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ESTIMATION AND EVALUATION OF A HARVEST THRESHOLD FOR A W. BEHM CANAL HERRING FISHERY BASED ON A PERCENTAGE OF AVERAGE UNFISHED BIOMASS

by

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ABSTRACT

Average unfished biomass (AUB) was estimated for a spawning population of herring at W. Behm Canal. Population parameters used in the estimation of AUB were derived from an age-structured analysis (ASA). Based on estimates of AUB under an empirical spawner-recruit relationship, and random recruitment, alternatives to the current 2,000-ton W. Behm Canal threshold were estimated and evaluated. Using a 25% of AUB criterion, alternative thresholds of 2,035 and 5,258 t were estimated. The alternative thresholds were evaluated, along with the current threshold, using several fishery performance statistics. Based on this evaluation it is recommended that the harvest threshold for W. Behm Canal be increased from the current 2,000 tons, to 5,258 tons.

INTRODUCTION

Herring in Southeast Alaska have been managed using a threshold and variable harvest rate policy since 1983. The department establishes thresholds that are biomass reference levels established for each fishing area. If the spawning biomass at an area is forecast to be below its threshold, no harvest is allowed. When the spawning biomass forecast for an area equals the threshold, the department exploitation rate is 10% of the estimated spawning biomass. For each incremental increase in the spawning biomass equal to the threshold, the exploitation rate increases by 2%. The maximum 20% exploitation rate is achieved when the spawning biomass is six times the threshold level. The exception to this relationship is at Sitka. In 1996, the Board of Fisheries established a regulation that increased the Sitka threshold and changed the harvest rate formula. At Sitka, for each incremental increase in the spawning biomass equal to the threshold, the exploitation rate increases by 8%.

The original goal of the department's threshold/variable harvest rate policy was to maintain herring populations above the established threshold escapement levels. These levels and the variable harvest rate schedule were intended to protect herring stocks from sharp reductions due to recruitment failure, to maintain adequate abundance of herring as prey for commercially important predator species such as salmon, and to provide for the highest quality commercial herring products. Funk and Rowell (1995) make an important distinction between conservation and productivity thresholds. A conservation threshold is a point "...below which a population may experience complete reproductive failure" and is in danger of extinction. Conversely, productivity thresholds, used to manage Pacific herring in Southeast Alaska, are points below which commercially optimal productivity levels may not be maintained. As Funk and Rowell (1995) point out, "Thresholds defined in terms of commercial productivity are always higher than conservation thresholds designed to...prevent extinction."

Initially, area-specific thresholds were established based on a variety of factors. These included: historical estimates of abundance (determined from hydroacoustic surveys, linear miles of spawn, and diver surveys); historical and personal knowledge; judgment of research and area management biologists personal contacts with fishers and other public regarding the relative size and area of various stocks, and; biologist's judgment regarding minimum quotas that could be managed and controlled. The thresholds were established with the expressed recognition that the levels would be subject to change as new data and research became available.

Since the original establishment of the thresholds, up to an additional 17 years of spawning biomass, harvest, fecundity, and growth data have been collected, analyzed, and evaluated for many Southeast Alaska herring populations. Biomass estimates have been improved with the implementation and refinement of diver surveys to estimate total egg deposition. In addition to the availability of more data, recent research on threshold management strategies provides new guidelines for setting harvest thresholds based on an improved understanding of fish population dynamics.

Quinn et al. (1990) evaluated the influence of threshold management policies on yield, standard deviation of yield, and population rebuilding time of Bering Sea pollock. Assuming that maximizing yield and minimizing the standard deviation of yield were of equal importance, they determined an optimal threshold that generally ranged from 20 to 35% of the average unfished biomass (AUB), with an optimal fishing mortality close to 0.4. Using the same approach of Quinn et al. (1990), Zheng et al. (1993) evaluated threshold management strategies for Pacific herring in some areas of Alaska. For herring in the eastern Bering Sea, they determined a median optimal threshold of 20% of AUB, given an exploitation rate of 20%. For Prince William Sound herring they found a median optimal threshold of 15% of pristine biomass given an exploitation rate of 20%. Throughout Alaska, 20% is currently the maximum allowable exploitation rate for Pacific herring. Both Quinn et al. and Zheng et al. accounted for environmental variation, possible stock-recruitment relationships, and correlation in recruitment among years (i.e. autocorrelation) as part of the process of estimating optimal threshold levels.

Acceptable thresholds in the range of 15 to 35% of AUB have emerged from recent research. Thresholds of 25% of AUB have been used effectively in the management of some Pacific coast herring and groundfish fisheries for as long as ten years. A level of 25% of the average unfished biomass (AUB) is used as a cutoff in the management of herring in British Columbia (Haist and Schweigert, 1990). When British Columbia herring stocks are above "cutoff levels," a straight 20% exploitation rate is used to determine recommended catch. The 25% AUB criterion was used to establish the current 22,000-ton threshold for management of the Prince William Sound herring fisheries. Zheng et al. (1993) suggest that under a 20% exploitation rate a threshold of 25% of AUB provides protection to herring populations and "...approximately maximizes the sustained yields." Funk and Rowell (1995) recently applied the methods of Zheng et al. (1993) to estimate the AUB and recommend a new threshold for management of the Togiak herring fishery consistent with the 25% AUB criterion.

The re-evaluation of the productivity threshold described here is generally based on the methods of Zheng et al. (1993) and Funk and Rowell (1995) to estimate the AUB and a 25% AUB threshold for herring spawning in W. Behm Canal.

METHODS

The AUB of W. Behm Canal herring was estimated by simulating a long time series of biomasses in the absence of fishing (Funk and Rowell 1995). Annual biomasses were simulated by accounting for gains to the mature population from recruitment, maturation, and growth and losses due to natural mortality. Parameter estimates needed to account for changes in biomass were estimated using an age-structured analysis (ASA, Carlile et al. 1995, Funk and Sandone 1990). Parameter estimates included the historical time series of numbers of age-three recruits, annual survival, and age-specific maturity. Weights-at-age were estimated from annual age-weight-length (AWL) sampling at W. Behm Canal.

Threshold management policies tacitly assume some density dependent population regulation. However, based on the ASA-estimated W. Behm Canal spawner-recruit data (Figure 1, Table 1), the form and strength of the density dependence for W. Behm Canal herring is difficult to define using conventional spawner-recruit models like a Ricker model. This is due, in part, to the small number of estimates. Zheng (1996) reached the same conclusion with respect to most major Southeast Alaska herring populations. For this reason, the simulated recruitment time series used for the biomass simulations were generated from an empirical spawner recruit model (Funk and Rowell 1995) and a random recruitment model.

For simulations based on the empirical spawner-recruit model, age-three recruitment was simulated for 2,500 years by repeated, random sampling of recruits from two strata containing the ASA-estimated age-three recruits (Figure 1). The strata boundary of 5,000 tonnes of spawners was determined as a perceived natural breakpoint in the pattern of spawners and recruits. Age-three recruits for a given year ($N_{3,y}$) were randomly selected from one of two strata based on the value of B_{y-3}, where B_{y-3} is the estimated spawning biomass in year y-3. If B_{y-3} was less than or equal to 5,000 metric tons, recruits were chosen randomly from among the two recruit values in Stratum A, otherwise they were randomly selected from the recruit values in Stratum B (Table 1). This process of recruit selection from specific strata defined the empirical spawner-recruit model used for the simulations. For the totally random spawner recruit model, recruit were selected completely at random from among the six recruit values (Table 1).

Annual spawning biomass (B_y) was estimated from the ASA as:

$$B_y = \sum_a \rho_a \cdot W_a \cdot N_{a,y} , \tag{1}$$

where ρ_a is the ASA-estimated proportion of mature herring at age a, W_a is the mean annual weight of W. Behm Canal herring at age a from 1991 to 2002, and $N_{a,y}$ is the number of age a herring in year y.

The numbers of ages-4 – 8+ fish were estimated as

$$N_{a,y} = S \cdot N_{a-1,y-1} \tag{2}$$

Average unfished biomass was calculated as the average of the last 2,000 simulated annual spawning biomasses (B_y). The first 500 simulated biomasses were excluded from calculation of AUB to allow the estimates of B_y to stabilize before estimating AUB.

We evaluated the influence of different thresholds on catch and biomass by simulating future catch under the current W. Behm Canal bait fishery threshold (2,000 tons) and the estimated 25% AUB thresholds. We also explored two different spawner-recruit models based on spawner-recruit estimates from the W. Behm Canal ASA model (Figure 1). For the harvest simulations,

$$N_{a+1,y+1} = S \cdot (N_{a,y} - C_{a,y}) \tag{3}$$

Equations for estimating $C_{a,y}$ are provided in Appendix A. Total catch was simulated using the Southeast sliding scale harvest rate formula applied to simulated biomasses. The mean seine gear selectivities from the 2002 Craig, Tenakee Inlet and Sitka ASAs were used as the estimates of seine gear selectivity for the catch simulations. Average fished biomass (AFB) and catch were simulated for 2,000 years. Each 2,000-year simulation was repeated ten times and the average AFB, catch, coefficient of variation (CV) of catch and percent of years with fisheries were estimated.

In addition to estimating AUB for the two recruitment models, simulated catch histories were compared under four differing scenarios. The scenarios differed with respect to the thresholds and the underlying spawner-recruit relationships that were assumed representative of the herring that spawn at W. Behm Canal. Under Scenario A, the 2,000 year catch times series was simulated using the current 2,000-ton threshold in combination with a random recruitment process in which age-three recruits were selected completely at random from among the ASA-generated recruit time series (Table 2.). Scenario B used the same threshold, but age-three recruits were chosen randomly from the ASA-recruitment time series using the empirical spawner-recruit relationship (Figure 1). Scenario C used the threshold equivalent to 25% of the AUB estimate from the completely random recruitment model and generated the catch time series using the random recruitment model (Table 2). A 25% AUB threshold as generated under the empirical spawner-recruit model and a catch time series, also generated using the empirical spawner-recruit model, defined Scenario D.

RESULTS

I obtained the best fits of modeled to observed data using age-specific estimates of survival. The annual survival rate (S) for ages —4 and 7+ was .679 and for age 5–6, 0.31. Estimates of alternative thresholds and the associated harvest and recruitment scenarios are listed in Table 2. Maturities, gear selectivities, and weights-at-age used for biomass simulations are included in Table 3.

Plots used to assess goodness of fit of ASA-estimated to observed population parameters are depicted in Appendices B–C. Generally there was sufficient agreement between the ASA estimates and observed data, to warrant using the ASA-generated population parameters as the basis for initial population projection simulations for estimating AUB and evaluating the influence of various thresholds on fishery performance. However, the time series of age composition and spawn deposition is quite short, relative to other spawning populations of herring in Southeast Alaska for which ASAs have been used to model the populations. Only nine years of spawn deposition data were available with which to model the dynamics of the spawning herring in W. Behm Canal. For comparison, as of 2002 there were 25 and 16 years of spawn deposition data available for the Sitka and Tenakee Inlet spawning populations.

Estimated AUB for W. Behm Canal under the random recruitment model is 8,139 (Figure 2). Application of the 25% of AUB criterion for determining a threshold would yield a new W. Behm Canal threshold of 2,035 tons, 35 tons above the current threshold (Table 2). With the empirical spawner-recruit model, the estimated AUB was 21,032 tons (Figure 3). A threshold equivalent to 25% of this AUB is 5,258 tons (Table 2).

Under Alternative Harvest Scenario A, the AFB was 6,825 tons (Figure 4). Under Scenario B, the current 2,000 ton threshold combined with an assumed empirical spawner recruit relationship, the AFB increased to 8,508 tons (Figure 4). Because there was little difference between the current threshold and the 25% AUB threshold, the AFBs under Scenarios C and D were 6,825 tons and 8,508 tons, the same as their counterparts under Scenarios A and B (Figure 4).

Estimated mean annual, long-term catches under these scenarios were 1,063 and 964 tons for the random recruitment (Scenario C, Table 2) and empirical spawner recruit (Scenario D, Table 2) models, respectively (Figure 5). Harvest scenarios based on the current threshold had mean annual, long-term catches of 1,070 for the random recruitment model (Scenario A, Table 2), and 1,427 for the empirical spawner-recruit (Scenario B; Table 2) model (Figure 5).

The percent of years with fisheries was 100% for Scenarios A–C. Only for Scenario D, the empirical-spawner recruit relationship with a 25% AUB threshold, did the percent of years with fisheries decline slightly, to 95%.(Figure 6).

The CVs of catch for the scenarios based on random recruitment, both the current 2,000 ton threshold and the 25% AUB threshold, were the same, 59% (Scenarios A and C; Table 2; Figure 7.). Catch CV for the 25% AUB threshold (Scenario D) was slightly higher, at 52% than the 46% CV under the existing 2,000 ton threshold (Scenario B; Figure 7).

These results address some possible long-term effects (i.e. over a simulated 2,000-year time horizon) of two threshold levels under two assumed spawner-recruit models. Figure 8 can be used to evaluate the possible shorter-term impacts of candidate thresholds on harvests. This figure shows the maximum allowable quotas under the three alternative threshold levels over a range of forecast biomass levels.

Among the three thresholds, the current 2,000 ton threshold is least restrictive of harvest. Under this threshold, the 10% harvest rate could occur given a forecast of 2,000 tons. The maximum 20% harvest rate would be allowed with a forecast of 11,500 tons (Figure 8). A biomass at least this high occurred only once in the ASA estimated 12 year time-series of biomass. Use of the 25% AUB threshold criterion, under a random recruitment scenario, would result in a very slight increase in harvest. The increase would be very slight because the 25% AUB-random recruitment scenario yielded a threshold of 2,035 tons; only 35 tons above the current 2,000 ton threshold. Under this scenario, the 10% harvest could occur beginning at 2,035 tons and would achieve the maximum 20% harvest with forecasts at and above 12,000 tons.

Lowest harvests would be achieved under the 25% AUB threshold-empirical spawner recruit relationship scenario. With this scenario, harvest at the 10% rate could begin with a forecast of 5,258 tons and reach the maximum, 20% harvest rate with a forecast of 30,500 tons. Biomass estimated from the ASA exceeded the 5,258 threshold in each of the 12 years represented in the model, but never attained the 30,500 ton level at which the 20% harvest could be invoked. The maximum biomass was estimated as 12,446 which would have provided a harvest rate of 13% and an allowable quota of 1,594 tons.

DISCUSSION

A herring harvest strategy with a harvest rate of 20% when a population is above a threshold of 25% of the AUB has been suggested as an approach that would protect herring populations yet approximately maximize sustained yield (Zheng et al. 1993). This type of harvest strategy is used in British Columbia (Schweigert 1993) and Prince William Sound, Alaska, and was recommended for use in the management of herring fisheries at Togiak (Funk and Rowell 1995) Sitka, (Carlile 1998a) and Tenakee Inlet, Alaska (Carlile 1998b). Based on the 25% AUB criterion, a recommendation was made to increase the Sitka threshold from the historical threshold of 7,500 tons to a new, more conservative, threshold of 16,759 tons (Carlile 1998). The Alaska Board of Fisheries (BOF) subsequently increased the Sitka threshold to 20,000 tons to provide additional protection for subsistence users. The recommendation for Togiak, while rejected by the BOF, would have also resulted in an increased, more conservative, threshold for that herring population. In contrast to Togiak and Sitka, application of the 25% AUB criterion at Tenakee Inlet would yield a threshold lower, and therefore less conservative, than the established 3,000-ton threshold.

Relative to Sitka and Tenakee Inlet, the two other areas in Southeast Alaska for which recent threshold analyses have been conducted, the time series of data available for ASA modeling and threshold analysis for W. Behm Canal is short. At least 25 and 16 years of spawn deposition and age composition data were available for analyses for Sitka and Tenakee Inlet. Only nine years of spawn deposition and age composition data were available for W. Behm Canal. Longer time series of data increase the likelihood that ASA modeling will correctly estimate population parameters which more accurately characterize the dynamics of a herring population. A longer time series is more likely to include the wider range of abundance levels that a population might normally exhibit.

In addition to the relatively short times series of W. Behm Canal data, spawn deposition sampling began in 1993 only after general field observations indicated an apparent increase in spawning activity reflected by an increase in the miles of spawn along the shores of W. Behm Canal. Therefore, prior years, during which spawning activity was apparently much lower, based on miles of spawn, are not represented in the ASA model, nor in the simulations aimed at estimating a threshold. Consequently, population parameters estimated from the ASA and threshold analyses may be biased, and not adequately reflect the populations levels, or degree of population fluctuation, which might characterize the W. Behm Canal spawning abundance over longer time periods.

Marked changes in apparent abundance of herring at W. Behm Canal, as presumably reflected by the sharp decline in spawn deposition between 1999 and 2000, may have been due largely to natural mortality. However movement may have also contributed, to an unknown degree, to these apparent changes in local spawning abundance. Recurrent spawning activity has occurred at nearby areas such as Kasaan Bay, Ernest Sound, and Revillagigedo Channel. It is possible that inter-annual movement of herring has occurred, and continues to occur, among these areas and W. Behm Canal. The ASA model used to estimate key population parameters for the W. Behm Canal spawning population does not expressly account for losses from, or gains to, the spawning population due to herring movement. However the model fits predicted to observed age composition and spawn deposition data that may have been influenced, at least partly, by movement. Therefore model estimates of numbers of age-3 recruits, maturity and annual survival, may be influenced, and perhaps biased, by movement. This may have resulted in biased estimates of AUB, thresholds based on AUB and parameters such as long-term catch, used to evaluate the influence of various thresholds.

In the past, concerns about the possible movement of herring between W. Behm Canal and adjacent areas have been sufficient to preclude a winter bait fishery in W. Behm Canal. There has been a concern that winter harvest of herring in W. Behm Canal could lead to overharvest of herring which may overwinter in W. Behm Canal but spawn and are subjected to harvest on spawning grounds at areas close to W. Behm Canal.

As concluded for the Tenakee Inlet threshold analysis (Carlile 1998), the W. Behm Canal spawner-recruit estimates do not suggest ready definition of an underlying spawner-recruit relationship using conventional spawner-recruit models such as a Ricker or Beverton-Holt model. This is due partly to the small number of years (6) of available spawner-recruit data. However, the apparent lack of a readily definable spawner-recruit relationship is consistent, with Zheng's (1996) finding of no apparent spawner-recruit relationship for Sitka herring. Zebdi and Collie (1993) did define an environmentally dependent Ricker model that incorporated sea surface temperature anomalies and spawners as explanatory variables affecting Sitka herring recruitment.

Although the data seems insufficient to define a possible underlying spawner recruit relationship for W. Behm Canal herring using conventional spawner-recruit models, available estimates may suggest a lower probability of high recruitments with high levels of spawners. This suggested relationship is similar to that found by Funk and Rowell (1995) for Togiak herring. For Togiak herring, Funk and Rowell (1995) found that the highest levels of recruits tended to be associated with lower levels of spawners over the range of spawning biomass for which they had data. In contrast, Zheng (1996) concluded that for herring in the North Atlantic and Northeast Pacific Oceans, higher levels of spawners tended to be associated with higher levels of recruitment. Myers and Barrowman (1996) reach a similar conclusion about a much wider variety of fish species worldwide.

Depending upon whether the actual spawner-recruit relationship of W. Behm Canal spawning herring is closer to the random or the empirical recruitment relationship, projected reductions in long-term mean annual catch could be as little as 0.7%, under the random recruitment, to as much as 33% with the empirical spawner-recruit relationship (Figure 5). However the percent of year with fisheries would be very similar under the two scenarios. Assuming random recruitment, there would be no difference in the estimated percent of years with fisheries. Only under Scenario D (Table 2), based on the empirical spawner-recruit relationship and the 25% AUB threshold criterion, would the percent of years with fisheries drop below 100%; in this case down to 95% (Figure 6). Catch variation, expressed as coefficient of variation in catch levels, would be projected to increase somewhat, from 46 to 52%, under the 25% AUB threshold value of 5,258.

The short time series of spawn deposition, age, and weight data upon which the ASA model and threshold analysis are based, the lack of data from the period when W. Behm Canal spawning activity was relatively low, potential movement of herring between W. Behm Canal and other spawning areas, and limited data on which to define any inherent relationship between spawners and subsequent recruits, all introduce uncertainty into the population model and threshold analysis. Consequently, I recommend adopting a threshold more conservative than the current 2,000 t threshold. In this case, the most conservative threshold would be the 5,258 ton threshold from Scenario D. Establishment of a 5,258 t quota, would afford additional protection to W. Behm Canal spawning population.

In addition to increasing the threshold from 2,000 to 5,258, I recommend continuation of annual stock assessment sampling of the herring spawning at W. Behm Canal, regardless of the apparent spawning population levels. Within the next two to three years, a re-evaluation of W. Behm Canal threshold should be conducted, utilizing the additional two or three years of stock assessment data. These additional data could provide a better indication of a possible spawner-recruit relationship for W. Behm Canal herring. A better definition of the underlying spawner-recruit relationship may be useful in further evaluating, and perhaps revising, the recommended threshold of 5,258 tons for W. Behm Canal herring.

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Table 1. W. Behm Canal herring spawner-recruit data estimated from ASA.

Year Class	Biomass (B_{y-3}; tonnes) that spawned Age 3 recruits	Age 3 Recruits (millions)	Stratum for Empirical Spawner Recruit Model
1993	3495.9	239.68	A
1994	2367.0	115.86	A
1998	13896.9	95.03	B
1997	8308.9	61.05	B
1999	12215.4	33.91	B
1996	5257.3	18.01	B

Table 2. Alternative harvest scenarios for W. Behm Canal herring.

Harvest Scenario	Threshold (tons)	Recruitment Relationship
A	2,000 (current)	Random
B	2,000 (current)	Empirical spawner-recruit
C	2,035 (25% AUB)	Random
D	5,258 (25% AUB)	Empirical spawner-recruit

D:\HER\ASA\2002\W. Behm Canal\Age Specific Survival\Ages 3-4_7+ & 5-6\Threshold Analysis\WBehmSim98.xls (Tables for RIR) 12/10/2002 2:48:59 PM

Table 3. W. Behm Canal herring population parameter estimates used in biomass simulations.

Parameter	Age Category 3	4	5	6	7	8+
Mean Wt. (g) 1991-2002	54.90	71.48	86.12	104.56	113.73	122.72
Maturity*	0.23	0.59	0.87	0.97	0.99	1.00
Gear Selectivity	0.24	0.59	0.84	0.95	0.99	1.00

*Maturity and gear selectivity are proportions of herring in the age category that are mature or selected by the gear.

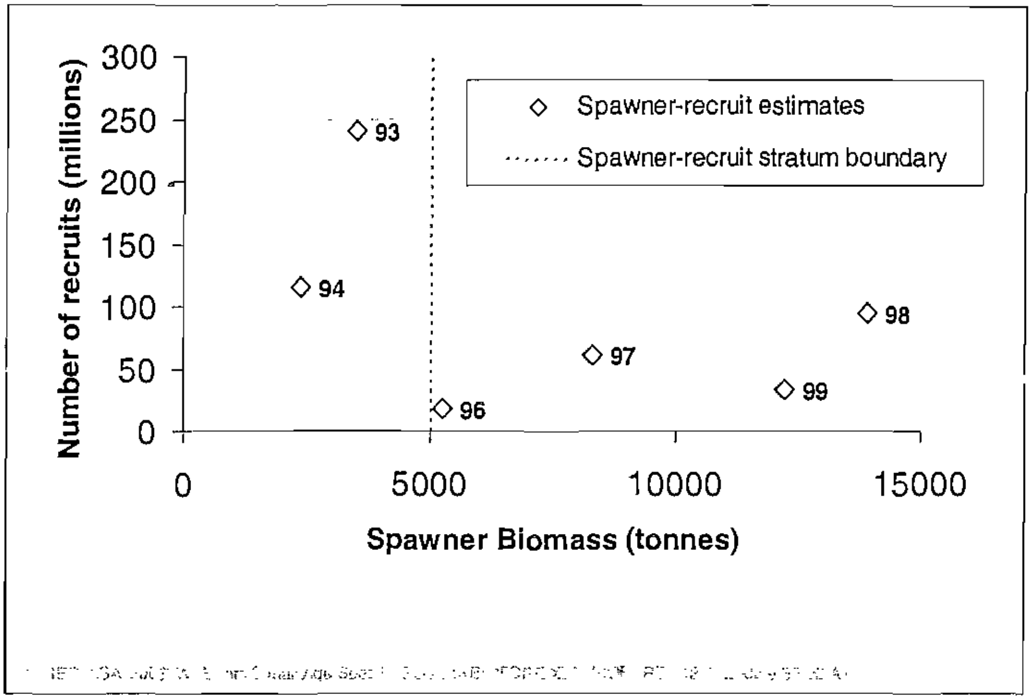


Figure 1. W. Behm Canal spawner-recruit estimates from ASA. Values near each data point are year classes.

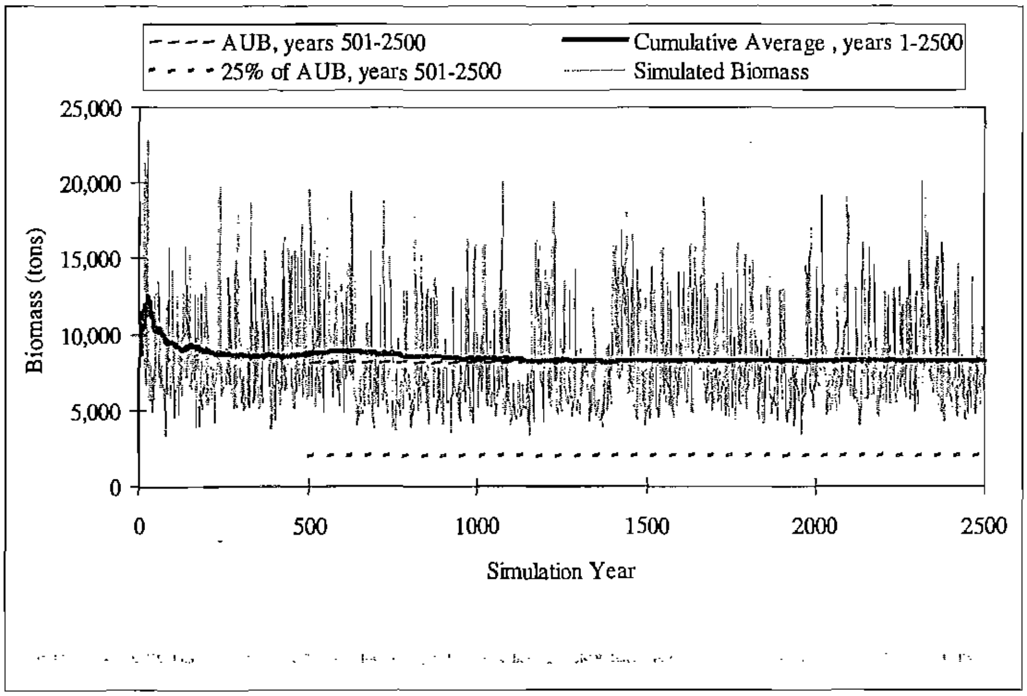


Figure 2. Simulated unfished biomass, AUB and 25% AUB for W. Behm Canal herring based on assumption of completely random recruitment.

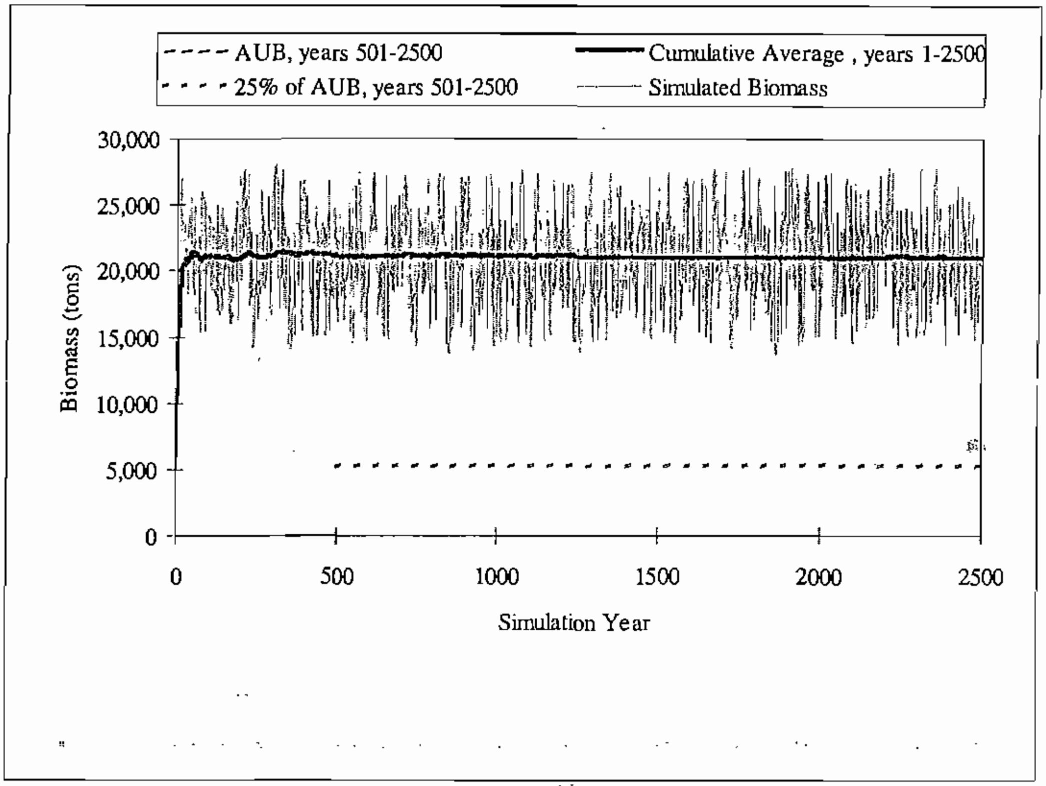


Figure 3. Simulated unfished biomass, AUB and 25% AUB for W. Behm Canal herring based on assumed empirical spawner-recruit relationship.

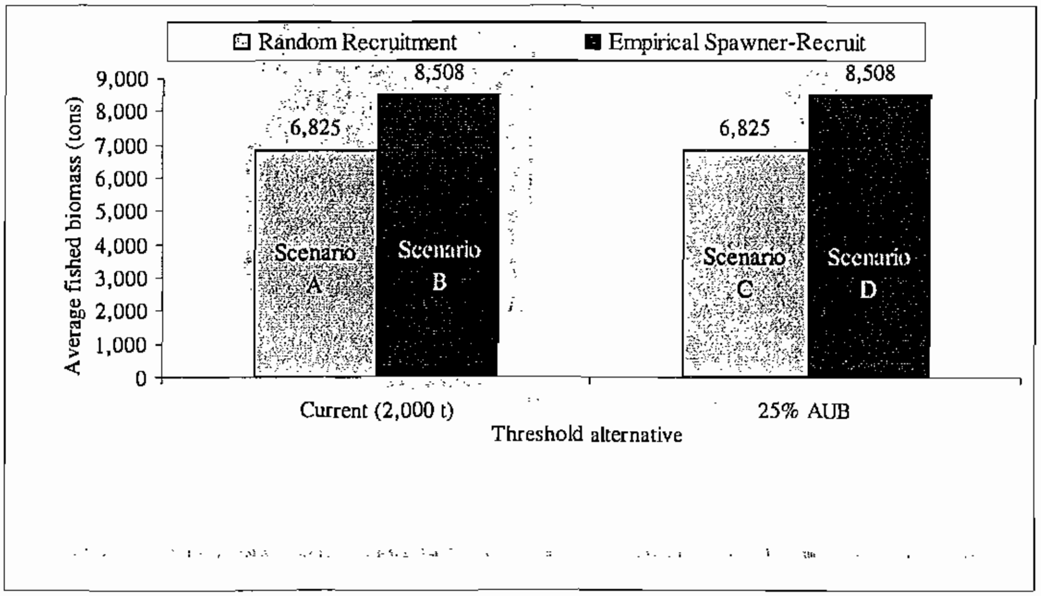


Figure 4. Average fished biomasses under different combinations of threshold alternatives and recruitment relationships.

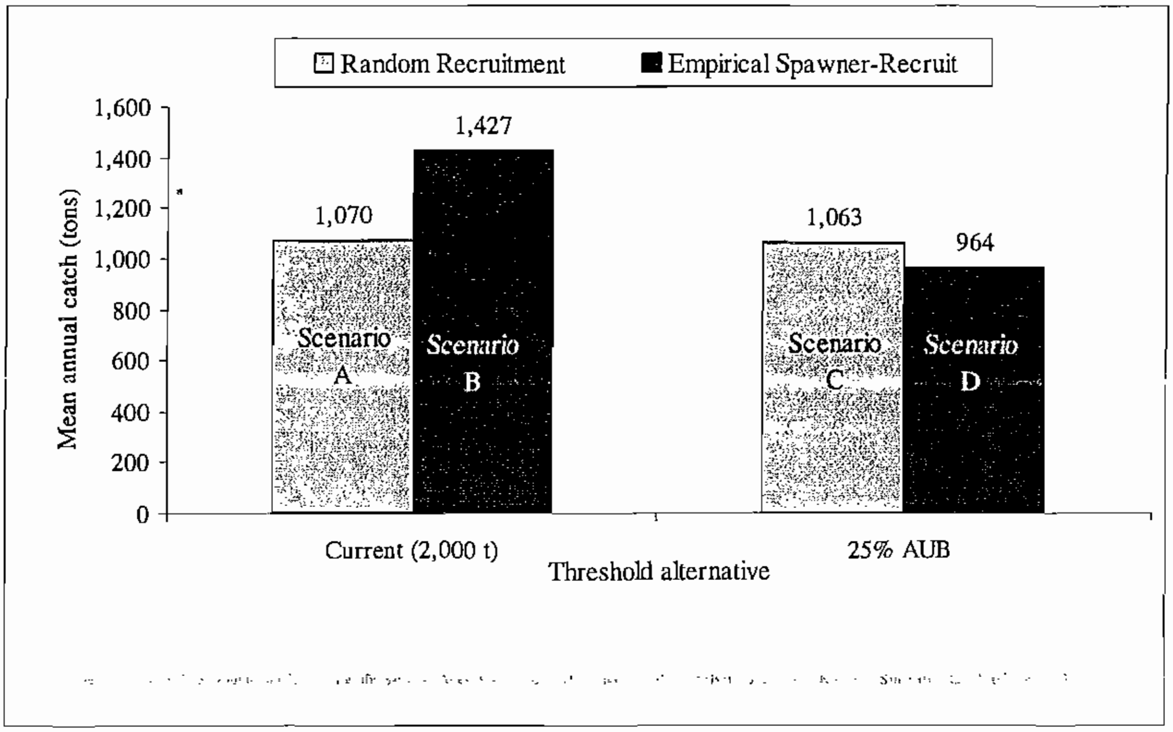


Figure 5. Mean annual, long-term catches under different combinations of threshold alternatives and recruitment relationships.

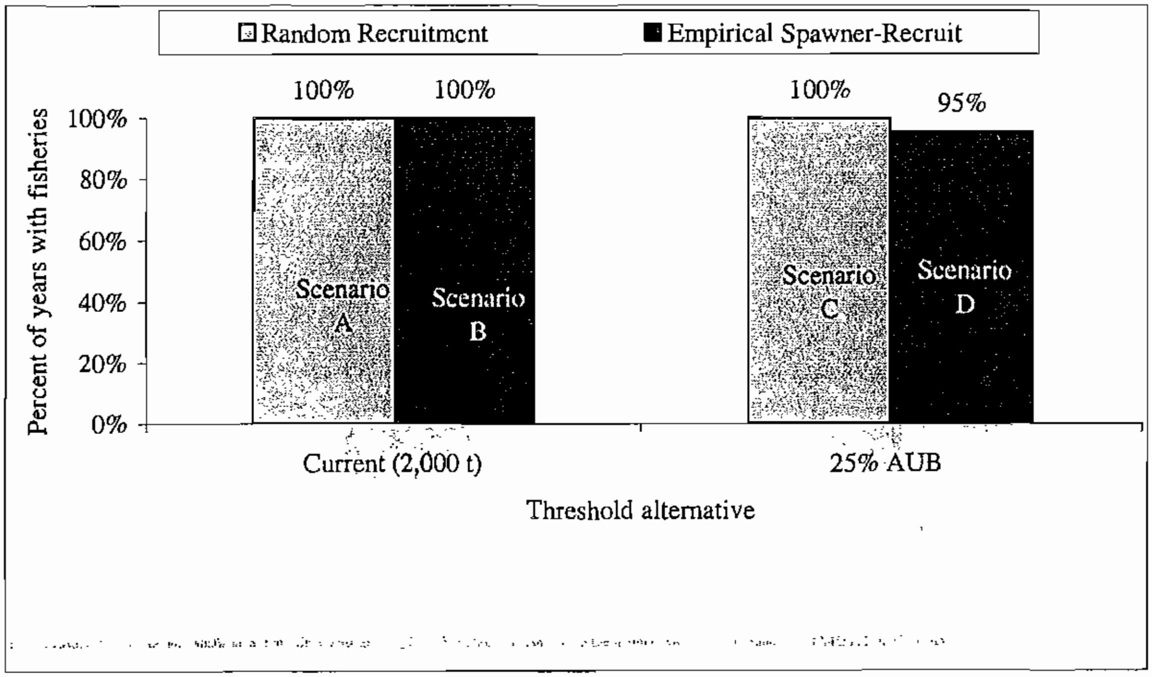


Figure 6. Percents of years with fisheries under different combinations of threshold alternatives and recruitment relationships.

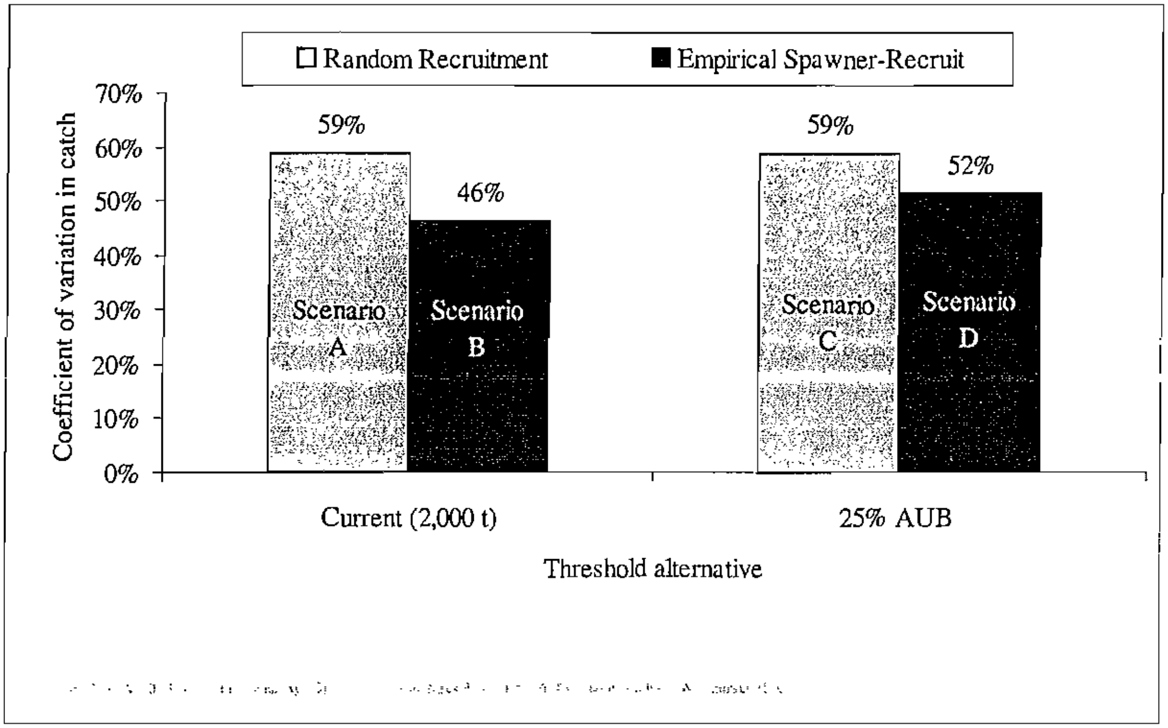


Figure 7. Coefficients of variation in catch under different combinations of threshold alternatives and recruitment relationships.

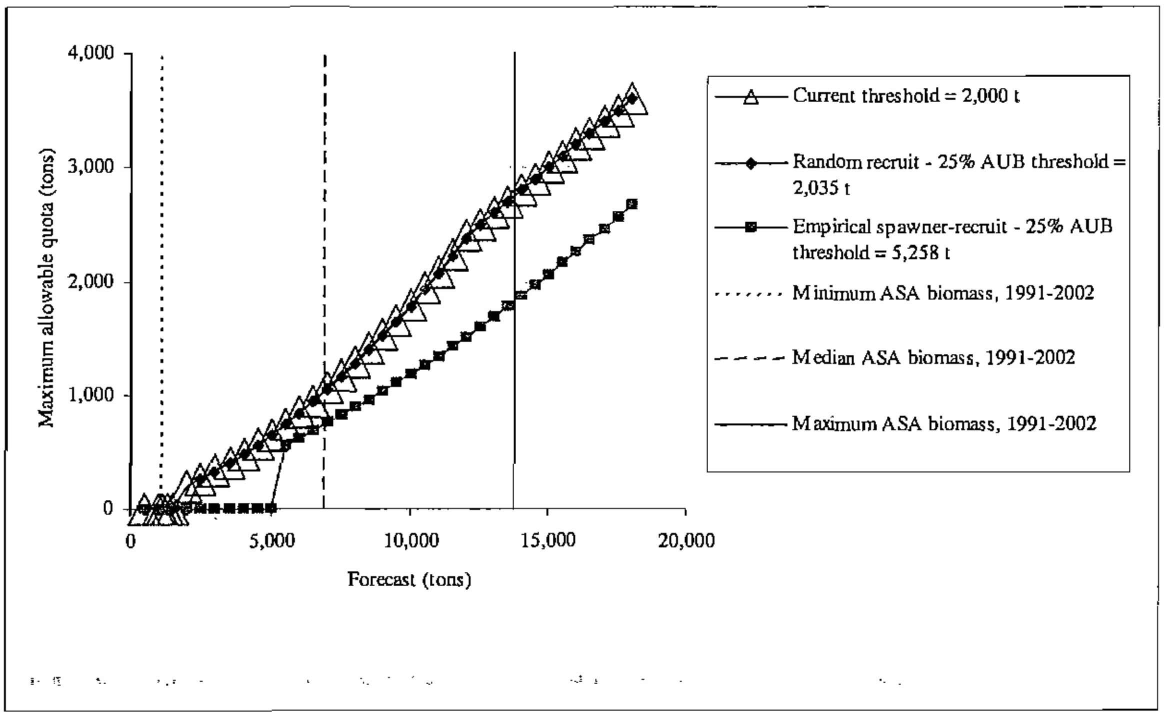


Figure 8. Maximum allowable bait quotas under three alternative thresholds.

APPENDIX

Appendix A. Estimation of catch.

The following equations are used to calculate the catch of age a fish in year y. These equations yield estimates of catch-at-age in numbers of fish, accounting for exploitation rates that are applied to the biomass.

The catch of age a-1 herring in year y-1 was estimated as

$$C_{a,y} = \frac{P_{a,y} \cdot \mu_y \cdot B_y}{\sum_a P_{a,y} \cdot W_a}, \qquad \text{(A1)}$$

and the proportion of catch-at-age (numbers) is

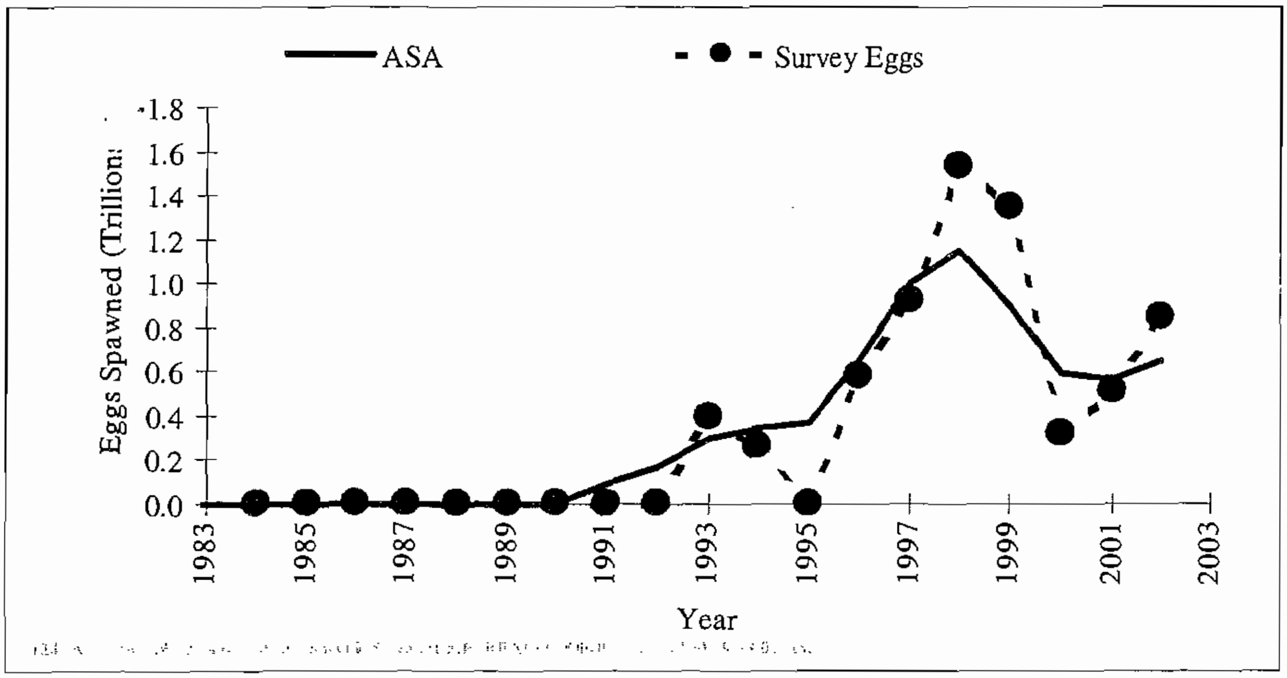
$$P_{a,y} = \frac{V_a \cdot N_{a,y}}{\sum_a V_a \cdot N_{a,y}} \qquad \text{(A2)}$$

where V_a is the ASA-estimated seine vulnerability for age a herring. The exploitation rate in year y is

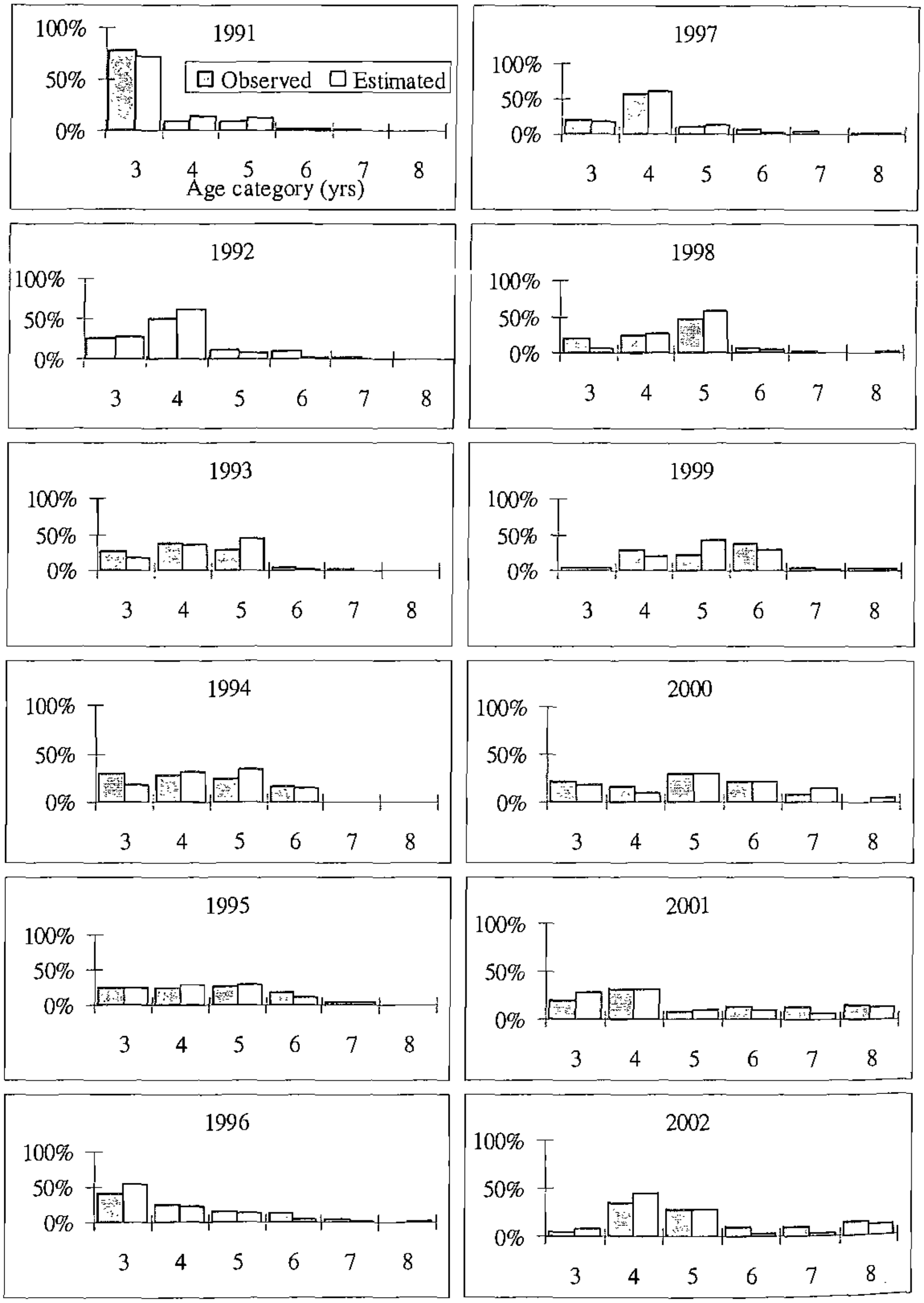
$$\mu_y = 0 \ \ when \ \ forecast \prec threshold$$

$$\mu_y = \left[8 + 2 \cdot \left(\frac{forecast}{threshold}\right)\right]^{-100} \ \ when \ \ 0.1 \le \left[8 + 2 \cdot \left(\frac{forecast}{threshold}\right)\right]^{-100} \le 0.2 \qquad \text{(A3)}$$

$$\mu_y = 0.2 \ \ when \ \ \left[8 + 2 \cdot \left(\frac{forecast}{threshold}\right)\right]^{-100} \succ 0.2$$



Appendix B. Goodness of fit of ASA estimated eggs spawned to observed estimate of eggs spawned, W. Behm Canal.



Appendix C. W. Behm Canal observed and ASA-estimated herring spawning run age compositions. Years without observed data were not used to tune the model, due to the absence of samples representative of the spawning population.