Spawning biomass of Australian sardine *Sardinops sagax* in gulf and shelf waters of South Australia in 2006

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PREFACE

The daily egg production method (DEPM) has been used to assess the status of the adult stock of Australian sardine (pilchard, *Sardinops sagax*) in South Australian waters since 1995 (Rogers and Ward 2006). The annual estimate of spawning biomass is a performance indicator for decision rules that are outlined in the Management Plan for the fishery (Shanks 2005), and which are used to set the Total Allowable Catch. This report provides an estimate of the spawning biomass of Australian sardine in shelf and gulf waters of South Australia during February and March 2006.

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EXECUTIVE SUMMARY

1. This report provides estimates of the spawning biomass of Australian sardine (pilchard, *Sardinops sagax*) in gulf and shelf waters of South Australia during 2006.

2. Estimates of spawning biomass were obtained from data collected from surveys conducted on *RV Ngerin* in February and March 2006. The total survey area was ~114,490 km^2.

3. Sea surface temperatures ranged from 15.4 to 21.9 °C and were lowest off Coffin Bay Peninsula, which reflects strong upwelling during the surveys.

4. Estimates of adult reproductive parameters (95% CI) were: mean female weight, W = 57.2 g (*50.86-65.16*); mean sex ratio, R = 0.64 (*0.55–0.77*); mean spawning fraction, S = 0.13 (*0.09–0.16*) and mean batch fecundity, F = 14,290 (*11,013–17,580*) hydrated oocytes.

5. A total of 3,083 eggs were collected from 341 stations. High densities (254–5,126 eggs.m^{-2}) were recorded in southern Spencer Gulf, Investigator Strait, and west of Anxious Bay. Few eggs were found south of the Eyre Peninsula between Cape Catastrophe and Cape Finnis, and there were distinct eastern and western spawning areas.

6. The total spawning area of 44,891 km^2 was the highest recorded and was comprised of an eastern spawning area of 10,936 km^2 and a western spawning area of 33,954 km^2.

7. The proportion of eggs collected from the region east of Coffin Bay declined between 2004 and 2005 and increased slightly in 2006.

8. Daily egg production, P (95% CI), for the entire spawning area was 104.7 eggs.day^{-1}. m^{-2} (*67.95–158.44*).

9. The estimate of spawning biomass (95% CI) for the entire spawning area was 226,088 t (*136,060–417,612*). Estimates of spawning biomass for the eastern and western spawning areas were 55,079 t (*25,406–134,141*) and 171,009 t (*86,360–299,656*), respectively.

10. The large proportion of the spawning biomass located in the western spawning area highlights the large disparity between the historical distribution of fishing effort and the distribution of the spawning stock in 2006.

1. INTRODUCTION

1.1 South Australian Sardine Fishery

The South Australian Sardine Fishery (SASF) was established in 1991 to supply fodder for the grow-out of southern bluefin tuna (*Thunnus maccoyii*) captured by purse seine vessels in the Great Australian Bight and ranched in sea-cages off Port Lincoln. Most sardines are taken from southern Spencer Gulf. Catches increased from 3,241 t in 1994 to 42,475 t in 2005, based on annual assessments of the adult biomass provided by SARDI Aquatic Sciences since 1995 (Rogers and Ward 2006). The gross value of production for the fishery in 2005 was ~A$21M.

The conservative approach to management of the fishery that has been established by PIRSA Fisheries has allowed both rapid growth of the industry and rapid recovery of the stock from mass mortality events in 1995 and 1998, that each killed >70% of the adult population (Ward *et al.* 2001; Rogers and Ward 2006). Between 2002 and 2005 spawning biomass remained relatively stable, ranging from ~160,000 to 196,000 t (Rogers and Ward 2006).

1.2 Management

The SASF is managed by PIRSA Fisheries in accordance with the *Fisheries (General) Regulations 2000* and the *Fisheries* (*Scheme of Management – Marine Scalefish Fisheries*) *Regulations 1991* under the *Fisheries Management Act* 2006. Goals, objectives and fishery management strategies are outlined in the *Management Plan* for the fishery (Shanks 2005).

Annual estimates of spawning biomass are the key performance indicator (PI) for the SASF and provide the basis for setting the total allowable catch (TAC) for the following year (Shanks 2005). Annual TACs are set at between 10 and 17.5% of spawning biomass, based on the size of the spawning biomass and the relative strength of two and three year old age classes in catch samples (Rogers and Ward 2006). The TAC for 2006 was set at 25,463 t, or 15% of the best estimate of spawning biomass of 169,750 t (Ward *et al.* 2005a). The decision rules for the fishery are currently being reviewed (see Rogers and Ward 2006).

1.3 Daily Egg Production Method

The Daily Egg Production Method (DEPM) was developed to estimate the spawning biomass of northern anchovy (*Engraulis mordax*) and can be applied to pelagic fishes, such as *S. sagax*, that produce multiple batches of pelagic eggs during an extended spawning season (Parker 1985). This method is used to assess the spawning biomass of *S. sagax* in California (Lo and Macewicz 2004) and South Africa (van der Lingen and Huggett (2003). The application of the DEPM relies on the premise that spawning biomass can be calculated from the abundance of pelagic eggs produced per day in the spawning area (daily egg production) and the number of eggs produced per unit mass of population (daily fecundity). Spawning biomass (*B*) is calculated according to equation 1:

$$B = \frac{P \cdot A \cdot W}{R \cdot F \cdot S} \qquad \text{…….. Eq. 1}$$

where *P* is mean daily egg production per unit area, *A* is the spawning area, *W* is the mean weight of mature females, *R* is the sex ratio (proportion of females by weight), *F* is the mean batch fecundity (number of oocytes in a batch) and *S* is the mean spawning fraction (proportion of mature females that spawn each night) (Lasker 1985; Parker 1985; Alheit 1993).

1.4 Aim and Objectives

This report provides the assessment of spawning biomass for 2006 that will provide the scientific basis for establishing the TAC for the SASF in 2007. The four objectives of the report are:

1. To describe the patterns of distribution and abundance of *S. sagax* eggs in South Australian waters during the 2006 spawning season;
2. To estimate the spawning area (*A*) and mean daily rate of egg production (*P*);
3. To estimate the adult reproductive parameters (*W*, *R*, *F*, *S*);
4. To use the DEPM to estimate the spawning biomass of *S. sagax* in gulf and shelf waters of South Australia during 2006.

A review by Smith and Smith (2006) confirmed the suitability of the DEPM for assessing the status of *S. sagax* in South Australia and suggested options for refining the approach taken in previous years (Rogers and Ward 2006). Where possible, these suggestions have been adopted in the formulation of this report.

2. METHODS

2.1 Study Area and Environmental Variables

2.1.1 Study area

Two surveys were conducted from *RV Ngerin* in shelf and gulf waters of South Australia during February and March 2006. Plankton samples were collected at 341 stations on 34 transects between Victor Harbor and Head of Bight (Fig. 1). In response to recommendations of Smith and Smith (2006), 15 stations where no eggs were collected between 1998 and 2005, were not sampled in 2006. To provide additional information on egg abundance in the main fishing area, four new transects comprising 22 stations were sampled in Spencer Gulf (SGAB1-SGAB8, SGBC1-SGBC8 and SGD1-SGD4, Fig. 2).

2.1.2. Water temperature and primary production

At each station (Fig. 1), a vertical temperature profile was obtained by lowering a *Sea-Bird* Conductivity-Temperature-Depth (CTD) instrument to a depth of 70 metres, or to 10 metres from the bottom in waters less than 80 m deep. Sea surface temperatures (SST) and salinity data were extracted from each profile at a depth of 3 m. Temperature-salinity-egg abundance (TSE) plots were prepared using classed-post maps in Surfer™ Version 8. Samples of surface water (<3 m) were collected at each station and filtered using a Millipore filtration system with GFC filters. The filters and residue were dissolved in methanol and placed in the dark for 24 hours. Fluorescence was then measured using a Sequonia-Turner fluorometer (Model 450) with wavelengths of 665 and 750 *nm*. Fluorescence is an indicator of primary productivity. The concentration of chlorophyll-*a* in each sample was calculated according to the method of Parsons *et al.* (1984).

2.1.3. Zooplankton abundance - secondary production

An index of zooplankton abundance at each station was estimated by dividing the volume of zooplankton (ml) collected during plankton tows by the total volume of water filtered (m^3) by the nets. The large fraction (±1 mm) of zooplankton samples that was mostly gelatinous taxa (salps, scyphozoans) and krill *Nyctiphanes australis*, and the small fraction (< 1 mm) that was mostly copepods, cladocerans and 'other' small zooplankton taxa, were analysed separately. Contour maps of SST, extracted chlorophyll-*a* and zooplankton abundance were prepared using minimum curvature algorithms in Surfer™.

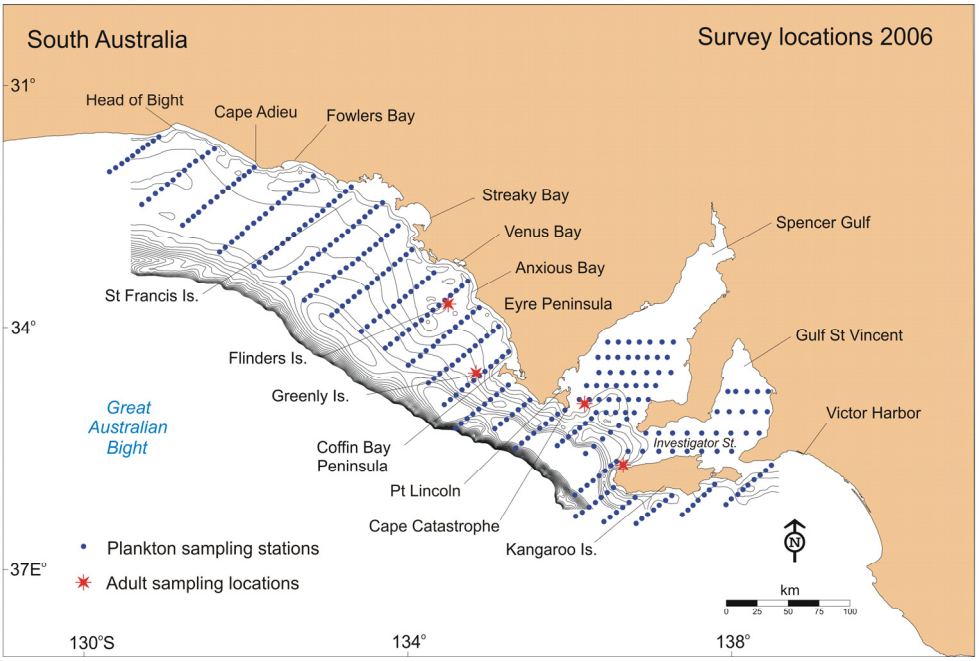

Figure 1. Map of South Australia showing locations where plankton and adult samples were collected during the 2006 DEPM surveys.

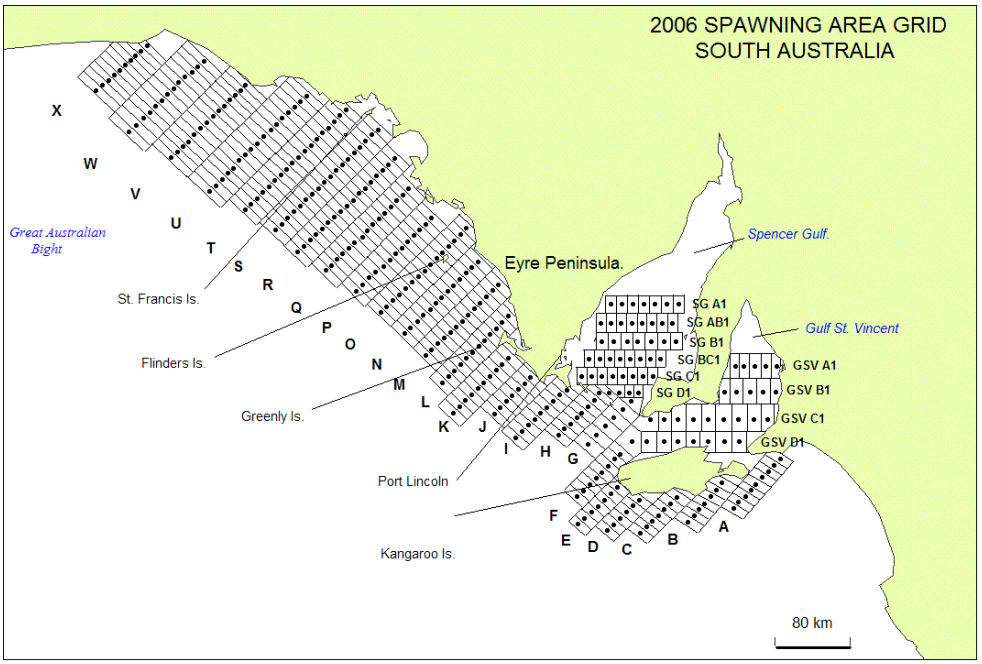

Figure 2. Location of plankton stations and the areas surrounding each station used to estimate the total spawning area in 2006.

2.2 Daily Egg Production and Spawning Area

2.2.1. Plankton sampling

Plankton samples were collected at each station using Californian Vertical Egg Tow (CalVET) plankton nets. CalVET nets had an internal diameter of 0.3 m, 330 μm mesh and plastic cod-ends. During each tow the CalVET net was deployed to within 10 m of the seabed at depths <80 m or to a depth of 70 m at depths >80 m. The net was retrieved vertically at a speed of~1 $m.s^{-1}$. General Oceanics™ 2030 flow-meters and factory calibration coefficients were used to estimate the distance travelled by the net during each tow. Upon retrieval of the net following each tow, the samples from each of the two cod-ends were washed into two sample containers. Plankton samples were fixed using 5% buffered formaldehyde and seawater.

2.2.2 Laboratory analysis

S. sagax eggs and larvae were identified in each sample using published descriptions by White and Fletcher (1996) and Neira *et al.* (1998). Eggs in each sample were staged, assigned approximate ages and counted according to descriptions and temperature-development keys in White and Fletcher (1996). Yolk-sac larvae (≤5 mm, body length, BL) were classified as those that had a visible yolk-sac or those that showed evidence of having one prior to the net wash-down procedure.

2.2.3. Egg density

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

$$P_t = \frac{C.D}{V} \qquad \text{…… Eq. 2}$$

where C is the number of eggs 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 MapInfo Professional Ver.8 GIS software.

To assess the changes in the patterns of egg abundance by region over time, the proportions of eggs east and west of Coffin Bay (transect L) at uniform stations were calculated for each year between 2000 and 2006. However, bad weather prevented four transects (44 stations) in the central GAB from being sampled in 2004. To compensate for this, the mean number of eggs sampled from the same stations in all other years was added to the 2004 total.

2.2.4 Spawning time and density weightings

A previous study showed that peak spawning time of *S. sagax* in South Australia was ~0200 hours (e.g. Ward *et al.* 2001). Ages were assigned to day-1 eggs (i.e. stages 0–24 hours old) by subtracting the estimated spawning time from the sampling time. Ages of day-2 eggs were assigned using the same approach, but an additional 24 hours was added to their ages. 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

After the cruises were completed, the survey area was divided into a series of contiguous grids approximately centred on each sampling station (Fig. 2). The area represented by each station (km^2) was calculated using MAPINFO® software. The spawning area (A) was defined as the total area of grids where live, Stage 1–8 (0–24 hour old) *S. sagax* eggs were found. We estimated the spawning area for the entire survey area and separately for the areas east and west of Coffin Bay Peninsula (transect L, Fig. 2).

2.2.6 Daily egg production and egg mortality

Biased 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 station (Picquelle and Stauffer 1985). The linear version of the exponential egg mortality model is:

$$lnP_b = \ln(P_i) - Zt \qquad \text{……. Eq. 4}$$

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 mean egg production (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) to provide an unbiased estimate of mean daily egg production (P):

$$P = e^{(\ln P_b + \sigma^2/2)} \quad \text{……Eq. 5}$$

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, locations where *S. sagax* schools were known to aggregate were searched using a dual frequency echo sounder (*Furuno* - 60 and 180 KHz). Once several schools were located, *RV Ngerin* was anchored and a gillnet was set. This net comprised 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 (500 W) were illuminated near the net to attract fish. Net soak times varied from 15 minutes to 3 hours depending on the number of fish caught per shot. After the net was retrieved, fish were removed and dissected immediately with each shot comprising a single sample. Mature and immature males and females were counted. Mature females were fixed in 5% buffered formaldehyde solution. Immature females and males were frozen. Female weight, sex ratio, batch fecundity and spawning fraction were based on samples collected from Scotts Cove in Investigator Strait, Thistle Island in southern Spencer Gulf and Flinders Island in the eastern GAB.

2.3.2 Female weight

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:

$$W = \overline{\left[\overline{W}_i * \frac{n_i}{N} \right]} \quad \text{….. Eq. 6}$$

where $\overline{W_i}$ 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

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

$$R = \overline{\left[\overline{R_i} * \frac{n_i}{N} \right]} \qquad \text{…… Eq. 7}$$

where *n* is the number of fish in each sample, *N* is the total number of fish collected in all samples and $\overline{R_i}$ is the mean sex ratio of each sample calculated from the equation:

$$\overline{R_i} = \frac{F}{(F+M)} \qquad \text{….. Eq. 8}$$

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

2.3.5 Batch fecundity

Batch fecundity was estimated from ovaries containing hydrated oocytes using the methods of Hunter *et al.* (1985). Both ovaries were dissected, weighed and the number of hydrated oocytes in three ovarian sub-sections were counted and weighed. 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 was used to estimate the batch fecundities of mature females in all samples.

2.3.6 Spawning fraction

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 0-24 hrs old), day-1 POFs (*d*1, 24-48 hrs old) and day-2 POFs (*d*2, 48+ hrs old). The mean spawning fraction was then calculated from the average of sample means weighted by sample size.

$$S = \overline{\left[\overline{S_i} * \frac{n_i}{N} \right]} \qquad \ldots\ldots \text{Eq. 9}$$

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

$$\overline{S_i} = \frac{[(d0 + d1 + d2POFs)/3]}{n_i} \qquad \ldots\ldots \text{Eq. 10}$$

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. Re-sampling: bootstrapping procedures

The 95% confidence intervals (CI) for the mean estimates of each parameter were calculated using 'bootstrap replacement' procedures and the percentile method. (Bracketed italicised ranges following all estimates are 95% CI). Bootstrap routines were run using Visual Basic in Excel. Each parameter was estimated 10,000 times by randomly reselecting individuals from randomly selected samples. A balanced bootstrap design was employed (i.e. the number of samples and sample sizes reselected in each recalculation were the same as those in the original datasets).

2.5. Spawning Biomass

Spawning biomass was calculated using the estimates of each parameter (Eq. 1). The 95% CI of spawning biomass were estimated using the percentile method and by calculating the spawning biomass 10,000 times using the 10,000 bootstrapped estimates of each parameter.

3. RESULTS

3.1. Environmental Variables

3.1.1. Sea surface temperature

Sea surface temperatures (SST) ranged from to 15.4 to 21.9^{o}C (Fig. 3). Low SSTs were recorded along the southern coast of Eyre Peninsula near Coffin Bay Peninsula, Avoid Bay and around the western tip of Kangaroo Island. High SSTs (> 19^{o}C) were recorded in central Spencer Gulf, Gulf St Vincent and across the mid-outer shelf waters of the eastern and central GAB. Sardine-egg presence-absence data are shown on all spatial plots of environmental parameters.

3.1.2. Extracted chlorophyll-a – primary production

Chlorophyll-*a* measured at each station ranged between 0 and 3.3 μg.L^{-1} (Fig. 4). The highest values were recorded in Avoid Bay off Coffin Bay Peninsula (3.3 μg.L^{-1}) near Fowlers Bay and Cape Adieu (1.4 μg.L^{-1}). Relatively high chlorophyll-*a* concentrations were also recorded SSW of Cape Catastrophe. The remainder of coastal and shelf waters mostly had chlorophyll-*a* concentrations ranging between 0.2 and 1 μg.L^{-1}.

3.1.3. Zooplankton abundance – secondary production

Total zooplankton densities for each station ranged from 0.36 to 46.05 ml per m^{3}. Total small fraction densities ranged between 0.18 and 13.01 ml per m^{3} (Fig. 5). Large fraction densities ranged between 0 and 37.2 ml per m^{3} and were recorded south-west of Kangaroo Island (Fig. 6). The patch of large zooplankton taxa observed south-west of Kangaroo Island, were mostly salps and krill (*N. australis*). Highest densities of small zooplankton taxa were found in Spencer Gulf, Investigator Strait, south-east of Kangaroo Island and west of Fowlers Bay.

3.2. Distribution and Abundance of Eggs and Yolk-sac Larvae

3.2.1. Distribution and abundance of eggs

A total of 3,083 *S. sagax* eggs were collected at 135 of 341 (39.6%) stations on 34 transects between the Head of Bight and Victor Harbor (Fig. 7). Densities ranged between 0 and 5,126 eggs. m^{-2}. The stations with the highest egg densities offshore from Streaky Bay. The TSE plot (Fig. 8) shows that

the highest densities of eggs were found in waters between 17.5 and 21.5 °C, at salinities of 35.75 and 37.25 ppt. No eggs were collected at water temperatures <17°C.

3.2.2. Yolk-sac larval abundance and distribution

A total of 1,372 *S. sagax* yolk-sac larvae were collected at 39% of stations sampled between Head of Bight and Victor Harbor (Fig. 9). Densities ranged between 0 and 372 larvae.m^{-2}, and were highest west of Venus Bay, in Spencer Gulf and Investigator Strait and south-east of Kangaroo Island. Spatial distributions of yolk-sac larvae (Fig. 9) were similar to eggs (Fig. 7).

3.3. Spawning Area

The estimated spawning area was 44,891 km^2, and comprised 39.2% of the total area sampled (114,490 km^2). Spawning area estimates for the eastern (east of Coffin Bay, transect L) and western (west of Coffin Bay) regions were 10,626 and 33,954 km^2, respectively.

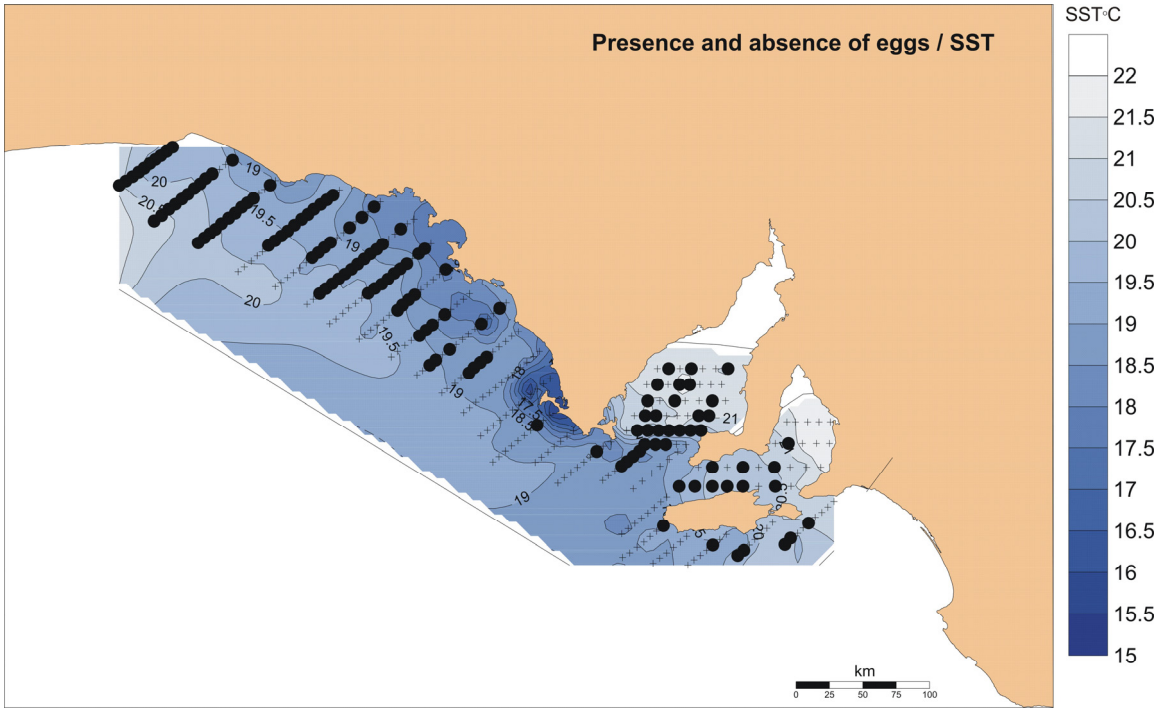

Figure 3. *S. sagax* egg distribution (black dots) and sea-surface temperature (°C) in 2006.

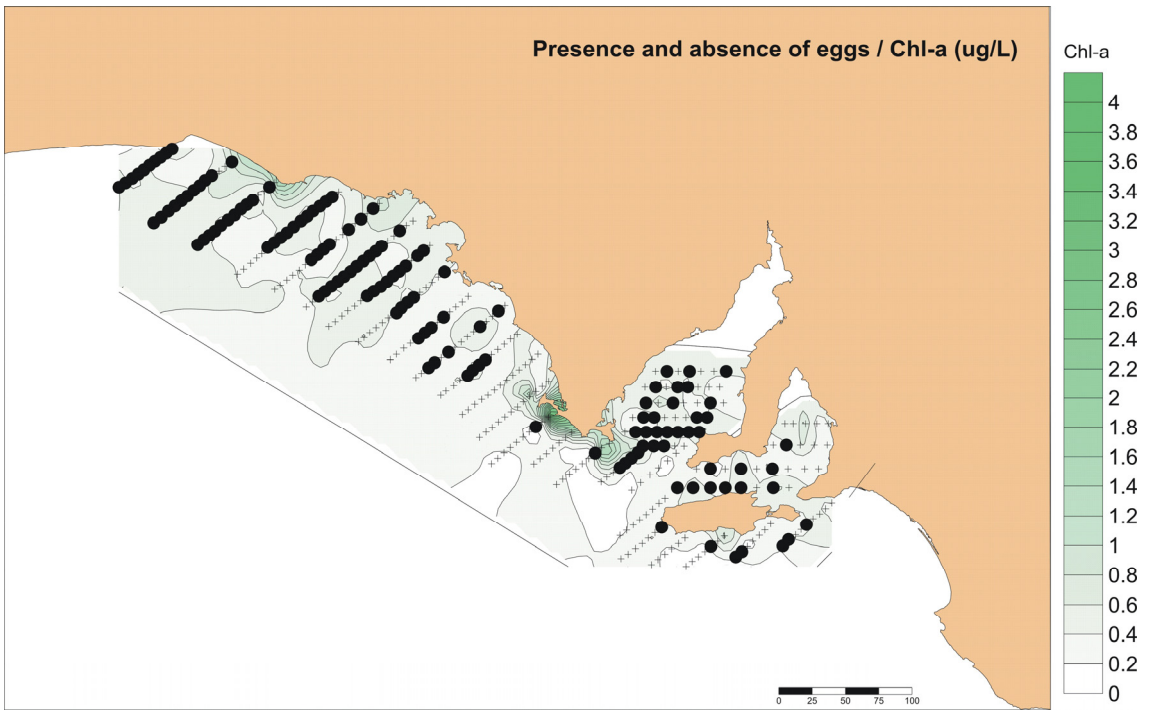

Figure 4. *S. sagax* egg distribution (black dots) and chlorophyll-*a* concentration (µg.L^{-1}) in 2006.

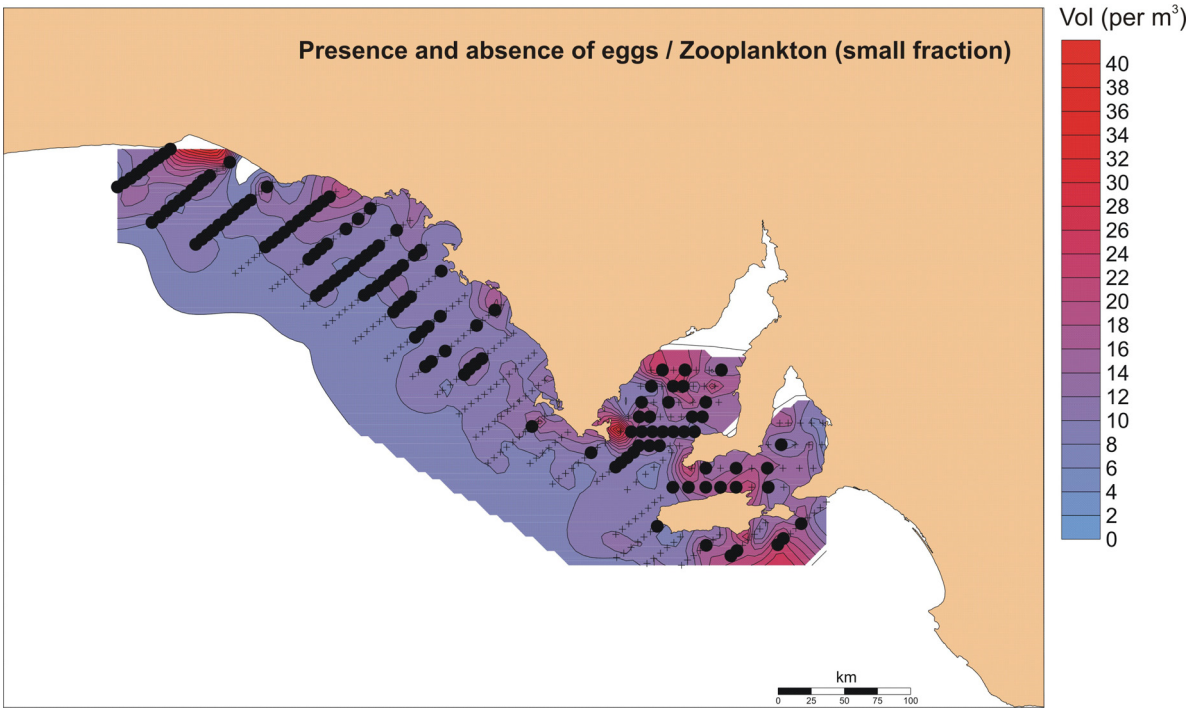

Figure 5. *S. sagax* egg distribution (black dots) and zooplankton (small fraction) distribution and abundance (ml per m^3) in 2006.

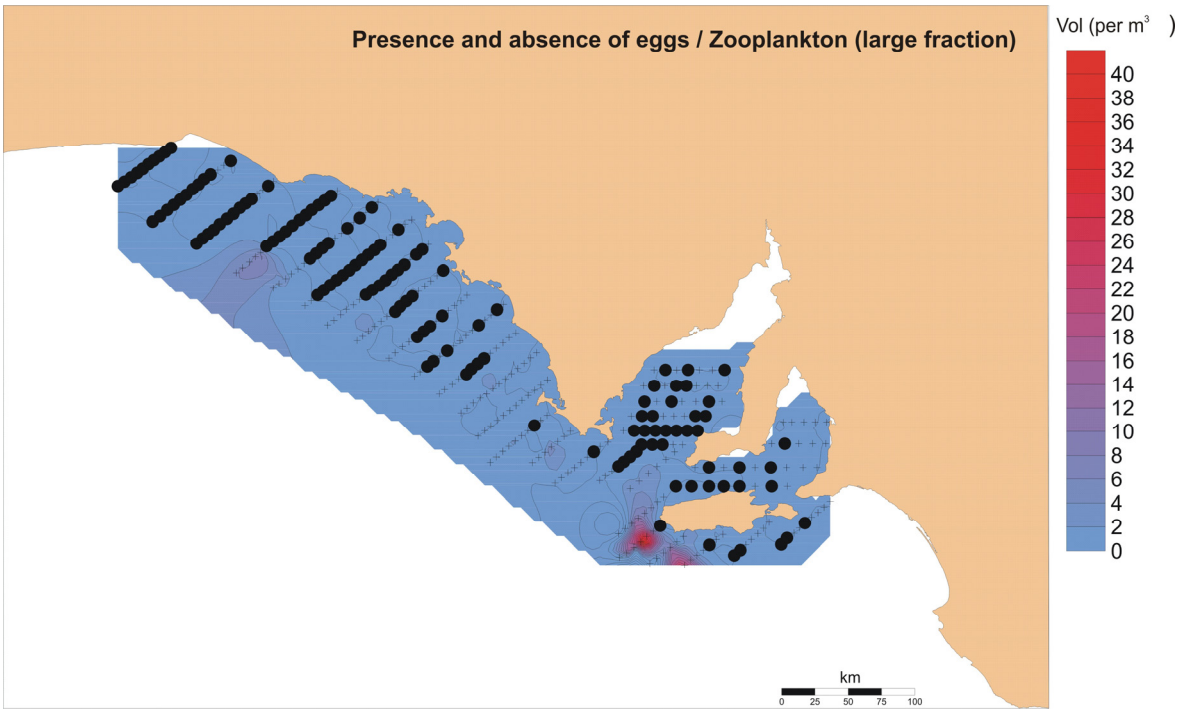

Figure 6. *S. sagax* egg distribution (black dots) and zooplankton (large fraction) distribution and abundance (ml per m^3) in 2006.

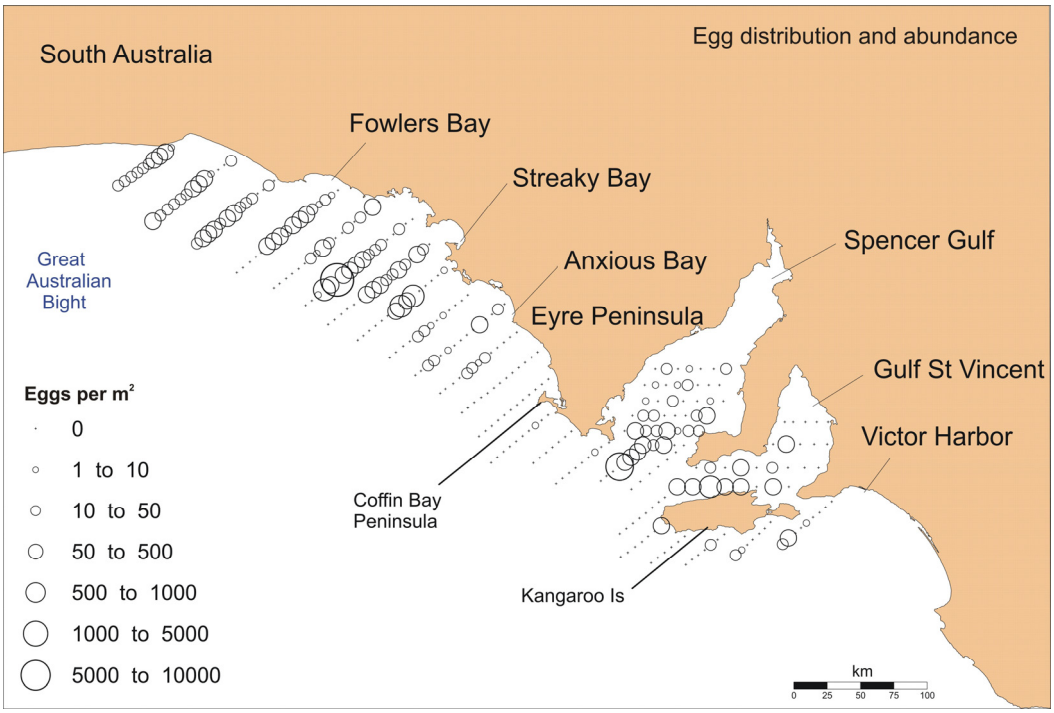

Figure 7. *S. sagax* egg distribution and abundance in 2006.

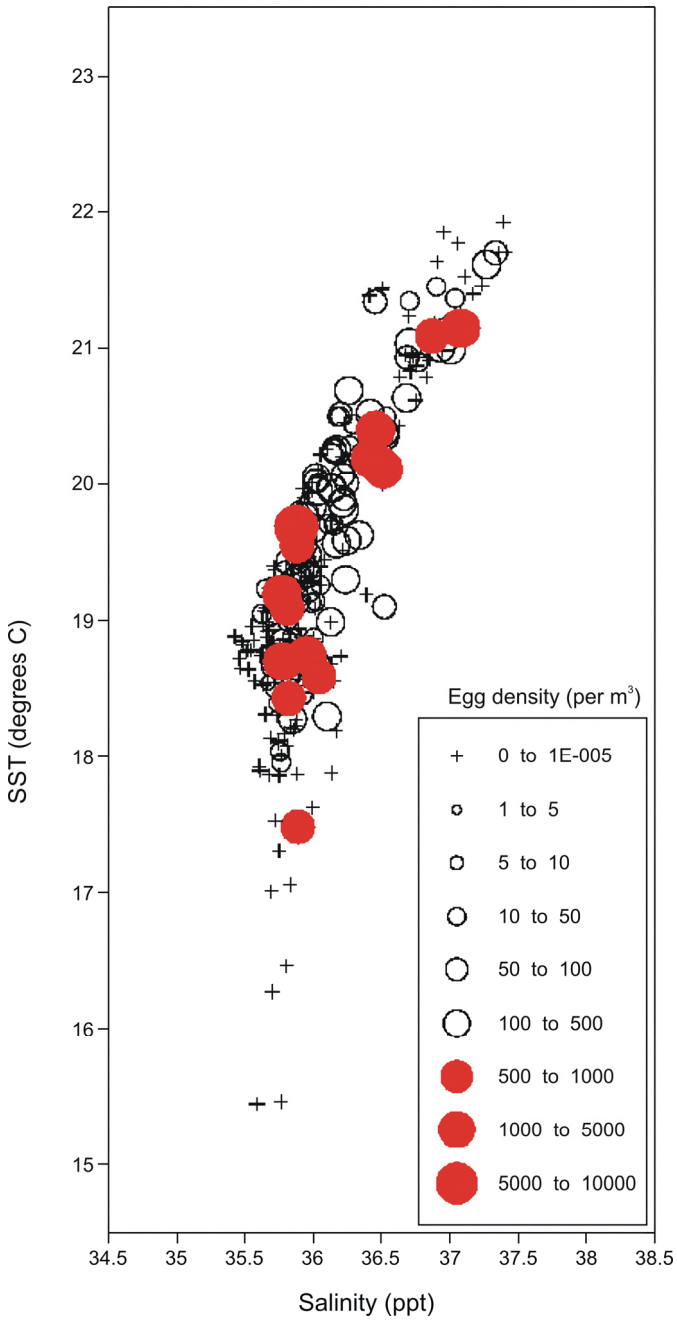

Figure 8. Relationship between *S. sagax* egg density, sea-surface temperature and salinity in 2006. Red dots highlight the highest densities.

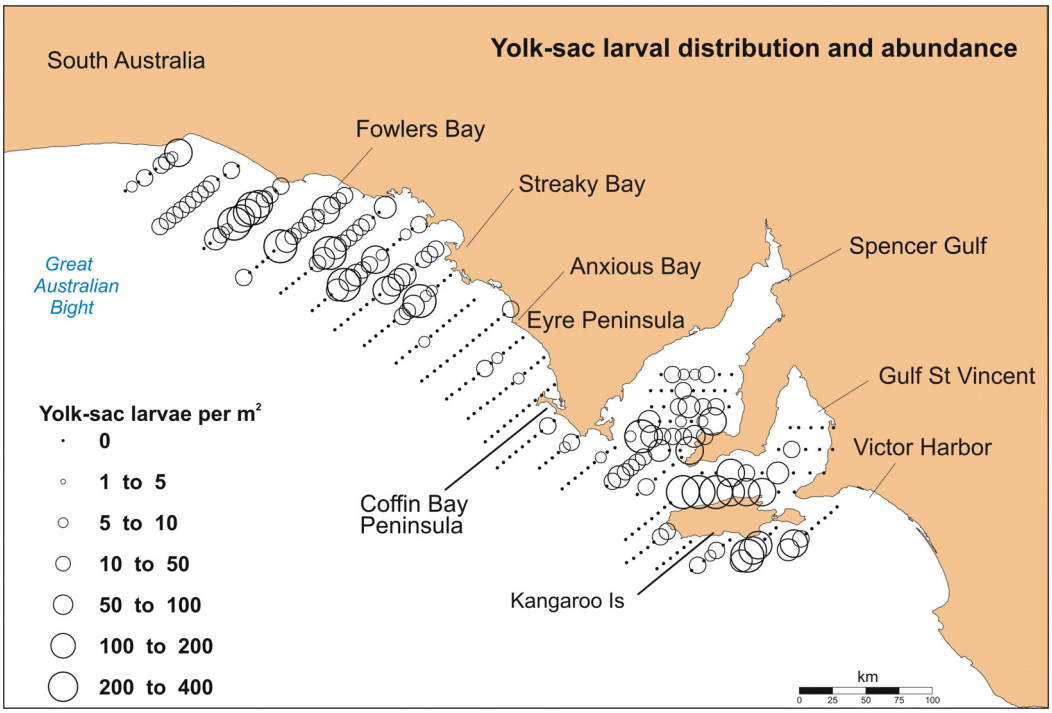

Figure 9. *S. sagax* yolk-sac larval distribution and abundance in 2006.

3.4. Daily Egg Production (*P*)

The estimate of *P* for the entire survey area was 104.70 eggs.day^{-1}.m^{-2} (*67.95–158.44*). The estimate of mean egg mortality (*Z*) was 0.32 (Fig. 10). The daily egg production estimate, its associated variance (σ^2) term, total area sampled, spawning area estimates by region and spawning area as a proportion of the total area sampled over the entire survey and in each region is shown in Table 1.

Table 1. Area sampled, spawning area (*A*), spawning area as a proportion of the total area sampled over the entire survey and in the regions east and west of Coffin Bay. Table shows variance (σ^2) term used in the estimate of *P* estimate. CB = Coffin Bay.

Region	Area sampled	*A* (km ^{2})	*A*/ Area sampled	$\sigma^2 P_b$	*P* (eggs.d^{-1}.m^{-2})
Total survey	114,490	44,890.5	0.39	1.83	104.70
East of CB	36,618	10,626.3	0.29		
West of CB	77,872	34,264.2	0.44		

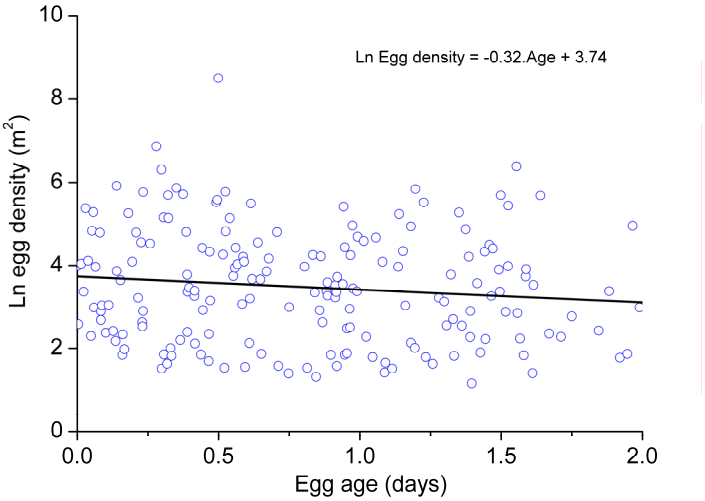

Figure 10. Linear regression of ln-transformed *S. sagax* egg density and age in 2006.

3.5. Adult Reproductive Parameters

A total of 19 samples comprising 2,433 mature *S. sagax* were collected at four locations throughout the 2006 survey area (Table 2). A total of eight samples containing 447 adult fish obtained from Greenly Island were omitted from the analysis as limited spawning was occurring in this region. Estimates of adult reproductive parameters calculated from the 11 remaining samples (Table 2) were used to estimate spawning biomass across the entire survey and in each region.

3.5.1. Mean female weight

The mean weight of mature females in samples ranged from 45.0 to 93.9 g (Table 3). The weighted mean weight of mature females was 57.2 g (*50.86–65.16*).

3.5.2. Sex ratio

The sex ratio of samples ranged from 0.44 to 0.89 (Table 3). The weighted mean sex ratio was 0.64 (*0.55–0.77*).

3.5.3. Batch fecundity

Batch fecundities ranged from 10,271 to 26,521 hydrated oocytes per batch and the weighted mean was 14,289.6 hydrated oocytes per batch (*11,013–17,580*) (Table 4) (Fig. 11).

3.5.4. Spawning fraction

Of the 874 ovaries examined, 92 had hydrated oocytes and/or day-0 POFs, 208 had day-1 POFs and 42 had day-2 POFs (Table 4). The percentage of females in samples with hydrated oocytes and/or day-0 POFs ranged from 0 to 22.6%. The weighted mean spawning fraction was 0.13 (*0.09–0.16*).

Distribution of bootstrapped parameter estimates (*P*, *W*, *R*, *S*, *F*) are shown in Fig. 12.

Table 2. Collection details for *S. sagax* obtained from Investigator Strait and in the eastern GAB during the 2006 surveys.

Date	Location	Survey	*N* samples	*n* fish
23/02/06	Kangaroo Is.	1	2	105
02/03/06	Greenly Is.	1	1	97
02/03/06	Flinders Is.	1	2	193
03/03/06	Flinders Is.	1	3	650
05/03/06	Greenly Is.	1	1	73
06/03/06	Greenly Is.	1	2	209
06/03/06	Thistle Is.	1	1	76
07/03/06	Thistle Is.	1	3	441
26/03/2006	Greenly Is.	2	1	51
27/03/2006	Greenly Is.	2	3	538
		Total	**19**	**2,433**

Table 3. Number of *S. sagax* in individual samples and estimates of female weight (*W*) and sex ratio *(R)* (proportion of females (♀) by weight) for samples collected in 2006. Values in bottom row are sums (*) and weighted means (#) for samples excluding Greenly Island**. Inputs of DEPM are highlighted in bold. Wting = weighting.

Sample	Date	Survey	Location	*n* fish	*n* ♂	*n* ♀	*Wting R*	♂ *W* (g) $(\overline{x})$	♀ *W* (g) $(\overline{x})$	*Wting* ♀*wt*	Wted $(\overline{x})$ ♀ wt (g)	Wt ♂ (g) (Σ)	Wt ♀ (g) (Σ)	*R*	Wted *R*
1	23/02/06	1	Kangaroo Is.	45	8	37	0.35	59.6	73.1	0.53	38.6	476.5	2,704.8	0.85	0.30
2	23/02/06	1	Kangaroo Is.	60	11	49	0.47	54.2	71.9	0.70	50.3	595.7	3,523.3	0.86	0.40
**3	02/03/06	1	Greenly Is.	97	42	55	0.76	60.8	93.9	0.79	73.8	2552.5	5,162.5	0.67	0.51
4	02/03/06	1	Flinders Is.	152	67	85	1.19	48.8	56.7	1.21	68.9	3270	4,820.6	0.60	0.71
5	02/03/06	1	Flinders Is.	41	15	26	0.32	41.5	61.6	0.37	22.9	621.8	1,602.4	0.72	0.23
6	03/03/06	1	Flinders Is.	154	90	64	1.20	48.7	65.3	0.91	59.7	4386.9	4,178.6	0.49	0.59
7	03/03/06	1	Flinders Is.	282	170	112	2.20	53.2	67.4	1.60	107.9	9048.7	7,551.8	0.45	1.00
8	03/03/06	1	Flinders Is.	214	119	95	1.67	56.4	72.2	1.36	97.9	6705.7	6,856.3	0.51	0.84
**9	05/03/06	1	Greenly Is.	73	27	46	0.57	62.2	93.4	0.66	61.4	1680.4	4,298.5	0.72	0.41
**10	06/03/06	1	Greenly Is.	107	65	42	0.84	52.2	81.6	0.60	49.0	3390.3	3,426.7	0.50	0.42
**11	06/03/06	1	Greenly Is.	102	47	55	0.80	56.8	85.3	0.79	67.0	2669	4,693.1	0.64	0.51
12	06/03/06	1	Thistle Is.	76	9	67	0.59	42.6	46.1	0.96	44.1	383.3	3,087.3	0.89	0.53
13	07/03/06	1	Thistle Is.	76	15	61	0.59	40.2	48.5	0.87	42.3	603.7	2,957.5	0.83	0.49
14	07/03/06	1	Thistle Is.	209	46	163	1.63	41.6	46.6	2.33	108.6	1911.5	7,600.1	0.80	1.30
15	07/03/06	1	Thistle Is.	156	35	121	1.22	40.4	45.0	1.73	77.8	1414	5,443.2	0.79	0.97
**16	26/03/06	2	Greenly Is.	51	28	23	0.40	49.3	52.3	0.33	17.2	1381.6	1,202.2	0.47	0.19
**17	27/03/06	2	Greenly Is.	203	110	93	1.59	57.3	66.8	1.33	88.7	6303.1	6,210.3	0.50	0.79
**18	27/03/06	2	Greenly Is.	38	23	15	0.30	61.9	78.3	0.21	16.8	1423.4	1,174.5	0.45	0.13
**19	27/03/06	2	Greenly Is.	297	176	121	2.32	53.1	61.1	1.73	105.7	9350	7,397.8	0.44	1.02
				1,465*	585*	880*					**57.19#**	29 418*	50 326*	0.71	**0.64#**

Table 4. Number of female *S. sagax* in samples and estimates of spawning fraction, *S* and batch fecundity, *F* for samples collected in 2006. Values in bottom row are sums* and weighted (wted) means# for samples excluding Greenly Island.

Sample	Location	Survey	Date	*n*	*Wting*	Day 0 # (%)	Day 1 # (%)	Day 2 # (%)	*S*	***S* (%)** wted	♀ *W* (g) Ovary removed	♀ *W* (g) Ovary removed wted	*F N* oocytes	F wted
1	Kangaroo Is.	1	23/02/06	37	0.53	0 (0.0)	2 (5.4)	4 (10.8)	5.41	2.88	70.34	37.43	19937.9	10610.4
2	Kangaroo Is.	1	23/02/06	49	0.70	1 (2.0)	2 (4.1)	1 (2.0)	2.72	1.92	69.13	48.72	19510.5	13750.4
**3	Greenly Is.	1	02/03/06	55	0.79	7 (12.7)	8 (14.5)	2 (3.6)	10.30	8.15	88.96	70.37	26520.6	20979.6
4	Flinders Is.	1	02/03/06	85	1.22	15 (17.6)	5 (5.9)	1 (1.2)	8.24	10.07	52.54	64.23	13643.4	16679.8
5	Flinders Is.	1	02/03/06	26	0.37	1 (3.8)	4 (15.4)	1 (3.8)	7.69	2.88	57.77	21.60	15494.8	5794.4
6	Flinders Is.	1	03/03/06	64	0.92	15 (23.4)	8 (12.5)	0 (0.0)	11.98	11.03	61.20	56.33	16706.0	15378.1
7	Flinders Is.	1	03/03/06	112	1.61	19 (17.0)	8 (7.1)	0 (0.0)	8.04	12.94	63.56	102.39	17540.6	28256.2
8	Flinders Is.	1	03/03/06	93	1.34	21 (22.6)	12 (2.9)	2 (2.2)	12.54	16.78	68.88	92.13	19421.0	25977.9
**9	Greenly Is.	1	05/03/06	46	0.66	0 (0.0)	0 (0.0)	0 (0.0)	0.00	0.00	86.46	57.20	25636.4	16961.5
**10	Greenly Is.	1	06/03/06	42	0.60	1 (2.4)	2 (4.8)	0 (0.0)	2.38	1.44	75.62	45.68	21804.4	13171.8
**11	Greenly Is.	1	06/03/06	55	0.79	4 (7.3)	1 (1.8)	1 (1.8)	3.64	2.88	79.82	63.14	23289.3	18423.4
12	Thistle Is.	1	06/03/06	67	0.96	2 (3.0)	29 (43.3)	5 (7.5)	17.91	17.26	44.03	42.43	10634.6	10248.2
13	Thistle Is.	1	07/03/06	60	0.86	0 (0.0)	31 (51.7)	6 (10.0)	20.56	17.74	46.45	40.09	11491.5	9917.0
14	Thistle Is.	1	07/03/06	160	2.30	5 (3.1)	63 (39.4)	14 (8.8)	17.08	39.31	44.85	103.22	10926.3	25144.6
15	Thistle Is.	1	07/03/06	121	1.74	13 (10.7)	44 (36.4)	8 (6.6)	17.91	31.16	43.00	74.83	10270.6	17874.4
**16	Greenly Is.	2	26/03/06	23	0.33	0 (0.0)	1(4.3)	0 (0.0)	1.45	0.48	49.97	16.53	12736.0	4213.2
**17	Greenly Is.	2	27/03/06	92	1.32	1 (1.1)	1 (1.1)	0 (0.0)	0.72	0.96	62.88	83.20	17299.9	22891.9
**18	Greenly Is.	2	27/03/06	15	0.22	0 (0.0)	0 (0.0)	0 (0.0)	0.00	0.00	73.39	15.83	21015.7	4534.0
**19	Greenly Is.	2	27/03/06	119	1.71	0 (0.0)	4 (3.4)	0 (0.0)	1.12	1.92	58.24	99.69	15661.3	26805.6
				874*		92*	208*	42*	11.82	**13.04#**	56.52	54.36	15052.5	**14289.6#**

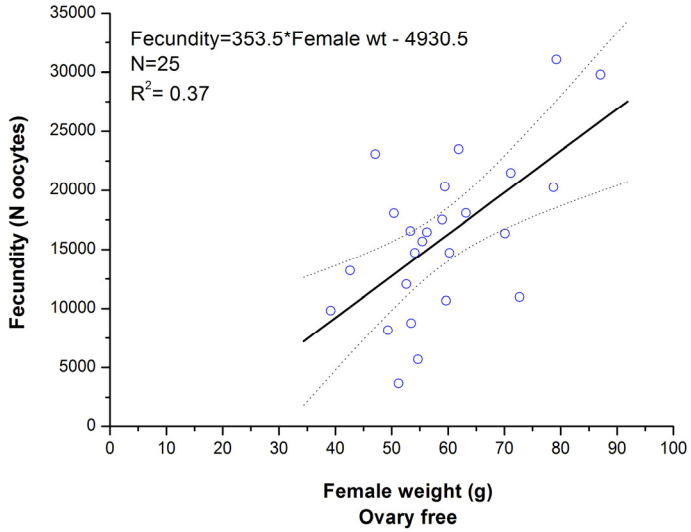

Figure 11. Relationship between ovary-free weight and batch fecundity in 2006 (dotted line = 95% CI).

3.6 Spawning Biomass

The estimate of spawning biomass for the total spawning area was 226,088 t (*136,060–417,612*). The estimates for the eastern and western spawning areas were 55,079 t (*25,406–134,141*) and 171,009 t (*86,360–299,656*), respectively. Distributions of bootstrapped spawning biomass estimates (95% CI) are shown in Fig. 12.

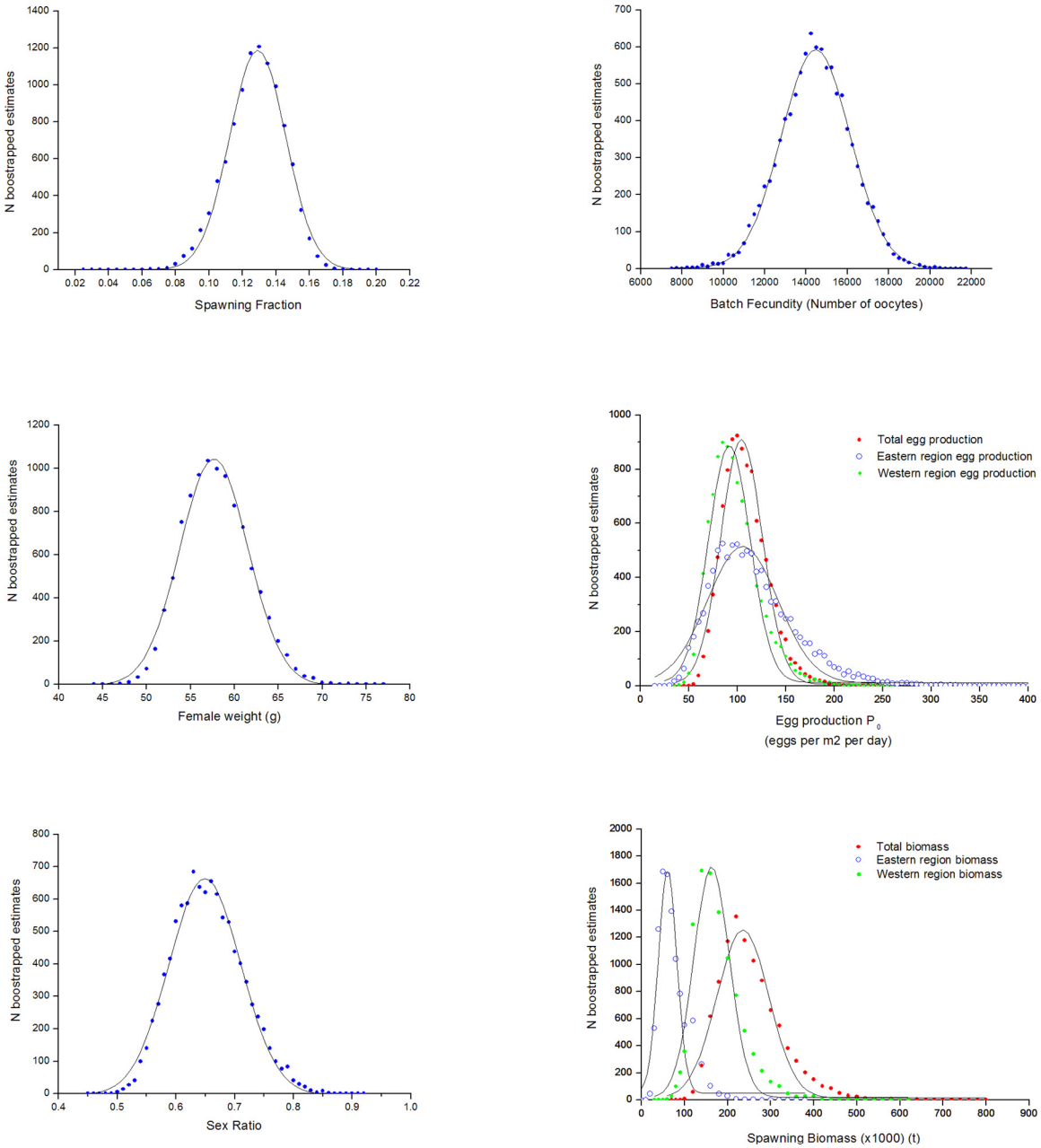

Figure 12. Distributions of bootstrapped parameter estimates (*P*, *W*, *R*, *S*, *F*) and spawning biomass estimates (95% CIs). Egg production data based on estimates from the linear version of egg mortality model with varying estimates of *Z*. Black lines represent estimates of egg production and spawning biomass calculated using the exponential mortality model.

4. DISCUSSION

During the 2006 surveys, samples of adult *S. sagax* were collected from Scotts Cove, Thistle Island, Greenly Island and Flinders Island. Detailed examination of the ovarian characteristics of fish from Greenly Island suggested that there was minimal spawning activity in this location during the surveys. The low abundance of eggs and yolk-sac larvae in plankton samples collected from stations south of the Eyre Peninsula between Cape Catastrophe and Venus Bay supports the assessment that minimal spawning was occurring around Greenly Island in 2006. As samples of adult *S. sagax* collected from Greenly Island were not representative of the spawning biomass, these samples were omitted from the analysis of adult reproductive parameters. Estimates of adult parameters calculated for samples from Scotts Cove, Thistle and Flinders Islands appeared to be suitable for use in the DEPM calculations.

The low abundance of eggs and yolk-sac larvae between Cape Catastrophe and Venus Bay in 2006 may be related to the low SSTs (<17°C) in that region during the surveys, which were in turn related the upwelling favourable conditions that occurred during that period (unpublished data). The TSE plot (Fig. 8) shows that no *S. sagax* eggs were collected at stations with SSTs of <17°C, which confirms the findings of previous studies that suggest the preferred temperatures for spawning by *S. sagax* in South Australian waters are between 17–21°C (e.g. Ward *et al.* 2001a; Rogers and Ward 2005). The lack of eggs in the region between Cape Catastrophe and Venus Bay during the 2006 surveys split the spawning area into eastern and western components, and emphasises the effects of environmental factors on the patterns of spawning activity of *S. sagax* in South Australia. The separation of the spawning area into eastern and western components has occurred in other years, and the implications of these spatial and temporal variations in the distribution and abundance of the spawning stock are currently being investigated.

The total number of eggs collected in 2006 was higher than in most previous years (Table 5), even when the changes in sampling design implemented in 2006 were taken into account. The most significant increases in egg abundance occurred in the western spawning area. Although the number of eggs collected from Spencer Gulf was higher than in 2005, this figure was lower than in 2004, when a similar total number of eggs was collected (Table 5). Importantly, the proportion of the total number of eggs collected from the region east of Coffin Bay (based on a standard number of stations) declined between 2004 and 2005, and in 2006 remained below values recorded from 2000 to 2004 (Fig. 13). This finding provides some support for the previous suggestion that fishing in southern Spencer Gulf may have depleted the abundance of spawning adults in that region (Ward *et al.* 2005a).

Table 5. Numbers of *S. sagax* eggs collected throughout the survey area and in Spencer Gulf during the DEPM surveys between 2000 and 2006.* denotes inclusion of new stations.

Year	n eggs (live and dead all regions)	n eggs (live all regions)	n eggs (live and dead) SG	n eggs (live) SG	% total eggs (live) in SG	n SG stations sampled	n SG stations with eggs	% SG stations with eggs
2000	1,362	992	711	545	54.9	56	25	44.6
2001	1,449	1,122	508	349	31.1	52	16	30.8
2002	1,475	1,117	236	204	18.3	53	11	20.8
2003	1,718	1,260	223	185	14.7	53	17	32.1
2004	3,186	2,576	906	735	28.5	53	18	34.0
2005	1,808	1,303	86	68	5.2	54	9	16.7
2006	3,083	2,866	369(508*)	347(472*)	12.1(16.5*)	45(65*)	18(28*)	40(43.1*)

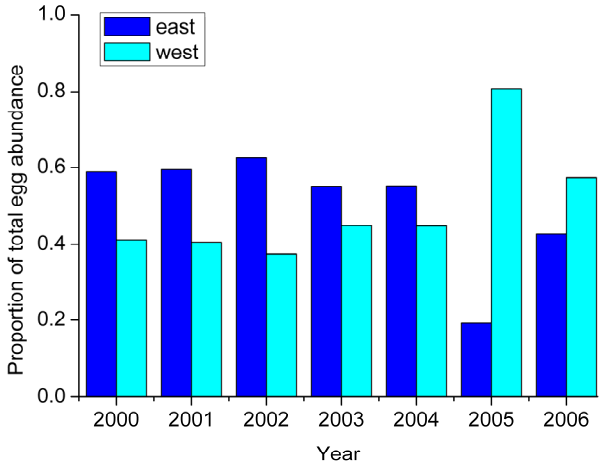

Figure 13. Proportion of *S. sagax* eggs collected at uniform stations located east and west of Coffin Bay during surveys between 2000 and 2006.

In the recent independent review, Smith and Smith *et al* (2006) did not consider that sufficient evidence was available to support the hypothesis of localised depletion in Spencer Gulf, but recommended that the issue warranted further investigation. The main finding provided by Smith and Smith *et al* (2006) regarding this matter was:

> "The information available to this review does not strongly support a case for localised depletion in Spencer Gulf. Nevertheless such depletion may be occurring and recommendations are made on further analyses and data collection strategies to resolve this issue."

The estimate of total spawning area for 2006 (44,890.5 km^2) is the highest recorded for *S. sagax* in South Australia since the mass mortality event in 1998. This is a positive indicator for the status of the South Australian population and suggests that environmental conditions suitable for spawning by *S. sagax* were widespread in gulf and shelf waters during 2006. However, the large proportion of the total spawning area that lies to the west of the key fishing grounds (i.e. 34,264.2 km^2, 76% of the total spawning area) highlights the large disparity between the historical distribution of fishing effort and the distribution of the spawning stock during the surveys. The distribution patterns of yolk-sac larvae, which are an indicator of spawning activity ~2–5 days prior to an egg survey, suggests that the spatial patterns of spawning activity observed in 2006 may have extended beyond the period during which the surveys were conducted.

The estimate of mean daily egg production for 2006 (104.7 eggs.day^{-1}.m^{-2}, *67.95–158.44*) was lower than the estimates for 2003 (117.16 eggs.day^{-1}.m^{-2}, *77.39–186.40*) and 2004 (132.17 eggs.day^{-1}.m^{-2}, *83.60–215.60*), but higher than estimates for all other years (Rogers and Ward 2006), which is another positive indicator for the status of the spawning stock. Similarly, the spawning biomass estimate for the total spawning area of 226,088 t (*136,060–417,612*) is ~13% higher than the previous highest estimates of spawning biomass (Ward and Rogers *et al.* 2006). As this estimate does not include adult fish that were located outside the main spawning area (e.g. in the region between Cape Catastrophe and Cape Finnis), this figure is considered to be a conservative estimate of total biomass of adult sardine in South Australia and suitable for use in discussions regarding future management of the SASF (Fig. 14).

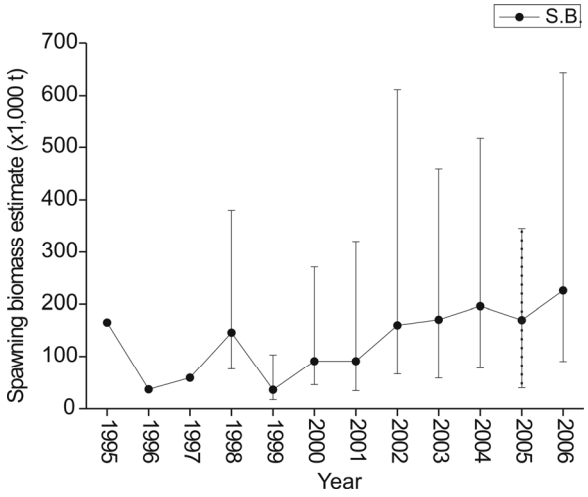

Figure 14. Revised estimates of spawning biomass between 1995 and 2006, with 95% confidence intervals. The dotted line represents the range of estimates for 2005 obtained using a range of assumed values of egg mortality.

Previous studies have shown that estimates of spawning biomass are sensitive to estimates of daily egg production and spawning area (Ward *et al.* 2004). A recent review of the worldwide application of the DEPM confirmed that the methods used in the present study to estimate egg production and spawning area (see Picquelle and Stauffer 1985) are still applied widely, but also indicated that continuous underway fish egg samplers (CUFES) are used to estimate spawning area in some jurisdictions (Stratoudakis *et al.* 2006). The recent review of the application of the DEPM in South Australia by Smith and Smith (2006) also confirmed the suitability of the methods used here to estimate egg production and spawning area, but suggested that other methodologies for estimating egg production should also be examined and that the use of a CUFES to estimate spawning area warranted investigation. These recommendations are supported by the authors of the current report and have been identified as being priorities for future research in numerous previous studies (e.g. Ward *et al.* 2005a; Rogers and Ward 2006).

In addition to the recommendations regarding the methods for estimating egg production and spawning area, Smith and Smith (2006) also identified the need to address several other matters pertaining to the application of the DEPM, including the:

- collection of additional plankton samples in the key fishing areas;
- assessment of the potential for industry involvement in the egg and adult sampling programs;

- examination of the sensitivity of estimates of egg production to estimates of spawning time;
- investigation of interannual variation in all DEPM parameters; and

Smith and Smith (2006) acknowledged that it would be difficult to address these issues within the "constraints imposed by resources and logistics" and that this was an "area that should be considered carefully by PIRSA in relation to the value and importance of the fishery." One option that has been mooted for addressing the recommendations of Smith and Smith (2006), without acquiring the additional resources that the review suggested may be required, would be to conduct a comprehensive DEPM survey every second year (instead of annually) and to address matters pertaining to the application of the DEPM raised by Smith and Smith (2006) in the alternate year. This approach may also facilitate (i) the establishment of an expanded industry-based sampling program and (ii) the more effective utilisation of the fishery's age structured assessment model (Ward *et al.* 2005b). However, the risks/benefits of reducing the frequency of full-scale assessment of this large, valuable and high profile fishery need to be considered carefully before a decision to move to biannual assessment of the resource is taken.

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APPENDIX 1. BIAS CORRECTION FOR THE LOGNORMAL DISTRIBUTION.

Selection of the variance term in the "bias correction" for the lognormal distribution (Smith and Smith 2006) as used in Picquelle and Stauffer (1985).

Explanation provided by Dr Mark Bravington, CSIRO Mathematics and Information Sciences, Hobart in Smith and Smith (2006)

Suppose Y_i is the density in the i^{th} haul, and that

$$E[Y_i] = \mu$$

We want to estimate μ. Now suppose that Y_i is log-Normally distributed so that

$$\log Y_i \sim N(\upsilon, \sigma^2)$$

In this case,

$$\mu = E[Y_i] = \exp(\upsilon + \sigma^2/2)$$

We can estimate μ by the sample mean of the Y_i's (which is unbiased but inefficient). It is more efficient to use

$$\mu = \exp(u + s^2/2)$$

where u and s^2 are estimated from the sample mean and variance of the log Y_i's. Note that it is definitely wrong to use the standard error of u in this "bias correction".

If there is an age-of egg covariate a_i associated with the i^{th} haul, then

$$E[Y_i] = \mu e^{-Z a_i}$$

where Z is the egg mortality parameter.

This will likely have a multiplicative effect on variance (assuming Z is constant):

$$V[Y_i \mid a_i] = e^{-2Z a_i} V[Y_i \mid a_i = 0]$$

so we might well find that a reasonable model is

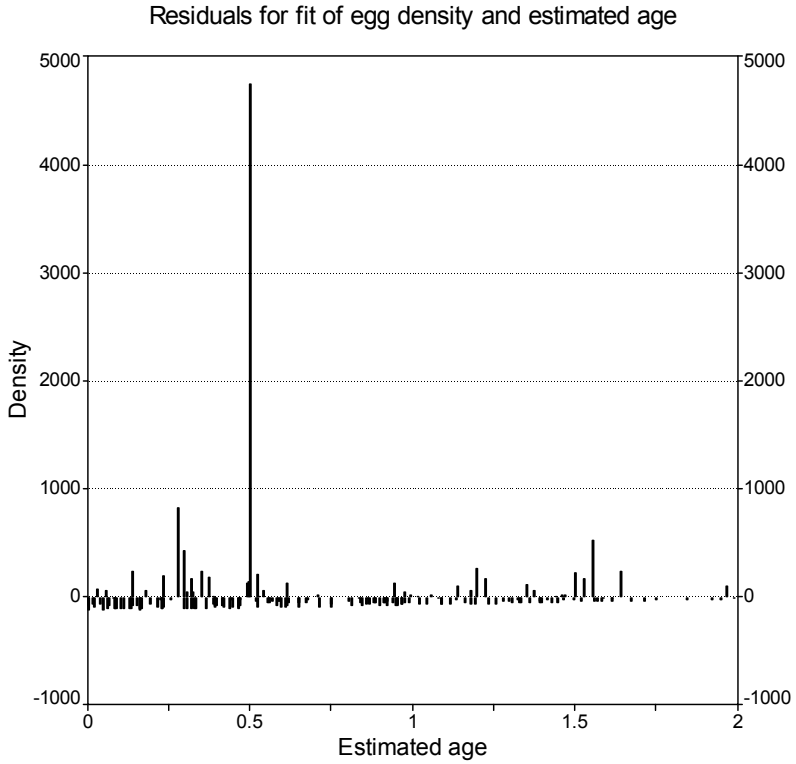
$$\log Y_i \mid a_i \sim N(\upsilon - Z a_i, \sigma^2)$$

implying that

$$E[Y_i \mid a_i] = \exp(\upsilon - Z a_i + \sigma^2/2)$$

For $a_i = 0$, we would again have

$$\mu = \exp(u + s^2/2)$$

This time, u and s^2 would be estimated by regression on a_i (u is the intercept, s^2 the residual variance about the regression), rather than by sample means, but the basic correction is the same.

APPENDIX 2. RESIDUALS FOR LINEAR FIT OF EGG DENSITY AND AGE