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Productivity of Pacific Herring (*Clupea harengus pallasi*) in the Eastern Bering Sea under Various Patterns of Exploitation[1]

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Pacific herring (*Clupea harengus pallasi*) is a major food source for western Alaska native people and has been commercially exploited in the eastern Bering Sea since the early 1900's. Commercial harvests were small and localized in coastal waters until foreign factory fleets located and developed a fishery on wintering herring concentrations in the early 1960's. Harvests peaked near 150 000 t in the early 1970's and then declined along with catch per unit effort. Foreign harvests were eliminated following establishment of the United States 200 mile Fishery Conservation Zone. In recent years a fishery has developed in State of Alaska coastal waters which harvests herring for sac roe (ovaries) during the spring spawning period. Proposals have been put forth by trawl fishermen to reestablish a food and bait fishery within Federal waters. Development of offshore mixed stock fisheries has been opposed by inshore commercial and subsistence users who fear that stocks will be overexploited. While both State and Federal managers have agreed to give subsistence users and inshore domestic commercial fishermen top priority, they have been unable to agree upon plans for dealing with potential offshore commercial harvests. In this paper we present results of a computer model that we developed to examine effects of various fishing patterns upon herring productivity and yield. Within our model, maximum sustainable yield (MSY) is achieved at an exploitation rate (E) of 0.3 (i.e. harvest of 30% of total spawning biomass). However, since stocks still appear to be below MSY biomass and since productivity and yield drop sharply at E values greater than 0.3, we suggest that an E of 0.2 be maintained under current conditions. This will result in a potential loss in yield of only 7% from an E of 0.3, but will allow a 52% increase in spawning biomass. Four fishing patterns in which both discrete and mixed stock fishery removals were allowed to occur were also examined. During years in which inshore fisheries fail to harvest 20% of available spawning biomass, an offshore allocation of up to 10 000 t could be permitted with minimal risk to damaging the reproductive potential of small spawning stocks. However, results indicated that mixed stock fisheries should be restricted to lower levels than would be appropriate for fisheries targeting on discrete stocks to avoid risks of overharvesting some stocks.

Le hareng du Pacifique (*Clupea harengus pallasi*), qui représente une importante source de nourriture pour les autochtones de l'Alaska occidental, fait l'objet d'une pêche commerciale dans l'est de la mer de Béring depuis le début du siècle. Jusqu'à ce que les flottilles étrangères de bateaux-usines découvrent et exploitent, au début des années 1960, une pêcherie où se regroupait les harengs en hiver, les captures commerciales étaient faibles et se resteignaient aux eaux côtières. Au début des années 1970, les prises ont atteint presque 150 000 t pour ensuite péricliter, tout comme la prise par unité d'effort. L'établissement de la zone de conservation des pêches jusqu'à 200 milles des côtes américaines a éliminé l'exploitation étrangère. Récemment, on a vu se développer dans les eaux côtières de l'Alaska une pêche axée sur l'exploitation de la rogue (ovaires) du hareng au cours de la fraie printanière. Les pêcheurs au chalut ont présenté des propositions visant le rétablissement d'une pêche du hareng comme aliment et comme appât, dans les eaux relevant de la compétence fédérale. Les pêcheurs commerciaux et autochtones côtiers, qui craignent la surexploitation des stocks, s'opposent au développement de pêches hauturières de stocks mixtes. Quoique les gestionnaires du palier fédéral et de l'État de l'Alaska ont consenti à donner la priorité aux pêcheurs autochtones et aux pêcheurs commerciaux côtiers de l'endroit, ils n'ont pu s'entendre sur des plans d'exploitation commercial hauturière. Le présent rapport porte sur les résultats d'un modèle informatisé que les auteurs ont élaboré en vue d'étudier l'incidence de différents schèmes de pêche sur la productivité et le rendement du hareng. Dans ce modèle, le rendement maximal soutenu (RMS) est atteint à un taux d'exploitation (E) de 0,3 (c.-à-d. la pêche de 30 % de la biomasse totale de géniteurs). Toutefois, on croit que E devrait être maintenu à 0,2 dans les conditions actuelles, étant donné que les stocks semblent encore être inférieurs à la biomasse au RMS et que la productivité et le rendement chutent quand la valeur de E dépasse 0,3. Cela ne représenterait qu'une baisse potentielle du rendement de l'ordre de 7 % par rapport à une valeur de $E = 0,3$, mais permettrait une augmentation de 52 % de la biomasse de géniteurs.

[1]is paper was presented at the International Symposium on the Biological Characteristics of Herring and Their Implication for Management, ...vened at Nanaimo, B.C., June 20–22, 1983, commemorating the 75th anniversary of the Pacific Biological Station.

[2]Authors listed alphabetically.

On a aussi examiné quatre schèmes de pêche où des captures dans les stocks isolés et mixtes étaient effectuées. Au cours des années où les pêches côtières n'exploitent pas 20 % de la biomasse disponible de géniteurs, on pourrait allouer un contingent hauturier totalisent jusqu'à 10 000 t sans risque majeur pour le potentiel reproducteur de petites fraies. Toutefois, les résultats portent à croire qu'une pêche visant les stocks mixtes devrait être restreinte à des niveaux inférieurs à ceux appropriés pour une pêche axée sur des stocks isolés afin qu'il n'y ait pas surexploitation de certains stocks.

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Although Pacific herring, *Clupea harengus pallasi*, have been harvested for food by people living in eastern Bering Sea coastal villages since at least 500 B.C. (Hemming et al. 1978), development of large-scale commercial fisheries did not begin until the twentieth century. The first commercial fisheries occurred in Norton Sound (1909) and off Unalaska Island (1928) (Rounsefell 1929). Annual harvests were low (3–2700 t), and these fisheries ended in the late 1940's (Wespestad and Barton 1981). Beginning in 1959, Soviet trawl vessels, joined in later years by Japanese trawl and gillnet vessels, began to harvest large quantities of herring in eastern Bering Sea offshore waters. Annual harvests reached a peak of 146 000 t in 1970 and then declined along with catch per unit of effort. Offshore herring fishing was eliminated in 1980 when herring was made a prohibited species within the Fishery Conservation Zone. As foreign offshore herring harvests declined, inshore domestic harvests rose from an annual mean of less than 100 t during 1967–76 to 17 000 t during 1977–83. Most of the domestic harvest has been taken for sac roe (ovaries) (30 750 t in 1983) during the spring spawning period; some has been taken for other food uses and bait (3243 t in 1982) during the summer. A herring spawn on kelp harvest (rockweed kelp, *Fucus* sp.) has also developed along with sac roe fisheries (148 t in 1983). Total value of these harvests to United States fishermen has risen from less than $1 million in 1977 to $13 million in 1983.

Due to the limited information available on population biology of eastern Bering Sea herring, and in view of stock collapses that have commonly plagued herring fisheries in other parts of the world (see e.g. Cushing 1981; Blaxter and Hunter 1982, and references therein), much controversy surrounds management practices. Inshore fisheries, regulated by the State of Alaska, have been limited to a maximum exploitation rate of 20% of available spawning biomass for sac roe harvests, while quotas have been established for summer food and bait harvests (3200 t) and spring spawn on kelp harvests (10% of available kelp standing crop). Offshore herring fisheries, pending development of a management plan by the North Pacific Fisheries Management Council, have been prohibited, although about 2000 t of herring are taken incidentally during groundfish trawl fisheries. Opponents of offshore fisheries contend that eastern Bering Sea herring stocks are already fully utilized by inshore commercial and subsistence users and that offshore fisheries present the added risk of fishing upon unknown mixtures of spawning stocks. Proponents of offshore fisheries counter that assessment techniques and exploitation rates used for inshore fisheries are overly conservative (i.e. herring stocks are not being fully utilized) and that too much of the harvest is allocated to the sac roe fishery (i.e. markets for other herring products need to be developed).

Wespestad and Francis (1980) used a deterministic model, in which complete randomness was assumed for stock distribution and fishery removals, to examine effects of mixed stock harvests on eastern Bering Sea herring. They concluded that exploitation rates would be proportional to individual stock abundance. However, little data exist on the offshore distribution of herring, making it difficult to verify assumptions used in their analysis.

The purpose of this study was to determine effects of various exploitation rates on biomass and yield of eastern Bering Sea herring stocks and to examine consequences of mixed stock fisheries using a stochastic simulation model. Specific objectives were to determine whether the model's behavior was consistent with available information and to evaluate current and proposed management strategies within the context of these results. No attempt was made to simulate density-dependent or environmental effects upon growth and natural mortality rates or sexual maturity schedule within the model.

Model Parameters

Stock Composition and Distribution

Six spawning groups of herring have been recognized management purposes by the State of Alaska: Togiak, Sec Cove, Goodnews Bay, Nelson Island, Cape Romanzof, a... Norton Sound (Fig. 1). Spawning stock affinities of herring on the winter grounds have not been determined, but are thought to be a mix of the above-cited stocks. Aerial survey assessments of these spawning groups during 1978–82 indicated that Togiak comprised the largest group of spawners each year, averaging 82% of total estimated spawning biomass (Fried et al. 1982a). Security Cove, Goodnews Bay, Nelson Sound, Cape Romanzof, and Norton Sound averaged 3, 2, 3, 2, and 8%, respectively. Although electrophoretic studies failed to demonstrate significant genetic differences among these spawning groups (Grant 1981), consistent differences in growth patterns among these groups have been found (Walker and Schnepf 1982; Barton and Steinhoff 1980; Rowell 1980; also see Age and Growth section below). Therefore, each of the six spawning groups was assumed to be a valid stock for the purposes of the present study. Other minor spawning groups occur along the Alaska Peninsula and Aleutian Islands (Warner and Shafford 1977; Wespestad and Barton 1981), but were excluded from consideration within the present study.

Age and Growth

Herring usually enter eastern Bering Sea commercial catches between the ages of 3 and 5 yr (Wespestad and Barton 1981; Fried et al. 1982b, 1982c). Herring older than 9 or 10 yr are uncommon in commercial and survey catches, although some may reach a maximum age of at least 15 yr. Within simula... herring were allowed to attain a maximum age of 10 yr.

Mean size at each age decreases for eastern Bering ... herring spawning stocks located progressively northward from

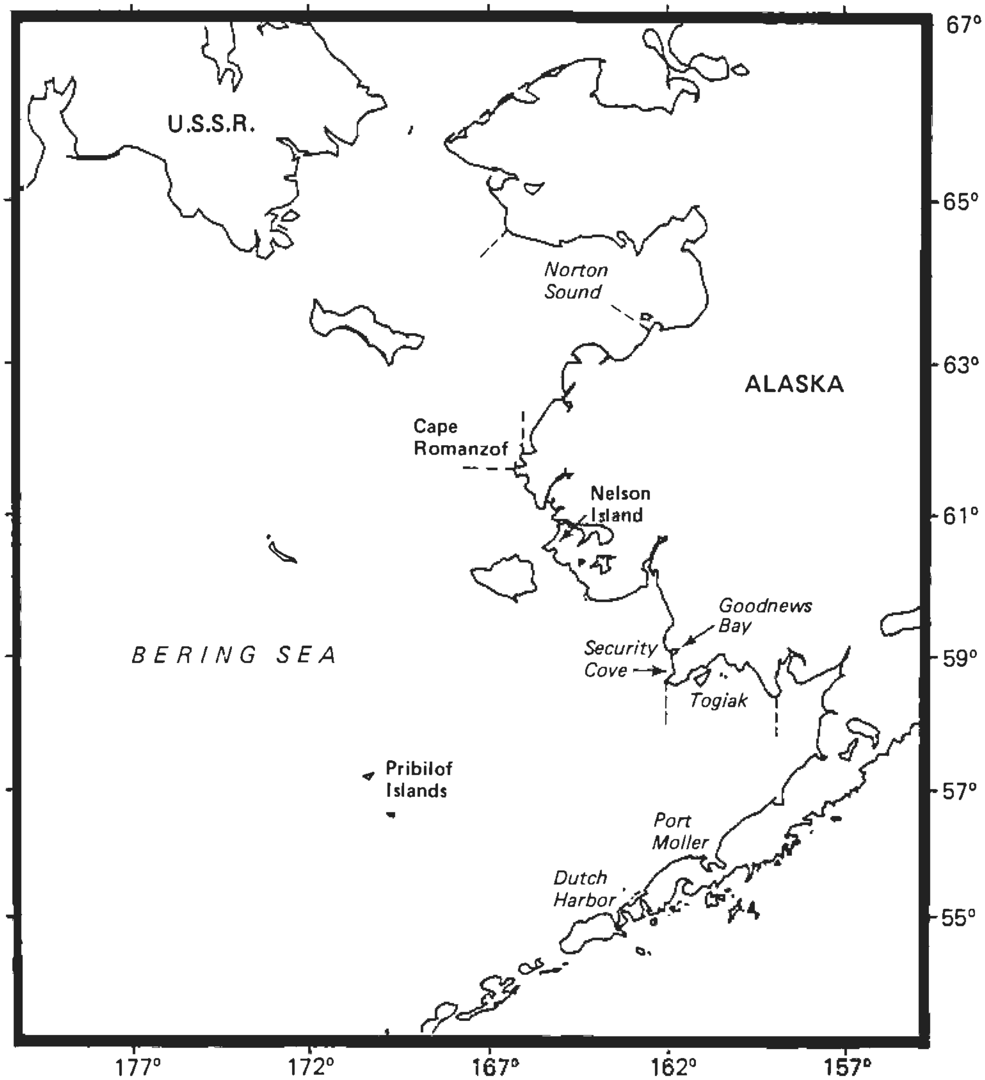

FIG. 1. Eastern Bering Sea, Alaska, showing locations discussed in the text.

Togiak (Barton and Steinhoff 1980; Fried et al. 1982b, 1982c). However, comparisons of von Bertalanffy age–length growth curves for these six stocks, using the least squares technique of Kappenman (1981), revealed that two different curves described growth: one for the southern stocks (Togiak, Security Cove, and Goodnews Bay), $L_S = 314.44\{1 - \exp[-0.22(t + 2.23)]\}$, and another for the northern stocks (Nelson Island, Cape Romanzof, and Norton Sound), $L_N = 289.07\{1 - \exp[-0.29(t + 0.97)]\}$, where L_S and L_N are standard lengths (millimetres). Age-specific lengths computed from the two von Bertalanffy curves were converted to weights using a weight–length regression (Ricker 1975). A single weight–length equation was calculated for all spawning groups, since geographic trends were not evident: $W = 10^{-6}L^{3.479}$, where W and L are weight (grams) and standard length (millimetres), respectively. Seasonal changes in growth rate were not simulated in our model, since most commercial harvests under present and proposed management regimes would occur when herring were at or near maximum age-specific weights (i.e. spring sac roe and winter harvest periods). Growth was increased uniformly in :rly increments each year so that herring reached maximum age-specific weight in the spring of each year, prior to spawning (Fig. 2).

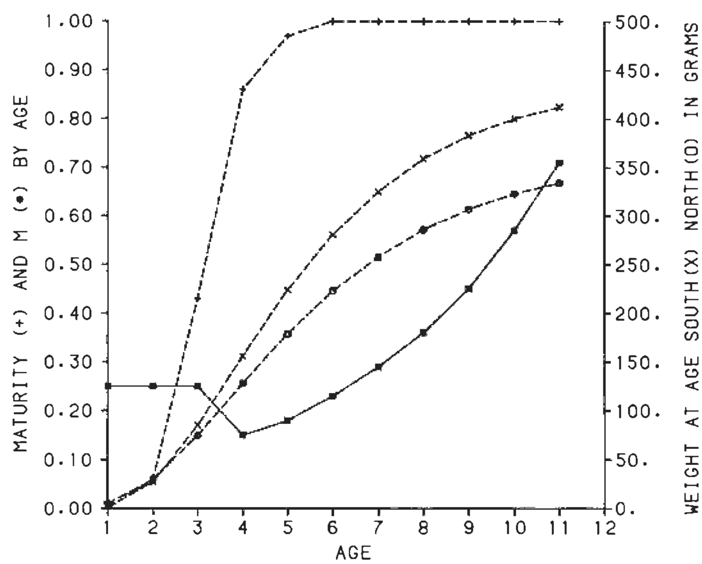

FIG. 2. Population parameters used in the model to simulate responses of eastern Bering Sea Pacific herring stocks to various patterns of exploitation. Maturity and instantaneous natural mortality schedules from Wespestad (1982).

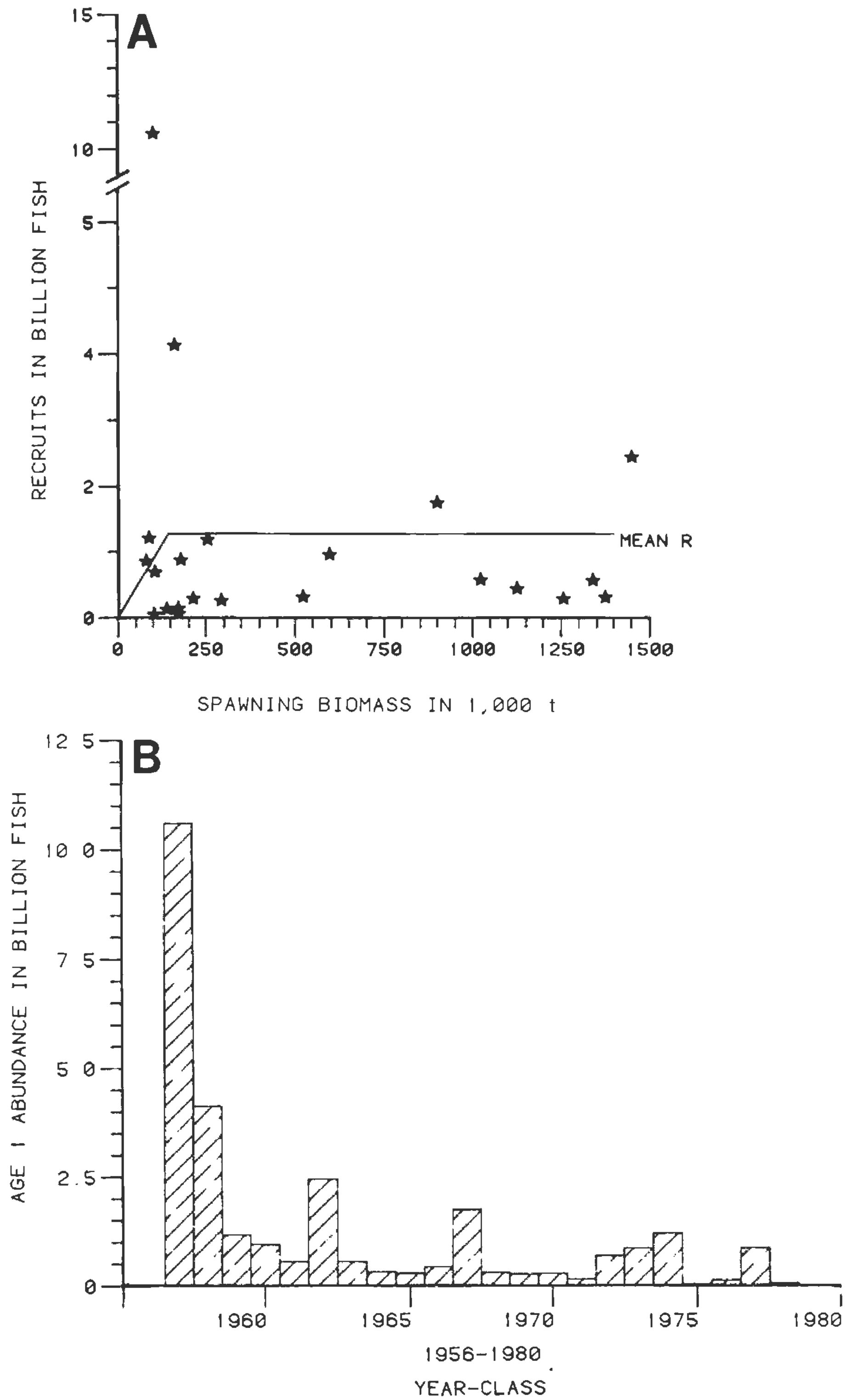

FIG. 3. Estimated number of age 1 recruits for all six eastern Bering Sea Pacific herring stocks, Alaska, 1957–77. (A) Plot of total number of age 1 recruits and the total spawning biomass of the parental populations; (B) annual fluctuations in the population size at age 1 of the 1957–77 year-classes. Data from cohort analysis (Wespestad 1982).

Natural Mortality

Little information on natural mortality rates is available for eastern Bering Sea herring. Wespestad (1982), using the Alverson and Carney (1975) procedure, estimated average instantaneous natural mortality (M) for Bering Sea herring to be 0.39, only slightly higher than the 0.36 value obtained for British Columbia herring by Schweigert and Hourston (1980). However, age-specific M values calculated from catch (e.g. 0.15 for age 4 to 0.36 for age 9) (see Fig. 4) were [illegible] than those available for either British Columbia (e.g. 0.4[illegible] age 4 to 1.18 for age 9) (Tester 1955; Taylor 1964) or Gulf of

TABLE 1. Values used in a model to generate recruitment vectors for eastern Bering Sea Pacific herring spawning groups.

	Spawning group						
	Togiak	Security Cove	Goodnews Bay	Nelson Island	Cape Romanzof	Norton Sound	Total
Mean recruitment: billions of age 1 herring (biomass, t)	1.051 (65 264)	0.038 (2388)	0.026 (1592)	0.038 (2388)	0.026 (1592)	0.102 (6367)	1.281 (79 591)
Critical biomass (t)	118 982	4353	2902	4353	2902	11608	145 100
Correlation matrix: year-class association between spawning groups							
Togiak	1.0	0.9	0.9	0.9	0.8	0.8	
Security Cove		1.0	0.9	0.9	0.8	0.8	
Goodnews Bay			1.0	0.9	0.8	0.8	
Nelson Island				1.0	0.8	0.8	
Cape Romanzof					1.0	0.9	
Norton Sound						1.0	

Alaska (e.g. 0.20 for age 4 to 0.85 for age 9) (Skud 1963) herring. For most of our simulations, Wespestad's (1982) age-specific M values were used for all stocks (see Fig. 4). However, to test sensitivity of the model's behavior to changes in M, some simulations were done with a constant M of either 0.30 (slightly higher than the mean age-specific rate of 0.27) or 0.39 (the highest estimated M value for these stocks). Values of M were applied in quarterly increments each year using a standard population decay function (Ricker 1975).

Sexual Maturity

Sexual maturity of eastern Bering Sea herring coincides with recruitment into sac roe fisheries. Although some herring reach maturity by 2 yr of age, most do not mature until they are 3–5 yr old (N. I. Naumenko, Pac. Res. Inst. Fish. Oceanogr. (TINRO), Vladivostok, USSR, unpubl. data; Wespestad 1982). Data from 1959–77 offshore herring harvests indicate that recruitment into that fishery also coincided with sexual maturity, since few 1- and 2-yr-old herring were caught. The reported mean maturity schedule for 1959–77 was used to calculate spawning stock size within our model (Fig. 2).

Recruitment

The spawner–recruit relationship was derived from estimates of spawning biomass and numbers of 1-yr-old herring obtained by cohort analysis (Wespestad 1982) (Fig. 3A). A Ricker recruitment curve did not fit our data (ANOVA, $P > 0.05$), although such a relationship has been used to describe recruitment within British Columbia and Southeastern Alaska herring stocks (International North Pacific Fisheries Commission 1961). Lack of fit does not preclude the existence of such a relationship for Bering Sea herring stocks. However, the relationship may be masked by environmental factors, which have been shown to be important in determining year-class strength in other herring populations (Taylor 1964; Iles and Sinclair 1982; Skud 1982).

Since a Ricker recruitment curve did not fit our data, we incorporated a nonrandom, linear spawner–recruit relationship within our simulations at low levels of spawning biomass, and assumed that recruitment varied randomly about a mean value [illegible] million 1-yr-old herring) above a critical threshold [illegible]ing biomass of 145 100 t (10% of maximum estimated spawning biomass). Recruitment was generated for each of the six stocks within our model by apportioning threshold biomass and mean number of recruits according to the mean observed distribution of total spawning biomass (Table 1). We assumed that adjacent stocks would have a high level of correlation in recruitment within a given year and that stocks spawning at increasing distances from one another would have less similar levels of recruitment. A correlation matrix, used to simulate these interstock relationships, and the coefficient of variation of annual numbers of 1-yr-old recruits, calculated from cohort analysis estimates (1.78), were used to produce a covariance matrix for generating multivariate normal residuals (Naylor 1966). These residuals were added to the mean recruitment value to simulate recruitment for spawning biomass above the threshold. Negative recruitment values were converted to zero.

Fishery Simulation Characteristics

During sac roe and subsistence fishery simulations, catchability was assumed to be equal for all sexually mature herring. Harvests were taken prior to spawning, were considered to be instantaneous, and preceded natural mortality for the spring quarter. All stocks except Nelson Island were subjected to sac roe fisheries. Nelson Island spawning herring were only exploited at a rate equivalent to current subsistence removals.

During winter trawl fishery simulations, only sexually mature herring 4 yr of age and older were made available for harvest. All stocks were assumed to be present on the winter grounds. Herring biomass was randomly distributed among various sized schools, composed of individuals of the same age and stock, according to a gamma distribution (mean school size 100 t, minimum size 10 t). Similar skewed frequency distributions of pelagic fish school sizes have been postulated by other investigators (Anderson 1981). Each school was randomly assigned to 1 of 100 locations within an array according to a univariate normal distribution, since catch data show biomass to be normally distributed on the winter grounds (Wespestad 1978).

Fishing was started within the location containing the greatest herring biomass. One school was randomly selected and 20% of its biomass harvested. This procedure continued until the specified harvest was taken, or 90% of the total biomass within each location was removed. Although simulated catch per unit of effort (mean approximately 20 t per trawl haul) was higher than that achieved historically by Soviet and Japanese vessels (3.5–8.5 t per trawl haul) (Shaboneev 1965; fishery observer data, Northwest and Alaska Fishery Center, NMFS), we felt

TABLE 2. Eastern Bering Sea Pacific herring sac roe yield and spawning biomass from computer simulations using different levels of constant and variable exploitation. Results of 20 replicated 100-y simulations for each level of E and E_{MSY}.

Sac roe exploitation rate (E)	Spawning biomass (t) remaining after sac roe harvest			Sac roe harvest (t)		
	Mean	SD	Range	Mean	SD	Range
Constant proportion of spawning biomass removed						
0.0	791 041	131 279	247 631 – 1 023 287	531[a]	83[a]	183 – 679[a]
0.1	547 264	82 960	221 272 – 705 141	59 010	8 898	23 910 – 76 122
0.2	377 870	51 767	180 854 – 471 237	88 915	12 205	43 071 – 115 814
0.3	248 812	29 280	143 969 – 321 450	95 716	11 253	55 679 – 124 009
0.4	127 832	22 980	83 071 – 179 749	68 818	14 209	41 365 – 98 066
0.5	41 740	22 902	17 969 – 130 151	22 171	22 114	1 919 – 121 033
0.6	24 571	14 713	15 620 – 106 656	9 720	21 789	503 – 145 204
Variable proportion of spawning biomass removed based on different E_{MSY} values						
0.2	324 817	25 862	209 475 – 374 350	96 792	17 966	28 995 – 140 673
0.3	194 791	9 417	155 910 – 216 837	102 319	15 783	46 077 – 140 425
0.4	84 809	4 209	64 440 – 95 025	51 749	15 828	28 995 – 187 603

[a]Nelson Island stock exploited at constant rate of 0.03 in all cases to simulate subsistence harvest.

these values were reasonable with presently available fishing gear and electronics.

Management Strategies

Management of Alaska roe fisheries is based on applying exploitation rates (E) of 0.10–0.20 on discrete stocks. However, the rationale for this range of E values has not been investigated quantitatively. We used our model to examine effects of E values ranging from 0.00 to 0.60 on total yield and spawning biomass of eastern Bering Sea herring. Each experiment consisted of 20 replicated 100-yr simulations at a constant level of E. For each experiment, E was incremented by 0.10 for each stock except Nelson Island. This stock was harvested at an E of only 0.03 during all experiments to simulate subsistence removals. To begin each simulation the total population was set equal to that estimated by cohort analysis for 1978 (Wespestad 1982): total biomass 255 000 t (1- to 3-yr-old herring 40% of total population); spawning population 171 000 t.

Federal draft plans for an offshore mixed stock herring fishery (North Pacific Fishery Management Council 1983) propose that harvests be based upon a variable E calculated annually by the following equation:

$$E_i = E_{MSY}(B_i/B_{MSY})$$

where E_{MSY} = exploitation rate that achieves maximum sustainable yield (MSY), B_{MSY} = spawning biomass that produces MSY, and B_i = estimated spawning biomass in year i. The proposed E_{MSY} is 0.20, the maximum E allowed by State guidelines; B_{MSY} is 244 000 t, which is based upon past offshore harvest under an assumed E value of 0.20.

We examined effects of using a variable E on yield and spawning biomass in the same manner used for constant E: 20 replicated 100-yr simulations for each case investigated; initial population size and age structure set at the 1978 level. Three different cases were tested by substituting three pairs of E_{MSY} (0.20, 0.30, and 0.40) and B_{MSY} (obtained from simulations in which constant E values of 0.20, 0.30, and 0.40 were used) values into the above equation.

To investigate effects of offshore mixed stock harvests on inshore catches and spawning biomass, we assumed that all stocks were available to the winter trawl fishery and that the five smallest stocks (18% of total biomass) were always exploited at the presently accepted maximum rate of 0.20 for inshore fisheries. Surplus for harvest offshore was provided by decreasing inshore exploitation rate on the Togiak stock to either 0.00 or 0.15. This provides a potential offshore allocation equal either to 20 or 5% of the Togiak spawning biomass. Four patterns of fishing were examined by replicating 100-yr sir tions 20 times for each pattern: (1) Togiak inshore E = ι offshore harvest = maximum of 10 000 t; (2) Togiak inshore E = 0.15, offshore harvest = maximum of 10 000 t (maximum harvest currently proposed); (3) Togiak inshore E = 0.00, offshore harvest = 20% Togiak spawning biomass; (4) Togiak inshore E = 0.15, offshore harvest = 5% Togiak spawning biomass. To begin each simulation the total population was set equal to that estimated for 1959: total biomass 1 446 000 t (1- to 3-yr-old herring 89% of total population); spawning biomass 255 000 t.

Results and Discussion

Behavior of the Model

Without commercial removals, mean total spawning biomass for the model was 791 041 t (SD 131 279 t) (Table 2; Fig. 4A). Maximum yield was reached with a constant E of 0.30 where mean total spawning biomass was 248 812 t (SD 29 280 t) and mean total sac roe harvest was 95 716 t (SD 11 253 t). Both mean total spawning biomass and harvest declined sharply when E values exceeded 0.30. Similar results were obtained using a variable E calculated from specified values of E_{MSY} and B_{MSY}. Maximum yield occurred when E_{MSY} was set at 0.30. Although mean spawning biomass was less variable (F-test, $P < 0.05$), but lower (t-test, $P < 0.05$), when using variable E values, yield was not less variable (F-test, $P > 0.05$) or greater (t-test, $P > 0.05$) than when using constant E values. These resul not surprising, since the variable E procedure is based assumption of a Ricker spawner–recruit relationship. The spawner–recruit relationship within our model was not domed

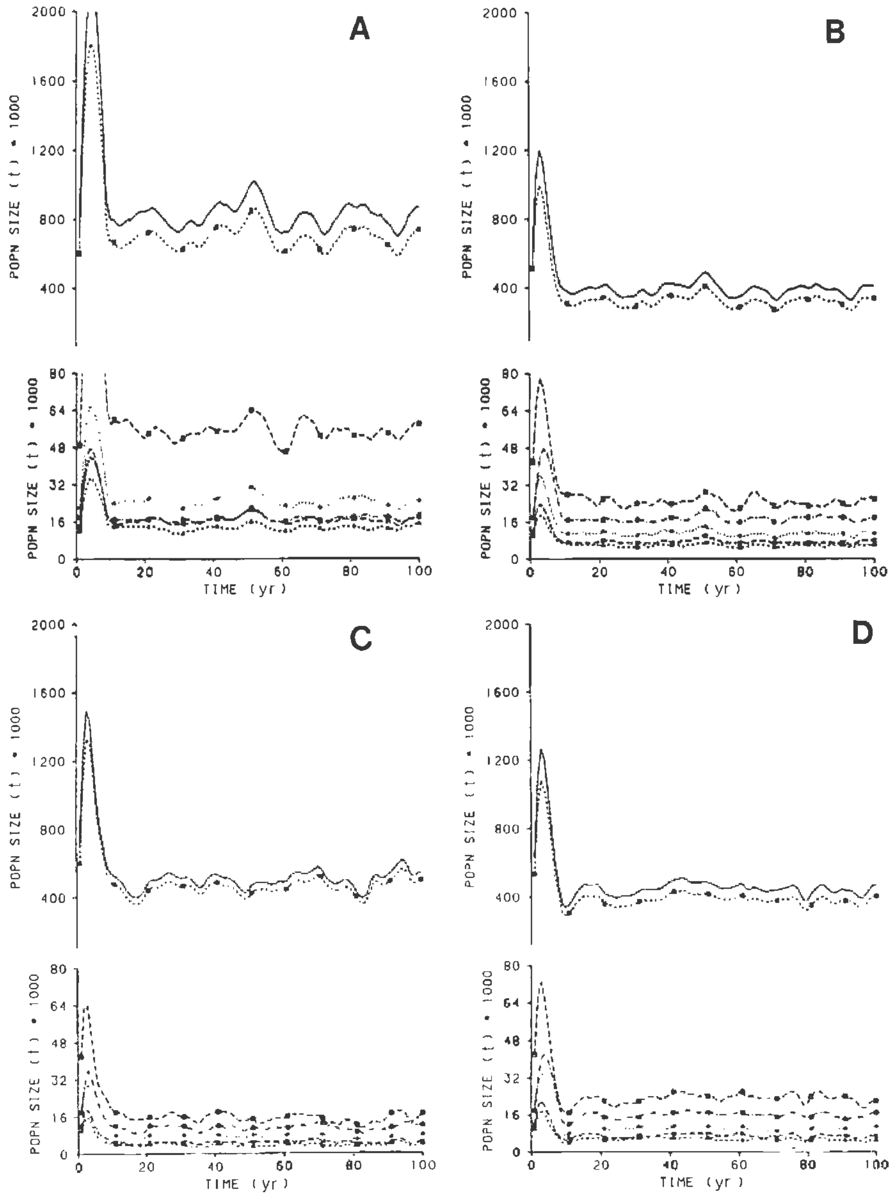

FIG. 4. Annual fluctuations in biomass in simulated eastern Bering Sea Pacific herring spawning populations subjected to various patterns of exploitation. (A) All stocks unexploited except Nelson Island (E = 0.03); (B) all stocks exploited at E = 0.20 except Nelson Island (E = 0.03); (C) exploitation pattern III in Table 5; (D) exploitation pattern IV in Table 5. Solid line = all stocks combined; asterisk = Togiak; cross = Security Cove; × = Goodnews Bay; circle = Nelson Island; triangle = Cape Romanzof; square = Norton Sound.

but generated random recruitment values about a specified mean over a wide range of spawning biomass values.

Simulations in which constant M values (greater than the mean of age-specific M values) were used achieved maximum yield with a constant E of 0.20 (Table 3). Mean yield at both constant M values tested was less than that achieved at similar E values when age-specific M values were used.

Model results conform to historical trends of spawning biomass and exploitation rates for the fishery (Table 4). Estimated mean total spawning biomass during a period of low exploita- 1960–66) was 1 166 000 t (SD 291 430 t). Although this is 1.5 times greater than the mean spawning stock size, results from cohort analysis (Wespestad 1982) indicate that population structure was unusual during 1960–66 due to presence of the extremely abundant 1957 and 1958 year-classes. The 1957 year-class was 8 times greater than estimated mean annual recruitment of age 1 herring, (mean 1.3×10^9 individuals; 1957 year-class, 10.6×10^9). No other year-class has since approached this abundance (Fig. 3B).

During the most intensive period of offshore exploitation (1968–77) mean E was 0.33, but reached a maximum of 0.68 one year. Mean spawning biomass and harvest declined during this period as occurred during simulations with the model at E values greater than 0.30 (Tables 2 and 4). In more recent years (1978–82) E has been below 0.3, and often below 0.2. However, populations have probably not yet recovered from previous high exploitation rates. Estimated mean total spawning biomass during 1968–82 has been about 160 000 t.

TABLE 3. Eastern Bering Sea Pacific herring sac roe yield and spawning biomass from computer simulations using two different values of constant natural mortality (M) and several levels of constant exploitation (E). Results of 20 replicated 100-yr simulations for each level of E.

Sac roe exploitation rate (E)	Spawning biomass (t) remaining after sac roe harvest			Sac roe harvest (t)		
	Mean	SD	Range	Mean	SD	Range
			$M = 0.30$			
0.1	391 090	174 288	50 237 – 1 254 038	42 113	18 838	5 319 – 135 221
0.2	265 337	128 778	28 944 – 907 412	62 169	30 496	6 518 – 214 163
0.3	150 330	95 385	4 860 – 539 818	56 768	37 607	854 – 211 320
0.4	53 810	52 835	1 028 – 34 076	25 877	31 305	82 – 198 140
			$M = 0.39$			
0.1	235 925	116 192	24 841 – 814 276	25 360	12 539	2 617 – 87 708
0.2	130 286	88 098	2 739 – 492 306	30 123	20 896	300 – 116 220
0.3	44 772	49 110	519 – 313 526	15 464	19 495	44 – 122 263
0.4	19 398	26 874	445 – 162 811	7 663	16 413	14 – 93 998

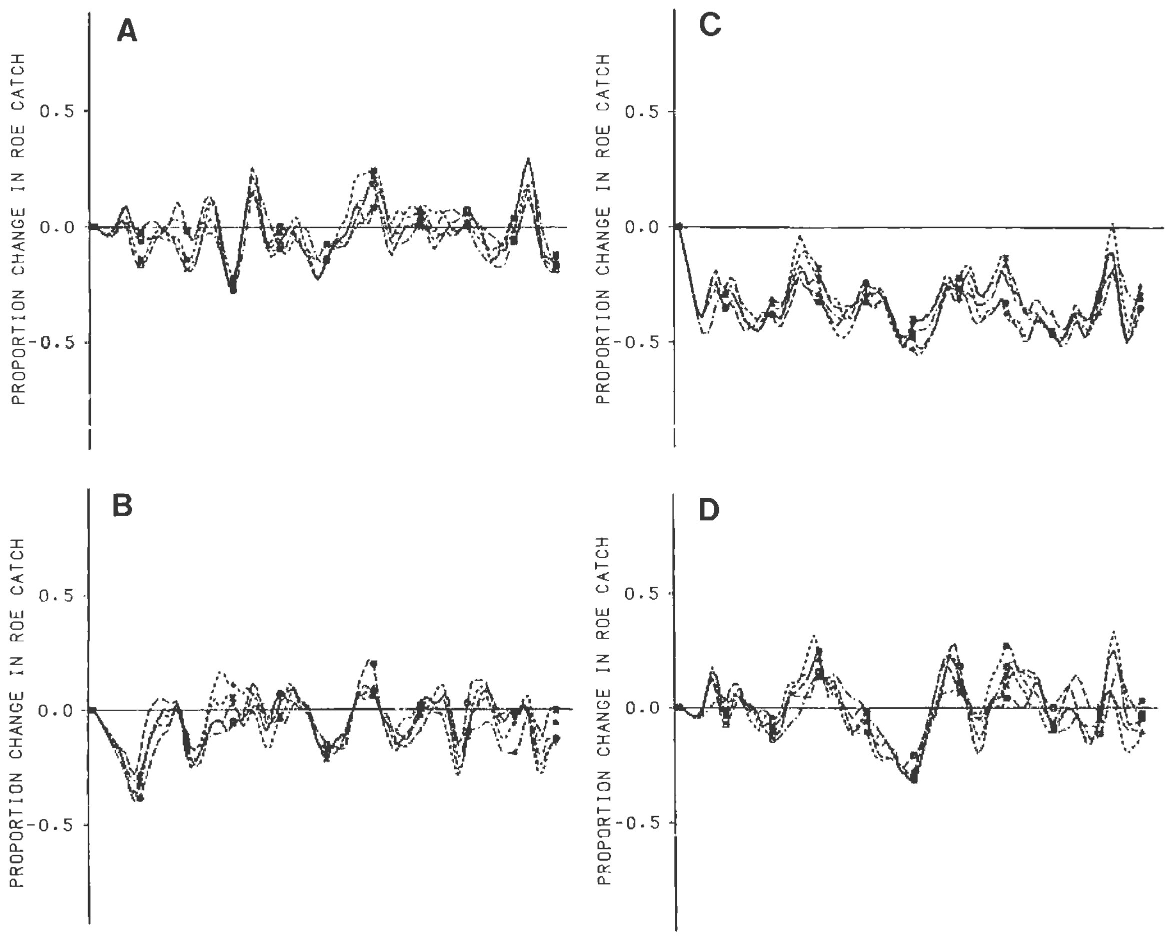

FIG. 5. Annual departures from expected mean yield (based upon $E = 0.03$ for Nelson Island and $E = 0.20$ for all other stocks) when different combinations of discrete and mixed stock fishery removal occur. (A) Exploitation pattern I in Table 5; (B) exploitation pattern II in Table 5; (C) exploitation pattern III in Table 5; (D) exploitation pattern IV in Table 5. Symbols as defined in Fig. 4.

TABLE 4. Eastern Bering Sea Pacific herring spawning biomass and commercial fishery exploitation rates during 1960–82. Spawning biomass estimates obtained from cohort analysis (Wespestad 1982) unless otherwise indicated. Total and spawning biomass exploitation rates (E_T and E, respectively) were calculated from catches listed by North Pacific Fishery Management Council (1983) unless otherwise indicated.

Period	Area of catch	Spawning biomass		E_T		E	
		Mean	SD	Mean	Range	Mean	Range
1960–66	Offshore[a]	1 166 000	291 430	0.01	0.01–0.03	0.02	0.01–0.04
1968–77	Offshore[b]	189 400	134 638	0.21	0.09–0.44	0.33	0.12–0.68
1978–81	Inshore[c]	166 750	7 228	0.11	0.09–0.13	0.15	0.12–0.18
1978–82[d]	Inshore	161 540	68 472	Not available		0.14	0.04–0.29

[a]Entire harvest offshore except 18 t in 1964.
[b]Less than 1% of total harvest inshore except 1977 when 12% inshore.
[c]Transition to total inshore harvest: 1978 and 1979, 31 and 38%, respectively, inshore; 1980–82 entire harvest inshore.
[d]Data from Alaska Department of Fish and Game aerial assessments and inshore sac roe harvests (Fried et al. 1982a).

TABLE 5. Probability of achieving various total annual exploitation rates (E_T) for eastern Bering Sea Pacific herring stocks subjected to four different fishing patterns simulated with the computer model. Results of 20 replicated 100-yr simulations for each pattern examined. Spawning stocks used in the model were Togiak (TOG), Security Cove (SC), Goodnews Bay (GB), Nelson Island (NI), Cape Romanzof (RO), and Norton Sound (NS).

Annual exploitation rate or quota for each fishery					Probability of obtaining various ranges of total annual exploitation rates for spawning stock					
Sac roe (E)		Subsistence (E) (NI only)	Food/bait (t), all stocks offshore	Range of E_T						
TOG	All others				TOG	SC	GB	NI	RO	NS
				Fishing pattern I						
0.00	0.20	0.03	10 000 max.	<0.10	0.996	0.000	0.000	0.919	0.000	0.000
				0.10–0.19	0.004	0.000	0.000	0.073	0.000	0.000
				0.20–0.29	0.000	0.960	0.947	0.004	0.922	0.983
				0.30–0.39	0.000	0.032	0.046	0.003	0.062	0.013
				>0.39	0.000	0.008	0.007	0.001	0.016	0.004
				Fishing pattern II						
0.15	0.20	0.03	10 000 max.	<0.10	0.000	0.000	0.000	0.884	0.000	0.000
				0.10–0.19	0.940	0.000	0.000	0.110	0.000	0.000
				0.20–0.29	0.060	0.933	0.922	0.006	0.894	0.973
				0.30–0.39	0.000	0.057	0.065	0.000	0.081	0.023
				>0.39	0.000	0.010	0.013	0.000	0.025	0.004
				Fishing pattern III						
0.00	0.20	0.03	Entire surplus	<0.10	0.000	0.000	0.000	0.020	0.000	0.000
				0.10–0.19	0.998	0.000	0.000	0.287	0.000	0.000
				0.20–0.29	0.002	0.129	0.174	0.583	0.216	0.075
				0.30–0.39	0.000	0.591	0.525	0.097	0.452	0.711
				>0.39	0.000	0.320	0.301	0.013	0.332	0.214
				Fishing pattern IV						
0.15	0.20	0.03	Entire surplus	<0.10	0.000	0.000	0.000	0.656	0.000	0.000
				0.10–0.19	0.969	0.000	0.000	0.340	0.000	0.000
				0.20–0.29	0.031	0.922	0.885	0.004	0.865	0.978
				0.30–0.39	0.000	0.077	0.106	0.000	0.127	0.021
				>0.39	0.000	0.001	0.009	0.000	0.008	0.001

Effects of Mixed Stock Harvest

To simulate effects of mixed stock harvests on individual spawning stocks and inshore harvest levels, we examined four combinations of inshore and offshore fishing patterns (Table 5). Inshore commercial and subsistence harvests were taken from discrete spawning stocks; the offshore food/bait harvest was taken from mixed stocks of mature herring. Probability of overharvesting individual spawning stocks (where overharvest is defined as $E > 0.3$) was generally less than 0.06 when offshore fishing was limited to a 10 000 t maximum harvest (patterns I and II) or an amount equal to 5% of the Togiak surplus (pattern IV). In these cases, total biomass and mean sac roe and subsistence harvests for stocks other than Togiak were similar to those obtained when $E = 0.2$ and no mixed stock fishery occurred (Fig. 4B, 4D; 5A, 5B, 5D). However, when no inshore harvest was taken from the Togiak stock and an amount equal to 20% of this spawning biomass was allocated offshore (pattern III), effects upon other (smaller) spawning stocks were dramatic (Table 5; Fig. 4C). Probability of overharvesting ($E > 0.30$) these smaller spawning stocks increased to 0.78 or more for all stocks except Nelson Island, which had a probability of overharvest of 0.11. A marked overall decline in inshore harvests from those obtained when $E = 0.2$ and no mixed stock fishery occurred was also shown for these groups (Fig. 5C). Effects of offshore mixed stock harvests were always greatest for the smallest spawning groups, which were already harvested at a constant inshore E of 0.2.

Conclusions

Although the computer model gives our best estimate of long-term consequences of different harvest strategies, simulation results must be used with caution. Pacific herring lack strong density-dependent regulatory mechanisms and are subject to large abundance fluctuations due to biotic and abiotic factors (Cushing 1981; Blaxter and Hunter 1982). Fishing may intensify or increase the possibility of stock declines. Since the model cannot be used to forecast events for a given year, management procedures must remain flexible to react to unforeseen abundance fluctuations.

Eastern Bering Sea herring stocks are still recovering from heavy exploitation that occurred during the peak of the foreign offshore trawl fishery (1968–77). Therefore, although maximum yield within the model was obtained at an E of 0.30, it may be prudent to maintain the current maximum E of 0.20. This may allow stocks to regain their former abundance more quickly and provide a measure of protection against overharvest, while only decreasing mean harvests by 7% and increasing mean spawning biomass by 52% from levels obtained at an E of 0.30.

During years in which the inshore fisheries fail to harvest the Togiak group at an E of 0.20, an offshore harvest to 10 000 t could be allowed with minimal risk to other spawning groups. While a somewhat higher offshore harvest could be taken during some years, it is necessary to restrict offshore (and inshore) mixed stock fisheries to lower levels than would be appropriate for fisheries targeting upon discrete stocks, since the risk of overharvesting individual stock components increases with size of harvest (Table 5).

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