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Assessment of walleye pollock stocks in the eastern North Pacific Ocean: an integrated analysis using research survey and commercial fisheries data

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Walleye pollock (*Theragra chalcogramma*) is the single most abundant fish species in the North Pacific Ocean. Concentrations of this species, which occur in the eastern Bering Sea and western Gulf of Alaska, support the largest single-species commercial fishery in the world. Exploitation of these stocks began in the early 1960s primarily by foreign national fleets. Currently the fishery is in a transitional phase. Over a relatively short time a combination of events dramatically reshaped the fishery from a multispecies foreign bottom-trawl fishery to a joint-venture fishery and finally to an expanding domestic presence. In the process, patterns and methods of fishing have changed as have the fishery parameters estimated from assessment models.

In the past, fishery assessments were based on limited non-directed bottom-trawl survey c.p.u.e., fishery c.p.u.e., and length-frequency analysis. Beginning in 1979, the use of hydroacoustic surveys allowed the assessment of the midwater portion of the stock which normally was not available to the bottom-trawl surveys or the commercial fishery. The hydroacoustic survey provided data which made it possible to tune sequential population models. Also described are current assessment methods which allow direct integration of hydroacoustic survey information into separable fishery assessment models. With an integrated approach, estimated abundance levels are more consistent with survey estimates. The hydroacoustic surveys in coming years will be especially important to the estimation of new tuning parameters.

This paper reviews past catch, management, and assessment results. Also presented are results from current assessments. In particular we emphasize how survey results, especially results from hydroacoustic surveys, can be integrated with age-structured fishery assessment models to examine the validity of assumptions inherent in each method.

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Introduction

Walleye pollock (*Theragra chalcogramma*) is the single most abundant fish species in the North Pacific Ocean. This member of the gadid family ranges completely around the Pacific rim, from Washington State to the Sea of Japan. In the eastern North Pacific, principal concentrations occur in the eastern Bering Sea and western Gulf of Alaska. Pollock stocks from this region support the largest single-species commercial fishery in the world (FAO, 1987). In the North Pacific, off Alaska, pollock make up 80 % of the total catch of groundfish species (Bakkala *et al.*, 1986). Large stocks of pollock also occur in waters off Asia as indicated by catches in the 4 to 6 million tonne range for 1980–1985; however, published abundance data are not available for these stocks.

Pollock is a semi-demersal species which is primarily pelagic during the first few years of life and becomes increasingly demersal in behaviour as it ages. The species is found in greatest abundance along the outer continental shelf between the 100–300-m depth contour. They have also been found to occur pelagically in the deep waters of the Aleutian Basin (Okada and Yamaguchi, 1985), but only at low densities.

Several studies have attempted to delineate the stock structure of pollock (Grant and Utter, 1980), yet unit stocks are still poorly understood and several hypotheses have been proposed (Bakkala *et al.*, 1986). For management purposes three stocks are recognized. In

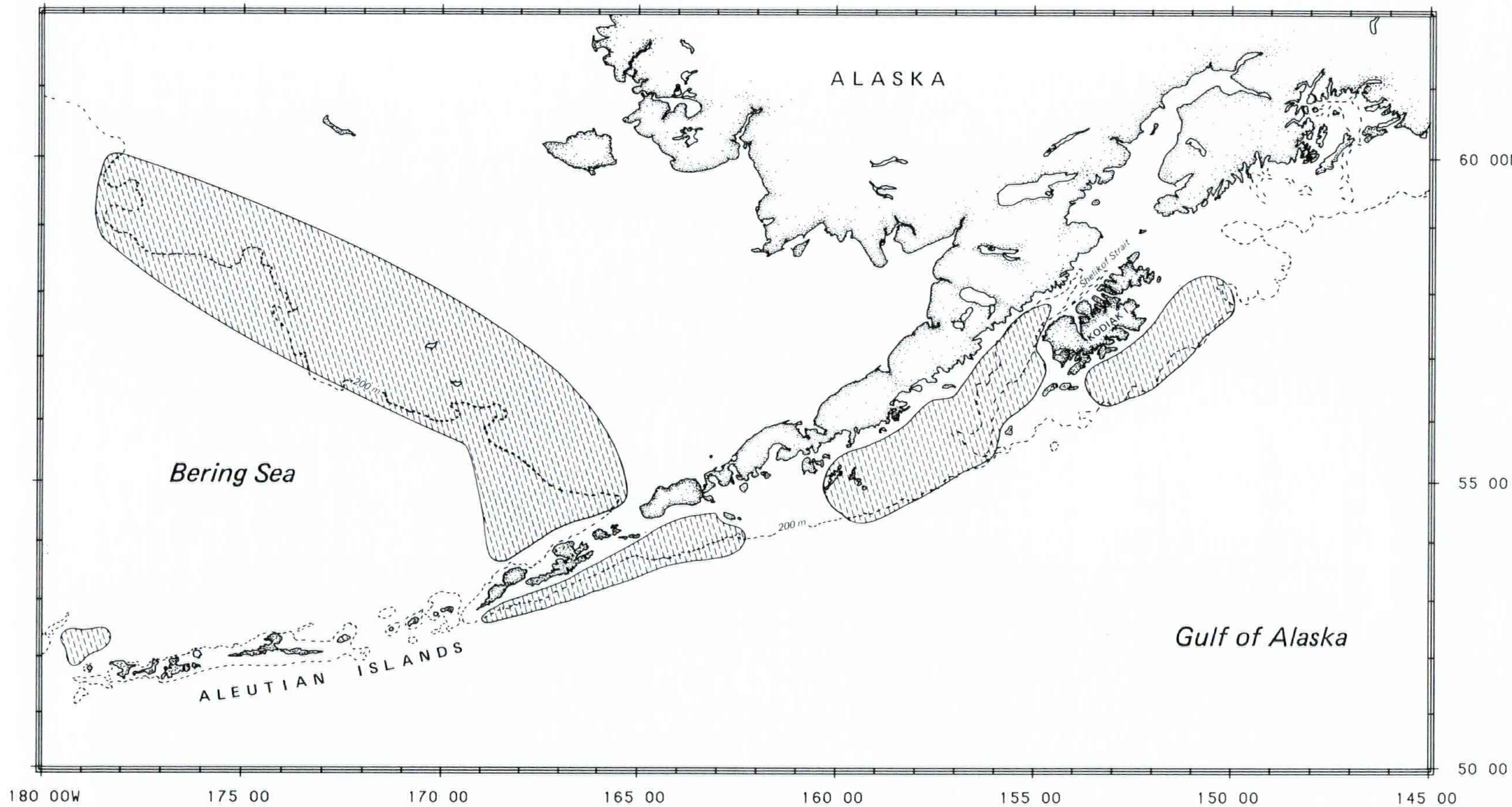

Figure 1. Locations of major exploitable concentrations of walleye pollock stocks in the eastern Bering Sea and western Gulf of Alaska.

order of abundance, these are: eastern Bering Sea, western Gulf of Alaska, and Aleutian Islands. In this paper we review the fisheries and assessment histories of two of these stocks, eastern Bering Sea and western Gulf of Alaska (Fig. 1).

Pollock fisheries in the eastern Bering Sea and Gulf of Alaska

In the waters off Alaska, large distant-water fleets operated by foreign nationals have historically been the principal exploiters of the pollock resource. Fleets of Japanese trawlers harvested pollock at low levels in the eastern Bering Sea from 1954 to 1963. In 1965 the Japanese fleets began directed pollock fisheries, and catches of pollock in the Bering Sea increased rapidly during the late 1960s, reaching a peak in 1970–1975 when catches ranged from 1.3 to 1.9 million tonnes annually (Fig. 2). Following the peak catch of 1.9 million t in 1972, pollock catches were steadily reduced through bilateral agreements. Since 1977, the North Pacific Management Council has established quotas ranging from 950 thousand t to 1.2 million t. Catches

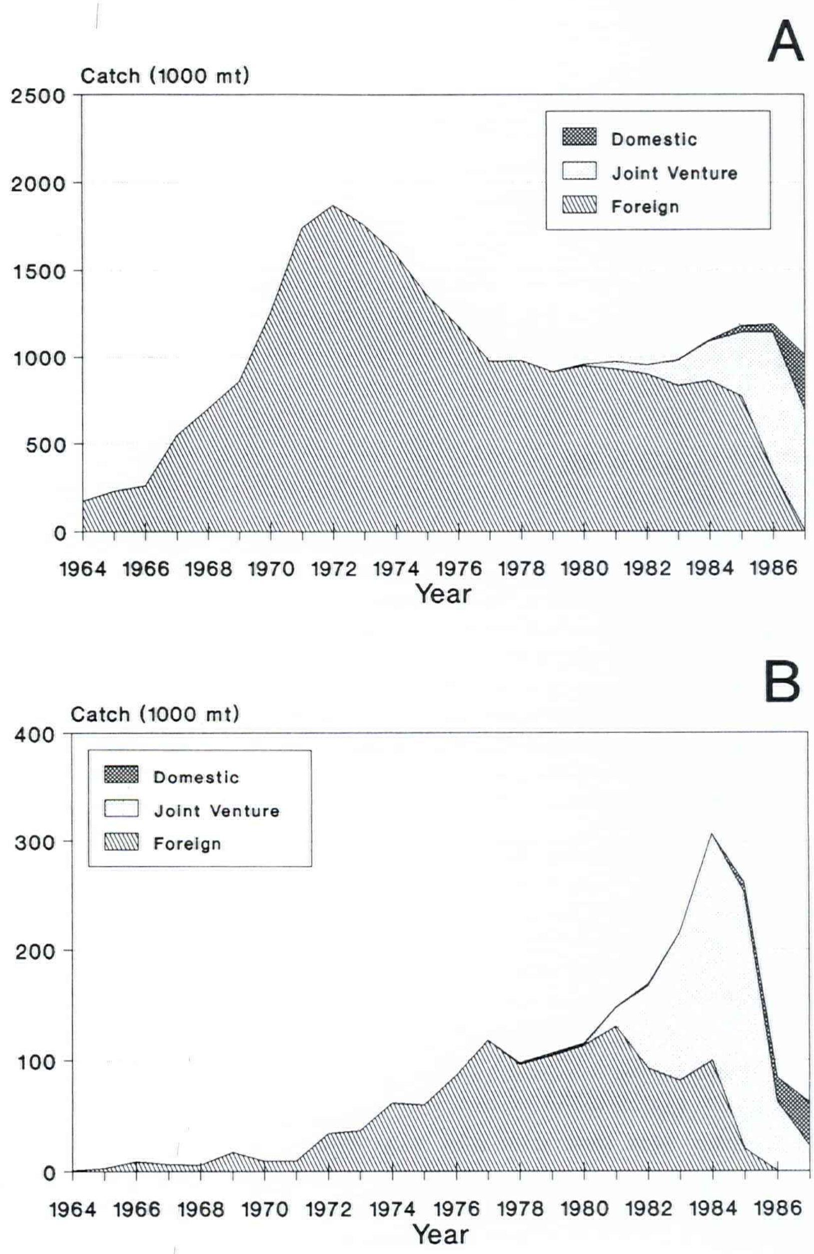

Figure 2. Catch of pollock in the eastern Bering Sea (panel A) and western Gulf of Alaska (panel B) by foreign, joint-venture, and domestic fisheries, 1964–1987.

during this period have ranged from 914 thousand t to 1.1 million t.

In the early 1960s, pollock catches in the Gulf of Alaska were primarily a by-catch in the larger Pacific ocean perch (*Sebastes alutus*) fishery. By 1972 Pacific ocean perch had been depleted. Foreign fleets shifted their efforts to pollock and catch increased to four times the 1971 level (Alton, 1981). Pollock catches continued to rise during the 1970s and into the 1980s with a peak catch of 307 thousand t recorded in 1984 (Fig. 2). The rapid growth of the Gulf of Alaska fishery in the 1980s is partially due to the discovery in 1981 of large spawning aggregations of pollock in Shelikof Strait (Fig. 1) (Nunnallee *et al.*, 1982). These dense spawning aggregations support a large efficient fishery since fishable schools are easy to locate and are readily available to the fleet.

Resource assessment methods

Three methods of assessment are used to evaluate the status and condition of exploited stocks in the North Pacific. These are: bottom-trawl research surveys, hydroacoustic/midwater-trawl (HMWT) research surveys, and analysis of commercial fisheries statistics through the application of c.p.u.e. and age-structured assessment models.

In the early 1970s annual pollock assessments and harvest recommendations were developed by the International North Pacific Fisheries Commission (INPFC). At that time the only assessment data available, apart from some exploratory surveys by the US and the USSR, were the catch and effort data collected by the Japan Fisheries Agency. Scientists from Japan and the US utilized these data in c.p.u.e. analyses to determine the status of the pollock resource.

Several effort standardization procedures and efficiency adjustments were devised to determine the trend of pollock abundance (Low and Berger, 1984; Okada, 1984). However, indices of abundance calculated from complicated effort standardization procedures have become increasingly difficult to interpret owing to the large mix of gear types, foreign participants, and vessel classes.

Fishery research surveys have also been an important source of data for pollock assessment. US bottom-trawl surveys were initially designed to assess the abundance of commercial crab species, and low opening bottom-trawl gear was used (Bakkala *et al.*, 1987). Indices of abundance or biomass estimates were made by the area-swept method (Baranov, 1918; Alverson and Pereyra, 1969) assuming a trawl-catch efficiency that ranged from 0.5 to 1.0.

Combination HMWT research surveys began in the late 1970s. Soviet scientists reported using "echo-ranging techniques" to estimate pollock abundance in the Bering Sea in 1975 and 1976 (Fadeev and Moiseev, 1978). The US initiated surveys combining hydroacoustic estimates of the midwater biomass component with bottom-trawl assessment of the on-bottom biomass component. In the Bering Sea these surveys have been repeated triennially. In the Gulf of Alaska, HMWT surveys are conducted on the spawning stocks in Shelikof Strait. These surveys occurred in 1981 and have taken place annually since 1983 (Nelson and Nunnallee, 1986).

Hydroacoustic/midwater-trawl surveys

In the Gulf of Alaska, HMWT surveys are conducted in Shelikof Strait primarily in March and early April, the period of peak spawning. The main objective of the Shelikof Strait survey is to obtain age-specific estimates of the size of the midwater component of the pollock stock during the spawning period when the abundance of adult fish is at a maximum. All survey data are collected aboard the National Oceanic and Atmospheric Administration RV "Miller Freeman", a 66-m stern trawler. Acoustic data are collected using a 38-kHz echo sounder and a digital echo integrator. The transducer for the sounder is mounted in a deadweight body and towed behind the research vessel at a depth of 5 to 20 m at speeds of 8 to 10 knots. Echo integration and initial data processing and storage are carried out in real time using a digital integrator interfaced to a minicomputer. Before and after each survey the entire acoustic system is calibrated (Traynor and Nelson, 1985a).

Survey operations are conducted continuously over a 24-hour period. The research vessel follows predetermined transects which are laid out in a zig-zag pattern. The survey covers the area between the 91-m (50-fathom) bottom depth contour on either side of the strait. The distance between adjacent transects averages 5 nautical miles. Along each transect, echo-integrator density estimates are obtained at 5-minute intervals for up to 30 preselected and nonoverlapping depth strata in the depth zone between about 30 m and the bottom. The echo-integrator system automatically compensates for intrusion of the bottom into the preselected depth strata. This arrangement allows the detection and isolation of targets to within 3 m of the bottom. The area is surveyed several times, depending on the length of the research cruise.

In order to provide data on the biological composition and length distributions of the pollock stock and the occurrence of other midwater species, echo sign is sampled during each survey with a Diamond 1000 midwater trawl equipped with a cable netsounder system. The midwater trawl has a vertical opening of about 12–20 m. The trawl has stretch mesh sizes ranging from 81 cm to 8.9 cm (codend) and uses a 3.8-cm mesh codend liner. The distribution of trawl-haul stations is roughly proportional to relative abundance of pollock echo sign. The trawl is usually towed at 3 knots.

Pollock biomass estimates for each survey are determined by multiplying the average biomass density per unit surface area (kg/m^2) by the survey area. Surface density estimates are calculated by summing volumetric densities (kg/m^3) over depth. Echo-integrator data are scaled to estimates of absolute density for all but age-1 fish by assuming an average target strength of −31.3 dB/kg. The use of this value is based on target-strength measurements reported by Traynor and Williamson (1983). Density estimates are calculated for age-1 fish assuming an average target strength of −23.0 dB/kg. The separate target-strength parameter for age-1 fish is used because these animals are confined primarily to the midwater layer during the day. During the spawning period almost all of the fish biomass in Shelikof Strait is made up of pollock, so no corrections are made for the contribution of other species to the echo-integrator output. Methods to estimate the variance and confidence intervals for total biomass estimates are described in Williamson (1982).

Knowledge of the target-strength scaling coefficient is critical to determining the accuracy of the acoustic survey estimates of absolute abundance. Target-strength measurements (−31.3 dB/kg) used to scale all of the echo-integrator data from Shelikof Strait surveys are based on results obtained for nonspawning Bering Sea pollock at relatively shallow depths (50−85 m), and are an average value of day and night measurements for fish with a mean length of 47 cm (Traynor and Williamson, 1983). Ideally, target-strength measurements of Shelikof pollock should be obtained for different size groups and for different environmental (day vs. night) and physiological (prespawning, spawning, postspawning) conditions.

The HMWT survey in the Bering Sea is similar to that described for Shelikof Strait except that the survey is conducted during summer months when pollock are feeding and less concentrated. The HMWT survey covers the water column from 20 m to within 3 m of the bottom. The bottom-trawl survey samples from the sea floor to a height of 2.3 to 5.5 m depending on the type of trawl used. The HMWT and bottom-trawl surveys do not sample the same areas simultaneously, and the biomass estimate produced from the combined surveys may be biased if there were shifts in the midwater and demersal abundance between the surveys. At present the following average target-strength values are used for Bering Sea HMWT surveys: −23.6 dB/kg for 1−18-cm fish, −27.0 dB/kg for 18−29-cm fish, and −30.0 dB/kg for fish >29 cm.

Age-structured stock-assessment models

The US places observers on each foreign fishing vessel to monitor catches and collect biological information. Because of problems with abundance indices mentioned above, it was becoming increasingly difficult to maintain a time series of consistent catch and effort statistics, and assessment methods were directed towards use of age-structured models.

Age-structured stock-assessment models are very powerful tools that allow fisheries scientists to estimate absolute population abundance and vital population rates of exploited stocks. The main advantage of age-structured stock assessment models over more traditional approaches such as stock production (Schaefer, 1957) or dynamic pool (Beverton and Holt, 1957) models is that they can be applied without knowledge of effective effort, catchability, or gear selectivity. These stock-assessment techniques permit the population dynamics of an exploited stock to be reconstructed from catch data alone.

Input data to age-structured stock-assessment models typically consist of catch-at-age data (in numbers) and an estimated rate of natural mortality. Age-structured stock assessment models can be categorized as either sequential population models (Fry, 1949; Gulland, 1965; Murphy, 1965; Pope, 1972) or separable models (Doubleday, 1976; Pope and Shepherd, 1982; Fournier and Archibald, 1982; Deriso *et al.*, 1985). More specifics regarding details on these models are described by Megrey (1989a).

An advantage of sequential models is that results are very robust to violations of the underlying assumptions. However, cohort analysis and other sequential methods suffer from three major shortcomings. First, the results are very sensitive to the choice of the estimated fishing mortality on the oldest age of a cohort (terminal F) and the estimate of natural mortality. The accuracy of fishing mortality estimates increases if the ratio of fishing to total mortality is large and natural mortality is reasonably estimated (Pope, 1972; Ulltang, 1977; Jones, 1981). Given that population estimates are only as good as the estimate of terminal fishing mortality, it follows that abundance estimates in the terminal year (the most recent fishing year) are necessarily the least accurate. Unfortunately, in fisheries management the size of the population in the terminal year of the analysis and the immediately preceding years is precisely the period of greatest interest. Secondly, sequential stock assessment models do not provide variance estimates for the model parameters. Finally, sequential models provide a means to link age groups within any one cohort, but they do not link age groups across cohorts.

In order to improve estimates from sequential models, procedures have been developed to calibrate or "tune" sequential models (Pope and Shepherd, 1985). The process of tuning sequential age-structured models usually involves an ad hoc approach in which terminal F's are adjusted to catch/effort indices. Tuning the more structured separable model allows fishery-independent data to be incorporated simultaneously into the analysis along with the fishery data.

In the assessment of pollock stocks off Alaska several age-structured stock-assessment methods are employed. Traditional methods such as sequential population models (Gulland, 1965) and cohort analysis (Pope, 1972) have been used. Also a newer model (Deriso *et al.*, 1985) has been used in recent years. The catch/age analysis (CAGEAN) model of Deriso *et al.* (1985) is a very flexible generalization of the nonlinear log catch model employing the separability assumption first proposed by Doubleday (1976). Parameters estimated from the separable model include estimates of absolute population abundance for any age and year, annual effective effort values, and age-specific selectivity. CAGEAN offers three significant advantages over more traditional approaches. These are: 1) parameters for all cohorts are estimated simultaneously using a nonlinear least-square solution procedure, 2) it allows the incorporation of auxiliary information such as fishing effort or survey abundance estimates directly into the estimation procedure by augmenting the objective function with additional terms, and 3) the model provides variance estimates for all model parameters via a Monte Carlo bootstrap analysis.

Deriso *et al.* (1988) discuss extensions to the CAGEAN model that permit the incorporation of fishery-independent data into the analysis with the expectation that fishery-independent data would help calibrate or "tune" resulting population biomass estimates and stabilize the fit. If effective effort data are available but believed to be measured with error, then the relationship between fishing mortality and effort is not exact and can be described by:

$$\hat{f}(y) = q\,f(y)\,\exp[\varepsilon(y)], \qquad (1)$$

where $\hat{f}(y)$ is the predicted effective effort parameter resulting from analysis of catch-at-age data, $f(y)$ is the observed effective effort value estimated from fishery-independent data, q is the catchability coefficient, and $\varepsilon(y)$ is a random variable distributed $N(0,\sigma^2)$ with constant variance. Expressed in terms of the difference between observed and predicted effort (1) is written

$$\varepsilon(y) = \{\ln \hat{f}(y) - [\ln(q) + \ln f(y)]\}. \qquad (2)$$

Briefly, this approach is implemented as follows. Hydroacoustic population estimates for fully recruited ages (B_h) are used along with the catch estimates (B_c) to calculate an annual full-recruitment exploitation fraction ($\mu = B_c/B_h$). These calculated exploitation fractions, along with an estimate of natural mortality (M), are used to approximate the annual instantaneous full-recruitment fishing mortality rate (F) from the catch equation

$$\mu = F/(F+M)\,[1-\exp(-F-M). \qquad (3)$$

Solutions for F from Equation (3) are used as estimates of annual effective fully recruited fishing effort. This information is incorporated into the CAGEAN model by adding an auxiliary effort sums-of-squares term, Equation (2), to the objective function. Since the catchability coefficient is constrained to be equal to 1.0, these values are considered independent estimates of full-recruitment fishing mortality. In this approach annual effective-effort parameters estimated from the CAGEAN model can be different from values calculated from Equation (3). The degree of difference depends on how strongly the auxiliary effort sum-of-squares term is weighted (see equation 9 in Deriso *et al.*, 1985). Means and variances of population biomass estimates presented in this paper were calculated with a Monte Carlo bootstrap analysis using 50 bootstrap replications.

Stock assessment of the eastern North Pacific pollock resource

I. Eastern Bering Sea

Survey-based assessments

Early exploratory fishery surveys by the US and the USSR in the late 1950s to early 1960s estimated the standing stock of pollock in the eastern Bering Sea to be 1.5 million t (Alverson and Pereyra, 1969) and 400 to 500 thousand t (Fadeev and Moiseev, 1978). In both cases a standard low opening bottom-trawl was the gear employed and no midwater assessment was conducted.

In the mid-1970s Soviet scientists reported results from combined trawl/hydroacoustic surveys (Fadeev and Moiseev, 1978). Much of the Soviet survey methodology is unknown, but their estimates do suggest a rise in pollock abundance in the 1960s and illustrate the difference in biomass estimates with and without hydroacoustic data (Table 1).

US groundfish surveys conducted since the early 1970s are difficult to interpret since they did not cover a major portion of the pollock range until 1975. In earlier years no biomass estimate was made and only c.p.u.e. was reported (Table 1). Interpretation of data at the time was that the pollock stocks were declining from overfishing and that increases in c.p.u.e. in the mid-1970s were a result of improved recruitment. A biomass estimate was obtained from the first large-scale eastern Bering Sea survey in 1975. This estimate of 2.0 million t suggested that the fishery was large relative to the biomass and supported the argument that overfishing had occurred in the early 1970s.

In 1979 the Northwest and Alaska Fisheries Center (NWAFC) conducted its first HMWT survey of the eastern Bering Sea pollock resource (Traynor and Nelson, 1985b). The incorporation of hydroacoustic techniques into the Bering Sea groundfish survey provided an assessment of both the demersal and pelagic component of the pollock resource. The 1979 survey estimated the eastern Bering Sea pollock stock to be 10.5 million t, much higher than previously estimated. The 1979

Table 1. Pollock abundance estimates from surveys conducted in the eastern Bering Sea, 1959–1986.

Year	US Stern trawl		USSR Stern trawl	Japan Danish seine
	Million t	Kg/ha	Million t	Million t[a]
1959–1961	–	–	0.5	–
1964–1965	–	–	1.5	–
1970–1971	–	–	1.2	–
1971	–	59.4	–	–
1972	–	19.2	–	–
1973	–	29.2	–	–
1974	–	27.5	–	–
1975	2.0	–	4.7	–
1976	–	46.7	6.6	0.8
1977	–	37.5	–	0.8
1978	–	33.5	12.0[b]	0.8
1979	10.5[b]	–	–	0.6
1980	1.5	–	–	1.0
1981	2.5	–	–	0.7
1982	7.8[c]	–	–	0.6
1983	6.1	–	–	–
1984	4.6	–	–	–
1985	9.4[c]	–	–	–
1986	5.0	–	–	–

[a]Japanese relative biomass estimates.
[b]Shelf bottom-trawl and hydroacoustic estimates.
[c]Shelf bottom-trawl, hydroacoustic estimates, and Japanese continental-slope survey estimates.

HMWT survey showed that more than twice as much biomass occupied the pelagic zone with an estimate of 7.5 million t compared with an estimate of 3.0 million t from bottom-trawl surveys in the same year.

Fishery-based assessment

Several c.p.u.e. series were developed for eastern Bering Sea pollock, and each indicated different trends in the pollock resource (Table 2). Differences between US and Japanese interpretations of c.p.u.e. data were often a major issue at annual INPFC meetings. A common method was adopted in 1979 (Low and Ikada, 1980); however, in recent years this and the other c.p.u.e. trends appear to be in conflict with observed biomass trends. This is believed to be due to pollock shifting from pelagic to a more demersal distribution as they age and thus becoming more available to bottom trawls (Bakkala *et al.*, 1987).

Chang (1974) was the first to obtain abundance estimates of eastern Bering Sea pollock using cohort analysis (Pope, 1972). The results he obtained indicated that the unexploited population was between 3 and 4 million t and that pollock underwent a sharp decline as harvests approached 1 million t in the late 1960s (Table 3).

A later cohort analysis (Bakkala *et al.*, 1979) based on 1970–1978 catch data indicated a stable trend in the abundance of age 2–12 pollock. The biomass estimated for 1970 was 6.3 million t, roughly three times greater than that estimated by Chang for the same year. The estimated pollock biomass increased to 7.8 million t in 1972, declined to 5.4 in 1976, and then increased to an estimated 6.2 million t in 1978, the last year in the analysis (Table 3).

The results of the cohort analysis of Bakkala *et al.* (1979) suggested that the biomass of pollock may be much greater than previously estimated. Their results approached the level of pollock biomass estimated by multispecies ecosystem analyses which estimated total and exploitable pollock biomass to be 9.2 and 6.5 million t, respectively (Laevastu *et al.*, 1982).

As stated previously, a difficulty in cohort analysis is the estimation of the appropriate terminal fishing mortality. Bakkala *et al.* (1979) followed the approach of Chang (1974) and assumed large terminal F-values. Chang used $F = 0.5$, and Bakkala *et al.* (1979) used $F = 0.8$ for year classes 1958–1964, 0.6 for 1965–1968, 0.5 for 1969–1971, 0.4 for 1972–1973, and 0.3 for 1974–1976. However, the relationship of these analyses to the actual biomass of eastern Bering Sea pollock could not be determined because neither analysis attempted to reconcile terminal F's with the actual rate of fishing mortality (tuning).

The 1979 HMWT survey indicated that the biomass was much higher than previously estimated. Also changes in the fisheries brought about by increased regulatory control under exclusive US jurisdiction were invalidating trend indicators such as c.p.u.e. With the

Table 2. Catch per unit effort (c.p.u.e.) of eastern Bering Sea walleye pollock by Japanese pair-trawl vessels as computed by different methods, 1964–1985.

Year	Japan (t/h)	US (t/1000 hp/h)	INPFC (%)[a]
1964	3.1	9.5	–
1965	6.0	18.3	–
1966	7.4	23.6	–
1967	8.1	21.3	–
1968	11.2	23.8	130
1969	14.3	31.5	132
1970	12.1	18.7	145
1971	11.2	14.2	152
1972	12.2	14.2	184
1973	10.2	8.6	164
1974	10.1	9.9	115
1975	9.1	9.2	100
1976	9.2	10.0	98
1977	9.2	8.7	97
1978	9.7	9.2	100
1979	9.8	9.9	103
1980	9.3	9.7	92
1981	9.6	6.4	95
1982	10.9	6.0	100
1983	11.5	9.3	121
1984	14.6	9.2	173
1985	14.6	9.9	155

[a]Percentages calculated relative to 1975 (Low and Ikada, 1980).

Table 3. Biomass of eastern Bering Sea walleye pollock (million t) as estimated by various assessment methods, 1963–1985. CAGEAN biomass estimates are expressed as means and 95 % confidence intervals.

Year	Chang (1974)[a,b]		Bakkala *et al.* (1979)[c]	Cohort analysis[d]	CAGEAN[e]
1964	3.8	3.6	–	1.9	–
1965	4.0	3.7	–	2.7	–
1966	3.9	3.5	–	3.7	–
1967	3.5	3.1	–	6.0	–
1968	3.8	2.7	–	8.1	–
1969	2.3	2.4	–	9.9	–
1970	2.4	2.3	6.3	11.5	–
1971	–	–	7.5	12.4	10.2±7.2
1972	–	–	7.8	11.8	9.6±6.6
1973	–	–	7.8	11.0	8.8±5.6
1974	–	–	6.4	9.4	7.2±5.0
1975	–	–	5.4	8.2	6.6±4.0
1976	–	–	5.2	8.5	7.1±3.6
1977	–	–	5.3	8.3	4.9±1.1
1978	–	–	5.8	7.8	5.1±1.2
1979	–	–	–	7.8	6.1±1.2
1980	–	–	–	9.1	8.9±2.0
1981	–	–	–	9.9	11.3±2.9
1982	–	–	–	10.5	12.6±3.4
1983	–	–	–	9.9	12.5±3.4
1984	–	–	–	9.6	12.2±3.7
1985	–	–	–	8.4	11.6±8.3
1986	–	–	–	6.7	–

[a]Column 1. Cohort analysis (Pope, 1972); M = 0.65.
[b]Column 2. Cohort analysis (Pope, 1972); M variable.
[c]Cohort analysis (Pope, 1972); M = 0.4.
[d]Cohort analysis (Pope, 1972) tuned to HMWT survey estimates for years 1979, 1982, and 1985; M variable.
[e]CAGEAN model (Deriso *et al.*, 1985) tuned with HMWT survey estimates for years 1979, 1982, and 1985; M = 0.3. Means and confidence intervals based on 50 bootstrap replications.

HMWT surveys occurring only triennially and the realization that the bottom-trawl surveys might indicate only gross trends in the stock, an additional monitoring method was needed to assess the stock. Cohort analysis was selected as an alternative assessment method. One major modification from previous cohort analyses of eastern Bering Sea pollock was the use of survey data to tune terminal fishing mortality.

The cohort analysis and CAGEAN models were "tuned" using auxiliary information based on data from NWAFC HMWT and bottom-trawl surveys of eastern Bering Sea pollock. The combined results of these surveys provide an assessment of the pelagic and demersal portions of the stock.

In order to tune the models used to assess Bering Sea pollock five assumptions regarding the fishery-independent information are necessary: 1) the relative age composition of pollock obtained from combined HMWT and bottom-trawl surveys are true estimates of the age composition of the population, 2) interannual changes in survey abundance estimates are proportional to abundance changes in the population, 3) the average target-strength coefficient used to scale echo-integrator data to estimates of absolute density is correct, 4) the catchability of pollock is constant from year to year, and 5) the whole stock is present in the survey area.

The cohort-analysis model was tuned using the following procedure. Based on the first assumption, terminal F's were adjusted until the proportional age composition from the model was identical to the proportional age composition observed in the survey conducted in that year. The vector of F-values in the terminal year was then scaled up or down under the second assumption so that the population trend from the cohort analysis approximated the abundance trend observed in surveys. For trend adjustment the ratios of numbers of age 3 and older pollock estimated in the 1979, 1982, and 1985 HMWT surveys were used to adjust the cohort analysis trend. The F for the terminal age, age 9, in years prior to the terminal year, were computed as the average of ages 7 and 8, assuming that catchability was similar for these ages.

The CAGEAN model was tuned using survey data from 1979, 1982, and 1985, the years in which HMWT and bottom-trawl surveys were carried out. The survey data were used to estimate F for age 4 (the fully recruited age) from the exploitation fraction (catch in numbers/survey estimate). In the application of the CAGEAN model to Bering Sea pollock, the effort sum of squares weighting factor, lambda (see equation 9 in Deriso *et al.*, 1985), was set to 1.0, which gives equal weight to the survey and fisheries data.

Initial estimates of the parameters in the CAGEAN model were obtained from cohort-analysis results. In the CAGEAN model relative selectivity was set equal to 1.0 for age 4 and computed for all other ages. Previous analysis has shown that F peaks at age 4 and then decreases in older ages (Wespestad and Terry, 1984).

A critical factor in the accuracy of results from age-structured models is the instantaneous natural-mortality rate (M). Estimates from natural fish stocks can be highly variable even for the same species (Vetter, 1988). In a recent review, Lynde (1984) suggests that for the eastern Bering Sea, estimates of natural mortality for pollock are on the order of 0.3–0.4, which is much lower than the 0.65 estimated by Chang (1974) but similar to the estimate of 0.4 used by Bakkala *et al.* (1979). Wespestad and Terry (1984) estimated $M = 0.45$ for age 2 and $M = 0.30$ for ages 3–9. These values have been used since 1982 in cohort analysis and stock forecasts and seem to give credible approximates of the true rate of natural mortality for pollock. In the CAGEAN model a constant value of 0.30 was used.

Biomass estimates from the two models are presented in Table 3 along with earlier estimates of abundance. The tuned cohort analysis shows a major increase in the late 1960s, with a peak in the early 1970s. Results indicate that abundance was low around the time the fishery began, with an estimated biomass in 1964 of about 2 million t but then increasing 4- to 6-fold in the following 8 to 9 years. The cohort analysis estimated peak abundance in 1971 at 12.4 million t, but the CAGEAN model estimates for 1971 were lower, 10.2 ± 7.2 million t depending on the time series. Following the peak level of abundance in 1971 the population declined to a low of 5.1 ± 1.2 million t in the late 1970s, again depending on the time series and model. From 1979 to 1982, biomass increased, but it has been declining in recent years following low recruitment in the early 1980s. The cohort analysis and CAGEAN model tuned to the HMWT data indicate much higher levels of abundance than untuned models.

II. Gulf of Alaska

Survey-based assessments

The pollock stock in the Gulf of Alaska is much smaller than in the eastern Bering Sea and until recently has been exploited less intensively. As in the Bering Sea, the first assessment of pollock abundance was in exploratory fishery surveys. Soviet surveys (Fadeev and Moiseev, 1978) estimated the abundance of pollock in the Gulf of Alaska to be 110 thousand t in 1961–1963. Alverson and Pereyra (1969) produced estimates of a standing stock of 130 thousand t of pollock in 1964–1965.

A large-scale bottom-trawl survey of the Gulf of Alaska was conducted in 1973–1974 and estimated exploitable pollock biomass at 0.95–1.9 million t (Alton, 1981). These survey results indicate that pollock in the Gulf of Alaska experienced a large increase in abundance similar to that observed in the Bering Sea. Alton *et al.* (1987) discuss the increase in Gulf of Alaska pollock and possible causes of abundance increases.

Table 4. Estimates of population biomass (ages 3–10) of western Gulf of Alaska walleye pollock (million t) as estimated by various research surveys and stock assessments. CAGEAN and hydroacoustic biomass estimates are expressed as means and 95 % confidence intervals.

Year	Alton *et al.* (1987)	Megrey (1988)[a]	Nelson and Nunnallee (1986)[b]
1963–1975	0.95–1.90	–	No survey
1976	–	0.98 ± 0.53	No survey
1977	–	0.84 ± 0.49	No survey
1978	–	1.14 ± 0.69	No survey
1979	–	1.69 ± 0.84	No survey
1980	–	2.00 ± 1.03	No survey
1981	–	2.43 ± 1.17	3.41 ± 0.91
1982	–	2.40 ± 1.06	No survey
1983	–	1.82 ± 0.81	2.37 ± 0.74
1984	–	1.27 ± 0.64	1.84 ± 0.63
1985	–	0.70 ± 0.46	0.68 ± 0.21
1986	–	0.43 ± 0.42	0.49 ± 0.25

[a]CAGEAN model (Deriso *et al.*, 1985) tuned with 1981, 1983–1985 HMWT data; $M = 0.4$. Means and confidence intervals based on 50 bootstrap replications.
[b]HMWT biomass estimates of the Shelikof Strait spawning aggregations. Surveys conducted at time of peak spawning (March–April).

Large-scale trawl surveys are not conducted on an annual basis in the Gulf of Alaska. A narrow shelf and rugged bottom topography limit quantitative assessment. The mode here has been to index general abundance and estimate absolute standing stock on selected fishing grounds. In 1980, while surveying to the northwest of Kodiak Island, large midwater spawning concentrations of pollock were discovered in Shelikof Strait (see Fig. 1). Since 1980, HMWT surveys have been conducted in the Shelikof Strait region every year except 1982.

Surveys have taken place in Shelikof Strait at the same time as surveys in the western and central Gulf of Alaska. Comparisons have shown that at the time of spawning (March through April) most of the mature pollock are found in Shelikof Strait and only minor concentrations occur in other areas.

The HMWT estimates of abundance for ages 3–10 have shown a downward trend since 1981 (Table 4), declining from 3.41 million t in 1981 to 0.49 million t in 1986. The primary reason for the decline is the passing of five strong year classes (1975–1979) followed by below-average recruitment in 1980, 1981, and 1982. This decline in population biomass is believed to be ending. Observations from HMWT surveys of pre-recruit abundance levels from the 1984 and 1985 cohorts indicate that these year classes may be above average in strength. Individuals from the 1984 and 1985 year classes recruited to the exploitable population in 1987 and 1988.

Fishery-based assessment

For many years the use of fishery data to assess Gulf of Alaska pollock was limited to analysis of Japanese c.p.u.e. data in conjunction with length-frequency analysis. Megrey (1989b) applied a fishing-power model to a reconstructed set of Japanese catch and effort data for 1973–1983 using methodology described by Kimura (1981). The log-linear fishing-power model attempted to relate variability in c.p.u.e. to factors affecting underlying population density (year, quarter, and INPFC statistical area) and factors affecting vessel efficiency (trawler type (surimi trawler vs. freezer trawler) and vessel size (gross tonnes)). Effort was standardized to a particular tonnage class of surimi trawler operating in the Chirikof INPFC area during the third quarter of the year. The results of the adjusted c.p.u.e. estimates indicate that throughout the mid-1970s pollock abundance rose sharply, peaked in 1976, then gradually declined (Fig. 3). Kimura's Analysis of Variance (ANOVA) index also suggests an increase which peaked in 1978, declined in 1979 and 1980, increased in 1981, and has been decreasing since 1981. Also presented in Figure 3 are abundance indices calculated by a procedure described in Yamaguchi *et al.* (1984). There is little agreement between the trends in relative abundance derived from the various methods, which suggests that, because of estimation problems, c.p.u.e. data are basically inadequate for monitoring changes in pollock abundance. Nevertheless, the ANOVA indices may prove useful since the 1980–1983 trend is similar to that for trends in biomass estimated by the age-structured analysis (Fig. 3).

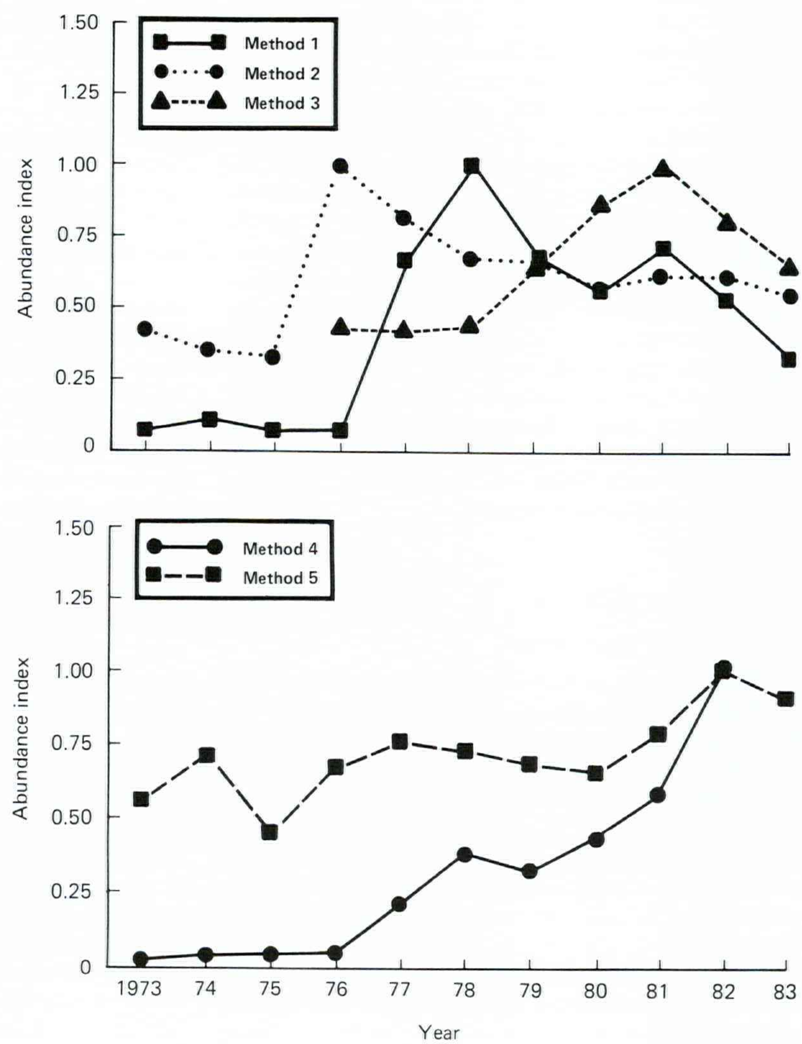

Figure 3. Comparison of relative abundance estimates calculated by different procedures. Method 1: ANOVA population indices (Kimura, 1981); Method 2: Adjusted c.p.u.e. estimates from a fishing power analysis with effort standardized to a 2505–3504 gross tonne surimi trawler fishing in the INPFC Chirikof area in the third quarter; Method 3: Annual trend in relative population biomass as determined from application of the CAGEAN age-structured stock-assessment method; Model 4: Japanese adjusted c.p.u.e. estimates with effort standardized to a 2505–3504 gross tonne freezer trawler in 1973; Method 5: Japanese adjusted c.p.u.e. estimates with effort standardized to a 2505–3504 gross tonne surimi trawler in 1978. See Yamaguchi *et al.* (1984) for details regarding the Japanese effort standardization procedure (Methods 4 and 5).

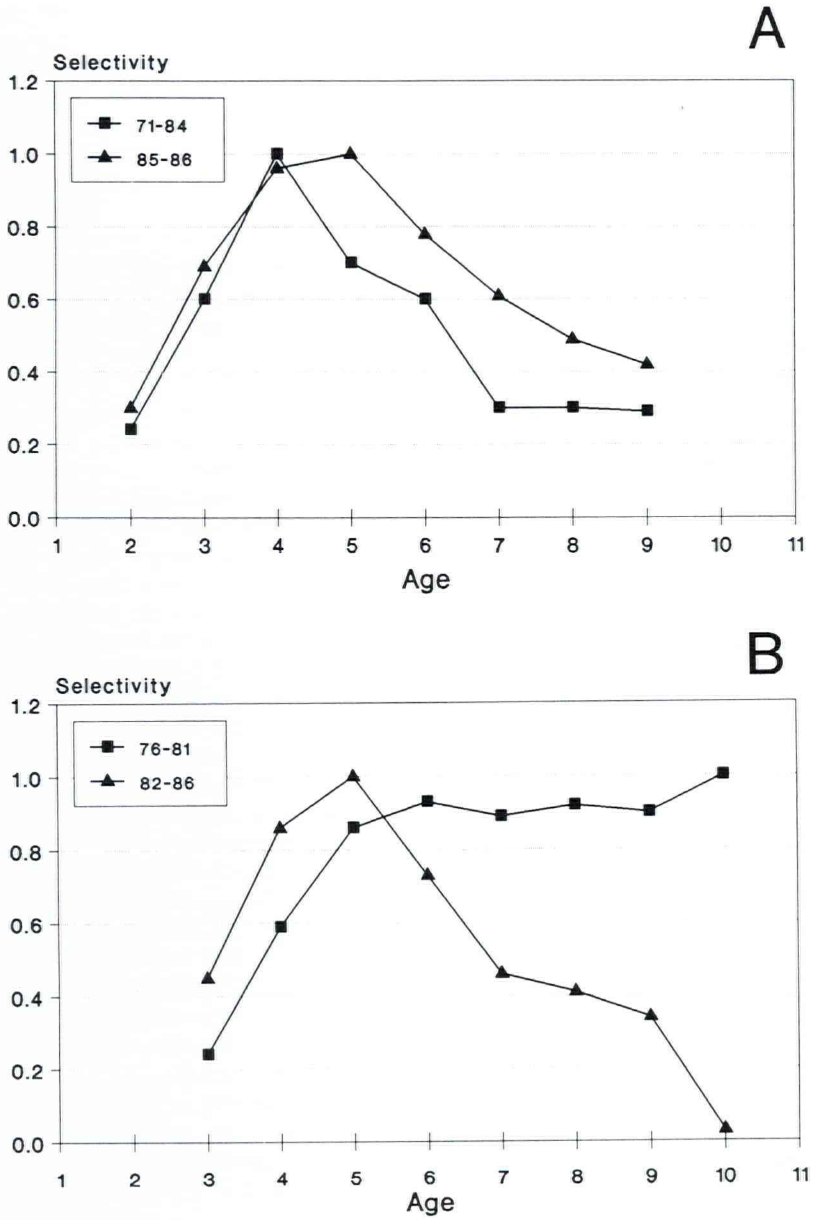

Figure 4. Trends in age-specific selectivity for eastern Bering Sea (panel A) and western Gulf of Alaska (panel B) pollock as estimated with the CAGEAN model.

Soon after the location of the Shelikof spawning stock was discovered, a fishery developed on the prespawning pollock. This fishery has been primarily a US joint-venture fishery with fishermen delivering to foreign processor ships. In joint-venture fisheries US fishery observers are placed aboard the floating processor ships in order to quantify the catch and collect biological data. In the case of the Shelikof Strait fishery, 100 % of the fleet is sampled and excellent statistics are obtained.

The fishery and biological data collected in Shelikof Strait, together with similar data collected by observers on foreign vessels fishing in the Gulf of Alaska since 1976, provide sufficient data to perform an age-structured analysis. The annual HMWT surveys in Shelikof Strait provide an opportunity for validation and calibration of results from age-structured stock assessment techniques.

Fitting the catch-at-age data to the CAGEAN model was somewhat difficult because the assumption that selectivities were constant over the 1976–1986 time period was not valid (Megrey 1989b). Over the 1976–1981 period, a time when foreign trawlers using bottom trawls were the primary harvesting fleet, the estimated selectivity trend with age curve was asymptotically shaped. However, over the 1982–1986 period, younger pollock became more vulnerable to the gear and older ages less vulnerable as the primary harvesting fleet shifted from foreign trawlers to joint-venture trawlers using midwater trawls. The resulting age-specific selectivity trend for the 1982–1986 period became more dome-shaped reflecting the interaction between fish behavior (young pollock are pelagic and become more demersal as they get older) and fishing gear.

To accommodate this change the CAGEAN model was configured as follows: selectivities for ages 3 to 6 were estimated by the model and assumed to be constant over the 1976–1981 period, and the selectivity for ages 7–10 was assumed to be 1.0 (i.e., fully recruited). For the 1982–1986 period, the selectivities for ages 3–6 were assumed equal to the values estimated from the 1976–1981 period and selectivities for ages 7–10 were estimated from the 1982–1985 data. A constant natural mortality of 0.4 was used for all ages and years. Figure 4 (panel B) presents a comparison of the selectivity curves from the two periods.

The CAGEAN model was tuned using the hydroacoustic biomass estimates as follows. Hydroacoustic population biomass estimates and catch biomass estimates for ages 3 to 10 were used to calculate an annual full-recruitment exploitation fraction using Equation (3) for years 1981, 1983, 1984, 1985, and 1986. Recall that hydroacoustic data was not available in 1982. The weighting factor for the effort auxiliary sum-of-squares term (see equation 9 in Deriso *et al.*, 1985) was set to 0.5. This number determines the amount of influence the auxiliary data has on the simultaneous parameter estimation procedure. Normally the auxiliary data should be restricted to only the age group(s) fully recruited to the fishery, since the goal is to provide an alternative estimate of full-recruitment fishing mortality. However, to remove uncertainty regarding age determination, the Gulf of Alaska analysis used total population biomass estimates from the HMWT surveys to calculate the auxiliary fishing mortality values from Equation (3). Because these calculations are based on biomass estimates that include age classes other than the fully recruited age class, the weighting factor for the effort auxiliary sum-of-squares term was set at 0.5. Adoption of this approach allows incorporation of the hydroacoustic biomass estimates into catch-at-age analysis but weights the auxiliary data (fishing mortality values estimated from the hydroacoustic biomass) half as much as the primary data (catch-at-age). The specific choice of a weighting value of 0.5 was based on results of an analysis of the sensitivity of the model output to the value of the weighting factor. One final caveat needs to be mentioned. Technically Equation (3) should include a growth-rate term (G) because calculations are done in units of biomass. However, in practice growth is considered negligible since the time interval between the spring fishery and the Shelikof survey is short.

Results from the analysis indicate that the 1980–1982 year classes were all below average in abundance, with the 1982 year class being the weakest on record. These three successive poor year classes have contributed to a declining population biomass.

Estimates of total population biomass from the catch-at-age analysis agree well with hydroacoustic biomass estimates (Table 4). The rates of decline from the two estimates over the 1983–1986 period appear similar, and biomass estimates from catch-at-age analysis are consistently lower than the hydroacoustic estimates. The estimates all but converged in 1986. Results from the tuned model indicated that auxiliary information did not significantly improve the fit of the model to the data. Possible reasons for this are discussed below.

Discussion

For most of the history of the fishery, it was assumed that data from bottom-trawl fisheries and research surveys were accurately assessing the trend if not the abundance. Individuals involved in assessment of pollock recognized that there was an off-bottom component, but its magnitude was not considered to be great. The value of hydroacoustic assessment in the estimation of pollock standing stocks is illustrated in Table 1, where it can be seen that bottom-trawl surveys estimate only a small fraction of the total estimated biomass.

The HMWT data provided a means of calibrating age-structured stock-assessment models. The results of these models showed that in earlier periods the abundance of pollock was at very high levels owing to a series of strong year classes in the mid-1960s and these year classes had greatly increased the abundance of pollock through the late 1960s and early 1970s (Bakkala *et al.*, 1987). In retrospect, the assessments based on c.p.u.e. and mean length which concluded that overfishing occurred in the early 1970s now appear to indicate a decline in the strong year classes and a shift in the fishery to less abundant younger year classes.

In recent years, we have witnessed an unusual event in the Bering Sea pollock resource which would be difficult to explain without hydroacoustic data. The 1978 year class has been the most abundant of any year class in the history of the fishery. As this year class recruited to the fishery it became the dominant portion of the catch (Fig. 5). The strong 1978 year class was followed by several weak year classes, and therefore it was dominant in the catch for longer than would normally be expected. The survey and fishery c.p.u.e. increased as the 1978 year class aged, which, in the absence of additional data, would suggest that abundance was increasing. Age-structured stock-assessment models, on the other hand, showed that the stock was actually decreasing. The hydroacoustic surveys verified the results of age-structured models and provided data for interpreting the c.p.u.e. trend. Examination of data from the three combined hydroacoustic and bottom-trawl surveys clearly shows the dominance of the 1978 year class in midwater and a diminishing of the mid-

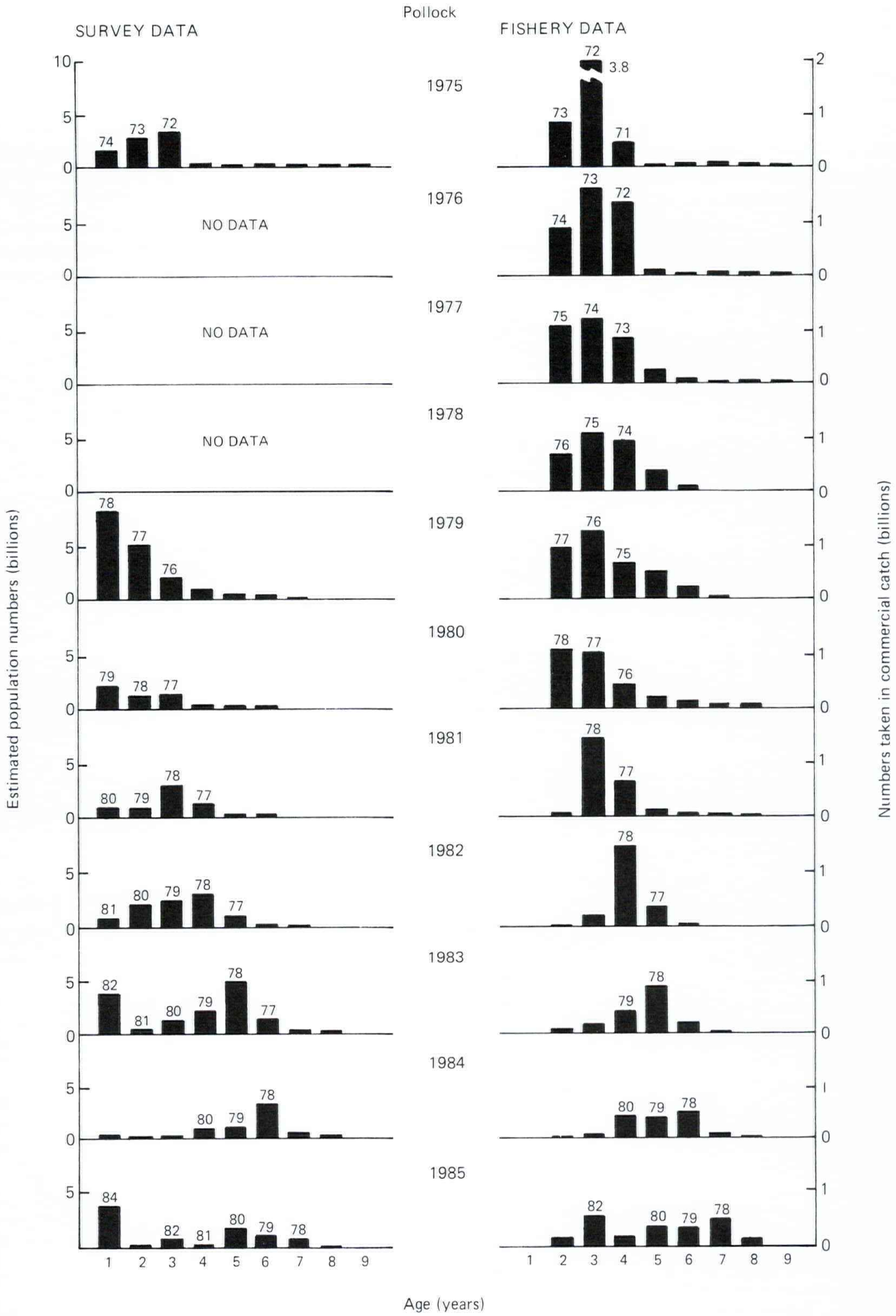

Figure 5. Age composition of pollock in the eastern Bering Sea as shown by data from NWAFC research-vessel surveys and by data collected in the commercial fishery by US observers. Numbers above bars indicate the principal year classes.

water component in later years. Without the hydroacoustic data to confirm that the increase in c.p.u.e. was a result of a shift of the pollock to demersal distribution there would be no way to evaluate the differences between the survey and fisheries data.

In the Shelikof Strait fishery there has been excellent agreement between abundance estimates derived from age-structured models and hydroacoustic surveys. Even before tuning was attempted (i.e., when the hydroacoustic biomass estimates were totally independent of biomass estimates derived from application of the assessment model) results were consistent in trend but not in absolute abundance. Inclusion of hydroacoustic data in the analysis has not markedly improved the fit of the model to the data. The good fit of the CAGEAN model using just catch-at-age data in this fishery is believed to be due to the extensive coverage of the fishing fleet by fisheries observers and the collection of excellent fisheries statistics.

Recent results from age-structured stock-assessment models indicate that the changes in the pollock fisheries in the eastern Bering Sea and Gulf of Alaska have altered age-specific selectivities (Fig. 4). The reason why selectivity increases with age and then declines is unknown, but may involve an interaction between pollock behavior and fishing practices. Since pollock be-

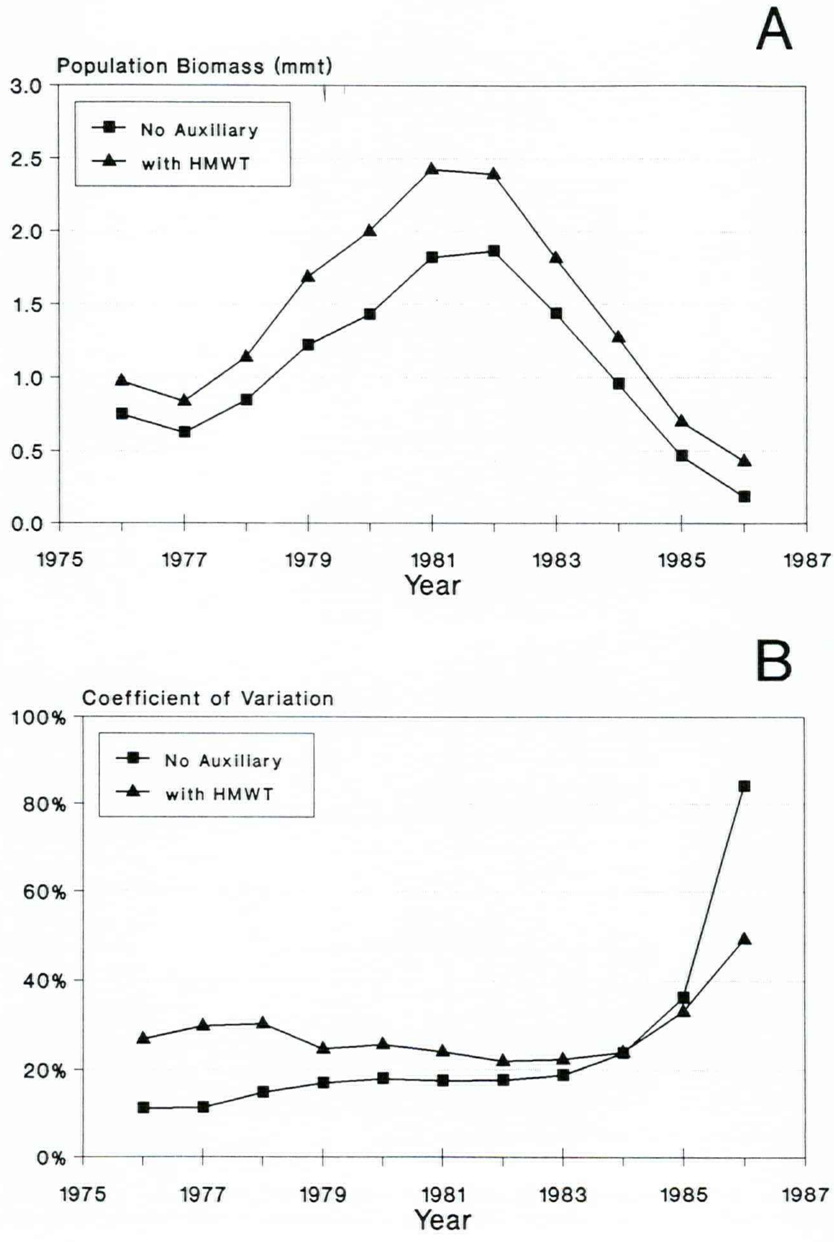

Figure 6. Comparison of Gulf of Alaska bootstrap population biomass estimates (panel A) and their coefficient of variation (panel B) with the addition of hydroacoustic/midwater-trawl fishery-independent data to the CAGEAN stock-assessment model. Biomass means (million metric tonnes) and variances are based on fifty bootstrap replications.

come more demersal as they age and tend to school less strongly the reduction in selectivity may be a result of fishing vessels' locating the more abundant younger fish which aggregate in large schools. In the Gulf of Alaska, the change from an asymptotically shaped selectivity curve to a dome-shaped curve can be partially explained by a change from bottom-trawl gear when fleets of foreign stern trawlers were the primary harvesters to use of midwater pelagic trawls now that the fisheries are dominated by domestic catcher vessels and joint-venture operations.

Changes in selectivity have introduced substantial variation into fishing mortality estimates and subsequently into population biomass estimates. When an assessment model is run using only catch-at-age data, the variance is the greatest in the most recent fishing year. Unfortunately, the most recent fishing year is exactly the time period of interest to fisheries managers. The fact that catch-at-age data alone do not contain enough information to estimate fishing mortality in the most recent fishing year with acceptable precision, even from separable models, has been recognized for some time (Doubleday, 1976; Pope, 1977; Pope and Shepherd, 1982; Shepherd and Nicholson, 1986). One compelling reason to include HMWT data (or any fishery-independent data) in the stock-assessment analysis is that variances in the population biomass estimates are reduced in the most recent fishing year. Figure 6 illustrates this feature from the Gulf of Alaska analysis. Similar results have been obtained from the Bering Sea data.

We think currently we have good estimates of the abundance of pollock in both the Bering Sea and Gulf of Alaska through the use of age-structured stock-assessment analysis and HMWT estimates. However, the change in the fisheries is introducing increasing variation into the estimates. Also, with the change from foreign to domestic fisheries we may lose much of the catch-at-age and other fishery data, since regulations do not require observers on domestic fishing vessels. If fisheries data cannot be collected in the future, hydroacoustic and bottom-trawl surveys will be our only reliable means of estimating pollock abundance.

As the fisheries continue their transition to complete domestication, HMWT surveys will play an increasingly important role in the assessment of Bering Sea and Gulf of Alaska pollock stocks. This will take place through tuning age-structured stock-assessment models and also through early looks at abundance of pre-recruits. However, in the Bering Sea, the surveys should be increased beyond the current triennial schedule in order to improve examination of interannual changes in population parameters.

One aspect of the procedures now utilized in assessing Bering Sea pollock that should be critically examined is the combining of estimates from HMWT and bottom-trawl surveys. At present, it is assumed that the two surveys estimate independent components of the stock; however, it is conceivable that in years when the bulk of the population is composed of adults, the surveys could be deriving estimates from the same group of fish. If this occurs, it would lead to gross overestimates of stock abundance.

Our experience has shown that age-structured models can provide satisfactory abundance estimates as long as adequate samples are collected from the fishery and fishing is a major cause of mortality in the exploited population. However, ancillary information is required to develop accurate estimates, especially in the most recent fishing year. For Alaska pollock, hydroacoustic surveys provide an independent means of calibrating age-structured model estimates. In addition to providing abundance estimates each year, HMWT surveys provide valuable information on 1) the location and movement patterns of young fish, 2) early abundance estimates of pre-recruits which are extremely useful in predictive management models, and 3) factors that affect the availability and catch of pollock.

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