

Spawning biomass of Sardine, *Sardinops sagax*, in waters off South Australia in 2017



Ward, T.M., Ivey, A.R. and Smart, J.J.

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**SARDI Aquatics Sciences
PO Box 120 Henley Beach SA 5022**

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Report to PIRSA Fisheries and Aquaculture

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South Australian Research and Development Institute

SARDI Aquatic Sciences
2 Hamra Avenue
West Beach SA 5024

Telephone: (08) 8207 5400
Facsimile: (08) 8207 5415
<http://www.pir.sa.gov.au/research>

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Author(s): Ward, T.M., Ivey, A.R. and Smart, J.J.

Reviewer(s): Linnane, A., Wiltshire, K. (SARDI), Shanks, S. and Presser, J. (PIRSA)

Approved by: Mayfield, S.
Science Leader - Fisheries

Signed: 

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EXECUTIVE SUMMARY

This report provides an estimate of the spawning biomass of Sardine, *Sardinops sagax*, in waters off South Australia in 2017.

Surveys were conducted during 23 February to 8 March and 22 March to 4 April 2017. The total survey area was 119,739 km².

A total of 4,658 live Sardine eggs were collected at 181 of 343 (52.8%) sites.

The spawning area (A) in 2017 was 66,408 km².

Mean daily egg production (P_0) calculated using the linear version of the exponential egg mortality was 108.6 eggs.day⁻¹.m⁻² (95% CI = 75.0–154.0 eggs.day⁻¹.m⁻²). Four other models produced higher estimates of P_0 .

Seven samples comprising 1,005 mature fish were collected at three inshore locations; no adult samples were collected from offshore waters where most spawning occurred. No reliable method is currently available for sampling adult Sardine in offshore waters.

Estimates of adult parameters were generally similar to historical means, with the exception of batch fecundity which was higher (i.e. 21,750 oocytes) than previous years (18,401 oocytes).

The estimate of spawning biomass for 2017 of 305,086 t (95% CI 176,923–521,285) is the highest estimated from DEPM surveys for Sardine off South Australian, and above the upper reference point of 190,000 t. The high estimate of spawning biomass combined with the large spawning area provides unequivocal evidence that the southern Australian stock of Sardine is **Sustainable**.

Keywords: Sardine, Biomass, South Australia.

1. INTRODUCTION

1.1. Daily Egg Production Method

The Daily Egg Production Method (DEPM) was developed for stock assessment of the Northern Anchovy, *Engraulis mordax* (Parker 1980, Lasker 1985), and has been applied to at least 18 species of small pelagic fishes worldwide (Stratoudakis et al. 2006, Dimmlich et al. 2009, Neira et al. 2009, Ward et al. 2009). The method is widely used because it is often the most practical option available for stock assessment of small pelagic species.

The DEPM relies on the premise that the biomass of spawning adults can be calculated by dividing the mean number of pelagic eggs produced per day throughout the spawning area (i.e. total daily egg production) by the mean number of eggs produced per unit mass of adult fish (i.e. mean daily fecundity; Lasker 1985). Total daily egg production is the product of mean daily egg production (P_0) and total spawning area (A). Mean daily fecundity is calculated by dividing the product of mean sex ratio (by weight, R), mean batch fecundity (number of oocytes in a batch, F), mean spawning fraction (proportion of mature females spawning each day/night, S) and mean female weight (W). Spawning biomass (SB) is calculated according to the equation:

$$SB = P_0 * A / (R * F * S / W) \quad \text{Equation 1}$$

The DEPM can be applied to fishes that spawn multiple batches of pelagic eggs over an extended spawning season (see Parker 1980). Data used to estimate DEPM parameters are typically obtained during fishery-independent surveys involving vertical plankton tows at sites located at regular intervals along parallel cross-shelf transects. Adult samples are often taken opportunistically during the survey and may be complemented by samples collected concurrently from commercial vessels (Stratoudakis et al. 2006). The key assumptions of the DEPM are that: 1) surveys are conducted during the main (preferably peak) spawning season; 2) the entire spawning area is sampled; 3) eggs are sampled without loss and identified without error; 4) levels of egg production and mortality are consistent across the spawning area; and 5) representative samples of spawning adults are collected during the survey period (Parker 1980, Alheit 1993, Hunter and Lo 1997, Stratoudakis et al. 2006).

The DEPM is used widely but a range of challenges have been encountered and estimates of spawning biomass are generally considered to be accurate (unbiased) but relatively imprecise (e.g. Alheit 1993, Hunter and Lo 1997, Stratoudakis et al. 2006). There are considerable uncertainties associated with the estimation of P_0 and S in particular (Fletcher et al. 1996,

McGarvey and Kinloch 2001, Ward *et al.* 2001a, 2001b, Gaughan *et al.* 2004). P_0 has been determined using a variety of statistical approaches. Ward *et al.* (2011) showed that these approaches provide different estimates of P_0 and suggested that the log-linear model of Piquelle and Stauffer (1985) should be used because it fits strongly over-dispersed Sardine egg density data better and provides more logically consistent and precautionary estimates of P_0 than the exponential mortality model and most generalised linear models. Bernal *et al.* (2011) suggested using an “all-years” estimate of mortality to estimate egg production which reduces the number of degrees of freedom in each yearly regression but loses information about inter-annual variations in mortality. FRDC Project 2014/026 is currently evaluating a variety of methods for estimating egg production. Uncertainties in the estimation of S mainly relate to difficulties obtaining representative samples of the adult population, but also in the accurate ageing of post-ovulatory follicles. An international expert in fish reproductive biology, Dr Kostas Ganaias (University of Aristotle Greece) recently undertook a review of methods that are used to estimate S for Sardine off South Australia. Findings of this review will be presented to PIRSA Fisheries and Aquaculture and industry when the report is finalised.

1.2. Application of the DEPM off South Australia

The DEPM has been used to estimate the spawning biomass of Sardine, *Sardinops sagax*, in South Australian waters since 1995 (Ward *et al.* 1998, 2011, 2016). Application of this method has facilitated rapid and sustainable development of the South Australian Sardine Fishery, despite the effects of mass mortality events in 1995 and 1998 that each killed over 70% of the adult population of Sardine off South Australia (e.g. Ward *et al.* 2001b, 2011).

1.3. Aim and Objectives

This report provides an estimate of the spawning biomass of Sardine in gulf and shelf waters of South Australia during February-April 2017. The objectives of the report are:

1. To describe the distribution and abundance of Sardine eggs in relation to environmental variables;
2. To estimate DEPM parameters (A , P_0 , W , R , F , S);
3. To use the DEPM to estimate the spawning biomass in 2017;
4. To evaluate the uncertainty associated with this assessment and make recommendations regarding future research needs.

2. METHODS

2.1. Study Area and Biophysical Variables

2.1.1. Study area

Two surveys were conducted aboard the *RV Ngerin* in shelf and Gulf waters of South Australia during February and April 2017. Plankton samples were collected at 343 sites on 34 transects between Victor Harbor and the Head of Bight (Fig. 1). Of these 343 samples, 3 were additional to the pre-determined survey design. In these cases, additional samples were taken on the seaward end of transects when Sardine eggs were observed in the Continuous Underway Fish Egg Sampler (CUFES, Fig. 1).

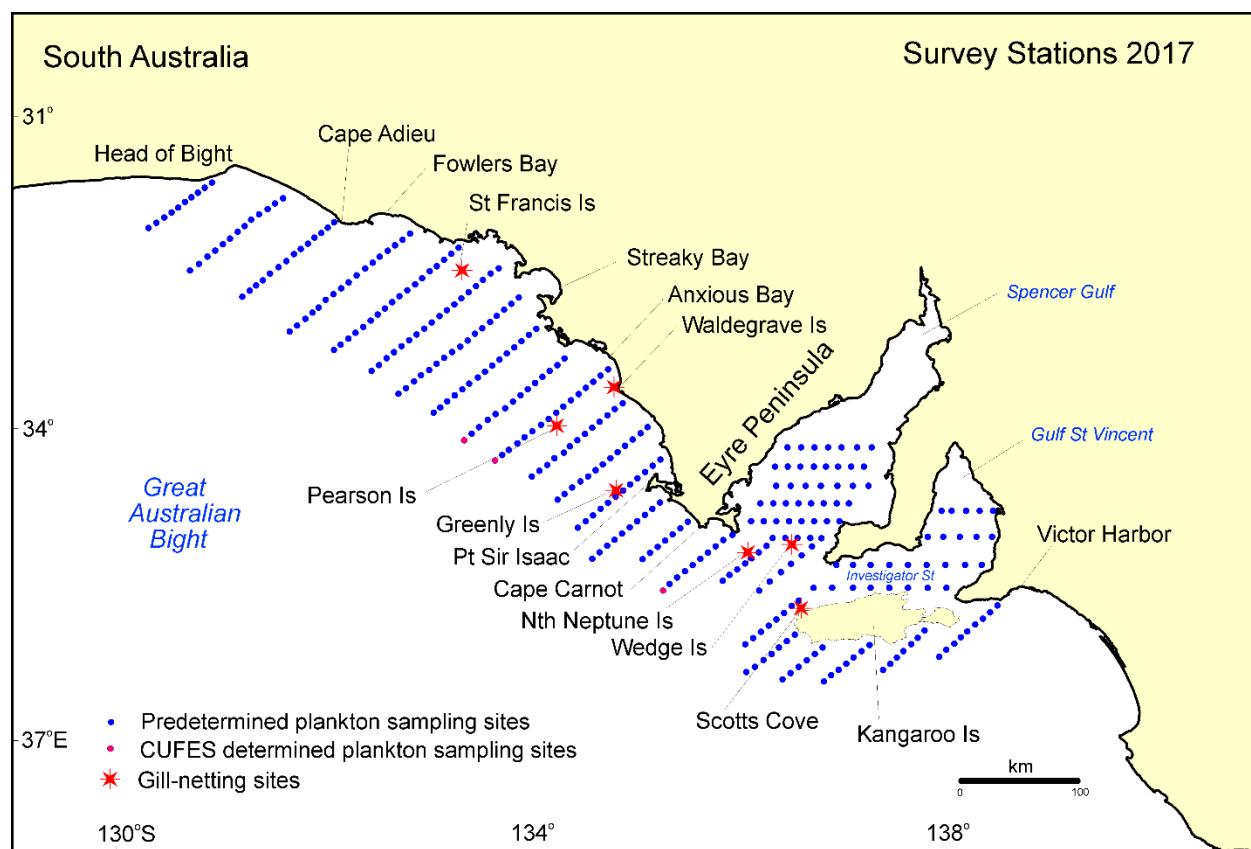


Figure 1. Map of South Australia showing sites where plankton and adult samples were collected during the 2017 DEPM surveys.

2.1.2. Water temperature and primary production

At each site (Fig. 1), a Sea-Bird Conductivity-Temperature-Depth (CTD) recorder fitted with a fluorometer was lowered to a depth of 70 m, or to 10 m from the bottom in waters less than 80 m

deep. Estimates of water temperature and fluorescence at the surface were extracted from each profile. Where CTD temperature was absent the midpoint of the adjacent stations was used. Fluorescence is an indicator of primary production and gives an un-calibrated measure of chlorophyll-a concentration ($\mu\text{g.L}^{-1}$). Spatial plots of SST and chlorophyll-a concentration were prepared using minimum curvature algorithms in Surfer[®] (Ver. 8).

2.2. Daily Egg Production and Spawning Area

2.2.1. Plankton sampling

Plankton samples were collected at each site using paired Californian Vertical Egg Tow (CalVET) plankton nets. Each CalVET net had an internal diameter of 0.3 m, length of 1.8 m, 330 μm mesh and plastic cod-ends. During each tow the CalVET nets were deployed to within 10 m of the seabed at depths <80 m or to a depth of 70 m at depths >80 m and retrieved vertically at a speed of $\sim 1 \text{ m.s}^{-1}$. General Oceanics 2030 flow-meters and factory calibration coefficients were used to estimate the distance travelled by the net during each tow. Where there was a discrepancy of more than 5% between flow-meters, the relationship between wire length released and flow-meter units was used to determine which was correct and that value was used for both nets. Upon retrieval of the nets, the samples from each of the two cod-ends were washed into a single sample container. Plankton samples in $\sim 1 \text{ L}$ of seawater were fixed using 75 ml of 40% formaldehyde.

2.2.2. Laboratory analysis

Sardine eggs and larvae were identified in each sample using published descriptions (Neira *et al.* 1998, White and Fletcher 1998). Eggs in each sample were counted and staged based on descriptions and temperature-development keys in White and Fletcher (1996).

2.2.3. Egg density

The number of eggs of each day class under one square metre of water (P_t) was estimated at each site according to Equation 2:

$$P_t = \frac{C.D}{V} \quad \text{Equation 2}$$

Where C is the number of eggs of each age in each sample, V is the volume filtered (m^3), and D is the depth (m) to which the net was deployed (Smith and Richardson 1977). Plots of egg distribution and abundance were prepared using Surfer® (Ver. 8).

2.2.4. Spawning time and density weightings

The development time of Sardine eggs is dependent on water temperature (Picquelle and Stauffer 1985). A peak spawning time of 2:00 am was established based on the assumption that Stage 2 eggs are approximately 3–4 hours old. Approximate ages were determined from the developmental stage of the eggs and the temperature dependent egg development relationship of Lo *et al.* (1996). Densities of day-1 and day-2 eggs were weighted according to the relative size of the area from which they were taken.

2.2.5. Spawning area

The Voronoi natural neighbour (VNN) method (Watson 1981) was applied using the statistical package ‘R’ (Baddeley and Turner 2005; R Development Core Team 2014) to generate a polygon around each sampling site with the boundary as the midpoint equidistant between each sampling site (Fig. 2). The area represented by each site (km^2) was then determined. The spawning area (A) was defined as the total area of grids where live Sardine eggs were found.

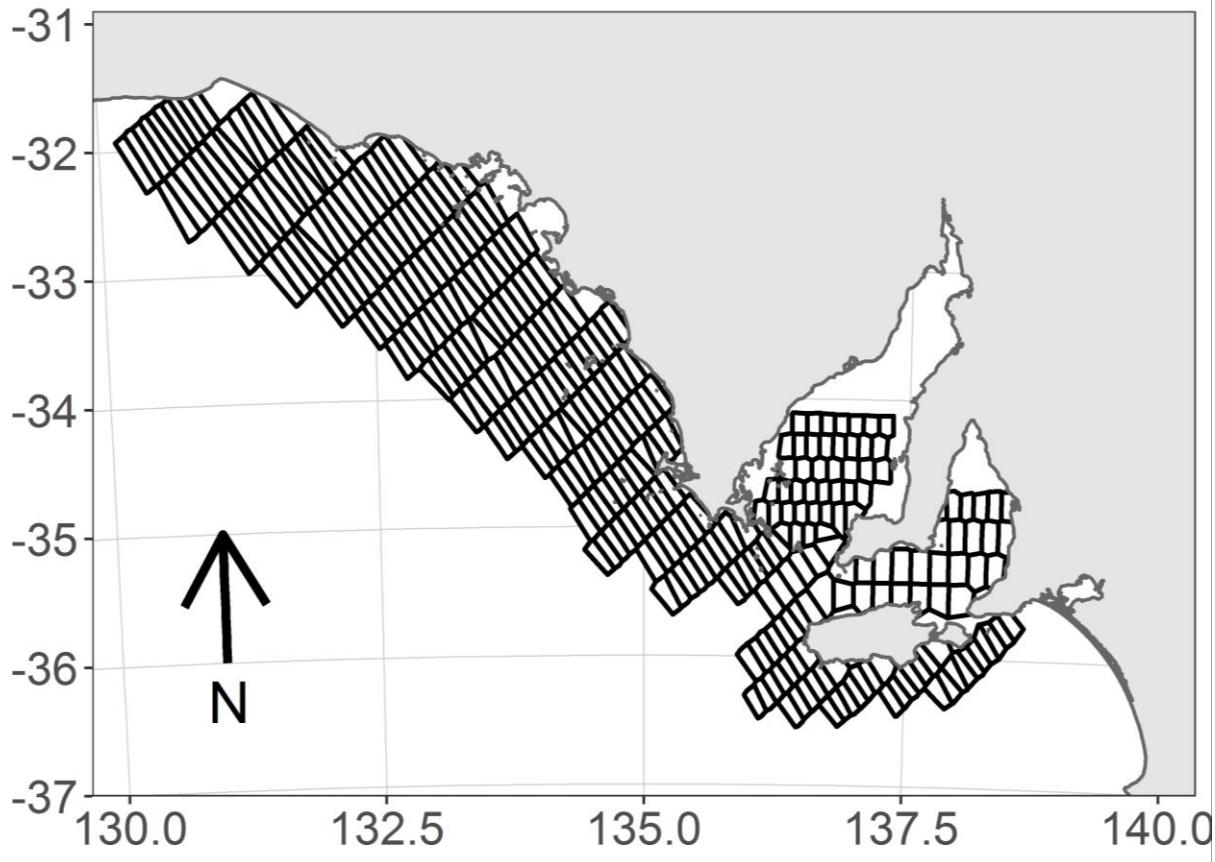


Figure 2. Voronoi nearest neighbour polygons generated in R, used to estimate the total spawning area in 2017.

2.2.6. Daily egg production (P_0) and egg mortality (Z)

Mean daily egg production (P_b) was calculated by fitting the linear version of the exponential egg mortality model to estimates of egg age and density at each site (Picquelle and Stauffer 1985). To allow the inclusion of data from sites where either day 1 or day 2 eggs were absent, zero-egg records were introduced at ages corresponding to these measurements. The linear version of the exponential egg mortality model is:

$$\ln P_b = \ln(P_i + 1) - Zt , \quad \text{Equation 3}$$

where P_i is the density of eggs of age t at site i and Z is the instantaneous rate of egg mortality.

Estimates of P_b obtained using the linear version of the exponential mortality model have a strong negative bias, therefore a bias correction factor was applied following the equation of Picquelle and Stauffer (1985):

$$P_0 = e^{(\ln P_b + \sigma^2/2)} - 1 \quad \text{Equation 4}$$

where, σ^2 is the variance of the estimate of biased mean daily egg production (P_b).

2.3. Adult Reproductive Parameters

2.3.1. Sampling methods

Each afternoon when the *RV Ngerin* was in areas where Sardine schools were known to aggregate and conditions were suitable for gillnetting (i.e. adequately protected from the swell), searching was undertaken using a dual frequency echo sounder (*Furuno* 60 and 180 KHz) (Fig. 1). The *RV Ngerin* was then anchored where several schools were observed. Samples of adults were collected using a gillnet comprising three panels, each with a different multi-filament nylon mesh size (*double diamond*: 210/4 ply meshes 25, 28 and 32 mm). Surface and sub-surface lights (150 W) were illuminated near the net after it was set. Net soak times varied from 15 minutes to 3 hours depending on the number of fish caught. After the net was retrieved, fish were removed and dissected immediately. All Sardines collected were counted and sexed. Mature and immature males and females were frozen. Mature females were fixed in 10% buffered formaldehyde solution. Calculations of female weight, sex ratio, batch fecundity and spawning fraction were based on samples collected from Scotts Cove in Investigator Strait, Greenly Island and Waldegrave Island in the eastern Great Australian Bight (GAB, Fig. 1).

2.3.2. Female weight (W)

Mature females from each sample were removed from formalin and weighed (± 0.01 g). Fixation in formalin has a negligible effect on fish weight (Lasker 1985). The mean weight of mature females in the population was calculated from the average of sample means weighted by proportional sample size:

$$W = \overline{\left[\bar{W}_i * \frac{n_i}{N} \right]} \quad \text{Equation 5}$$

where, \bar{W}_i is the mean female weight of each sample i ; n is the number of fish in each sample and N is the total number of fish collected in all samples.

2.3.3. Male weight

Mature males in each sample were thawed and weighed (± 0.01 g).

2.3.4. Sex ratio (R)

The mean sex ratio of mature individuals in the population was calculated from the average of sample means weighted by sample size:

$$R = \overline{\left[\bar{R}_i * \frac{n_i}{N} \right]} \quad \text{Equation 6}$$

where, n is the number of fish in each sample, N is the total number of fish collected in all samples and \bar{R}_i is the mean sex ratio of each sample calculated from the equation:

$$\bar{R}_i = \frac{F}{(F + M)} \quad \text{Equation 7}$$

where, F and M are the respective total weights of mature females and males in each sample i .

2.3.5. Batch fecundity (F)

Batch fecundity was estimated from ovaries containing hydrated oocytes using the methods of Hunter and Macewicz (1985). Both ovaries were weighed and the number of hydrated oocytes in three weighed ovarian sub-sections counted. The total batch fecundity for each female was calculated by multiplying the mean number of oocytes per gram of ovary segment by the total weight of the ovaries. The relationship between female weight (ovaries removed) and batch fecundity was determined by linear regression analysis and used to estimate the mean batch fecundities of mature females in all samples.

2.3.6. Spawning fraction (S)

Ovaries of mature females were sectioned and stained with haematoxylin and eosin. Several sections from each ovary were examined to determine the presence/absence of post-ovulatory follicles (POFs). POFs were aged according to the criteria developed by Hunter and Goldberg (1980) and Hunter and Macewicz (1985). The spawning fraction of each sample was estimated as the mean proportion of females with hydrated oocytes plus day-0 POFs (d_0) (assumed to be spawning or have spawned on the night of capture), day-1 POFs (d_1) (assumed to have spawned the previous night) and day-2 POFs (d_2) (assumed to have spawned two nights prior). The mean spawning fraction of the population was then calculated from the average of sample means weighted by proportional sample size.

$$S = \overline{\left[\bar{S}_i * \frac{n_i}{N} \right]} \quad \text{Equation 8}$$

where, n is the number of fish in each sample, N is the total number of fish collected in all samples and \bar{S}_i is the mean spawning fraction of each sample calculated from the equation:

$$\bar{S}_i = \frac{[(d_0 + d_1 + d_2 \text{POFs}) / 3]}{n_i} \quad \text{Equation 9}$$

where, d_0 , d_1 and d_2 POFs are the number of mature females with POFs in each sample and n_i is the total number of females within a sample.

2.4. Spawning Biomass

2.4.1. Spawning biomass estimates

Spawning biomass was calculated according to Equation 1 using the estimate of P_0 obtained using the log-linear model, spawning area (A) and adult parameters for S , R and W estimated from the 2017 survey. Due to the low number of hydrated females collected in 2017, the batch

fecundity relationship for all-years was also applied to the mean gonad free female weight for 2017 to estimate F .

Spawning biomass was also estimated using three other models for estimating egg production (*i.e.* the negative binomial GLM, non-linear least squares model, quasi GLM and Quasi-Poisson GLM).

2.4.2. *Bootstrapping procedures and confidence intervals*

To account for the covariance of adult parameters within individual samples, confidence intervals for all four adult parameters were calculated using a two stage bootstrap with 10,000 bootstrap iterations (Efron and Tibshirani 1993). For each iteration, the individual samples were resampled with replacement to obtain the bootstrapped samples. For each of the bootstrapped samples, the fish were resampled with replacement to generate a complete survey. The adult parameters W , R , S and F were calculated from the bootstrapped survey using the method described above. Batch fecundity (F) was also calculated from the bootstrapped gonad-free female weight using the batch relationship obtained from all females with hydrated oocytes sampled since 1998. For each bootstrap iteration the sampled values of W , R , F , and S were used in the calculation of spawning biomass. The 95% confidence intervals of spawning biomass were estimated by calculating the spawning biomass 10,000 times from A and the 10,000 bootstrapped estimates of P_0 and W , R , F , and S using the percentile method. Parameter estimates were calculated independently in Excel 2013 and R 3.3.1 (for quality assurance) with confidence intervals estimated with R 3.3.1.

2.4.3. *Sensitivity analysis*

Sensitivity analyses were conducted to assess the effects on estimates of spawning biomass of variations in the range of values obtained for each parameter in 2017 and between 1998 and 2016.

3. RESULTS

3.1. Distribution and Abundance of Eggs

A total of 4,658 live Sardine eggs were collected at 181 of 343 (52.8%) sites on 34 transects between the Head of Bight and Victor Harbor between February and April 2017 (Fig. 3). The sites with the highest egg densities were located in the mouth of Spencer Gulf, north-west of Anxious Bay and in mid/outer shelf waters of the eastern and central GAB. The highest egg density recorded was 1,297 eggs.m⁻².

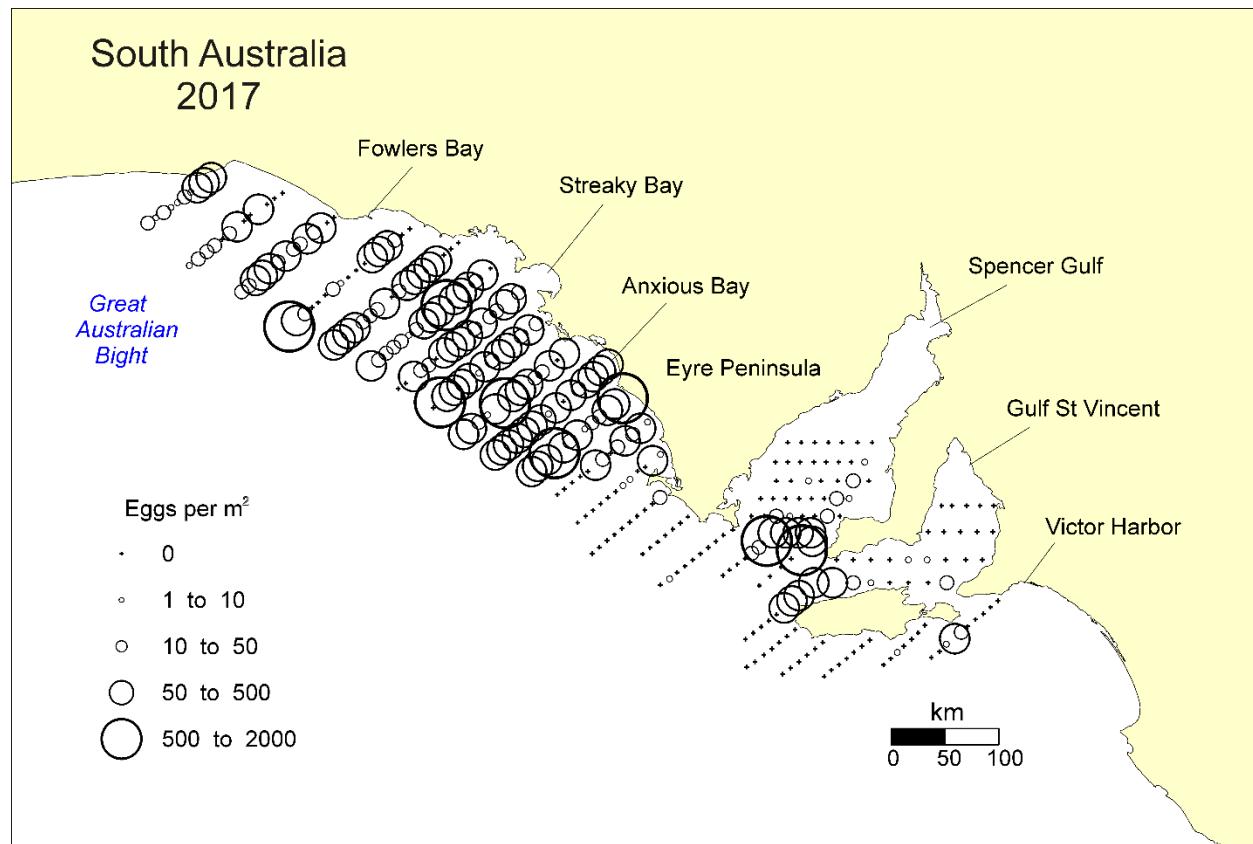


Figure 3. Spatial patterns of live Sardine egg distribution and abundance between February and April 2017.

3.2. Biophysical Variables

3.2.1. Sea surface temperature

Sea surface temperatures (SSTs) ranged from 16.8 to 22.6°C (Fig. 4) between February and April 2017. High SSTs ($>20^{\circ}\text{C}$) were recorded in Spencer Gulf, Gulf St Vincent and throughout the central Great Australian Bight (GAB). A plume of cool water ($<19^{\circ}\text{C}$) extended along the coast of the southern Eyre Peninsula.

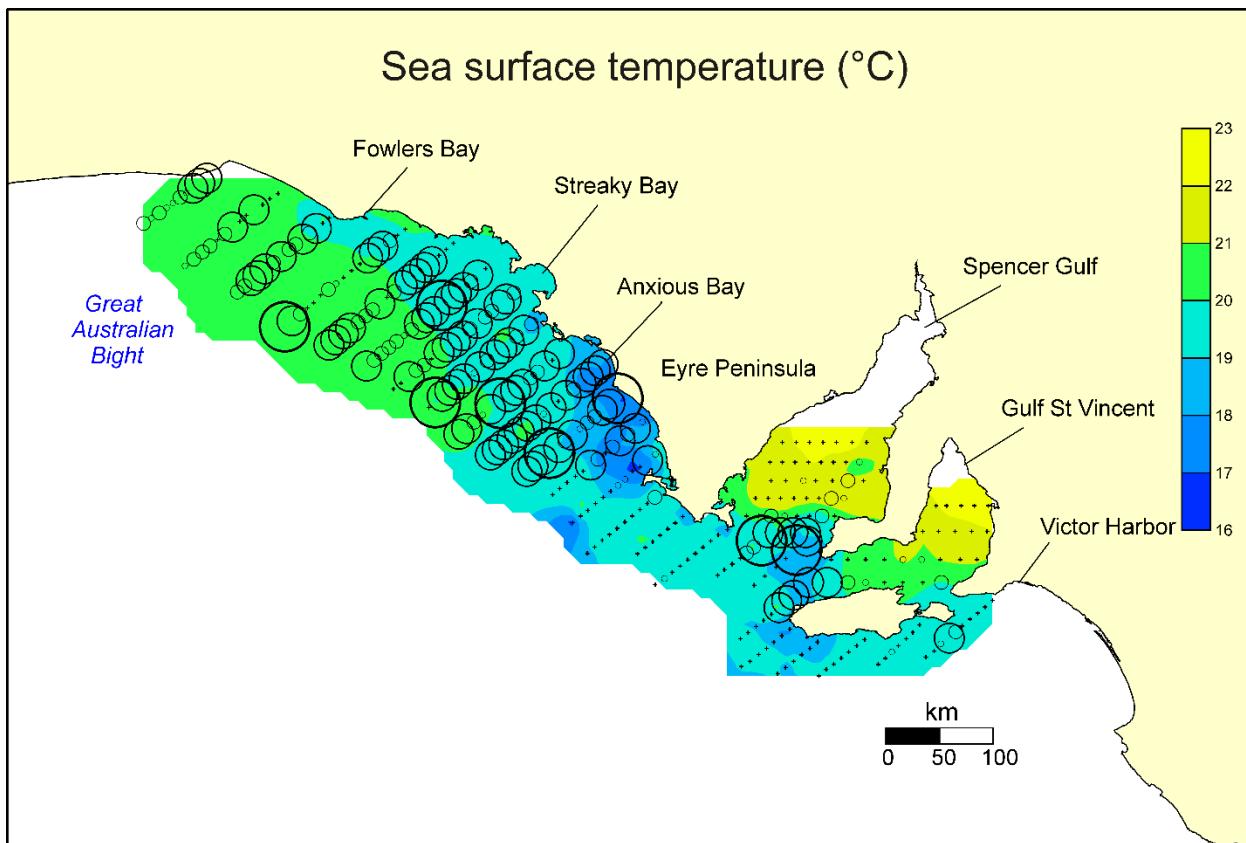


Figure 4. Sea surface temperature profile across the 2017 February-April survey, overlaid with Sardine egg distribution and abundance.

3.2.2. Fluorescence

Chlorophyll-a concentration at each site ranged between 0.019 and 0.606 $\mu\text{g.L}^{-1}$ (Fig. 5) between February and April 2017. The highest values were recorded in the central Great Australian Bight (GAB), west of Point Sir Isaac and in the Gulfs. The remainder of coastal and shelf waters mainly had chlorophyll-a concentrations ranging between 0 and 0.2 $\mu\text{g.L}^{-1}$.

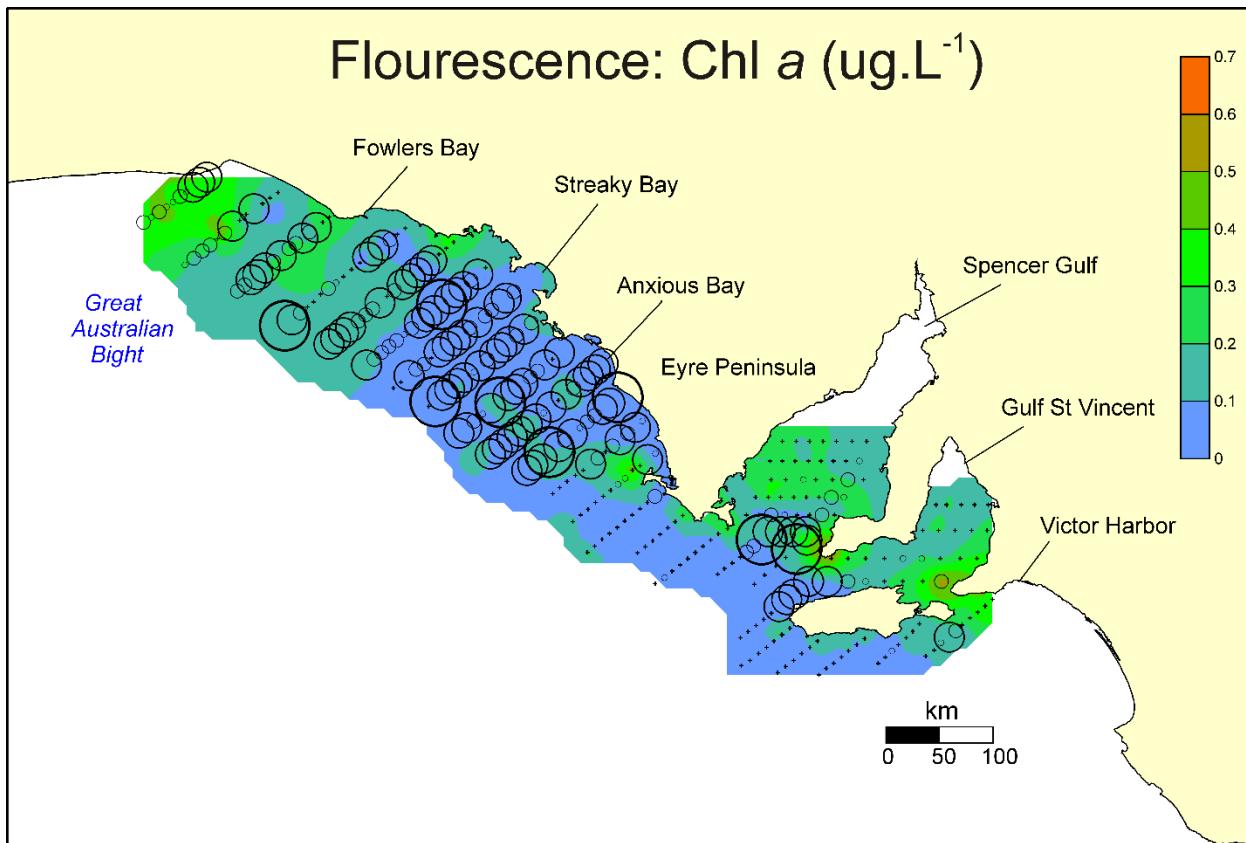


Figure 5. Surface concentration of chlorophyll-a inferred from fluorescence readings across the 2017, February-April survey area, overlaid with Sardine egg distribution and abundance.

3.3. Spawning Area

The estimated spawning area was 66,408 km^2 , comprising 55.5% of the total area sampled (119,739 km^2 , Table 1). The presence of eggs in CUFES samples was used as a basis for extending some transects (Fig. 1). An additional four sites were sampled in 2017, representing an additional 1,465 km^2 , two of these samples contained live Sardine eggs and contributed 737 km^2 to the spawning area.

Table 1. Total area surveyed and spawning area (A) estimated in 2017.

Total area sampled (km ²)	Spawning area, A (km ²)	Spawning area percentage
119,739	66,408	55.5

3.4. Daily Egg Production (P_0)

The estimate of mean daily egg production, P_0 obtained using the linear version (Eq. 3) of the exponential egg mortality (recommended by Ward *et al.* 2011a) was 108.6 eggs.day⁻¹.m⁻² (95% CI = 75.0–154.0, Fig. 6, 7, Table 2). The use of alternate egg production models produced estimates of between 133.4 and 138.6 eggs.day⁻¹.m⁻² (Fig. 6, 7, Table 2).

Table 2. Mean daily egg production (P_0) and instantaneous daily mortality (Z) estimated with four alternate models.

Model fit	P_0 (eggs·day ⁻¹ ·m ⁻²) (95% CI)	Z (days)	Z (hours)
Linear version of exponential model, $\ln(p+1) \sim \text{age}$, corrected	108.6 (75.0–154.0)	0.33	0.014
GLM, $p \sim \text{age}$, Negative Binomial family	137.8 (90.3–206.6)	0.63	0.026
Exponential model, $p \sim \exp(\text{age})$, NLS	135.2 (89.1–201.2)	0.60	0.025
GLM, $p \sim \text{age}$, Quasi family, log link, var $\sim \mu^2$	138.6 (90.9–208.6)	0.64	0.027
GLM, $p \sim \text{age}$, Quasi-Poisson family	133.4 (82.3–207.4)	0.63	0.026

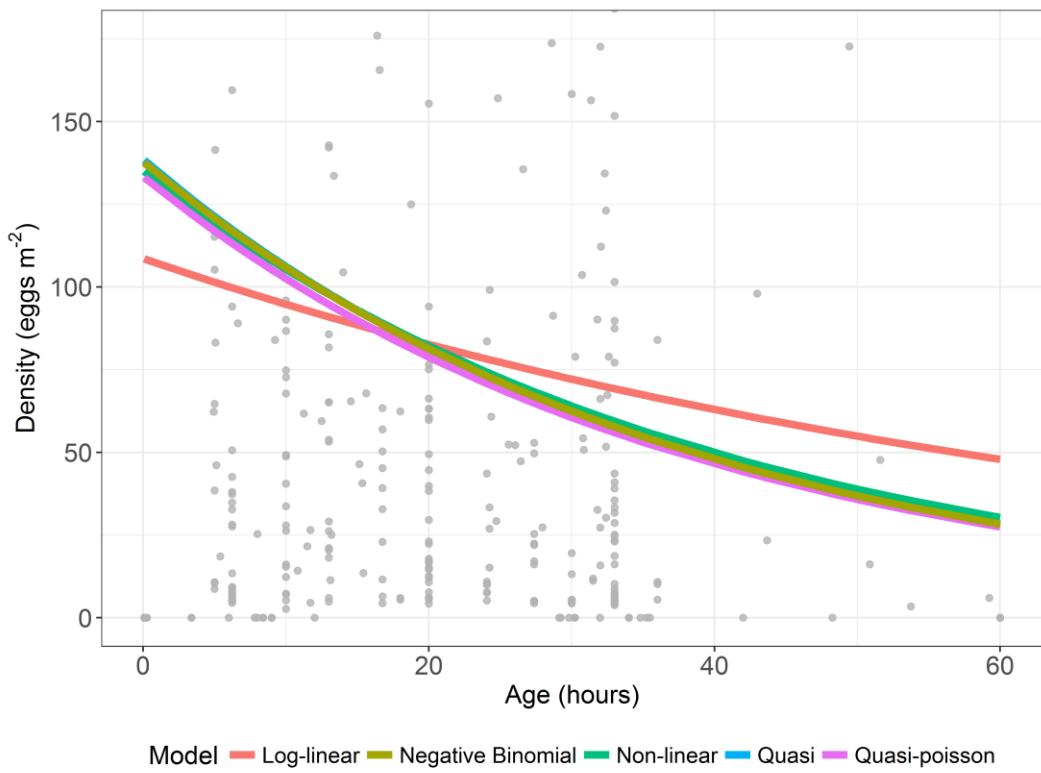


Figure 6. Regressions between Sardine egg density (eggs.m^{-2}) and age (days) data in 2017.

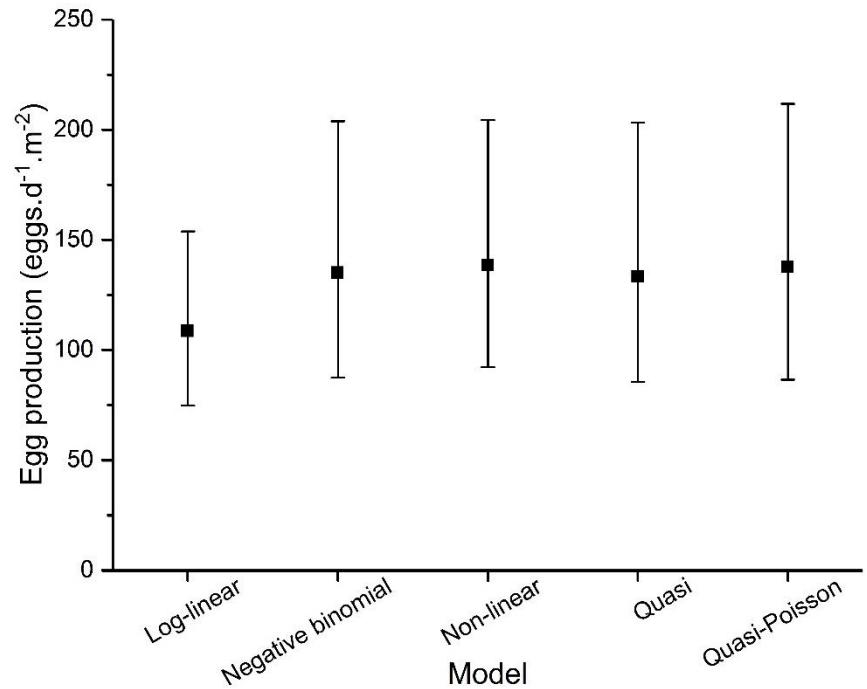


Figure 7. Egg production estimates ($\text{eggs.d}^{-1} \cdot \text{m}^{-2}$) from the four alternate models (Error bars are 95% CI).

3.5. Adult parameters

A total of seven samples comprising 1,005 mature Sardines were collected at Scotts Cove, Greenly Island and Waldegrave Island (Table 3). Estimates of the adult female reproductive parameters used in calculations of spawning biomass are provided in Tables 3, 4 and 5. The means and ranges of adult parameters in samples collected between 1998 and 2017 and the bootstrapped 95% confidence intervals are shown in Table 6.

Table 3. Sampling details for adult Sardine collected during the 2017 DEPM surveys.

Date	Location	Survey	N samples	<i>n</i> fish
26/02/2017	Scotts Cove	1	3	482
04/03/2017	Greenly Island	1	2	301
24/03/2017	Waldegrave Island	2	2	222
Total			7	1,005

3.5.1. Mean female weight

The mean weight of mature females in samples collected in 2017 ranged from 41.1 to 68.2 g (Table 4). The weighted mean weight of mature females in 2017 was 59.5 g (95% CI = 52.2–64.4, Table 4, 6). The mean weight of mature females collected between 1998 and 2016 was 57.0 g (min-max = 45.2–78.7, Table 6).

3.5.2. Sex ratio

The sex ratio calculated from the 2017 survey was 0.54 (95% CI = 0.45–0.60, Table 4, 6). The mean sex ratio between 1998 and 2016 was 0.54 and ranged between 0.36 and 0.68 (Table 6).

Table 4. Number of Sardine in samples by sex and estimates of female weight, W and sex ratio, R (proportion of females by weight) for samples collected in 2017. Values in bottom row are sums (*) and weighted means (#).

Location	Date	Male	Female	Mean Male Weight (g)	Mean Female Weight (g, W)	Sex Ratio by weight (R)
Scotts Cove	26/02/17	62	59	55.9	60.5	0.51
Scotts Cove	26/02/17	81	94	53.9	61.4	0.57
Scotts Cove	26/02/17	92	94	53.8	57.9	0.52
Greenly Is.	04/03/17	50	94	63.3	68.2	0.67
Greenly Is.	04/03/17	66	91	63.3	65.0	0.59
Waldegrave Is.	24/03/17	49	15	41.6	41.1	0.23
Waldegrave Is.	24/03/17	99	59	40.4	41.2	0.38
		499*	506*	52.4#	59.5#	0.54#

3.5.3. Batch fecundity

Eleven females with hydrated oocytes were collected in 2017. Based on the relationship (Batch Fecundity = $718 \times$ Gonad Free Female Weight – 19,423, $R^2 = 0.75$) for all females with hydrated oocytes collected in 2017 (Fig. 8) and the mean gonad free female weight for all samples collected in 2017 (57.4 g), mean batch fecundity was 21,750 oocytes per batch (95% CI = 13,951–28,648; Table 6). Based on the relationship (Batch Fecundity = $336 \times$ Gonad Free Female Weight – 880, $R^2 = 0.54$) for all females with hydrated oocytes collected between 1998 and 2017 (Fig. 8) and the mean gonad free female weight for all samples collected in 2017 (57.4 g), mean batch fecundity was 18,401 oocytes per batch. The mean batch fecundity for samples collected between 1998 and 2016 was 17,116 oocytes per batch (min-max = 10,904–24,790, Table 6).

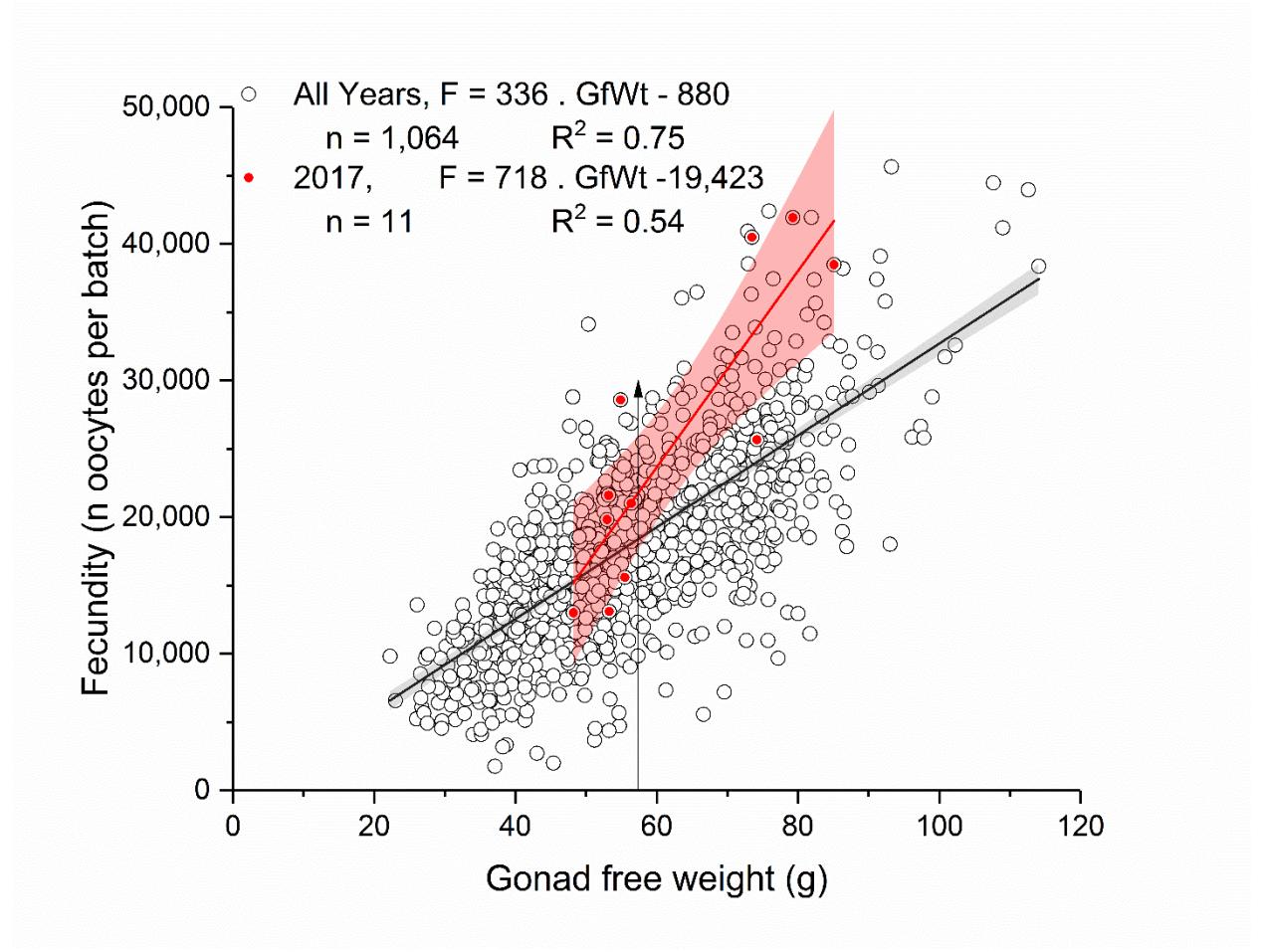


Figure 8. Relationship between gonad-free weight and batch fecundity for all hydrated Sardine collected in 2017 (red circle) and between 1998 and 2017 (open black circles, dotted line = 95% CI). The vertical arrow is the mean gonad free weight for 2017 (57.4 g).

3.5.4. Spawning fraction

Of the 499 ovaries examined, 61 had day-0 POFs or hydrated oocytes, 63 had day-1 POFs and 56 day-2 POFs (Table 5). The spawning fraction of females in each sample ranged from 0.07 to 0.25. The weighted mean spawning fraction for all 2017 data was 0.121 (95% CI = 0.088–0.167). For 1998–2016, the mean spawning fraction was 0.114 and ranged between 0.040 and 0.179 (Table 6).

Table 5. Number of female Sardine in samples and estimates of spawning fraction (S) for samples collected in 2017. Values in bottom row are sums* and weighted means[#].

Sample	Location	Date					Spawning Fraction	
			Day 0	Day 1	Day 2	Total	(S)	
1	Scotts Cove	26/02/2017	5	7	7	59	0.11	
2	Scotts Cove	26/02/2017	8	16	8	94	0.11	
3	Scotts Cove	26/02/2017	5	15	14	91	0.12	
4	Greenly Is.	04/03/2017	2	12	13	92	0.10	
5	Greenly Is.	04/03/2017	1	8	9	90	0.07	
6	Waldegrave Is.	24/03/2017	5	1	1	15	0.16	
7	Waldegrave Is.	24/03/2017	35	4	4	58	0.25	
			61*	63*	56*	499*	0.12[#]	

Table 6. Parameters used in the calculations of spawning biomass. Values for 2017 and the mean, minimum and maximum for 1998 to 2016 are presented (for spawning area, 2005 to 2016 only are considered as the surveys were previously not of consistent area). Note * indicates historically estimated values which were adjusted to historical means.

Parameter	2017 (95% CI)	Mean 1998–2017 (min-max)
Egg Production (P _o , eggs.day ⁻¹ .m ⁻²)	108.6 (75.0–154.0)	71.7 (38.1–120.9)
Sex Ratio (R)	0.535 (0.446–0.602)	0.54 (0.36*–0.68*)
Fecundity (F, eggs.female ⁻¹)	21,751 (13,951–28,647)	17,116 (10,904–24,790)
Spawning Fraction (S)	0.121 (0.088–0.167)	0.114 (0.040–0.179)
Female Weight (W, g)	59.5 (52.2–64.4)	57.0 (45.2–78.7)
Spawning Area (A, km ²)	66,408	49,226 (36,549–71,859)

3.6. Sensitivity Analysis

The sensitivity analysis shows where the parameter estimates for 2017 fall in comparison to the mean, minimum and maximum estimated for each parameter since 1998, and their relative influence on spawning biomass (Fig. 9).

The estimate for spawning area (A) for 2017 (Fig. 9) was the second highest recorded since 1998. The estimate of egg production (P_o) using the log-linear model was the third highest on record. Estimates of egg production obtained using alternative models were even higher (Fig. 9).

The estimates of sex ratio (R), spawning fraction (S) and female weight (W) obtained in 2017 were similar to the historical means. Varying these values did not strongly influence the estimates of spawning biomass.

Batch fecundity estimated using 2017 data was relatively high (Fig. 9). Batch fecundity was also estimated using the all-years fecundity relationship and 2017 mean gonad free female weight, which produced a higher estimate of spawning biomass than using the 2017 data (Fig. 9).

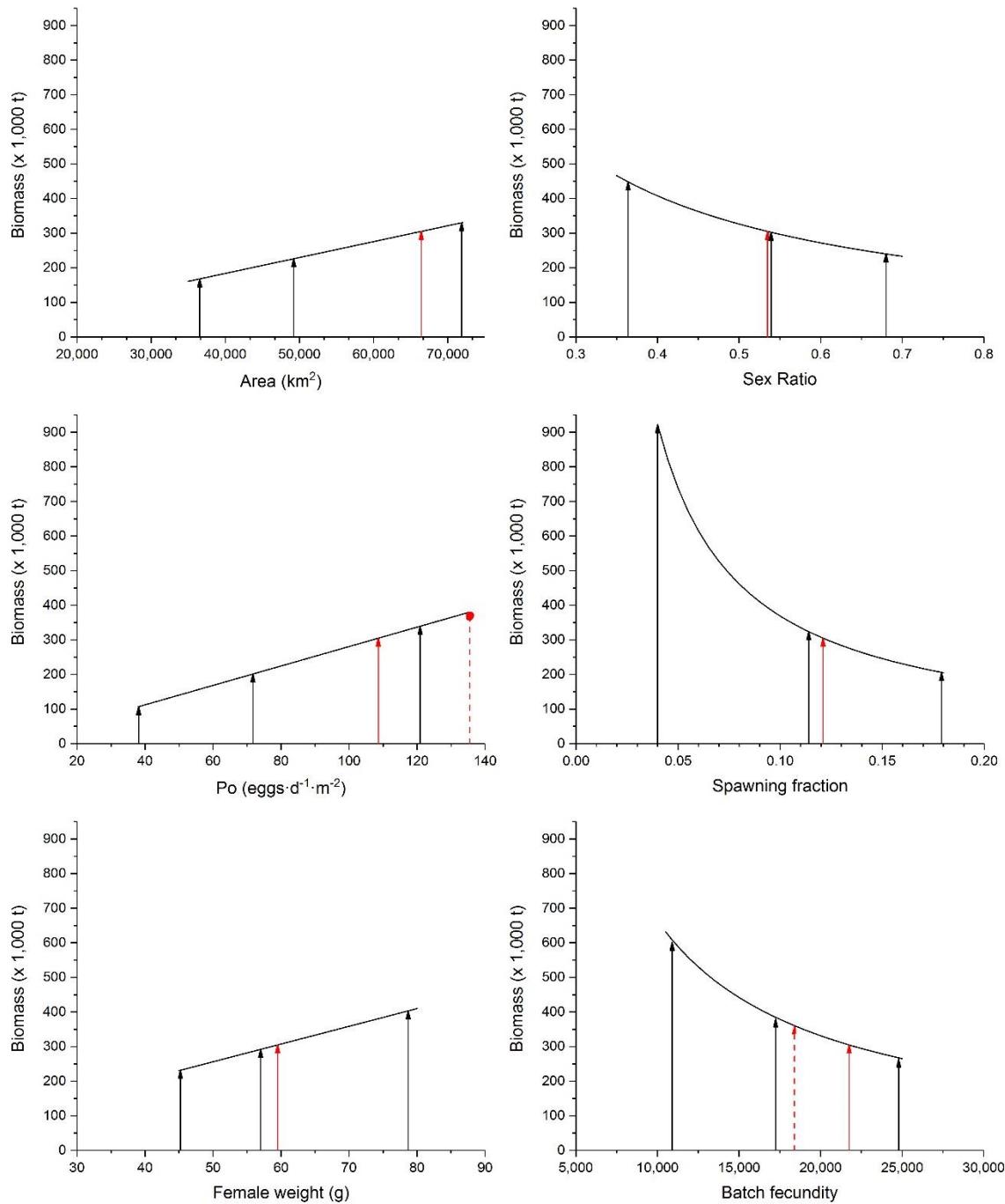


Figure 9. Sensitivity plots showing where 2017 parameter estimates (red arrow) are in comparison to the range of values recorded between 1998 and 2016 (2005 and 2016 for spawning area) and their influence on estimates of spawning biomass. Black arrows are the minimum, mean and maximum values for 1998–2016. Note that the influence of each 2017 estimate on spawning biomass was tested using all other 2017 parameters. Dashed red arrows indicate alternate models for egg production and all-years regression for batch fecundity estimation.

3.7. Spawning Biomass

The estimate of spawning biomass calculated using the log-linear model and all other parameters estimated in 2017 was 305,086 t (95% CI = 176,973–521,285).

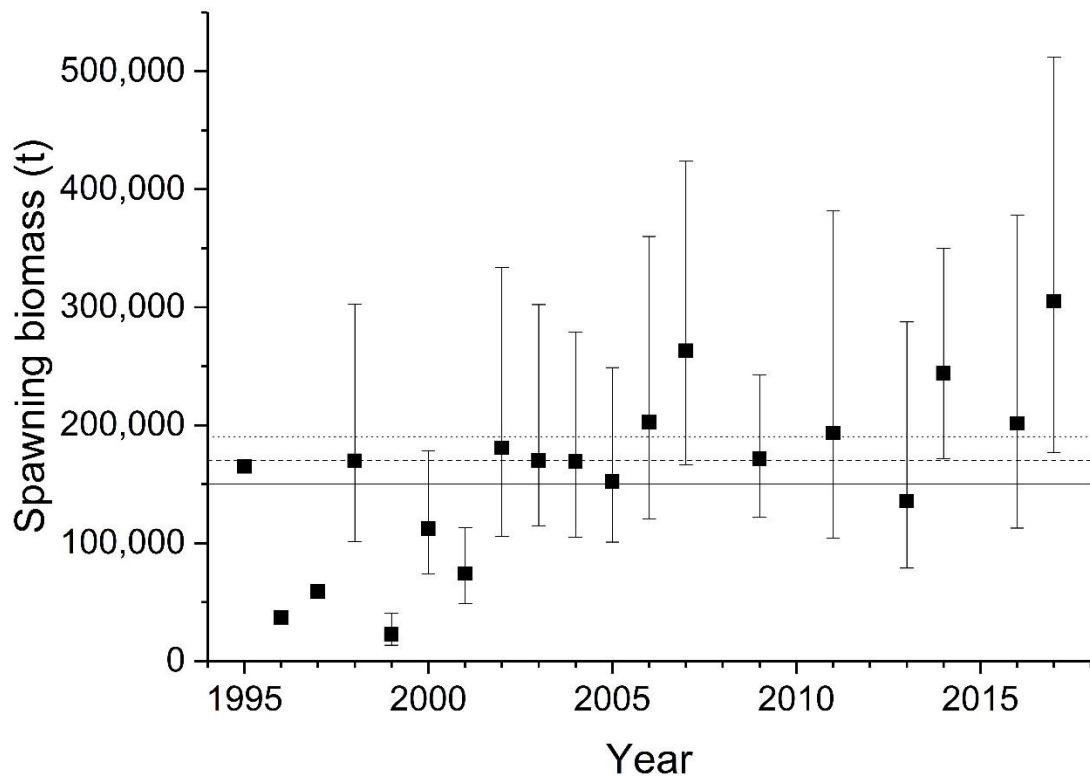


Figure 10. Spawning biomass estimates for Sardine in South Australian waters from 1995 to 2017 using the log-linear egg production model. Error bars are 95% confidence intervals. The horizontal lines indicate the 150,000 (solid), 170,000 (dashed) and 190,000 t (dotted) reference points in the harvest strategy (PIRSA 2014).

4. DISCUSSION

4.1. Biophysical Variables and Egg Distribution

Although patterns of sea surface temperature (SST) and fluorescence are consistent with seasonal upwelling in the eastern GAB during late summer (see McClatchie *et al.* 2006), the intensity was relatively weak. For example, in previous years the SST in inshore waters between Point Sir Isaac and Anxious Bay has often been below 15°C (e.g. Ward *et al.* 2016), whereas in 2017 the lowest SST recorded was 16.8°C. Similarly, there was no indication of elevated fluorescence along the western Eyre Peninsula, with only a few sites exhibiting values comparable to the gulfs and the Head of Bight.

Plankton samples collected in 2017 contained 4,658 live sardine eggs from 181 of 343 samples, the second highest on record after 2014 when 7,955 live eggs were collected. However, the 2014 count was driven largely by a single site containing 3,582 eggs, whereas the highest count for a site in 2017 was 441 eggs.

Eggs were distributed over almost the entire continental shelf in the eastern GAB, from Point Sir Isaac to the Head of Bight and from inshore, out to the shelf break. A relatively small area with high egg densities was also recorded in southern Spencer Gulf and off the north-west coast of Kangaroo Island. The broad distribution of eggs in the eastern GAB and the contraction in the gulfs has been a consistent pattern in recent surveys (e.g. Ward *et al.* 2016).

4.2. Spawning Area

The estimate of spawning area in 2017 of 66,408 km² was the second highest on record after the estimate of 71,859 km² for 2014. The high proportion of the spawning area occurring west of Cape Carnot continues the trend observed over the last decade (e.g. Ward *et al.* 2016).

4.3. Egg Production

The estimate of egg production (P_0) obtained in 2017 using the log-linear model of 108.6 eggs.day⁻¹.m⁻² is in the upper range of estimates recorded in South Australian DEPM surveys. The other models considered produced higher estimates in the range of ~133–138 eggs.day⁻¹.m⁻². The use of the log-linear model was recommended by Ward *et al.* (2011) as it is less influenced by extreme values than the other models.

4.4. Adult Sampling

During the 2017 DEPM survey, seven samples comprising 1005 adult sardine were collected from three locations, namely: Scotts Cove, Greenly Island and Waldegrave Island. Samples obtained from Wedge, Neptune and Pearson Islands contained few or no fish. No adult samples were collected west of Waldegrave Island or from shelf waters of the GAB where the majority of the eggs occurred, but gill-nets do not work effectively due to the exposed nature of shelf waters.

4.5. Spawning Biomass

The estimate of spawning biomass for 2017 of 305,086 t (95% CI 176,923–521,285) is the highest estimated from DEPM surveys for Sardine off South Australian, and above the upper reference point of 190,000 t (PIRSA 2014). The high estimate of spawning biomass combined with the large spawning area provides unequivocal evidence that the southern Australian stock of Sardine is **Sustainable**. Options for addressing the low precision of estimates of spawning biomass are addressed in the 2017 stock assessment report for the South Australian Sardine Fishery (Ward *et al.* in review).

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