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

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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_{MSY} and an upper stock reference point of 0.8B_{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_{MSY}, and a 0.87 probability of being above the upper stock reference point of 0.8B_{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.

RÉSUMÉ

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 **??**). 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 1), 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 1). 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 **??**). 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 **??**) 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 **??**, 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 **??**). 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 **??** shows the MCMC results for the estimated vulnerable biomass, together with the reconstructed historical catches, and Figure **??** 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 **??** 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 **??**.

The estimated recruitments (age-1 fish, Figure **??**) 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 **??** 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 2 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 2 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 **??** 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 **??** 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 **??**). 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 **??**).

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 **??** and **??**). The heavy exploitation during this period was followed by reduced recruitment (Figure **??**). 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 **??**), 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 **??**). 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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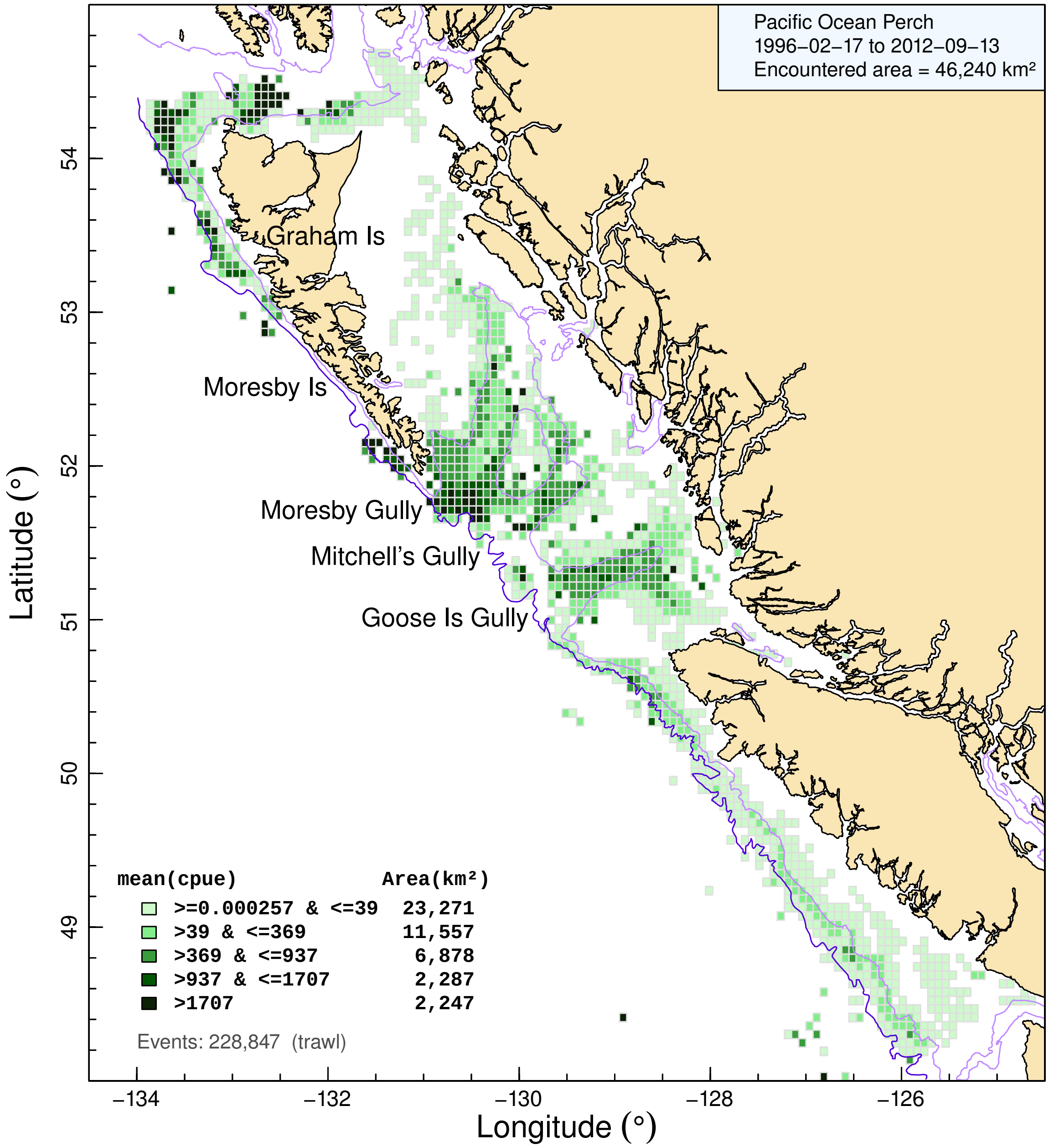

Figure 1. Mean catch-per-unit-effort (CPUE, kg/h) of POP in grid cells 0.075° longitude by 0.055° latitude (roughly 32 km^2). The shaded cells give an approximation of the area where POP was encountered by fishing events from the groundfish trawl fishery from February 1996 to September 2012. Named gullies are to the northeast of their labels. Contours are 200 m and 1000 m isobaths.

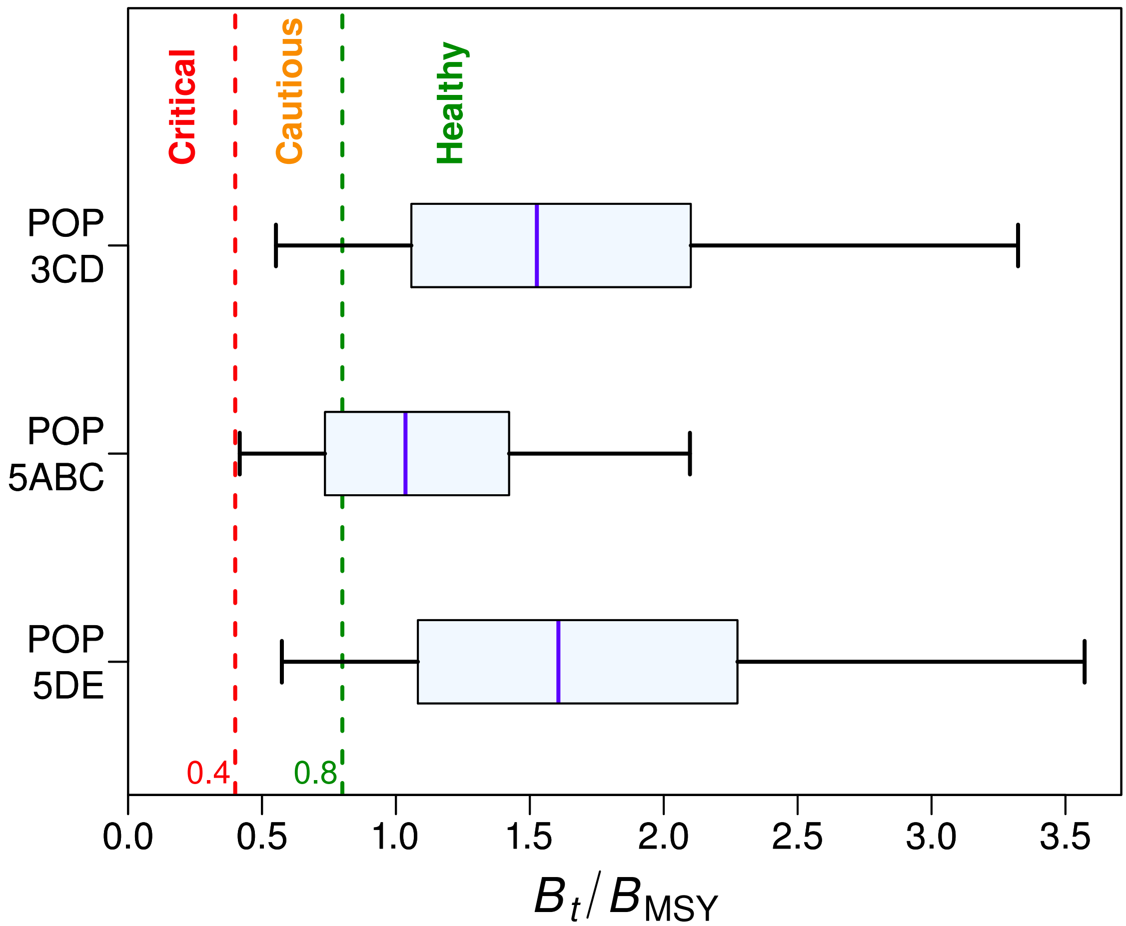

Figure 2. Current status of the three Canadian POP stocks relative to the DFO Precautionary Approach provisional reference points of $0.4B_{\text{MSY}}$ and $0.8B_{\text{MSY}}$. The value of B_t/B_{MSY} is for $t = 2013$ for 3CD (this assessment) and 5DE (Edwards et al., 2013), and for $t = 2011$ for 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.

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		
$0.4B_{\text{MSY}}$	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 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 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.

A.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

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

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

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

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 A.1, and were used as fixed inputs to the stock assessment model (to calculate w_{as} for each a and s). Figure A.1 shows the resulting mean lengths-at-age and mean weights-at-age.

Table A.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	$-$1.021
α_s	9.258$\times$10^{-6}	8.126$\times$10^{-6}
β_s	3.116	3.155

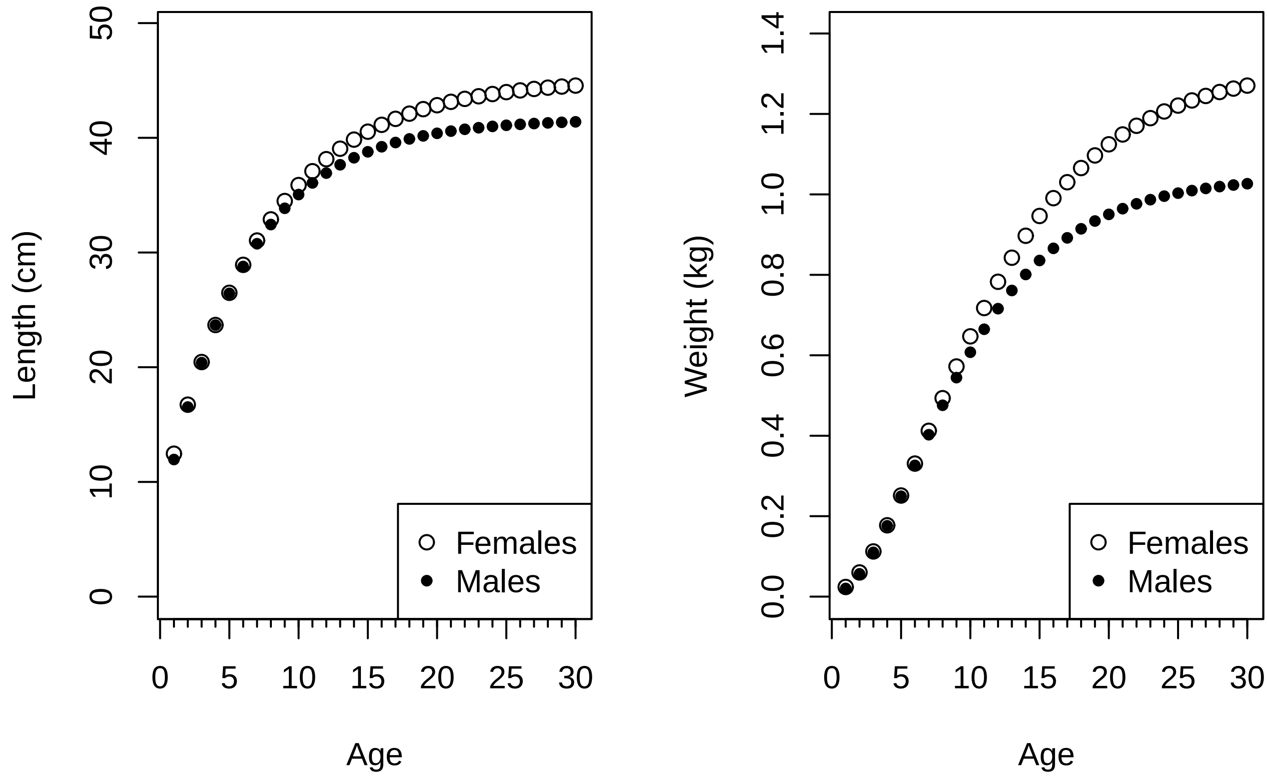

Figure A.1. Mean lengths-at-age and mean weights-at-age for each sex, as given by (A.2) and (A.1) with parameter values from Table A.1.

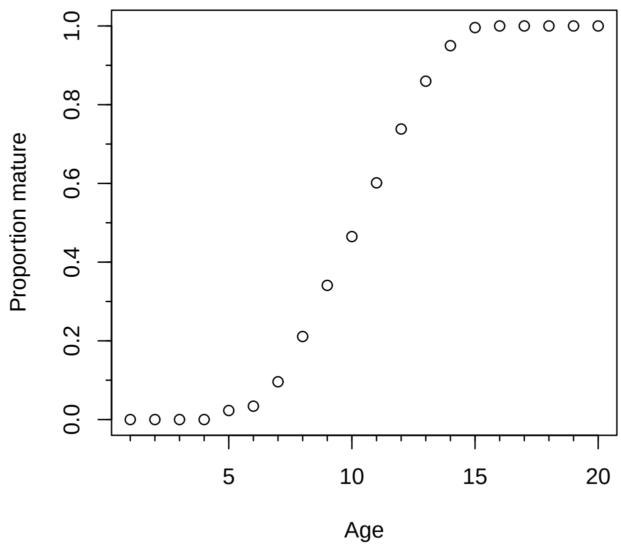

Figure A.2. Maturity ogive for females used in the stock assessment model. Values are given in Table A.2.

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

B DESCRIPTION OF CATCH-AT-AGE MODEL

B.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.

B.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.

B.3 MODEL NOTATION AND EQUATIONS

The notation for the model is given in Table B.1, the model equations in Tables B.2 and B.3, and description of prior distributions for estimated parameters in Table B.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 B.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 B.3.

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

Table B.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 B.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 B.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 (B.4)-(B.6), and then state dynamics are iteratively calculated through time using the main equations (B.1)-(B.3), selectivity functions (B.7) and (B.8), and the derived states (B.9)-(B.13). Estimated observations for survey biomass indices and proportions-at-age can then be calculated using (B.14) and (B.15). In Table B.3, the estimated observations of these are compared to data.

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

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

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

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

Initial conditions ($t = 1$)

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

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

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

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

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

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

Table B.2 (cont.)

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

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

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

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

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

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

Estimated observations

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

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

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

Estimated parameters

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

Recruitment deviations

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

Log-likelihood functions

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

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

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

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

Joint prior distribution and objective function

$$\log(\pi(\boldsymbol{\Theta})) = \sum_j \log(\pi_j(\boldsymbol{\Theta})) \tag{B.22}$$

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

Table B.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 $\pi_j(\boldsymbol{\Theta})$ functions that contribute to the joint prior distribution in (B.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

B.4 DESCRIPTION OF DETERMINISTIC COMPONENTS

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

B.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.

B.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.

B.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 B.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.

B.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 B.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.

B.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.

B.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.

B.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.

B.4.8 STATE DYNAMICS

The crux of the model is the set of dynamical equations (B.1)-(B.3) for the estimated number N_{ats} of age-class a fish of sex s at the start of year t. Equation (B.1) states that half of new recruits are males and half are females. Equation (B.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 (B.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.

B.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 (B.4) and (B.5) are obtained by setting $R_t = R_0$ (virgin recruitment), $N_{ats} = N_{a1s}$ (equilibrium condition) and $u_{ats} = 0$ (no fishing) into (B.1)-(B.3). The virgin spawning biomass B_0 is then obtained from (B.9).

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

B.4.11 DERIVED STATES

The spawning biomass (biomass of mature females, in tonnes) B_t at the start of year t is calculated in (B.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 (B.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 (B.12) shows is the ratio of total catch to vulnerable biomass in the middle of the year, V_t, given by equation (B.11). So (B.12) calculates the proportion of the vulnerable biomass that is caught, and (B.13) partitions this out by sex and age.

B.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 (B.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.

B.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 (B.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 (B.14) is not needed to convert kg into tonnes, because N_{ats} is in 1000s of fish (true also for (B.6) and (B.9)).

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

B.5 DESCRIPTION OF STOCHASTIC COMPONENTS

B.5.1 PARAMETERS

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

B.5.2 RECRUITMENT DEVIATIONS

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

$$R_t = \frac{B_{t-1}}{\alpha + \beta B_{t-1}} e^{\epsilon_t - \sigma_R^2/2} \tag{B.24}$$

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

(B.17) and log-likelihood function (B.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.

B.5.3 LOG-LIKELIHOOD FUNCTIONS

The log-likelihood function (B.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 (B.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 (B.20). The total log-likelihood $\log L(\mathbf{\Theta})$ is then the sum of the likelihood components – see (B.21).

B.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 (B.23) shows is the negative of the sum of the total log-likelihood function and the logarithm of the joint prior distribution, given by (B.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.

B.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.

B.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

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

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 (B.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 (B.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

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

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):

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

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

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

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

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

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.

B.6.3 PRIOR DISTRIBUTIONS

Descriptions of the prior distributions for the 18 estimated parameters are given in Table B.4. The resulting probability density functions give the $\pi_j(\mathbf{\Theta})$, whose logarithms are then summed in (B.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 (B.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).

B.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).

B.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 $0.4B_{\mathrm{MSY}}$ and $0.8B_{\mathrm{MSY}}$ (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 (B.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).