Australian Sardine

(Pilchard)

Sardinops sagax

Fishery Assessment Report

P.J. Rogers and T.M. Ward

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This is the sixth fishery assessment report on Australian sardine (pilchard) *Sardinops sagax* in South Australia. It synthesises information relevant to the South Australian Sardine Fishery (SASF) and assesses the status of the sardine stock in South Australia, comments on the biological performance indicators in the management plan, and identifies future management options and research priorities.

Fishery Assessment Report: Australian Sardine (pilchard) 2005

Report to PIRSA Fisheries

South Australian Research and Development Institute

SARDI Aquatic Sciences

2 Hamra Avenue

West Beach SA 5024

Telephone: (08) 82075400

Facsimile: (08) 82075406

http://www.sardi.sa.gov.au

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Authors: P. J. Rogers and T. M. Ward

Reviewers: Dr Steven Mayfield, Dr Anthony Fowler, Dr Mike Steer and Dr Craig Noell

Approved by: Dr Anthony Fowler

Signed:

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PREFACE

This is the sixth fishery assessment report on Australian sardine (pilchard) *Sardinops sagax* in South Australia. Since 1998, SARDI Aquatic Sciences has assessed the status the stock of Australian sardine in South Australia and provided scientific advice to PIRSA Fisheries to assist management of the South Australian Sardine Fishery (SASF). Under the service level agreement with PIRSA Fisheries, SARDI Aquatic Sciences is required to provide an annual fishery assessment report. This report is a ‘living document’ that includes a synthesis of information relevant to the SASF and assesses the status of the stock, comments on the biological suitability of current management arrangements and identifies future research needs.

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EXECUTIVE SUMMARY

1. This report synthesises scientific information relevant to the South Australian Sardine Fishery (SASF), assesses the status of the South Australian (SA) stock, comments on the biological performance indicators, reference points and decision rules in the management plan, and identifies future management options and research priorities.

2. Logbook data indicate that the annual catch in the SASF increased from 9 t in 1991 to 39,185 t in 2005. Quota monitoring data closely followed the total catches estimated from logbooks and ranged from 2,597 t in 1995 to 42,475 t in 2005.

3. The spatial distribution of fishing effort increased from 2001 to 2005, with catches and effort expanding from traditional fishing grounds north-east and east of Thistle Island and Dangerous Reef, outwards to southern Spencer Gulf, Investigator Strait and the eastern Great Australian Bight.

4. Between 1995 and 1999, sardine taken from Spencer Gulf were mostly 120 – 160 mm, with modes at 130 and 140 mm. Between 2000 and 2002, catch samples mostly consisted of sardine >150 mm with modal sizes of 160 and 170 mm. In 2003 and 2004, significant quantities of juveniles (80 – 120 mm) were present in samples from Spencer Gulf for the first time in the history of the fishery.

5. Female and male sardine reach L_{50} at 151 and 145 mm, corresponding to ~1.5 – 2 years of age, respectively. All males <120 mm and females <125 mm were immature (juveniles). Approximately 18% of sardine in 2004 had immature gonads.

6. Best estimates of spawning biomass since 1998 ranged from 36,000 t (95% C.I. = 19,000 – 67,000) in 1999, following the second mass mortality event, to 196,222 t (95% C.I. = 117,874 – 321,123) in 2004. Estimation of spawning biomass in 2005 was impeded by difficulties estimating egg mortality and egg production. Estimates of spawning biomass obtained using a range of assumed egg mortality estimates declined to between 129,729 – 175,389 t.

7. It is unclear whether the apparent decline in spawning biomass between 2004 and 2005 is related to variability in environmental conditions, fishing pressure, uncertainties in the assessment technique or a combination of these factors.

8. Fishing in the SASF is conducted in only one third of the mean spawning area, suggesting that a significant part of the spawning stock is virtually unfished. This finding suggests that the SA sardine stock is not overexploited.

9. Reductions in egg abundance combined with the spatial expansion of catches and effort and increased proportion of juveniles (≤ 100 mm) in catches suggests that fishing may have reduced the abundance of adult sardine in southern Spencer Gulf between 2004 and 2005. A recent review (Smith and Smith 2006) concluded that available information did not strongly support a case for localised depletion, but recommended that further analyses and data collection were needed to address this potentially serious issue.

10. The framework of decision rules established for the SASF has enabled PIRSA Fisheries to respond quickly to fluctuations in stock size, and allowed the stock to recover quickly from two mass mortality events, whilst also allowing the fishery to grow. The negative aspect of the strategy is the high potential for large inter-annual variations in the TACs resulting from both fluctuations in biomass estimates and the application of different exploitation rates at different biomass levels.

11. This report outlines an alternative management option for the SASF that could involve setting a target TAC, based on a target exploitation rate that reflects current knowledge of the capacity of the stock to sustain fishing pressure. Under this option, a target TAC would be maintained unless specified upper or lower exploitation rates were triggered. The target exploitation rate, target TAC and trigger exploitation rates could also involve regular review of management arrangements (e.g. every 3 years).

1. GENERAL INTRODUCTION

1.1 Rationale and Objectives

This is the sixth fishery assessment report on Australian sardine *Sardinops sagax* (Clupeidae) by SARDI Aquatic Sciences. It is a living document that summarises all of the biological and fishery specific information available for the SASF up until February 2006.

The objectives of this report are to:

1. review international scientific literature on clupeoids and describe the history and development of the South Australian Sardine Fishery (SASF) (Chapter 1);
2. present fishery data from 1991 to 2005 (Chapter 2);
3. summarise size, age, growth and reproductive information for sardine in South Australia (SA) (Chapter 3);
4. provide estimates of spawning biomass of sardine in SA between 1995 and 2005 (Chapter 4);
5. assess the status of the resource, comment on the biological performance indicators, reference points and decision rules in the management plan, suggest future management options and identify future research priorities (Chapter 5).

1.2 Review of Recent Literature

1.2.1 Taxonomy

The Australian sardine is broadly known as *Sardinops sagax*. Most fisheries scientists throughout the world follow the taxonomy of the genus *Sardinops* proposed by Parrish *et al.* (1989) who suggested the genus *Sardinops* is mono-specific and that there are no valid sub-species. Recently, 11 new polymorphic micro-satellites were isolated, which may be used to resolve some of the minor taxonomic arguments identified in previous genetic studies (Pereya *et al.* 2004).

1.2.2 Stock Structure

No comprehensive studies of the stock structure of sardine have been undertaken in SA waters. A study in southern Western Australia provided no conclusive evidence that genetic variation existed at the scales necessary to justify spatial management of the stock (Dixon *et al.* 1993). However, Gaughan *et al.* (2002) suggested that spatial management is justified by the existence of separate assemblages of adult sardine within a single breeding stock that are linked by recruitment processes.

1.2.3 Distribution

S. sagax is found off Australia, Japan, the Americas, Africa and New Zealand. In Australia this species is found throughout southern temperate waters from Rockhampton in Queensland (Qld) to Shark Bay in WA (Gomon *et al.* 1994). In SA, sardine aggregations inhabit continental shelf and southern gulf waters (Ward *et al.* 2001a, b, c). Larval sardine aggregate near sea surface temperature (SST) and salinity interfaces that form near the mouths of the gulfs during summer and autumn (Bruce and Short 1990). Juveniles are found in the EGAB, southern Spencer Gulf and upper Gulf St Vincent (Ward *et al.* 2005a). Australian anchovy *Engraulis australis* dominate the clupeoid assemblage in the northern regions of the gulfs (Dimmlich *et al.* 2004).

Gaughan *et al.* (2004) indicated that the spatial distribution of sardine in southern Western Australia was highly variable between years in response to poor recruitment, fishing mortality and mass mortality events in 1995 and 1998. The distribution of clupeoids is often linked to variation in environmental conditions driven by upwelling, frontal systems and eddies (Watanabe 1996; Lynn 2003; Dimmlich *et al.* 2004; Skogen 2005). Patterns in distribution are also related to the demographics of clupeoid populations (Curtis 2004).

1.2.4 Schooling Behaviour

Several factors influence schooling behaviour of sardine. Misund *et al.* (2003) found schools were highly dynamic and densities changed during the afternoon, whereas Barange and Hampton (1997) found schools remained at similar densities throughout the day. Habitat heterogeneity (Giannoulaki *et al.* 2003), predation and vessel noise also influence schooling behaviour of small pelagic fishes (Freon 1993).

1.2.5 Movement

There is no published information describing the seasonal movement patterns of sardine in SA. Schools of sardine migrate into southern Queensland waters to spawn during winter-spring (Ward and Staunton Smith 2002). Off the coast of Africa, sardine schools migrate north and south (return) in June/July and November/December to access favourable environmental conditions for spawning and survival of recruits (van der Lingen and Huggett 2003).

1.2.6 Food and Feeding

In the productive boundary current systems off Africa, sardine particulate-feed on zooplankton when prey densities are low, and filter-feed on micro-zooplankton and phytoplankton when prey densities are high (Louw *et al.* 1998; van der Lingen 1994, 2002). There are no published studies of the feeding ecology of sardine in Australia.

1.2.7 Age, Growth and Size

In Australian waters sardine live up to nine years of age (Fletcher and Blight 1996) and reach maximum sizes of ~23 cm, FL. In SA waters, sardine larvae have maximum growth rates of ~0.76 mm.day^{-1} (Ward *et al.* 2005a), which are higher than those found in WA (Gaughan *et al.* 2001, 2004). Adult and juvenile sardine grow rapidly in the productive upwelling systems off the coast of California and South Africa and growth is slower in SA waters (Baird 1970; Beckley and van der Lingen 1999; Quinonez-Velazquez 2000; Butler *et al.* 1996; Ward *et al.* 2005a).

1.2.8 Reproduction

In SA, sardines attain sexual maturity (L_{50}) at ~150 mm. Females produce multiple batches of pelagic eggs (~10,000 to 30,000) at frequencies of approximately once per week during summer and early autumn. The spatial distribution of eggs across shelf waters varies considerably between years (Ward *et al*. 2001a, b; Ward *et al.* 2003, 2004a). In WA, sardine have two spawning seasons (summer and early winter), which may be due to the influence of the Leeuwin Current that flows south-ward and into the western GAB in early winter (Fletcher 1990; Pearce and Walker 1991). Spawning occurs during late summer and autumn in Victoria, (Blackburn 1950; Hoedt and Dimmlich 1995) and from winter to spring in southern Queensland (Ward and Staunton Smith 2002). Contraction in the inshore extent of spawning has been associated with coastal upwelling events and transitions between disparate water masses (Ward *et al.* 2003; Checkley *et al.* 2000; Lynn 2003; Twatwa *et al.* 2005).

1.2.9 Early Life History

Sardine spawn below the upper mixed layer and the pelagic eggs float into the surface layer (Stenevik *et al.* 2001). Eggs hatch approximately two days after fertilisation and yolk-sac larvae are ~2.2 to 2.5 mm in total length, TL (Neira *et al.* 1998). Larvae metamorphose at ~1 – 2 months of age and at lengths of 35 – 40 mm, TL. Juveniles occupy nursery areas close to where adults aggregate (Blaxter and Hunter 1982; Gaughan 2004). In SA, these include the embayments and semi-protected waters of southern Spencer Gulf and near inshore islands. Larvae undertake vertical migrations that may reduce passive transport away from regions characterised by favourable environmental conditions for survival (Watanabe *et al.* 1996; Logerwell *et al.* 2001; Stenevik *et al.* 2001; Curtis 2004).

1.2.10 Recruitment

There is currently no published information on sardine recruitment and or the underpinning physical and/or biological processes in SA waters. Un-fished areas, where environmental conditions are often favourable for growth and survival (e.g. where upwelling occurs) form important refuge areas for recruits (Lluch-Belda *et al.* 2003; Gaughan 2004). The importance of natal homing in sardine has not been determined and this factor may influence the rate of population recoveries following declines in spawning stock size (Blaxter and Hunter 1982; Gaughan *et al.* 2002).

1.2.11 Stock Assessment

The Daily Egg Production Method (DEPM) was developed to assess the status of northern anchovy *E. mordax* stocks off the coast of California (Parker 1980; Lasker 1985) and has been used as the integral tool for estimating the spawning biomass of sardine in SA since 1995. Annual estimates of spawning biomass are the key biological indicator in the management plan for the SASF (Shanks 2005). The advantages of having direct, annual estimates of spawning biomass with which to base management decisions outweigh the disadvantages, which include the high degrees of uncertainty in the point estimates of biomass, high running costs of vessels, and extensive laboratory time required to identify eggs from ichthyoplankton samples (Cochrane 1999; Stratoudakis *et al.* 2006).

Acoustic techniques have been used widely for assessing small pelagic fish stocks (Beckley and van der Lingen 1999; van der Lingen and Huggett 2003) and these studies have contributed to the understanding of sardine movement (Barange *et al*. 1999); stock structure (Barange and Hampton 1997); relationships with oceanographic features (Tameishi *et al.* 1996; Lynn 2003); predator-prey interactions and inter-annual variability in abundance (Barange *et al.* 1999). Changes in fish behaviour represent a major limitation to the adoption of this technique for routine stock assessment (Freon *et al.* 1993) and acoustic assessment methods require rigorous target strength validation for each species (S. McClatchie pers comm.).

1.2.12 Management Procedures in Small Pelagic Fisheries

The *FAO Code of Conduct for Responsible Fisheries* suggests that exploitation rates should be constrained within biologically sustainable limits while maximising potential yields, and that performance indicators, reference points and trigger limits should be incorporated into the management procedures (Gabriel and Mace 1999). Management procedures that include agreed operational targets and agreed decision rules have been successfully incorporated into the management systems for the South African Pelagic Fishery, Western Australian Pilchard Fishery, Pacific Sardine Fishery and the SASF (Cochrane 1999; Cochrane *et al.* 1998; De Oliveira. *et al.*1998; Hill *et al.* 2005; Gaughan *et al.* 2004; Gaughan and Leary 2005a, b).

Patterson (1992) reviewed 28 stocks of 11 species of small pelagic fish, and suggested that management targets based on maximum sustainable yields (MSY) were inappropriate for these species, as they commonly led to stock declines. He also concluded that a key objective of the management arrangements for small pelagic fish stocks should be to minimise the likelihood of biomasses declining below 40% of the virgin stock size. However, recent studies (e.g. Punt 2003) have highlighted the high level of uncertainty associated with estimating virgin biomass, and hence difficulties applying this approach.

Patterson (1992) also investigated the relationship between exploitation rates (*E*) and biomass trajectories and stability, where:

$$E = \frac{F}{Z},$$

where F = fishing mortality Z = total mortality ($Z=F+M$ (natural mortality)),

Patterson (1992) found that small pelagic stocks commonly remained stable at exploitation rates of ~40%, and that exploitation rates of >40% usually led to stock decline. Patterson (1992) also concluded that exploitation rates below 30% were commonly associated with increases in stock abundance and were suitable for small pelagic fishes as they minimized the probability of stock decline.

In the South African Pelagic Fishery and Pacific Sardine Fishery, operational targets and decision rules are based around the outputs of age-structured models that use survey data and other information to generate estimates of 1+ biomass. Similarly, the TACs for the three sardine fisheries in Western Australia are based on estimates of spawning biomass generated using an age-structured model (Gaughan and Leary 2005a, b). In these three Western Australian fisheries, where the stocks are recovering from substantial declines, the decision rules indicate that exploitation rates should not exceed 15 – 20% of the spawning biomass (Cochrane 1999; Gaughan and Leary 2005a, b).

1.2.13 Bycatch Issues

The estimated amount of catch lost or released of unwanted catch may contribute significantly to fishing mortality in purse seine fisheries (Mitchell *et al.* 2002, Stratoudakis and Marcalo 2002). Stratoudakis and Marcalo (2002) suggested mortality rates as a result of release of unwanted catch are likely to be dependent on whether the catch is 'dried up' in the net prior to release. A recent study in Western Australia found mortality rates for sardine ranged between 11 and 55% when discarded catch was rolled over the headline of purse seine nets (Mitchell *et al.* 2002).

The issue of marine mammal bycatch in the SASF was addressed during an observer program undertaken by SARDI Aquatic Science in 2005. The fishery has since introduced a *Code of Conduct* for managing interactions with Threatened Endangered and Protected Species (TEPS) and implemented a program of 10% independent observer coverage. There have also been significant cultural changes within the fishery with regard to the voluntary reporting of interactions with TEPS.

1.3 The South Australian Sardine Fishery (SASF)

The estimated Gross Value of Production of the SASF is approximately $24 M in 2006. The SASF experienced significant economic expansion in response to the recovery of the spawning biomass following the second mass mortality event in 1998/9 and increases in the TACs. Australian sardine is a ‘low price-high volume’ product with values ranging between 40 and 80 cents per kg for southern bluefin tuna SBT fodder and $2.50 per kg for recreational bait. Most of the catch is used to supplement imported baitfish used as fodder by the SBT mariculture industry. There is considerable potential for expansion of Australian sardine products to export markets aimed at human consumption.

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* 1982. Goals, objectives and fishery management strategies are outlined in the *Management Plan for the South Australian Pilchard Fishery* (Shanks 2005). To achieve complete management of the fishery, a number of services are required (e.g. policy, compliance and research), the costs of which are fully recovered by licence fees. Management measures include entry limitations, gear restrictions and individual transferable quotas (ITQs). Gear restrictions include, purse seine net length limits of 1,000 m or a depth of 200 m and mesh size restrictions of 14 to 22 mm. There are currently 14 licence holders and some fishing companies operate several licenses.

The Pilchard Fishery Working Group (PFWG) was established to facilitate the consultation process between PIRSA Fisheries, SARDI researchers and licence holders and to ensure the equitable sharing and allocation of the resource. Biological Performance Indicators (BPIs) used to manage the SASF include estimates of spawning biomass and age structures of catch samples collected from processors. These BPIs are linked to management responses outlined in Shanks (2005) and precautionary annual TACs are based on exploitation rates ranging from 10 to 17.5% of annual spawning biomass estimates and the relative strength of two and three year old age classes in catch samples.

Conservative spawning biomass estimates are used to compensate for uncertainties involved in estimating spawning stock size. The TAC for 1999 was initially set at 11,500 t, but was reduced to 3,500 t following the second mass mortality event in 1998/9. The TACs increased from 3,800 t in 2000 to 51,100 t in 2005. In 2006, the TAC was reduced to 25,463 t.

Since 1999, the fishery has mostly operated in southern Spencer Gulf. During 2002, catches were mostly taken in Spencer Gulf and Investigator Strait and a small proportion of the catch was taken in southern Gulf St Vincent and off the west coast of Kangaroo Island. In 2003 and 2004 the fishery expanded to include Wedge and Althorpe Islands and a large area along the northern coast of Kangaroo Island in Investigator Strait.

In 2005, an independent observer program was established by SARDI Aquatic Sciences to monitor interactions with TEPS. On August 25, 2005, the Minister for Agriculture Food and Fisheries closed the fishery for one month, under section 43 of the *Fisheries Management Act 1982*, in response to reports of dolphin mortalities during the pilot observer program. Following discussions between the fishery licence holders, SARDI scientists, the Director of Fisheries and the Minister for Agriculture Food and Fisheries, a fishery *Code of Conduct* was establish to mitigate interactions with TEPS. This was followed by a trial period where each vessel resumed fishing under full observer coverage and fishers operated according to guidelines stipulated in the code. The *Code of Conduct* involved modification of the purse seine nets to include ‘gates’ in the headline and clip-on weights to aid the release of trapped animals. As of February 2006, the fleet operated under 10% independent observer coverage.

2. FISHERY STATISTICS

2.1 Introduction

This chapter summarises catch, effort and catch-per-unit-effort (CPUE) data for the SASF between 1 January 1991 and 31 December 2005. Catch and effort data were collated from fishery research logbooks provided by each licence holder. Total annual catches are based on aggregated estimates of daily catches. In 2001, logbooks were improved to include information on the location of fishing, searching time, shot time, water temperature, estimated catch, catch lost and bycatch. Actual total annual catches are based on data collated from Catch Disposal Records (CDR) provided by PIRSA Fisheries.

In 1991 and 1992, the annual TACs were set at 1,200 t (Fig. 1). This was increased to 3,500 t between 1993 and 1996 (Mackie 1995). Since 1997, the TACs have been based on annual spawning biomass estimates provided to PIRSA Fisheries by SARDI Aquatic Sciences. The TAC for 1999 was initially set at 11,500 t, but was reduced to 3,500 t in response to second mass mortality event in October-November 1998 (Fig. 1). TACs for the 2000, 2001, 2002 and 2003 seasons were set at 3,800, 9,100, 17,700, and 36,050 t, respectively. In 2004 and 2005, TACs were set at 40,350 and 51,100 t, respectively. The TAC for 2006 was set at 25,463 t.

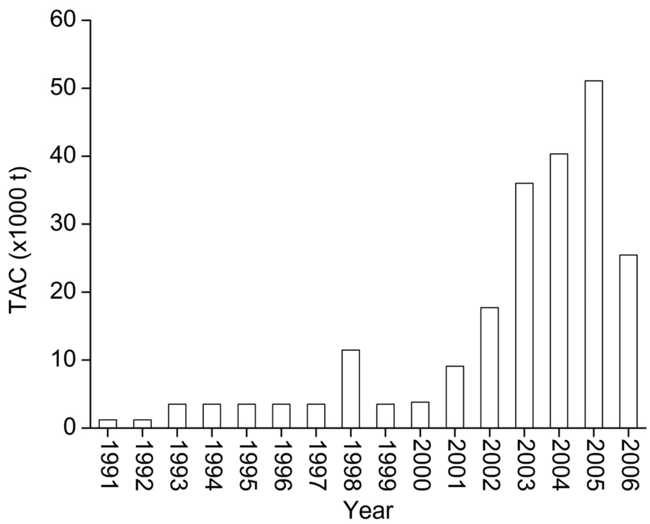

Figure 1. TAC for the SASF between 1991 and 2006.

2.2. Annual Patterns

2.2.1 Catch and effort

Total effort and catches increased from 37 boat days and ~9 t during 1991 to 803 boat days and 3,241 t in 1994 (Fig. 2a, b). This was followed by a decline in total effort and catch following the first mass mortality event. Total effort increased to 831 boat days and total catch increased to 6,431 t by 1998, and declined to 415 boat days and 3,548 t in 1999 following the second mass mortality event (Fig. 2). In 2001, total effort was 575 net-shots over 417 boat days and total catch increased to 4,548 t. Total effort increased rapidly reaching 1,600 net-shots over 1,261 boat days in 2005, the total estimated catch reached 39,185 t, despite the temporary closure of the fishery in September 2005.

CDR data for the period between 1995 and 2005 indicate that total catches ranged between 2,597 and 42,475 t (Fig. 2).

2.2.2. Catch-per unit effort

Mean CPUE was calculated using boat days as units of effort between 1991 and 2005 and net shots as units of effort between 2001 and 2005 (Error bars represent ±1 SE of mean). Mean $CPUE_{boat\ day}$ increased gradually from 1.1 t.boat day^{-1} in 1991 to 8.6 t.boat day^{-1} in 1999 (Fig. 3) and declined to 7.4 t.boat day^{-1} in 2000. Between 2001 and 2003 mean $CPUE_{boat\ day}$ increased from 11.1, to 36.9 t.boat day^{-1}. In 2004, $CPUE_{boat\ day}$ declined to 32.3 t.boat day^{-1} (Fig. 3) and further to 31 t.boat day^{-1} in 2005.

The higher resolution measure of catch rate, Mean $CPUE_{net\text{-}shot}$, increased from 9.5 t.net-shot^{-1} in 2001, to 25.1 t.net-shot^{-1} in 2003. This upward trend continued in 2004 as the mean $CPUE_{net\text{-}shot}$ was 27 t.net-shot^{-1} and 28 t.net-shot^{-1} in 2005 (Fig. 3).

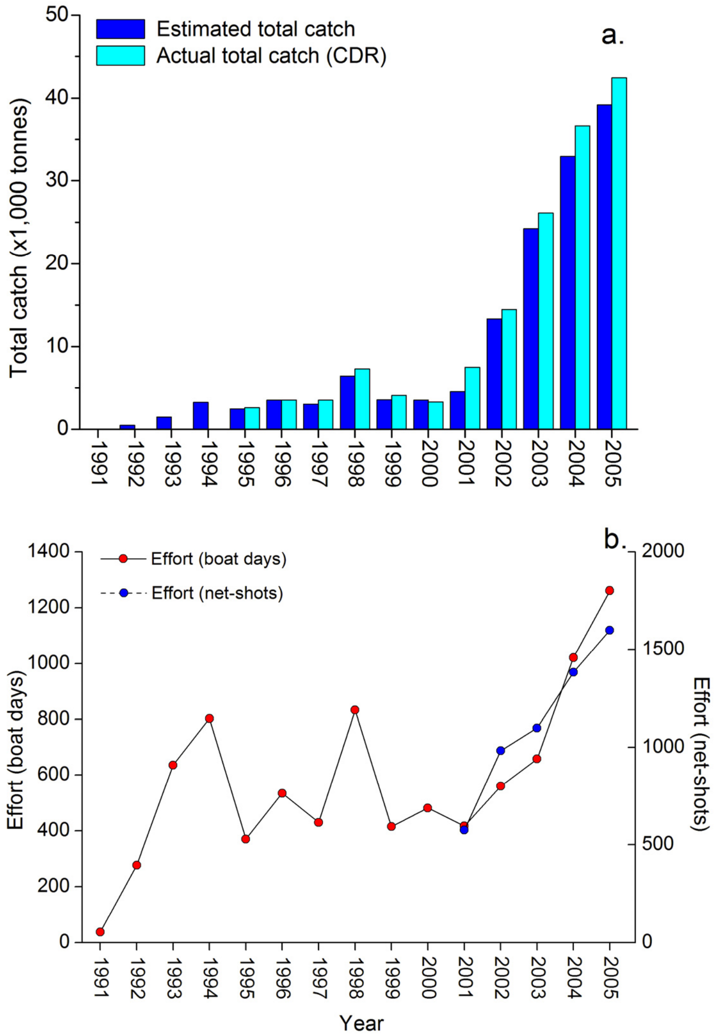

Figure 2. (a) Total estimated and actual (CDR) annual catches, (b) total fishing effort in boat days between 1991 and 2005 and in net shots between 2001 and 2005.

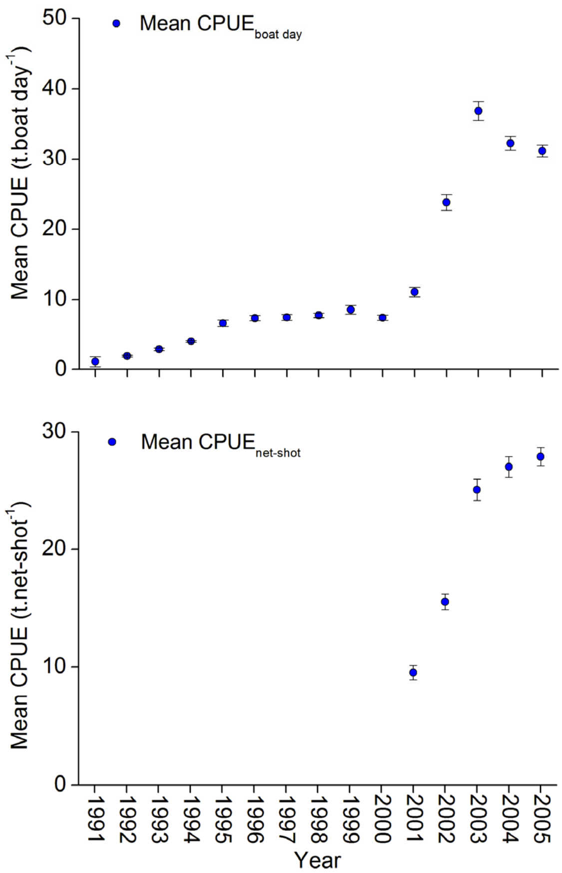

Figure 3. Mean catch-per-unit effort$_{boat\text{-}day}$ between 1991 and 2005 (above) and mean catch-per-unit effort$_{net\text{-}shot}$ between 2001 and 2005 (below).

2.3. Intra-Annual Patterns

2.3.1 Catch and effort

Figure 4 shows the intra-annual patterns of catch and effort between 1991 and 2005. During this period, peak catches have mostly been taken from March to June in response to (a) the demand for sardine to feed SBT following their capture during summer and (b) extended periods of calm weather between April and June that are favourable for purse seining. Significant catches have also occurred in November and December.

During 2004, 58% of the annual catch (18,963 t) and 56% of the effort (573 boat days) occurred between March and June (Fig. 4). Notable monthly catches and effort were also recorded during February (2,518 t, 90 boat days) and November (2,573 t, 59 boat days).

In 2005, fishing activity peaked in April and May, with 44% of the total catch and 36% of total effort (boat days) occuring in these two months. As mentioned previously, the fishery was closed between 30 August and 30 September 2005. Despite this closure, the overall patterns of catch and effort were similar to those in 2004, with the main difference being that catches and effort were reduced in October and November during the roll-out of the *Code of Conduct* for manageing interactions with TEPS. The total catch in December 2005 was slightly higher than in the previous year.

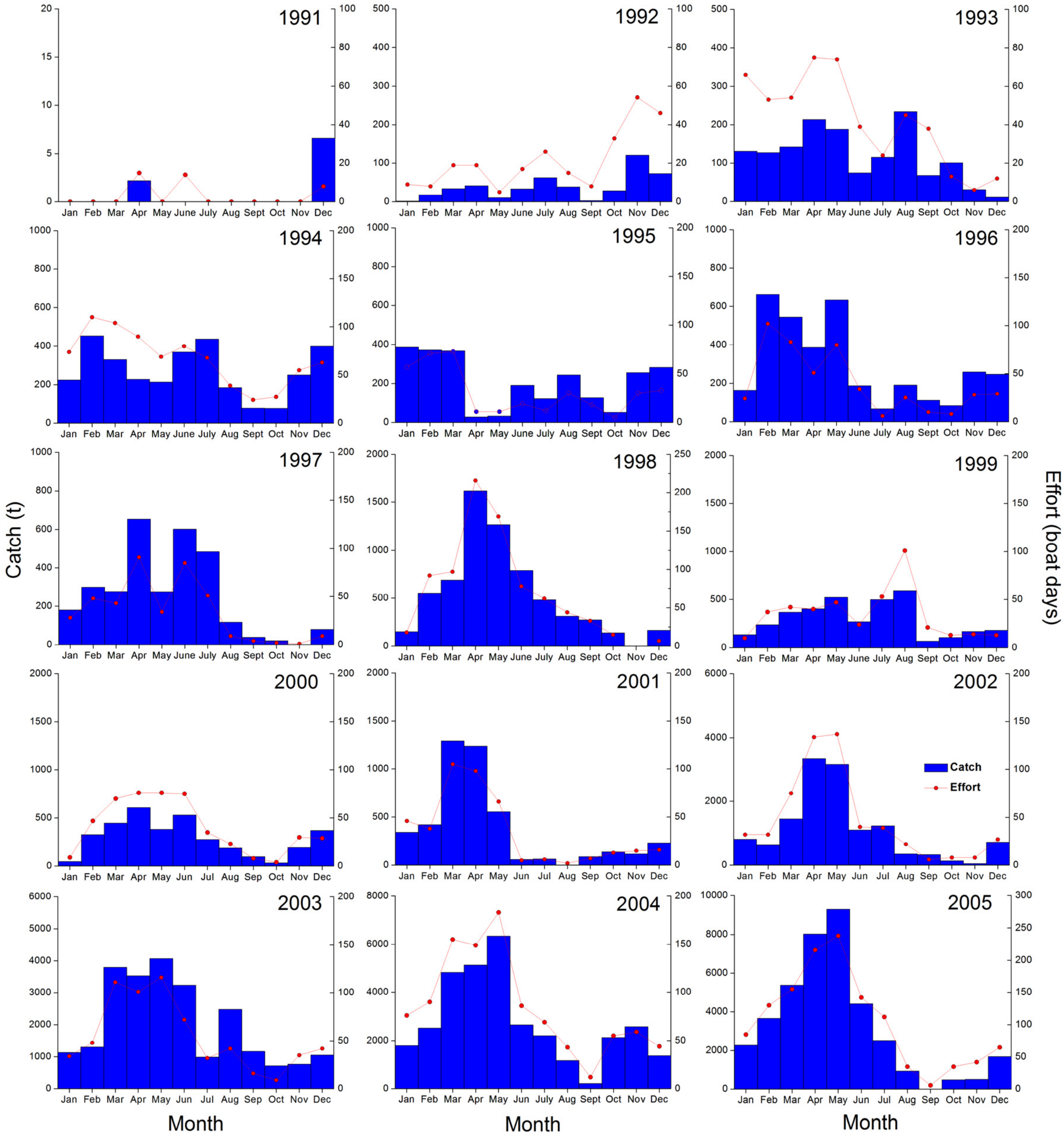

Figure 4. Intra-annual patterns in catch and effort between 1991 and 2005.

2.4. Spatial Patterns

2.4.1 Catch and effort

Prior to 2001, catch locations were recorded under broad Marine Scalefish Fishery (MSF) blocks based on whole degrees of latitude and longitude (Fig. 5, inset). Between 2001 and 2005, fishers recorded the locations of catches using Global Positioning Systems (GPS) and this information was provided to SARDI Aquatic Sciences in logbook returns.

The Geographical Information System (GIS) analysis of aggregated catches and effort in 10 x 10 km grid squares is based on data collected and provided to SARDI Aquatic Sciences by the fishers between 2001 and 2005. Figures and text referring to “Coffin Bay” represent information on fishing in the broad area adjacent to Coffin Bay Peninsula (CBP). Locations mentioned in the text are shown in Fig. 5.

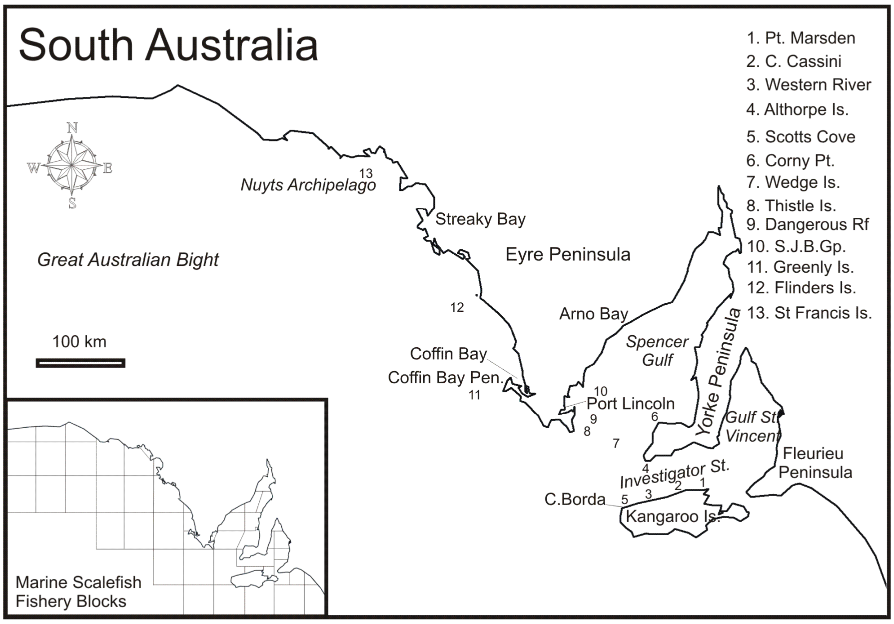

Figure 5. Locations mentioned in the text of this report. Inset shows MSF fishery blocks used for spatial analysis of catch and effort data between 1991 and 2000.

2.4.2 Inter-annual patterns

Between 1992 and 1995, fishing mostly occurred in Spencer Gulf. In 1996 and 1998 a significant proportion of the total annual catch was taken off Coffin Bay (Fig. 6). Fishing effort declined off Coffin Bay and retracted into southern Spencer Gulf between 1999 and 2001 (Figs. 6 and 7)

Figures 7 – 8 show the spatial expansion of the SASF between 2001 and July 2005. Spatial patterns in effort closely follow the patterns in catches (Fig. 8). During 2001, most of the effort and catches occurred in southern Spencer Gulf, north-east of Thistle Island and east of Dangerous Reef (Figs. 7 and 8) and no fishing occurred off Coffin Bay. In 2002, approximately 90% of the catch was taken in the area north-east of Thistle Island and ~9.5% was taken off Coffin Bay. The fishery also expanded north toward Arno Bay and to Wedge Island.

In 2003, the catch was taken over the broad area in Spencer Gulf, extending from Thistle Island to Arno Bay. A small proportion of the catch was also taken in Investigator Strait. As the fishery expanded northwards in Spencer Gulf, more effort and catches occurred closer to shore. Although some effort occurred off Coffin Bay, no major catches were recorded in this region.

Further spatial expansion of the fishery occurred during 2004, and a large proportion of the total catch was taken near Wedge Island and east of Althorpe Island. Catches also occurred along the northern coast of Kangaroo Island, between Cape Borda and Marsden Point (Fig. 7). Approximately 87% of the total catch was taken in Spencer Gulf and the western end of Investigator Strait.

In 2005, large catches were taken near Thistle, Wedge and Althorpe Islands and further north, off Arno Bay. The inshore areas around the Sir Joseph Banks Group and along the western coast of Spencer Gulf were fished more than in previous years. In 2005, the spatial extent of the SASF expanded significantly and catches (Fig. 7) and effort (Fig. 8) occurred in the EGAB, off the south coast of Kangaroo Island, southern Gulf St Vincent and Coffin Bay.

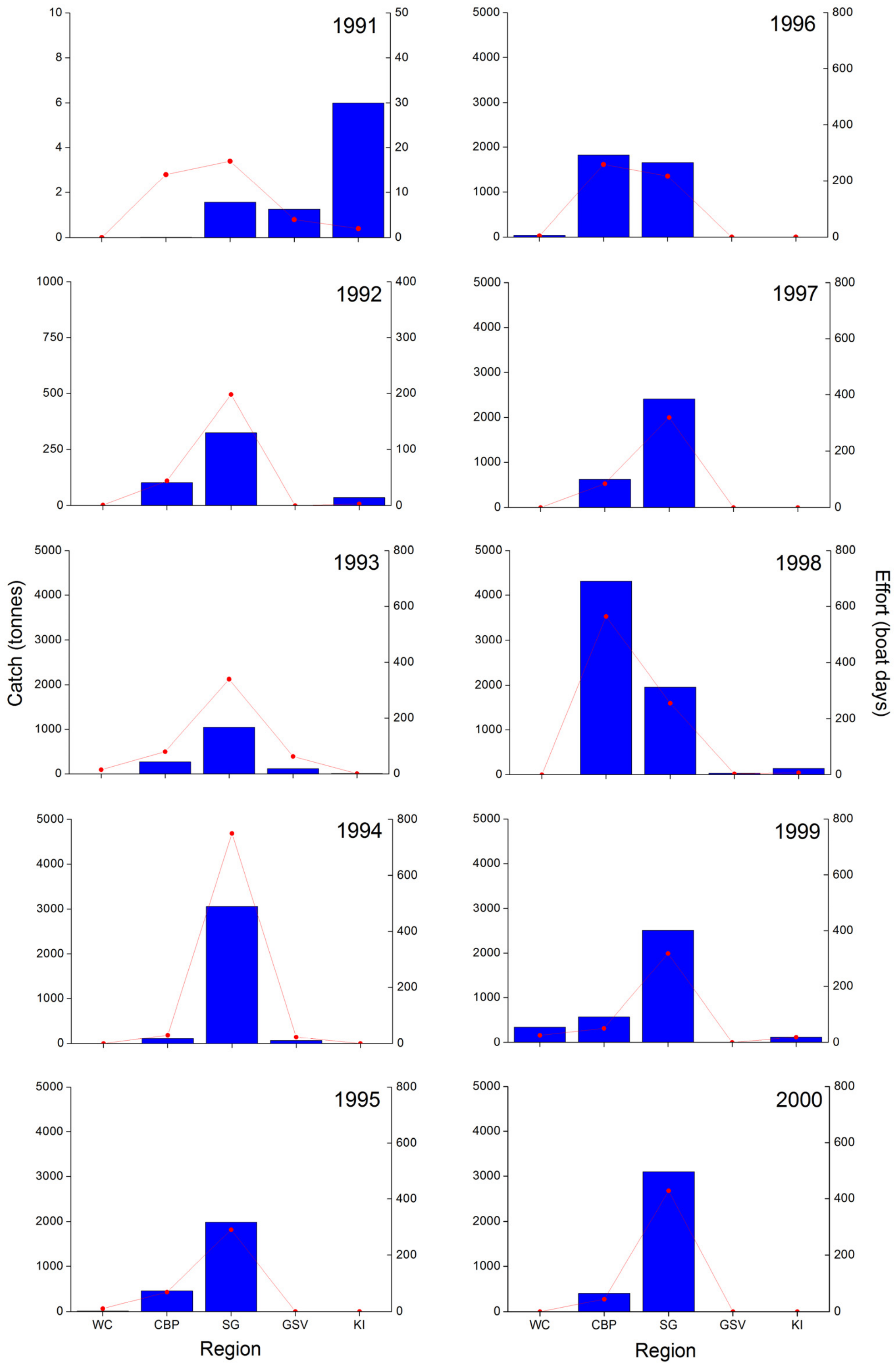

Figure 6. Spatial trends in catch and effort between 1991 and 2000.

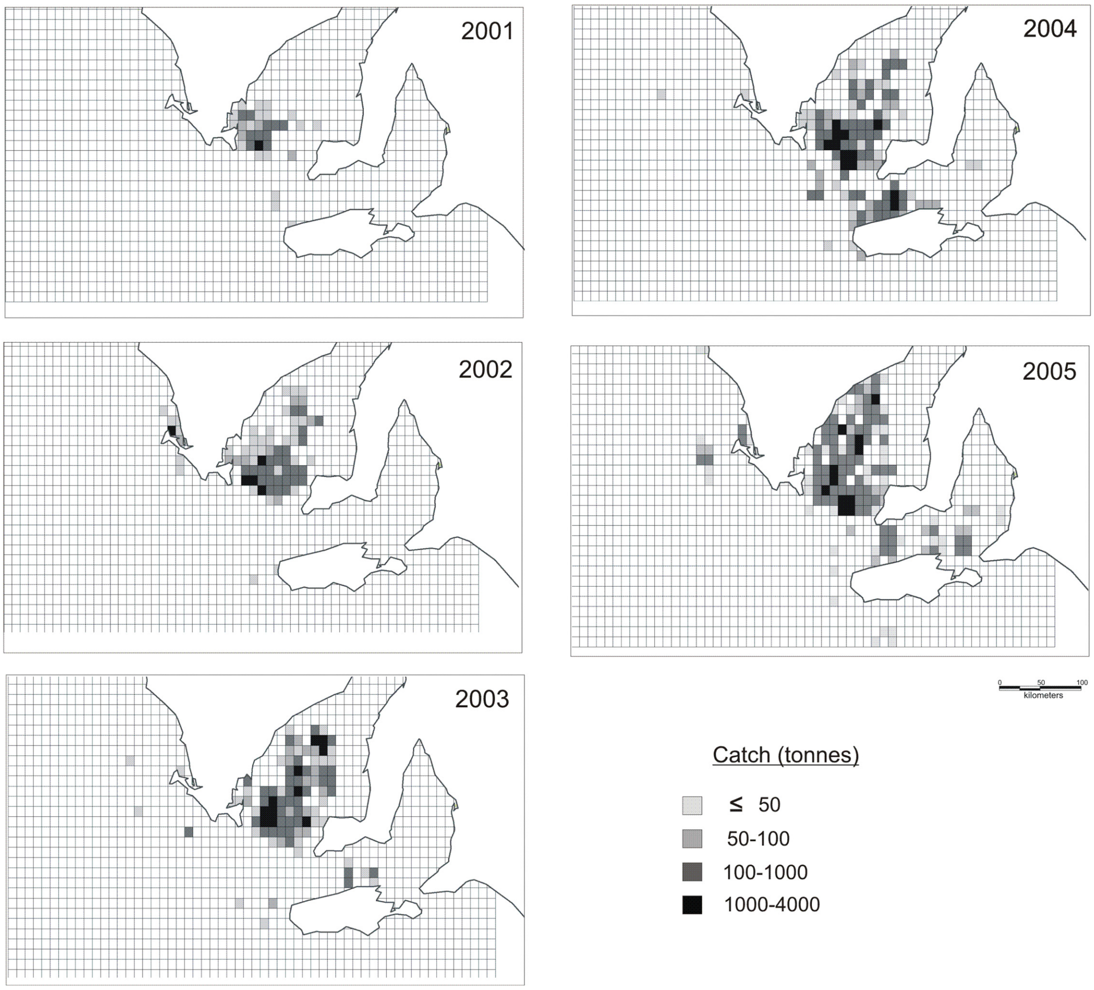

Figure 7. Spatial trends in annual catches between 2001 and 2005.

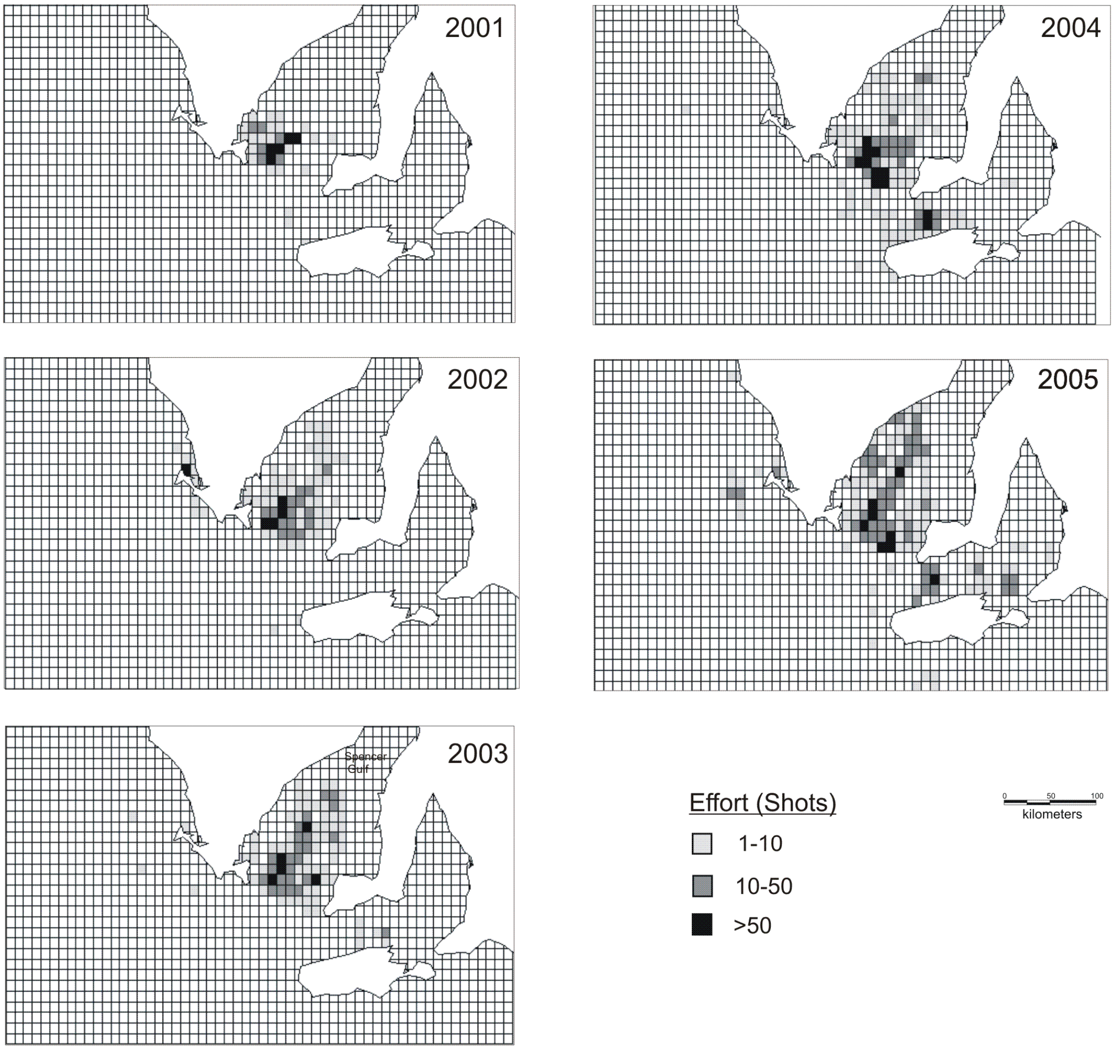

Figure 8. Spatial trends in annual effort between 2001 and 2005.

2.4.3 Intra-annual patterns

Figure 9 shows that the waters of southern Spencer Gulf were fished during the first quarter (January – March) of 2005 with large catches taken near Wedge and Thistle Islands and east of Dangerous Reef. During the second quarter (April – June), the fishery expanded northward in Spencer Gulf and southward into Investigator Strait, which was reflected in the peaks in monthly catches (Fig. 4). The area off Arno Bay was fished extensively during this quarter. Catches were also taken in Investigator Strait, near Althorpe Island and between Cape Cassini and Marsden Point on the northern coast of Kangaroo Island. Effort and catches declined significantly during the third quarter (July – September), however the fishery continued to expand out of Spencer Gulf into the EGAB, Coffin Bay and southern Gulf St Vincent. This spatial expansion continued during the last quarter of the year (October – December), and the fishery operated in areas south of Kangaroo Island, off Corny Point and in the EGAB (Fig. 9).

2.5 Estimated Lost Catch

Fishers have recorded the estimated amount of catch lost per shot since 2001. During the 2003 and 2004 fishing seasons an estimated 3,660 t and 2,911 t of catch were lost, respectively (Fig. 10). The estimated amount of catch lost declined to 2,507 t in 2005. Recent communication with licence holders suggested there was confusion regarding the classification of lost catch and therefore estimates should be interpreted with caution.

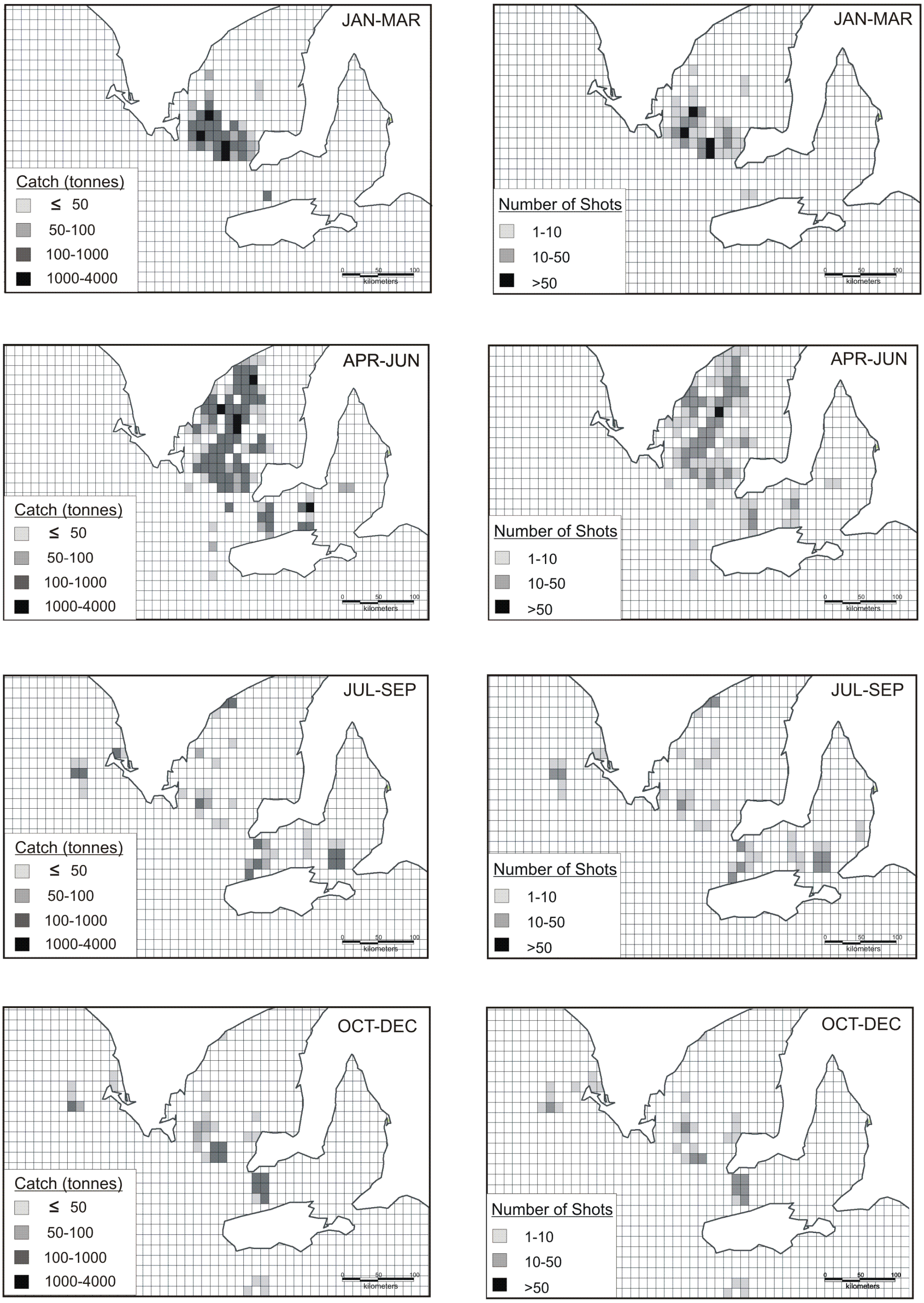

Figure 9. Spatial trends in quarterly cumulative catch and effort in 2005.

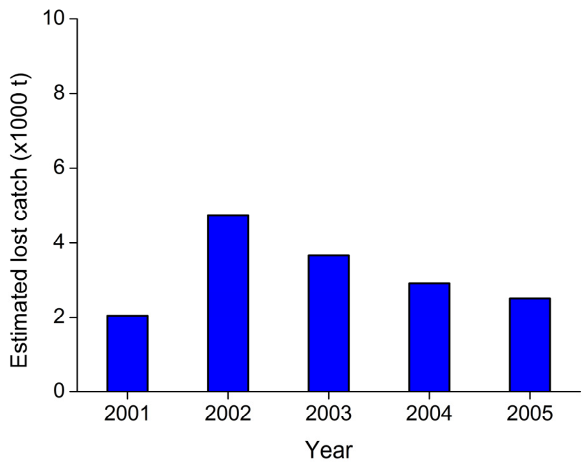

Figure 10. Total estimated lost catch between 2001 and 2005.

2.6 Discussion

Despite the large increases in the total catch since 1999, the SASF has mostly operated near the entrance to Spencer Gulf with effort in Coffin Bay and Investigator Strait varying between years. The quarterly spatial and monthly catch patterns showed that, as in previous years, total catches and the total area fished peaked between April and June. This is largely in response to the high demand for SBT fodder at that time of the year and because weather conditions are often favourable for purse seining.

In 2004 and 2005, the total catches and effort were the highest recorded since the inception of the fishery. During this two year period, ~72,115 t were landed by the fishery, most of which came from the area off Arno Bay, Dangerous Reef, Thistle, Wedge and Althorpe Islands, and along the northern coast of Kangaroo Island. This was the result of unprecedented levels of fishing effort in this region, which culminated in 2,983 net-shots over 2,282 boat days in 2004 and 2005 (combined). This level of exploitation of the stock in this relatively small geographical area is of concern because; (1) the annual spawning biomass estimates used to set TACs are based on an area ~9x larger than the main fishing area and (2) an increasing proportion of the catch were juveniles (See section 3.3, Fig. 12 and 14).

Analysis of mean catch rates (CPUE) using boat days and net-shots as units of effort showed that the CPUE calculated using the low resolution measure of effort (boat days) declined between 2003 and 2005, whereas the converse occurred when the higher resolution measure of effort (net-shots) was used. This further supports the notion that CPUE is a poor indicator of abundance and is not suitable for assessing the status of sardine stocks (Cochrane 1999).

Estimates of lost catch have declined since 2002. Recent communication with licence holders suggests that there has been confusion regarding the classification of lost catch. Hence, estimates of lost catch presented herein should be interpreted with caution until this issue is clarified in 2006. Studies in other small pelagic fisheries suggest that the release of unwanted catch has the potential to contribute significantly to overall fishing mortality (Mitchell *et al.* 2002; Stratoulakis and Marcelo 2002).

3. BIOLOGICAL RESEARCH

3.1 Introduction

Data included in this section were obtained from (a) the commercial catch sampling program between 1995 and 2004 and (b) fishery independent surveys between 1998 and 2005. These data are used to describe the size, age, growth and reproductive patterns of sardine in SA waters.

3.2. Methods

3.2.1 Size Structure

Sampling

Samples were collected from commercial catches between 1995 and 2004. During the mid-late 1990'samples were collected straight from commercial vessels by Mr Sid Hanson, Mr Tony Jones, Mr Tony Rowlings and samples were supplied by SA Premium Pilchards between 2000 and 2006.

Fishery independent samples were collected from *RV* Ngerin 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). This net was set during annual DEPM surveys at locations in Spencer Gulf, Investigator Strait and the EGAB. Surface and sub-surface lights (500 W) were used to attract sardine schools within the vicinity of the vessel. Soak times typically varied from 15 minutes to three hours.

The size structures of catch samples were monitored using length frequency analysis. In 2005, all fishery independent samples (N = 32, n = 4,828) used in the DEPM were measured for length frequency analysis, whereas in previous years only additional samples for age determination were measured. Fish were 'binned' in 10 mm length classes in both the fishery-independent and -dependent samples. All lengths refer to caudal-fork length, CFL unless otherwise indicated.

3.2.2 Age Structure

Otolith preparation and interpretation

Both otoliths (sagittae) were removed from 10 – 20 fish from each sample. Otoliths were soaked overnight in 10% Sodium Hypochlorite solution to remove excess tissue, rinsed in distilled water and dried in IWAKI™ plastic microplates. Translucent zone counts were made for one whole otolith from each fish under reflected light against a flat black background.

Readability indices (RI)

Sardine otoliths were classified as 1 = excellent, 2 = good, 3 = average, 4 = poor and 5 = unreadable based on standard criteria relating to their interpretability.

Relationship between age and otolith weight

Relationships between otolith weight and age were determined for otoliths with the highest readabilities (1 – 2) from fish sampled in each year. Linear regression analyses were used to describe these relationships. These regressions were used to calculate the ages of fish with otoliths that were difficult to interpret.

Age structure

Otolith weight-age regressions were used to calculate the age structures of catch samples. Age structures were derived from the percentages of sardine in each age class and ages were rounded to the nearest whole year.

Growth patterns

Otoliths collected from catch samples between 2002 and 2003 were used to determine growth patterns. Von Bertalanffy (*VB*) growth model fits to length at age data were estimated using non-linear least-squared procedures and Levenberg-Marquardt iterations. The von Bertalanffy model (Xiao 1996) is represented by the equation:

$$L(t) = L_\infty - \left(L_\infty - L(t_0)\right)\exp\left(-k\left(t - t_0\right)\right)$$

where $L(t_0)$ = 2.2 mm TL (Size at hatch for sardine larvae from Neira *et al.* 1998), and t_0 = 0 years, L_∞ is the asymptotic length predicted by the equation and k is a constant describing the rate at which the asymptotic length is reached.

3.2.3 Reproduction

Macroscopic gonad staging

Ovaries were staged macroscopically based on the following physical criteria where stage 1 = immature, stage 2 = maturing, stage 3 = mature, stage 4 = hydrated (spawning) and stage 5 = spent (recently spawned). Testes were staged where stage 1= immature, stage 2 = mature and stage 3 = mature (running ripe).

Size at maturity (L_{50})

Sizes at 50% sexual maturity (L_{50}) were estimated for sardine collected from catches between 1995 and 2004. The L_{50} was determined by fitting a logistic curve to the percentages of maturing and mature (macroscopic gonad stages ≥ 2) fish grouped into 5 mm size classes during the spawning season. The logistic curve fitted is represented by the equation:

$$P_L = 1/\left[1 + e^{(a+bL)}\right]$$

where P_L is the proportion in each size class and a and b are constants estimated by minimising the sum of squares using the *Solver* function in Excel™. The length at 50% maturity was estimated from $L_{50} = -a/b$. Differences between sexes were determined using Kolmogorov Smirnov tests (KS)

Sex ratio

Sex ratio (*SR*) was calculated for commercial catch samples collected from Spencer Gulf and Coffin Bay between 1995 and 2004 using the equation:

$$SR = \frac{nF}{(nF + nM)},$$

where *nF* is the number of females and *nM* is the number of males in samples. Pearson's chi –square tests were used to determine if there were significant differences in sex ratios between sexes in each region.

Macroscopic analysis of gonads

Ovaries were assigned macroscopic stages, based on the following criteria where Stage 1 = immature, Stage 2 = maturing, Stage 3 = mature, Stage 4 = hydrated (spawning) and Stage 5 = spent (recently spawned). Testes were classified as Stage 1= immature, Stage 2 = mature and stage 3 = mature (running, sperm present).

Gonosomatic index (GSI)

Mean monthly gonosomatic indices were calculated using the equation:

$$GSI = \left[\frac{Gwt}{Fwt_{gonadfree}} \right].100$$

where *Gwt* is gonad weight and *Fwt* is gonad-free fish weight for fish with gonads of macroscopic stages ≥ 2. It is important to note that it is difficult to macroscopically distinguish between Stage 2 and Stage 5 gonads in some frozen samples.

3.3 Results

3.3.1 Size Structure

Commercial catch – All combined in 2004

During 2004, sardine (n = 3,818) from commercial catches were between 90 and 200 mm. The majority (95.6%) were collected in Spencer Gulf, 2.1% were from Investigator Strait and 2.4% were from Coffin Bay. Size modes were present at 120 and 160 mm (Fig. 11). In 2004, sardine <150 mm, comprised 24% of the catch samples for all locations combined.

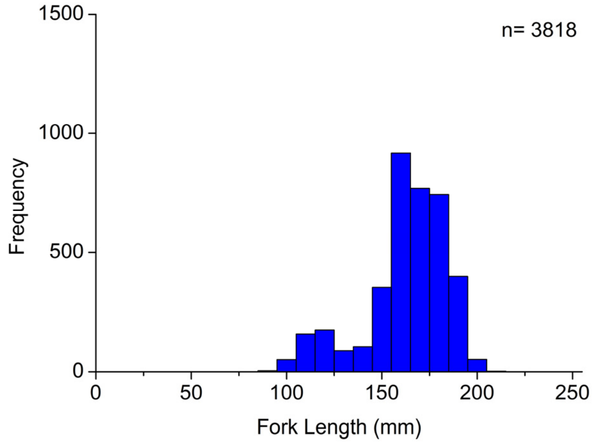

Figure 11. Length frequency distributions for catch samples from Spencer Gulf, Investigator Strait and Coffin Bay in 2004.

Annual patterns - Spencer Gulf

Between 1995 and 1999, sardine taken in Spencer Gulf were mostly 120 to 160 mm, with modes at 130 – 140 mm (Fig. 12). Between 2000 and 2002, sardine from catches were mostly >150 mm with modal sizes ranging between 160 and 170 mm. In 2003 and 2004 catch samples were bimodal as significant quantities of juveniles between 80 and 120 mm were taken from Spencer Gulf. The remainder of the catch samples were mostly 150 – 180 mm during these years (03/04) (Fig. 12). Between 1996 and 2003 no sardine in commercial catch samples were ≤100 mm, CFL.

Annual patterns - Coffin Bay

Between 1995 and 1998 samples from Coffin Bay mostly consisted of fish ranging between 150 and 180 mm (Fig. 13). Following the second mass mortality event in 1998/9 there was a decline in the modal size to 150 mm. Fishing effort declined in this region following the second mass mortality event. Samples off Coffin Bay had modal sizes of 150 – 180 mm sardine in 2002 and 2003, however few individuals (n = 312) were measured during this period. In 2004, only n = 90 fish were collected from catches in Coffin Bay and the modal size was 140 mm (Fig. 13).

Monthly patterns - Spencer Gulf

In 2004, significant quantities of 100 – 120 mm fish were taken in June and September, which is similar to the pattern in 2003, when small fish were taken in July and November (Fig. 14). Length frequency distributions were mostly uni-modal with the exception of in June and September. Samples mostly consisted of fish in the 160 – 180 mm size classes during the remainder of the year.

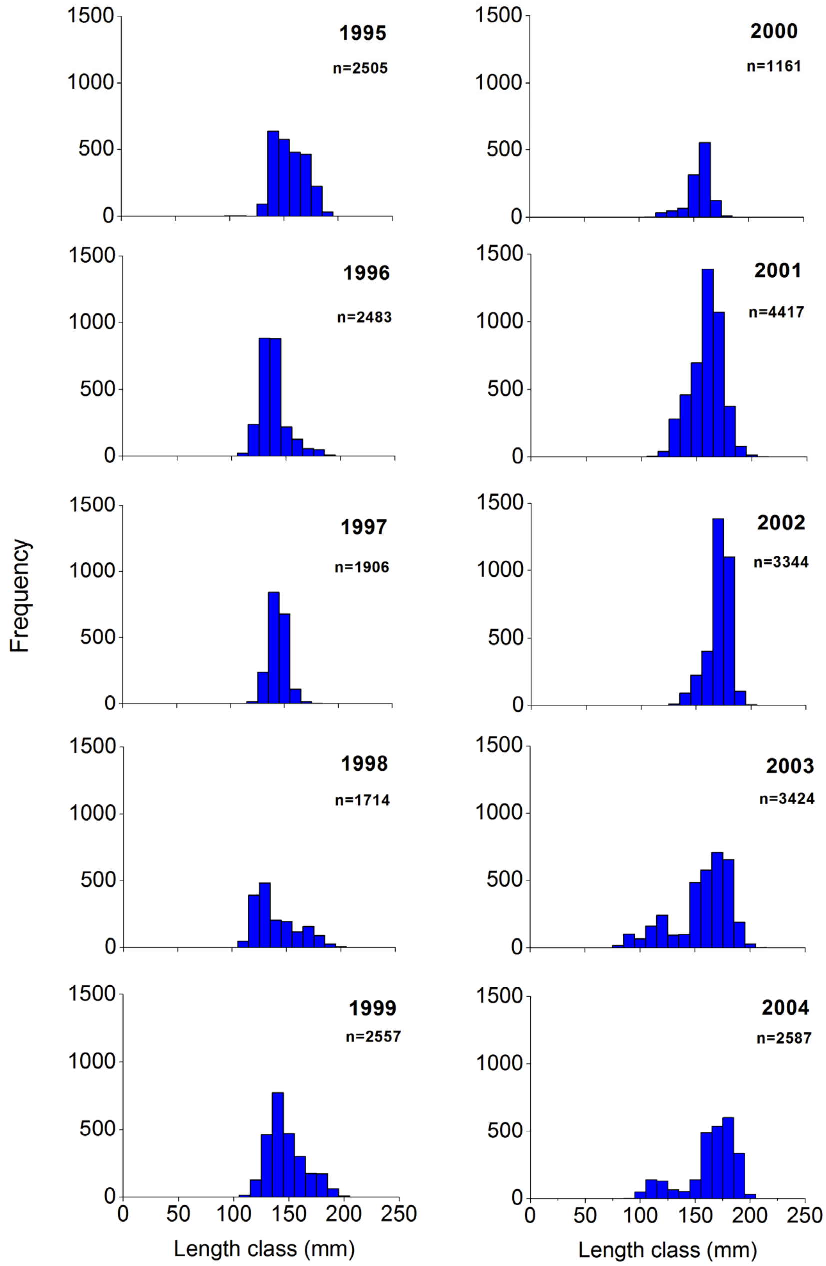

Figure 12. Length frequency distributions by year for catch samples from Spencer Gulf between 1995 and 2004.

Fishery Independent

Samples of larger fish with length frequency modes ≥170 mm have consistently been collected from waters around offshore islands, including Flinders, St Francis and Greenly Islands in the EGAB (Fig. 15 and 16).

During 1998, size classes ranged from 120 – 190 mm and dual modes were present at 130 and 170 mm. In 1999, the modal size remained at 170 – 180 mm, which represented ~51% of samples. During 2000, fish between 150 and 180 mm dominated samples with a single mode at 160 mm. There appeared to be a modal progression from the 160 mm size class in 2000 to the 170 mm size class in 2001. The 150 – 180 mm size classes present during 2000, again represented ~97% of fish collected in 2001.

Samples of adult sardine were difficult to obtain in the EGAB during 2002 and 2003. This coincided with strong south-easterly winds during summer/autumn and cool (14.5 –16°C) patches of surface water across the inner shelf. Size frequency distributions for samples collected in 2002 and 2003 showed sardine ranged in size between 110 and 220 mm. In 2002, most fish were 140 to 190 mm with a single mode at 180 mm. During 2003, sardine mostly ranged in size between 140 and 180 mm and dual size modes were present at 140 and 170 mm. In 2004, most fish sampled were 180 – 190 mm and few were <170 mm.

In 2005, sardine were measured from samples collected at five locations from Investigator Strait (IS) to St Francis Island in the Nuyts Archipelago (EGAB). Locations included Scotts Cove (IS), Wedge (SG), Greenly (GAB), Flinders (FI), and St Francis Islands (EGAB). These sardine were mostly 170 – 200 mm with few <170 mm, as observed in 2004 (Fig. 16).

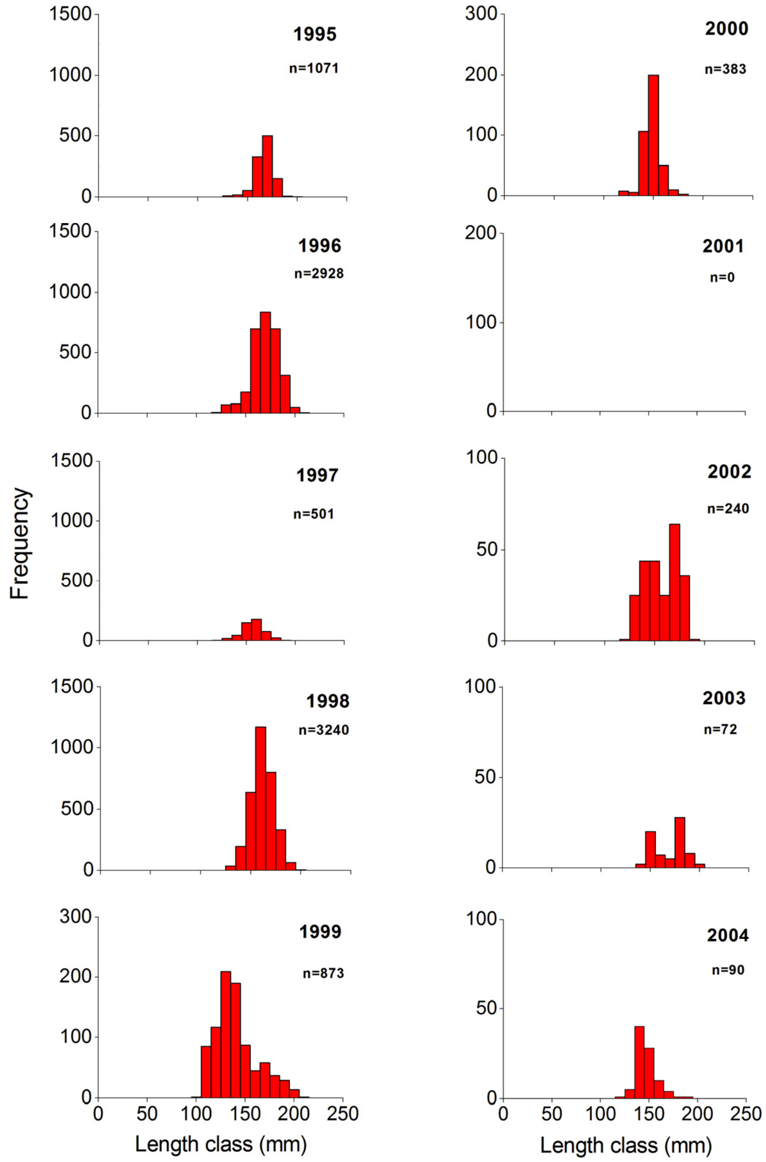

Figure 13. Length frequency distributions for catch samples from Coffin Bay between 1995 and 2004.

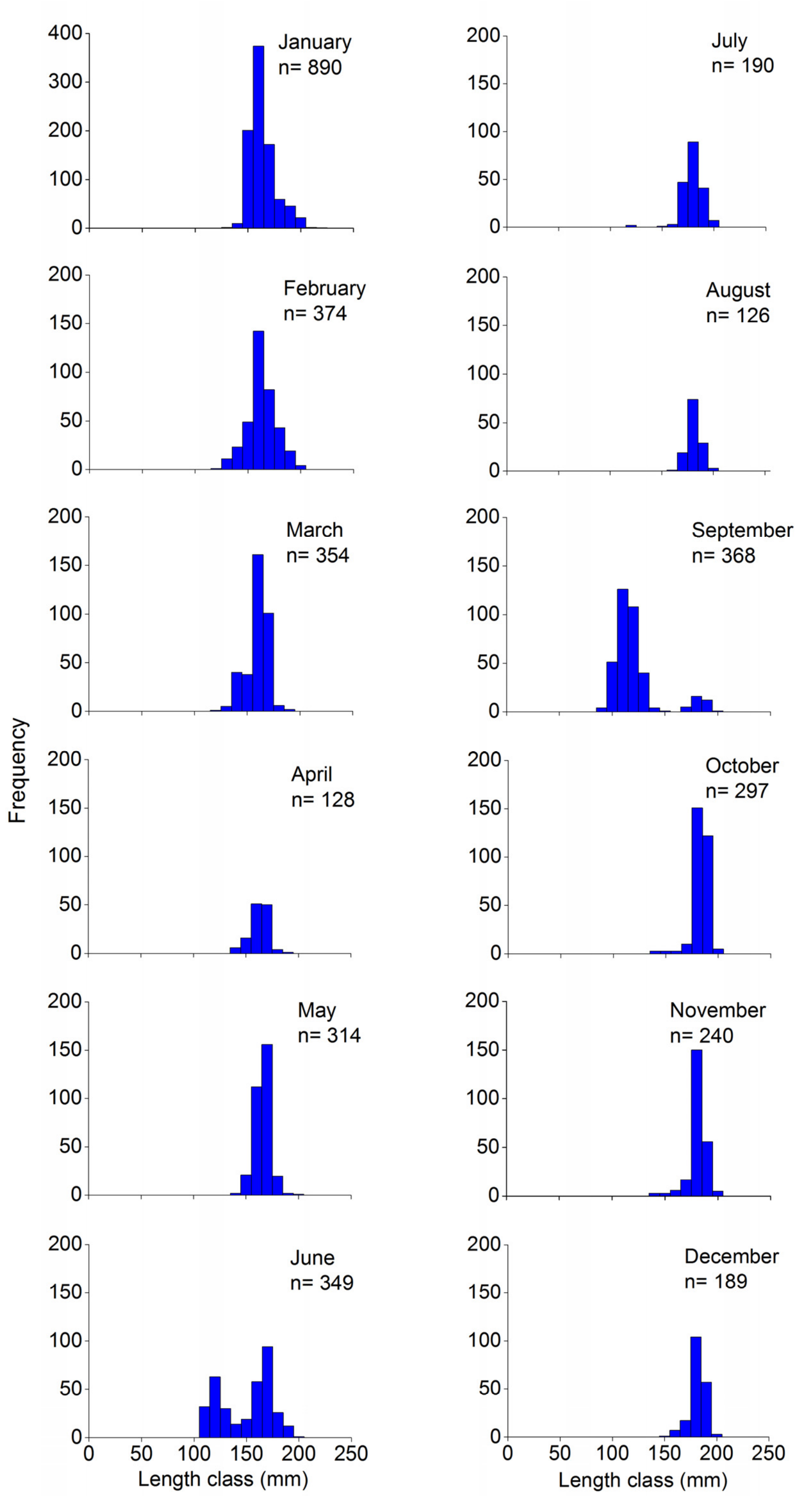

Figure 14. Length frequency distributions by month for catch samples from Spencer Gulf in 2004.

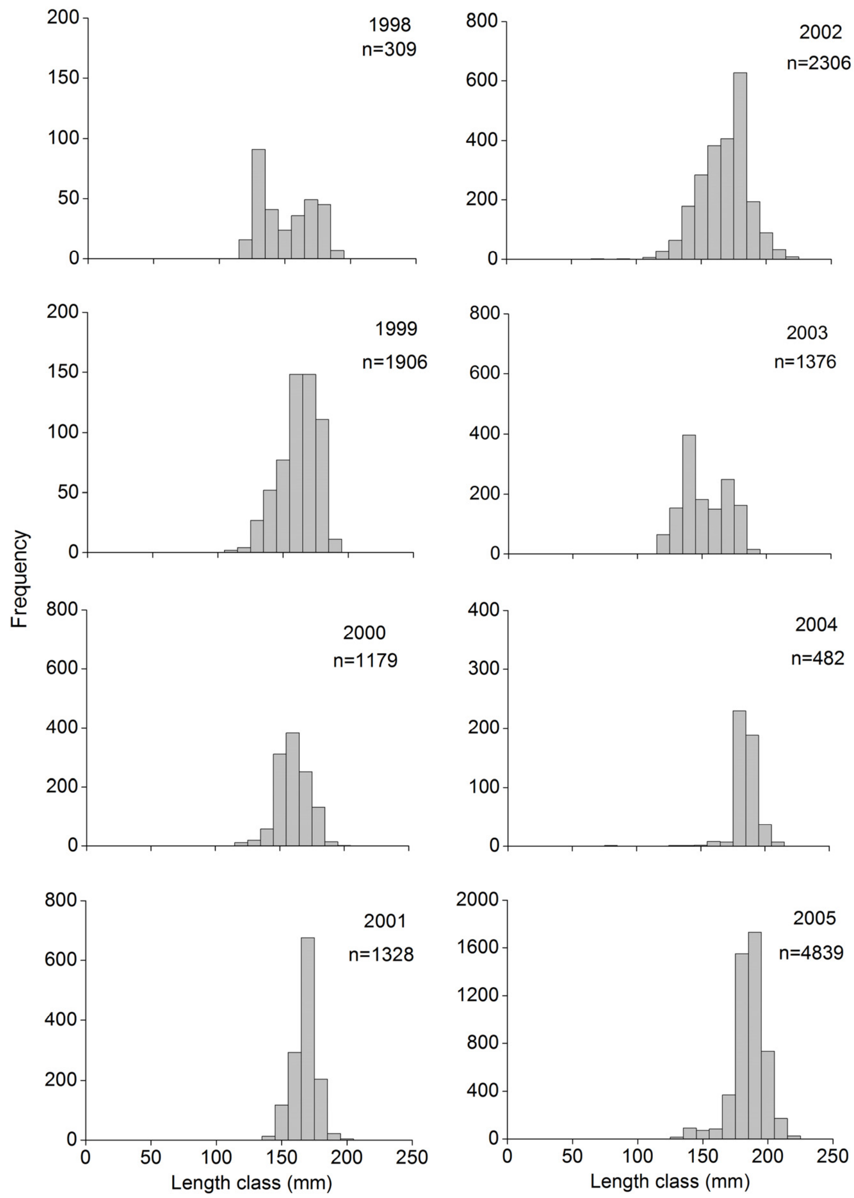

Figure 15. Length frequency distributions for fishery independent samples collected between 1998 and 2005.

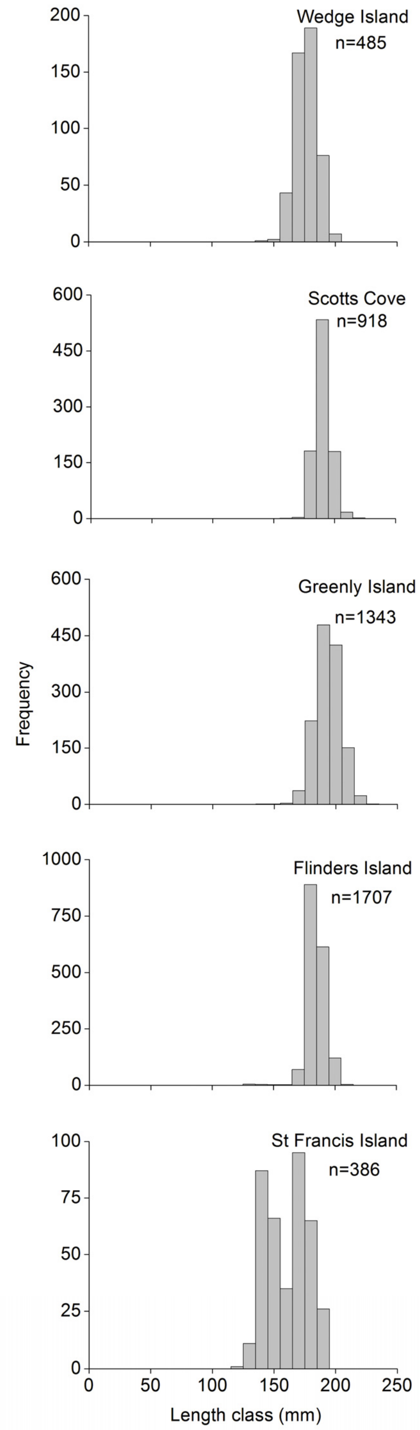

Figure 16. Length frequency distributions by location for fishery independent samples collected in February and March 2005.

3.3.2 Age Structure

Readability indices (RI)

A total of 1,542 otoliths collected in 2004 were assigned RI scores between 1 and 5. Of these otoliths, 0.6% were assigned an RI score of 1, 7.8% were assigned scores of 2, 44.4% were 3s, 30.1% were 4s and ~17.2% were 5s (Fig. 17).

Relationship between age and otolith weight

The relationship between age and otolith weight was determined from otoliths with readabilities of 1 to 2. In 2004, the significant linear relationship, Age = 2.90.Oto.wt - 0.64, (R^2 = 0.72, P<0.0001, n = 129) was used to estimate the age of fish whose otoliths had been assigned readabilities of 3 to 5. Rounded ages were then used to generate age structures for n = 1,525 sardine collected from catches during 2004. Otolith weight as a function of age is shown in Figure 18.

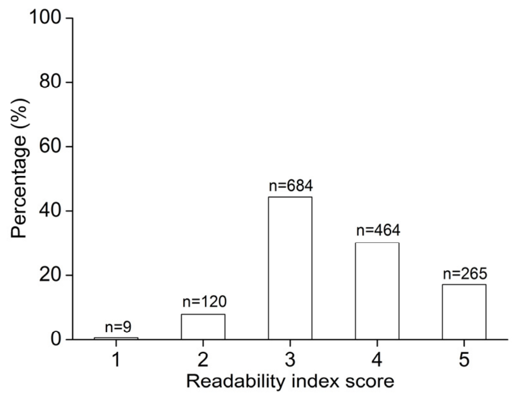

Figure 17. Readability index (RI) scores assigned to sardine otoliths from catch samples in 2004.

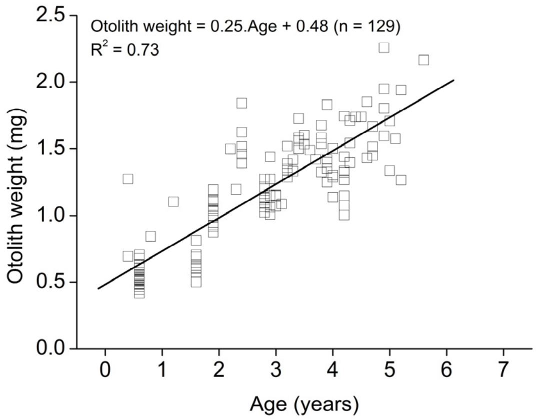

Figure 18. Otolith weight as a function of age for otoliths (RI scores 1 and 2) collected from catch samples during 2004.

Commercial catch – all combined in 2004

In 2004, the combined age structures of commercial catches comprised samples from Spencer Gulf and Investigator Strait. Catch samples were dominated by sardine in the 3 (37%) and 4 (32%) year old ages classes (Fig. 19). The 1 and 2 year old age classes each comprised approximately 9% of samples. Sample sizes of sardine for age determination from Coffin Bay were less than 20 and were excluded from this analysis.

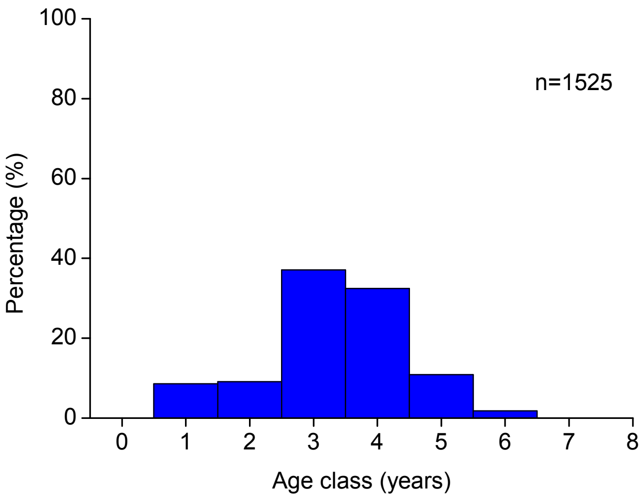

Figure 19. Age structures of catch samples from Spencer Gulf and Investigator Strait in 2004.

Annual patterns - Spencer Gulf

Catch samples from Spencer Gulf during 1995, were dominated by 2 to 4 year olds (Fig. 20). In 1995/6, catch samples mostly comprised 1 and 2 year olds. This trend continued during 1996 to 1998 seasons, with 1 and 2 year olds comprising >60% of samples. The 2 year old age classes dominated samples during 1999 and progressed to the 2 and 3 year old age classes in 2000. During 2001, the 2 and 3 year old age classes continued to dominate the catch samples in Spencer Gulf. The 2 and 3 year old age classes from the previous year progressed to the 3 and 4 year old age classes in 2002. During 2003, the 0 and 1 year old age classes were present in samples for the first time. The 2 and 3 year old age classes in 2003 progressed to the 3 and 4 year old age classes in 2004. In 2004, the age structure was characterised by fewer 2 year old fish, with the 1 and 2 year old age classes comprising ~18% of the samples (Fig. 20). The 2 and 3 year old age classes comprised 9.3% and 37.6% of samples, respectively.

Annual patterns - Coffin Bay

The 2 to 4 year olds dominated the age structure of samples off Coffin Bay between 1995 and 1999 (Fig. 21). Between 1999 and 2003, few samples were collected from the commercial catch from Coffin Bay due to the contraction of fishing effort away from this region. No commercial catch samples were collected from Coffin Bay during 2001.

In 2002, catch samples collected off Coffin Bay were mostly comprised of 2 and 3 year olds (Fig. 21). The strong 3 year old age class present in 2002 was still evident in samples as a 4 year old age class in 2003. During 2003, the 5 year old age class, which had not been evident in the age distributions since 1997/8, reappeared in samples collected off Coffin Bay. However, these data require cautious interpretation due to the small sample sizes. In 2004 less than 20 fish were aged from Coffin Bay and therefore no meaningful age structure could be constructed.

Monthly patterns in Spencer Gulf in 2004

Monthly analysis of age structures in Spencer Gulf shows that during 2004, catch samples during most months were dominated by 3 and 4 year olds (Fig. 22). As shown in the monthly length frequency analysis, young fish (1 year olds) were taken in June and September 2004.

Fishery Independent

Adult sardine (n = 3,067) sampled by fishery independent methods between 1998 and 2003 ranged in age between 2 and 7 years old (Fig. 23). In 1998, the 3, 4 and 5 year old age classes comprised 36.7%, 20.3% and 30.4% of samples, respectively. During 2000, the 3 to 5 year old age classes continued to dominate. This pattern continued in 2001, as the 4 (43.3%) and 5 (35.8%) year old age classes were common (Fig. 23). Similarly during 2002, the 3 to 5 year old age classes were prominent. A decline in the modal age occurred during 2003 and the 1 and 2 year old age classes were common. This was matched by a decline in modal size (See Fig. 15).

3.3.3 Growth Patterns

Sardine collected from catch samples in Spencer Gulf and Coffin Bay in 2002 and 2003 ranged from approximately 4 months to 7 years of age. Von Bertalanffy (*VB*) growth parameter estimates are shown in Table 1 and the curve representing the relationship between length and age is shown in Figure 24.

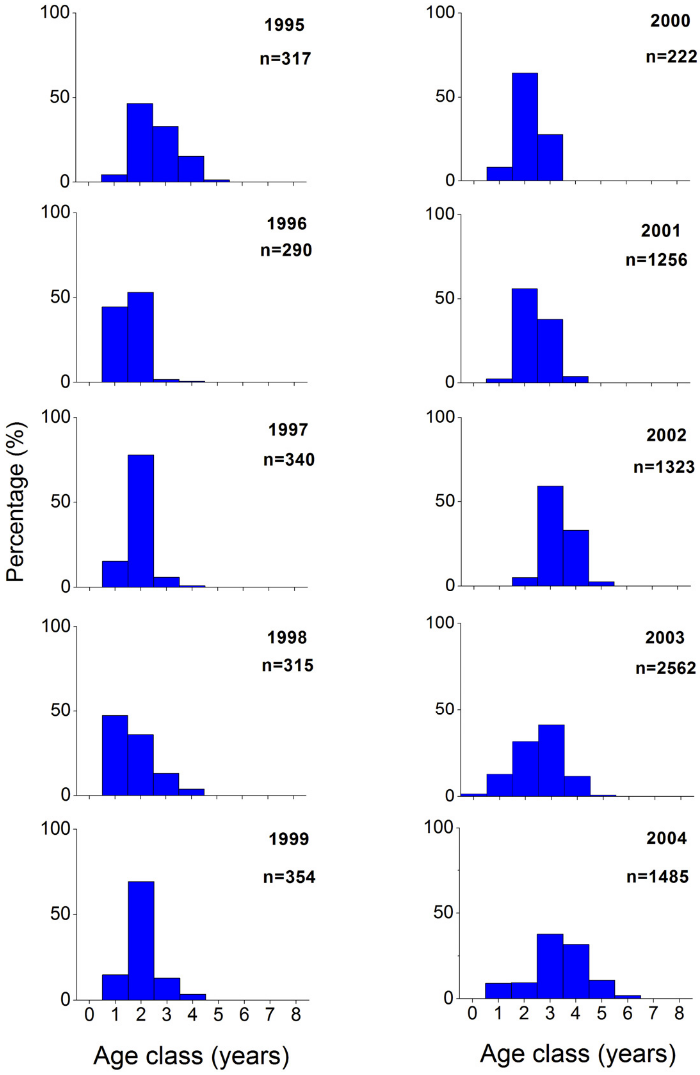

Figure 20. Age structures by year for catch samples from Spencer Gulf between 1995 and 2004.

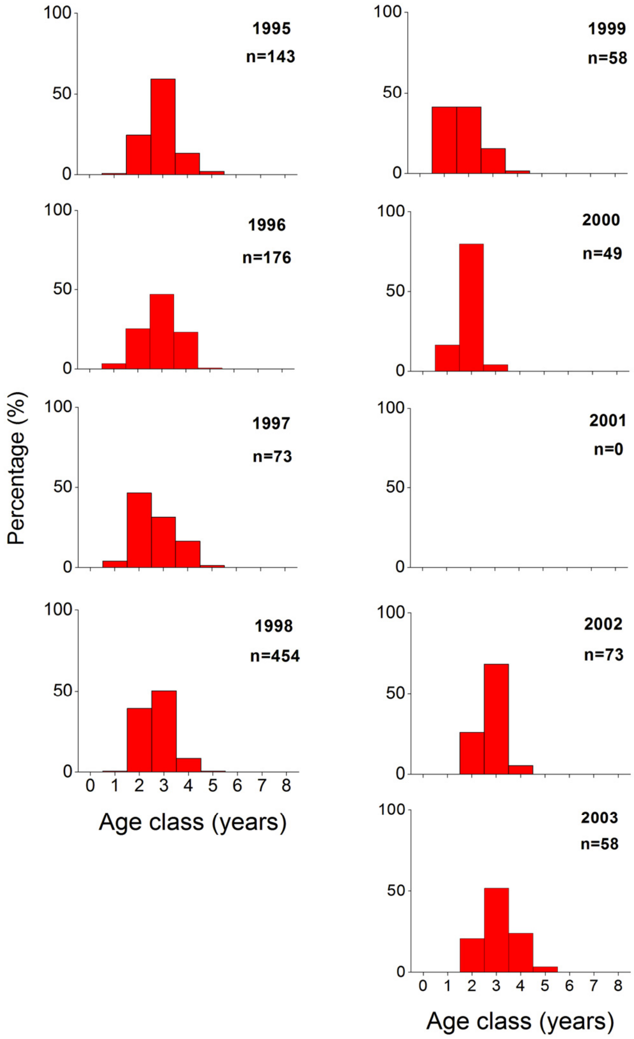

Figure 21. Age structures by year for catch samples from Coffin Bay between 1995 and 2003.

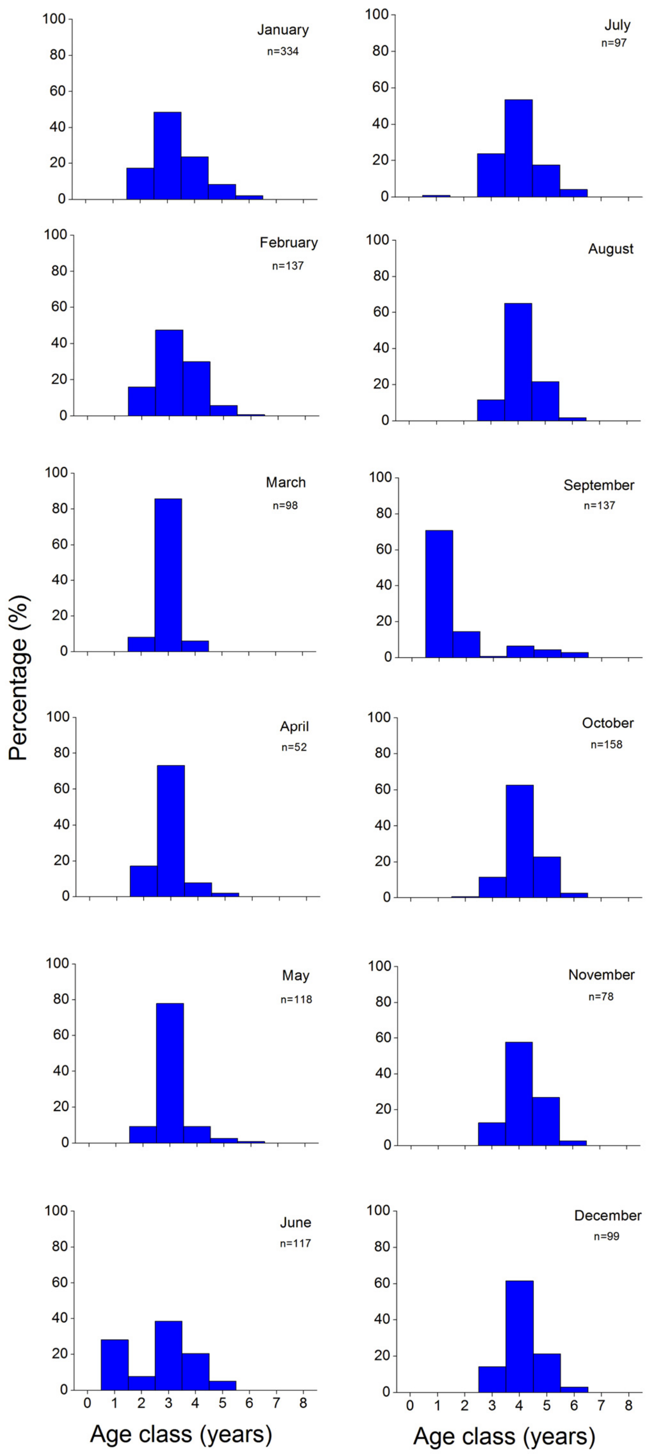

Figure 22. Age structures by month for catch samples from Spencer Gulf in 2004.

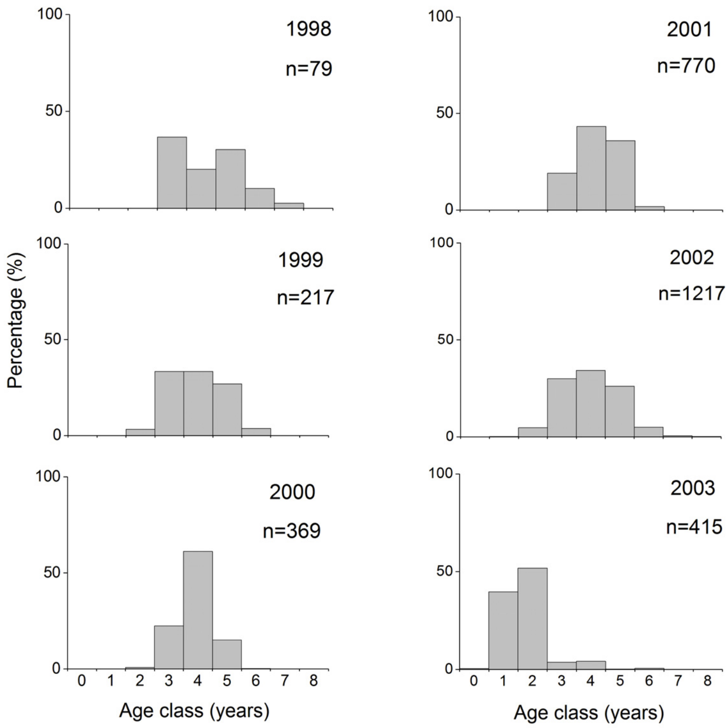

Figure 23. Age structures of sardine collected using fishery independent methods between 1998 and 2003.

Table 1. Von Bertalanffy growth parameters for sardine sampled from catches in 2002/03. The values of the correlation coefficients (r^2) and (*n*) the number of sardine used in each non-linear fit are shown. The 95% confidence intervals for parameter estimates are shown in parentheses.

Source	Length at infinity L_∞ (mm)	Growth coefficient k (yr^{-1})	r^2	n
All Commercial	169.19	1.29	0.32	1,489
	(*168.55 & 169.82*)	(*1.22 & 1.36*)		
Spencer Gulf	168.88	1.47	0.35	1,411
	(*168.34 & 169.43*)	(*1.39 & 1.56*)		

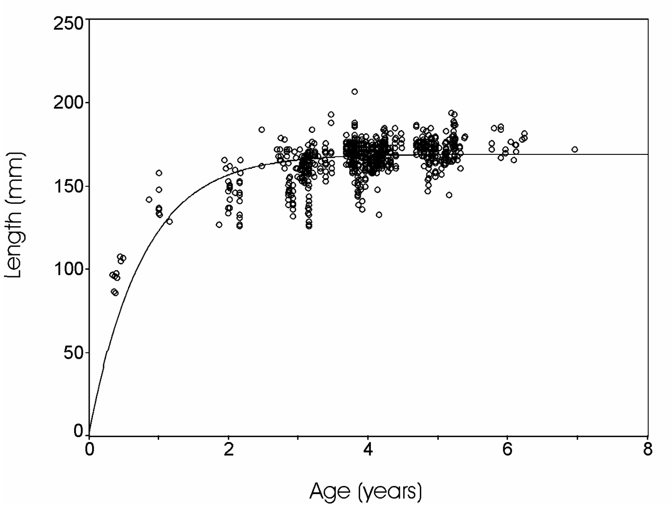

Figure 24. Von Bertalanffy growth curve for sardine from catch samples collected in Spencer Gulf and Coffin Bay in 2002/03.

3.3.4 Reproduction

Size at maturity (L_{50})

Fitting of the logistic curve to the proportion of mature (Stage 2+) fish in each size class showed that 50% of male and female sardine collected from catches between March 1995 and December 2004 reached sexual maturity at 145 and 151 mm, respectively (Fig. 25). There were no significant differences in the logistic curve fits between sexes ($KS = 0.095$, P-value = 1). All males below the 120 mm size class and all females below the 125 mm size class had immature gonads. This analysis showed that of all males (n = 9,048) collected from catches during this period, 21% were smaller than the estimated L_{50} and of females (n = 11,917), 25% were smaller than the estimated L_{50}.

During 2004, 9.2% of female sardine from catch samples were smaller than the estimated L_{50} and 6% of males were smaller than the estimated L_{50}. Of all sardine (both sexes and unidentified sex) collected from catches during 2004, 18% had immature (Stage 1) gonads.

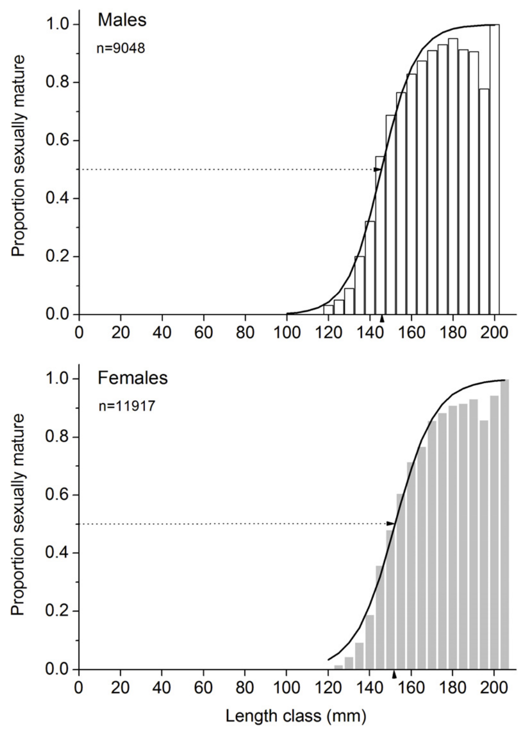

Figure 25. Relationship between length and the proportion of male and female sardine at sexual maturity between 1995 and 2004. Arrows show lengths at which 50% of males and females were sexually mature.

Sex Ratio

Sex ratios for samples from catches were combined between 1995 and 2004 (Fig. 26). As in previous years, sex ratios were skewed toward females (>50%) in Spencer Gulf and off Coffin Bay. Nevertheless, the differences in sex ratios were not significant for either Spencer Gulf = 132, df = 121, P = 0.233) or Coffin Bay (X^2 = 132, df = 121, P = 0.233), even though males were only more common than females off Coffin Bay during two months (September and October).

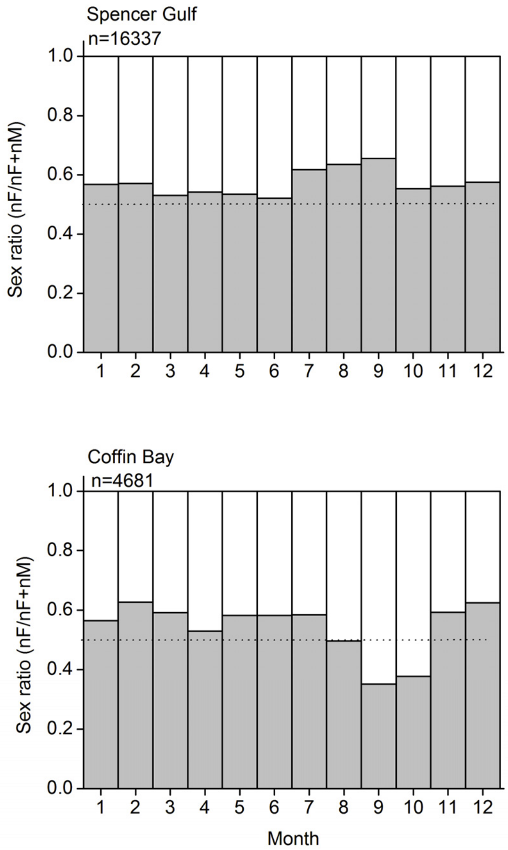

Figure 26. Sex ratios for sardine collected from catches in Spencer Gulf and Coffin Bay between 1995 and 2004.

Macroscopic analysis of gonads

Male (n=7,051) and female (9,127) sardine from catches in Spencer Gulf between 1995 and 2004 mostly had immature Stage 1 and maturing Stage 2 gonads. Mature females (Stage 3) were present in samples between January and April (Fig. 27). Small proportions (<20%) of males and females with mature, Stage 3 gonads were present throughout the year and were most common in February. Females with Stage 4 ovaries have comprised a very low proportion (n=29, <1%) of catch samples collected since 1995.

There were clear seasonal patterns in the gonad stages of male (n=1,856) and female (n=2,527) sardine collected from catches off Coffin Bay between 1995 and 2004. Fish with mature, Stage 3 gonads comprised >50% of the catch samples collected between January and March (Fig. 27). Small proportions (<5%) of the samples also comprised spawning females between November and April. No fish that were spawning (Stage 4) were present in samples in May. Most fish had Stage 1 and to a lesser extent, Stage 2 gonads between June and October. This pattern continued in September and October as >80% of males and females had Stage 1 gonads.

Gonosomatic Index (GSI)

Patterns in mean GSI indicated that the reproductive period for female sardine in Spencer Gulf was between November and March with males showing a similar seasonal pattern (Fig. 28). Mean GSI for females were highest (>3.5) in January and February. The mean GSI for males was >3.5 between January and April. For females, mean GSI was lowest in August and September and for males mean GSI was low between June and September.

For fish collected off Coffin Bay, the patterns in mean GSI indicated that the reproductive period for males and females (GSI >3) was between January and March, with highest mean GSI for both sexes occurring in March. The high mean GSI value for females for September is only based on n = 3 individuals and is likely to be an outlier. The lowest mean GSI for fish sampled off Coffin Bay were between July and October.

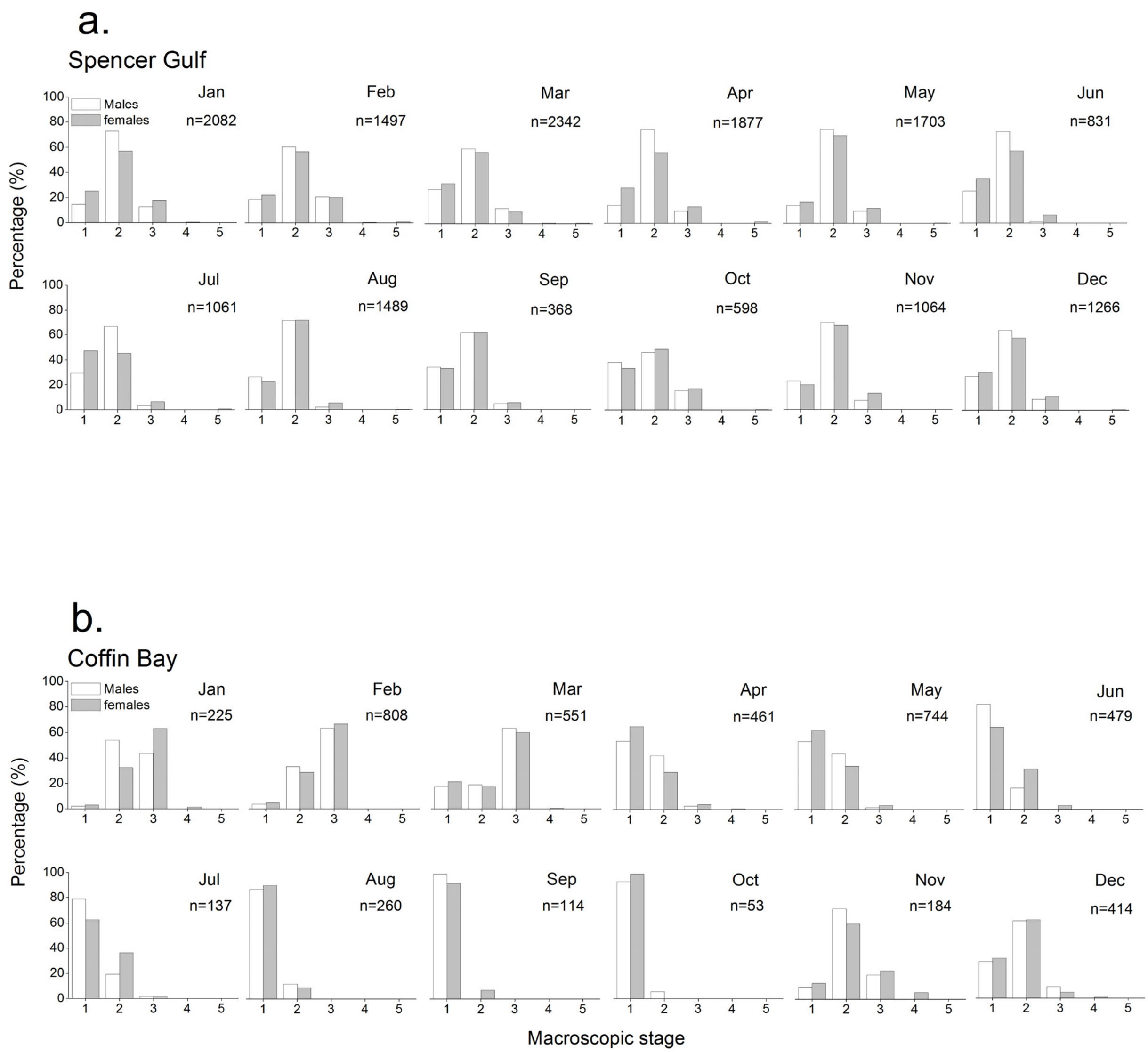

Figure 27. Macroscopic gonad stages for males and females in Spencer Gulf (a) above and Coffin Bay (b) between 1995 and 2004.

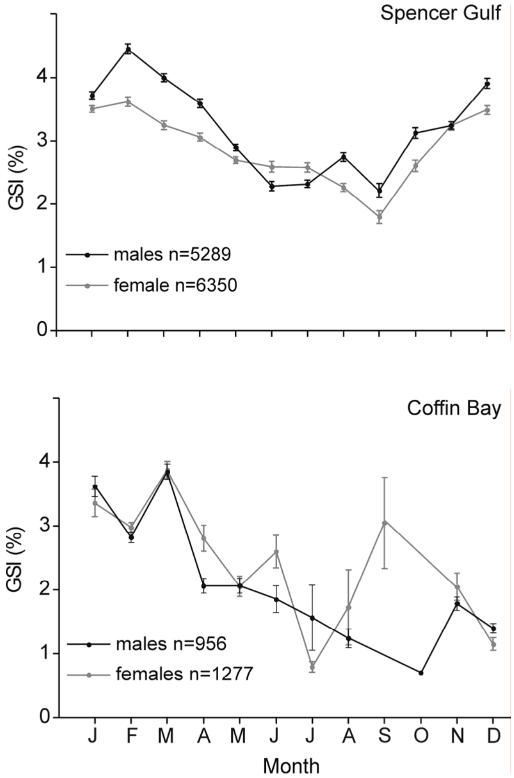

Figure 28. Mean monthly GSI for males and females in Spencer Gulf and Coffin Bay between 1995 and 2004.

3.4 Discussion

This analysis supports previous comparisons of the size and age structures of fishery independent and commercial catch samples, which have shown that samples collected from catches may not be representative of the broader population (Ward *et al.* 2005a). Fishery independent sampling in 2004–2005 provided further evidence that larger sardine (180 – 220 mm) occur around offshore islands in the EGAB, whereas the catch samples taken in Spencer Gulf had a broader size distribution, with fish ranging from 100 to 190 mm. This may, in-part, be related to differences in fishery and fishery independent gear types, however multi-panel gillnets used during fishery independent surveys have proven to be effective at sampling a range of juvenile and adult size classes (~60 – 220 mm).

The previous fishery assessment showed that uncertainty in sardine age estimates is relatively high (Average Percent Error = 15.6%, CV = 22.1%) due to difficulties in interpreting annual zones in otoliths (Rogers *et al.* 2005). This issue has partly been overcome by using age-otolith weight relationships based on a subset of the best otoliths to determine age structures of samples from catches during each year. However, the underlying uncertainties in the age estimates need to be considered when interpreting the age structure information. Further work is required to refine the analytical and validation techniques underpinning these age estimates. Maximum likelihood models that incorporate information on fish length, age and otolith weight to construct age structures are currently being evaluated for SA sardine (see Francis and Campana 2004; Francis *et al.* 2005). Age structures showed the catches in southern Spencer Gulf were mostly comprised of 1 to 4 year olds, and with the exception of 2003, the age structure of the fishery independent samples was mostly comprised of 2 to 6 year olds. With the expansion of the fishery into the EGAB and off Kangaroo Island, it is expected that larger, older sardine may comprise an increasing proportion of catches in future years.

Growth analysis suggests that sardine exhibit considerable variation in length at age in SA waters. The magnitude of the *VB* growth parameters (k and L_∞), reflect the moderate to high growth of sardine prior to the onset of sexual maturity and slower growth during adulthood. SA sardines grow faster than those in WA and slower than those in more productive ecosystems, including the California and Benguela Current systems off the coast of North America and South Africa (Ward *et al.* 2005a).

The monthly patterns in the macroscopic stages of gonads and mean GSI provide evidence that sardine are in reproductive condition in summer and autumn in SA, with the peak occurring in February-March. Although the most important fishing months are between March and June (ie partially overlap with the spawning season), our analysis shows that spawning females (Stage 4) have comprised a low proportion (< 1%) of catch samples since 1995. This provides further evidence that spawning aggregations of clupeoids may have behaviours that influence their vulnerability to certain gear types (Hewitt 1985) and demonstrates the importance of obtaining fishery independent samples to estimate the reproductive parameters used in the DEPM.

Of samples collected from catches since 1995, all males below 120 mm and all females below 125 mm were immature (juveniles). Since 1996, samples from commercial catches were exclusively comprised of sardine larger that the 100 mm size class. However, in 2003 and 2004, samples from catches contained significant quantities of small juveniles (≤ 100 mm) and in the later year, 9.2% of females and 6% of males were smaller than the estimated L_{50} for each sex.

4. SARDINE SPAWNING BIOMASS ESTIMATES BETWEEN 1995 AND 2005

4.1 Introduction

This section provides the current "best estimates" of the spawning biomass of sardine in SA for the period 1995 to 2005, following reviews of previous estimates conducted by SARDI Aquatic Sciences and two external agencies (Neira *et al.* 2005; Smith and Smith 2006).

4.2 Methods

4.2.1 The Daily Egg Production Method

SARDI Aquatic Sciences has used the DEPM to estimate the spawning biomass of sardine in SA since 1995. This method relies on the premise that spawning biomass can be calculated from estimates of the number of pelagic eggs produced per day in the spawning area (daily egg production) and the number produced per female (daily fecundity). Spawning biomass (B) is calculated according to equation 1:

$$B = \frac{P_0 \cdot A \cdot W}{R \cdot F \cdot S} \quad \ldots\ldots\ldots\ldots\ldots \qquad (1)$$

where P_0 is mean daily egg production, A is the spawning area, W is the mean weight of mature females, R is the sex ratio, F is the mean batch fecundity and S is the mean spawning fraction (Lasker 1985; Parker 1985; Alheit 1993).

4.2.2 Sampling Area

Between 1995 and 2005, 2 – 3 DEPM surveys of 10 – 14 days duration have been conducted annually from *RV Ngerin* during the spawning season (January – March). The DEPM surveys are undertaken in gulf and shelf waters and the location of transects and stations where plankton samples were collected is shown in Fig. 29. The number of stations and orientation of transects has varied between years as the survey design has been improved to incorporate the entire spawning area.

During the 1995 and 1996 DEPM surveys, sampling stations and transects were widely spaced, as the primary goal was to identify the main spawning area and its edges. Between 1997 and 2005, transects were orientated northeast-southwest to both improve the efficiency of the survey design and to encompass more of the total spawning area (Fig. 29).

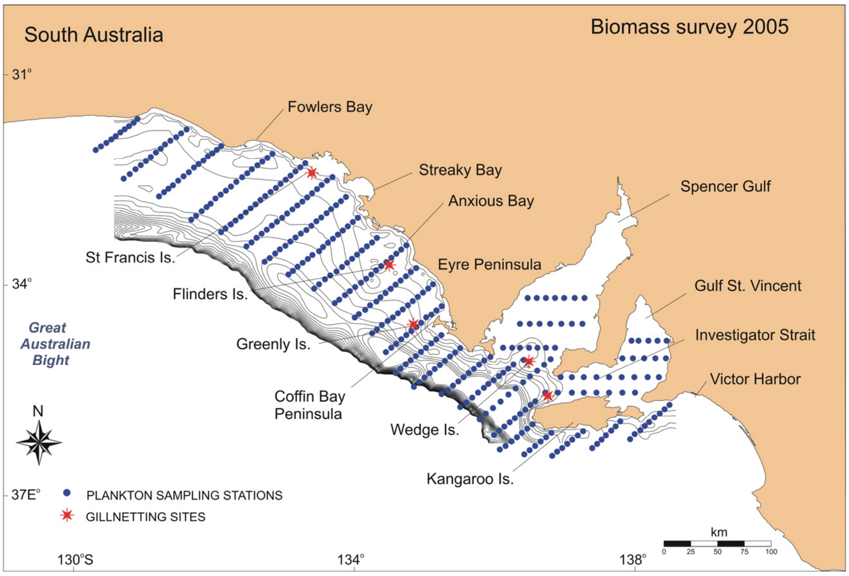

Figure 29. Map showing stations where sardine eggs and adults were collected during the 2005 DEPM surveys.

4.2.3. 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 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. Nets were retrieved vertically at a speed of ~1 $m.s^{-1}$. General Oceanics™ flowmeters were used to estimate the distance travelled by each net. Samples from the two cod-ends were combined and stored in 5% buffered formaldehyde and seawater.

4.2.4 Egg Distribution and Abundance

Sardine eggs are identified, counted, staged and assigned ages according to descriptions and temperature-development keys in White and Fletcher (1996). The number of eggs of each stage under one square metre of water (P_t) is estimated at each station according to equation 2:

$$P_t = \frac{C.D}{V} \qquad (2)$$

where C is the number of eggs of each age in each sample, V is the volume of water filtered (m^3), and D is the depth (m) to which the net was deployed (Smith and Richardson 1977).

4.2.5 Spawning Time

Sardine eggs in each sample were counted and staged according to criteria in White and Fletcher (1996). The age of each developmental stage was estimated using the temperature development keys in White and Fletcher (1996) assuming ambient SST. The time of spawning was estimated by subtracting the assigned ages of each egg (hours) from the time when each sample was collected.

4.2.6 Spawning Area

A key premise of using the DEPM is to accurately estimate the entire spawning area (Lasker 1985; Somarakis 2004). After the surveys are completed, the survey area is divided into a series of contiguous grids approximately centred on each station (Figure 30). The area represented by each station (km^2) was calculated using MAPINFO® software. The spawning area (A) is defined as the total area of grids where live, Stage 1 – 8 (0 – 24 hour old) sardine eggs were found (See Fletcher *et al.* 1996).

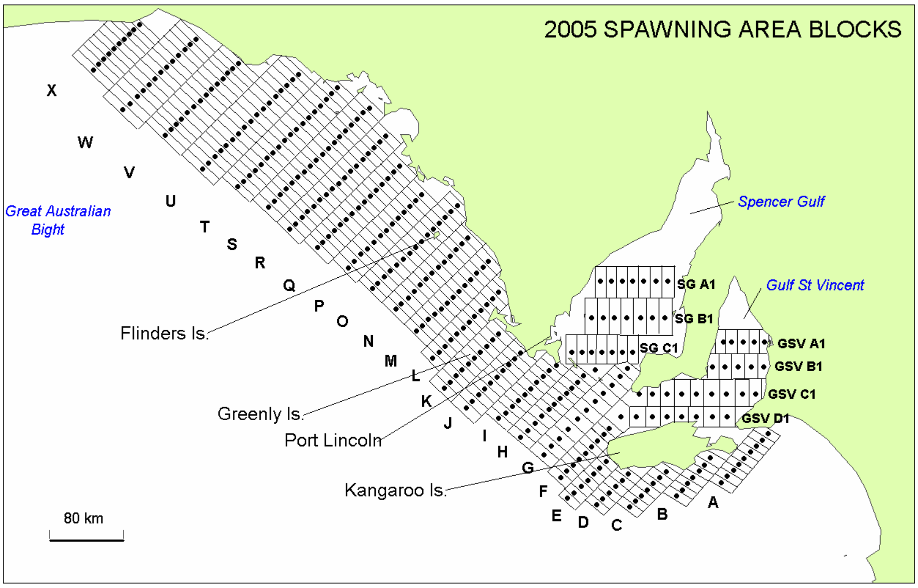

Figure 30. Spatial grids used to estimate the spawning area of sardine in 2005

4.2.7 Egg Production

Methods used to estimate egg production between 1995 and 2005 follow those of Smith and Richardson (1977) and Picquelle and Stauffer (1985). These methods are widely used by scientists to estimate daily egg production by small pelagic fish stocks in Australia and overseas.

Mean daily egg production (P_b) is estimated using the exponential decay model of Lo *et al*. (1996), which is shown in equation 3:

$$P_t = P_0 e^{-zt} \tag{3}$$

where P_t is density of eggs of age *t* and *z* is the instantaneous rate of egg mortality.

Biased mean daily egg production (P_b) was also calculated by fitting the linear version of the exponential egg mortality model to estimates of egg age and density at each station. The linear version of the exponential egg mortality model is shown in equation 4:

$$lnP_b = \ln(P_i) - Zt \tag{4}$$

where P_i is the density of eggs of age *t* at station *i* and *Z* is the instantaneous rate of egg mortality (Lasker 1985).

Estimates of mean daily egg production (P_b) obtained using the linear version of the exponential mortality model, have a strong negative bias. The bias correction factor was applied as in equation 5:

$$P = e^{(\ln P_b + \sigma^2 / 2)} \tag{5}$$

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

When egg production models 3 and 5 were applied to sardine egg data collected during 2005, the mortality rate (Z) of eggs declined with age, which is not biologically possible (Ward *et al.* 2005b). This required that rates of egg mortality be constrained at values ranging from $Z = 0.1$ to 0.5 to calculate egg production. The range of suitable Z-values was based on previous rates of instantaneous egg mortality ($Z = 0.1$ to 0.5) calculated using the linear version of the exponential mortality model in previous years (Ward and McLeay 1999, Ward *et al.* 2000; 2001a, 2002, 2003a, 2004). Equations 3 and 5 were fitted using the Solver ™ function in Excel for each of the constrained instantaneous egg mortality values.

4.2.8 Adult Reproductive Parameters

Between 1995 and 1997, SARDI scientists experienced difficulties collecting samples of mature sardine. Mid-water trawling and sampling from commercial catches during the spawning season was attempted with minimal success. The resultant lack of data on adult reproductive parameters impeded the estimation of spawning biomass during this period. Estimates of adult parameters that had been obtained in previous studies were used to estimate spawning biomass of sardine during these developmental years (Ward *et al.* 2001a).

Between 1998 and 2005, samples of mature sardine were collected in the EGAB, southern Spencer Gulf and the Investigator Strait using surface and sub-surface lights and a multi-panelled gillnet (Ward *et al.* 2001a). Upon retrieval of the net, fish were removed and dissected by ventral incision. Mature and immature males and females were counted. Mature females were fixed in 5% buffered formaldehyde solution and immature females and males were frozen. Calculations of female weight, sex ratio, batch fecundity and spawning fraction were mostly based on samples with >20 mature females.

Female weight

Mature females from each sample were removed from formalin and weighed ($\pm$ 0.01 g). Fixation in formalin has a negligible effect on sardine 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 as in equation 7:

$$W = \overline{\left[\overline{W_i} * \frac{n_i}{N} \right]} \quad (7)$$

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.

Male weight

Mature males in each sample were thawed and weighed ($\pm$ 0.01 g).

Sex ratio

The mean sex ratio of mature sardine in the population was calculated from the average of sample means weighted by proportional sample size as in equation 8.

$$R = \overline{\left[\overline{R_i} * \frac{n_i}{N} \right]} \quad (8)$$

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 equation 9.

$$\overline{R_i} = \frac{F}{(F + M)} \quad (9)$$

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

Spawning fraction

Ovaries of mature females were sectioned and stained with haematoxylin and eosin. Sections from each ovary were examined to determine the presence/absence of post-ovulatory follicles (POFs) within the ovarian matrix. 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 – 23 hrs old), day-1 POFs (*d*1) (assumed to be 24 – 48 hrs old) and day-2 POFs (*d*2) (assumed to be 48+ hrs old). The mean spawning fraction of the population was then calculated from the average of sample means weighted by proportional sample size using equation 10.

$$S = \overline{\left[\overline{S_i} * \frac{n_i}{N} \right]} \tag{10}$$

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 equation 11:

$$\overline{S_i} = \frac{\left[(d0 + d1 + d2POFs)/3 \right]}{n_i} \tag{11}$$

where *d0*, *d1* and *d2* POFs are the number of mature females with POFs in each sample and n_i is the total number of females within a sample. Note: *d0* includes hydrated oocytes.

Batch fecundity

Batch fecundity was estimated from ovaries containing hydrated oocytes using the methods of Hunter *et al*. (1985). Both ovaries were 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 used to estimate the batch fecundity of mature females in all samples.

Bootstrapping procedures

The 95% confidence intervals (95% C.I.) for each variable were calculated using 'bootstrap replacement' procedures and the percentile method. 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 calculation were the same as in the original datasets).

4.3 Results

4.3.1 Sampling Area

The total area sampled during the DEPM surveys varied from 53,853 to 119,679 km^2 between 1999 and 2005. In 2005, plankton samples were collected at 334 stations along 28 different transects encompassing a total survey area of 119,679 km^2.

4.3.2 Egg Distribution and Abundance

Since 1995, the distribution and abundance of sardine eggs has varied considerably between years. Important spawning areas include the EGAB, between Coffin Bay and Ceduna, southern Spencer Gulf and the western end of Investigator Strait. Mass mortality events in 1995 and 1998 had substantial effects on both the abundance of eggs and their spatial distribution (Ward *et al.* 2001a). Figures 31 and 32 show the distribution and abundance of sardine eggs collected during surveys between 1995 and 2005. Figure 32 and Table 2 show that live egg abundance in southern Spencer Gulf declined steadily from 545 to 185 eggs between 2000 and 2003 despite egg abundance increasing from 992 to 1,260 eggs across all regions. Between 2003 and 2004 there was an increase in total live egg abundance in all regions followed by a decline between 2004 and 2005. In 2005, live egg abundance in southern Spencer Gulf declined from 906 eggs (in 2004) to 86 eggs and both the number of stations with eggs and percentage of positive stations were the lowest recorded since 2000.

Table 2. Numbers of sardine eggs collected throughout the survey area and in Spencer Gulf during the DEPM surveys between 2000 and 2005.

Yr	N eggs (Live and dead all regions)	N eggs (Live all regions)	N eggs (Live and dead) SG	N eggs (Live) SG	% of total live eggs in SG	N of SG stations sampled	N of SG stations with eggs	% of 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

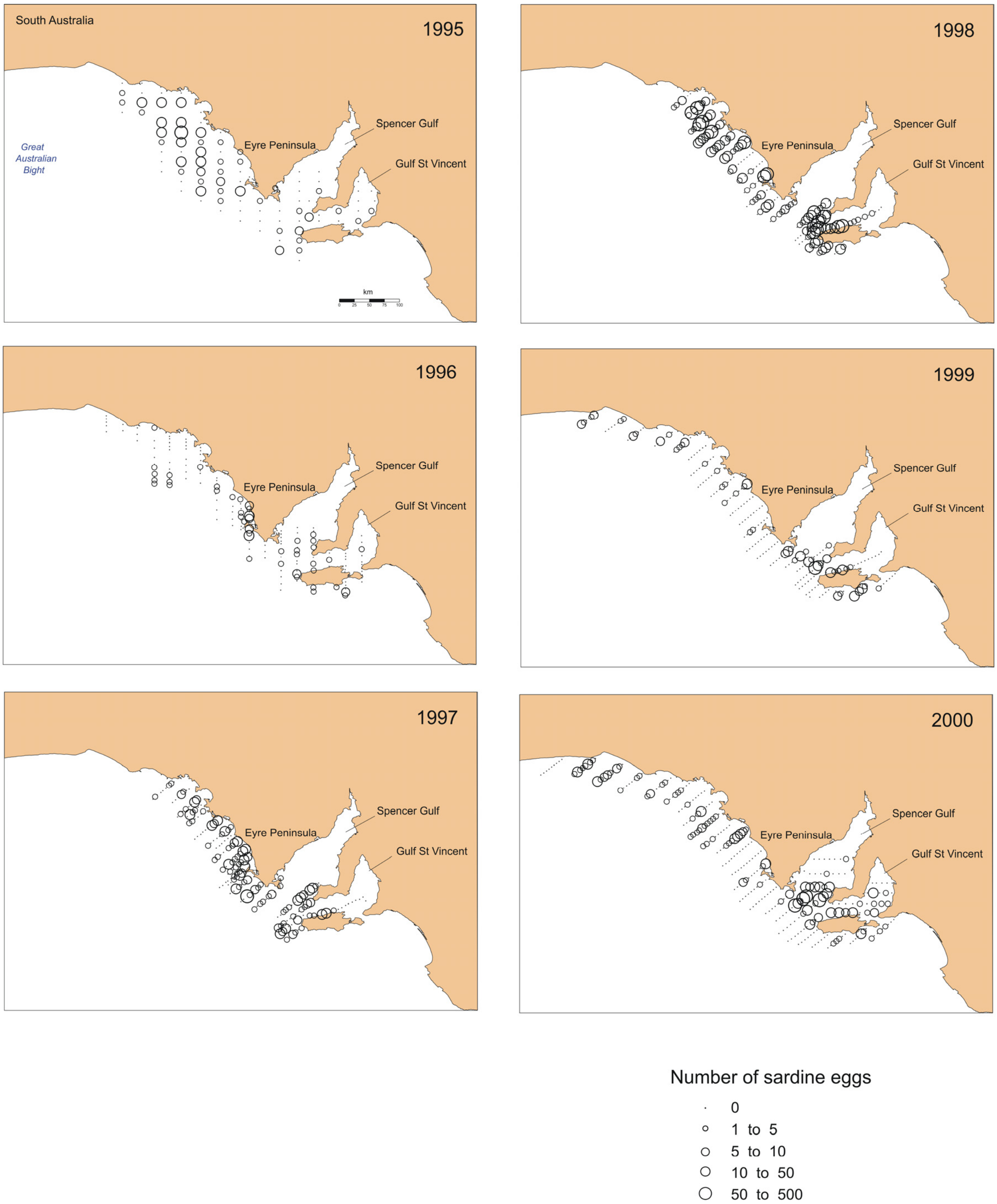

Figure 31. Distribution and abundance of sardine eggs collected during surveys between 1995 and 2000.

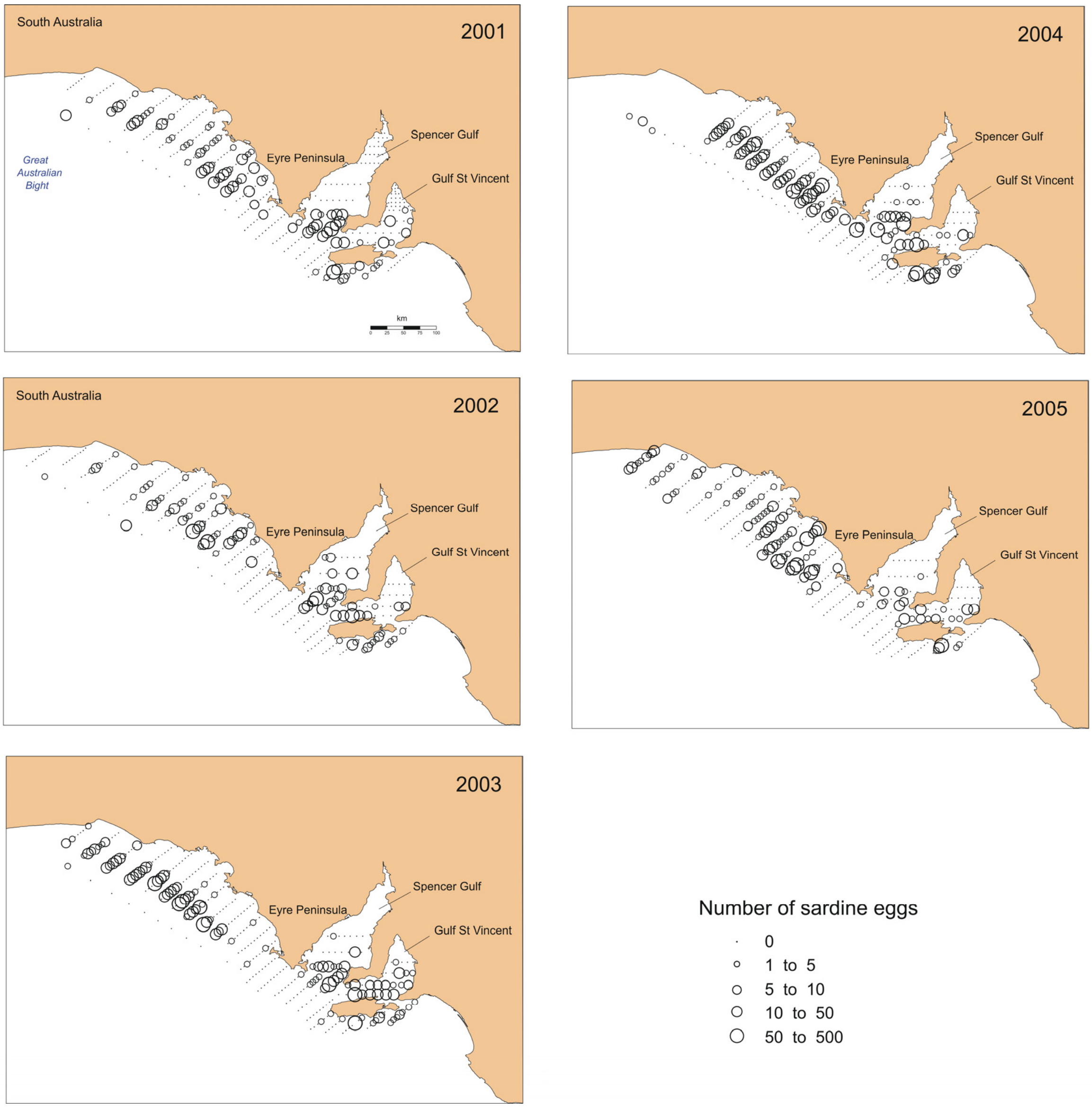

Figure 32. Distribution and abundance of sardine eggs collected during surveys between 2001 and 2005.

4.3.3 Spawning Time

The peak spawning time calculated from combined data between 1995 and 1999 was 0200 hours (Ward *et al.* 2001b). This was used as the standard spawning time in subsequent egg production and spawning biomass calculations.

4.3.4 Spawning Area

Estimates of spawning area varied among years and reflected both the size of the sampling area and the status of the spawning biomass. Spawning area declined substantially following the two mass mortality events in 1995/6 and 1998/9, from 68,260 km^2 in 1995 to 17,990 km^2 in 1996 and from 32,232 km^2 in 1998 to 16,301 km^2 in 1999 (Table 3). The spawning area increased between 2000 and 2005 from 31,000 km^2 and 36,379 km^2. The overall mean spawning area during this period was 32,947 km^2 (SD = 13,463.40). It is important to note that the survey design also varied between years, e.g. four transects were excluded in the central GAB in 2004 due to bad weather.

Table 3. Spawning area estimates for sardine in South Australia between 1995 and 2005.

Year	Spawning area (km^2)
1995	68,260
1996	17,990
1997	26,276
1998	32,232
1999	16,301
2000	31,374
2001	34,935
2002	32,962
2003	31,967
2004	33,745
2005	36,379

4.3.4 Egg Production

Table 4 shows estimates of egg production, their associated 95% C.I. between 1995 and 2005. Following the second mass mortality event, egg production declined from 99.56 eggs per m^{-2} in 1998 to 53.66 eggs per m^{-2} in 1999. In 2001 and 2002, estimates of egg production were 82.91 and 91.41 eggs per m^{-2}, respectively. These estimates increased further to 117.16 and 132.17 eggs per m^{-2} in 2003 and 2004, respectively. In 2005, egg production rates were calculated for a range of egg mortality rates between 0.1 and 0.5 and the estimates ranged between 53.53 and 72.36 eggs per m^{-2}.

Table 4. Egg production estimates and associated confidence intervals between 1995 and 2005. Note that no 95% C.I.s were calculated in 1997 and a range of estimates were provided in 2005.

Year	Egg production (eggs per m^{-2})	Upper and lower 95% C.I.
1995	26.35	*14.98 – 37.71*
1996	22.16	*17.38 – 26.94*
1997	47.32	
1998	99.56	*70.29 – 128.83*
1999	53.66	*33.68 – 73.64*
2000	62	*35 – 111*
2001	82.91	*50.49 –136.58*
2002	91.41	*63.09 – 191.36*
2003	117.16	*77.39 – 186.40*
2004	132.17	*83.60 – 215.60*
2005	53.53 – 72.36	

4.3.5 Adult Reproductive Parameters

Estimates of adult reproductive parameters between 1995 and 2005 including sex ratio, female weight, batch fecundity and spawning fraction are shown in Table 5. Over this 11 year period, the mean sex ratio was 0.52 (SD = 0.04), mean female weight was 52.31 gm (SD = 8.75), mean batch fecundity was 16,687.78 (SD = 4,241.79) and mean spawning fraction was 0.15 (SD = 0.03).

Table 5. Adult reproductive (R.P.) parameter estimates used to calculate spawning biomass between 1995 and 2005. (*W* is the mean weight of mature females, *R* is the sex ratio, *F* is the mean batch fecundity and *S* is the mean spawning fraction).

R.P.	95	96	97	98	99	00	01	02	03	04	05
R	0.51	0.58	0.54	0.51	0.47	0.48	0.56	0.59	0.44	0.51	0.50
W	42.9	46.30	43.0	45.20	52.28	48.83	51.90	62.40	52.69	56.37	73.5
F	N/A	N/A	13,947	13,615	15,252	13,650	17,359	18,393	10,907	24,796	22,271
S	N/A	0.16	0.16	0.14	0.18	0.16	0.18	0.11	0.11	0.17	0.10

4.2.6 Spawning Biomass

The spawning biomass estimate for 1995 of 165,000 t may be negatively biased, as the survey did not coincide with the peak spawning season or sample the entire spawning area, and also because estimates of adult reproductive parameters were obtained from other studies, conducted during the peak spawning period in those areas (Table 6). The estimate of spawning biomass declined to 37,000 t in 1996 following the first mass mortality event but increased to 59,000 t in 1997 (Ward *et al.* 2001a). The estimate of spawning biomass in 1998 was 146,000 t, but declined to 36,000 t in 1999, following the second mortality event (Ward *et al.* 2000, 2001a, Table 6).

Estimates of spawning biomass provided for 2001 to 2004 have been revised from those provided in the original reports (Ward *et al.* 2000, 2001a, 2003a; 2004a). Spawning biomass estimates increased from 91,000 t in 2000 to 196,222 in 2004. Estimation of spawning biomass in 2005 was impeded by difficulties estimating egg mortality and egg production. In 2005, estimates of spawning biomass ranged between 129,729 and 175,389 t (Table 6) for a range of egg mortality (*Z*) and egg production (P_0) values.

Table 6. Spawning biomass estimates between 1995 and 2005. Note no 95% CI in 2005 as a range of spawning biomass estimates based on a range of *Z* and *Po* was provided. Estimates of spawning biomass provided for 2001 to 2004 have been revised.

Year	Spawning biomass estimate (t)	Upper and lower 95% C.I.
1995	165,000	
1996	37,000	
1997	59,000	
1998	146,000	70,000 – 234,000
1999	36,000	19,000 – 67,000
2000	91,000	45,000 – 180,000
2001	90,830	56,424 – 229,537
2002	159,899	93,435 – 451,772
2003	170,225	111,691 – 288,347
2004	196,222	117,874 – 321,123
2005	129,729 – 175,389	

4.2.7 Exploitation Rates of Spawning Biomass (SB)

Estimates of actual exploitation rates (CDR catch/SB) since 1996 have ranged between 2 and 22%. The actual exploitation rate in both 2004 and 2005 was 22% (Fig. 33). The expected exploitation rate (TAC/SB), i.e. that which may have occurred if the entire TAC was taken in 2005 was ~26% (51,100 t/196,222 t, (Fig. 33), which is higher than the previously reported, predicted exploitation rate of 17.5% (Ward *et al.* 2004).

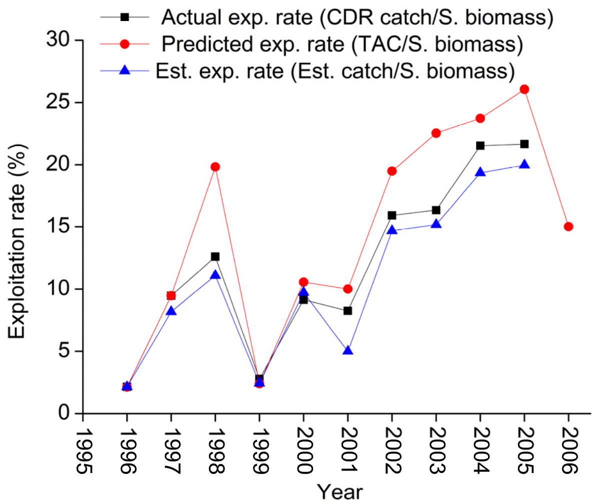

Figure 33. Actual, predicted and estimated exploitation rates of spawning biomass between 1996 and 2005/6.

4.4 Discussion

The DEPM has been used to monitor the recovery of the stock from mass mortality events in 1995 and 1998 and has supported the development of the SASF since 1995. Estimates of spawning biomass suggest that the SA sardine spawning stock recovered quickly from the second mass mortality event in 1998/9. Estimates of spawning biomass obtained using the DEPM are considered to be accurate, yet relatively imprecise (Cochrane 1999). This has mainly been attributed to patchiness in egg distribution and abundance (McGarvey and Kinloch 2001; Gaughan *et al.* 2004; Stratoudakis *et al.* 2006), and the high variance levels associated with estimates of egg production. Hence, C.I. and C.Vs for estimates of spawning biomass are large (e.g. C.V.s commonly >35% of the mean) (Fletcher *et al.* 1996; Ward *et al.* 2001a Gaughan *et al.* 2004; Stratoudakis *et al.* 2006). In South Australia, this uncertainty has been managed by building negative biases into processes for estimating egg production (Ward *et al.* 2000, 2001c, 2002a, 2003a, 2004a) and having a framework of conservative decision rules for using spawning biomass estimates to set TACs (Ward *et al.* 2001d, Shanks 2005).

Despite the uncertainties associated with the DEPM-based estimates of spawning biomass, it is clear that this is approach is highly suitable for assessing the sardine stock in South Australia. However, numerous SARDI reports have identified the need to continue to refine approach taken to applying the DEPM in SA. In particular, SARDI has frequently identified the need to refine methods for estimating egg mortality and egg production. For example use of a Continuous Underway Fish Egg Sampler (CUFES) during the annual DEPM surveys would refine estimation of egg abundance/patchiness, spawning area and egg production (Lo *et al.* 2001; Lo and Macewicz 2004; ICES 2002).

A review conducted by CSIRO in 2006 (Smith and Smith 2006) supported the approach that has been taken to applying the DEPM for the SASF and identified several potential refinements that warrant consideration, including:

- collecting additional egg samples from the main fishing areas;
- investigating options for using a Continuous Underway Fish Egg Sampler to enhance the egg sampling program;
- evaluating the potential for industry involvement in the egg sampling program;

- evaluating the potential for industry to provide additional samples of adult fish throughout the spawning season;
- investigating alternative approaches to estimating egg mortality and egg production.

SARDI supports these recommendations and will refine the approaches taken to applying the DEPM in SA during 2006, in consultation with scientists at National Marine Fisheries Service (NMFS). In particular, SARDI is investigating the inclusion of yolk-sac larvae in embryonic mortality curves, the use of a CUFES and Laser Optical Plankton Counter (LOPC) during DEPM surveys, and the use of General Additive Models (GAM) and Bayesian approaches to estimating egg production.

Yolk-sac larvae are included in embryonic mortality curves used to estimate egg mortality rates, egg production and spawning biomass of sardine in California (Lo and Macewicz 2002, 2004). This approach requires that assumptions are made regarding the trajectories of mortality rates of eggs and yolk-sac larvae and has the potential to improve the accuracy of these estimates. Use of yolk-sac larvae will be evaluated during the calculation of egg production and spawning biomass of sardine in SA waters during 2006.

The precision of egg production and spawning area estimates can be improved by incorporating a CUFES, during annual DEPM surveys (Lo *et al.* 2001; Ward *et al.* 2004). CUFES provide high-resolution information on the distribution and abundance of sardine eggs in the surface layer and are used by research agencies in South Africa, California and Europe during egg-based stock assessment surveys (Lo *et al.* 2001; Lo and Macewicz 2004; van der Lingen and Huggett 2003) (See Appendix 1). The performance of CUFES may be significantly enhanced if combined with a LOPC. This technology has the potential to identify pelagic fish eggs based on size class, as the vessel steams along transects, which allows ‘adaptive’ sampling in areas of high egg abundance and facilitates accurate identification of the spawning area. This approach has the potential to save on vessel time and reduce future costs (Lo *et al.* 2001; van der Lingen and Huggett 2003). Smith and Smith (2006) recommended that support be given to SARDI to obtain funds for a CUFES and LOPC and PIRSA Fisheries supported this recommendation during the PFWG meeting in March 2006.

GAMs resemble a non-parametric (non-linear) version of General Linear Models (GLM) and involve fitting a range of models to the observed data. This type of model has been used to estimate egg production for Atlantic mackerel, *Scomber scomberus* (Borchers *et al.* 1997). That study showed that the use of GAMs reduced the variance associated with estimates of egg abundance, and consequently improved confidence in estimates of egg production and spawning biomass (Stratoudakis *et al.* 2006). There is also potential for development of 'probabilistic' approaches for estimating egg production, where egg mortality estimates from previous years are incorporated into predictive models.

5. DISCUSSION

This section assesses the status of the sardine resource in SA, comments on the biological performance indicators, reference points and decision rules in the management plan, and identifies future management options and research priorities for the fishery.

Status of the Resource

Estimates of spawning biomass suggest that the SA sardine spawning stock has recovered from the second mass mortality event in 1998/9, with estimates increasing from 36,000 t in 1999 to 196,222 t in 2004, before declining to between 129,729 and 175,389 t in 2005. This finding supports the assertion of Murray and Gaughan (2003), who used predictive models to suggest that under favourable conditions sardine stocks recover quickly from large-scale mortality events. It is unclear whether the apparent decline in spawning biomass between 2004 and 2005 is related to environmental conditions, fishing pressure or uncertainties in the assessment technique. As such, the estimate of spawning biomass for 2006 will be critical for determining the status of the SA sardine resource.

In recent years, the SASF has mainly operated in southern Spencer Gulf but biomass estimates used to establish TACs have been provided for waters between GSV and Head of Bight. Hence, fishing has only been conducted in approximately one third of the mean spawning area (~10,300 of 30,000 km^2). The positive element of this situation is that approximately two thirds of the spawning stock appears to be virtually unfished. Whilst this provides a high level of confidence that the status of the South Australian sardine stock as a whole is strong, the down side is the potential negative effects on local abundance. Furthermore, there is a lack of available information on the movement of sardine between these regions. Several reports since 1998 (e.g. Ward and McLeay 1998, 1999; Ward *et al.* 2003, 2004, 2005) have indicated that the spatial disparity between fishing activities and biomass estimation has the potential to lead to localised depletion. In particular, Ward *et al.* (2005) suggested that reductions in egg abundance in Spencer Gulf reflected localised declines in adult abundance. In the present report we show that there has also been a spatial expansion of fishing effort away from the traditional fishing areas in southern Spencer Gulf and that an increased proportion of juveniles (≤ 100 mm) has been recorded in catch samples in recent years. In our opinion, this information provides evidence that fishing may have reduced the abundance of adult sardine in southern Spencer Gulf.

In contrast to our interpretation, the review by Smith and Smith (2006) concluded that:

> "*The information available to this review did 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*".

However, the review also stated that:

> "*given the potentially serious implications of localised depletion, these recommendations should be dealt with urgently*".

Recommendations by Smith and Smith (2006) regarding approaches that may be suitable for addressing the question of localised depletion were:

1. Future DEPM surveys should include additional plankton stations in Spencer Gulf;
2. Catch, effort and CPUE analyses should be undertaken at finer spatial scale;
3. Size and age data should be re-analysed at a finer spatial scale;
4. Sampling for key indicators such as size and age composition of catches should be increased to ensure that the analysis of trends in these data can be undertaken at the appropriate spatial scale;
5. A collaborative SARDI/industry sampling program to support additional commercial catch sampling should be evaluated and if feasible, should be developed and implemented;
6. Potential for industry collaboration in an industry-based egg sampling program, to complement the SARDI program, should be evaluated.

SARDI, PIRSA Fisheries and members of the SASF are currently working to assess and implement these recommendations. However, the issue of localised depletion for the SASF has not yet been resolved, and needs to be addressed as a matter of high priority.

Biological Performance Indicators, Reference Points and Decision Rules

The management plan for the SASF is sophisticated, and provides a framework of decision rules that has allowed PIRSA Fisheries to respond quickly to fluctuations in stock size. Under the current rules, two biological performance indicators are used to monitor the performance of the fishery: the magnitude of the spawning biomass and the relative strength (≥ or ≤ 40%) of two and three year old age classes in catch samples. TACs are set for the year ahead, based on an exploitation rate that is set at between 10 and 17.5% of the estimate of spawning biomass, depending on the size of the biomass and the relative strength of the two and three year old age classes. This management framework has worked effectively for the SASF, and allowed the stock to recover from the two mass mortality events of the 1990s, whilst also allowing the fishery to grow rapidly.

Use of annual estimates of spawning biomass to set the TAC served the fishery well during its development phase, when the level of knowledge regarding the potential of the stock to support fishing pressure was relatively low. However, this approach has some negative aspects, the most significant being the high potential for large inter-annual variations in the TAC (Fig. 34a), resulting from both fluctuations in the estimates of spawning biomass and the application of different exploitation rates at different biomass levels (Shanks 2005). Given the relatively imprecise nature of biomass estimates obtained using the DEPM, and the logistical impacts of large fluctuations in TAC on the fishery, there is a case for considering the value of establishing a new management framework that would reduce the scale of inter-annual fluctuations in TAC, whilst continuing to ensure that catches are constrained within biologically sustainable limits. The following discussion of alternative management options is provided as background for future discussions of the PFWG.

Research conducted over the last decade has resulted in the development of an improved understanding of the capacity of the stock to support fishing pressure (Fig. 34a – d). It may now be suitable to use this knowledge to revise the framework that has been established for managing the SASF. One option for the revised management strategy would be to set a TAC that is based on a target exploitation rate that reflects our current knowledge of the capacity of the stock to sustain fishing pressure, and which is maintained unless upper or lower exploitation rates are triggered. A revised management strategy of this type, including the target exploitation rate, target TAC and trigger exploitation rates, could also be reviewed every 3 years.

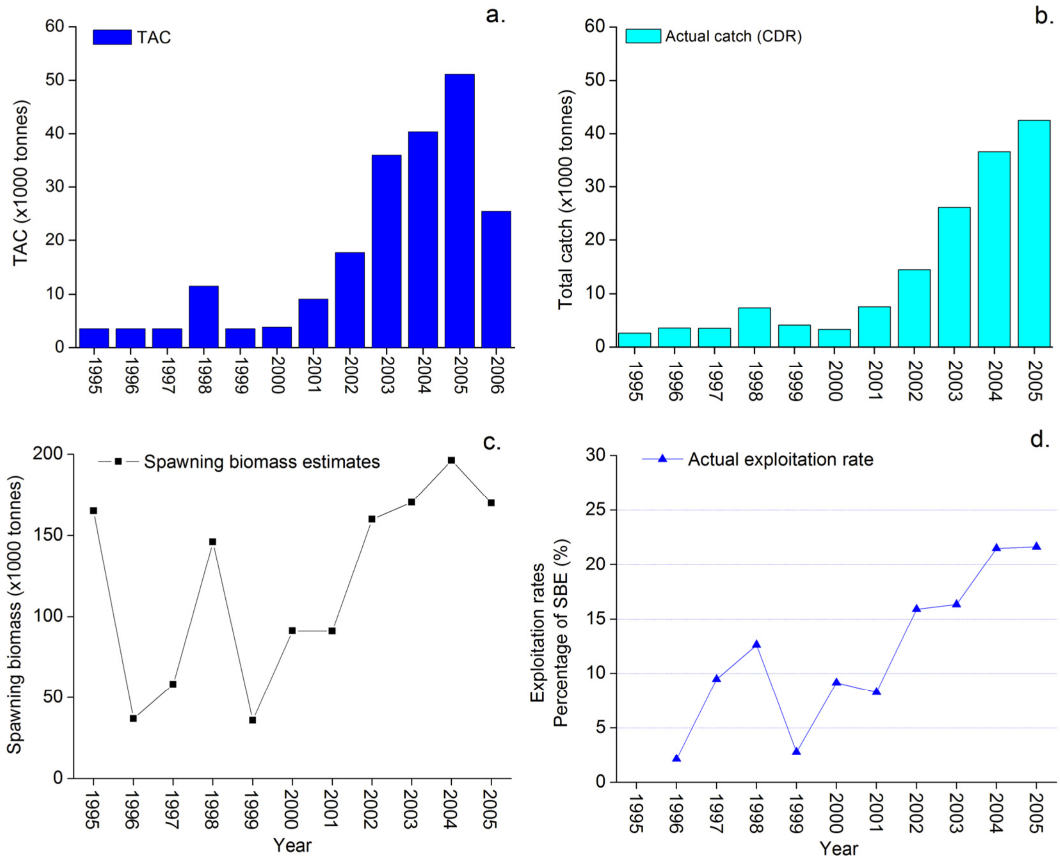

Figure 34. (a) TACs for the SASF, (b) total annual catches, (c) spawning biomass estimates, and (d) actual exploitation rates.

Since 2002, actual exploitation rates in the SASF (based on revised spawning biomass estimates) have ranged between 15 and 22%, and were 22% in both 2004 and 2005. Figure 34 indicates that the spawning biomass has remained relatively stable during this period, but may have declined slightly in 2005. On the basis of this information, it seems reasonable to suggest that a target exploitation rate of up to but not exceeding 20% may be appropriate for this fishery. Similarly, given the rapid recovery of the stock from the two mass mortality events when exploitation rates were set below 15%, it seems reasonable to suggest that a lower trigger limit (i.e. that would trigger an increase in TAC) of up to 15% may be appropriate for the SASF. Furthermore, based on (i) the studies of Patterson (1992) and others, (ii) the range of actual exploitation rates and estimates of spawning biomass since 2001, it seems reasonable to suggest that an upper trigger limit (i.e. which would trigger a reduction in the TAC) of up to 25% may be suitable for the fishery.

The following is an example of the way that this revised management option could be implemented.

If a target exploitation rate of 20% was applied to the mean spawning biomass estimate for 2002 – 2005 of ~170,000 t, the target TAC could be set at ~34,000 t. If the upper trigger limit were set at 25%, a decrease in TAC would be triggered if the annual estimate of spawning biomass declined below 136,000 t. Similarly, if the lower trigger limit were set at 15%, an increase in TAC would be triggered if the estimate of spawning biomass exceeded 226,700 t. Under this regime, the TAC would remain at 34,000 t whilst the spawning biomass remained between 136,000 and 226,700 t.

Target and trigger exploitation rates could be set either more or less conservatively than the example provided above, depending on the level of risk considered to be appropriate when all issues are considered. All aspects of this management option, including the target exploitation rate, target TAC and trigger exploitation rates, could also be reviewed every 3 years. Other decision rules could also be incorporated in these arrangements. For example, it could be agreed that if trigger levels were exceeded, TACs would not be changed by more than 25% between years, except in predefined 'exceptional circumstances', such as a mass mortality event or some other rare occurrence.

The main advantage of the kind of management system described above over the existing management system is that it is likely to provide greater stability in the fishery, by reducing the level of interannual fluctuations in TAC resulting from natural variations in abundance, the imprecision of spawning biomass estimates obtained using the DEPM and the application of different exploitation rates at different biomass levels. Most importantly, it would achieve these advantages whilst continuing to ensure that catches are constrained within biologically sustainable limits.

Establishing performance indicators, reference points and trigger limits into fisheries management procedures is in accordance with the *FAO Code of Conduct for Responsible Fisheries* and consistent with approaches used in other small pelagic fisheries (Chapter 1).

Target and limit exploitation rates of <25% also reflect the findings of Patterson (1992), who suggested that exploitation rates of <30% were typically associated with increases in the size of pelagic fish stocks and minimised the chance of stock decline. The main difference in the alternative approach outlined above to that taken in many other pelagic fisheries is estimates of spawning biomass generated by DEPM surveys are used as the basis for management decisions, rather than biomass estimates generated from age structured models. This approach is consistent with both the confidence of stakeholders in the survey methods used in SA and our concerns that age structure data obtained from the SASF are not representative of the sardine population (Ward *et al.* 2005a).

Other Management Issues

Another key question for the SASF is whether a spatial management system is needed for the fishery. As previously indicated, most of the TAC is taken from southern Spencer Gulf. In the present report we suggest that: (1) recent reductions in egg abundance in Spencer Gulf; (2) the expansion of effort away from traditional fishing areas; and (3) the recent increase in the abundance of juveniles in catches, may collectively provide evidence of localised depletion, but note that Smith and Smith (2006) disagree with this view. Following Ward *et al.* (2005c), we suggest that options for spatial management should be considered by the Working Group for the SASF on the basis of the evidence available.

The establishment of zones in the SASF was discussed extensively at the TAC setting meeting in Port Lincoln in September 2005. Zones were not established due to the perceived lack of scientific evidence to support localised depletion, and the significant increase in operating costs that may result from such changes (Smith and Smith 2006). The suggestion that a spatial management system may be needed for the fishery raises questions such as: (1) where could zones be established, and (2) what proportion of the total TAC could be taken from each zone? A simple option would be to establish two zones (e.g. East and West) and split the total TAC between zones according to some simple ratio (e.g. 50:50). However, another option would be to calculate separate biomass estimates, and potentially establish separate decision rules, for each zone. If/when agreement is reached that zones should be established in the SASF, it is recommended that a detailed analysis of options for spatial management of the fishery is undertaken.

The remaining management question that needs to be addressed in the SASF is the increase in the proportion of juveniles in the catch samples taken during 2003 and 2004. It is a central tenet of modern fisheries management that a significant proportion of 'recruits' are allowed to spawn prior to capture (Mace and Sissenwine 1993; FAO 1995; Gabriel and Mace 1999). Modelling conducted by Murray and Gaughan (2003) showed that increased rates of juvenile mortality can reduce the rates at which adult sardine stocks recover from declines in abundance resulting from fishing pressure and/or mass mortality events. From a biological perspective, it is imperative that measures are implemented to ensure that the SASF does not harvest significant quantities of juveniles. A variety of approaches could be used to achieve this outcome, including: spatial management (e.g. closure of nursery grounds), regulated minimum size limits or the establishment of an industry code of practice around the issue. Recent advice from representatives of the SASF indicates that an industry-based approach to managing this issue has been implemented. Whatever approach is taken, it is imperative that a robust sampling program is established to monitor the size composition of future catches.

Future Research Priorities

The DEPM has provided the scientific basis for management of the SASF since 1995. This method is widely considered to be the most appropriate stock assessment technique for clupeoids as it provides critical information on the magnitude of fluctuations in stock size (e.g. Cochrane 1999). However, spawning biomass estimates obtained using this method, are imprecise and lead to uncertainty for fishers, scientists and management agencies (Cochrane 1999). This lack of precision in biomass estimates results mainly from difficulties associated with estimating egg production and spawning area. Sensitivity analysis by Ward *et al.* (2004) and others have shown that these parameters have the largest overall effects on estimates of spawning biomass. SARDI Aquatic Sciences is currently undertaking a review of methods used for calculating egg production, which includes consideration of: (1) the inclusion of yolk-sac larvae in embryonic mortality curves; (2) the use of a Continuous Underway Fish Egg Sampler (CUFES) and Laser Optical Plankton Counter (LOPC) during DEPM surveys; and (3) the statistical techniques that may be employed. This review will be undertaken in conjunction with scientists at the National Marine Fisheries Service (NMFS).

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7. APPENDIX 1. Continuous Underway Fish Egg Sampler.

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