F1264

Estimation and Evaluation of a Harvest Threshold for Management of the Tenakee Inlet Herring Bait Fishery Based on a Percentage of Average Unfished Biomass

By

David W. Carlile

Regional Information Report No.[1] 1J98-21

Alaska Department of Fish and Game
Division of Commercial Fisheries
Juneau, Alaska

October 1998

---

[1] The Regional Information Report Series was established in 1987 to provide an information access system for all unpublished divisional reports. These reports frequently serve diverse ad hoc informational purposes or archive basic uninterpreted data. To accommodate timely reporting of recently collected information, reports in this series undergo only limited internal review and may contain preliminary data, this information may be subsequently finalized and published in the formal literature. Consequently, these reports should not be cited without prior approval of the author or the Division of Commercial Fisheries.

AUTHORS

David W. Carlile is the Region I herring and groundfish biometrician for the Alaska Department of Fish and Game, Division of Commercial Fisheries, P.O. Box 240020, Douglas, Alaska 99824-0020.

ACKNOWLEDGEMENTS

Robert Larson supervised the field and laboratory collection and preliminary data reduction of much of the stock assessment data used in conducting these analyses. Fritz Funk introduced the author to the approach for estimating AUB.

TABLE OF CONTENTS

TABLES

FIGURES

APPENDIX

ABSTRACT

Average unfished biomass (AUB) was estimated for a spawning population of herring at Tenakee Inlet. Population parameters used in the estimation of AUB were derived from an age-structured analysis (ASA). Based on estimates of AUB under two assumed spawner-recruit relationships, alternatives to the current 3,000-ton Tenakee Inlet threshold were estimated and evaluated. Using a 25% of AUB criterion, alternative thresholds of 1,096 and 1,299 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 current 3, 000-ton threshold be maintained.

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 S.E. 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 15 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 Tenakee Inlet herring.

METHODS

The AUB of Tenakee Inlet 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, and (seine) gear selectivity. Weights-at-age were estimated from annual age-weight-length (AWL) sampling at Tenakee Inlet.

Threshold management policies tacitly assume some density dependent population regulation. However, based on the ASA-estimated Tenakee Inlet spawner-recruit data (Figure 1, Table 1), the form and strength of the density dependence for Tenakee Inlet herring are difficult to define using conventional spawner-recruit models like a Ricker model. 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.

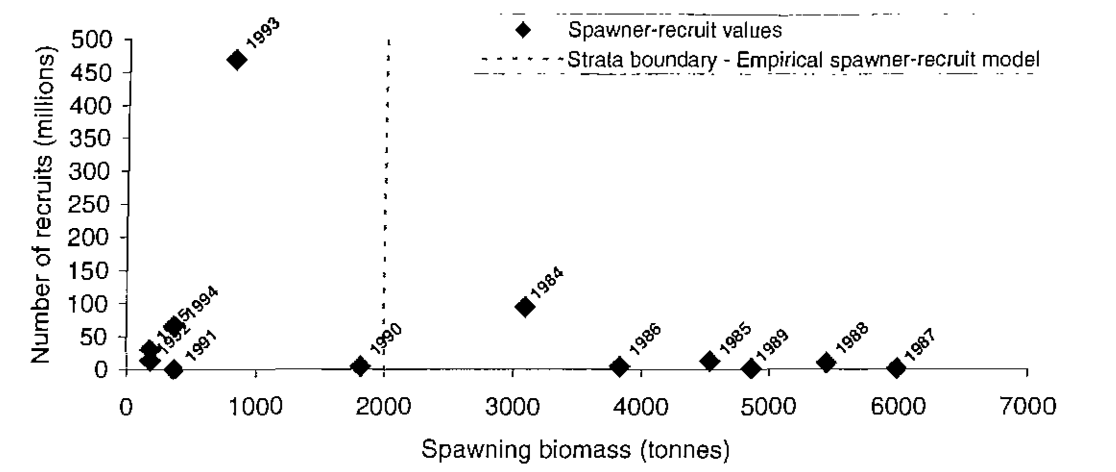


Figure 1. Tenakee Inlet spawner-recruit data estimated from ASA. Values near each data point are year classes.

D:\HER\ASA\1999\Tenakee\THRESHOLD\Tenakee Spawner Recruit.xls (Tenakee Deterministic Ricker)

Table 1. Tenakee Inlet 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
1992	181.4	13.64	A
1995	181.4	30.03	A
1991	362.9	0.04	A
1994	362.9	65.24	A
1993	819.7	469.87	A
1990	1814.4	4.32	A
1984	3099.1	94.34	B
1986	3829.5	4.27	B
1985	4535.9	12.75	B
1989	4862.5	1.66	B
1988	5443.1	9.96	B
1987	5987.4	1.28	B

D:\HER\ASA\1999\Tenakee\THRESHOLD\TenRick99.xls (Tenakee Deterministic Ricker)

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 2,000 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 2,000 metric tons, recruits were chosen randomly from among the six 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 twelve 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 Tenakee herring at age a from 1971 to 1996, and N_{ay} 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 Tenakee Inlet bait fishery threshold (3,000 tons) and the estimated 25% AUB thresholds. We also explored two different spawner-recruit models based on spawner-recruit estimates from the Tenakee Inlet 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_{ay} are provided in Appendix A. Total catch was simulated using the Southeast sliding scale harvest rate formula applied to simulated biomasses. Estimates of seine gear selectivity used in catch simulations were obtained from the ASA. 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 was 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 Tenakee Inlet. Under Scenario A, the 2,000 year catch times series was simulated using the current 3,000-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

The ASA-estimated annual survival rate (*S*) was 0.484. Estimates of alternative thresholds and the associated harvest and recruitment scenarios are listed in Table 2.

Table 2. Alternative harvest scenarios for Tenakee Inlet herring.

Harvest Scenario	Threshold (tons)	Recruitment
A	3,000 (current)	Random
B	3,000 (current)	Empirical spawner-recruit
C	1,299 (25% AUB)	Random
D	1,096 (25% AUB)	Empirical spawner-recruit

Maturities, gear selectivities and weights-at-age used for biomass simulations are included in Table 3.

Table 3. Tenakee Inlet herring population parameter estimates used in biomass simulations.

	Age Category					
Parameter	3	4	5	6	7	8+
Mean Wt. (g) 1984-1998	68.17	82.40	103.27	120.77	136.78	156.18
Maturity	0.13	0.54	0.90	0.99	1.00	1.00
Gear Selectivity	0.17	0.57	0.90	0.98	1.00	1.00

Plots used to assess goodness of fit of ASA-estimated to observed population parameters are depicted in Appendices B-D. In general there was sufficient agreement between the ASA estimates and observed data, particularly during more recent years, to warrant using the ASA-generated population parameters as the basis for population projection simulations for estimating AUB and evaluating the influence of various thresholds on fishery performance.

Estimated AUB for Tenakee Inlet under the random recruitment model is 5,198 tons (Figure 2). Application of the 25% of AUB criterion for determining a threshold would yield a new Tenakee Inlet threshold of 1,299 tons (Table 2).

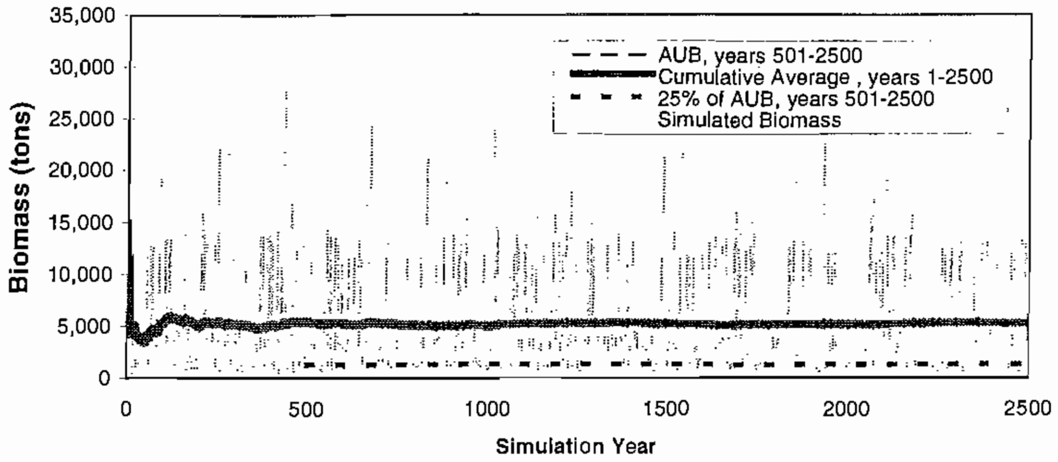


Figure 2. Simulated unfished biomass, AUB and 25% AUB for Tenakee Inlet herring based on assumption of completely random recruitment.

D:\HER\ASA\1999\Tenakee\THRESHOLD\TenSim98.xls (AUB Graph for Report)

With the empirical spawner-recruit model, the estimated AUB was 4,385 tons (Figure 3). A threshold equivalent to 25% of the AUB would be 1,096 tons (Table 2).

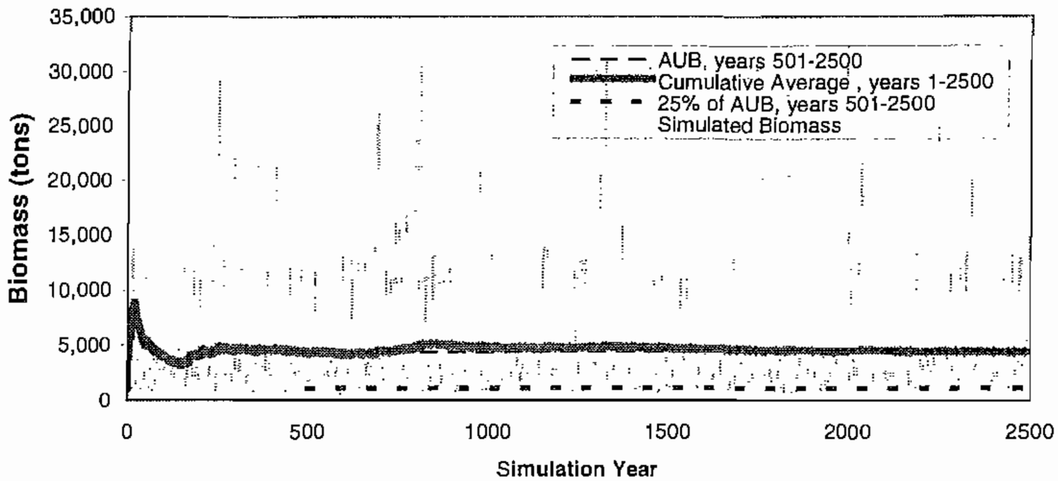


Figure 3. Simulated unfished biomass, AUB and 25% AUB for Tenakee Inlet herring based on assumed empirical spawner-recruit relationship.

D:\HER\ASA\1999\Tenakee\THRESHOLD\TenSim98.xls (AUB Graph for Report)

Under Alternative Harvest Scenario A, the AFB was 4,585 tons (Figure 4). Under Scenario B, the current 3,000 ton threshold combined with an assumed empirical spawner recruit relationship, the AFB declined to 4,297 tons (Figure 4). The AFB under Scenarios C and D were 4,559 tons and 4,206 tons (Figure 4).

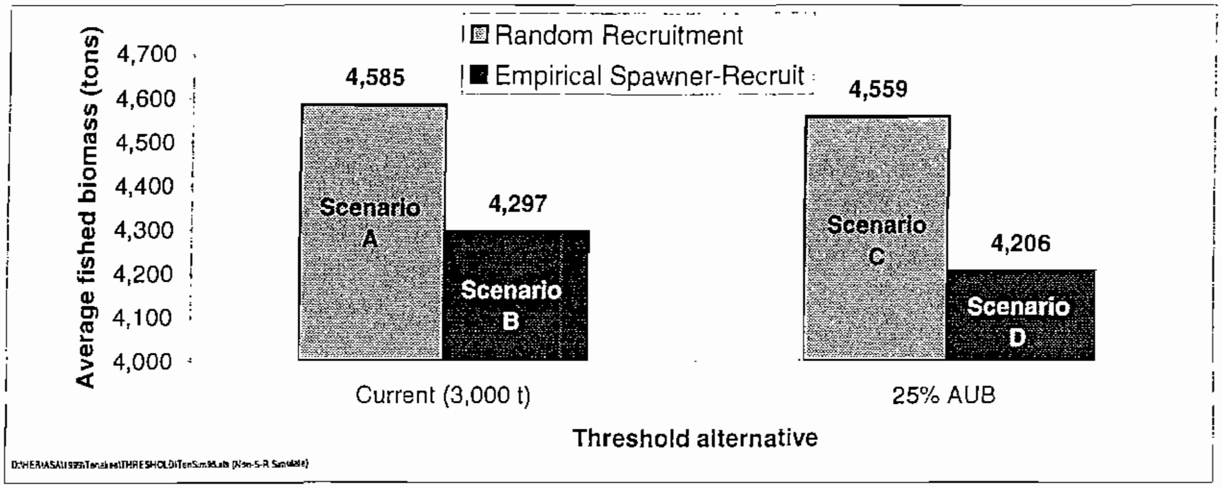


Figure 4. Average fished biomasses under different combinations of threshold alternatives and recruitment relationships.

As expected, the highest simulated catches occurred under Harvest Scenarios C and D, with a threshold equal to 25% of the AUB. Estimated mean annual, long-term catches under these scenarios were 767 and 715 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 552 for the random recruitment model(Scenarios A, Table 2), and 501 for the empirical spawner-recruit (Scenarios B; Table 2) model.

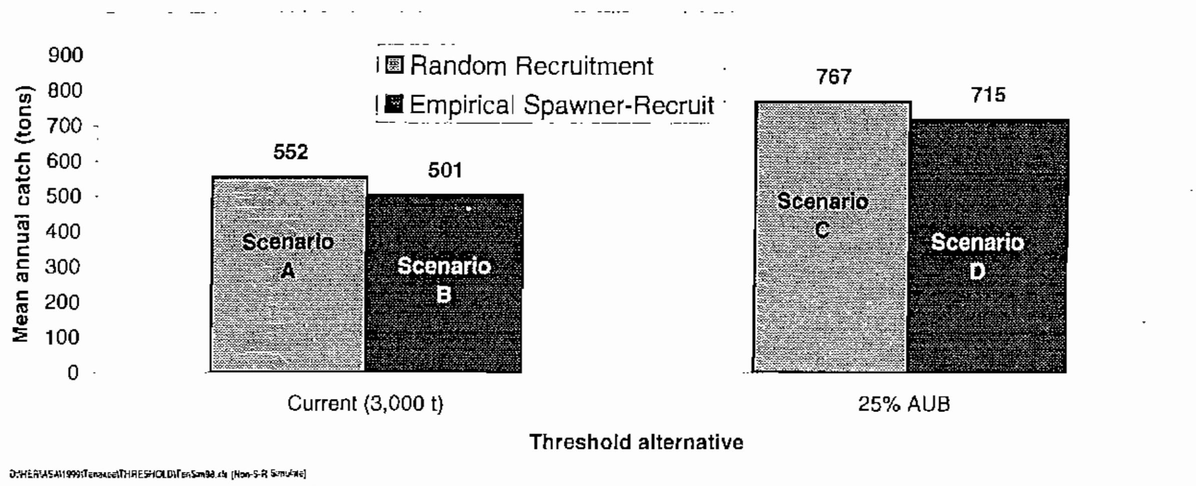


Figure 5. Mean annual, long-term catches under different combinations of threshold alternatives and recruitment relationships.

Also as expected, because the threshold based on 25% of AUB was lower than the current 3,000 ton threshold, the percent of years with fisheries were higher under Scenarios C and D, the scenarios based on 25% of AUB. Percent of years with fisheries were 77 and 79% under the random recruitment and the empirical spawner-recruit assumptions (Figure 6). Percents of years with fisheries for Scenarios A and B, based on the 3,000-ton threshold, were lower, at 47 and 44% for the random recruitment and the empirical spawner-recruit assumptions, respectively (Figure 6).

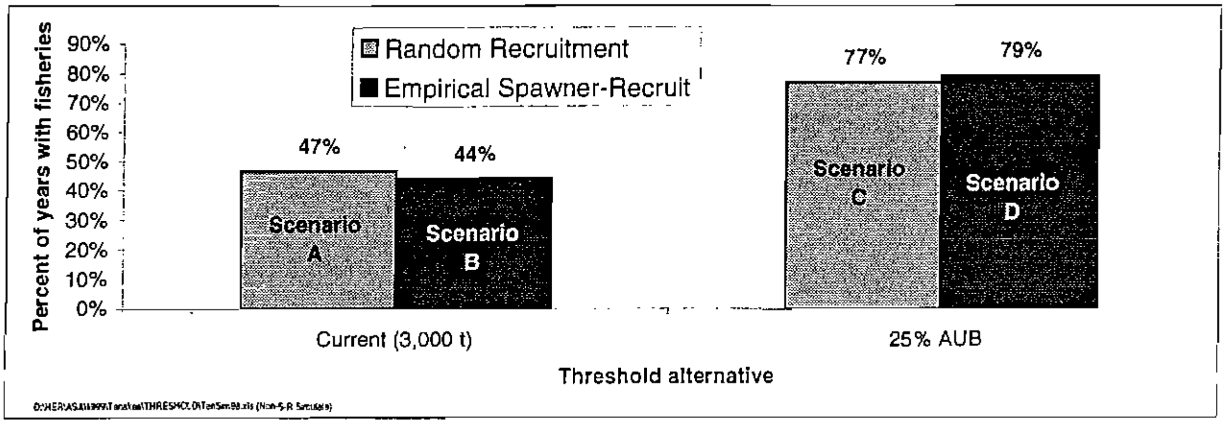


Figure 6. Percents of years with fisheries under different combinations of threshold alternatives and recruitment relationships.

The CVs of catch for the scenarios based on the current 3,000 ton threshold (Scenarios A and B; Table 3) were higher than the CVs for the scenarios based on the 25% AUB thresholds (Scenarios C and D; Table 3). Under the 3,000-ton threshold scenarios, CVs of catch were 156 and 170% for the random recruitment and empirical spawner-recruit assumptions. Under the 25% AUB scenarios, the corresponding CVs were 124 and 130% (Figure 7).

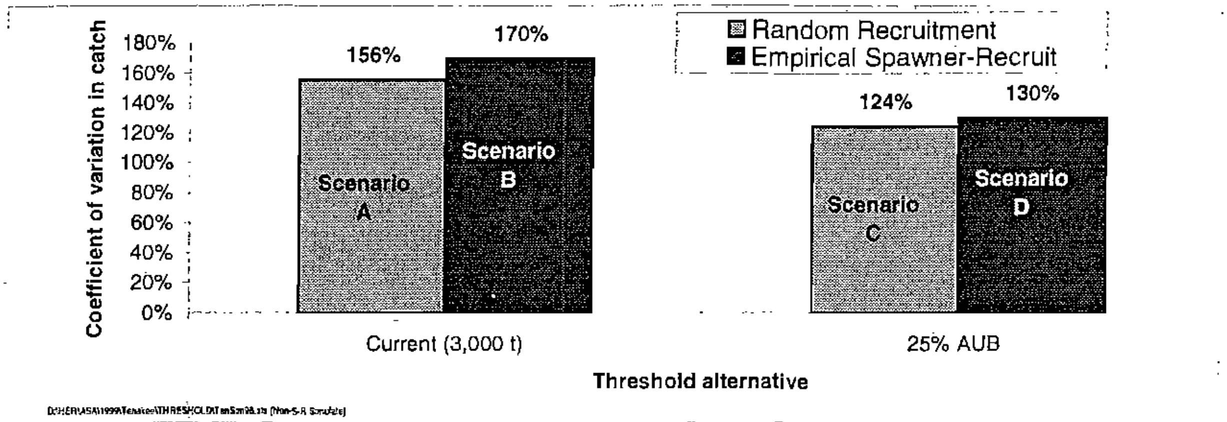


Figure 7. Coefficients of variation in catch under different combinations of threshold alternatives and recruitment relationships.

The above results address the possible longer-term results (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 one based on the 25% AUB criterion and the empirical spawner-recruit model is the least restrictive of harvest. Under this threshold, the 10% harvest rate could occur given a forecast of 1,096 tons. The maximum allowable 20% rate would be allowed with a forecast of 6,500 tons (Figure 8). Biomasses at least this high occurred in the ASA estimated time-series of biomasses in 41% of the years. Intermediate in restriction on harvest is the 1,299-ton threshold based on the 25% AUB criterion and a random recruitment process. Under this threshold, the 10% harvest rate could occur given a forecast of 1,299 tons. Maximum allowable harvest rate of 20% would be possible with a forecast of 8,000 tons. Biomasses at least this high occurred in the ASA estimated time-series of biomasses in only 29% of the years. Among the three alternative thresholds considered here, the current 3,000-ton threshold is the most restrictive of harvest. Under this threshold the 10% harvest rate is allowed given a forecast of 3,000 tons. The maximum allowable harvest rate of 20% would be possible only given a forecast of 18,000 tons. Biomass this high did not occur in the ASA estimated time-series of biomasses. The maximum biomass was estimated as 10,924, which would have provided a harvest rate of 15.3% and an allowable quota of 1,670 tons.

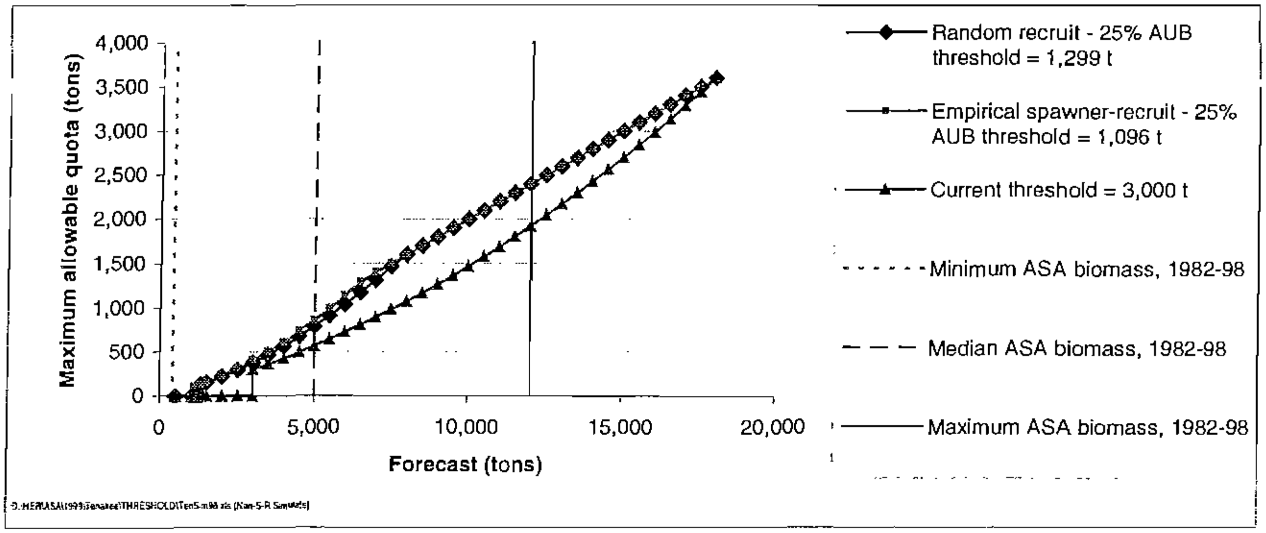


Figure 8. Maximum allowable bait quotas under three alternative thresholds.

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 Togiak, Alaska (Funk and Rowell 1995) and Sitka, Alaska (Carlile 1998) herring fisheries. 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 Board of Fisheries subsequently increased the Sitka threshold to 20,000 tons to provide additional protection for subsistence users. The recommendation for Togiak, while rejected by the Alaska Board of Fisheries, 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 current 3,000-ton threshold.

In contrast to analyses conducted for Sitka (Carlile 1998), assumptions about the possible form of an underlying recruitment relationship at Tenakee Inlet did not substantially affect conclusions about the possible long term impact of a particular harvest strategy. This may be due largely to the fact that the spawner recruit data from the Tenakee Inlet ASA exhibited only a single data point, from the 1993 year class, that was markedly greater than the recruitment for the other years. Consequently, as the basis for the 2,000-year simulations, recruit selection from the two strata defining the empirical spawner-recruit relationship did not differ appreciably from the selection of recruits under completely random recruitment scenario. This modest difference in potential recruitment levels resulted in estimates of AUB that also differed relatively little, 5,198 under the random recruitment scenario, and 4,385 under the empirical spawner-recruit scenario. Accordingly, other comparative measures of impact also differed relatively little between the two alternative recruitment scenarios. For example, average fished biomass under the random and empirical recruitment scenarios using the 25% AUB threshold were 4,559 and 4,206 tons, respectively (Figure 4). Under the current 3,000-ton threshold, there was also relatively little difference, 4,585 tons for the random recruitment and 4,297 tons for the empirical spawner-recruit model (Figure 4).

Of note also were the minor differences in AFB for the current 3,000 ton threshold vs. thresholds based on 25% AUB. For the random recruitment scenario, the AFB for the 3,000 ton threshold was 4,585 while the AFB for the 25% ABU scenario was 4,559, a difference of less than 1% (Figure 4). There is a similarly small difference in AFBs for the empirical spawner-recruit scenario (Figure 4).

As indicated previously, the Tenakee Inlet data do not suggest ready definition of an underlying spawner-recruit relationship using conventional spawner-recruit models such as a Ricker or Beverton-Holt model. Consistent with this general observation, Zheng (1996) found no apparent spawner-recruit relationship for Sitka herring. However, Zebdi and Collie (1993) defined an environmentally dependent Ricker model that incorporated sea surface temperature anomalies and spawners as explanatory variables affecting Sitka herring recruitment.

Despite the difficulty in describing an underlying spawner recruit relationship for Tenakee Inlet herring using conventional spawner-recruit models, spawner-recruit data for Tenakee Inlet (Figure 1) if anything, suggest a lower probability of high recruitments with high levels of spawners. This tendency prevails whether the highest recruitment (from the 1993 year class) is included or not (Figure 1). 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.

Despite the tendency for lower levels of spawners to be associated with higher recruitment, it is inadvisable at this point to consider lowering the threshold for Tenakee Inlet herring from the current 3,000-ton threshold to one consistent with the 25% AUB criterion. This caution is based primarily on the fact that only 12 years of spawner-recruit data were available upon which to base assumptions about possible underlying spawner-recruit relationships for Tenakee Inlet herring. Only two or three data points drive the tendency for higher recruitment with lower biomass. This data limitation may result in greater uncertainty in the parameter estimates that were used to estimate AUB. In addition, under the current 3,000 ton threshold, abundance of spawning herring at Tenakee Inlet appears to have increased recently (since 1996) to at least the highest levels of the previous twenty years, if not higher (Appendix B). Unknown is whether management under a lower threshold would have yielded a similar return to historic abundance levels. Primarily because of these uncertainties in the underlying spawner-recruit relationship and the potential population response to a lowered threshold, I recommend maintaining the current 3,000-ton threshold for the present rather than adjusting the threshold to be consistent with the 25% AUB criterion.

In addition to the unknown population response at a lowered threshold, it would be difficult to manage a fishery with thresholds between 1,100 and 1,300 tons. Thresholds at these levels could result in quotas as low as 110 tons. It would be difficult to limit catches to such low quotas. Quotas would probably often be exceeded.

In addition to maintaining the current 3,000-ton threshold, I recommend continuation of annual stock assessment sampling of the Tenakee Inlet herring, regardless of the apparent spawning population levels. Within the next two to three years, a re-evaluation of Tenakee Inlet threshold should be conducted, utilizing the additional two or three years of stock assessment data. These additional data may provide a better indication of a possible spawner-recruit relationship for Tenakee Inlet herring. A better definition of the underlying spawner-recruit relationship may be useful in re-evaluating, and perhaps revising, the current and currently recommended threshold of 3,000 tons for Tenakee Inlet herring.

LITERATURE CITED

Blankenbeckler, Dennis and Robert Larson. 1985. Herring spawning threshold levels, Southeast Alaska 1985. (Region I unpublished report), Ketchikan.

Carlile, D.W., R.C. Larson, and T.A. Minicucci. 1996. Stock assessments of Southeast Alaska herring in 1994 and forecasts for 1995 abundance. Alaska Department of Fish and Game, Regional Information Report No. 1J96-05.

Funk, F.C. and K.A. Rowell. 1995. Population model suggests new threshold for managing Alaska's Togiak fishery for Pacific herring in Bristol Bay. Alaska Fisheries Research Bulletin 2:125-136.

Funk, F.C. and G.J. Sandone. 1990. Catch-age analysis of Prince William Sound, Alaska, herring, 1973-1988. Alaska Department of Fish and Game, Fishery Research Bulletin No. 90-01.

Haist, V. and J.F. Schweigert. 1990. Stock assessments for British Columbia herring in 1989 and forecasts of the potential catch in 1990. Canadian Manuscript Report of Fisheries and Aquatic Sciences No. 2049.

Myers, R.A. and N.J. Barrowman. 1996. Is fish recruitment related to spawner abundance?. Fishery Bulletin 94:707-724.

Quinn, T.J., II, R. Fagen, and J. Zheng. 1990. Threshold management policies for exploited populations. Canadian Journal of Fisheries and Aquatic Science 47:2016-2029.

Schweigert, J. F. 1993. Evaluation of harvesting policies for the management of Pacific herring stocks, *Clupea pallasi*, in British Columbia. Pages 167-190 *in* G. Kruse, D.M. Eggers, R.J. Marasco, C. Pautzke, and T.J. Quinn II (Editors). Proceeding of the international symposium on management strategies for exploited fish populations. Alaska Sea Grant College Program Report No. 93-02, University of Alaska Fairbanks.

Zebdi, A. and J.S. Collie. 1995. Effect of climate on herring (*Clupea pallasi*) population dynamics in the northeast Pacific Ocean. *in* R.J. Beamish (Editor), Climate change and northern fish Populations. Canadian Special Publication Fisheries and Aquatic Science, 121:277-290.

Zheng, J. 1996. Herring stock-recruitment relationships and recruitment patterns in the north Atlantic and northeast Pacific oceans. Fisheries Research 26:257-277.

Zheng, J., F.C. Funk, and G. H. Kruse. 1993. Threshold management strategies for Pacific herring in Alaska. Pages 141-165 *in* G. Kruse, D.M. Eggers, R.J. Marasco, C. Pautzke, and T.J. Quinn II (Editors). Proceeding of the international symposium on management strategies for exploited fish populations. Alaska Sea Grant College Program Report No. 93-02, University of Alaska Fairbanks.

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

$$C_{a,y} = \frac{P_{a,y} \cdot \mu_y \cdot B_y}{\sum_a P_{a,y} \cdot W_a}, \tag{A1}$$

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

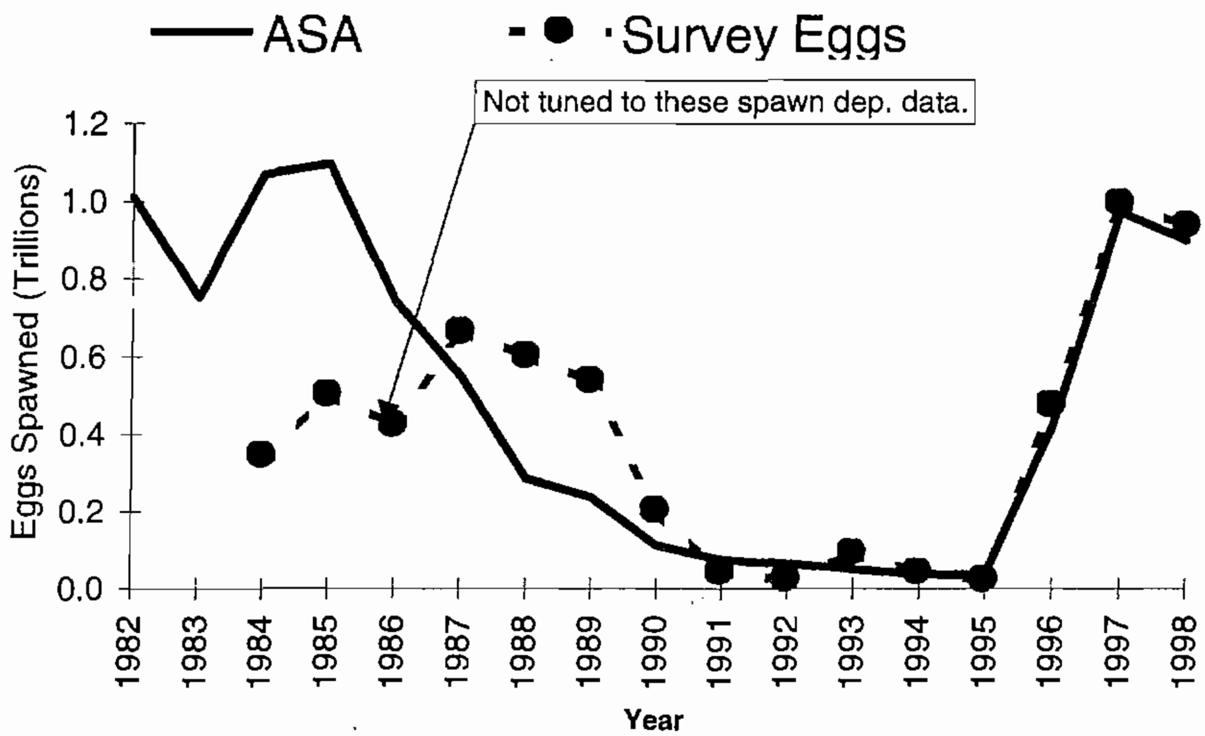
$$P_{a,y} = \frac{V_a \cdot N_{a,y}}{\sum_a V_a \cdot N_{a,y}} \tag{A2}$$

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

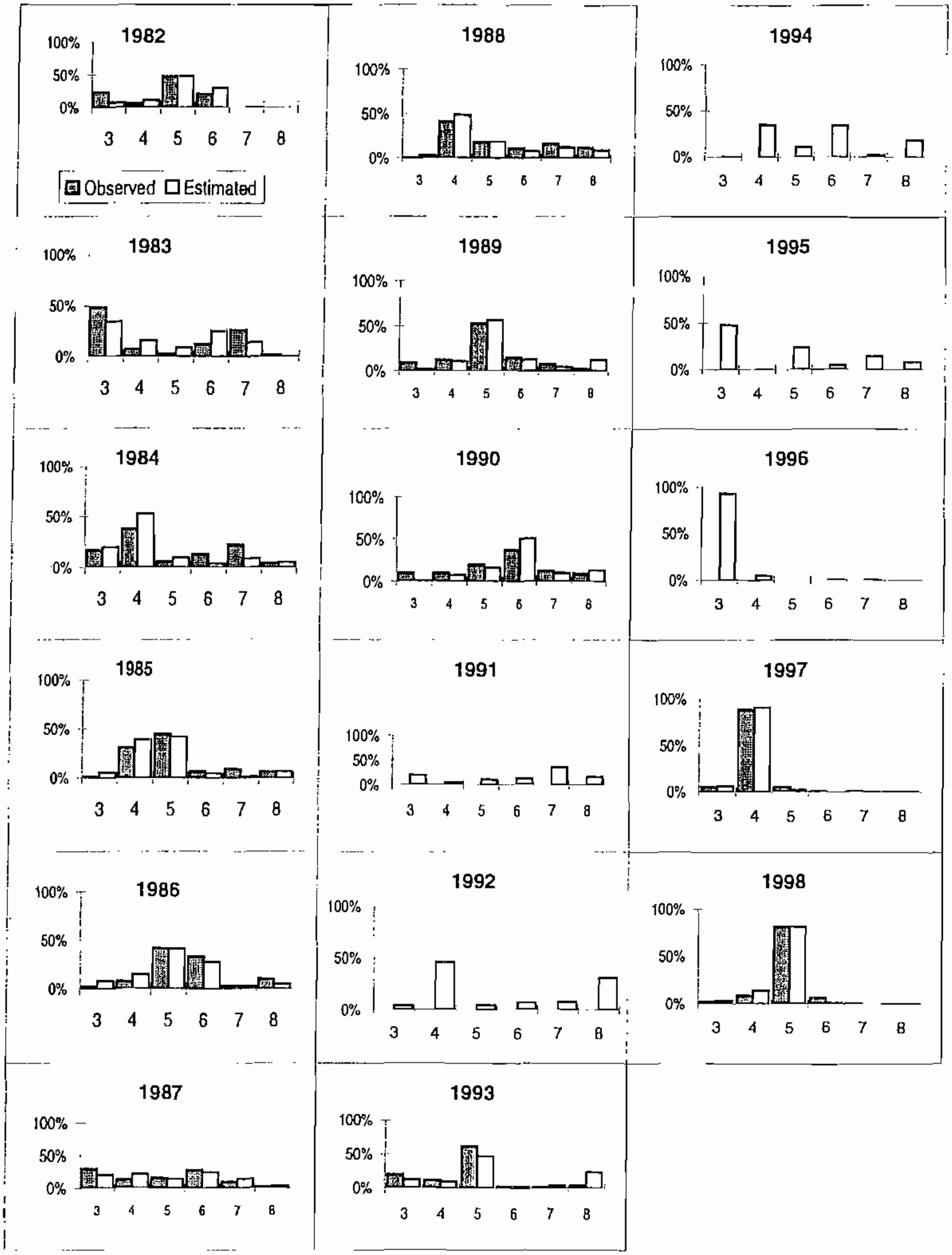
$$\mu_y = 0 \;\; when \;\; forecast \prec threshold$$

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

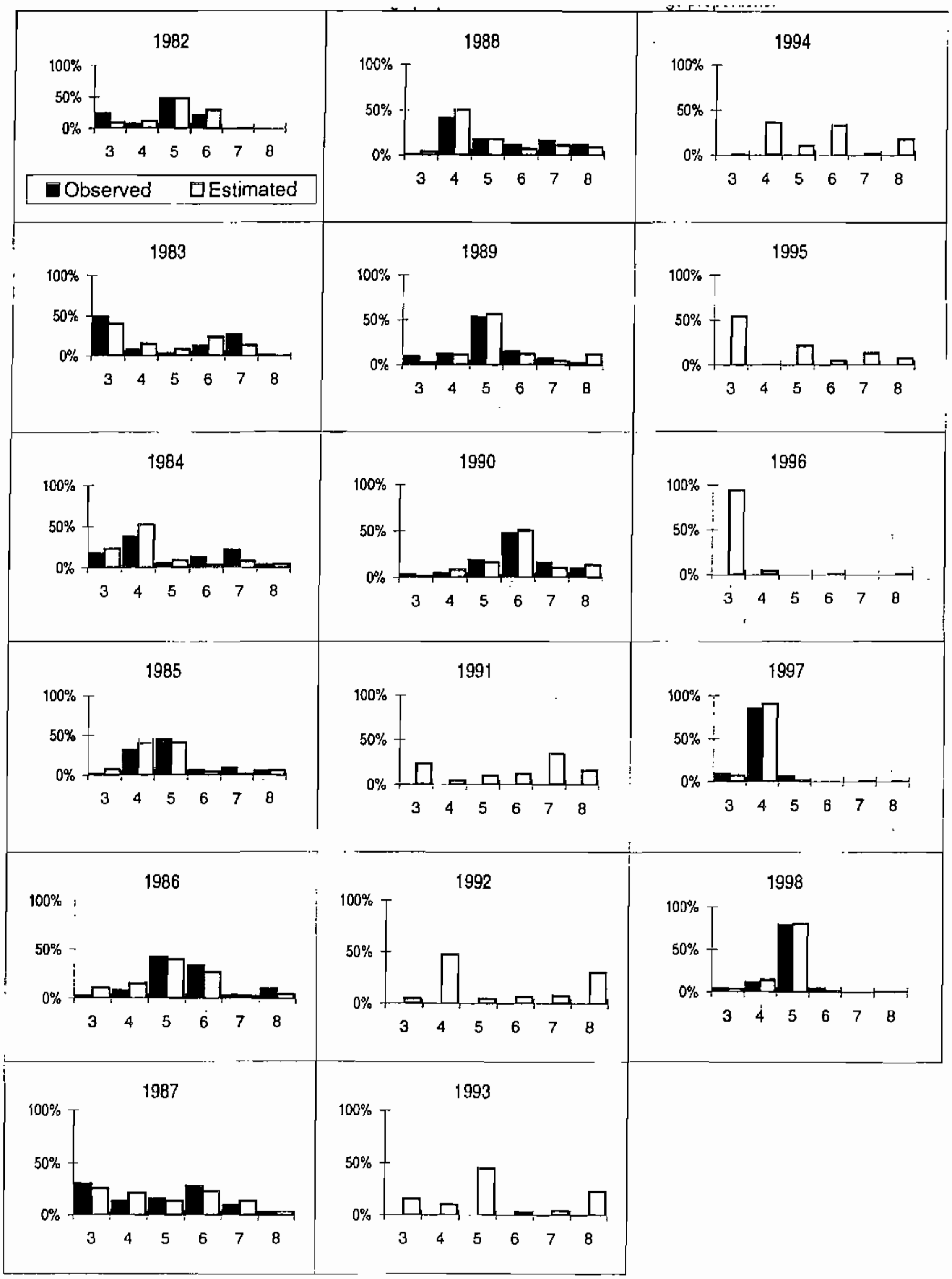
$$\mu_y = 0.2 \;\; when \;\; \left[8 + 2 \cdot \left(\frac{forecast}{threshold}\right)\right]^{-100} \succ 0.2$$



Appendix B. Goodness of fit of ASA estimated eggs spawned to observed estimate of eggs spawned, Tenakee Inlet.



Appendix C. Tenakee Inlet 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.



Appendix D. Tenakee Inlet observed and ASA-estimated herring catch age compositions used to assess goodness of fit of ASA model-estimated catch-at-age proportions to observed catch-at-age proportions.