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EXECUTIVE SUMMARY

The 2015 daily egg production method (DEPM) survey for Pacific sardine (*Sardinops sagax*) was conducted in March/April off the west coast of the USA from about Winchester Bay, Oregon (43.75°N) to Morro Bay, California (California Cooperative Fisheries Investigation, CalCOFI line 75.0). Pacific sardine eggs, larvae and adults were most abundant between 41.0 °N and 42.9°N (north of Eureka, CA to north of Cape Blanco, OR) indicating that the stock was located outside of the spawning core traditional area, which has been mostly centered between north of San Francisco to San Diego (CalCOFI lines 60.0 - 93.0) over the last decade. The spawning biomass of the Pacific sardine in April 2015 was estimated from the DEPM based on two methods: 1) the traditional method where egg production (P_0) was a weighted mean, and each adult parameter was an unstratified estimate; and 2) a stratified procedure where the estimate of total spawning biomass is the sum of the estimated spawning biomass in each of two regions representing high and low spawning activity. The two estimates of the spawning biomass were 33,412 mt (CV = 0.74) and 39,495 mt (CV = 0.56), respectively within a total survey area of 181,250 km^2. The daily egg production estimate (P_0, an average weighted by area) was 0.17/.05m^2 (CV = 0.72). The estimates of female spawning biomass calculated by the two methods were 16,207 (CV = 0.74) and 19,376 (CV = 0.58), respectively.

Pacific sardine spawning biomass was estimated from 62 sardines collected from 7 positive trawls during the survey. Trawling was conducted randomly, which resulted in sampling adult sardines in both the high and the low sardine egg-density regions of the surveyed area. During the 2015 survey, 25 mature female sardines were captured in 4 trawls (2 within the high egg-density region and 2 trawls with the low egg-density region). The daily specific fecundity (*RSF/W*) of this group of females was 18.1 eggs/population weight (g)/day using the following estimates of reproductive parameters: *F*, mean batch fecundity, 60,916 eggs/batch (CV = 0.02); *S*, fraction spawning per day, 0.12 females spawning per day (CV = 0.16); W_f, mean female fish weight, 192 g (CV = 0.05); and *R*, sex ratio of females by weight, 0.485 (CV = 0.08). Due to the low number of females collected in the 2015 DEPM survey, batch fecundity was estimated from a regression model using data collected from 2013, 2014 and 2015 surveys.

The time series of spawning biomass presented in the table below was one of the fishery-independent indices of relative abundance in the annual stock assessment of the Pacific sardine from 1994 to 2015.

Calendar year	Total egg production	Female spawning biomass (CV)	Total spawning biomass[a] (CV)
1994	73374	69065 (0.30)	128531 (0.31)
2004	307795	145274 (0.23)	234958 (0.28)
2005	486950	459943 (0.60)	755657 (0.52)
2007	306297	198404 (0.31	380601 (0.39)
2008	128118	66395 (0.28)	126148 (0.40)
2009	162188	99162 (0.24)	185084 (0.28)
2010	97838	58447 (0.42)	108280 (0.46)
2011	364798	219386 (0.28	383286 (0.32)
2012	227632	113178 (0.27)	282110 (0.43)
2013	198472	82182 (0.30)	144880 (0.36)
2015	30396	19376 (0.58)	33412 (0.74)

[a] based on data in Table 6

Since 2009, the time series of total spawning biomass was replaced by female spawning biomass for years when sufficient trawl samples were available. In other years when not enough mature females were captured (i.e.1996-2003 and 2006), the total egg production was used as inputs to the stock assessment of Pacific sardine. In 2015, sufficient mature females were collected in the spring survey, and thus female spawning biomass was computed and was directly used in the 2015 stock assessment update. The 1994-2013 time series of biomass were based on survey data collected within the DEPM standard area, whereas the 2015 estimate was computed using the whole survey area. The time series of spawning biomass showed that this parameter fluctuated considerably during the 1994-2013 period. Spawning biomass peaked in 2005, declined from 2007 to 2010, but increased in 2011 before declining again from 2012 to 2015.

INTRODUCTION

Fishery independent surveys are critical for assessing and managing Pacific sardine stocks along the North American Pacific coast. These surveys provide relative abundance indices to calibrate stock assessment and to monitor stock productivity as environmental conditions change. The Daily Egg Production method (DEPM) is one of two fishery-independent surveys that are currently used to assess the northern Pacific sardine stock from Ensenada to British Columbia and to set harvest guidelines for annual management in the USA. The DEPM was developed by Lasker (1985) to estimate the spawning stock biomass of northern anchovy (*Engraulis mordax*) based on growth, mortality and abundance of eggs and larvae, and the adult reproductive biology of this species. The method was later applied to assess the spawning of Pacific sardine off California from 1986 to 1996 (Wolf 1988a, Wolf 1988b, Lo et al. 1996, Scannel et al. 1996, Barnes et al. 1997). Since 2004, spawning biomass computed from the DEPM has been integrated in annual stock assessments of Pacific sardine by: 1) calculating the daily egg production from ichthyoplankton survey data; 2) computing the reproductive parameters of females from adult fish samples; and 3) calculating the biomass of spawning adults.

Historically, various methods have been used to survey the spawning ground of Pacific sardine off California for the DEPM estimation. Prior to 1996 sardine egg production was estimated from CalCOFI Vertical Egg Tow (CalVET a.k.a Pairovet) plankton net samples; whereas adult fish were sampled to obtain specimens for batch fecundity, spawning fraction, sex ratio, and average female fish weight (Wolf 1988a, 1988b; Scannell et al. 1996; Macewicz et al. 1996; Lo et al. 1996). Since 1996, in addition to CalVET and Bongo nets, a Continuous Underway Fish Egg Sampler (CUFES) has been used to collect sardine eggs (Checkley, et al. 1997) in the upper 3m of surface water. During the 1997 sardine egg survey, CUFES was used to allocate CalVET tows in an adaptive sampling design (Hill et al. 1998, Lo et al. 2001). From 1998 to 2000, data on sardine eggs collected with both CalVET and CUFES during each April California Cooperative Oceanic Fisheries Investigations (CalCOFI) cruise were used to estimate daily egg production (Hill et al. 1999). Starting in 2001, a cost-effective alternative was adopted to calculate the DEPM index that reduced effort in calculation and egg staging of the CUFES collections. Egg production estimated from this revised index only uses CalVET egg samples, and yolk-sac larvae samples from both CalVET and Bongo net samples collected in the high-egg density area.

During the past decade, full-scale surveys were conducted to collect of Pacific sardine eggs, larvae, and adults to better estimate the spawning biomass in the area off California (CA) between San Diego and San Francisco (Lo and Macewicz 2004; Lo et al. 2005; Lo and Macewicz 2006; Hill et al. 2006a, b; Lo et al. 2007a, b, 2008, Lo et al. 2009, 2010b, 2011, Lo et al. 2013). In 2004 the adult samples were taken primarily in the high egg-density area, but beginning in 2005 adult Pacific sardine samples for reproductive output were taken in both high and low sardine egg-density areas. The ichthyoplankton samples taken during regular April CalCOFI cruises were also included in the spawning biomass computation. During 2006, 2008, and 2010-2012, the survey area was extended north to the US-Canadian border. The spawning biomass was computed for both the whole survey area (Cape Flattery, WA to San Diego, CA) and the standard DEPM survey area (from San Diego to San Francisco, CalCOFI line 95 to 60) in 2006, 2008 and 2010. However, in 2011 and 2012 biomass was only computed for the standard area because few eggs and adults were observed in the area north of CalCOFI line 60.0. Further, only biomass computed for the DEPM standard area was used in stock assessment. In some years the most southern CalCOFI line occupied was not line 95. For examples, in 2012 and 2013 the most southern line was 93.8 and

91.7 respectively. In 2014, the DEPM survey was restricted to within the core spawning area of sardine (North of San Francisco to San Diego, a.k.a. standard DEPM area); however no eggs or larvae were collected in CalVET and Bongo tows, preventing the estimation of the spawning biomass (see Appendix). Since 2009, in addition to the estimates of spawning biomass based on the past procedure (i.e., where egg production was weighted by the size of each region and the adult parameters were estimated from all trawl samples in the entire survey area), an alternative estimator based on stratified sampling for each parameter was also included (Hill et al. 2009, 2010) for years when adequate adult samples were available (1986, 1987, 1994, 2004, 2005, 2007-present).

Throughout the 1994-2013 period, the northern Pacific sardine stock was mostly distributed off California between just north of San Francisco and San Diego in April during the DEPM survey, although residual spawning had been observed north of this area in 2006, 2008, and 2010 (Lo et al. 2013). However, likely due the North Pacific Ocean warming in 2014 (commonly known as the Warm Blob), very few eggs were collected from CUFES and no eggs and larvae were collected from CalVET and Bongo tow (see Appendix). These data indicated that the survey might have missed the spawning peak or the spawning stock moved into cooler water off northern California, Oregon and Washington. As the North Pacific Ocean continued warming in the spring of 2015 under the effects of the Warm Blob combined with the transition to one of the strongest El Niño in decades, suitable spawning sardine habitats were predicted to be around northern California and Oregon (Zwolinski et al., 2011). Information reported by fishers also indicated abundant Pacific sardines in coastal waters off Oregon (OR) in March 2015. Consequently, the 2015 April DEPM survey was designed to cover the area from Waldport, OR to Point Conception, CA, to maximize the chance of sampling regions of higher occurrence of eggs, larvae and spawning adults. Here, we describe methods of survey and data analyses, and report time series of spawning biomass, female spawning biomass, and total egg production. We used both the traditional method (with no stratification) and post-stratification of the sampling frame to analyze these data for biomass estimation. However, contrary to previous years, the 2015 biomass estimate for the stock assessment update was based on the whole DEPM survey area, rather than the standard DEPM area.

MATERIALS AND METHODS

Data

The spring 2015 CPS-Sardine DEPM survey was conducted aboard the NOAA ship *Bell M. Shimada* (March 28 – May 1). The *Shimada* covered the area off the west coast of the US from south of Waldport, Oregon (44.2°N) to Morro Bay, California (CalCOFI line 75.0). During the DEPM survey, CalVET tows, Bongo tows, CUFES sampling and surface trawls were conducted from Winchester Bay, OR (43.75°N) to CalCOFI line 75 (34.68°N) (Figures 1 and 2). The spring CalCOFI survey was conducted on the Scripps Institution Oceanography research vessel *New Horizon* (April 4 – April 29) from San Diego to San Francisco Bay, California. However, data from the CalCOFI survey were not used because no trawling was conducted since *New Horizon* is not equipped to tow mid-water trawls. Further, the number of sardine eggs and larvae collected during CalCOFI was low for all nets, with only 1 egg and 1 larva collected from CalVET tows

(Table 1). Consequently, only data from the DEPM survey on the *Shimada* were included in the estimation of spawning biomass of Pacific sardine.

All ichthyoplankton tows follow specific protocols developed within the CalCOFI program. CalVET tows are fished vertically from 70 meters depth to the surface at a retrieval rate of 70 m/minute. The mesh size of the net body and the codend are 150 µm and the frame opening diameter is 25 cm. Water flow through the net opening is measured with a GO digital flowmeter. Bongo tows consist of paired 71 cm rings connected by a central swivel. With depth permitting, the Bongo nets fish to a depth of 210 m at an oblique (~45°) trajectory. The paired nets have mesh sizes of 505 µm and the codends have 333 µm mesh. The amount of water strained during a tow is measured by a GO digital flowmeter. For a more detailed description refer to Smith and Richardson (1977) and McClatchie (2014).

In addition to sardine eggs and yolk-sac larvae collected with the CalVET net, yolk-sac larvae collected with the Bongo net have been included to model the sardine embryonic mortality curve since 2000. First, CUFES data from the ichthyoplankton surveys was used to map the spatial distribution of the sardine spawning population and to post-stratify the survey area into high egg-density (Region 1) and low egg-density (Region 2) areas (see Lo et al. 2001). Second, staged eggs from CalVET tows and yolk-sac larvae from CalVET and Bongo tows in the high density area were used to model embryonic mortality in the high density area and the whole survey area. Third, the daily egg production (P_0) for these two areas were derived from the mortality curve equation.

The 2015 CPS-Sardine DEPM survey was initially designed with thirty distinct transects covering the area from the California-Mexico border in the south to Cape Mendocino in the north at 20 mile spacing. Based on Zwolinski et al. (2011)'s habitat model forecast for April 2015, consecutive years of warming in the north eastern Pacific, and information received from sardine fishermen off Oregon, an additional fourteen transect lines were added to the north of the existing pattern, starting just south of Waldport, Oregon. The survey began at the northern most transect and occupied the lines from the north to the south. Since the northern extent of the population was not known, the ship traveled northward and sampled the predetermined northern most transect, located at 44.2°N. If Pacific sardine were encountered during operations (either eggs or adults) an additional transect would have been located twenty nautical miles north of that transect. However, the CUFES broke in route and was not used for sampling eggs on the first two transects and no sardines were caught in the four trawls in that area. Hence, the whole DEPM survey area is between 43.75°N and 35.68°N (Figures 1 and 2) and does not include those two transects. After repairing the CUFES, transect spacing was reduced, as much as ten nautical mile, whenever sardine eggs, larvae or fish were encountered. In areas with no observed eggs, fish or larvae, transect spacing was increased as much as forty nautical miles to save time and cover a broader area of the coast.

For the CPS-Sardine DEPM survey, CalVET tows were taken at 5-nm intervals on each line after the egg density from a CUFES sample exceeded 0.3 egg/min, and CalVET tows were stopped after the egg density from each of two consecutive CUFES samples was less than 0.3 egg/min. The threshold of 0.3 egg/min was reduced from the number used in years prior to 2002 (2 eggs/min) and 2014 (1 egg/min) to increase the area identified as the high egg-density area and, subsequently, to increase the number of CalVET samples. The catch ratio of egg densities from CUFES (egg/min) to that by CalVET tow (eggs/0.05m^2) depends on the degree of water mixing.

This adaptive allocation sampling was similar to that used in the 1997 survey (Lo et al. 2001). Because the threshold changed in 2002 and again in 2015, caution should be taken when comparing the size of the area of Region 1.

In 2015, the whole DEPM survey area (181,250 km^2) was mostly north of the standard DEPM survey area. The survey covered 56,963 km^2 within the DEPM standard area (CalCOFI line 75.0 to line 60.0) and extended northward over 124,287 km^2 (CalCOFI line 60 to near Winchester Bay, OR, 43.75°N). The whole DEPM survey area was used to estimate the initial P_0, and was post-stratified in two Regions: the high egg-density region (Region 1) and the low egg-density region (Region 2). The high density area was located between 41.0 °N and 42.9°N (north of Eureka, CA to north of Cape Blanco, OR), where the egg density in CUFES collections was at least 0.3 eggs per minute. The high density area (Region 1) was estimated to be 8,814 km^2. The low density area (Region 2) was estimated to be 172,436 km^2 (Table 1, Figure 1). The sizes of all surveyed areas were computed after a 2.5 nautical mile expansion (i.e. half of the distance between CUFES samples) from survey line or station, using the "*Projections and Transformations Tools*" of the ArcGIS software program (Version 10.2.2).

A total of 351 CUFES samples were collected by *Shimada* over the whole survey area. CUFES sampling intervals ranged from 10 to 69 minutes with a mean of 36.3 minutes and a median of 30 minutes depending on egg densities observed onboard. The total number of CalVET tows was 66 for the entire survey area. A total of 56 CalVET samples caught at least one egg, and 25 of them were located in Region 1(Table 1). Egg densities from each CalVET sample and from the CUFES samples taken within an hour before and after the CalVET tow were paired and used to derive a conversion factor (E) from eggs/min of CUFES sample to CalVET catch (eggs/tow). We used a regression estimator to compute the ratio of mean eggs/min from CUFES to mean eggs/tow from CalVET: $E = {}^{\mu_y}/_{\mu_x}$ where *y* is eggs/min and *x* is eggs/tow.

For adult samples, the survey plan was to use the *Shimada* to conduct 3 – 5 trawls a night either near regular CalCOFI stations or at random sites on the survey transect regardless of the presence of sardine eggs in CUFES collections. At night a Nordic 264 rope trawl with 3.0 m^2 foam core doors was towed for 30 minutes at the surface (0 – 11 meters). The trawl was modified for surface trawling with Polyform floats attached to the head rope and trawl wings. The trawl was modified with a marine mammal excluder device placed midsection just forward of the codend. For the whole CPS-Sardine DEPM survey, trawling occurred from March 30 to April 30, 2015 and 9 of the 51 trawls conducted at night were positive for Pacific sardines. Seven trawls caught adult sardines and two caught a single larva each. All positive trawls were located north of the standard DEPM area (north of CalCOFI line 60) (Table 2, Figure 1).

The normal processing target of 50 randomly selected sardines was not achieved in any of the trawls because of low sardine abundance (Table 2). The maximum number of sardine caught in a single trawl was 30. Each fish was sexed, standard length (mm) and weight (g) were measured, otoliths were removed for aging, tissue was preserved in 95% ethanol for genetics, and, for females, ovaries were removed and preserved in 10% neutral buffered formalin. Each preserved ovary was blotted and weighed to the nearest milligram in the laboratory. Ovary wet weight was calculated as preserved ovary weight times 0.78 (unpublished data, CDFG 1986). A piece of each ovary was removed and prepared as hematoxylin and eosin (H&E) histological slides. All slides were analyzed for oocyte development, atresia, and postovulatory follicle age to assign female maturity and reproductive state (Macewicz et al. 1996).

Daily egg production (P_0)

From 1994 to 2013 DEPM parameters estimates were based on survey data collected each spring, generally April, within the standard DEPM area between San Diego and San Francisco, California, although in some years the surveys were extended as far north as Washington. In 2015, as the population moved northward due to warmer oceanic conditions, the high density area was located north of the standard DEPM area. Contrary to previous years (e.g. 2006 and 2012 when most eggs were collected in the DEPM standard area), the estimate of P_0, and thus spawning biomass for 2015 were based on the whole survey area. Appropriate parameter estimates required by the DEPM were obtained for each sardine egg-density region.

Similar to the 2001-2005 procedure (Lo 2001), we used a net tow as the sampling unit. Sardine eggs from CalVET tows and sardine yolk-sac larvae from both CalVET and Bongo tows in Region 1 were used to compute egg production, primarily based on data from 5 transects (Figure 1 and 2). In the high egg-density region, 14 CalVET samples were collected and all contained at least 1 sardine egg (Table 1). These eggs were examined for their developmental stages following similar methods as in Moser and Ahlstrom (1985). In Region 2, 3 out of 52 CalVET tows caught sardine eggs.

Based on laboratory counts of sardine eggs in CUFES samples, 56 of the 351 collections were positive for sardine eggs over the whole DEPM survey area. In Region 1, there were 25 positive out of 28 total collections. In Region 2, 31 of the total 323 collections were positive (Figure 1 and Table 1).

To model the embryonic mortality curve, we included yolk-sac larvae (preserved larvae ≤ 5 mm notochord length), assuming that the mortality rate of yolk-sac larvae was the same as that of eggs (Lo 1986). Yolk-sac larval production was computed as the number of yolk-sac larvae/0.05m^2 divided by the duration of the yolk-sac stage (number of larvae/0.05m^2/day). Duration was computed based on the temperature-dependent growth curve (Table 3 of Zweifel and Lasker 1976) for each tow. For yolk-sac larvae caught by the Bongo net, larval abundance was further adjusted for size-specific extrusion from 0.505 mm mesh (Table 7 of Lo 1983) and for the percent of each sample that was sorted. The adjusted yolk-sac larvae/0.05m^2 was then computed for each tow and termed daily larval production/0.05m^2.

In the whole DEPM survey area, 12 of 66 CalVET and 13 of 56 Bongo samples had at least one yolk-sac larva (Table 1). In Region 1 (Figure 2), 7 of 14 CalVET tows and all 4 Bongo samples were positive for yolk-sac larvae (Table 1).

Daily egg production in the high egg-density region ($P_{0,1}$)

Sardine eggs and yolk-sac larvae and their ages were used to construct an embryonic mortality curve (Lo et al. 1996). Pelagic egg samples typically comprised various groups of eggs representing different stages from several days of spawning, and the number of days (i.e. age) to reach these developmental stages is temperature dependent (Lasker 1985, Lo et al. 1996). A temperature-dependent stage-to-age model (Lo et al. 1996) was used to assign age to each stage, and to compute sardine egg density for each stage based on CalVET samples (Figure 3). Sardine eggs and estimated ages were used directly in nonlinear regression. Eggs ≤ 3h old and eggs older than 2.5 days were excluded because of possible bias. The average sea surface temperature for all CalVET tows from the *Shimada* was 12.64°C (CV= 0.08) for the tows in the whole DEPM survey area.

The sardine embryonic mortality curve was modeled by an exponential decay curve (Lo et al. 1996):

$$P_t = P_{\mathbf{0}} e^{-zt} \qquad [1]$$

where P_t is either eggs/0.05m^2/day from CalVET tows or yolk-sac-larvae/0.05m^2/day from CalVET and Bongo tows, t is the age (days) of eggs or yolk-sac larvae from each tow and z is the daily instantaneous mortality rate. A weighted nonlinear regression was used to estimate two parameters in equation (1) where the weights were 1/SD. The standard deviation (SD) of eggs caught in CalVET was 2.16, 1.38, and 1.83 for day-one, day-two and day-three age groups respectively. The SD for yolk-sac larvae collected in CalVET and Bongo nets was 6.9 and 0.01, respectively.

A simulation study (Lo 2001) indicated that $P_{0,1}$ computed from a weighted nonlinear regression based on the original data points has a relative bias (RB) of -0.04 from the estimate, where the RB = (mean of 1,000 estimates - true value)/mean of 1,000 estimates. Therefore the bias-corrected estimate of egg production in Region 1 is calculated as $P_{0,1,c} = P_{0,1}$ * (1- RB) = $P_{0,1}$ *(1.04), and SE($P_{0,1,c}$) = SE($P_{0,1}$) * 1.04.

Daily egg production in the low egg-density region ($P_{0,2}$)

Although 52 CalVET samples were taken in Region 2, only 8 tows had one or more sardine eggs or yolk sac larvae (Table 1). In this region eggs caught per tow ranged from 1 to 2 eggs (Figure 1), whereas catches of yolk sac larvae ranged from 1 to 6 larvae per tow. Therefore, we estimated daily egg production in Region 2 ($P_{0,2}$) as the product of the bias-corrected egg production in Region 1 ($P_{0,1,c}$) and the ratio (q) of egg density in Region 2 to Region 1 from CUFES samples (Table 3), assuming the catch ratio of eggs/min from CUFES to eggs/tow from CalVET was the same for the whole DEPM survey area:

$$P_{\mathbf{0,2}} = P_{\mathbf{0,1},c} q \qquad [2]$$

$$q = \frac{\sum_i \frac{\bar{x}_{\mathbf{2},i}}{\bar{x}_{\mathbf{1},i}} m_i}{\sum_i m_i} \qquad [3]$$

$$\mathrm{var}(q) = \frac{[n/(n-1)]\sum_i m_i^2 (q_i - q)^2}{\left(\sum_i m_i\right)^2}$$

where q is the ratio of eggs/min between the low density and high density areas, m_i was the total CUFES time (minutes) in the i[th] transect, $\bar{x}_{j,i}$ is eggs/min of the i[th] transect in the j[th] Region, and $q_i = \frac{\bar{x}_{2,i}}{\bar{x}_{1,i}}$ is the catch ratio in the i[th] transect. The estimates of q were computed from a total of 5 transect lines occupied by the *Shimada* in Region 1.

Daily egg production (P_0)

P_0 was computed as the weighted average of $P_{0,1}$ and $P_{0,2}$:

$$\begin{aligned} P_0 &= \frac{P_{0,1,c} A_1 + P_{0,2} A_2}{A_1 + A_2} \\ &= P_{0,1,c} w_1 + P_{0,2} w_2 \\ &= P_{0,1,c} [w_1 + q w_2] \end{aligned} \qquad [4]$$

and

$$mse(P_0) = mse(P_{0,1,c})(w_1 + w_2 q)^2 + P_{0,1,c}^2 w_2^2 V(q) - mse(P_{0,1,c}) w_2^2 V(q)$$

(Goodman 1960) where $mse\ (P_{0,1,c}) = v(P_{0,1}) + bias^2 = v(P_{0,1}) + (P_{0,1}\ RB)^2$
and $w_i = \frac{A_i}{A_1 + A_2}$, and A_i is the area size for $i = 1$ or 2 for the DEPM survey area.
The above P_0 was computed for the whole DEPM survey area between Winchester Bay, OR and CalCOFI line 75 (between 43.75°N and 34.68°N). The size of the survey area is 181,250 km^2. The total egg production (TEP) is the numerator of equation 4 [P_0 * (A_1+A_2)].

Adult parameters

Four adult parameters are needed to estimate of spawning biomass: 1) daily spawning fraction or the number of spawning females per mature female per day (S); 2) the average batch fecundity (F); 3) the proportion of mature female fish by weight (sex ratio, R); and 4) the average weight of mature females (g, W_f). Population values for S, R, F and W_f were estimated using the methods of Picquelle and Stauffer (1985). Daily specific fecundity (number of eggs per population weight (g) per day) is $(RSF)/W_f$. The parameters were estimated for the whole survey DEPM area and separately for sardine females caught in each egg-density region. Correlations among all pairs of adult parameters were calculated for computing the variance of the estimate of the whole area spawning biomass (Parker 1985). In the past, the predicted batch fecundity for each female fish was calculated as $y = a + b$x where x is the female weight (without ovary) and y is the predicted value. Therefore, to account for the deviation of batch fecundity from the regression line, we added an error term to the predicted value as $y = a + bx + e$ where error term e was a random number generated from a normal distribution with mean zero and a variance of the error terms from the regression analysis. An MS[1] Visual Basic program (Chen et al. 2003) was modified to more accurately describe batch fecundity variance and was used to summarize the trawl adult parameters, calculate adult parameter correlations and covariance, and estimate spawning biomass and its coefficient of variation.

Spawning fraction (S): In total, 25 mature female sardines were analyzed and considered to be a random sample of the population in the whole DEPM survey area. Histological criteria can be used to identify four different spawning nights: postovulatory follicles aged 44 – 54 hours old indicated spawning two nights before capture (A), postovulatory follicles aged about 20 – 30 hours old indicated spawning the night before capture (B), hydrated oocytes or new (without deterioration) postovulatory follicles indicated spawning the night of capture (C), and early stages of migratory-nucleus oocytes indicated that spawning would have occurred the night after capture (D). The daily spawning fraction can be estimated using the number of females spawning on one night, an average of several nights, or all nights. We used the average of the number of females identified as having spawned the night before capture (B) and those having spawned two nights before capture (A) since 2009 plus the adjusted number of mature females caught in each trawl (Table 2) to estimate the 2015 population spawning fraction (S_{12}) and variance (Picquelle and Stauffer 1985, Hill et al. 2009).

Batch fecundity (F): Batch fecundity (number of oocytes per spawn) was considered to be the number of migratory-nucleus-stage oocytes or the number of hydrated oocytes in the ovary (Hunter et al., 1985). We used the gravimetric method (Macewicz et al. 1996; Hunter et al. 1985, 1992) to estimate mean batch fecundity for six females from spring 2015 and one female from spring 2014. Since only seven females were available, we included the mean batch fecundities from 35 females caught during the April 2013 survey to determine the relationship of batch fecundity to female weight. The relationship of batch fecundity (F_b) to female weight (without ovary, W_{of}), as determined by simple linear regression, was $F_b = -5112 + 365.85W_{of}$,where $r^2 = 0.485$, variance of the slope was 3553.35, and W_{of} ranged from 69 to 196 g (Figure 4); the intercept did not differ from zero ($p = 0.537$). We used the equation $F_b = -5112 + 365.85W_{of} + e$ where the error term, e, was generated from a normal distribution with mean zero and variance of 79,541,570 to estimate batch fecundity for each of the 25 mature Pacific sardine females that were analyzed to estimate spawning frequency.

Female weight (W_f): The observed female weight was adjusted downward for females with hydrated ovaries, because their ovary weights were temporarily inflated. We obtained the adjusted female weight by the linear equation $W_f = -8.7 + 1.13W_{of}$ where W_f is wet weight and W_{of} is ovary-free wet weight based on data from non-hydrated mature females taken during the April 2015 Sardine DEPM survey.

Sex ratio (R): The female proportion by weight was determined for each trawl (or each collection). The average weight of males and females (calculated from the first 10 males and 25 females) was multiplied by the number of males or females in the collection of randomly selected fish to calculate total weight by sex in each collection. Thus, the female proportion by weight in each collection (Table 2) was calculated as estimated total female weight divided by estimated

[1] Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

total weight in the sample. The estimate of the population's sex ratio by weight was also calculated (Picquelle and Stauffer, 1985).

Spawning biomass (B_s)

The spawning biomass was computed as:

$$B_s = \frac{P_0 AC}{RSF / W_f} \qquad [5]$$

where A is the survey area in units of 0.05m^2, S is the fraction of mature females spawning per female per day, F is the batch fecundity (number of eggs per mature female released per spawning event), R is the fraction of mature female fish by weight (sex ratio), W_f is the average weight of mature females (g), and C is the conversion factor from grams (g) to metric tons (mt). P_0A is the total daily egg production in the whole DEPM survey area, and the denominator (RSF/W_f) is the daily specific fecundity (number of eggs/population weight (g)/day).

The variance of the spawning biomass estimate $(\hat{B}_s)$ was computed using Taylor expansion and in terms of the coefficient of variation (CV) for each parameter estimate and covariance for adult parameter estimates (Parker 1985):

$$VAR(\hat{B}_s) = \hat{B}_s^{\,2}\left[CV(\hat{P}_0)^2 + CV(\hat{W}_f)^2 + CV(\hat{S})^2 + CV(\hat{R})^2 + CV(\hat{F})^2 + 2COVS\right] \qquad [6]$$

The last term, involving the covariance term, on the right-hand side is

$$COVS = \sum_i \sum_{i<j} sign \frac{COV(x_i, x_j)}{x_i x_j}$$

where x's are the adult parameter estimates, and subscripts i and j represent different adult parameters, e.g., $x_i = F$ and $x_j = W_f$. The sign of any two terms is positive if they are both in the numerator of B_S or denominator of B_S (equation 5); otherwise, the sign is negative. The covariance term is

$$COV(x_i, x_j) = \frac{[n/(n-1)]\sum_k m_k (x_{i,k} - x_i) g_k (x_{j,k} - x_j)}{\left(\sum_k m_k\right)\left(\sum_k g_k\right)}$$

where k refers to k^{th} tow, and k = 1,…,n. The terms of m_k and g_k are sample sizes and $x_{i,k}$ and $x_{j,k}$ are sample means from the k^{th} tow for x_i and x_j respectively.

The survey area was post-stratified into two regions based on the presence of sardine eggs: Region 1 (high density area) and Region 2 (low density area). Thus, equation (5) can be applied to the whole survey area and/or to each of the two regions depending on the availability of data. For the female spawning biomass (fs.biomass), one of the inputs to the stock assessment, the sex ratio (*R*), was excluded from equations (5) and (6). The estimate of female spawning biomass was the sum of the estimate from each of the two regions, which is referred to as the stratified procedure. The traditional method is to obtain a weighted mean for P_0 (equation 4), while each of the adult parameters was not a stratified estimate.

RESULTS

Egg density from CalVET

The stages of eggs collected from CalVET ranged from 1 to 11 (Figure 3). Stage 1 are newly spawned eggs with no cell divisions; whereas stage 12 included newly hatched sardines. In 2015 the distribution of egg density by egg developmental stage peaked at stages 3, 6 and 11. Egg development stages follows those described by Ahlstrom (1943) and Moser and Ahlstrom (1985): stage 3 begins with the formation of the segmentation cavity (i.e., the space formed between the blastodisc and the yolk mass during late cleavage); stage 6 begins with the closure of the blastopore and ends when the tail starts to separate from the yolk mass; and stage 11 is the final stage before hatching and is defined by a tail length greater than three-quarters of the length of the yolk sac. The distribution of egg density-at-stage in the whole DEPM survey area and the high egg density region followed similar trends. The maximum number of eggs caught per CalVET tow during the survey was 14 (Figure 5). Finally, the average sea surface temperature computed for CalVET tows with ≥ 1 egg in the DEPM survey area was 12.02°C (Table 4). This estimate was weighted by the number of eggs caught in each positive tow.

Daily egg production (P_0) for the standard DEPM survey area

In Region 1, the initial daily egg production ($P_{0,1}$) from the mortality curve was 1.64/0.05 m^2/day (CV = 0.71; equation 1 and Figure 6). The 2015 bias-corrected egg production, ($P_{0,1,c}$) was 1.71 (CV = 0.71) (Table 3) for an area of 8,814 km^2 (Eureka, CA to Cape Blanco, OR; between 41.0 °N and 42.9°N). The ratio (*q*) of egg density between Region 2 and Region 1 from CUFES samples was 0.05 (CV = 0.27) (equation 3). In 2015, the egg production ($P_{0,2}$) in Region 2 of the whole survey area was 0.09 (CV = 0.73) for an area of 172,436 km^2, compared to 0.27/0.05m^2/day (CV = 0.44) in 2013 for an area of 112,221 km^2. Egg mortality (1.10 (CV = 0.15)) was higher than estimates from the 1994-2013 period (Table 4). The P_0 for the whole DEPM survey area was 0.17/0.05m^2 (CV = 0.72) (equation 4) for 181,250 km^2.

Catch ratio between CUFES and CalVET (E)

Although this ratio is no longer needed in the current estimation procedure, we computed it for comparison purposes. The catch ratio of eggs/min to eggs/tow (eggs/min = E * eggs/0.05 m^2) was computed from 66 pairs of CalVET tows and CUFES collections from the *Shimada* cruise (Figure 5). The eggs/min corresponding to each positive CalVET tow was the mean of all CUFES collections taken from one hour before to one hour after each positive CalVET tow. The catch ratio, 0.051 (CV = 0.17) was lower than in 2013 (0.1216, CV = 0.17) and slightly higher than in 2012 (0.0338, CV = 0.34). A ratio of 0.05 means that one egg/tow from a CalVET tow was equivalent to approximately 0.05 egg/min from a CUFES sample, or one egg/minute from the

CUFES was equivalent to 19.61 eggs/tow from the CalVET sample.

The ratio of egg densities of two regions from CUFES samples (q)

The *q* value (ratio of eggs/min in Region 2 to eggs/min in Region 1) served as the calibration factor to estimate $P_{0,2}$ in Region 2 (equation 2). It was needed because low abundance of eggs observed in Region 2 prevented us from using the egg mortality curve to directly estimate $P_{0,2}$. For the 2015 survey, *q* was obtained from transects in Region 1 that had at least five CUFES collections taken. A total of 5 transect lines, all north of Eureka, CA between 41.0 °N and 42.9°N, were used to compute *q*. The estimate was 0.05 (CV = 0.27).

Adult parameters

In the April 2015 whole DEPM survey area off Oregon and California (from Winchester Bay, OR to CalCOFI line 75 near Morro Bay, CA; about 43.75° – 34.68° N), Pacific sardines were found in seven tows (Figure 1, Table 1). Mature female sardine were caught in four tows; one tow caught a single immature female; and two tows contained only male sardine (Table 2). Standard length (SL) of the randomly obtained sardines in each trawl ranged from 185 to 256 mm for 33 males (one additional male was not measured) and from 173 to 258 mm for 28 females. The smallest mature female was 234 mm SL. Although three immature female sardines were captured during the 2015 survey, the length at which 50% of females are mature (ML_{50}) was not calculated due to the low total number of females (28).

The whole DEPM survey area in 2015 was 181,250 km^2. Estimates of reproductive parameters of sardines for the individual trawls (ideally, up to 25 mature females would have been analyzed per trawl) are given in Table 2. The mature female sardine reproductive parameters in the DEPM area, estimated from 4 positive trawls (Table 2) and 25 mature females, were *F*, mean batch fecundity, 60,916 eggs/batch (CV = 0.02); *S*, fraction spawning per day, 0.118 females spawning per day (CV = 0.16); W_f, mean female fish weight, 192.2 g (CV = 0.05); and *R*, sex ratio of females by weight, 0.485 (CV = 0.08) (Table 5). The average interval between spawning events (spawning frequency) was about 8 days (inverse of spawning fraction or 1/0.118), and the daily specific fecundity was 18.09 eggs/population weight (g)/day (Table 5). We provide estimates of each adult parameter in each region (Table 5), primarily because they are used to compute female spawning biomass, which is the input of fishery-independent spawning biomass time series to the stock assessment (Hill et al. 2011).

Spawning biomass (B_s)

The final estimate of spawning biomass of Pacific sardines in 2015 using the traditional method (equation 1 and 4, Tables 3, 4, and 6) was 33,412 mt (CV = 0.74) for the whole DEPM survey area of 181,250 km^2 off Oregon and California. The yearly point estimates of spawning biomass of Pacific sardine off California in the 1994 – 2013 period were all higher than 2015 (Table 4). Based on the stratified procedure, the estimate of the 2015 spawning biomass was 39,495 mt (CV = 0.56) (Table 3).

The estimate of the female spawning biomass for the whole area was 19,375 mt (CV = 0.58) and 16,207 mt (CV = 0.74) based on the stratified procedure and the traditional method respectively (Table 6). The former and similar estimates of previous years were use as one of the two relative abundance index time series in the Pacific sardine stock assessment (Table 6). Note the spawning biomass estimates prior to 2009 could be different between Tables 4 and 6 due to the different estimation procedure for the spawning fraction. Beginning in 2009, the spawning fraction was the average of spawning fraction on 1 and 2 nights before the capture (S_{12}) (Table 6) while before 2009, the spawning fraction was based only on females spawning 1 night before capture (S_1) (Table 4).

DISCUSSION

Sardine eggs

The distribution of sardine eggs is highly dynamic along the Pacific coast, although it is generally associated with temperature and chlorophyll concentration (Zwolinski et al. 2011). In the spring of 2015 the spawning stock of Pacific sardine was mostly distributed north of San Francisco, CA and south of Winchester Bay, OR (Figure 1). Unprecedented warming of the North Pacific Ocean over the 2014-15 period (known as Warm Blob), coupled with the transition to one of the strongest El Nino in decades, likely caused a northward shift of the spawning stock of Pacific sardine that in the past was mainly located between San Diego and San Francisco. Consequently, in April 2015 the region of high density of eggs was concentrated within one main expanse between 41.0 °N and 42.9°N (just north of Eureka, CA to just north of Cape Blanco, OR). This area defined as Region 1 was much smaller than the high density areas computed from 2011 to 2013 (Lo et al. 2013, Dorval et al. 2014), when spawning occurred mainly off California, between San Francisco and San Diego. In the spring of 2014, the DEPM survey was restricted south of San Francisco within the standard DEPM area, and neither eggs nor larvae were collected in CalVET and Bongo tows over 160,305 km^2 (Appendix-Table A1). However, in 2014 it was not known whether spawning occurred north of this area as in 2015. In previous warmer years such as 2006, eggs were observed around latitudes 40°N to 43°N in the California Current Ecosystem (CCE); whereas in cooler years such as in 2008 no eggs were collected at these latitudes in CCE surveys (Figure 7).

The distribution of egg density by egg development stage in 2015 peaked at stages 3, 6 and 11, and thus was different from 2013 which exhibited only one peak at stage 3. This distribution followed similar patterns as in 2007 when stages 3, 6, and 9 had the highest density (Lo et al. 2007). The average sea surface temperature for positive CalVET tows in 2015 DEPM survey was 12.02°C, which was the lowest mean temperature-at-catch observed since 1986 (Table 6).

The daily egg production rate of 1.71 /0.05m^2 in the high egg-density area was approximately five times smaller than production estimated from 2011 to 2013, but similar to estimates from the 2007-2010 period (Table 6). In 2015 the high density area was 5% of the whole survey area, indicating that spawning stock was contracted over a much smaller area compared to previous years (e.g. > 20% in 2009-2013).

The adaptive allocation sampling procedure was used aboard the *Shimada*, based on a threshold of 0.3 eggs/min in CUFES samples. A total of 66 CalVET tows were taken in the whole surveys area. Although in 2015 the threshold was lowered from 1 to 0.3 eggs/min, the number of CalVET tows was smaller than the number of samples collected adaptively within the standard DEPM area since 2005, which varied from 74 to 151. Starting in 2011, adaptive sampling was used during the April CalCOFI survey. In 2015 the CalCOFI survey data were not used to compute the daily egg production (P_0), but were partially used in other years (such as 2012 and 2013) to compute the daily egg production (P_0). Despite varying issues with trawling and timing of this survey with DEPM, we still highly recommend that adaptive allocation sampling be applied during the spring (March-April) routine CalCOFI survey in the future to enhance the quality of the estimate of the spawning biomass.

Embryonic mortality curve

While the daily egg production at age 0 (P_0/0.05m^2 = 1.70 with CV = 0.71) was much lower than in recent years (i.e. 2011-2013), the daily embryonic mortality (1.1, CV = 0.15) was the highest recorded since 1994 from the mortality curve (Figure 6) in Region 1. This may be the result of spawning in less suitable habitats. In many past years, the peak egg developmental stage was stage 6, whereas in 2012 the egg development stage peaked at stages 3 and 5. In 2015, egg density peaked at ages 3, 6, and 11, with the later stage showing the highest abundance (Figure 3). Another extreme case were recorded in 2010, when the peak densities spread from stage 6 to 9 (Lo et al. 2010b). The cause of these extremes cases is not understood and needs thorough investigation. The overall P_0 in the DEPM (0.16 eggs/0.05m^2) was smaller than in most previous years (Table 3 and 4) but similar to the 1994 estimate (Figure 2). Yolk-sac larvae were mostly distributed north of San Francisco, with few positive net tows in the Standard DEPM area (Figure 2). Note that yolk-sac larvae collected in Region 2 were not used in the computation of spawning biomass.

Catch ratio between CUFES and CalVET (E)

The 2015 catch ratio between CUFES and CalVET (0.051) computed from data obtained from the *Bell M. Shimada* was lower than estimate in 2013 (0.1216), but was slightly higher than 2012' estimate (0.0338). This decrease in catch ratio may suggest that relatively less eggs were in upper 3m of the water column in 2015 than in 2013. The 2015'catch ratio was generally similar to ratios estimated from 2010-2012 but lower than those estimated during 1996-2009 period. As these distribution patterns may be related to mixing in the water column, it would be informative to examine the relationship between the catch ratio and the degree of water mixing over the years (Lo et al. 2001).

The ratio of egg densities of two regions from CUFES samples (q)

The q value of 0.05 (CV = 0.27) (ratio of eggs/min in Region 2 to eggs/min in Region 1) (equation 2) was similar to the 2013'estimate, but lower than in 2011 (0.164 (CV = 0.23)) and other previous years for the standard DEPM sampling area. The q values have ranged from 0.036 to 0.085 in 2001-2006 with an increasing trend until 2011. The low q value indicated that the egg densities in Region 1 were much higher than in Region 2 and sardine eggs were more concentrated in Region 1 than Region 2. Otherwise, the difference of densities of eggs between these two regions would be less.

Adult parameters

The April 2015 Sardine DEPM survey caught sardine adults off southern Oregon (2 0f 12 trawls), and northern California (5 of 22 trawls) and none (0 of 13 trawls) in the part of the standard DEPM area off California from Point Reyes to Morro Bay (CalCOFI lines 60 to 75). Past coast-wide spring surveys, i.e. in 2006, 2008, and 2010 (Lo et al. 2007a, 2008, 2010b, 2011, 2013) did not capture adults in trawls off Oregon or Washington (NW) but did in some trawls off northern California (NCA) and in many trawls in the standard DEPM area (DEPM) off California (Figure 7). We examined sea temperatures at 3m depth, recorded during trawl operations, in these areas (Table 7 and Table 8 in Lo et al. 2010). Temperatures were much warmer in 2015 north of the standard DEPM areas than, even, in the warm 2006 survey. It is not surprising that in 2015 spawning adults were found in the northern area because 6 of the 7 positive trawls were at 12° to 13.4° C which is similar to sardines spawning in the standard DEPM area since 2007 (Table 2 and 7).

During the April 2015 survey in the whole DEPM survey area, we were again able to collect trawl samples (Table 2) in areas of high (Region 1) and low (Region 2) sardine egg densities which is beneficial to better estimate Pacific sardine spawning biomass for the whole population. The fraction of females spawning per day, S_{12}, (based on the average of females that spawned the night before capture and 2 night before capture or "average of day 1+day 2") was higher in Region 1 (0.143 females/day (CV = 0.19)) than Region 2 (0.077 females/day (CV = 0.31)) (Table 5). This regional difference in the fraction of females spawning (high in 1 and lower in 2) was similar to that in past DEPM surveys in 2005-2013 (Lo and Macewicz 2006, Lo et al. 2007-2013, and Dorval et al. 2014). Although there were more trawls conducted in Region 2 (40 trawls) than in Region 1 (7 trawls), most trawls taken in Region 2 failed to catch any sardines. In the future, we recommend reducing the number of trawls in Region 2 when the egg density is zero or consistently less than 1 egg/min. However, because more females were spawning per day in Region 1 than Region 2, it is necessary to continue to trawl in both regions to ensure an unbiased estimate of spawning biomass for the whole population. In addition, exploration of results from the habitat model of Zwolinski et al. (2011), which predicted in 2015 that the northern areas off the coast were suitable for spawning sardines, should continue prior to conducting future sardine spawning surveys.

In 2015 the CV (0.16) of the spawning fraction estimate in the DEPM area was similar to those in 2013 (CV = 0.16), 2012 (CV = 0.24), 2011 (CV = 0.18), 2010 (CV = 0.22), and 2009 (CV = 0.15) but lower than in earlier years (CVs of 0.33 in 2007 and 0.31 in 2005 and 2008) (Lo et al. 2006, 2007b, 2008, 2009, 2010b, and 2011). A factor in improvement of the CV was the change in the calculation of daily spawning fraction. In the past (1994, 1997, 2004, 2005, 2007, and 2008), calculation of the original daily spawning fraction (S_1) was based on the number of females that spawned the night before capture (night B, "day 1") and followed the procedure for northern anchovies (Picquelle and Hewitt, 1983) to replace the number of females spawning the night of capture (night C, "day 0") with the number of night B spawning females to adjust the number of total mature females. By contrast, since 2009 we calculated the daily spawning fraction (S_{12}) using the mean number of night-B and night-A (two nights before capture, "day 2") spawning females for each trawl and replaced the night-C females by this mean to adjust the number of total mature females. Therefore for continued improvement of spawning fraction precision, we recommend using S_{12} to calculate daily spawning fraction and that the number of trawls sampled be increased, in both high and low egg density areas, for future biomass surveys.

We examined the relative frequency of length by sex of sardines collected in spring 2015 and compared them to length distributions and fish taken during similar periods 2010 to 2014 (Figures 8). The mean size of sardines (male and females, SL) caught during 2015 (235 mm) was larger than the previous five years (Figure 8). In 2015 the sardine were caught off Oregon and northern California and only 13% were less than 204 mm. These small fish indicated that a minor recruitment event in 2013-2014 might have occurred from summer spawning off Oregon, since sardine smaller than 200 mm do not migrate (Lo et al. 2010a, Demer et al. 2011). The length distribution in 2015 has a major size mode peaking in the 240 mm size class, which is larger than the single size modes seen in 2014 (at 230 mm) and 2013 (at 220 mm), and is indicative of increasing size of the strong recruitment from 2009-2010. The length distribution in 2012 showed two modes, the first mode in 2012 peaked at about 210 mm for both sexes, whereas the second mode peaked at 230 mm for males and 240 mm for females. Fish collected in 2011 had also a bi-modal distribution in their length and age. This change to one from two modes in 2012 and 2011 might be due to the increasing size of the recruits from 2009-2010 (Hill et al. 2012, Zwolinski et al. 2013) and few fish remaining from the strong recruitment class in 2003-2005. Another interesting pattern is that males tend to dominate the smaller sizes and younger ages while females dominate the larger and older classes. Finally, we believe that a likely explanation for the scarcity of smaller fish in 2012-2014 is high mortality rate on those year classes. It could also be due to sampling issues, such as: 1) the lack of inshore sampling, where sardines are known to be small relative to offshore (Lo et al. 2007a); or 2) not conducting trawls in inshore areas that are known (because they have been commercially fished) to have sardines, e.g. around Catalina Island or the Channel Islands. To improve the whole population adult parameter analyses we recommend more trawls should continue to be added in the inshore areas or samples taken on commercial vessels during fishing to obtain spawning and maturity information to avoid possible bias against smaller fish.

Spawning biomass

In the DEPM survey area, the 2015 estimate of spawning biomass using the traditional method was 33,412 mt, based on the egg production of 0.17 eggs/0.05m^2/day, and the daily specific fecundity of 18.09 eggs/g/day. This production was concentrated in the areas located between Eureka, CA and Cape Blanco, OR. The 2015 spawning biomass was lower than all previous estimates since 2004 (Table 6) except 2014 when biomass was not estimated. This estimate was based on the stratified sampling for each parameter because adequate female samples were available. As such it may not be comparable to estimates derived in years where not enough adult fish samples were collected (i.e. 2006, 1996-2003). In those years P_0 was weighted by the size of each region and the adult parameters were estimated from all trawl samples in the survey area.

The egg production rate in the high density area, 1.71 eggs/0.05m^2, was similar to 2007-2010 but lower than estimates from 2011 to 2013 (Table 6). The overall daily egg production, 0.17 eggs/0.05m^2, is much lower than all years since 2004.

Over the years, although the standard DEPM survey area has varied in size, it has been approximately between CalCOFI line 60 (near San Francisco) and line 95 (near San Diego).

However, in 2015 the spawning stock moved northward of this area, and high egg densities were found from north of Eureka, CA to north of Cape Blanco, OR. Therefore, spawning biomass was estimated based the whole DEPM survey area, which extended from about Winchester Bay, OR to Morro Bay, CA (Figure 1). The region of high-egg density (8,814 km^2) was much smaller than any other estimates from the 1994-2013 period. Note that the threshold of 0.3 egg/min in CUFES was reduced from the number used in years prior to 2002 (2 eggs/min) and 2014 (1 egg/min) to increase this the surface area of this region and, subsequently, to increase the number of CalVET samples. This adaptive allocation sampling was similar to that used in the 1997 survey (Lo et al. 2001). Because the threshold changed in 2002 and 2015, caution should be taken when comparing the size of the area of Region 1.

The adult daily reproductive output (daily specific fecundity) was lower than in 2013 (26.22, the largest recorded since 2004) and similar to 2009 and 2010. However, the higher values in early years were due to the fact that trawl samples were taken in the high density area only. Since 2005, trawl samples have been taken in both Region 1 and Region 2. For the stock assessment we provided the estimates of female spawning biomass for years where adequate adult samples were available (Table 6).

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Table 1. Number of positive tows of sardine eggs from CalVET, yolk-sac larvae from CalVET and Bongo, eggs from CUFES and positive sardine trawls[a] in Region 1 (high, eggs/min ≥ 0.3), Region 2 (low, eggs/min < 0.3) for *New Horizon* CalCOFI survey and *Bell M. Shimada* Sardine DEPM survey in spring 2015. The *Shimada* whole DEPM survey area (181,250 km^2, between latitudes 43.75°N and 34.68°N) includes both a northern non-standard area (124,287 km^2) from Winchester Bay, Oregon to CalCOFI line 75 and a part of the standard DEPM area (56,963 km^2) from Point Reyes to Morro Bay, California (CalCOFI line 60.0 to 75.0).

Gear	Tows and Sampling type	CalCOFI April 4-15, 2015 *New Horizon*	DEPM March 30 – April 30, 2015 *Bell M. Shimada*		
			Region 1	Region 2	Whole
CalVET (Pairovet)	Total tows	59	14	52	66
	Total positive tows	2	14	8	22
	Positive egg tows		14	3	17
	Eggs	1	81	5	86
	Positive larvae tows		7	5	12
	Yolk sac larvae	1	24	12	36
BONGO	Total tows	70	4	52	56
	Total positive tows	2	4	11	15
	Positive egg tows[b]	2	2	9	11
	Eggs[b]	31	167	57	224
	Positive larvae tows	1	4	9	13
	Yolk sac larvae	1	19	49	68
CUFES	Total samples	444	28	323	351
	Positive samples	8	25	31	56
	Eggs	35	260	65	325
Trawl	Total tows	n/a	7	40	47
	Total positive tows		4	3	7
	Total sardine		30	32	62
	Female sardine		12	16	28
	Area in km^2		8,814	172,436	181,250

[a] All sardines were captured at night; table does not include 4 trawls without sardine that were conducted north of the first CUFES transect.
[b] Egg data from the Bongo net are not used in the daily egg production (P_0) estimation.

Table 2. Sardine egg-density region, individual trawl information, sex ratio[a], and parameters for mature female *Sardinops sagax*, used in the estimation of the April 2015 spawning biomass in the whole DEPM survey area off Oregon and California[b].

COLLECTION INFORMATION									MATURE FEMALES							
				Location										Number spawning		
Region 1=high 2=low	No.	Month-Day	Time	Latitude °N	Longitude °W	Surface Temp. °C	No. of fish	Sex Ratio	No. analyzed	Body weight (g) Ave.	Weight without ovary (g) Ave.	Batch Fecundity Ave.	Adj. No.[c]	Night of capture	Night before capture	2 Nights before capture
2	3369	4-01	20:53	43.534	-124.904	12.6	30	0.496	13	202.79	186.15	60645	5.5	8	0	1
2	3377	4-04	23:00	43.155	-124.923	12.6	1[d]	0.000	0	0	0	0	0	0	0	0
1	3382	4-07	23:19	41.980	-125.807	13.0	3[e]	0.000	0	0	0	0	0	0	0	0
1	3387	4-07	22:43	41.311	-125.552	13.4	3	0.710	2	177.75	169.50	63568	2.5	0	1	0
1	3386	4-09	20:02	41.183	-125.778	13.2	23	0.415	9	177.95	166.78	58562	8	2	2	0
1	3391	4-11	2:17	41.027	-125.808	13.4	1[e]	0.000	0	0	0	0	0	0	0	0
2	3394	4-17	21:23	39.795	-124.490	9.6	1	1.000	1	212.00	196.47	80331	1	0	0	0
all							62		25				17	10	3	1

[a] Sex ratio, proportion of females by weight, based on average weights from subsamples and number of fish sampled in each trawl(Picquelle and Stauffer 1985).
[b] Two trawls located at 39.8°N 124.3°W and 38.6°N 123.7°W caught only a single sardine larva each.
[c] Mature adjusted by the average number of females spawning the night before capture and females spawning 2 nights before capture.
[d] Only a single immature female captured.
[e] Only male(s) captured.

Table 3. Egg production (P_0) of the Pacific sardine in 2015 based on egg data from CalVET and yolk-sac larval data from CalVET and Bongo in Region 1 (eggs/min ≥ 0.3) and Region 2 (eggs/min < 0.3) *Bell M. Shimada* (Mar.30 – Apr.30, 2015) cruise, adult parameters from positive trawls (April 1 – 17), and 2015 spawning biomass estimates.

Parameter	Region 1	Region 2	DEPM Area
CUFES samples	28	342	**370**
CalVET samples	14	52	**66**
P_0 / 0.05m^2	1.71[a]	0.09	**0.168**
CV of P_0	0.71	0.73	**0.72**
Area (km^2)	8814	172436	**181250**
% of DEPM Area	5	95	100
Year of adult samples	2015	2015	2015
Female fish wt (W_f)	177.9	203.4	**192.2**
Batch fecundity (F)	59472	62051	**60916**
Spawning fraction (S)	0.143	0.077	**0.118**
Sex ratio (R)	0.448	0.514	**0.485**
(RSF)/W_f	21.38	12.07	**18.09**
Spawning biomass (mt) : *Traditional method* [b]			**33,412**
CV of spawning biomass			**0.74**
Spawning biomass (mt) : *Stratified procedure* [c]	14,087	25,408,	**39,495**
CV of spawning biomass	0.74	0.78	**0.56**
Daily mortality (*Z*)			**1.10**
CV of daily mortality			**0.15**
eggs/min	0.358	0.0058	**0.034**
CV	0.98	4.31	**4.10**
q = eggs/min in Reg.2 / eggs/min in Reg.1			**0.052**
CV of q			**0.27**
E = (eggs/min)/(eggs/tow)			**0.051**
CV			**0.17**
Bongo samples	4	52	**56**

[a] 1.71 was corrected for bias of P_0.

[b] biomass was computed from estimates of parameters in each column, e.g., DEPM area is an average of adult parameters from Region 1 and Region 2.

[c] biomass was computed by the stratified procedure, i.e., total spawning biomass = the sum of the estimates of spawning biomass in Region 1 and Region 2: 14,087 + 25,408 = 39,495

Table 4. Estimates of daily egg production (P_0)[a] for the DEPM survey area, daily instantaneous mortality rates (Z) from high-density area (Region 1), daily specific fecundity (RSF/W), spawning biomass of Pacific sardines using the traditional method (which differs from the stratified method) and average sea surface temperature for the years 1994 to 2015.

Year	P_0 (CV)	Z (CV)	Area (km²) (Region 1)	RSF[h]/W	Spawning biomass (mt) (CV)[b]	Mean Temp. for positive egg or yolk-sac samples	Mean temperature all CalVETs
1994	0.193 (0.210)	0.120 (0.91)	380,175 (174,880)	11.38	127,102 (0.32)	14.3	14.7
1995	0.830 (05)	0.400 (0.4)	113,188.9 (113188.9)	23.55[c]	79,997 (0.6)	15.5	14.7
1996	0.415 (0.42)	0.105 (4.15)	235,960 (112,322)	23.55	83,176 (0.48)	14.5	15.0
1997	2.770 (0.21)	0.350 (0.14)	174,096 (66,841)	23.55[d]	409,579 (0.31)	13.7	13.9
1998	2.279 (0.34)	0.255 (0.37)	162,253 (162,253)	23.55	313,986 (0.41)	14.38	14.6
1999	1.092 (0.35)	0.100 (0.6)	304,191 (130,890)	23.55	282,248 (0.42)	12.5	12.6
2000	4.235 (0.4)	0.420 (0.73)	295,759 (57,525)	23.55	1,063,837 (0.67)	14.1	14.4
2001	2.898 (0.39)	0.370 (0.21)	321,386 (70,148)	23.55	790,925 (0.45)	13.3	13.2
2002	0.728 (0.17)	0.400 (0.15)	325,082 (88,403)	22.94	206,333 (0.35)	13.6	13.6
2003	1.520 (0.18)	0.480 (0.08)	365,906 (82,578)	22.94	485,121 (0.36)	13.7	13.8
2004	0.960 (0.24)	0.250 (0.04)	320,620 (68,234)	21.86[e]	281,639 (0.3)	13.4	13.7
2005	1.916 (0.417)	0.579 (0.20)	253,620 (46,203)	15.67	621,657 (0.54)	14.21	14.1
2006	1.936 (0.256)	0.31 (0.25)	336,774 (98,034)	15.57[f]	837,501[f] (0.46)	14.95	14.5
2007	0.864 (0.256)	0.133 (0.36)	356,159 (142,403)	15.68	392,492 (0.45)	13.7	13.6
2008[g]	0.43 (0.21)	0.13 (0.29)	297,949 (53,514)	21.82	117,426 (0.43)	13.3	13.1
2009[h]	0.59 (0.22)	0.25 (0.19)	274895 (74,966)	17.53	185,084 (0.28)	13.6	13.5
2010[i]	0.36 (0.40)	0.33 (0.23)	271,773 (27,462)	18.07	108,280 (0.46)	13.7	13.9
2011	1.16 (0.26)	0.51 (0.14)	314,481 (41,878)	19.04	383,286 (0.32)	13.5	13.6
2012	0.84 (0.27)	0.66 (0.11)	270,991 (32,322)	16.14	282,110 (0.43)	13.57	13.3
2013	1.34 (0.30)	0.64 (0.16)	141,397 (29,176)	26.22	144,880 (0.36)	13.51	13.47
2014[j]	--	--	160,350 (0)	23.70	--	--	14.51
2015	1.71 (0.71)	1.095 (0.15)	181,250 (8,814)	18.09	33,412 (0.74)	12.02	12.64

a weighted non-linear regression on original data and bias correction of 1.04, except in 1994 and 1997 when grouped data and a correction factor of 1.14 was used (appendix Lo 2001).

b $CV(B_s) = (CV^2(P_0) + allotherCOV^2)^{1/2} = (CV^2(P_0)+0.054)^{1/2}$. For years 1995 – 2001 allotherCOV² was from 1994 data (Lo et al. 1996). For year 2003, allotherCOV was from 2002 data (Lo and Macewicz 2002)

c 23.55 was from computation for 1994 based on S = 0.149 (the average spawning fraction (day 0 + day 1) of active females from 1986–1994; Macewicz et al. 1996).

d is 25.94 when calculated from parameters in 1997 (table 9) and estimated spawning biomass is 371,725 mt with CV = 0.36

e uses R = 0.5 (Lo and Macewicz 2004); if use actual R = 0.618, then value is 27.0 and biomass is estimated at 227,746 mt

f value for standard DEPM sampling area off California when calculated using S = 0.126, the average of females spawning the night before capture ("day 1") from 1997, 2004, 2005, and 2007. When 2006 survey S of 0.0698 was previously used (Lo et al. 2007a), the 2006 DEPM spawning biomass was estimated as 1,512,882 mt (CV 0.46) and the 2006 coast-wide spawning biomass was estimated as 1,682,260 mt

g within standard DEPM sampling area off California from San Diego to CalCOFI line 66.7 whole 2008 survey area off west coast of North America from about 31°N to 48.47°N latitude, spawning biomass was estimated as 135,301 mt(CV=0.43)

h RSF/W from 2009 forward is based on S_{12},:average of day1 and day2 females.

i The whole survey area was 477,092 km² from San Diego, CA to Cape Flattery, Wa. .Very few sardine eggs were observed north of the standard DEPM survey area (CalCOFI line 60.0 is the northern boundary of the standard DEPM area)

j No eggs were collected by CalVET tows and daily egg production was not estimated

Table 5. Estimated 2015 adult parameters for each region[a] in the DEPM area

Region 1 DEPM area

Statistic Results:

	Average	Variance
Whole Body Weight	177.910270636	0.00339658537
Gonad Fee Weight	167.273054545	0.65665707688
Batch fecundity	59472.2586466	9729808.33855
Spawners, Day 0	0.18181818182	0.00437128611
Spawners ave (day1 + day2)	0.14285714286	0.00074043223
Sex Ratio	0.44779097223	0.00339641363
Daily specific fecundity	21.3840866642	
Number of Sets	2	

Region 2 DEPM area

Statistic Results:

	Average	Variance
Whole Body Weight	203.445088929	1.49360211102
Gonad Fee Weight	186.888657143	1.87421687797
Batch fecundity	62051.0011958	25811011.9524
Spawners, Day 0	0.57142857143	0.00666389005
Spawners ave (day1 +day2)	0.07692308462	0.00056020459
Sex Ratio	0.51430528127	0.00128706268
Daily specific fecundity	12.0664427787	
Number of Sets	2	

DEPM whole area

Statistic Results:

	Average	Variance
Whole Body Weight	192.20976888	78.1131467281
Gonad Fee Weight	178.257792	46.6001937504
Batch fecundity	60916.3544741	16668373.0222
Spawners, Day 0	0.4	0.02389333333
Spawners ave (day1+day2)	0.11764706176	0.00037515508
Sex Ratio	0.48507233245	0.00135471884
Daily specific fecundity	18.0861462302	
Number of Sets	4	

[a] Area of Region 1 is 8814 km^2, Region 2 area is 172,436 km^2, and the DEPM whole area is 181,250 km^2

Table 6. The spawning biomass related parameters using the stratified method: daily egg production/0.05m^2 (P_0),daily mortality rate (z), survey area (km^2), two daily specific fecundities: (RSF/W), and (SF/W); s. biomass, female spawning biomass, total egg production (TEP) and sea surface temperature for 1986, 1987, 1994, 2004, 2005 and 2007-2015

Calendar Year	Month	Region	[1]P_0/0.05m^2 (cv)	Z (CV)	[2]RSF/W based on S_1	[3]RSF/W based on S_{12}	[3]FS/W based on S_{12}	[4]Area (km^2)	[5]S. biomass (cv)	S. biomass females (cv)	S. biomass females (Sum of R1andR2) (cv)	Total egg production (TEP)	Mean temperature (°C) for positive eggs	Mean temperature (°C) from Calvet
1986	Aug.	[6]S	1.48(1)	1.59(0.5)	38.31	43.96	72.84	6478	4362 (1.00)	2632 (1)		9587.44		
		N	0.32(0.25)		8.9	13.34	23.89	5333	2558 (0.33)	1429 (0.28)		1706.56		
		whole	0.95(0.84)		23.61	29.89	49.97	11811	7767 (0.87)	4491 (0.86)	4061 (0.66)	11220.45	18.7	18.5
1987	July	1	1.11(0.51)	0.66(0.4)	38.79	37.86	57.05	22259	13050 (0.58)	8661 (0.56)		24707.49		
		2	0					15443	0	0		0		
		whole	0.66(0.51)		38.79	37.86	57.05	37702	13143 (0.58)	8723 (0.56)	8661 (0.56)	25637.36	18.9	18.1
1994	April	1	0.42(0.21)	0.12(0.91)	11.57	11.42	21.27	174880	128664 (0.30)	69065 (0.30)		73449.6		
		2	0(0)	-				205295	0	0		0		
		whole	0.193(0.21)		11.57	11.42	21.27	380175	128531 (0.31)	68994 (0.30)	69065 (0.30)	73373.775	14.3	14.7
2004	April	1	3.92(0.23)	0.25(0.04)	27.03	26.2	42.37	68204	204118 (0.27)	126209 (0.26)		267359.68		
		2	0.16(0.43)		-	-	-	252416	30833 (0.45)	19065 (0.44)		40386.56		
		whole	0.96(0.24)		27.03	26.2	42.37	320620	234958 (0.28)	145297 (0.27)	145274 (0.23)	307795.2	13.4	13.7
2005	April	1	8.14(0.4)	0.58(0.2)	31.49	25.6	46.52	46203	293863 (0.45)	161685 (0.42)		376092.42		
		2	0.53(0.69)		3.76	3.2	7.37	207417	686168 (0.86)	298258 (0.89)		109931.01		
		whole	1.92(0.42)		15.67	12.89	27.11	253620	755657 (0.52)	359209 (0.50)	459943 (0.60)	486950.4	14.21	14.1
2007	April	1	1.32(0.2)	0.13(0.36)	12.06	13.37	27.54	142403	281128 (0.42)	136485 (0.36)		187971.96		
		2	0.56(0.46)		24.48	23.41	38.94	213756	102998 (0.67)	61919 (0.62)		119703.36		
		whole	0.86(0.26)		15.68	16.17	31.52	356159	380601 (0.39)	195279 (0.36)	198404 (0.31)	306296.74	13.7	13.6
2008	April	1	1.45(0.18)	0.13(0.29)	57.4	53.89	68.54	53514	29798 (0.20)	22642 (0.19)		77595.3		
		2	0.202(0.32)		13.84	12.6	22.57	244435	78359 (0.45)	43753 (0.42)		49375.87		
		whole	0.43(0.21)		21.82	20.31	32.2	297949	126148 (0.40)	79576 (0.35)	66395 (0.28)	128118.07	13.1	13.1
2009	April	1	1.76(0.22)	0.25(0.19)	19.50	20.37	36.12	74966	129520 (0.31)	73048 (0.29)		131940.16		
		2	0.15(0.27)		14.25	14.34	22.97	199929	41816 (0.38)	26114 (0.38)		29989.35		
		whole	0.59(0.22)		17.01	17.53	29.11	274895	185084 (0.28)	111444 (0.27)	99162 (0.24)	162188.05	13.6	13.5

continue table 6

Calendar Year	Month	Region	[1]P0/0.05m2 (cv)	Z (CV)	[2]RSF/W based on S_1	[3]RSF/W based on S_{12}	[3]FS/W based on S_{12}	[4]Area (km^2)	[5]S. biomass (cv)	S. biomass females (cv)	S. biomass females (Sum of R1andR2) (cv)	Total egg production (TEP)	Mean temper-ature (°C) for positive eggs	Mean temper-ature (°C) from Calvet
2010	April	1	1.70(0.22)	0.33(0.23)	21.08	24.02	51.56	27462	38875 (0.44)	18111 (0.39)		46685.4		
		2	0.22(0.42)		14.55	16.20	26.65	244311	66345 (0.58)	40336 (0.58)		53748.42		
		whole	0.36(0.29)		16.08	18.07	31.49	271773	108280 (0.46)	62131 (0.46)	58447 (0.42)	97838.28	13.7	13.9
2011	April	1	5.57(0.24)	0.51(0.14)	19.03	24.26	41.16	41878	192332 (0.31)	113340 (0.30)		233260.5		
		2	0.487(0.33)		11.40	14.67	25.04	272603	181016 (0.48)	106046 (0.49)		132757.7		
		whole	1.16(0.26)		14.85	19.04	32.40	314481	383286 (0.32)	225155 (0.32)	219386 (0.28)	364798.0	13.5	13.6
2012	April	1	5.28 (0.27)	0.66(0.11)	17.76	19.25	42.17	32322	177289 (0.37)	80930 (0.33)		170660.16		
		2	0.24 (0.27)		15.34	14.67	35.52	238669	78102 (0.60)	32248 (0.46)		57280.56		
		whole	0.84 (0.27)		16.14	16.14	37.65	270991	282110 (0.43)	120902 (0.36)	113178 (0.27)	227632.44	13.57	13.3
2013	April	1	5.47 (0.29)	0.64(0.16)	32.35	27.41	47.91	29176	116455 (0.40)	66633 (0.36)		159592.72		
		2	0.27 (0.44)		13.20	24.71	39.00	112221	24547 (0.48)	15549 (0.49)		30299.67		
		whole	1.34 (0.299)		26.22	26.22	44.70	141397	144880 (0.36)	84972 (0.33)	82182 (0.30)	198471.98	13.51	13.47
2014	April	1	--	--	--	--	--	--	--	--	--	--		
		2	--	--	0	23.70	42.28		--	--	--	--		
		whole	--	--	0	23.70	42.28	160305	--	--	--	--	--	14.51
2015	April	1	1.71 (0.71)	1.095(0.15)	37.42	21.38	47.75	8814	14087 (0.79)	6308 (0.74)		15071.9		
		2	0.09 (0.73)		0	12.07	23.46	172436	25408 (0.76)	13068 (0.78)		15329.6		
		whole	0.17 (0.72)		25.62	18.09	37.28	181250	33412 (0.74)	16207 (0.74)	19376 (0.58)	30395.6	12.02	12.64

1: P_0 for the whole is the weighted average with area as the weight.

2. The estimates of adult parameters for the whole area were unstratified and RSF/W was based on original S_1 data of day-1 spawning females. For 2004, 27.03 was based on sex ratio= 0.618 while past biomass used RSF/W of 21.86 based on sex ratio = 0.5.(Lo et al. 2008).

3. The estimates of adult parameters for the whole area were unstratified. Batch fecundity was estimated with error term. For 1987 and 1994, estimates were based on S_1 using data of day-1 spawning females. For 2004, all trawls were in Region 1 and value was applied to Region 2.

4. Region 1 area is based: in 2015, on CUFES ≥ 0.3 eggs/min; in 2004-2013, on CUFES ≥1 eggs/min; and prior to 1997, from CalVET tows with eggs/0.05m^2 >0.

5: For the spawning biomass, the estimate for the whole area uses unstratified adult parameters.

6. Within southern and northern area, the survey area was stratified as Region 1 (eggs/0.05m2>0 with embedded zero) and Region 2 (zero eggs).

Table 7. Pacific sardine female adult parameters for surveys conducted in the standard daily egg production method (DEPM) sampling area off California in during 1994-2014 (1994 includes females from off Mexico) and whole DEPM survey area off Oregon and northern California in 2015.

		1994	1997	2001	2002	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Midpoint date of trawl survey		22-Apr	25-Mar	1-May	21-Apr	25-Apr	13-Apr	2-May	24-Apr	16-Apr	27-Apr	20-Apr	8-Apr	19-Apr	25-Apr	26-Apr	14-Apr
Beginning and ending dates of positive collections		04/15-05/07	03/12-04/06	05/01-05/02	04/18-04/23	04/22-04/27	03/31-04/24	05/01-05/07	04/19-04/30	04/13-04/27	04/17-05/06	04/12-04/27	03/23-04/25	04/08-04/28	04/18-05/03	04/25-05/03	04/01-04/17
N collections with mature females		37	4	2	6	16	14	7	14	12	29	17	30	16	15	3	4
N collection within Region 1		19	4	2	6	16	6	2	8	4	15	3	14	8	8	3	2
Average surface temperature (°C) at collection locations		14.36	14.28	12.95	12.75	13.59	14.18	14.43	13.6	12.4	12.93	13.62	13.12	13.18	13.65	12.96	12.54
Female fraction by weight	R	0.538	0.592	0.677	0.385	0.618	0.469	0.451	0.515	0.631	0.602	0.574	0.587	0.429	0.586	0.560	0.485
Average mature female weight (grams): with ovary	W_f	82.53	127.76	79.08	159.25	166.99	65.34	67.41	81.62	102.21	112.40	129.51	127.59	141.36	138.17	155.82	192.21
without ovary	W_{of}	79.33	119.64	75.17	147.86	156.29	63.11	64.32	77.93	97.67	106.93	121.34	119.38	131.58	129.76	146.35	178.26
Average batch fecundity[a] (mature females, oocytes)	F	24283	42002	22456	54403	55711	17662	18474	21760	29802	29790	39304	38369	38681	41339	46124	60916
Relative batch fecundity (oocytes/g)		294	329	284	342	334	270	274	267	292	265	303	301	274	299	296	317
N mature females analyzed		583	77	9	23	290	175	86	203	187	467	313	244	126	121	7	25
N active mature females		327	77	9	23	290	148	72	187	177	463	310	244	125	119	7	25
Spawning fraction of mature females[b]	S	0.074	0.133	0.111	0.174	0.131	0.124	0.0698	0.114	0.1186	0.1098	0.1038	0.1078	0.1376	0.149	0.143	0.118
Spawning fraction of active females[c]	S_a	0.131	0.133	0.111	0.174	0.131	0.155	0.083	0.134	0.1187	0.1108	0.1048	0.1078	0.1388	0.153	0.143	0.118
Daily specific fecundity	$\frac{RSF}{W}$	11.7	25.94	21.3	22.91	27.04	15.67	8.62	15.68	21.82	17.53	18.07	19.04	16.14	26.22	23.70	18.09

[a] 1994-2001 estimates were calculated using F_b = -10858 + 439.53 W_{of} (Macewicz et al. 1996), 2004 used F_b = 356.46W_{of}. (Lo and Macewicz 2004), 2005 used F_b = -6085 + 376.28 W_{of} (Lo and Macewicz 2006), 2006 used F_b = -396 + 293.39 W_{of} (Lo et al. 2007a), 2007 used F_b = 279.23W_{of} (Lo et al. 2007b), 2008 used F_b = 305.14W_{of} (Lo et al. 2008), 2009 used F_b = -4598 + 326.78W_{of} + e (Lo et al. 2009), 2010 used F_b = 5136 + 287.37W_{of} + e (Lo et al. 2010), 2011 used F_b = -2252 + 347.6W_{of} + e (Lo et al. 2011), 2012 used F_b = -12724 + 402.3W_{of} + e (Lo et al. 2013), 2013 used F_b = -9759 + 404.24W_{of} + e (Dorval et al. 2014), 2014 used equation from 2013, and 2015 used F_b = -5112 + 365.85W_{of} + e .

[b] Mature females include females that are active and those that are postbreeding (incapable of further spawning this season). S_1 was used for years prior to 2009 and S_{12} was used staring 2009.

[c] Active mature females are capable of spawning and have ovaries containing oocytes with yolk or postovulatory follicles less than 60 hours old.

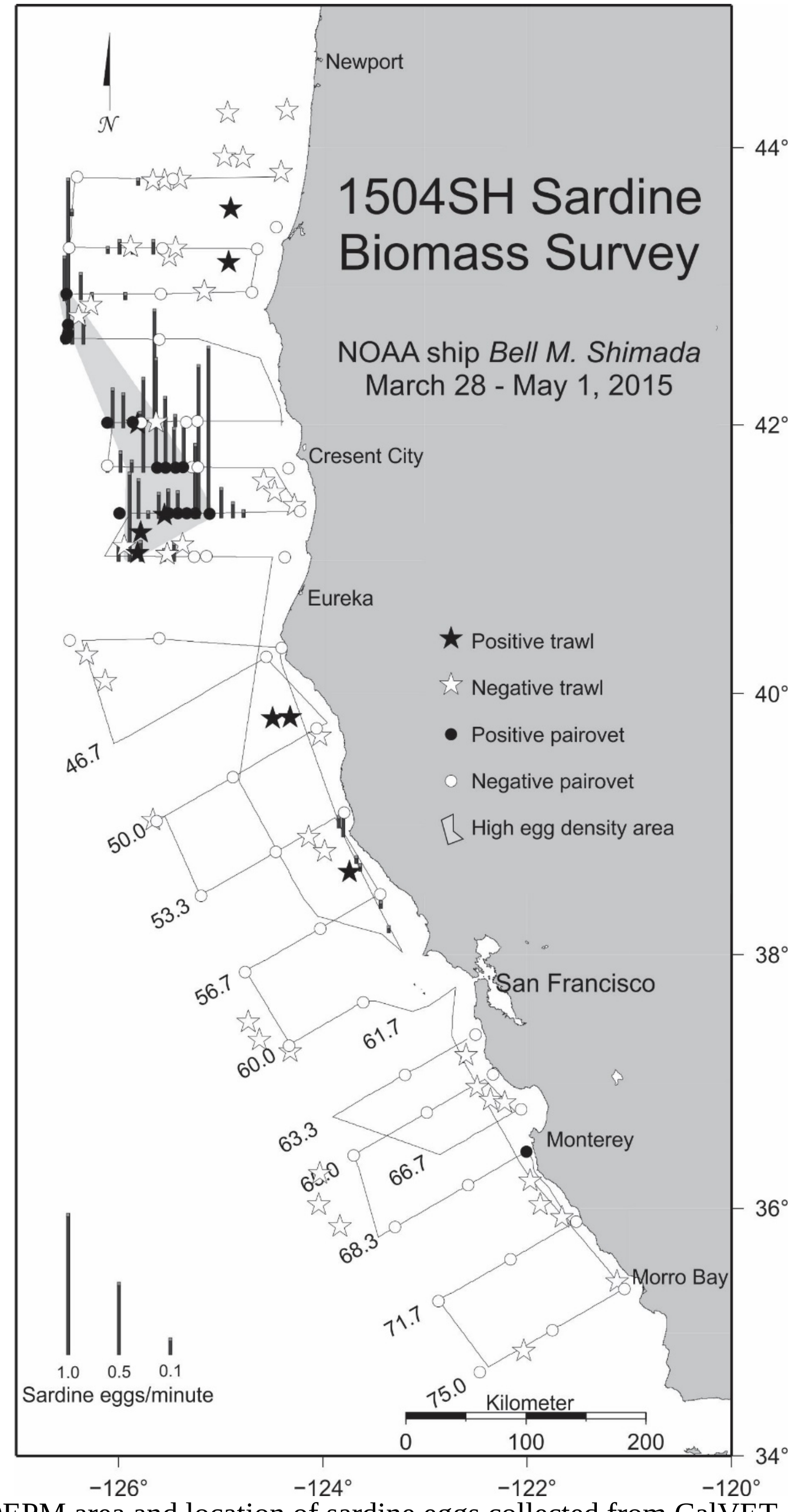

Figure 1. DEPM area and location of sardine eggs collected from CalVET, a.k.a. Pairovet; (solid circle is a positive catch and open circle is zero catch) and from CUFES (Bar denotes positive collection), and trawl locations (solid star is catch with sardine adults and open star is catch without sardines) during the 2015 survey aboard the NOAA ship *Bell M. Shimada* (solid line). Shaded area is Region 1, the high egg-density area, and the rest of survey area is Region 2.

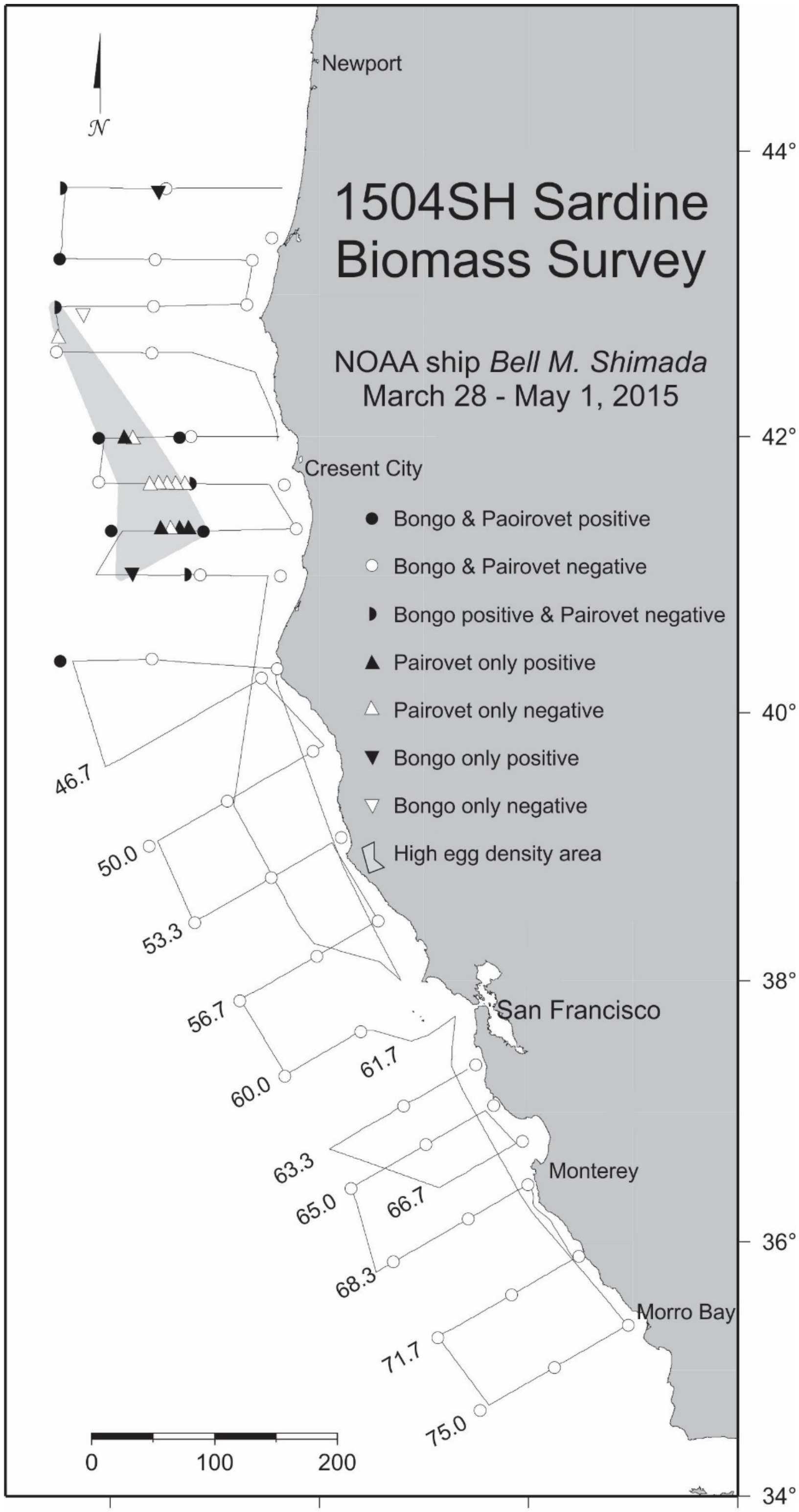

Figure 2. Location of yolk-sac larvae collected from CalVET (or Pairovet; circle and triangle) and from Bongo (circle and semi-circle) during the 2015 survey the NOAA ship *Bell M. Shimada* (gray line). Solid symbols are positive and open symbols are zero catch. The shaded area is Region 1: the high egg-density area, and the rest of the survey area is Region 2.

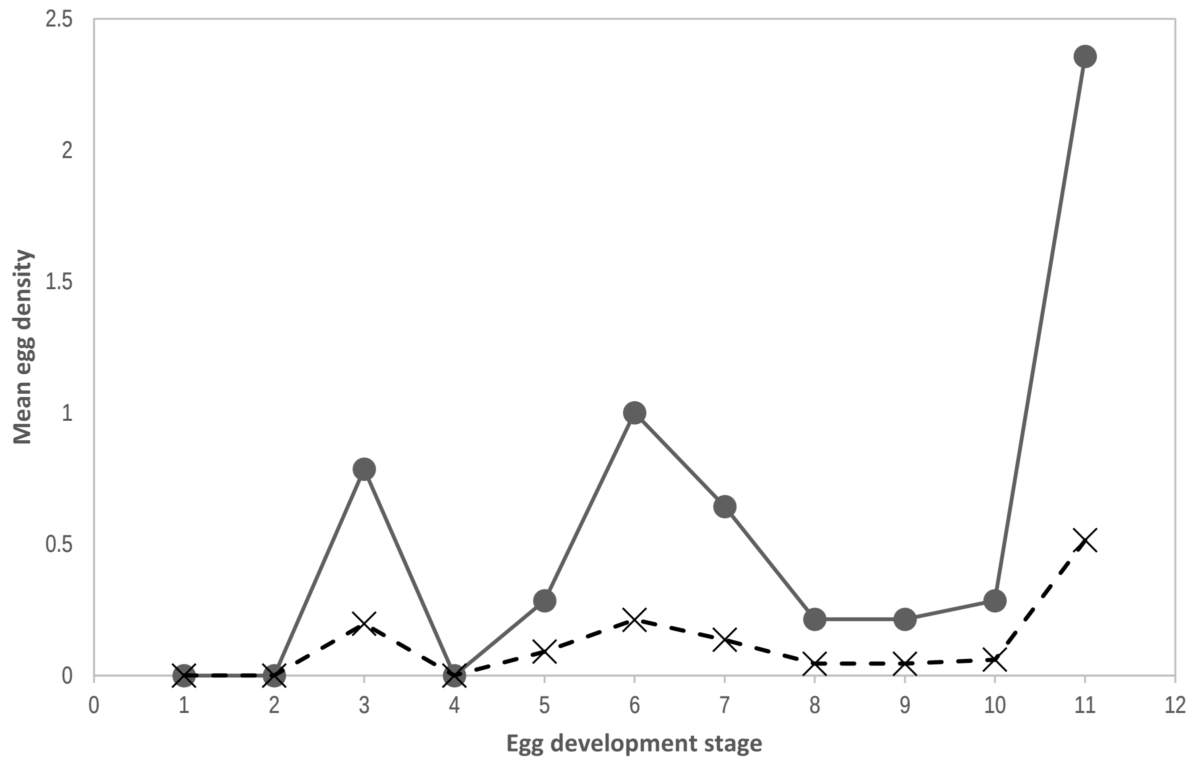

Figure 3. April 2015 mean sardine egg density (eggs per $0.05m^2$) for each developmental stage within the high egg-density region (black line with solid circles) and the whole DEPM survey area (from Winchester Bay, Oregon to Morro Bay, California; broken line with symbol X).

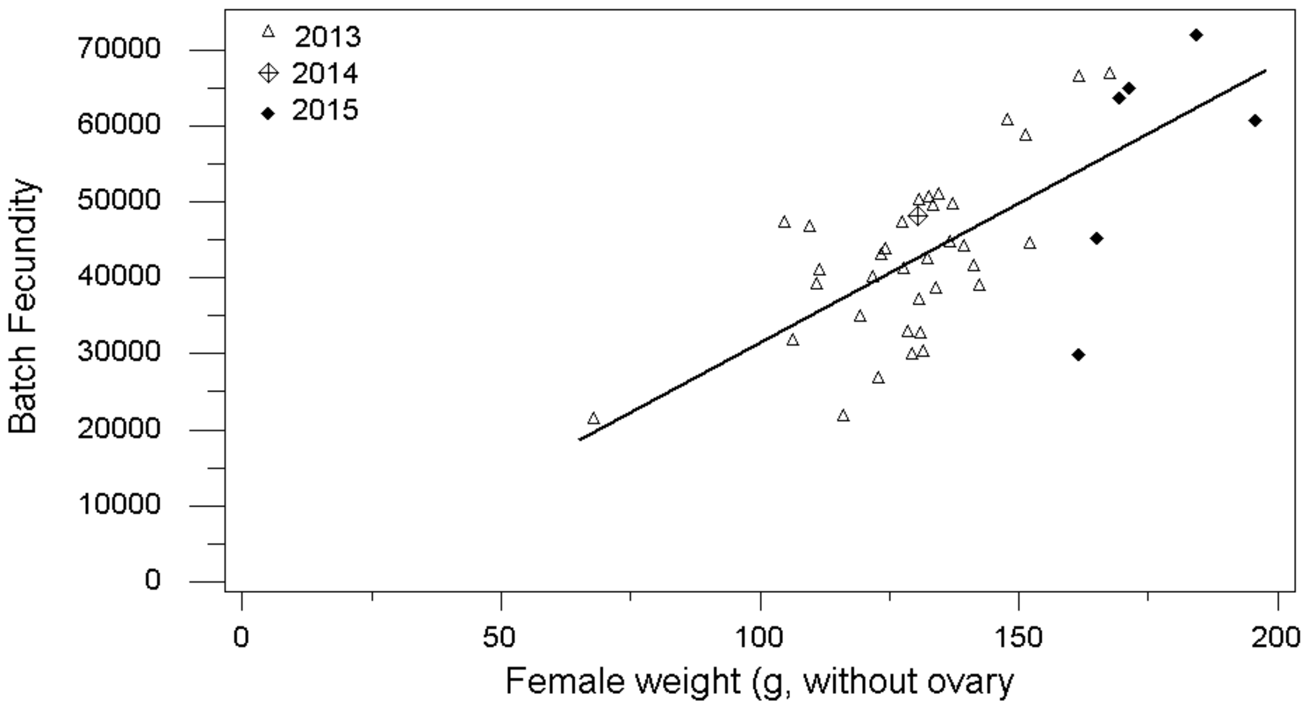

Figure 4. Batch fecundity (F_b) of *Sardinops sagax* as a function of female body weight (W_{of}, without the ovary) for a total of 42 female sardine: 6 females taken in April 2015 (solid triangle) and 1 female taken in April 2014 (plus triangle) onboard the *Bell M. Shimada* cruises and 35 females taken in April 2013 onboard the *Bell M. Shimada* and *Ocean Starr* cruises (triangle). The batch was estimated from the number of hydrated or migratory-nucleus-stage oocytes.

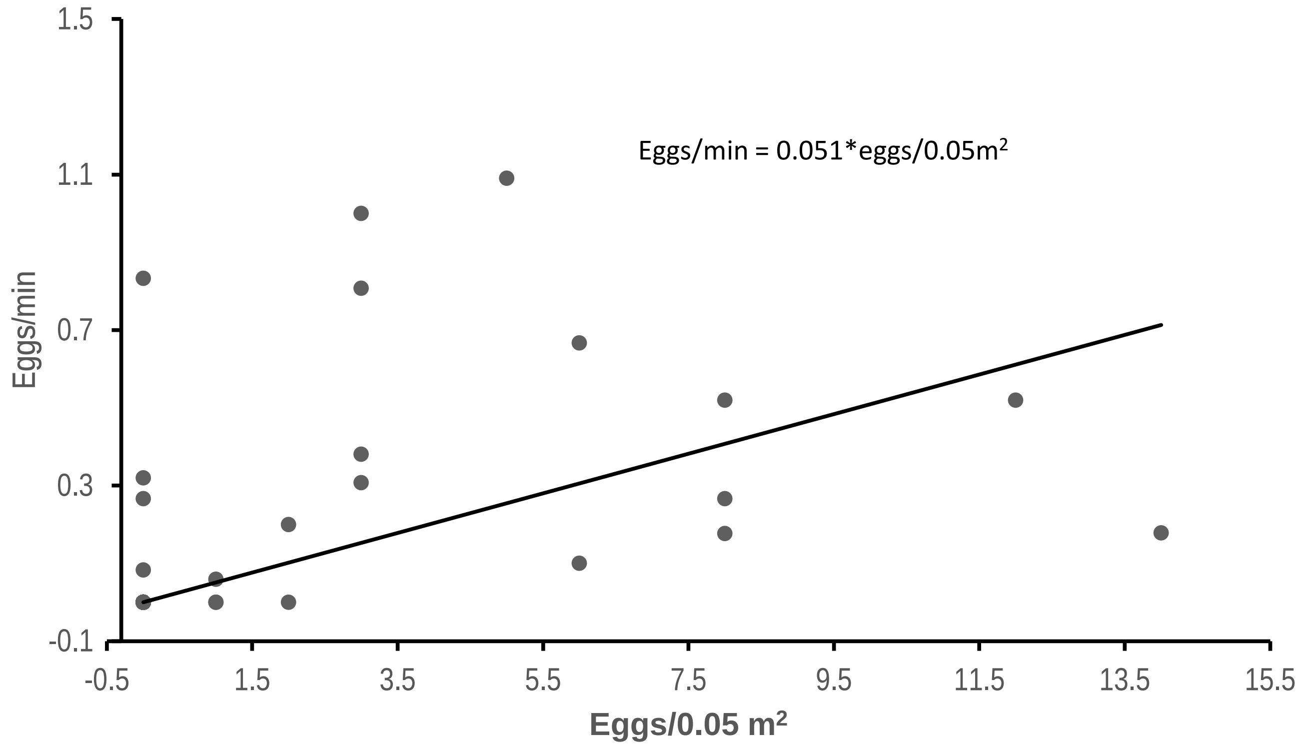

Figure 5. Catch ratio of eggs/min from CUFES to eggs/$0.05m^2$ from CalVET during April 2015 from *Bell M. Shimada* collections.

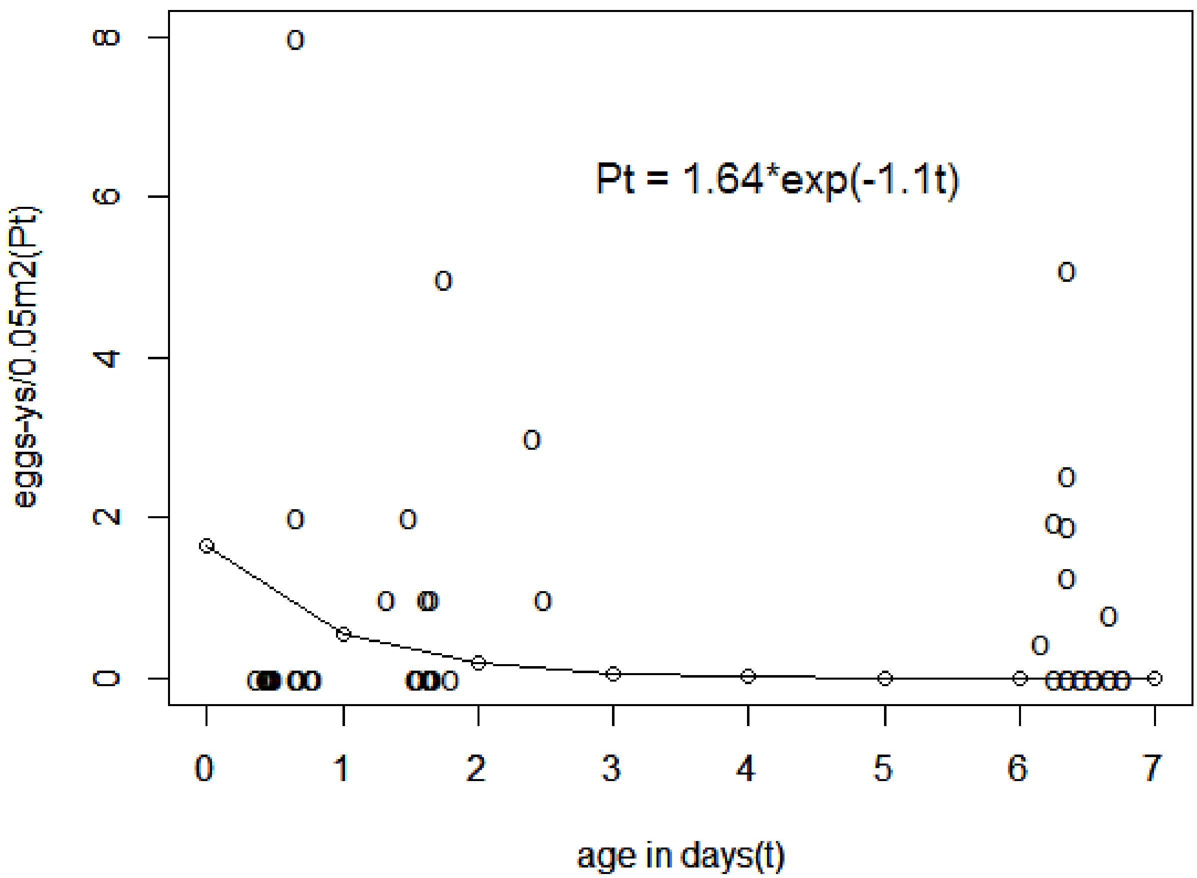

Figure 6. Embryonic mortality curve of Pacific sardines. Staged egg data were from CalVET and yolk-sac larval data were from CalVET and Bongo during April 2015, onboard *Bell M. Shimada*. The number, 1.64, is the estimate of daily egg production at age 0 (P_0) before correction for bias.

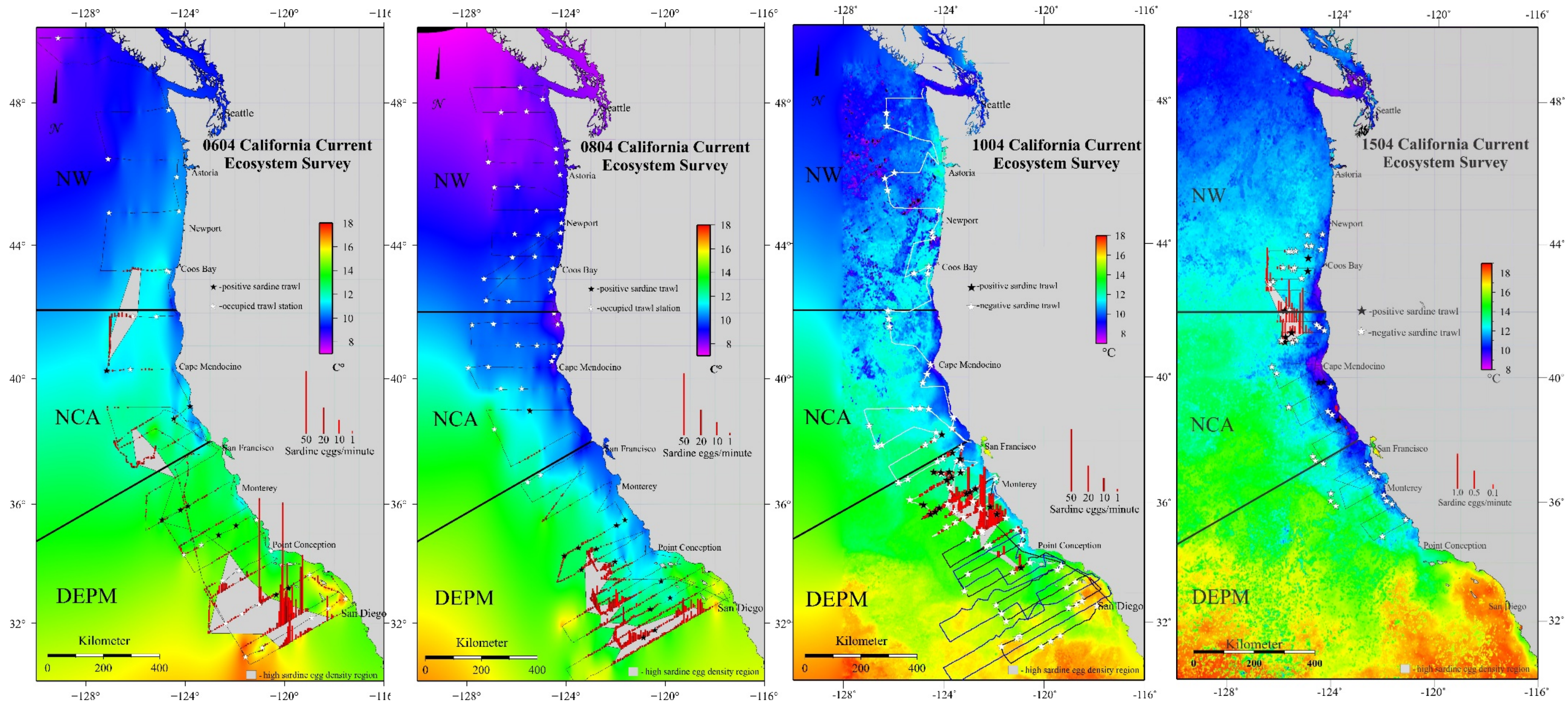

Figure 7. Temperature distribution of Pacific sardine eggs, larvae and adults caught in the 2006, 2008, 2010, 2015 surveys occupying areas off Washington, Oregon and California. Shaded area is the high sardine egg-density area (Region 1).

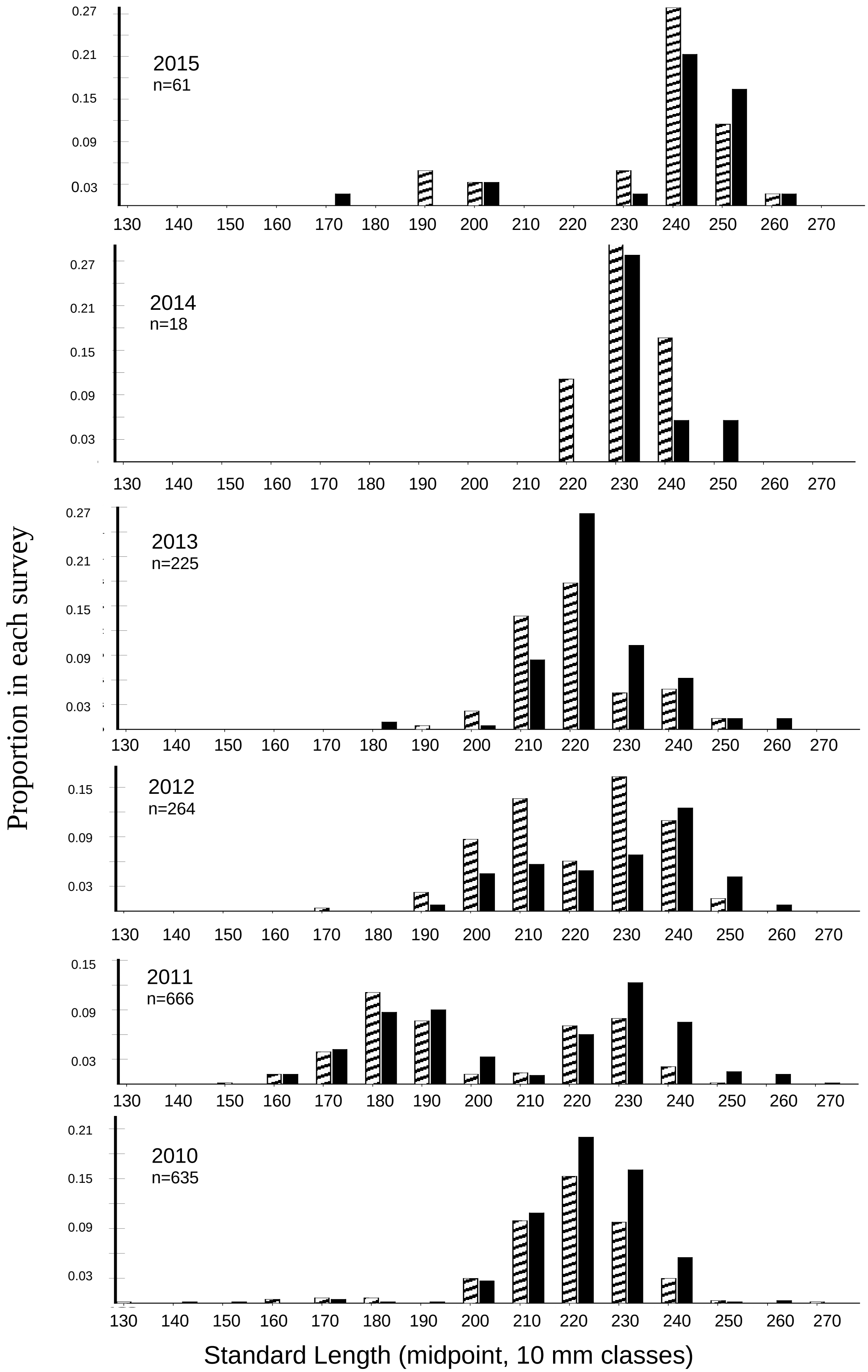

Figure 8. Length distribution of Pacific sardines caught in the DEPM survey areas during 2010 to 2015. Males indicated by cross hatching bars and females by solid bar.

APPENDIX

Pacific sardine (*Sardinops sagax*) 2014 DEPM survey

From 1994 to 2013 the times series of TEP and DEPM and estimates of SSB were based on SWFSC ship-based surveys conducted each April between San Diego and San Francisco. The DEPM index of female SSB is used when adult daily specific fecundity data are available from the survey. The total egg production (TEP) index of SSB is used when survey specific fecundity data are unavailable. In 2014 neither the TEP and nor the DEPM biomass could be estimated from the survey, because no eggs and no larvae were collected in the Calvet or in the bongo nets (see below).

In 2014 the SWFSC conducted the sardine DEPM biomass survey aboard the chartered research vessel R/V *Ocean Starr* (April 23 – April 28) and the NOAA ship *Bell M. Shimada* (April 15 – May 8) within the standard DEPM area (CalCOFI line 60 to 95). The *Ocean Starr* covered the area from Del Mar, California up to the northern Channel Islands, California while the NOAA ship *Bell M. Shimada* covered the area north of Point Reyes, California (line 56.7) to Point Conception, California (Figure A1). The *Ocean Starr* also conducted the standard spring CalCOFI survey from March 28 to April 22. Because no trawls were taken during the CalCOFI survey, only the data from the DEPM portion of *Ocean Starr* are reported in this assessment (i.e., data from April 23 to April 28). The DEPM survey from both research vessels employed all the usual methods for collecting data for estimating sardine SSB (Lo et al. 2010). The survey included a complete sampling of the 'standard'DEPM area for the assessment models' DEPM time series, i.e. San Francisco to San Diego (Figure A1).

The 2014 DEPM index area off California (CalCOFI lines 56.7 to 93.8, about 38.49˚ – 31.85˚N) was 160,305 km^2 (Figure A1). During the survey 69 CalVET tows were performed from the two vessels, but no eggs and no larvae were caught in these tows. Similarly, no larvae were captured in 40 bongo tows cast over the period of the survey (Table A1). Because no eggs and no larvae were collected in the CalVET or in the bongo tows, the mortality rate of eggs-at-age couldn't be derived. Therefore, both the egg production (P_0) and the female spawning biomass for 2014 couldn't be estimated based on previous year methods.

In the April 2014 DEPM survey area off California, Pacific Sardines were captured in 7 of the 53 trawl tows conducted and a total of 18 male and female sardines were caught (Table A2, Figure A1). Mature female sardine were caught in 3 tows, and 4 tows contained only male sardine (Table A2). Standard length (SL) of the randomly obtained sardines in each trawl ranged from 222 to 236 mm for 11 males and from 228 to 246 mm for 7 mature females. Since no immature female sardines were captured during the 2014 survey, the length at which 50% of females are mature (ML_{50}) was not calculated.

Adult reproductive parameters for the survey are presented in Table A3. The estimated daily specific fecundity was 23.70 (number of eggs/population weight (g)/day) using the following estimates of reproductive parameters from 7 mature females collected from 3 positive trawls: mean batch fecundity (*F*) was 46,124 eggs/batch (CV = 0.08), spawning fraction (*S*) was 0.143 females spawning per day (CV = 0.49), mean female fish weight (W_f) was 155.82 g (CV = 0.03), and sex ratio of females by weight (*R*) was 0.560 (CV = 0.26). Since 2005, trawling has been conducted randomly, at CalCOFI stations, or near daytime positive acoustic CPS locations, which resulted in sampling adult sardines in both high and low sardine egg-density areas. In 2014 there was no post stratification of the DEPM area, it only consisted of a low egg-density area (< 1 egg/min in CUFES).

Table A1. Number of positive tows of sardine eggs from CalVET, yolk-sac larvae from CalVET and Bongo, eggs from CUFES and positive sardine trawls[a] for *Ocean Starr* and *Bell M. Shimada* cruises of 2014 CalCOFI - Sardine DEPM survey. Both *Shimada* and *Ocean Starr* occupied part of the standard DEPM survey area. *Shimada* occupied the area north of San Francisco to Point Conception, California (CalCOFI line 56.7 to 81.7). *Ocean Starr* occupied the area from Del Mar, California to Avila Beach, California (CalCOFI line 93.3 to 76.7).

Sampling type and tows, eggs, larvae, or adult sardines		CalCOFI	DEPM		
		March 28-April 15, 2014	April 15, 2014 – May 8, 2014		
		Ocean Starr	*Ocean Starr*	*Shimada*	TOTAL
CalVET (Pairovet)	Total tows	53	9	60	69
	Positive tows	0	0	0	0
	Eggs	0	0	0	0
	Larvae	0	0	0	0
BONGO	Total tows	64	9	60	69
	Total positive tows	7	0	0	0
	Positive egg tows	6	0	0	0
	Eggs	90	0	0	0
	Positive larvae tows	4	0	0	0
	Larvae	73	0	0	0
CUFES	Total samples	316	72	379	451
	Positive samples	11	2	1	3
	Eggs	98	2	1	3
Trawl	Total tows	n/a	14	39	53
	Total positive tows		0	7	7
	Total sardine		0	18	18
	Female sardine		0	7	7

[a] All sardines were captured at night.

Table A2. Sardine egg density region, individual trawl information, sex ratio[a], and reproductive parameters for mature female *Sardinops sagax* caught during the spring 2014 DEPM survey off California.

COLLECTION INFORMATION									MATURE FEMALES							
				Location										Number spawning		
Region 1=high 2=low w=whole	No.	Month-Day	Time	Latitude °N	Longitude °W	Surface Temp. °C	No. of fish	Sex Ratio	No. anal-yzed	Body weight (g) Ave.	Weight without ovary (g) Ave.	Batch Fecundity Ave.	Adj. No.[b]	Night of capture	Night before capture	2 Nights before capture
w	3239	4-25	20:25	36.095	-122.339	14.1	1[c]	0.000	0	0	0	0	0	0	0	0
w	3240	4-26	00:44	35.963	-121.982	12.6	1[c]	0.000	0	0	0	0	0	0	0	0
w	3244	4-27	20:44	35.592	-121.727	11.9	1[c]	0.000	0	0	0	0	0	0	0	0
w	3246	4-28	02:56	35.926	-121.772	10.6	1	1.000	1	153.78	144.59	59872	0	1	0	0
w	3253	4-30	20:00	34.983	-121.03	12.3	2[c]	0.000	0	0	0	0	0	0	0	0
w	3254	4-30	23:36	34.826	-120.947	14.1	6	0.357	2	164.25	154.65	53907	2	0	0	0
w	3256	5-02	02:51	34.778	-121.572	14.7	6	0.697	4	152.13	142.64	42057	5	0	0	2
all							18		7				7	1	0	2

[a] Sex ratio, proportion of females by weight, based on average weights from subsamples and number of fish sampled in each trawl(Picquelle and Stauffer 1985).
[b] Mature adjusted by the average number of females spawning the night before capture and females spawning 2 nights before capture
[c] Only male(s) captured

Table A3. Estimated 2014 adult parameters for the DEPM area using batch fecundity regression from 2013

Statistic Results:

	Average	Variance
Whole Body Weight	155.825323543	15.5257208386
Gonad Fee Weight	146.34894	15.2624771371
Batch fecundity	46124.1839115	23550394116.1
Spawners, Day 0	0.14285714286	0.03498542274
Spawners ave (day 1+day 2)	0.14285714286	0.00499791753
Sex Ratio	0.56044289502	0.02126056471
Daily specific fecundity	23.69867066	
Number of Sets	3	

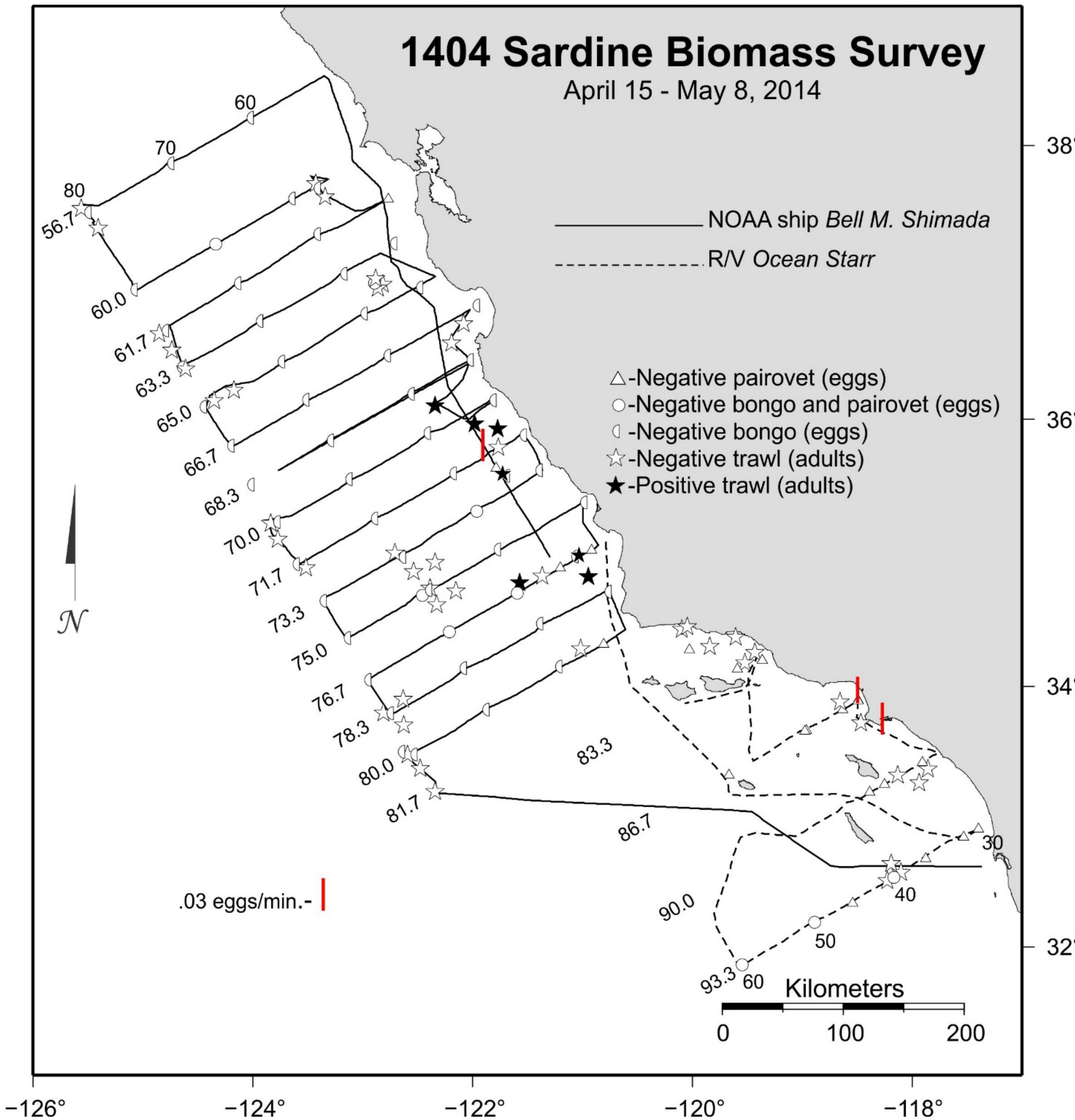

Figure A1. DEPM area and location of CalVET, a.k.a. Pairovet, and Bongo tows (open symbol is zero catch) and CUFES (stick denotes positive collection), and trawl locations (solid star is catch with sardine adults and open star is catch without sardines) during the 2014 survey aboard the NOAA ship *Bell M. Shimada* (solid line) and the chartered research vessel R/V *Ocean Starr* (dash line).