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Erik H. Williams and Terrance J. Quinn II

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Abstract: For many exploitable Pacific herring *Clupea pallasi* stocks in Alaska, age-structured assessment models are used to forecast the abundance of returning herring. The purpose of this study was to develop such a model for Norton Sound herring. Commercial catch and sampling data for Norton Sound herring were obtained from the Alaska Department of Fish and Game. Natural mortality estimates were obtained from analysis of life history parameters. Initial starting values for the age-structured model were obtained from cohort analysis. Better results were obtained when age-composition data for age 10 and older were pooled into a plus group. A parametric bootstrap analysis using a beta distribution by incorporating variability from the age-composition residuals provided standard errors of the estimates. The analysis suggested that aerial surveys underestimated actual biomass in the early 1980s. However, a sensitivity analysis suggested that higher natural mortality in those years could have produced similar results. The fit of this model to the data was comparable to that obtained with age-structured assessments of other Alaska herring stocks. We believe this model can be used as a stock-assessment tool for management of Norton Sound herring.

INTRODUCTION

Commercial harvest of Pacific herring *Clupea pallasi* from Norton Sound, Alaska (Figure 1) has been recorded as far back as 1916. Until World War II, the product was mostly salt-cured. After World War II the demand for herring dropped, and only limited roe herring harvests were taken from 1964 to 1978. After passage of the Magnuson Act in 1978, a large-scale herring sac roe fishery began to develop. In 1979, purse seiners began working in Norton Sound; local fishers, using gillnets and beach seines, could not compete with them. The Alaska Board of Fisheries recognized this and implemented regulations that prevented purse seining north of the Togiak fishery. Since 1981 only gillnets and beach seines could be used to harvest herring in Norton Sound (Lean 1989). In 1992 the gillnet fishery for herring in Norton Sound could not be opened because of late-thawing of the pack ice.

The Alaska Department of Fish and Game (ADF&G) performs annual stock assessments of Norton Sound herring based on information from commercial catch samples, aerial surveys, and test fishing (i.e., samples done with a variable-mesh gillnet by ADF&G personnel). Herring sampled from commercial and test fishery catches are used to estimate age, sex, size, and sexual maturity. Aerial surveys are flown annually to estimate biomass derived from observed herring-school surface area and miles of spawn (Lebida and Whitmore 1985). Quality of aerial survey estimates varies, and in some cases herring abundance cannot be determined. Herring forecasts, calculated by projecting spring biomass estimates forward to the next year, account for growth, natural mortality, harvests, and recruitment. Forecasts are used to set harvest levels for the upcoming year (Funk 1993).

Harvest levels are limited to a maximum exploitation rate of 20% of the spawning population. A threshold level, below which harvests are not allowed, has been established to ensure a minimum stock size of 7,000 tons is maintained. Exploitation rates may be lowered if stock sizes decline to levels near the thresh-

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Authors: Erik H. Williams is a doctoral candidate and Terrance J. Quinn II is an associate professor at the University of Alaska Fairbanks, School of Fisheries and Ocean Sciences, Juneau Center, 11120 Glacier Highway, Juneau, AK 99801-8677.

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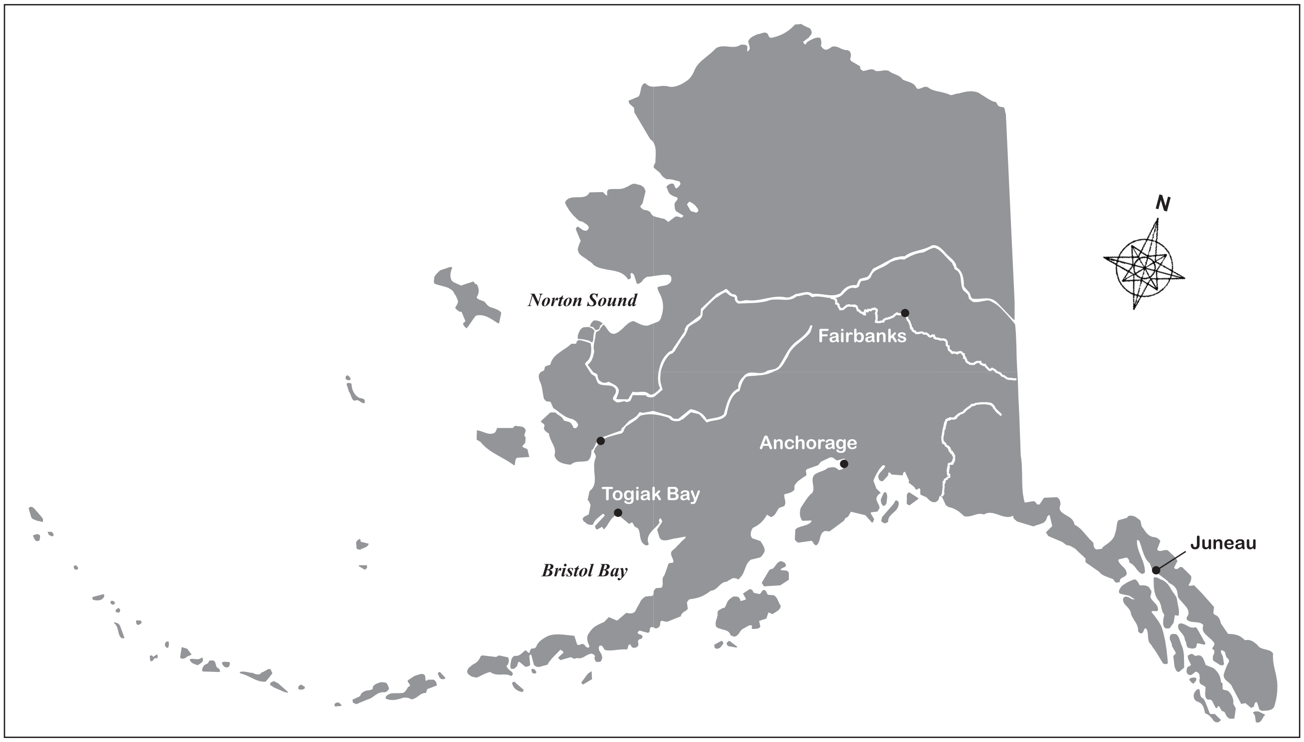

Figure 1. Map of Alaska showing the location of Norton Sound and Togiak Bay.

old level (Funk 1993). The occurrence and length of fishing periods is managed through emergency order authority. The Alaska Board of Fisheries has established regulations that allocate 10% of the preseason projected harvest to beach seine gear and 90% to gillnet gear (Funk 1993).

For many exploitable herring stocks, ADF&G uses age-structured assessment models to forecast the abundance of returning herring (Funk et al. 1992; Brannian et al. 1993; Yuen et al. 1994). These models incorporate auxiliary information, similar to models developed by Deriso et al. (1985). The purpose of this study was to develop an age-structured assessment model for Norton Sound herring that would allow assimilation of available data, provide standard error estimates, and could be used by ADF&G for forecasting purposes.

DATA

Annual sampling reports with records of weight-at-age for Norton Sound herring and a spreadsheet-based, age-structured analysis model used for the analysis of herring from Togiak Bay were obtained from ADF&G (Brannian et al. 1993; F. Funk, ADF&G, Juneau, personal communication; Figure 1). We also obtained ADF&G age-based data for Norton Sound herring beach seine catches, gillnet catches, total run estimates, and aerial biomass survey results (H. Hamner, ADF&G, Anchorage, personal communication).

The beach seine and gillnet age-composition data are based on samples taken from the respective commercial fisheries. Total run age composition is based on the test fishery. Aerial survey biomass estimates are based on the survey results, timing of peak biomass in the survey, and timing of the fishery. These data sets were then input into a spreadsheet-based model that uses the beach seine catches (Figure 2), gillnet fishery age compositions (Figure 3), total run age compositions (Figure 4), and aerial survey biomass estimates (Figure 5) as its data sources. Visual analysis of the year class data in Figures 2–4 suggests that 4 strong year classes were recruited to the fishery and persisted a number of years: 1977 year class persisted from 1982 to 1985, 1979 year class persisted from 1984 to 1987, 1982 year class persisted from 1989 to 1991, and 1988 year class persisted from 1993 to 1995. The observed aerial biomass in Figure 5 indicates a small increase in biomass from 1981 to 1988, a larger increase from 1989 to a peak in 1992, and then a decrease from 1992 to 1995.

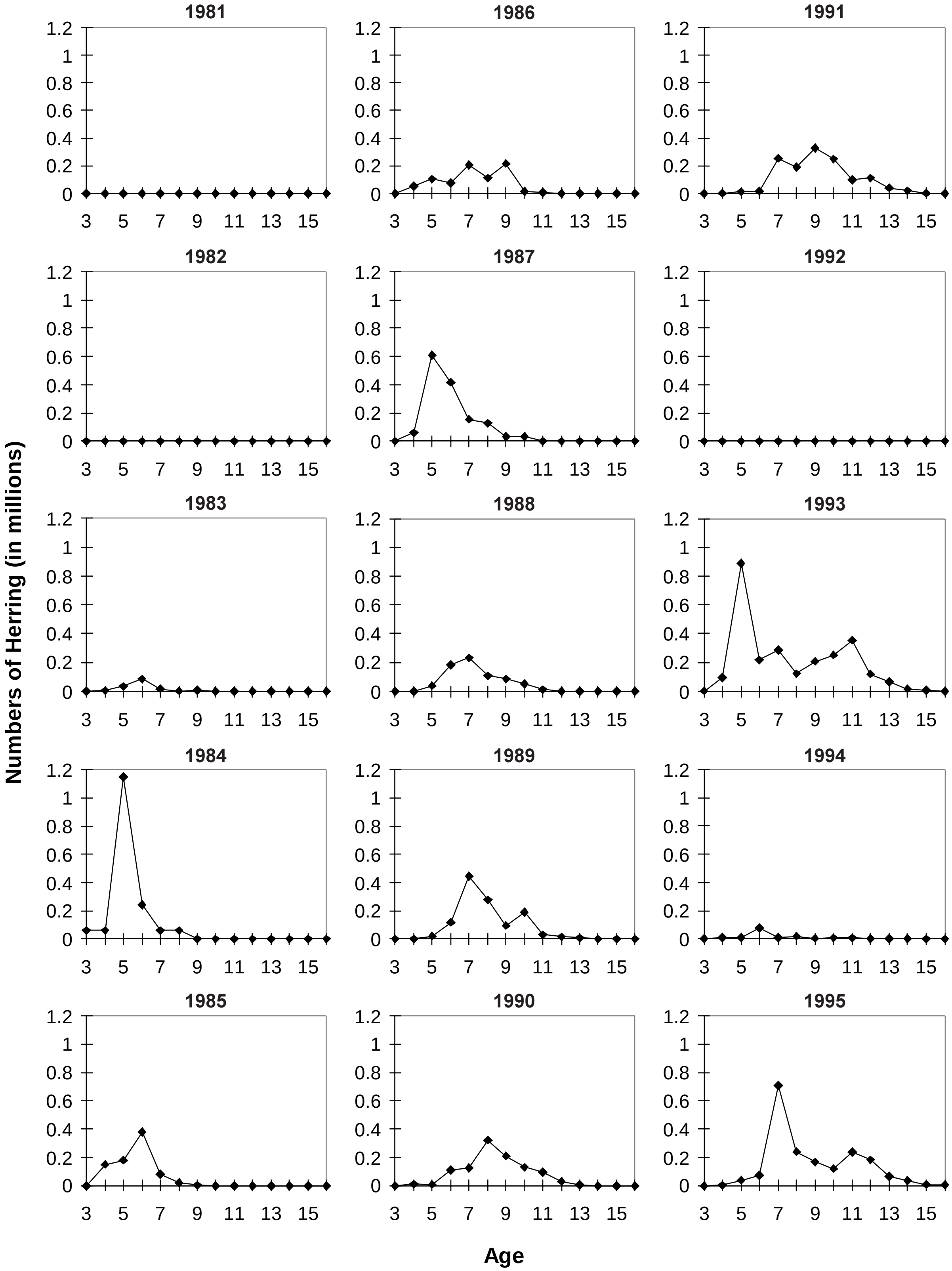

Figure 2. Yearly (1981–1995) observed beach seine catches of Pacific herring from Norton Sound in millions of fish for ages 3 to 16.

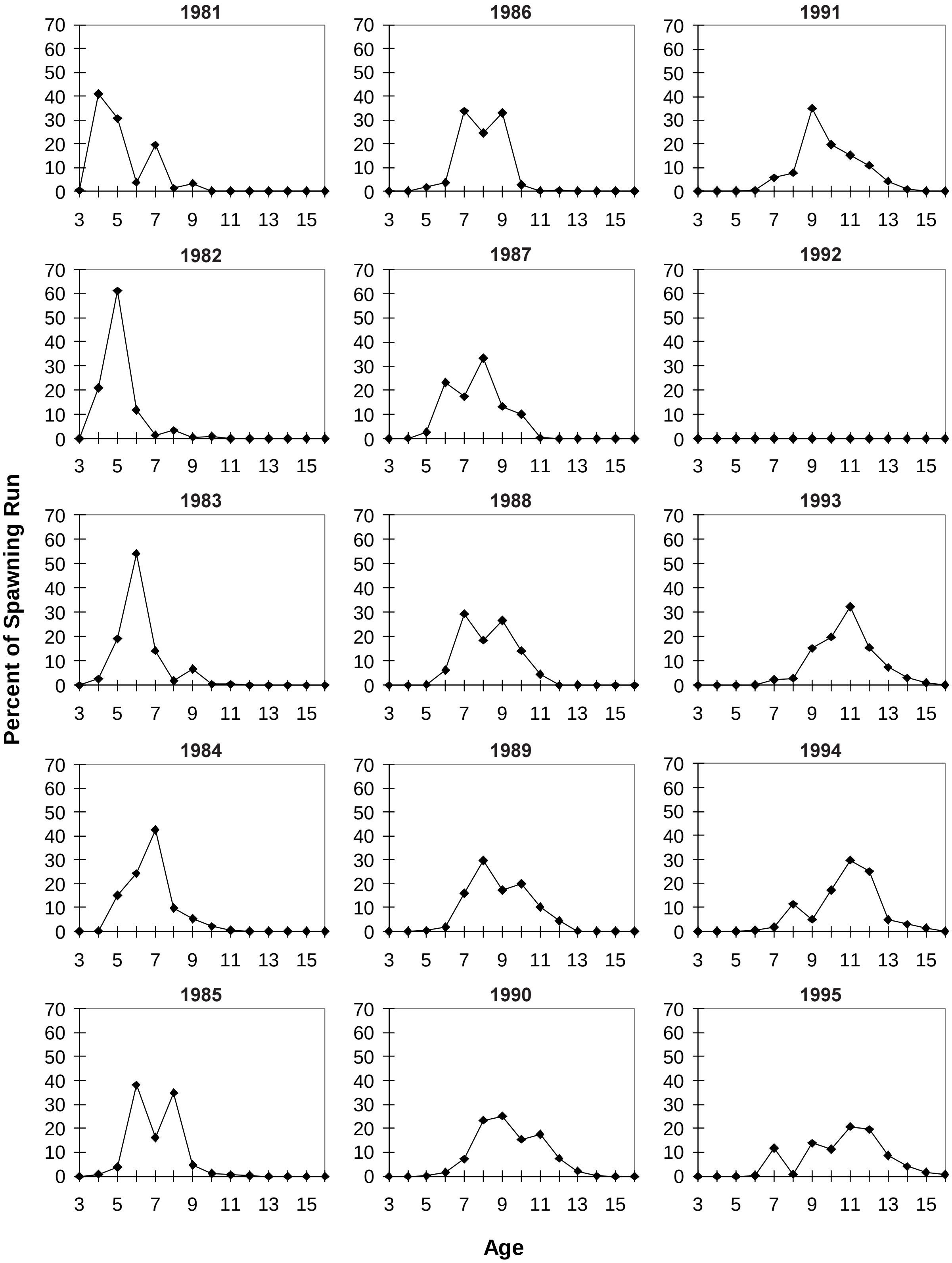

Figure 3. Yearly (1981–1995) observed gillnet catch age compositions of Pacific herring from Norton Sound for ages 3 to 16.

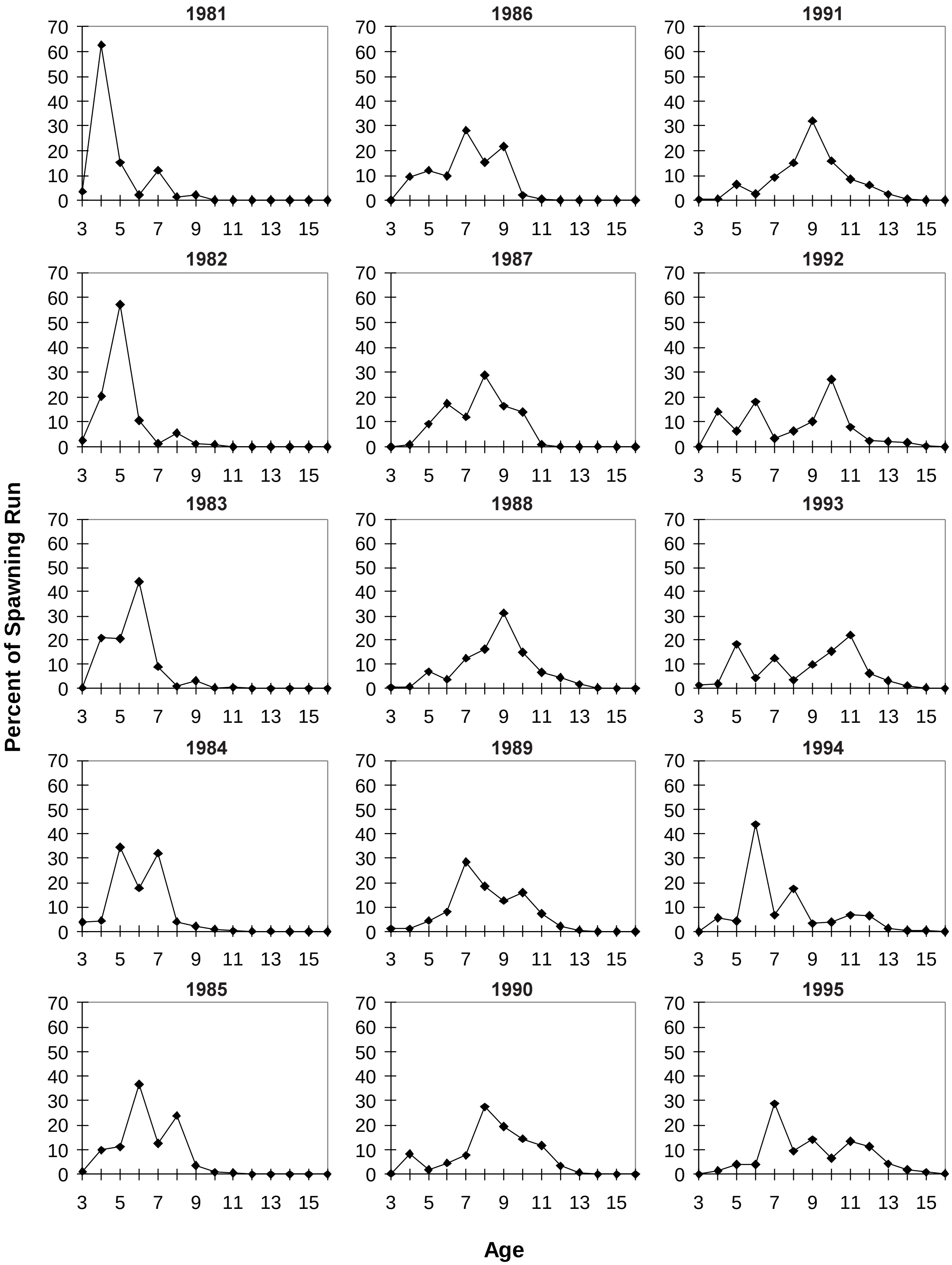

Figure 4. Yearly (1981–1995) observed total-run age compositions of Pacific herring from Norton Sound for ages 3 to 16.

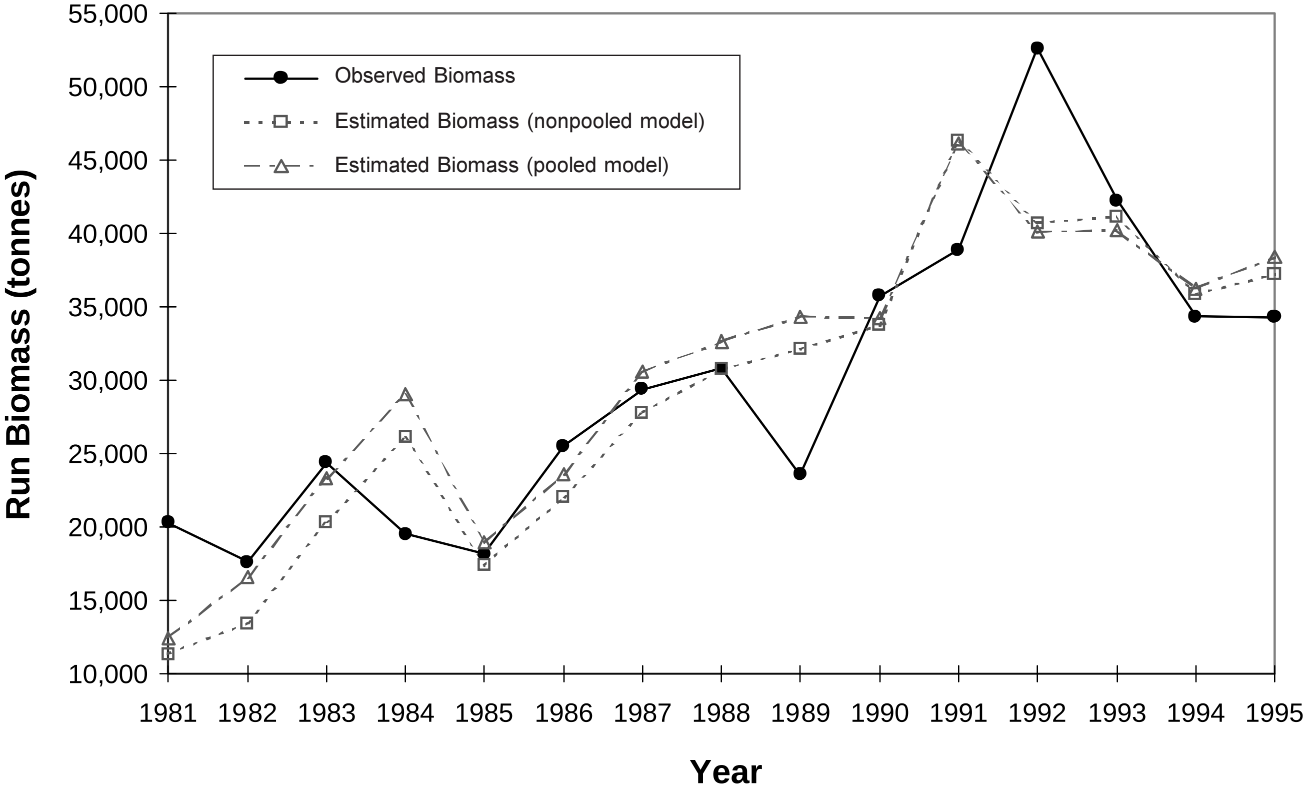

Figure 5. Yearly (1981–1995) observed and estimated aerial survey run biomass for Pacific herring from Norton Sound. The 1982 and 1989 observed values were removed from the analyses.

METHODS

An estimate of natural mortality is required for use in cohort analysis and age-structured analysis. Typically, for lack of a better estimate, natural mortality is assumed to be 0.2. Based on catch-curve analyses, Pacific herring natural mortality ranges from 0.1 to 0.4, the rate decreasing northward (Trumble and Humphreys 1985; Wespestad 1991). Estimates of Southeast Alaska and British Columbia herring natural mortality range from 0.33 to 0.46 for age-4 fish and 0.79 to 0.85 for age-8 fish, based on a mark-recapture experiment and catch-curve analyses (Skud 1963; Tester 1955). Hence, the overall potential range of natural mortality for Norton Sound herring is 0.10 to 0.85.

We assume a single value for instantaneous natural mortality (M) for all ages and years, recognizing this value might actually vary among years. For catch-age analysis, it is difficult to estimate a single value for natural mortality, let alone a series of values (Schnute and Richards 1995). Nevertheless, we do explore the sensitivity of the model to different values of M.

Several estimators of natural mortality are based on life history parameters, such as the Brody growth coefficient, K, of the von Bertalanffy growth curve. Gulland (1965) and Beverton and Holt (1957) provided estimates of natural mortality for clupeoids as $1.5K$ and $1.2K$, respectively. Two other methods of estimating natural mortality include the Alverson and Carney (1975) and Pauly (1980) methods.

For these methods, estimates of growth parameters are necessary. A von Bertalanffy growth curve for body weight was fitted to Norton Sound herring weight-at-age data from 1989 to 1994 using a nonlinear least squares technique. An estimate of the allometric growth parameter for spawning fish from Norton Sound was obtained, $\beta = 3.48$ (Wespestad 1991). The results from the fit of the equation were $W_\infty =$ 382.9 g and $K = 0.29$. The Alverson-Carney method for estimating instantaneous natural mortality uses the age of maximum biomass of the fish stock. Based on an empirical regression analysis, Alverson and Carney (1975) determined that age of maximum biomass was positively correlated to maximum age of the fish, which for Norton Sound herring is 17, based on age samples collected pre and postfishery. Because a fishery has the effect of decreasing the age of maximum biomass and maximum age, a conservative estimate of 18 years was used for the maximum observed age for Norton Sound herring. For the Pauly method, the mean water temperature experienced by the stock was set at 4°C based on research of eastern Bering Sea herring stocks (Wespestad 1991). The results from this analysis were then used to calculate estimates for natural mortality.

Cohort analysis was performed on the Norton Sound herring catch data to obtain initial starting values for use in the age-structured analysis. The available Norton Sound herring data involved catches from 2 gear types, beach seine and gillnet, which were pooled for the cohort analysis. The data covered years 1981 to 1995 and included ages 3 through 16. As mentioned earlier there was no gillnet fishery in 1992. Age-specific gear-selectivity values were based on a logistic function, which resulted in full selection at ages 12 and higher. Terminal fishing mortality was set at 0.35 based on the level of catches compared to survey estimates of total abundance. Instantaneous fishing mortality (F) for younger years was calculated by multiplying terminal fishing mortality by an age-specific gear-selectivity value obtained from the Togiak Bay herring fishery. Numbers of fish at age a and year t were estimated by

$$N_{a,t} = N_{a+1,t+1}\, e^{M} + C_{a,t}\, e^{M/2}$$

and for terminal values were

$$N_{A,t},\ t = 1, \ldots, T(\text{last year}) \text{ and}$$

$$N_{a,T},\ a = 1, \ldots, A(\text{last age}) = \frac{C_{a,t}}{\dfrac{F_{a,t}}{Z_{a,t}}\left(1 - e^{-Z_{a,t}}\right)},$$

where $C_{a,t}$ is the total catch at age a and time t, and total instantaneous mortality is $Z_{a,t} = M + F_{a,t}$.

The age-structured model used in this analysis was based on a model currently in use by ADF&G (Brannian et al. 1993). The model calculates prefishery abundance at age and aerial survey abundance at age using beach seine and gillnet catch data supplemented with total run and aerial survey data. The following notation is used in the formula for the age-structured analysis:

S_a = annual survival at age a,

$W_{a,t}$ = weight at age a and year t in grams,

$s_{a,g}$ = gillnet gear vulnerability at age a,

$s_{a,r}$ = total-run gear vulnerability at age a,

$C_{t,g}$ = total gillnet catch at year t in millions of fish,

$C_{a,t,s}$ = beach seine catch at age a and year t in millions of fish,

$\Theta'_{a,t,g}$ = observed gillnet age composition at age a and year t,

$\Theta_{a,t,g}$ = estimated gillnet age composition at age a and year t,

$X_{t,g}$ = exploitable abundance relative to gillnets in millions of fish,

$\Theta'_{a,t,r}$ = observed prefishery total run age composition at age a and year t,

$\Theta_{a,t,r}$ = estimated prefishery total run age composition at age a and year t,

$X_{t,r}$ = surveyed abundance relative to the total run in millions of fish,

$N_{a,t}$ = estimated total prefishery population abundance at age a and year t in millions of fish,

B'_t = observed total aerial survey biomass in tonnes,

$B_{a,t}$ = estimated aerial survey biomass for age a in tonnes, and

$B_{t,q}$ = adjusted total aerial survey estimate in tonnes.

Some assumptions of the model are

(1) beach seine catch and gillnet total catch are measured without error;

(2) catch occurs instantaneously at the start of the year and natural mortality occurs during the entire year;

(3) gillnet selectivity is constant over time and can be modeled with a logistic function; and

(4) the survey may take place either before the fishery or after, but the survey selectivity is assumed constant over time.

All necessary data were entered into the spreadsheet by year and age. Prefishery total population abundance, $N_{a,t}$, was calculated by the formula,

$$N_{a,t} = S_a \left[N_{a-1,t-1} - \left(C_{a-1,t-1,s} + \Theta_{a-1,t-1,g}\, C_{t,g} \right) \right] ,$$

where $a = 4$ to 16, $t = 1982$ to 1994, and $N_{a,1981}$ and $N_{3,t}$ were the initial starting values obtained from cohort analysis. The estimated gillnet age composition in the model was calculated as follows, b and c being parameters of the logistic function:

$$\Theta_{a,t,g} = s_{a,g}\, N_{a,t} \big/ X_{t,g} ,$$

$$s_{a,g} = 1 \Big/ \left(1 + e^{-[b+(c\,a)]} \right) , \text{ and}$$

$$X_{t,g} = \sum_{a=1}^{A} s_{a,g}\, N_{a,t} .$$

Gillnet residuals are $\Theta'_{a,t,g} - \Theta_{a,t,g}$. The estimated total-run age composition in the model is as follows, d and e being parameters of the logistic function:

$$\Theta_{a,t,r} = s_{a,r}\, N_{a,t} \big/ X_{t,r} ,$$

$$s_{a,r} = 1 \Big/ \left(1 + e^{-[d+(e\,a)]} \right) , \text{ and}$$

$$X_{t,r} = \sum_{a=1}^{A} s_{a,r}\, N_{a,t} .$$

Total run residuals are $\Theta'_{a,t,r} - \Theta_{a,t,r}$. The estimated aerial survey biomass in the model is

$$B_{a,t} = W_{a,t}\, s_{a,r}\, N_{a,t} , \quad \text{and}$$

$$B_t = \sum_{a=1}^{A} B_{a,t} ,$$

and the adjusted aerial survey biomass is

$$B_{t,q} = B_t\, q ,$$

where q_t is a survey calibration parameter. The survey underestimates true abundance when q_t is <1, is unbiased when q_t is equal to true abundance, and overestimates when q_t is >1. The aerial survey residuals are $B'_t - B_{t,q}$.

The solver function in the Microsoft Excel® spreadsheet program, based on a quasi-Newton optimization algorithm (Chong and Zak 1996), was then used to minimize total sums of squares, SSQ_{total}, which consisted of 3 components: (1) gillnet age compositions, SSQ_g, (2) total run age compositions, SSQ_r, and (3) aerial survey biomass estimates, SSQ_b. Each represents the sum of the squared residuals:

$$SSQ_g , SSQ_r , SSQ_b = \Sigma (\text{residual})^2 .$$

To keep the magnitude of the sums of squares similar, each component was multiplied by a weighting term, λ, such that

$$SSQ_{\text{total}} = \lambda_g\, SSQ_g + \lambda_r\, SSQ_r + \lambda_b\, SSQ_b .$$

A bootstrap analysis was performed to obtain standard errors of the estimates from the age-structured model. At first, an ordinary bootstrap of the aerial survey and age composition residuals, a random sample with replacement of residuals added to predicted values, was performed (Efron 1982; Efron and Tibshirani 1993). This technique worked for the aerial survey residuals, but resulted in negative age compositions because of the presence of negative residuals and many observed age compositions of low to zero value. Alternatively, the age composition data could be fitted to a multinomial distribution and to age compositions generated based on this fit, but this method required subjective determination of the effective sample sizes; we observed that residual variation was larger than we expected for a multinomial distribution.

Our purpose in performing a bootstrap exercise was to obtain quick and easy estimates of the standard errors that could be obtained from the observed residual variation in age composition. We developed an alternative approach by performing a parametric bootstrap based upon a fit of the age compositions to a beta distribution (Efron 1982; Efron and Tibshirani 1993), details of which we intend to publish elsewhere. The beta distribution uses the beta function, which is a U-shaped curve with 2 shape parameters, v and w, given by

$$B(v,w) = \int_0^1 u^{v-1} (1-u)^{w-1} d .$$

The beta function is related to the gamma function (Evans et al. 1993). The gamma function and its interrelationship with the beta function are

$$\Gamma(c) = \int_0^\infty \exp(-u)\, u^{c-1}\, d$$

and

$$B(v,w) = \frac{\Gamma(v)\,\Gamma(w)}{\Gamma(v+w)} = B(w,v) .$$

We assumed the observed age compositions, $\Theta'_{a,t}$, follow the beta distribution, parameters $v_{a,t}$ and $w_{a,t}$ given by

$$v_{a,t} = z\,\Theta_{a,t} \text{ and } w_{a,t} = z\left(1-\Theta_{a,t}\right) ,$$

where $z = v_{a,t} + w_{a,t}$ and the beta distribution variance of $\Theta_{a,t}$ is

$$\operatorname{var}\left(\Theta_{a,t}\right) = v_{a,t}\,w_{a,t} \big/ \left[z^2(z+1)\right] .$$

The parameter z represents a common variance and allows age compositions across years to be modeled by the same overall distribution. The z parameter is inversely related to the amount of variation in the age-composition residuals. Given the above information, the beta distribution was fitted to the observed gillnet and total-run age composition data by maximizing the log likelihood with respect to z:

$$\ln L\left(z \middle| \left\{\Theta'_{a,t}\right\}\right) = \sum\Big[\left(v_{a,t}-1\right)\ln\Theta'_{a,t} + \left(w_{a,t}-1\right)\ln\left(1-\Theta'_{a,t}\right) - \ln B\left(v_{a,t}, w_{a,t}\right)\Big] ,$$

where

$$\ln B\left(v_{a,t}, w_{a,t}\right) = \ln\Gamma\left(v_{a,t}\right) + \ln\Gamma\left(w_{a,t}\right) - \ln\Gamma(z) .$$

A bootstrap analysis was performed by using the log-likelihood-fitted beta function parameters $v_{a,t}$ and $w_{a,t}$ in a visual basic program, modified from Cheng (1978), to generate beta-distributed random age compositions. Efron and Tibshirani (1993) suggest a bootstrap sample of 50–200 be used for standard error estimates. We anticipated a few convergence failures and therefore chose a bootstrap sample of 110 for this exercise. The nature of this log-likelihood function does not allow zero-valued observed age compositions to be estimated. For the Norton Sound data the observed gillnet ages that were unrepresented (zero) include all ages for 1992, age 3 for all years, age 4 for 1988–1995, and age 5 for 1991 and 1995; in the observed total run only age 3 in 1994 and 1995 was unrepresented. These zeros were left alone in the bootstrap procedure.

Two sensitivity analyses were performed to determine the sensitivity of model parameters and output to changes in model specifications. The first sensitivity analysis was performed to examine the effect of changes in aerial survey sums-of-squares weighting on survey calibration coefficients (q_t) and biomass estimates. A second sensitivity analysis was performed to determine how changes in natural mortality (M) affect q_t.

Table 1. Four estimates of natural mortality for Norton Sound herring; $M = 0.16$ (Alverson-Carney method) was selected for use in this study.

Method	Estimate of M
1.5K, Gulland (1965)	0.44
1.2K, Beverton and Holt (1957)	0.35
Alverson and Carney (1975)	0.16
Pauly (1980)	0.31

RESULTS

The Alverson-Carney estimate of natural mortality resulting from the analysis of growth parameters was 0.16 (Table 1). We chose this estimate for use in the cohort analysis because research indicated natural mortality for Pacific herring decreases to the north and could be as low as 0.10 in the eastern Bering Sea (Trumble and Humphreys 1985; Wespestad 1991).

Estimates of abundance obtained from cohort analysis are shown in Figure 6. The results from the cohort analysis provided initial starting values for use in the age-structured analysis. Specifically, the estimated abundances for age 3 (all years) and year 1981 (all ages) were used as starting values for the age-structured analysis.

A total of 35 parameters were estimated in the optimization function to minimize the total sums of squares of the residuals, SSQ_{total}. The estimated total population abundance, N, for all ages in 1981 and all years, except 1995 at age 3, accounted for 27 parameters. The logistic parameters of gear-selectivity functions for gillnet in years 1981–1990, for gillnet in years 1991–1995, and for sampling gear added an additional 6 parameters. Lastly, the survey calibration coefficients for the aerial survey estimates for years 1981–1984 and 1985–1990 accounted for 2 parameters. Years 1991–1995 were assumed to have total aerial survey coverage; therefore, there was no survey calibration parameter for these years.

At first, the survey calibration coefficients were not used in the analysis. Initial solver runs revealed undesirable patterns in the residuals. In an attempt to obtain a better fit of the model to the data, several weighting schemes were used for the various sums of squares. The aerial survey residuals for years 1982

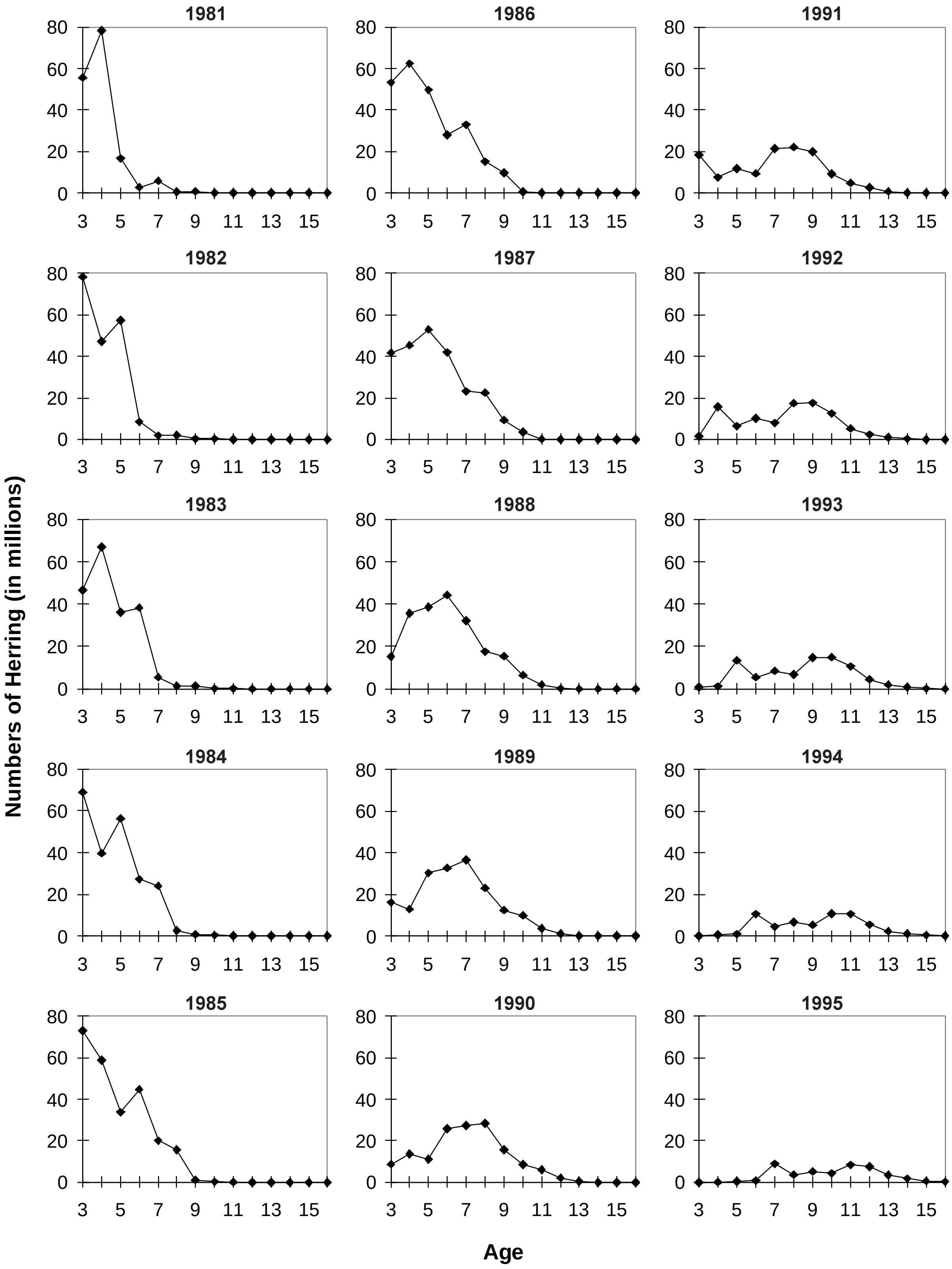

Figure 6. Yearly (1981–1995) estimated abundance of Norton Sound herring from cohort analysis for ages 3 to 16.

Table 2. Parameter estimates of Pacific herring from Norton Sound from the nonpooled age-structured model.

Initial Cohort Sizes

Year	Age	Parameter Estimate (millions of fish)	Year	Age	Parameter Estimate (millions of fish)
1981	3	73.5133	1981	4	123.6259
1982	3	127.9579	1981	5	18.8811
1983	3	58.3050	1981	6	0.8600
1984	3	98.0477	1981	7	6.0544
1985	3	119.0715	1981	8	1.6593
1986	3	65.0653	1981	9	1.0670
1987	3	63.5074	1981	10	0.4910
1988	3	15.8540	1981	11	0.5680
1989	3	39.5981	1981	12	0.3430
1990	3	3.0684	1981	13	0.6342
1991	3	117.8595	1981	14	0.6569
1992	3	0.2907	1981	15	0.6727
1993	3	0.3414	1981	16	0.7488
1994	3	0.3142			

Gear Vulnerability Function Values

Gear	Years	Parameter	Estimate
Gillnet	1981–1989	*a*	-6.907
Gillnet	1981–1989	*b*	1.0412
Gillnet	1990–1995	*a*	-12.302
Gillnet	1990–1995	*b*	1.5574
Sampling	all	*a*	-4.5595
Sampling	all	*b*	0.6683

Aerial Survey Calibration Coefficients

Years	Coefficient Value
1981–1984	1.9162
1985–1990	0.7826

and 1989 were removed from the total sums-of-squares calculation because of poor viewing conditions during those years. Initial runs of the age-structured analysis also revealed poor fitting of the gear-selectivity functions, especially for later ages. Analysis of catch curves revealed peaks in catches averaging around ages 8–9; therefore, gear vulnerability was fixed at 1 (indicating full vulnerability) for all ages >7 in years 1981–1990 and age 8 in years 1991–1995.

The results of various weighting schemes revealed that when more weight was placed on a particular sum of squares, the results tended to conform to the more heavily weighted data set and bias appeared in the residual patterns of the other data sets. The weighting runs revealed an apparent contradiction in the data between the gillnet age composition data and the aerial survey data. The question then became: which data set was more reliable? The aerial biomass survey experienced changes in coverage throughout its history. Changes in the amount of area flown sometimes resulted in minimal biomass estimates, and variation in viewing conditions introduced subjectivity (C. F. Lean,

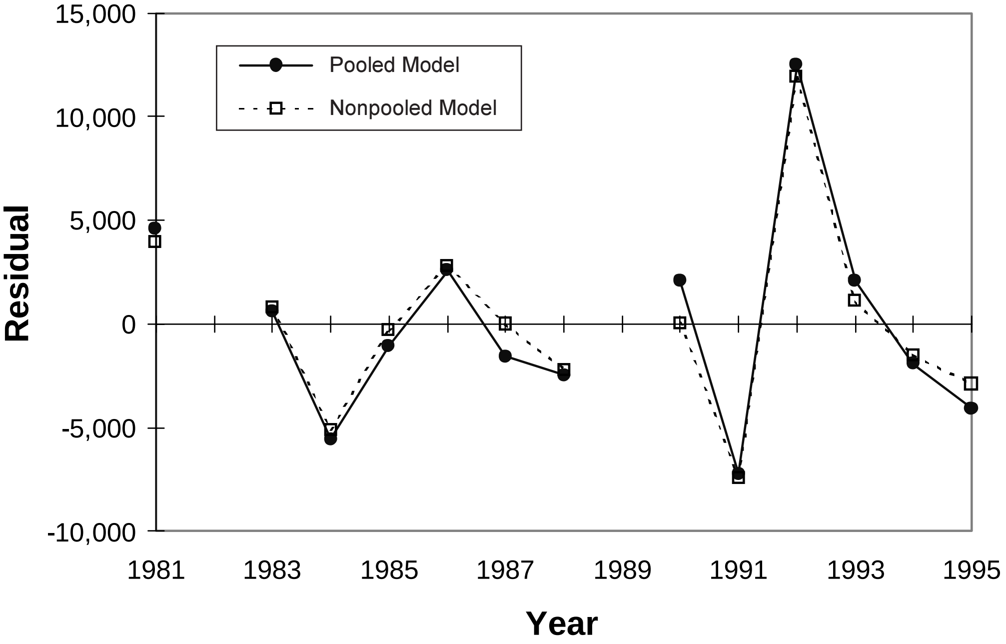

Figure 7. Aerial survey biomass residuals from the pooled and nonpooled age-structured models for Norton Sound herring.

ADF&G, Nome, personal communication). Two survey calibration coefficients for years 1981–1984 and 1985–1990 were added to compensate for incomplete aerial survey biomass estimates. These 2 intervals were chosen after several runs with various combinations of 1 and 2 survey calibration coefficients.

The age-structured model was optimized as a function of 35 parameters. The resulting values for these parameters are shown in Table 2. The values of the survey calibration coefficients indicate the aerial survey was overestimating the biomass in 1981–1984 and underestimating the biomass in 1985–1990. An analysis of the residuals was used to reveal whether the model fit the data well. Although not apparent in the biomass data (Figure 7), in the following years a bias in the model fit became apparent for the gillnet and total-run age composition data (Figures 8, 9). This bias was a direct result of unrepresented older ages in the early years of these data sets (Figures 3, 4). As the years progressed, older fish began to appear in the data set. This apparent trend of older fish being captured in the gillnet fishery, which began around 1990, can partly be explained by a shift in the fishery to targeting older fish (C. F. Lean, ADF&G, Nome, personal communication). However, why older fish were absent in the sampling gear in the early years is a mystery.

A pooled age group or plus group for ages 10–16 was added to the age-structured analysis to eliminate bias in the model fit for the older ages. This reduced the number of parameters being estimated by the optimization function to 29. Several weighting schemes were tested, but it became apparent that changes in the weighting affected the outcome greatly, often causing initial starting values to go to zero. The contradiction between the gillnet and aerial survey data sets in the nonpooled analysis was also apparent in this analysis. The final set of weighting schemes was determined by the minimum aerial survey weight necessary to obtain acceptable residual patterns. Based on this analysis, it appeared the best weighting scheme was $2 \cdot 10^{-9}$ for the aerial survey and 1 for the gillnet and total run sums of squares. Another minor change for the pooled-group analysis was to set the sum-of-squares weight for age 3 in the gillnet data to zero because most of the observed age compositions were zero.

Resulting parameter estimates for the age-structured model with the pooled age group are shown in Table 3. As in the previous analysis, the estimates of the survey calibration parameters indicate the aerial survey overestimated biomass in 1981–1984 and underestimated biomass in 1985–1990. In the prefishery estimates, several recruitment year classes can be seen moving through time as the years progress (Figure 10). The first strong year class, 1977, appeared in 1981 followed by an equally strong year class, 1979, that appeared in 1983. In 1986 a moderate year class, 1982, was apparent, and there was not another appar-

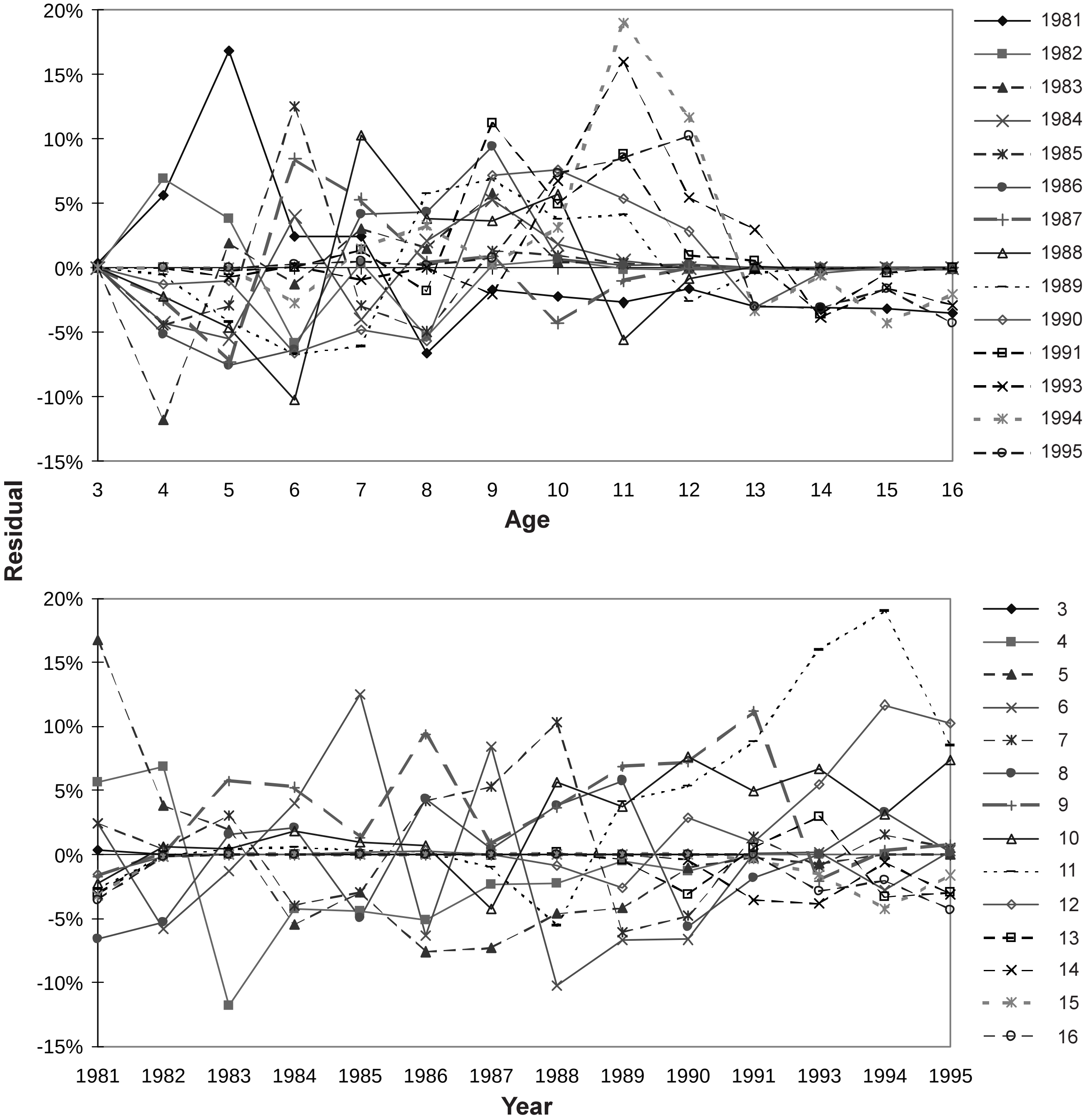

Figure 8. Gillnet age composition residuals from the nonpooled age-structured model for Norton Sound herring.

ent year class until 1990, when a relatively weak year class, 1986, became visible. In 1992 another strong year class, 1988, was apparent in the estimates. The input data revealed the same year classes, except for the 1988 year class, which first appeared in 1992 at age 4 (Figures 2, 3, 4). This year class was not noticeable until 1995 in the gillnet age composition data (Figure 3). This is a direct result of older fish being targeted in the gillnet fishery, as mentioned earlier. In the aerial survey biomass estimates, the year classes are difficult to distinguish (Figure 11) because of the differences in abundance and biomass. For these estimates the pooled age group predominated the biomass, particularly in later years.

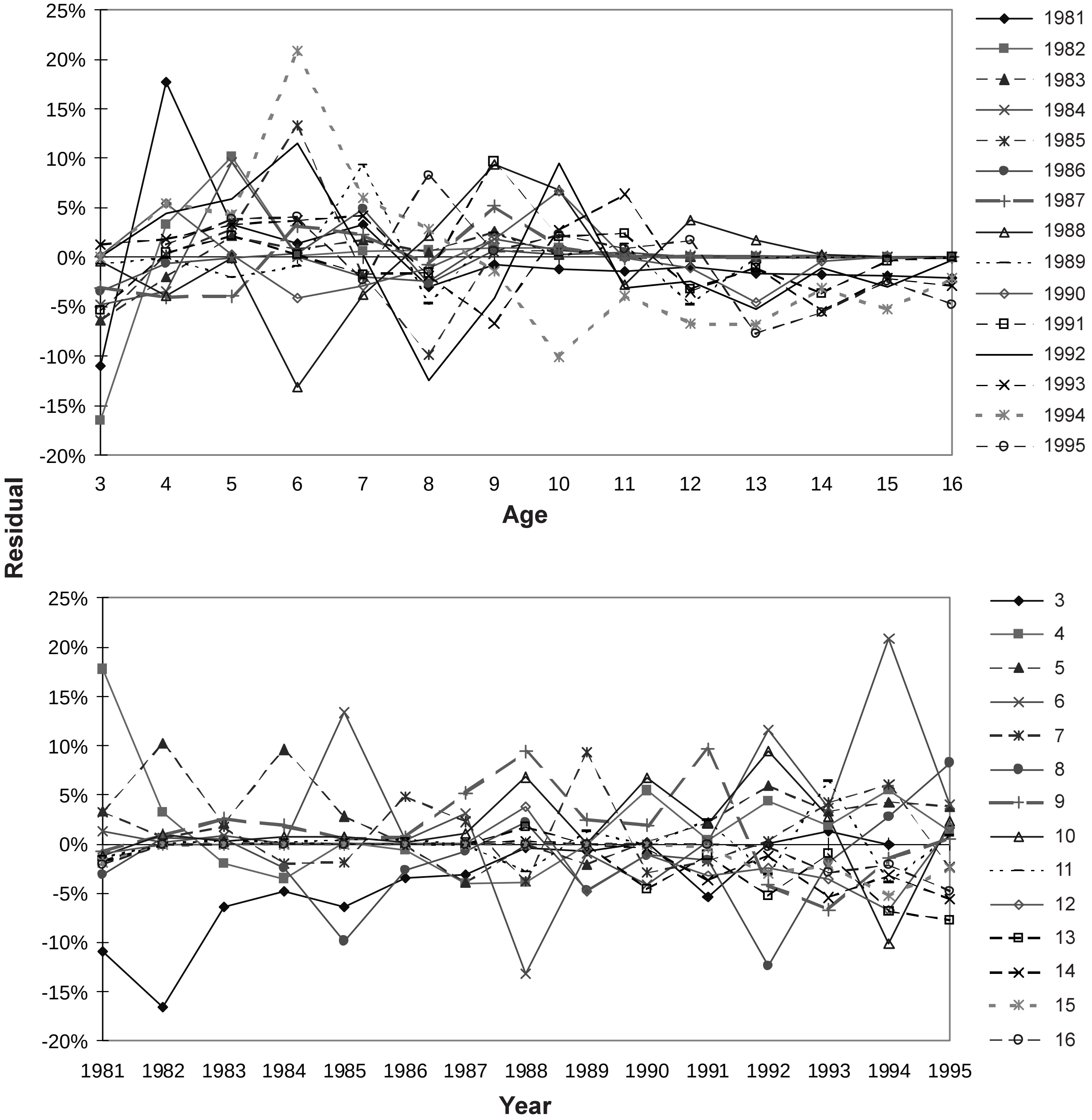

Figure 9. Total-run age composition residuals from the nonpooled age-structured model for Norton Sound herring.

The aerial survey biomass estimates have a similar residual pattern as the first analysis (Figure 7). The bias in age composition residuals for older ages in the first analysis disappeared (Figures 12, 13). The residuals appear well-distributed, except for some possible outliers for the pooled age group, but nevertheless indicate a good overall fit of the age-structured model. The gear vulnerability functions for the gillnet catch and total run sampling gear provided a reasonable fit (Figure 14). The increased age of vulnerability in the later years for the gillnet fishery followed management changes that occurred in the early 1990s.

To obtain standard error estimates, a beta distribution was fitted to the age compositions. For both sets

Table 3. Parameter and bootstrap standard deviation estimates of Pacific herring from Norton Sound from the pooled age-structured model.

Initial Cohort Sizes

Year	Age	Parameter Estimate (millions of fish)	Year	Age	Parameter Estimate (millions of fish)
1981	3	75.2905	1981	4	134.4280
1982	3	128.6008	1981	5	22.9469
1983	3	55.1008	1981	6	2.4164
1984	3	98.4900	1981	7	8.1430
1985	3	108.1296	1981	8	2.3919
1986	3	41.0858	1981	9	1.7709
1987	3	42.5257	1981	10+	1.5745
1988	3	12.0766			
1989	3	38.7258			
1990	3	1.4502			
1991	3	113.9561			
1992	3	10.7807			
1993	3	17.2471			
1994	3	27.7576			

Gear Vulnerability Function Values

Gear	Years	Parameter	Estimate	Bootstrap Standard Deviation
Gillnet	1981–1989	*a*	-6.6600	0.7334
Gillnet	1981–1989	*b*	1.0140	0.1370
Gillnet	1990–1995	*a*	-15.0118	1.4534
Gillnet	1990–1995	*b*	1.9373	0.2342
Sampling	all	*a*	-4.2435	0.5525
Sampling	all	*b*	0.6154	0.0886

Aerial Survey Calibration Coefficients

Years	Coefficient Value	Bootstrap Standard Deviation
1981–1984	1.7064	0.1262
1985–1990	0.7395	0.0746

of age compositions, the beta distribution fits appear adequate and may actually be a bit high (Figure 15). The 110 bootstrap replicates required approximately 15 h of computing time using a 100-mHz computer. The majority of this computing time was involved in the optimization function in the spreadsheet program. It must be noted that 6 optimization trials either failed to converge or settled on unreasonable solutions and were removed from the analysis. Because this technique for bootstrapping was only performed as a means of getting rough estimates of variation, failure to converge with a reasonable solution is probably inconse-

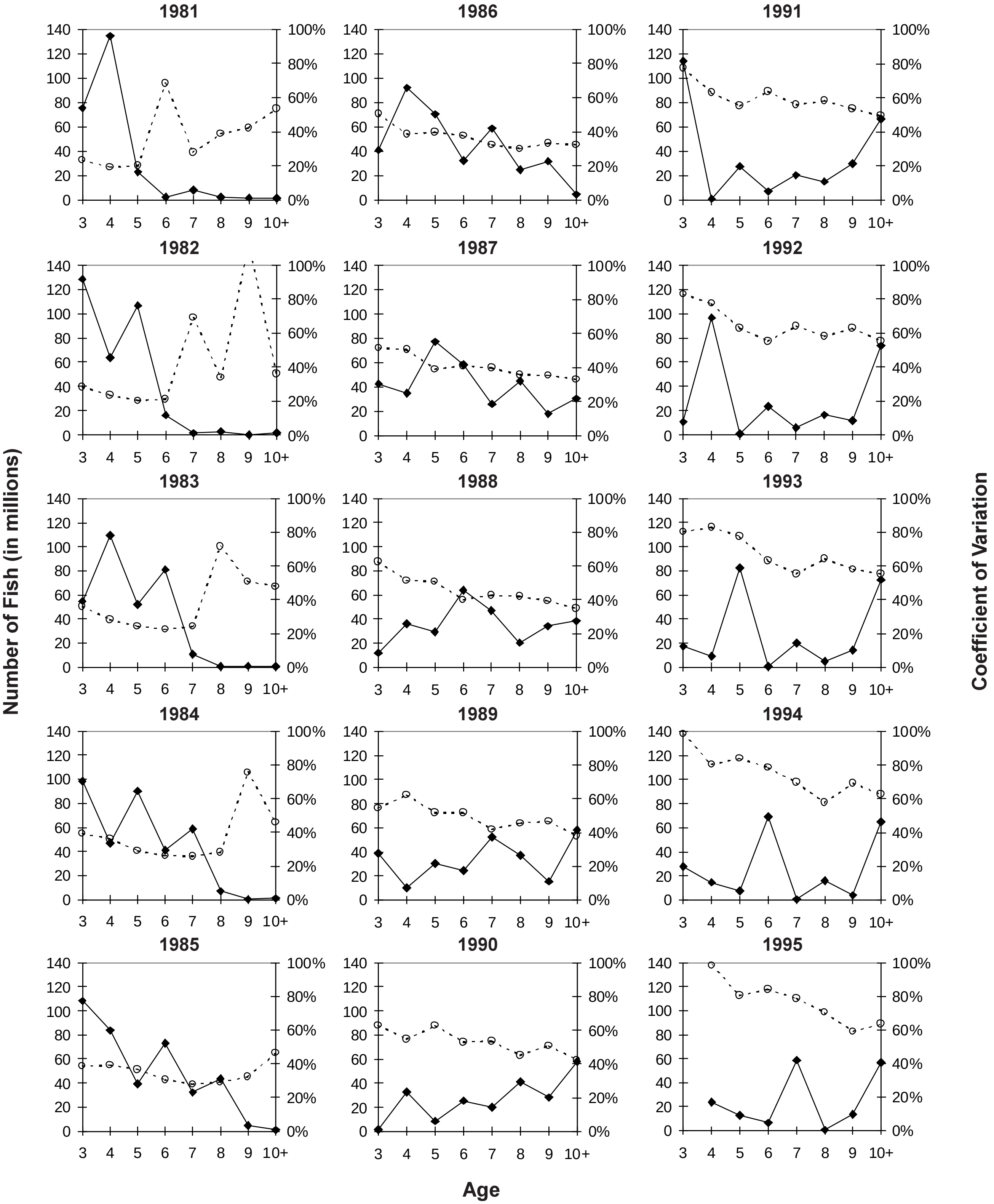

Figure 10. Yearly estimated prefishery abundance of Norton Sound herring from the pooled age-structured model in millions of fish (marked as diamonds) and bootstrap estimates of coefficients of variation (percentages marked as circles) for ages 3 to 10+.

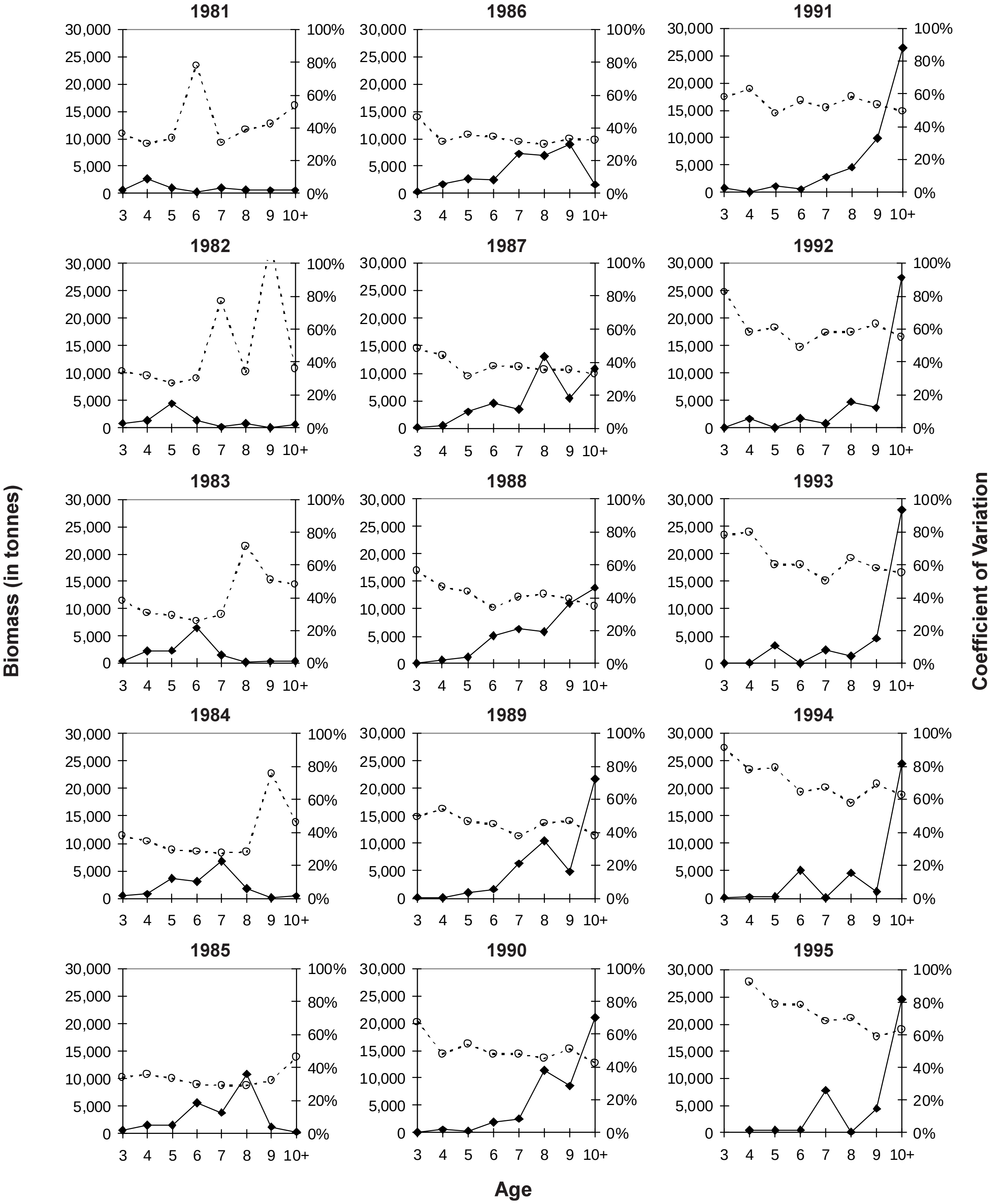

Figure 11. Yearly estimated aerial survey biomass of Norton Sound herring from the pooled age-structured model in tonnes (marked as diamonds) and bootstrap estimates of coefficients of variation (percentages marked as circles) for ages 3 to 10+.

quential to the final results. From the bootstrap samples, the standard error was calculated for prefishery abundance estimates, aerial survey biomass estimates, gear vulnerability function parameters, and aerial survey calibration coefficients.

The standard errors for prefishery abundance and aerial survey biomass estimates were converted to coefficients of variation. In Figures 10 and 11 the coefficients of variation appear to increase as the estimates approach zero. This is a common phenomenon for coefficients of variation, and the extreme result can be seen for age 9 in 1982 in both figures. Aside from this extreme example, the majority of the coefficients of variation appear to range from 20 to 60%. The standard deviations for the gear vulnerability function parameters and aerial survey calibration coefficients are

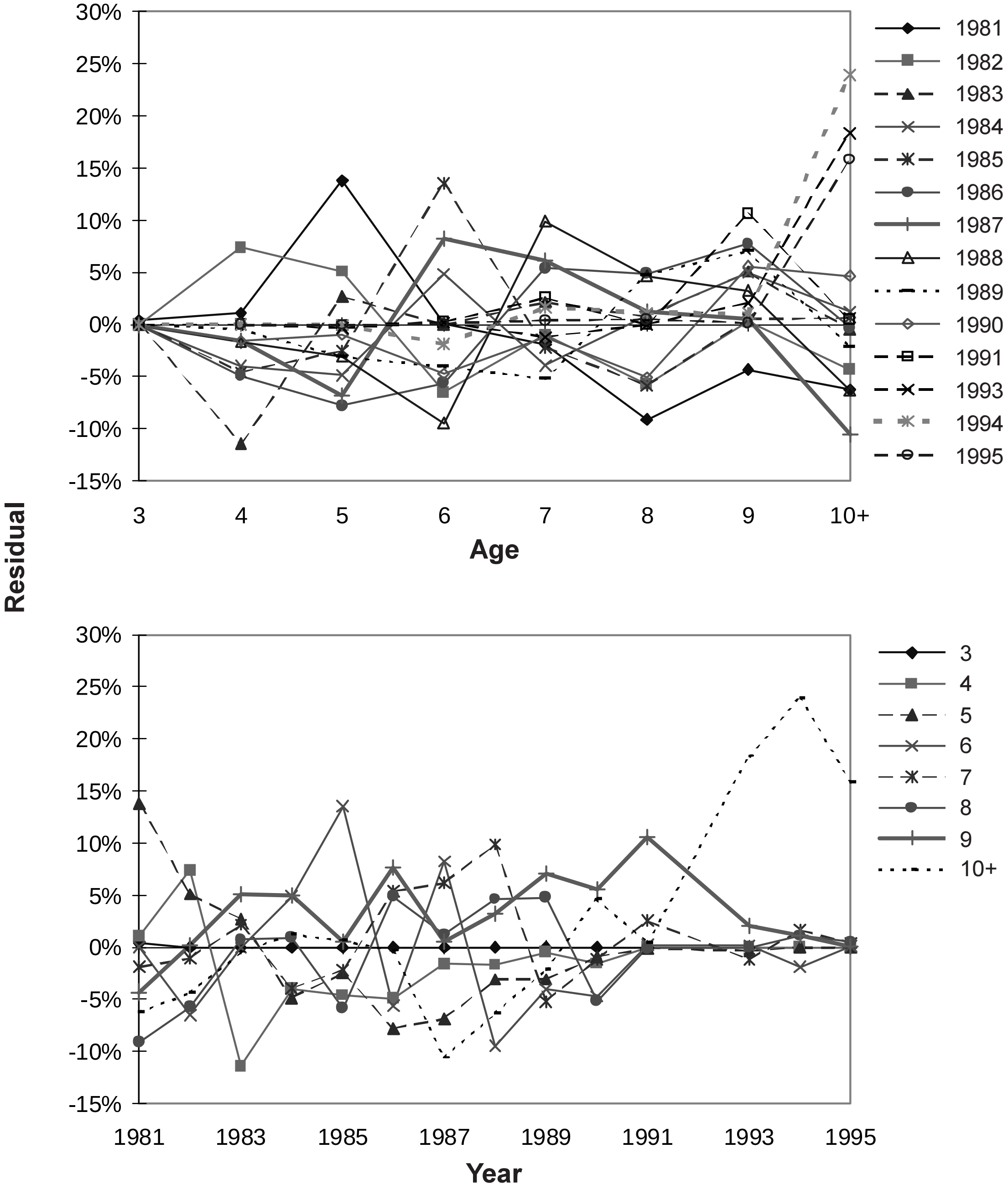

Figure 12. Gillnet age-composition residuals from the pooled age-structured model for Norton Sound herring.

shown in Table 3. The coefficients of variation for these parameters was relatively small, ranging from 7 to 17%.

Sensitivity Analysis to Changes in Aerial Survey Weighting

As mentioned earlier, several aerial survey sums of squares weights were tested for their effects on residual patterns. Changes in the aerial survey sums of squares weights also affected the biomass and survey calibration estimates. A weighting range of $2 \cdot 10^{-7}$ to $2 \cdot 10^{-11}$ for the aerial survey sums of squares indicated that increasing weight resulted in biomass estimates that increasingly conformed to observed values (Figure 16). The aerial survey weighting values were positively correlated with the 1981–1984 survey calibration pa-

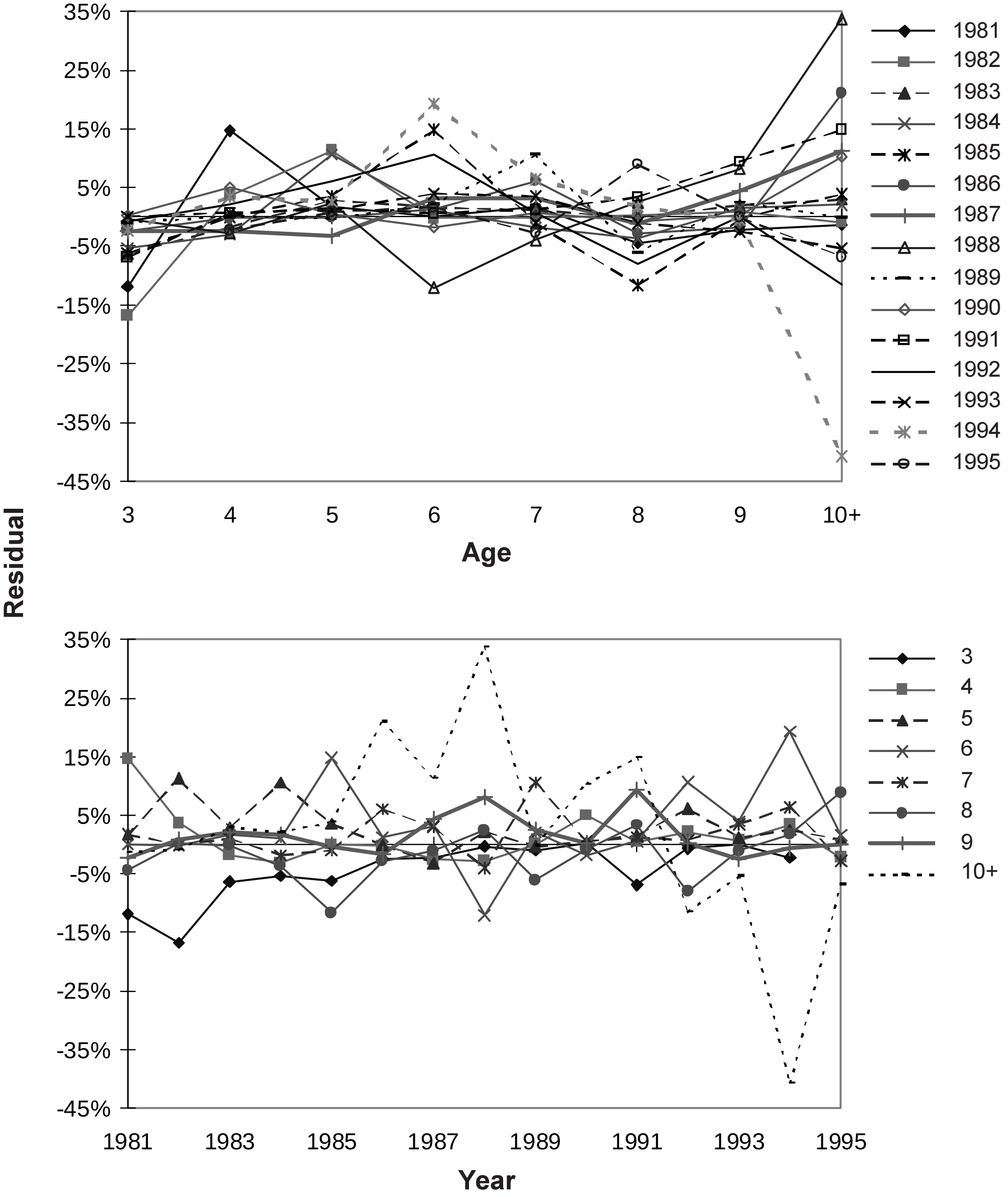

Figure 13. Total-run age composition residuals from the pooled age-structured model for Norton Sound herring.

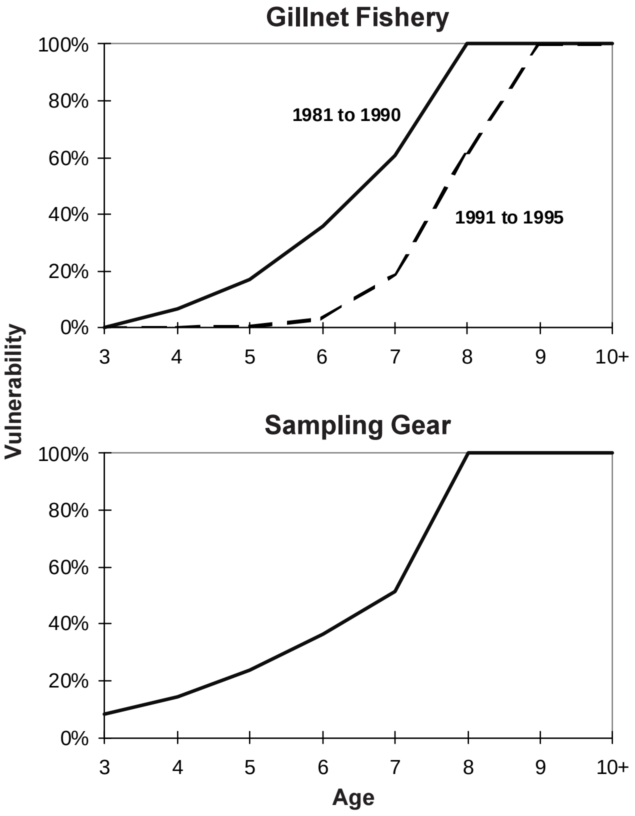

Figure 14. Fishing and sampling-gear vulnerabilities estimated from the pooled age-structured model for Norton Sound herring.

rameter, whereas the 1985–1990 survey calibration parameters were not (Figure 17). Nevertheless, the trend in biomass estimates appeared robust, despite the large weighting range used in this analysis.

Sensitivity Analysis to Changes in Natural Mortality

A range for M of 0.16 to 0.60, which corresponds to an annual survival rate (S) of 0.85 to 0.55, was placed in the model for the year groupings corresponding to aerial survey calibration groupings, and all model parameters were reestimated. A positive correlation occurs between q_t and M for 1981–1984. Increases in M resulted in increases in the aerial survey calibration parameter, which approached 1, indicating changes in M may explain changes in the aerial survey capability in the years 1981–1984. The other aerial survey parameters for years 1985–1990 did not vary much with M. Changes in M for years 1985–1990 did not affect the corresponding aerial survey calibration coefficient, but increases in M in years 1985–1990 effected decreases in the aerial survey calibration parameter for years 1981–1984 (Figure 18).

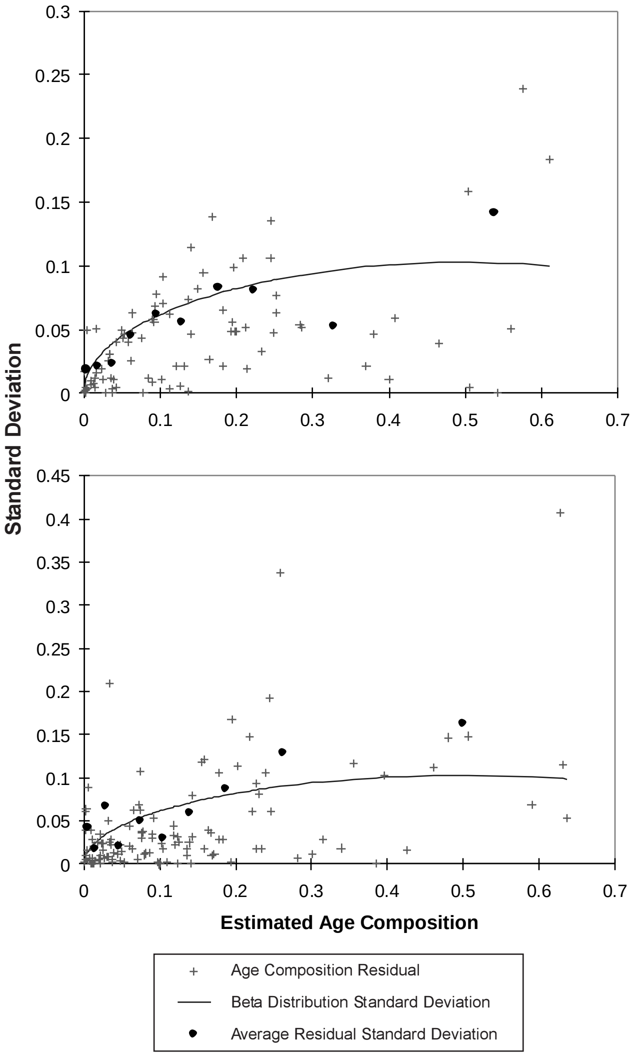

Figure 15. Beta distribution fit to Norton Sound herring gillnet (top) and total-run (bottom) age compositions.

DISCUSSION

It appears the pooled-group age-structured analysis produced a better fit to the data than the non-pooled age-structured analysis. Addition of the pooled age group eliminated the bias caused by a lack of older-age representatives in the early years of the gillnet and total-run age composition data sets. One explanation for this lack of older fish in the early years of the gillnet fishery is related to the timing of the fishery relative to the timing of the run. The Norton Sound herring run,

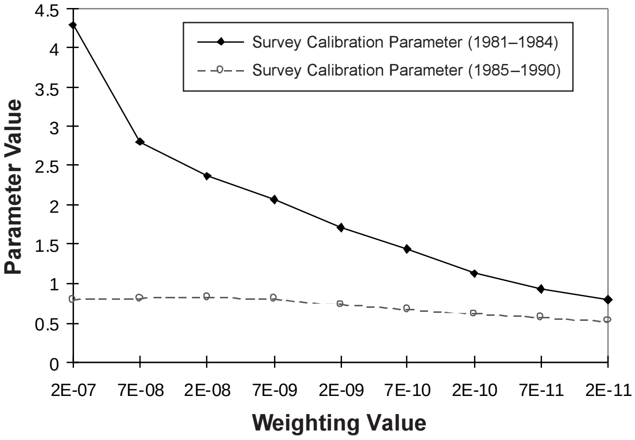

Figure 16. Effects of changes in aerial survey sums of squares weighting on the survey-calibration parameter values in the pooled age-structured model for Norton Sound herring.

like many herring stocks, begins with the arrival of older fish, later followed by younger fish. The fishery may have been targeting the end of the spawning run in the early years, and gradually there may have been a shift to target the early part of the run in recent years. The fishery manager for Norton Sound has, in the last few years, attempted to target the early part of the run, as mentioned earlier. However, this management change does not explain the lack of older fish in the early years of the total-run age compositions, so the total explanation remains a mystery.

The bootstrap analysis chosen for this data and model did not utilize sample size or the sampling scheme used to collect the data, but rather used the variation in residuals of age composition. The method is, however, easily performed without the complications of sample size or major changes in the model structure. The parametric beta distribution provided a concise synthesis of the variability found in the age composition data. The estimates of variation are probably sufficient for most uses. To date ADF&G does not calculate any type of variance estimate for their age-structured assessments of exploitable herring stocks. The bootstrapping technique provided here might prove useful for other age-structured herring assessments.

The sensitivity analysis to changes in aerial survey sums of squares weighting indicates the biomass estimates are fairly robust to large changes in weighting values. However, increases in the aerial survey weighting resulted in biomass estimates conforming to observed values, which coincided with bias in the age composition residuals. These weighting changes also affected the survey calibration parameters, par-

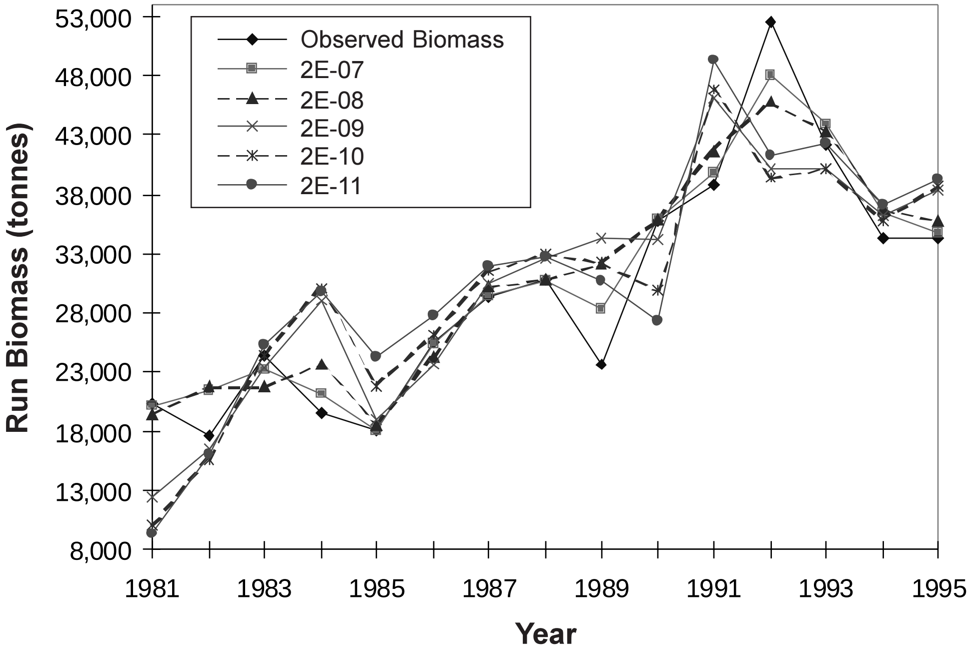

Figure 17. Effects of changes in aerial survey sums of squares weighting on the estimated run biomass in the pooled age-structured model for Norton Sound herring.

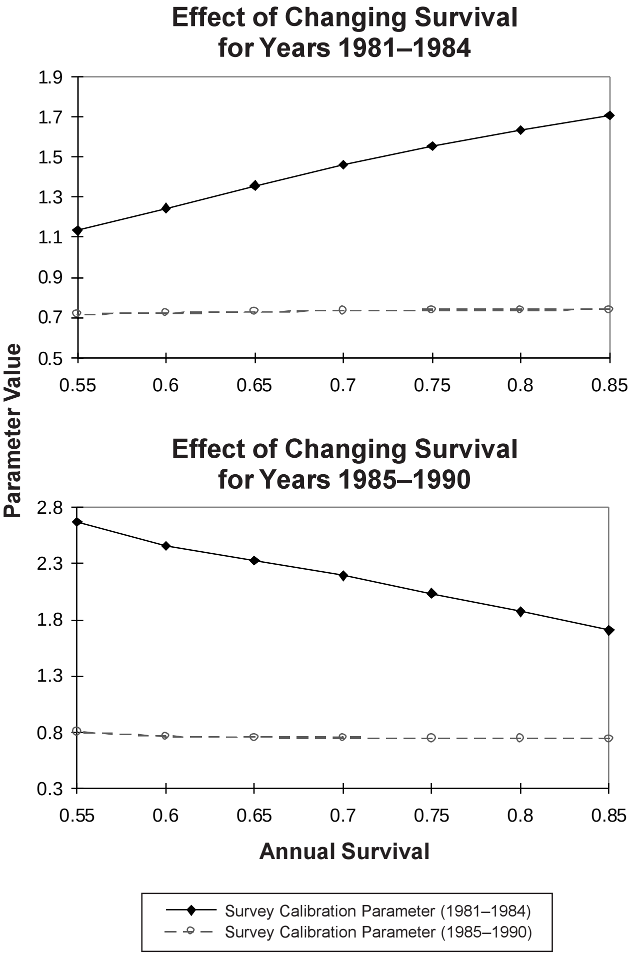

Figure 18. Effects of changes in annual survival on the aerial survey calibration parameters in the pooled age-structured model for Norton Sound herring.

ticularly the 1981–1984 parameter. The residual bias and inflated survey-calibration parameter are indicators of a data conflict.

Changes in the aerial survey calibration parameters in this age-structured model suggest the influence of age composition data tends toward lower biomass in years 1981–1984 and higher biomass in 1985–1990 than the aerial survey data. This data conflict could have arisen from 3 different causes: (1) a change in the aerial survey capability, (2) a change in aging-error (age determination) bias, and (3) a change in the natural mortality rate. If this age-structured model is to be used in future Norton Sound herring assessments and forecasts by ADF&G, reasons for the data conflict will need to be explored further.

The data conflict in this model was treated by the incorporation of aerial survey calibration parameters. Factors affecting biomass estimates from aerial surveys include surveyor bias, changes in ratios of herring biomass to school surface area, changes in viewing conditions, and changes in area covered. Given the high degree of subjectivity and variability involved, we believe the aerial survey data is a likely candidate for impropriety.

If the data conflict arose from changes in aging-error bias, then the bias had to be toward younger ages in 1981–1984 and older ages in 1985–1990. The lack of older-aged fish in the early years of the age composition data sets suggests an underaging bias. Given the available information, it is difficult to make any further conjectures regarding aging-error bias in Norton Sound herring. The best means of understanding aging-error bias in Norton Sound herring would come from a reanalysis of the scale samples by ADF&G. A change in scale readers could be the simplest cause for any aging-error bias.

Changes in survival rate were explored in the first sensitivity analysis. It appears natural mortality and the survey calibration coefficients are confounded. Higher natural mortality in the early years seems to explain the data conflict, as indicated by the correlation between changing survival rates and the 1981–1984 survey calibration parameter (Figure 18). However, the lack of any relationship between survival rate and the 1985–1990 survey calibration parameter (Figure 18) indicates this does not fully explain the data conflict. Furthermore, aging error in the early data could create the perception that natural mortality (M) changed. Until aging error is resolved, the conclusion of a change in M remains speculative.

Overall, age-structured stock assessment techniques, such as the type presented here, are among the best methods available to fisheries managers. This type of analysis is very useful for synthesizing much information and providing estimates that are in line with available data. As shown in this analysis, age-structured techniques can also highlight contradictions among data sets. Evaluation of the goodness of fit for this model by graphical techniques of residuals indicated the model provided a fairly good fit. The residuals were randomly distributed and did not show any patterns relating to age, year, or year class. The fit of this model to the data was comparable to previous age-structured assessments for Alaska herring stocks (Brannian et al. 1993). We believe this model should be used in future Norton Sound herring assessments and forecasts.

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