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An evaluation of alternative age-structured models for risk assessment of Pacific herring stocks in British Columbia

Évaluation d'autres modèles fondés sur la structure d'âge pour l'évaluation des risques auxquels font face les stocks de hareng du Pacifique en Colombie-Britannique

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ABSTRACT

Recent declines in two of five major stocks have raised concerns about the assessment and management of Pacific herring in British Columbia. Fisheries and Oceans Canada has committed to a science-based review of the stock assessment and fishery management framework for the herring stocks. As a first step in this review process, we have developed a new age-structured model (NASM) in a Bayesian context. The purpose of this paper is to compare its performance with that of the existing age-structured model (EASM), first, by conducting simulation-estimation experiments and second, by reconstructing the dynamics of the five major herring stocks.

The simulation-estimation experiments indicate that the EASM only performs as well as the NASM if, as has been assumed previously, the conversion factor (*q*) required to scale the survey index of spawn to total spawning biomass changed abruptly at a known date (e.g., the year the survey design changed). In this case, model selection becomes difficult because no single model performs consistently better on all measures. However, if the underlying *q* changed randomly, the new model NASM-3 that fixes *q* but estimates annual variations in natural loss (*M*) performs best. When the underlying mean *M* shifted drastically from one period of time to another (i.e., regime shift), NASM-3 and NASM-4, which account for annual variations in *M* perform significantly better than other models. However, if *M* changed only randomly around a constant level, the advantage of estimating annual variations in *M* becomes less obvious. Overall, NASM-3 seems promising based on the simulation results.

In applying the four models (NASM-3, NASM-4, EASM-1, and EASM-2) to the five herring stocks, parameter estimates differed among models just as expected from the simulation results for three of the five stocks (QCI, GS and WCVI); for these stocks we are reasonably confident in identifying the most plausible reconstructions. The promising NASM-3 model tends to overestimate the proportion at age 3 in all the five stocks suggesting that the selectivity functions are not entirely appropriate. If this model is to be used for future stock assessment and risk assessment, a further investigation into different selectivity functions is warranted.

RÉSUMÉ

Les récentes baisses d’effectifs chez deux des cinq principaux stocks ont soulevé des préoccupations relatives à l’évaluation et à la gestion du hareng du Pacifique en Colombie-Britannique. Pêches et Océans Canada s’est engagé à réaliser un examen scientifique du cadre pour l’évaluation des stocks de hareng et pour la gestion de la pêche de cette espèce. À titre de première étape dans ce processus d’examen, nous avons élaboré un nouveau modèle fondé sur la structure d’âge dans un contexte bayesien. Le but de ce document est de comparer la performance de ce nouveau modèle à celle du modèle existant : d’abord en réalisant des expériences de simulation et d’estimation, puis en reconstituant la dynamique des cinq principaux stocks de hareng.

Les expériences de simulation et d’estimation révèlent que le modèle existant ne donne d’aussi bons résultats que le nouveau modèle que lorsque, comme nous l’avions supposé, le facteur de conversion (*q*), requis pour obtenir la biomasse totale des géniteurs à partir de l’indice de relevé du frai, a varié subitement à une date connue (p. ex. l’année où le plan du relevé a été modifié). Dans ce cas, le choix du modèle à utiliser devient difficile parce qu’aucun des deux n’est toujours meilleur que l’autre pour l’ensemble des mesures. Cependant, si le facteur *q* a varié de manière aléatoire, le nouveau modèle n° 3 est le meilleur. Ce modèle fixe la valeur de *q*, mais estime les variations annuelles de la mortalité naturelle (*M*). Lorsque la mortalité naturelle moyenne a varié subitement d’une période à une autre (c.-à-d. changement de régime), les nouveaux modèles n° 3 et n° 4, qui tiennent compte des variations annuelles de la mortalité naturelle, donnent des résultats significativement meilleurs que les autres modèles. Cependant, si *M* a varié aléatoirement autour d’une valeur constante, l’avantage lié à l’estimation des variations annuelles de la mortalité naturelle devient moins évident. En général, d’après les résultats des simulations, le nouveau modèle n° 3 semble prometteur.

Lorsque nous avons appliqué les quatre modèles (nouveaux modèles n° 3 et 4 et modèles existants n° 1 et 2) aux cinq stocks de hareng, les estimations des paramètres ont varié entre les modèles de la manière prévue d’après les résultats des simulations pour trois des cinq stocks (soit ceux des îles de la Reine-Charlotte, du détroit de Georgia et de la côte ouest de l’île de Vancouver). Pour ces stocks, nous sommes raisonnablement confiants que nous pourrons déterminer les reconstitutions les plus plausibles. Le nouveau modèle n° 3 tend à surestimer la proportion de harengs de trois ans dans les cinq stocks, ce qui suggère que les fonctions de sélectivité ne sont pas entièrement appropriées. Un examen plus approfondi de fonctions de sélectivité différentes est nécessaire si nous souhaitons utiliser ce modèle à l’avenir pour évaluer l’état des stocks et les risques auxquels ceux-ci font face.

Introduction

Pacific herring (*Clupea pallasi*) has been one of the most important components of the commercial fishery in British Columbia (B.C.) with catch records dating from 1877 (Schweigert 2001). A reduction fishery started in the 1930s and collapsed in the late 1960s. After a four-year fishery closure, a roe fishery began in 1972 and has continued to the present. Since 1983, the herring roe fisheries have been managed to achieve a constant harvest rate with the quota for each stock set at 20% of forecasted stock size. In 1986, a threshold biomass or "Cutoff" level for each stock was introduced to restrict harvest at low stock abundance (Schweigert 2001).

The herring population in B.C. has been described as a metapopulation with five major stocks associated with the Queen Charlotte Islands (QCI), the Prince Rupert District (PRD), the Central Coast (CC), the Georgia Strait (GS), and the west coast of Vancouver Island (WCVI) (Figure 1). For each of the five stocks, assessment has been carried out annually since 1982 using an age-structured population model. Each stock has been assessed and managed independently.

The assessment model provides an estimate of current abundance at age for each stock. Stock abundance is forecast one year ahead by applying an estimated survival rate (assumed constant over all years and vulnerable age classes) to the current estimate and adding age-3 recruitment at each of three possible levels: poor (the mean of the lowest 33% of estimated historic recruitment), average (the mean of the median 33%), and good (the mean of the highest 33%). Likelihood profiles for the predicted total biomass are then determined (Schweigert 2001). When the forecasted spawning stock biomass is above the preset cutoff, a 20% harvest rate is adopted to set the quota for the next year, otherwise, the forecasted catch is set at the difference between forecasted biomass and cutoff.

For the past two decades, most B.C. herring stocks have sustained a relatively stable harvest. However, recent declines in two of the five major stocks (QCI and WCVI) have raised concerns among some First Nations and others who have relied on herring as a food source for over a century, about the assessment and management of Pacific herring stocks. Fisheries and Oceans Canada is committed to a science-based review of the stock assessment and fishery management framework for Pacific herring to address these concerns. In this science-based review, the current stock assessment model will be expanded to address concerns about flexibility of the model structure, to incorporate temporal variations in survival rate, and to include model and environmental uncertainties. A framework will be developed to evaluate conservation limits for harvest levels and to re-evaluate the merit of the current management policy of 20% harvest rate with the fixed cutoff level.

As a first step in this process, we have developed a new age-structured model in a Bayesian context. The new model is more flexible and has more options to investigate alternative scenarios of concern. In this paper, we describe both models and compare their performance by conducting simulation-estimation experiments and by reconstructing the dynamics of the five major herring stocks. The specific objectives are identified in the Request For Working Paper (Appendix 1).

Methods

Existing model structure

The existing stock assessment model is an age-structured population dynamics model (abbreviated as EASM). Since its first application to herring stocks in 1982, several revisions to the model have been made to improve its fit to the life history of herring and the fisheries in B.C. In the EASM, a year has three consecutive fishing periods: the first encompasses all catch prior to the spring roe herring fisheries, including catches in the reduction fishery prior to 1968 and in the winter food and bait fisheries since 1970; the second includes non-selective roe herring catch in the seine fishery; and the third includes roe herring catch in the gillnet fishery that is selective for larger, older herring.

Throughout this paper, we use subscripts *t* for year, *a* for age, *p* for fishing period, and *g* for gear. Let the recruitment age be *r* and maximum age (or "plus group" age) be *A*. The EASM estimates the initial abundance in year 1951 ($N_{1951,a}$ with $r < a \le A$) and recruitment over time ($N_{t,r}$) as free parameters. One unique feature of the EASM is that it accounts for the availability of herring to the fishery using parameters $l_{t,a}$ (proportion of age *a* herring which are available to the fishery in year *t*) to convert total number of herring $T_{t,a}$ to the abundance available to the fishery $N_{t,a,p}$ in period *p*. Thus, the abundance at age *a* available at the start of period 1 in year *t* is given by $N_{t,a,1} = l_{t,a} T_{t,a}$, where $0 < l_{t,a} < 1$. Previously, availabilities for ages 2 and 3 over time were estimated as free parameters, those for ages 4 to 6 were assumed constant between years, and those for age 7 and older were set to 1.0.

Abundance in the following periods of the same year is calculated as

$$N_{t,a,p+1} = N_{t,a,p} e^{-(F_{t,a,p} + M_p)}$$

where $F_{t,a,p}$ is the fishing mortality of age *a* in year *t* for period *p* and M_p is the natural mortality for period *p*. Total abundance in the next year is

$$T_{t+1,a+1} = N_{t,a,3} e^{-(F_{t,a,3} + M_3)} + T_{t,a}(1 - l_{t,a}) e^{-\sum_{p=1}^{3} M_p}$$

For the selective gillnet fishery (i.e., fishing period 3), fishing mortality is assumed separable following Doubleday (1976),

$$\ln(F_{t,a,3}) = a_{t,3} + b_{t,a}$$

where $a_{t,3}$ represents the fishing mortality due to the gillnet fishery in year *t* and fishing period 3, and $b_{t,a}$ represents the relative selectivity of the gear for age *a*. The $b_{t,a}$ is reparameterized such that age selectivity is modelled as a function of annual average weights-at-age

$$b_{t,a} = \left[1 + e^{r - t w_{t,a}^{geo}}\right]^{-1}$$

where $w_{t,a}^{geo}$ is $\log_e$ of the geometric mean weight-at-age *a* in year *t*, and r and t are the logistic shape parameters.

Instantaneous annual natural mortality (*M*), is assumed constant throughout the year so the EASM partitions *M* within the three fishing periods in proportion to duration, with fishing period 1 accounting for 95% of the year, and periods 2 and 3 only 2.5% each. This assumption is reasonable because of the short season of roe fisheries (periods 2 and 3) which occur over a roughly 2 week period at the end of the year.

The EASM incorporates a spawning index conversion factor *q* to scale the spawn survey index to the actual spawning biomass level. Prior to 1988, the spawn survey index was only based on surface observation, but since then dive surveys have also been carried out. It was suggested that the EASM should fit separate *q* parameters for the surface and dive spawn survey eras. However, there is no clear rationale for choosing among models that estimate one *q*, two *q*'s or fix both *q*'s for the two eras (Schweigert 2001).

Data used for stock reconstruction are sampled catch-at-age ($CA_{t,a,p}$), catch in number ($C_{t,p}$), spawning biomass index (SB_t), mean weight-at-age ($w_{t,a}$), and the natural logarithm of geometric mean weight-at-age ($w_{t,a}^{geo}$). The $CA_{t,a,p}$ data are obtained from ageing random samples of fish from the catch assuming there are no ageing errors. The error structure suggested by Fournier and Archibald (1982) is used for the $CA_{t,a,p}$ data. Errors in $C_{t,p}$ and SB_t data are assumed to be log-normal.

New model structure

The new model (NASM) expands the EASM to address concerns about flexibility of model structure to incorporate temporal variations in survival rate, model and environmental uncertainties. A particular concern has been that natural mortality in the EASM was assumed constant over time and across all age groups. Because a certain percentage of fish stray among stocks in the metapopulation (Ware and Schweigert 2001, Hay et al. 2001), natural mortality estimated in the model will reflect net loss due to both emigration and natural death. Both emigration and natural death rates are thought to vary over time and across ages (Tanasichuk 2000, Hay et al. 2001), so it is important to be able to examine the consequences of natural loss varying over time and across ages. The NASM is designed to allow estimation of age- and year-specific rates of natural loss.

The biggest difference between the EASM and NASM is that the NASM takes a Bayesian approach to parameter estimation. Estimating uncertainty in parameters can be very important, and the Bayesian approach has become an accepted method in stock assessment to determine uncertainty in parameters (Punt and Hilborn 1997). The uncertainty is incorporated by including prior distributions for all parameters in the model, and posterior distributions for the parameters are calculated by integrating all values of the model parameters weighted by the likelihood of each parameter combination (Maunder and Starr 2001). However, for the purpose of comparing the EASM and the NASM, this paper will not address the Bayesian aspect, and the prior distributions for all parameters are non-informative.

Unlike the EASM that starts the dynamics from the first year of data (1951), the NASM starts the dynamics from a virgin unfished status with the virgin recruitment (R_0) and the virgin spawning biomass (SB_0), assuming the initial 0 year to be $[1951-(A-r+1)+r-1]$ following Ianelli and Zimmerman (1998). The virgin spawning biomass is calculated as $SB_0 = \sum_{a=r}^{A} N_{0,a} f_{0,a} = \sum_{a=r}^{A} N_{0,a} m_{0,a} w_{0,a}$, where variables N, $f, m,$ and w are abundance, fecundity, maturity ogive and weight at age *a*, respectively. In the subsequent initial years t_0, the dynamics of abundance is $N_{t_0+1,a+1} = N_{t_0,a} e^{-M_{t_0,a}}$, where $M_{t_0,a}$ is the initial instantaneous natural loss at age *a*. The plus group for the initial years is given by: $N_{t_0,A} = \dfrac{N_{t_0,A-1}}{(1-e^{-M_{t_0,A-1}})}$.

Therefore, the NASM estimates the abundance at recruitment age *r* for initial years t_0 starting from year $1951-(A-r+1)+r-1$ up to 1951 when data become available, and for years *t* from 1951 to 2003. Although the NASM provides options for incorporating different stock-recruitment functions into the parameter estimation procedure, to allow direct comparison with the EASM in this analysis, the NASM estimates recruitment over time as free parameters.

Rather than separate the year into three periods as the EASM does, the NASM assumes that fish experience instantaneous natural loss ($M_{t,a}$) before they are encountered by different types of gear during the short fishing season. Thus,

$$N_{t,a} = N_{t-1,a-1} e^{-M_{t,a}} \text{, and } N_{t,a} = N_{t,a}(1-u_{t,a})$$

where $u_{t,a}$ is the exploitation rate for all gears $u_{t,a} = \sum_g {}^g u_{g,t,a}$.

To avoid a difficulty previously encountered with the EASM of estimating individual availability parameters along with the recruitment, the NASM accounts for availability implicitly using selectivity functions with time-dependent parameters. The selectivity function is defined using a logistic curve ($s_{g,t,a} = \frac{1}{1+e^{-g_g(a-a^{50}_{g,t})}}$) for each gear which can vary over time through the time-varying parameter $a^{50}_{g,t}$, the age at which 50% of fish are vulnerable to the fishing gear. Parameter g_g is the gear-specific shape parameter.

Therefore, the exploitation rate for each gear is a product of its age-specific relative selectivity and the exploitation rate of fully selected fish at a specific time *t*: ${}^{g}u_{g,t,a} = s_{g,t,a} m_{g,t}$. Assuming the total commercial catches in biomass for each gear $C_{g,t}$ are known without error, and that fishing takes place in a short time interval at the end of the year, the annual exploitation rate by gear is given by:

$$m_{g,t} = \frac{C_{g,t}}{\sum_{a} N_{t,a} s_{g,t,a} w_{t,a}}$$

Only two options of natural loss are considered in this paper: (1) Natural loss is assumed to be constant over time and across all ages, $M_{t,a} = M$; or (2) natural loss is assumed to be equal across all ages but varies over time, $M_{t,a} = M_t$. Like the EASM, the spawning biomass conversion factor *q* is either fixed at 1.0 or estimated for the period from 1950 to 1987, and fixed at 1.0 for the period after 1988.

Data input to the stock reconstruction include the age composition matrix ($CA_{g,t,a}$), ageing sample sizes, catch in weight ($C_{g,t}$), spawning biomass index (SB_t), and mean weight-at-age ($w_{t,a}$). Although the NASM has options to use eight different likelihood functions to accommodate various error structures in the data, the same log-normal error structure is selected in this analysis for comparison with the EASM.

Simulation model structure

A simulation model was developed to generate simulated data sets for spawn survey index, catch-at-age and catch data (SB'$_t$, $CA'_{t,a}$ and C'_t). It starts with a given recruitment R_{1951}, calculates abundance in 1951 for other ages, and incorporates log-normal errors with coefficient of variation (CV) = 0.2 into the initial total abundance $T_{1951,a}$ at age *a*. The dynamics of the simulated stock follows the EASM in the sense that the total abundance is converted to available abundance by multiplying total abundance by the proportion of availability $l_{t,a}$ for each year *t* and age *a*. The availability proportion for age 2 is generated randomly from a uniform distribution between 0.0 and 0.2, and that for age 3 between 0.5 and 1.0. Availability proportion for older ages is set at 1.0. Uncertainties in the process of recruitment are incorporated by imposing a log-normal error with CV = 0.5 and autocorrelation parameter r of 0.3 upon a chosen spawner-recruit relationship. The maturity ogive is fixed at 0.03 for age 2 (Hay and McCarter 1999), simulated as a uniform random number between 0.6 and 1.0 for age 3, and fixed at 1.0 for older ages. In this study, only the Ricker stock-recruitment relationship is used. Exploitation rates by each gear on fully-recruited individuals are set at the estimated values from each stock assessment. Two options of natural loss are simulated: (1) *M* varies around a constant value (0.4) with log-normal error (CV = 0.2); (2) *M* varies around 0.2 from 1951 to 1969 and 0.6 from 1970 to 2003, with log-normal error of CV = 0.2 for both periods. In both cases, *M* is assumed to be the same for all ages above 2.

Uncertainties in the measurement of SB'_t, $CA'_{t,a}$, and C'_t are incorporated using independent log-normal errors with CV = 0.2.

Simulation-Estimation Experiments

Simulation-estimation experiments are conducted to evaluate model performance under six plausible scenarios concerning values for natural loss and the spawn index conversion factor (Table 1). In Scenarios 1 and 2, *q* is set at 0.7 and *M* either varies randomly around 0.4 (Scenario 1) or around a mean that shifts once from 0.2 to 0.6 during the simulation (Scenario 2). In Scenarios 3 and 4, *q* is drawn each year as a random number from log-normal distributions with mean = 0.5 before 1988 and mean = 1.0 thereafter; *M* varies randomly around 0.4 (Scenario 3) or around a mean that shifts once from 0.2 to 0.6 during the simulation (Scenario 4). In Scenarios 5 and 6, *q* is drawn each year as a uniform random number between 0.5 and 1.5; *M* varies randomly around 0.4 (Scenario 5) or around a mean that shifts once from 0.2 to 0.6 during the simulation (Scenario 6). For each scenario, 50 sets of simulated data are generated with process errors in parameters and measurement errors in the data. For each scenario, the same random seed is used such that the parameter estimates are comparable when conditions are changed experimentally. Each simulated data set is assessed using six model options: (1) NASM-1 estimates a constant *M* but sets *q* at 1.0, (2) NASM-2 estimates a constant *M* and a constant *q*, (3) NASM-3 estimates annual variations in *M* but sets *q* at 1.0, (4) NASM-4 estimates annual variations in *M* and a constant *q*, (5) EASM-1 sets *q* at 1.0, (6) EASM-2 estimates a constant *q*. Parameters estimated by each model are listed in Table 2.

Estimation bias ratios, i.e., the ratios of estimated to true parameter values on $\log_2$ scale can be used to evaluate the performance of the six models because all parameters are known within the simulation realm. A value of 0.0 indicates unbiased estimation; a value of 1.0 stands for two-fold overestimation, and a value of –1.0 for two-fold underestimation (Schnute and Richards 1995). We calculate the bias ratios for parameters most closely related to fisheries management including spawning biomass, abundance at age 2 (recruitment) and at age 3, and natural loss. We also examine the bias ratio for *q* to compare how well it can be estimated by the six models.

For simplifying comparisons among models, the bias ratios are averaged over time to determine mean deviations (MDs). However, the MD can be 0.0 when positive and negative bias ratios are equally large. We wish to have a criterion that is also large in this circumstance. Therefore, we also calculate mean absolute deviations (MADs) by taking the absolute values of the bias ratios and averaging them over time. The MAD is thus a combined measure of bias and variability across time for each parameter. The MADs and MDs from the 50 replicates are displayed using notched boxplots to facilitate graphic comparison among the six models. Overlapped notches indicate that differences are not statistically significant between two models, whereas non-overlap indicates statistical significance. Table 1 provides ranking of the six models under each of the six scenarios based on the mean of MADs in spawning biomass, the quantity of most concern in the stock assessment. A positive sign (+) following the average MAD for spawning biomass indicates that the model performs significantly better (produces lower MADs) than the next best model, otherwise, the difference is not statistically significant.

ParameterEstimation for the Five B.C. Herring Stocks

Because of their inferior performance in the simulations, we exclude NASM-1 and NASM-2 (which estimate only a constant natural loss) from subsequent analyses where we fit

NASM-3, NASM-4, EASM-1, and EASM-2 to each of the five B.C. herring stocks. The model assumes that recruitment occurs at age 2 (r = 2) and the maximum age is 10. Proportions maturing at age are assumed constant over time at 0.03 for age 2, 0.94 for age 3, and 1.0 for age 4 and older in all stocks based on histological analyses of ovaries (Hay and McCarter 1999). We compared the four models for their ability to fit the spawning biomass index, catch in weight, and age composition data, and show their corresponding estimates of recruitment, natural loss, and SB conversion factor.

Results

Simulation-Estimation Experiments Under Scenario 1

NASM-3 results in the lowest absolute mean deviations in spawning biomass SB (average MAD = 0.189, Table 1) (Figure 2) under the scenario of constant spawn index conversion factor with q = 0.7 during the period from 1951 to 1988 and natural loss M varying randomly around 0.4 through the whole period. By estimating q, NASM-4 produces much higher MADs for SB (average MAD = 0.466, the highest among all the models). In contrast, EASM-1 produces higher MADs than EASM-2 by not estimating q. The mean deviations (MDs) indicate that by estimating q, NASM-2 and NASM-4 tend to overestimate SB, whereas by not estimating q, the EASM tends to underestimate SB. The MDs show that both NASM-3 and EASM-2 are nearly unbiased on average.

For the estimates of age 3 abundance (N_3), NASM-3 results in the lowest MADs, but the estimates tend to be negatively biased. EASM-2, though estimating SB well, produces higher MADs for N_3 than EASM-1; the bias ratios tend to be positive for both models. There is no significant difference in MADs for the R estimates among NASM-2, NASM-3, NASM-4, and EASM-1. The MDs for R estimates have similar tendencies to those for N_3 estimates.

Although NASM-3 estimates SB, N_3, and *R* relatively well, the MADs of *M* are high and MDs tend to be negative. These highly negative biases in *M* are eliminated in NASM-4 by estimating *q*. On the other hand, both EASM-1 and EASM-2 estimate the constant *M* well.

Simulation-Estimation Experiments Under Scenario 2

To examine how annual variations in natural loss affect model performance, we allow *M* to vary randomly with a shift in average value from 0.2 prior to 1970 to 0.6 thereafter, while setting *q* at 0.7 for years before 1989. As in Scenario 1, NASM-3 produces the lowest MADs for SB (average MAD = 0.302), but NASM-4 results in significantly lower MADs than NASM-3 for N_3 *R*, and *M* (Figure 3). Also as in Scenario 1, EASM-1, though underestimating SB, has significantly lower MADs and MDs for N_3 and *R* than EASM-2. NASM-4 achieves the lowest MADs for *M* and the estimation is nearly unbiased on average with the MDs averaging 0.0. However, the tendency to overestimate SB, N_3, and *R* undermines the overall performance of this model.

Simulation-Estimation Experiments Under Scenario 3

The tendency of NASM-3 to underestimate N_3, *R*, and *M* in both Scenarios 1 and 2 may result from the false assumption that *q* = 1.0 before 1989, which implicitly assumes that the stock is lower than the actual level. To see how serious the underestimation can become, we further reduced the simulated *q* level for years before 1988; we drew *q* from two log-normal distributions (CV = 0.2) with mean = 0.5 before 1988 and mean = 1.0 thereafter. With *M* varying randomly around 0.4 through the whole period, EASM-2 results in the lowest MADs in SB (mean = 0.247) (Figure 4). NASM-3, which produced the lowest MADs in SB in

Scenarios 1 and 2, falls to second rank with its mean MAD = 0.277. Although NASM-3 is required to use a *q* value that is twice the simulated level (mean = 0.5), it produces significantly lower MADs in SB than all other models. In contrast, EASM-1 that is also required to use *q* = 1.0 is less robust to such violations of assumptions about *q*, producing the highest MADs in SB, even worse than those in Scenario 1.

Simulation-Estimation Experiments Under Scenario 4

As in Scenario 3, we drew *q* from two log-normal distributions (CV = 0.2) with mean = 0.5 before 1988 and mean = 1.0 thereafter but allowed *M* to vary randomly with a shift in average value from 0.2 prior to 1970 to 0.6 thereafter. As in Scenario 3, EASM-2 produces the lowest MADs for SB (mean = 0.339), and NASM-3, the second lowest (mean = 0.378) (Figure 5). As in Scenario 2, NASM-4 results in the lowest MADs for N_3 *R*, and *M* among all the models. Also as in Scenario 3, EASM-1, produces significantly lower MADs and MDs for N_3 and *R* than EAMS-2 but underestimates SB.

Simulation-Estimation Experiments Under Scenario 5

Because the spawn indices from surface and dive surveys are poorly correlated, we simulated additional scenarios where *q* varies randomly and uniformly between 0.5 and 1.5 (mean = 1.0). When *M* varies randomly around 0.4, NASM-3 produces the lowest MADs for SB (mean = 0.233) followed by EASM-1 (mean = 0.244) (Figure 6). The negative bias ratios for SB seen with EASM-1 in the previous scenario now disappear. NASM-3 also produces the lowest MADs for N_3 and *R*. As expected, the tendency to underestimate N_3 and *R* is diminished when *q* varies randomly around 1.0. Although EASM-1 is able to estimate SB well, the tendency to overestimate N_3 and *R* becomes more severe. NASM-3 again tends to underestimate *M* producing higher MADs than all other models except NASM-1. Again, EASM-1 and EASM-2 produce acceptably small MADs for *M*, but tend to be overestimate *M* slightly.

Simulation-Estimation Experiments Under Scenario 6

NASM-3 also produces the lowest MADs for SB (mean = 0.293), again followed by EASM-1 (mean = 0.359) in Scenario 6 (Figure 7), which resembles Scenario 5 except that *M* was allowed to vary randomly with a shift in average value from 0.2 prior to 1970 to 0.6 thereafter. EASM-1 and EASM-2 perform similarly in the estimation of SB, both producing significantly lower MADs for SB than all other models except NASM-3. As expected, the underestimation of N_3 and *R* by NASM-3 diminishes when *q* varies around 1.0. The MADs for N_3 from NASM-3 are significantly lower than those from other models. MADs for *R* and *M* are similar between NASM-3 and NASM-4, and significantly lower than those from all other models (which do not estimate annual variations in *M*). Although NASM-3 tends to underestimate *M* compared with NASM-4, it performs better than NASM-3 in estimating N_3 and *R*. In general, for scenarios with significant trends in natural loss (mortality or emigration), NASM- 3 and NASM-4 (which explicitly estimate annual variations in *M*) should out-perform the other models.

A general conclusion from all scenarios is that the estimates of N_3 and *R* from the NASM models, which do not account explicitly for the varying availability to the fishery of age 2 and 3 herring, are just as reliable as those from the EASM models which explicitly account for availability.

Stock Reconstruction and Parameter Estimation for the QCI Stock

The QCI herring stock is reconstructed using the four models (NASM-3, NASM-4, EASM-1, and EASM-2) of greatest interest and likely utility. We interpret the alternative stock reconstructions with reference to the simulation-estimation results from Scenario 6 (Figure 7) which we consider most plausible for the QCI stock. The simulation-estimation experiments indicate that SB tends to be slightly overestimated by NASM-3 but slightly underestimated by EASM-1, and these two models provide better SB estimates than their counterparts, NASM-4 and EASM-2 (Figure 7). Indeed, the SB estimates from NASM-3 tend to be higher than those from EASM-1, even though they are rather close in most years (Figure 8, Appendix 2). Based on the simulations, the true values could lie between the solid and dashed lines (Figure 8, Column 1). NASM-4 results in much higher SB estimates (Figure 8, Column 2), a result expected from the simulations.

Catch estimates from NASM-3 fit the observations better than those from EASM-1. Catch estimates varied only slightly under different assumptions about *q*. The simulation-estimation experiments indicate that NASM-3 provides the most accurate and nearly unbiased estimates of *R*, whereas EASM-1 tends to overestimate *R* (Figure 8, Column 1). Nevertheless, the pattern of recruitment peaks is consistent between the two models. Consistent with simulation results, NASM-4 produces higher estimates of *R* than NASM-3 but the overestimation is less severe than with EASM-1 or EASM-2. Therefore, estimates of *R* from NASM-3 are probably credible. As in the simulations, estimates of *M* from NASM-4 are generally higher than those from NASM-3, and are likely to be closer to the actual values, but as with estimates of *R*, the pattern of variations in the estimated time series of *M* is similar for NASM-3 and NASM-4. The estimated time series of *M* seems to have an increasing trend during the last decade, which is consistent with the recently observed decline in stock size.

The estimated q is lower for NASM-4 than for EASM-2 (Figure 8, Column 2), as shown in the simulation-estimation experiments.

Although the simulation-estimation experiments with NASM-3 do not reveal greater biases in the estimates of age-2 (recruitment) and age-3 abundances than with all other models, but the estimated proportions at ages 2 and 4 from NASM-3 tend to be higher than the observed values (Figure 9). This could be due partially to the fact that NASM-3 falsely assumes 100% availability for these three age classes. On the other hand, EASM-1 tends to underestimate the proportions at these three ages (Table 3). Both NASM-3 and EASM-1 underestimate the proportions at ages from 5 to 9 and overestimate that of age 10 (Table 3). Age composition estimates from NASM-4 and EASM-2 resemble those from NASM-3 and EASM-1, respectively.

Due to concerns that data may be inconsistent between the reduction fishery period before 1972 and the roe fishery period afterwards, the models were also fitted to data sets that excluded years before 1972. For NASM-3 and EASM-1, the estimates of SB based on just the recent data (Figure 10) are lower than those based on the whole time series (Figure 8). For NASM-4 and EASM-2, q is estimated to be higher for the recent period relative to the whole series (Figure 10, Column 2). This suggests that data after 1972 are more consistent with those after 1988 than the data prior to 1972. The estimates of R from NASM-3 and NASM-4 are lower for the recent period relative to the whole series. Nevertheless, the patterns in all parameter estimates are similar using either data set.

Stock Reconstruction and Parameter Estimation for the PRD Stock

Compared with parameter estimation results for the QCI stock, the most remarkable result for the PRD stock is that the estimates of annual natural loss are consistently lower (by about 0.2) for EASM-1 than for NASM-3 (Figure 11, Column 1), contrary to our expectation from the simulation-estimation experiments under Scenario 6 (Figure 7). The lower estimates of *M* from EASM-1 are associated with lower estimates of *R*, which again contradicts our expectation from the simulation-estimation experiments. However, if the relative weight on catch-at-age is reduced, the estimates of *R* and *M* are increased, and the fit to catch and SB improved, but the residuals for age composition in Figure 12 become larger. Nevertheless, we retain the original weightings under our original assumption that CVs are identical among the five stocks, but it is worth noting that the estimates of SB, *R*, and *M* from EASM-1 could be negatively biased. Again, NASM-4 overestimates SB and *R* (Appendix 3, Figure 11, Column 2). The estimates of *M* from NASM-4 are generally higher than those from NASM-3, but they may represent the actual *M* values better, as expected from the simulation results. EASM-1 and EASM-2 produce lower residuals in age composition than NASM-3 and NASM-4 (Figure 12). NASM-3 and NASM-4 greatly overestimate the proportion at age 4 but underestimate those at higher ages (Table 3). Similar parameter estimates are obtained using only the recent data series (after 1972) (Figure 13 compared to Figure 11). As for the QCI stock, the estimate of *q* from NASM-4 (Figure 13, Column 2) is higher for the recent series than for the whole series (Figure 11), again suggesting more consistency in data after 1972.

Stock Reconstruction and Parameter Estimation for the CC Stock

As for the PRD stock, the estimates of natural loss from EASM-1 are consistently lower than those from NASM-3 (Figure 14, Column 1). Consequently, recruitment estimates from EASM-1 also tend to be lower than those from NASM-3. NASM-3 fits the catch data better than EASM-1. Again, if the relative weight on catch-at-age in EASM-1 is reduced, the fit to catch is improved, the estimates of *M* and *R* are increased, but residuals for age composition become larger. Estimating *q* causes NASM-4 to overestimate SB (Appendix 4) and *R*, and to underestimate *q*, but the estimates of *M* may be more realistic (Figure 14, Column 2), as in the simulation-estimation experiments. Patterns in the residuals for age composition from all models (Figure 15, Table 3) are similar to those in the PRD stock with EASM-1 and EASM-2 producing low residuals. Restricting analysis to the recent data series since 1972 did not change parameter estimates appreciably for any model (Figure 16).

Stock Reconstruction and Parameter Estimation for the GS Stock

Estimates of SB from NASM-3 and EASM-1 for the GS stock show smaller discrepancies (Appendix 5, Figure 17) than for the previous three stocks, and both series of estimates fit the SB index data well. NASM-3 fits catch data better than EASM-1. The recruitment estimates from EASM-1 tend to be higher than those from NASM-3, again consistent with the simulation results under Scenario 2. The estimates of *M* from NASM-3 and EASM-1 are also very close on average (Figure 17, Column 1). When *q* is estimated (Figure 17, Column 2), the estimates of SB, *R*, and *M* from EASM-2 are reduced because *q* is estimated to be much larger than 1.0. In contrast, NASM-4 estimates *q* to be close to 1.0, and thus the parameter estimates from NASM-3 and NASM-4 are nearly equivalent. The residuals for age composition from NASM-3 and NASM-4 are smaller for the GS stock than for the previous three stocks (Figure 18, Table 3). The overestimation of proportion at age 4 is greatly reduced for this stock compared to other stocks (Table 3), which may imply that age 4 herring in GS are more completely available to the fishery. Parameter estimates are not changed significantly by analyzing only the recent data series since 1972 (Figure 19).

Stock Reconstruction and Parameter Estimation for the WCVI Stock

As for the GS stock, estimates of SB from NASM-3 and EASM-1 are similar (Appendix 6, Figure 20, Column 1) and NASM-3 fits the catch data better than EASM-1. Recruitment estimates from EASM-1 are generally higher than those from NASM-3. The estimates of *M* from NASM-3 are unique for the WCVI stock in the sense that natural loss peaks every 13 to 15 years. These cyclic peaks in *M* persist even if *q* is estimated by NASM-4. On average, the *M* levels are similar to those in the QCI and GS stocks. The estimate of *q* by NASM-4 is around 0.7, so the SB estimates from NASM-4 are likely to be less biased for WCVI (Figure 20, Column 2) than those for QCI, PRD, and CC. The estimates of *R* from EASM-2 are not consistently higher than those from NASM-4. Overestimation of proportion at age 4 in the age composition data is less frequent (Figure 21) and the cumulative difference is smaller (Table 3) in this stock than in the QCI, PRD, and CC stocks to the north. A much smaller *q* value (0.8 vs 1.2) is estimated by EASM-2 using only data from the recent period (after 1972); other parameter estimates are not much affected (Figure 22).

Discussion

Simulation-estimation experiments presented in this paper allow us to evaluate the performance of different stock assessment models under various scenarios. This paper focuses only on scenarios that differ in two parameters – the spawn index conversion factor *q* which is very uncertain and controversial, and the rate of natural loss which is very influential in fish population dynamics. Three general conclusions can be drawn from the simulation-estimation experiments. (1) If *q* changes from one constant value to another and the time of change is known (as simulated here), model selection becomes difficult because no single model performs consistently better on all measures. For example, NASM-3 provides better estimates of SB and N_3 but poorer estimates of *M* on average. Similarly, EASM-2 provides better estimates of SB but poorer estimates of N_3 and *R*. (2) If *q* changes randomly around 1.0, NASM-3 performs better than or at least as well as all other models in estimating SB, N_3, and *R*. Neither EASM-1 nor EASM-2 could be considered superior to one another based on MADs and MDs for the estimated parameters. (3) When the mean value of *M* changes drastically from one period of time to another (i.e., regime shift), NASM-3 and NASM-4 (which account for annual variations in *M*) perform significantly better for all parameters than their counterpart models (i.e., EASM-1 and EASM-2). However, if *M* changes only randomly round a constant level, the advantage of estimating annual variations in *M* becomes less obvious. Haist et al. (1993) parameterized *M* as a function of SB and obtained a statistically better fit to the data than assuming a constant *M*, which led them to conclude that *M* was density-dependent with higher *M* at lower SB. In our analysis, variations in *M* are estimated explicitly. The correlation between the estimates of *M* and SB are negative for all five stocks with values of -0.55, -0.55, -0.48, -0.22, and -0.36 for the QCI, PRD, CC, GS, and WCVI stocks, respectively. However, the correlation between the estimated *M* and the observed SB index is neither consistently negative nor significant with values of -0.12, -0.12, 0.11, -0.04, and 0.04 for the above five stocks.

For three of the five stocks (QCI, GS and WCVI), the differences in parameter estimates were as expected from the simulation results under Scenario 6, and we are reasonably confident in identifying the most plausible reconstructions. For the PRD and CC stocks, the inconsistencies with our expectations from the simulations can be eliminated when the relative weight on catch-at-age data is reduced in EASM-1 and EASM-2, suggesting that the sampling errors in the catch-at-age data might be relatively higher in PRD and CC than in other stocks.

Because the main purpose of this paper is to compare the performance of the new and existing models, the simulation-estimation experiments investigate only two relevant parameters, *q* and *M*. Once the Pacific Scientific Advice Review Committee has determined which model to recommend, we suggest that more thorough simulation-estimation experiments be undertaken with the preferred model to investigate the relative merits of other options for representing error structures, likelihood functions, data discontinuity, and stock-recruitment relationships in both the simulation and the estimation procedures. The NASM does provide options for different likelihood functions and stock-recruitment relationships and offers the flexibility to use time-varying sampling errors. In addition, the NASM has a Bayesian framework which can provide estimates of uncertainty for use in risk assessment and decision-making processes in the future. Overall, NASM-3 seems promising based on the simulation results. Its tendency to overestimate the proportion at age 3 in the age composition in all the five stocks suggests that more appropriate selectivity functions should be used. Richards et al. (1997) suggested using selectivity functions with more than two parameters to provide a better fit to the data after they encountered similar overestimation for proportions of the second and third vulnerable age classes of Pacific ocean perch (*Sebastes alutus*). If this model is to be used for future stock assessment and risk assessment, a further investigation into different selectivity functions is warranted.

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Table 1. Model ranking based on the mean absolute deviation (MAD) in spawning biomass under each of the six simulation scenarios. An absolute deviation of 1.0 is equivalent to a 100 percent deviation in estimated spawning biomass. A "+" indicates that model performance was significantly better statistically than the next best model.

q=0.7 before 1988, and 1.0 thereafter				q log-normal distributions with mean=0.5 before 1988 and 1.0 thereafter				q uniformly distributed between 0.5 and 1.5 throughout			
M: mean = 0.4 throughout		*M*: < 1970 mean=0.2 >= 1970 mean = 0.6		*M*: mean = 0.4 throughout		*M*: < 1970 mean=0.2 >= 1970 mean = 0.6		*M*: mean = 0.4 throughout		*M:* < 1970 mean=0.2 >= 1970 mean = 0.6	
Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5		Scenario 6	
NASM3	0.189+	NASM3	0.302+	EASM2	0.247+	EASM2	0.339+	NASM3	0.233+	NASM3	0.293+
EASM2	0.221+	EASM2	0.347+	NASM3	0.277+	NASM3	0.378	EASM1	0.244	EASM1	0.359
NASM1	0.326+	NASM4	0.395+	NASM2	0.385+	NASM4	0.402+	NASM1	0.258	EASM2	0.378+
EASM1	0.372	EASM1	0.467+	NASM4	0.471+	NASM2	0.559+	EASM2	0.307+	NASM4	0.455+
NASM2	0.411+	NASM2	0.566+	NASM1	0.514+	NASM1	0.708	NASM2	0.419+	NASM2	0.565
NASM4	0.466	NASM1	0.645	EASM1	0.690	EASM1	0.743	NASM4	0.505	NASM1	0.579

Table 2. List of parameters estimated by NASM and EASM.

Parameters	NASM-1	NASM-2	NASM-3	NASM-4	EASM-1	EASM-2
Virgin recruitment (R_0)	1	1	1	1		
$\overline{R}$ in NASM or $\overline{N}$ in EASM	1	1	1	1	1	1
Deviations of R_0 and $\overline{R}$ or $\overline{N}$	61	61	61	61	61	61
Full recruit fishing mortality					65	65
gillnet selectivity r and t					2	2
Gear selectivity parameter g_g	2	2	2	2		
Gear selectivity parameter $a_{g,t}^{50}$	65	65	65	65		
Availability curve slope					1	1
Age of 50% available to fishery					53	53
Natural mortality M	1	1	53	53	1	1
Spawn index conversion factor q		1		1		1
Total number of parameters	**131**	**132**	**183**	**184**	**184**	**185**

Table 3. Cumulative differences between the predicted and observed age composition proportions across all years for ages 2 to 10.

Stock	Model \ Age	2	3	4	5	6	7	8	9	10	**Total**
QCI	NASM-3	0.195	0.570	3.566	-1.096	-1.608	-1.199	-0.492	-0.150	0.217	**0.004**
	EASM-1	-0.040	-3.752	-0.230	-0.207	-1.084	-0.721	-0.223	-0.014	0.265	**-6.005**
	NASM-4	0.167	-0.148	3.734	-0.834	-1.464	-1.119	-0.444	-0.127	0.238	**0.002**
	EASM-2	-0.043	-3.622	-0.251	-0.286	-1.126	-0.728	-0.229	-0.007	0.289	**-6.003**
PRD	NASM-3	0.547	-0.473	5.169	-1.330	-2.396	-1.178	-0.351	-0.103	0.115	**0.000**
	EASM-1	-0.095	-1.351	0.904	-0.140	-0.703	-0.235	0.181	0.149	0.289	**-1.001**
	NASM-4	0.510	-0.462	5.117	-1.310	-2.368	-1.164	-0.343	-0.099	0.119	**0.001**
	EASM-2	-0.085	-1.362	0.908	-0.151	-0.717	-0.238	0.183	0.155	0.301	**-1.005**
CC	NASM-3	0.382	0.772	3.584	-1.479	-1.810	-1.078	-0.374	-0.133	0.135	**-0.001**
	EASM-1	-0.440	-0.246	1.121	-0.150	-0.091	-0.234	-0.057	-0.033	0.133	**0.003**
	NASM-4	0.086	0.837	3.547	-1.340	-1.743	-1.053	-0.360	-0.126	0.149	**-0.002**
	EASM-2	-0.408	-0.244	1.114	-0.166	-0.098	-0.235	-0.056	-0.032	0.135	**0.009**
GS	NASM-3	0.222	0.381	0.931	-0.740	-0.553	-0.203	-0.070	0.003	0.026	**-0.005**
	EASM-1	0.669	-0.265	-0.202	-0.125	-0.045	-0.041	-0.024	0.009	0.022	**-0.001**
	NASM-4	0.199	0.396	0.938	-0.739	-0.552	-0.203	-0.070	0.003	0.025	**-0.004**
	EASM-2	0.590	-0.203	-0.204	-0.090	-0.040	-0.050	-0.032	0.004	0.017	**-0.008**
WCVI	NASM-3	0.642	-0.627	2.782	-0.434	-1.256	-0.762	-0.341	-0.067	0.056	**-0.007**
	EASM-1	-0.574	-2.366	-0.385	-0.265	-0.279	-0.281	-0.103	0.070	0.185	**-3.997**
	NASM-4	0.606	-0.622	2.798	-0.418	-1.251	-0.761	-0.341	-0.067	0.054	**-0.002**
	EASM-2	-0.416	-2.463	-0.437	-0.274	-0.279	-0.282	-0.104	0.069	0.183	**-4.003**

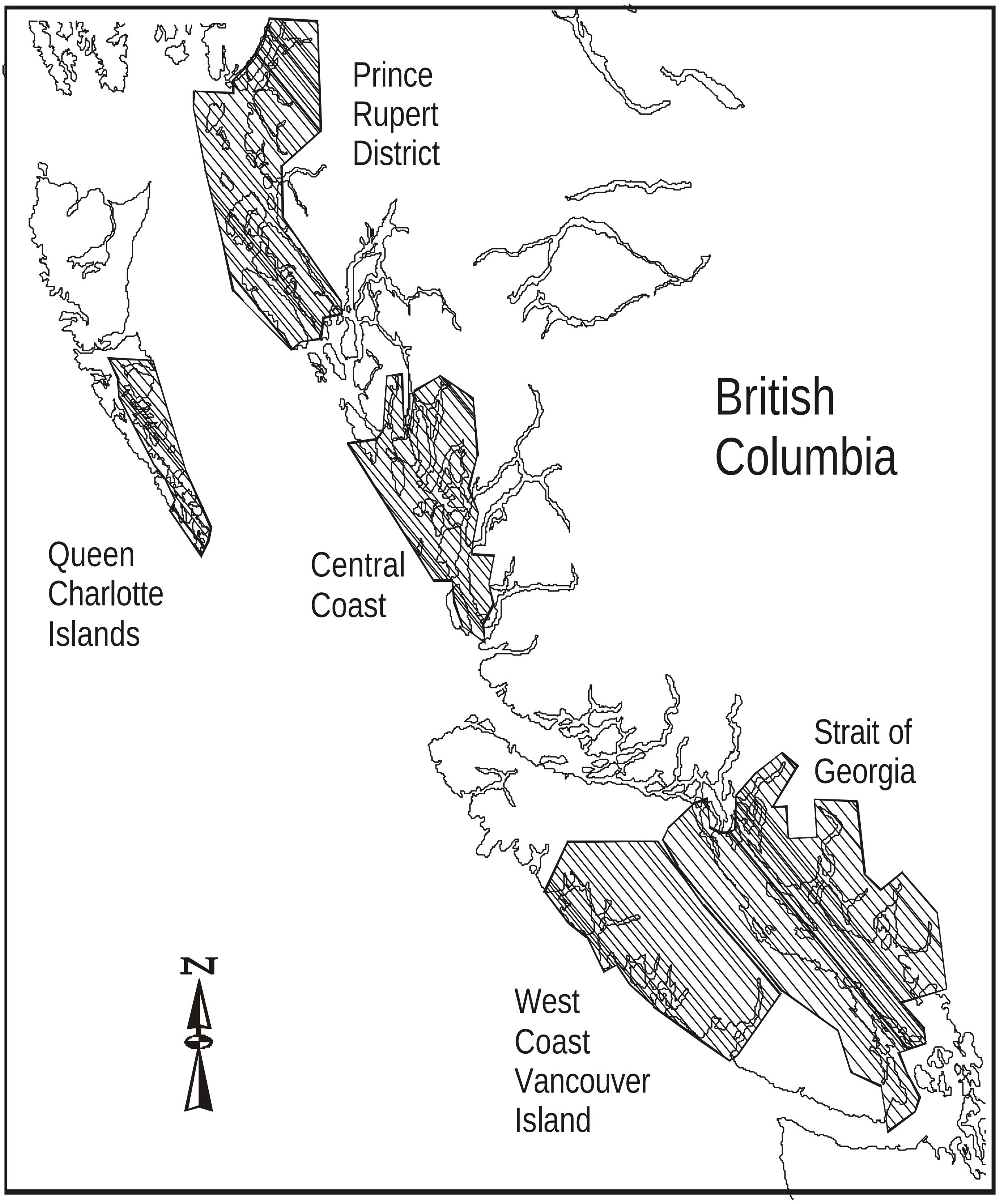
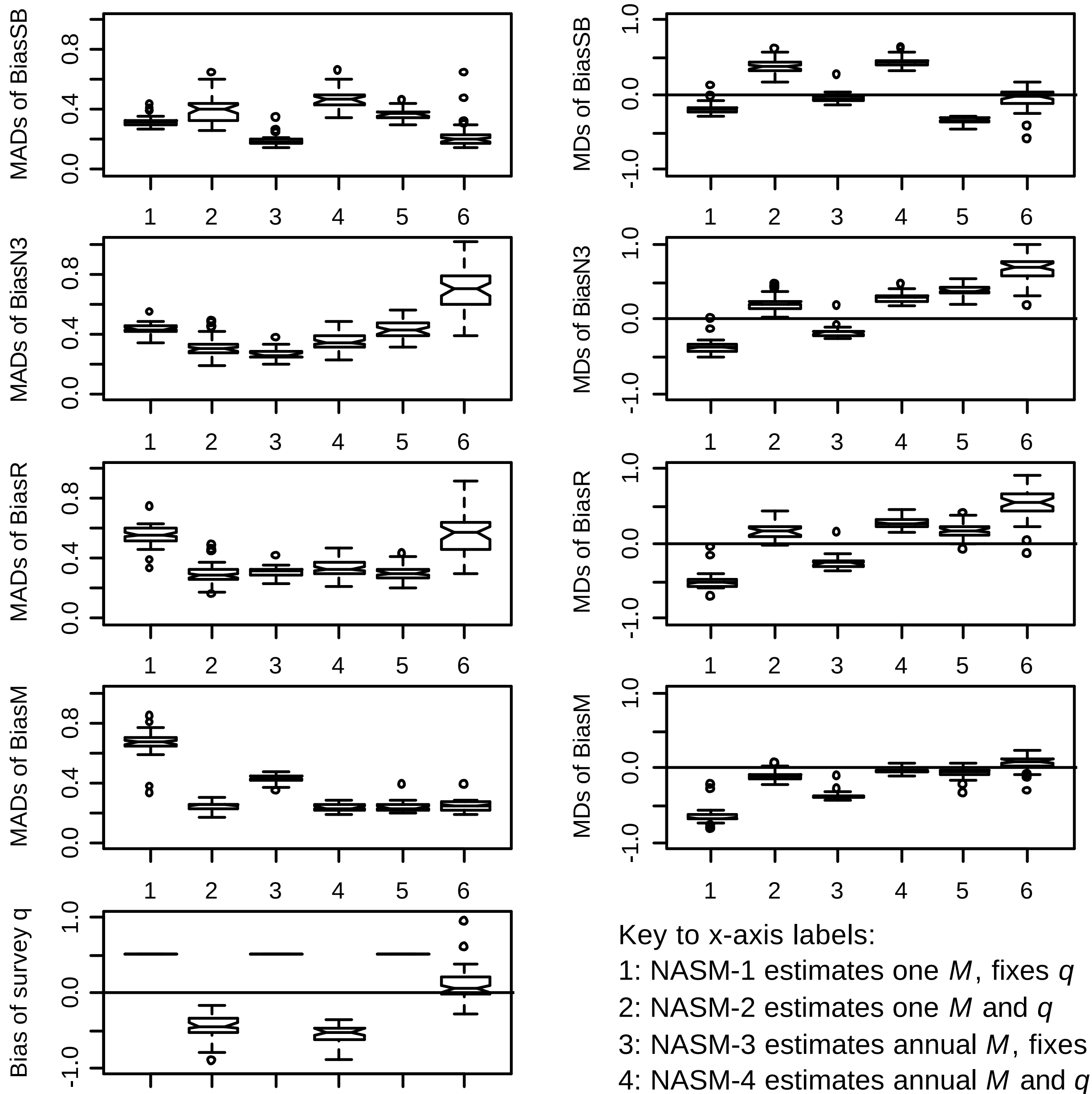


Figure 1. Herring stock assessment regions in British Columbia, Canada.

Simulation results under Scenario 1:
q = 0.7, M from a log-normal distribution (mean = 0.4, CV = 0.2)



Key to x-axis labels:
1: NASM-1 estimates one *M*, fixes *q*
2: NASM-2 estimates one *M* and *q*
3: NASM-3 estimates annual *M*, fixes *q*
4: NASM-4 estimates annual *M* and *q*
5: EASM-1 fixes *q*
6: EASM-2 estimates *q*

Figure 2. Results for simulation-estimation under Scenario 1. Mean absolute deviations (MADs) and mean deviations (MDs) of the biases for the estimated spawning biomass (BiasSB), age-3 abundance (BiasN3), recruitment (BiasR), and natural loss (BiasM), and bias for the estimated spawn index conversion factor (q). The simulated q is 0.7 before year 1988 and 1.0 thereafter, and natural loss (M) is from a log-normal distribution with mean = 0.4 and coefficient of variation (CV) = 0.2. The comparisons are for the following six models: (1) NASM-1 estimating one constant M and setting q at 1.0, (2) NASM-2 estimating one constant M and one constant q, (3) NASM-3 estimating annual M and setting q at 1.0, (4) NASM-4 estimating annual M and one constant q, (5) EASM-1 setting q at 1.0, and (6) EASM-2 estimating one constant q.

Simulation results under Scenario 2:
q = 0.7, *M* from log-normal distributions (1950 - 1969: mean = 0.2, CV = 0.2; 1970 - 2003: Mean = 0.6, CV = 0.2)

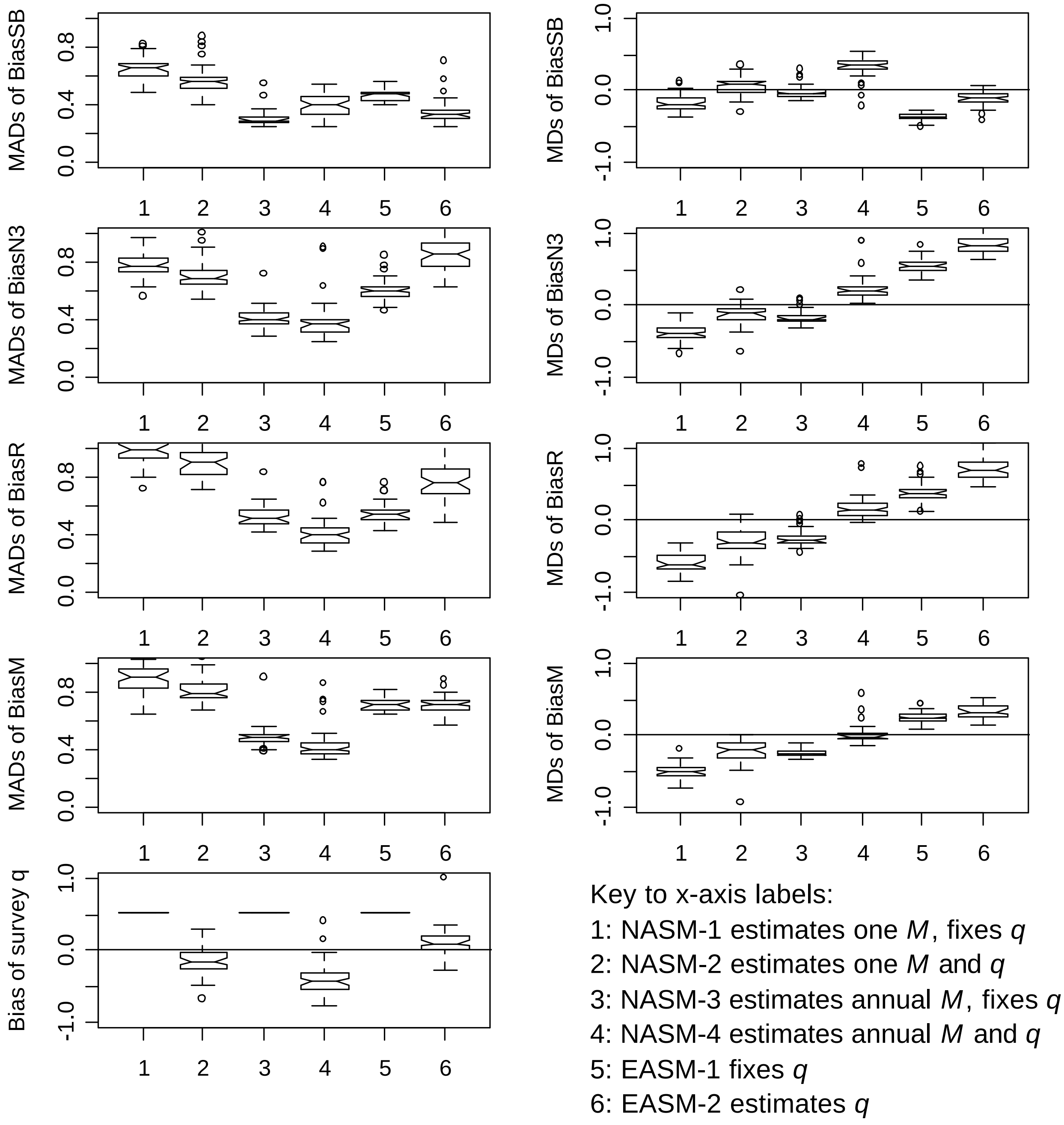


Figure 3. Results for simulation-estimation under Scenario 2. Mean absolute deviations (MADs) and mean deviations (MDs) of the biases for the estimated spawning biomass (BiasSB), age-3 abundance (BiasN3), recruitment (BiasR), and natural loss (BiasM), and bias for the estimated spawn index conversion factor (*q*). The simulated *q* is 0.7 before year 1988 and 1.0 thereafter, and natural loss (*M*) is from log-normal distributions with coefficient of variation (CV) = 0.2 (mean = 0.2 from 1951 to 1969, and 0.6 from 1970 to 2003). The comparisons are for the following six models: (1) NASM-1 estimating one constant *M* and setting *q* at 1.0, (2) NASM-2 estimating one constant *M* and one constant *q*, (3) NASM-3 estimating annual *M* and setting *q* at 1.0, (4) NASM-4 estimating annual *M* and one constant *q*, (5) EASM-1 setting *q* at 1.0, and (6) EASM-2 estimating one constant *q*.

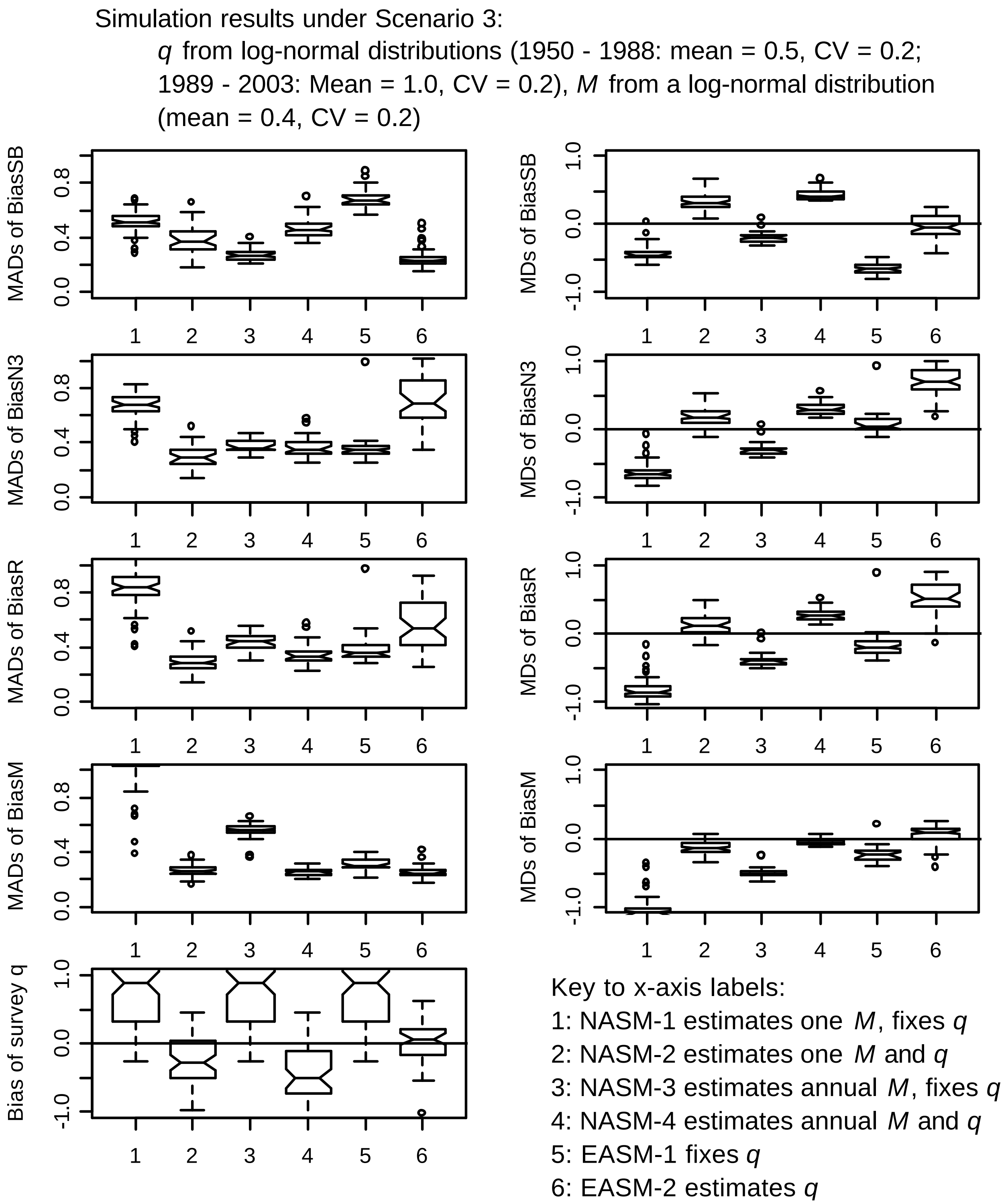


Figure 4. Results for simulation-estimation under Scenario 3. Mean absolute deviations (MADs) and mean deviations (MDs) of the biases for the estimated spawning biomass (BiasSB), age-3 abundance (BiasN3), recruitment (BiasR), and natural loss (BiasM), and bias for the estimated spawn index conversion factor (*q*). The simulated *q* is from log-normal distributions with coefficient of variation (CV) = 0.2 (mean = 0.5 from 1951 to 1988, and 1.0 from 1989 to 2003); and natural loss (*M*) is from a log-normal distribution with mean = 0.4 and CV = 0.2. The comparisons are for the following six models: (1) NASM-1 estimating one constant *M* and setting *q* at 1.0, (2) NASM-2 estimating one constant *M* and one constant *q*, (3) NASM-3 estimating annual *M* and setting *q* at 1.0, (4) NASM-4 estimating annual *M* and one constant *q*, (5) EASM-1 setting *q* at 1.0, and (6) EASM-2 estimating one constant *q*.

Simulation results under Scenario 4:

q from log-normal distributions (1950 - 1988: mean = 0.5, CV = 0.2; 1989 - 2003: Mean = 1.0, CV = 0.2), *M* from log-normal distributions (1950 - 1969: mean = 0.2, CV = 0.2; 1970 - 2003: Mean = 0.6, CV = 0.2)

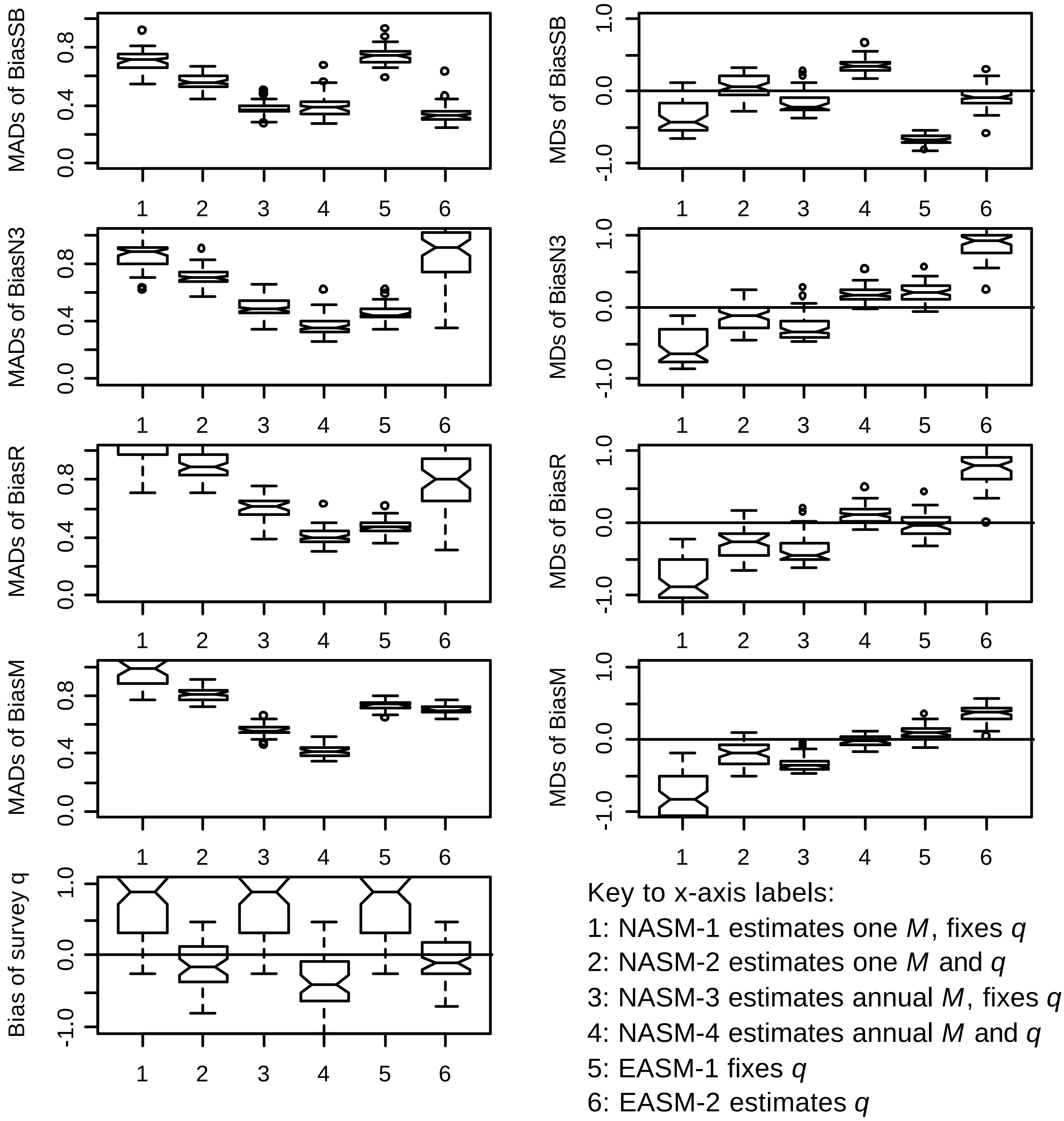


Figure 5. Results for simulation-estimation under Scenario 4. Mean absolute deviations (MADs) and mean deviations (MDs) of the biases for the estimated spawning biomass (BiasSB), age-3 abundance (BiasN3), recruitment (BiasR), and natural loss (BiasM), and bias for the estimated spawn index conversion factor (*q*). The simulated *q* is from log-normal distributions with coefficient of variation (CV) = 0.2 (mean = 0.5 from 1951 to 1988, and 1.0 from 1989 to 2003); and natural loss (*M*) is from log-normal distributions with CV = 0.2 (mean = 0.2 from 1951 to 1969, and 0.6 from 1970 to 2003). The comparisons are for the following six models: (1) NASM-1 estimating one constant *M* and setting *q* at 1.0, (2) NASM-2 estimating one constant *M* and one constant *q*, (3) NASM-3 estimating annual *M* and setting *q* at 1.0, (4) NASM-4 estimating annual *M* and one constant *q*, (5) EASM-1 setting *q* at 1.0, and (6) EASM-2 estimating one constant *q*.

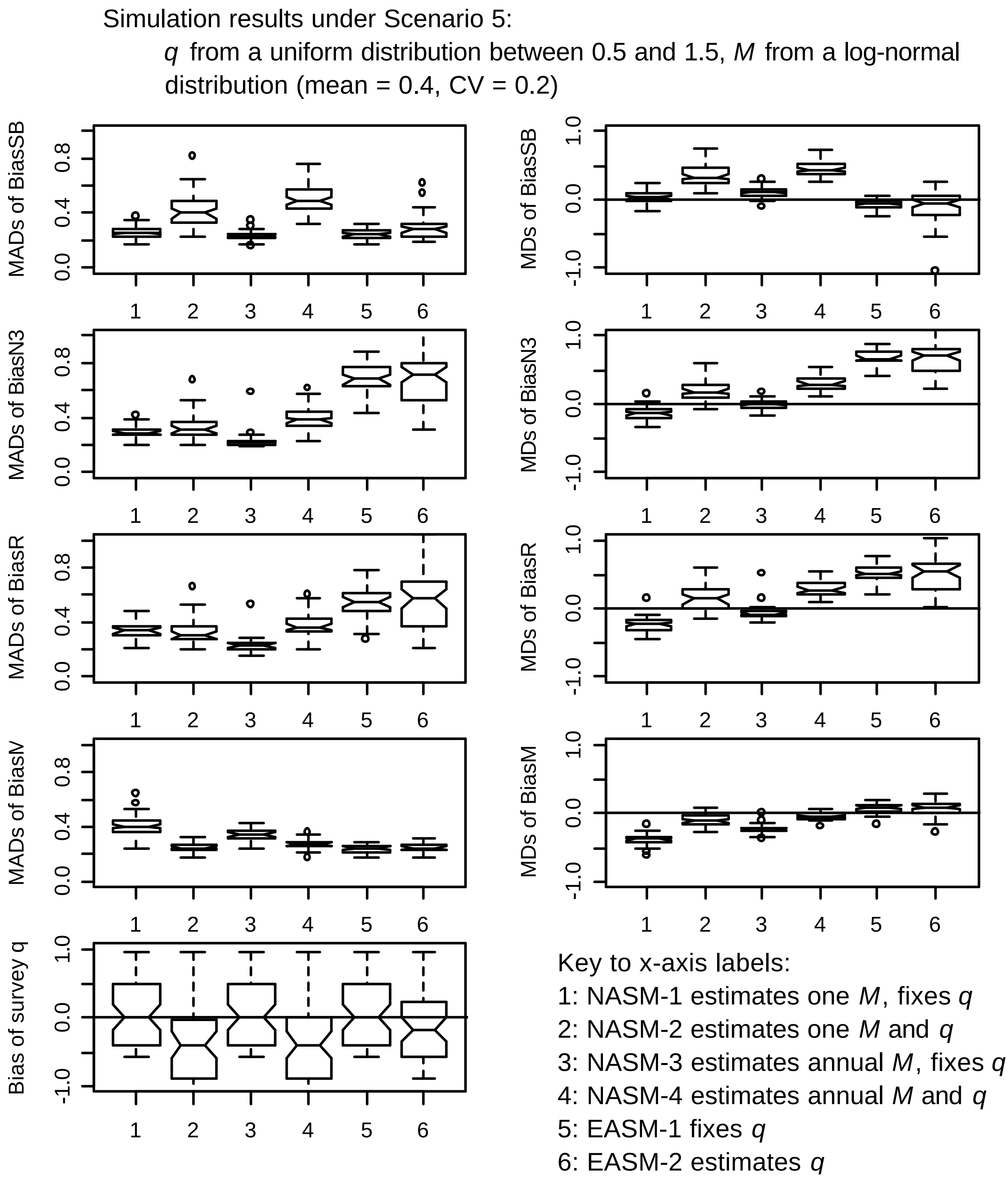


Figure 6. Results for simulation-estimation under Scenario 5. Mean absolute deviations (MADs) and mean deviations (MDs) of the biases for the estimated spawning biomass (BiasSB), age-3 abundance (BiasN3), recruitment (BiasR), and natural loss (BiasM), and bias for the estimated spawn index conversion factor (*q*). The simulated *q* is from a uniform distribution between 0.5 and 1.5, and natural loss (*M*) is from a log-normal distribution with mean = 0.4 and coefficient of variation (CV) = 0.2. The comparisons are for the following six models: (1) NASM-1 estimating one constant *M* and setting *q* at 1.0, (2) NASM-2 estimating one constant *M* and one constant *q*, (3) NASM-3 estimating annual *M* and setting *q* at 1.0, (4) NASM-4 estimating annual *M* and one constant *q*, (5) EASM-1 setting *q* at 1.0, and (6) EASM-2 estimating one constant *q*.

Simulation results under Scenario 6:

q from a unifrom distribution between 0.5 and 1.5, M from log-normal distributions (1950 - 1969: mean = 0.2, CV = 0.2; 1970 - 2003: Mean = 0.6, CV = 0.2)

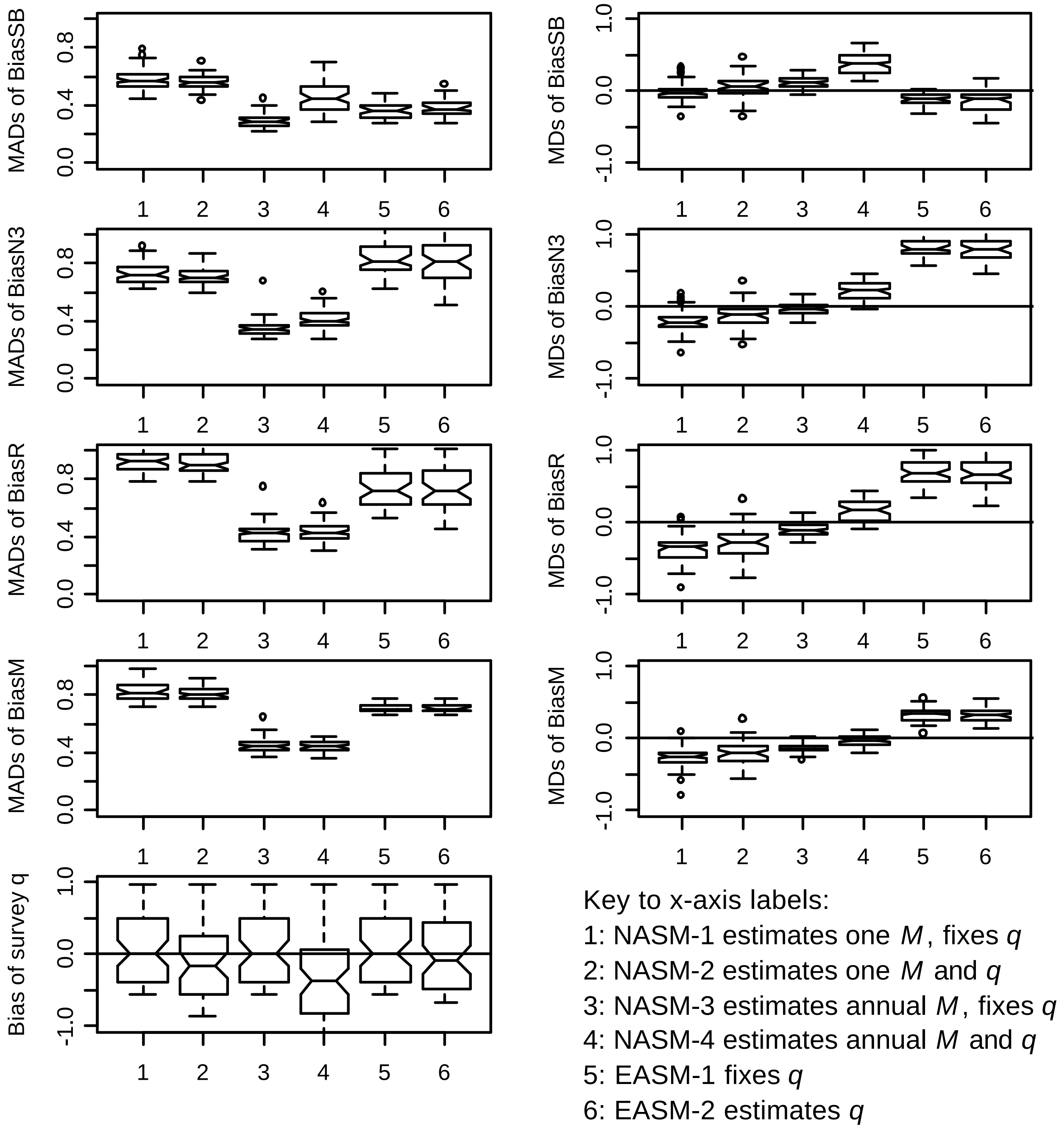


Figure 7. Results for simulation-estimation under Scenario 6. Mean absolute deviations (MADs) and mean deviations (MDs) of the biases for the estimated spawning biomass (BiasSB), age-3 abundance (BiasN3), recruitment (BiasR), and natural loss (BiasM), and bias for the estimated spawn index conversion factor (q). The simulated q is from a uniform distribution between 0.5 and 1.5, and natural loss (M) is from log-normal distributions with coefficient of variation (CV) = 0.2 (mean = 0.2 from 1951 to 1969, and 0.6 from 1970 to 2003). The comparisons are for the following six models: (1) NASM-1 estimating one constant M and setting q at 1.0, (2) NASM-2 estimating one constant M and one constant q, (3) NASM-3 estimating annual M and setting q at 1.0, (4) NASM-4 estimating annual M and one constant q, (5) EASM-1 setting q at 1.0, and (6) EASM-2 estimating one constant q.

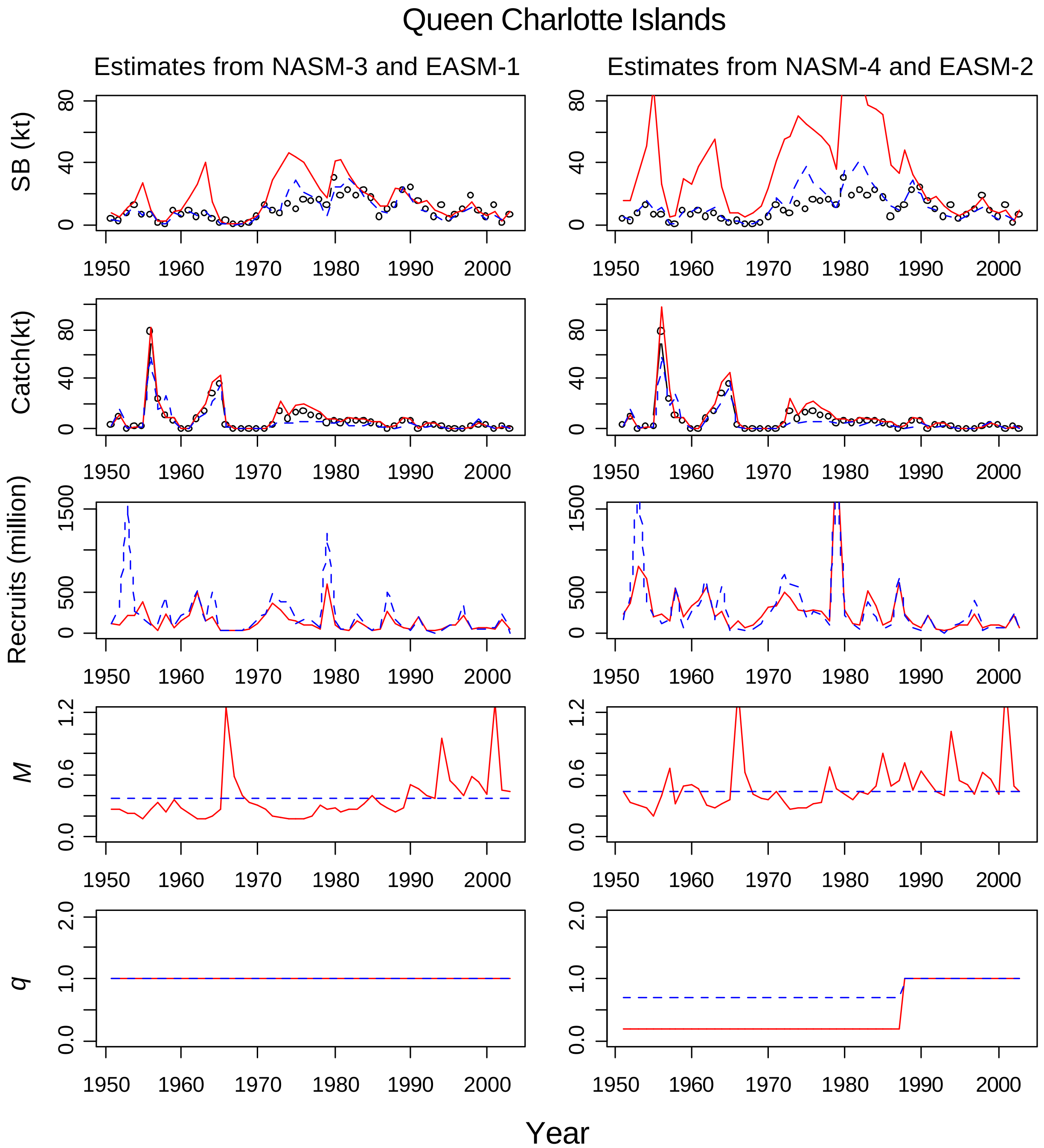


Figure 8. Reconstructions for the QCI herring stock, 1951 – 2003. Estimated spawning biomass (SB), catch, recruits, natural loss (*M*), and spawn index conversion factor (*q*) are compared among four models: Column (1): NASM-3 estimating annual *M* and setting *q* at 1.0 (solid line) and EASM-1 setting *q* at 1.0 (dashed line); Column (2): NASM-4 estimating annual *M* and one constant *q* (solid line) and EASM-2 estimating one constant *q* (dashed line). Circles show reported catch and spawn survey indices.

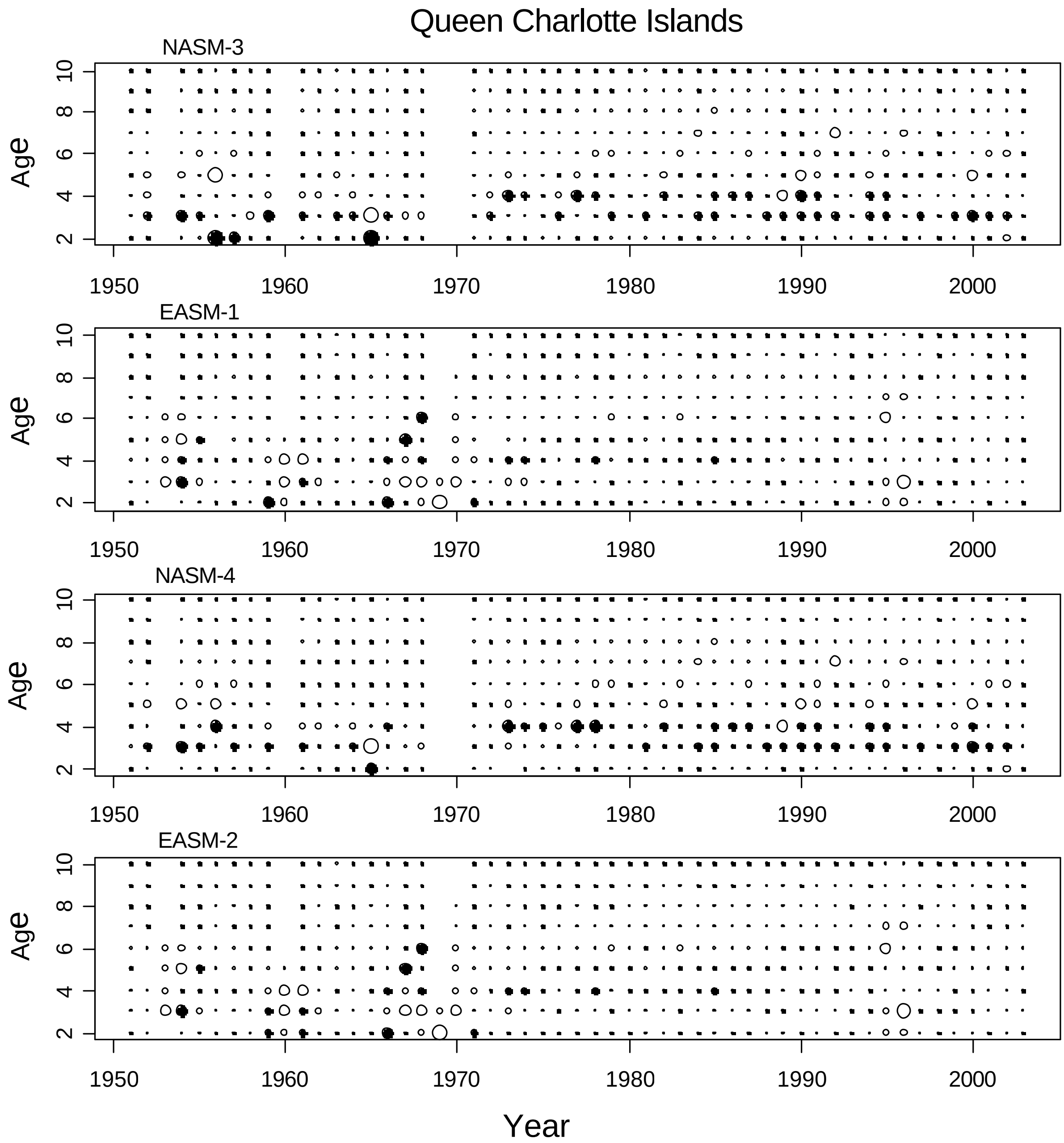


Figure 9. Comparisons of age composition residuals (solid circle for negative and open circle for positive residuals) for the QCI herring stock among four models. Panel (1): NASM-3 estimating annual *M* and setting *q* at 1.0; Panel (2): EASM-1 setting *q* at 1.0; Panel (3): NASM-4 estimating annual *M* and one constant *q*; Panel (4): EASM-2 estimating one constant *q*.

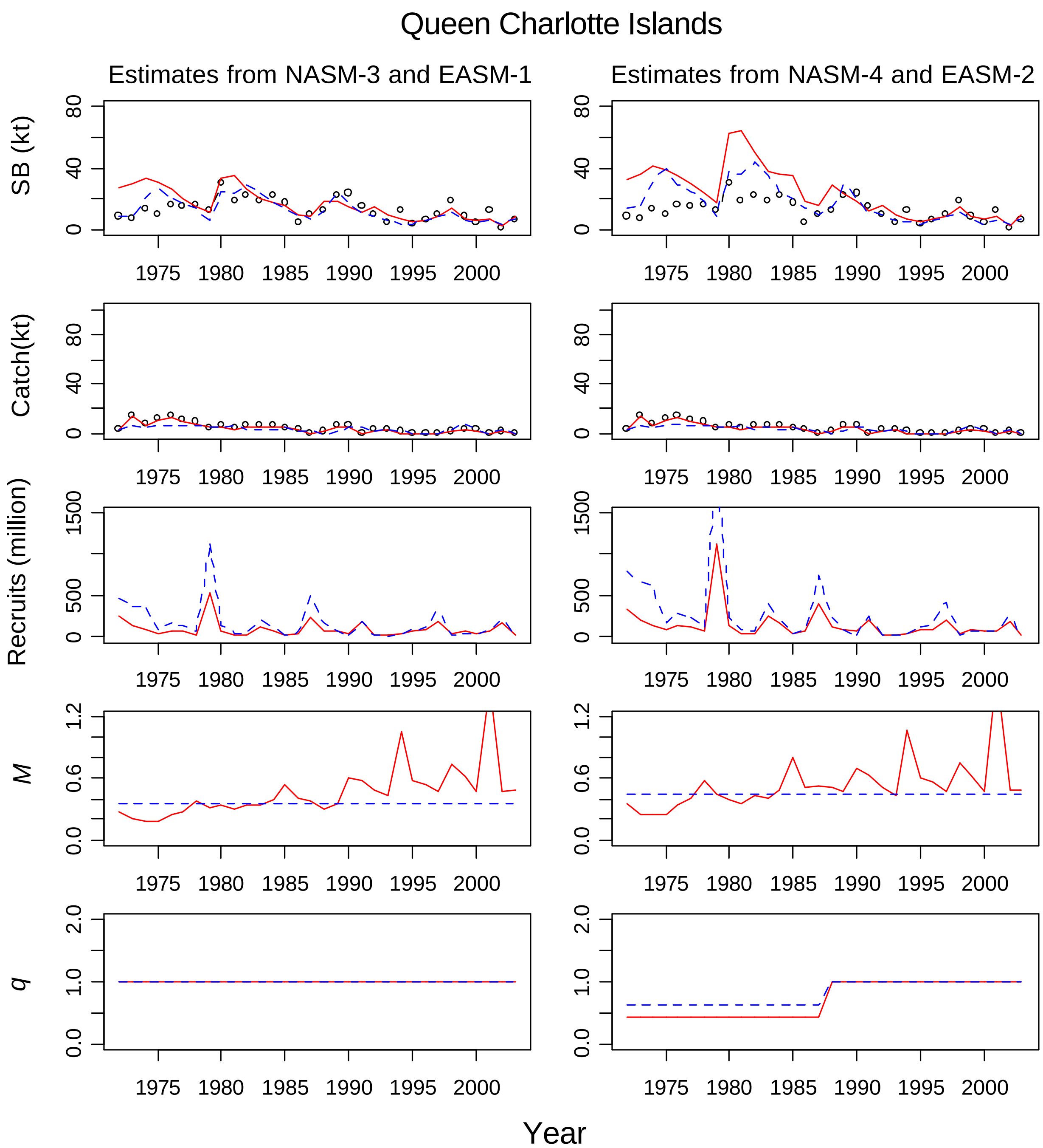


Figure 10. Reconstructions for the QCI herring stock, 1972 – 2003. Estimated spawning biomass (SB), catch, recruits, natural loss (*M*), and spawn index conversion factor (*q*) are compared among four models: Column (1): NASM-3 estimating annual *M* and setting *q* at 1.0 (solid line) and EASM-1 setting *q* at 1.0 (dashed line); Column (2): NASM-4 estimating annual *M* and one constant *q* (solid line) and EASM-2 estimating one constant *q* (dashed line). Circles show reported catch and spawn survey indices.

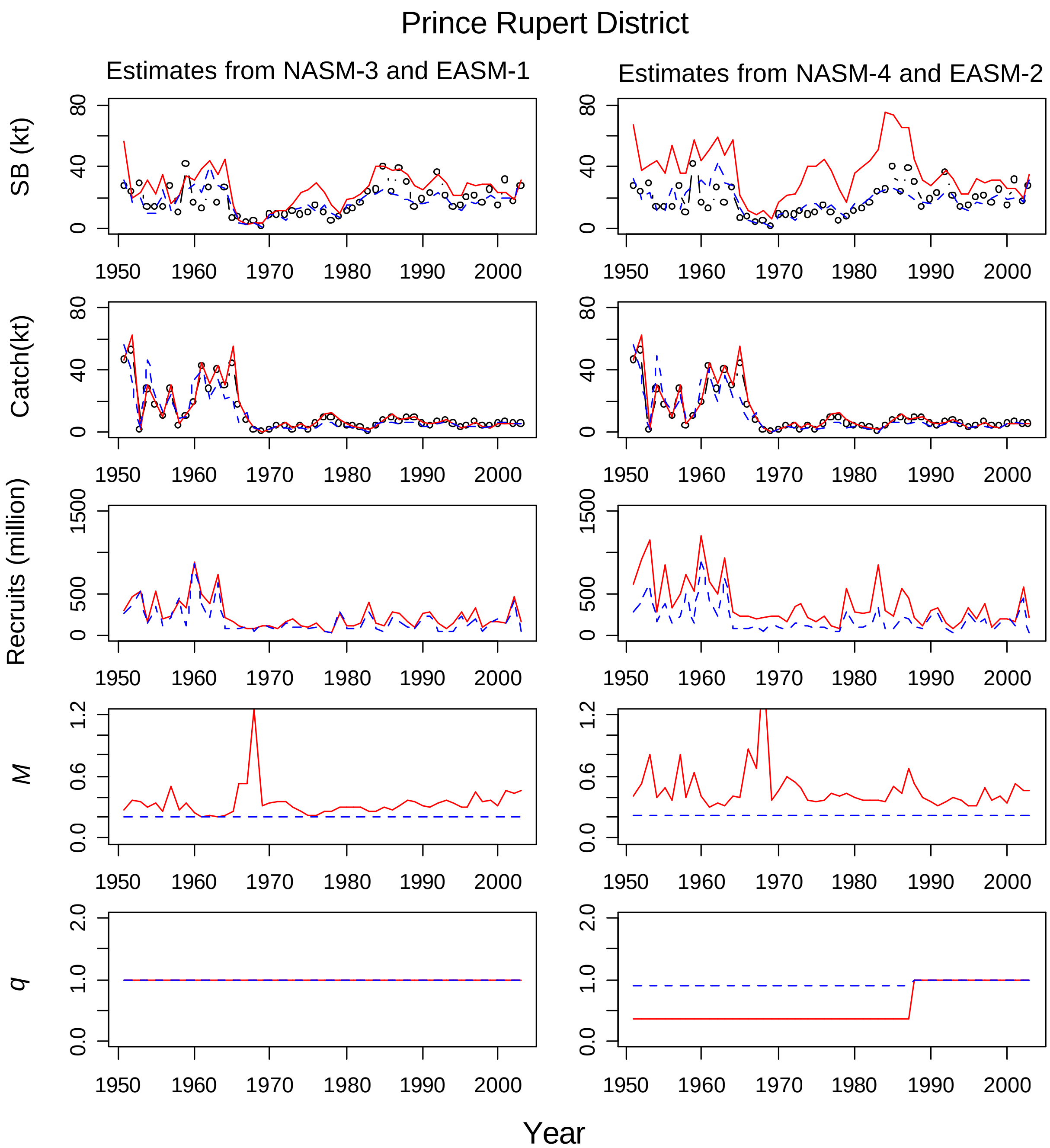


Figure 11. Reconstructions for the PRD herring stock, 1951 – 2003. Estimated spawning biomass (SB), catch, recruits, natural loss (*M*), and spawn index conversion factor (*q*) are compared among four models: Column (1): NASM-3 estimating annual *M* and setting *q* at 1.0 (solid line) and EASM-1 setting *q* at 1.0 (dashed line); Column (2): NASM-4 estimating annual *M* and one constant *q* (solid line) and EASM-2 estimating one constant *q* (dashed line). Circles show reported catch and spawn survey indices.

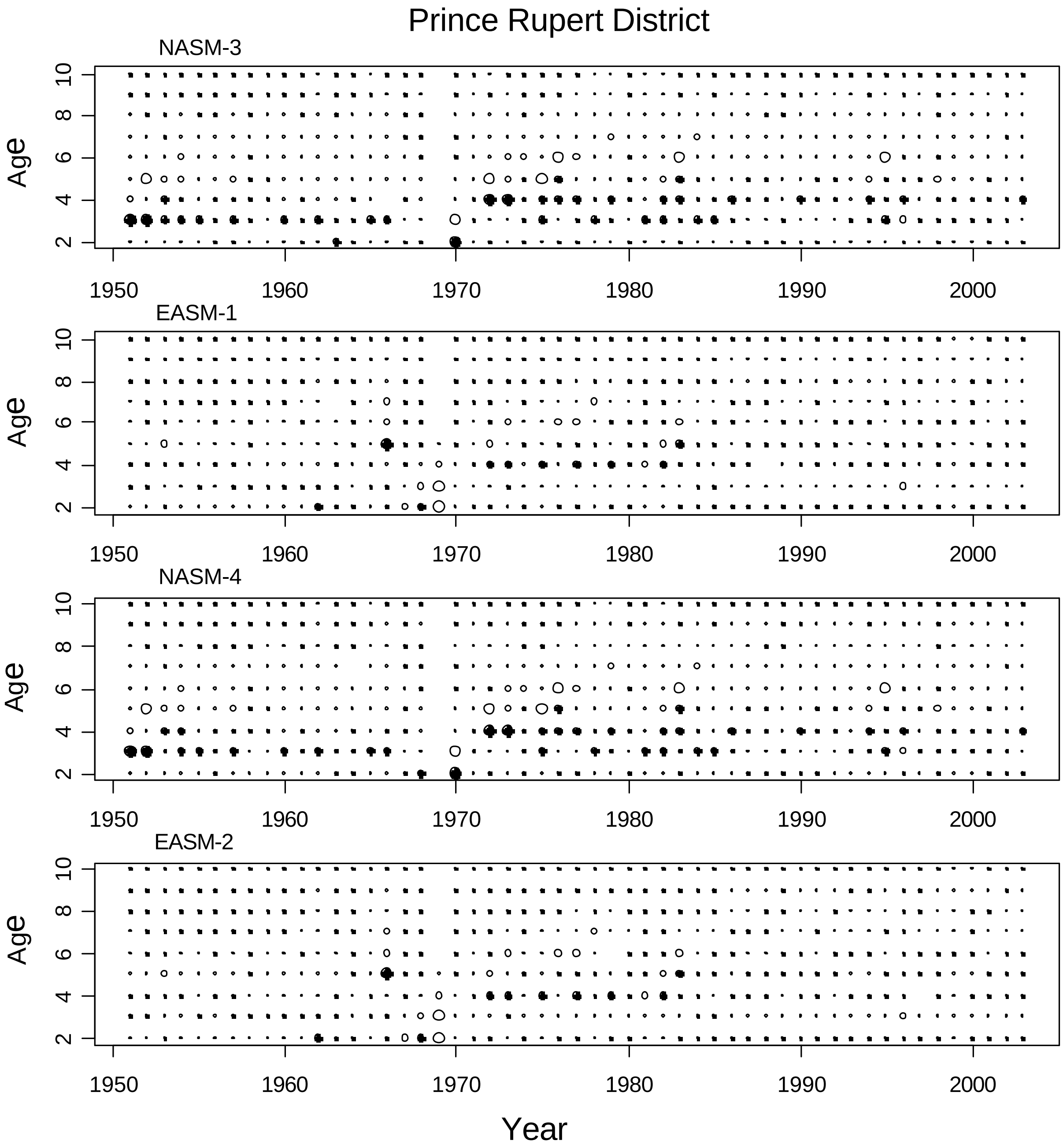


Figure 12. Comparisons of age composition residuals (solid circle for negative and open circle for positive residuals) for the PRD herring stock among four models. Panel (1): NASM-3 estimating annual *M* and setting *q* at 1.0; Panel (2): EASM-1 setting *q* at 1.0; Panel (3): NASM-4 estimating annual *M* and one constant *q*; Panel (4): EASM-2 estimating one constant *q*.

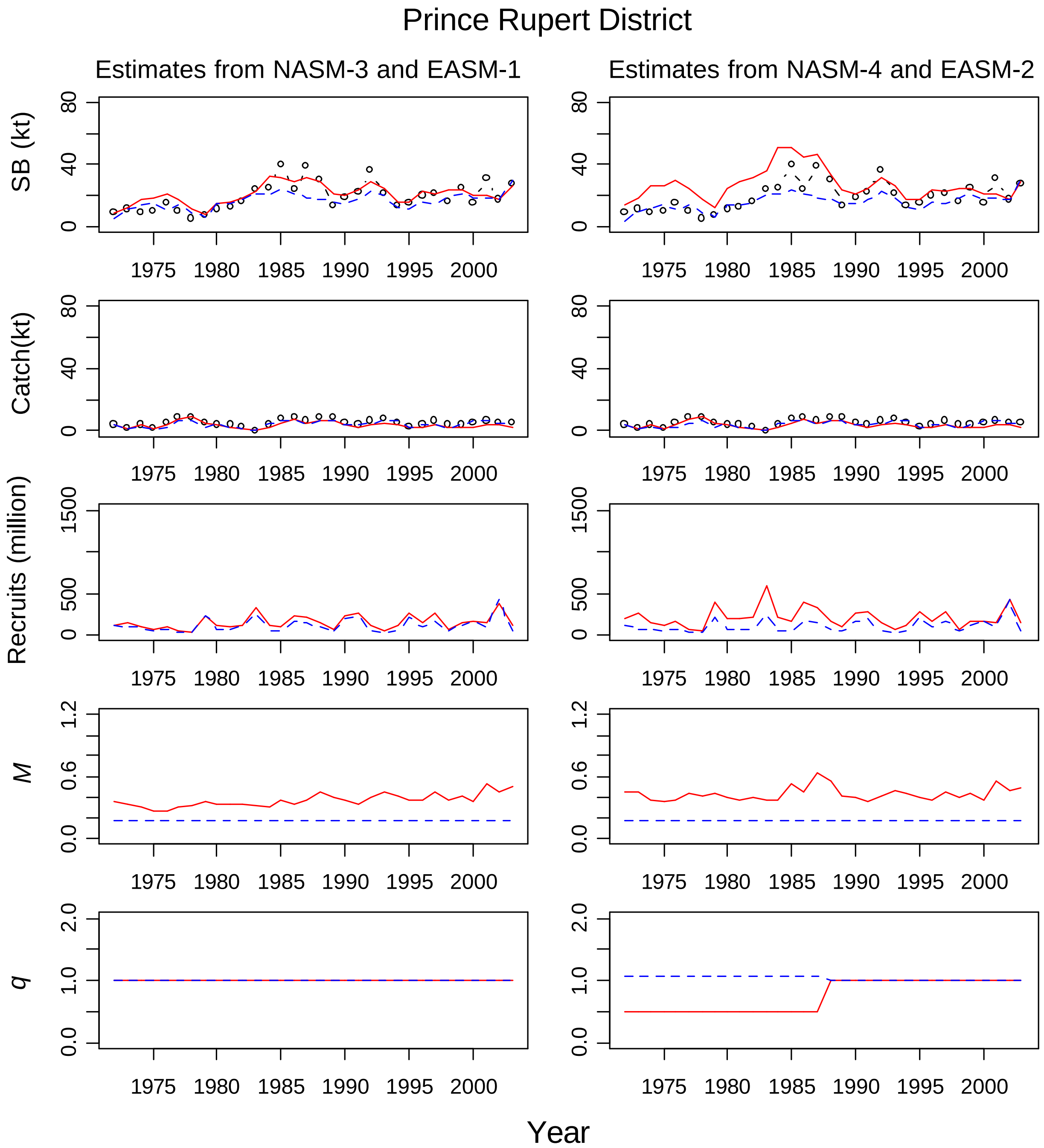


Figure 13. Reconstructions for the PRD herring stock, 1972 – 2003. Estimated spawning biomass (SB), catch, recruits, natural loss (*M*), and spawn index conversion factor (*q*) are compared among four models: Column (1): NASM-3 estimating annual *M* and setting *q* at 1.0 (solid line) and EASM-1 setting *q* at 1.0 (dashed line); Column (2): NASM-4 estimating annual *M* and one constant *q* (solid line) and EASM-2 estimating one constant *q* (dashed line). Circles show reported catch and spawn survey indices.

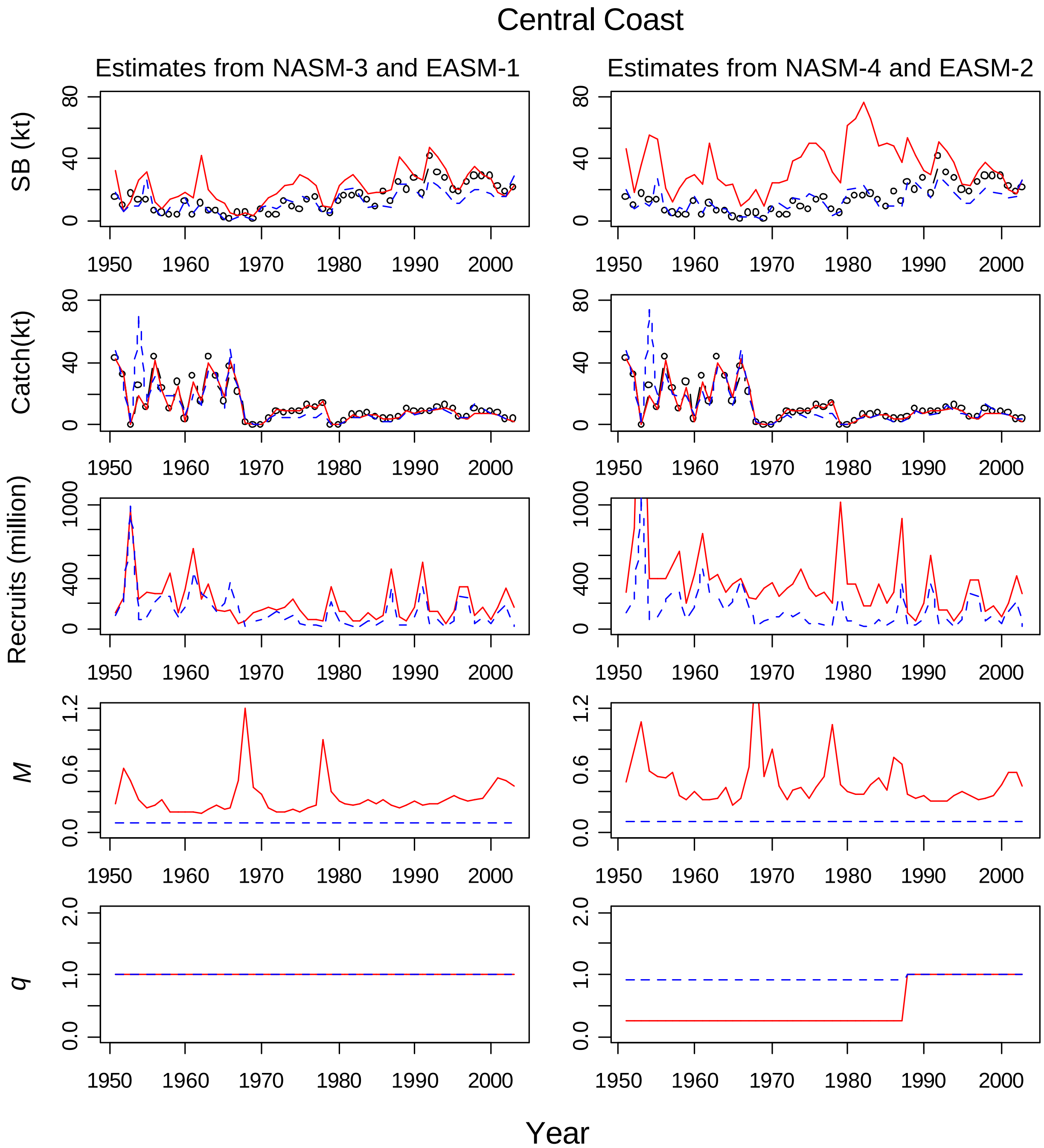


Figure 14. Reconstructions for the CC herring stock, 1951 – 2003. Estimated spawning biomass (SB), catch, recruits, natural loss (*M*), and spawn index conversion factor (*q*) are compared among four models: Column (1): NASM-3 estimating annual *M* and setting *q* at 1.0 (solid line) and EASM-1 setting *q* at 1.0 (dashed line); Column (2): NASM-4 estimating annual *M* and one constant *q* (solid line) and EASM-2 estimating one constant *q* (dashed line). Circles show reported catch and spawn survey indices.

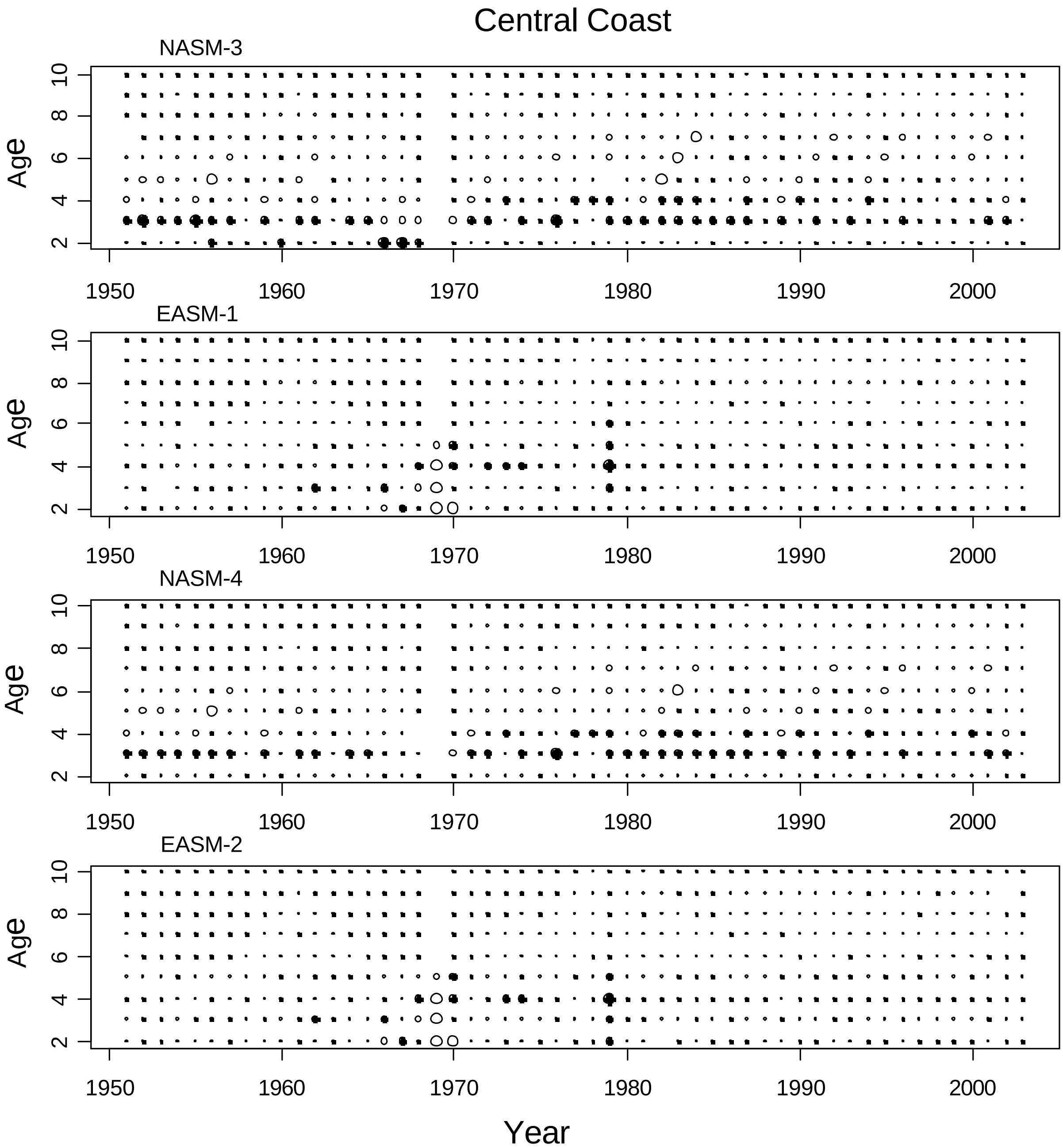


Figure 15. Comparisons of age composition residuals (solid circle for negative and open circle for positive residuals) for the CC herring stock among four models. Panel (1): NASM-3 estimating annual *M* and setting *q* at 1.0; Panel (2): EASM-1 setting *q* at 1.0; Panel (3): NASM-4 estimating annual *M* and one constant *q*; Panel (4): EASM-2 estimating one constant *q*.

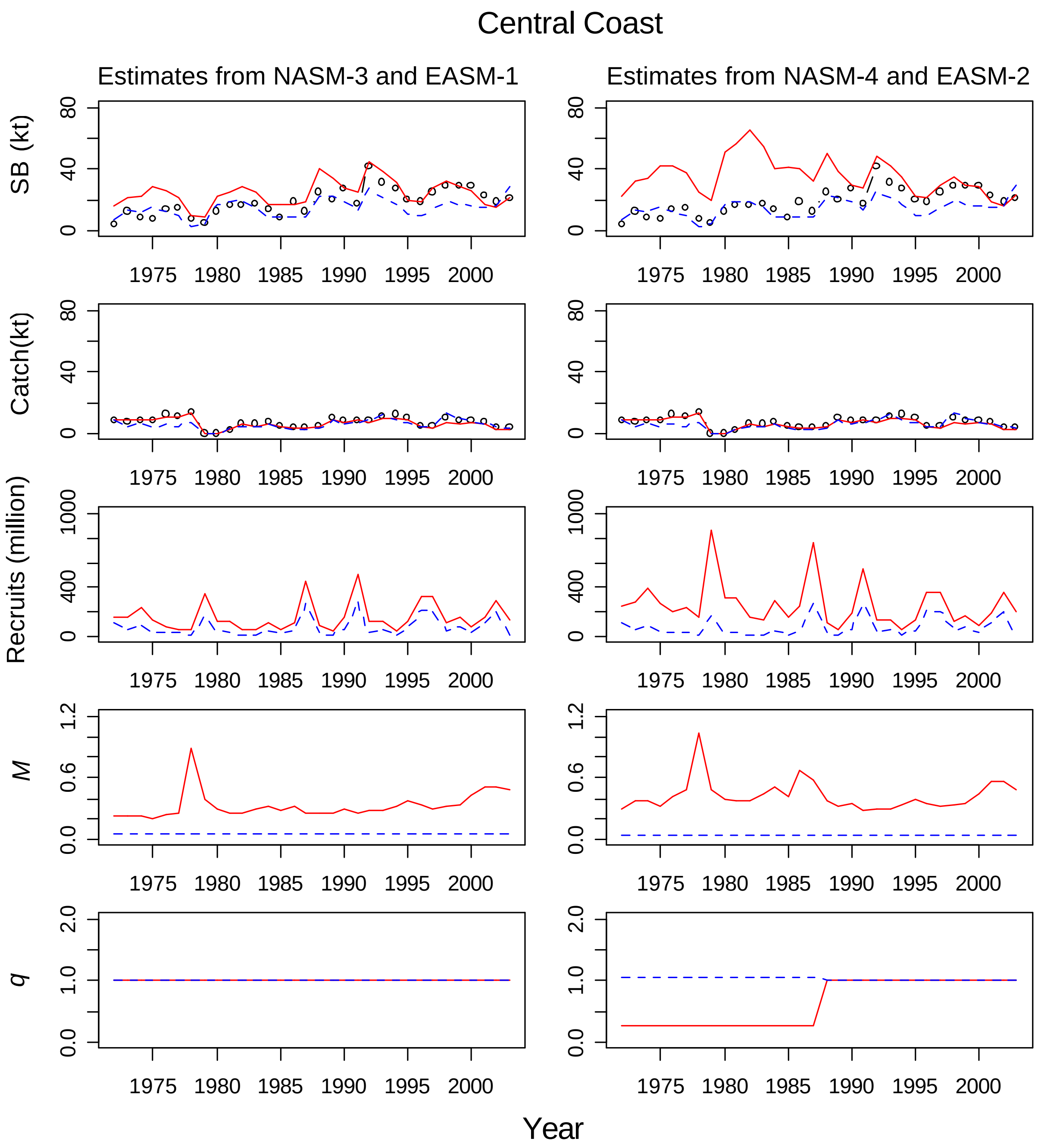


Figure 16. Reconstructions for the CC herring stock, 1972 – 2003. Estimated spawning biomass (SB), catch, recruits, natural loss (*M*), and spawn index conversion factor (*q*) are compared among four models: Column (1): NASM-3 estimating annual *M* and setting *q* at 1.0 (solid line) and EASM-1 setting *q* at 1.0 (dashed line); Column (2): NASM-4 estimating annual *M* and one constant *q* (solid line) and EASM-2 estimating one constant *q* (dashed line). Circles show reported catch and spawn survey indices.

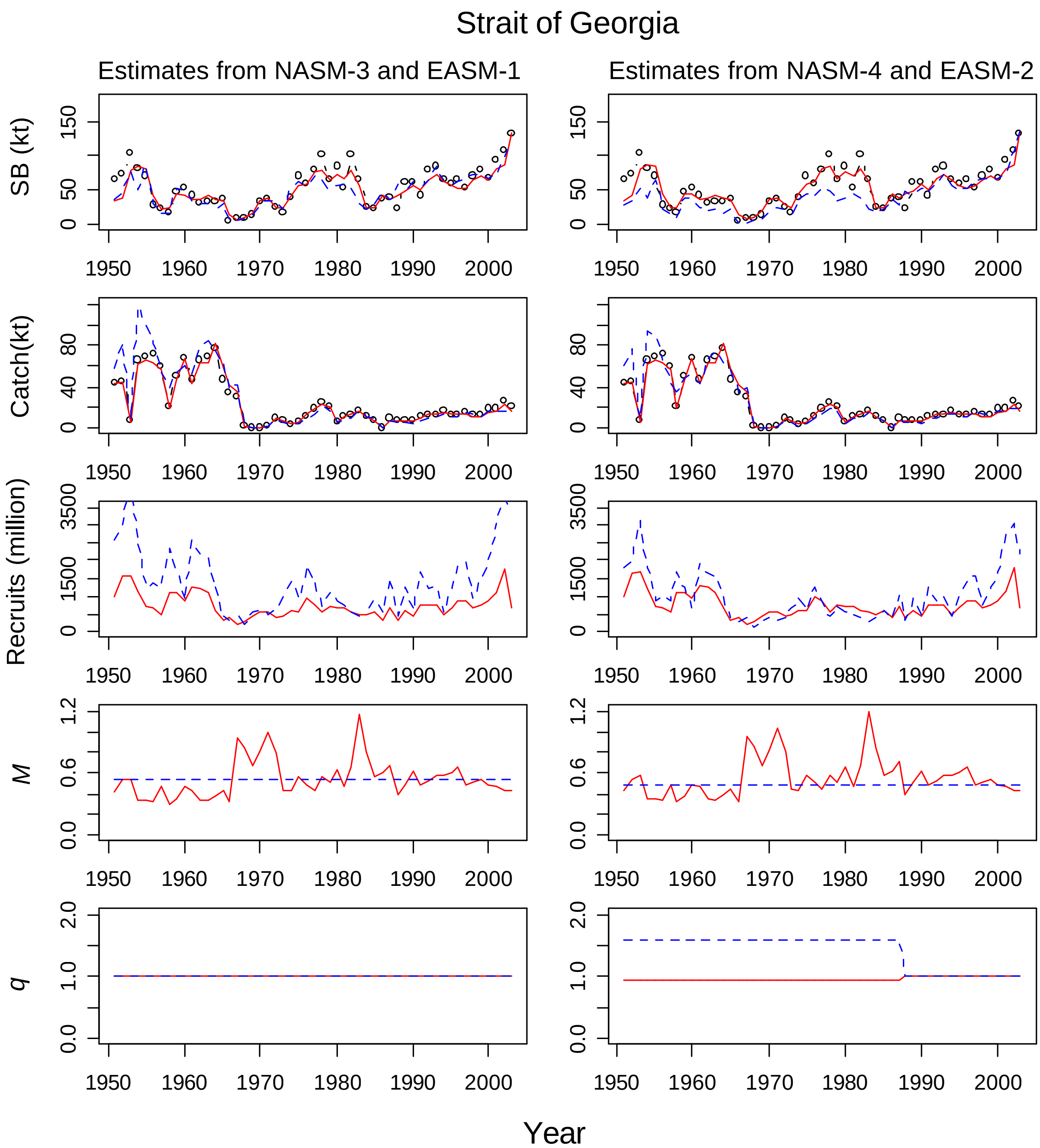


Figure 17. Reconstructions for the GS herring stock, 1951 – 2003. Estimated spawning biomass (SB), catch, recruits, natural loss (*M*), and spawn index conversion factor (*q*) are compared among four models: Column (1): NASM-3 estimating annual *M* and setting *q* at 1.0 (solid line) and EASM-1 setting *q* at 1.0 (dashed line); Column (2): NASM-4 estimating annual *M* and one constant *q* (solid line) and EASM-2 estimating one constant *q* (dashed line). Circles show reported catch and spawn survey indices.

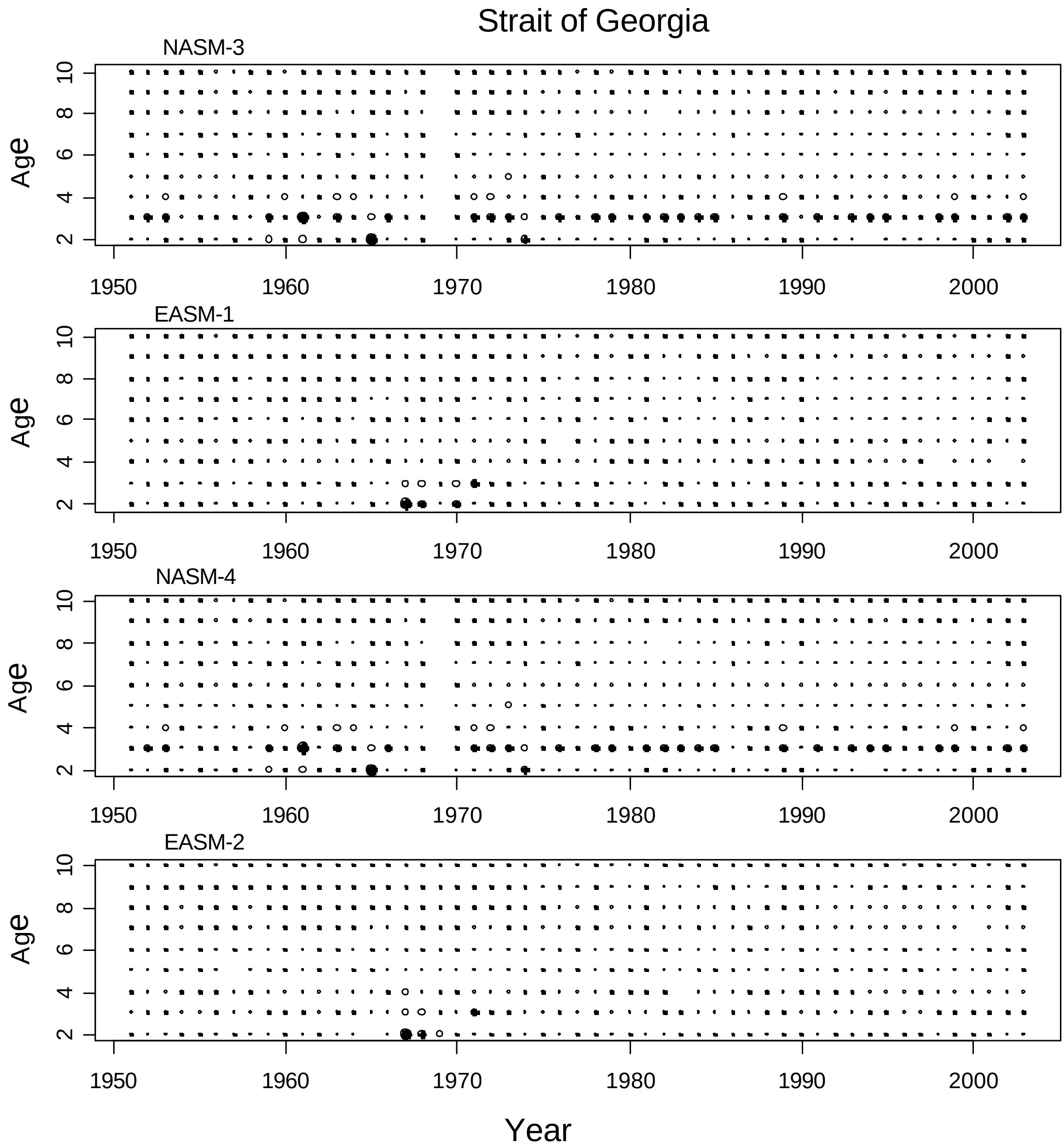


Figure 18. Comparisons of age composition residuals (solid circle for negative and open circle for positive residuals) for the GS herring stock among four models. Panel (1): NASM-3 estimating annual *M* and setting *q* at 1.0; Panel (2): EASM-1 setting *q* at 1.0; Panel (3): NASM-4 estimating annual *M* and one constant *q*; Panel (4): EASM-2 estimating one constant *q*.

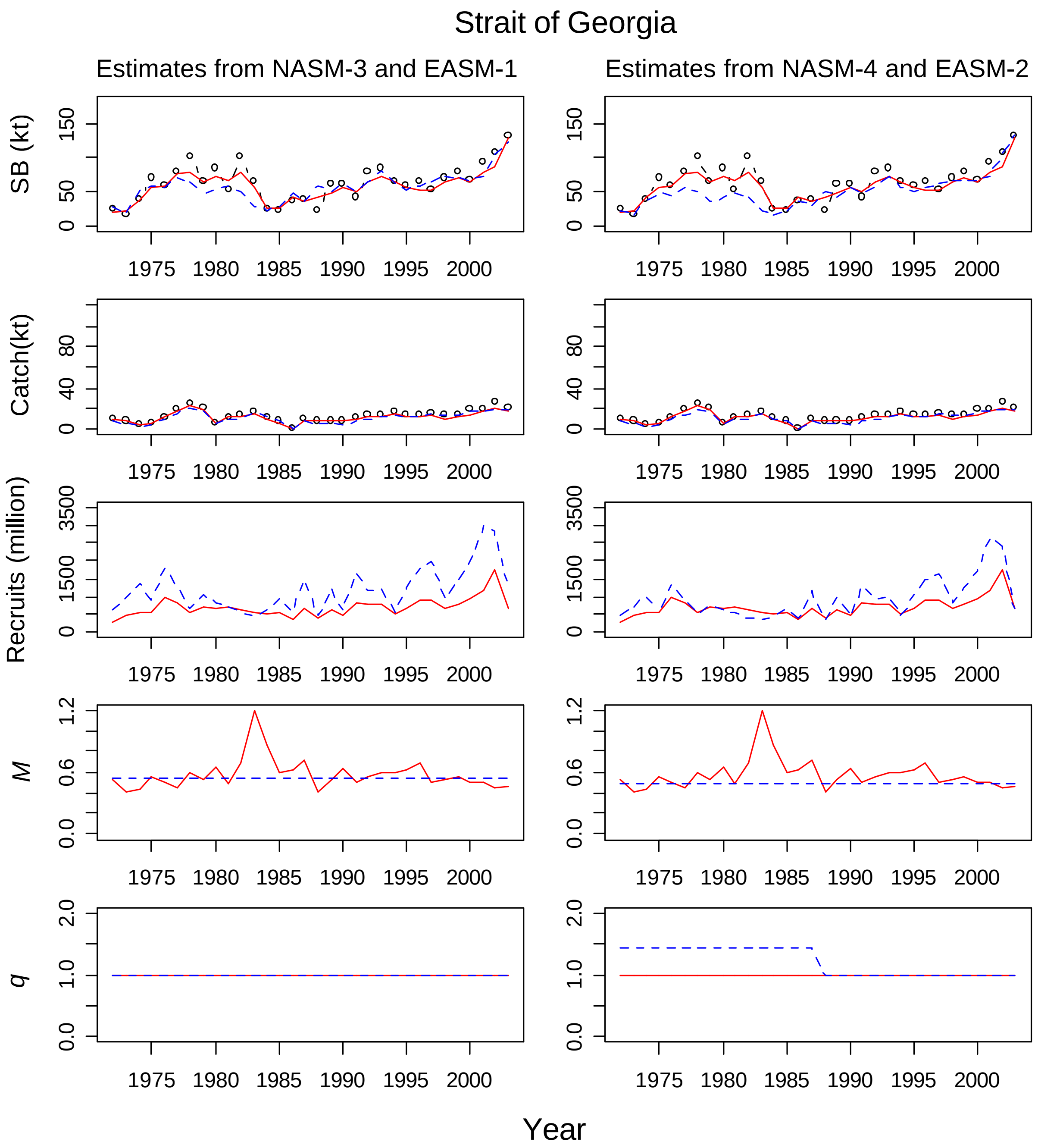


Figure 19. Reconstructions for the GS herring stock, 1972 – 2003. Estimated spawning biomass (SB), catch, recruits, natural loss (*M*), and spawn index conversion factor (*q*) are compared among four models: Column (1): NASM-3 estimating annual *M* and setting *q* at 1.0 (solid line) and EASM-1 setting *q* at 1.0 (dashed line); Column (2): NASM-4 estimating annual *M* and one constant *q* (solid line) and EASM-2 estimating one constant *q* (dashed line). Circles show reported catch and spawn survey indices.

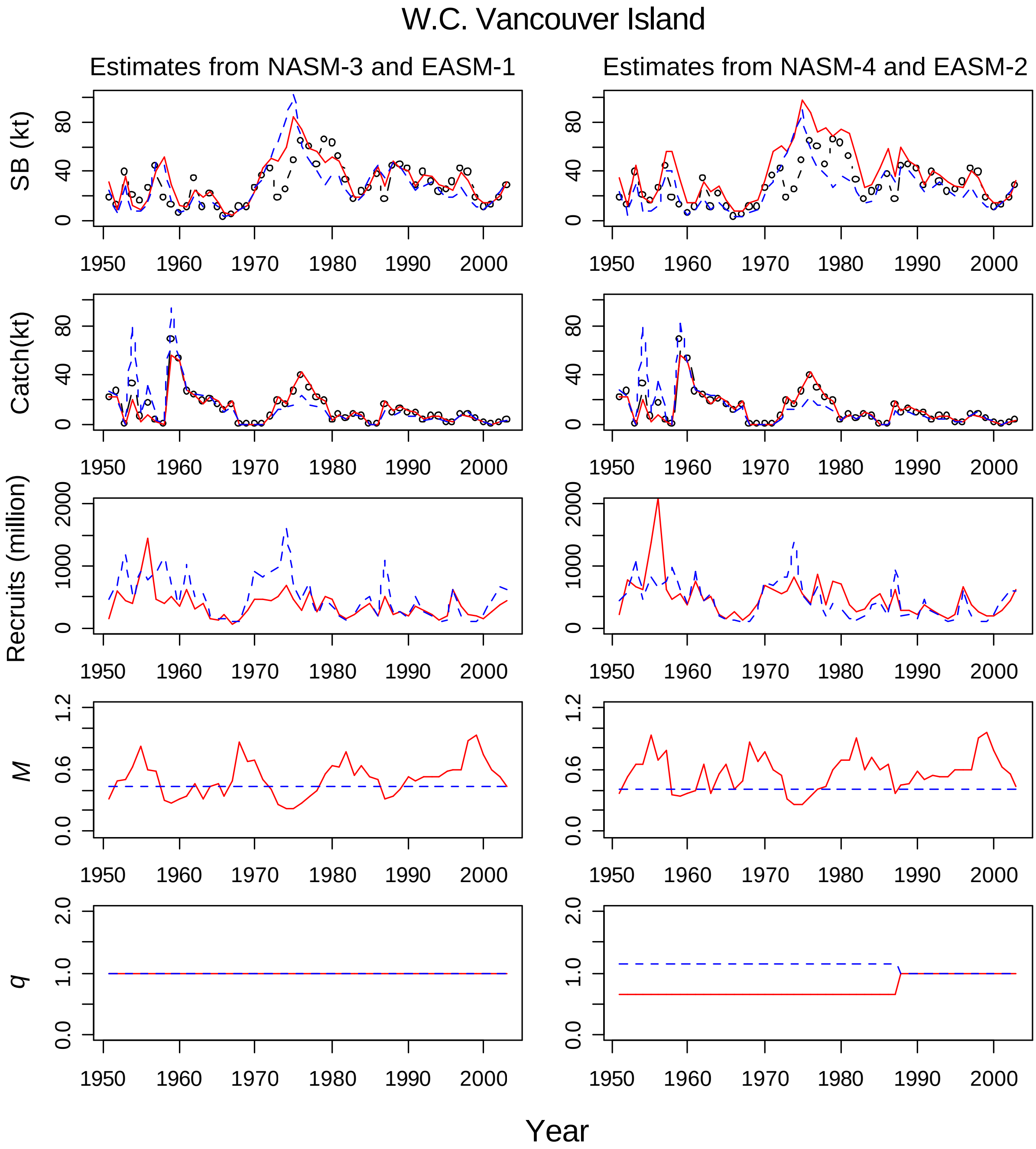


Figure 20. Reconstructions for the WCVI herring stock, 1951 – 2003. Estimated spawning biomass (SB), catch, recruits, natural loss (*M*), and spawn index conversion factor (*q*) are compared among four models: Column (1): NASM-3 estimating annual *M* and setting *q* at 1.0 (solid line) and EASM-1 setting *q* at 1.0 (dashed line); Column (2): NASM-4 estimating annual *M* and one constant *q* (solid line) and EASM-2 estimating one constant *q* (dashed line). Circles show reported catch and spawn survey indices.

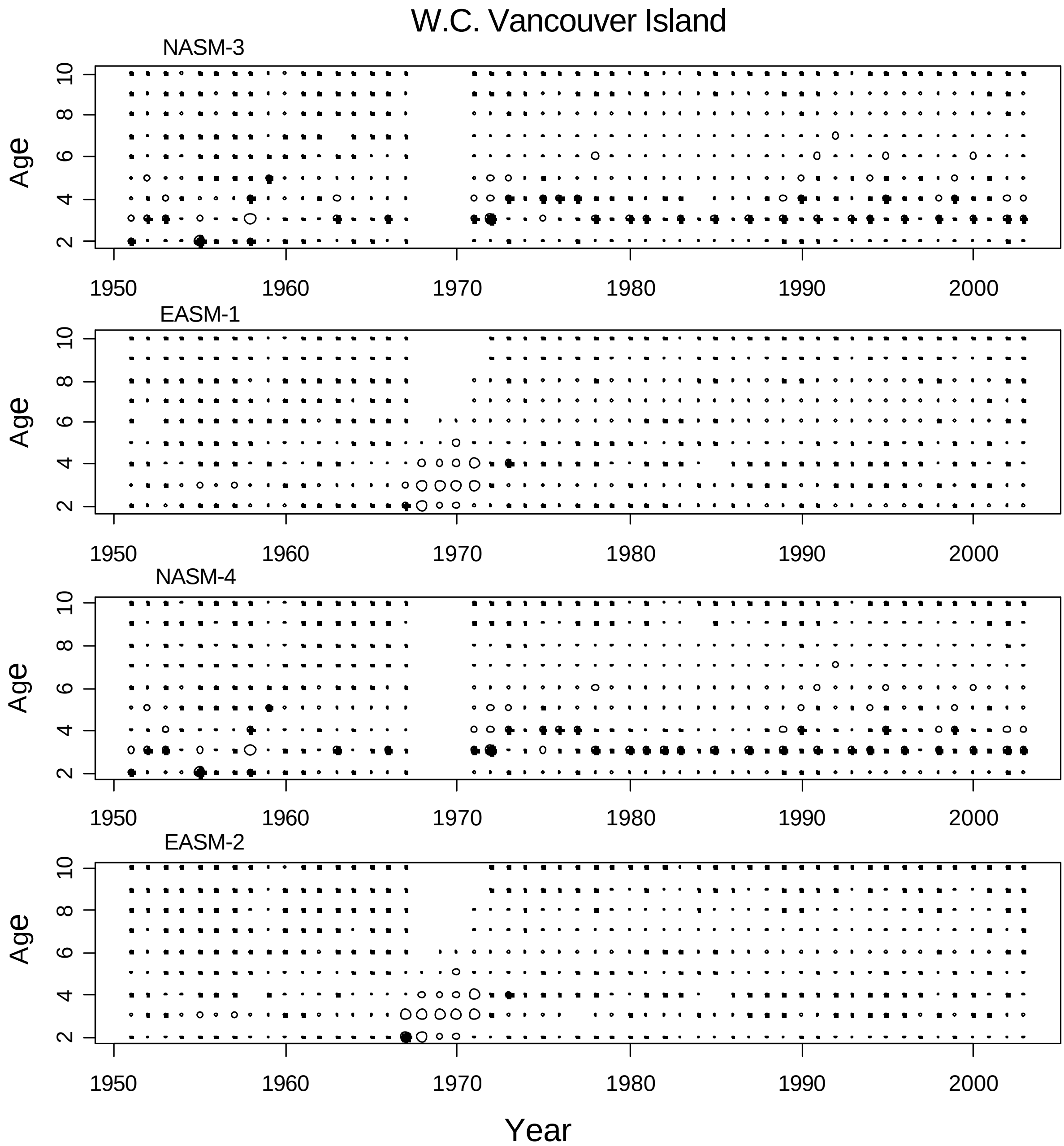


Figure 21. Comparisons of age composition residuals (solid circle for negative and open circle for positive residuals) for the WCVI herring stock among four models. Panel (1): NASM-3 estimating annual *M* and setting *q* at 1.0; Panel (2): EASM-1 setting *q* at 1.0; Panel (3): NASM-4 estimating annual *M* and one constant *q*; Panel (4): EASM-2 estimating one constant *q*.

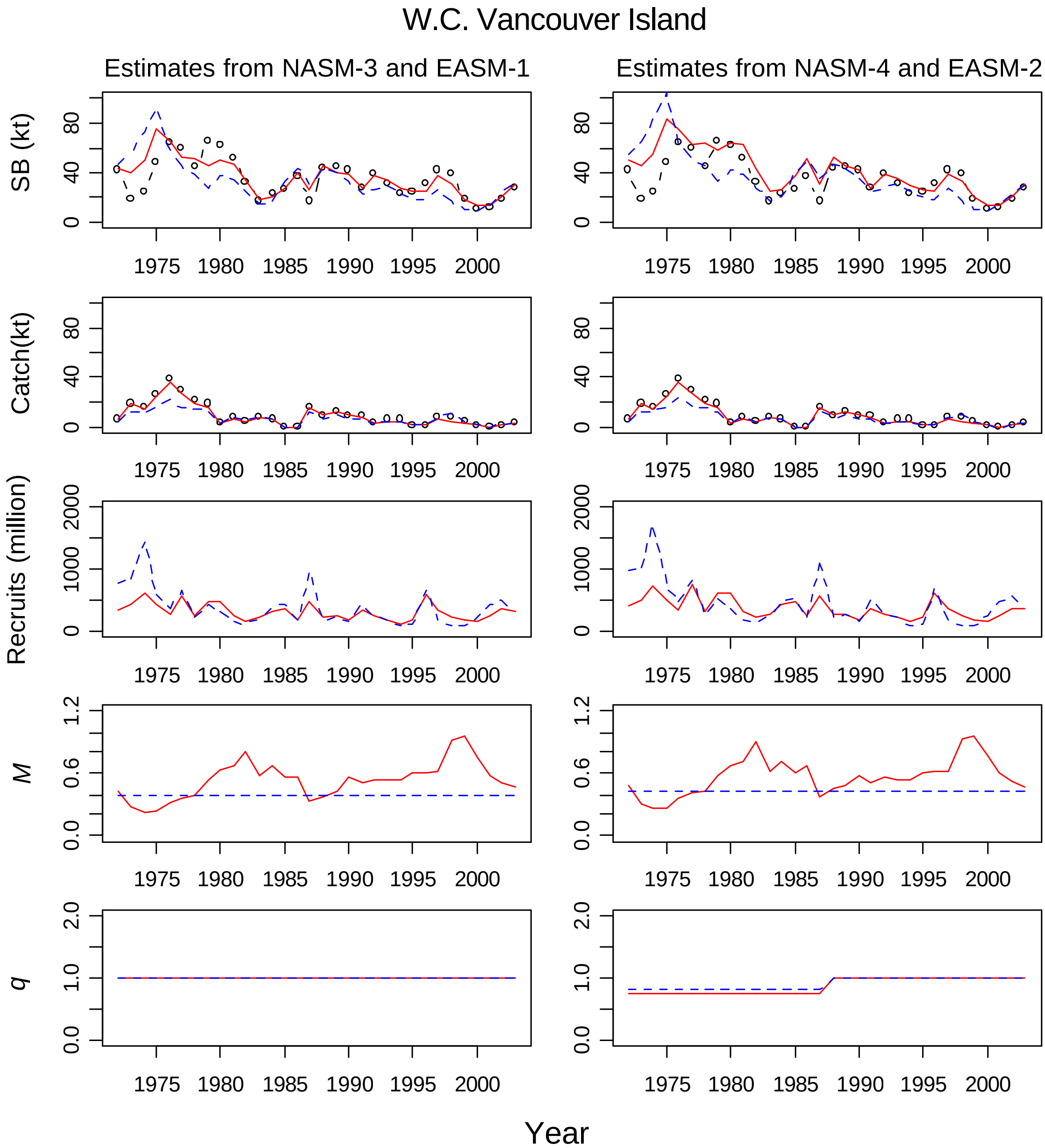


Figure 22. Reconstructions for the WCVI herring stock, 1972 – 2003. Estimated spawning biomass (SB), catch, recruits, natural loss (*M*), and spawn index conversion factor (*q*) are compared among four models: Column (1): NASM-3 estimating annual *M* and setting *q* at 1.0 (solid line) and EASM-1 setting *q* at 1.0 (dashed line); Column (2): NASM-4 estimating annual *M* and one constant *q* (solid line) and EASM-2 estimating one constant *q* (dashed line). Circles show reported catch and spawn survey indices.

Appendix 1
PSARC Request for Working Paper

Date Submitted: July 29, 2003

Individual or group requesting advice: Fisheries Management

Proposed PSARC Presentation Date: November 17-21, 2003

Subject of Paper (title if developed): Risk Assessment: Evaluation of different age-structured simulation models for Pacific herring.

Stock Assessment Lead Author: C. Fu

Fisheries Management Author/Reviewer:

Rationale for request:

The establishment of clear and measurable conservation limits will be used as a mechanism to prevent herring stocks from being put at risk. The limits will also provide a focus for Fisheries Management and Science stock assessment activities.

The purpose of this Working Paper is to decide which, of several plausible, age-structured models should be used for the risk analysis.

Performing a risk analysis and defining the conservation limits for Pacific herring are required as part of the Objective Based Fisheries Management initiative

Question(s) to be addressed in the Working Paper:
(To be developed by initiator)

1. How well does the existing herring stock assessment model estimate spawner biomass and other population parameters on known, simulated data?

2. How well do alternative model formulations estimate the same parameters using the simulated data?

3. How well do the existing and alternative models fit the spawn index time series and age composition data for each of the five major herring stocks?

4. Which model should be used for the risk analysis? And why?

Objective of Working Paper:

As the first step in the risk assessment, this working paper will review the existing herring age-structured model with regard to model assumptions, and will develop new alternative models that are more flexible in evaluating other possibilities, such as a time-varying natural mortality rate. Specifically, the paper will:

- Describe the existing herring age-structured model, and the new model with respect to the underlying assumptions about herring population dynamics.
- Develop a simulation model and generate simulated spawn data, catch-at-age, and catch data.
- Compare the accuracy of the existing and new models in estimating population parameters from the simulated data.
- Compare the performance of the different models in fitting the historical catch, age composition and spawn data in each of the five major stock assessment regions.
- Provide the rationale for deciding which model should be used for the risk assessment.

Stakeholders Affected:

First Nations
Herring Resource Users

How Advice May Impact the Development of a Fishing Plan:

When the risk analysis is completed in the next step, the results will identify reference points that will be used to define conservation limits and appropriate harvest rates.

Timing *Issues Related to When Advice is Necessary*

Appendix 2. Spawn index and spawning biomass estimates (metric tons) for the QCI herring stock from the four models NASM-3, NASM-4, EASM-1, and EASM-2.

		Spawning biomass estimates from the following models			
Year	Spawn index	NASM-3	NASM-4	EASM-1	EASM-2
1951	4213	7113	15936	4007	5300
1952	2578	5132	16727	2729	4035
1953	7555	10918	33934	7555	10714
1954	12408	15064	51027	11878	16690
1955	6437	28239	90491	6597	9298
1956	6042	10082	26069	8923	10936
1957	1592	2202	5500	1178	1577
1958	815	2274	6916	926	1340
1959	8981	9140	29582	7117	9234
1960	6599	9816	26805	6599	9358
1961	8981	17814	38149	8416	11809
1962	5730	26384	46256	6559	9344
1963	7297	40637	55059	8457	11746
1964	4104	15509	25005	3640	4891
1965	1378	3253	7908	1318	1824
1966	2824	1997	7514	1641	2450
1967	710	1317	5388	804	1177
1968	833	1873	7177	1007	1434
1969	2075	3395	12610	2075	2943
1970	5552	6890	24474	5552	7873
1971	13291	15257	41893	12486	17464
1972	9542	28480	54525	9112	12218
1973	7960	37046	57957	9811	14071
1974	14510	46657	69994	22479	30325
1975	9686	43265	64974	28471	36969
1976	15986	39753	61632	20835	26670
1977	15717	31031	57425	18374	23172
1978	16885	22970	50772	13657	17369
1979	12236	17630	35902	6268	8342
1980	30455	40864	123516	25476	34999
1981	18823	42266	125457	24610	34738
1982	22159	32174	100248	30319	41307
1983	19470	25020	77616	24710	32789
1984	22120	21378	74659	18399	23940
1985	17232	19105	71398	14057	18834
1986	5679	12541	39054	9247	12665
1987	10751	12505	34284	7307	9700
1988	12814	23677	49378	12435	15026
1989	22031	23062	32591	25402	29396
1990	23263	17867	23576	17956	20201
1991	15061	14014	16321	9941	11068
1992	9990	16955	18914	9128	9829
1993	5801	10616	12081	6008	6679
1994	12149	7857	9158	4447	4965
1995	4061	5654	6308	4061	4061
1996	6646	7744	8646	6646	6646
1997	9576	10159	11352	9351	9501
1998	18673	15509	17255	11697	11626
1999	8475	9242	10320	7169	7904
2000	4925	6906	7821	4041	4390
2001	12757	8810	10132	6077	6242
2002	2029	2278	2319	3459	3495
2003	6985	9005	10308	8172	7893

Appendix 3. Spawn index and spawning biomass estimates (metric tons) for the PRD herring stock from the four models NASM-3, NASM-4, EASM-1, and EASM-2.

		Spawning biomass estimates from the following models			
Year	Spawn index	NASM-3	NASM-4	EASM-1	EASM-2
1951	27149	56645	67067	30935	33138
1952	24047	19600	37579	17653	19321
1953	28468	24169	40964	21817	23419
1954	13535	30908	43465	10015	10851
1955	14482	22611	36720	10463	11419
1956	14533	35363	53793	25218	27250
1957	27518	16987	36245	11787	12918
1958	9882	21704	36457	21708	23716
1959	40961	33524	57850	25262	27538
1960	16545	31644	43448	29396	31950
1961	12059	38779	51335	23614	25778
1962	26329	43483	59195	40585	43719
1963	16981	35563	47227	27747	29919
1964	26919	44779	57212	26061	28016
1965	6055	15197	21001	13107	14244
1966	7105	5150	11086	4471	4951
1967	3386	3267	8551	3134	3481
1968	5197	4253	12003	3366	3737
1969	965	3472	6392	965	1077
1970	8814	9451	17255	8358	9252
1971	8480	11212	20878	9368	10182
1972	8774	11734	22400	4892	5415
1973	10959	16509	29423	11106	12110
1974	9244	23306	39504	13674	14932
1975	10565	25358	39914	14962	16146
1976	15199	29760	45187	10797	11781
1977	10425	24275	37163	14644	15644
1978	4734	15727	25134	9706	10476
1979	7600	9985	17992	7174	7844
1980	11001	18513	36465	15189	16694
1981	12939	19978	40497	15142	16701
1982	16108	22244	44430	18444	20168
1983	23575	27477	51676	21572	23266
1984	25667	39811	74520	22792	24522
1985	39606	39848	74173	24731	26434
1986	24055	37409	64965	22296	23754
1987	38673	39112	65541	19989	21138
1988	30519	35707	44484	18622	19475
1989	13487	28122	31108	16920	17630
1990	19209	25341	27450	15825	16422
1991	22340	29657	32066	18005	18601
1992	35773	34951	38049	23465	24207
1993	21594	29690	32306	20429	21048
1994	13613	20895	22534	13454	13881
1995	15486	21615	23144	11397	11697
1996	20487	29637	32066	17070	17670
1997	21078	27314	29839	16450	16943
1998	16271	28885	31333	19477	19868
1999	25033	29137	31456	21191	21453
2000	15478	24014	25887	18543	18669
2001	31277	23745	25856	19866	19876
2002	17868	19132	20629	18489	18195
2003	28216	31022	35396	31957	30873

Appendix 4. Spawn index and spawning biomass estimates (metric tons) for the CC herring stock from the four models NASM-3, NASM-4, EASM-1, and EASM-2.

		Spawning biomass estimates from the following models			
Year	Spawn index	NASM-3	NASM-4	EASM-1	EASM-2
1951	15390	32607	46495	19356	20416
1952	10295	6463	19273	6884	7435
1953	18237	13162	36589	10319	10978
1954	13967	26001	55227	9673	10347
1955	13564	31666	52856	25841	27399
1956	6626	13184	21608	8045	8502
1957	4607	7183	12192	3040	3236
1958	3549	13653	21326	8573	9132
1959	3909	16912	27829	5076	5476
1960	12615	19394	29612	15537	16451
1961	4265	15608	23428	5248	5656
1962	11948	42137	50577	11608	12479
1963	6485	20360	28201	5946	6340
1964	6464	14303	22775	7030	7458
1965	2097	10946	23415	2078	2281
1966	1863	5410	10185	1913	2090
1967	5434	3569	13939	2648	2836
1968	5790	4901	20620	2718	2992
1969	1837	3686	9796	1837	2007
1970	8230	10478	24929	9250	10012
1971	4156	15764	25705	10400	11149
1972	3572	17244	25939	7272	7751
1973	12447	22953	38916	14503	15398
1974	8924	23496	40826	12874	13641
1975	8060	29696	50361	16344	17253
1976	13893	27476	49655	13897	14659
1977	14619	22690	45440	10987	11634
1978	7749	10416	31548	3658	3943
1979	5676	9276	25129	5446	5970
1980	12958	23076	61693	19007	20340
1981	15845	25969	66588	20645	21936
1982	16238	29824	75825	21109	22356
1983	18217	25678	66453	16085	16999
1984	13795	18221	48327	9119	9627
1985	8498	19249	49821	9565	10103
1986	19061	19023	48338	9777	10307
1987	12493	20143	37845	9455	9936
1988	25134	41837	54108	24228	25132
1989	20708	36011	42343	24028	24845
1990	27629	29083	33001	20082	20614
1991	17833	26597	29555	15291	15706
1992	41559	47125	51842	27861	28487
1993	30917	41546	45403	22831	23363
1994	27468	33892	37234	19031	19387
1995	20272	21943	24302	11666	11925
1996	18665	20542	22614	11003	11231
1997	24999	29771	32527	16240	16478
1998	28363	34770	38133	20253	20768
1999	28464	29868	32916	18906	19331
2000	28484	27446	30443	17940	18233
2001	22552	18791	20655	15253	15386
2002	18917	15832	17169	16853	16739
2003	20993	23004	26118	28875	28197

Appendix 5. Spawn index and spawning biomass estimates (metric tons) for the GS herring stock from the four models NASM-3, NASM-4, EASM-1, and EASM-2.

		Spawning biomass estimates from the following models			
Year	Spawn index	NASM-3	NASM-4	EASM-1	EASM-2
1951	66143	34004	35290	37692	28466
1952	72112	40577	42810	49470	33942
1953	104220	78991	82190	74852	54553
1954	82141	84298	86489	52186	38460
1955	69854	83033	85144	86789	64368
1956	29202	43666	44732	31762	23577
1957	24126	24235	24992	17945	13347
1958	16149	25339	26082	17438	11926
1959	47864	44561	45864	54350	40041
1960	55082	42412	43990	49478	36273
1961	42864	35724	37000	34534	24544
1962	31078	37846	38725	30079	21184
1963	35135	42262	43515	31422	22563
1964	33117	37815	38821	22718	15934
1965	37116	34993	36164	30916	22199
1966	7153	15225	15602	7511	4566
1967	9619	7374	7829	7223	4524
1968	9128	10998	11775	8009	4892
1969	14644	17986	19160	14760	9217
1970	33953	33584	35743	32127	20680
1971	38180	38465	40918	35132	25410
1972	25165	26452	28005	29998	21294
1973	16191	25663	26958	22057	15024
1974	40354	43753	46061	54294	38233
1975	70208	57279	60452	62156	45864
1976	60511	59469	62211	57158	42540
1977	78113	77215	81161	71241	53222
1978	101735	78988	83697	65480	48470
1979	63915	64279	68371	49622	35085
1980	85679	72510	76994	56707	40866
1981	54754	67079	70800	60503	44385
1982	100611	78142	83028	53500	39935
1983	64243	57146	60750	30368	22383
1984	26054	24742	26168	23325	16733
1985	22890	24688	26117	30997	21889
1986	37844	43883	46305	48672	36252
1987	38905	36773	38713	38150	29296
1988	22813	43686	45087	60448	48315
1989	62432	47636	48699	50844	41936
1990	61239	57597	58446	63433	54113
1991	42468	49739	50195	53161	46934
1992	77802	65890	66531	65748	58132
1993	84050	72970	73651	83744	73155
1994	63917	63256	63851	64645	57136
1995	60317	57335	57848	55806	49860
1996	65984	53379	53864	60878	55055
1997	54640	54696	55171	67707	61666
1998	70018	64739	65316	73481	68345
1999	78766	70520	71127	71456	68016
2000	67643	64797	65321	68702	67441
2001	94255	80747	81349	71580	73686
2002	108173	86626	87240	98693	107287
2003	132782	133458	134491	121640	136882

Appendix 6. Spawn index and spawning biomass estimates (metric tons) for the WCVI herring stock from the four models NASM-3, NASM-4, EASM-1, and EASM-2.

Year	Spawn index	Spawning biomass estimates from the following models			
		NASM-3	NASM-4	EASM-1	EASM-2
1951	19597	31933	34088	25941	23589
1952	13310	10205	13469	4331	4284
1953	39571	35378	44660	31593	30770
1954	20648	13166	18984	7137	6983
1955	15112	9565	13956	8766	8430
1956	27183	17188	24940	13729	11854
1957	44114	41145	55849	46988	40549
1958	18986	51786	56833	46147	40292
1959	12979	29833	32695	15163	13348
1960	6015	12683	14285	6616	5695
1961	10556	11764	14253	9994	9026
1962	34470	25150	31991	20442	19403
1963	11245	19650	23256	11253	10038
1964	22761	22908	28699	16171	14945
1965	11891	14006	17901	10571	9486
1966	3722	6934	8261	3994	3303
1967	4813	5591	8274	4362	4134
1968	11029	9812	14437	8866	7213
1969	10465	12016	17302	10465	9007
1970	26912	23603	33427	26912	23164
1971	36206	42212	55628	36206	31163
1972	41857	50008	61272	52033	45285
1973	19481	49225	56274	63452	54435
1974	25540	59598	66458	82371	71366
1975	49149	84902	96047	101033	88562
1976	64200	73641	86747	60500	54239
1977	58679	57897	72140	47790	43422
1978	45607	56276	75651	40868	37604
1979	66397	47247	68155	29520	27257
1980	62308	51444	74048	38213	35483
1981	52014	48412	70623	35350	32696
1982	33047	35448	50939	25507	23617
1983	16771	19040	27056	16048	14338
1984	23872	19619	29163	18435	16088
1985	27437	29847	41804	35731	31742
1986	36971	44348	58569	45797	41569
1987	16858	29042	35848	34627	31533
1988	44193	48026	58759	46607	43347
1989	45735	42592	48725	43173	40575
1990	42887	40165	44246	34514	32834
1991	27736	28213	30172	24459	23396
1992	39476	37992	40270	28075	27295
1993	32061	35378	37294	31532	30804
1994	23656	29143	30734	24644	24320
1995	25496	26390	27841	19670	19758
1996	30902	25296	26607	19117	19553
1997	42573	38946	41054	27031	27649
1998	39419	32387	34419	16889	17067
1999	18498	19540	20704	10957	10997
2000	11553	13892	14557	9602	9755
2001	12113	14488	14870	13544	13894
2002	19154	19835	20103	23168	24032
2003	27684	31700	32624	28684	30205