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Modeling herring population dynamics Herring Catch-at-Age Model version 2

Modélisation de la dynamique des populations de hareng : modèle des captures à l'âge de harengs, Version 2

Line Bang Christensen, Vivian Haist and Jake Schweigert

Fisheries and Oceans Canada
Pacific Biological Station
Nanaimo, BC V9T 6N7

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Abstract

The herring catch-at-age model (HCAM) is an age-structured stock assessment model developed specifically for Pacific herring which is assumed to be a multi-stock population that has experienced periods of significant fishery impact and a recent decline in size-at-age (Figure 56 in Appendix II). The first implementation of the HCAM model, HCAMv1, used in the 2006 and 2007 stock assessments has some lingering issues concerning estimates of the proportion of mature fish and natural mortality rates and annual fluctuations in these estimates as well as potential problems with retrospective bias. To address these issues we develop a second implementation of the HCAM model referred to as HCAMv2. In this implementation we simplify the model and change some structural assumptions, resulting in a model that we feel more accurately represents the stock dynamics of the five geographic stocks of Pacific herring. HCAMv2 is a more numerically stable model and retrospective bias, which is a major concern when predicting future stock sizes, is addressed so that such impacts are minimized. We compare the 2007 stock assessment results produced using HCAMv1 and HCAMv2 respectively. HCAMv2 results are in general more conservative than estimates from HCAMv1. The paper also touches on estimates of unfished biomass assumed in current assessments relative to the estimates produced in both HCAMv1 and HCAMv2.

Résumé

Le modèle de captures à l’âge de harengs (HCAM) est un modèle d’évaluation de structure par âge mis au point particulièrement pour le hareng du Pacifique que l’on estime être une population de stocks variés qui a connu des périodes d’incidence importante de la pêche et plus récemment, une diminution de la taille selon l’âge (Figure 56 de l’appendice II). La première version du modèle HCAM, le HCAMv1, utilisée lors des évaluations des stocks de 2006 et de 2007, laisse planer des questions concernant l’estimation de la proportion de poissons adultes et des taux de mortalité naturelle, de la fluctuation de ces estimations ainsi que des problèmes possibles de biais rétrospectif. Afin de nous attaquer à ces problèmes, nous avons mis au point une deuxième version du modèle HCAM appelé le HCAMv2. Pour cette version, nous avons simplifié le modèle et modifié certaines hypothèses structurelles pour donner un modèle qui, selon nous, représente plus fidèlement la dynamique des stocks des cinq stocks géographiques de harengs du Pacifique. Le HCAMv2 est un modèle numériquement plus stable et tient compte du biais rétrospectif qui est une préoccupation importante lorsque l’on prévoit l’importance éventuelle des stocks, de sorte qu’il est possible de réduire de tels effets au minimum. Nous comparons les résultats de l’évaluation des stocks de 2007 produite à l’aide du HCAMv1 et du HCAMv2 respectivement. Les résultats du HCAMv2 sont, en général, plus modérés que les estimations obtenues avec le HCAMv1. Le document aborde également les estimations de biomasse non exploitée présumées dans les évaluations actuelles par rapport aux estimations produites avec le HCAMv1 et le HCAMv2.

Introduction

A revised version of the herring catch-at-age model (HCAMv2), modeled closely after the herring catch-at-age model (HCAM) previously developed by Haist and Schweigert (2006), is presented. The stock assessment model used for the 2006 and 2007 assessments of British Columbia herring, is referred to as HCAMv1 (Schweigert and Haist 2006, Schweigert and Haist 2007) and represents the first implementation of HCAM. Ongoing issues regarding the estimation of natural mortality rates and proportions of fish available to the fishery (sexually mature population) as well as potentially pervasive effects of retrospective bias have spurred the development of a second implementation of the model, HCAMv2. This version of the model simplifies the assumptions made in HCAMv1 and reduces the types of parameters that are estimated without compromising model performance. The core of HCAMv2 closely mimics HCAMv1, but has some significant differences including model initialization, availability parameter estimates and deviations, fishing mortality calculations and natural mortality components. Results produced by HCAMv2 are conservative relative to results produced by HCAMv1.

The following sections present the rationale for developing this implementation of the model, the components of the HCAMv2 model as well as the priors and likelihoods that are included. The model fit and residuals are then detailed, and Markov Chain Monte Carlo simulations are presented along with abundance forecasts, information on retrospective bias patterns and lastly unfished biomass estimates produced in the different model versions are briefly discussed.

Model

Rationale

The current model used for herring stock assessments, HCAM, has been through external review at PSARC and has seen a series of modifications. HCAMv1 is the model implementation used for the 2006 and 2007 assessments. HCAMv2 attempts to address some lingering issues with the HCAMv1 implementation. These include the realism of estimates of natural mortality (see Figure 1) where average mortalities are estimated at 0.83 for the Queen Charlotte Island (QCI) region, 0.56 for the Prince Rupert District (PRD) region, 0.70 for the Central Coast (CC) region, 0.72 for the Strait of Georgia (GS) region, and 0.93 for the West Coast Vancouver Island (WCVI) region. Some of these estimates are significantly higher than the estimates of 0.16-0.77 that were presented by Schweigert and Tanasichuk (1999). Additionally, the annual variability in natural mortality rates is significant (see Figure 1) and perhaps larger than is biologically realistic.

All mature fish are assumed to be available to the fishery (however, not all mature/available fish are selected by the fishery), and thus availability and maturity are used interchangeably. Estimation of availability/maturity parameters (see Figure 2) in the HCAMv1 implementation raises another issue regarding model behaviour. The estimate of availability/maturity for the Strait of Georgia (dark blue circles) seems quite reasonable, but there is concern that in the remaining four regions the proportion of spawning fish is significantly underestimated. Hypothetically, a consequence of this could be that in the model a large body of immature fish with the potential to replenish the population at any time would exist. Few immature fish are taken in the fishery (Hay and McCarter, 1999) but there has been little sampling in the offshore at this time, to confirm or refute this assumption.

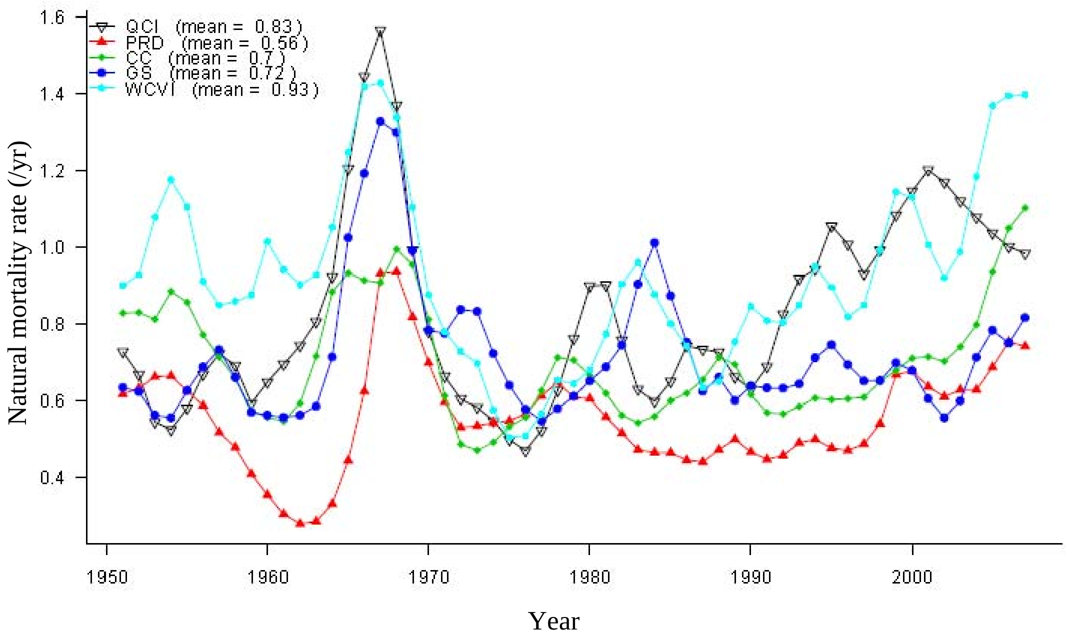

Figure 1, Natural mortality estimates from the 2007/2008 HCAMv1 for the Queen Charlotte, Prince Rupert District, Central Coast, Strait of Georgia and West Coast Vancouver Island stocks of herring from 1951-2007.

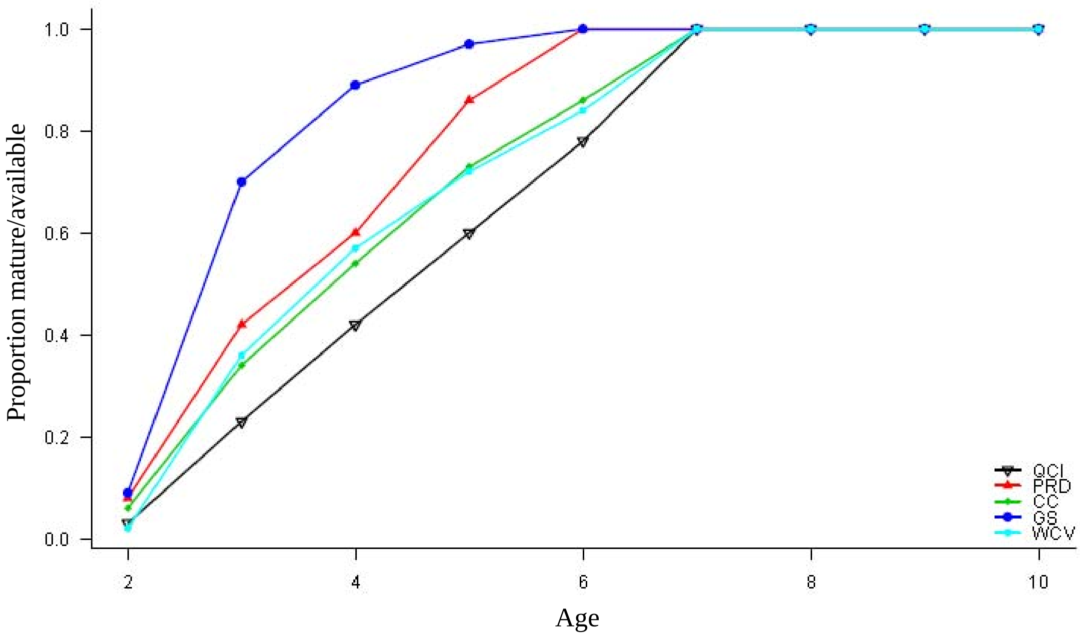

Figure 2, Maturity/availability estimates from the 2007/2008 HCAM for the Queen Charlotte, Prince Rupert District, Central Coast, Strait of Georgia and West Coast Vancouver Island stocks of herring from 1951-2007.

Additionally, the fluctuations in annual maturity/availability rates are large. Figure 3 shows the annual estimates of maturity/availability in the Strait of Georgia. The estimated proportion of mature age three herring fluctuates between 0.22 and 0.92 of the age class and could be considered biologically unrealistic.

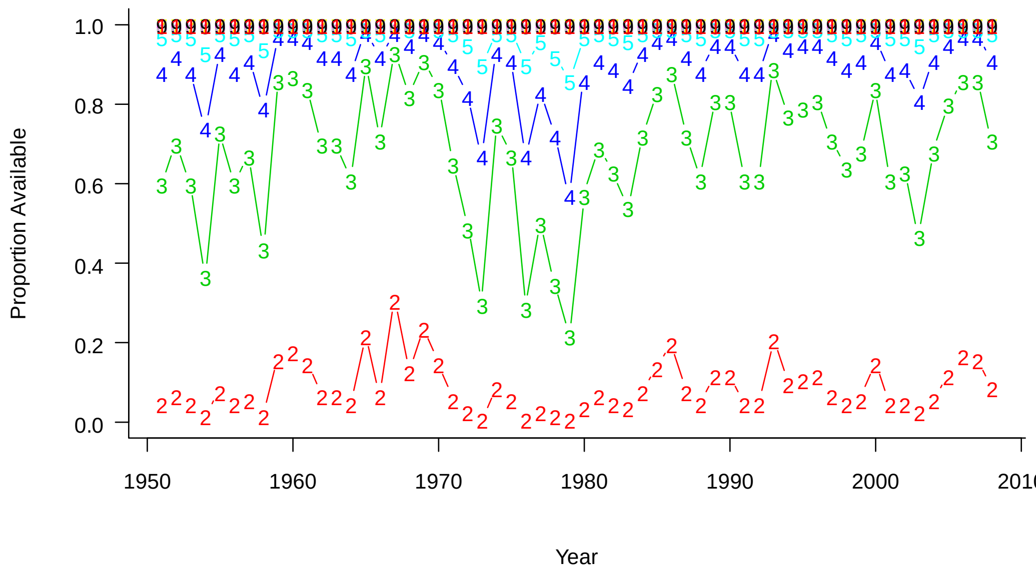

Figure 3, Annual variation in maturity/availability estimates from the 2007/2008 HCAM for the Strait of Georgia stock of herring from 1951-2007. Numbers identifying the different lines indicate the different age groups of herring.

Retrospective bias, implies a persistent over- or underestimation of a quantity of the stock, and presents itself as another potential issue. In the HCAMv1 implementation, there is evidence of some positive retrospective bias (see Schweigert and Haist, 2007) for all stocks except the Queen Charlotte Islands. As a result, in a given year the addition of a subsequent year of data could result in a reduction of that year's stock size producing a consistent trend of overestimation of abundance. If the trend persists it could result in overfishing, in which case the HCAMv1 implementation would not result in a precautionary management approach.

To determine the optimal approach to improving on the current stock assessment we tested a number of extensions to the HCAM model to assess whether they resolved some of the issues presented above. The extensions included extending the time series of catches back in time to 1933, which we found did not enhance our ability to estimate the size of the stock. We also attempted to estimate the spawn index proportionality constant (or alternatively the survey scaling or catchability parameter) for the spawning index post 1988 in addition to the pre-1988 estimate. While this gave reasonable estimates in some areas, other areas were estimated to have low spawn index proportionality parameter. This suggests that only a fraction of the population is being surveyed in the dive era. As this is not what we believe to be happening, we conclude that while it may be possible to estimate the spawn index proportionality parameter post 1988 in some areas, it cannot be done in all areas and so we did not adopt this model extension.

We also tested the inclusion of a density-dependent mortality rate which in general resulted in high estimates of recruitment and coinciding high estimates of available harvest. This did not resolve the model issues identified earlier. We also checked that the fishing mortality penalty multiplier was not causing increased model instability. There were some problems with this in the HCAMv1 model, including the inability of the model to reach a solution with some multipliers. Lastly, we attempted to add predation mortality directly from an Ecopath model (Preikshot, 2007) as an additional mortality source and found that predictions were similar, but not identical to, the earlier results—but more optimistic about stock size using this parameterization.

These analyses suggested that to improve upon the HCAM framework the basic model structural assumptions would have to be revisited. Accordingly, we opted not to use any of the these parameterizations, but developed HCAMv2, as an alternative version of the HCAM model.

Model components

HCAM is described in detail in Appendix A in Haist and Schweigert (2006). The model structure in HCAMv2 is identical to HCAMv1 except for the components listed in the paragraphs below. Equations differing between the models are listed in Appendix I.

The modifications result in HCAMv2 estimating 135 parameters plus fishing mortality parameters for each period/year combination for a total of 199, 238, 225, 267, and 214 parameters for the QCI, PRD, CC, GS and WCVI stocks respectively. The HCAMv1 implementation has 190 estimated parameters and uses the Newton-Raphson algorithm to analytically solve the catch equations (i.e., no fishing mortality parameters are estimated). Concerns over model ability to converge to a global minimum were alleviated by estimating the fishing mortality parameters in HCAMv2 rather than using the Newton-Raphson algorithm and are therefore used. Comparatively, excluding those fishing mortality parameters, the HCAMv2 implementation has 55 (135 v. 190) fewer parameters than the HCAMv1 implementation.

The changes were implemented to address the following list of issues. Firstly the aformentioned issue of fluctuations in annual maturity/availability rates in HCAMv1 resulted in the elimination of annual natural maturity/availability deviations in HCAMv2, i.e., maturity/availability are assumed to be time invariant. Additionally, in HCAMv2 the maturity/availability parameters are fixed (rather than estimated as in HCAMv1) in accordance with Figure 4, i.e. 25% of age 2 fish are mature, 90% of age 3 fish are mature and all fish of age 4 and older are mature. This is consistent with the findings of Hay and McCarter (1999). Thus, HCAMv2 assumes a fixed time-invariant maturity schedule.

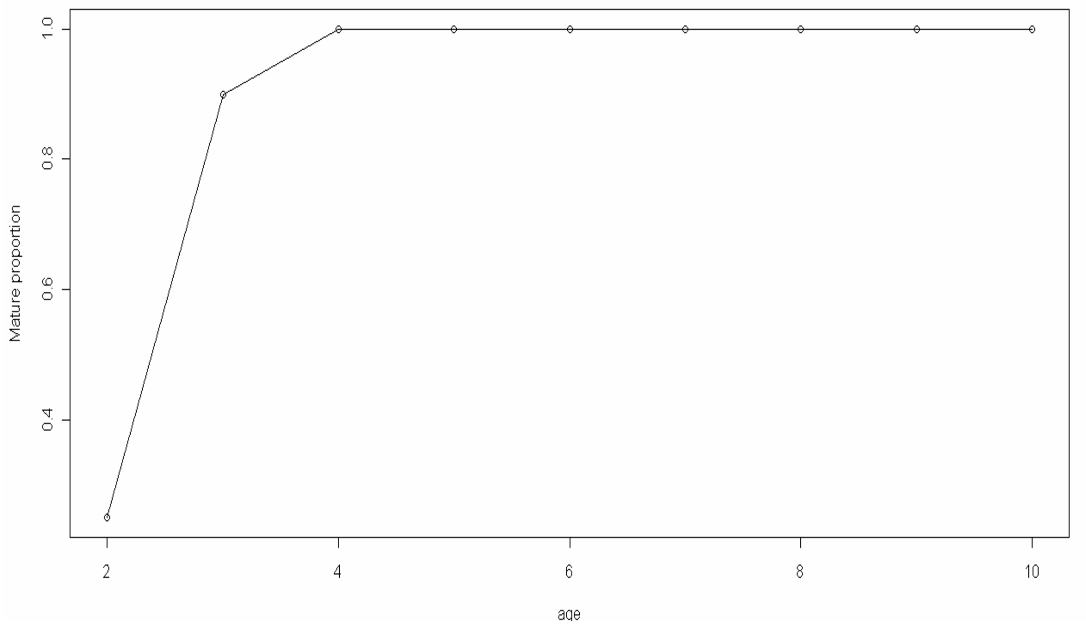

Figure 4, HCAMv2 maturity/availability assumption.

The initialization of the age-structure differs between HCAMv1 and HCAMv2. In HCAMv1 there are three options: first, assuming the age structure is at equilibrium, second, assuming that the age structure is at equilibrium, but that there is some initial fishing mortality multiplier and third, estimating the size of each age group in the initial year. HCAMv1 assumes the latter parameterization. In HCAMv2 we assume a fourth option, that the stock is in a fished state in 1951 and accordingly initialize the population age structure by starting the model at unfished equilibrium in 1942 (1951 – 9, where 9 is the number of age classes 2, 3 … 10). The fishing mortality rates in each of these 9 initial years are assumed to be identical and this initial fishing mortality rate is estimated as a free parameter.

Selectivity is also modeled differently between HCAMv1 and HCAMv2. There are three periods for which selectivity is defined. Period 1 (the winter fishery), period 2 (the seine roe fishery) and period 3(the gillnet roe fishery). Both models assume that the gillnet roe fishery (period 3) is parameterized as a logistic function of the geometric mean weight at age (see Table 6 for details). The period 1 and 2 fisheries are assumed to have a selectivity of 1 in HCAMv1. However, in HCAMv2, selectivity for period 1 and 2 is assumed to be a logistic function of age.

The spawn index proportionality constant (survey scaling) was estimated as a free parameter in HCAMv1. In HCAMv2 this quantity is calculated using the conditional maximum likelihood estimate. Because the variance term for the error distribution is assumed to be known *a priori*, this is not an issue in the MCMC routines. The variation in stock recruitment deviations is estimated as a free parameter in HCAMv1, but is fixed in HCAMv2 at either 0.6 (CC, GS) or 0.8 (QCI, PRD, WCVI) to avoid attempting to estimate both recruitment deviations and the variance of these deviations simultaneously. The values were chosen to reflect the observed variation in recruitment fluctuation in the different regions.

Finally, natural mortality is estimated and assumed to be age-independent in both HCAMv1 and HCAMv2. The proportion of mortality assigned to each of the three fishing periods differs, (0.45, 0.45, 0.1) and (0.9, 0.05, 0.05) in HCAMv1 and HCAMv2 respectively. In HCAMv2 we reverted to the implementation of proportionalities assumed in the original HCAM formulation to make it more consistent with the timing of the fisheries. In both implementations, annual variations in natural mortalityare modeled as a random walk.

Likelihoods and priors

The likelihood components include the spawn survey estimates, catch-at-age composition data and regional total catch. These three observations are weighted relative to their assumed variances in the likelihood. The spawn survey is fit by calculating the differences between observed and predicted estimates of spawning biomass. The series is split into 2 sub-series, the first being pre-1988 and the second from 1988 until the present. For the latter series, the spawn index proportionality parameter is fixed at one. Prior to 1988, the conditional maximum likelihood estimate (Walters and Ludwig, 1994) of the spawn index proportionality parameter is used to predict the spawn survey series. The assumed coefficient of variation for the spawn survey was 0.35 for the first series and 0.3 for the series from 1988 to present. Both HCAM implementations use the multinomial distribution for the age-composition data. Sample sizes are scaled to be between 0 and 110 by assuming a process error of 0.009, that is dividing the sample size by (1 + 0.009*sample size). HCAMv2 has an additional likelihood component that represents the difference between observed and predicted catch because fishing mortality parameters are estimated in HCAMv2. The difference is assumed to be log-normally distributed with a mean of zero and a standard deviation of 0.005, indicating that we attribute a very large certainty to the observed catch. Predicted and observed catches are presented for the five stocks in Figure 39 to Figure 43 in Appendix II.

Priors incorporated in HCAM and HCAMv2 are listed in Table 7 in Appendix I. In HCAMv2 the first-difference residual deviations in natural mortality rates are assumed to be normally distributed with mean 0 and standard deviation 0.1. The average natural mortality rate is assumed to be normally distributed with mean 0.45 and standard deviation 0.2, chosen so that the 10th and 90th percentiles of the normal distribution are 0.2 and 0.7. Recruitment deviations are assumed to be log-normally distributed with mean 0 and standard deviations of 0.6 (GS, CC) or 0.8(QCI, PRD, WCVI). The steepness parameter was assumed to be log-normally distributed with a mean of 0.67 and a log-standard deviation of 0.17 (Hilborn, pers. comm. with Schweigert). This is comparable to the Myers et. al (1999) estimate of 0.74 for Atlantic herring. The posterior distribution for the steepness parameter is shown in Figure 57 in Appendix II. Lastly, the initial fishing mortality rate was assumed to be log-normally distributed with 10th and 90th percentiles of 0.3 and 0.6 respectively, i.e., with a mean of 0.04 and a log-standard deviation of 0.6633. Priors for the parameters that are no longer estimated (e.g., recruitment deviation variance), are assumed to be known and are not considered in HCAMv2.

Model fit and residuals

The trends in the five stocks are alike in HCAMv1 and HCAMv2. The following figures present the results in terms of the fits to the age-composition and spawning index data. For the Queen Charlotte Islands the dominating 1955 and 1977, 1981, 1985 and 1996 cohorts are all clearly tracked in the model (Figure 5). Pearson residuals evaluate the fit of the data—it is the residual relative to the variability of the observations. Consequently, because of the model's ability to fit the data there are no patterns of concern in the pearson residual bubble plots (Figure 46 in Appendix II). Quantile-quantile plots allow for the evaluation of whether residuals are normally distributed, indicating whether the observed and predicted observations come from the same population. In a quantile-quantile plot, the intercept represents the mean and the slope represents the standard deviation of the residuals. Figure 51 in Appendix II depicts the quantile-quantile plot for the age-composition data of the Queen Charlotte Island stock for all three fishing periods. The residuals do not appear over-dispersed relative to the assumed error and it can be assumed that the observed and predicted samples come from the same statistical population. The HCAMv2 model fits the spawning index well, capturing the apparent upward trend in 2007 (Figure 6). The HCAMv1 model also fits the spawning index well and is very similar to the HCAMv2 trend; however, it is much more sensitive to annual fluctuations (Figure 6). The only significant difference between the model fits is that for the mid 1970s to mid 1980s the HCAMv1 trend is generally larger than the HCAMv2 trend. The HCAMv2 spawning index proportionality parameter is estimated to be 30% prior to 1988 (i.e., an estimated 30% of the total spawn was surveyed from 1951-1987). In Figure 6 the bottom left panel shows the natural logarithm of the observed and predicted spawn and the bottom right shows the residuals between the observed and predicted indices.

Figure 7 presents the observed and predicted age-composition data for Prince Rupert District. The large 1977, and somewhat smaller 1981, 1989 and 2000 cohorts are tracked reasonably well. This is further evident when considering the lack of patterns in the bubble plots of the pearson residuals of the age-composition for each of the three fishing periods (Figure 47 in Appendix II). The quantile-quantile plot for this age-composition data indicates that in periods 2 and 3 the residuals are not over-dispersed relative to the assumed error, however, in period 1 there may be a slight over-dispersion indicating perhaps that the data is mildly over-weighted (Figure 52 in Appendix II). Figure 8 shows the fit to the observed spawning index, the model is unable to recreate the very high numbers in the mid 1980s and overestimates the numbers in the 1990s and early 2000s. The spawning index proportionality coefficient estimated for the 1951-1987 time period is 52%, i.e., the estimate of the proportion of total spawn that was surveyed on average in this period. The large residual in the bottom two figures is the 1969 index that is predicted to be quite a bit larger than the observed spawn.

Figure 9 shows the observed and predicted age-composition data for the Central Coast. The 1964, 1977, 1984 and 1990 cohorts are all tracked closely by the model. Similarly, no patterns are visible in the pearson residual bubble plots for the age-compositions in the first and third fishing periods, although there is a slight overestimation of the 1979 year class in fishing period 2 (Figure 48 in Appendix II). The quantile-quantile plot indicates that the observed and predicted data appear to come from the same population (Figure 53 in Appendix II). The spawning index is fit closely showing a drop in the last two years (Figure 10). The spawning index proportionality coefficient for 1951-

1987 was 28% in the Central Coast, suggesting that about a third of the spawn was surveyed on average prior to 1988.

The observed and predicted age-composition indices are presented in Figure 11 for the Strait of Georgia. It is evident that there is not much information on cohort size in the Strait of Georgia. Further, the pearson residual plots do not show any clear patterns (Figure 49 in Appendix II), and the quantile-quantile plots indicate that the observed and predicted data come from the same population (Figure 54 in Appendix II). The observed and predicted spawning indices are plotted in Figure 12 and show that 95% of the spawn was surveyed on average before 1988. The model estimates of biomass in the late 1970s were smaller than observed.

On the west coast of Vancouver Island the observed and predicted age-composition data are presented in Figure 13. The 1959, 1972, 1984 and 1994 cohorts are tracked in the model predictions although perhaps less strongly than in the northern areas. Thus, no obvious patterns exist in the pearson residuals, although there seems to be some overestimation of the age-3 class and underestimation of the age-4 class in period 2 (Figure 50 in Appendix II). The quantile-quantile plots indicate that the observed and predicted data come from the same population (Figure 55 in Appendix II). The predicted spawning index closely mirrors the observed index, but is unable to replicate the large spawns in the late 1970's (Figure 14). In the period from 1951 – 1987 63% of the spawn was estimated to have been surveyed on average.

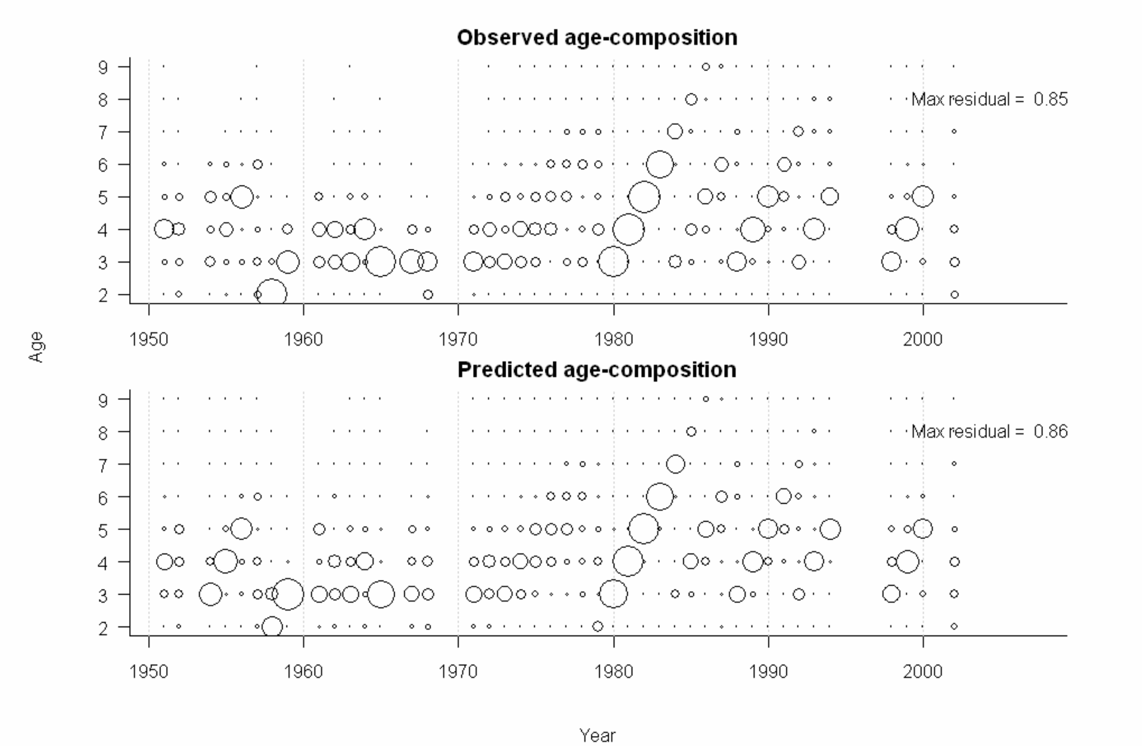

Figure 5, Observed and HCAMv2 predicted age-compositions for the Queen Charlotte Islands herring stock from 1951-2007.

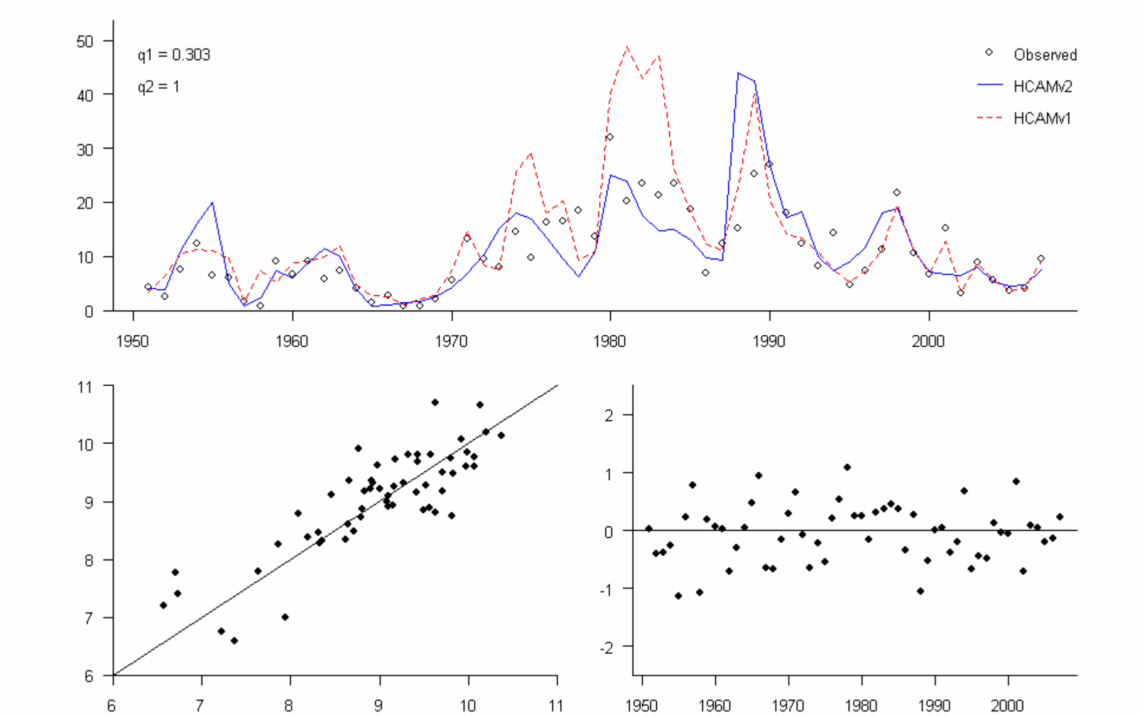

Figure 6, Observed, HCAMv1 and HCAMv2 predicted spawn-indices for the Queen Charlotte Islands herring stock from 1951-2007. Also plotted are the natural logarithms of HCAMv2 model vs. observed spawn (bottom left) and residuals (bottom right).

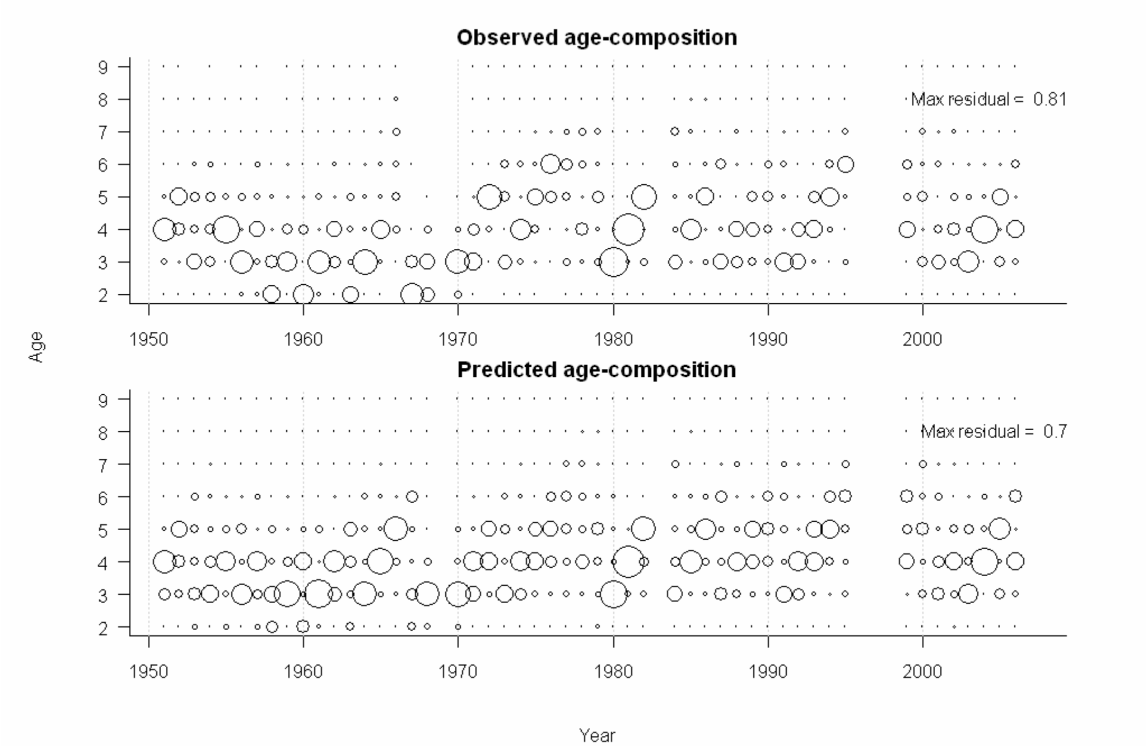

Figure 7, Observed and HCAMv2 predicted age-compositions for Prince Rupert District herring stock from 1951-2007.

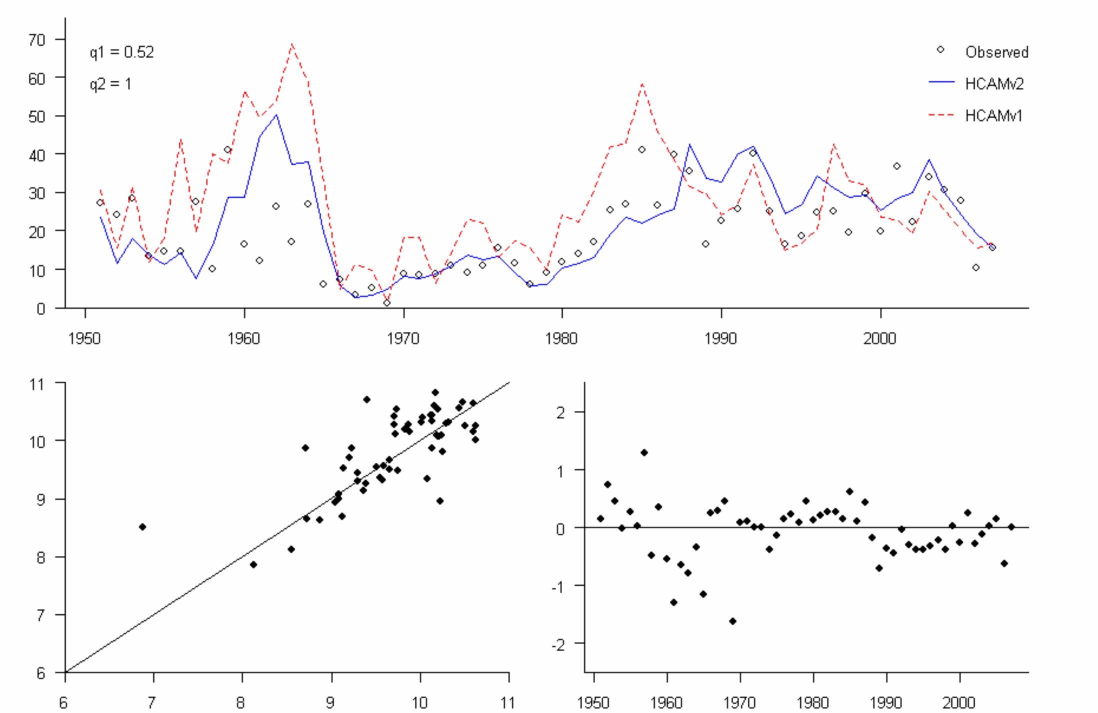

Figure 8, Observed, HCAMv1 and HCAMv2 predicted spawn-indices for Prince Rupert District herring stock from 1951-2007. Also plotted are the natural logarithms of HCAMv2 model vs. observed spawn (bottom left) and residuals (bottom right).

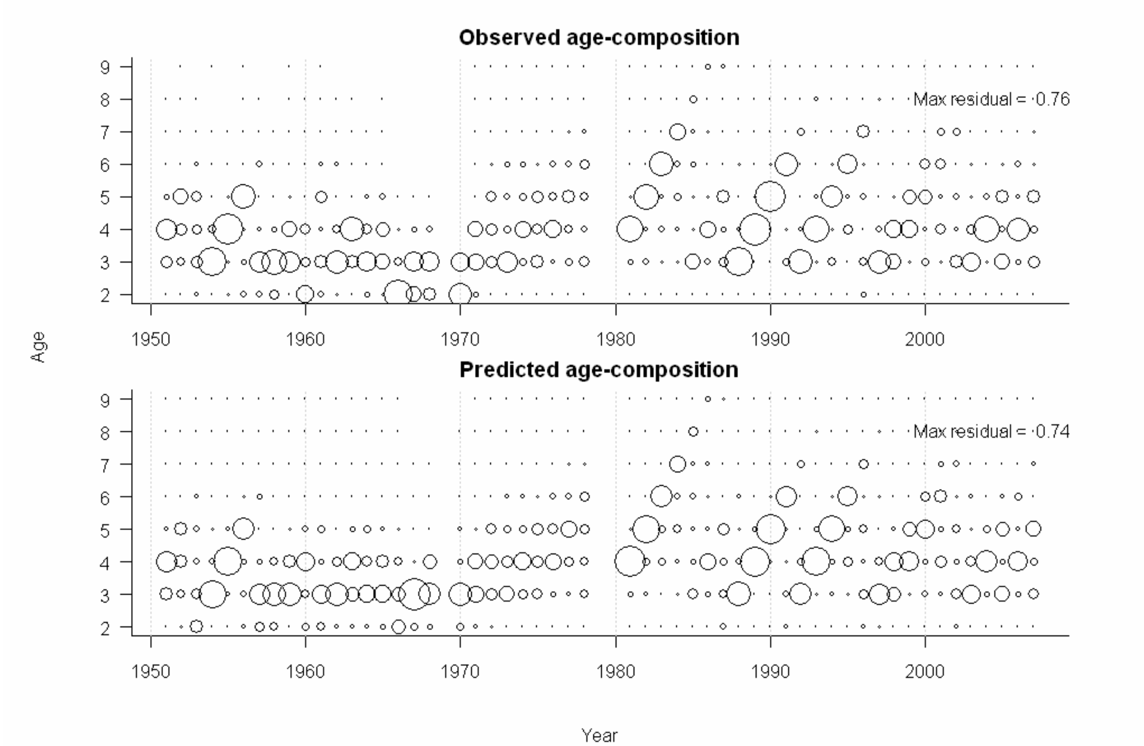

Figure 9, Observed and HCAMv2 predicted age-compositions for the Central Coast herring stock from 1951-2007.

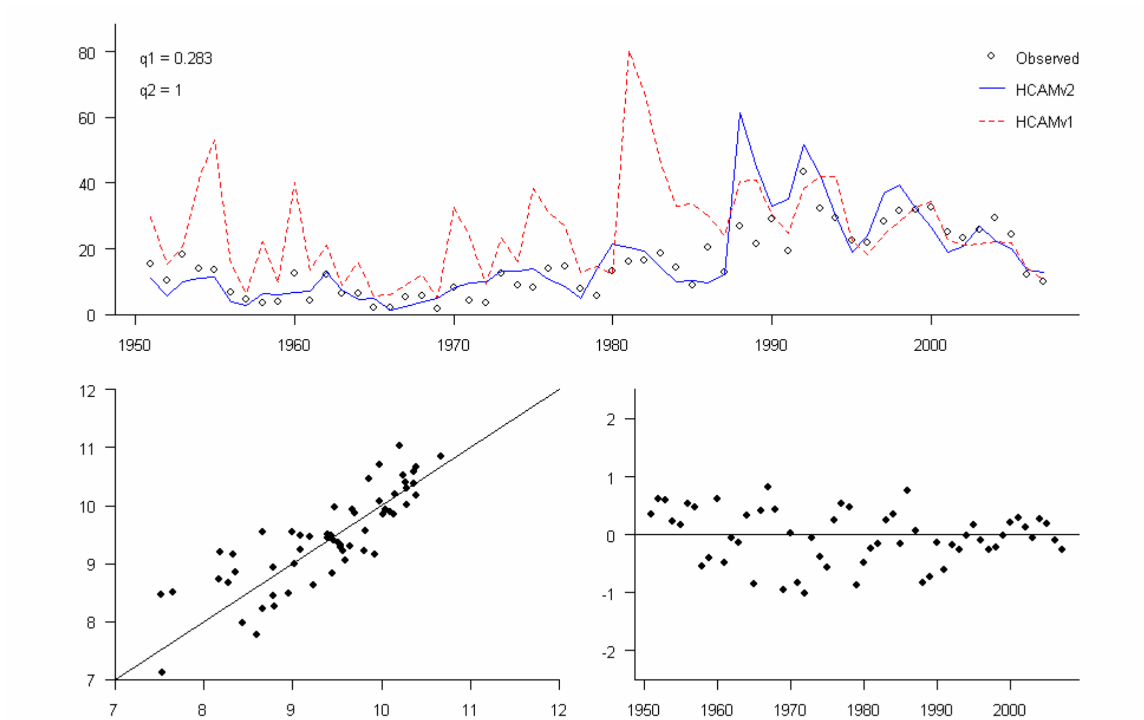

Figure 10, Observed, HCAMv1 and HCAMv2 predicted spawn-indices for the Central Coast herring stock from 1951-2007. Also plotted are the natural logarithms of HCAMv2 model vs. observed spawn (bottom left) and residuals (bottom right).

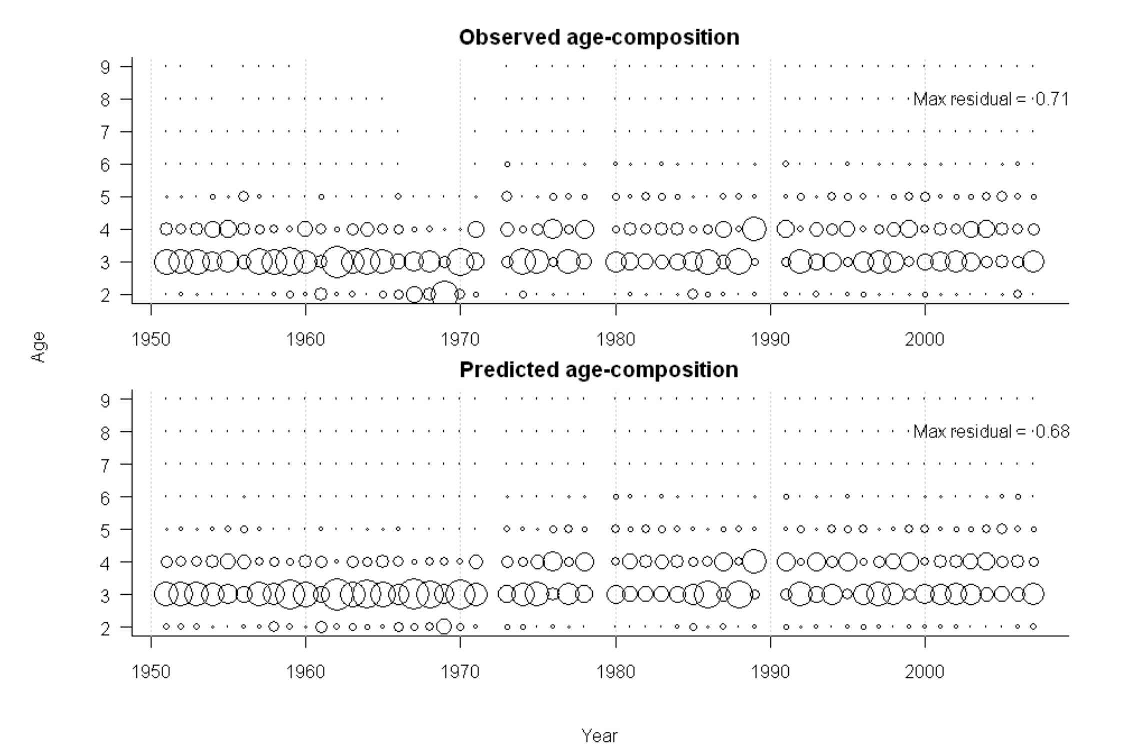

Figure 11, Observed and HCAMv2 predicted age-compositions for the Strait of Georgia herring stock from 1951-2007.

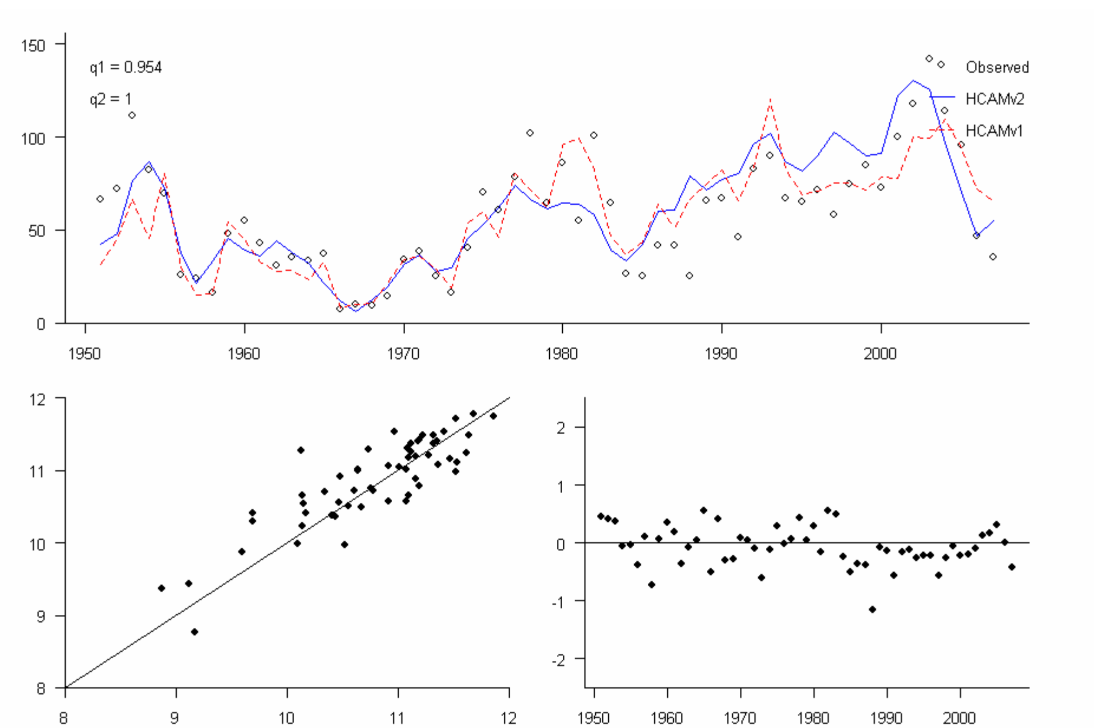

Figure 12, Observed, HCAMv1 and HCAMv2 predicted spawning-indices for the Strait of Georgia herring stock from 1951-2007. Also plotted are the natural logarithms of HCAMv2 model vs. observed spawn (bottom left) and residuals (bottom right).

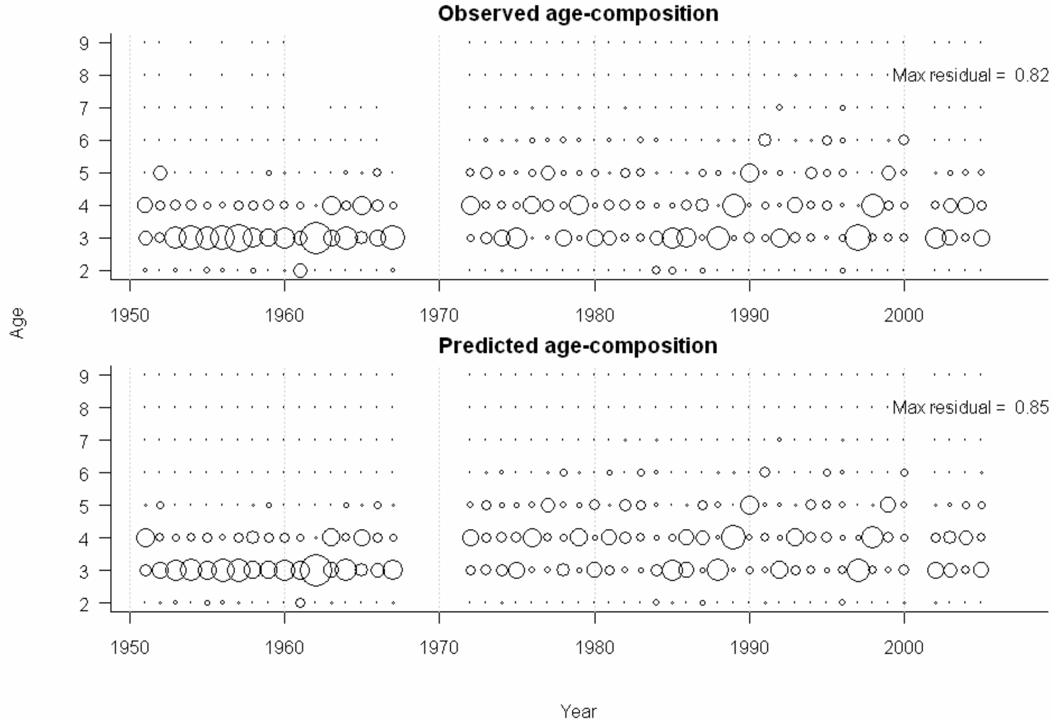

Figure 13, Observed and HCAMv2 predicted age-compositions for the West Coast of Vancouver Island herring stock from 1951-2007.

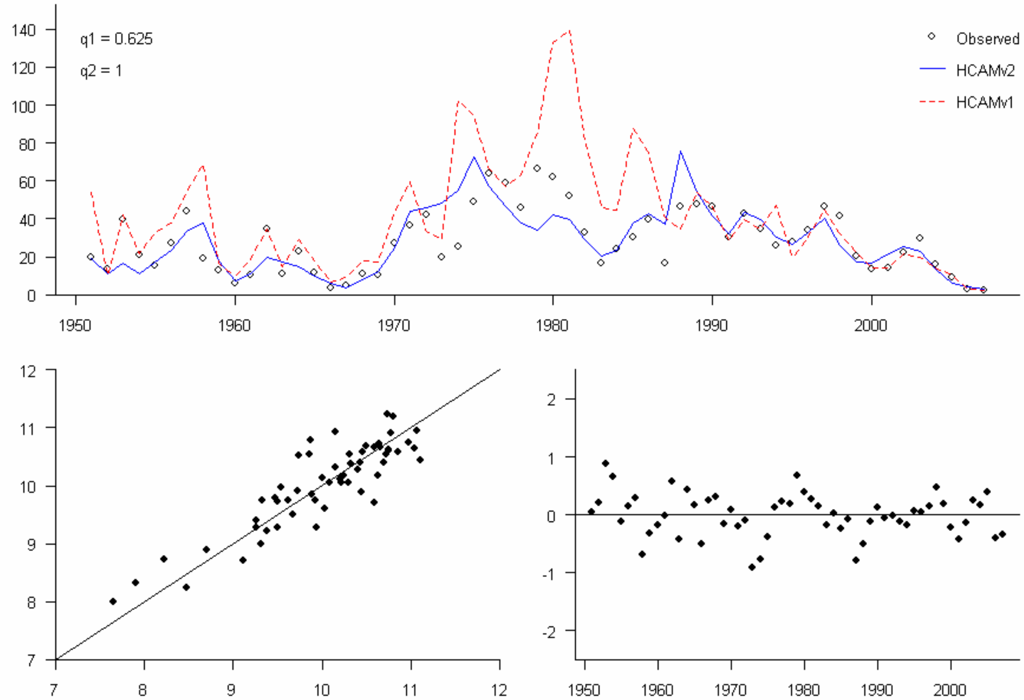

Figure 14, Observed, HCAMv1 and HCAMv2 predicted spawning-indices for the West Coast of Vancouver Island herring stock from 1951-2007. Also plotted are the natural logarithms of HCAMv2 model vs. observed spawn (bottom left) and residuals (bottom right).

Modal natural mortality rates were 0.69 for the QCI herring stock, 0.46 for the PRD herring stock, 0.48 for the CC herring stock, 0.60 for the GS herring stock and 0.66 for the WCVI herring stock. These are substantially lower than those estimated in HCAMv1, and remain so for the most of the time period, especially for the WCVI stock (Figure 15). This trades off with the number of estimated age 2 recruits, i.e., HCAMv1 consistently estimates a higher number of age 2 recruits than HCAMv2 (Figure 58 in Appendix II). Natural mortality rates were allowed to vary according to a random walk, which resulted in predictions of similar patterns in mortality rates between stocks (Figure 15). The QCI, PRD, CC and GS stocks all show a spike in natural mortality rates in the late 1960's. However, this is not the case for the WCVI stock. All 5 stocks do indicate that natural mortality rates have been steadily increasing since about the year 2000. In the Queen Charlotte Islands this increase does seem to have leveled off in the last couple of years. This could explain the lack of recovery faced by the three stocks (QCI, CC and WCVI) that have not been fished in recent years along with the lack of new recruits.

In the original implementation, HCAMv1, fisheries selectivity parameters are estimated only in the third period gillnet fishery as discussed above. In HCAMv2 selectivity parameters are estimated for all three periods of the fishery, the winter fishery in period 1, the seine roe fishery in period 2 and the gillnet roe fishery in period 3. The selectivity curves (Figure 16, Figure 17 and Figure 18) are constant from 1951 – 2007. Fish are fully vulnerable to the fishing gear at age 4 for the Strait of Georgia and west coast of Vancouver Island in the first period. For the Queen Charlotte Islands, Prince Rupert District and Central Coast stocks the fishery selectivity curves have smaller proportions of selected fish. In fact, the QCI stock is fully selected only at age 9 while the CC and PRD stocks remain less than fully selected. In period 2, the selectivity curves are all steeper and all the stocks are fully selected by age 8. This implies that fewer ages 2 and 3 fish are selected in the northern areas in the first two periods of the fishery.

Estimates of fishing mortality over the time period 1951 – 2007 are presented in Figure 19 for the 5 stocks for both the HCAMv1 and HCAMv2 implementations. The mortality rates are similar between the two models. Fishing mortality rates are very high through to 1970 for all five stocks, and have a smaller peak in 1978 when the large 1977 year class becomes vulnerable. Post 1980 the fishing mortality rates level out at much lower rates under 0.5/yr.

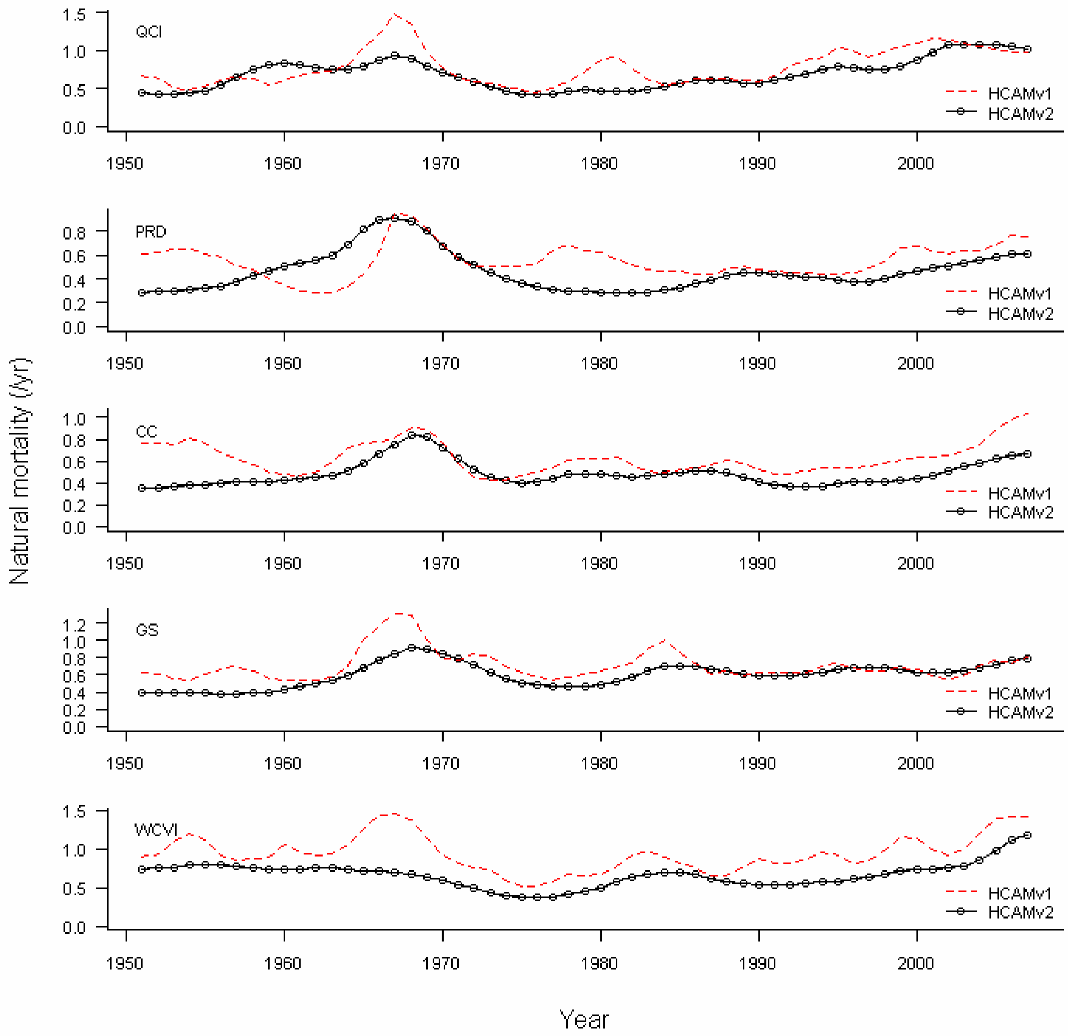

Figure 15, Time series HCAMv1 and HCAMv2 estimates of natural mortality for (from top to bottom) the Queen Charlotte Islands, Prince Rupert District, Central Coast, Strait of Georgia and West Coast Vancouver Island herring stocks from 1951 – 2007.

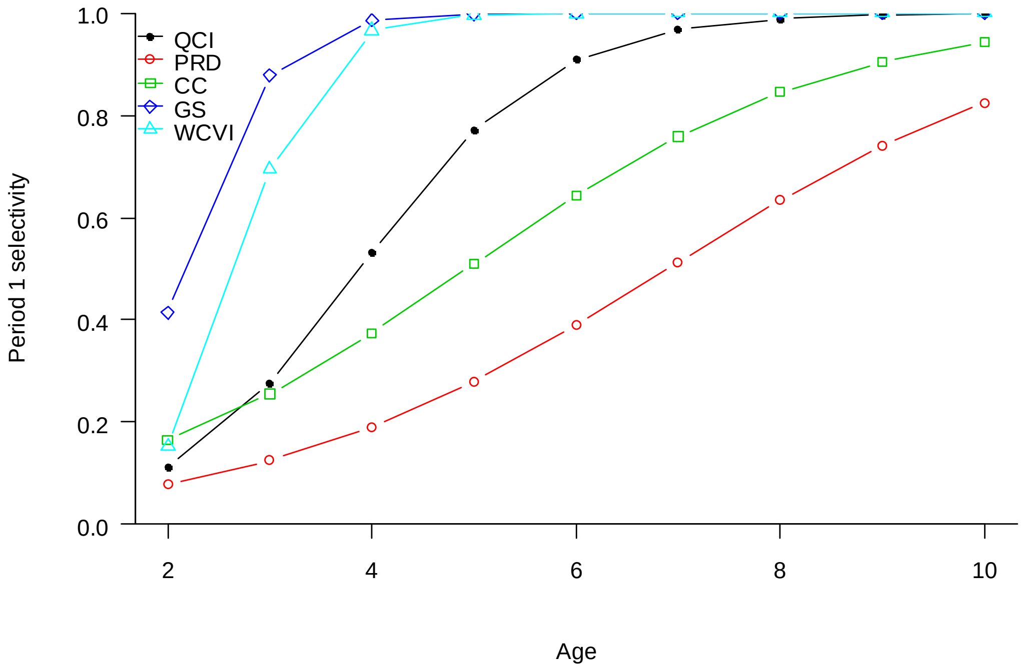

Figure 16, Fisheries selectivity in period 1 (winter fishery) for ages 2-10+ herring for the Queen Charlotte Islands, Prince Rupert District, Central Coast, Strait of Georgia and West Coast Vancouver Island herring stocks.

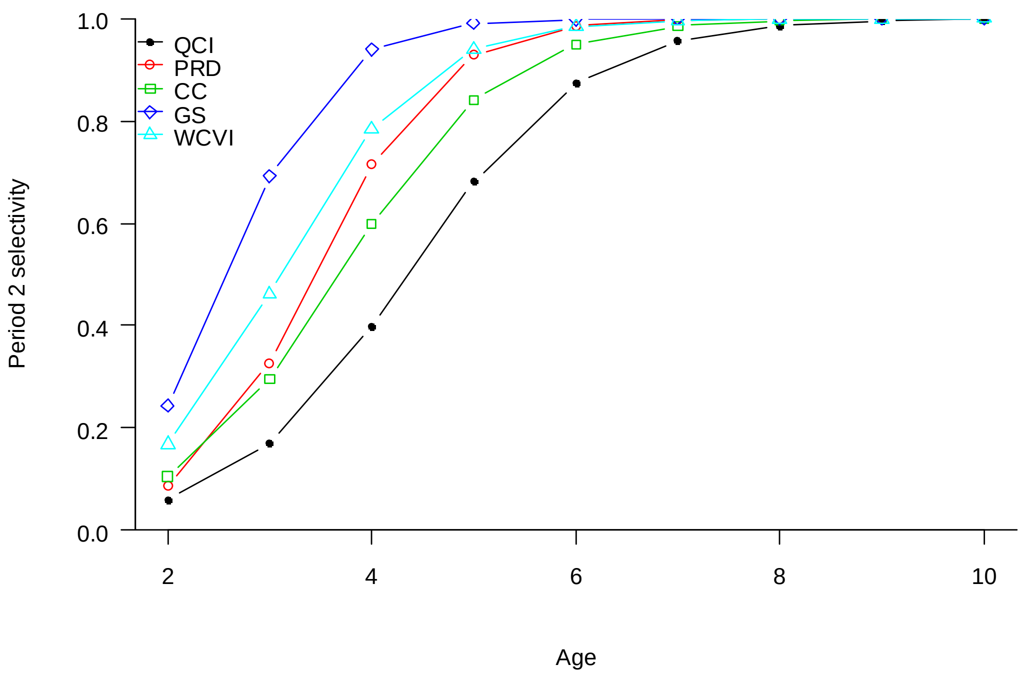

Figure 17, Fisheries selectivity in period 2 (seine roe fishery) for ages 2-10+ herring for the Queen Charlotte Islands, Prince Rupert District, Central Coast, Strait of Georgia and West Coast Vancouver Island herring stocks.

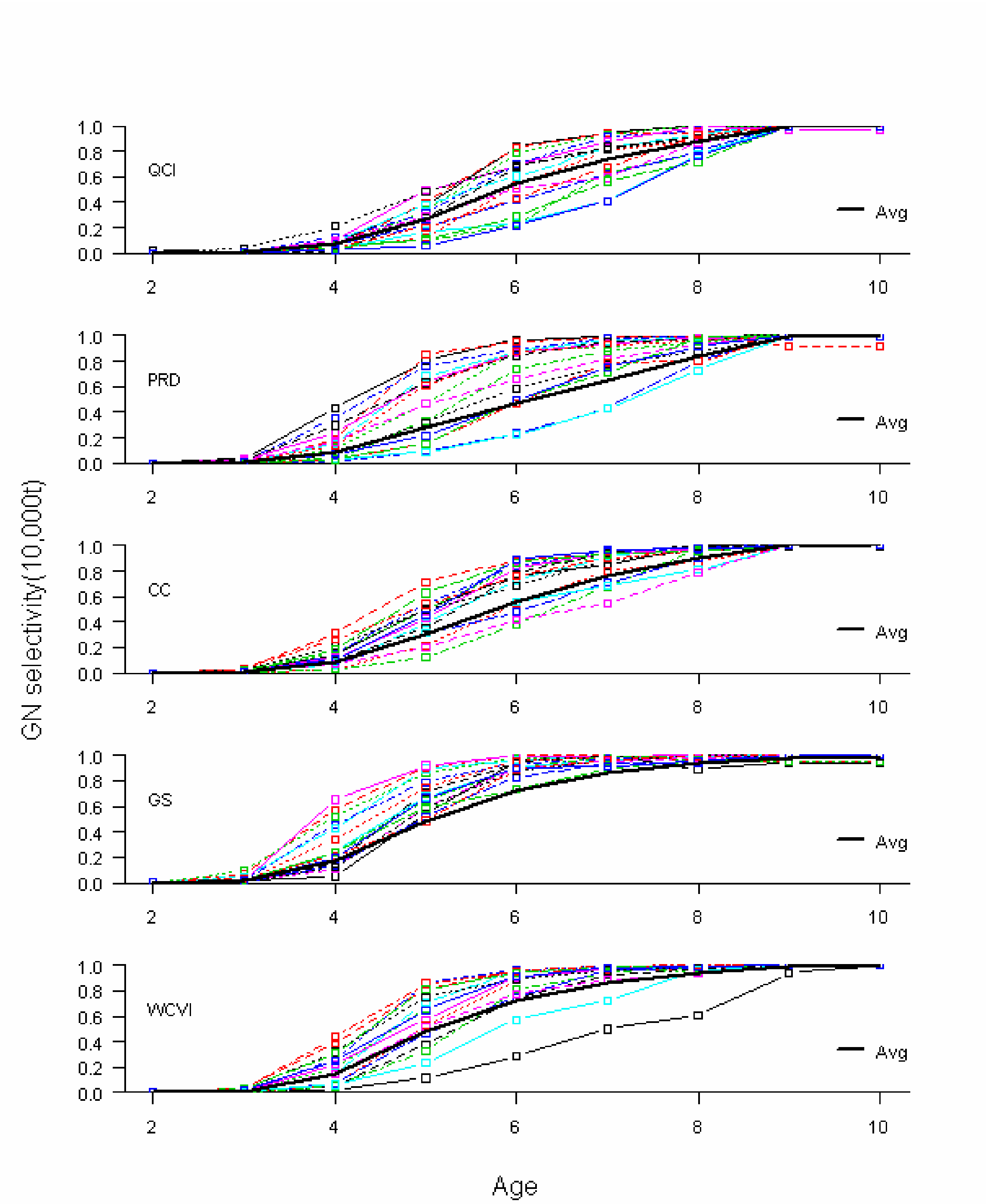

Figure 18, Fisheries selectivity in period 3 (gillnet roe fishery) for ages 2-10+ herring for the Queen Charlotte Islands, Prince Rupert District, Central Coast, Strait of Georgia and West Coast Vancouver Island herring stocks. Each of the light lines is a selectivity curve calculated for a distinct year, weight, age combination (16 total) and the dark bold solid line is the average year, weight, age selectivity.

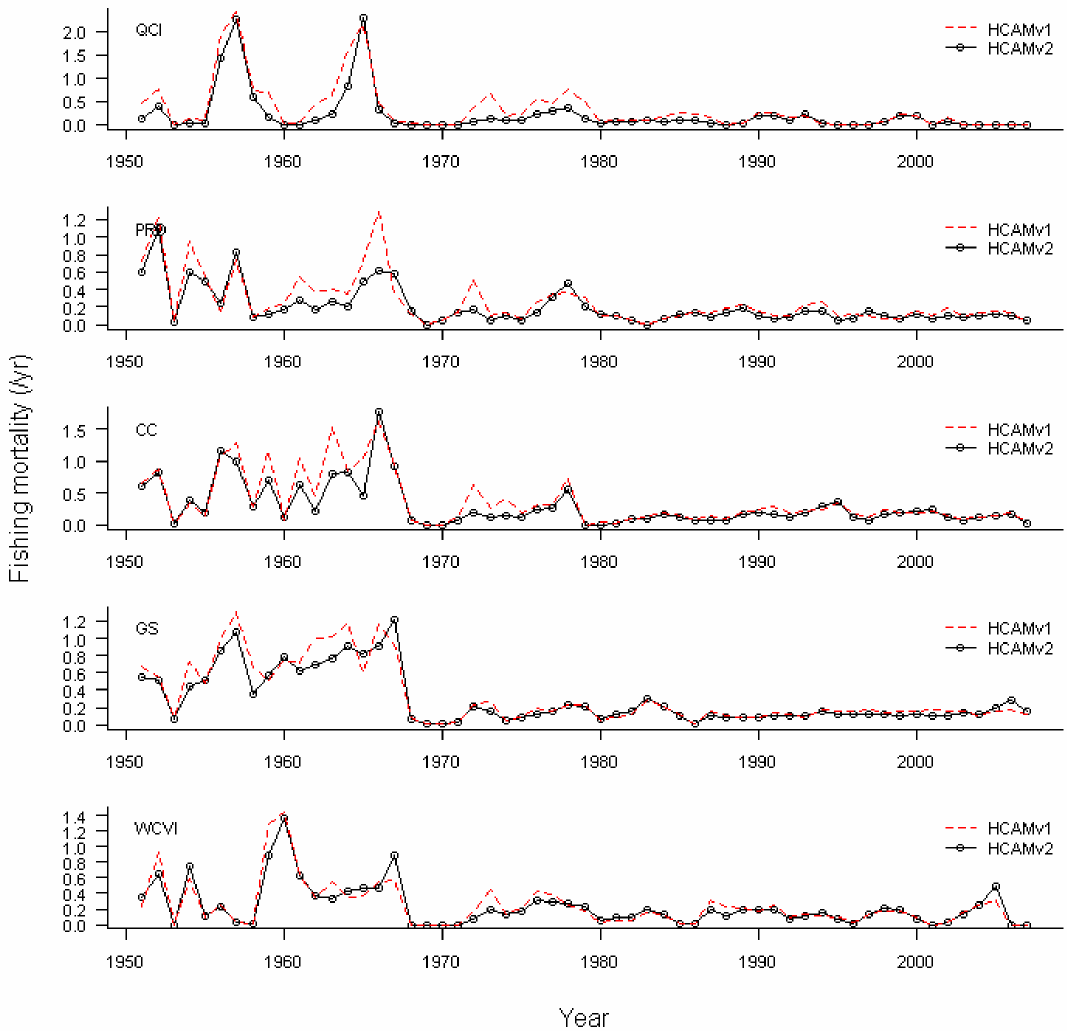

Figure 19: Estimates of annual fishing mortality rates for the Queen Charlotte, Prince Rupert District, Central Coast, Strait of Georgia and west coast of Vancouver Island stocks of herring from 1951-2007.

Markov Chain Monte Carlo Simulations

Figure 20 though Figure 29 show trace plots from the MCMC analysis depicting the sub-samples of estimated spawning biomass in 2007. The MCMC chain is of length 1.1 million, with every 100 samples saved and the first 100,000 samples discarded as burn-in. There is some variation in the plots, but no trends are present. Trace plots from HCAMv1 are available in Schweigert and Haist (2007), the MCMC chain is of length 1 million and a sub-sample of 2000 is plotted. There are no notable differences between HCAMv1 and HCAMv2 trace plots.

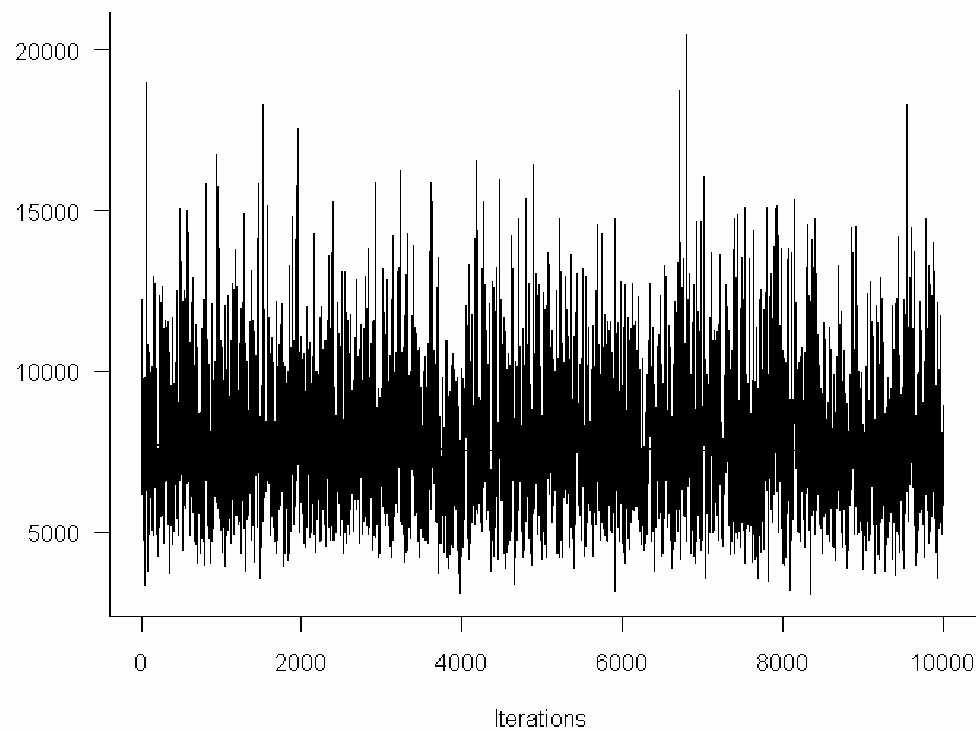

Figure 20, Trace plots from the MCMC analysis showing the sub-samples of estimated spawning biomass in 2007 for the Queen Charlotte Island herring stock.

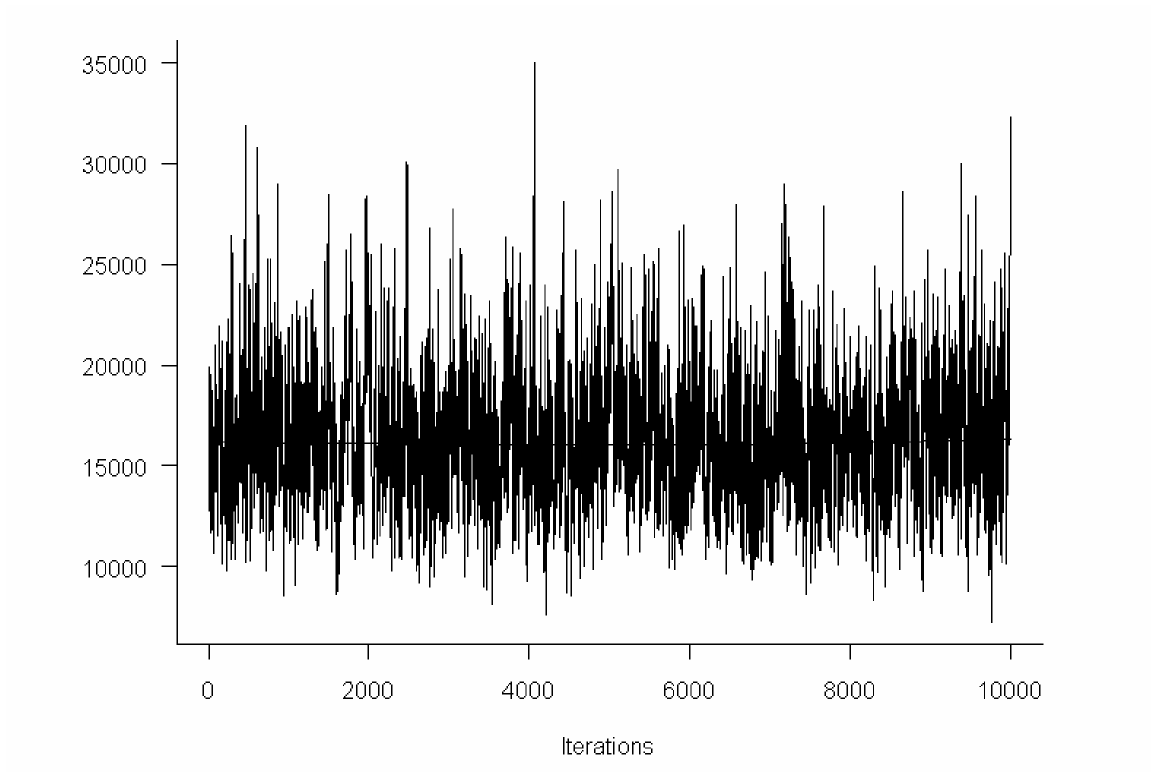

Figure 21, Trace plots from the MCMC analysis showing the sub-samples of estimated spawning biomass in 2007 for the Prince Rupert District herring stock.

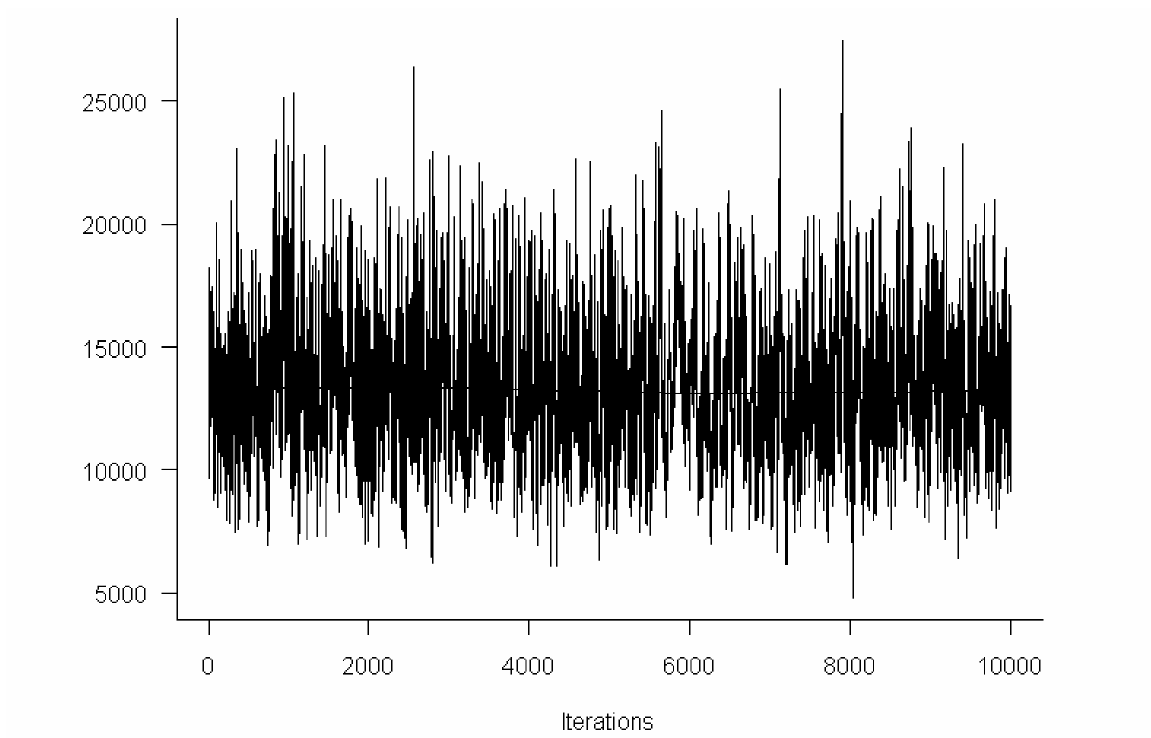

Figure 22, Trace plots from the MCMC analysis showing the sub-samples of estimated spawning biomass in 2007 for the Central Coast herring stock.

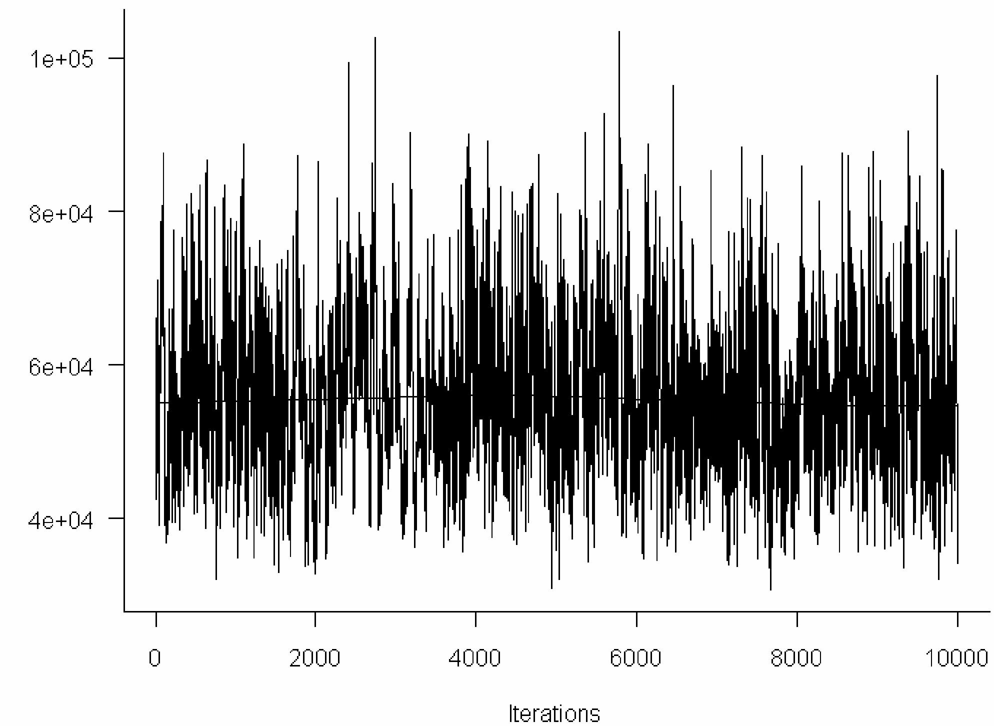

Figure 23, Trace plots from the MCMC analysis showing the sub-samples of estimated spawning biomass in 2007 for the Strait of Georgia herring stock.

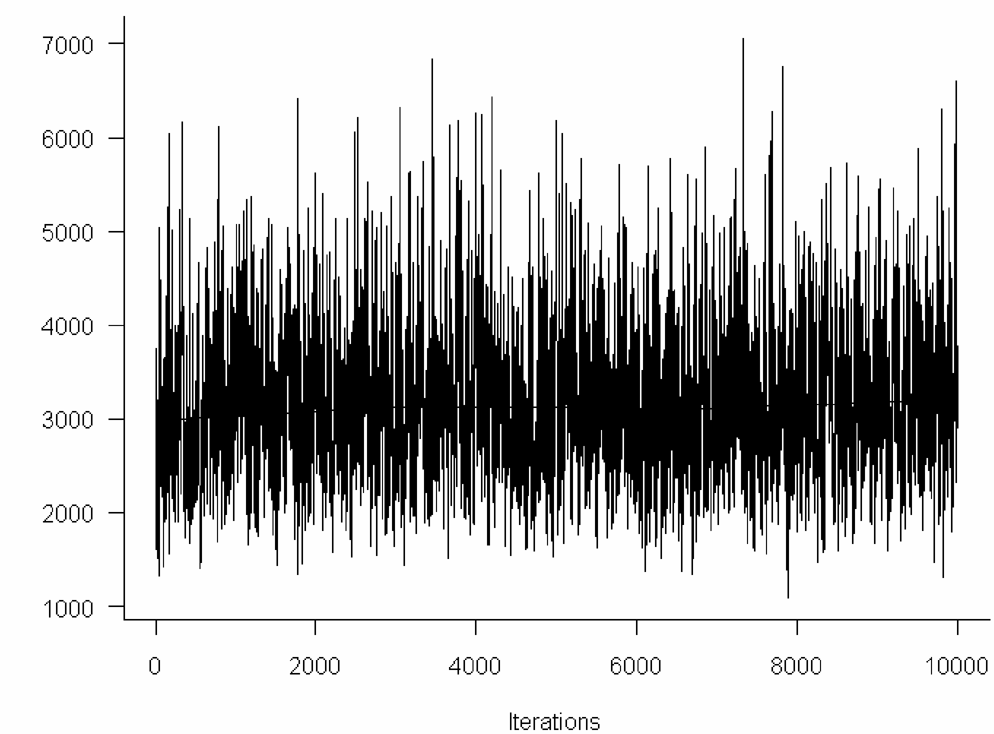

Figure 24, Trace plots from the MCMC analysis showing the sub-samples of estimated spawning biomass in 2007 for the west coast of Vancouver Island herring stock.

Abundance forecasts

The total and available estimated biomass is presented in Figure 44 in Appendix II. The difference between these lines indicates the size of the juvenile population that will not spawn in a given year. In all regions age 3 herring make up the majority of the available biomass, except in the Central Coast where the majority age class is a year older (Figure 45 in Appendix II). The predicted abundance in 2008 is calculated from the medians of the marginal posterior distributions for the forecast of age 4 and older biomass summed with the medians of the marginal posterior distributions for the forecasts of age 3 recruits for poor, average and good recruitment scenarios. The medians of the distributions are calculated from the sub-sample of 10000 from the MCMC chain. There are significant differences between the results presented here and those from HCAMv1 and these results are presented in Figure 25 and Figure 26.

Queen Charlotte Islands

For the Queen Charlotte Islands stock the 2007 spawning biomass and the 2008 4+ biomass both have a narrower posterior distributions in HCAMv2 than they do in HCAMv1.The median (or 50% percentile) of the posterior distribution for the estimate of 2007 spawning biomass is 7500 tonnes, this is lower than the estimate of 10000 tonnes from HCAMv1 (Table 1). This mean that the distribution of forecast biomass with poor recruitment will be just under 4000 tonnes and is lower than the 6900 tonnes predicted with HCAMv1. The predicted biologically allowable catch assuming poor recruitment is 0 (Table 1), the same as in HCAMv2.

Prince Rupert District

For the Prince Rupert District stock the posterior distributions of the 2007 spawning biomass and 2008 4+ biomass also have narrower posteriors in HCAMv2 compared to HCAMv1. The median posterior distribution for the estimate of 2007 spawning biomass is 16000 tonnes, which is lower than the HCAMv1 estimate of 18000 tonnes (Table 1). Average recruitment would mean that the forecast biomass would be 17000 tonnes, lower than the HCAMv1 estimate of 20000. The predicted biologically allowable catch assuming average recruitment is 3428 tonnes (Table 1), lower than the estimate of 4000 tonnes from HCAMv1.

Central Coast

For the Central Coast stock, however, HCAMv1 and HCAMv2 predictions of the posterior distributions for the 2007 spawning biomass and 2008 4+ biomass are quite similar. The median posterior distribution for the estimate of 2007 spawning biomass is 13000 tonnes, slightly larger than the 11000 predicted by HCAMv1 (Table 1). Poor recruitment results in a forecast biomass of 12000, again just slightly larger than the 11000 estimate from HCAMv1. The predicted biologically allowable catch assuming poor recruitment is identical at zero for both HCAMv1 and HCAMv2 (Table 1).

Strait of Georgia

Most significantly, the Strait of Georgia stock has narrower posterior distributions for the 2007 spawning biomass and 2008 4+ biomass. The median posterior distribution for the estimate of 2007 spawning biomass is 55000 tonnes, smaller than the 68000 estimate from HCAMv1 (Table 1). Poor recruitment results in a forecast biomass of 35000 almost half of the 69000 predicted in HCAM. The predicted biologically allowable catch differs significantly between HCAMv1 (13000) and HCAMv2 (7000) (Table 1). The large difference is due in part to the fact that the result presented for the Strait of Georgia was obtained at a local rather than global minima, i.e. the HCAMv1 result was incorrect. The HCAMv2 estimate of population size is also more consistent with what fishermen observed in the Strait of Georgia this year.

West Coast Vancouver Island

For the west coast of Vancouver Island stock, the posterior distribution is a little wider for the 2007 spawning biomass, but much narrower for the 2008 4+ biomass. The median posterior distribution for the estimate of 2007 spawning biomass is 3000 tonnes, larger than the 2100 tonnes predicted in HCAMv1 (Table 1). Poor recruitment results in a forecast biomass of 5000, much lower than the 12000 estimate produced in HCAMv1. The predicted biologically allowable catch is identical at zero for both HCAMv1 and HCAMv2 (Table 1).

Table 1, Marginal posterior estimates of spawning biomass in 2007, prediction of biomass of ages 4+ fish in 2008, forecast biomass for the poor, average and good recruitment scenarios, and available harvest for the poor, average, and good recruitment scenarios from HCAMv1 (top panel) and HCAMv2 (bottom panel). The red highlighted numbers indicate the predicted harvest for 2008 for the HCAMv1 and HCAMv2 models.

			Forecast Biomass			**Available Harvest**		
	2007 SB	**2008 4+**	**Poor**	**Avg**	**Good**	**Poor**	**Avg**	**Good**
HCAM v1								
QCI	9127	5978	6891	8869	15191	**0**	0	3038
PRD	18678	14074	15757	20071	29834	2815	**4014**	5967
CC	11129	8608	11124	15634	27397	**0**	0	5479
GS	68880	49200	67350	85484	104843	**13470**	17097	20969
WCVI	2144	6178	11690	19117	35417	**0**	317	7083
HCAM v2								
QCI	7504	2360	3986	6368	16118	**0**	0	3224
PRD	16061	10448	13384	17145	30749	1284	**3429**	6150
CC	13160	8477	12303	16438	27318	**0**	0	5464
GS	55178	23523	35765	46292	63695	**7153**	9258	12739
WCVI	3084	1049	4650	9191	18525	**0**	0	0

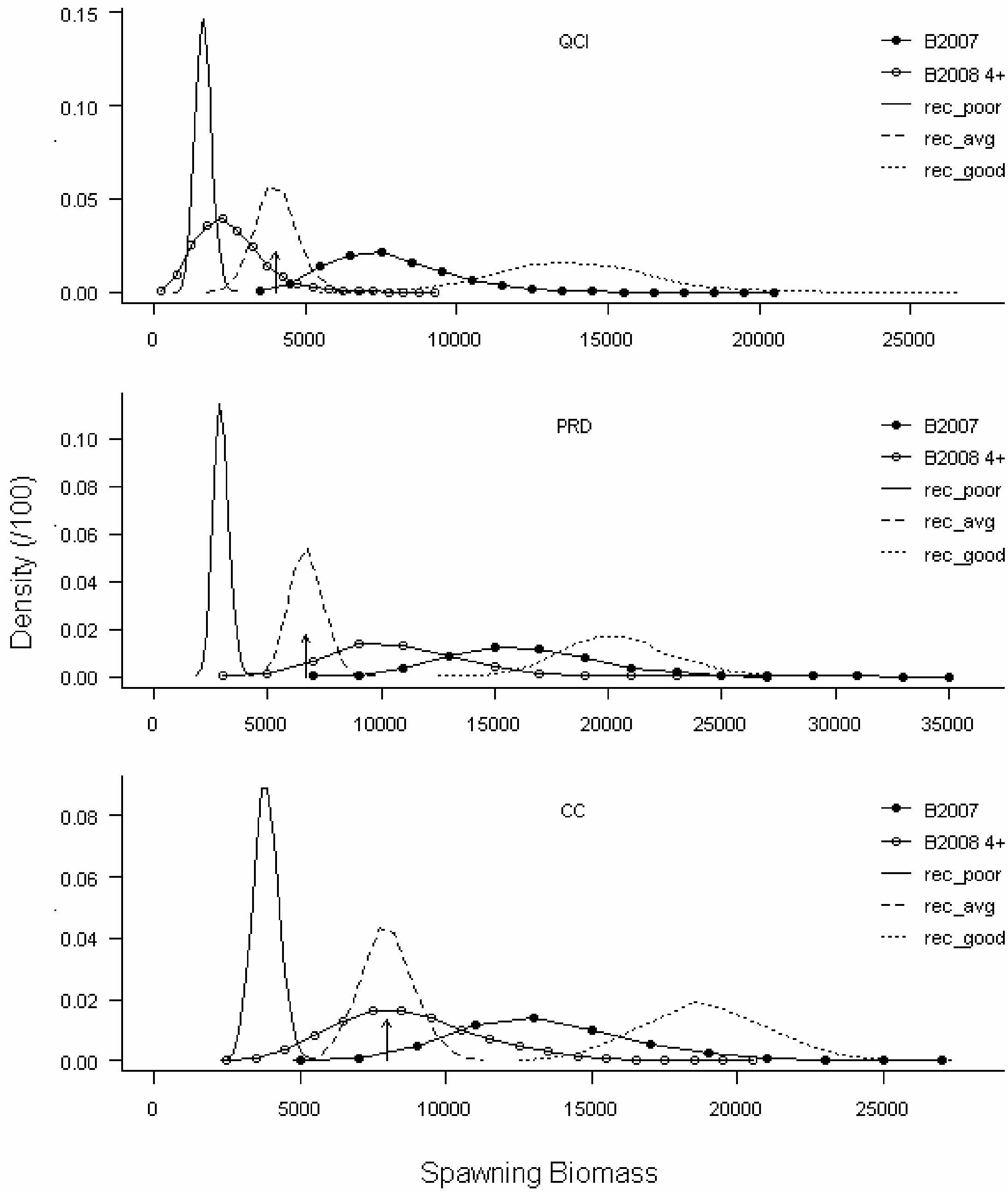

Figure 25, Estimated Markov chain Monte Carlo (MCMC) Bayesian profile likelihood distributions for spawning biomass in 2007 and the forecast pre-fishery biomass in 2008 for the QCI, PRD and CC stock assessment regions. Arrow represents the 50th percentile of the forecast assuming an average recruitment.

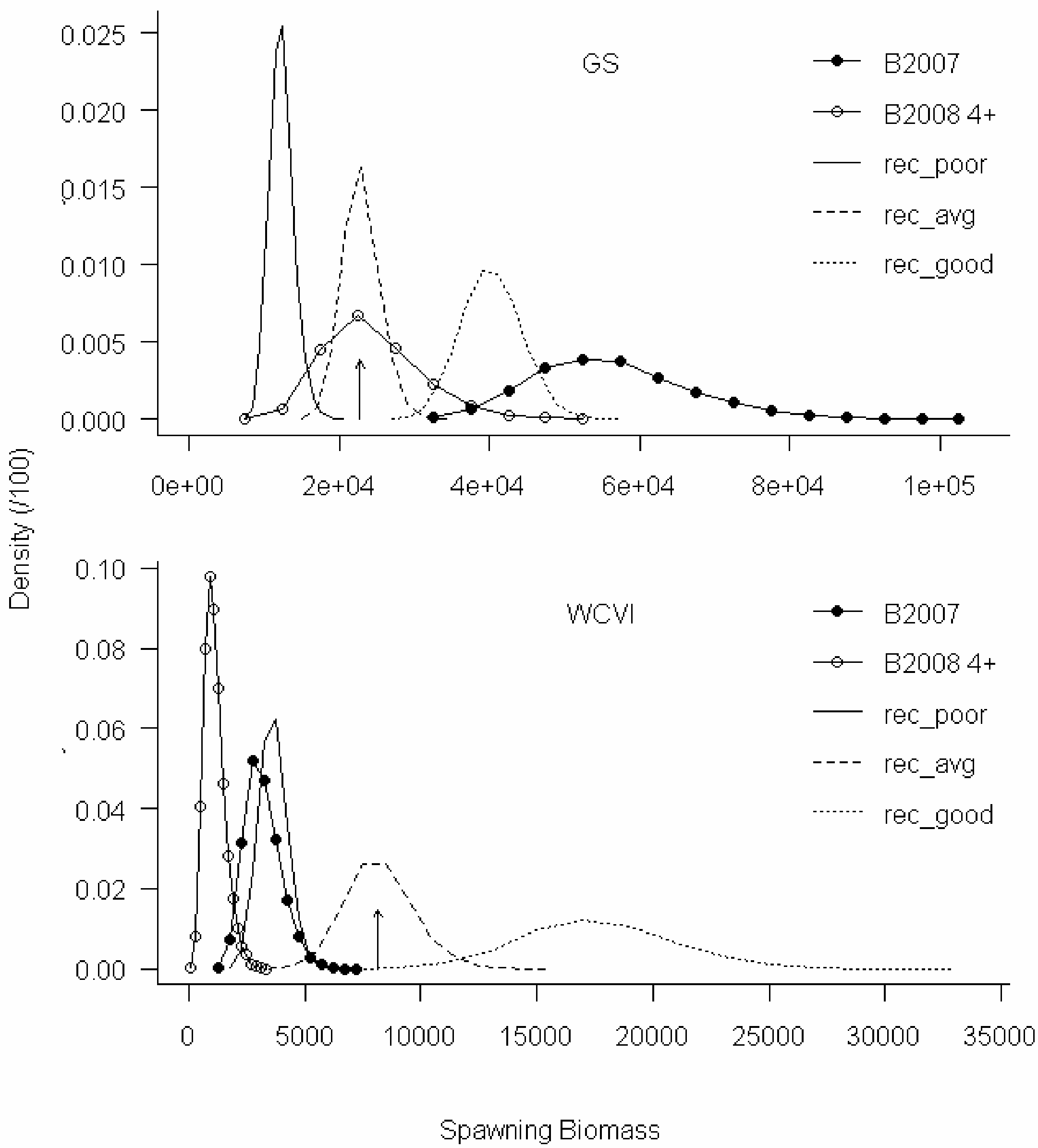

Figure 26, Estimated Markov chain Monte Carlo (MCMC) Bayesian profile likelihood distributions for spawning biomass in 2007 and the forecast pre-fishery biomass in 2008 for the GS and WCVI stock assessment regions. Arrow represents the 50th percentile of the forecast assuming an average recruitment.

Retrospective Analysis

A retrospective analysis was performed to determine the effect of additional data on model performance. This was done for the last 10 years, i.e., from 1998 – 2007. Spawning biomass results are presented in Figure 27 through Figure 31. To evaluate whether retrospective bias is present we use a summary statistic similar to that in Haist and Schweigert (2006). We compare the estimates of spawning stock biomass for year 1998 from the 1998 retrospective, 1999 from the 1999 retrospective, 2000 from the 2000 retrospective etc. to the spawning stock biomass estimates from the 2007 assessment for the years 1998-2006. This statistic illustrates how spawning stock biomass has changed from the estimate that is obtained in that year relative to the current year's assessment. In Table 2 we present these results along with the mean and absolute mean differences. If all "errors" are either positive or negative, this would indicate a persistent bias problem, i.e., retrospective bias. Table 2 indicates that there is no retrospective bias for any of the stocks and that the mean error is between -3.6 and 16.7 percent for the five stocks. For the HCAMv2 analyses the mean retrospective "error" is 9 percent, and the absolute mean error is 19.2 percent.

Table 2, Summary statistics for retrospective changes in stock spawning biomass estimates from HCAMv2 for the QCI, PRD, CC, GS and WCVI stocks.

	$100\frac{B_y^y - B_y^{2007}}{B_y^{2007}}$									
Stock	Mean	Absolute mean	1998	1999	2000	2001	2002	2003	2004	2005	2006
QCI	11.2	18.1	-9.7	10.3	17.0	89.0	-1.3	5.6	9.7	-4.0	-16.3
PRD	8.7	16.4	-13.3	22.8	17.5	31.0	-10.1	7.9	8.7	25.1	-10.9
CC	12.0	21.7	-22.8	-20.6	4.1	28.7	18.3	15.8	28.7	36.1	20.0
GS	-3.6	14.5	-11.4	-6.6	-27.8	-19.0	-16.2	3.8	12.3	23.5	9.4
WCVI	16.7	25.5	46.3	33.5	6.3	-22.1	-17.6	5.6	16.6	53.5	28.0
Total	9.0	19.2									

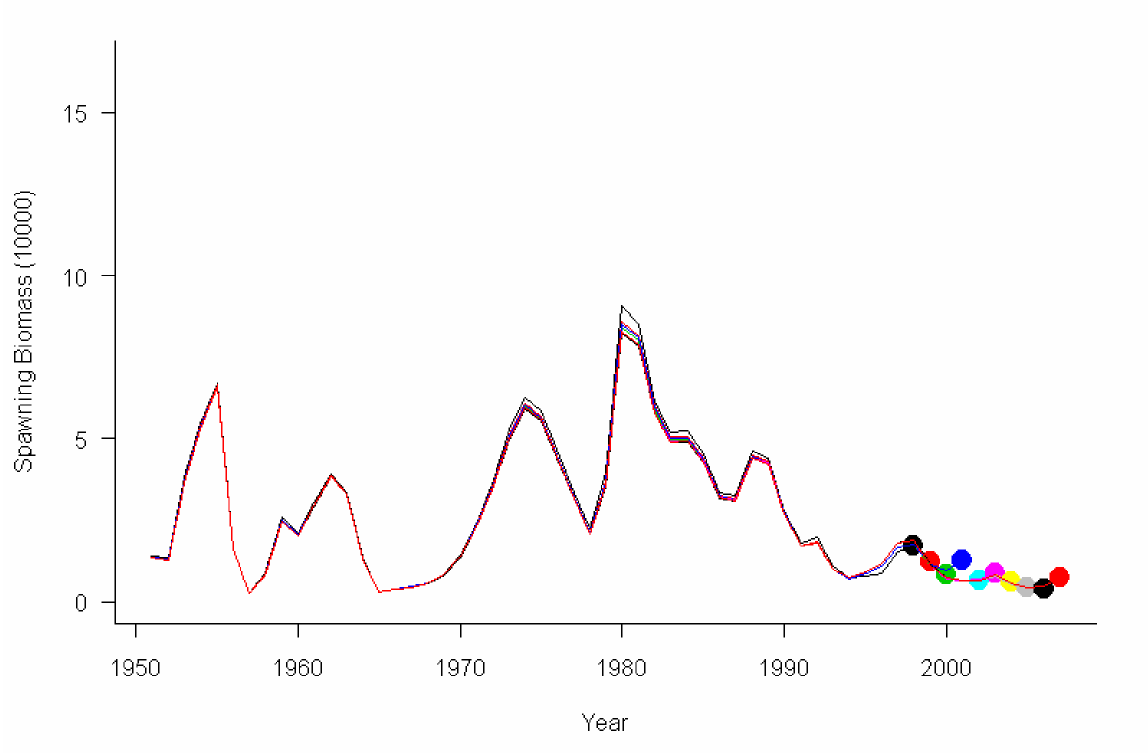

Figure 27. Retrospective bias patterns for 1998-2007 for the Queen Charlotte Islands.

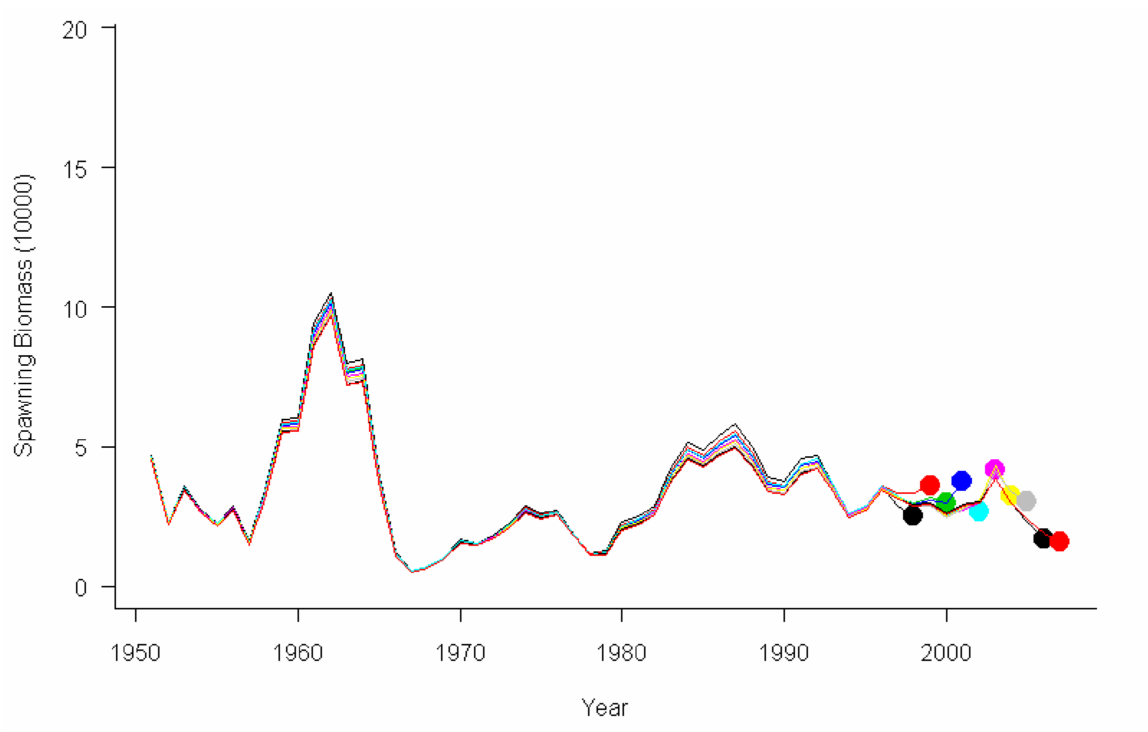

Figure 28. Retrospective bias patterns for 1998 – 2007 in the Prince Rupert District.

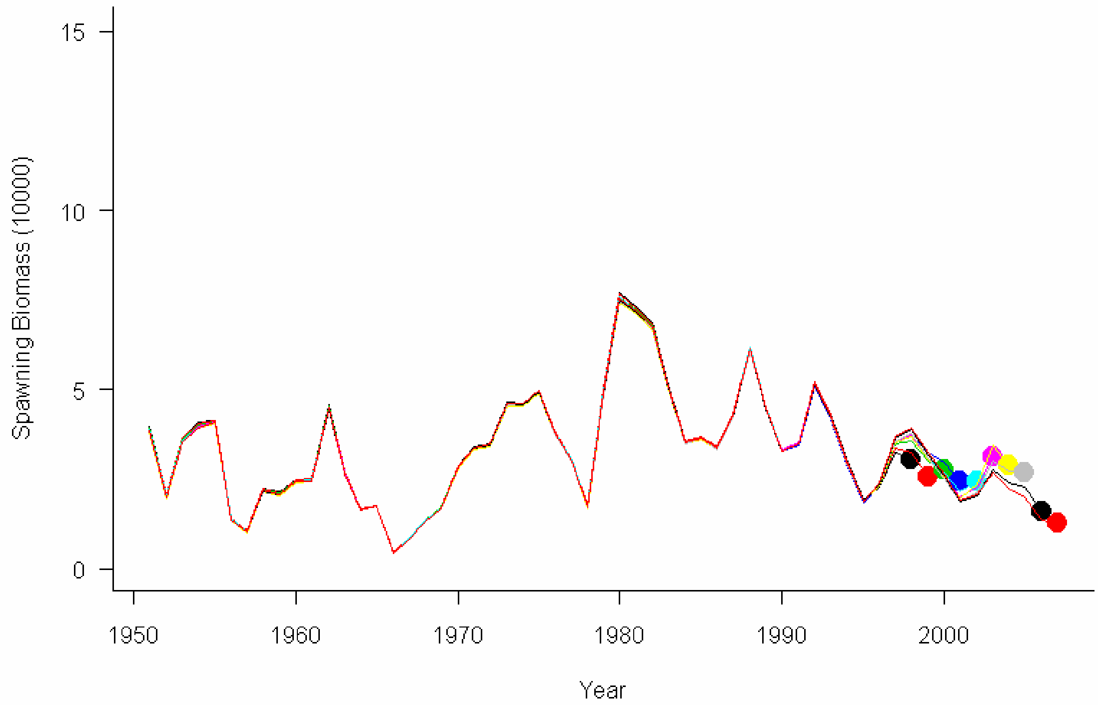

Figure 29. Retrospective bias patterns for 1998 - 2007 in the Central Coast.

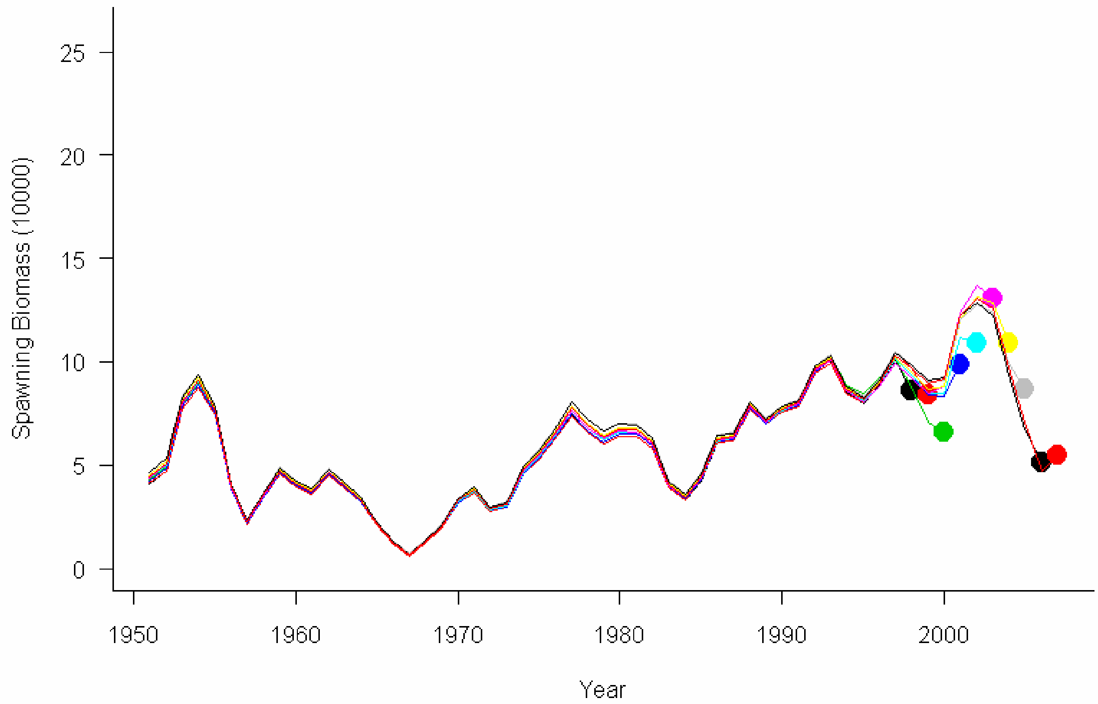

Figure 30. Retrospective bias patterns for 1998 - 2007 in the Strait of Georgia

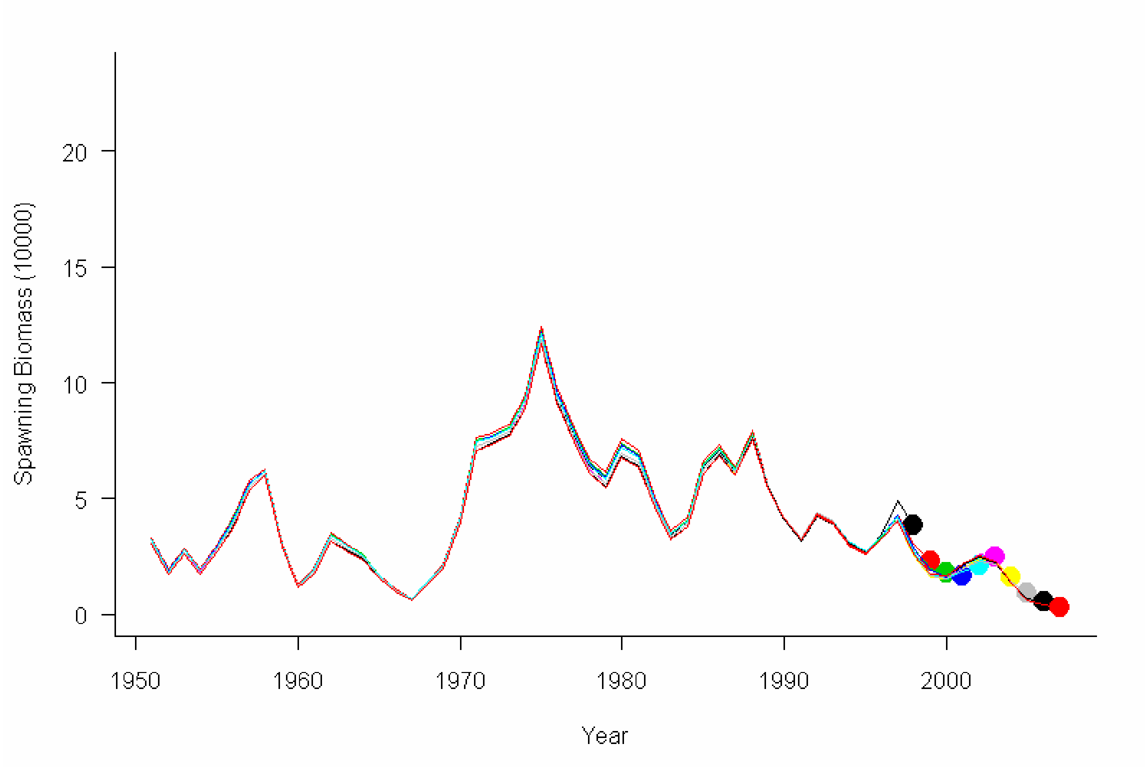

Figure 31. Retrospective bias patterns for 1998 - 2007 on the west coast of Vancouver Island

The quantity used to predict the available/mature biomass for the upcoming year is the biomass of available/mature age-3 fish at the beginning of period 2 (it is assumed that only natural mortality occurs during period 1) and the available/mature biomass of age 4 and older fish. Figure 32 through Figure 36 depict four datasets that are each either a prediction or an estimate of the biomass of available/mature age-3 recruits calculated in 4 different ways. Series 1 is the forecast recruitment biomass for year t+1 from the retrospective model ending in year t (whether poor, average or good recruitment is used is determined by what was actually assumed in the assessment for year t). Series 2 represents the predicted number of age 3 recruits for year t+1 from the retrospective model ending in year t calculated by aging the age 2 recruits from year t. Series 3 shows the recruitment predicted for year t+1 as was actually estimated in the assessment performed in year t (these estimates are from previous versions of assessment models rather than HCAMv2). Series 4 are the 'best' estimates, i.e., the predicted age 3 recruits from the 2007 stock assessment (HCAMv2) for 1998-2007. These values are all plotted for comparison. For example, the differences between series 1 and 2 give an indication of whether predicting recruits in year t+1 using the (poor, average, good) recruitment method for recruits up until year t is comparable to calculating age-3 recruits in year t+1 from predicted age 2 recruits in year t.

For all stocks except the Strait of Georgia stock the series 3 estimate is generally slightly lower or equal to the three other indices for 1998-2004 (and later for some of the stocks). However, there is no evidence of consistent bias in the 1998-2007 assessment results (that were produced using HCAMv1 and earlier models) relative to the HCAMv2 predictions.

For all series except the CC stock, series 1 and 2 are comparable, with no persistent trends in bias. This means that calculating age-3 recruits in year t+1 from the assessment in year t is comparable to predicting next year's recruitment using the poor, average, good recruitment formulations. For the CC stock, series 2, the number of age 3 recruits in year t+1 calculated from age 2 recruits in year t are smaller (except in 2003 and 2008 where they are the same) than the series 1 estimates of age 3 recruits in year t+1 from the (poor, average, good) formulations. This indicates that perhaps mortality of this age-class is lower than expected. For the QCI, CC, SG and WCVI stocks, series 2 outperforms series 1 in terms of bias (i.e., the mean difference (over 1999-2007) between series 2 (or series 1) and series 4, which are the 'best' estimates). For all five stocks, series 2 outperforms series 1 in terms of precision (i.e., the root mean squared error between series 2 (or series 1) and series 4, which are the 'best' estimates). This indicates that recruitment forecasting using age-2 fish outperforms the poor, average, good recruitment approach.

Table 3 illustrates the difference between predicting age 3 recruitment in 2008 1) using the poor, average, good parameterization (method 1 in Table 3) and 2) from the estimate of the number of age 2 recruits in 2007 subject to natural mortality (method 2 in Table 3) for the 2007 HCAMv2 assessment model. The 2008 estimates of age 3 recruitment are based on poor recruitment (i.e., calculated as the mean of the lowest third of the estimates of historic numbers of age 3 recruits) for all stocks except PRD for which the average recruitment level was used (i.e., calculated as the mean of the middle third of the estimates of historic numbers of age 3 recruits). The two methods are comparable for PRD and CC, while method 1 results in predictions of smaller stock forecasts for the QCI and GS stocks and a larger forecast for the WCVI stock. Therefore we can conclude that for the QCI and GS stocks fewer age 2 recruits from 2007 are expected to survive to become age 3 recruits in 2008 than we would expect to see if the only process determining that survival was natural mortality. Similarly, the reverse would hold for the WCVI stock.

Table 3, Age 3 recruitment biomass estimated for 2008 in HCAMv2 using poor, average and good recruitment (method 1) and age 3 recruitment biomass estimated by predicting age 3 recruits in 2008 from age 2 recruits in 2007 subject to natural mortality processes (method 2).

	QCI	**PRD**	**CC**	**GS**	**WCVI**
HCAMv2 method 1	1626 (poor recruitment)	6697 (average recruitment)	3826 (poor recruitment)	12242 (poor recruitment)	3601 (poor recruitment)
HCAMv2 method 2	3898	6273	3111	36725	1312

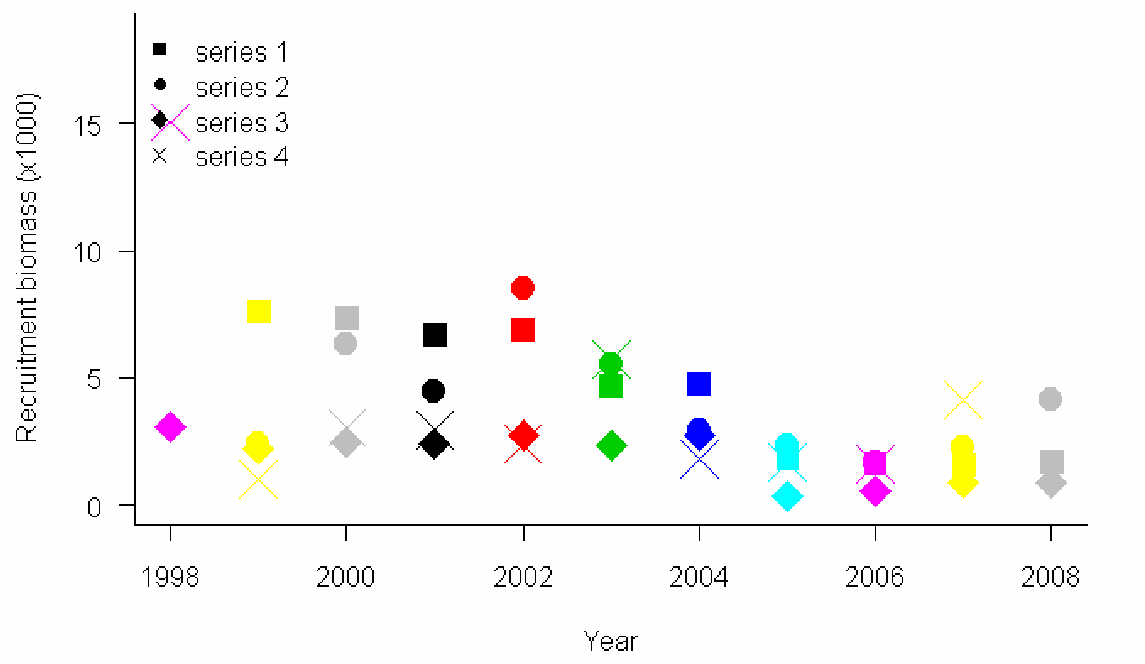

Figure 32, Recruitment biomass versus year for the QCI stock determined using series 1 (forecast recruitment biomass for year t+1 for the retrospective model ending in year t), series 2 (predicted number of age 3 recruits for year t+1 for the retrospective model ending in year t calculated by aging the age 2 recruits from year t), series 3 (recruitment estimates for year t determined from the assessment performed in year t) and series 4 ('best' estimates, i.e., the predicted age 3 recruits from HCAMv2 for 1998-2007).

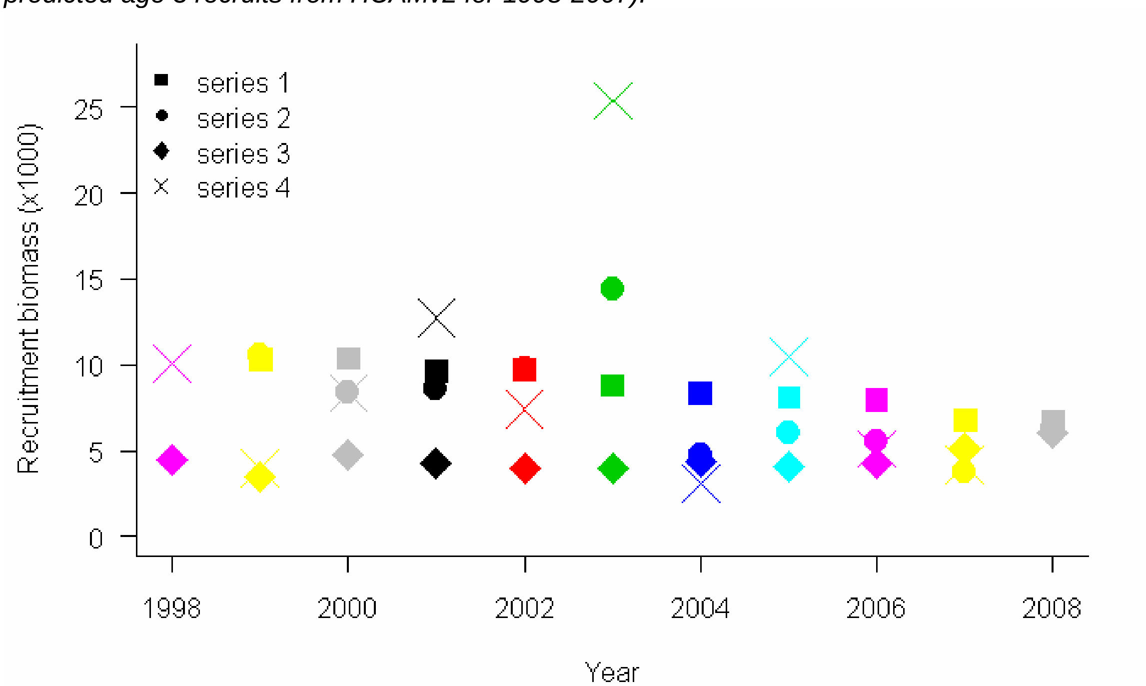

Figure 33, Recruitment biomass versus year for the Prince Rupert District stock determined using series 1 (forecast recruitment biomass for year t+1 for the retrospective model ending in year t), series 2 (predicted number of age 3 recruits for year t+1 for the retrospective model ending in year t calculated by aging the age 2 recruits from year t), series 3 (recruitment estimates for year t determined from the assessment performed in year t) and series 4 ('best' estimates, i.e., the predicted age 3 recruits from HCAMv2 for 1998-2007).

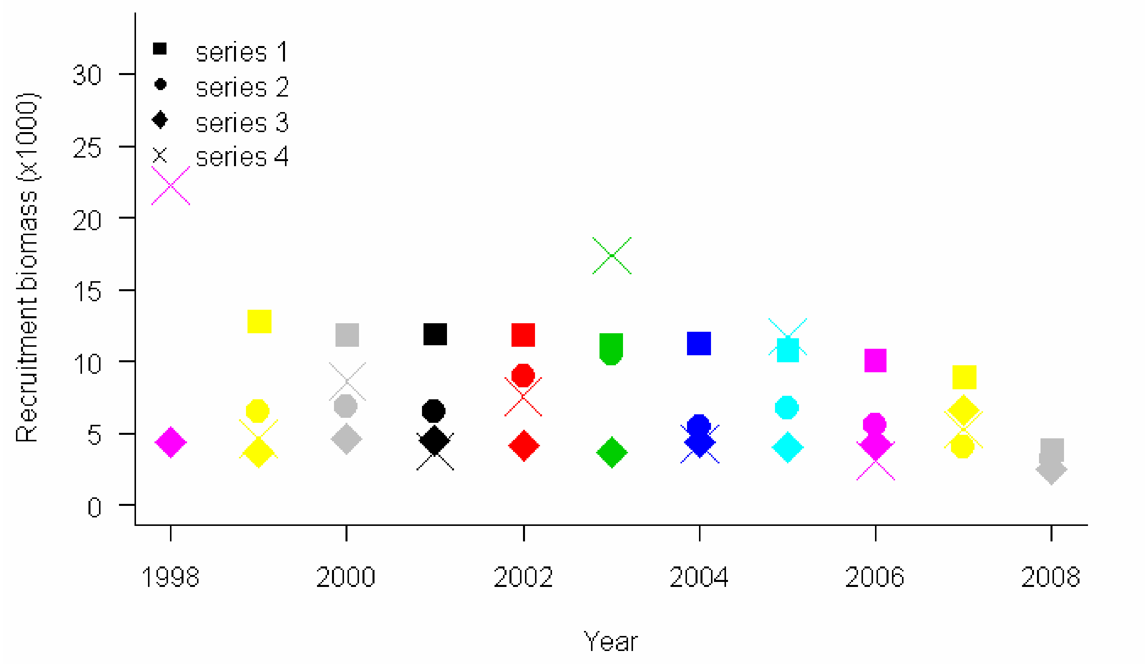

Figure 34, Recruitment biomass versus year for the Central Coast stock determined using series 1 (forecast recruitment biomass for year t+1 for the retrospective model ending in year t), series 2 (predicted number of age 3 recruits for year t+1 for the retrospective model ending in year t calculated by aging the age 2 recruits from year t), series 3 (recruitment estimates for year t determined from the assessment performed in year t) and series 4 ('best' estimates, i.e., the predicted age 3 recruits from HCAMv2 for 1998-2007).

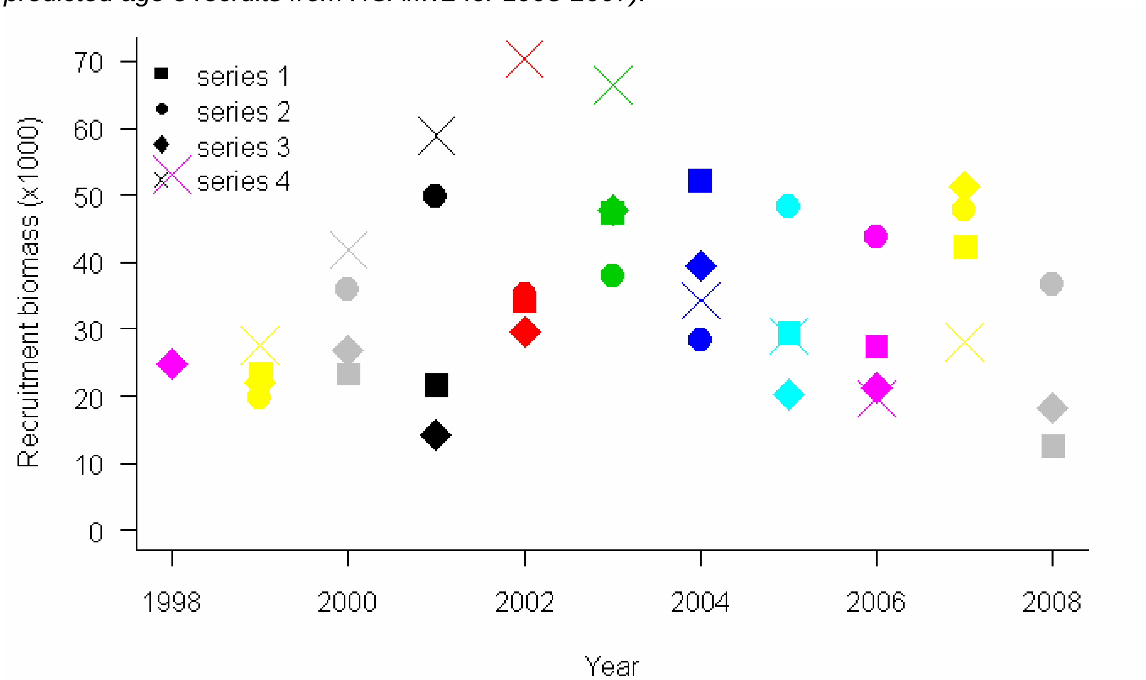

Figure 35, Recruitment biomass versus year for the Strait of Georgia stock determined using series 1 (forecast recruitment biomass for year t+1 for the retrospective model ending in year t), series 2 (predicted number of age 3 recruits for year t+1 for the retrospective model ending in year t calculated by aging the age 2 recruits from year t), series 3 (recruitment estimates for year t determined from the assessment performed in year t) and series 4 ('best' estimates, i.e., the predicted age 3 recruits from HCAMv2 for 1998-2007).

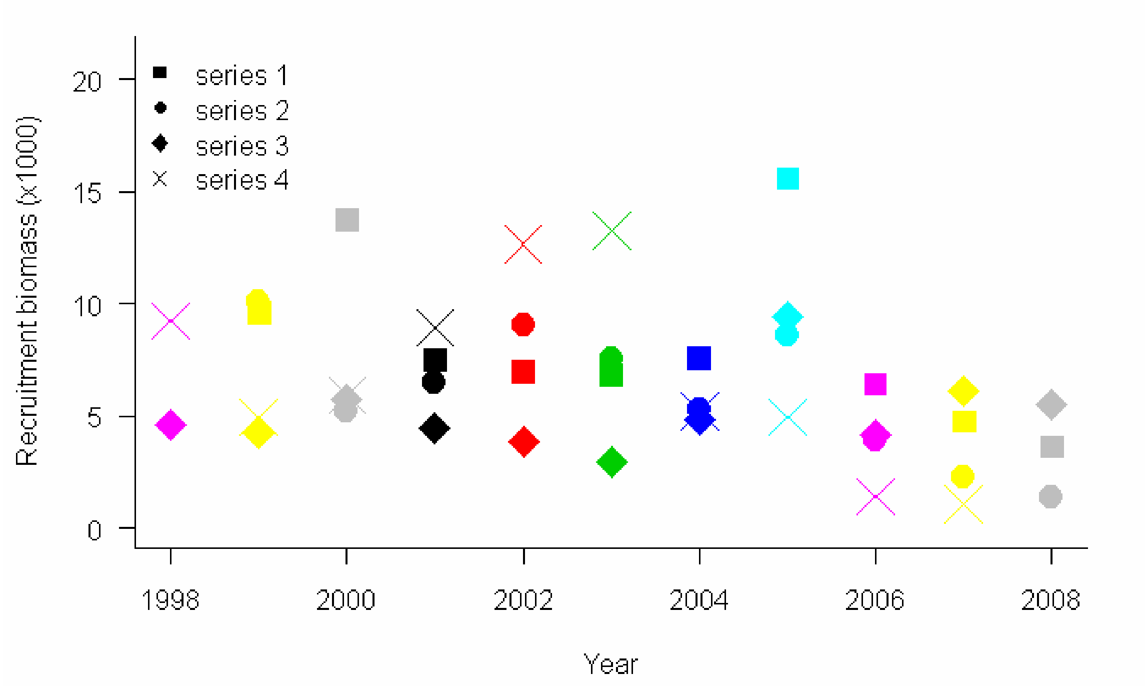

Figure 36, Recruitment biomass versus year for the west coast of Vancouver Island stock determined using series 1 (forecast recruitment biomass for year t+1 for the retrospective model ending in year t), series 2 (predicted number of age 3 recruits for year t+1 for the retrospective model ending in year t calculated by aging the age 2 recruits from year t), series 3 (recruitment estimates for year t determined from the assessment performed in year t) and series 4 ('best' estimates, i.e., the predicted age 3 recruits from HCAMv2 for 1998-2007).

Unfished Biomass

The estimate of the unfished biomass (B_o) that was calculated in 1996/97 to determine the current fishery cutoff levels (which are defined as 25% of B_o) was compared to the estimate of unfished biomass from the HCAMv1 and HCAMv2 models (Table 4). Figure 37 shows the HCAMv2 posterior distributions of B_o for the five stocks from which the medians in Table 4 are calculated. For PRD and GS, the estimates generated by HCAMv2 are significantly larger than those from HCAMv1 and the values used for the current cutoff level. If one accepts the HCAMv2 estimates for these two stocks, this would indicate that if these stocks recovered fully, the potential yield could be much greater than is currently assumed.

Table 4, Estimates of unfished biomass (tonnes) from 1996/97 (when the current cutoff levels were establised) and from the HCAMv1 and HCAMv2 models.

	QCI	PRD	CC	GS	WCVI
B_o estimates from 1996/97	42,800	48,400	70,400	84,800	75,200
B_o from HCAMv1	10,417	36,852	79,475	77,645	71,193
B_o from HCAMv2	26,770	69,394	57,424	156,801	64,946

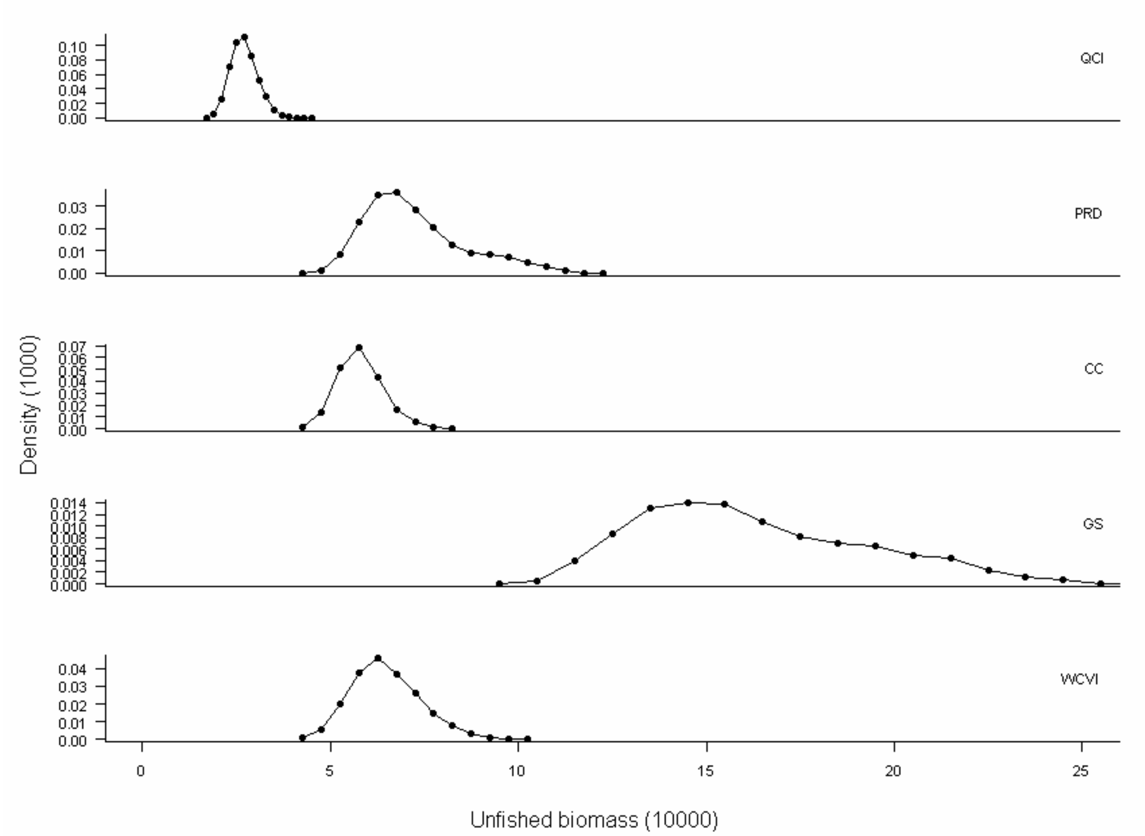

Figure 37, Estimated Markov chain Monte Carlo (MCMC) Bayesian profile likelihood distributions for unfished biomass (Bo) for the QCI, PRD, CC, GS and WCVI stock assessment regions.

Figure 38 presents the trends in estimates of the size of the unfished biomass for the retrospective analysis. The size of the unfished stock is increasing for the Strait of Georgia, but decreasing slightly for the remaining four stocks. Sharply declining estimates of B_o is a potential indicator that a stock could face detrimental consequences as the fishing pressure exerted on it is exacerbated as we scale back our expectations of the recovery potential. However, this does not seem to be a concern in the HCAMv2 implementation of HCAM.

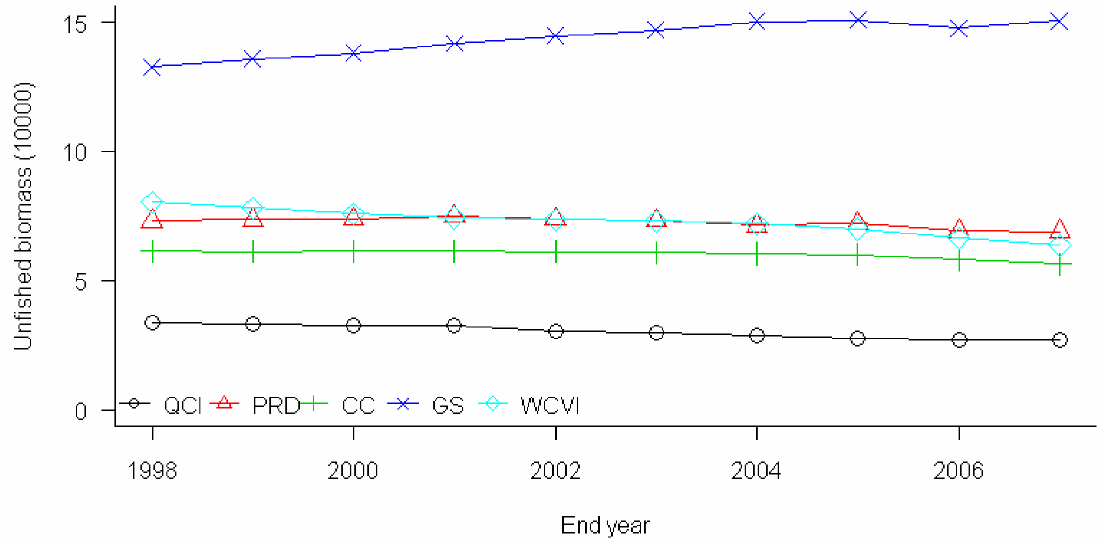

Figure 38, Retrospective estimates of unfished biomass (Bo) for the QCI, PRD, CC, GS and WCVI herring stocks.

Summary and Conclusions

A revised implementation of the herring catch-at-age model (HCAMv2) is presented and compared to HCAMv1. The first implementation of HCAM was used in the 2006 and 2007 BC herring stock assessments. In particular, HCAMv2 differs from HCAMv1 as follows:

1) **Fishing mortality** parameters are estimated in HCAMv2 and calculated analytically in HCAMv1.
2) **Maturity/availability** parameters are assumed known and time invariant in HCAMv2, but were calculated as free parameters and assumed to vary over time in HCAMv1.
3) **Population initialization**, in HCAMv2 we assume that the stock is in a fished state in 1951 and accordingly initialize the population age structure by starting the model in 1946. In HCAMv1 the population in 1951 was estimated as free parameters.
4) The **natural mortality** accredited to each fishery period (winter, seine roe, gillnet roe) differ between HCAMv2 (0.9, 0.05, 0.05) and HCAMv1 (0.45, 0.45, 0.1).
5) **Selectivity** parameters are estimated using a logistic equation for the winter and seine roe fisheries (periods 1 and 2) in HCAMv2 whereas they are fixed at 1 for HCAMv1.
6) **Spawning proportionality constant** (survey scaling) for 1951 – 1987 is calculated using the conditional maximum likelihood estimate of the differences between observed and predicted spawning biomass in HCAMv2. In the prior implementation, HCAMv1, this quantity was estimated as a free parameter.
7) The **variance of recruitment deviations** was estimated as a free parameter is HCAMv1, but is fixed in HCAMv2.

8) In HCAMv2 fishing mortality parameters are estimated, and the difference between the observed and predicted catch is minimized as part of the **likelihood component** in HCAMv2.
9) The **priors assumed** in HCAMv2 differ mainly for the steepness parameter (assumed to have a mean of 0.67 in HCAMv2 and 0.5 in HCAMv1. An additional prior occurs in HCAMv2 for the initial fishing mortality rate in HCAMv2 (log-normal with log-mean 1.15 and log-standard-deviation of 0.66), while other priors from HCAMv1 do not carry over to HCAMv2 as they are no longer estimated (e.g., deviations in availability/maturity and variance of recruitment deviations).

The HCAMv2 implementation of HCAM is an improvement over the HCAMv1 formulation for a number of reasons. Most importantly, model numerical stability has been significantly improved by estimating the fishing mortality parameters rather than calculating analytical solutions. The issue of 'getting stuck' at a local minimum (for the GS stock in the 2007 assessment) appears to be eliminated in HCAMv2. Further, retrospective patterns in HCAMv2 do not indicate substantial bias (Table 2) and are very similar to the results from HCAMv1. The standardization of availability/maturity assuming that 90% of age-3 herring are sexually mature appears more consistent with biological observation and estimation of selectivity parameters for the winter and seine roe fisheries in HCAMv2 improves realism as recruiting fish may show delayed inshore migration in the northern areas of BC. Additionally, we believe that the lower estimates of natural mortality in HCAMv2 are biologically more consistent with the observed lifespan for herring.

Finally, further work is recommended on a full scale management strategy evaluation framework. This would prove useful in examining the stability of this model, and determining the best model to deal with the uncertainties inherent in this data set as well as questions of the relative importance of the different input data sets.

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Appendix I – Differences between HCAMv1 and HCAMv2

Table 5, Model parameter descriptions

Indices	
y	Year
syr	Model start year
nyr	Model end year
a	Age
p	Fishery period
Derived parameters	
$N'_{y,p,a}$	The number of fish of age a at the beginning of fishing period p of year y that are available to the fishery/mature.
$F_{y,p,a}$	The instantaneous fishing mortality rate for fish of age a during fishing period p of year y
$s_{y,p,a}$	Selectivity at age a during fishing period p of year y
$M_{y,p,a}$	The instantaneous natural mortality rate for fish age a during fishing period p of year y
$\hat{C}_{y,p,a}$	Fitted catch at age a during fishing period p of year y
S_y	Spawning stock biomass in year y
$M_{y,p,a}$	The instantaneous natural mortality rate for fish of age a during fishing period p and year y
$\dot{M}_{y,a}$	The total natural mortality rate for fish of age a during year y
Parameters estimated through minimization	
v_k	Availability ogive parameters
d_y^v	Annual deviations from average availability
$\eta_{syr,a}$	Parameters for the number of fish of age a in the first year syr
$F_{initial}$	Fishing mortality rate used to initialize the population
d_y^r	Recruitment deviation in year y
ψ_1	Average natural mortality rate
d_y^M	Natural mortality deviation in year y
a_h	age at 50% vulnerability and
Δ_a	Standard deviation in a_h
q	The spawn index proportionality rates (catchability) parameter for the spawn-survey prior to 1988.
σ^2	Variance of recruitment deviations

Table 6, Equations of model components differing between the HCAMv1 and HCAMv2 model implementations.

<table>
<tr><td>Parameter</td><td>HCAMv1</td><td>HCAMv2</td></tr>
<tr><td>Fishing mortality</td><td>Not estimated:
The instantaneous (Baranov) fishing mortality equation is:
$$\hat{C}_{y,p,a} = \frac{F_{y,p,a}}{F_{y,p,a} + M_{y,p,a}}(1 - \exp(-F_{y,p,a} - M_{y,p,a})N'_{y,p,a})$$
where $F_{y,p,a} = s_{y,p,a}F''_{y,p}$ and s is selectivity and F'' is the fully selected fishing mortality rates which are calculated iteratively using the Newton-Raphson algorithm, and thus not estimated.</td><td>The discrete catch equation is:
$$\hat{C}_{y,p,a} = \exp(-M_{y,p,a})s_{y,p,a}F'_{y,p}N'_{y,p,a}$$
Where $F_{y,p,a} = -\ln(s_{y,p,a}F''_{y,p})$ and F' is the fishing mortality which is estimated as a free model parameter. Note that this implementation assumes the potential for errors in the catch data.</td></tr>
<tr><td>Availability</td><td>Parameterized as free-age:
$$\lambda'_{y,a} = \begin{cases} 0 & a < l_{\min} \\ v_a & l_{\min} < a < l_{\max} \\ 1 & a > l_{\max} \end{cases}$$
Where $l_{\min}$ is the first age to estimate availability for and $l_{\max}$ is the last age to estimate availability for.

Deviations are applied using odds-ratios to ensure the resultant parameter values remain between 0 and 1:
$$\lambda''_{y,a} = \frac{\exp(d_y^v)\lambda'_{y,a}}{1 - \lambda'_{y,a}}$$
$$\lambda_{y,a} = \frac{\lambda''_{y,a}}{1 + \lambda''_{y,a}}$$</td><td>Not estimated:
$$\lambda_{y,a} = \begin{cases} 0.25 & a = 2 \\ 0.9 & a = 3 \\ 1 & a > 3 \end{cases}$$</td></tr>
</table>

Population initialization	Initialization with free parameters: $N_{syr,a} = \eta_a$	Initializing age-structure: First calculate the relative proportion of fish in the different age groups, relN. Then calculate N in syrR-1 (syr-9) and then manually age the fish in syrR as no mortality component is applied here, rather it is applied in the end of the year: $relN_a = \begin{cases} \exp(-\overline{M}_a) & a = 2 \\ relN_{a-1}\exp(-\overline{M}_a) & a > 2 \end{cases}$ $N_{syrR-1,a} = Ro\ relN_a$ $N_{syrR,a} = N_{syrR-1,a}$ $N_{syrR,a} = \begin{cases} N_{syrR,a} + N_{syrR-1,a-1} & a = 10 \\ N_{syrR,a-1} & 10 > a > 2 \\ \frac{\alpha S_{syrR-1}}{\beta + S_{syrR-1}}\exp(d^r - 0.5\sigma^2) & a = 2 \end{cases}$ The numbers in year syrR<yr<syr are then calculated as follows: $N_{y+1} = N_y \lambda_{syr} \exp(-M_{syr} - F_{initial}) +$ $N_y(1-\lambda_{syr})\exp(-M_{syr})$ And the population is again manually aged for the next year: $N_{y+1,a} = \begin{cases} N_{y+1,a} + N_{y+1,a-1} & a = 10 \\ N_{y+1,a-1} & 10 < a < 2 \\ \frac{\alpha S_{y-1}}{\beta + S_{y-1}}\exp(d^r_{y+1} - 2\sigma^2) & a = 2 \end{cases}$

Natural mortality	Natural mortality is apportioned across the fishing periods based on user specified mortality fractions: $M_{y,p,a} = \begin{cases} 0.45\dot{M}_{y,a} & p=1 \\ 0.45\dot{M}_{y,a} & p=2 \\ 0.10\dot{M}_{y,a} & p=3 \end{cases}$ $\dot{M}_{y,a} = \begin{cases} \psi_1 & yr = syr \\ \dot{M}_{y-1,a}\exp(d_y^M) & syr < yr \le nyr \end{cases}$	Natural mortality is apportioned across the fishing periods based on user specified mortality fractions: $M_{y,p,a} = \begin{cases} 0.90\dot{M}_{y,a} & p=1 \\ 0.05\dot{M}_{y,a} & p=2 \\ 0.05\dot{M}_{y,a} & p=3 \end{cases}$ $\dot{M}_{y,a} = \begin{cases} \psi_1 & yr = syr \\ \dot{M}_{y-1,a}\exp(d_y^M) & syr < yr \le nyr \end{cases}$
Selectivity	Period 1 and 2: $s_{y,p,a} = 1$ for all years y and age a fish in periods 1 (the winter fishery) and 2 (the seine roe fishery) Period 3: Age-dependent selectivity is modeled based on a weight-based logistic equation: $s_{y,p,a} = (1+\exp(-\Delta_w - w_h * w_{y,a}^g))^{-1}$ Where Δ_h and w_h are the estimated selectivity ogive parameters and $w_{y,a}$ is the geometric mean weight of age a fish in year y in the gillnet catch.	Period 1 and 2: Age-dependent selectivity is modeled after the logistic equation: $s_{y,p,a} = (1+\exp(-\Delta_a(a-a_h)))^{-1}$ Period 3: Age-dependent selectivity is modeled based on a weight-based logistic equation: $s_{y,p,a} = (1+\exp(-\Delta_w - w_h * w_{y,a}^g))^{-1}$ Where Δ_h and w_h are the estimated selectivity ogive parameters and $w_{y,a}$ is the geometric mean weight of age a fish in year y in the gillnet catch.
Spawn index proportionality (survey scaling)	Estimated as a free parameter	Not estimated: Calculated using the conditional maximum likelihood estimate. $q' = \exp(mean(\log(spawn\_obs_{1951-1987}) - \log(S_{1951-1987})))$ Where spawn_obs is the observed spawning-index.
Variance of recruitment deviations	Estimated as a free parameter	Not estimated: σ^2 fixed at 0.6 (for GS, CC) and 0.8 (for QCI, PRD, WCVI).

Table 7, Model priors

Parameter	HCAMv1	HCAMv2
Steepness	$p(h) \sim normal(0.5, 0.25)$	$p(h) \sim \log normal(0.67, 0.17)$
Average natural mortality	$p(\psi_1) \sim normal(0.45, 0.2)$	$p(\psi_1) \sim normal(0.45, 0.2)$
Initial fishing mortality	None	$p(F_{initial}) \sim \log normal(0.317, 0.6633)$
Natural mortality residuals	$p(d_y^m) \sim \sum_{y=syr+1}^{nyr} \frac{d_y^{m\,2}}{2*0.1^2}$	$p(d_y^m) \sim \sum_{y=syr+1}^{nyr} \frac{d_y^{m\,2}}{2*0.1^2}$
Recruitment residuals	$p(d_y^r) \sim (nyr - syr)\ln(\sigma) + \sum_{y=syr+1}^{nyr} \ln \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{d_y^{r\,2}}{2*\sigma^2}}$ NB: σ is estimated	$p(d_y^r) \sim \sum_{y=syr+1}^{nyr} \ln \frac{d_y^{r\,2}}{2*\sigma^2}$ NB: σ is fixed at 0.6 for CC and GS and 0.8 for QCI, PRD, and WCVI
Availability residuals	$p(d_y^v) \sim \frac{d_y^{v\,2}}{2*0.3^2}$	$p(d_y^v) \sim \ln \frac{d_y^{v\,2}}{2*0.1^2}$
Recruitment residual variance	$p(\sigma) = normal(0.6, 0.2)$	None
Selectivity deviations	$p(d_y^s) \sim \frac{d_y^{s\,2}}{2*0.3^2}$	None

Appendix II – Additional figures

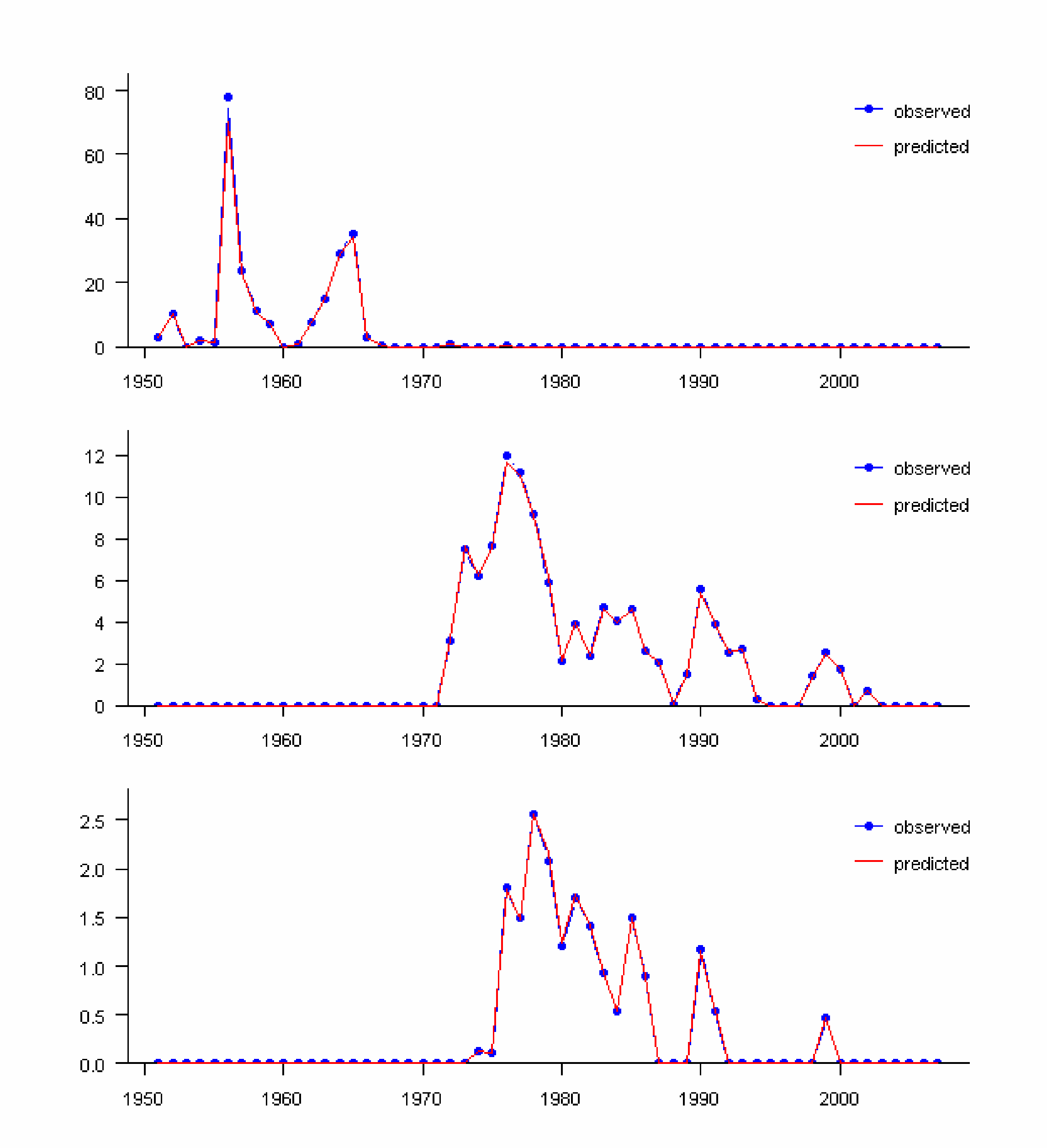

Figure 39, Observed and predicted catch in QCI for periods 1 - 3 (top to bottom), i.e., the winter, seine roe and gillnet roe fisheries.

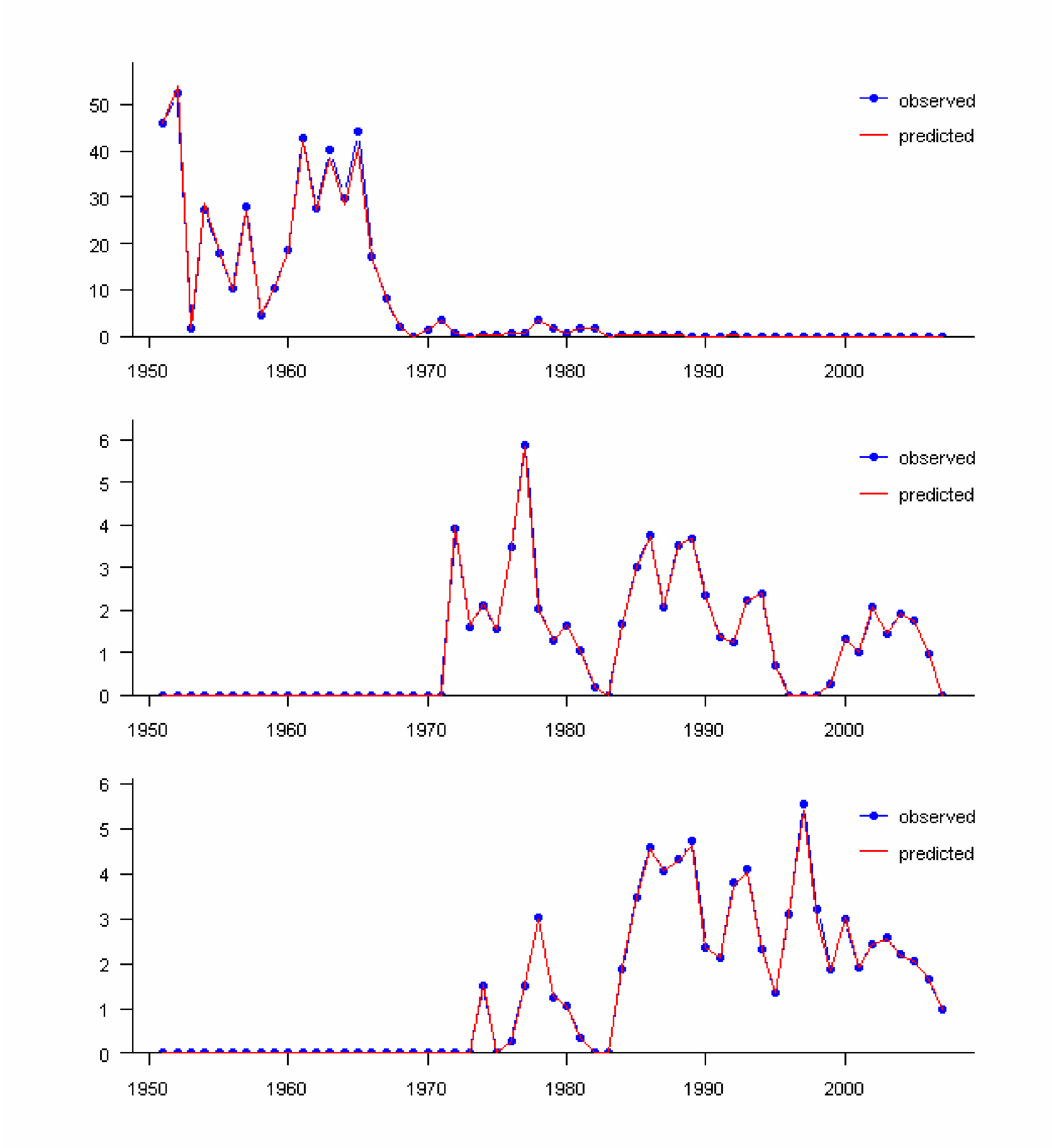

Figure 40, Observed and predicted catch in PRD for periods 1 - 3 (top to bottom), i.e., the winter, seine roe and gillnet roe fisheries.

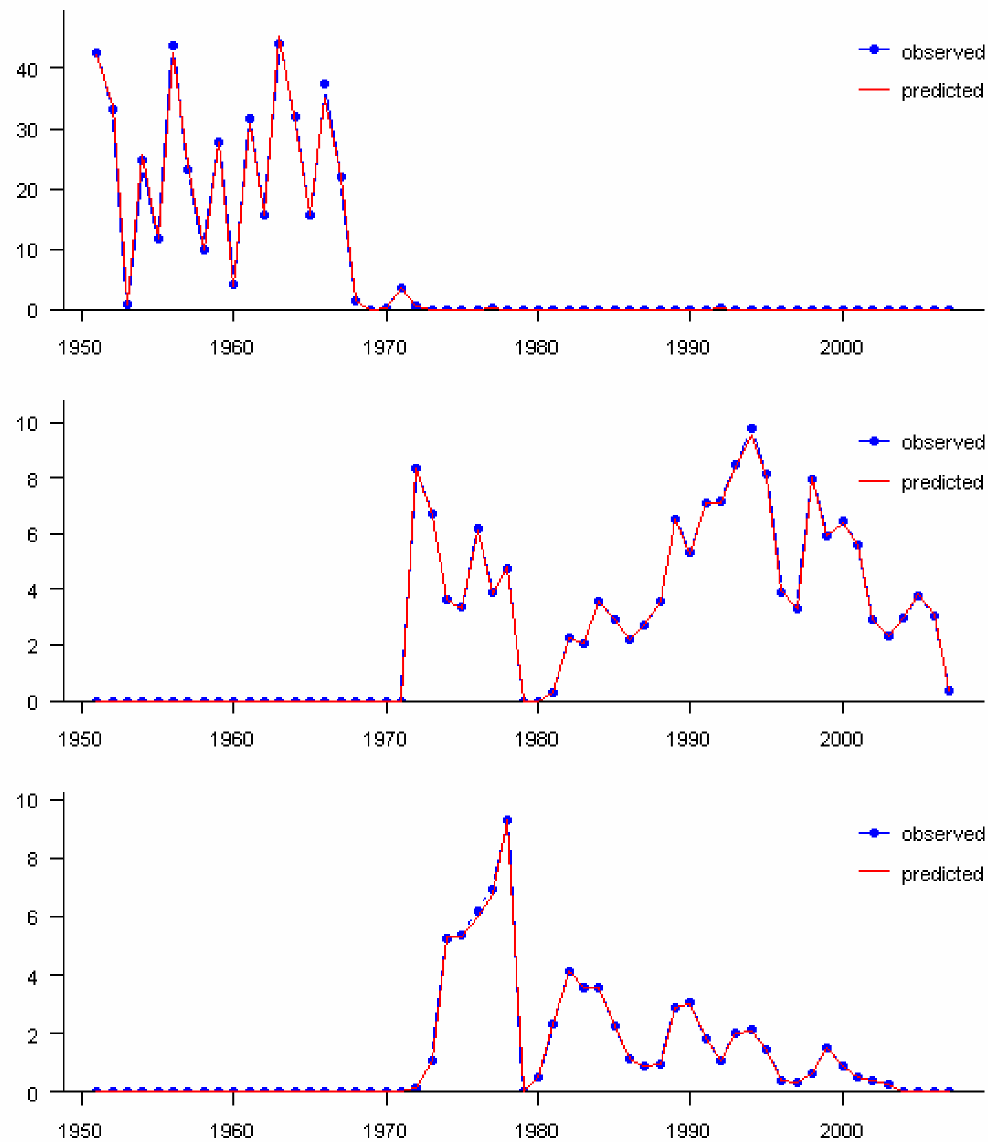

Figure 41, Observed and predicted catch in CC for periods 1 - 3 (top to bottom), i.e., the winter, seine roe and gillnet roe fisheries.

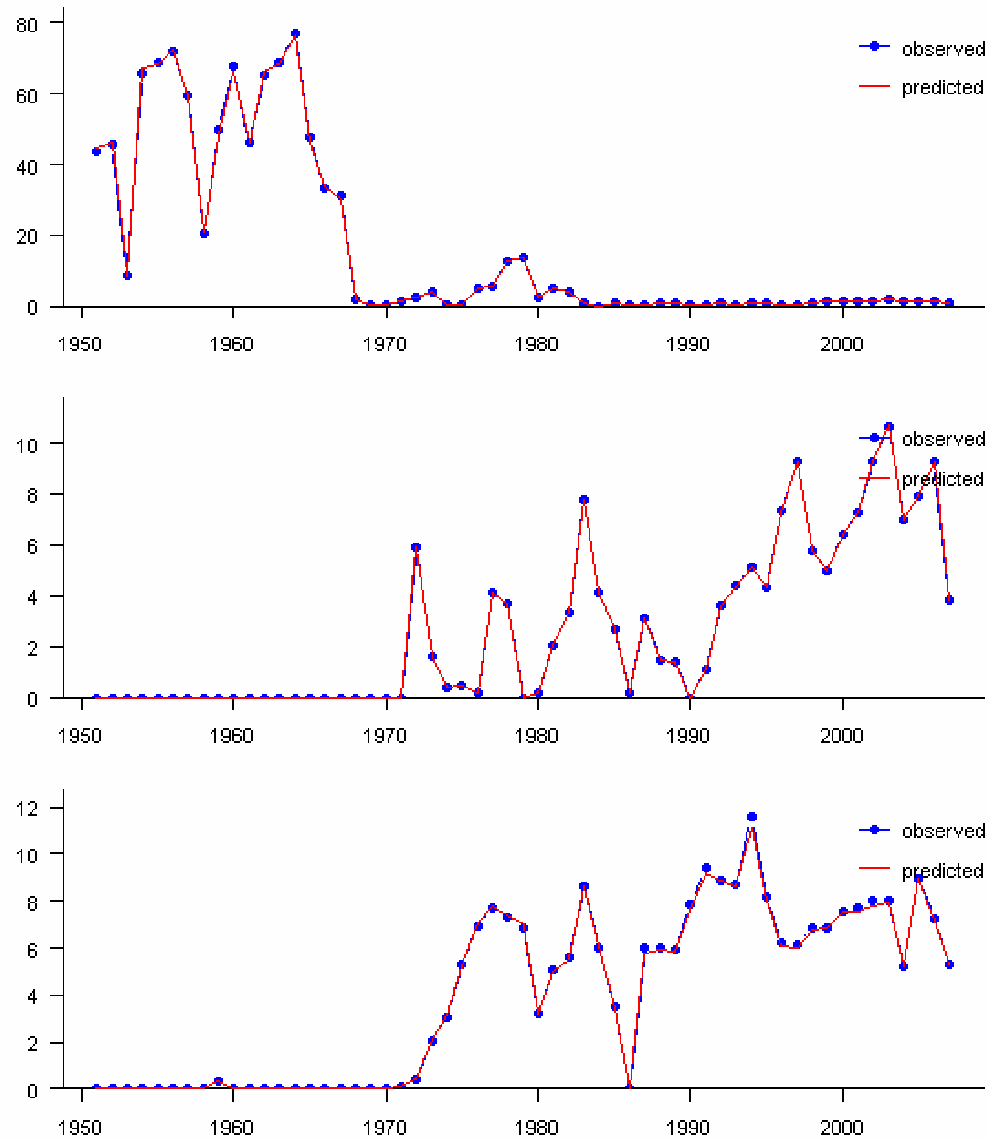

Figure 42, Observed and predicted catch in GS for periods 1 - 3 (top to bottom), i.e., the winter, seine roe and gillnet roe fisheries.

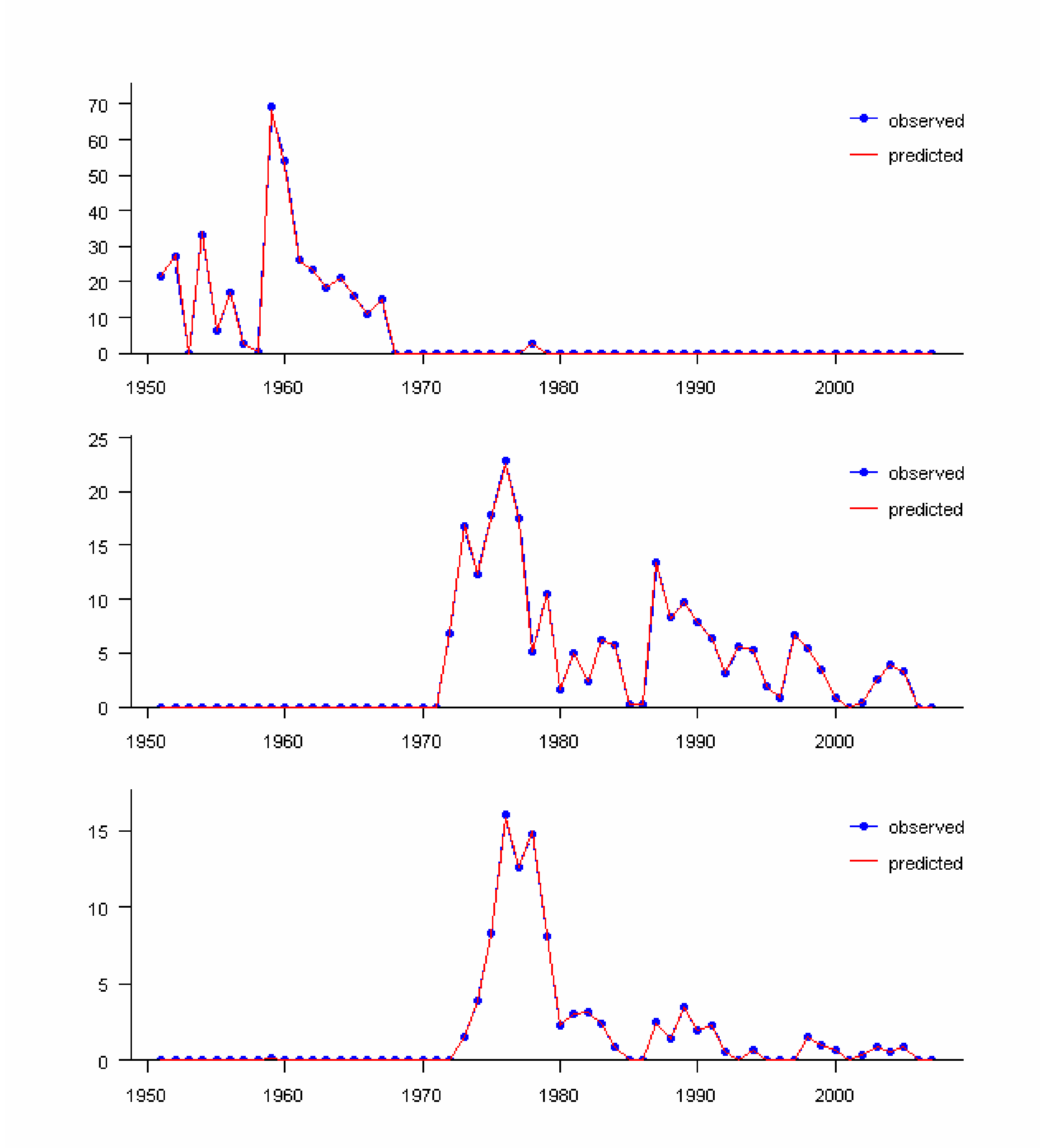

Figure 43, Observed and predicted catch in WCVI for periods 1 - 3 (top to bottom), i.e., the winter, seine roe and gillnet roe fisheries.

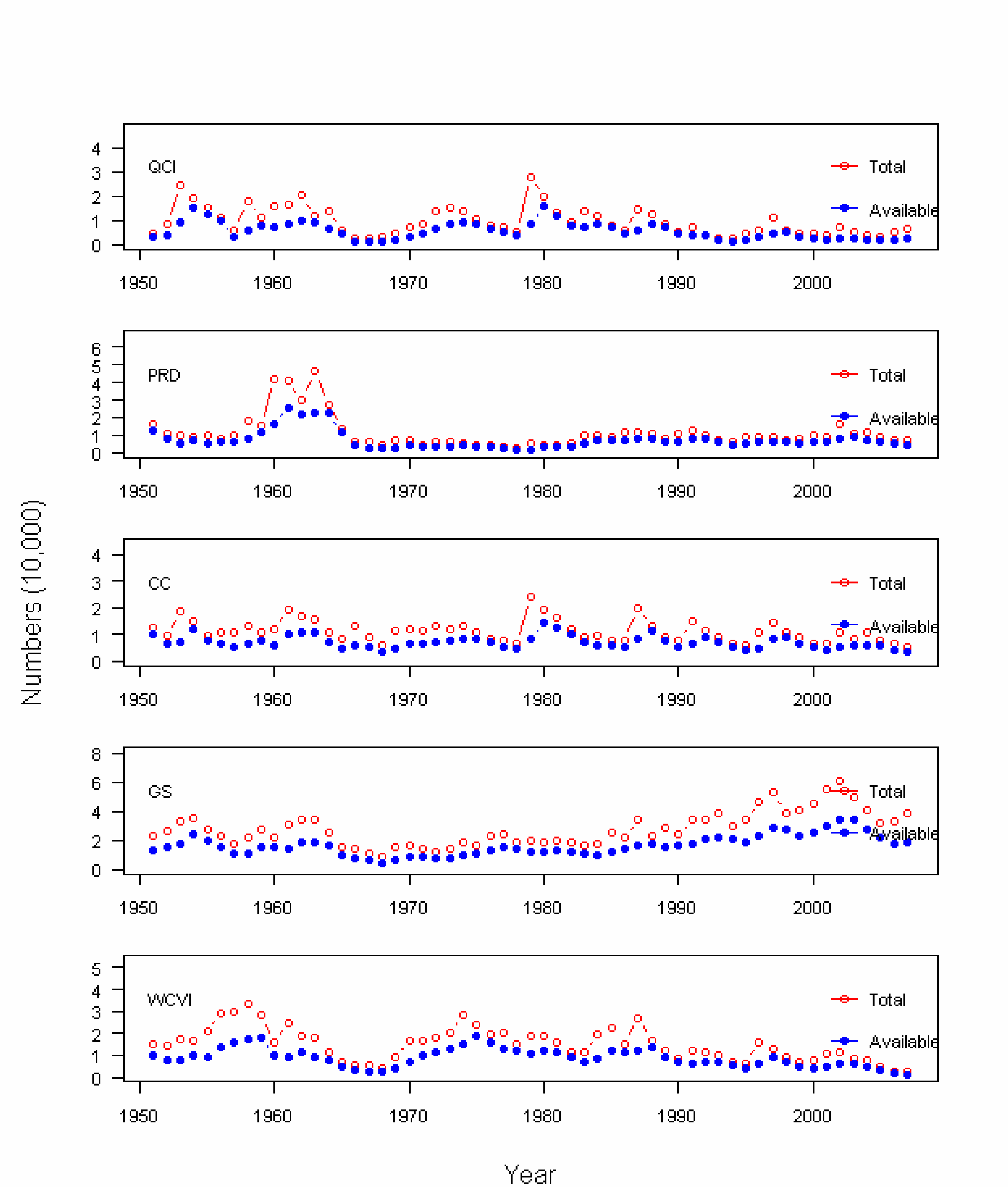

Figure 44, Total and available biomass for 1951 – 2007 for the QCI, PRD, CC, GS and WCVI herring stocks.

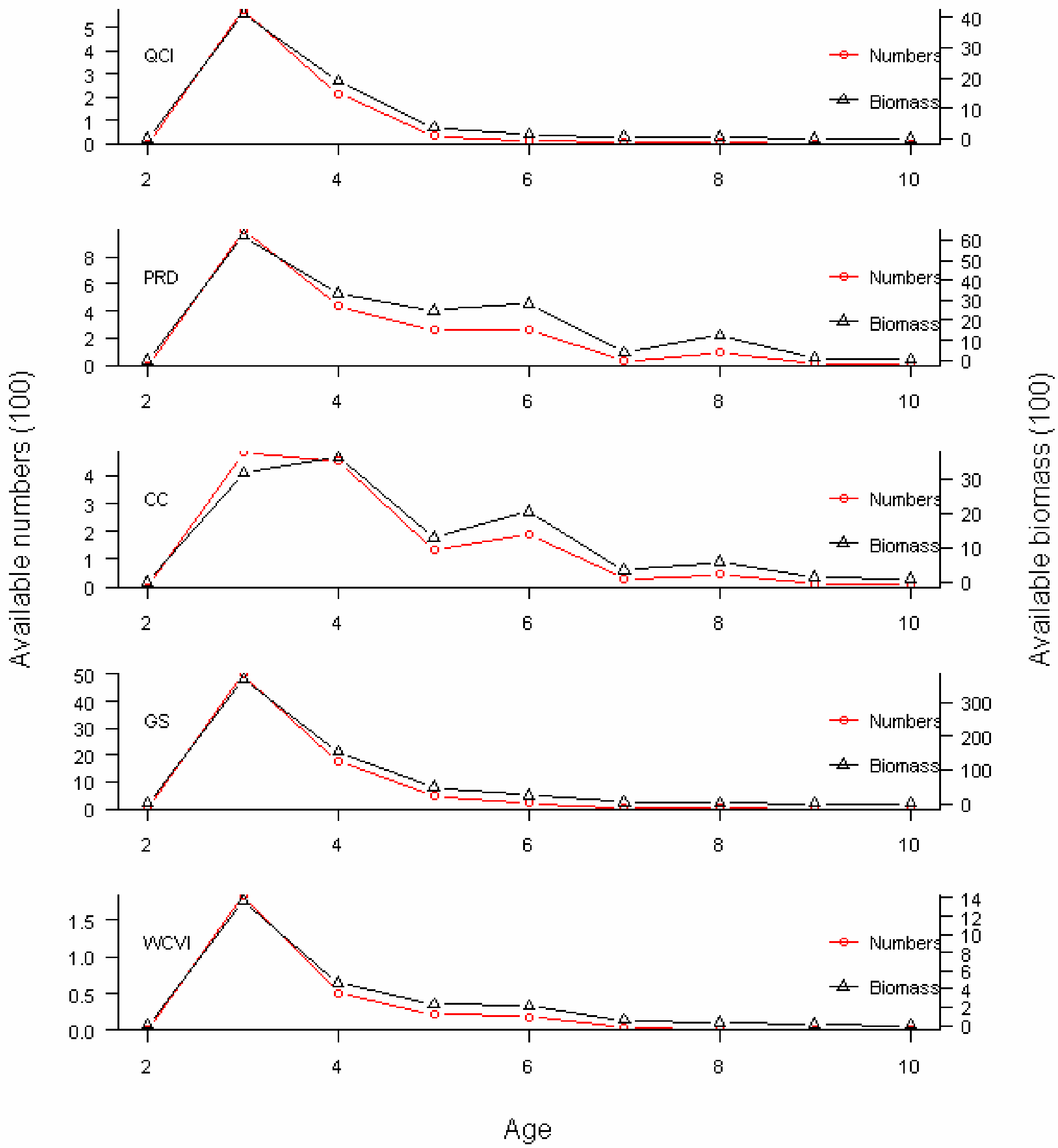

Figure 45, Available numbers and biomass averaged over 1951 – 2007 indicating that the age 3 year classes make up the largest proportion of the stock available to the fishery except in the CC where age 4's are the largest proportion.

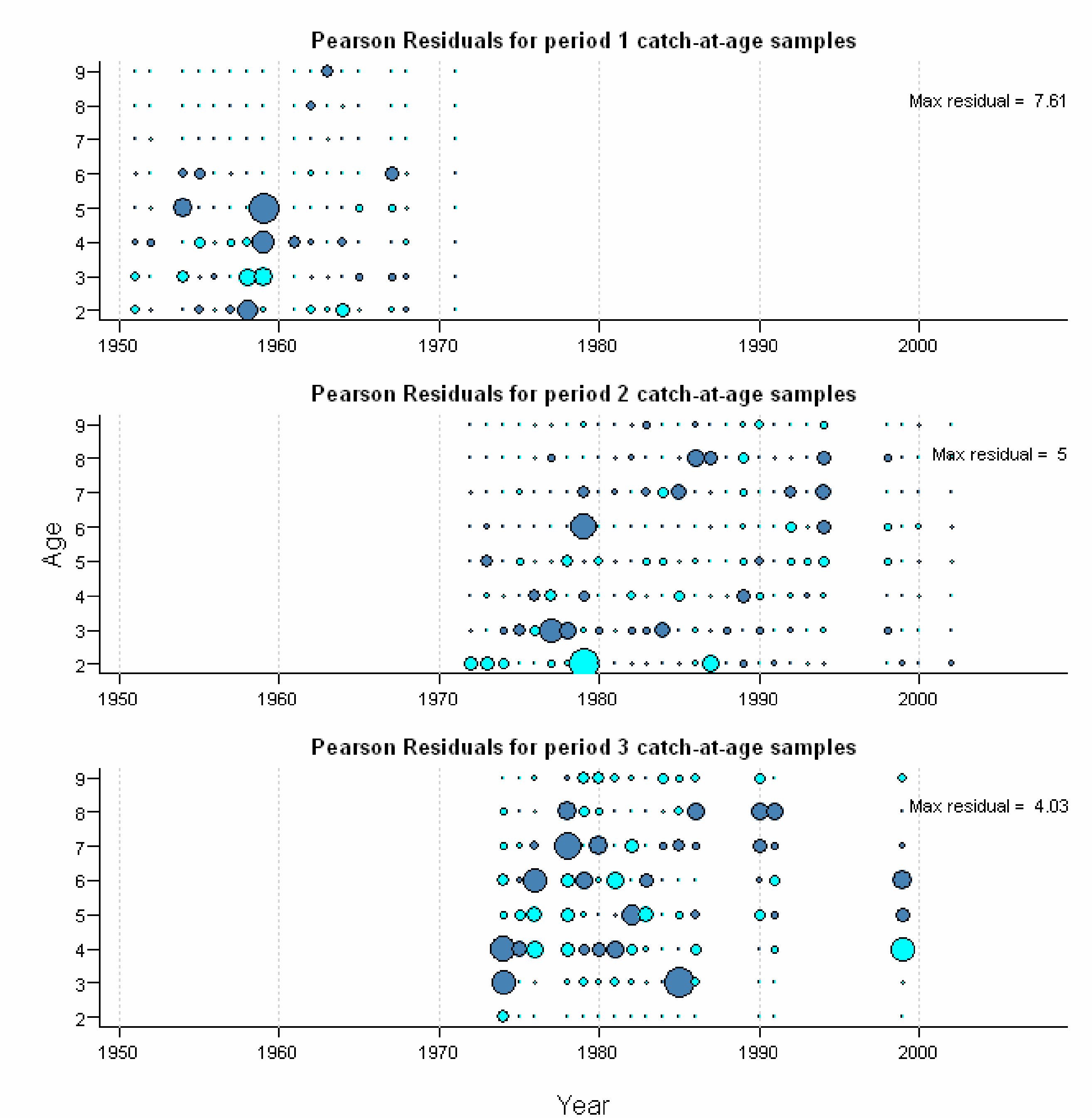

Figure 46, Bubble plots of pearson residuals for the age-structured model fit to the catch-at-age data by year and fishing period for the Queen Charlotte Islands, 1951-2007. Dark coloured circles are positive residuals and light coloured circles are negative residuals.

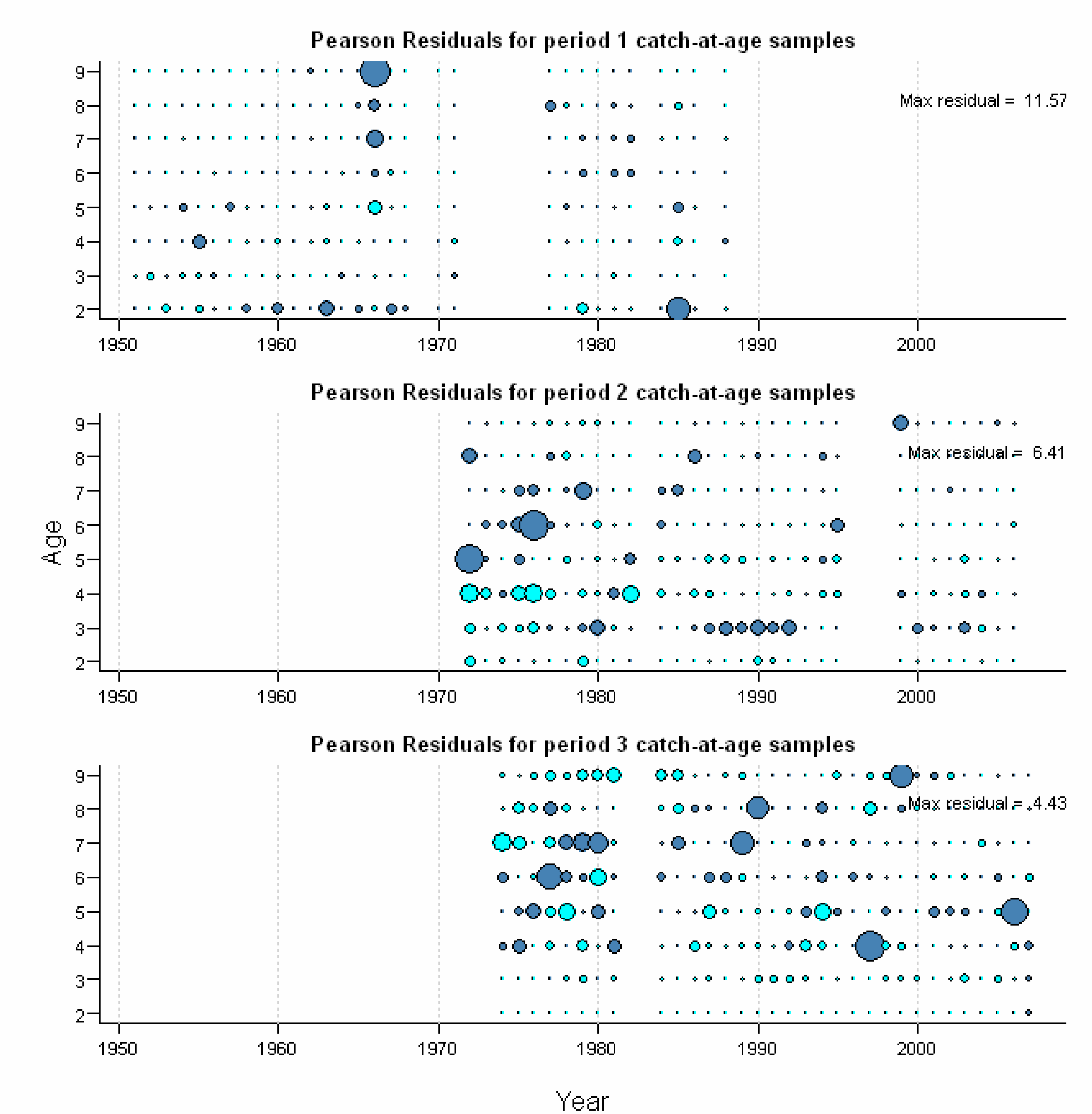

Figure 47, Bubble plots of pearson residuals for the age-structured model fit to the catch-at-age data by year and fishing period for Prince Rupert District, 1951-2007. Dark coloured circles are positive residuals and light coloured circles are negative residuals.

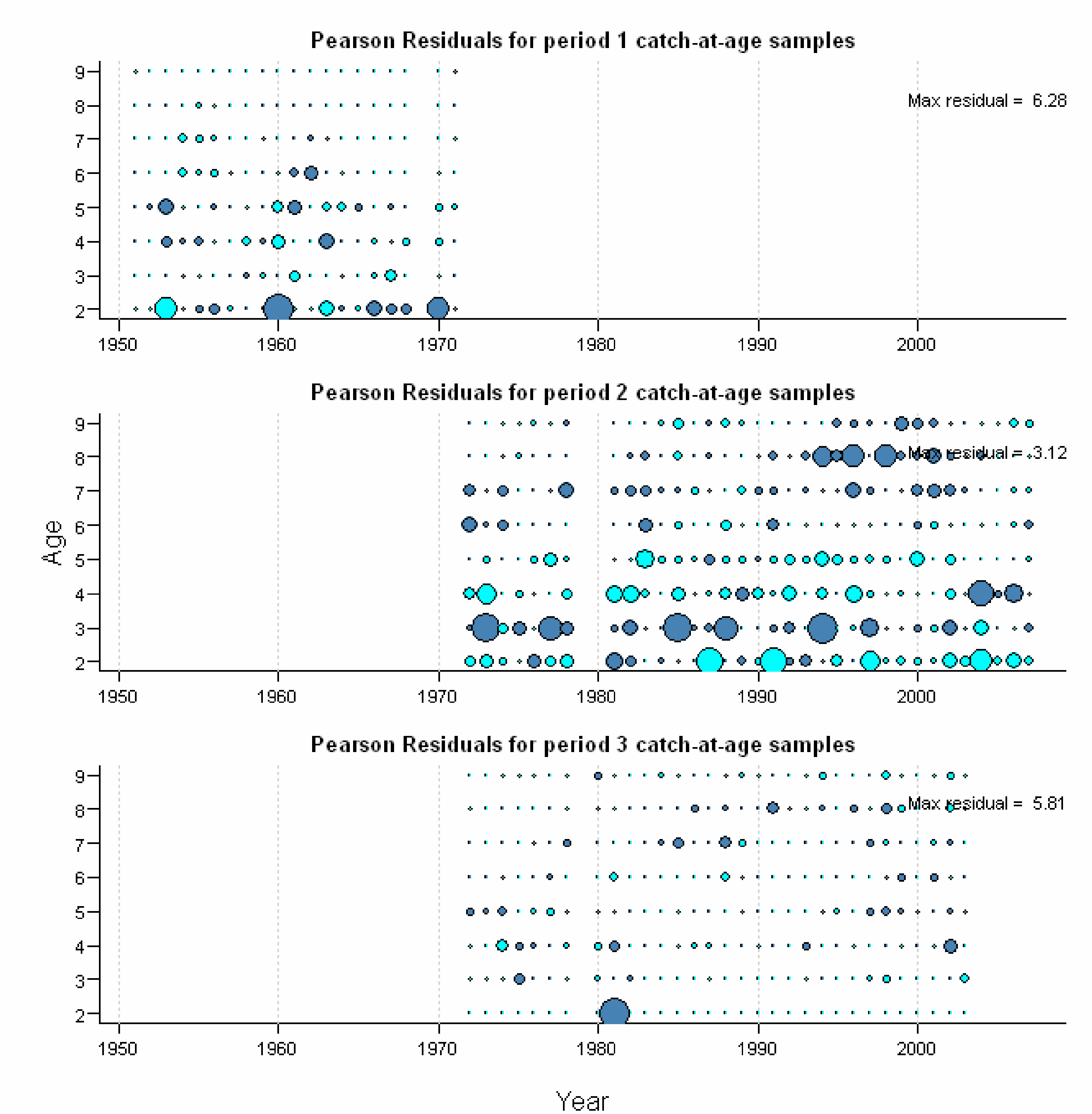

Figure 48, Bubble plots of pearson residuals for the age-structured model fit to the catch-at-age data by year and fishing period for the Central Coast, 1951-2007. Dark coloured circles are positive residuals and light coloured circles are negative residuals.

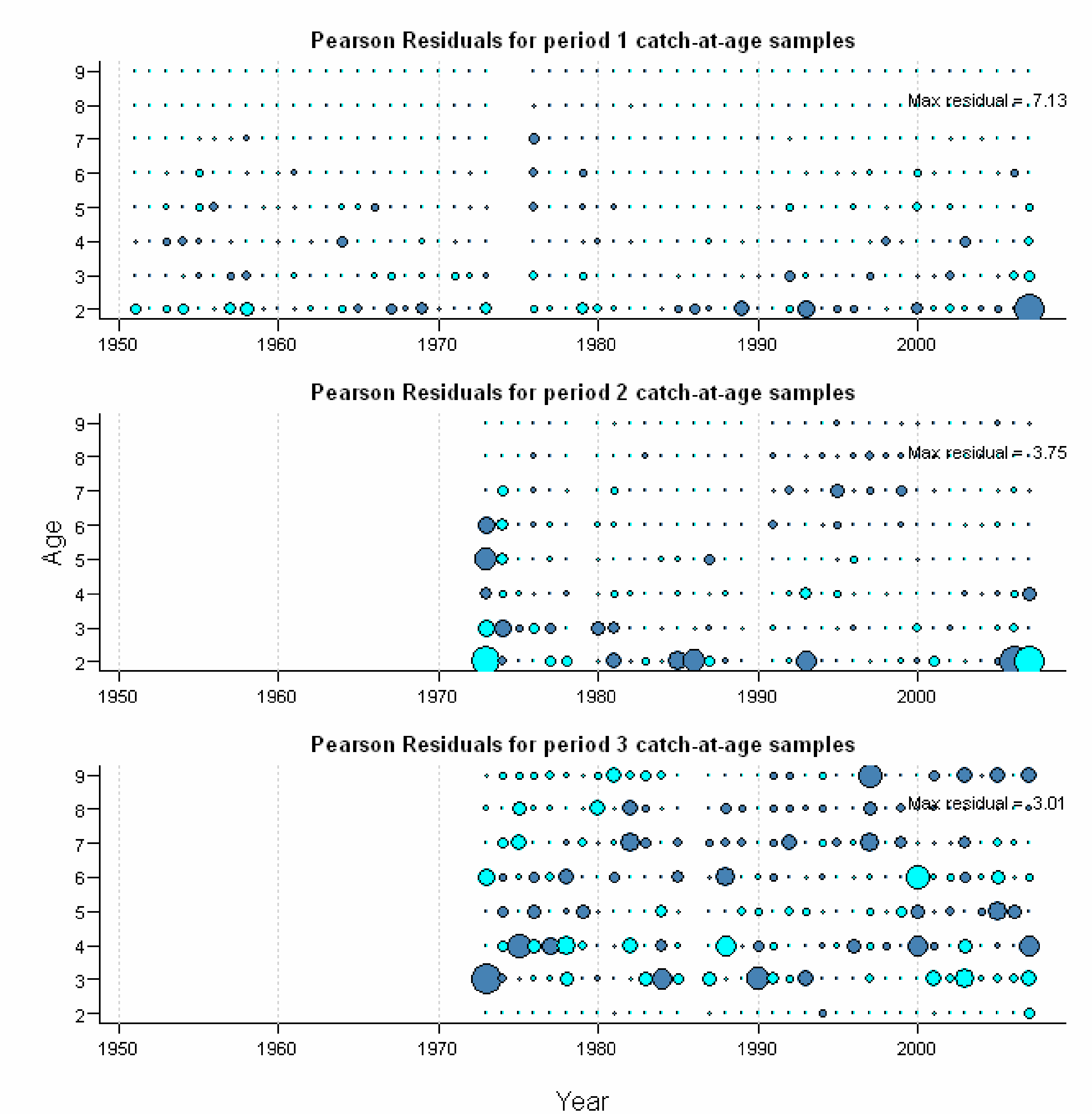

Figure 49, Bubble plots of pearson residuals for the age-structured model fit to the catch-at-age data by year and fishing period for the Strait of Georgia, 1951-2007. Dark coloured circles are positive residuals and light coloured circles are negative residuals.

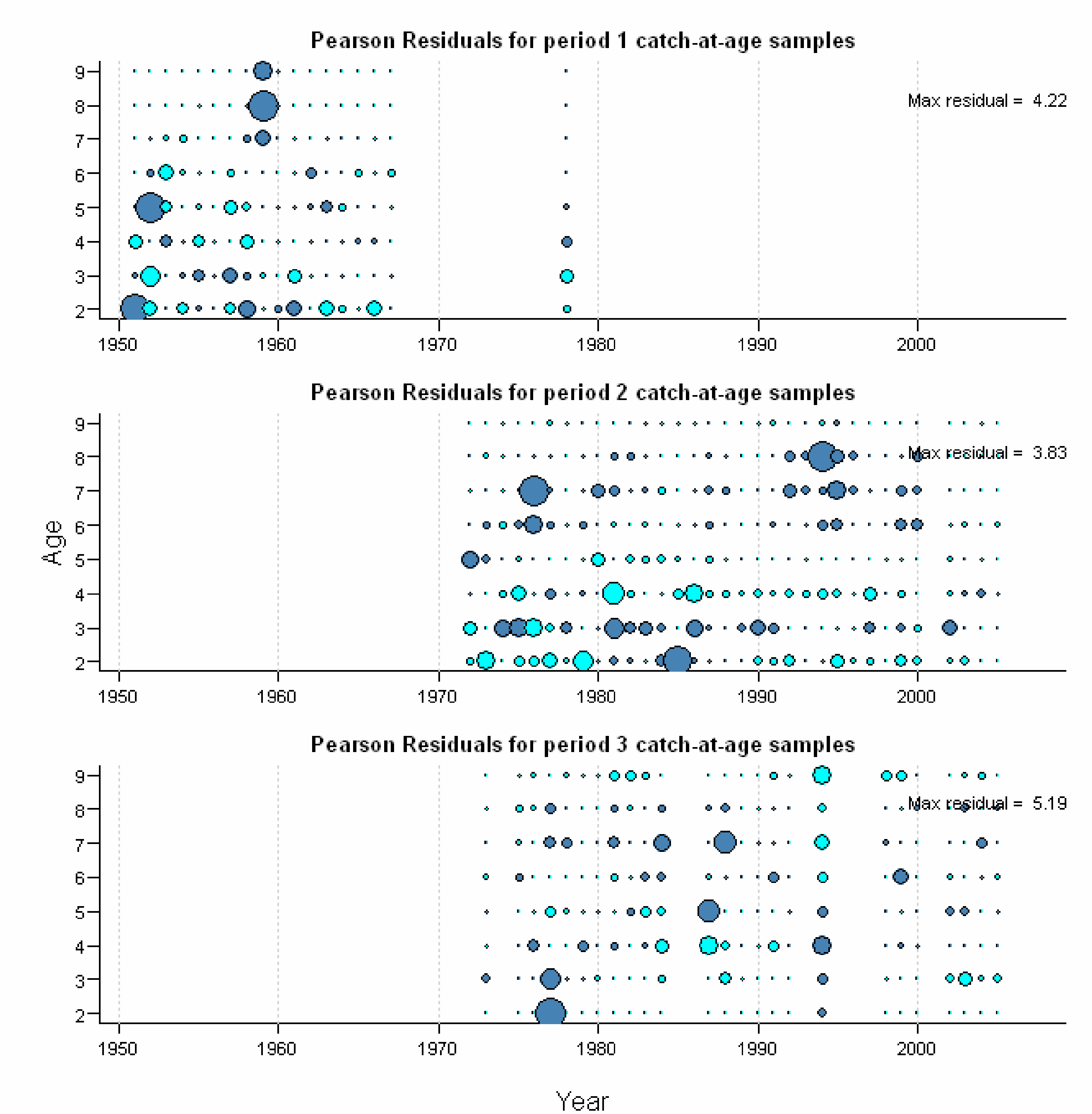

Figure 50, Bubble plots of pearson residuals for the age-structured model fit to the catch-at-age data by year and fishing period for the west coast of Vancouver Island, 1951-2007. Dark coloured circles are positive residuals and light coloured circles are negative residuals.

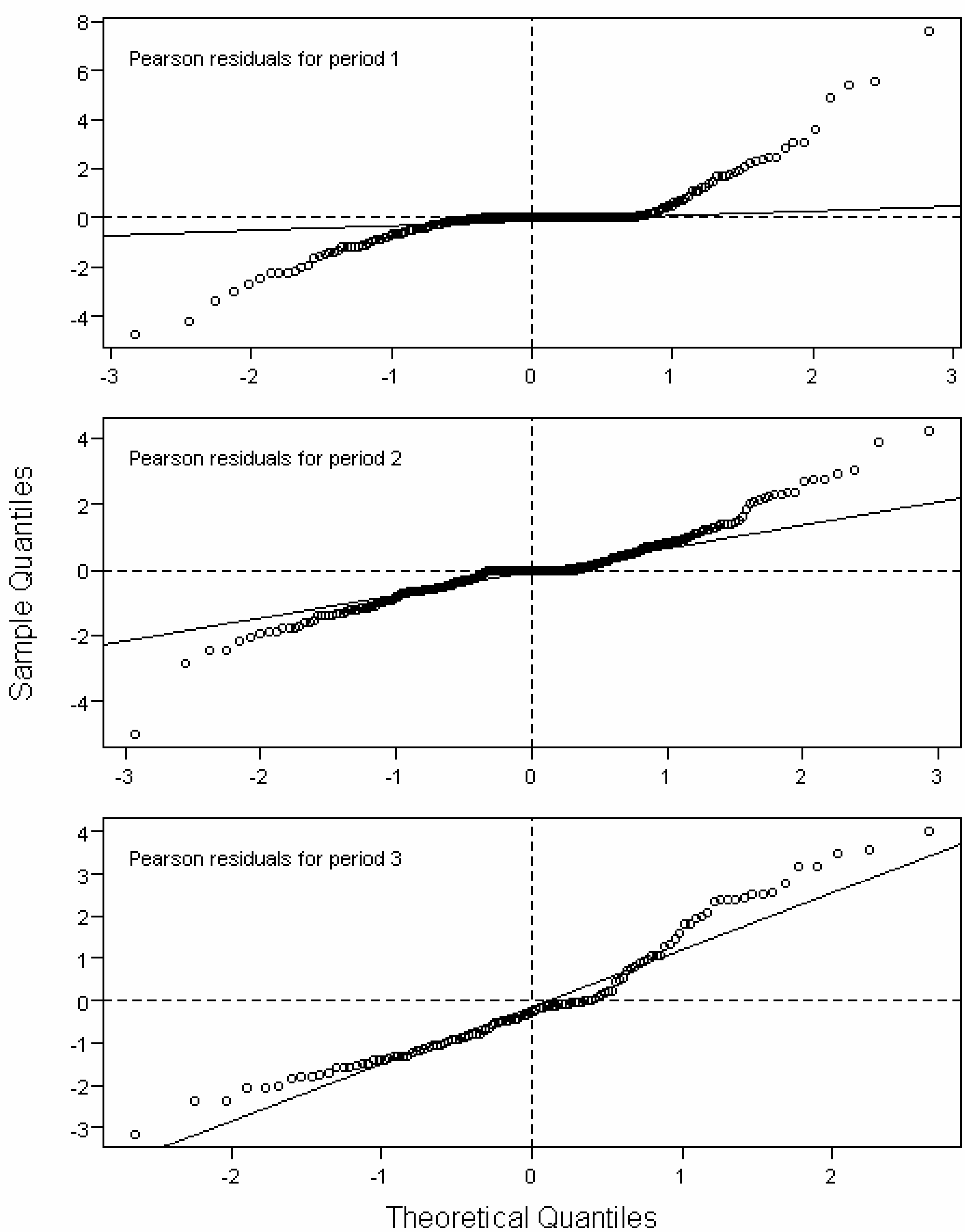

Figure 51, Quantile-Quantile plot of Pearson residuals for the three fishing periods in the Queen Charlotte Islands.

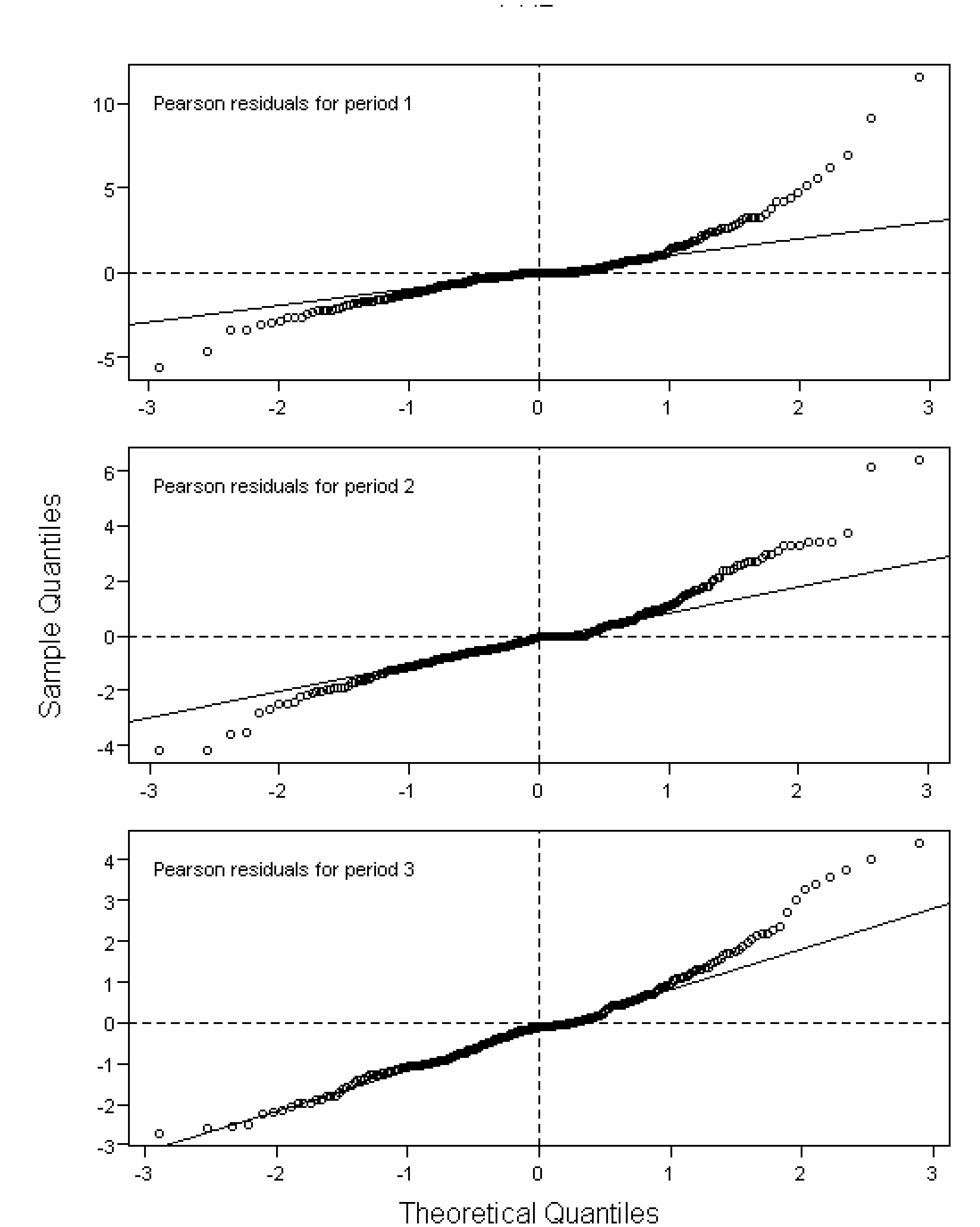

Figure 52, Quantile-Quantile plot of Pearson residuals for the three fishing periods in Prince Rupert District.

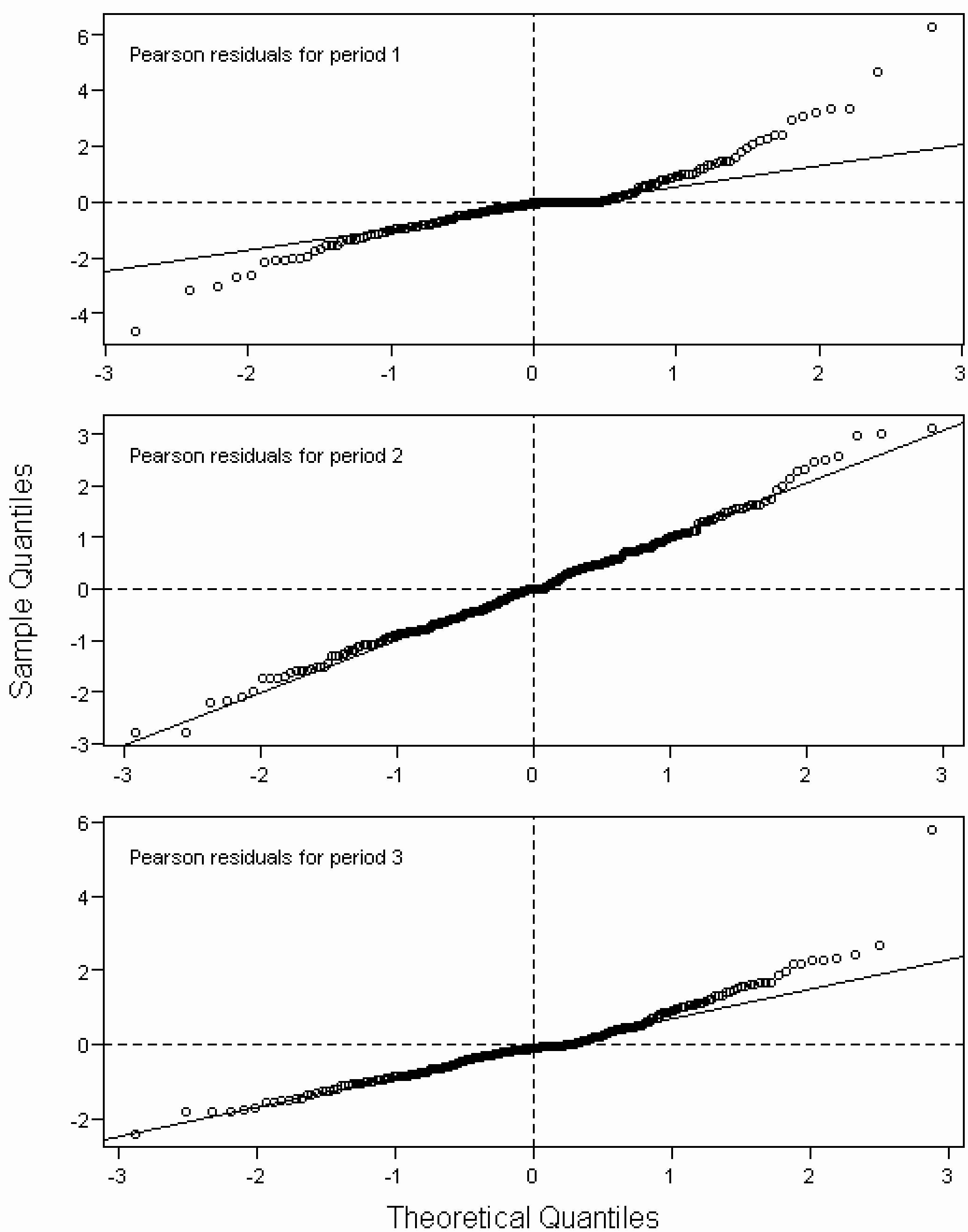

Figure 53, Quantile-Quantile plot of Pearson residuals for the three fishing periods on the Central Coast.

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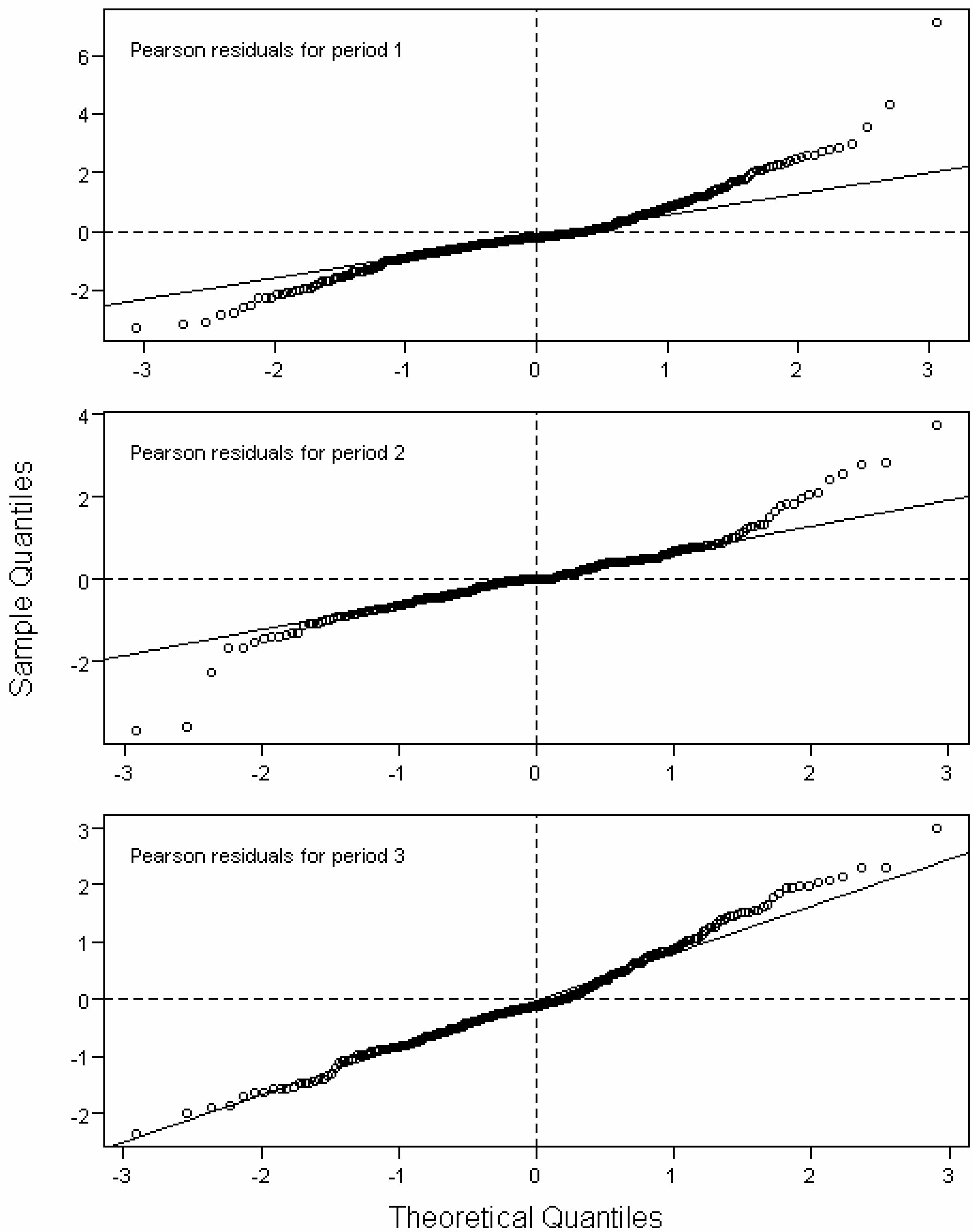

Figure 54, Quantile-Quantile plot of Pearson residuals for the three fishing periods in the Strait of Georgia.

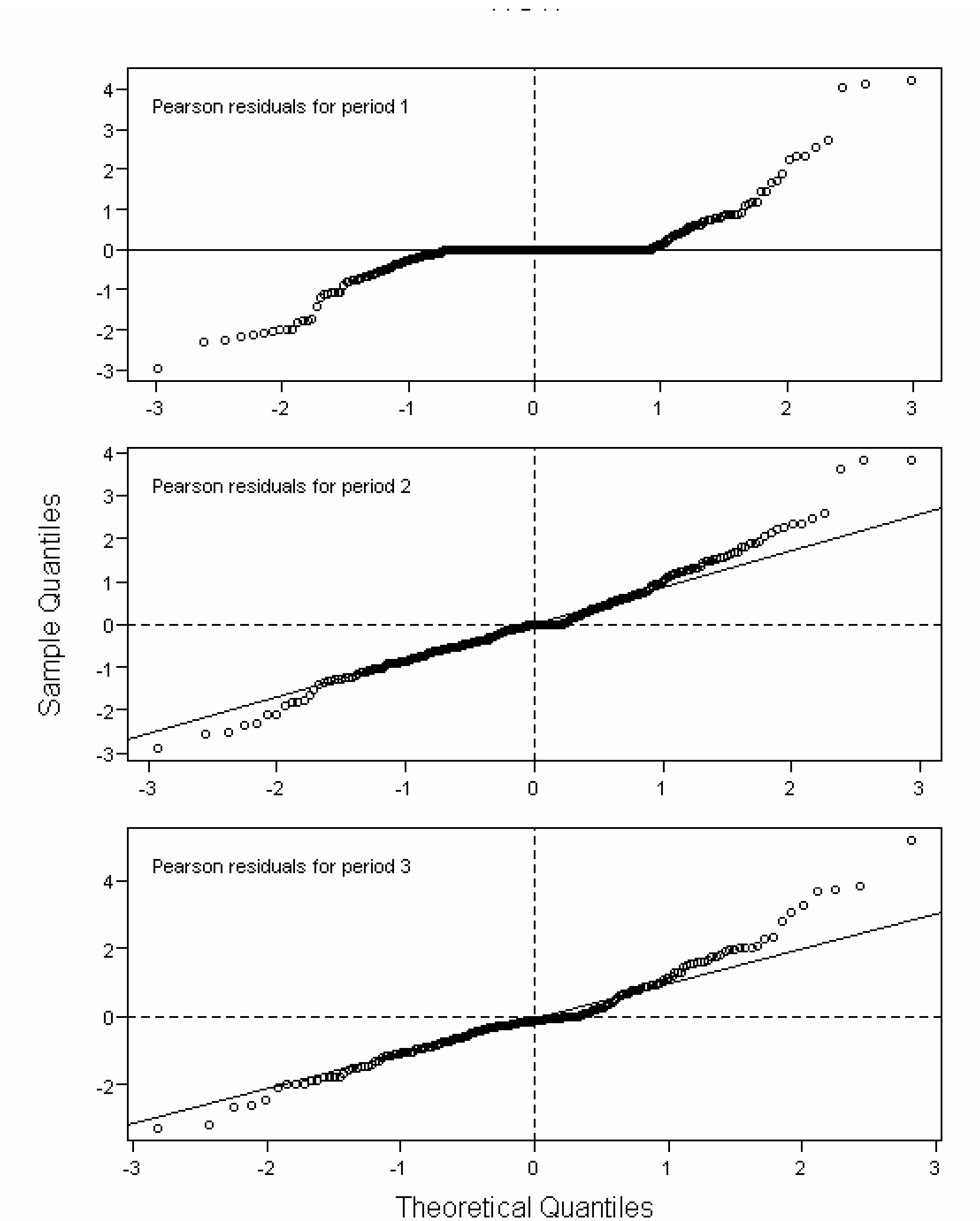

Figure 55, Quantile-Quantile plot of Pearson residuals for the three fishing periods on West Coast Vancouver Island

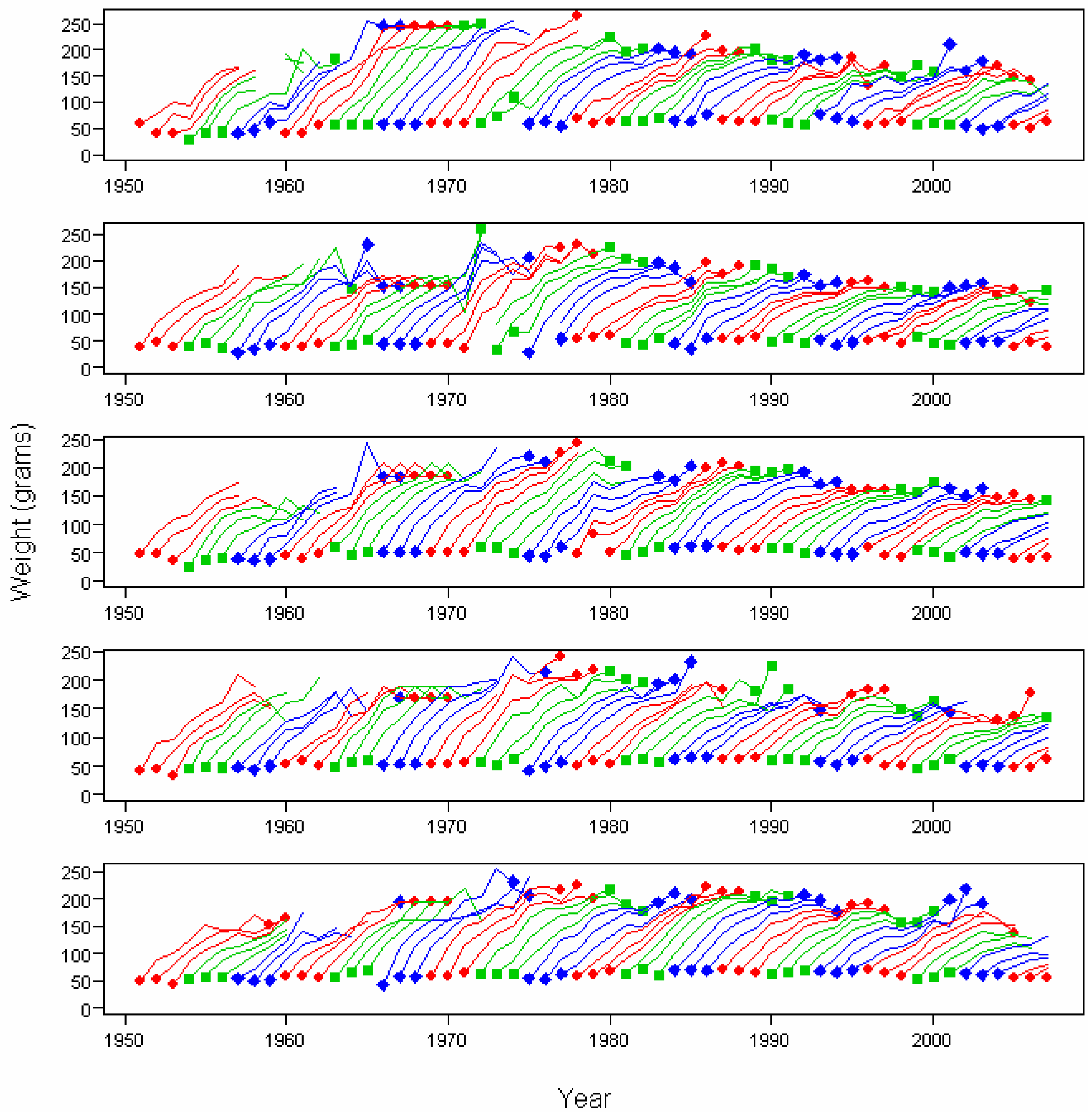

Figure 56, Growth trajectory by cohort (mean weight at age) for the Queen Charlotte Island, Prince Rupert District, Central Coast, Strait of Georgia and West Coast Vancouver Island stocks of herring.

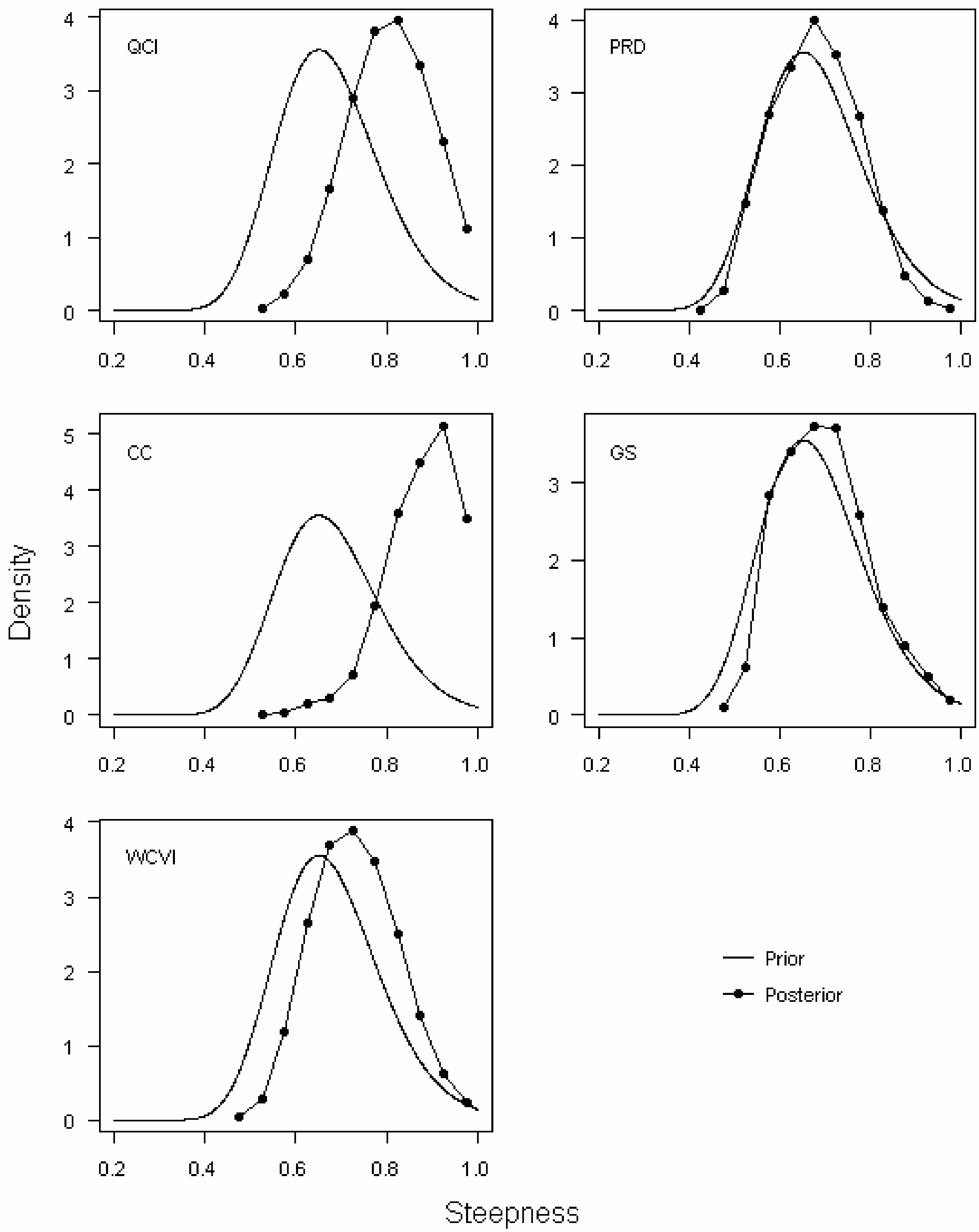

Figure 57, Estimated Markov chain Monte Carlo (MCMC) Bayesian profile likelihood distributions for steepness for the QCI, PRD, CC, GS and WCVI stock assessment regions.

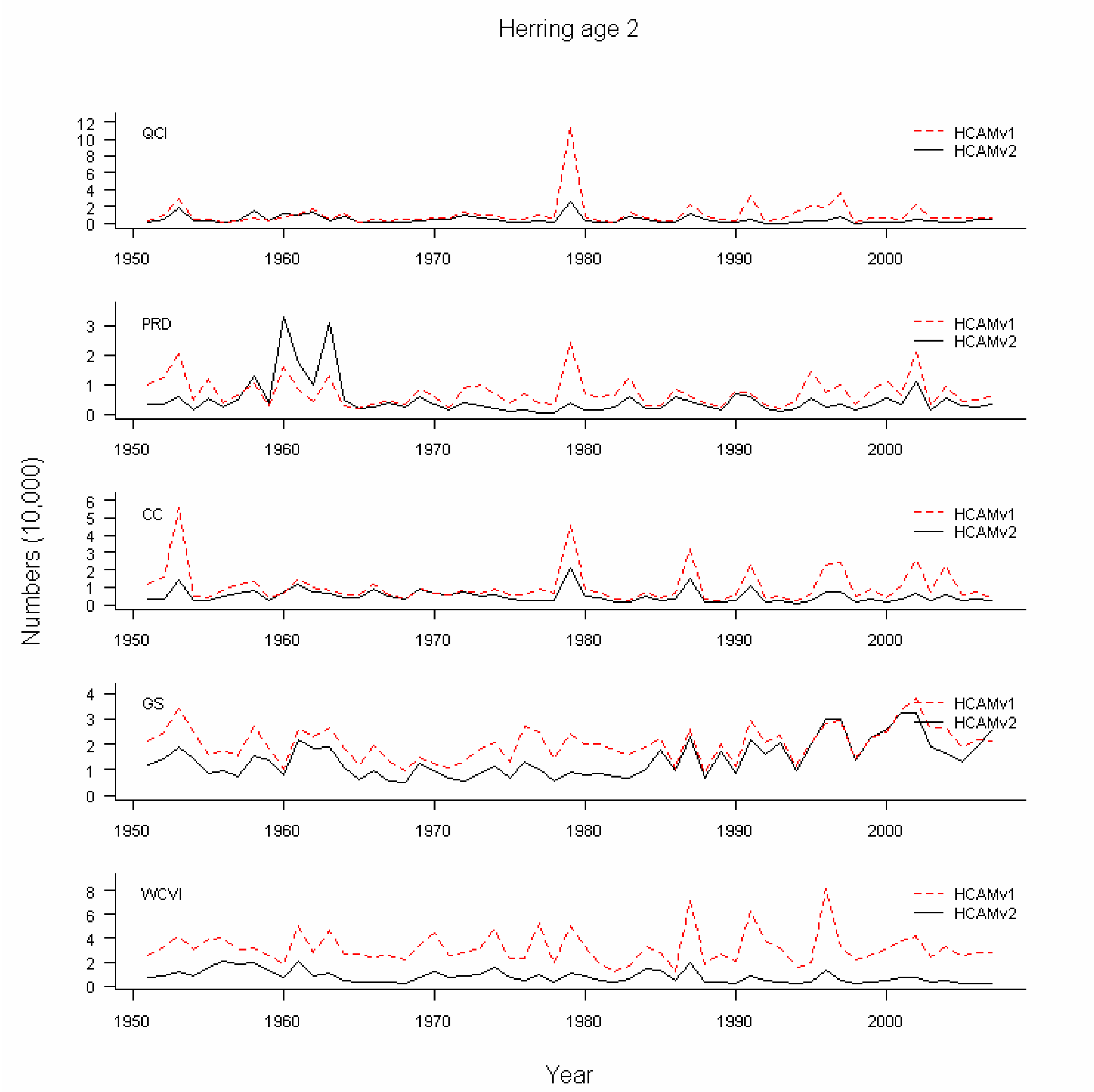

Figure 58, Predicted number of age 2 herring in HCAMv1 and HCAMv2.