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SPAWNING BIOMASS OF THE NORTHERN ANCHOVY IN 1993

By

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SUMMARY

The estimated spawning biomass for the central subpopulation of northern anchovy on February 15, 1993 was 282,000 mt (CV 31%). The model used for the 1993 anchovy spawning biomass estimate was similar to that used previously except that all available survey data for the 1963 to 1992 fishing seasons were included.

PURPOSE

Management of the central subpopulation of northern anchovy (Engraulis mordax) by the Pacific Fishery Management Council involves an optimum yield formula that depends on the estimated spawning biomass in each year (Pacific Fishery Management Council 1991). The purpose of this report is to describe the spawning biomass estimate for anchovy used to determine optimum yield for the 1993 fishing season.

DATA

Fishing seasons (rather than calendar years) were used to aggregate most of our data. Fishing seasons for northern anchovy begin on July 1, end on June 30 and are identified by the first calendar year. The 1992 season, for example, began on July 1, 1992 and ended on June 31, 1993. Peak spawning for northern anchovy is assumed to occur on February 15 for management purposes (Pacific Fishery Management Council 1991) and we assumed that indices of abundance for anchovy (Table 1) measured abundance during the peak spawning season.

Indices of abundance used to estimate anchovy biomass included: 1) spawning biomass estimated by the egg production method (EPM, Lasker 1985), 2) a historical egg production index (HEP, Lo 1985), 3) the new egg production index (EPI), 4) relative biomass of schooled fish (SPOTTER) estimated from fish spotter data (Lo et al. 1992), and 5) relative biomass of schooled fish (SONAR) estimated from California Department of Fish and Game sonar data (Mais 1974; Methot 1989).

Age composition data for anchovy from fisheries in Mexico and the U.S. were available for most seasons prior to 1991 but were not used in the model because they are difficult to interpret (Jacobson and Lo 1992; 1991) and because none were available for recent seasons. As described below, we used a constraint based on a prior estimate of log scale recruitment variability in lieu of age composition data

Fishery Landings

Total landings of northern anchovy (Table 1 and Figure 1) during the 1963 to 1992 seasons were used. Total landings during the 1992 season (2,943 mt) were less than during the 1991 season (8,250 mt) due to declines in all segments of the fishery (Table 2, data for January to June of the 1992 season are preliminary).

Spawning Biomass by the Egg Production Method (EPM)

Estimates of spawning biomass for northern anchovy obtained by the egg production method (EPM, Lasker 1985) for the 1979 to 1984 seasons are an important part of our model for northern anchovy (Table 1 and Figure 2). EPM spawning biomass estimates are important because they measure spawning biomass in absolute, rather than relative units, and are thought to be relatively precise with coefficients of variation (CV) < 27%. Although only six EPM observations were available, they helped scale other indices of relative abundance for anchovy in the model to units of absolute biomass.

Biomass Index from Sonar Data

The SONAR index (Table 1 and Figure 2) of relative schooling biomass for northern anchovy covers the 1969 to 1985 calendar years (Methot 1989) and was used in our model to estimate spawning biomass during the 1968 to 1974 and 1976 to 1984 seasons. The sonar index for season 1972 for example, was based on data collected during the 1973 calendar year and used in our model to predict anchovy biomass on February 15, 1973. SONAR data did not include estimates of precision which were used in our model to estimate parameters. We inverted equation [12] (see below) and used the standard deviation (ϵ=0.439) of residuals for log scale observed and predicted SONAR values from a previous study and different model (Jacobson and Lo 1991) to obtain a crude estimate (0.461) of the arithmetic scale coefficient of variation for sonar index values.

Biomass Index from Fish Spotter Data

"Fish spotters" are pilots in small aircraft employed by fishers to locate, identify and estimate the size of pelagic fish schools. Since 1963, fish spotters working off southern California and Mexico have recorded the location, time of sighting, species and size of all anchovy schools sighted (Squire

1983). Lo et al. (1992) used delta-lognormal linear models to obtain an index (SPOTTER) of relative schooling biomass for northern anchovy from fish spotter data and validated the index by comparing it to independent biomass estimates. The SPOTTER index used in this study (Table 1 and Figure 2) was an updated version of the one described in Lo et al. (1992) that covered the 1963 to 1991 seasons. The only differences were that April to March, rather than January to December, annual periods were used to aggregate data and data for years after 1990 were included. The SPOTTER index included in our model used data for April 1988 to March 1989, for example, to estimate relative schooling biomass of anchovy on February 15 of calendar year 1989 and fishing season 1988. April to March annual periods were used instead of calendar years or fishing seasons in order to facilitate annual assessment and management activities (Jacobson and Lo 1992).

The SPOTTER index value for the 1963 season was anomalously low (Figure 2). Following Lo et al. (1992), we excluded the 1963 value from our analysis because the data collection program was new in 1963 and the information may not have been reliable. Spotter index values for the 1978 to 1980 and 1988 seasons were anomalously high. The high values for 1978 to 1980 were also apparent in the results of Lo et al. (1992). The high value for 1988 occurred when we aggregated the spotter data by April to March annual periods and was not evident in Lo et al. (1992). We examined the data carefully and found that problems with the index for 1988 were partially due to observations by pilot number 26 who participated in the data collection program for a short time. The parameter used to calibrate sightings by pilot 26 in the lognormal linear model for anchovy sighting density during positive flights (Lo et al. 1992) changed over time. At the outset, pilot 26 reported extremely high anchovy sightings but, after discussions SWFSC staff, reduced sightings to more typical levels. The change in sightings data from pilot 26 could not be accounted for in the lognormal linear model and caused problems with the fish spotter index value for 1988. No reason for the high index values during 1978 to 1980 was found. In order to avoid an outlier problem with the fish spotter index value for 1988, we fit the assessment model to fish spotter index values calculated without observation Pilot 26. Omitting Pilot 26 from the data used to calculate the fish spotter index resulted in a smoother time series and an 11% increase in the spawning biomass estimate for 1992.

Fish spotter data indicate a 65% decline in relative abundance of anchovy during the 1991 to 1992 seasons (Figure 2). Precision of the fish spotter index values for 1991 (463 tons, CV 36%) and 1992 (162 tons, CV 45%) was low, however, so the apparent decline was not statistically significant.

Historical Egg Production Index (HEP)

The Historical Egg Production index (HEP, Lo 1985), measures anchovy egg production during the peak spawning period of most seasons during 1963 to 1984. The HEP index is based on data collected from a relatively large grid of CalCOFI (California Cooperative Oceanic Fishery Investigation) sampling stations occupied prior to the 1986 calendar year (Hewitt 1988).

New Egg Production Index (EPI)

The new Egg Production Index (EPI) (Jacobson and Lo 1992) measures peak egg production by northern anchovy during the 1979 to 1992 seasons over a smaller area than that used for the HEP index (Hewitt 1988). The smaller sampling grid was routinely used for CalCOFI surveys beginning in the 1985 calendar year. The EPI makes use of all available data and is more precise than egg production indices for anchovy used previously for seasons after 1984 when the HEP index is unavailable. Both the HEP and EPI indices of egg production for northern anchovy during the 1979 to 1984 seasons were used so that the model could effectively calibrate the HEP and EPI against each other and against EPM spawning biomass estimates.

EPI index data indicate a 134% increase in egg production and abundance of anchovy during the 1991 to 1992 seasons (Figure 2). Precision of the EPI index values for 1991 (0.86 eggs/0.05 m^2/day, CV 32%) and 1992 (2.01 eggs/0.05 m^2/day, CV 36%) was low, however, so the apparent increase was not statistically significant. The EPI index for 1992 (CV 36%) was more precise than the fish spotter index (CV 45%) for the same season.

Scripps Pier Sea Surface Temperature Data

Following Methot (1989), mean sea surface temperatures at Scripps Pier in San Diego, California during January to February of each spawning season (Table 1) was used to determine the fraction of one-year-old anchovy that were sexually mature and the fraction actively spawning on February 15. The distinction between fraction sexually mature and fraction active is important because the EPM measures biomass of mature fish while egg production indices measure, in effect, the biomass of actively spawning fish.

Sea surface temperatures at Scripps Pier during January and February of 1993 were 15.4° C. Almost all (99%) of one year old anchovy are sexually mature at 15.4° C.

MODEL

The assessment model for northern anchovy was similar to that used last year for the 1992 spawning biomass estimate (Jacobson and Lo 1992). The model was based on a forward simulation approach (Hilborn and Walters 1992) like that used in the stock synthesis model (Methot 1989; Methot 1990) and CAGEAN (Deriso et al. 1985). The model simulated trends in abundance of anchovy during the 1963 to 1991 seasons given a set of parameter estimates, initial conditions and data for catches and ocean temperatures. Parameters were estimated by comparing observed and simulated indices by maximum likelihood. Assessment models based on backward solutions to the catch equation, such as virtual population analysis, cohort analysis and ADAPT (Hilborn and Walters 1992; Gavaris 1988) were not suitable because anchovy age composition data were not complete for the US fishery in recent years. The forward simulation approach was better because comprehensive catch-at-age data are not necessary and the simulated population can be compared to any data that happen to be available. Catch data for anchovy and temperature data were assumed to be without error while abundance indices were assumed to include measurement error.

Population dynamics

Fishing seasons were used in our model as annual time steps and anchovies ages 0 to 4+ were included (age group 4+ includes anchovy age four and older). Ages were incremented in the model on July 1 at the beginning of each season when recruitment of age zero anchovy was assumed to occur. In reality, anchovy recruitment occurs throughout the year (MacCall and Prager 1986) so estimates of recruitment on July 1 from our model should be regarded as estimates of "effective" recruitment, i.e. the recruitment that would have been necessary on July 1 to account for the abundance of older age groups in later years.

Numbers of northern anchovy were not included in the model; abundance was measured solely in units of biomass. This approach was advantageous because weight at age for northern anchovy changes rapidly throughout the year, depends on where and when samples are taken (Parrish et al. 1985) and is difficult to determine for the population as a whole. In addition, weight at age data from commercial fisheries for anchovy were not available for recent seasons.

Biomass dynamics were modeled as:

$$B_{a+1,y+1} = B_{a,y}\, e^{-\eta_y} \qquad [1]$$

where $B_{a,y}$ is the biomass of northern anchovy age a (a > 0, i.e. excluding new recruits) at the beginning of season y and η_y is the net instantaneous rate of change for anchovy in season y. In common with most other types of assessment models (Deriso et al. 1985; Gavaris 1988; Methot 1989), biomass dynamics in [1] are deterministic; no stochastic variations in growth and natural mortality were included. Random "process" errors (e.g. variation in growth and natural mortality, Hilborn and Walters 1992) were captured in the model by recruitment estimates. For example, increased biomass in a particular year due to rapid growth or reduced natural mortality in the anchovy population would tend to show up in the model as increased recruitment. This property of forward simulation type models is advantageous because assumptions about stationary growth and mortality can be relaxed but it makes recruitment estimates more difficult to interpret.

For modeling purposes, recruitment of northern anchovy in each year was assumed independent of spawning stock size:

$$B_{0,y} = \overline{B}_0 \, e^{\delta_y} \qquad [2]$$

where $B_{0,y}$ is recruitment (biomass age zero fish) in season y, $\overline{B}_0$ is mean recruitment during the study period, and δ_y is a lognormally distributed error for season y with mean zero and standard deviation σ. We assumed that mean recruitment and the standard deviation of log scale recruitments was constant during the 1963 to 1992 seasons (see below). Recruitments in each season ($B_{0,y}$) were treated as parameters and estimated by the model. Another approach (e.g. Deriso et al. 1985) involves using a spawner-recruit function in the model. We used the simpler approach [2] because it involved fewer parameters.

The net instantaneous rate of change for anchovy biomass in each season (η_y in [1]) is the sum of rates for fishing mortality, growth and natural mortality:

$$\eta_y = F_y + M - G \qquad [3]$$

where F_y is the rate for fishing mortality in season y, M is the rate for natural mortality, G is the rate for growth and all rates are defined as positive values. The rate for fishing mortality in each season (F_y) was assumed constant over ages but variable over time while rates for natural mortality (M) and growth (G) were assumed constant over ages and time.

The fishing mortality rate for season (F_y) was calculated by solving Baranov's catch equation (Ricker 1975) iteratively using the "forward solution" algorithm in Sims (1982):

$$C_y = \frac{F_y}{(F_y + M - G)} B_y \left(1 - e^{-F_y - M + G}\right) \qquad [4]$$

where C_y was the total catch in season y and B_y is total anchovy biomass.

The rate of natural mortality for northern anchovy (M) was assumed to be 0.8 yr^{-1} which is reasonable for a fish that seldom exceeds seven years in age (Hoenig 1983). The model for northern anchovy used by Methot (1989) and Lo and Methot (1989) assumed that natural mortality was at least 0.8 yr^{-1} and dependent on the biomass of Pacific mackerel which feed on northern anchovy. This assumption was based on the perception that natural mortality for northern anchovy increased during the late 1970's after Pacific mackerel increased in abundance (Methot 1989) and anchovy older than five years became rare (Mais 1981). Natural mortality was assumed constant over time in the model because quantitative estimates of Pacific mackerel biomass have not been available in recent years (Jacobson and Lo 1991) and because anchovy biomass is low despite low fishing mortality rates and Pacific mackerel biomass levels that are declining (Patty Wolf, California Department of Fish and Game, 330 Golden Shore, Suite 50, Long Beach, CA, 90802, January 1993). Methot (1986) found that different levels of natural mortality had only modest effects on biomass estimates for northern anchovy because the estimates were anchored by EPM spawning biomass measurements used as data.

The theory behind modeling growth as an instantaneous rate (G) is explained in Zhang and Sullivan (1988). This approach is advantageous for northern anchovy because fish grow rapidly throughout the season. By treating growth as an instantaneous rate, northern anchovy in the model are, in effect, allowed to continue growing right up until the time at which they are caught.

The rate for growth used in our model for anchovy (G = 0.198 yr^{-1}, SE = 0.0166) was estimated by fitting a linearized exponential growth model to mean weight at age data from three sources (Jacobson and Lo 1992). Growth was assumed to be constant over age groups because the model fit the data adequately (R^2=93%).

Survey data

Survey data (EPI, HEP, SONAR, EPM and SPOTTER abundance indices) were assumed to be measured with log-normally distributed random errors. Predicted values for survey data during each season were calculated in the model as:

$$\hat{I}_{t,y} = Q_t \sum_{a=0}^{4+} \rho_{t,a} \; B_{a,y} \; e^{-\tau_{t,y} \eta_y} \qquad [5]$$

where hats (^) denote estimates, $I_{t,y}$ is the index for survey t and season y, Q_t scales biomass to the units of survey t, $\rho_{t,a}$ is the relative contribution of age a to survey t and $\tau_{t,y}$ is the elapsed time in season y when survey t was conducted. Indices were assumed to measure anchovy abundance during peak spawning (February 15) so $\tau_{t,y}$ = 0.625 in all cases. Values of $\rho_{t,a}$ were relative measures of contribution scaled to the interval [0,1] and the age with maximum relative contribution for survey type t had $\rho_{t,a}$=1.0. The parameters Q_t and $\rho_{t,a}$ enter the model as products in [5] and were not all separately estimable. Fortunately, external estimates of the scaling parameter for EPM surveys (Q_{EPM}=1) and age specific parameters ($\rho_{t,a}$) for EPM and EPI surveys were available for northern anchovy (Methot 1989).

Two year old anchovy are all sexually mature during the peak spawning season ($\rho_{EPM,2+}$ = 1.0) while the fraction of one-year-olds that is mature ($\rho_{EPM,1}$) depends on water temperatures (Methot 1989). All age zero fish are immature so $\rho_{EPM,0}$ = zero. Following Methot (1989), maturity of age one anchovy was calculated as:

$$\rho_{EPM,1} = \frac{e^{-33.4 + 2.44T_y}}{1+e^{-33.4 + 2.44T_y}} \qquad [6]$$

where T_y is the mean temperature (°C) at Scripps Pier during January and February of season y (Table 1).

Estimates of age specific relative egg production for actively spawning anchovy during the peak spawning season were used to estimate the age specific parameters ($\rho_{HEP,a}$ and $\rho_{EPI,a}$) for egg production indices. No age zero anchovy spawn during the peak season but all are actively spawning by age two. The fraction actively spawning at age 1 (A_1) depends on water temperatures (Methot 1989):

$$A_1 = \frac{e^{-17.51 + 1.21T_y}}{1 + e^{-17.51 + 1.21T_y}}. \qquad [7]$$

The distinction between fraction mature [6] and fraction actively spawning [7] is important because EPM data measure the biomass of mature anchovy while egg production data (i.e. the HEP and EPI indices) measure the biomass of actively spawning anchovy. The fraction of one year old anchovy actively spawning is always less than the fraction mature (Methot 1989). At very low temperatures (see Figure 1 in Methot 1989), fraction anchovy actively spawning (A_1) predicted by [8] is slightly higher than the fraction mature ($\rho_{EPM,1}$) predicted by [9]. In order to avoid this minor problem, we constrained $A_1 \leq \rho_{EPM,1}$ in the model.

Age specific parameters for contribution to egg production indices ($\rho_{HEP,a}$ and $\rho_{EPI,a}$) were assumed to be the product of relative egg production and fraction active. Relative egg production data were the same as used by Methot (1989) and were originally obtained from Parrish et al. (1986).

age	Egg Production (eggs gm^{-1} day^{-1})	Egg Production (relative)	Fraction Active	$\rho_{HEP,a}$ and $\rho_{EPI,a}$
0	0	0.00	0.0	0.00
1	2,464	0.27	A_1	$0.27A_1$
2	4,867	0.54	1.0	0.54
3	7,599	0.84	1.0	0.84
4+	9,030	1.00	1.0	1.00

Following Jacobson and Lo (1991), relative age specific contributions to indices of schooling biomass (SPOTTER and SONAR) for anchovy ages 1 and older ($\rho_{SPOTTER,1+}$ and $\rho_{SONAR,1+}$) were assumed to be 1.0. The contribution of age zero anchovy to the SPOTTER and SONAR indices was estimated as:

$$\rho_{SPOTTER,0} = \rho_{SONAR,0} = \frac{e^{\Pi}}{1 + e^{\Pi}} \qquad [8]$$

where Π is a parameter estimated by the model. The relationship [8] was convenient because it mapped all possible parameter values (Π) onto (0,1) which is the interval of feasible values for $\rho_{SPOTTER,0}$ and $\rho_{SONAR,1+}$.

Objective function

Parameters in the assessment model for northern anchovy were estimated by minimizing the negative log-likelihood (equivalent to maximizing the likelihood):

$$L_{total} = \lambda_1 L(\boldsymbol{I} \mid \boldsymbol{P}) + \lambda_2 L(\boldsymbol{B_0} \mid \sigma) = \frac{1}{2}\left(\lambda_1 \sum_{t=1}^{3} \sum_{y=1}^{N_t} D^2_{t,y} + \lambda_2 \sum_{y=1}^{N_y} R^2_{y}\right) \qquad [9]$$

where L_{total} and L() are negative log likelihoods, the vector **I** holds survey data, the vector **P** holds parameter estimates (including recruitments), the vector $\mathbf{B_0}$ holds recruitment parameters (a subset of **P**), N_t is the number of observations for survey type t, N_y is the number of recruitment estimates, and σ is the log scale standard deviation for recruitments from [2]. The weights (λ_1 and λ_2) were both set equal to 1.0 except during sensitivity analyses not reported here. $D_{t,y}$ is the log scale standardized residual for survey t in season y and R_y is the log scale standardized residual for recruitment in season y:

$$D_{t,y} = \frac{\ln\ (I_{t,y}\ /\ \hat{I}_{t,y})}{\epsilon_{t,y}} = \frac{\ln\ (I_{t,y})\ -\ \ln\ (\hat{I}_{t,y})}{\epsilon_{t,y}} \quad [10]$$

$$R_y = \frac{\ln(B_{0,y}\ /\ \overline{B}_0)}{\sigma} = \frac{\delta_y}{\sigma} \quad [11]$$

where $\epsilon_{t,y}$ is the log scale standard error for survey t in season y. Log scale standard errors for survey data ($\epsilon_{t,y}$) were calculated from arithmetic scale coefficients of variation:

$$\epsilon_{t,y} = \sqrt{\ln(CV^2{}_{t,y} + 1)} \quad [12]$$

where ln(x) denotes the natural log of x.

The last term in the right hand side of [9] gives the log likelihood for estimates of recruitment during the 1963 to 1991 seasons assuming that recruitments were log-normally distributed with mean $\ln(\bar{B}_0)$ and standard deviation σ. Mean recruitment $(\bar{B}_0)$ is a "nuisance" parameter in [11] that was set equal at each iteration to the mean of current recruitment estimates. The log scale standard deviation for recruitments (σ) was assumed to be 0.71 which was calculated from recruitment estimates for northern anchovy in Jacobson and Lo (1991). Biomass estimates are not very sensitive to the assumed level of σ (Jacobson and Lo 1992).

The likelihood term for recruitments in [9] is a constraint that penalizes individual recruitment estimates that are different from the mean. The magnitude of the penalty, for a given recruitment estimate $(B_{0,y})$, depends on the deviation from the mean $[\ln(B_{0,y}/ \bar{B}_0)]$ and σ. The penalty is inversely proportional to σ so that smaller values of σ result in higher penalties and recruitment estimates nearer the average. Conversely, the magnitude of the penalty for given σ depends on the size of the deviation so that an recruitment estimate farther from the mean gets a larger penalty. The constraint in [11] does not penalize recruitment estimates that are serially correlated so that "runs" of good or bad recruitments can be estimated by the model. This was important because anchovy recruitments tend to be serially correlated (see below).

Jacobson and Lo (1991) showed that an anchovy model without age composition data or a constraint like [9] was over parameterized because recruitments need occur only once every two to three years for the model to match observed and predicted abundance data. We included the constraint [9] in our model to obtain reasonable recruitment estimates for each season (age composition data indicate that some recruitment occurs every season) and to obtain a more realistic model for northern anchovy. In addition, the constraint stabilizes recruitment estimates for the most recent year which tend to have high variance and be difficult to estimate.

The constraint on recruitment tends to bias recruitment and biomass estimates towards the mean since recruitment estimates will be high in years with poor recruitment and low in years with high recruitment. Bias in biomass estimates is believed to be minor because of sensitivity analysis results and because biomass estimates for anchovy from models with the constraint were similar to estimates and trends from models without it (Jacobson and Lo 1991). Bias in recruitment estimates has, however, not been evaluated.

Parameters in the assessment model were estimated using the simplex algorithm from Press et al. (1990) with some modifications. The program as a whole was similar to that described by Mittertreiner and Schnute (1985) and coded in standard single precision FORTRAN-77. The model and program ran quickly on a personal computer and global best estimates were reasonably easy to find. Variances and correlations for parameter and biomass estimates were calculated using a parametric bootstrap approach (Efron 1982) as described in Lo et al. (1992) except that simulated abundance data was generated assuming log-normal errors with variance equal to the average squared log scale deviations for each data type. Parameters for bootstrap runs were estimated as described for the original model using the observed CV's for each survey index observation. Fifty bootstrap iterations were used to estimate variances and correlations. Parameters with all feasible values positive [i.e. initial abundances ($B_{a,1979}$, a>0), recruitments ($B_{0,y}$), scaling parameters for surveys ($Q_{SPOTTER,y}$ and $Q_{EPI,y}$), and the parameter (Π) for contribution of age zero anchovy to the SPOTTER index] were estimated as log transformed values. The log transformation constrains parameters to feasible values and improves the statistical characteristics of the final parameter estimates. Standard errors for log scale parameter estimates were transformed to arithmetic scale CV's by inverting [12]. We used parameter "sections" and "profiles" (Mittertreiner and Schnute 1985) to depict changes in the log likelihood surface that results from varying parameter values in our model.

RESULTS

Preliminary runs indicated that estimates of biomass for anchovy age one and older were imprecise for the first season (1963) in the model. In effect, the model could not decide what fraction of the biomass during the first season was in each age group. This problem did not affect biomass estimates but did interfere with calculation of variances and correlations for parameters. For final runs, parameters for biomass of anchovies ages one to three in the first season were set equal to a small value (1,000 mt) and not estimated. In final runs, the only parameters for the first season estimated were recruitment ($B_{0,1963}$) and biomass of the oldest age group ($B_{4+,1963}$).

The estimate obtained from preliminary runs for the parameter (Π in [13]) that determined contribution of age zero anchovy to the SPOTTER and SONAR indices was small indicating that availability of age zero anchovy to indices of schooling biomass was close to zero (Π = -16.3 giving $\rho_{SPOTTER,0} = \rho_{SONAR,-0} = 8.34 \times 10^{-8}$). Moreover, likelihood sections and profiles indicated that the likelihood surface was flat in the area of the best estimate. This situation did not affect biomass estimates but did interfere with calculations of variances and correlations. For final runs, $\rho_{SPOTTER,0}$ and $\rho_{SONAR,0}$ were set to zero and not estimated in the model.

Model fit

There was evidence of serial correlation in plots of residuals versus time for all abundance indices but no systematic patterns in plots of residuals versus predicted value (i.e. the model did not consistently over or under predict any index of abundance). One outlier in the EPI data ($D_{EPI,1983}$=4.17) was identified using a simple t-test with Bonferroni p-values (Weisberg 1980) but, in accordance, with preferences expressed by the Council's Scientific and Statistical Committee (Jacobson and Lo 1992), the outlier was not omitted. Parameter and biomass estimates, bootstrap standard errors and CV's are given in Table 3.

Biomass Estimates for 1993

The estimated spawning biomass for the central subpopulation of northern anchovy on February 15, 1993 was 282,000 mt (CV 31%). The estimate for 1993 was almost equal to the estimate for 1992 and similar to estimates for 1987 to 1990 indicating that anchovy biomass levels have been stable following the decline after 1986 (Table 4 and Figure 3).

Status of the Stock

Anchovy biomass (Figure 3) and recruitment levels (Figure 4) declined after the 1985 season to levels similar to those during the 1963 to 1971 seasons. Anchovy have been too scarce off Baja California, Mexico since the 1990 season to support a significant fishery (Table 1 and Figure 1). Relatively low anchovy biomass levels during recent years were probably due to low recruitment rather than high fishing mortality rates (Table 4) since fishing mortality rates were moderate after the 1986 season ($< 0.13\ yr^{-1}$) and very low ($< 0.02\ yr^{-1}$) since the 1990 season. The recent period of low anchovy biomass occurred as sardine biomass levels began to increase in the early 1980's and water temperatures began to warm (Soutar and Isaacs 1974; Barnes et al. 1992).

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Table 1. Abundance, landings (thousand mt) and temperature data (degrees C.) for northern anchovy during the 1963-1992 seasons. Units for SPOTTER are tons per block, units for HEP and EPI are eggs / 0.05 sq. m / day. Units for EPM are thousand mt. "CV" is for coefficient of variation. Landings data for the 1993 season are preliminary. Spotter data were calculated after omitting Pilot 26.

Season	SPOTTER	SPOTTER-CV	HEP	HEP-CV	EPI	EPI-CV	SONAR	EPM	EPM-CV	Mexican Landings	US Landings	Total Landings	Scripps Pier Temperature
1963	16.5	24%	4.1	65%						0.000	1.795	1.795	15.0
1964	146.2	28%	4.0	29%						0.000	2.324	2.324	13.3
1965	137.6	29%	5.3	34%						0.000	18.958	18.958	13.8
1966	204.8	26%								0.000	42.725	42.725	14.0
1967	121.6	27%								0.000	13.470	13.470	14.5
1968	83.2	29%	3.8	28%			0.44			0.000	33.224	33.224	14.3
1969	308.1	26%					0.28			0.000	83.391	83.391	13.6
1970	161.7	28%					0.23			0.000	81.854	81.854	13.1
1971	216.6	26%	1.7	48%			0.82			0.000	55.624	55.624	12.8
1972	191.7	28%					1.67			0.000	76.059	76.059	15.0
1973	1163.4	26%					0.95			0.000	116.666	116.666	13.1
1974	712.1	26%	19.7	53%			3.09			28.088	113.782	141.870	13.2
1975	925.8	25%								35.287	135.573	170.860	13.9
1976	566.4	27%					1.98			108.962	104.095	213.057	16.0
1977	524.4	26%	2.3	192%			0.39			127.229	76.236	203.465	15.7
1978	800.6	31%	5.4	48%			0.29			195.675	55.966	251.641	13.9
1979	1373.4	29%	2.7	47%	2.16	27%	0.60	870	26%	157.543	40.091	197.634	15.0
1980	1002.9	32%	4.4	48%	2.96	14%	0.57	635	22%	287.547	65.906	353.453	14.6
1981	511.7	32%	3.3	41%	1.90	17%	0.25	415	26%	255.086	53.212	308.298	14.1
1982	449.3	33%	3.9	30%	2.24	34%	0.53	652	21%	156.725	11.003	167.728	15.9
1983	172.3	39%	2.9	37%	5.75	11%	0.57	309	17%	66.260	7.507	73.767	15.0
1984	599.8	35%	2.6	26%	6.89	48%	1.02	521	19%	123.359	4.762	128.121	13.8
1985	611.3	34%			7.13	32%				85.801	6.321	92.122	15.2
1986	260.8	34%			4.97	16%				116.334	4.783	121.117	15.0
1987	201.9	36%			6.26	33%				98.498	5.794	104.292	14.0
1988	805.8	35%			1.47	29%				86.361	5.795	92.156	13.0
1989	403.4	35%			2.31	35%				55.647	8.228	63.875	14.4
1990	184.9	38%			1.82	23%				0.796	10.328	11.124	14.9
1991	462.7	36%			0.86	32%				1.896	6.353	8.249	15.3
1992	161.5	45%			2.01	36%				0.562	2.381	2.943	15.4

Table 2. Landings (mt) for northern anchovy taken by Mexican and US fisheries during the 1991 and 1992 fishing seasons. Data for January to June in the 1992 season are preliminary.

1991 Season	Mexico	US Non-reduction	US Reduction	US Live bait	US Total	Grand Total
Jul	32	514	0	911	1,425	1,457
Aug	0	314	0	858	1,172	1,172
Sep	0	180	0	636	816	816
Oct	102	139	0	365	504	606
Nov	0	127	0	311	438	438
Dec	0	24	0	167	191	191
Jan	0	24	0	102	126	126
Feb	0	55	0	95	149	149
Mar	0	46	0	137	183	183
Apr	0	109	0	214	323	323
May	271	140	0	283	423	694
Jun	1,491	289	0	312	601	2,093
1991 Season Total	1,896	1,963	0	4,391	6,353	8,250
1992 Season						
Jul	0	138	0	421	558	558
Aug	0	157	0	401	558	558
Sep	0	19	0	222	241	241
Oct	0	48	0	164	212	212
Nov	552	58	0	168	226	778
Dec	10	42	0	56	98	107
Jan	0	0	0	63	63	63
Feb	0	21	0	55	76	76
Mar	0	140	0	75	215	215
Apr	0	89	0	45	134	134
May	0	0	0	0	0	0
Jun	0	0	0	0	0	0
1992 Season Total	562	711	0	1,670	2,381	2,943

Table 3. Parameter and biomass estimates with variances, standard errors and coefficients of variation (CV) calculated by bootstrapping.

------------------------parametric bootstrap results-------------------------

number of runs = 50
number of quantities bootstrapped = 95
name of file with intermediate values: bootabc.xyz

runs with too many axial search cycles 2
runs with no convergence 0

id	label	best estimate	mean	std err	c.v.	p<.05
1	lnQ-egg prod	-4.119560E+00	-4.190751E+00	2.472395E-01	6%	
2	lnQ-fish spt	-1.846525E-01	-2.572039E-01	1.796012E-01	70%	
3	lnQ-HEP	-3.823475E+00	-3.934383E+00	1.986547E-01	5%	
4	lnQ-SONAR	-6.639100E+00	-6.782806E+00	2.075951E-01	3%	
5	ln age 4+ 63	6.495380E+00	6.230314E+00	4.672177E-01	7%	
6	ln recrut 63	5.340644E+00	5.824320E+00	4.882528E-01	8%	
7	ln recrut 64	5.469656E+00	5.640628E+00	4.440282E-01	8%	
8	ln recrut 65	5.937237E+00	5.641810E+00	3.951374E-01	7%	
9	ln recrut 66	5.545306E+00	5.652358E+00	3.761848E-01	7%	
10	ln recrut 67	5.532836E+00	5.631553E+00	4.758196E-01	8%	
11	ln recrut 68	6.400797E+00	6.176386E+00	4.286764E-01	7%	
12	ln recrut 69	5.713037E+00	5.834098E+00	4.119655E-01	7%	
13	ln recrut 70	6.503915E+00	6.379640E+00	4.657025E-01	7%	
14	ln recrut 71	6.483925E+00	6.432343E+00	5.051072E-01	8%	
15	ln recrut 72	8.004777E+00	7.809218E+00	4.533558E-01	6%	
16	ln recrut 73	7.118133E+00	6.989938E+00	5.764710E-01	8%	
17	ln recrut 74	7.277665E+00	6.892445E+00	6.228483E-01	9%	
18	ln recrut 75	6.863067E+00	6.865104E+00	4.003881E-01	6%	
19	ln recrut 76	6.440541E+00	6.369248E+00	4.528242E-01	7%	
20	ln recrut 77	6.699916E+00	6.725892E+00	4.719660E-01	7%	
21	ln recrut 78	7.376042E+00	7.282865E+00	4.011930E-01	6%	
22	ln recrut 79	6.925820E+00	6.801305E+00	2.795054E-01	4%	
23	ln recrut 80	6.593604E+00	6.678552E+00	3.694692E-01	6%	
24	ln recrut 81	7.501120E+00	7.298394E+00	2.685473E-01	4%	
25	ln recrut 82	5.851466E+00	6.286304E+00	3.431860E-01	5%	
26	ln recrut 83	7.372844E+00	7.169424E+00	3.381003E-01	5%	
27	ln recrut 84	7.062113E+00	6.709675E+00	4.871915E-01	7%	
28	ln recrut 85	6.028413E+00	6.243640E+00	4.147800E-01	7%	
29	ln recrut 86	5.813282E+00	6.186383E+00	4.249950E-01	7%	
30	ln recrut 87	6.854302E+00	6.463708E+00	3.768355E-01	6%	
31	ln recrut 88	5.767207E+00	5.947934E+00	4.502402E-01	8%	
32	ln recrut 89	5.446468E+00	5.768888E+00	3.967342E-01	7%	
33	ln recrut 90	6.141200E+00	5.987388E+00	3.439133E-01	6%	
34	ln recrut 91	5.832788E+00	6.145796E+00	4.125355E-01	7%	
35	ln recrut 92	6.405414E+00	6.408166E+00	1.224847E-01	2%	
36	TB_2/15/1963	4.554935E+02	3.869144E+02	1.778496E+02	46%	
37	TB_2/15/1964	3.261715E+02	3.540602E+02	1.209790E+02	34%	
38	TB_2/15/1965	2.604323E+02	3.025987E+02	8.737169E+01	29%	
39	TB_2/15/1966	2.593828E+02	2.562507E+02	6.995541E+01	27%	
40	TB_2/15/1967	2.177247E+02	2.343559E+02	6.549151E+01	28%	
41	TB_2/15/1968	2.014505E+02	2.306362E+02	6.354464E+01	28%	
42	TB_2/15/1969	2.861759E+02	2.778963E+02	9.054736E+01	33%	
43	TB_2/15/1970	2.214381E+02	2.391519E+02	7.400691E+01	31%	
44	TB_2/15/1971	3.184379E+02	3.237931E+02	1.105797E+02	34%	
45	TB_2/15/1972	3.879859E+02	4.077065E+02	1.432443E+02	35%	
46	TB_2/15/1973	1.249233E+03	1.156214E+03	4.433139E+02	38%	

47	TB_2/15/1974	1.054060E+03	1.014704E+03	3.494644E+02	34%
48	TB_2/15/1975	9.927383E+02	8.822985E+02	3.164139E+02	36%
49	TB_2/15/1976	7.444968E+02	7.138227E+02	1.953173E+02	27%
50	TB_2/15/1977	5.006296E+02	4.926964E+02	1.330095E+02	27%
51	TB_2/15/1978	4.452334E+02	4.751439E+02	1.398895E+02	29%
52	TB_2/15/1979	6.570922E+02	6.612744E+02	1.826681E+02	28%
53	TB_2/15/1980	5.227703E+02	5.042575E+02	9.946309E+01	20%
54	TB_2/15/1981	3.794126E+02	3.969119E+02	8.917090E+01	22%
55	TB_2/15/1982	6.506105E+02	5.767022E+02	1.204699E+02	21%
56	TB_2/15/1983	4.225516E+02	4.542505E+02	8.529976E+01	19%
57	TB_2/15/1984	7.501907E+02	6.789333E+02	1.364567E+02	20%
58	TB_2/15/1985	7.510853E+02	6.305694E+02	1.930756E+02	31%
59	TB_2/15/1986	4.797102E+02	4.773530E+02	1.622592E+02	34%
60	TB_2/15/1987	3.246441E+02	3.847328E+02	1.268625E+02	33%
61	TB_2/15/1988	4.425708E+02	3.878339E+02	1.138368E+02	29%
62	TB_2/15/1989	3.025650E+02	3.125882E+02	1.038855E+02	33%
63	TB_2/15/1990	2.284303E+02	2.738549E+02	9.101014E+01	33%
64	TB_2/15/1991	2.916640E+02	3.012775E+02	8.025441E+01	27%
65	TB_2/15/1992	2.839355E+02	3.529044E+02	1.094334E+02	31%
66	SB_2/15/1963	4.377343E+02	3.718411E+02	1.708840E+02	46%
67	SB_2/15/1964	2.700349E+02	2.509595E+02	9.842601E+01	39%
68	SB_2/15/1965	2.230022E+02	2.533237E+02	7.310335E+01	29%
69	SB_2/15/1966	2.186023E+02	2.233816E+02	6.027225E+01	27%
70	SB_2/15/1967	2.074796E+02	2.219669E+02	6.107705E+01	28%
71	SB_2/15/1968	1.852576E+02	2.106273E+02	5.557721E+01	26%
72	SB_2/15/1969	1.809261E+02	1.850452E+02	5.058620E+01	27%
73	SB_2/15/1970	1.511628E+02	1.514059E+02	4.663913E+01	31%
74	SB_2/15/1971	1.311254E+02	1.390622E+02	3.903276E+01	28%
75	SB_2/15/1972	3.792780E+02	3.983079E+02	1.386236E+02	35%
76	SB_2/15/1973	4.031937E+02	3.926256E+02	1.126262E+02	29%
77	SB_2/15/1974	7.346983E+02	6.849087E+02	2.338714E+02	34%
78	SB_2/15/1975	8.170732E+02	7.389436E+02	2.439677E+02	33%
79	SB_2/15/1976	7.434921E+02	7.127382E+02	1.949992E+02	27%
80	SB_2/15/1977	4.993884E+02	4.914134E+02	1.325573E+02	27%
81	SB_2/15/1978	3.630910E+02	3.802744E+02	9.992474E+01	26%
82	SB_2/15/1979	6.394146E+02	6.439000E+02	1.762334E+02	27%
83	SB_2/15/1980	4.977514E+02	4.813251E+02	9.537568E+01	20%
84	SB_2/15/1981	3.356662E+02	3.455140E+02	7.008519E+01	20%
85	SB_2/15/1982	6.484350E+02	5.748899E+02	1.199368E+02	21%
86	SB_2/15/1983	4.185090E+02	4.475514E+02	8.350335E+01	19%
87	SB_2/15/1984	5.184587E+02	4.832337E+02	8.038482E+01	17%
88	SB_2/15/1985	7.418777E+02	6.233412E+02	1.892057E+02	30%
89	SB_2/15/1986	4.747660E+02	4.704303E+02	1.587547E+02	34%
90	SB_2/15/1987	2.937057E+02	3.341671E+02	1.068316E+02	32%
91	SB_2/15/1988	1.999383E+02	2.144208E+02	6.770752E+01	32%
92	SB_2/15/1989	2.884733E+02	2.934528E+02	9.531120E+01	32%
93	SB_2/15/1990	2.247716E+02	2.682729E+02	8.898700E+01	33%
94	SB_2/15/1991	2.884156E+02	2.983190E+02	7.941740E+01	27%
95	SB_2/15/1992	2.820789E+02	3.501094E+02	1.081250E+02	31%

Table 4. Total, spawning and recruitment biomass estimates (thousand mt) for northern anchovy and fishing mortality estimates for the 1963 to 1992 seasons. Recruitment estimates are for the beginning of the season (July 1). Other estimates are for the peak spawning season (February 15). Total biomass is anchovy age one and older. CV denotes coefficient of variation obtained by from a bootstrap procedure with fifty iterations.

Season	Biomass Age 1+	CV	Spawning Biomass	CV	Recruitment Biomass	CV	Fishing Mortality
1963	455	46%	438	46%	209	52%	0.003
1964	326	34%	270	39%	237	47%	0.005
1965	260	29%	223	29%	379	41%	0.040
1966	259	27%	219	27%	256	39%	0.107
1967	218	28%	207	28%	253	50%	0.037
1968	201	28%	185	26%	602	45%	0.059
1969	286	33%	181	27%	303	43%	0.184
1970	221	31%	151	31%	668	49%	0.134
1971	318	34%	131	28%	655	54%	0.080
1972	388	35%	379	35%	2,995	48%	0.034
1973	1,249	38%	403	29%	1,234	63%	0.061
1974	1,054	34%	735	34%	1,448	69%	0.076
1975	993	36%	817	33%	956	42%	0.113
1976	744	27%	743	27%	627	48%	0.197
1977	501	27%	499	27%	812	50%	0.213
1978	445	29%	363	26%	1,597	42%	0.184
1979	657	28%	639	27%	1,018	29%	0.161
1980	523	20%	498	20%	730	38%	0.384
1981	379	22%	336	20%	1,810	27%	0.218
1982	651	21%	648	21%	348	35%	0.202
1983	423	19%	419	19%	1,592	35%	0.053
1984	750	20%	518	17%	1,167	52%	0.090
1985	751	31%	742	30%	415	43%	0.096
1986	480	34%	475	34%	335	44%	0.185
1987	325	33%	294	32%	948	39%	0.119
1988	443	29%	200	32%	320	47%	0.151
1989	303	33%	288	32%	232	41%	0.150
1990	228	33%	225	33%	465	35%	0.022
1991	292	27%	288	27%	341	43%	0.017
1992	284	31%	282	31%			0.005

Figure 1. Anchovy landings for US and Mexican fisheries by calendar year.

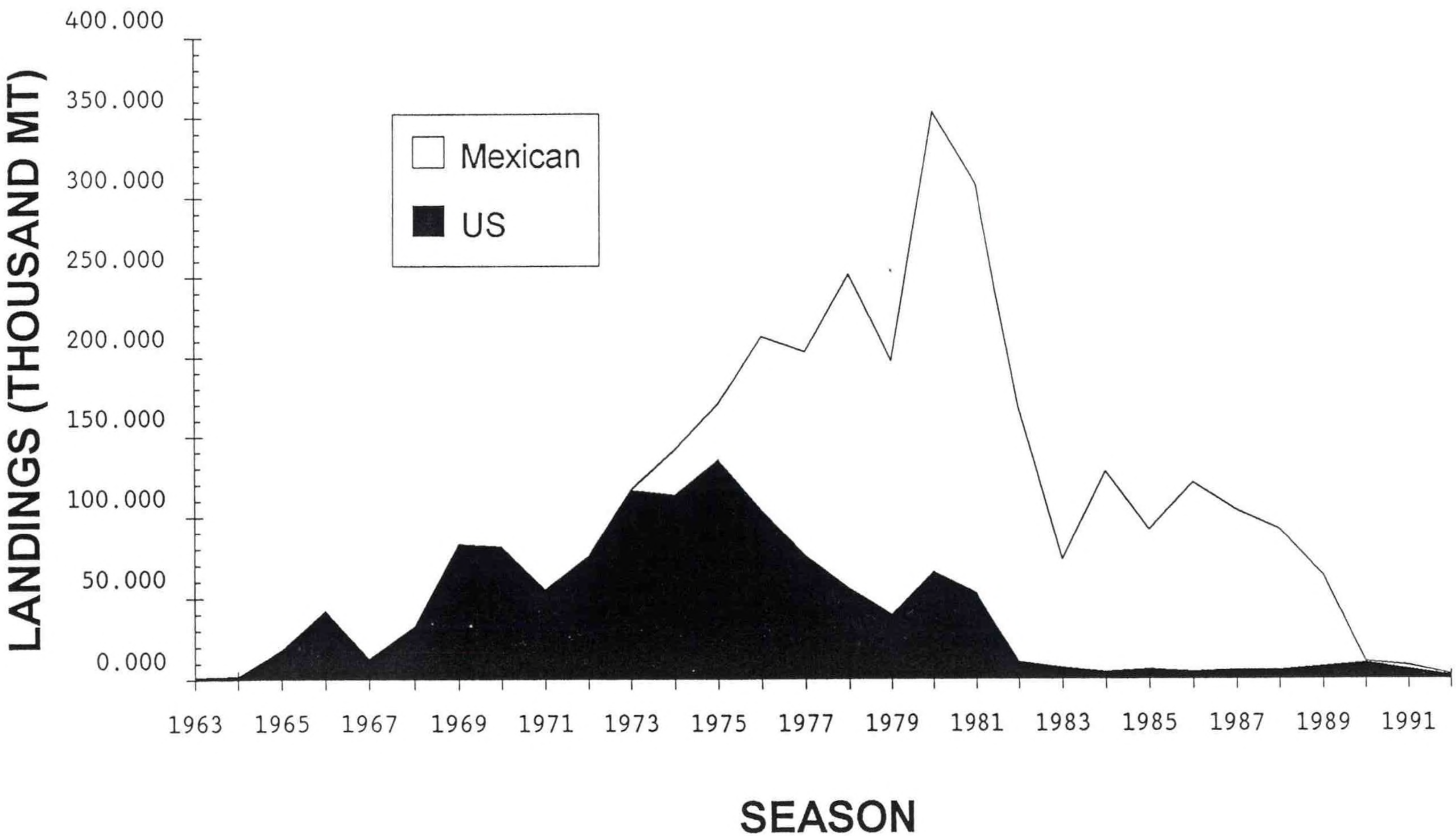

400.000
350.000
300.000
250.000
200.000
150.000
100.000
50.000
0.000
LANDINGS (THOUSAND MT)
Mexican
US
1963
1965
1967
1969
1971
1973
1975
1977
1979
1981
1983
1985
1987
1989
1991
SEASON

Figure 2. Indices of abundance for northern anchovy plotted in log scale to facilitate comparison.

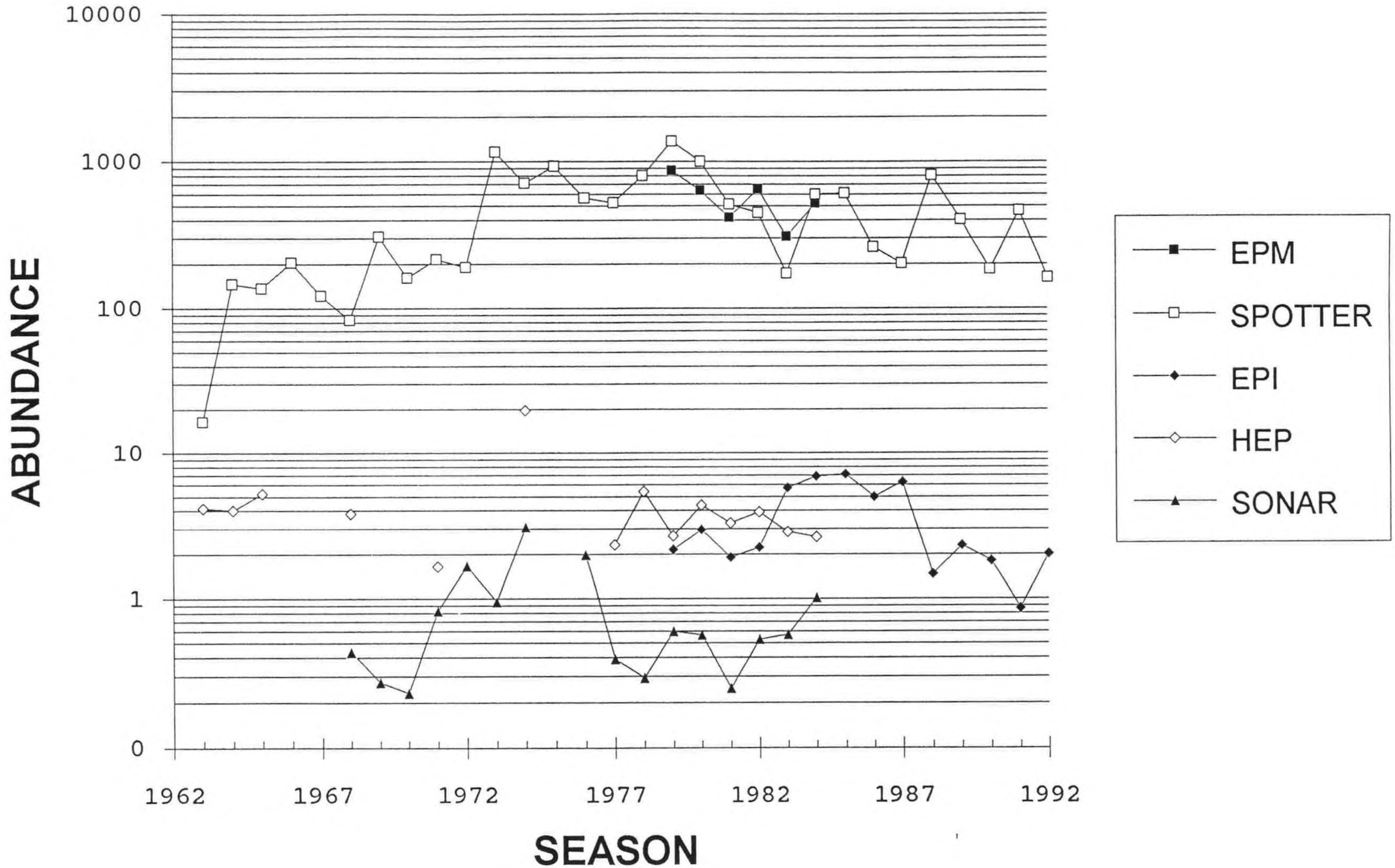

10000
1000
100
10
1
0
ABUNDANCE
1962
1967
1972
1977
1982
1987
1992
SEASON
EPM
SPOTTER
EPI
HEP
SONAR

Figure 3. Spawning and total (age one and older) biomass in the middle of February during the 1963 to 1992 seasons (1964 to 1992 calendar years).

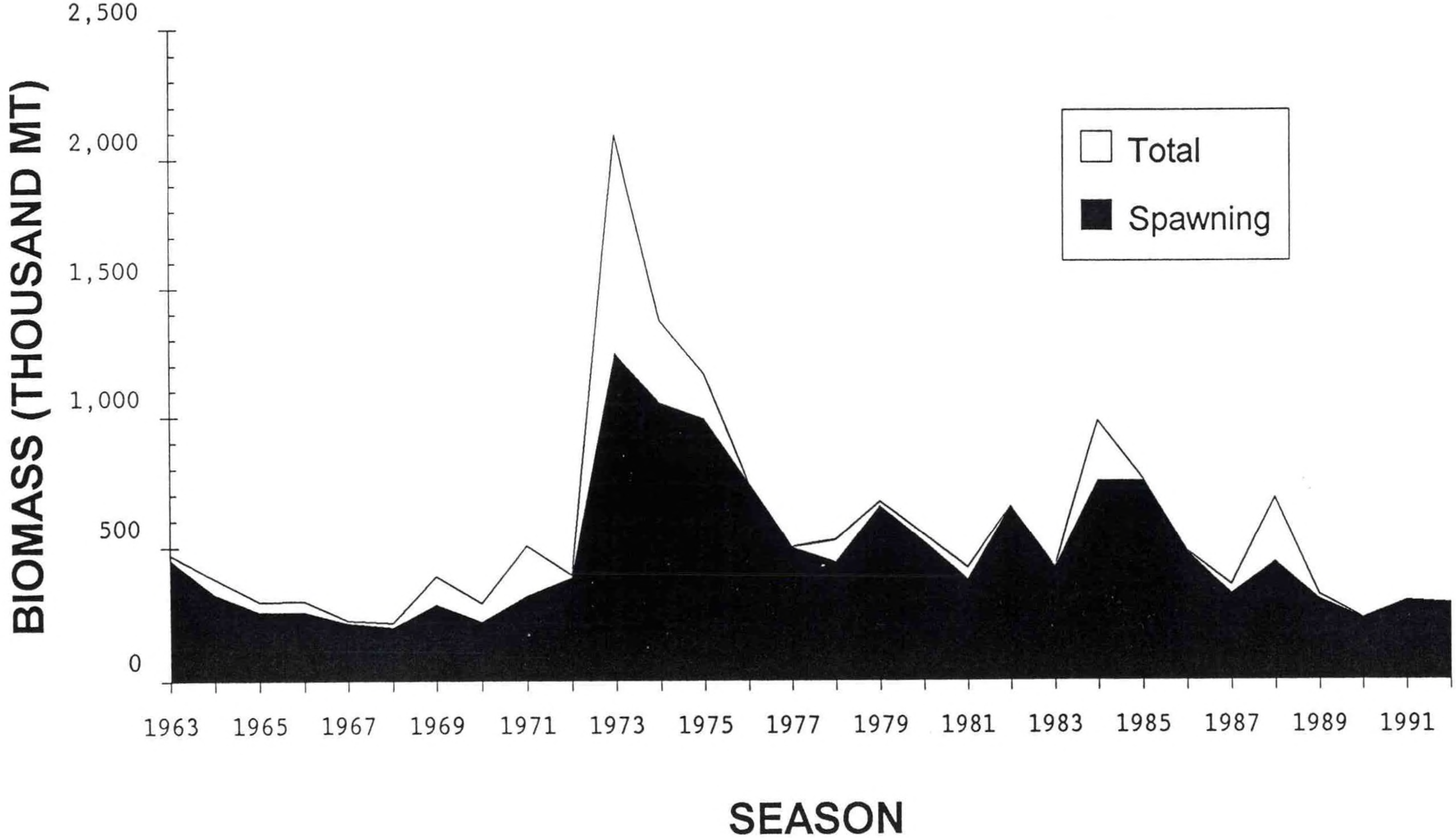
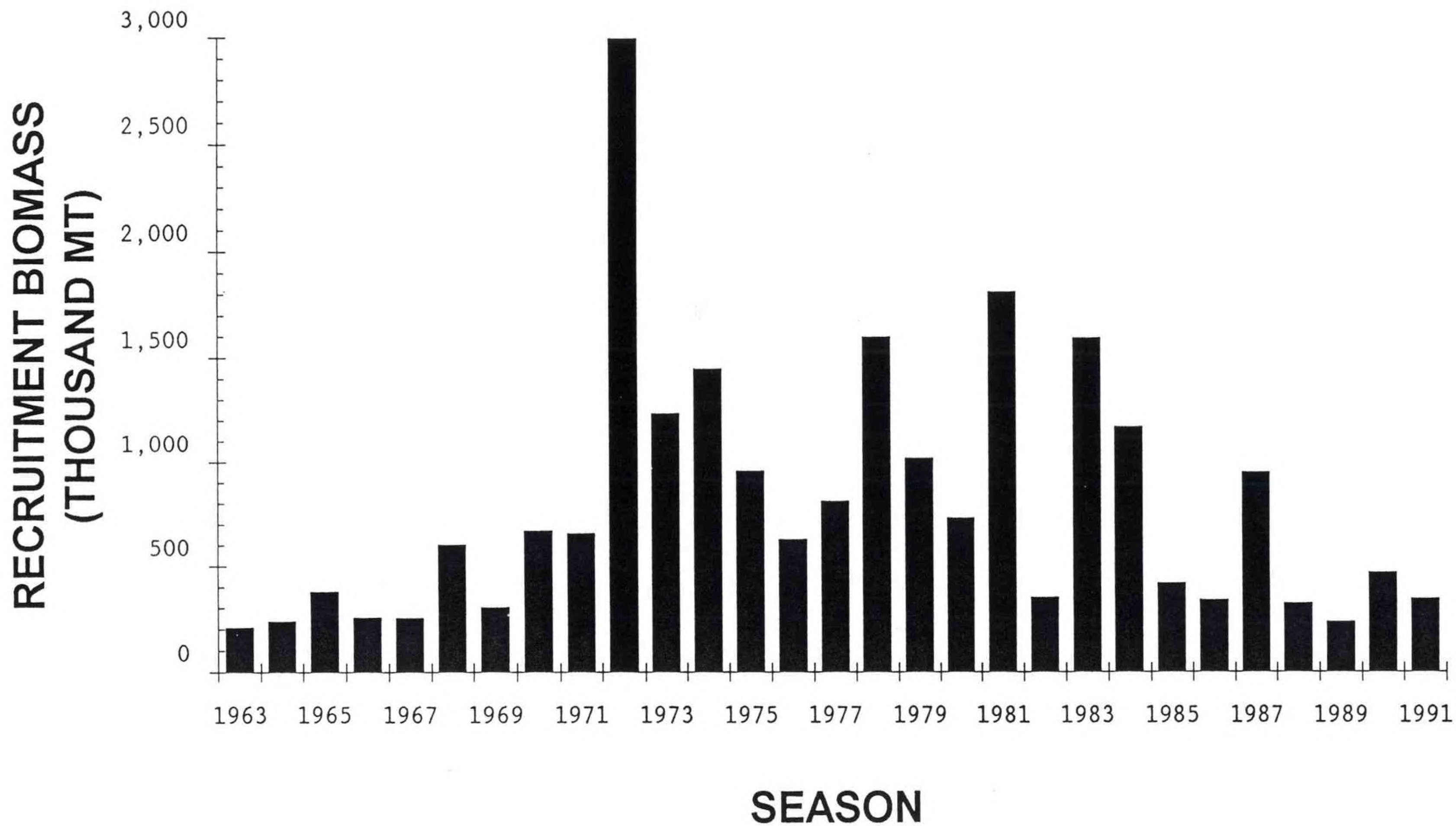

2,500
2,000
1,500
1,000
500
0
BIOMASS (THOUSAND MT)
Total
Spawning
1963
1965
1967
1969
1971
1973
1975
1977
1979
1981
1983
1985
1987
1989
1991
SEASON

Figure 4. Recruitment estimates (thousand mt of age zero anchovy on July 1) for the 1963 to 1992 seasons.


RECRUITMENT BIOMASS (THOUSAND MT)
3,000
2,500
2,000
1,500
1,000
500
0
1963
1965
1967
1969
1971
1973
1975
1977
1979
1981
1983
1985
1987
1989
1991
SEASON