Stock Assessment of Pacific Sardine for 1998 with Management Recommendations for 1999

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EXECUTIVE SUMMARY

The primary goal of sardine management as directed by the California Fish and Game Code is rehabilitation of the resource with an added objective of maximizing sustained harvest. Accordingly, the Code states that the annual sardine quota can be set at an amount greater than 1,000 tons, providing that the level of take allows for continued increase in the spawning population.

We estimated the sardine population size within the range of the fishery and survey data (Ensenada, Baja California to San Francisco, California) to have been 1,182,881 short tons on July 1, 1998. Our estimate was based on output from a modified version of the integrated stock assessment model called CANSAR (Deriso et al. 1996). CANSAR is a forward-casting, age-structured analysis using fishery-dependent and fishery-independent data to obtain annual estimates of sardine abundance, year-class strength and age-specific fishing mortality for 1983 through the first semester of 1998. Non-linear least-squares criteria are used to find the best fit between model estimates and input data.

Questions about stock structure and range extent remain major sources of uncertainty in assessing current sardine population biomass. Recent survey results and anecdotal evidence suggest increased sardine abundance in the Pacific Northwest and areas offshore from central and southern California. It is difficult to determine if those fish were part of the stock available to the California fishery. Last year, in an attempt to address this problem, the original CANSAR model was reconfigured into a Two-Area Migration Model (CANSAR-TAM; Hill et al. 1998) which accounted for sardine lost to the areas of the fishery and abundance surveys due to population expansion and net emigration. While the model includes guesses and major assumptions about net emigration and recruitment, it provides an estimate which is likely closer to biological reality than original CANSAR assessments. Corroborative results from a new, preliminary sardine stock assessment model, 'SAM', are also presented in this report.

Based on the 1998 estimate of age 1+ biomass within the range of the fishery and survey data, and a proposed harvest formula in the draft Coastal Pelagic Species Fishery Management Plan (Amendment 8), we recommend a 1999 sardine harvest quota of 132,800 tons for the California fishery. The 1999 quota is a significant increase from the final 1998 sardine harvest quota for California of 48,000 tons.

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INTRODUCTION

Section 8150.7 of the Fish and Game Code states that it is the intent of the California Legislature that the sardine resource be rehabilitated. During the process of rehabilitation, a small fishery of 1,000 tons shall be allowed once the spawning population has reached 20,000 tons as determined by the Department of Fish and Game during the first 60 days of each calendar year. As the spawning population increases in excess of 20,000 tons, the Department may increase the seasonal quota, but only at such a rate as to allow continued rehabilitation and maximized sustained-harvest of the sardine resource.

Our evaluation of the 1998 sardine resource was based on results from a modified version of the CANSAR stock assessment model (Deriso et al. 1996; Hill et al. 1998) that has been used by the Department for sardine management since 1993. Significant improvements to this year's assessment included: 1) an additional year of fishery-dependent and fishery-independent data, 2) modified exponents for saturated survey indices, 3) modified migration parameters in the CANSAR-TAM model, and 4) corroborative results from the new sardine assessment model 'SAM'.

The following report summarizes the 1998 sardine fishery, describes trends in biological and fishery-independent data, and details changes to the recently completed stock assessment work. Based on this work, we recommended the 1999 sardine fishing quota. All weights (*e.g.* biomass and catches) in this report are in short tons (1 short ton = 2,000 U.S. lbs.).

THE 1998 SARDINE FISHERY

The July 1, 1997 biomass estimate for Pacific sardines (age 1+) was 464,000 tons. Though this was a decline from the previous year's estimate, it was still the second highest since the reopening of the fishery. Due to this decline, the quota was reduced by 11% (6,000 tons) to 48,000 tons. Landings through November totaled 37,922 tons and projections from previous and current fishing trends indicated the 1998 quota would not be filled by the year's end (Tables 1&2, Figure 1).

Section 8150.8 of the Fish and Game Code states that the annual sardine quota shall be divided so that two-thirds are allocated to the southern California directed fishery (south of San Simeon Point, San Luis Obispo County) and one-third to the northern California fishery (north of San Simeon Point). For 1998, that formula resulted in an initial southern fishery quota of 32,000 tons, and a northern fishery quota of 16,000 tons. Section 8150.9 states the Department shall reallocate the total remaining quota on or before October 15 equally between northern and southern California and that resulted in a 11,266 ton quota for each area for the remainder of 1998.

Ex-vessel revenue generated by the directed sardine fishery during 1998 totaled $3.5 million, down slightly from $4.1 million in 1997 (Table 3, Figure 2). The ex-vessel price for sardine ranged from $60-100 per ton, averaging $81.2 for January through September 1998. In

addition to the wetfish fishery for sardine, a small live bait fishery exists, which is not subject to a quota and usually takes less than 5,000 tons per year. Live bait ex-vessel prices averaged $900 per ton in 1998. The overall revenue generated by the live bait fishery exceeds that of the directed fishery.

The 1997 directed sardine fishery ended with a total of 50,923 tons against a 54,000 ton quota. The reallocation in October divided the remaining quota of 31,635 tons to 15,817.5 tons split between northern and southern California. By the end of the year, about 94% of the quota was landed (Figure 1), although, southern California exceeded their portion of the reallocation by 2,671 tons while northern California still had 5,749 tons remaining. Even though the southern fishery was filled in late December, management opted to keep the fishery open because the total quota was not filled and the 1997 season closure was near.

Starting around the turn of the century (ca. 1894), round haul nets (lampara nets and purse seines) have been used to harvest sardine in California (Heimann et al. 1970). Today there are 30 active (having made 10 or more landings this year) purse seine vessels in the fishery and these vessels are commonly referred to as the "wetfish fleet." Nearly all directed fishing for sardine in California is conducted by the wetfish fleet. Other target species pursued by the wetfish fleet are Pacific and jack mackerel, market squid, tunas, Pacific herring[1], and northern anchovy. Along with purse seines, other gear types such as, drum seines and lampara nets are utilized to harvest sardines.

As with most commercial fisheries, sardine landings varied by month due to availability, participation in other fisheries, and demand (markets and canneries). Pacific sardine landings during the winter and spring were impacted by the effects of the 1997-98 El Niño phenomenon and the loss of overseas markets. Ocean conditions (i.e., storms, warm seas) reduced the availability of Pacific mackerel and market squid, which may have moved into cooler and/or deeper waters. Added to the environmental conditions was the lack of buyers for frozen whole sardines and mackerel. The Australians and Japanese, who had been buying large quantities of California-caught wetfish, found new, less expensive sources. As a result, the ex-vessel price for sardine ranged from $60 to 100/ton, and demand for sardine exports in 1998 declined from previous years. Alternative target species such as tunas ($500-2,000 per ton), market squid ($400-1,000 per ton), Pacific herring ($200-400 per ton), Pacific mackerel ($100-140 per ton), and jack mackerel ($140-300 per ton) were often preferred over sardine, with the latter two subject more to demand than availability.

Besides San Pedro and Monterey, California, significant Pacific sardine landings are made in Ensenada, Mexico. Between 1983 to 1997 Ensenada fishermen landed approximately 70,000 tons or 34% more than all ports in California combined (Table 1, Figure 3). Currently, January through July 1998, Ensenada fishermen have landed approximately 26,000 tons compared to California's 23,000 tons. If sardine landings follow last year's pattern, total sardine landings from all sources (California and Mexico) could be in excess of 85,000 tons for 1998.

[1] This fishery is seeing a gradual change from purse seines or round haul nets to size selective gill nets.

During 1998, most Pacific sardine landings in southern California were sold to market processors (78%) or to the canneries (22%). This ratio has changed dramatically since 1991, when canneries purchased about 75% of the landings. Currently fish are processed for human consumption (fresh or canned), pet food or export. Of the exported sardines, most are either sold for human consumption or used as feed in aquaculture facilities. About 15% of all sardines landed in California were canned domestically for human consumption. The only existing southern California cannery that packs fish for human consumption continued intermittent canning of sardines, landing 2,200 tons. In northern California, two canneries produced fish for human consumption, processing 4,600 tons of sardines.

For the first time since 1968, reduction of sardine was approved by the Fish and Game Commission. The Commission stipulated that sardines comprising no more than 15% by weight mixed with anchovy and that no more than 10% of any pure haul be reduced. Only one Monterey company was given approval to reduce sardine with the preceding limitations. The reduction of sardine must be reported to the Department and counts against the annual sardine quota.

SARDINE BIOMASS ESTIMATES

BACKGROUND

CANSAR is a computer program used to estimate sardine abundance. CANSAR provides confidence intervals for abundance estimates, which improves the usefulness of the estimates for fishery managers. CANSAR is an extension of methods used in the CAGEAN model for halibut (Deriso et al. 1985) and is tailored to the characteristics of information currently available for sardine including landings, size and age composition of landings, egg and larval abundance, spawning area, aerial fish spotter observations, and daily egg-production method (DEPM; Lasker 1985) spawning biomass estimates.

CANSAR is a forward-projecting, age-structured analysis that uses both fishery-dependent and fishery-independent data to obtain annual estimates of sardine abundance, year class strength, and age-specific fishing mortality. We used it to fit data for 1983 through the first semester of 1998. CANSAR combines a simulation model of the population dynamics of sardine with all or most of the available data. Non-linear least-squares criteria were used to find the best fit or match between model predictions and actual catch-at-age and abundance data for sardine. In 1997, CANSAR was modified into a Two-Area Migration model (CANSAR-TAM; Hill et al. 1998) which accounts in part for a fraction of the available biomass moving outside the range of the fishery and survey data. CANSAR-TAM was used again in the current assessment to estimate the July 1, 1998 biomass and recommend the 1999 harvest quota.

A new sardine assessment model 'SAM' was developed this year. SAM results are preliminary, but provide corroborative evidence for biomass estimates derived from CANSAR-TAM. A complete description of SAM is provided in Appendix A. Preliminary SAM results are compared to CANSAR-TAM in the following sections.

THE DATA

Fishery-dependent data used in the assessment models include weight-at-age and catch in numbers-at-age, estimated population weight-at-age, and tons landed by semester for the California and Ensenada fisheries for the period 1983 through semester 1, 1998. The models also require estimates of landings in California and Ensenada during second semester 1998. For California, the mean of semester 2 (July through December) landings for 1995 and 1997 were used, the only two recent years in which second semester landings were not severely hampered by quota restrictions. In Ensenada, mean landings for the period 1995 through 1997 were utilized. Size and age composition data were available for the U.S. fishery for nearly all semesters, but were lacking for the Ensenada fishery since 1992.

Fishery-independent data include an index of sardine egg and larvae abundance in the Southern California Bight, an annual estimate of spawning area, an index of adult sardine abundance from aerial spotter logbooks, and DEPM spawning biomass estimates.

Catch-at-Age Data

For the California fishery, age composition data were available during the study period from all except two semesters, but were available for the Ensenada fishery for only five semesters between July 1990 - December 1992. Approximately 4,207 sardines were collected in 1997 through port sampling programs from Long Beach and Monterey, and another 1,411 were collected in the first semester of 1998 from both locations. Age was determined for these specimens by reading sagittal otoliths for annuli (Yaremko 1996). For the 15-year period covered by this study, a combined sample of 35,345 sardines was aged from California and Ensenada fishery samples. The oldest sardines were nine years of age. Mean round weight from port samples was used to estimate number of fish in landings by dividing total tons landed by mean fish weight. Total numbers were prorated by age based on the age composition of port samples.

From the 1989-90 to 1994-95 fishing seasons, an approximate 50% decrease in mean weight-at-age was observed in fishery data (Figure 4). This trend has reversed over the past two years, but has not quite recovered to fishery weights-at-age measured in the 1980s and is still lower than estimated population weights-at-age (Figure 5).

In 1996, our systematic sampling of the Monterey sardine fishery adopted the protocol established for Long Beach in 1983. Both age composition and weight-at-age information were weighted proportionally by semester based on commercial landings totals in the north and south beginning with semester 1, 1996. Prior to that time, age composition and weight-at-age information collected in southern California were assumed to characterize the northern component of the catch.

Population Weight-at-Age

CANSAR and CANSAR-TAM calculate population biomass at the beginning of each semester of each year by summing the products of abundance at age and population weight-at-age. For the period 1983-1990, population weight-at-age was assumed to be the same as weight-at-age for the California fishery. Since 1991, size-at-age for sardine taken in southern California was much smaller than previously reported for the population. Therefore, population weights-at-age in 1991-1998 for the whole stock were not assumed to be the same as those of the southern California fishery.

For the period 1983-1990, a better estimate of population weight-at-age was calculated by fitting a von Bertalanffy growth curve ($L_t=L_\infty(1-e^{-k(t-t_0)})$) to the fishery data (Figure 5) collected each semester in order to improve values that may be impacted by small sample size in each semester and year. Once the curve was fitted, half ages were used to allow for differences in weight-at-age between semesters (*i.e.*, semester 1 = x.5). The curve was generated using the assumption that a fish of age zero in the second semester is 1.5 g in weight (Butler, 1987).

For the 1991-1997 period, fishery weight-at-age values were calculated in the same manner from three sources of non-fishery data that were collected from within the range of the existing fishery. These sources included weight-at-age data from a) approximately 1,400 fish collected on the 1994 DEPM cruise spanning Monterey, CA, to Cedros Island, Mexico, b) approximately 470 fish collected offshore in the Southern California Bight during the March 1997 LIDAR cruise, and c) approximately 1,800 fish sampled from 1949 through 1957 (Murphy 1966). We felt these samples provided a better estimate of population weight-at-age than existing fishery weight as they included fish collected offshore, which are likely under represented in fishery samples. Existing weight-at-age information from British Columbia, Humboldt Bay (CA), Halfmoon Bay (CA), and coastal Washington State was not included as those fish were not within the range of existing fisheries. With expansion of CANSAR to include a migration component, it is possible that this information will be included in future assessments.

CalCOFI Egg and Larvae Abundance

Like Hill et al. (1998), Barnes et al. (1997), and Deriso et al. (1996), we used a generalized additive model (GAM) to standardize presence/absence sardine egg and larval data from California Cooperative Oceanic Fisheries Investigations (CalCOFI) surveys during 1984-1998. The standardized data measure trends in the probability of a positive net tow and, by assumption, egg abundance and spawning biomass. CalCOFI data were for bongo net tows within the current CalCOFI sampling grid (Lo and Methot 1989) from station nearest shore out to station 67.5 and latitudes as far north as 35 degrees (Pt. Sal). The current CalCOFI grid is smaller than the geographic range of Pacific sardine but is the largest area occupied by the survey in all assessment years. Samples taken farther offshore than station 67.5 were omitted because sardine were seldom offshore and the data were highly variable. There were data for only 35 tows during June and seven tows during December, so data for June and December were omitted from the index.

As described in Deriso et al. (1996), the GAM was fit by logistic regression to a dependent variable that was either 1 (if the tow captured at least one sardine egg or larvae) or zero (if the tow captured zero sardine eggs and zero larvae). There was one observation for each bongo tow. The independent variables (all factors) were year, month, standard CalCOFI line, and a dummy variable for inshore/offshore location (see Figure 4 in Barnes et al. 1997). A step-wise variable selection routine (step.glm in Splus) based on AIC scores resulted in a model with main effects for year, line, month, and inshore/offshore as well as two-way interactions between inshore/offshore and month and between inshore/offshore and standard line. The interaction terms were omitted from the final model, however, because they had no effect on parameter estimates for year effects and because year effect parameter estimates from models with interactions were more variable. SAS code used to process the data and Splus code used to fit the models are given in Appendix B.

Patterns in parameter estimates from the final model (Figure 6) were similar to patterns in Deriso et al. (1996). The CalCOFI abundance index was calculated by predicting the probability of a positive tow during April on the inshore side of standard line 83.3 using the predict.gam function in Splus which also provides standard errors. The CalCOFI index indicates an increase in the probability of a positive tow during 1997-1998. The index shows a general increasing trend over most of the entire study period, and increased 56% between the 1997 and 1998 seasons (Table 4, Figure 7). The 1998 index value of 0.836 (i.e. 83.6% probability of a positive tow) is the highest of the time series and close to the upper bound of 1.0.

As described in Hill et al. (1998), CalCOFI indices based on presence absence data are nonlinear measures that tend to "saturate" as sardine abundance increases. Saturation likely occurs because the dependent variable (a probability or proportion) is bounded by zero and one, because sardine are relatively abundant, and because the area of the stock is much larger than the area of the survey (Figure 8). CalCOFI data are useful, despite problems with saturation, because they are relatively precise (Mangel and Smith 1990; Deriso et al. 1996) and because other abundance information is limited for sardine. Like Hill et al. (1998), we accommodated saturation in our assessment model by assuming the CalCOFI index was a nonlinear function of sardine egg production. Suspected saturation was dealt with by using an exponent. To estimate the degree of saturation in the index, we regressed log CalCOFI index values on log DEPM spawning biomass estimates. The slope of the regression line (β=0.2433) was used in CANSAR-TAM as an exponent to adjust predicted CalCOFI values for saturation. No trend was apparent in residuals, and the model adequately fits the data (Figure 7).

Spawning Biomass

Spawning biomass was estimated independently during 1986 (Scannel et al. 1996), 1987 (Wolf 1988a), 1988 (Wolf 1988b), 1994 (Lo et al. 1996), 1996 (Barnes et al. 1997), and 1997 (Hill et al., 1998) using the DEPM (Lasker 1985). DEPM estimates spawning biomass by: 1) calculating the daily egg production from ichthyoplankton survey data, 2) estimating the maturity and fecundity of females from adult fish samples, and 3) calculating the biomass of spawning adults. Before 1996, sardine egg production was estimated from direct CalVET plankton net sampling. Since 1996, the Continuous Underway Fish Egg Sampler (CUFES;

Checkley, et al. 1997) has been a routine sampler to collect fish eggs, and data of sardine eggs collected from CUFES have been incorporated in the estimation procedures of the daily egg production in various ways depending on the survey design. In 1998, data of sardine eggs collected from both CalVET and CUFES during the April CalCOFI cruise were used to estimate daily egg production. Adult fish have been sampled in various ways in the past to obtain our current estimates of batch fecundity, spawning fraction, sex ratio, and average fish weight (Wolf, 1988a, 1988b, Scannell et al. 1996, Lo et al. 1996).

1998 DEPM Estimate

In 1998, no survey was conducted specifically for estimation of sardine biomass, therefore sardine eggs collected from both CalVET and CUFES during CalCOFI cruise 9804 (*R/V David Starr Jordan*, April 2-23) were the data source for estimating daily egg production of sardine. Sardine eggs collected from both samplers during 9804 cruise were staged and were used to model the sardine egg mortality curve. CUFES data mapped the spatial distribution of sardine spawning population. Daily egg production together with number of eggs per population weight (23.55 eggs/population weight (gm)/day) modified from the 1994 DEPM cruise (Macewicz et al. 1996) was used to estimate the spawning biomass. Because this 1998 CalCOFI survey pattern was different from survey designs in 1996 (Barnes et al. 1996) and 1997 (Hill et al. 1998), a variation of daily egg production (P_0) estimation procedures was used.

During the 9804 cruise, CalVET tows were taken at each station up to CalCOFI station 70 while CUFES sampled each transect line entirely (Figure 9). The survey area covers waters from San Diego to Monterey, and extends to 120 nm - 360 nm miles offshore. The survey area was post-stratified into two regions, separated by station 70: Region 1 covers area from the coastline to station 70 where all the positive CUFES collections were located and Region 2 covers area beyond station 70 where no sardine eggs were found in any CUFES collection (Figure 9). As a result, sardine spawning biomass was estimated for Region 1 only.

A total of 688 CUFES samples (383 in Region 1 and 305 in Region 2) was collected at an interval ranging from 5 to 60 minutes with a mean of 26.36 minutes and median of 30 minutes. A total of 58 CalVET samples was collected, out of which 24 had at least one sardine egg. Because no paired collections from CalVET and CUFES were available, egg density for CalVET and CUFES from a portion of each transect where positive CUFES egg counts were observed were used to derive a conversion factor from eggs/minute of pump sample to CalVET catch (R). We used a regression estimator to compute the ratio of eggs/tow from CalVET to eggs/minute from CUFES: $R=\mu_y/\mu_x$ where y is the eggs/minute and x is eggs/tow.

Nine transects were occupied during cruise 9804 (excluding data collected on the way back to San Diego). All transects were parallel and 40 nm apart (Figure 9). Variogram analyses on sardine eggs collected in 9603 leg 2 indicated the range was 12 nm where the range is the distance at which eggs were no longer uncorrelated (Petitgas 1993, Cressie 1991). Because the

distance between transects was greater than 12 nm, egg data from transects were uncorrected, and we used transects as the sampling units (Armstrong et al. 1988) to compute egg production for each group from both CalVET and CUFES samples. The mortality curve (p_0 and mortality rate) was modeled based on two egg data sets, each from CalVET and CUFES plus yolk-sac larvae from CalVET. All eggs in 24 positive collections of CalVET samples were in Region 1 and all were examined for their developmental stages.

Subsample of CUFES collection for developmental stage of sardine eggs.

Each of the CUFES collections was sorted for sardine eggs during the survey and number of sardine eggs was recorded. In Region 1, based on the ship counts, there were 197 positive CUFES collections and 186 collections with zero count (zero-collections). In Region 2, all but three of 305 CUFES collections were zero-collections. In order to ascertain the accuracy of egg counts on board, all positive collections were recounted in the laboratory and sixty collections were selected from 186 zero-collections in Region 1 by choosing every 3rd zero-collection, with a random starting point within the first 3 zero-collections.

For Region 1, we examined the validity of zero-collections based on ship counts embedded between positive collections. While some were indeed zero-collections, sardine eggs were found in other zero-collections. There were also positive-collections from ship counts (2 had counts over 150 eggs) which were recorded as inadvertently recorded as zero-collections in the database. For Region 2, we systematically selected 20 collections and they were all indeed zero-collections. The final enumeration shows that in Region 1, there were 207 positive CUFES collections and 176 zero-collections. In Region 2, we assumed that all but three were zero-collections.

For each of the positive collections, 30 eggs were randomly selected for assigning developmental stages, and the proportion of staged eggs was multiplied by the total number of eggs in each collection to derive the final estimate of number of eggs in each of 11 developmental stages.

Daily egg production (p_0):

Since no CalVET samples were taken in Region 2, and very few sardine eggs were identified in CUFES, we assumed that no spawning was taking place in this region. The daily egg production (p0) and spawning area were estimated for Region 1 only.

Sardine egg density for each developmental stage was computed based on CalVET and CUFES samples (Figure 10). Both data sets indicated that egg densities were high for stage 2, 3, 5-7 and 11 and low for stages 4 and 8. There seems to be little bias introduced by CUFES which reaches to 3 m in depth. Staged sardine eggs from both samplers and yolk-sac (ys) larvae (5 mm captured size) from CalVET were used to construct the egg mortality curve (Lo et al. 1996):

$$p_t = p_0 \exp(-zt) \qquad [1]$$

where p_t is mean eggs-ys/0.05m^2 (transect is the sampling unit) and t is the mean age for each of 6 half-day age groups of eggs and yolk-sac larvae. A weighted nonlinear regression procedure was used to estimate $p_{0,1}$ and z, where the weight is $1/SE(p_t)$. For details on computation of p_t and $SE(p_t)$, refer to Appendix C.

Catch ratio between CUFES and CalVET (R)

The ratio of eggs/minute to eggs/tows was 0.32 (CV= 0.19) from 8 pairs of eggs/min and eggs/0.05m^2, each was from one transect excluding the first transect (CalCOFI line 93) because very few eggs were observed by CUFES and zero catch by CalVET (Figures 9 and 11). A ratio of 0.32 means that one egg/tow from CalVET tow was equivalent to approximately 0.32 egg/min from pump sample, or one egg/minute from the pump was equivalent to 3 eggs/tow from the CalVET sample.

The catch ratio between CalVET and CUFES (0.32) was not much different from that obtained in 1997 (0.25). This value of 0.32 was again quite different from 1996 estimate of 0.73. This could be because 1996 CalVET samples were taken only in the southern area near San Diego while 1997 and 1998 CalVET samples were taken in a larger area north of San Diego.

Daily egg production (p_0) results

The daily egg production in Region 1 (p_0) was 2.45/0.05m^2/day (CV=0.14) (equation 1) and egg mortality was Z=0.20 (CV=0.19) for an area of 162,253 km^2 (40,408 nm^2) (Table 5 and Figure 12).

1998 spawning biomass (B_s) estimate

The spawning biomass was computed according to:

$$B_s = \frac{P_0 A C}{R S F W_f} \qquad [2]$$

where A is the survey area in unit of 0.05 m^2, S is the proportion of mature females that spawned per day, F is the batch fecundity, R is the fraction of mature female fish by weight (sex ratio), W_f is the average weight of mature females(gm), and C is the conversion factor from gm to mt. P_0 A is the total daily egg production in the survey area, and the denominator is the daily specific fecundity (number of eggs/population weight (gm)/day).

The biomass of sardine has been stable for the period 1996 to 1998, and high relative to DEPM spawning biomass estimates conducted in the mid-1980s. Assuming the daily specific fecundity was the same as 1994-1996 (23.55), sardine spawning biomass (females) for 1998 was 372,136 tons (337,596 mt) for an area of 40,408 nm^2 (162,253 km^2) from San Diego to Monterey. For 1997, the egg production was 2.43/0.05m^2 (CV=0.21) and the spawning biomass was 396,039 short tons for an area of 174,096 km^2 (50,868 nm^2) (Tables 4&5, Figure 13). In the 1996 sardine egg pump survey, the egg production was 2.86/0.05m^2 (CV=0.75) and the spawning biomass was 424,053 short tons for an area of 156,717 km^2.

The CV (0.14) of daily egg production in 1998 was lower than the CV (0.21) of estimate in 1997, because staged sardine eggs from both CUFES and CalVET were included in the estimation procedures of egg production in 1998. Moreover, in 1997, egg density in low density area was prorated from CUFES data, which introduced extra variance to the estimate of egg production in 1997. In 1998, spawning biomass was estimated in Region 1 only and no proration was necessary. Although the CalCOFI survey pattern did not use egg counts from CUFES to allocate CalVET samples, the data of staged sardine eggs from the CUFES and yolk-sac larvae did contribute information to the estimation of daily egg production.

Egg mortality in 1998 (Z=0.20; CV=0.19) was slightly lower than the estimate in 1997 (Z=0.35; CV=0.14) and CV for 1998 was slightly higher than that in 1997.

Spawning Area

Methods used for estimating spawning area in past assessments (1983-97) are described in Barnes et al. (1997) and Hill et al. (1998). For the current assessment, spawning areas were recalculated over the entire time series (1983-1998) using all available geographic information on sardine egg distribution from CalCOFI and DEPM cruises. Sampling gears included bongo nets, CalVET nets, and CUFES. Standard CalCOFI bongo tows sample to a maximum depth of 250 m, CalVET tows to 100 m, and CUFES down to 3 m.

Geographic Information System software (ArcView™, GIS) was used to generate annual maps of egg distributions based on bongo (1983-1998), CalVET (1983-1998), and CUFES (1996-1998) samples. Complex polygons were drawn around major egg concentrations, and the area of each polygon was calculated using GIS. Polygon areas were summed to give total spawning area (square nautical miles) per calendar year.

The 1998 total spawning area estimate of 33,447 nmi^2 decreased 18% from the 1997 estimate of 40,592 nm^2 (Table 4, Figure 14). Sardine eggs were distributed along the entire latitudinal range of the sampling area (San Diego to Monterey Bay), but were generally closer to shore in 1998, thus contracting the total apparent spawning area. Predicted values fit well to the observed data and residuals were not serially correlated.

Aerial Spotter Data

Spotter pilots were employed by wetfish fishermen to help locate and capture fish schools. The pilots were also contracted by National Marine Fisheries Service (NMFS) to complete and submit logbooks, creating a record of their observations from each flight. Data recorded include species identification, school size (metric tons), and geographic location for all observed fish schools, regardless of target species for a particular flight or fishing operation. An index of relative abundance of schooling sardine was obtained from spotter data using a delta-lognormal model developed by Lo et al. (1992). Data for 1997-1998 were tabulated using a July through June fishing year, consistent with analyses in previous years. The resulting 1997-98 index showed a 78% increase from the value of the previous fishing year (Table 4, Figure 15), but the overall trend in this index of relative abundance may have reached its asymptote over the past three years.

Like the CalCOFI index, the spotter index covers a relatively small portion of the total sardine distribution (Figure 8). Spotter pilot effort tends to be nearshore, southerly, and within the range of the wetfish fleet (Figure 16). Sardine sightings are also primarily concentrated in nearshore areas where the majority of spotter and fishing effort occurs (Figure17). Large quantities of sardine were recorded both in the nearshore regions of the Southern California Bight as well as the entire Monterey Bay area. Based on our knowledge of sardine egg distributions, it is highly likely that the area of the stock extends well beyond the area of this survey, which has a northern bound of Half Moon Bay, south of San Francisco (Figure 16). Like the CalCOFI index, we accommodated index saturation in our assessment model by assuming the aerial spotter index was a nonlinear function of sardine biomass. Suspected saturation was dealt with by using an exponential function. To estimate the degree of saturation in the index, we regressed log spotter index values on log biomass estimates. The slope of the regression line (β=0.5171) was used in CANSAR-TAM as an exponent to adjust predicted spotter values for saturation. No trend was apparent in residuals, and the model adequately fits the data (Figure 15).

Weighting Factors Used for Abundance Index and Catch Data

The relative influence of input data on biomass estimates from CANSAR-TAM can be controlled by specifying weighting factors (λ_r) for each data type (r) (Deriso et al. 1996). Weights $\delta_{r,j}$ may also be applied to observations (j) within a data type (r) to account for relative precision or variance of each observation.

For the 1998 assessment, we chose to weight equally catch-at-age and fishery-independent data types to λ_r=1.0, as was the case for the 1997 assessment (Hill et al. 1998). Weights for individual observations within data type ($\delta_{r,j}$) were set to 1.0 for survey indices and catch data. We set weighting for spawner-recruit estimates to a small value (λ_{SR}= 0.1) because recruitment

variability is large for sardine (Jacobson and MacCall 1995). However, to obtain more reasonable estimates of recruitment and biomass for recent years, we increased weights on spawner-recruit predictions for 1996-98 to $\delta_{r,j} = 5.0$, 7.5, and 10.0, which, with $\lambda_{SR} = 0.1$ gave total effective weights on spawner-recruit predictions of 0.5, 0.75, and 1.0 for those years, respectively. Thus the spawner-recruit calculations for 1998 were given the same weight in parameter estimation as a catch or abundance datum (Deriso et al. 1996).

SARDINE ABUNDANCE ESTIMATES

Previous sardine assessments have revealed major uncertainty regarding availability of older sardine (age 3+) to the fishery (e.g., Barnes et al. 1997). Past assessments indicated that the population was composed mostly of new recruits which dominated the fishery age composition data due to their high abundance (Figure 18). An alternative explanation for lack of older fish in fishery samples was that these sardine moved to northern or offshore areas where fishing did not occur.

The notion that older, larger sardine were unavailable and not selected by the fishery compelled us to address effects of migration on biomass available to the fishery. This biological uncertainty is important because biomass estimates might be higher if older fish exist but were unavailable to the fishery. In an effort to address these uncertainties, we developed a Two-Area Migration Model (CANSAR-TAM; Hill et al. 1998) based on the original CANSAR model. CANSAR-TAM provided biomass estimates both within and outside the range of the fishery and survey data without radically changing the data or modeling approach. For comparison, we also estimated sardine biomass using the original CANSAR model used in previous assessments.

CANSAR TWO-AREA MIGRATION MODEL

Fishing mortality rates estimated by the original CANSAR were unreasonably large for the oldest age groups and the problem was pronounced for estimated rates during the first semester (Table 6). The results show that selectivity patterns are implausible with very low selectivities on all but the oldest fish. A biological interpretation of these results is that estimated abundances of old fish are not large enough to account for the observed catch, particularly during the first semester. This problem has become more pronounced over the last two years and indicates serious problems in model structure. The goal in working with our two-area migration (CANSAR-TAM) model was to determine if more reasonable fishing mortality rate and selectivity estimates could be obtained from the fishery as a whole based on assumptions about migration.

Barnes et al. (1997) attempted to solve these problems by re-estimating egg production rates (used to estimate model parameters) for young fish and by applying several types of assessment

models. Deriso et al. (1996), in contrast, did not report any difficulties with estimated fishing mortality rates or selectivities. Based on results from several models, data not included in assessment models, and anecdotal information, Barnes et al. (1997) concluded that sardine biomass estimates from CANSAR for later years should be regarded as regional estimates because fish likely existed outside the geographic range of the available data. They suggested that sardine had moved beyond the area utilized by the fishery, data, and model as sardine abundance increased during the 1980s and 1990s.

CANSAR-TAM assumes two habitat areas. Sardine in Area 1 are "inside" and assumed to be adequately sampled by the fishery and abundance indices. Sardine in Area 2 are "outside" and completely unavailable to the fishery or abundance indices. Area 2 includes areas that might be to the north, south or offshore of Area 1. Area 1 is likely centered around the Southern California Bight where most of our fishery and abundance data were collected. In contrast to CANSAR-TAM, the original CANSAR model assumes Area 1 only.

Sardine move from Area 1 to Area 2 in the CANSAR-TAM model but there is no movement back from Area 2 to Area 1. Unidirectional movement may be unrealistic because sardine during the historical fishery were thought to migrate north to feed and south to spawn on an annual basis (Radovich, 1982) and because sardine in the southern stock off Baja California may migrate seasonally (Felix-Uraga et al., 1996). This is a concept for future research.

CANSAR-TAM Model Calculations

As far as the fishery and abundance indices in Area 1 are concerned, natural mortality and emigration are indistinguishable in the CANSAR-TAM model because both result in permanent losses of fish from Area 1. However, this model extends the original CANSAR to adequately account for net emigration. This confounding of natural mortality and migration in Area 1 is the central idea behind the CANSAR-TAM model.

The "apparent" rate of natural mortality in Area 1 for sardine age a during year y and semester s is:

$$M_{y,s,a} = m + \mu_{y,s,a} \qquad [3]$$

where m=0.2 sem^{-1} (equivalent to 0.4 yr^{-1}) is the assumed instantaneous rate for deaths from natural causes and $\mu_{y,s,a}$ is an instantaneous emigration rate parameter that is time- and age-dependent. In theory, CANSAR would measure sardine abundance and biomass in Area 1 if the apparent rate of natural mortality $M_{y,s,a}$ was used instead of m=0.2 in calculations (see below).

In the CANSAR-TAM model, migration rates (Table 7, Figure 19a) were calculated:

$$\mu_{y,s,a} = v_{y,s}\,\phi_a \qquad [4]$$

where $v_{y,s}$ was a year- and semester-specific migration multiplier (constrained to the interval [0,1]) and $\phi_a \geq 0$ was an age-specific emigration parameter. We assumed that migration was more common in recent years with highest biomass than in early years with low biomass. Based on this *ad-hoc* assumption and trial model runs, we used $v_{y,s}$ values that increased linearly from zero in 1983 to 1.0 in 1992-1997 (Table 7, Figure 19a). The change from an increasing trend to constant maximum emigration rates in 1992 coincided with the 1992-1993 El Niño when age zero fish became more common in U.S. fishery, pure sardine loads became more common, weight-at-age in the U.S. fishery declined dramatically (Figure 4), more than 1,000 tons of sardine were landed in Monterey, and sardine were reported off Vancouver Island, B.C. (Hargreaves et al. 1994).

We assumed that semester-specific migration rates parameters ϕ_a were zero for sardine in the first year of life and increased as a function of body length to 0.2 at age 5+ (Figure 19b). We assumed that the ability to emigrate from Area 1 was a function of minimum swimming speed, which has been shown to be proportional to body length ($L^{0.6}$) in other small pelagic fishes (Hunter 1971). This proportional relationship was applied to sardine mean length-at-age and rescaled from zero at age 0 to a maximum of 0.2 at age 5+ (Figure 19b). This choice seemed reasonable because sardine (Butler et al. 1996) and other pelagic fish (Parrish et al. 1985) off the west coast are distributed with the largest individuals to the north and offshore and probably beyond the range of our data and fishery.

Abundance and biomass estimates for sardine in Area 1 were obtained by running CANSAR-TAM with the apparent rates of natural mortality ($M_{y,s,a}$) substituted for m. In this mode, CANSAR-TAM and CANSAR are identical except for the assumed rates m and $M_{y,s,a}$. Estimates of sardine abundance and biomass in Area 2 were based on the output for Area 1 and calculations described below.

The number of recruits in Area 2 on 1 July of each year (the beginning of the second semester) was assumed to be a fraction θ_y of total recruitment. Number of recruits $R_{y,2}$ in Area 2 was:

$$R_{y,2} = \frac{\theta_y}{1-\theta_y} R_{y,1} \qquad [5]$$

where $R_{y,1}$ was the number of recruits (already estimated) for Area 1. Like migration parameters, the recruitment fractions $\theta_y = \gamma\zeta_y$ were the product of a scaling parameter γ=0.2 and

year specific multipliers ζ_y (both constrained to the interval [0,1]). For all model runs, γ was assumed to increase in proportion to estimated biomass in Area 2. This ad-hoc assumption means that the proportion of total recruitment in Area 2 increased to a maximum of 0.2 at a rate that was roughly in proportion to sardine biomass in Area 2 (Figure 20).

After-recruitment abundance of sardine in Area 2 was the sum of surviving migrants from Area 1 during the previous semester and the surviving sardine already in Area 2. The number $n_{y,2,a}$ of sardine that migrated from Area 1 during semester 1, survived, and were counted at the beginning of semester 2 in Area 2 was:

$$n_{y,2,a} = \frac{\mu_{y,1,a-1}}{Z_{y,1,a-1}} (1-e^{-Z_{y,1,a-1}}) A_{1,y,1,a-1} e^{-m} \qquad [6]$$

where $A_{1,y,1,a-1}$ was the number of sardine in Area 1 at the beginning of semester 1 and $Z_{y,1,a}=m+\mu_{y,1,a}$ was the total "apparent" mortality rate in Area 1. A similar calculation for semester 1 was:

$$n_{y,1,a} = \frac{\mu_{y-1,2,a}}{Z_{y-1,2,a}} (1-e^{-Z_{y-1,2,a}}) A_{1,y-1,2,a} e^{-m} \qquad [7]$$

The subscripts for age and year differ in equations [6] and [7] because the birthday for sardine is assumed to be 1 July (the beginning of the second semester) rather than the beginning of the calendar year.

The number of sardine already in Area 2 at the beginning of semester 1 that survive natural mortality and counted at the beginning of semester 2 was:

$$k_{y,2,a} = A_{2,y,1,a-1} e^{-m} \qquad [8]$$

and the equivalent calculation for semester 1 was:

$$k_{y,1,a} = A_{2,y-1,2,a} e^{-m}. \qquad [9]$$

The age and year specific abundance in Area 2 was $N_{2,y,s,a}=n_{y,s,a}+k_{y,s,a}$. We assumed population weights-at-age were the same in both areas so that the "total" biomass in areas 1 and 2 was $B_{y,s,a} = S(A_{1,y,s,a} + A_{2,y,s,a}) w_{y,s,a}$.

To obtain estimates of age and year specific fishing mortality rates $F_{y,s,a}$ for the sardine stock as a whole (Area 1+Area 2), we solved the catch equation:

$$C_{y,s,a} = \frac{F_{y,s,a}}{Z_{y,s,a}} (1 - e^{Z_{y,s,a}}) (N_{1,y,s,a} + N_{2,y,s,a}) \qquad [10]$$

where $C_{y,s,a}$ was the total catch in number for Area 1 and $Z_{y,s,a}=F_{y,s,a}+M_{y,s,a}$. Selectivities at age for the sardine stock as a whole were calculated by scaling year and age specific fishing mortality rates so that the largest was equal to 1.0.

MODELING RESULTS

Age 2 fish were an important component of the catch in all years, and they may be used to explore the least squares fit between observed catch-at-age and model predictions. Catch of age 2 fish during the first semester of each year parallels the upward trend in landings (Figure 21). Regression analysis residuals (observed age 2 catch minus CANSAR-TAM predicted age 2 catch) were not serially correlated, and the model appeared to fit these data.

To improve the fit between model predictions and the catch-at-age data, we used different age-specific fishery selectivities: 1) during 1983-1992 when the range of the stock was largely confined to waters south of Point Conception and 2) during 1993-1998 when the directed fisheries became more significant and the stock began to expand beyond the Southern California Bight (Figure 22).

CANSAR-TAM Model Abundance Estimates

As expected, the CANSAR-TAM gave higher biomass estimates in Area 1 (within the range of the fishery) than original CANSAR due to the higher assumed value of apparent natural mortality (Figure 23). In effect, CANSAR-TAM had to estimate higher recruitments and abundance levels to account for losses (i.e., apparent mortality) due to net emigration. Biomass estimates for the entire stock (Areas 1+2) were substantially larger than for Area 1 and increases due to recruitment in Area 2 were about the same as increases due to migration. Fishing mortality rates (Table 6) and selectivity estimates (Table 8) from CANSAR-TAM for the stock as a whole were more plausible than estimates from CANSAR and had few large values for the oldest age groups.

Complicated models such as CANSAR and CANSAR-TAM can converge to local rather than global minima when estimated with limited data (Deriso et al. 1996). To test for this, we reran CANSAR-TAM 30 times using different initial parameter values to confirm that our final

estimates were at the global minima.

Based on CANSAR-TAM, we estimate the July 1, 1998 Area 1 (inside the range of the fishery and survey data) biomass to have been 1,182,881 tons (95% confidence interval = 735,539 - 2,232,096 tons, based on 1,000 bootstrap runs). This estimate includes a bias correction based on bootstrap results. The CANSAR-TAM estimate of total biomass (Areas 1 and 2) was 1,783,551 short tons. This estimate is speculative, but provides an approximation of coastwide population biomass. Sardine biomass (Age 1+) has increased dramatically from 1983 to 1998 (Table 9, Figure 24). Current biomass estimates for both Area 1 (inside) and Areas 1 and 2 (total) exceed the 1 million ton criteria established to define recovery of the sardine population.

Preliminary results from the experimental sardine assessment model, SAM (Appendix A), provided comparable biomass estimates to CANSAR and CANSAR-TAM. Under a one area configuration (no migration), SAM estimated 1,066,358 tons, compared to 892,711 tons from CANSAR with no migration (Table 9, Figure 23). Configured as a two area model, SAM estimated 1,988,669 tons for the whole population, which is similar to the total or 'coastwide' biomass of 1,783,552 tons from CANSAR-TAM (Table 9, Figure 23). While SAM holds much potential for application in future sardine stock assessments, a decision was made to continue use of CANSAR-TAM for management of the 1999 fishery. The reader is referred to Appendix A for detailed discussion of SAM.

CANSAR-TAM Model Discussion

Sardine appear to migrate and recruit in areas that are not covered by fishery or survey data. Abundance estimates from CANSAR *for the area covered by the fishery and survey data* (*i.e.* Area 1) are, therefore, biased low. Estimates of sardine abundance from CANSAR-TAM for Area 1 are more reliable in principle but, as indicated above, assumed migration rates were crude guesses and CANSAR-TAM estimates depend on several assumptions (see below). It is particularly important to remember that CANSAR-TAM estimates for the area not covered by the fishery or survey data (Area 2) are crude guesses that are meant only to indicate the potential importance of sardine outside the area covered by the fishery and survey data.

The use of complicated migration models could be avoided if abundance surveys could be extended over the entire coast. In the absence of coast wide survey data, migration parameters are a key uncertainty. A number of issues need to be resolved if sardine migration models are to be further developed.

We assumed that the area covered by the fishery and our abundance data were the same even though our abundance data likely cover a much broader geographic range. The fishery operates primarily nearshore and around islands while CalCOFI data, for example, cover the

entire California Bight out to about 200 miles. In a more realistic model, areas covered might differ among surveys and the fishery. Nonlinear relationships between abundance indices and sardine biomass, assumed in both CANSAR and CANSAR-TAM, account for changes that are expected to occur as sardine biomass increases beyond the range of the survey.

The CANSAR-TAM model assumed that migrants were permanently lost from Area 1, even though some seasonal migration in and out of Area 1 is likely. CANSAR-TAM gave higher estimates of fishing mortality for old fish during semester 1 than during semester 2. This may result from differences in abundance of old fish between semesters due to seasonal spawning or feeding migrations. In future models, it might be necessary to include seasonal movement patterns.

The change in migration patterns we assumed during 1992-1993 occurred during a change in selectivities for the U.S. fishery assumed in CANSAR and CANSAR-TAM. Deriso et al. (1996) hypothesized that the apparent change in selectivities was due to a change in the fishery from incidental to directed catches as abundance increased. Our results suggest that changes in selectivity and migration (availability) are likely confounded.

The largest sardine tend to be further north and offshore and outside the range of the current sardine fishery. Thus, weights at age may be larger in Area 2 than in Area 1. An improved model might require different weights at age for sardine inside and outside of Area 1. The CANSAR-TAM model assumes two areas and estimates sardine biomass within each, but we cannot describe the geographic boundaries for Area 2.

FISHERY MANAGEMENT

BACKGROUND

Current regulations give considerable latitude to the Department in setting annual sardine harvest quotas. Section 8150.7 of the California Fish and Game Code states that the quota can be set at a level greater than 1,000 tons, providing that the biomass is found to be in excess of 20,000 tons and the added level of take allows for continued increase in the spawning population. The primary goal of management is rehabilitation of the resource, while maximizing sustained harvest. The sardine population biomass has increased dramatically in recent years, and the stock has now surpassed the one million ton level that defines stock recovery (established during the Department's annual Sardine Biomass Workshops, 1989-1993). Moreover, the stock has expanded to occupy its historic geographic range (Baja California to Vancouver, British Columbia), and historic age classes are represented.

THE RECOMMENDED 1999 QUOTA

To calculate the recommended 1998 fishery quota, we used the Pacific Fishery Management Council's (PFMC) preferred MSY control rule defined in Amendment 8 of the Coastal Pelagic Species-Fishery Management Plan (Option J; Table 4.2.5-1 in PFMC 1998) (Table 10). As part of the CPS-FMP review process the formula underwent extensive scientific and user-group review and received the endorsement of the fishing industry and the scientific community. A decision was made to recommend this formula as it should theoretically perform well at preventing overfishing and maintain relatively high and consistent catch levels over the long term.

The recommend harvest formula for sardine is:

$$\mathbf{H_{t+1} = (BIOMASS_t\text{-}CUTOFF) \times FRACTION \times STOCK\ DISTRIBUTION}$$

where H_{t+1} is the total California harvest (quota), CUTOFF is the lowest level of estimated biomass at which harvest is allowed, FRACTION is an environmentally-dependent fraction of biomass above CUTOFF that can be taken by fisheries, and STOCK DISTRIBUTION is the fraction of total $BIOMASS_t$ in U.S. waters. $BIOMASS_t$ is the estimated biomass of fish age 1+ for the whole stock at the beginning of season t.

Under Option J (PFMC 1998), formula values (CUTOFF weight converted from metric to short tons) for the 1999 California fishery are as follows:

BIOMASS	CUTOFF	FRACTION (F_{msy})	U.S. DISTRIBUTION	QUOTA
1,182,881	165,347	15%	87%	132,800

FRACTION in the MSY control rule for Pacific sardine is a proxy for F_{msy} (i.e., the fishing mortality rate for deterministic equilibrium MSY). FRACTION depends on recent ocean temperatures because F_{msy} and productivity of the sardine stock is higher under ocean conditions associated with warm water temperatures. An estimate of the relationship between F_{msy} for sardine and ocean temperatures is:

$$F_{msy} = 0.248649805\ T^2 - 8.190043975\ T + 67.4558326$$

where T is the average three season sea surface temperature at Scripps Pier, California during the three preceding seasons. Under Option J (PFMC 1998), F_{msy} varies between 5% and 15%.

The value for STOCK DISTRIBUTION was selected using average conditions over time. Since the sardine stock can undergo large fluctuations, the status of the stock in any given year may not match those average values used in the formula, particularly for STOCK DISTRIBUTION. However, it is not possible to routinely make adjustments to STOCK DISTRIBUTION as part of sardine management. No survey data were available covering the entire range of the stock in recent years. Subjective observations and geographically or temporally limited studies (e.g.: Bentley et al. 1996) were difficult to interpret on a year-by-year basis concerning STOCK DISTRIBUTION. The formula currently apportions 87% of the allowable harvest to the U.S. based on distributional analyses of spotter data.

LITERATURE CITED

Armstrong, M., P. Shelton, J. Hampton, G. Jolly, and Y. Melo. 1988. Egg production estimates of anchovy biomass in the southern Benguela system. Calif. Coop. Oceanic Fish. Invest. Rep. 29:137-157.

Barnes, J. T., M. Yaremko and D. Hanan. 1996. Status of the Pacific sardine resource and fishery, 1994 and 1995. Calif. Dept. of Fish and Game, MRD Admin. Rep. 96-1. 19p.

Barnes, J. T., M. Yaremko, L. Jacobson, N. C. H. Lo, and J. Stehly. 1997. Status of the Pacific sardine (*Sardinops sagax*) resource in 1996. NOAA-TM-NMFS-SWFSC-237.

Bentley, P. J., R. L. Emmett, N. C. H. Lo and G. Moser. 1996. Egg production of Pacific sardine (*Sardinops sagax*) off Oregon in 1994. Calif. Coop. Oceanic Fish. Invest. Rep. 37:193-200.

Butler, J. L. 1987. Comparisons of the larval and juvenile growth and larval mortality rates of Pacific sardine and northern anchovy and implications for species interactions. Ph. D. Thesis, Univ. Calif., San Diego, 240 pp.

Butler, J. L., M. L. Granados, J. T. Barnes, M. Yaremko, and B. J. Macewicz. 1996. Age composition, growth, and maturation of the Pacific sardine (*Sardinops sagax*) during 1994. Calif. Coop. Oceanic Fish. Invest. Rep. 37: 152-159.

Checkley, D. M. Jr., P. B. Ortner, L. R. Settle, and S. R. Cummings. 1997. A continuous, underway fish egg sampler. Fish. Oceanogr. 6(2): 58-73.

Cressie, N. 1991. Statistics for spatial data. John Wiley & sons, Inc., New York, Chichester, Toronto, Brisbane, Singapore. 900p.

Deriso, R., T. J. Quinn and P. R. Neal. 1985. Catch-age analysis with auxiliary information. Can. J. Fish. Aquat. Sci. 42:4.

Deriso, R. B., J. T. Barnes, L. D. Jacobson, and P. J. Arenas. 1996. Catch-at-age analysis for Pacific sardine (*Sardinops sagax*), 1983-1995. Calif. Coop. Oceanic Fish. Invest. Rep. 37:175-187.

Felix-Uraga, R., R. Alvarado-Castillo, and R. Carmona-Pina. 1996. The sardine fishery along the western coast of Baja California, 1981 to 1994. Calif. Coop. Oceanic Fish. Invest. Rep. 37: 188-192.

Goodman,L. A. 1960. On the exact variance of products. Journal of American Statistical Association, 55(292): 708-713.

Hargreaves, N.B., D.M. Ware, and G.A. McFarlane. 1994. Return of the Pacific sardine (*Sardinops sagax*) to the British Columbia coast in 1992. Can. J. Fish. Aquat. Sci. 51: 460-463.

Heimann, Richard F. G. and Carlisle, John G., Jr. 1970. The California Marine Fish Catch for 1968 and Historical Review 1916-68. Calif. Dept. of Fish & Game Fish Bulletin 149.

Hill, K.T., M. Yaremko, L.D. Jacobson, N.C.H. Lo, and D.A. Hanan. 1998. Stock assessment and management recommendations for Pacific sardine (*Sardinops sagax*) in 1997. Calif. Dept. Fish. Game. Marine Region Admin. Rep. 98-5. 53 pp.

Hunter, J. R. 1971. Sustained speed of jack mackerel, *Trachurus symmetricus*. Fish. Bull. 69(2):267-271.

Jacobson, L. J. and A. D. MacCall. 1995. Stock-recruitment models for Pacific sardine (*Sardinops sagax*). Can. J. Fish. Aquat. Sci. 52:566-577.

Lasker, R. 1985. An egg production method for estimating spawning biomass of pelagic fish: application to the northern anchovy (*Engraulis mordax*). NOAA Technical Report NMFS 36. 99p.

Lo, N. C. H., and R. D. Methot. 1989. Spawning biomass of the northern anchovy in 1988. Calif. Coop. Ocean. Fish. Invest. Rep. 30: 18-31.

Lo, N. C. H., L. D. Jacobson and J. L. Squire. 1992. Indices of relative abundance from fish spotter data based on delta-lognormal models. Can. J. Fish. Aquat. Sci. 49:2515-2526.

Lo, N. C. H., Y. A. Green Ruiz, Merecedes J. Cervantes, H. G. Moser, R. J. Lynn. 1996. Egg production and spawning biomass of Pacific sardine *(Sardinops sagax)* in 1994, determined by the daily egg production method. CalCOFI 37:160-174.

Macewicz B. J, J. J. Castro-Gonzalez, C. E. Cotero Altamirano, and J. R. Hunter. 1996. Adult reproductive parameters of Pacific Sardine (*Sardinops sagax*) during 1994 CalCOFI 37:140-151.

Mangel, M., and P. E. Smith. 1990. Presence-absence sampling for fisheries management. Can. J. Fisheries Aquat. Sci. 47(10):1875-1887.

Murphy, G. I. 1966. Population biology of the Pacific sardine (*Sardinops caerulea*). Proc. Calif. Acad. Sci. Vol. 34 (1): 1-84.

Parrish, R. H., and D. L. Mallicoate, and K. F. Mais. 1985. Regional variations in the growth and age composition of northern anchovy, *Engraulis mordax*. Fish. Bull, U.S. 483-496.

Petitgas, P. 1993. Geostatistics for fish stock assessments: a review and an acoustic application. ICES J. Mar. Sci., 50: 285-298.

PFMC 1998. Amendment 8 (to the northern anchovy fishery management plan) incorporating a name change to: the coastal pelagic species fishery management plan. Pacific Fishery Management Council, Portland, OR.

Radovich, J. 1982. The collapse of the California sardine fishery: what have we learned? Calif. Coop. Ocean. Fish. Invest. Rep. 23: 56-78.

Scannell, C. L., T. Dickerson, P. Wolf, and K. Worcester. 1996. Application of an egg production method to estimate the spawning biomass of Pacific sardines off southern California in 1986. Southwest Fisheries Science Center, National Marine Fisheries Service, Admin. Rep. LJ-96-01, 37 pp.

Wolf, P. 1988a. Status of the spawning biomass of Pacific sardine, 1987-1988. Calif. Dep. Fish Game, Mar. Res. Div., Rep. to the legislature, 9 pp.

Wolf, P. 1988b. Status of the spawning biomass of Pacific sardine, 1988-1989. Calif. Dep. Fish Game, Mar. Res. Div., Rep. to the legislature, 8 pp.

Yaremko, M. L. 1996. Age determination in Pacific sardine, *Sardinops sagax*. NOAA Tech. Mem. NOAA-TM-NMFS-SWFSC-223. 32 p.

Zweifel, J. R., and R. Lasker. 1976. Prehatch and posthatch growth of fishes - a general model. Fish. Bull. 74(3):609-621.

Table 1. Pacific sardine landings (short tons), 1983-1998.

Year	Semester	California	Ensenada	Total
1983	1	269.67	164.80	434.47
1983	2	269.02	136.80	405.82
1984	1	206.82	0.11	206.93
1984	2	206.50	0.11	206.61
1985	1	364.28	3,498.96	3,863.24
1985	2	369.15	604.18	973.33
1986	1	885.73	109.35	995.08
1986	2	532.48	158.07	690.55
1987	1	1,791.31	1,074.75	2,866.07
1987	2	1,428.06	1,605.63	3,033.68
1988	1	2,773.75	683.65	3,457.40
1988	2	1,776.23	1,559.44	3,335.67
1989	1	2,382.50	508.17	2,890.67
1989	2	1,720.80	6,350.64	8,071.43
1990	1	2,504.87	6,503.64	9,008.51
1990	2	1,138.62	6,035.49	7,174.11
1991	1	6,261.45	10,219.53	16,480.98
1991	2	3,697.10	24,384.01	28,081.11
1992	1	8,842.17	3,666.84	12,509.01
1992	2	14,568.19	34,438.09	49,006.28
1993	1	14,278.47	20,557.01	34,835.48
1993	2	5,389.16	14,766.57	20,155.72
1994	1	9,964.78	6,290.01	16,254.79
1994	2	5,522.78	16,716.56	22,239.33
1995	1	32,590.18	20,092.94	52,683.12
1995	2	15,349.26	18,924.49	34,273.74
1996	1	19,726.56	17,268.81	36,995.37
1996	2	20,019.06	25,792.99	45,812.05
1997	1	13,945.91	14,879.55	28,825.46
1997	2	36,510.60	60,561.66	97,072.26
1998	1	24,955.06	22,309.46	47,264.52
1998	2	16,534.67	44,092.46	60,627.14

Table 2. Pacific sardine quotas, landings, and revised allocations (short tons) for California's 1998 directed fishery.

Initial Allocation (January 1 to September 30)

	Quota	Landings	Remaining Quota
Statewide	48,000	25,468	22,532
Northern Allocation	16,000	3,670	12,330
Southern Allocation	32,000	21,798	10,202

Revised Allocation (effective October 1 to December 31)

	Revised Quota	Landings	Remaining Quota
Statewide	22,532	19,585	2,947
Northern Allocation	11,266	5,868	5,398
Southern Allocation	11,266	13,717	-1,537

Table 3. Estimated annual sardine revenue (millions of dollars; no inflationary adjustment) as a component of overall wetfish fleet ex-vessel value.

Year	Tuna	Anchovy	Jack mackerel	Pacific mackerel	Sardine	Squid	Total
1983	11.19	0.41	1.76	3.25	0.10	0.74	17.45
1984	11.39	0.49	1.38	5.06	0.17	0.30	18.79
1985	3.20	0.38	1.28	3.33	0.14	3.61	11.94
1986	8.16	0.33	0.82	3.60	0.24	4.81	17.96
1987	9.77	0.26	1.12	4.08	0.30	4.14	19.67
1988	11.48	0.35	0.86	5.03	0.52	7.84	26.07
1989	6.88	0.45	1.52	3.24	0.67	7.16	19.92
1990	4.60	0.60	0.43	4.16	0.30	4.88	14.97
1991	4.85	0.52	0.24	5.30	0.91	6.07	17.91
1992	2.98	0.21	0.25	4.17	1.68	2.49	11.79
1993	1.94	0.50	0.26	1.50	1.61	9.97	15.79
1994	4.27	0.53	0.36	1.29	1.42	15.98	23.85
1995	5.30	0.32	0.22	1.13	3.66	21.38	32.01
1996	6.45	1.02	0.29	1.27	3.11	29.24	41.38
1997	5.51	0.61	0.25	2.55	4.07	20.76	33.75

Table 4. Fishery-independent abundance data for Pacific sardine.

Year	CalCOFI Egg and Larvae Index	CV	DEPM Spawning Biomass (Short tons)	CV	Spawning Area (N mi^2)	CV	Aerial Spotter Index	CV	3-Season Scripps Pier SST (Deg C)
1983	--	--	--	--	40	--	--	--	17.80
1984	22.49	0.24	--	--	480	--	--	--	17.87
1985	15.80	0.27	--	--	760	--	--	--	17.71
1986	24.66	0.24	8,443	0.51	1,260	--	52,916	0.30	17.55
1987	28.89	0.24	17,312	0.91	2,120	--	13,669	0.35	17.24
1988	50.05	0.14	14,910	1.60	3,120	--	82,940	0.35	17.19
1989	47.16	0.14	--	--	3,720	--	48,965	0.38	17.17
1990	39.59	0.16	--	--	1,760	--	28,542	0.36	17.61
1991	74.66	0.07	--	--	5,550	--	52,501	0.31	17.84
1992	61.12	0.10	--	--	9,697	--	62,929	0.31	17.97
1993	51.35	0.14	--	--	7,685	--	101,246	0.31	18.04
1994	71.43	0.07	122,900	0.45	24,539	--	253,058	0.30	18.06
1995	42.47	0.16	--	--	23,816	--	251,539	0.31	18.05
1996	62.33	0.10	424,053	--	25,889	--	155,102	0.33	18.45
1997	53.45	0.12	396,039	--	40,592	--	84,314	0.37	18.54
1998	83.59	0.05	372,136	--	33,447	--	157,605	0.34	18.79

Table 5. Egg production of Pacific sardine in 1998 based on egg data from CalVET and CUFES pump in Region 1 only (stations <=70), and 1997 results: q is a ratio of egg density of Region 2 to Region 1 from pump samples, and R is the catch ratio of eggs/min. from pump to eggs/tow from CalVET.

	[1] 1998	[2] 1997		
Parameter	**Region 1**	**Region 1**	**Region 2**	**Wtd. Avg.**
n: pump	383	456	395	
n: CalVET	58	141	0	
p0/0.05m2	2.45	4.76	1.004	2.43
CV	0.14	0.18	0.45	0.21
Area	162,253	66,841	107,255	174,096
km2;%	100	38	62	100
Fish wt (W)	82.5			
Batch fecundity (F)	24283			
Spawning freq. (S)	[3] 0.149			
Sex ratio (R)				
Eggs/gm biomass (RSF/W)	23.55			23.55
Spawning biomass (mt)	**337,596**			**356,280**
Daily mortality (Z)	0.2	0.35		
CV	0.19	0.14		
eggs/min	1.95	4.16	0.47	[4] 1.86
CV	0.22	0.42	0.45	0.31
q				0.211
CV				0.43
R=eggs min-1/egg tow-1	0.32			0.25
CV	0.19			0.08

[1] In 1998, Region 1 includes stations<=70

[2] In 1997, Region 1 includes eggs/min>=2; Region 2 includes eggs/min<2

[3] Spawning frequency from Macewicz (1996)

[4] 1.86 is the unweighted mean

Table 6. Fishing mortality rates estimated using original CANSAR (no migration) and the CANSAR-TAM Model.

F AT AGE FOR SEASON 1 - CANSAR NO MIGRATION MODEL

AGE	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
0	0.003	0.001	0.001	0.000	0.001	0.000	0.001	0.000	0.001	0.001	0.028	0.014	0.038	0.015	0.007	0.010
1	0.136	0.043	0.022	0.012	0.026	0.016	0.022	0.011	0.033	0.038	0.097	0.050	0.131	0.050	0.025	0.036
2	0.513	0.163	0.081	0.044	0.097	0.062	0.083	0.043	0.125	0.142	0.109	0.056	0.148	0.057	0.028	0.041
3	0.593	0.188	0.094	0.051	0.112	0.071	0.095	0.050	0.144	0.164	0.136	0.070	0.184	0.071	0.035	0.051
4	0.584	0.185	0.093	0.050	0.110	0.070	0.094	0.049	0.142	0.161	0.197	0.101	0.266	0.102	0.051	0.073
5+	>9.999	7.861	3.928	2.131	4.681	2.984	3.981	2.082	6.025	6.835	>9.999	>9.999	>9.999	>9.999	>9.999	>9.999

F AT AGE FOR WHOLE POPULATION IN SEASON 1 - CANSAR TWO-AREA MODEL

AGE	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
0	0.001	0.000	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.001	0.006	0.001	0.000	0.001
1	0.017	0.003	0.022	0.001	0.003	0.001	0.001	0.001	0.003	0.002	0.008	0.003	0.024	0.003	0.002	0.003
2	0.067	0.013	0.076	0.004	0.011	0.004	0.004	0.004	0.011	0.008	0.013	0.005	0.053	0.006	0.003	0.004
3	0.121	0.017	0.197	0.005	0.021	0.006	0.005	0.008	0.017	0.009	0.019	0.007	0.069	0.007	0.005	0.006
4	0.236	0.020	0.368	0.006	0.041	0.010	0.007	0.014	0.026	0.010	0.024	0.009	0.049	0.003	0.006	0.009
5+	7.527	0.827	0.557	0.003	0.083	0.058	0.066	0.046	0.036	0.014	0.004	0.005	0.006	0.000	0.002	0.004

F AT AGE FOR SEASON 2 - CANSAR NO MIGRATION MODEL

AGE	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
0	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000
1	0.026	0.007	0.011	0.004	0.010	0.006	0.006	0.004	0.009	0.028	0.016	0.011	0.034	0.022	0.033	0.011
2	0.111	0.031	0.046	0.018	0.041	0.026	0.024	0.017	0.037	0.119	0.036	0.025	0.078	0.049	0.077	0.025
3	0.143	0.040	0.059	0.023	0.053	0.033	0.031	0.022	0.047	0.153	0.036	0.025	0.079	0.050	0.077	0.025
4	0.132	0.037	0.054	0.021	0.049	0.030	0.028	0.021	0.044	0.141	0.033	0.023	0.072	0.046	0.071	0.023
5+	0.349	0.098	0.143	0.056	0.129	0.080	0.075	0.055	0.116	0.374	0.040	0.028	0.087	0.055	0.085	0.027

F AT AGE FOR WHOLE POPULATION IN SEASON 2 - CANSAR TWO-AREA MODEL

AGE	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
0	0.001	0.000	0.001	0.000	0.001	0.000	0.001	0.000	0.001	0.002	0.001	0.001	0.001	0.001	0.001	0.001
1	0.030	0.005	0.016	0.003	0.012	0.007	0.011	0.007	0.021	0.041	0.018	0.017	0.021	0.017	0.031	0.012
2	0.150	0.024	0.075	0.015	0.055	0.030	0.050	0.029	0.087	0.165	0.058	0.062	0.055	0.052	0.097	0.038
3	0.302	0.036	0.162	0.026	0.116	0.062	0.109	0.060	0.180	0.297	0.102	0.124	0.064	0.085	0.171	0.071
4	0.358	0.037	0.148	0.028	0.128	0.067	0.119	0.062	0.175	0.258	0.073	0.105	0.015	0.056	0.147	0.063
5+	1.228	0.112	0.033	0.063	0.318	0.180	0.287	0.120	0.278	0.252	0.049	0.075	0.000	0.014	0.093	0.088

Table 7. Year-specific migration rates (sem^{-1}) assumed in the CANSAR-TAM model for sardine during semesters 1 and 2 of each year. Add m=0.2 (sem^{-1}) to calculate total "apparent" natural mortality rate ($M_{y,s,a}$).

AGE	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	Age-specific Migration rate:
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	0.000	0.014	0.027	0.041	0.055	0.068	0.082	0.095	0.109	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123
2	0.000	0.018	0.037	0.055	0.073	0.092	0.110	0.129	0.147	0.165	0.165	0.165	0.165	0.165	0.165	0.165	0.165
3	0.000	0.021	0.041	0.062	0.082	0.103	0.124	0.144	0.165	0.185	0.185	0.185	0.185	0.185	0.185	0.185	0.185
4	0.000	0.022	0.043	0.065	0.087	0.109	0.130	0.152	0.174	0.196	0.196	0.196	0.196	0.196	0.196	0.196	0.196
5+	0.000	0.022	0.044	0.067	0.089	0.111	0.133	0.155	0.178	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200
Year Multiplier:	0.000	0.111	0.222	0.333	0.444	0.555	0.666	0.777	0.888	1.000	1.000	1.000	1.000	1.000	1.000	1.000	

Table 8. Age- and year-specific fishing selectivities (sem^{-1}) from CANSAR-TAM model for sardine in semesters 1 and 2.

SELECTIVITIES FOR SEASON 1 - CANSAR NO MIGRATION MODEL

AGE	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.001	0.001	0.001	0.001	0.001	0.001
2	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.001	0.001	0.001	0.001	0.001	0.001
3	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.001	0.001	0.001	0.001	0.001	0.001
4	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.001	0.001	0.001	0.001	0.001	0.001
5+	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

SELECTIVITIES FOR WHOLE POPULATION IN SEASON 1 - CANSAR TWO-AREA MODEL

AGE	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
0	0.000	0.000	0.007	0.009	0.005	0.002	0.001	0.004	0.009	0.009	0.082	0.100	0.081	0.124	0.081	0.075
1	0.002	0.004	0.040	0.148	0.037	0.020	0.018	0.029	0.087	0.164	0.314	0.370	0.347	0.471	0.312	0.282
2	0.009	0.016	0.137	0.576	0.132	0.075	0.067	0.096	0.290	0.558	0.526	0.555	0.756	0.762	0.509	0.434
3	0.016	0.020	0.353	0.834	0.255	0.111	0.083	0.168	0.455	0.636	0.796	0.832	1.000	1.000	0.829	0.684
4	0.031	0.024	0.661	1.000	0.491	0.174	0.101	0.307	0.715	0.722	1.000	1.000	0.703	0.404	1.000	1.000
5+	1.000	1.000	1.000	0.434	1.000	1.000	1.000	1.000	1.000	1.000	0.156	0.582	0.086	0.007	0.349	0.502

SELECTIVITIES FOR SEASON 2 - CANSAR NO MIGRATION MODEL

AGE	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
0	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.004	0.004	0.004	0.004	0.004	0.004
1	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.395	0.395	0.395	0.395	0.395	0.395
2	0.318	0.318	0.318	0.318	0.318	0.318	0.318	0.318	0.318	0.318	0.905	0.905	0.905	0.905	0.905	0.905
3	0.410	0.410	0.410	0.410	0.410	0.410	0.410	0.410	0.410	0.410	0.909	0.909	0.909	0.909	0.909	0.909
4	0.377	0.377	0.377	0.377	0.377	0.377	0.377	0.377	0.377	0.377	0.835	0.835	0.835	0.835	0.835	0.835
5+	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

SELECTIVITIES FOR WHOLE POPULATION IN SEASON 2 - CANSAR TWO-AREA MODEL

AGE	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
0	0.001	0.002	0.005	0.002	0.002	0.002	0.002	0.003	0.004	0.007	0.007	0.007	0.009	0.007	0.006	0.005
1	0.025	0.044	0.098	0.051	0.038	0.038	0.040	0.056	0.074	0.137	0.175	0.140	0.333	0.204	0.181	0.135
2	0.122	0.216	0.465	0.239	0.172	0.168	0.173	0.242	0.314	0.555	0.571	0.499	0.861	0.613	0.570	0.438
3	0.246	0.319	1.000	0.421	0.366	0.342	0.380	0.504	0.648	1.000	1.000	1.000	1.000	1.000	1.000	0.811
4	0.291	0.334	0.912	0.443	0.404	0.369	0.413	0.520	0.629	0.868	0.710	0.853	0.234	0.664	0.862	0.725
5+	1.000	1.000	0.200	1.000	1.000	1.000	1.000	1.000	1.000	0.849	0.476	0.607	0.006	0.170	0.541	1.000

Table 9. Estimates of Pacific sardine age 1+ biomass (short tons, semester 2) estimated using CANSAR-TAM, CANSAR (no-migration), and SAM Models. CANSAR-TAM 'inside' biomass (bold type) was chosen to calculate the 1999 management quota.

	CANSAR TWO-AREA MODEL					CANSAR	SAM Models	
Year				Confidence Limits (Inside)		No Migration	1 Area	2 Area
(July 1)	**Inside**	Outside	Total	lower 95%	upper 95%	(1 Area Model)	Model	Model
1983	**6,721**	0	6,721	4,453	13,061	5,175	10,587	20,459
1984	**16,812**	75	16,887	12,529	27,619	12,283	9,675	19,330
1985	**27,265**	570	27,834	21,116	42,489	17,364	22,713	41,735
1986	**38,546**	1,890	40,435	30,834	57,915	23,248	29,748	53,979
1987	**89,858**	4,189	94,048	74,362	128,862	46,810	40,411	73,330
1988	**129,825**	11,077	140,902	109,055	177,968	67,176	46,341	86,420
1989	**193,172**	21,534	214,707	161,725	268,538	101,512	74,295	134,885
1990	**205,102**	36,526	241,628	168,885	292,078	114,804	108,734	192,297
1991	**254,654**	39,149	293,802	196,618	407,702	136,484	162,878	258,914
1992	**393,281**	68,851	462,132	295,987	623,549	216,778	223,284	377,015
1993	**372,922**	109,230	482,152	276,791	609,557	204,904	268,578	471,883
1994	**603,973**	162,236	766,209	476,698	942,109	340,804	393,932	685,274
1995	**749,763**	246,482	996,245	554,123	1,187,102	364,247	480,829	865,711
1996	**959,487**	343,554	1,303,041	702,372	1,569,126	514,016	568,647	1,040,658
1997	**1,142,985**	475,535	1,618,519	803,176	1,957,903	722,125	751,050	1,384,305
1998	**1,182,881**	600,670	1,783,552	735,539	2,232,096	892,711	1,066,358	1,988,669

Table 10. Pacific sardine quotas (short tons) for 1999. The statewide quota is based on the following formula and a CANSAR-TAM 'inside' biomass (age 1+) estimate of 1,182,881 short tons.

$$QUOTA = (BIOMASS_{inside} - 165{,}347) \times 15\% \times 87\%$$

Directed Fishery Quota (available 1/1/99)	**132,800 tons**
Southern California Allocation	88,500 tons
Northern California Allocation	44,300 tons

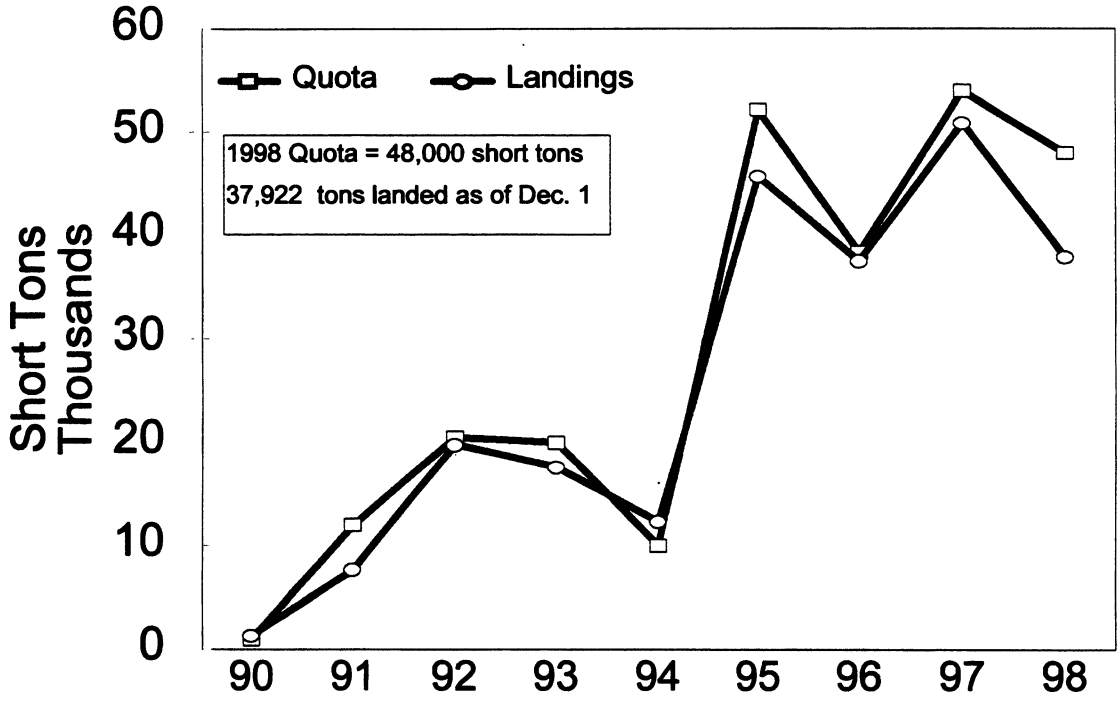


Figure 1. California sardine landings relative to quota, 1990-1998.

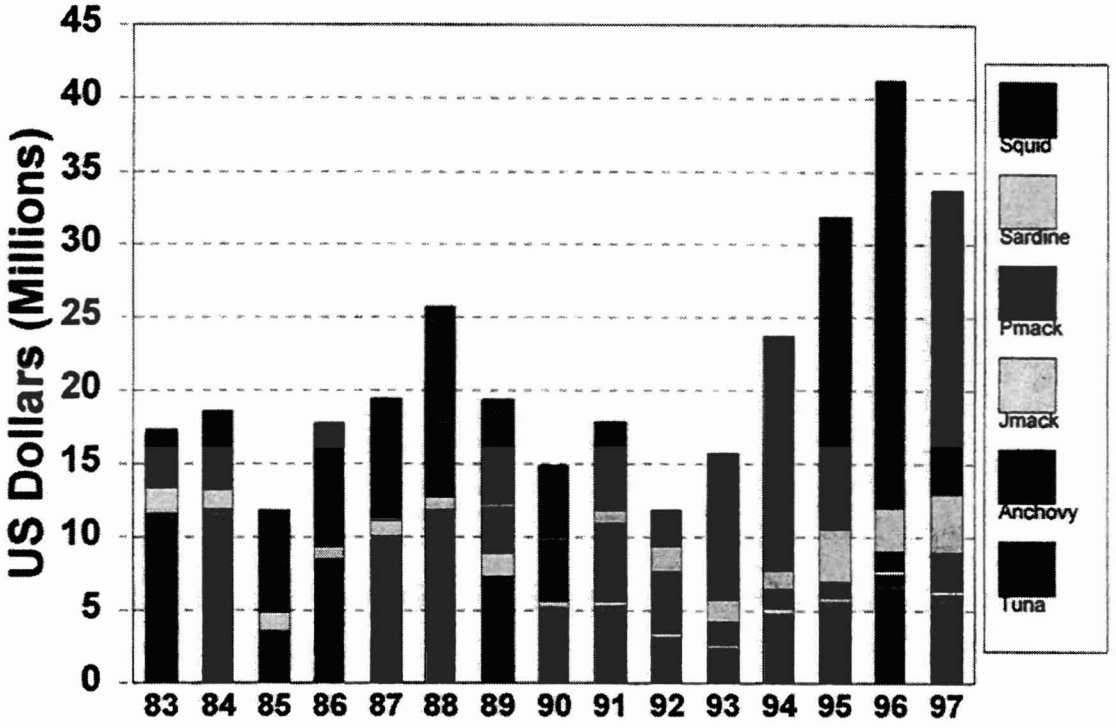


Figure 2. Estimated annual sardine revenues (millions of dollars; no inflationary adjustment) as a component of overall wetfish fleet ex-vessel value.

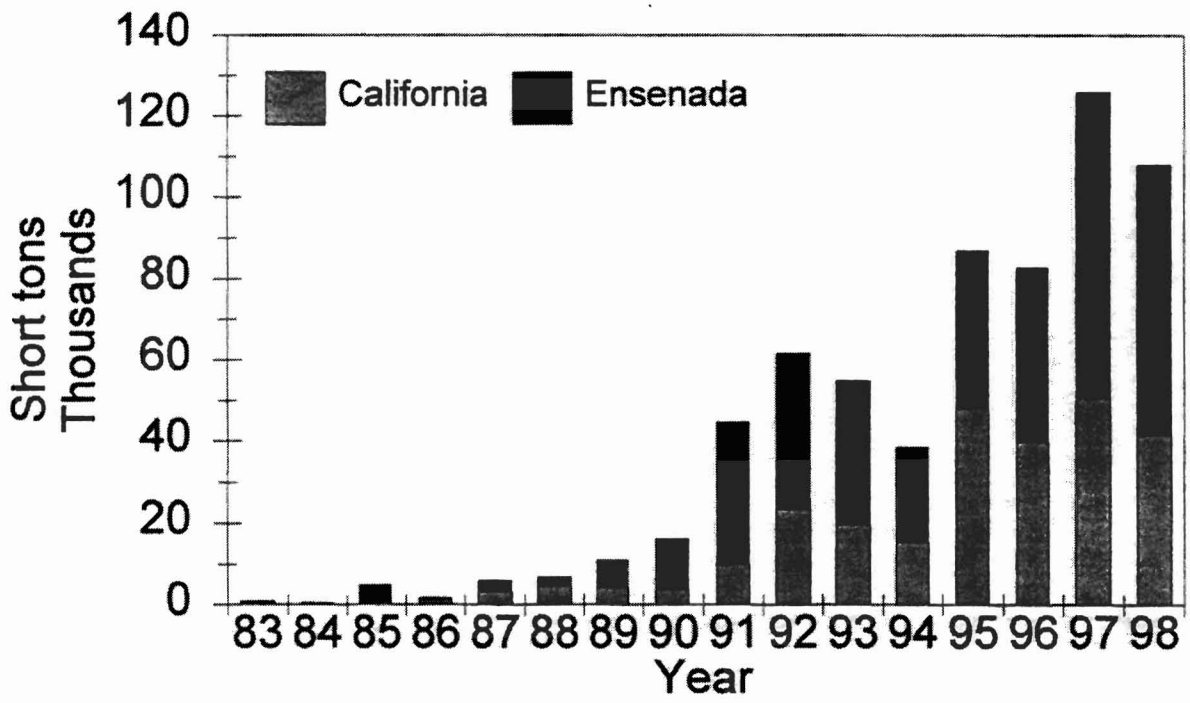


Figure 3. Annual sardine landings by directed fisheries in California and Ensenada, 1983 through 1998. Projected values were substituted for the remainder of 1998.

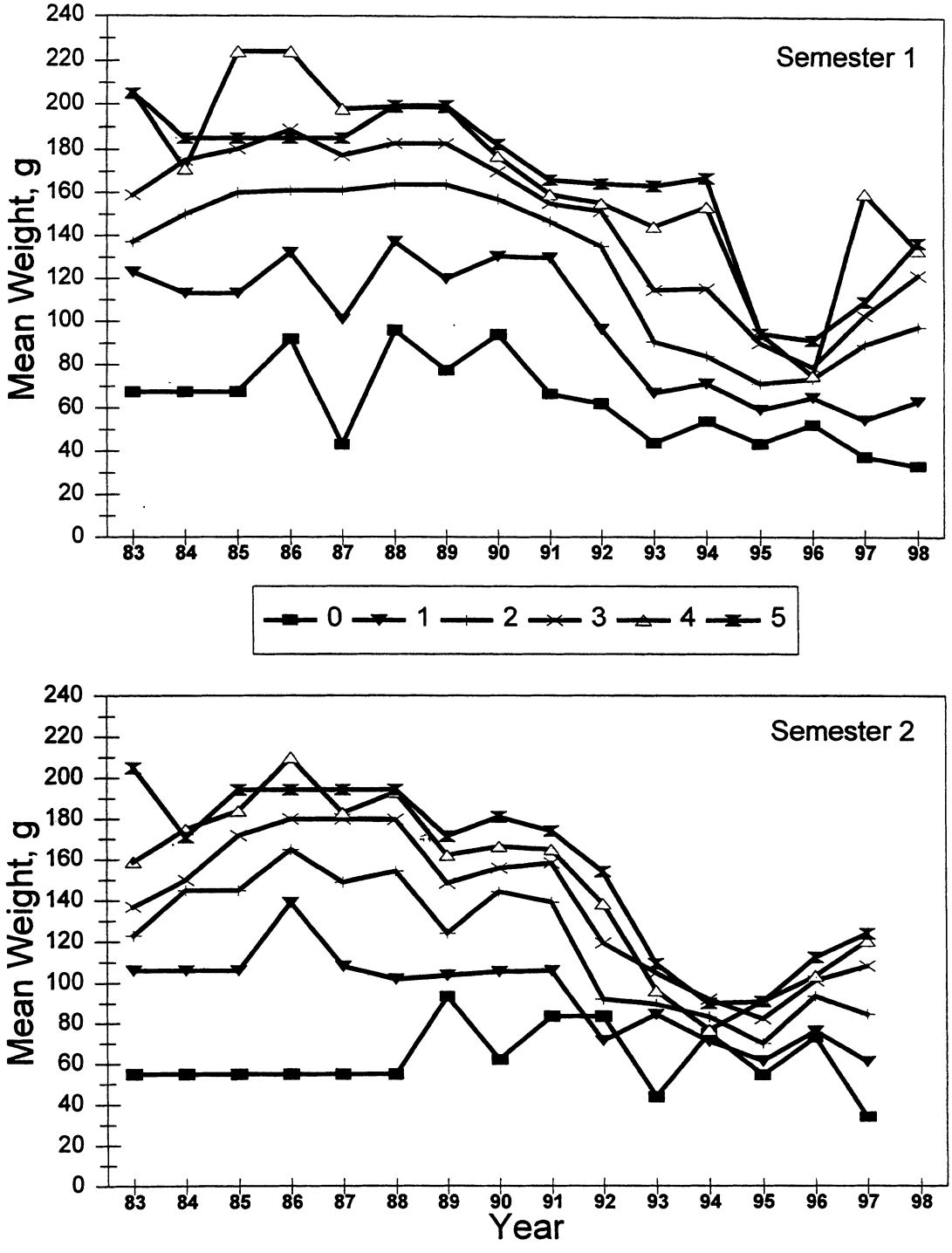


Figure 4. Pacific sardine weights-at-age for the California fishery, 1983-1998.

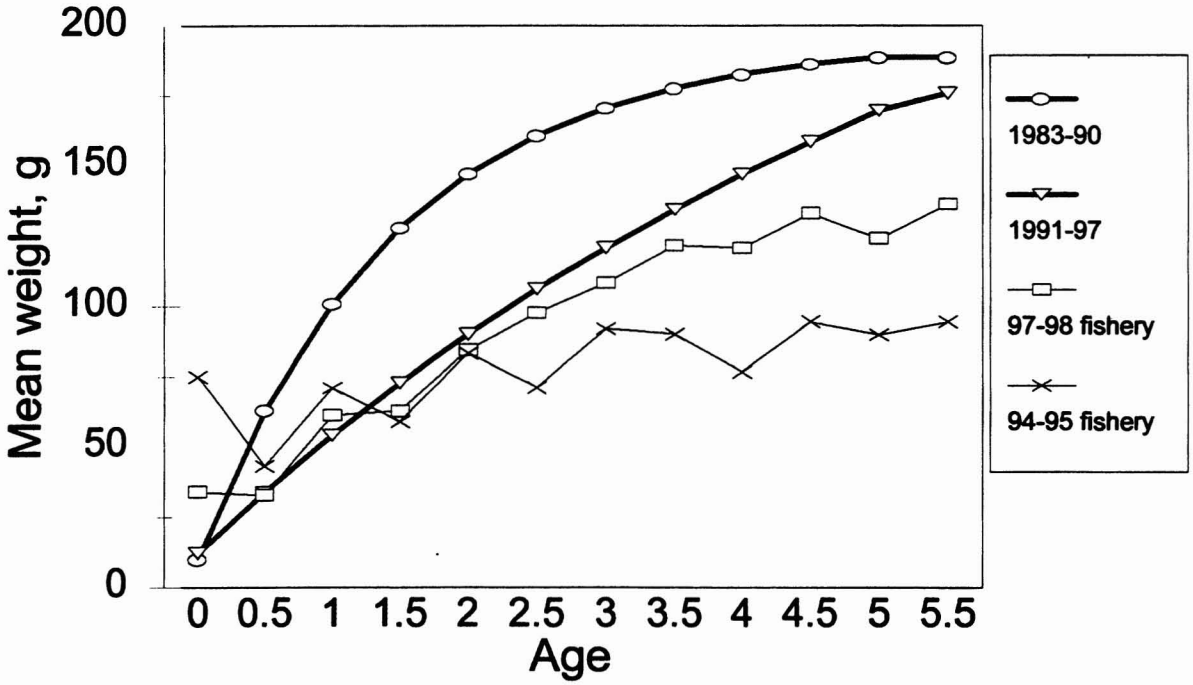


Figure 5. Sardine population weight-at-age estimates as applied in CANSAR-TAM for the periods 1983-90 and 1991-98. Mean weights-at-age for the 1994-95 and 1997-98 fisheries are shown for comparison.

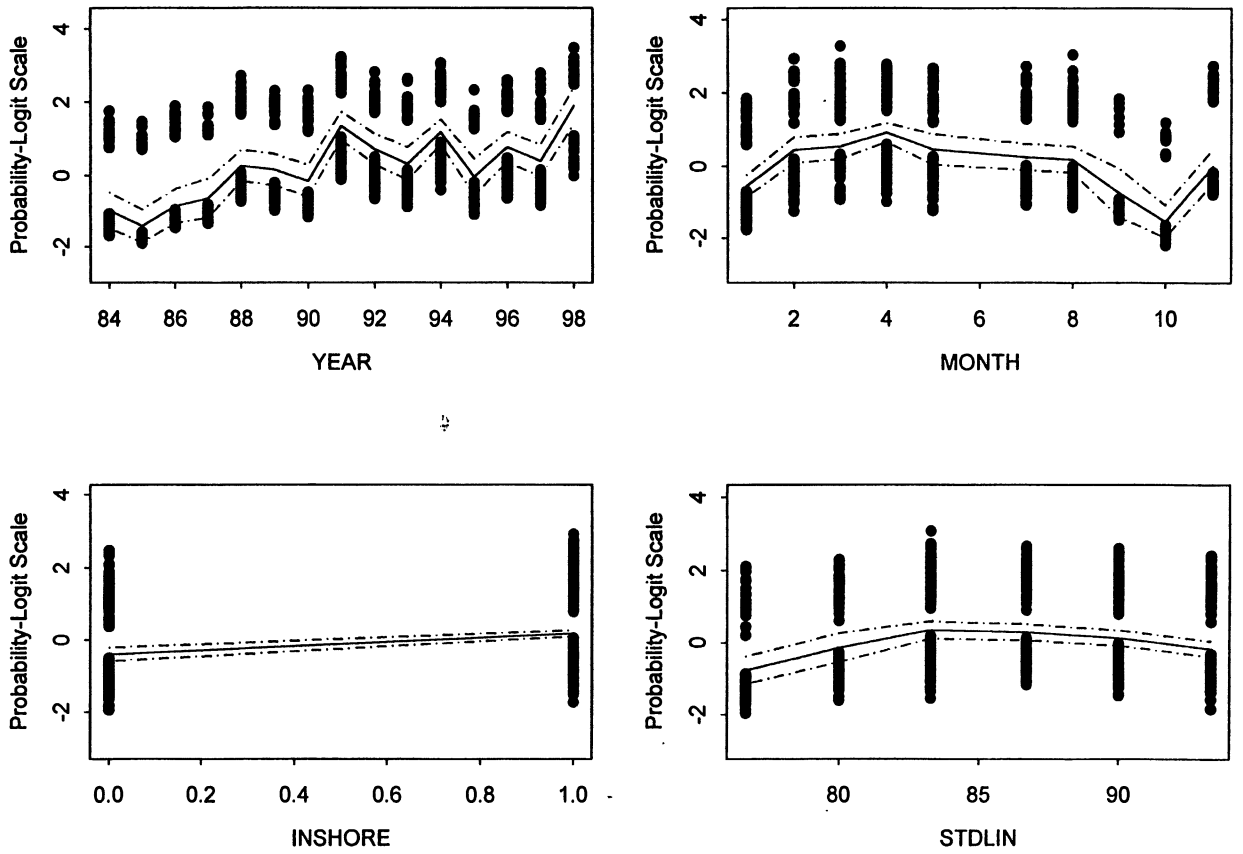


Figure 6. Fitted values and residuals (with approximate 95% confidence intervals) for a generalized additive model fit to CalCOFI data for Pacific sardine.

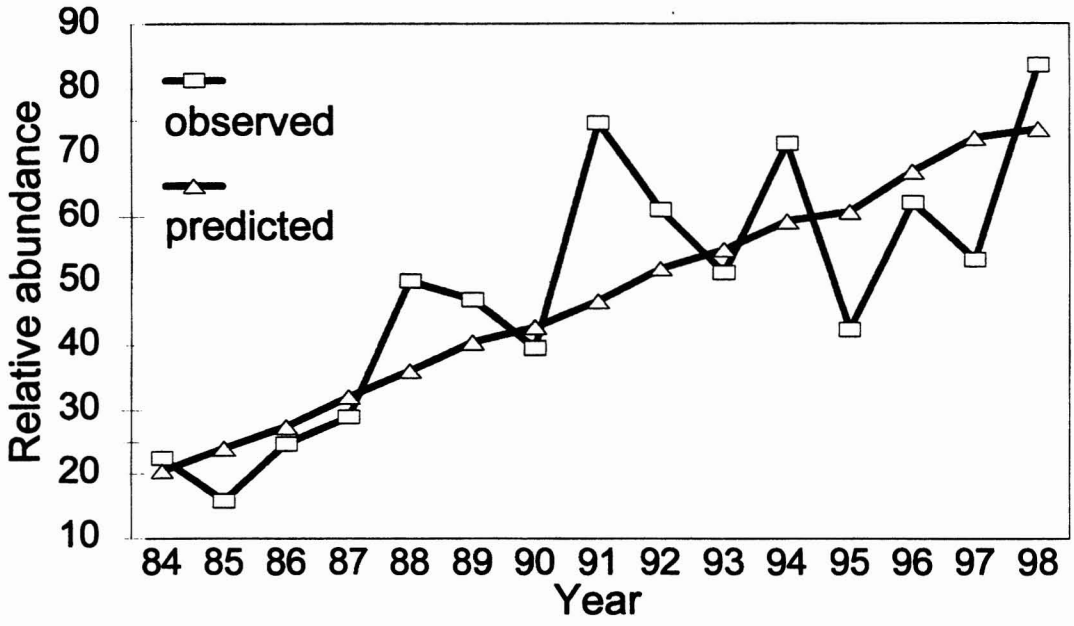


Figure 7. Observed and predicted CalCOFI egg and larvae index, 1984-98, Sept.-Oct. season, from CANSAR-TAM, 1998.

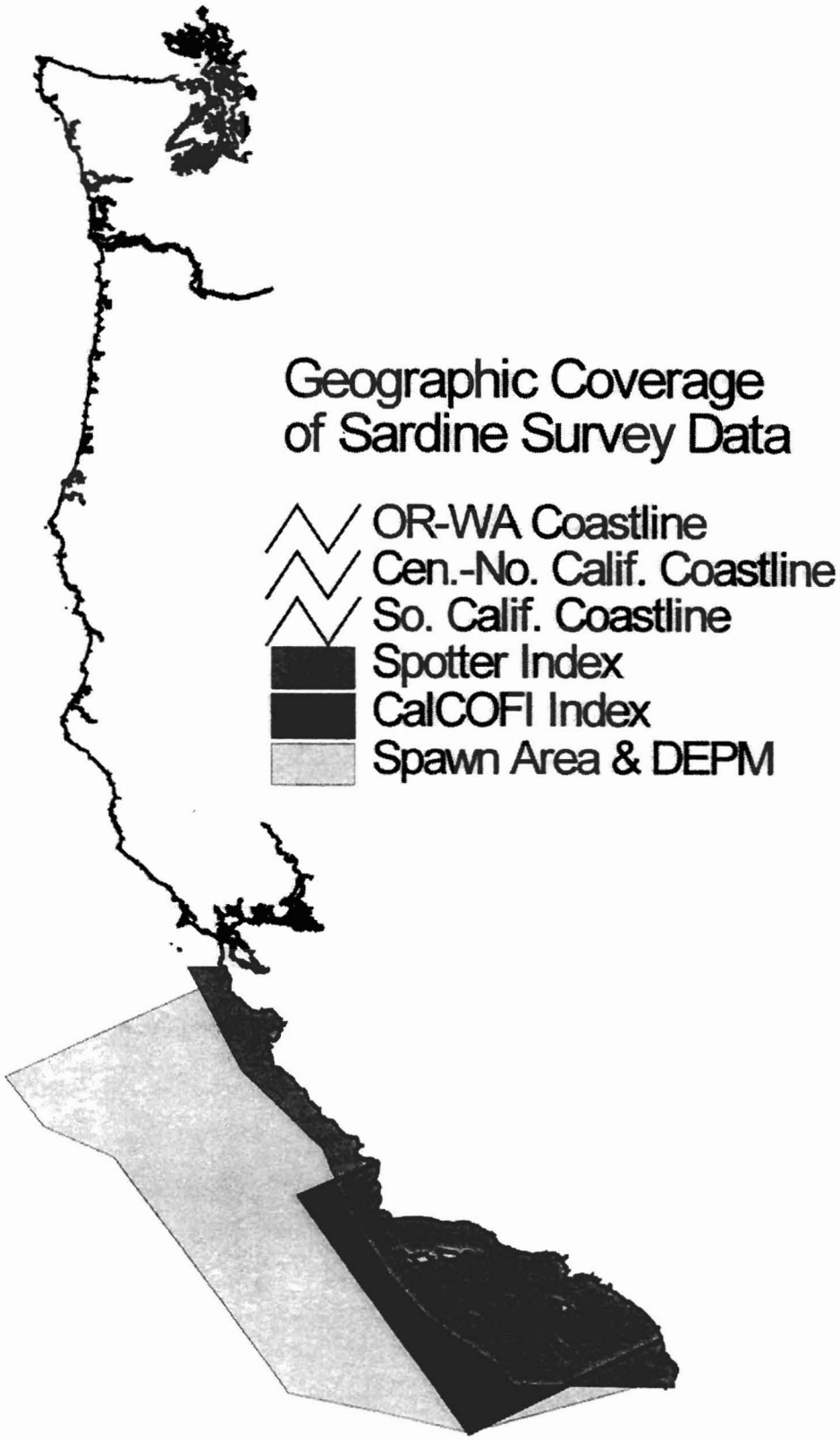


Figure 8. Geographic ranges covered by fishery-independent sardine indices used in CANSAR-TAM, 1998.

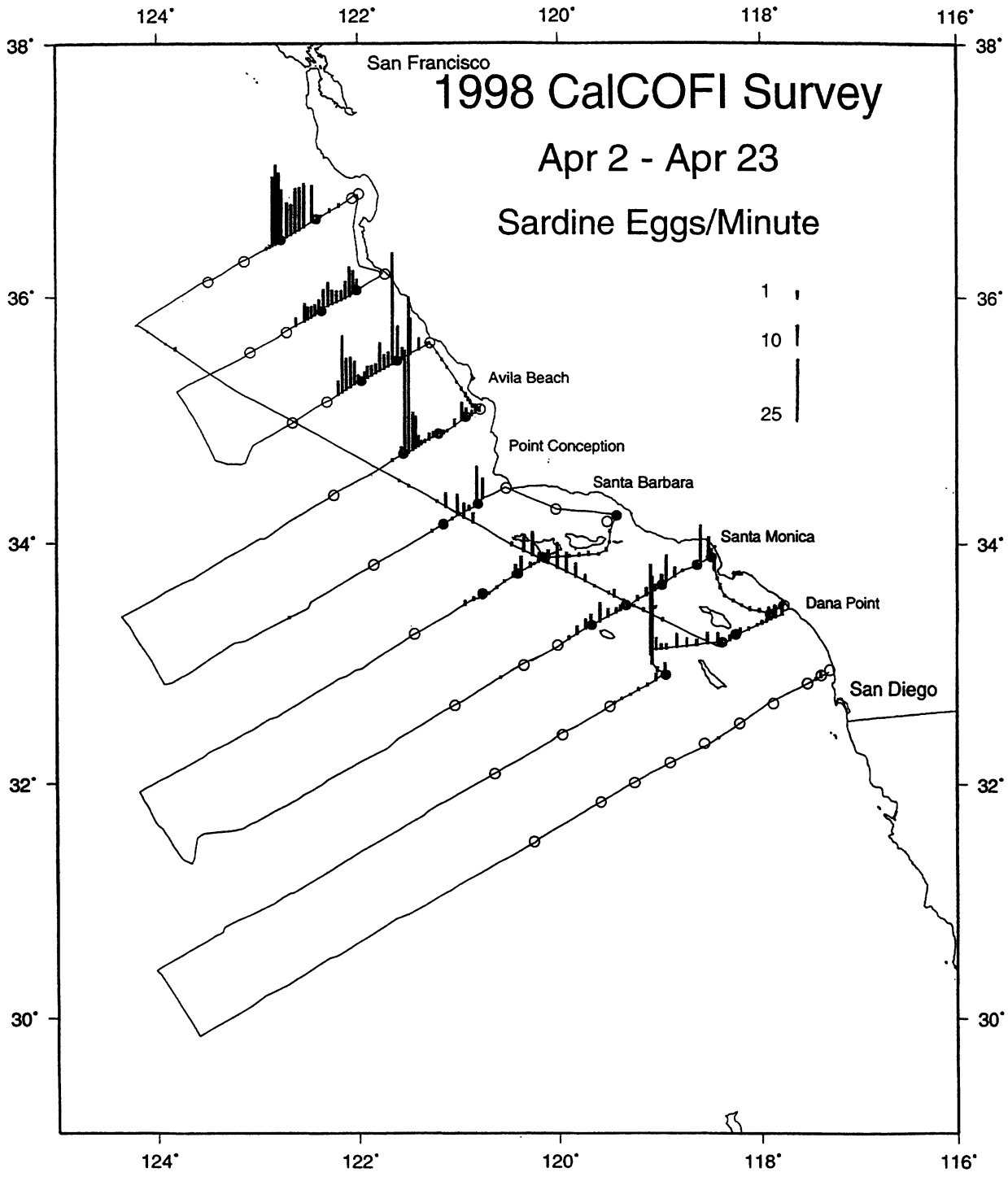


Figure 9. Sardine eggs from CalVET (solid circle denotes positive catch and open circle denotes zero catch) and from CUFES (stick denotes positive collection, dot denotes zero collection) in CalCOFI 9804 survey, April 2 - 23, 1998.

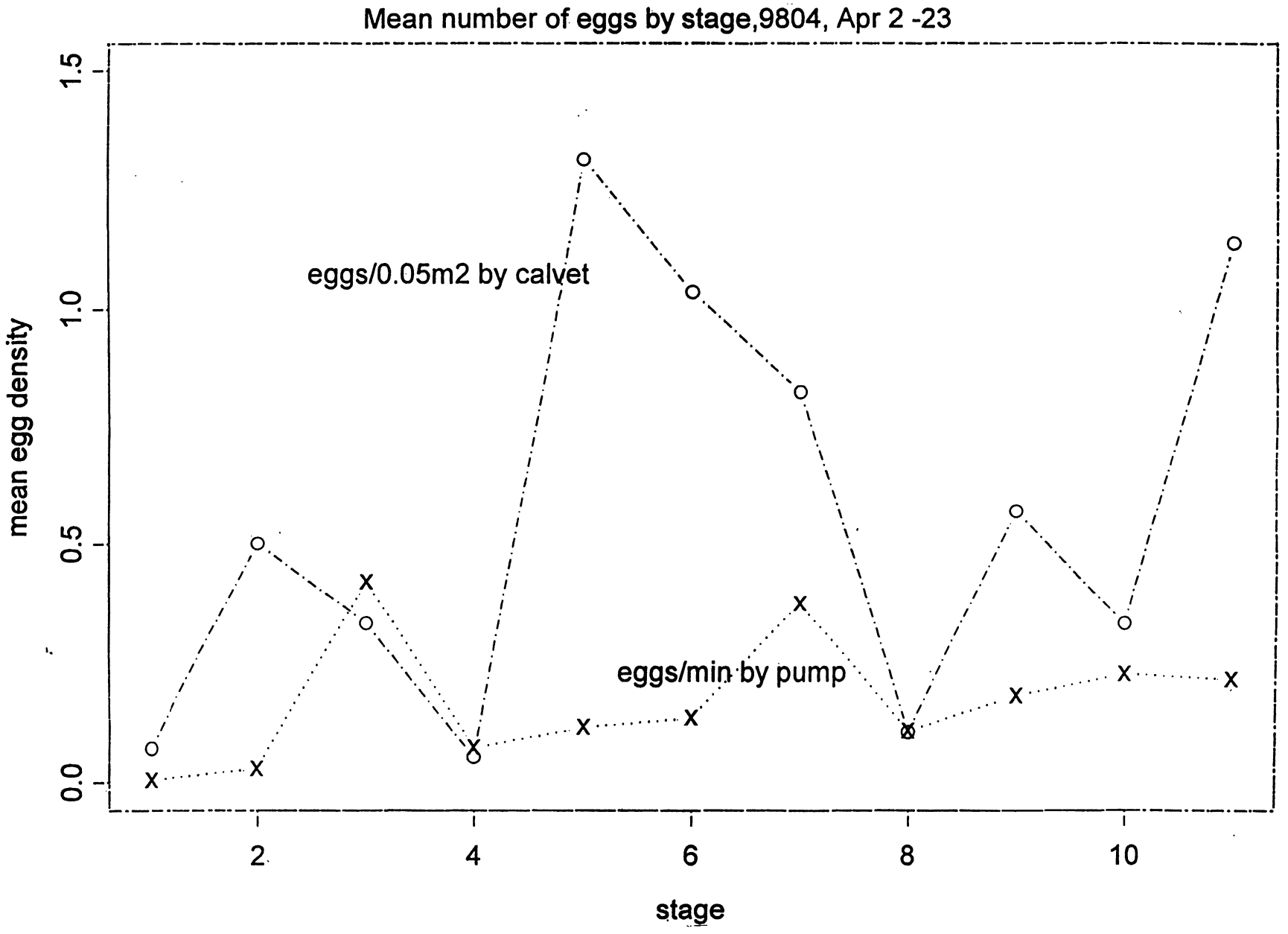


Figure 10. Sardine egg density from CUFES (eggs/minute) and CalVET (eggs/0.05m^2) for each developmental stage.

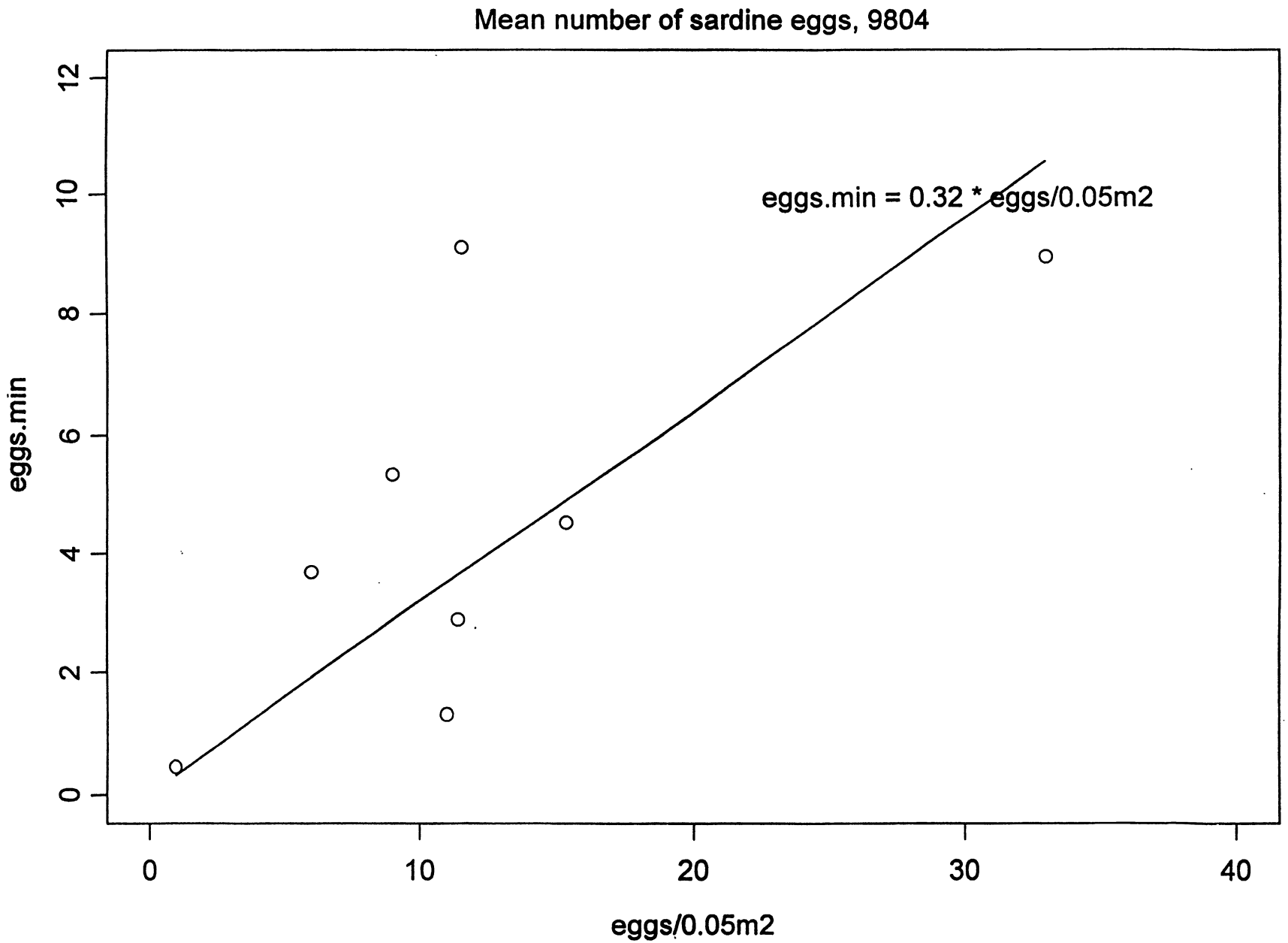


Figure 11. Eggs/minute from CUFES as a function of eggs/0.05m^2 from CalVET.

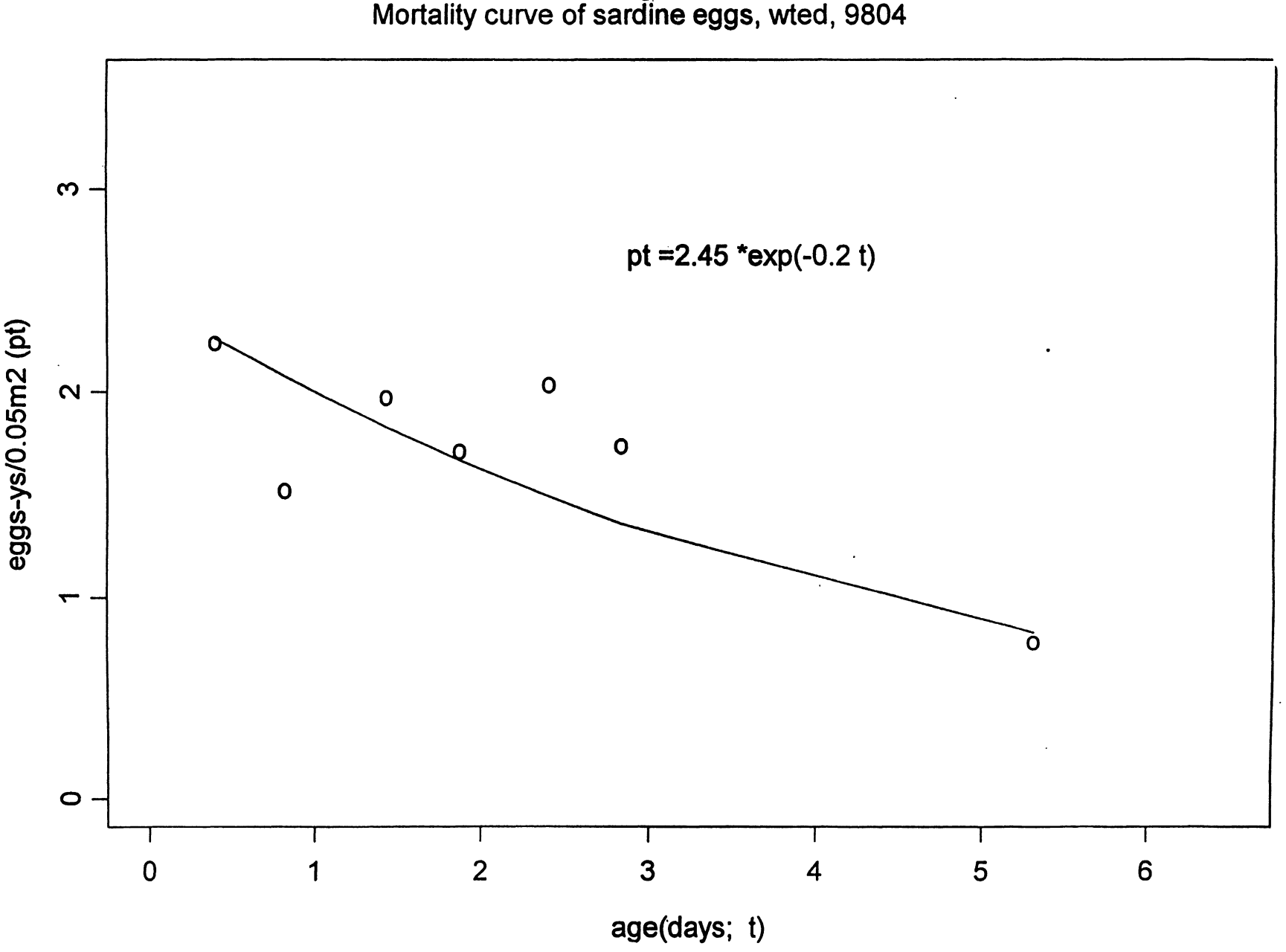


Figure 12. Embryo mortality curve of sardine. Data of staged eggs were from CUFES and CalVET, and data of yolk-sac larvae were from CalVET.

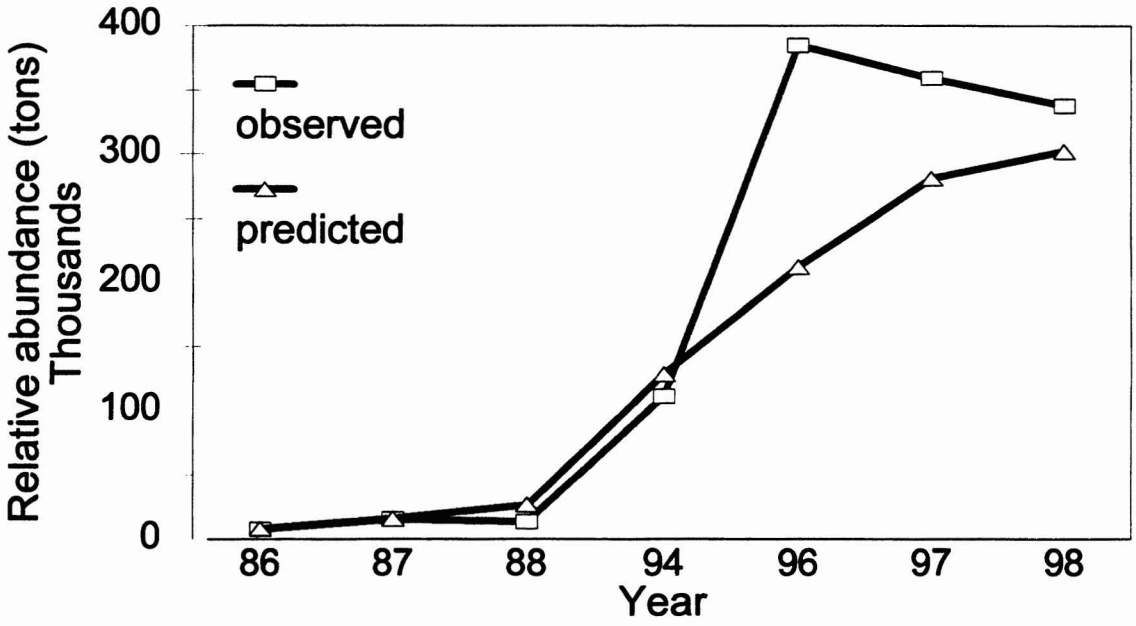


Figure 13. Observed and predicted Daily Egg Production Method sardine spawning biomass from CANSAR-TAM, 1998.

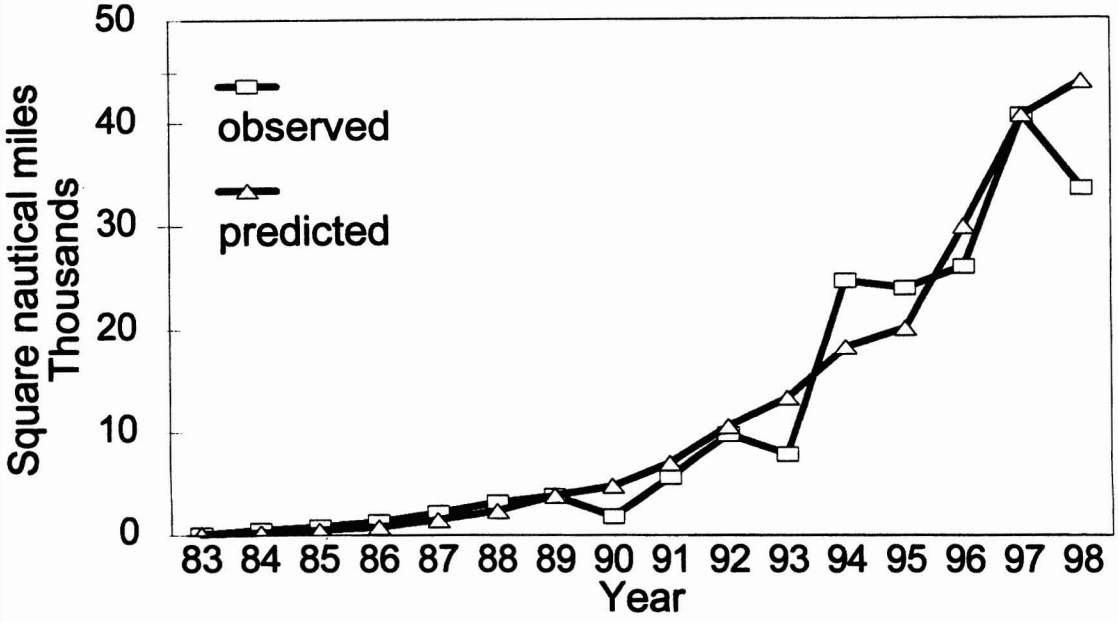


Figure 14. Observed and predicted sardine spawning area (Nmi2), from CANSAR-TAM, 1998.

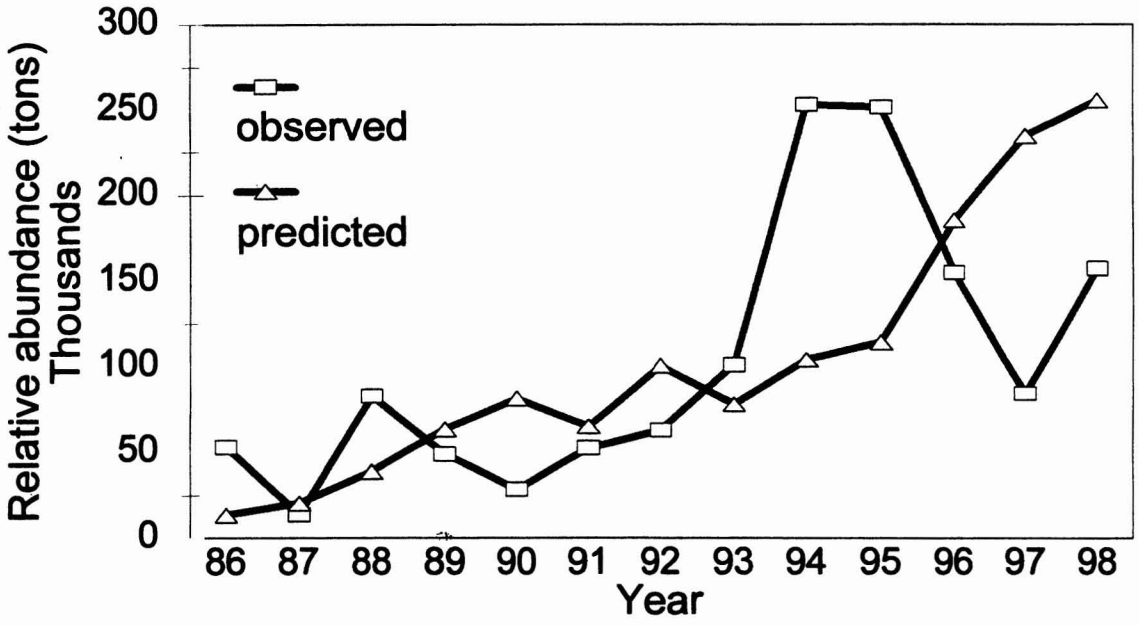


Figure 15. Observed and predicted spotter pilot observations of sardine abundance, 1986-1998, (July-June fishing years) from CANSAR-TAM, 1998.

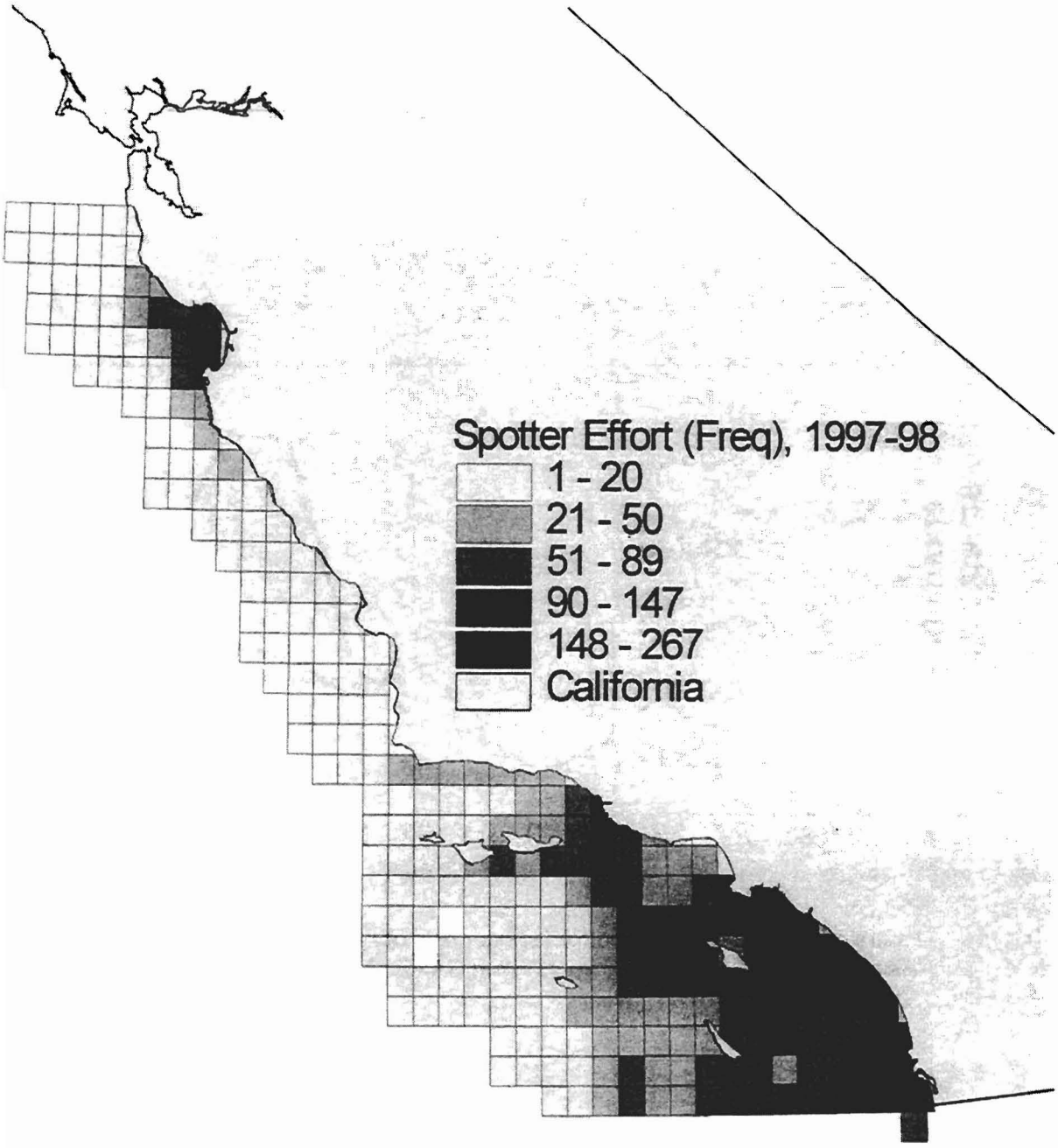


Figure 16. Distribution of aerial spotter pilot effort for the 1997-98 season. Tiles represent 10' latitude by 10' longitude spotter program squares which are equivalent in size and coverage to CDFG statistical blocks.

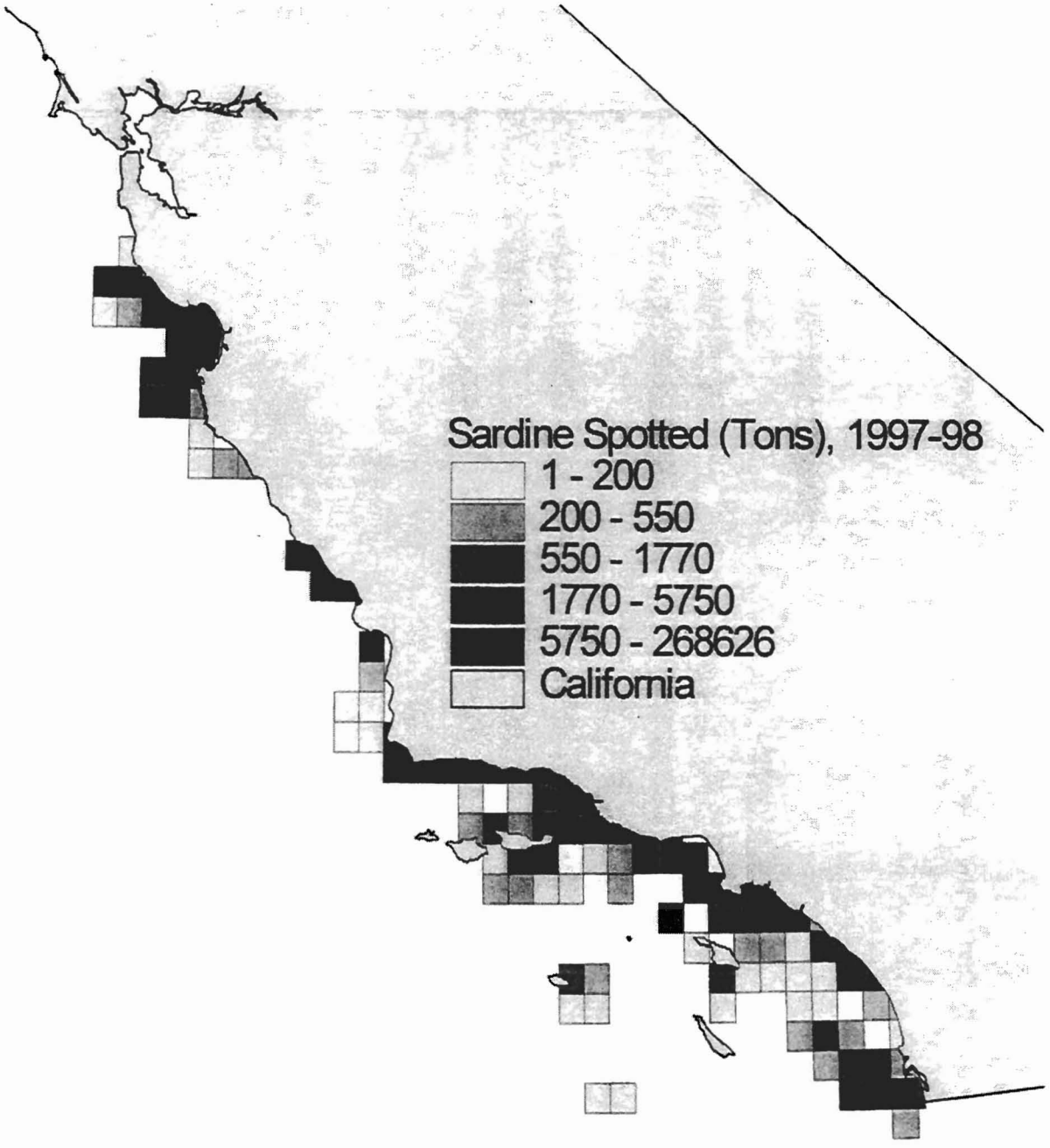


Figure 17. Distribution of sardine sightings (tons) by aerial spotter pilots in the 1997-98 season. Tiles represent 10' latitude by 10' longitude spotter program squares which are equivalent in size and coverage to CDFG statistical blocks.

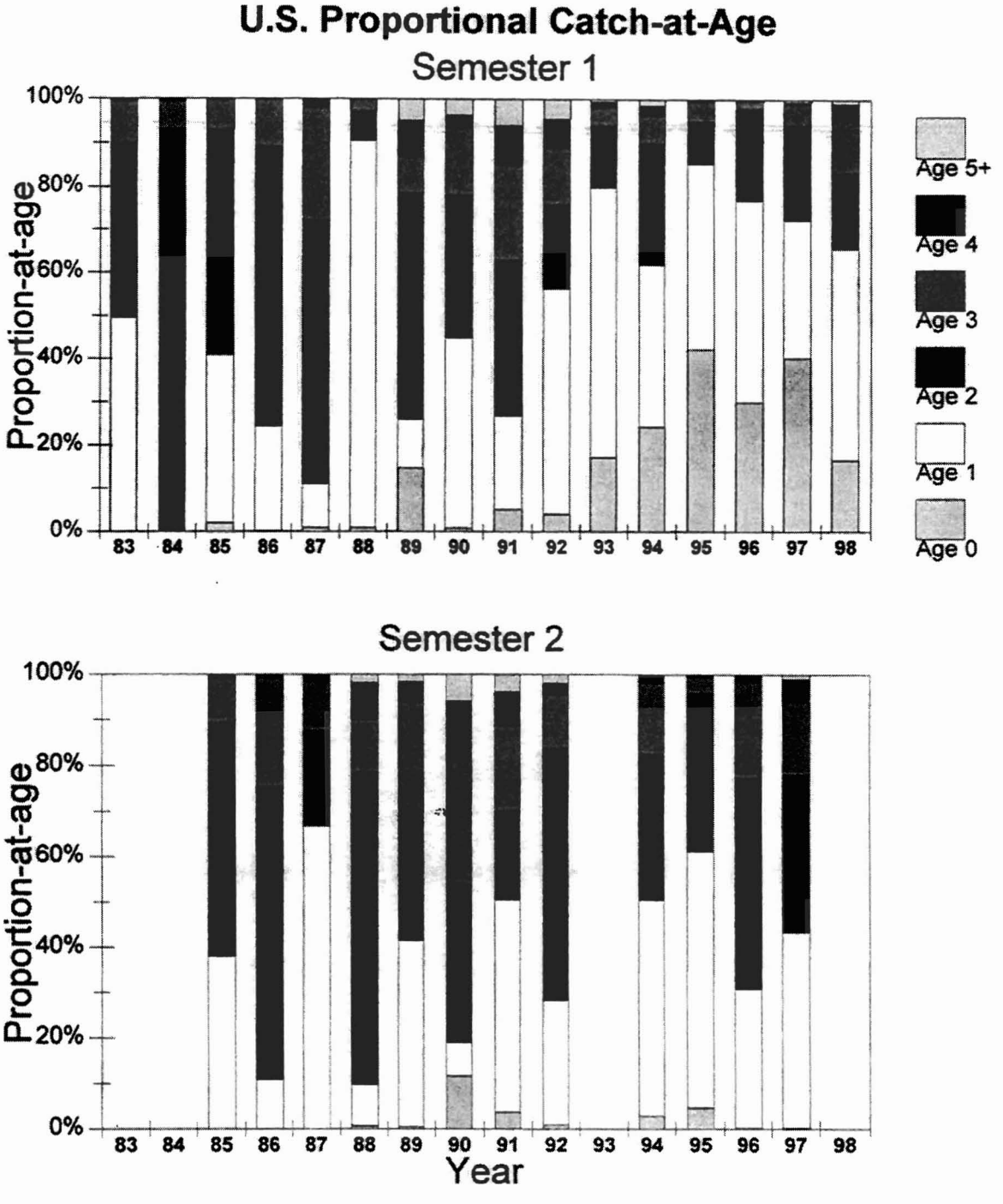
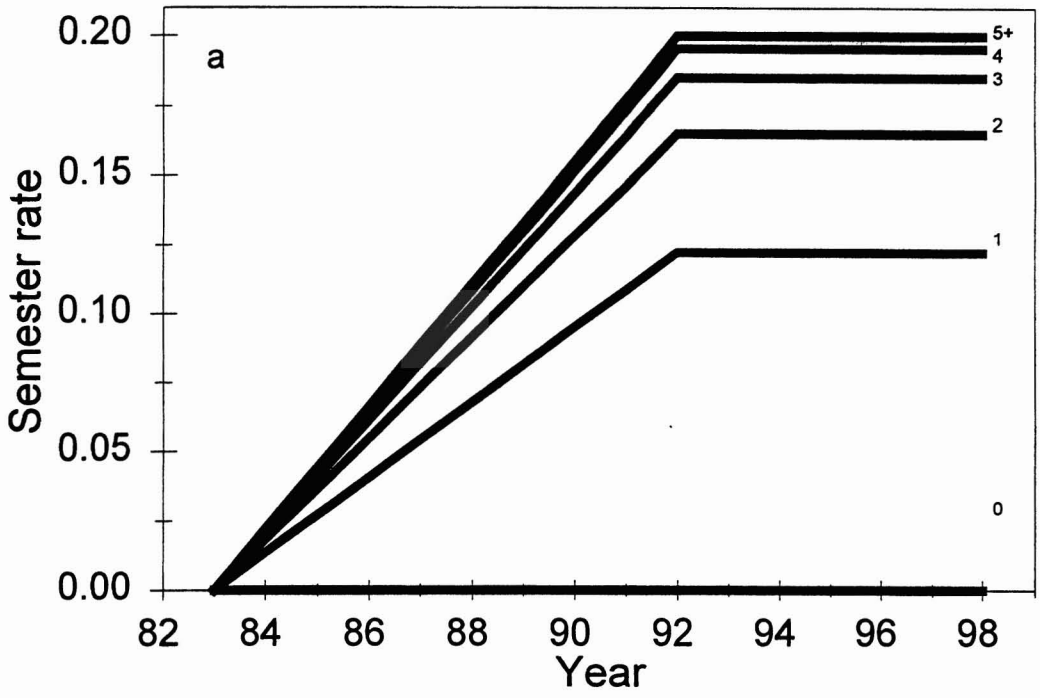


Figure 18. Proportional catch-at-age for the southern California sardine fishery, 1983-1998. No semester 2 age composition was available in 1993.



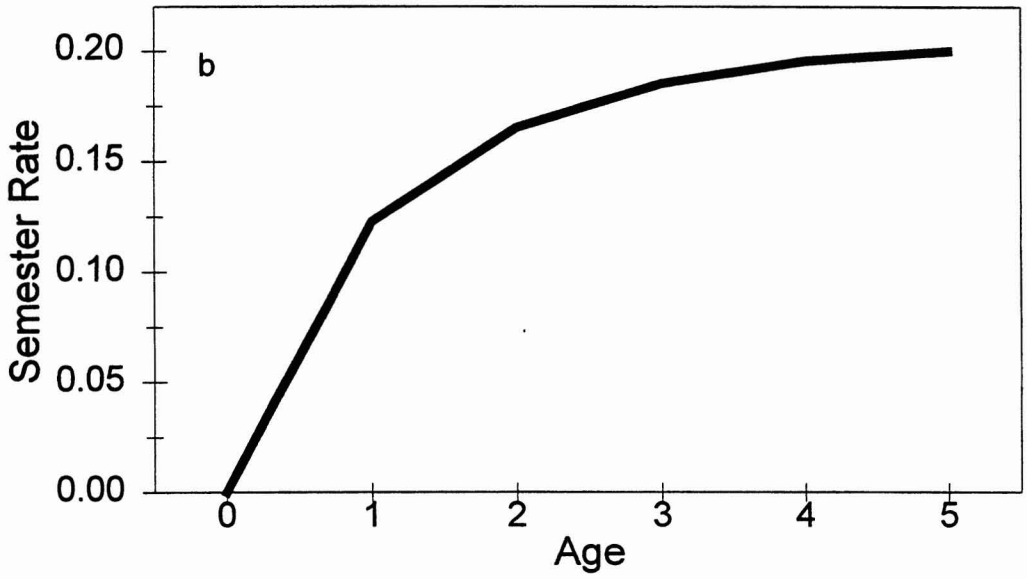


Figure 19. (a) Products of age- and year-specific migration rates (sem-1) assumed in th CANSAR-TAM model for sardine during semesters 1 and 2 of each year. Add m=0.2 (sem-1) to calculate total "apparent" natural mortality rate (My,s,a). Age-specific rates were based on a proportional function (L^0.6) of mean length-at-age (b).

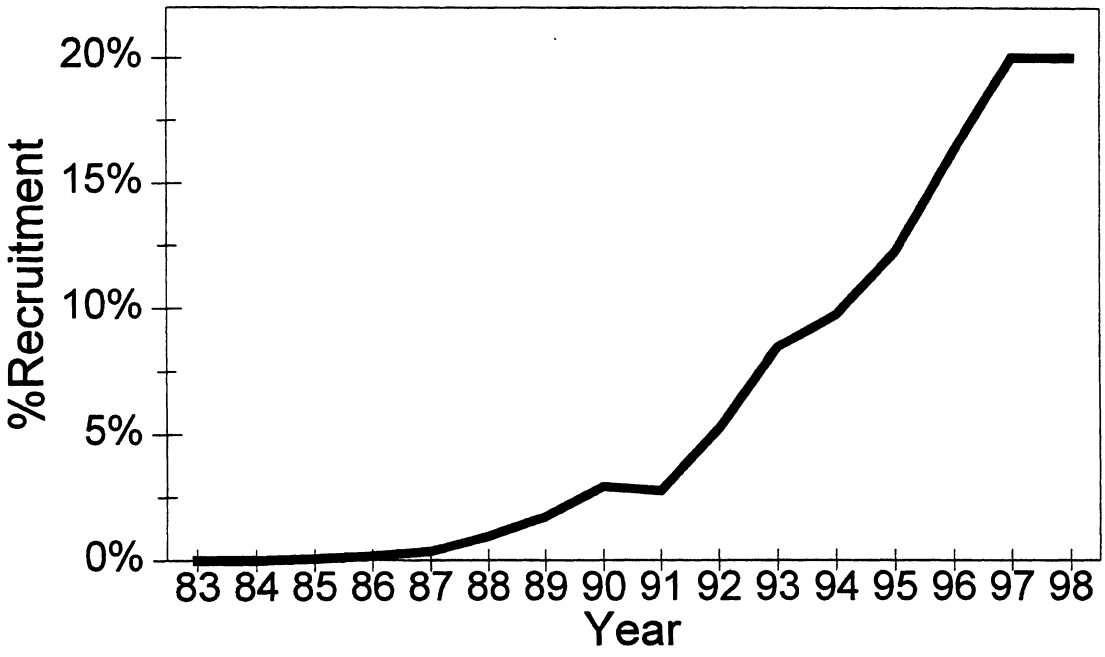


Figure 20. Percent sardine recruitment in 'outside' area as used in CANSAR-TAM.

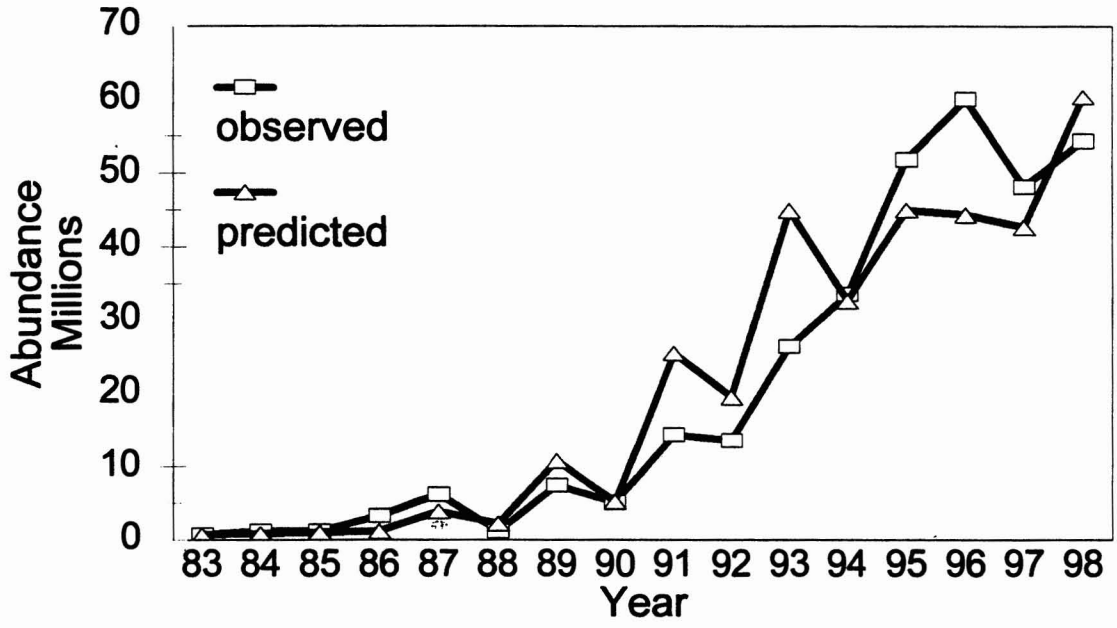


Figure 21. Observed and predicted catch (abundance) of age-2 sardine from CANSAR-TAM, 1998.

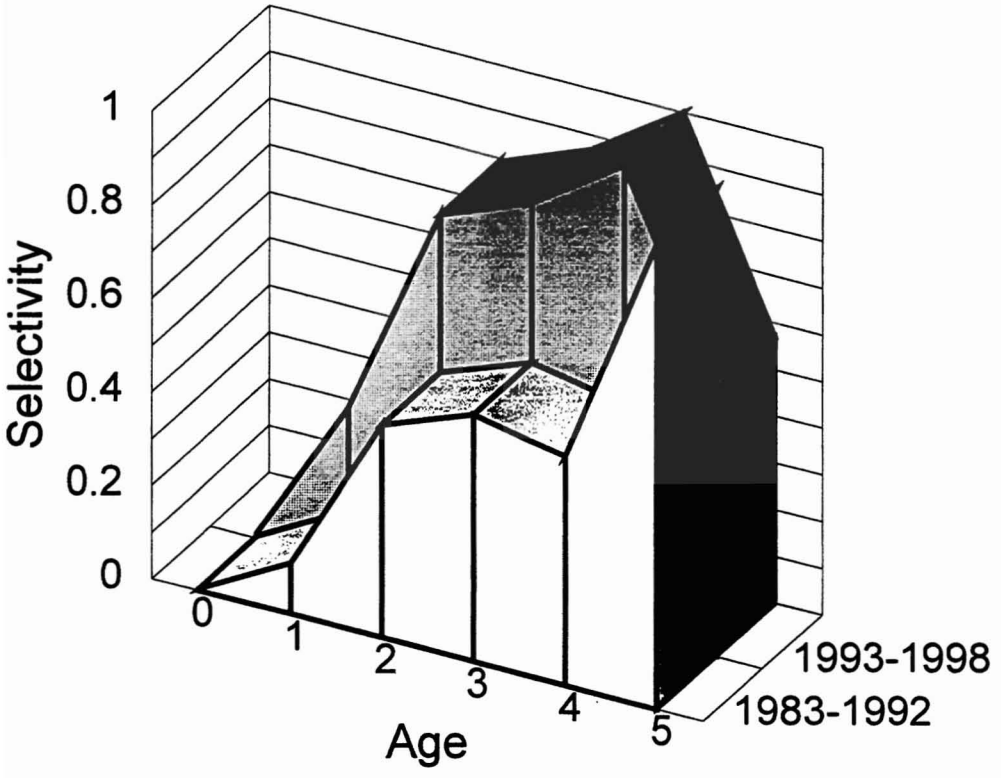


Figure 22. Fishery selectivity patterns (semester 2) used in 1998 CANSAR-TAM model.

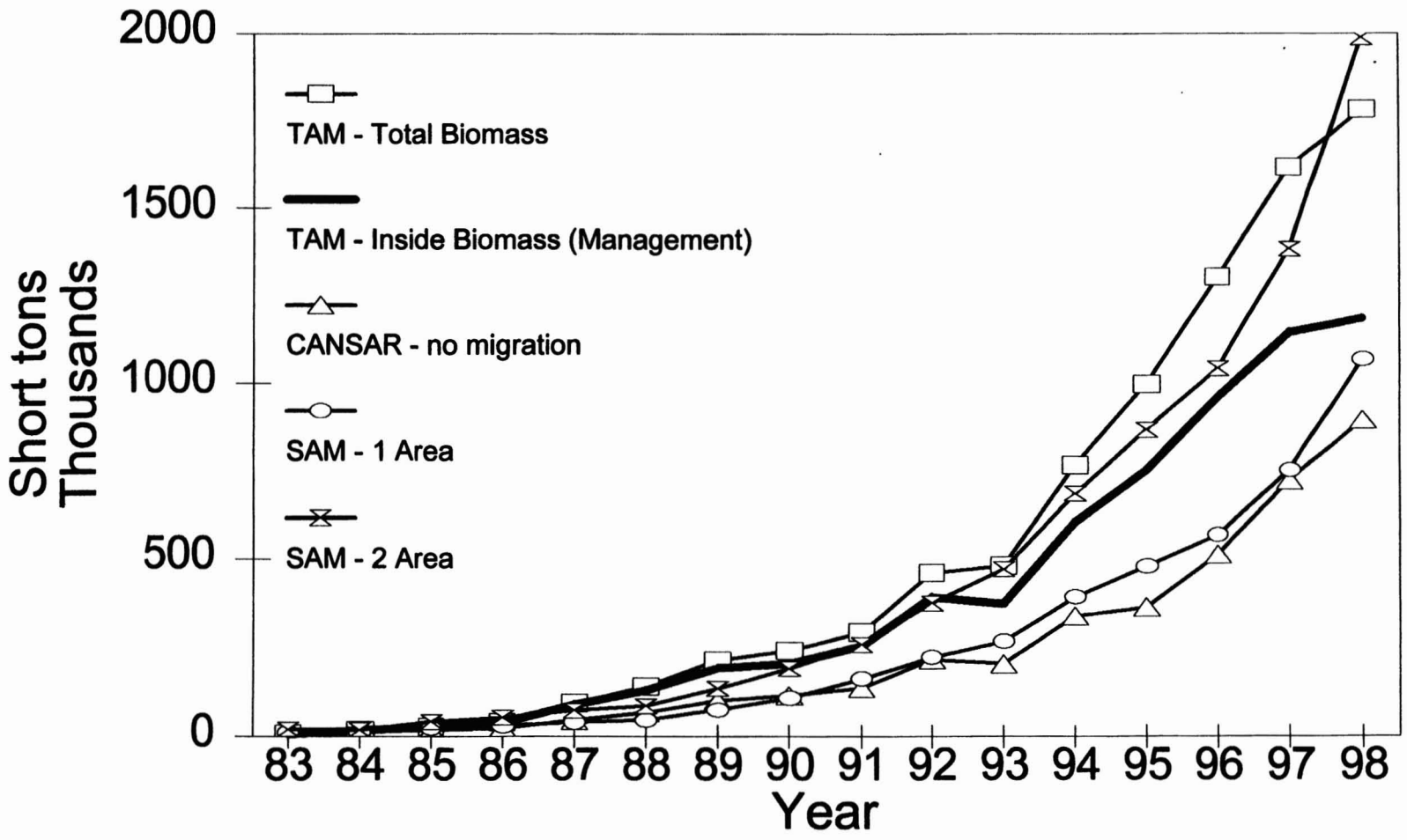


Figure 23. Estimates of Pacific sardine Age 1+ biomass (short tons, semester 2) estimated using CANSAR-TAM, CANSAR (no migration), and SAM models. Estimates are bias-corrected based on 1,000 bootstrap runs. CANSAR-TAM 'inside' biomass was chosen to calculate the 1999 management quota.

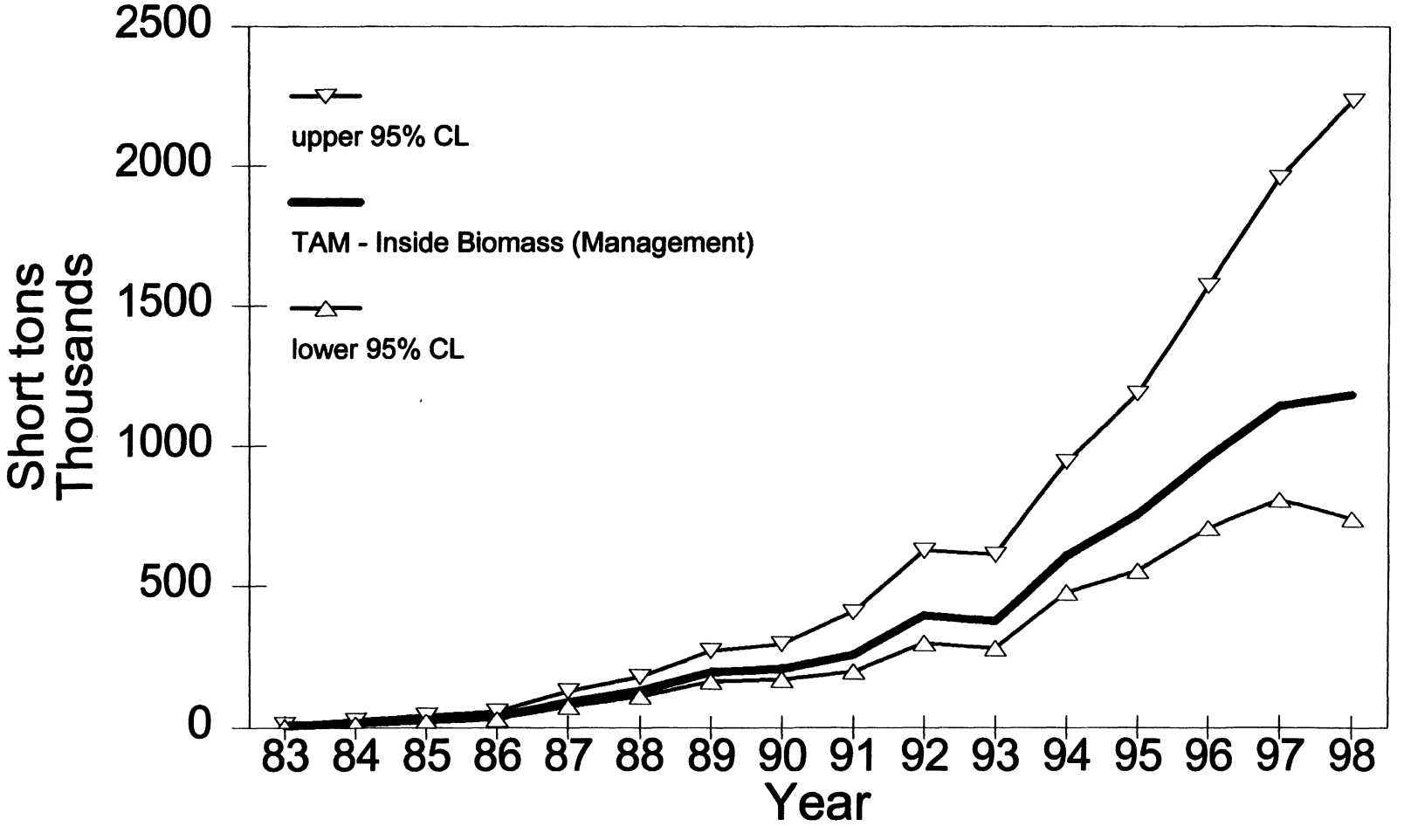


Figure 24. Pacific sardine July 1, age 1+ biomass estimates based on CANSAR-TAM. Estimate is for sardine inside the range of fishery and survey data. Estimates and 95% confidence limits are bias-corrected based on 1,000 bootstrap runs.

APPENDIX A

SAM: A New Sardine Assessment Model

This appendix describes a new Sardine Assessment Model (SAM) which was used for the first time (on an experimental basis) in California Department of Fish and Game's (CDFG) 1998 Pacific sardine stock assessment. For a description of the data and of sardine population biology, see the main body of this report.

SAM is a potential (with additional work) replacement for CANSAR (Deriso et al. 1996), the current stock assessment model for sardine. The chief potential advantages of SAM over CANSAR are flexibility and numerical stability. SAM is a C++ based AD-Model Builder application while CANSAR is a Fortran-77 based program based on code from the CAGEAN stock assessment program (Deriso et al. 1985). SAM is more flexible than CANSAR because program code can be changed much more easily by the user to incorporate new data or ideas about sardine biology. SAM is more stable numerically because it uses analytical (rather than numerical) derivatives to estimate parameters. Another advantage is that AD-Model Builder program like SAM can calculate variance estimates for any quantity estimated in the model (e.g. biomass) using analytic derivatives and the delta method.

SAM is a work in progress and not yet reliable enough to be used independently for sardine stock assessment work. There are a number of areas where additional work is needed and a number of issues related to the model, data and sardine population biology need further consideration (see below). In addition, data for sardine, ideas about sardine population biology, and condition of the stock are changing rapidly. Any stock assessment model used for sardine will require frequent modifications and adjustments to deal with these changing factors.

One or Two Geographic Areas

The Sardine Assessment Model (SAM) was designed to track population dynamics of the entire West Coast sardine stock. Depending on input and commands used to run the model, the whole stock can include one portion "available" to current fisheries and abundance surveys and another portion that is "unavailable" to current fisheries and abundance surveys. In other words, the model can be run assuming either one or two geographic areas. The notion of an available portion of the stock (with fisheries and surveys) and an unavailable portion of the stock (with no fisheries or surveys) is useful for sardine in the current assessment because almost all survey and fishery data are from the southern area between Ensenada and central California (at approximately San Francisco). Almost no survey or fishery data are currently available from the northern area between central California and British Columbia.

In the absence of data for the portion of the sardine stock not sampled by fisheries and surveys, we used SAM to obtain crude and speculative estimates of coast-wide biomass. These were based on data for the available portion of the stock, data and published accounts of the historical sardine fishery that operated as far north as British Columbia, ideas about sardine population biology, and anecdotal data for northern areas. Our approach will require modification when more survey and fishery data become available for areas of the coast not currently sampled. In the meantime, we believe that crude and speculative estimates of coast wide biomass will be useful to managers.

SAM is similar in intent but more general and flexible than the two area CANSAR-TAM model used by Hill et al. (1998) for the 1997 sardine stock assessment. CANSAR-TAM assumed that sardine left the area covered by surveys and the fishery permanently at rates that were age, season and year dependent. SAM can be configured, for example, to mimic CANSAR-TAM assumptions or to include seasonal migrations with movements north (decreased availability) for feeding during summer-fall and south (increased availability) during winter-spring for spawning.

A problem with estimates of available biomass from either SAM or CANSAR-TAM, is that area containing the available biomass of sardine is unknown. Presumably, the available portion of the stock is in an area is at least as large as the area covered by surveys and fisheries in recent years (i.e. Ensenada, Baja California to San Francisco). We do not know how much area farther north and offshore is occupied.

Population Dynamics

Time steps in SAM were calendar years (1983 to the present) and semesters (semester 1 and 2, often called "steps" or "seasons" in output and data files). Ages were zero to 5+ (age 5 and older). The assumed birthday for sardine was the beginning of semester 2 (July 1). The number of age groups, youngest and oldest ages, first and last years, assumed birthday and number of time steps per year are flexible and can be changed by the user at runtime.

Natural mortality rates for sardine in SAM were age specific and specified by parameters that could, at least in principle, be estimated (i.e. $M_a = e^{\zeta_a}$ where M_a was the annual instantaneous natural mortality rate for age a and ζ_a was a parameter). Like Deriso et al. (1996), we assumed that M=0.4 y^{-1} for all age groups. Instantaneous rates (e.g. M) can be expressed in either seasonal (semester^{-1}) or annual (y^{-1}) units (e.g. M=0.4 year^{-1} is equivalent to M=0.2 semester^{-1}). Model calculations were generally in steps of semesters. In what follows, units for instantaneous rates are seasonal (semester^{-1}) unless otherwise indicated.

By definition, all "parameters" (e.g. ρ and υ_y) are estimable, at least in principle. The model is coded in such a way that the user can try to estimate any parameter. Parameters fixed at initial values and parameters estimated can be changed at run time without recompiling the program.

Recruitments of Pacific sardine (assumed to occur on 1 July, the beginning of semester 2) to the 1983 and later year classes were calculated:

$$N_{y,2,0} = e^{\rho+\upsilon_y} \quad \langle 1 \rangle$$

where $N_{y,s,a}$ was the number of sardine age a in the whole population (available plus unavailable portions) during semester s of year y, ρ was a parameter measuring average log scale recruitment, and υ_y was a year specific recruitment deviation parameter. Abundance of age zero sardine in the first semester of 1983 (i.e. the 1982 year class) was calculated:

$$N_{83,1,0} = e^{\rho+\upsilon_{82}-M/2} = N_{82,2,0}e^{-M/2} \quad \langle 2 \rangle$$

where M was the instantaneous annual rate for natural mortality. In effect, the 1982 year class was assumed to have experienced six months of natural mortality between recruiting to the stock on in July 1982 and entering the model as age zero fish in the first semester of 1983. The deviation parameters υ_y were constrained to average zero (i.e. they are "bounded_dev_vectors" in AD-Model Builder) so e^{ρ} measures geometric mean recruitment.

Abundance at age for the youngest ages (ages 1 to k) in the first semester of the first year was:

$$N_{83,1,a} = e^{\omega_a} \quad \langle 3 \rangle$$

and for older ages > k:

$$N_{83,1,a} = N_{83,1,k}e^{-M(a-k)} \quad \langle 4 \rangle$$

where M was the annual instantaneous rate for natural mortality, and ω_a was one of the k initial abundance parameters for sardine ages zero to k. M was assumed constant over ages in the sardine assessment but age specific M values must be specified by the user. The initial abundance of the oldest age groups was calculated based on the abundance of sardine age k (k=1 for sardine, see below) and assuming natural mortality but no fishing. This is a crude but reasonable approach for sardine because initial abundance of the oldest age groups is difficult to estimate (Deriso et al. 1996), age composition data for the early and mid-1980s (that might be used to estimate initial abundance parameters) was not available or not used (see below), and fishing mortality on older fish was likely low in 1983. The number of initial age specific abundance parameters for ages zero and one was estimated in the model. Availability of age composition data is an important factor to consider in deciding how many initial abundance parameters to estimate and this feature can be changed by the user at run time.

Abundance at age after the first semester of the first year is normally calculated:

$$N_{y,1,a+1} = N_{y-1,2,a} e^{-Z_{y-1,2,a}} \quad \langle 5 \rangle$$

where $Z_{y,s,a} = M + F_{y,s,a}$ is the instantaneous total mortality rate (semester^{-1}), and $F_{y,s,a}$ is an instantaneous rate for fishing mortality for the coast-wide stock. The equivalent calculation used in SAM is:

$$N_{y,1,a+1} = A_{y-1,2,a} N_{y-1,2,a} e^{-Z_{y-1,2,a}} + (1 - A_{y-1,2,a}) N_{y-1,2,a} e^{-M}$$

$$-or- \quad \langle 6 \rangle$$

$$N_{y,1,a+1} = n_{y-1,2,a} e^{-Z_{y-1,2,a}} + (N_{y-1,2,a} - n_{y-1,2,a}) e^{-M}$$

where lower case symbols are abundance and mortality rates for the available stock, $A_{y,s,a}$ is an age specific availability (see below), and $z_{y,s,a}$ (lower case)$=M + f_{y,s,a}$. Equation <6> was more useful in calculations because estimates of $F_{y,s,a}$ for the whole stock are not required. Calculations for the plus groups were similar, for example:

$$N_{y,1,5+} = N_{y-1,2,4} e^{-Z_{y-1,2,4}} + N_{y-1,2,5+} e^{-Z_{y-1,2,5+}} \quad \langle 7 \rangle$$

In general, whole stock abundance estimates ($N_{y,s,a}$) were used in population dynamics calculations in the assessment model while abundance estimates for the available stock ($n_{y,s,a}$) were used in survey and catch calculations. As implied by equation <6>, abundance of sardine available to surveys and fisheries off the coast between Baja and central California was calculated $n_{y,s,a} = A_{y,s,a} N_{y,s,a}$.

Stock biomass was calculated:

$$B_{y,s,a} = N_{y,s,a} W_{y,s,a}$$

$$-or- \quad \langle 8 \rangle$$

$$b_{y,s,a} = n_{y,s,a} W_{y,s,a}$$

where $W_{y,s,a}$ (upper case) was a population weight at age $B_{y,s,a}$ was total biomass, and $b_{y,s,a}$ was available biomass. For convenience, fishery weights at age for sardine in the US fishery were used as default population weights at age. The user specifies alternative population weights at age that replace the default values at run time.

Availabilities of sardine to surveys and fisheries were from a preliminary seasonal sardine habitat/migration model developed by Richard Parrish (Pacific Fisheries Environmental Laboratory, Southwest Fisheries Science Center, NMFS, Pacific Grove, CA). According to the habitat/migration model, sardine move north during the second semester "feeding season" seeking plankton rich water at about 12° C. During the first semester "spawning season", sardine move south seeking optimal spawning temperatures of 14-16° C. The habitat/migration model used to estimate

availabilities was parameterized based on actual sea surface temperature data for the west coast from the COADS database for a warm year. Warm water conditions were used to parameterize the model because water conditions have been warm along the west coast for the first year included in SAM. Swimming speeds and migration rates in the habitat/migration model were assumed proportional to age specific body weights and age zero sardine were not assumed to migrate at all. Recruitment occurs in the habitat/migration model wherever suitable water conditions occur. Consequently, the habitat/migration model predicts some recruitment in northern areas where the stock is unavailable to fisheries and surveys.

Availabilities for sardine were estimated as the average age specific percent of population biomass for sardine south of Cape Mendocino during the first and second semesters (see below). Availabilities may have been one (i.e. no migration) for all age classes during early years when stock biomass was low and sardine were often captured in mixed schools of Pacific mackerel and sardine of different sizes. Availabilities in SAM were therefore scaled from one in 1983 to average values in 1988. The year 1988 was, in effect, assumed to be the year in which migration patterns became fully developed. This ad-hoc assumption was an average between 1986 (when stock biomass became high enough to allow a directed fishery targeting pure schools of sardine) and 1990 when patterns in fishery weight at age data for sardine caught off southern California changed dramatically. Availabilities were specified in the model as an array of year (1983 to 1998), semester (1 and 2) and age (0 to 5+) specific values (see below).

Availabilities for Pacific sardine used in SAM from a preliminary migration/habitat model.

Year	Age 0	Age 1	Age 2	Age 3	Age 4	Age 5+
Semester 1						
1983	1.00	1.00	1.00	1.00	1.00	1.00
1984	0.98	0.98	0.99	0.99	1.00	1.00
1985	0.96	0.97	0.98	0.98	0.99	1.00
1986	0.94	0.95	0.96	0.98	0.99	1.00
1987	0.92	0.94	0.95	0.97	0.98	1.00
1988-1998	0.90	0.92	0.94	0.96	0.98	1.00
Semester 2						
1983	1.00	1.00	1.00	1.00	1.00	1.00
1984	0.98	0.93	0.89	0.86	0.84	0.83
1985	0.96	0.86	0.79	0.72	0.69	0.66
1986	0.94	0.79	0.68	0.59	0.53	0.49
1987	0.92	0.72	0.58	0.45	0.37	0.32
1988-1998	0.90	0.65	0.47	0.31	0.21	0.15

Fishing

It is important to distinguish between fishing mortality rates for the entire stock ($F_{y,s,a}$) and corresponding rates for the available stock ($f_{y,s,a}$). Catch calculations can be carried out using abundances and mortality rates for either the whole or available stock. We used available stock for catch calculations so that fishery selectivity parameters (see below) would depend primarily on characteristics of the fishing gear, markets and fishing practices and would not depend primarily on availability. Either of the two rates ($f_{y,s,a}$ and $F_{y,s,a}$) can be calculated from the other once predicted catch, availability ($A_{y,s,a}$) and either $n_{y,s,a}$ or $n_{y,s,a}$ are known.

Fishing mortality rates were calculated individually for each fishery or "fleet" in each semester. There were generally two (e.g. U.S. and Mexico) or three (e.g. central California, southern California and Mexico) fleets. The model handles fishery data (landings, catch at age, fishery weight at age) for each fleet in each time period separately based on different sets of fishing mortality parameters. Logically, there may (or may not) be a connection between the operation of a single fleet in different semesters of the same year but there is no connection in computations. Thus, in a hypothetical example, data for a purse seine fishery in the first semester and data for a gill net fishery in the second semester could be modeled as data for a single fleet in two semesters. In other words, selectivity, fishing mortality rate and other parameters and calculations for a "fleet" in one semester are not linked to parameters and calculations for another semester.

Age specific fishing mortality rates for the available stock and whole stock were calculated by summing the contributions from each fleet:

$$f_{y,s,a} = \sum_{f=1}^{n_f} f_{y,s,f,a} \quad \text{-or-} \quad F_{y,s,a} = \sum_{f=1}^{n_f} F_{y,s,f,a} \qquad \langle 9 \rangle$$

Fishing mortality rates for available sardine and each fleet were modeled as the product of "separable" selectivity and fishing mortality multipliers:

$$f_{y,s,f,a} = p_{y,s,f}\, s_{y,s,f,a} \qquad \langle 10 \rangle$$

where $p_{y,s,f}$ was the year, semester and fleet specific fishing mortality rate multiplier and $s_{y,s,f,a}$ was the year, semester and fleet specific selectivity for available sardine age a.

Fishery selectivities were calculated:

$$s_{y,s,f,a} = e^{\sigma_{s,f,a}+\zeta_{y,s,f,a}} \quad \langle 11 \rangle$$

where $\sigma_{s,f,a}$ was an age-specific selectivity parameter for fleet f in semester s of all years, and $\zeta_{y,s,f,a}$ was an additional parameter (possibly equal to zero) used in year y. In effect, the $\sigma_{s,f,a}$ parameters measured a component of fleet, semester and age specific selectivity that was constant over time and the $\zeta_{y,s,f,a}$ parameters measured a year specific component or deviation. The user controls how selectivities for each fleet and year changed over time by specifying how the selectivity deviation parameters $\zeta_{y,s,f,a}$ were applied on a year specific basis. Selectivities at the oldest age were one by definition (Deriso et al. 1985) so constant selectivity and deviation parameters were stored and defined as vectors of length n_{a-1} where n_a was the number of age groups in the model. For example, n_a=6 for sardine, so selectivity parameters were stored as vectors of length five.

When the catch was non-zero for a year/semester/fishery, fishing mortality rate multipliers were calculated:

$$m_{y,s,f} = e^{\psi_{y,s,f}} \quad \langle 12 \rangle$$

where $\psi_{y,s,f}$ was a parameter. When the catch was zero, $m_{y,s,f}$ = zero and no parameter was estimated. Fishery selectivities were assumed to be one for the oldest age group (age 5+ for sardine, see above) so fishing mortality rate multipliers $m_{y,s,f}$ measured fishing mortality on the oldest age group.

Fishery catches were calculated using Baranov's catch equation:

$$c_{y,s,f,a} = \frac{f_{y,s,f,a}}{z_{y,s,a}}(1 - e^{-z_{y,s,a}})\, n_{y,s,a} \quad \langle 13 \rangle$$

where $c_{y,s,f,a}$ was catch in number and $z_{y,s,a} = M + \sum f_{y,s,f,a}$ was the instantaneous rate for all types of mortality on the available stock. Catches in weight were:

$$K_{y,s,f,a} = c_{y,s,f,a}\, w_{y,s,f,a} \quad \langle 14 \rangle$$

where $K_{y,s,f,a}$ is catch in weight and $w_{y,s,f,a}$ is a year, semester, fleet specific weight at age.

Stock-Recruitment

Two types of spawner-recruit models were included in SAM. The first (not used in the sardine assessment) predicts recruitments equal to the geometric mean:

$$\hat{r}_y = e^{\rho} \quad \langle 15 \rangle$$

where $\hat{r}_y$ is the predicted recruitment for year y. The second approach is based on Jacobson and MacCall's (1995) spawner-recruit model:

$$\hat{r}_y = S_y e^{\alpha + \beta S_y + \gamma T_y} \quad \langle 16 \rangle$$

where $S_y=B_{y,1,1+}$ is biomass of sardine ages 1+ on 1 January (a proxy for spawning biomass) and T_y is mean "three season" daily sea surface temperatures at Scripps Pier. For example, T_{91}, used to predict recruitment of age zero sardine on 1 July 1991 ($\hat{r}_{91}$) was the average of daily sea surface temperatures during the period 1 July 1990 to 30 June 1993 (see Jacobson and MacCall 1995 for a more complete explanation).

Spawner-recruit parameters for sardine can be taken from Jacobson and MacCall (1995), estimated in the sardine assessment model, or based on a combination of both approaches. Jacobson and MacCall's (1985) parameter estimates must be adjusted, however, because their model predicts recruitment of age two sardine in units of 10^6 fish based on spawning biomass in units of 10^3 mt during July of the year prior to recruitment. SAM, in contrast, measures recruitment of age zero sardine in units of 10^3 fish and spawning biomass in mt on 1 January during the year in which recruitment occurs. Adjusted spawner-recruit parameters used in SAM (and CANSAR, see Deriso et al. 1996) were α = -14.02, β = -3.147 x 10^{-7}, and γ = 0.961.

As described above, historical data used by Jacobson and MacCall (1995) to estimate spawner-recruit parameters for sardine were different than recent data and it is difficult to know if the adjustments to parameters were sufficient to account for the differences. Consequently, we set $\alpha=\alpha' + \iota$, where α' = -14.02 was the adjusted parameter from Jacobson and MacCall's (1995) and ι was a deviation parameter that could be estimated in the model. The additional parameter ι can be viewed as a correction for any other factor that might affect the intercept parameter in Jacobson and MacCall's (1995) model.

Observation Model for Abundance Index Data

Predicted values for abundance index data (used in objective function calculations, see below) were calculated based on available biomass:

$$\hat{I}_{t,y} = q_{t,y} h_{t,y}^{X_t} \quad \langle 17 \rangle$$

where "hats" denote model estimates, t is an index for survey type, $I_{t,y}$ was a survey, $q_{t,y}$ was a survey and year specific scaling factor, $h_{t,y}$ was selectivity filtered available biomass (see below), and X_t was an exponent that makes the relationship between the index and available biomass potentially nonlinear. The exponent was calculated:

$$X_t = e^{\chi_t} \quad \langle 18 \rangle$$

where χ_t was a parameter.

Scaling factors for surveys were calculated:

$$q_{t,y} = e^{\theta_t + \kappa_{t,y}} \qquad \langle 19 \rangle$$

where θ_t was a parameter that measured the geometric mean value of $q_{t,y}$ and $\kappa_{t,y}$ was a year specific deviation parameter. Deviation parameters were constrained so that the mean deviation for each survey was zero. The deviation parameters allow for year to year changes in survey scaling factors.

Survey filtered available biomass was calculated.:

$$h_{t,y} = \sum_{a=a_{min}}^{a_{max}} S_{t,a} b_{y,s,a} \qquad \langle 20 \rangle$$

where $S_{t,a}$ is a survey, year and age-specific survey selectivity in the semester when the survey was conducted. Survey selectivities were calculated:

$$S_{t,a} = e^{\tau_{t,a}} \qquad \langle 21 \rangle$$

where the $\tau_{t,a}$ were survey and age specific parameters. As with fishery selectivities, survey selectivities were one by definition at the oldest age and stored in vectors of length n_a-1.

Objective Function

The sardine stock assessment model was "tuned" (parameters were estimated) by minimizing a negative log-likelihood objective function:

$$L = \sum_{j=1}^{N_L} \ell_j \qquad \langle 22 \rangle$$

where L was the negative log-likelihood (objective function), and l_j was the likelihood for component j (see below). In some cases (see below), a likelihood component specific weight (λ_j) was used to increase or decrease the importance of the component l_j during parameter estimation. Likelihood components could be categorized generally as measures of goodness of fit for: 1) catch data; 2) survey data; 3) age composition data; 4) the spawner-recruit model fit to recent (1983 and later) temperature data and spawner-recruit estimates; 5) the spawner-recruit model fit to historical temperature and spawner-recruit estimates (1935-1963); 6) the constraint on inter-annual variation in fishery selectivities; and 7) other parameter constraints.

The objective function component for catch data (used primarily to estimate fishing mortality rate multipliers, $\psi_{y,s,f}$) was:

$$\ell = 0.5 \sum_{y=y_{min}}^{y_{max}} \sum_{s=1}^{s_{max}} \sum_{f=1}^{f_{max}} \left[\frac{\ln\left(\frac{\hat{K}_{y,s,f,.} + r}{K_{y,s,f,.} + r} \right)}{\sigma^{C}} \right]^2 \qquad \langle 23 \rangle$$

where "hats" denote model estimates year, semester and fishery specific catches, and r is a small constant (e.g. 1 x 10^{-30}). For convenience, the likelihood component for catch data also included an component specific weight λ. The log scale standard deviation σ^c is for measurement errors in the catch data. If σ^c is large, the model tends to fit the catch data imprecisely. If σ^c is small, the model tends to fit the catch data almost exactly. Log scale standard deviations for catch (and other types of data) were calculated from arithmetic CV's supplied by the user:

$$\sigma = \sqrt{\ln\left(1 + CV^2\right)} \qquad \langle 24 \rangle$$

The objective function component used for survey data was:

$$\ell = 0.5 \sum_{t=1}^{t_{max}} \sum_{y=y_{min}}^{y_{max}} \left[\frac{\ln\left(\frac{\hat{I}_{t,y}}{I_{t,y}} \right)}{\sigma_t^I} \right]^2 \qquad \langle 25 \rangle$$

where $z_{t,y}$ was an observation specific weight and σ^I_t was a survey specific log scale standard deviation. The number of years with survey observations can vary among survey types and missing values are allowed.

We tried a new, experimental approach to specifying log scale standard deviations for surveys (σ^I_t) and other types of data based on arithmetic scale CVs. The approach seemed useful because biologists often use CVs to judge the precision of data and because arithmetic CVs and log scale standard deviations are closely related (see above). The CV for each survey and observation was calculated:

$$CV_{t,y} = K_t V_{t,y} \qquad \langle 26 \rangle$$

where K_t was a survey specific CV multiplier and $V_{t,y}$ was an observation specific value. K_t changes the importance of (emphasis on) survey t during parameter estimation while

$V_{t,y}$ changes the importance of (emphasis on) the observation for year y. In some runs, for example, $V_{t,y}$ values were set equal to reported CVs for survey data *scaled to a median of one* and K_t values were set to either one (for surveys having a non-linear relationship with sardine biomass) or 0.4 (for surveys having a linear relationship with sardine biomass). Our approach was similar to systems of year and observation specific weights used by Deriso et al. (1996) and Methot (1989) except that larger values of K and V lead to larger assumed CVs and reduced emphasis (rather than increased emphasis) during parameter estimation. Survey specific CV multiplier's (K_t) make component specific likelihood weights (λ_t) redundant. Therefore, component weights (λ_t) were not used for data types with component specific (K_t) and observation specific ($V_{t,y}$) CV multipliers.

The objective function component for age composition data was:

$$\ell_{t,y} = -\sum_{f=1}^{f_{max}} \sum_{s=1}^{s_{max}} \sum_{y=y_{min}}^{y_{max}} S_{s,f} \sum_{a=a_{min}}^{a_{max}} \left[p_{y,s,a,f} \ln\left(\hat{p}_{y,s,a,f}\right) - p_{y,s,a,f} \ln\left(p_{y,s,a,f}\right) \right] \quad \langle 27 \rangle$$

where $p_{y,s,a,f}$ was a proportion (i.e. age composition observation for one age group) and $S_{s,f}$ was a fleet and season specific assumed sample size. As described in Fournier and Archibald (1982), $S_{s,f}$ might be set equal to the number of fish aged but fishery age composition are generally less precise than expected on this basis; the "effective" sample size is usually much lower.

Methot's (1989) ratio estimator can be used to calculate "effective sample sizes" for age composition data:

$$\tilde{s}_{y,s,f} = \frac{\sum_{a=a_{min}}^{a_{max}} \hat{p}_{y,s,a,f}(1 - \hat{p}_{y,s,a,f})}{\sum_{a=a_{min}}^{a_{max}} \left(p_{y,s,a,f} - p_{y,s,a,f} \right)^2} \quad \langle 28 \rangle$$

In the sardine stock assessment model, assumed sample size for age composition data from a particular fleet and season $s_{s,f}$ can be set equal to assumed average or typical values of $\tilde{s}_{y,s,f}$. An alternative log scale sum of squares objective function component (similar to one used by Deriso et al. 1995) can also be used for age composition data :

$$\ell = 0.5 \sum_{y=y_{min}}^{y_{max}} \sum_{s=1}^{s_{max}} \sum_{f=1}^{f_{max}} \sum_{a=a_{min}}^{a_{max}} \left[\frac{\ln\left(\frac{\hat{p}_{y,s,a,f}}{p_{y,s,a,f}} \right)}{\sigma^{p}} \right]^2 \quad \langle 29 \rangle$$

with log scale standard deviation σ^p. Note that the log scale sums of squares approach

can only be used for observations with $p_{y,s,a,f}$ and $\hat{p}_{y,s,a,f}$ greater than zero.

Likelihood components for recent (1983 and later) spawner-recruit estimates were calculated:

$$\ell = 0.5 \sum_{y=y_{min}}^{y_{max}} \left[\frac{\ln\left(\frac{\hat{r}_y}{N_{y,2,0}}\right)}{\sigma^r} \right]^2 \qquad \langle 30 \rangle$$

where σ^r=0.91 was based on the variance of residuals from Jacobson and MacCall's (1985) spawner-recruit model. A similar likelihood component for historical (1935-1963) spawner-recruit data was calculated except that spawning biomass, recruitment estimates and temperature data (T_y) were taken from Table 1 in Jacobson and MacCall. The use of historical (as well as recent) spawner-recruit data was an experimental approach that remains a subject for future research. The basic idea was to use all available data (historical and recent) in estimating spawner-recruit parameters for sardine.

The likelihood component that constrained variation in fishery selectivities was:

$$\ell = 0.5 \lambda \sum_{j=1}^{n_\zeta} \sum_{a=1}^{a_{max}-1} \left(\frac{\zeta_{j,a}}{\sigma^\zeta} \right)^2 \qquad \langle 31 \rangle$$

where n_ζ was the number of selectivity deviation parameters in the model, and σ^ζ was an assumed standard deviation. The constraint <31> is designed to smooth or dampen year to year variation in estimates of fishery selectivities. It is also possible to smooth or dampen variability from age to age but this was not done for sardine because there were only a few age classes and selectivities were expected to change substantially from one age to the next.

The likelihood function that constrained year to year variation in survey catchability coefficients was:

$$\ell = 0.5 \sum_{t=1}^{n_t} \lambda_t \sum_{y=y^t_{min}}^{y^t_{max}} \left(\frac{\kappa_{t,y}}{\sigma^t} \right)^2 \qquad \langle 32 \rangle$$

where n_t is the number of different surveys, y^t_{min} and y^t_{max} are the first and last years with

survey data (years with missing survey data are allowed but omitted from the calculations), and σ_t is an assumed standard deviation for survey t. The likelihood weights λ_t are survey specific.

Constraints on parameters were implemented as Bayesian priors. For example, a constraint on ι was implemented:

$$\ell = \left[\frac{\iota - 0.8}{\sigma}\right]^2 \qquad \langle 34 \rangle$$

where 0.8=2M (M=0.4 year^{-1}) and σ calculated assuming an arithmetic CV of 0.4 (equal to the CV of α in Table 5 of MacCall and Jacobson).

Basic Model Configuration

SAM was configured for three fisheries (Ensenada, southern California and Monterey, see below) rather than two (Ensenada and California) because: 1) several years of age composition data were available for Monterey; 2) fishery selectivities were expected to be different in Monterey than in southern California; 3) Monterey was the center of the historical sardine fishery; 4) catches in Monterey have been increasing in recent years; and 5) catches at Monterey will likely continue to increase due to expansion of processing plants in the area. Catches were assumed known without error in modeling.

Sardine landings (mt) by fleet and year.

Year	Southern California	Ensenada	Monterey	Total
1983	459	274	29	762
1984	352	0	23	375
1985	623	3,722	42	4,388
1986	1,122	243	165	1,529
1987	2,774	2,432	147	5,352
1988	4,066	2,035	62	6,163
1989	3,282	6,222	440	9,945
1990	3,129	11,375	176	14,681
1991	7,976	31,392	1,058	40,426
1992	18,007	34,568	3,230	55,806
1993	17,055	32,045	787	49,887
1994	11,624	20,871	2,426	34,921
1995	38,462	35,396	5,028	78,886
1996	27,071	39,065	8,985	75,122
1997	34,826	68,439	10,947	114,212

Sardine landings (mt) by fleet and year.				
1998	30,842	60,239	6,797	97,878
Total	201,672	348,318	40,343	590,332

Availability of sardine age composition data by fishery, semester, year and age.

Year	Age 0	Age 1	Age 2	Age 3	Age 4	Age 5+	Total
Semester 1-Southern California							
1983		1	1	1	1		4
1984			1	1	1		3
1985	1	1	1	1			4
1986	1	1	1	1	1		5
1987	1	1	1	1	1	1	6
1988	1	1	1	1			4
1989	1	1	1	1	1	1	6
1990	1	1	1	1	1	1	6
1991	1	1	1	1	1	1	6
1992	1	1	1	1	1	1	6
1993	1	1	1	1	1	1	6
1994	1	1	1	1	1	1	6
1995	1	1	1	1	1	1	6
1996	1	1	1	1	1	1	6
1997	1	1	1	1	1	1	6
1998	1	1	1	1	1	1	6
Subtotal	14	15	16	16	14	11	86
Semester 2-Southern California							
1985		1	1	1	1		4
1986		1	1	1	1		4
1987		1	1	1	1		4
1988	1	1	1	1	1	1	6
1989	1	1	1	1	1	1	6
1990	1	1	1	1	1	1	6
1991	1	1	1	1	1	1	6
1992	1	1	1	1	1	1	6
1994	1	1	1	1	1	1	6
1995	1	1	1	1	1	1	6
1996	1	1	1	1	1	1	6
1997	1	1	1	1	1	1	6

Availability of sardine age composition data by fishery, semester, year and age.							
Subtotal	9	12	12	12	12	9	66
Semester 1-Ensenada							
1991	1	1	1	1	1	1	6
1992	1	1	1	1	1	1	6
Subtotal	2	2	2	2	2	2	12
Semester 2-Ensenada							
1990		1	1	1	1	1	5
1991	1	1	1	1	1	1	6
1992	1	1	1	1	1	1	6
Subtotal	2	3	3	3	3	3	17
Semester 1-Monterey							
1996	1	1	1	1	1	1	6
1997	1	1	1	1	1	1	6
1998	1	1	1	1	1	1	6
Subtotal	3	3	3	3	3	3	18
Semester2-Monterey							
1996	1	1	1	1	1	1	6
1997	1	1	1	1	1	1	6
Subtotal	2	2	2	2	2	2	12

The multinomial log likelihood component (rather than the log normal option) was used to fit the model to age composition data. Effective sample sizes were set to an initial value and then revised as the model was fit so that the sample size for each fishery and semester assumed in parameter estimation was approximately equal to the average effective sample size for each observation. Effective sample sizes were generally very low, particularly for the Monterey and Ensenada fisheries and during semester 1.

Assumed effective sample sizes for age composition data.

	Southern California	Ensenada	Monterey
Semester 1	25	10	10
Semester 2	50	20	10

Multinomial calculations treat the whole age composition as one observation and "holes" (zeroes or missing data for some ages) were a problem because the holes were

likely due to variability outside the normal range of statistical variability accommodated by the multinomial distribution in sampling. CANSAR, in contrast, treats each the age composition for each age group as an observation and simply ignores ages where no sardine of a particular age were observed. To avoid problems with holes in final model runs, we excluded age composition data for southern California for 1983-1988 (first semester) and 1985-1987 (second semester) and Ensenada during 1990 (second semester).

Four sets of selectivity parameters were used to model age composition data for the southern California fishery in the first and second semesters. One set of selectivity parameters was used for first semester selectivities in the southern California fishery 1983-1992 and another was used for 1993-1998. Similarly, one set was used for second semester selectivities during 1983-1992 and another for 1993-1998. There were clear patterns in the residuals for southern California age composition data when selectivities were assumed constant over time.

A sensitivity analysis demonstrated that age composition data (as a whole) indicated relatively high estimates of sardine biomass (5-10 million mt) in 1998 whereas the abundance data (as a whole) indicated more moderate abundance levels (0.7 to 1.5 million mt). Very high estimates were not plausible and it seemed unlikely that sardine age composition data would contain any information about abundance. We therefore decreased the likelihood weights for age composition data to a low level (from 1 to 0.01, see below). In effect, we used the age composition data to estimate selectivity patterns but not for estimating abundance.

Selectivity patterns estimated for the Monterey fishery seemed unreasonable. To deal with this problem, we forced the model to use selectivity patterns estimated for the southern California during 1993-1998 in calculating mortality rates for the Monterey fishery. At the same time, we reduced the likelihood weight for Monterey catch at age data to a very low value (0.0001) so that the data would not affect selectivity estimates (see below).

Likelihood component weights for age composition data.

	Southern California	Ensenada	Monterey
Semester 1	0.01	0.01	0.0001
Semester 2	0.01	0.01	0.0001

In retrospect, the decision to separate the California fishery into southern California and Monterey segments seems premature because age composition data for sardine landed in Monterey were noisy and because separating the Monterey fishery meant that the model had to estimate an additional thirty-two fishing mortality rate parameters and ten additional selectivity parameters (until they were shut off, see

above). The noisy data and additional parameters made parameter estimation more difficult and reduced the potential benefits from using a more realistic model.

Scaling parameters (Q) for surveys were assumed constant over time and were not allowed to change from year to year. There was not enough time to explore this model feature although it might be useful as an alternative to using exponents (see below).

Following Hill et al. (this report), the exponent parameter for CalCOFI and fish spotter data were assumed to be 0.24 and 0.52, respectively. These exponents mean that fish spotter and CalCOFI data were assumed to be highly nonlinear measures of sardine abundance. DEPM and spawning area data were modeled with an exponent of one and assumed to be linear measures of sardine abundance.

Survey specific CV multipliers were assumed to be 0.4 for DEPM and spawning area data (i.e. linear abundance indices), and 0.6 for CalCOFI and fish spotter data (nonlinear abundance indices). Observation specific CV multipliers for CalCOFI and fish spotter data were calculated by rescaling original CVs for the data to a median value of one. Observation specific CV multipliers for DEPM and spawning area data were all one because original CV's were not available.

The CV multiplier for recent spawner-recruit observations (0.96) was set to the same value as for residuals in Jacobson and MacCall's (1995) spawner recruit model. Observation-specific multipliers 2 for 1983-1993 and 1 for 1994-1998. This means that the spawner-recruit constraint had almost no effect on biomass estimates for 1983-1993 but was more important in estimating biomass for recent years.

SAM converged to reasonable biomass estimates when run in one area mode but gave anomalously high estimates (5 to 10 million mt) for the entire coast when run in two area mode. In order to get more reasonable estimates in two area mode, we constrained the models estimate of the scaling parameter q_{DEPM} for DEPM data using:

$$\ell = \left[\frac{\ln(q_{DEPM}) - (-0.9416)}{0.49} \right]^2 \qquad \langle 35 \rangle$$

where -0.9416 was a log transformed q_{DEPM} value estimated by Hill et al (in prep.) based on CANSAR, and 0.49 was a crude estimate of the standard deviation of $\ln(q_{DEPM})$.

Results

Biomass estimates from SAM (one area and two area modes) are summarized below. CV's were generally large (approaching one in many cases) indicating poor precision. Despite many problems, biomass estimates from SAM were similar to estimates from CANSAR (Hill et al., in prep.).

Biomass estimates (mt ages 1+ on 1 July) from SAM.				
Year	Total (One Area Mode)	Total (Two Area Mode)	Available	Not Available
1983	9,604	18,561	18,561	0
1984	8,777	17,536	15,682	1,854
1985	20,605	37,862	30,932	6,930
1986	26,987	48,969	34,044	14,925
1987	36,661	66,524	39,086	27,438
1988	42,040	78,399	36,639	41,760
1989	67,399	122,366	61,695	60,670
1990	98,642	174,449	89,119	85,329
1991	147,760	234,883	127,639	107,244
1992	202,560	342,022	173,314	168,708
1993	243,650	428,085	210,803	217,281
1994	357,369	621,670	298,936	322,734
1995	436,201	785,360	363,131	422,230
1996	515,868	944,069	417,666	526,403
1997	681,341	1,255,820	568,492	687,331
1998	967,383	1,804,090	863,391	940,704

APPENDIX B

SAS and Splus code used to prepare the data fit generalized additive models to CalCOFI sardine data.

SAS command file GETDAT8.SAS used to prepare the CalCOFI data set for GAM analysis:

```
* sas command file GETDAT8.SAS;
/*
This SAS command file reads all the CalCOFI data from a text file, makes a
SAS data file, fits a GLM to generate an abundance index that Tom Barnes
uses to assess sardine biomass with CANSAR (procedures are
basically the same as described in my draft paper).  Finally, a text file
is generated for input to S+.
                              Larry Jacobson
                              October 20, 1995

Modified for use in 1996.  Two new variables are computed.  INTLINE
is the integer rounded CalCOFI line.  POSSAMPL is 1 if either an
egg or larvae were taken in a tow and 0 otherwise.  If a tow is on
a standard line and inshore of a particular station, then INSHORE is
1.  If a tow is on a standard line and offshore of a particular station,
then INSHORE is zero.  If  a tow is not on a standard line, then inshore is -999.
STDLDUMY is 1 if a station is on a standard line.
                              Larry Jacobson
                              October 30, 1996

Added code to compute distance from shore based on station and a linear
approximation to the coastline.
                              Larry Jacobson
                              Nov. 1, 1996

Modified for 1998.  No longer to necessary to write output data to a text file
because Splus can read SAS files.  Also, it is no longer necessary to read
the data initially from a text file.  It was easier to take Kevin's dbase
file, read in Splus, export directly to SAS for editing.
                              Larry Jacobson
                              October 27, 1998
*/

libname mydir  'F:\Sardine3.dir\sardine98all.dir\calcofi98.dir\sas_stuff.dir';

options pagesize=50 obs=max;

data temp1;
  set mydir.cofi5198;

* data transformations;

*stdlin is the nearest standard calcofi line;
if (line le  41.65) then stdlin =  40.00;
else if (line ge 41.65 and line le  45.00) then stdlin = 43.30;
```

```
else if (line ge 45.00 and line le  48.35) then stdlin = 46.70;
else if (line ge 48.35 and line le 51.65) then stdlin =  50.00;
else if (line ge 51.65 and line le 55.00) then stdlin = 53.30;
else if (line ge 55.00 and line le 58.35) then stdlin = 56.70;
else if (line ge 58.35 and line le 61.65) then stdlin = 60.00;
else if (line ge 61.65 and line le 65.00) then stdlin = 63.30;
else if (line ge 65.00 and line le 68.35) then stdlin = 66.70;
else if (line ge 68.35 and line le 71.65) then stdlin = 70.00;
else if (line ge 71.65 and line le 75.00) then stdlin = 73.30;
else if (line ge 75.00 and line le 78.35) then stdlin = 76.70;
else if (line ge 78.35 and line le 81.65) then stdlin = 80.00;
else if (line ge 81.65 and line le 85.00) then stdlin = 83.30;
else if (line ge 85.00 and line le 88.35) then stdlin = 86.70;
else if (line ge 88.35 and line le 91.65) then stdlin = 90.00;
else if (line ge 91.65 and line le 95.00) then stdlin = 93.30;
else if (line ge 95.00 and line le 98.35) then stdlin = 96.70;
else if (line ge 98.35 and line le 101.65) then stdlin = 100.00;
else if (line ge 101.65 and line le 105.00) then stdlin = 103.30;
else if (line ge 105.00 and line le 108.35) then stdlin = 106.70;
else if (line ge 108.35 and line le 111.65) then stdlin = 110.00;
else if (line ge 111.65 and line le 115.00) then stdlin = 113.30;
else if (line ge 115.00 and line le 118.35) then stdlin = 116.70;
else if (line ge 118.35) then stdlin = 120.00;
else stdlin=.;

* estimate the coastal station on this line using a crude linear approximation to
coastline;
if (line ge 40.0 and line le 43.3) then cst = -16.709091 + 1.272727 * line;
else if (line ge 43.3 and line le 46.7) then cst = -76.217647 + 2.647059 * line;
else if (line ge 46.7 and line le 50.0) then cst = 65.796970 + -0.393939 * line;
else if (line ge 50.0 and line le 53.3) then cst = -11.475758 + 1.151515 * line;
else if (line ge 53.3 and line le 56.7) then cst = 53.035294 + -0.058824 * line;
else if (line ge 56.7 and line le 60.0) then cst = 63.445455 + -0.242424 * line;
else if (line ge 60.0 and line le 63.3) then cst = 41.627273 + 0.121212 * line;
else if (line ge 63.3 and line le 66.7) then cst = 93.982353 + -0.705882 * line;
else if (line ge 66.7 and line le 70.0) then cst = -31.927273 + 1.181818 * line;
else if (line ge 70.0 and line le 73.3) then cst = 74.133333 + -0.333333 * line;
else if (line ge 73.3 and line le 76.7) then cst = 103.597059 + -0.735294 * line;
else if (line ge 76.7 and line le 80.0) then cst = -24.851515 + 0.939394 * line;
else if (line ge 80.0 and line le 83.3) then cst = 326.663636 + -3.454545 * line;
else if (line ge 83.3 and line le 86.7) then cst = 205.500000 + -2.000000 * line;
else if (line ge 86.7 and line le 90.0) then cst = 150.327273 + -1.363636 * line;
else if (line ge 90.0 and line le 93.3) then cst = 65.781818 + -0.424242 * line;
else if (line ge 93.3 and line le 96.7) then cst = -36.914706 + 0.676471 * line;
else if (line ge 96.7 and line le 100.0) then cst = 10.918182 + 0.181818 * line;
else if (line ge 100.0 and line le 103.3) then cst = 41.221212 + -0.121212 * line;
else if (line ge 103.3 and line le 106.7) then cst = -13.835294 + 0.411765 * line;
else if (line ge 106.7 and line le 110.0) then cst = 4.233333 + 0.242424 * line;
else if (line ge 110.0 and line le 113.3) then cst = 114.233333 + -0.757576 * line;
else if (line ge 113.3 and line le 116.7) then cst = 158.361765 + -1.147059 * line;
else if (line ge 116.7 and line le 120.0) then cst = 105.836364 + -0.696970 * line;
else if (line ge 120.0 and line le 123.3) then cst = -465.072727 + 4.060606 * line;
else if (line ge 123.3 and line le 126.7) then cst = 148.020588 + -0.911765 * line;
else if (line ge 126.7 and line le 130.0) then cst = 355.009091 + -2.545455 * line;
else if (line ge 130.0 and line le 133.3) then cst = 173.796970 + -1.151515 * line;
else if (line ge 133.3 and line le 136.7) then cst = 55.585294 + -0.264706 * line;
```

```
else cst = .;

* calculate distance from shore in km assuming 4 nautical miles between stations;
* a small negative number sometimes results where the the coast changes rapidly (Pt.
Conception);
* and the coastal station estimate in inaccurate;
kmtoshor=(station-cst)*4*1.853;
kmtoshor=max(kmtoshor,0);

  if (month le 3) then quarter=            1;
    else if (month le 6) then quarter=     2;
      else if (month le 9) then quarter=   3;
        else if (month le 12) then quarter=4;

  if (rawegg gt 0) then posegg=1;
    else posegg=0;

  if (rawlar gt 0) then poslar=1;
    else poslar=0;

  if (rawegg gt 0 or rawlar gt 0) then possampl=1;
    else possampl=0;

  if (percsort gt 1) then percsort=percsort/100;

  if (percsort gt 0) then do;
    adjechk=stdhfac*rawegg/percsort;
    adjlchk=stdhfac*rawlar/percsort;
    end;
  else do;
    put '%sort error at record ' _n_ ' cruise ' cruise ' orderoce ' orderoce ' percsort '
percsort
                                ' adjegg ' adjegg ' adjlar ' adjlar;
    adjechk=.;
    adjlchk=.;
  end;

    latitude=latdeg+latmin/60;

    longitud=longdeg+longmin/60;

    hour=int(begtime/100);
    minuts=(begtime/100-hour)*100;
    dechour=hour+minuts/60;

run;

proc contents data=mydir.bigdat1;
 run;

proc means data=mydir.bigdat1;
run;

data mydir.sindxdat;

  set temp1;
```

```
* cut down size of data set;
  if     (year ge 84) and
         (stdlin gt 76 and stdlin lt 94) and
         (station le 67.6);

* define inshore/offshore duumyies;
    intlin=round(stdlin);
    if (intlin eq 77 and station le 51) then inshore=1;
     else if (intlin eq 80 and station le 55) then inshore=1;
      else if (intlin eq 83 and station le 55) then inshore=1;
       else if (intlin eq 87 and station le 55) then inshore=1;
        else if (intlin eq 90 and station le 45) then inshore=1;
         else if (intlin eq 93 and station le 40) then inshore=1;
           else inshore=0;
run;

proc means data=mydir.sindxdat;
run;

title1;
title2;
title3;
```

Splus script file INDEX1.SSC used for CalCOFI GAM index based on proportion of tows positive for sardine eggs and larvae:

```
attach("d:\\Sardine3.dir\\sardine98all.dir\\calcofi98.dir\\_data",pos=1)

# import dbase file with all the calcofi data
import.data(FileName = "F:\\Sardine3.dir\\sardine98all.dir\\calcofi98.dir\\Cofi5198.dbf",
    FileType = "FoxPro",
    ColNames = "",
    Format = "",
    TargetStartCol = "1",
    DataFrame = "Cofi5198",
    NameRow = "",
    StartCol = "1",
    EndCol = "END",
    StartRow = "1",
    EndRow = "END",
    Delimiters = ", \t",
    SeparateDelimiters = F,
    PageNumber = "1",
    RowNameCol = "",
    StringsAsFactors = "Auto",
    VLabelAsNumber = F,
    Filter = "",
    OdbcConnection = "",
    OdbcSqlQuery = "")

# export data set in SAS format for further processing (i've got some nice sas code
    already)
export.data(DataSet = "Cofi5198",
    Columns = "ALL",
    Rows = "ALL",
    Delimiter = ",",
    ColumnNames = T,
    RowNames = T,
    Quotes = T,
    LineLength = "",
    FileName =
    "F:\\Sardine3.dir\\sardine98all.dir\\calcofi98.dir\\sas_stuff.dir\\Cofi5198.sd2",
    FileType = "SAS",
    OdbcConnection = "",
    OdbcTable = "",
    FormatString = "")

# now reimport the sas processed data
import.data(FileName =
    "F:\\Sardine3.dir\\sardine98all.dir\\calcofi98.dir\\sas_stuff.dir\\Sindxdat.sd2",
    FileType = "SAS",
    ColNames = "",
    Format = "",
    TargetStartCol = "1",
    DataFrame = "Sindxdat",
    NameRow = "",
    StartCol = "1",
```

```
    EndCol = "END",
    StartRow = "1",
    EndRow = "END",
    Delimiters = ", \t",
    SeparateDelimiters = F,
    PageNumber = "1",
    RowNameCol = "",
    StringsAsFactors = "Auto",
    VLabelAsNumber = F,
    Filter = "",
    OdbcConnection = "",
    OdbcSqlQuery = "")
#
#ftp data up to mainframe to fit the big models!
data.dump("Sindxdat","f:\\Sardine3.dir\\sardine98all.dir\\calcofi98.dir\\_data\\textfiles
    .dir\\Sindxdat.txt")
#
#get ready to fit the model on the mainframe
data.restore("sindxdat.txt")
attach(Sindxdat)

startglm<-glm(POSSAMPL~factor(YEAR)+factor(MONTH)+factor(INSHORE)+factor(STDLIN),
              family=quasi(link=logit,variance="mu(1-mu)"))
startgam<-gam(POSSAMPL~factor(YEAR)+factor(MONTH)+factor(INSHORE)+factor(STDLIN),
              family=quasi(link=logit,variance="mu(1-mu)"))
#
# need lots of memory
options(object.size=1e9)

#I like step.glm better than step.gam so use it
# note that the upper end of the scope term is year with all other factors and all
# 2 and 3 way interactions that don't involve year
bestglm<-step.glm(object=startglm,scope=list(
      upper=~factor(YEAR)+factor(MONTH)*factor(INSHORE)*factor(STDLIN),
      lower=~1),trace=T,direction="both")
best.formula<-formula(bestglm)
#
#short cut for pc, get formula for best model off mainframe and fit it again here
bestgam<-gam(best.formula,family=quasi(link=logit,variance="mu(1-mu)"))
win.graph()
par(mfrow=c(2,2))
plot.gam(bestgam,resid=T,se=T,main=
"GAM w/Interactions-All Months",
ylab="Probability-Logit Scale")
#
# I decided to use the model without interactions instead because the plots look better
# and because it is difficult to dream up a combination of MONTH, STDLIN etc. with
    combinations
# that match the original data.--even though the interations are highly significant
win.graph()
par(mfrow=c(2,2))
plot.gam(startgam,resid=T,se=T,main=
"GAM no/Interactions-All Months",
ylab="Probability-Logit Scale")
#
# estimates for months 6 and 12 are very weak cause there is only 35 and 7 tows in months
```

```
   6 and 12
# rerun models omitting data
Sindxdat.omit.june.dec<-Sindxdat[MONTH != 6 & MONTH != 12,]
detach("Sindxdat")
attach(Sindxdat.omit.june.dec)
bestgam.omit.june.dec<-gam(best.formula,family=quasi(link=logit,variance="mu(1-mu)"))
par(mfrow=c(2,2))
par(oma=c(1,1,1.5,1))
plot.gam(bestgam.omit.june.dec,resid=T,se=T,scale=9,rugplot=F,ylab="Probability-Logit
   Scale")
mtext("Sardine CalCOFI Data-GAM w/Interactions-Omit Jun/Dec",outer=T,cex=1.5)

startgam.omit.june.dec<-gam(formula(startgam),family=quasi(link=logit,variance="mu(1-
   mu)"))
win.graph()
par(mfrow=c(2,2))
par(oma=c(1,1,1.5,1))
plot.gam(startgam.omit.june.dec,resid=T,se=T,scale=7,rugplot=F,ylab="Probability-Logit
   Scale")
mtext("Sardine CalCOFI Data-GAM w/No Interactions-Omit Jun/Dec",outer=T,cex=1.5)

data2predict<-
   as.data.frame(cbind(YEAR=as.numeric(names(table(YEAR))),STDLIN=83.3,INSHORE=1,MONTH=4)
   )
junk1<-
   predict.gam(object=startgam.omit.june.dec,newdata=data2predict,type='response',se.fit=
   T)
CalCOFI.Index<-as.data.frame(cbind(Year=as.numeric(names(table(YEAR))),
                           Index=junk1$fit,
                           CV=junk1$se.fit/junk1$fit))
win.graph()
plot(CalCOFI.Index$Year,CalCOFI.Index$Index,ylim=c(0,0.85),xlab="Year",ylab="Probability
   Positive Bongo Tow",
     main="Pacific Sardine CalCOFI GLM Index",sub="(Calculated for April and Inshore
   Along Line 83.3)")
lines(CalCOFI.Index$Year,CalCOFI.Index$Index)
```

APPENDIX C

Computation of P_t and Var (P_t) for the Daily Egg Production Model:

For sardine eggs, mean eggs/minute ($P_{t,c}$), mean eggs/0.05m^3 ($P_{t,1}$) and their variances were computed as follows :

$$p_{t,j}=\frac{\sum_i p_{it,j}\, m_i}{\sum_i m_i} \qquad [1] \qquad var(p_{t,j})=\frac{n/(n-1)\sum_i m_i^2(p_{it,j}-p_{t,j})^2}{(\sum_i m_i)^2}$$

where j = 1 refers to CalVET and j=c refers to CUFES. m_i is the total pumping time (minute) for the ith transect for i= 2,...9.

$P_{t,c}$ from CUFES in each age group was then divided by R to be converted to eggs/0.05m^3 ($P_{t,2}$[1]):

$$P_{t,2}=P_{t,c}/R \qquad [2] \qquad var(P_{t,2})=var(P_{t,c}*1/R)$$

The final P_t (equation 1, main text) for sardine eggs was an average of $P_{t,1}$ and $P_{t,2}$ weighted by their CV^{-2} for each age group. That is:

$$P_t=\frac{P_{t,1}*CV_1^{-2}+P_{t,2}*CV_2^{-2}}{CV_1^{-2}+CV_2^{-2}}$$
$$=P_{t,1}*wt_1+P_{t,2}*wt_2 \qquad [3]$$

$$var(P_t)=var(P_{t,1})wt_1^2+var(P_{t,2})wt_2^2+2*wt_1*wt_2*cov(P_{t,1},P_{t,2})$$

---

[1] Variance of product of two independent random variables (Goodman 1960):

$$v(xy)=v(x)(Ey)^2+(Ex)^2\, v(y)-v(x)\, v(y)$$

and where:

$$wt_i = \frac{CV_i^{-2}}{CV_1^{-2} + CV_2^{-2}}$$

$$cov(p_{t,1}, p_{t,2}) = \frac{1}{R} cov(p_{t,1}, p_{t,c})$$

$$= \frac{1}{R} cor(x_{t,1}, x_{t,c}) SE(p_{t,1}) SE(p_{t,c}) \qquad [4]$$

$cov(P_{t,1}, P_{t,c})$ is the covariance of mean eggs/min and mean eggs/tow . $cor(x_{t,1}, x_{t,c})$ is the correlation coefficient of paired egg productions from CUFES and CalVET (n=8), transect being the sampling unit. R is the conversion factor for egg density from CalVET to CUFES. P_t and age (t) for yolk-sac larvae were computed from CalVET samples for larvae <= 5 mm captured size (Zweifel and Lasker 1976). A weighted nonlinear regression was used to obtain the estimates of $p_{0,1}$ and z, where the weight is $1/SE(p_t)$.