0 to 1). The median depth of cumulative catch (inverted red triangle) is indicated along the upper axis. ‘N’ reports the total number of tows; ‘C’ reports the total catch (t). The shaded histogram in the background reports the relative trawl effort on all species at all depths (deeper effort not shown).

The reported species caught in POP bottom tows comprise predominantly a mixture of flatfish and rockfish (Figure H.2, Table H.1). Arrowtooth Flounder *Atheresthes stomias* remains the most abundant species in these tows (30% by catch weight), followed by POP (16%), Dover Sole *Microstomus pacificus* (12%), Petrale Sole *Eopsetta jordani* (4.7%), and Yellowtail Rockfish *S. flavidus* (4.6%). Four species of rockfish of interest to COSEWIC (Committee on the Status of Endangered Wildlife in Canada) also occur in the top 25 caught – Rougheye Rockfish complex *S. aleutianus/melanostictus* (2.3%), Yellowmouth Rockfish *S. reedi* (1.9%), Canary Rockfish *S. pinniger* (1.3%), and Darkblotch Rockfish *S. crameri* (0.90%).

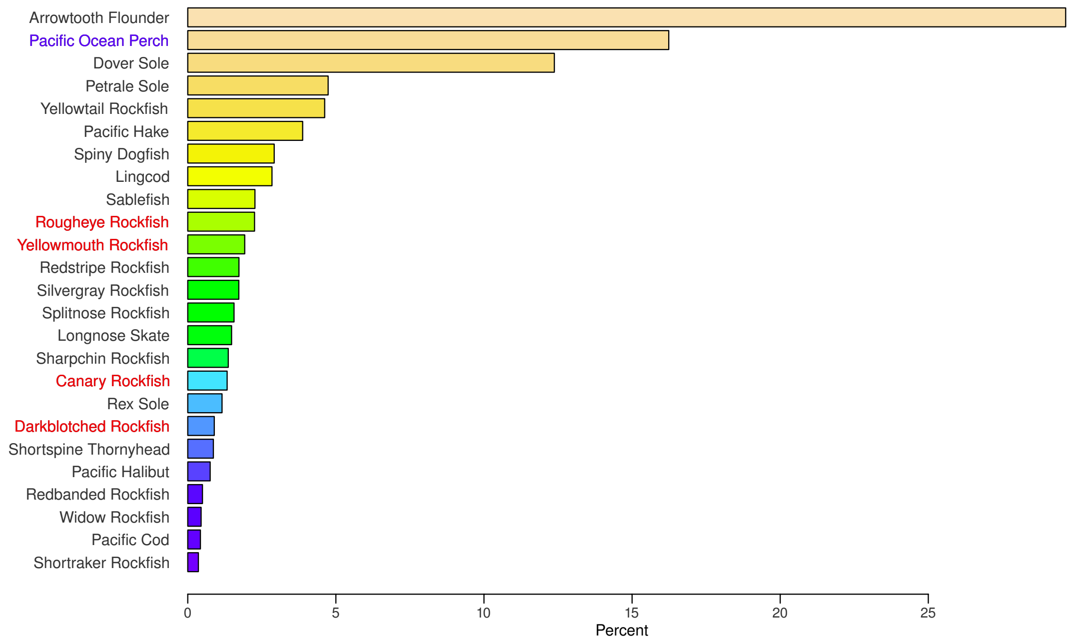


Figure H.2. Concurrence of species in POP bottom trawl tows (1996–2012 observer logs). Abundance is expressed as a percent of total catch weight. POP is indicated in blue on the y-axis; other species of interest to COSEWIC are indicated in red.

Table H.1. Top 25 species by catch weight (landed + discarded) that co-occur in POP bottom tows (total from 1996–2012). Rockfish species of interest to COSEWIC appear in shaded rows.

Code	Species	Latin name	Catch (t)	Catch (%)
602	Arrowtooth Flounder	*Atheresthes stomias*	15,172	29.637
396	Pacific Ocean Perch	*Sebastes alutus*	8,312	16.238
626	Dover Sole	*Microstomus pacificus*	6,335	12.375
607	Petrale Sole	*Eopsetta jordani*	2,426	4.739
418	Yellowtail Rockfish	*Sebastes flavidus*	2,366	4.622
225	Pacific Hake	*Merluccius productus*	1,985	3.878
044	Spiny Dogfish	*Squalus acanthias*	1,494	2.918
467	Lingcod	*Ophiodon elongatus*	1,455	2.843
455	Sablefish	*Anoplopoma fimbria*	1,161	2.268
394	Rougheye Rockfish	*Sebastes aleutianus*	1,154	2.254
440	Yellowmouth Rockfish	*Sebastes reedi*	984	1.923
439	Redstripe Rockfish	*Sebastes proriger*	885	1.728
405	Silvergray Rockfish	*Sebastes brevispinis*	882	1.723
412	Splitnose Rockfish	*Sebastes diploproa*	799	1.561
059	Longnose Skate	*Raja rhina*	757	1.479
450	Sharpchin Rockfish	*Sebastes zacentrus*	700	1.368
437	Canary Rockfish	*Sebastes pinniger*	680	1.329
610	Rex Sole	*Errex zachirus*	592	1.157
410	Darkblotched Rockfish	*Sebastes crameri*	458	0.895
451	Shortspine Thornyhead	*Sebastolobus alascanus*	443	0.865

Continued on next page

Table H.1 – continued from previous page

Code	Species	Latin name	Catch (t)	Catch (%)
614	Pacific Halibut	*Hippoglossus stenolepis*	387	0.756
401	Redbanded Rockfish	*Sebastes babcocki*	254	0.496
417	Widow Rockfish	*Sebastes entomelas*	231	0.450
222	Pacific Cod	*Gadus macrocephalus*	218	0.427
403	Shortraker Rockfish	*Sebastes borealis*	184	0.359

We refer to WCVI (PMFC 3CD) midwater tows that encounter POP between 102 and 1,185 m as "POP midwater tows" (Figure H.3). The 98% limits illustrate a long right-hand tail in the tow frequency distribution, probably because POP are caught at shallower depths as the net descends or ascends from deep midwater tows. Pacific Ocean Perch midwater tows are dominated by Pacific Hake *Merluccius productus* (87% by catch weight; Figure H.4, Table H.2). Other species in these tows are Yellowtail Rockfish *S. flavidus* (6.6%), Widow Rockfish *S. entomelas* (2.2%), and POP only comprises 1.3%. Five rockfish species of interest to COSEWIC occur in POP midwater tows - Canary Rockfish *S. pinniger* (0.48%), Rougheye Rockfish complex *S. aleutianus/melanostictus* (0.33%), Bocaccio *S. paucispinis* (0.11%), Yellowmouth Rockfish *S. reedi* (0.080%), and Darkblotched Rockfish *S. crameri* (0.063%) (Table H.2).

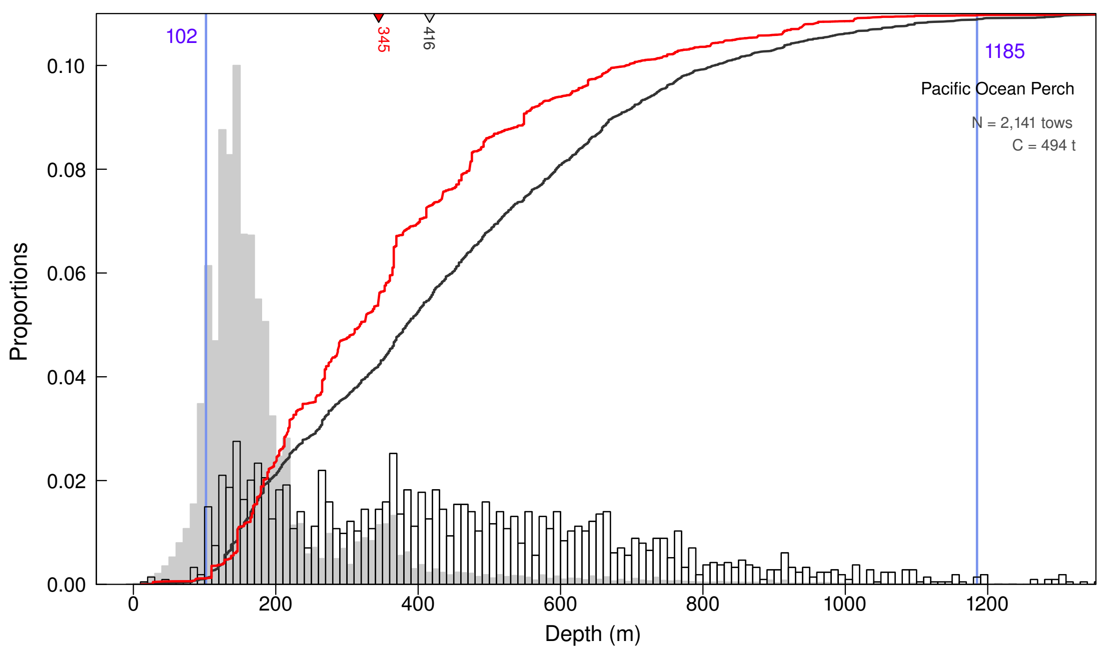


Figure H.3. Depth frequency of midwater tows that capture POP from commercial trawl logs (1996–2011) in BC offshore waters. The vertical solid lines denote the 1% and 99% quantiles. See Figure H.1 for plot details.

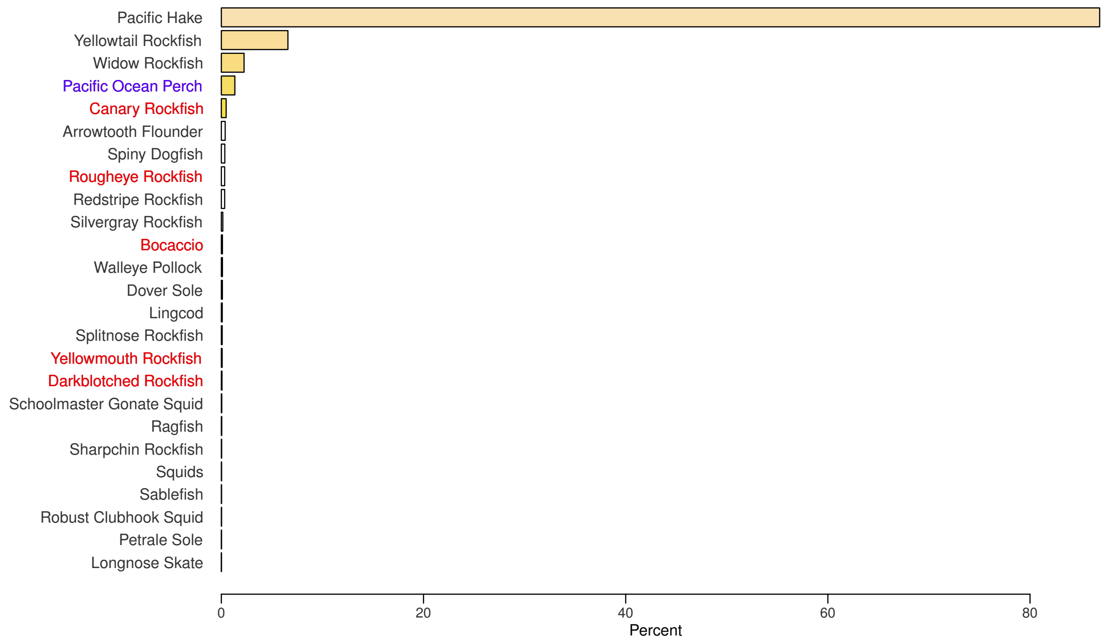


Figure H.4. Concurrence of species in POP midwater trawl tows (1996–2012 observer logs). Abundance is expressed as a percent of total catch weight. POP is indicated in blue on the y-axis; other species of interest to COSEWIC are indicated in red.

Table H.2. Top 25 species by catch weight (landed + discarded) that co-occur in POP midwater tows (total from 1996–2012). Rockfish species of interest to COSEWIC appear in shaded rows.

Code	Species	Latin name	Catch (t)	Catch (%)
225	Pacific Hake	*Merluccius productus*	23,488	86.889
418	Yellowtail Rockfish	*Sebastes flavidus*	1,780	6.586
417	Widow Rockfish	*Sebastes entomelas*	607	2.246
396	Pacific Ocean Perch	*Sebastes alutus*	361	1.334
437	Canary Rockfish	*Sebastes pinniger*	129	0.475
602	Arrowtooth Flounder	*Atheresthes stomias*	103	0.380
044	Spiny Dogfish	*Squalus acanthias*	92	0.341
394	Rougheye Rockfish	*Sebastes aleutianus*	88	0.327
439	Redstripe Rockfish	*Sebastes proriger*	88	0.326
405	Silvergray Rockfish	*Sebastes brevispinis*	39	0.145
435	Bocaccio	*Sebastes paucispinis*	29	0.108
228	Walleye Pollock	*Theragra chalcogramma*	29	0.107
626	Dover Sole	*Microstomus pacificus*	27	0.101
467	Lingcod	*Ophiodon elongatus*	23	0.086
412	Splitnose Rockfish	*Sebastes diploproa*	22	0.083
440	Yellowmouth Rockfish	*Sebastes reedi*	22	0.080
410	Darkblotched Rockfish	*Sebastes crameri*	17	0.063
095	Schoolmaster Gonate Squid	*Alosa sapidissima*	11	0.039
386	Ragfish	*Icosteus aenigmaticus*	10	0.037
450	Sharpchin Rockfish	*Sebastes zacentrus*	8	0.029

Continued on next page

Table H.2 – continued from previous page

Code	Species	Latin name	Catch (t)	Catch (%)
92A	Squids	*Teuthoidea*	6	0.024
455	Sablefish	*Anoplopoma fimbria*	6	0.022
96C	Robust Clubhook Squid	*Moroteuthis robusta*	6	0.021
607	Petrale Sole	*Eopsetta jordani*	5	0.019
059	Longnose Skate	*Raja rhina*	4	0.015

The distribution of POP along the WCVI is best viewed as CPUE density from commercial bottom trawl records that span 1996 to 2012 (Figure H.5). The 3CD population lies chiefly between 200 and 600 m with highest densities off the NW corner of Vancouver Island and the eastern walls of Clayoquot and Barkley Gullies. Relative to other regions along the BC coast (Fig. 2), POP density along the WCVI is not high. The grid cells in Figure H.5, roughly 7 km^2 each, identify regions of positive CPUE. Specifically, these cells cover 3,643 km^2 in 3C and 3,737 km^2 in 3D for an encountered area of 7,400 km^2 in PMFC 3CD.

The distribution of POP displayed in Figure H.5 stems from tow encounters by the commercial trawl fleet. An alternative proxy for potential habitat uses bathymetry limits. For instance, isobaths (128 m, 581 m), identified in Figure H.1 as POP bottom tows, outline bottom regions along the BC coast that might host POP (Figure H.6). This highlighted region covers 11,675 km^2; however, not all areas are amenable to POP habitation (e.g., Strait of Georgia, mainland inlets). The bathymetry limits within PMFC 3C cover an estimated 4,993 km^2 and within 3D cover 2,828 km^2 for a total 3CD estimate of 7,821 km^2.

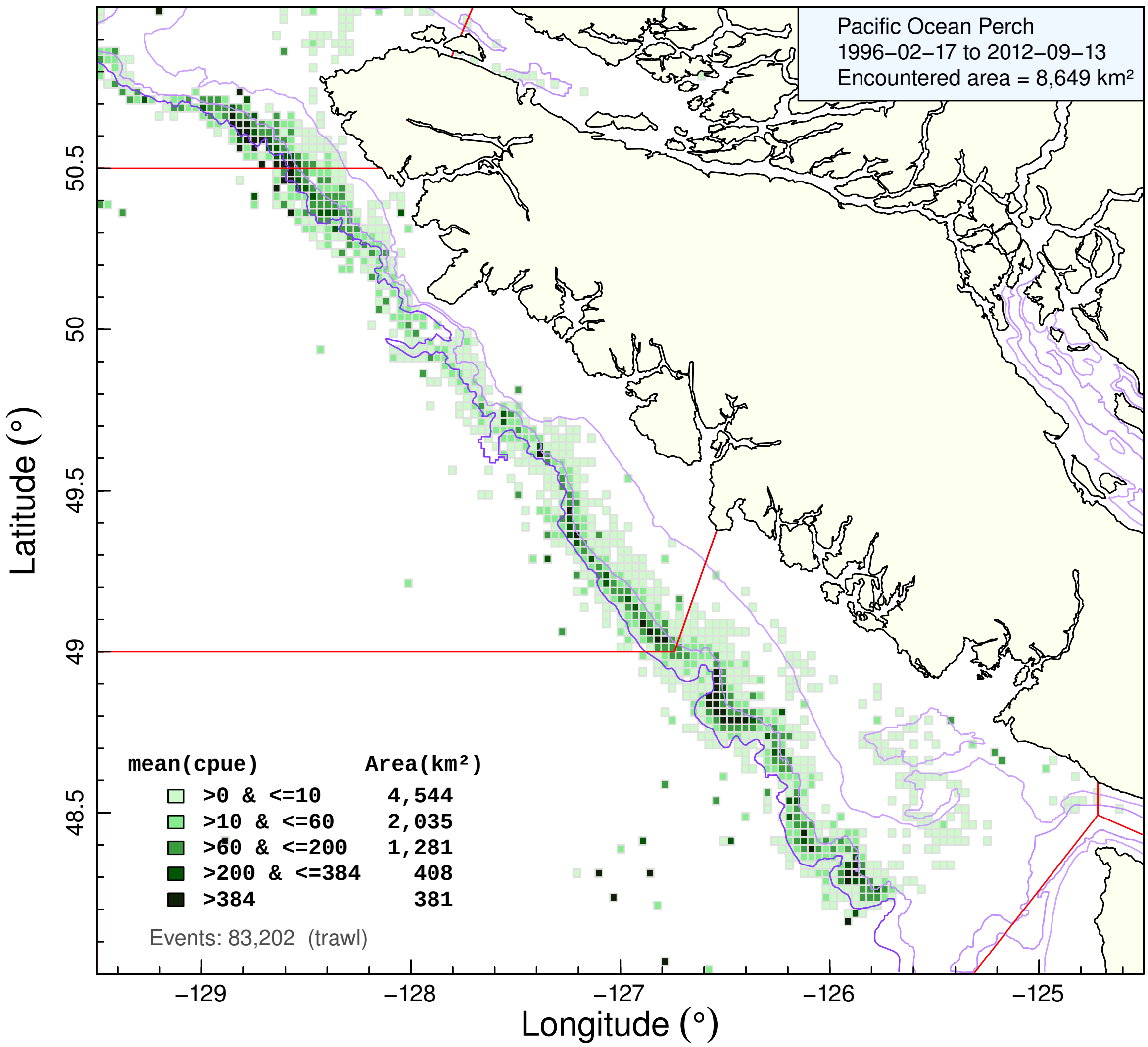


Figure H.5. Mean CPUE (kg/h) of POP in grid cells 0.035° longitude by 0.025° latitude (roughly 7 km^2). The shaded cells give an approximation of the area where POP was encountered by fishing events from the groundfish trawl fishery from Feb 1996 to Sep 2012. Encountered grid cells in 3C cover 3,643 km^2 and in 3D cover 3,757 km^2 for a total area of 7,400 km^2 in PMFC 3CD. Contour lines trace the 100, 200, and 600 m isobaths.

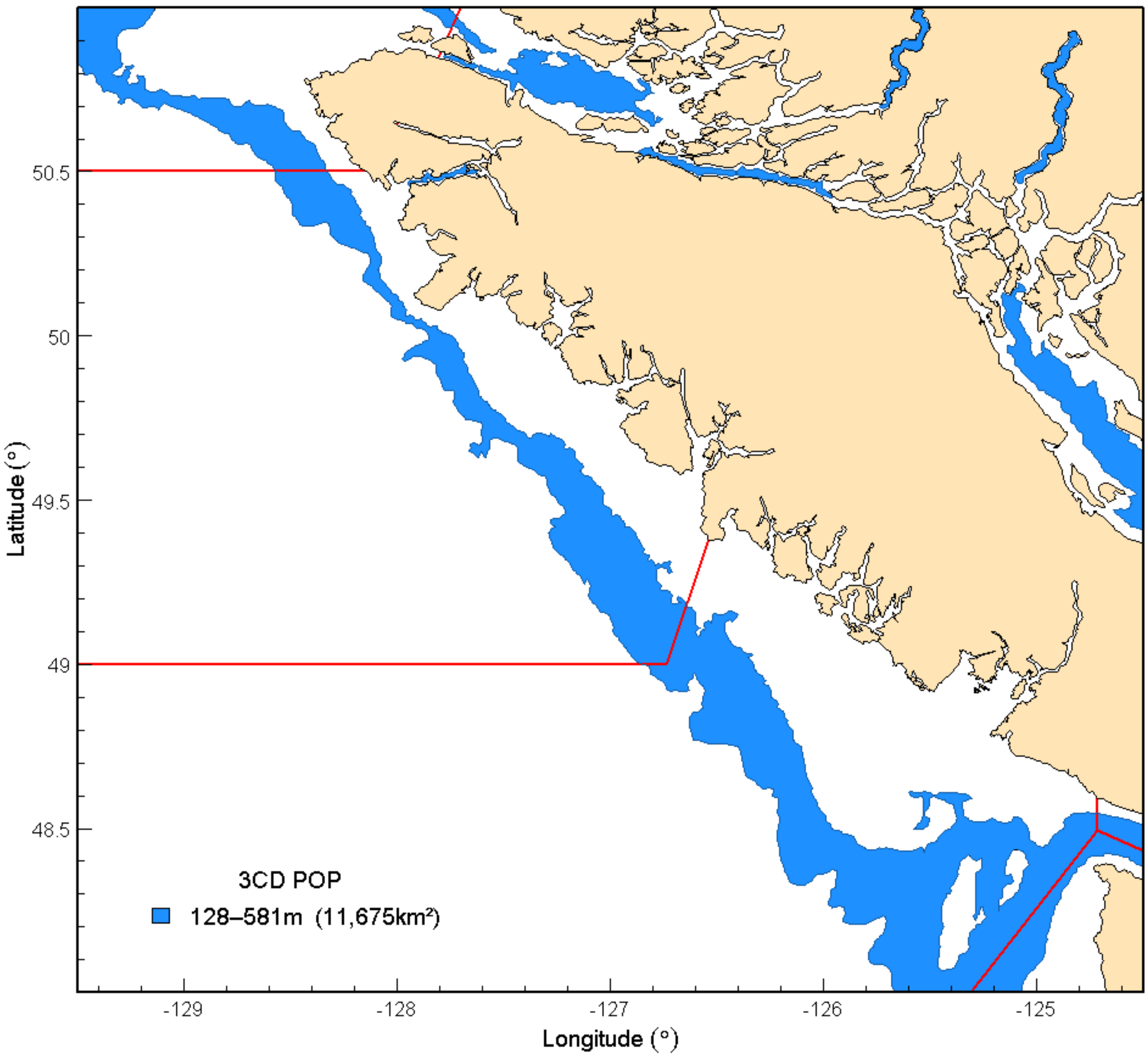


Figure H.6. Highlighted bathymetry (blue) between 128 and 581 m serves as a proxy for benthic Pacific Ocean Perch habitat along the WCVI. Highlighted region covers 11,675 km^2; however, the shaded region in 3C covers 4,993 km^2 and in 3D covers 2,828 km^2 for a total area of 7,821 km^2 in PMFC 3CD.

I SENSITIVITY RUNS

Two sensitivity runs were conducted on the base model run, namely:

Run S1: Dropping the early GB Reed survey series.

Run S2: Increasing the catches from 1987-1990 by 20%, from 1991-1992 by 40%, and from 1993-1995 by 60%.

The reason for run S1 was to test the sensitivity of the stock assessment to the assumption that this early series was linked, i.e. that it was obtaining consistent estimates of POP biomass that could be modelled using a single catchability parameter. This survey series was constructed from surveys that were not originally designed to be used in this fashion, although they were conducted in successive years by the same vessel. There is a lack of systematic surveys from the west coast of Canada prior to the early 2000s and the available surveys potentially provide information about relative biomass for a number of species. However, the indices were obtained by post-stratification and other modifications to the available data and this run tested the sensitivity of the model results to the use of these survey indices.

Run S2 was conducted because there may have been systematic misreporting of POP catch from the WCVI area from the mid-1980s to the mid-1990s, the decade immediately prior to the implementation of important changes to the management of the west coast Canada demersal fishing fleet. The proportional increases used to alter the reported POP 3CD catches (given above) were obtained in consultation with industry representatives familiar with the operation of this fishery.

As occurred for the base run, the MPD fits capture the main features of the data sets fairly well, and the MCMC diagnostics show good convergence (results not shown). Tables I.1-I.3 give the estimated parameter values for the three runs (with Table I.1 identical to Table G.2 but repeated here for ease of comparison). Both sensitivity runs estimate a more productive stock, with higher values of R_0 (initial unfished recruitment) and h (steepness of the Beverton-Holt recruitment function). Tables I.4-I.6 give the resulting derived quantities for the three model runs. The higher productivity for the sensitivity runs results in, for example, higher unfished equilibrium spawning biomass (B_0), higher maximum sustainable yield (MSY), and higher biomass at maximum sustainable yield (B_{MSY}).

Figure I.1 shows the medians of the changes in relative biomass over time (as in Figure 4) for the base run and the two sensitivity runs. The trajectories are similar for all three runs (though the increased catches for run S2 reduce the relative biomass in the late 1990s), with the median values of B_{2013}/B_0 (spawning biomass at the start of 2013 relative to unfished equilibrium level) of 0.41 for the base run, 0.50 for run S1, and 0.43 for run S2.

Figure I.2 shows the phase plots through time of the status of the stock. The increased catches for run S2 can be seen to increase the relative exploitation rate (the darkest points above the $u_t/u_{\mathrm{MSY}} = 1$ line in the bottom panel). The final status of the stock for the three model runs is summarised in Figure I.3. Both sensitivity runs suggest a stock that is higher in the healthy zone than for the base run. The probabilities of being in the healthy zone at the start of 2013, P$(B_{2013} > 0.8B_{\mathrm{MSY}})$, for each model run are, respectively, 0.87, 0.94 and 0.92. Thus, the status of the stock is slightly improved for the sensitivity runs.

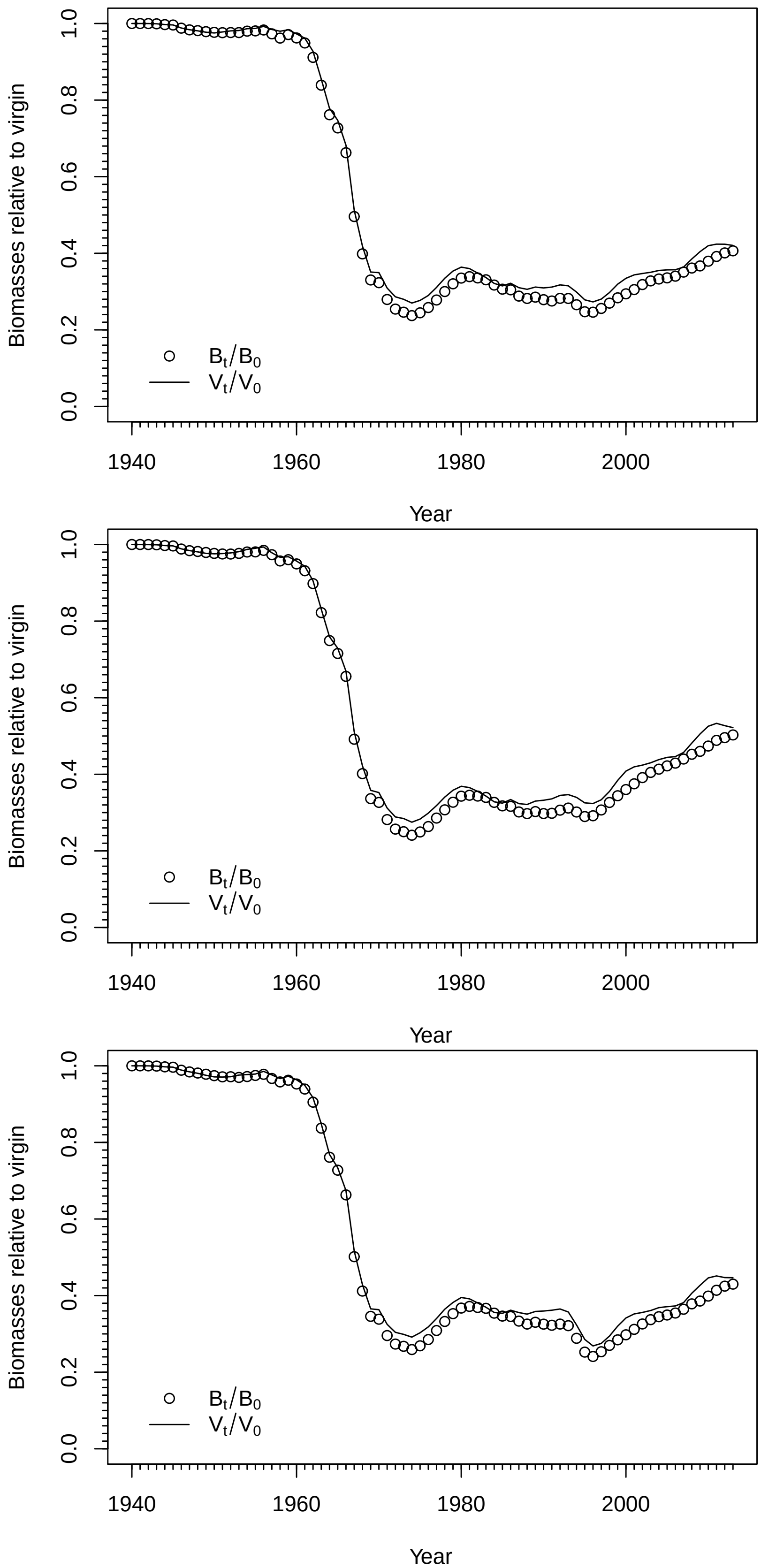
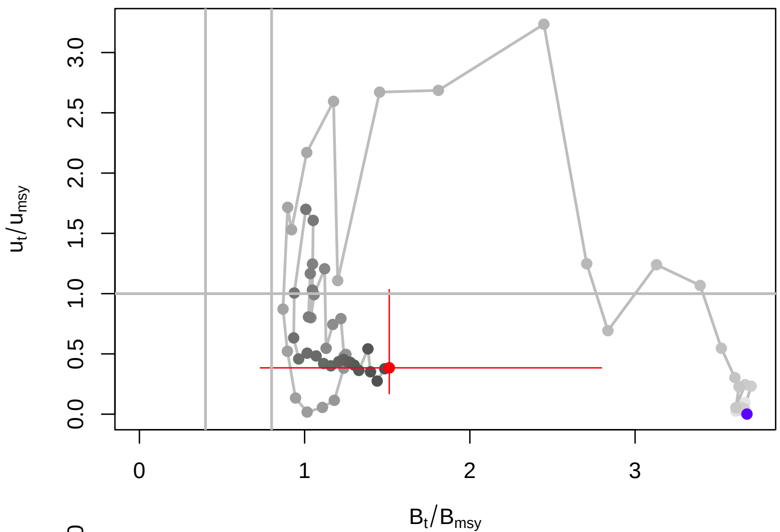
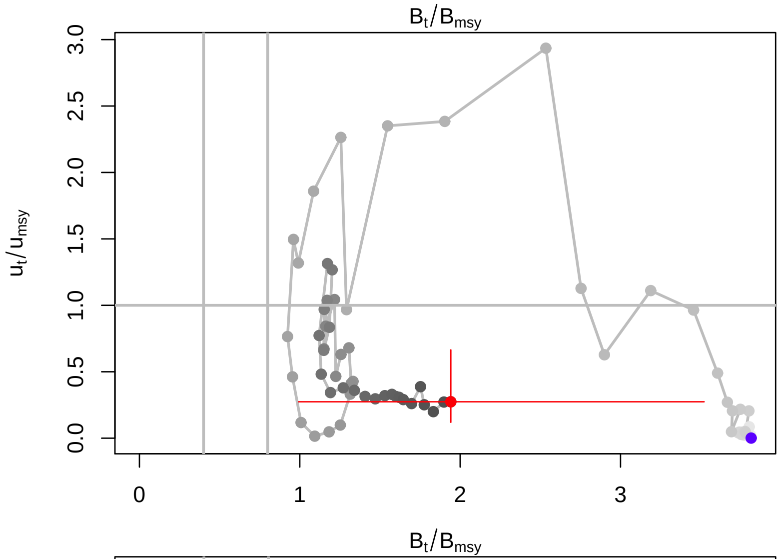


Figure I.1. Changes in B_t/B_0 and V_t/V_0 (spawning and vulnerable biomass relative to unfished equilibrium levels) over time, shown as the medians of the MCMC posteriors. Top: base run, middle: run S1, bottom: run S2.





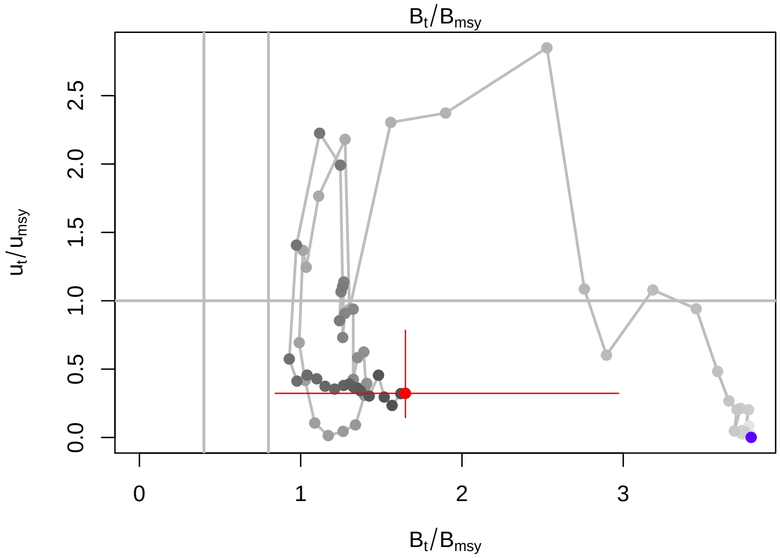


Figure I.2. Phase plot through time of the medians of the ratios B_t/B_{MSY} (the spawning biomass in year t relative to B_{MSY}) and u_t/u_{MSY} (the exploitation rate in year t relative to u_{MSY}). Blue filled circle is the starting year (1940). Years then proceed from light grey through to dark grey with the final year (2012) as a filled red circle, and the red lines represent the 10% and 90% percentiles of the posterior distributions for 2012. Vertical grey lines indicate reference points 0.4B_{MSY} and 0.8B_{MSY}, and horizontal grey line indicates u_{MSY}. Top: base run, middle: run S1, bottom: run S2. Axes not identical.

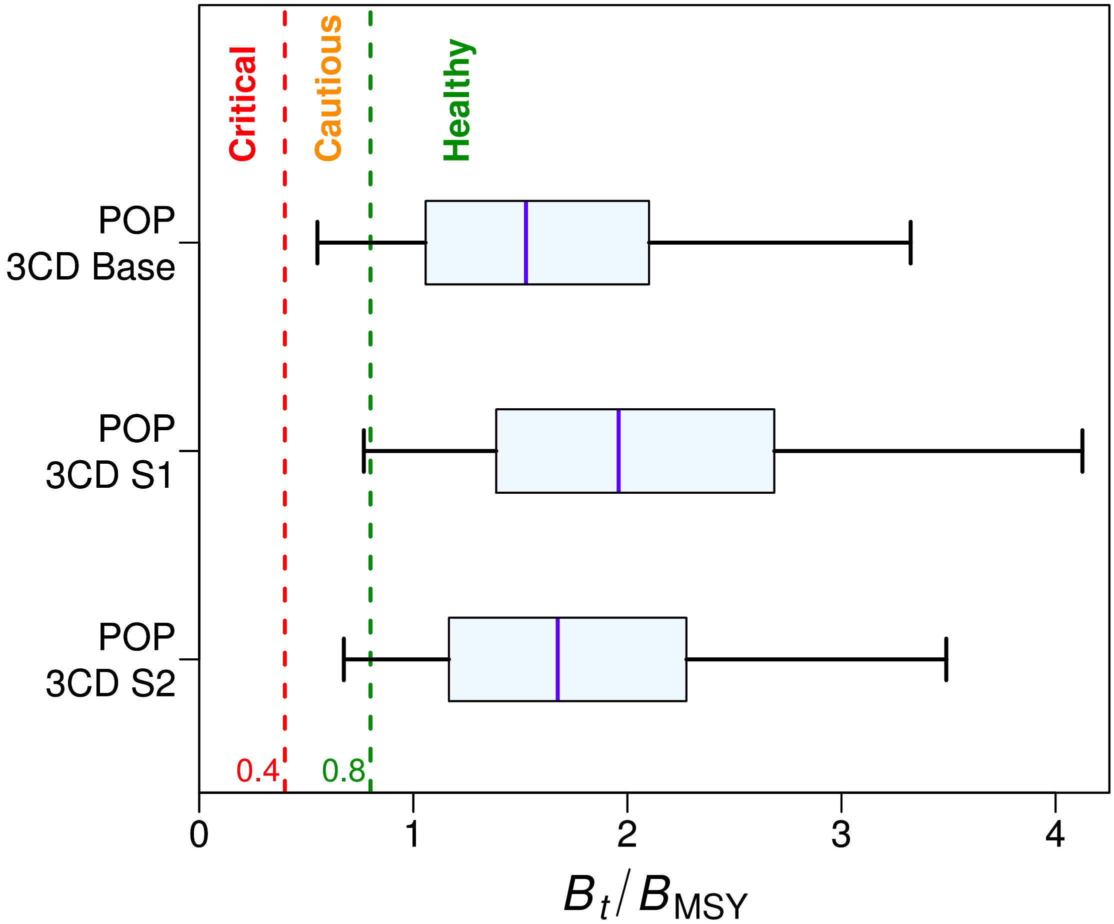


Figure I.3. Current status of the 3CD stock for the three model runs (Base run, sensitivity run S1 and sensitivity run S2), relative to the DFO Precautionary Approach provisional reference points of $0.4B_{\mathrm{MSY}}$ and $0.8B_{\mathrm{MSY}}$. B_t/B_{MSY} is for $t = 2013$. Boxplots show the 5, 25, 50, 75 and 95 percentiles from the MCMC results.

Table I.1. Base run summary statistics of MCMC results for estimated parameters (defined in Appendix F). Except for M_1 and M_2, subscripts 1 to 3 correspond to the fishery-independent surveys, and subscript 4 to the commercial fishery.

Parameter	Percentile		
	5%	50%	95%
R_0	3,941	5,052	6,831
M_1	0.0601	0.0694	0.0786
M_2	0.0629	0.0724	0.0820
h	0.476	0.700	0.909
q_1	0.1091	0.2284	0.5011
q_2	0.1246	0.2127	0.3400
q_3	0.1166	0.2041	0.3786
μ_1	12.2	15.4	20.2
μ_4	10.2	11.1	12.1
Δ_1	0.11	0.22	0.33
Δ_4	-0.37	0.04	0.45
$\log v_{1L}$	2.31	3.44	4.40
$\log v_{4L}$	1.13	1.78	2.38

Table I.2. For run S1, summary statistics of MCMC results for estimated parameters (defined in Appendix F). Except for M_1 and M_2, subscripts 1 and 2 correspond to the fishery-independent surveys, and subscript 4 to the commercial fishery. Parameter q_3 is not estimated because it represents the catchability of the GB Reed survey series, but that data set was removed for this sensitivity run.

Parameter	Percentile		
	5%	50%	95%
R_0	4,113	5,389	7,640
M_1	0.0602	0.0701	0.0798
M_2	0.0633	0.0724	0.0824
h	0.522	0.726	0.918
q_1	0.0795	0.168	0.381
q_2	0.0941	0.1762	0.2802
q_3	-	-	-
μ_1	11.9	15.1	19.4
μ_4	10.1	11	12
Δ_1	0.11	0.22	0.33
Δ_4	-0.37	0.06	0.49
$\log v_{1L}$	2.21	3.47	4.37
$\log v_{4L}$	1.08	1.77	2.35

Table I.3. For run S2, summary statistics of MCMC results for estimated parameters (defined in Appendix F). Except for M_1 and M_2, subscripts 1-3 correspond to the fishery-independent surveys, and subscript 4 to the commercial fishery.

Parameter	Percentile		
	5%	50%	95%
R_0	4,185	5,419	7,255
M_1	0.0601	0.0699	0.0791
M_2	0.0622	0.0721	0.0814
h	0.490	0.725	0.917
q_1	0.0999	0.2052	0.4141
q_2	0.1131	0.1907	0.2940
q_3	0.1052	0.1816	0.3343
μ_1	12.3	15.4	20.2
μ_4	10.2	11.1	12.1
Δ_1	0.11	0.22	0.33
Δ_4	-0.41	0.04	0.44
$\log v_{1L}$	2.35	3.47	4.39
$\log v_{4L}$	1.11	1.79	2.38

Table I.4. For the base run, the 5th, 50th and 95th percentiles of MCMC-derived quantities from the 1,000 samples of the MCMC posterior. Definitions are: B_0 – unfished equilibrium spawning biomass (mature females), V_0 – unfished equilibrium vulnerable biomass (males and females), B_{2013} – spawning biomass at the start of 2013, V_{2013} – vulnerable biomass in the middle of 2013, u_{2012} – exploitation rate (ratio of total catch to vulnerable biomass) in the middle of 2012, $u_{\max}$ – maximum exploitation rate (calculated for each sample as the maximum exploitation rate from 1940-2012), B_{MSY} – equilibrium spawning biomass at MSY (maximum sustainable yield), u_{MSY} – equilibrium exploitation rate at MSY, V_{MSY} – equilibrium vulnerable biomass at MSY. All biomass values (and MSY) are in tonnes. For reference, the average catch over the last 5 years (2007-2011) is 547 t.

Value	Percentile		
	5%	50%	95%
	From model output		
B_0	17,562	21,442	27,877
V_0	32,687	38,855	49,469
B_{2013}	3,888	8,745	17,269
V_{2013}	7,360	16,427	32,072
B_{2013}/B_0	0.189	0.406	0.684
V_{2013}/V_0	0.199	0.420	0.708
u_{2012}	0.018	0.035	0.077
$u_{\max}$	0.221	0.288	0.418
	MSY-based quantities		
$0.4B_{\text{MSY}}$	1,433	2,324	3,592
$0.8B_{\text{MSY}}$	2,866	4,647	7,183
B_{MSY}	3,583	5,809	8,979
B_{MSY}/B_0	0.178	0.272	0.357
B_{2013}/B_{MSY}	0.552	1.526	3.323
MSY	700	1,048	1,509
u_{MSY}	0.045	0.091	0.174
u_{2012}/u_{MSY}	0.134	0.384	1.434
V_{MSY}	7,586	11,729	17,112
V_{MSY}/V_0	0.213	0.301	0.379

Table I.5. For run S1, the derived quantities. See Table I.4 for definitions.

Value	Percentile		
	5%	50%	95%
	From model output		
B_0	18,392	22,767	30,086
V_0	34,206	41,355	53,416
B_{2013}	5,008	11,499	22,692
V_{2013}	9,707	21,279	42,233
B_{2013}/B_0	0.246	0.503	0.807
V_{2013}/V_0	0.259	0.522	0.834
u_{2012}	0.014	0.027	0.059
$u_{\max}$	0.206	0.277	0.395
	MSY-based quantities		
$0.4B_{\mathrm{MSY}}$	1,451	2,388	3,651
$0.8B_{\mathrm{MSY}}$	2,902	4,777	7,303
B_{MSY}	3,627	5,971	9,128
B_{MSY}/B_0	0.169	0.262	0.341
$B_{2013}/B_{\mathrm{MSY}}$	0.769	1.959	4.125
MSY	803	1,159	1,718
u_{MSY}	0.053	0.096	0.182
$u_{2012}/u_{\mathrm{MSY}}$	0.099	0.274	0.927
V_{MSY}	7,900	12,112	17,758
V_{MSY}/V_0	0.208	0.295	0.366

Table I.6. For run S2, the derived quantities. See Table I.4 for definitions.

Value	Percentile		
	5%	50%	95%
		From model output	
B_0	18,564	23,005	29,477
V_0	34,583	41,866	51,974
B_{2013}	4,746	9,882	18,563
V_{2013}	8,868	18,436	34,239
B_{2013}/B_0	0.216	0.43	0.695
V_{2013}/V_0	0.226	0.447	0.72
u_{2012}	0.017	0.031	0.063
$u_{\max}$	0.208	0.277	0.388
		MSY-based quantities	
$0.4B_{\mathrm{MSY}}$	1,428	2,407	3,727
$0.8B_{\mathrm{MSY}}$	2,856	4,815	7,454
B_{MSY}	3,570	6,018	9,318
B_{MSY}/B_0	0.171	0.264	0.354
$B_{2013}/B_{\mathrm{MSY}}$	0.676	1.674	3.489
MSY	786	1,155	1,627
u_{MSY}	0.048	0.096	0.183
$u_{2012}/u_{\mathrm{MSY}}$	0.117	0.323	1.118
V_{MSY}	7,750	12,199	17,701
V_{MSY}/V_0	0.205	0.293	0.376