AN INVERSE EGG PRODUCTION METHOD FOR DETERMINING THE RELATIVE MAGNITUDE OF PACIFIC SARDINE SPAWNING BIOMASS OFF CALIFORNIA

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ABSTRACT

The California Department of Fish and Game is required by state law to determine annually whether the spawning biomass of the Pacific sardine (*Sardinops sagax*) is more or less than 20,000 short tons[1]. The sardine biomass appears to be increasing; however, the population level is too low to be reliably estimated by existing techniques. An inverse egg production method is proposed, to allow an objective determination of the relative magnitude of the spawning biomass of Pacific sardines.

The normal egg production method estimates adult biomass by measuring daily egg production in the spawning area and specific fecundity of the population. The inverse method estimates the area over which a specified spawning biomass (20,000 tons) would be assumed to occur. Components of egg production and specific fecundity for sardines—including average female weight, batch fecundity, spawning fraction, and daily egg production rate—were estimated from previous studies. A survey was designed to cover the Southern California Bight and provide a 95% probability of encountering the calculated spawning area if the spawning biomass is at least 20,000 tons. Recommendations are made, based on possible survey results.

RESUMEN

Por ley estatal, el Department of Fish and Game de California debe determinar anualmente si la biomasa de desove de la sardina del Pacífico (*Sardinops sagax*) es menor o mayor que 20,000 toneladas cortas (1 tonelada corta = 0.907 toneladas métricas. La biomasa de la sardina parece estar aumentando; sin embargo, el nivel poblacional es demasiado bajo para poder ser evaluado fidedignamente mediante las técnicas actuales. Se propone un método inverso de producción de huevos; éste posibilitará una determinación objetiva de la magnitud relativa de la biomasa de desove de la sardina del Pacífico. La técnica de producción de huevos normal evalúa la biomasa de los adultos mediante la medición de la producción diaria de huevos en el área de desove, y la fecundidad específica de la población. El método inverso estima el área en la cual una biomasa de desove dada (20,000 toneladas) supuestamente tendrá lugar. Sobre la base de estudios previos se estimaron los componentes producción de huevos y fecundidad específica para la sardina, incluyendo el peso promedio de las hembras, fecundidad de la puesta, fracción desovante, y producción diaria de huevos. Se diseñó un estudio para cubrir la Bahía del Sur de California, ofreciendo un 95% de probabilidad de localizar el area de desove calculada si la biomasa del mismo es de, al menos, 20,000 toneladas. Sobre la base de los posibles resultados del estudio se efectúan las recomendaciones correspondientes.

INTRODUCTION

The Pacific sardine fishery increased dramatically beginning in 1915 to a maximum catch of nearly 800,000 tons landed in the 1936-37 season. Annual season catches fluctuated around 600,000 tons over the next decade, and then declined steadily (Murphy 1966). The Pacific sardine population collapsed under fishery and environmental pressure (Clark and Marr 1955) and declined from biomass levels estimated at more than 3 million tons in the mid-1930s to levels thought to be as low as 5,000 tons by the 1970s (Murphy 1966; MacCall 1979; Smith 1972) (Figure 1). California legislation enacted in 1974 (1) placed a moratorium on fishing sardines while the biomass remains below 20,000 tons, (2) allows a 1,000-ton fishery for sardines when the spawning biomass reaches 20,000 tons, and (3) requires the Department of Fish and Game to determine annually whether this biomass has been reached. The moratorium has remained in effect because the spawning biomass has been considered to be below 20,000 tons since 1974.

Signs of an increase in the Pacific sardine population have been evident in recent years (Wolf[2]; Klingbeil and Wolf 1984; Klingbeil 1981, 1982, 1983). Although information currently available is indirect

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[1]Commercial landings, biomass estimates (Murphy 1966), tonnages specified in legislation, and tonnages in this paper are reported in short tons.

[2]Wolf, P. MS. Status of the spawning biomass of the Pacific sardine, 1984-85.

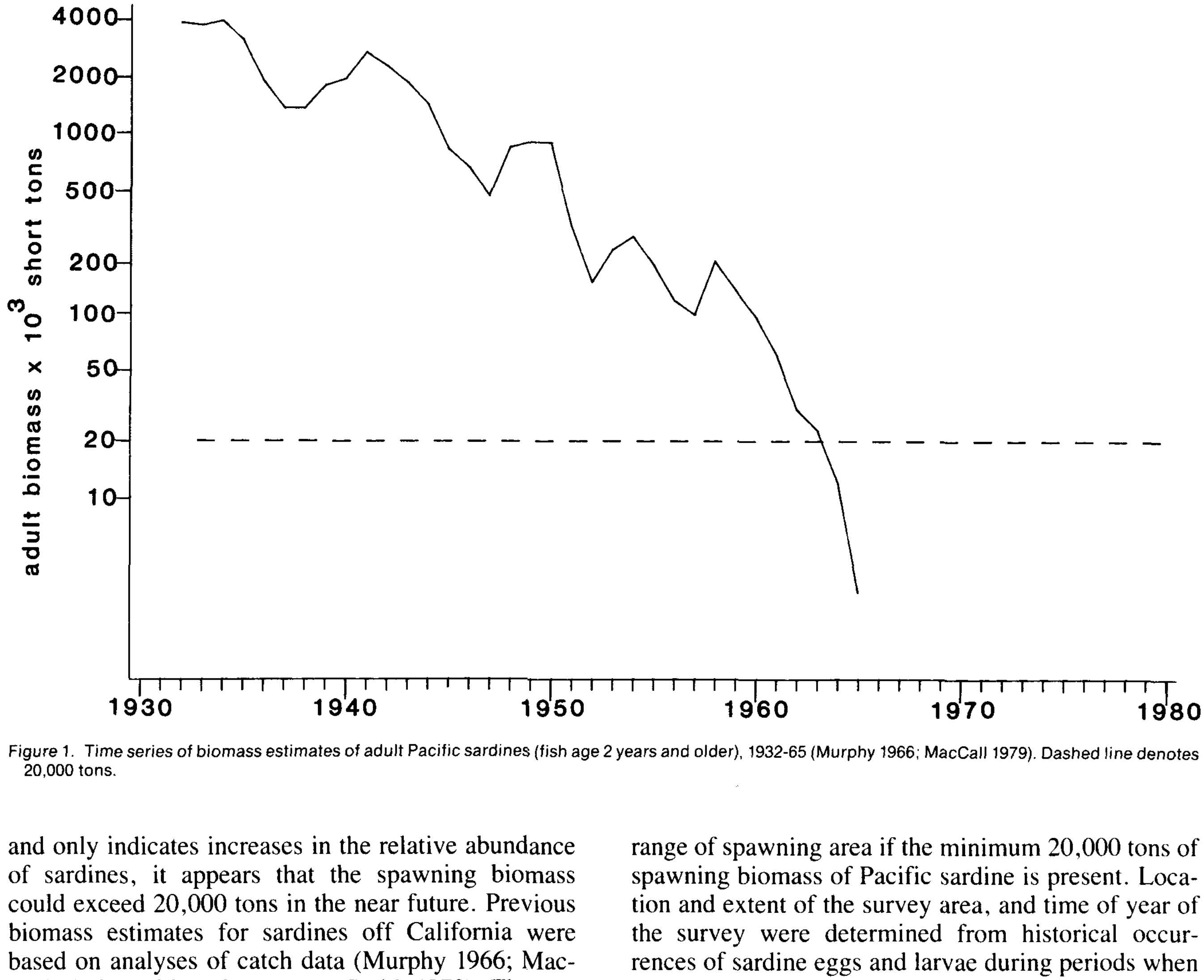

Figure 1. Time series of biomass estimates of adult Pacific sardines (fish age 2 years and older), 1932-65 (Murphy 1966; MacCall 1979). Dashed line denotes 20,000 tons.

and only indicates increases in the relative abundance of sardines, it appears that the spawning biomass could exceed 20,000 tons in the near future. Previous biomass estimates for sardines off California were based on analyses of catch data (Murphy 1966; MacCall 1979) and larval censuses (Smith 1972). The egg production method was developed by Parker (1980) and has been used to estimate the spawning biomass of anchovies off California (Picquelle and Hewitt 1983) and anchovies and sardines off Peru (Santander et al. 1982). However, no known method of biomass estimation is considered reliable at sardine biomass levels below 100,000 tons (MacCall 1984b).

The egg production method estimates spawning biomass as the quotient of the daily production of eggs in the spawning area and the daily fecundity of the population per ton of spawners (Parker 1980). The proposed inverse egg production method estimates the area over which the spawning products of a specified adult biomass could be assumed to occur, given certain conditions of average female weight, batch fecundity, spawning fraction, and daily egg production rate. These parameters were estimated from previous studies. We have designed a survey to cover the Southern California Bight and include the calculated range of spawning area if the minimum 20,000 tons of spawning biomass of Pacific sardine is present. Location and extent of the survey area, and time of year of the survey were determined from historical occurrences of sardine eggs and larvae during periods when sardine biomass levels were near 20,000 tons.

EGG PRODUCTION METHOD

The egg production method derived by Parker (1980) and applied by Picquelle and Hewitt (1983) and Hewitt (1984) estimates spawning biomass as

$$B = P_o A \frac{k W}{R F S}$$

where B = spawning biomass (MT)

P_o = daily egg production, number of eggs produced per 0.05 meter^2,

W = average weight of mature females (grams),

R = sex ratio, fraction of population that is female, by weight (grams),

F = batch fecundity, number of eggs spawned per mature female per batch,

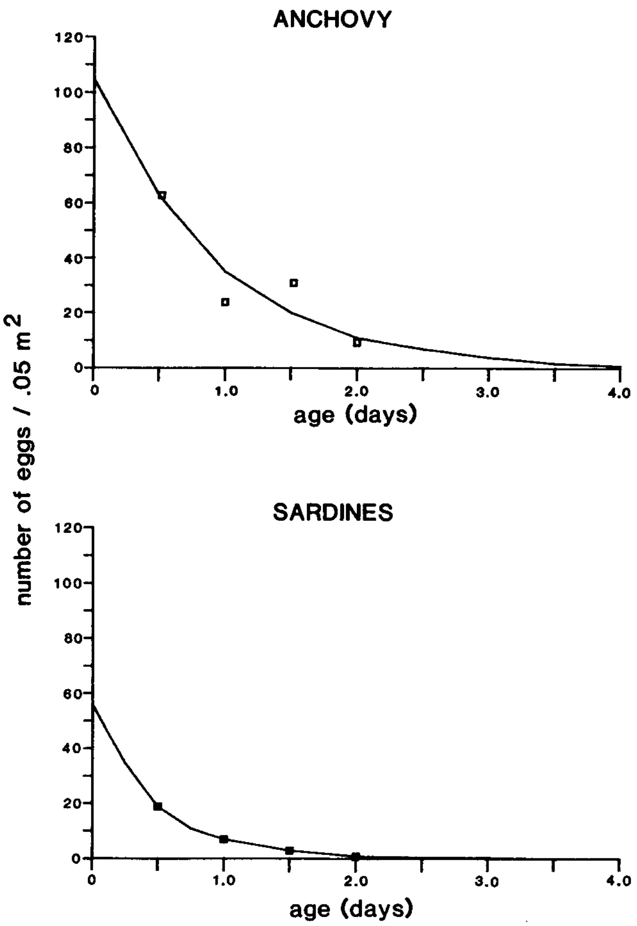

Figure 2. Exponential mortality model for estimating daily egg production rate of anchovies (*Engraulis ringens*) and sardines (*Sardinops sagax sagax*) off Peru (Smith, P.E., H. Santander, J. Alheit. MS. Comparison of the mortality and dispersal of sardine [*Sardinops sagax sagax*] and anchovy [*Engraulis ringens*] eggs off Peru.)

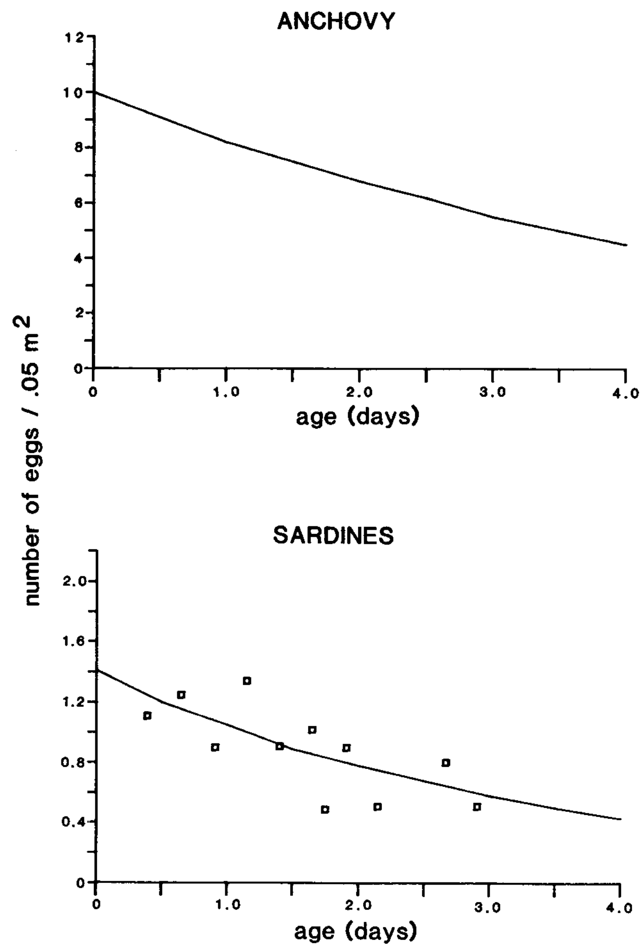

Figure 3. Exponential mortality model for estimating daily egg production rate of anchovies (*Engraulis mordax*) 1980-84, using CalVET nets, and sardines (*Sardinops sagax*), 1951-59, using oblique (CalBOBL) tows, off California.

S = fraction of mature females spawning per day,

A = total area of survey (0.05 meter^2), and

k = conversion factor from grams to metric tons.

INVERSE EGG PRODUCTION METHOD

In the egg production method, the parameters of daily egg production and population fecundity are estimated by measurements collected over the duration of the survey. The parameter P_o is estimated by fitting an exponential mortality curve to counts of aged eggs collected in plankton samples and extrapolating back to the number of eggs at the time of spawning. Parameters W, F, S, and R are estimated from samples of adult fish collected during the survey.

In the inverse egg production method, the spawning biomass was specified and the equation solved for A_1:

$$A_l = \frac{B_1\ RFSm}{P_o\ k_1\ W}$$

where A_1 = spawning area of biomass B_1 in nautical miles^2,

B_1 = spawning biomass, in short tons,

k_1 = conversion factor from grams to short tons,

m = conversion factor from 0.05 meter^2 to nautical miles^2.

We propose this inverse egg production method as a preliminary, relatively inexpensive technique for identifying whether the spawning biomass has exceeded a specified level. The parameters for sardines are estimated from previous studies, rather than measured during the survey. Where no reliable parameter values are available, we use a range of values.

TABLE 1
Values of Parameters Used to Estimate Spawning Area, and Resulting Estimates

B_1	W	R	F	P_o	S	A_1
Spawning biomass (short tons)	Average female weight (g)	Sex ratio (females/total)	Batch fecundity (eggs/batch/female)	Egg production (eggs/.05m^2-day)	Spawning fraction (spawning females/ total females)	Spawning area (nautical miles^2)
20,000	120	0.5	32,000	5.0	0.02	141
					0.05	353
					0.10	706
					0.15	1058
				1.5	0.02	470
					0.05	1176
					0.10	2352
					0.15	3528

Parameters P_o, W, F, S, and R

Estimates of daily egg production for sardines and anchovies off Peru[3] indicate that egg production rates are lower for sardines than for anchovies by a factor of 1:2 (Figure 2). Applying this relationship to 1980-84 annual estimates (Hewitt 1984) of daily egg production rate for anchovies (approximately 10 eggs/ 0.05m^2) off California (Figure 3) results in an estimated sardine daily egg production rate of approximately 5 eggs/0.05m^2. CalCOFI egg surveys conducted from 1951 through 1959 yielded an estimated California sardine daily egg production rate of approximately 1.5 eggs/0.05m^2 (Figure 3). This value is thought to be low because of the sampling technique (oblique tows instead of vertical egg tows), which may have overestimated the surface area of water sampled. Both tentative values of P_o were used in the inverse egg production method. The parameter W, average weight of mature females, is estimated to be 120 grams (MacGregor 1957). The female fraction of the population by weight, R, is assumed to be one-half. Batch fecundity, F, is estimated at 32,000 eggs (MacGregor 1957). Spawning fraction, S, for other pelagic species ranges from 0.02 females spawning per day (spawning once every 50 days) for Pacific sauries (Hatanaka 1956) to 0.14 females spawning per day (spawning once every 7 days) for anchovies (Hunter and Macewicz 1980). This range of values for S was used for sardines. Setting biomass, B_1, at 20,000 tons, and using the parameters described above, we calculated a range of values for the spawning area, A_1 (Table 1).

Spawning Area

The calculated area, A_1, over which the spawning products of 20,000 tons of Pacific sardines could be expected to occur ranges from 141 to 1,058 nm^2 for a high daily egg production rate of 5 eggs/0.05m^2, and from 470 to 3,525 nm^2 for a low daily egg production rate of 1.5 eggs/0.05m^2 (Table 1). Based on these results, a useful estimate of A_1 is 500 nm^2.

PROPOSED SURVEY

We examined historical CalCOFI egg and larval survey data to determine the area and time of year over which sardine spawning would be likely to occur. Mean number of eggs/10m^2 and larvae/10m^2 in CalCOFI regions 7 and 8 from 1954 to 1960 plotted by station and by month (Figure 4) indicate that sardine spawning occurs in the Southern California Bight from April through June. CalCOFI ichthyoplankton surveys during 1981 and 1984 showed evidence of sardine spawning in this area, primarily in coastal locations (Figure 5) from April through June. Brewer and Smith (1982) reported spring occurrences of sardine larvae in nearshore areas of the Southern California Bight from 1978 to 1980, including a relatively high occurrence of larvae in the late summer and fall of 1980.

We have designed a survey that covers CalCOFI regions 7 and 8 (CalCOFI lines 80-97, stations .20-.65) during May. CalCOFI regions 7 and 8 cover an area of approximately 32,000 nm^2 (Smith et al. 1976). The critical spawning area, A_1, estimated at 500 nm^2, is approximately 2% of the survey area. Using a table for determining confidence limits of a proportion (Natrella 1963), we determined a sample size of 374 CalVET samples (vertical egg tows) to be the minimum effort required to locate the spawning area within the survey area, with 95% confidence limits. For convenience, current practices for anchovy egg production cruises were adapted for the sardine spawning area survey. These samples are 4 nm apart offshore

[3]Smith, P.E., H. Santander, J. Alheit. MS. Comparison of the mortality and dispersal of sardine (*Sardinops sagax sagax*) and anchovy (*Engraulis ringens*) eggs off Peru.

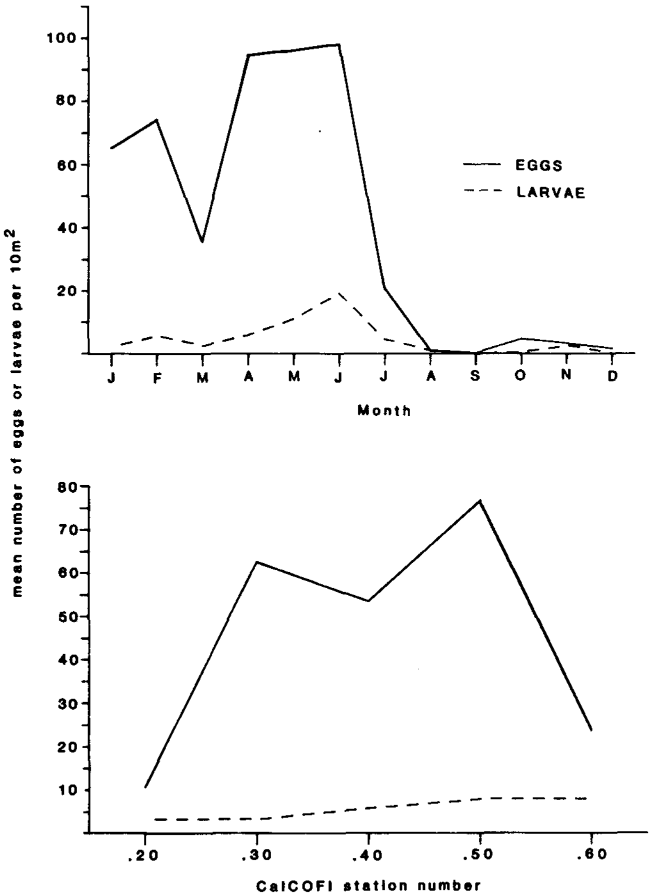

Figure 4. Occurrence of sardine eggs and larvae in CalCOFI regions 7 and 8, 1954-60, by month and by station.

and 10 nm apart alongshore for an area representative of 40 nm². The projected area of 500 nm² is therefore expected to contain 12 or 13 positive stations for 20,000 tons spawning biomass. If no positive stations result, the spawning biomass may be considered to be below 20,000 tons. Positive stations occurring over an area of 500 nm² would indicate that the spawning biomass of Pacific sardines is at least 20,000 tons. This proposed survey (Figure 6) is scheduled to be conducted in May 1985.

DISCUSSION

Indirect or incidental evidence of the relative abundance of sardines is adequate information for determining whether the spawning biomass is more or less than 20,000 tons only while biomass levels obviously remain very low. No estimation techniques are reliable at biomass levels as low as 20,000 tons. The proposed inverse egg production method allows an objective determination of the relative magnitude of the spawning biomass of Pacific sardines as required by state law.

The large range of values calculated for A_1 (the spawning area) resulted from using a range of values to estimate parameters P_o (daily egg production rate) and S (spawning fraction). These parameters are not known for Pacific sardines. The low estimate for P_o was based on California data, which were collected using an oblique tow instead of the vertical egg tow designed specifically for use in the egg production method[4]. The high estimate of P_o depends on the relationship between egg production rate of anchovies and sardines off Peru, a relationship that has not been demonstrated for sardines off California. Daily egg production rate and spawning rate must be determined for Pacific sardines. The remaining adult parameters must be recalculated for the current California population of sardines as well.

The area parameter of the egg production method was chosen as the first indicator of population recovery because under the conditions of small numbers of positive samples it is the most reliable indicator of spawning biomass (Smith and Hewitt 1984; Smith 1973). The estimated rate of egg production is inherently the most variable (Parker 1980). The reasons for this are that the eggs are spawned in dense patches; the dispersion rate is quite slow; and rate of production is estimated from the extrapolation of an exponential mortality curve based on a small number of days of spawning. Although this approach may be useful when there are hundreds of positive samples, the results are not reliable with the few positive samples predicted for the initial years of the sardine population recovery. A simulation model of the sampling process including the initial patchiness, the historical mortality rate, and the number of observations within the spawning habitat illustrates these points (Table 2). The upper part of the table demonstrates the need for hundreds of samples to obtain a useful egg production rate; the lower part of the table establishes the small number of observations necessary to obtain a precise estimate of spawning habitat.

The first step in managing a resurgence of sardines is detecting the onset of recovery. It is recommended that Pacific sardines be surveyed annually to determine when the biomass exceeds 20,000 tons. The second management step will require measuring the extent of recovery. Several techniques of abundance estimation may be successfully applied to sardines, including the egg production method, acoustic surveys, larval census, systematic aerial surveys, or combinations of these (MacCall 1984b). Selection or development of methods will depend on management goals, performance of the resource in recovery, and fishery develop-

[4]Smith, P.E., W. Flerx, and R. Hewitt. MS. The CalCOFI vertical egg tow (CalVET) net.

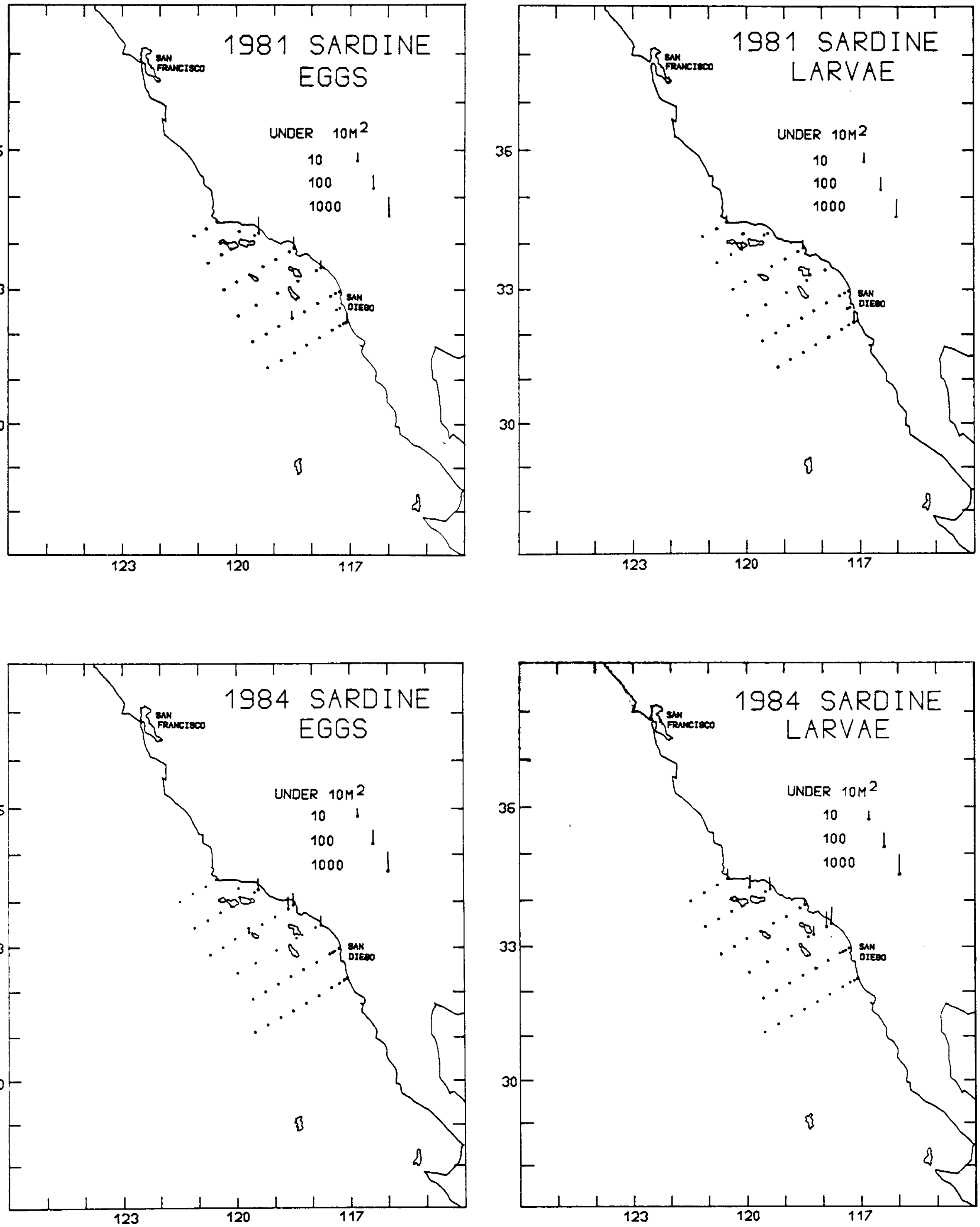

Figure 5. Abundance (total numbers) and location of sardine eggs and larvae in Southern California Bight captured during CalCOFI quarterly cruises in 1981 (January-December) and 1984 (January-July data only).

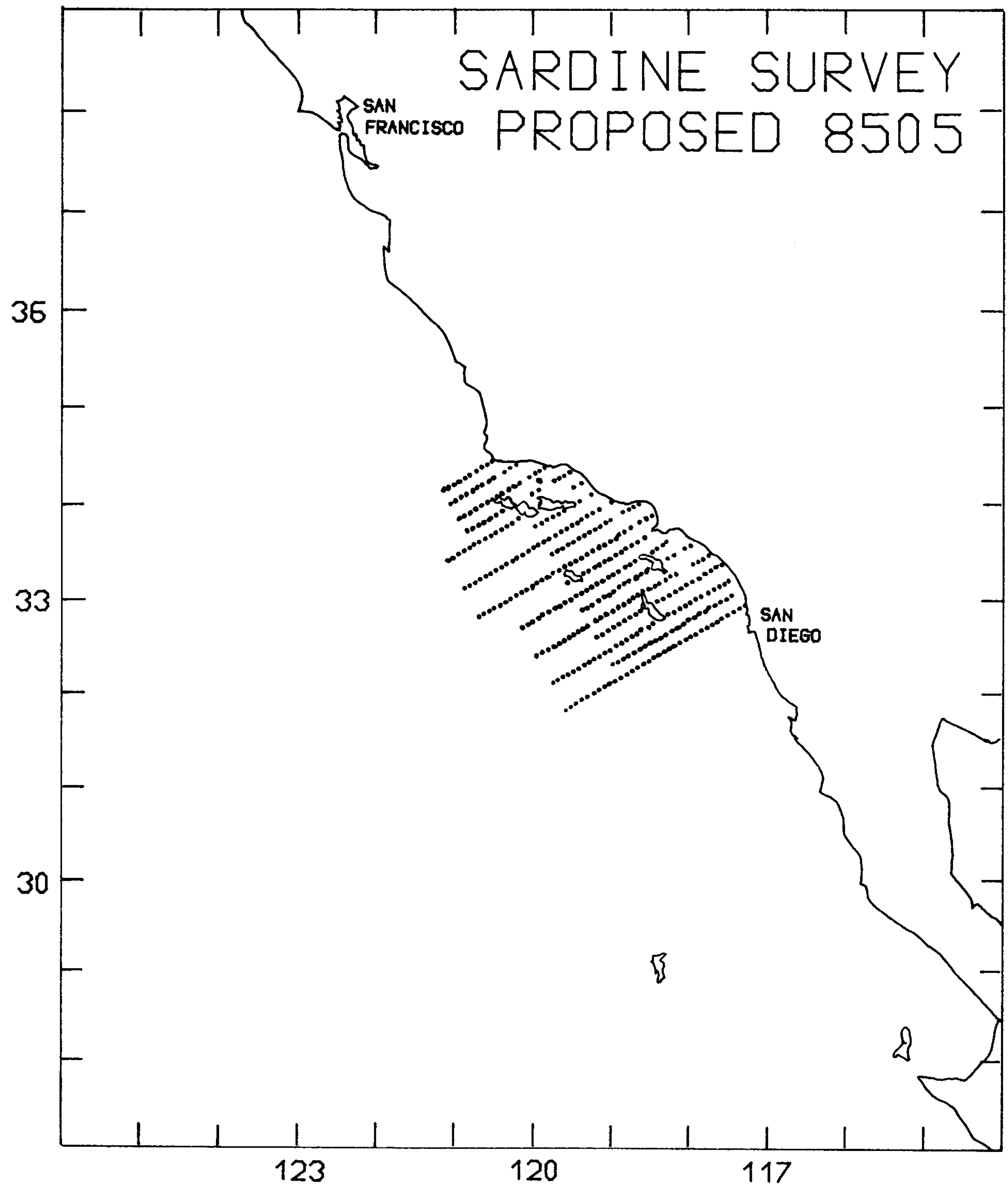

Figure 6. Proposed minimum probability sardine survey, May 1985.

ment. An inverse egg production method could be used as a regular, inexpensive technique, in combination with an alternative, periodic, absolute biomass estimation method.

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TABLE 2
Simulation of a 20,000-Ton Spawning Biomass of Pacific Sardine Based on Historical Samples

	Number of observations within spawning area								
	1	5	10	20	50	100	200	500	1000
Estimated biomass (× 10^3 tons)									
< 0	18	8							
0 – 2	36	8	7	3					
2 – 14	18	42	38	37	30	18	18	1	
14 – 26	8	27	25	27	48	64	67	96	100
26 – 38	8	6	10	18	21	18	15	3	
38 – 50	2	2	11	6	1				
50 – 62	1	3	5	6					
62 – 74	2	1	4	1					
74 – 86	0	0	0	1					
86 +	7	3							

	Number of observations within spawning area								
	1	5	10	20	50	100	200	500	1000
Probability of zero eggs									
One-day-old	.70	.35	.09	.01	0	0	0	0	0
Two-day-old	.59	.27	.03	.01	0	0	0	0	0
Three-day-old	.53	.12	.01	.01	0	0	0	0	0
Joint probability	.22	.01	0	0	0	0	0	0	0

Simulation based on Ab (0.375 days), Bb (1.375 days), Cb (2.375) (Smith 1973), negative binomial factors (m,k) Ab (4.47, .093), Bb (3.31, .179), Cb (2.45, .274), and habitat egg production parameters of 5 eggs per unit observation and instantaneous mortality rate of 0.3/day.

sardine egg data were entered and edited by Cindy Meyer and Celeste Santos.

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