Australian Sardine (*Sardinops sagax*) Fishery

Fishery Assessment Report for PIRSA

SARDI Aquatic Sciences Publication No. F2007/000765-2
SARDI Research Report Series No. 262

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January 2008

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This is the seventh 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.

This publication may be cited as:

Ward, T.M., Ferguson G.J., and P. Rogers (2008) The South Australian Sardine (*Sardinops sagax*) Fishery. Fishery Assessment Report to PIRSA Fisheries. South Australian Research and Development Institute (Aquatic Sciences), Adelaide, F2007/000765-2, Research Report Series No. 262. 75pp.

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Printed in Adelaide January 2008

SARDI Aquatic Sciences Publication No.F2007/000765-2
SARDI Research Report Series No. 262

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Signed:

Date: 31 January 2008
Distribution: PIRSA Fisheries and SARDI Aquatic Sciences Library
Circulation: Public Domain

PREFACE

This is the seventh fishery assessment report on Australian sardine (pilchard) *Sardinops sagax* in South Australia. Since 1998, SARDI Aquatic Sciences has assessed the status of 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.

TABLE OF CONTENTS

TABLE OF CONTENTS 5
LIST OF FIGURES 7
LIST OF TABLES 8
ACKNOWLEDGEMENTS 9
EXECUTIVE SUMMARY 10
1 GENERAL INTRODUCTION 11
1.1 RATIONALE AND OBJECTIVES 11
1.2 REVIEW OF THE RECENT LITERATURE 11
1.2.1 Taxonomy 11
1.2.2 Stock Structure 11
1.2.3 Distribution 12
1.2.4 Schooling Behaviour 12
1.2.5 Movement 12
1.2.6 Food and Feeding 13
1.2.7 Age, Growth and Size 13
1.2.8 Reproduction 13
1.2.9 Early Life History and Recruitment 13
1.2.10 Stock Assessment 14
1.2.11 Management Procedures in Small Pelagic Fisheries 14
1.2.12 Non-retained target catch 15
1.2.13 Role in the Ecosystem 15
1.2.14 Mass Mortality Events 16
1.3 THE SOUTH AUSTRALIAN SARDINE FISHERY 17
2 FISHERY STATISTICS 19
2.1 INTRODUCTION 19
2.2 ANNUAL PATTERNS 19
2.2.1 Effort and catch 19
2.2.2 Catch-per unit effort 19
2.3 INTRA-ANNUAL PATTERNS 20
2.3.1 Effort and catch 20
2.4 SPATIAL PATTERNS 22
2.4.1 Effort and catch 22
2.5 DISCUSSION 24
3 AGE, GROWTH AND REPRODUCTION 25
3.1 INTRODUCTION 25
3.2 METHODS 25
3.2.1 Size Structure 25
3.2.2 Age and Growth 25
3.2.3 Reproduction 26
3.3 RESULTS 27
3.3.1 Size Structures 27
3.3.2 Age Structure 32
3.3.3 Growth patterns 38
3.3.4 Reproduction 39
3.4 DISCUSSION 43
4 SPAWNING BIOMASS ESTIMATES 1995 TO 2007 44
4.1 INTRODUCTION 44
4.2 METHODS 44
4.2.1 The Daily Egg Production Method (DEPM) 44

4.2.2 Sampling Area 44
4.2.3 Plankton Sampling 45
4.2.4 Egg Distribution and Abundance 45
4.2.5 Spawning Time 46
4.2.6 Spawning Area 46
4.2.7 Egg production 46
4.2.8 Adult Reproductive Parameters 47
4.3 RESULTS 50
4.3.1 Sampling Area 50
4.3.2 Egg Distribution and Abundance 50
4.3.3 Spawning Time 55
4.3.4 Spawning Area 55
4.3.4 Egg Production 56
4.2.6 Spawning Biomass 57
4.2.7 Exploitation Rates of Spawning Biomass (SB) 58
5 GENERAL DISCUSSION 60
5.1 STATUS OF THE RESOURCE 60
5.2 MANAGEMENT FRAMEWORK 60
5.3 FUTURE RESEARCH PRIORITIES 61
REFERENCES 62

LIST OF FIGURES

Figure 1-1. TACC for the SASF between 1991 and 2007 (dotted line is baseline TACC)............................ 18

Figure 2-1. (a) Total catches (logbooks, CDR) and estimated lost catches, (b) fishing effort (boat days, net shots), and (c) Mean annual CPUE (boat days, net shots, ±SE).. 20

Figure 2-2. Intra-annual patterns in catch and effort between 1991 and 2006.. 21

Figure 2-3. 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.. 22

Figure 2-4. Spatial trends in catch and effort between 1991 and 2000 (NB different y-axis scale for 1991 and 1992). 23

Figure 2-5. Spatial trends in annual catches between 2001 and 2006. 24

Figure 3-1. Length frequency distributions by year for commercial catch samples from Spencer Gulf between 1995 and 2006. 28

Figure 3-2. Length frequency distributions for catch samples from Coffin Bay between 1995 and 2004 (no data available in 2005, 2006).. 29

Figure 3-3. Length frequency distributions for fishery independent samples collected between 1998 and 2007. 30

Figure 3-4. Length frequency distributions by location for fishery independent samples collected in 2005, 2006, and 2007.. 31

Figure 3-5. Readability index (RI) scores assigned to *S. sagax* otoliths from catch samples in 2004............ 32

Figure 3-6. Otolith weight as a function of age for otoliths (RI scores 1 and 2) collected from catch samples during 2004-06... 33

Figure 3-7. Age structures by year from catch samples from Spencer Gulf between 1995 and 2006.......... 34

Figure 3-8. Age structures by month for catch samples from Spencer Gulf in 2005 (few data available for 2006) 36

Figure 3-9. Age structures for fishery independent samples between 1998 and 2006 (no data available for 2004).. 37

Figure 3-10. Von Bertalanffy growth curve for *S. sagax* from Spencer Gulf and Coffin Bay in 2001/06... 38

Figure 3-11. Relationship between length and the proportion of male and female *S. sagax* at sexual maturity. (reference line is L_{50})... 39

Figure 3-12. Macroscopic gonad stages for males and females in Spencer Gulf (a) above and Coffin Bay (b) between 1995 and 2004 (limited data available for 2005-06). 42

Figure 4-1. Map showing stations where *S. sagax* eggs and adults were collected during the 2007 DEPM surveys.. 45

Figure 4-2. Spatial grids used to estimate the spawning area of *S. sagax* in 2007... 46

Figure 4-3. Distribution and abundance of *S. sagax* eggs collected during surveys between 1995 and 2000. 52

Figure 4-4. Distribution and abundance of *S. sagax* eggs collected during surveys between 2001 and 2006. 53

LIST OF TABLES

Table 1-1. Decision rules if the spawning biomass (SB) estimate is less than 150,000 t. (The exploitation rate is for a TACC of 30,000 t.) 18

Table 1-2. Decision rules if the spawning biomass (SB) estimate is greater than 300,000 t. (The exploitation rate is for a TACC of 30,000 t.). 18

Table 3-1. Von Bertalanffy growth parameters for *S sagax* from Spencer Gulf and Coffin Bay from 2001-06 (95% confidence bounds in parentheses). 38

Table 3-2. Mean annual sex ratios for commercial catch samples of *S. sagax* from Spencer Gulf (* $P<0.05$, ** $P<0.005$)........ 40

Table 3-3. Mean monthly sex ratios for commercial catch samples of *S. sagax* from Spencer Gulf, 2001 to 2006 (* $P<0.05$, ** $P<0.005$). 40

Table 4-1. Numbers of *S. sagax* eggs collected throughout the survey area and in Spencer Gulf during the DEPM surveys between 2000 and 2007. 51

Table 4-2. Spawning area estimates for *S. sagax* in South Australia between 1995 and 2007. 55

Table 4-3. Egg production estimates and associated confidence intervals between 1995 and 2007. Note that no 95% C.I.s were calculated in 1997 and a range of estimates were provided in 2005. 56

Table 4-4. Adult reproductive (R.P.) parameter estimates used to calculate spawning biomass between 1995 and 2007. (*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)........ 57

Table 4-5. Spawning biomass estimates between 1995 and 2007. 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. 58

ACKNOWLEDGEMENTS

The production of this report was funded by PIRSA Fisheries from licence fees collected from members of the South Australian Sardine Fishery. SARDI Aquatic Sciences provided in-kind support. We thank the fishers who provided the catch and effort information. We appreciate the efforts of Mr Sid Hanson, Mr Tony Jones, Mr Tony Rowlings and Mr Alex Jelanek who collected samples from commercial catches between 1995 and 2006. Mr Malcolm Knight, Mr Angelo Tsolos, Ms Emily Thompson and Ms Annette Doonan from the Statistics Unit at SARDI Aquatic Sciences have provided summaries of the annual catch and effort data. We thank the master and crew of the *RV* Ngerin, Mr Neil Chigwidden, Mr Dave Kerr, Mr Chris Small, Mr Ralf Putz and Mr John Collinson for help and advice during numerous research surveys. Mr Lachlan McLeay and Mr Wetjens Dimmlich contributed to the spatial analyses of fishery catch and effort information, analysis of reproductive parameters, development of the Small Pelagic Fishes database and assisted in numerous DEPM surveys between 1995 and 2005. Mr Lachlan McLeay also contributed to analyses and preparation of figures in Chapter 4. Mr Bryan MacDonald, Mr Paul Jennings, Mr Graham Hooper, Ms Megan Westlake, Mr Igor Pirozzi, Mr Nathan Strong, Mr Paul Van Ruth, Mr Richard Saunders and Mr Alex Ivey helped collect and sort plankton samples. Mr Alex Ivey contributed to preliminary analysis of size structure information. Ms Hanna Zapna, Ms Teresa Nguyen, Ms Erica Bowen, Ms Sandra Leigh, Mr Chris Leigh and Dr Bill Breed (University of Adelaide Anatomy Department) conducted histological analyses. This report was reviewed by Dr Shane Roberts and Dr Adrian Linnane (SARDI Aquatic Sciences) and Dr Craig Noell (PIRSA Fisheries).

EXECUTIVE SUMMARY

1. This report synthesizes scientific information relevant to the South Australian Sardine Fishery (SASF), assesses the status of the stock, comments on the new management framework and identifies future research priorities for the fishery.
2. Total annual catch (from logbooks) increased from 9 to 39,185 t from 1991 to 2005 and then declined to 23,705 t in 2006. Similarly, total annual catches estimated for quota monitoring increased from 2,597 t in 1995 to 42,475 t in 2005 and declined to 25,137 t in 2006. The Total Allowable Commercial Catch (TACC) for 2007 is 32,000 t.
3. Effort increased steeply from 417 boat days (575 net shots) to 1,261 boat days (1,600 net shots) between 2001 and 2005. Effort then declined to 582 boat days (839 net shots) in 2006.
4. The modal lengths of sardines from catch samples taken from Spencer Gulf (SG) increased from 1995 to 2004, and declined slightly in 2006. Length distributions were unimodal between 1995 and 2002, with all lengths >150 mm between 2000 and 2002. In 2003 and 2004, length distributions were bimodal due to increases in the proportion of juveniles in catch samples. Catch samples in 2005 and 2006 were unimodal.
5. Male and female sardine reach sexual maturity (L_{50}) at 141 and 147 mm, corresponding to ~1.5 and ~2 years of age, respectively. All males <95 mm and females <120 mm were immature.
6. Estimates of spawning biomass obtained using the Daily Egg Production Method increased from ~36,000 t (95% C.I. = 19,000–67,000 t) in 1999, following the second mass mortality event, to reach 263,747 t (95% CI = 147,947–489,520 t) in 2007.
7. The objectives of the management framework for the SASF are to ensure that the stock is fished sustainability and that catches remain as stable as possible over the next 3-5 years. The indicative TACC for the SASF is 30,000 t and the actual TACC will be set at 30,000 t while the most recent estimate of spawning biomass is within the target reference of 150,000 – 300,000 t, which corresponds to exploitation rates of 20% and 10%, respectively.
8. The estimate of spawning biomass for 2007 lies within the upper third of the target range. The baseline TACC of 30,000 t is ~11.3% of the 2007 spawning biomass. Hence, the sardine stock on which the SASF is based is in a strong position.
9. The management framework for the SASF is well designed to achieve the objectives of stock sustainability and catch stability. The stock-related research priorities for the SASF are to increase the precision of estimates of spawning biomass and to improve current understanding of movement patterns of sardine in South Australian waters.
10. A large-scale study that is assessing the potential benefits of establishing ecological performance indicators for the SASF will conclude in 2008 and will provide recommendations to further enhance the ecologically sustainable management of the fishery.

1 GENERAL INTRODUCTION

1.1 Rationale and objectives

This is the seventh fishery assessment report on Australian sardine *Sardinops sagax* (Clupeidae) by SARDI Aquatic Sciences. It is a living document that is designed to inform management of the South Australian Sardine Fishery (SASF) and which summarizes biological and fishery specific information available up until 31 December 2006. The objectives of the report are to:

1. review scientific literature on clupeoids and describe the history and development of the SASF (Chapter 1);
2. present fishery data from 1991 to 2006 (Chapter 2);
3. summarize 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 2007 (Chapter 4);
5. assess the status of the resource, comment on the biological performance indicators, reference points and decision rules for the fishery, identify future management options and assess future research priorities (Chapter 5).

1.2 Review of the 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 with no valid sub-species. Recently, 11 new polymorphic micro-satellites were isolated that have the potential to help resolve some of the minor taxonomic questions that remain for this species (Pereya *et al.* 2004).

1.2.2 Stock Structure

There is a high level of genetic heterogeneity within the Australian stock of *S. sagax*, but no evidence of spatially consistent stock structure (Ward *et al.* 1998). No detailed studies of stock structure have been undertaken within SA waters. Information on the movement rates of *S. sagax* between gulf and shelf waters would assist future management of the SASF. The most suitable approach to addressing questions of stock structure and movement rates would be in the context of an Australia-wide study that concurrently utilizes genetic, parasite and otolith based approaches that have recently been applied to several species of scombrids (see Buckworth et al. 2006; Ward and Rogers 2007).

1.2.3 Distribution

S. sagax is found in waters off Australia, Japan, North and South America, Africa and New Zealand. In Australia, it is found throughout temperate waters between Rockhampton (Queensland) and Shark Bay (Western Australia), including northern Tasmania (Gomon *et al.* 1994).

S. sagax is the dominant clupeid in South Australian waters, and occurs in the southern portions of Gulf St Vincent and Spencer Gulf, as well as over the continental shelf (Ward *et al.* 2001a, b, c). Other clupeids that occur in the region include Australian anchovy, *Engraulis australis*, maray *Etrumeus teres*, blue sprat, *Spratelloides robustus*, and sandy sprat, *Hyperlophus vittatus* (Rogers *et al.* 2003; Dimmlich *et al.* 2004; Dimmlich and Ward 2006; Rogers and Ward 2007). The Australian anchovy, *E. australis* is more abundant than *S. sagax* in the northern gulfs (Dimmlich *et al.* 2004) and utilizes shelf waters extensively during periods when the abundance of *S. sagax* is reduced (see Ward *et al.* 2001a, b).

1.2.4 Schooling Behaviour

The schooling behaviour of *S. sagax* is complex, and varies at a range of spatial and temporal scales. For example, Barange and Hampton (1997) found that schools remained at similar densities throughout the day, whereas Misund *et al.* (2003) found that schools were highly dynamic and densities changed during the afternoon. Factors including habitat heterogeneity, predation levels and vessel noise can influence schooling behavior (Freon 1993; Giannoulaki *et al.* 2003).

1.2.5 Movement

S. sagax is known to undergo extensive migrations. For example, schools of *S. sagax* migrate into waters off southern Queensland during winter-spring to spawn (Ward and Staunton Smith 2002). Similarly, off Africa, *S. sagax* migrates north and south along the coast to access conditions that are favorable for spawning and the survival of recruits (van der Lingen and Huggett 2003). The movement patterns of *S. sagax* in waters of SA are unknown.

1.2.6 Food and Feeding

S. sagax switches between particulate-feeding on macro-zooplankton to filter-feeding on micro-zooplankton and phytoplankton, depending on relative prey density (van der Lingen 1994; Louw et al. 1998; van der Lingen 2002). In a recent study in SA waters *S. sagax* were found to have consumed 12 prey taxa with krill (29.6% biomass) and unidentified crustacean (22.2% biomass) contributing the highest biomass (Daly 2007). Krill occurred in greater numbers (65.3%) than crustacean (27.0 %). Crab zoea, other decapods, copepods, polychaetes, fish eggs and larvae and gelatinous zooplankton were also present.

1.2.7 Age, Growth and Size

A detailed study of the age and growth of *S. sagax* in SA waters was completed recently (Rogers and Ward 2007). That study showed that the growth rates of *S. sagax* are higher in SA waters than off other parts of the Australian coastline, yet lower than those in more productive boundary current ecosystems (Ward *et al.* 2007). A notable finding of the study was that fish in commercial catches were younger (and smaller) than those obtained in fishery-independent samples. This finding has significant implications for the use of age structured models (based on fishery samples) for stock assessment of the SASF.

1.2.8 Reproduction

The reproductive biology of *S. sagax* in SA waters is relatively well known. Approximately 50% of males and females reach sexual maturity (L_{50}) at 146 and 150 mm, respectively (Ward and Staunton Smith 2002). Spawning occurs during the summer-autumn upwelling period of January-April (Ward *et al.* 2001a, b; Ward and Staunton Smith 2002). Females spawn batches of 10,000–30,000 pelagic eggs approximately once per week during the extended spawning season. Eggs are abundant in the southern gulfs and in shelf waters (Ward *et al.* 2001a, b; Ward *et al.* 2003, 2004a).

1.2.9 Early Life History and Recruitment

S. sagax eggs hatch approximately two days after fertilization 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. Larvae are known to undertake vertical migrations that may reduce passive transport away from regions with environmental conditions that are favorable for survival (Watanabe *et al.* 1996; Logerwell *et al.* 2001; Stenevik *et al.* 2001; Curtis 2004). *S. sagax* larvae are abundant at temperature and salinity fronts that form near the mouths of SA's two gulfs during summer and autumn (Bruce and

Short 1990). In SA, juveniles occupy nursery areas that include shallow embayments and semi-protected waters. The factors affecting recruitment success of *S. sagax* in SA are poorly understood.

1.2.10 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 (Lasker 1985; Parker 1980) and has been used to estimate the spawning biomass of sardine in SA since 1995. Estimates of spawning biomass are the key biological indicator in the management plan for the SASF (Shanks 2005). The advantages of this approach is that it provides direct, estimates of spawning biomass on which to base management decisions. The disadvantages include the high degrees of uncertainty that surrounds 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 (Lynn 2003Tameishi *et al.* 1996;); predator-prey interactions and inter-annual variability in abundance (Barange *et al.* 1999). Changes in fish behavior limit the adoption of this technique for routine stock assessment (Freon *et al.* 1993). Acoustic assessment methods also require rigorous target strength validation for each species (S. McClatchie pers comm.).

1.2.11 Management Procedures in Small Pelagic Fisheries

Modern fisheries management aims to constrain exploitation rates within biologically sustainable limits while maximizing potential yields, and establishes performance indicators and reference points that underpin harvest strategies (Gabriel and Mace 1999). Management procedures that include agreed operational targets and decision rules have been successfully incorporated into the management systems of several commercial fisheries, including the South African Pelagic Fishery, Western Australian Pilchard Fishery, Pacific Sardine Fishery and the SASF (Cochrane *et al.* 1998; De Oliveira. *et al.* 1998; Cochrane 1999; Gaughan *et al.* 2004; Gaughan and Leary 2005a, b; Hill *et al.* 2005;).

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 two 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 Western Australian fisheries, where the stocks are recovering from substantial declines in abundance, the decision rules indicate that exploitation rates should not exceed 15 – 20% of the spawning biomass (Cochrane 1999; Gaughan and Leary 2005a, b).

1.2.12 Non-retained target catch

The amount of catch that is (i) lost from nets or (ii) released as 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).

Estimated catch lost in the South Australian Sardine Fishery is defined as the estimated weight of sardine (t) that is lost after the net has 'dried up', just prior to transferring the net onboard (Sardine Fishery Working Group, 20 July 2006). Lost catch may result from: (i) damage to the net; (ii) unintentional submersion of the float line; or (iii) deliberate submersion of the float line to release excess sardine.

1.2.13 Role in the Ecosystem

Small pelagic fishes live mainly in the upper layers of the water column, and convert energy produced by phytoplankton into a form that is available to higher vertebrates. Small pelagic fishes are an important food source for predatory fishes (Hoedt & Dimmlich 1994; Alheit & Niquen 2004; Ward *et al.* 2006), squid (O'Sullivan and Cullen 1983), seabirds (Montevecchi *et al.* 1995; Dann *et al.* 2000; Crawford 2003), seals (Page *et al.* 2005) and dolphins (Ohizumi *et al.* 2000). Upwelling influences the production and distribution of sardine (S. *sagax*), anchovy (*E. australis*) and southern bluefin tuna (*Thunnus maccoyii*) in the Great Australian Bight (Ward et al 2006c).

Populations of predators fluctuate in response to changes in productivity in the regions where they feed. Therefore, aspects of the reproductive end feeding ecology of predators have been used to monitor the health of marine ecosystems, to assess changes in environmental conditions, and to monitor effectiveness of fishery management regimes (Wanless et al. 1982, Rindorf et al. 2000, reviewed in Boyd et al. 2006). An assessment of the need for an ecological allocation in the SASF (Ward et al 2005c) and the trophodynamics of the GAB, is currently being undertaken by the Pelagic Ecosystems SubProgram at SARDI Aquatic Sciences and the final report to FRDC will be presented in 2008.

1.2.14 Mass Mortality Events

Mass mortality events in 1995 and 1998/99, spread throughout the entire Australian range of *S. sagax*; and are thought to have killed more fish over a larger area than any other single-species fish-kill recorded (Jones et al. 1997). Each event killed over 70% of the spawning biomass in South Australian waters (Ward et al. 2001).

Characteristics of the mass mortalities, such as their focal origin, rapid spread throughout the entire geographical range of the population and high mortality rates suggest both were caused by an exotic pathogen to which Australian sardines were naïve (Jones et al., 1997; Gaughan et al., 2000). Recovery of the South Australian population following these events has been monitored using the daily egg production method (DEPM, Lasker 1985; Ward et al. 2001). Assessment of the impacts of the mortality events on the age structure of the South Australian population of *S. sagax*, and the use of age structured models to assess the capacity of the population to recover, has been impeded by difficulties associated with obtaining reliable estimates of age for this species (Ward et al. 2005a).

1.3 The South Australian Sardine Fishery

The SASF is currently managed by the Fisheries management (Marine Scalefish Fisheries) regulations, 2006 and the *Fisheries Management Act*, 2007 which came into effect in December 2007. Goals for the SASF are consistent with the objectives of the *Fisheries Management Act*, 2007 and are outlined in the SASF Management Plan (Shanks 2005). Management measures include entry limitations, gear restrictions and individual transferable quotas. Purse seine nets must not exceed 1,000 m in length or 200 m depth with meshes of 14 to 22 mm. There are currently 14 license holders with several companies operating multiple licenses. The full costs of the policy, compliance and research programs that are needed to manage the SASF are recovered through license fees collected by PIRSA Fisheries.

The key Biological Performance Indicator for the SASF is the annual/biannual estimate of spawning biomass obtained using the Daily Egg Production Method (Tables 1-1, 1-2). From 1997 to 2006, the Total Allowable Commercial Catch (TACC) for the following calendar year was set as a proportion of the spawning biomass (i.e. 10.0% – 17.5%, depending on the size of the spawning biomass). More recently, the indicative TACC was set at 30,000 t and this will be maintained as the effective TACC while the latest estimate of spawning biomass remains between 150,000 and 300,000, which correspond to exploitation rates of 20% and 10%, respectively. The TACC from 1991 to 2007 is shown in Figure 1-1.

The Sardine Fishery Management and Research Workshop in Port Lincoln on 31 May 2007 identified the following research needs for future assessment and management of the SASF:

1. Broaden spatio-temporal coverage of adult sampling to better represent the spawning population through collaboration between Industry and SARDI during the DEPM surveys;
2. Develop a temperature-dependent egg development model for sardine;
3. Develop a temperature-dependent model for the degeneration of postovulatory follicles;
4. Establish a quality control system for the stock assessment process;
5. Refine methods for estimating egg production, spawning area and spawning biomass.

Issues regarding the operational interactions of the SASF with Threatened, Endangered and Protected Species (TEPS) and other potential ecological effects are considered in separate reports (e.g. Hamer *et al.* 2006; Goldsworthy *et al.* in preparation).

Table 1-1. Decision rules if the spawning biomass (SB) estimate is less than 150,000 t. (The exploitation rate is for a TACC of 30,000 t.)

Spawning biomass (SB)	Exploitation rate	Decision rule	
		Setting of TACC	Frequency of SB estimates
142,857 t ≤ **SB** < 150,000 t	20–21%	Delay response and monitor situation, but only in the event of unforeseen circumstances or uncertainty of assessment	Biannual
120,000 t ≤ **SB** < 150,000 t	20–25%	TACC is reduced to 15% of the SB **OR**	Biannual
		TACC is reduced to 15% of the SB **OR**	Annual
		No change to TACC	Annual
SB < 120,000 t	>25%	TACC is reduced to 15% of the SB	Annual

Table 1-2. Decision rules if the spawning biomass (SB) estimate is greater than 300,000 t. (The exploitation rate is for a TACC of 30,000 t.).

Spawning biomass (SB)	Exploitation rate	Decision rule	
		Setting of TACC	Frequency of SB estimates
300,000 t < **SB** < 450,000 t	5–10%	Increase TACC up to a maximum of 10% of the SB **OR**	Biannual
		Increase TACC up to a maximum of 15% of the SB **OR**	Annual
		No change to TACC	Biannual

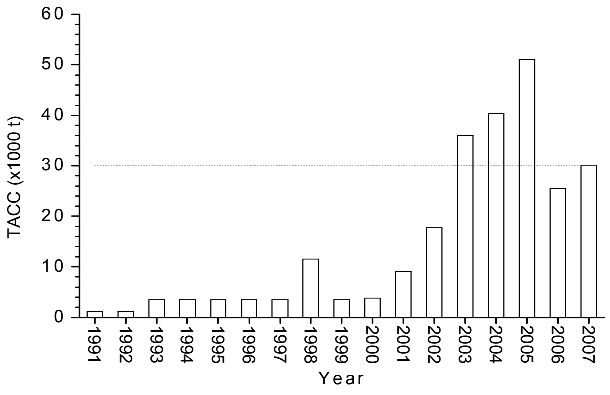

Figure 1-1. TACC for the SASF between 1991 and 2007 (dotted line is baseline TACC).

2 FISHERY STATISTICS

2.1 Introduction

This chapter summarizes catch, effort and catch-per-unit-effort (CPUE) data from the inception of the SASF in 1 January 1991 to 31 December 2006. Effort and catch data were collated from logbooks. Total annual catches are aggregates of daily catches. From 2001 additional information on effort (net shots) and non-retained target catch were also recorded. Actual total annual catches are estimated from Catch Disposal Records (CDR) collated by PIRSA Fisheries.

2.2 Annual Patterns

2.2.1 Effort and catch

Total effort and catches increased from 37 boat days and approximately 9 t during 1991 to 803 boat days and 3,241 t in 1994 (Figure 2-1). Total effort and catch declined following the first mass mortality event, but increased to 831 boat days and 6,431 t in 1998, before declining to 415 boat days and 3,548 t in 1999, following the second mass mortality event. Total effort increased rapidly to reach 1,600 net-shots over 1,261 boat days in 2005, with an estimated total catch of 39,185 t. In 2006, total effort was 839 net shots over 582 boat days and the catch was 23,705 t. The actual annual catches (CDR) increased from 2,597 t in 1995 to 42,475 t in 2005, and fell to 25,137 t in 2006. Actual catches exceeded estimated catches in most years. Lost catch declined from 2002.

2.2.2 Catch-per unit effort

Mean CPUE was calculated in boat-days only between 1991 and 2005 and both net-shots and boat-days between 2001 and 2005 (Figure 2-1). Mean $CPUE_{(boat\text{-}day)}$ increased from 1.1 t.boat-day^{-1} in 1991 to 8.6 t.boat day^{-1} in 1999 and reached 36.9 t.boat-day^{-1} in 2003 before declining to 31 t.boat day^{-1} in 2005. $CPUE_{(boat\ day)}$ in 2006 was 40.7 t.boat day^{-1}. Mean $CPUE_{(net\text{-}shot)}$, increased from 9.5 t.net-shot^{-1} in 2001 to 28 t.net-shot^{-1} in 2005. $CPUE_{(net\text{-}shot)}$ in 2006 was 28.3 t.net-shot^{-1}.

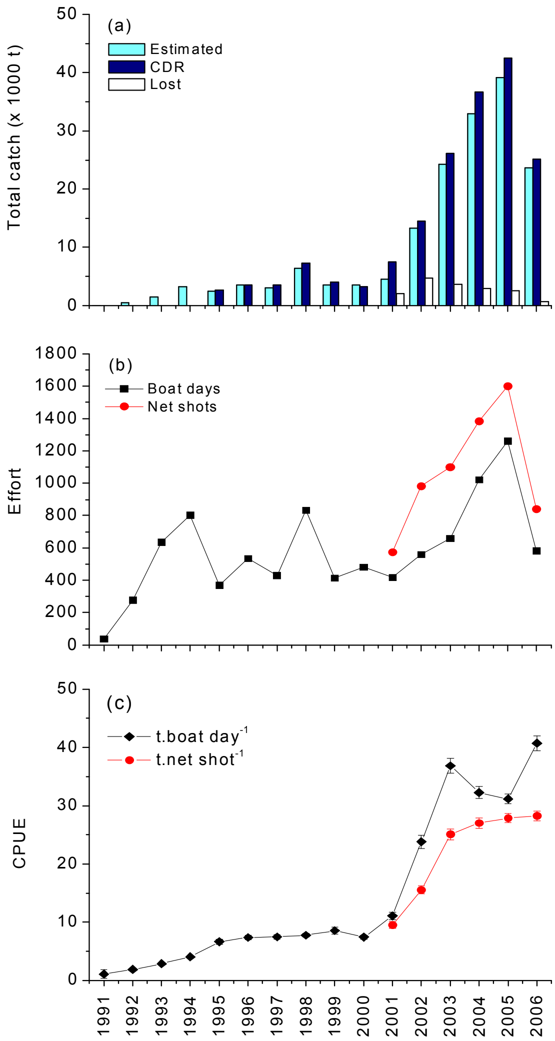

Figure 2-1. (a) Total catches (logbooks, CDR) and estimated lost catches, (b) fishing effort (boat days, net shots), and (c) Mean annual CPUE (boat days, net shots, ±SE).

2.3 Intra-Annual Patterns

2.3.1 Effort and catch

Between 1991 and 2006, the majority of the total annual catch has been taken from March to June (Figure 2-2), which reflects the extended periods of calm weather between April and June and the high demand for sardine to feed SBT following their capture during summer. Significant catches have also been taken in November and December, prior to the start of the SBT farming season. In 2006, most of the catch (71%) was taken during February to May.

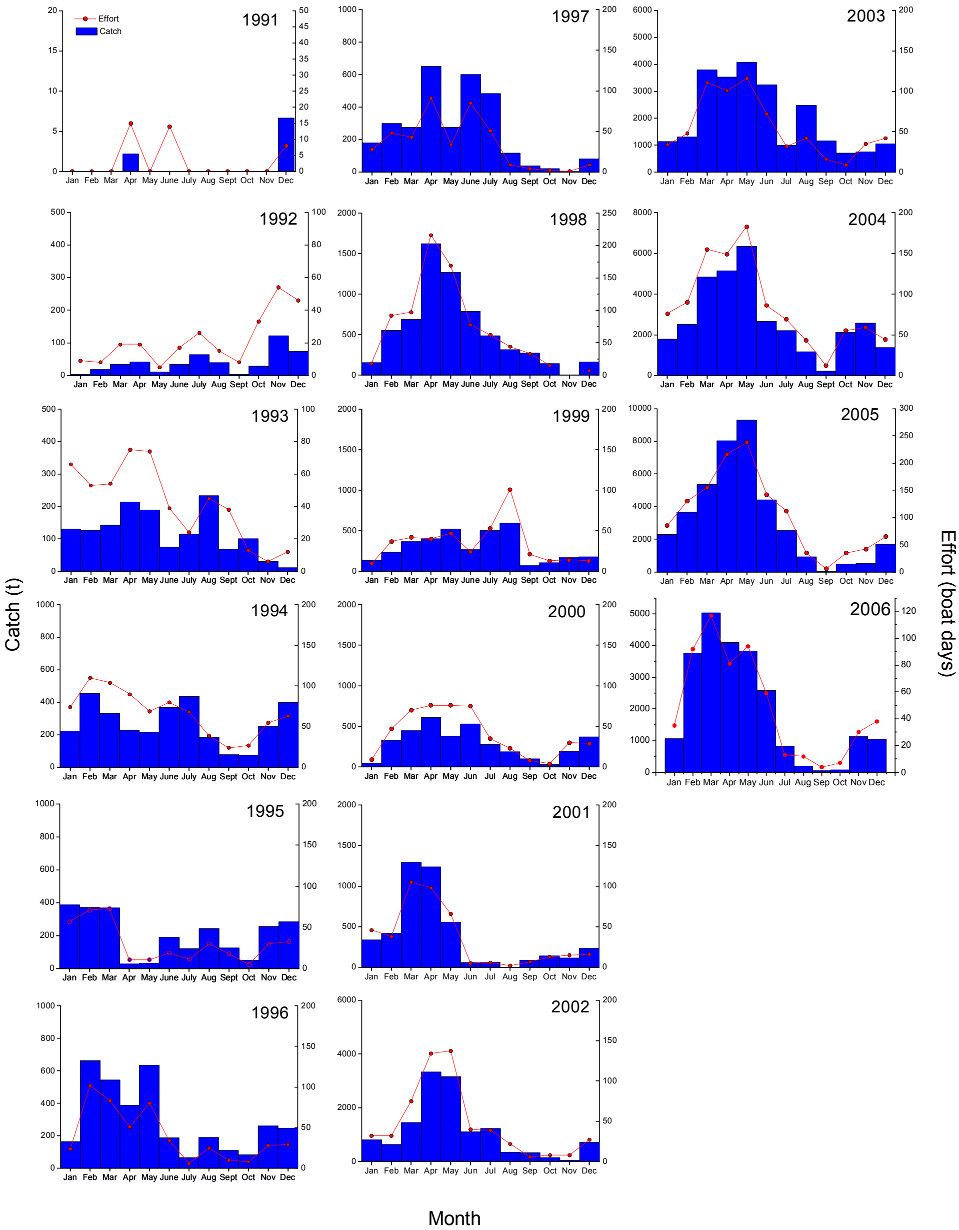

Figure 2-2. Intra-annual patterns in catch and effort between 1991 and 2006.

2.4 Spatial Patterns

2.4.1 Effort and catch

Prior to 2001, effort and catch were reported with respect to Marine Fishing Area (Figure 2-3, inset). After 2001 effort and catch were reported by latitude/longitude and aggregated with respect to 10 x 10 km grid squares. References in figures and text to "Coffin Bay" refer the broad area adjacent to Coffin Bay Peninsula (CBP). Locations mentioned in the text are shown in Figure 2-3.

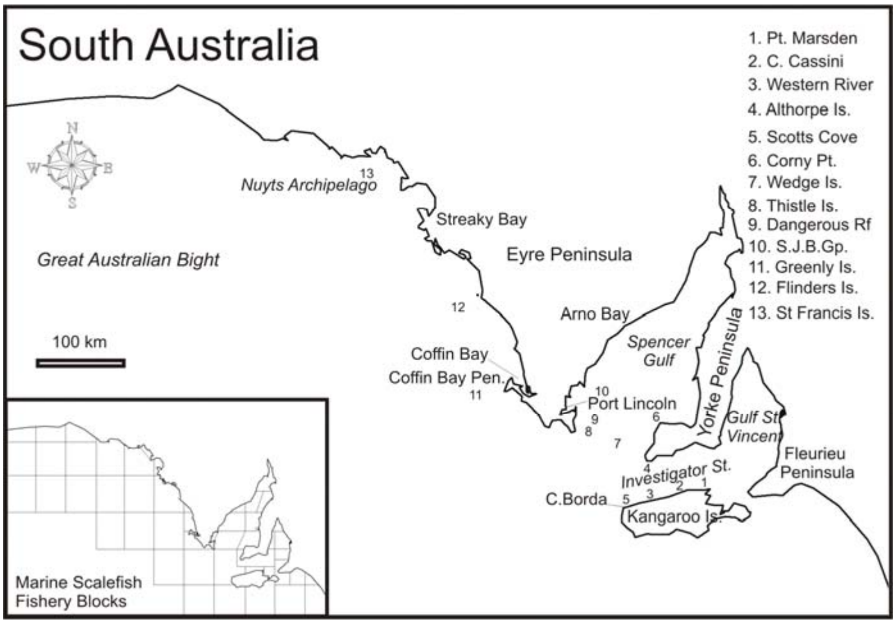

Figure 2-3. Locations mentioned in the text of this report. Inset shows MSF fishery blocks used for spatial analysis of catch and effort data between 1991 and 2000.

Between 1992 and 1995, fishing mostly occurred in Spencer Gulf. In 1996 and 1998 a proportion of the catch was taken off Coffin Bay (Figure 2-4). Catch and effort between 1999 and 2001 declined off Coffin Bay and retracted into southern Spencer Gulf (Figures 2-4, 2-5). In 2002, ~90% of the catch was taken north-east of Thistle Island and ~9.5% was taken off Coffin Bay. In 2003, the fishery expanded northwards in Spencer Gulf and an increasing proportion of the catch taken closer to shore. Further spatial expansion occurred during 2004, and a large proportion of the total catch was taken near Wedge Island and east of Althorpe Island. Catches were also taken along the northern coast of Kangaroo Island, between Cape Borda and Marsden Point. In 2005, the spatial extent of the SASF expanded substantially. The eastern Great Australian Bight and inshore areas around the Sir Joseph Banks Group and along the west coast of Spencer Gulf were fished more than in previous years. The fishery contracted in 2006, with the largest catches taken from southern Spencer Gulf, near Thistle, Wedge and

Althorpe Islands and further north near Arno Bay. Relatively large catches were also taken in Investigator Strait.

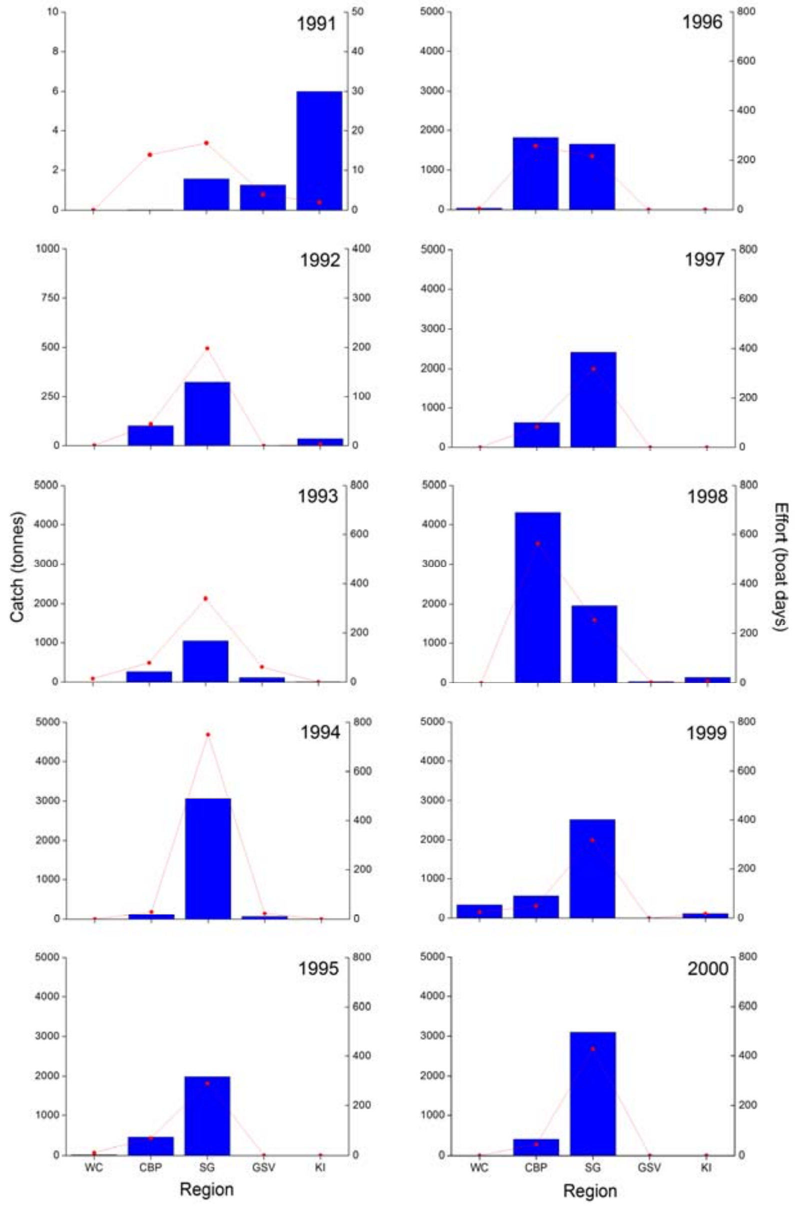

Figure 2-4. Spatial trends in catch and effort between 1991 and 2000 (NB different y-axis scale for 1991 and 1992).

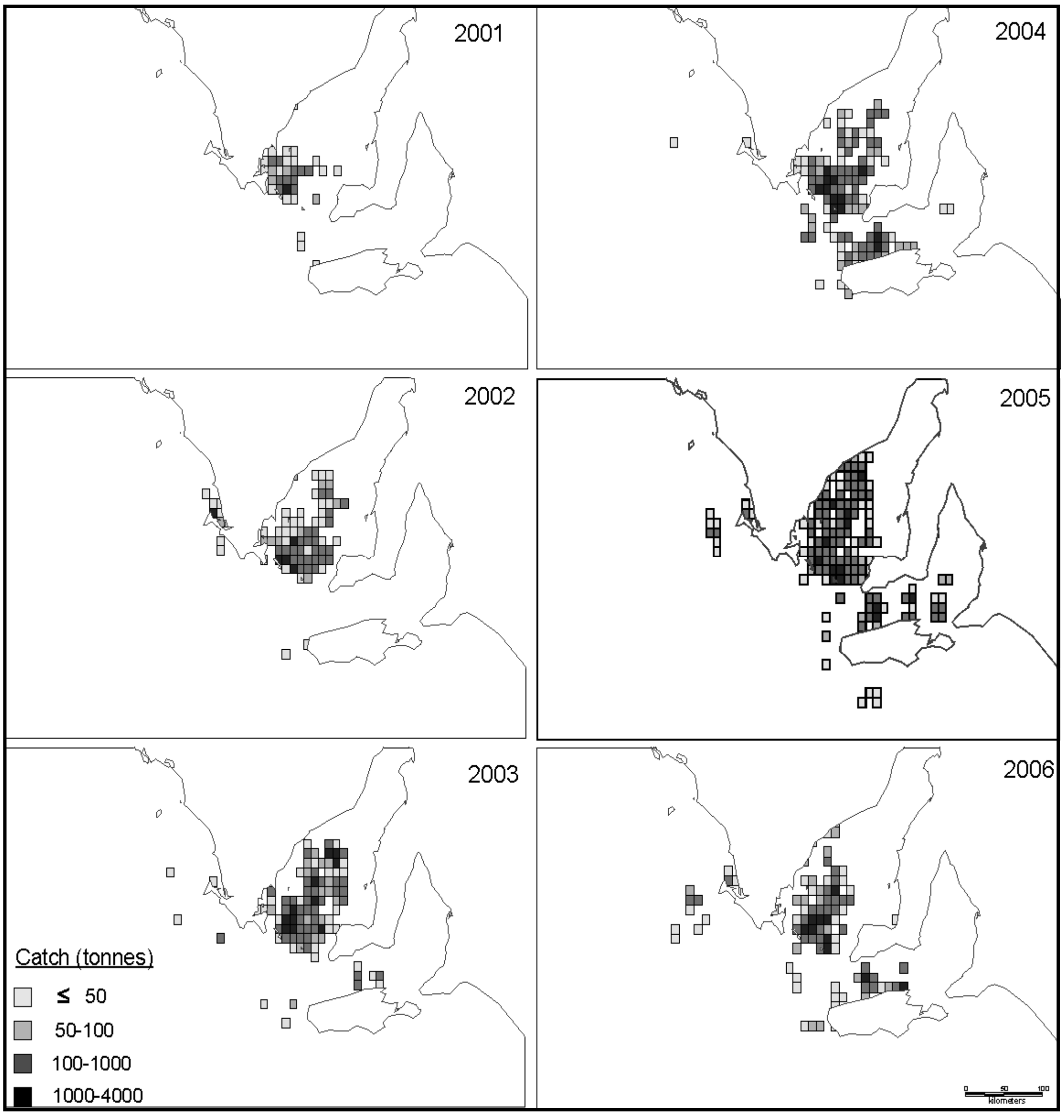

Figure 2-5. Spatial trends in annual catches between 2001 and 2006.

2.5 Discussion

Most of the catch of the SASF has been taken from southern Spencer Gulf, with significant catches taken from Coffin Bay and Investigator Strait in some years. Total catches and the size of the area fished usually peaked between April and June, largely in response to the high demand for SBT fodder at that time of the year and because weather conditions are often favorable for purse seining. In 2006, the total catch fell from the high levels recorded in 2004 and 2005 and the area fished also contracted. These changes reduced previous concerns regarding the spatial depletion of Spencer Gulf. The fishery statistics provide no evidence to suggest additional management arrangements are currently needed in the fishery.

3 AGE, GROWTH AND REPRODUCTION

3.1 Introduction

This chapter presents data from commercial catch sampling (1995–2006) and fishery independent-surveys (1998-2006). Data are collated to provide updated information on the size, age, growth and reproductive patterns of sardine in SA waters.

3.2 Methods

3.2.1 Size Structure

Samples were collected from commercial catches on an ad hoc basis between 1995 and 2006. Fishery independent samples were collected from Spencer Gulf, Investigator Strait and the EGAB using nylon multi-filament, multi-panel gillnets (*Double Diamond*: 210/4 ply meshes – 25, 28 and 32 mm) deployed from the *RV* Ngerin during annual DEPM cruises (see Ward *et al.* 1998, 2001b). Size frequencies were constructed from fork lengths (FL), aggregated into 10 mm length classes for all samples.

3.2.2 Age and Growth

Otolith preparation and interpretation

Sagittal otoliths were collected from sub-samples of the commercial catch sample (n = 10-20). 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 (see Rogers and Ward 2007).

Relationship between age and otolith weight

Relationships between otolith weight and age for each year were determined from otoliths with readabilities of 1 and 2 by linear regression. These relationships were then used to calculate the ages of fish with otoliths that were difficult to interpret.

Age structure

Otolith weight-age regressions were then used to calculate the age structure of 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

The relationship between length and age data collected between 2001 and 2007 was described using the von Bertalanffy growth function (*VBGF*):

$$L_t = L_\infty \left(1 - e^{-K[t - t_0]}\right)$$

Where, t is age in years, t_0 is the hypothetical age when length is zero, L_∞ is the asymptotic mean maximum length and K is the rate at which the asymptotic length is reached. Parameters for the VBGF were estimated using non-linear regression.

3.2.3 Reproduction

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).

Size at Maturity

Ovaries were staged macroscopically 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 sexual maturity (L_{50}) was estimated for males and females collected from 2001 and 2006. 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 is represented by the equation:

$$P_L = 1 \Big/ \left(1 + e^{-r[L - Lm]}\right)$$

where P_L is the proportion that are sexually mature in each size class, r is the slope of the curve and L_m is the mean length at sexual maturity (L_{50}).

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 sometimes difficult to macroscopically distinguish between Stage 2 and Stage 5 gonads in some frozen samples.

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–squared tests were used to determine if there were significant differences in sex ratios between sexes in each region.

3.3 Results

3.3.1 Size Structures

Annual patterns from commercial catches - Spencer Gulf

Between 1995 and 1999, sardine taken from Spencer Gulf were mostly 120 to 160 mm FL, with modes at 130–140 mm (Figure 3-1). Between 2000 and 2002, sizes were mostly >150 mm with modes between 160 and 170 mm. In 2003 and 2004, catch samples were bimodal as significant quantities of juveniles (80–120 mm) were caught in addition to adults (150–180 mm). Prior to 2003 no catch samples included sardine ≤100 mm, FL. In 2004, sardine from commercial catches ranged between 90 and 200 mm with those <150 mm (n = 3,818) comprising 24% of samples. In 2004 and 2005 sardine ranged from 120 to 200 mm with a mode at 150 mm. Similarly, fish from catch samples ranged from 120 to 210 mm with a mode at 150 mm in 2006.

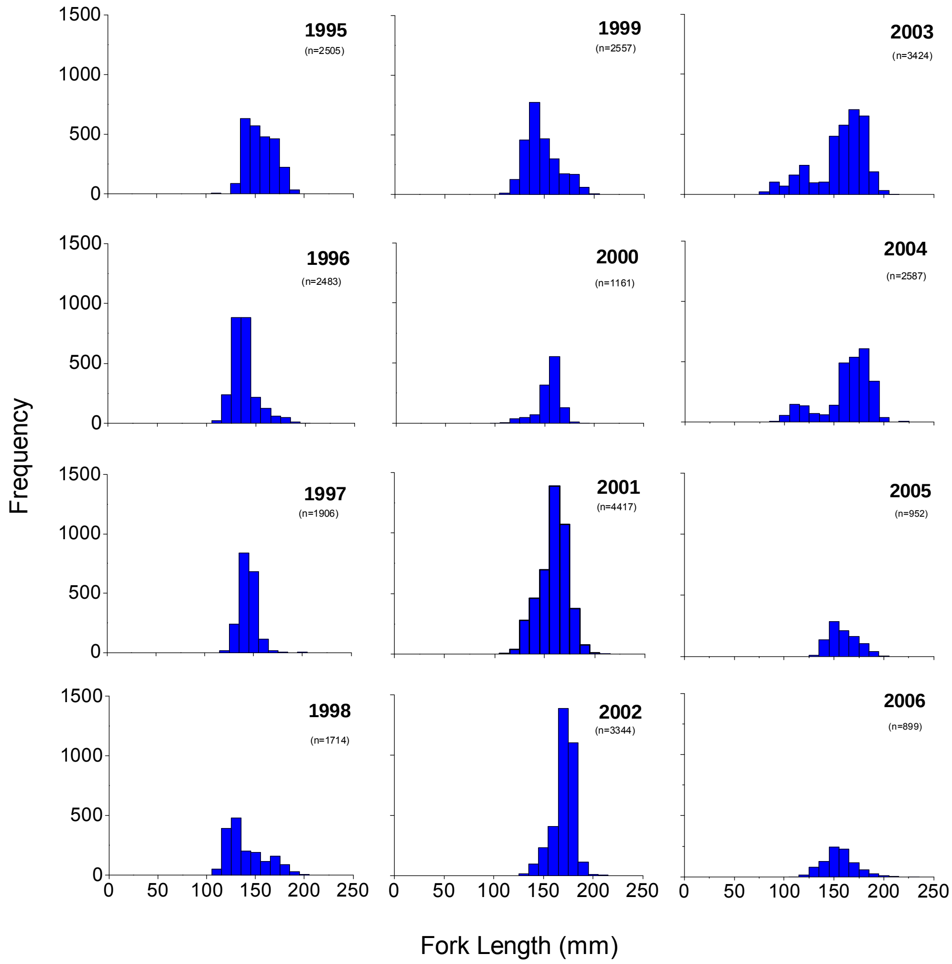

Figure 3-1. Length frequency distributions by year for commercial catch samples from Spencer Gulf between 1995 and 2006.

Annual patterns from commercial catches – Coffin Bay

Between 1995 and 1998 samples from Coffin Bay were unimodal with the length range from 150 and 180 mm (Figure 3-2). Following the second mass mortality event in 1998/9 the modal size declined to 150 mm. Subsequent to this fishing effort declined. In 2002 and 2003, samples suggested a bimodal size distribution of sizes 150–180 mm, although sample sizes were small (n = 240, n = 72, respectively). In 2004, a small number of fish (n = 90, mode 140 mm) were collected from catches in Coffin Bay.

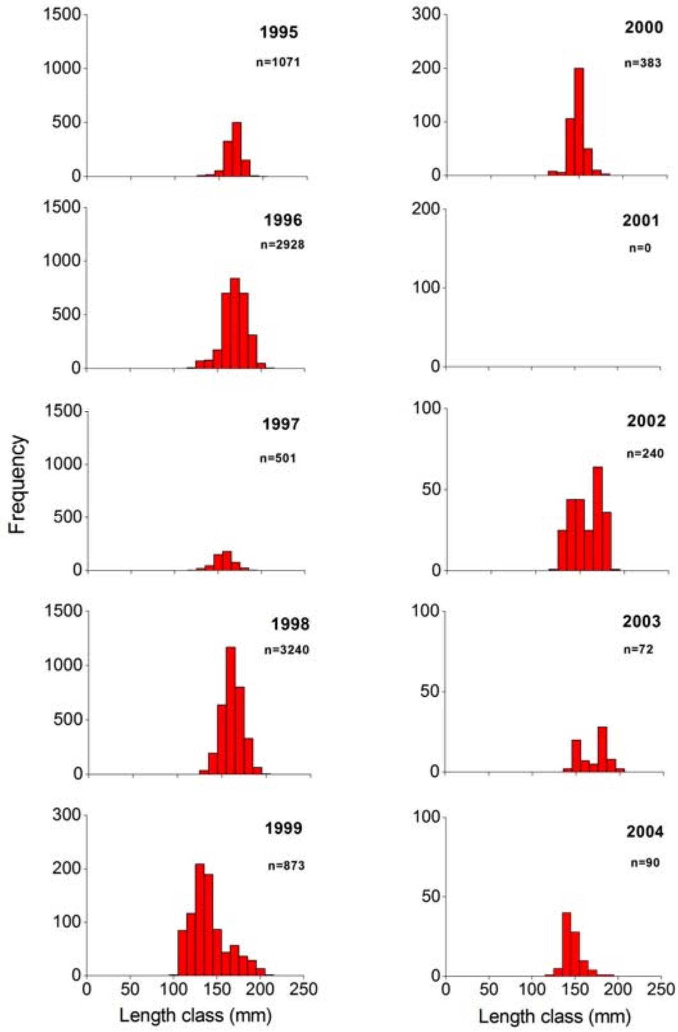

Figure 3-2. Length frequency distributions for catch samples from Coffin Bay between 1995 and 2004 (no data available in 2005, 2006).

Annual patterns from fishery independent sampling

Fishery independent size data were available from 1998 to 2007. Size distributions were unimodal in most years with the exception of 1998 and 2003 when they were bimodal due to the presence of juveniles (<140 mm) (Figure 3-3). The modal size of catch samples ranged from 130–190 mm between 1999 and 2006. In 2007 the modal size was 180 mm. Larger fish with length frequency modes ≥170 mm were consistently collected from waters around offshore islands, including Flinders, St Francis and Greenly Islands (Figure 3-4). With the exception of samples from Francis and Greenly Islands in 2005 and 2006, most size distributions from offshore sites were unimodal. In 2007, size distributions were available for Scotts Cove, and Wedge, Pearson and Neptune Islands. The size range was 130 to 210 mm across all locations with the smallest modal size from Wedge Island (140–150 mm) and the larger fish were from Scotts Cove (160–180 mm).

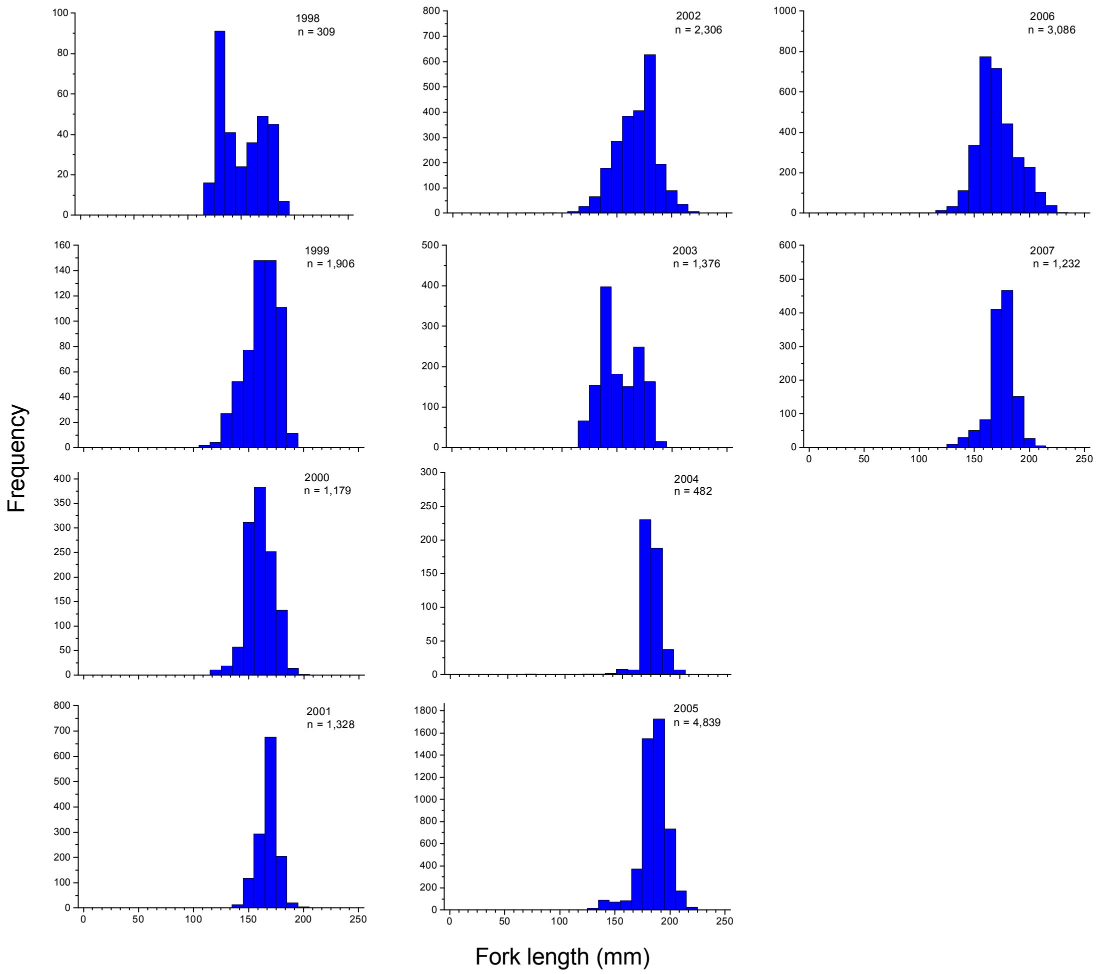

Figure 3-3. Length frequency distributions for fishery independent samples collected between 1998 and 2007.

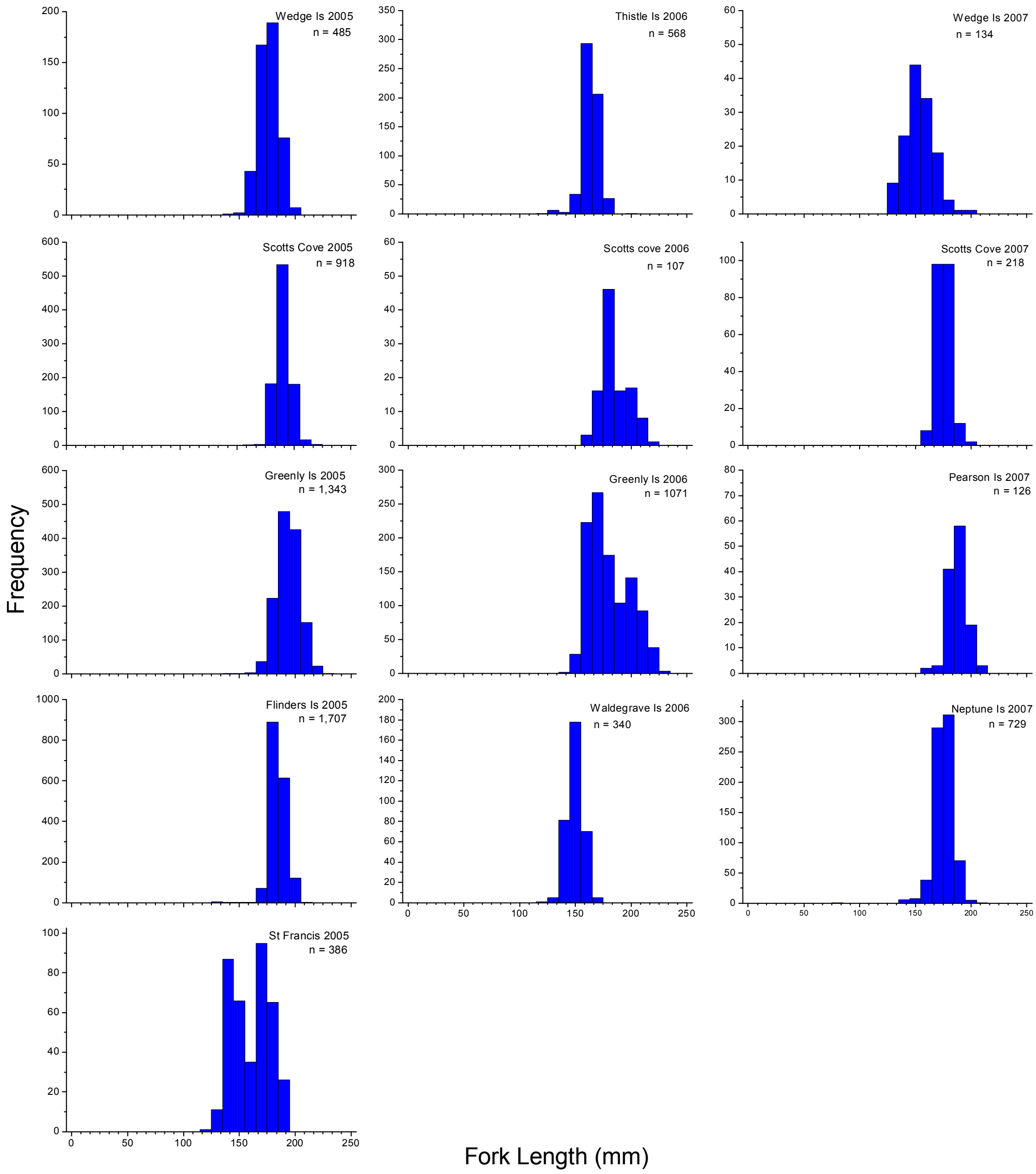

Figure 3-4. Length frequency distributions by location for fishery independent samples collected in 2005, 2006, and 2007.

3.3.2 Age Structure

Readability indices (RI)

The readability of otoliths was investigated in 2004 (n = 1,542). Of these otoliths, 0.6% were assigned an RI score of 1, while 7.8, 44.4 and 30.1% were assigned scores of 2, 3 and 4. Approximately 17.2% were assigned an RI of 5. (Figure 3-5).

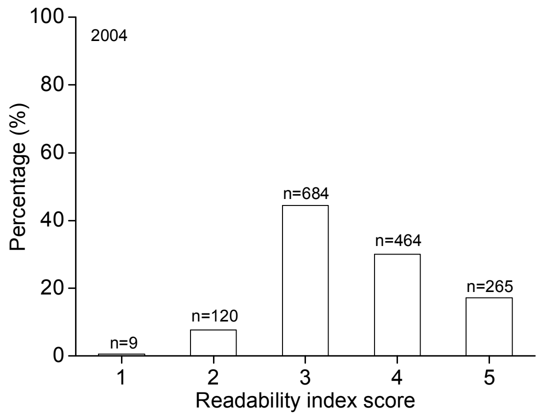

Figure 3-5. Readability index (RI) scores assigned to *S. sagax* otoliths from catch samples in 2004.

Relationship between age and otolith weight

Otoliths with high readability scores (1-2) were used to describe the relationship between age and otolith weight (Figure 3-6). The significant relationship, Age = 2.90*Oto.wt - 0.64, (LR: $r^2 = 0.72$, $P<0.0001$, n = 129) was used to estimate the age of fish and to construct the age structures.

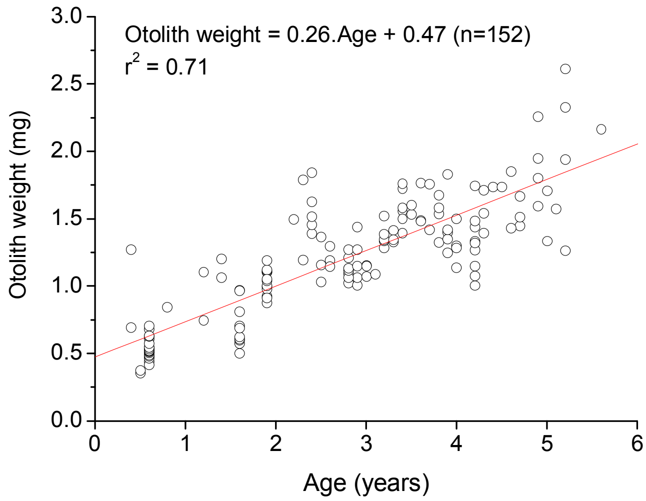

Figure 3-6. Otolith weight as a function of age for otoliths (RI scores 1 and 2) collected from catch samples during 2004-06.

Commercial catch sampling

Annual patterns

Ages from commercial catch samples, taken in Spencer Gulf, were available from 1995 to 2006 and ranged from 1 to 6 years. Age structures were dominated by 2 year olds from 1995 to 2001 with the exception of 1998 when the dominant age class comprised 1 year olds. From 2002 to 2004 the age structures were dominated by 3 year olds. In 2005, the age structure comprised mostly 2 year olds (50%) and 3 year olds (30%). In 2006, the dominant age class was 3 year olds (51%) (Figure 3-7). Four year olds comprised 12 and 14% of samples from 2005 and 2006, respectively.

Ages were available for catch samples from Coffin Bay from 1995 to 2003. Age structures were dominated by 2 to 4 year olds between 1995 and 1999 (Figure 3-8) although sample sizes were small after 1998. From 2002 to 2003 age structures were dominated by 2–3 year olds.

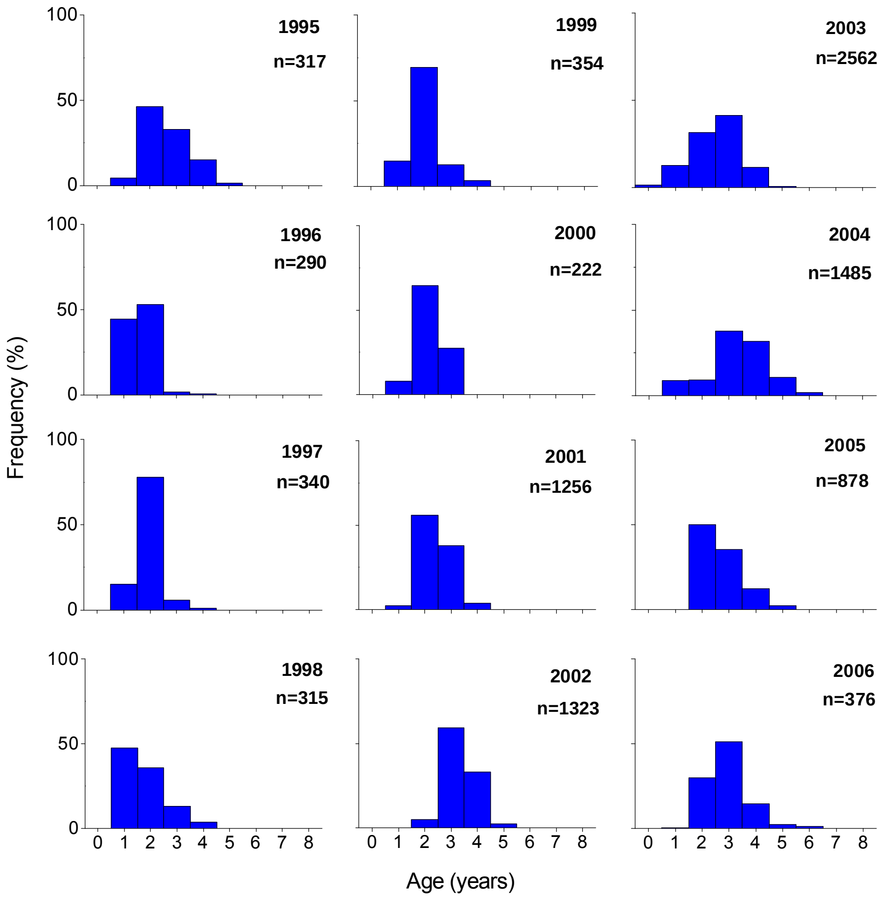

Figure 3-7. Age structures by year from catch samples from Spencer Gulf between 1995 and 2006.

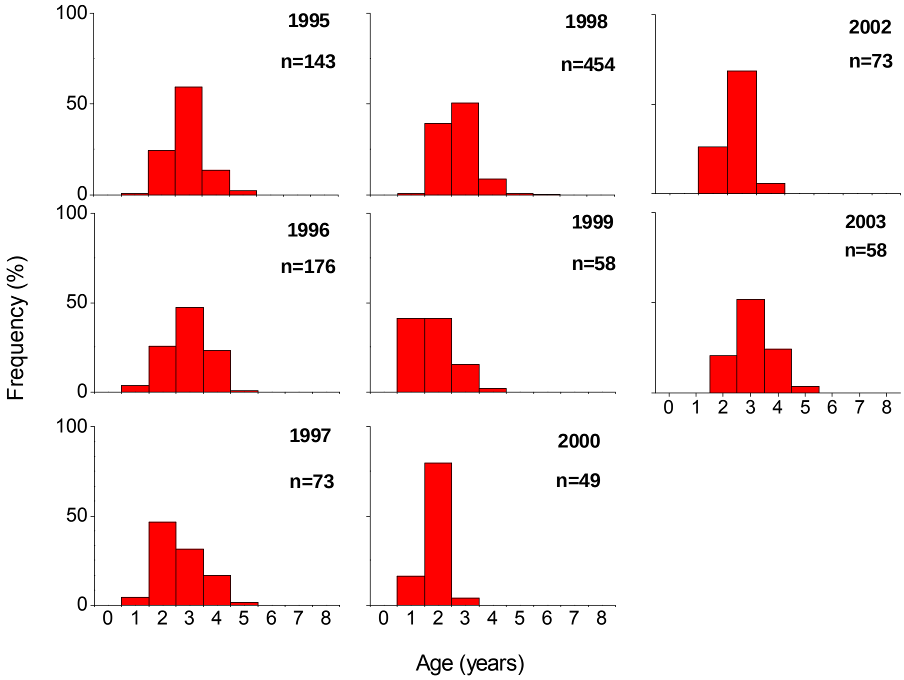

Figure 3-8. Age structures by year for catch samples from Coffin Bay between 1995 and 2003 (few data available for 2004–06).

Monthly patterns

Monthly age structures for Spencer Gulf in 2005 were available from January to March, October and December (Figure 3-8). Age structures from January to February were dominated by 2 year olds, 56 and 48%, respectively. Three year olds dominated in March (56%) and April (57%) but 2 year olds comprised the largest age class in May (47%) and December (63%). Sample sizes for all other months were small (n < 30).

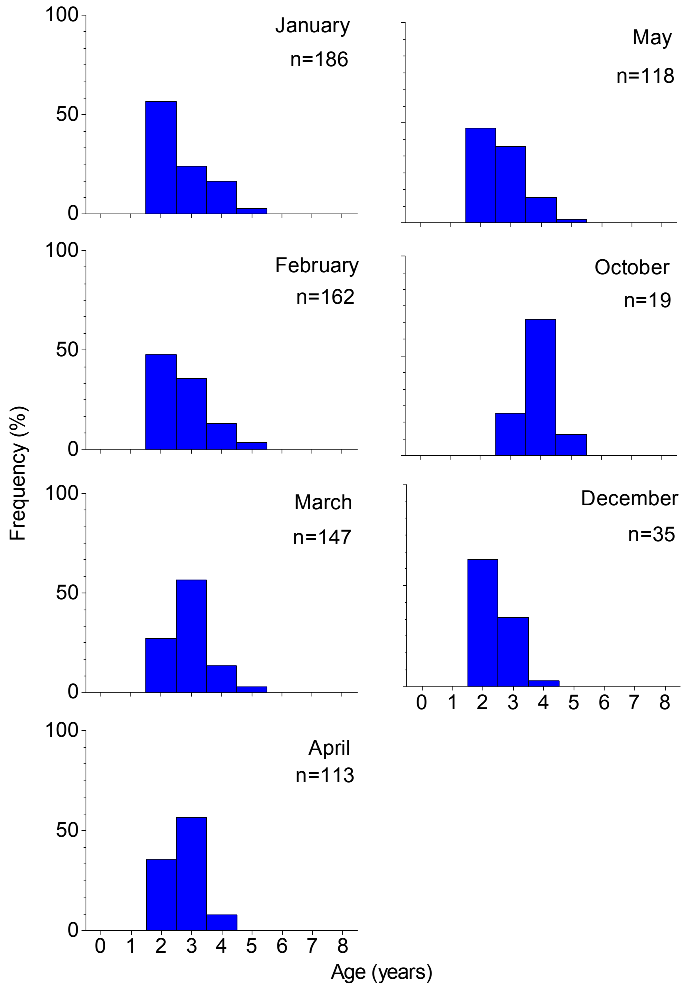

Figure 3-8. Age structures by month for catch samples from Spencer Gulf in 2005 (few data available for 2006)

Fishery Independent Sampling

Age structures were available for 1998 to 2006, with the exception of 2004. Adult ages ranged from 2 to 7 years between 1998 and 2003 (Figure 3-9). Ages ranged from 1 to 7 years old across all years. In 1998, the age structure was dominated by 3 year olds (37%) and in 1999 by 3 (33%) and 4 year olds (33%). From 2000 to 2002, 4 year olds dominate the age structures (33–61%). Two year olds dominated the age structure in 2003 (51%) and 3 year olds were prominent in 2005 (35%) and 2006 (60%).

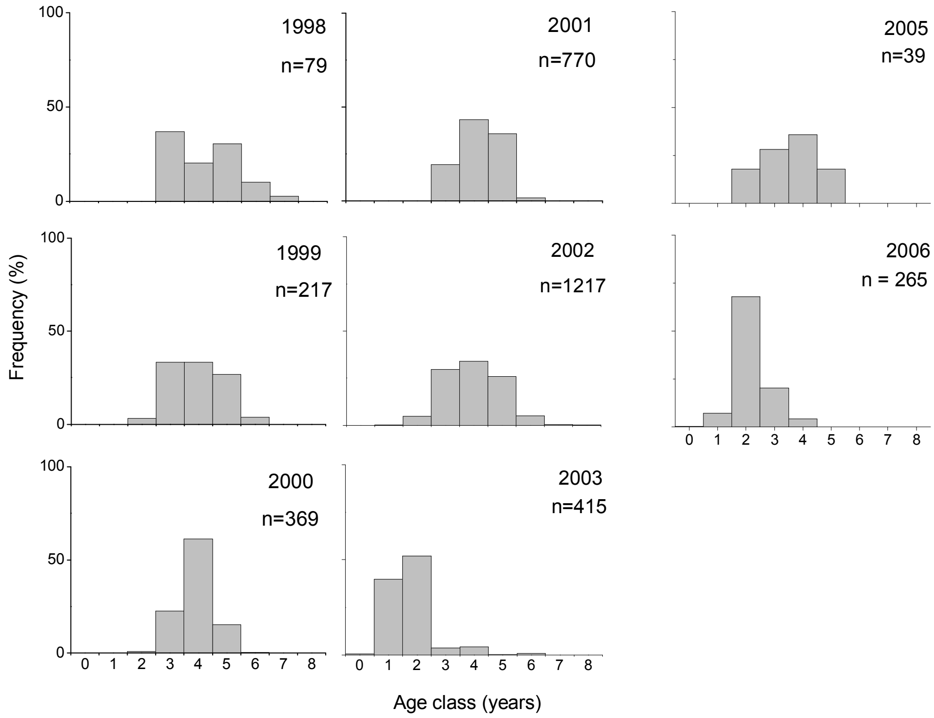

Figure 3-9. Age structures for fishery independent samples between 1998 and 2006 (no data available for 2004).

3.3.3 Growth patterns

Growth of *S. sagax* from Spencer Gulf was described using the Von Bertalanffy growth function (VBGF). Ages were estimated from otoliths that were sub-sampled from commercial catches between 2001 and 2006 as well as from fishery independent surveys in 2001. VBGF parameters and the fitted curve are shown in Table 3-1 and Figure 3-10.

Table 3-1. Von Bertalanffy growth parameters for *S sagax* from Spencer Gulf and Coffin Bay from 2001-06 (95% confidence bounds in parentheses).

Location	L_∞ (mm)	k (mm.yr^{-1})	r^2	n
Spencer Gulf	193.02 (*190.826 & 195.221*)	0.58 (*0.558 & 0.598*)	0.95	11,331

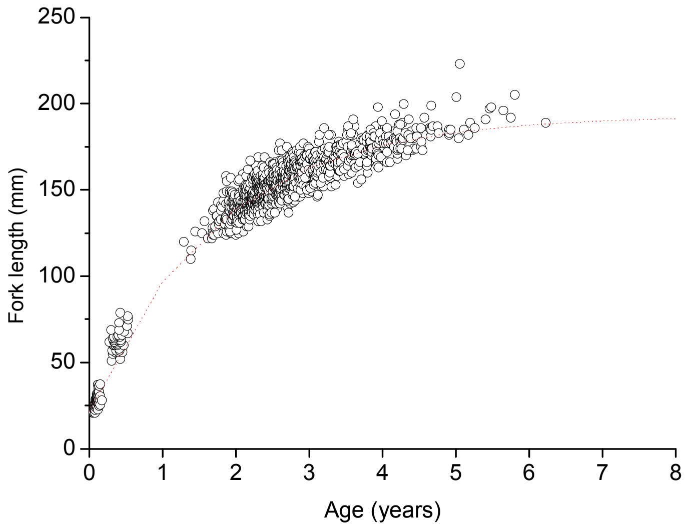

Figure 3-10. Von Bertalanffy growth curve for *S. sagax* from Spencer Gulf and Coffin Bay in 2001/06.

3.3.4 Reproduction

Size of maturity (L_{50})

Size of maturity (SOM, L_{50}) was estimated for *S.sagax* from commercial catch samples and fishery independent samples from Spencer Gulf and Coffin Bay between 2001 and 2006. SOM was 141 (95% CB: 140.0 and 142.0) and 147 mm (95% CB 146.3 and 147.0) for males and females, respectively (Figure 3-11). All males below 95 mm and females below 120 mm had immature gonads.

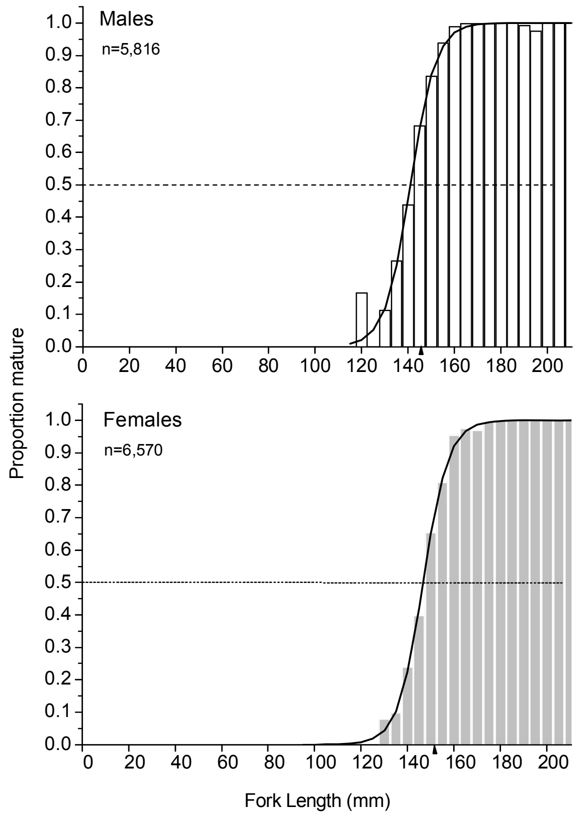

Figure 3-11. Relationship between length and the proportion of male and female *S. sagax* at sexual maturity. (reference line is L_{50}).

Sex Ratio

Mean annual sex ratios for catch samples from Spencer Gulf (2001–2006) are shown in Table 3-2. Females were more abundant in catch samples from all years except 2000 and 2006. Mean monthly sex ratios (2001–06 data pooled) are shown in Table 3-3. Females were more abundant in all months.

Table 3-2. Mean annual sex ratios for commercial catch samples of *S. sagax* from Spencer Gulf (* $P<0.05$, ** $P<0.005$).

Year	n_m	n_f	$N_f/(n_m + n_f)$	X^2	P	Significance
1995	181	343	0.65	49.467	0.000	* *
1996	397	459	0.54	4.346	0.037	*
1997	170	218	0.56	5.693	0.017	*
1998	234	277	0.54	3.452	0.063	*
1999	457	609	0.57	21.389	0.000	* *
2000	279	184	0.40	19.084	0.000	* *
2001	852	1400	0.62	132.863	0.000	* *
2002	1221	1469	0.55	22.679	0.000	* *
2003	1635	1955	0.54	28.345	0.000	* *
2004	1461	1796	0.55	34.251	0.000	* *
2005	917	1502	0.62	140.990	0.000	* *
2006	430	400	0.48	1.0132	0.314	*

Table 3-3. Mean monthly sex ratios for commercial catch samples of *S. sagax* from Spencer Gulf, 2001 to 2006 (* $P<0.05$, ** $P<0.005$).

Month	n_m	n_f	$N_f/(n_m + n_f)$	X^2	P	Significance
Jan	1143	1502	0.57	48.455	0.000	* *
Feb	811	1135	0.58	53.612	0.000	* *
Mar	1075	1317	0.55	24.281	0.000	* *
Apr	1055	1145	0.52	3.600	0.058	*
May	881	1127	0.56	29.892	0.000	* *
Jun	409	446	0.52	1.515	0.218	*
Jul	354	578	0.62	53.357	0.000	* *
Aug	594	988	0.62	97.628	0.000	* *
Sep	185	290	0.61	22.771	0.000	* *
Oct	308	354	0.53	3.059	0.080	*
Nov	642	757	0.54	9.289	0.002	* *
Dec	777	973	0.56	21.729	0.000	* *

Macroscopic staging of gonads

Male (n = 7,051) and female (n = 9,127) gonads sub-sampled from catches of *S. sagax* in Spencer Gulf between 1995 and 2004 were mostly immature (Stage 1) and maturing (Stage 2). Mature ovaries (Stage 3) were present in samples from January to April (Figure 3-12. Macroscopic gonad stages for males and females in Spencer Gulf (a) above and Coffin Bay (b) between 1995 and 2004 (limited data available for 2005-06). 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) *S. sagax* 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. 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 or Stage 2 gonads between June and October (i.e. >80% of males and females had Stage 1 gonads).

Gonosomatic Index (GSI)

Patterns in mean GSI indicated that the reproductive period for female *S. sagax* in Spencer Gulf was between November and March with males showing a similar seasonal pattern (Figures 3-12a, b). 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 in September was based on few individuals (n = 3). The lowest mean GSI for fish sampled off Coffin Bay were between July and October.

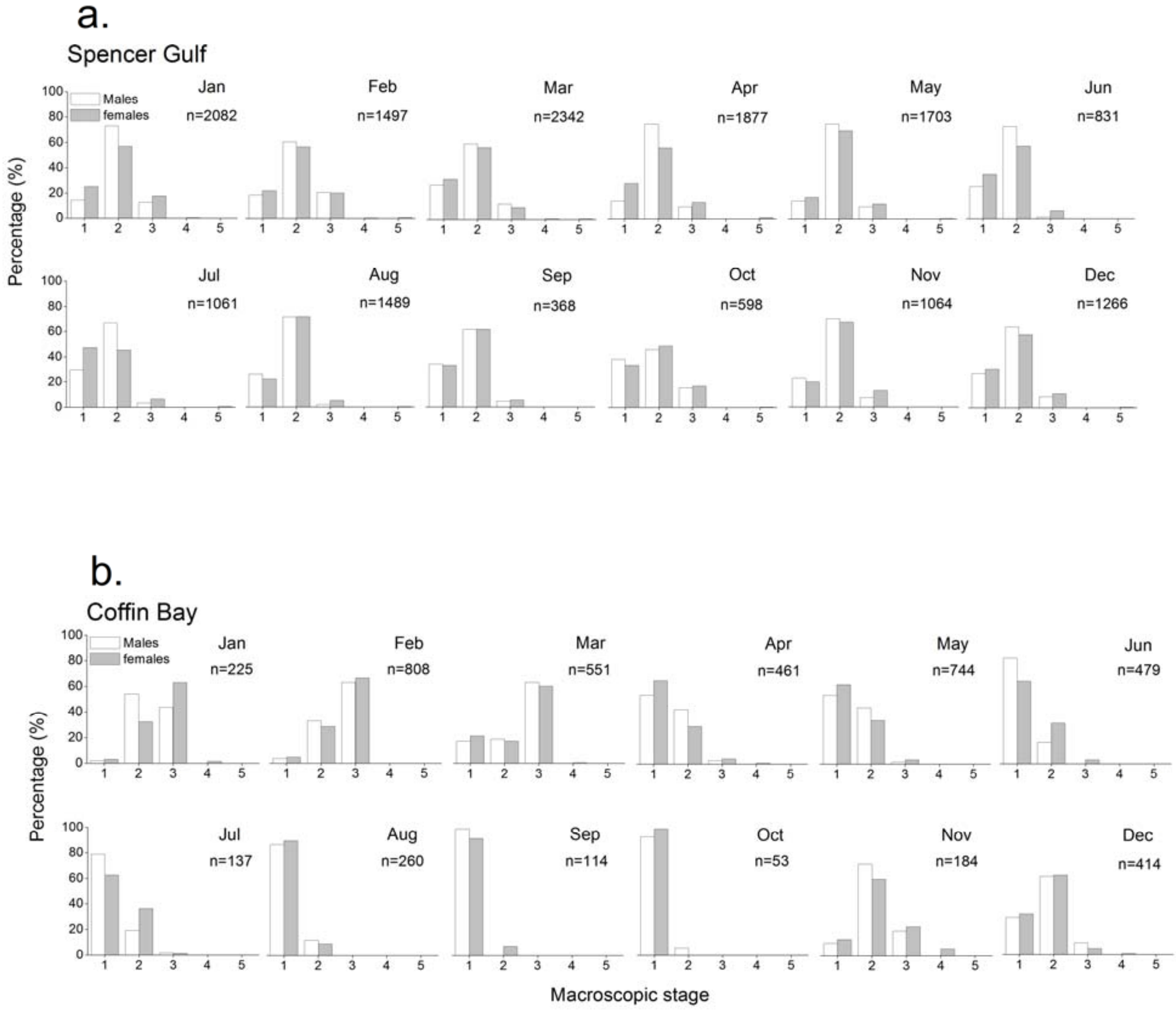

Figure 3-12. Macroscopic gonad stages for males and females in Spencer Gulf (a) above and Coffin Bay (b) between 1995 and 2004 (limited data available for 2005-06).

3.4 Discussion

The distinct differences in the size and age structures of fishery independent and commercial catch samples, suggest that neither may be representative of the broader population (Ward *et al.* 2005a). Larger fish (180–220 mm) occur around offshore islands in the EGAB, whereas fish from commercial catches tend to be smaller (100 to 190 mm). This may, in-part, be related to differences in fishery and fishery independent gear, 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) (Ward et al 2005a).

Uncertainty in estimates of sardine age is relatively high (Average Percent Error = 15.6%, CV = 22.1%) due to difficulties in interpreting annual zones in otoliths (Rogers and Ward 2007). This issue has partly been overcome by using age-otolith weight relationships developed from a subset of the best otoliths to determine age structures. Catches from 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.

Growth analysis suggests that sardine exhibit considerable variation in length at age in SA waters. The 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 Western Australia and slower than those in more productive ecosystems, including the California and Benguela Current systems off the coast of North America and South Africa (Rogers and Ward 2007).

Sardine spawn in summer and autumn in SA, with the peak occurring in February-March. Although the most important fishing months are between March and June (i.e. partially overlap with the spawning season) our analyses show that spawning females (Stage 4) comprise a small proportion (<1%) of the catch. This provides evidence that spawning sardines may be poorly sampled using purse seine gear, (Hewitt 1985) and further demonstrates the importance of obtaining fishery independent samples to estimate the reproductive parameters required for application of the DEPM.

4 SPAWNING BIOMASS ESTIMATES 1995 TO 2007

4.1 Introduction

This section provides the current "best estimates" of the spawning biomass of sardine in SA for the period 1995 to 2007. In some cases these estimates differ from those provided in previous reports.

4.2 Methods

4.2.1 The Daily Egg Production Method (DEPM)

SARDI Aquatic Sciences has used the DEPM to estimate the spawning biomass of *S. sagax* 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, P_0) and the number produced per female (daily fecundity). Spawning biomass (B) is calculated according to equation 1:

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

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 2007, ichthyplankton and adult sampling surveys of 10–14 days duration were conducted during each spawning season (January – March) from the *RV* Ngerin. The location of plankton sampling stations is shown in Figure 4-1. The number of stations and orientation of transects varied between years, as the survey design was refined. During 1995 and 1996, few stations were sampled, as the primary goal was to identify the main spawning area. After 1997, transects were orientated northeast-southwest (*c.f.* north-south) to improve sampling efficiency. In 2006, stations that had not yielded any eggs in the preceding decade were excluded in favor of additional stations in Spencer Gulf.

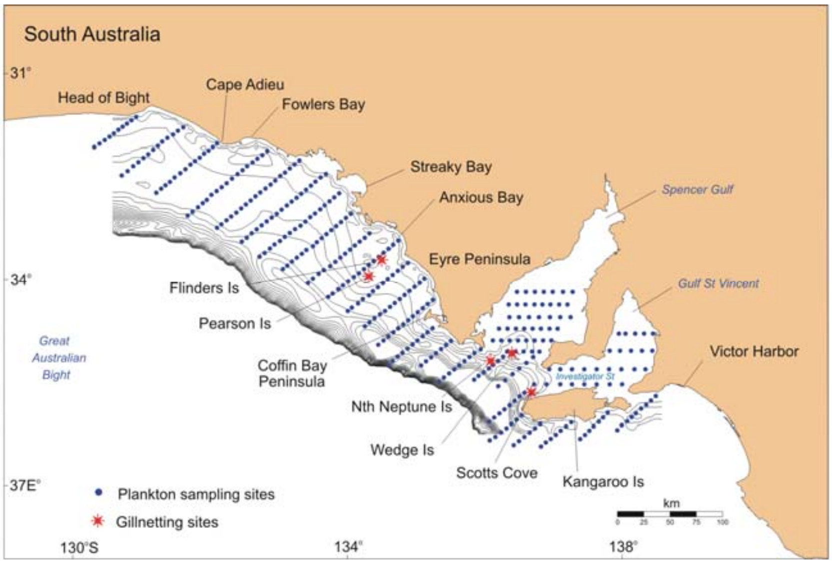

Figure 4-1. Map showing stations where *S. sagax* eggs and adults were collected during the 2007 DEPM surveys.

4.2.3 Plankton Sampling

lankton 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 traveled 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

S. sagax 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 (m3), and D is the depth (m) to which the net was deployed (Smith and Richardson 1977).

4.2.5 Spawning Time

S. sagax 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 (km²) 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) *S. sagax* eggs were found (See Fletcher et al. 1996).

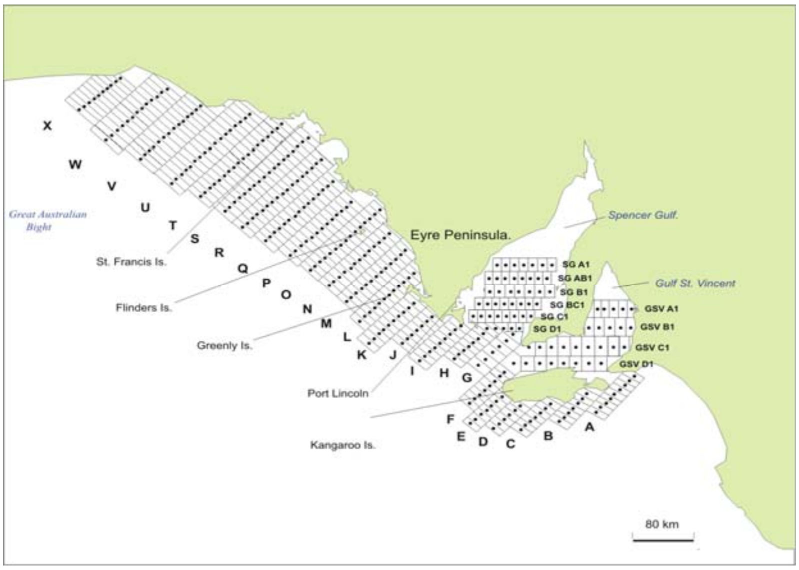

Figure 4-2. Spatial grids used to estimate the spawning area of *S. sagax* in 2007

4.2.7 Egg production

Methods used to estimate egg production between 1995 and 2007 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 (*Pb*) is estimated using the exponential decay model of Lo et al. (1996), which is shown in equation 3:

$$P_t = P_0 e^{-zt} \quad (3)$$

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

Biased mean daily egg production (*Pb*) 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:

$$lnP_b = \ln(P_i) - Zt \quad (4)$$

where *Pi* 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 (*Pb*) 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:

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

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

When egg production models 3 and 5 were applied to *S. sagax* 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 *S. sagax*. Mid-water trawling and sampling from commercial catches during the spawning season was attempted with minimal success. The resultant paucity of data and uncertainty associated with estimates of adult reproductive parameters reduced confidence in estimates of spawning biomass over this period (Ward et al. 2001a).

Between 1998 and 2007, samples of mature *S. sagax* were collected during research surveys 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 *S. sagax* 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:

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

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 (+ 0.01 g).

Sex ratio

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

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

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.

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

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 examined histologically. The ovaries were sectioned and stained with haematoxylin and eosin then examined to determine the presence/absence of post-ovulatory follicles (POFs). POFs were aged according to the criteria developed by Hunter and Goldberg (1980) and Hunter and Macewicz (1985). The spawning fraction of each sample was estimated as the mean proportion of females with hydrated oocytes plus day-0 POFs (*d*0) (assumed to be 0–23 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 2006. In 2006, plankton samples were collected at 334 stations along 28 different transects encompassing a total survey area of 114,490 km^2. Plankton samples were collected at 341 stations on 34 transects. Following the recommendation of Smith and Smith (2006), 15 stations where eggs were not collected in previous years were not sampled but 4 new transects were sampled to provide additional information on egg abundance in the main fishing area. In February and March 2007 two surveys were conducted aboard the *RV Ngerin* in shelf and gulf waters of South Australia. Plankton samples were collected at 341 stations on 34 transects between Victor Harbor and Head of Bight

4.3.2 Egg Distribution and Abundance

The distribution and abundance of *S. sagax* 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 4-3 to 4-5 show the distribution and abundance of *S. sagax* eggs collected during surveys conducted between 1995 and 2007. Table 4-1 shows 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 735 eggs (in 2004) to 68 eggs and both the number of stations with eggs and percentage of positive stations were the lowest recorded since 2000. Live egg abundance in Spencer Gulf increased from 369 to 690 eggs from 2006 to 2007. The percentage of stations with eggs increased from 2005 to 2007.

Table 4-1. Numbers of *S. sagax* eggs collected throughout the survey area and in Spencer Gulf during the DEPM surveys between 2000 and 2007.

	All regions		Spencer Gulf only					
Year	N eggs (Live & dead)	N eggs (Live)	N eggs (Live & dead)	N eggs (Live)	% of live eggs (% of total)	N of stations sampled	N of stations with eggs	% of stations with eggs
2000	1,362	992	711	545	54.9	56	25	44.6
2001	1,449	1,122	508	349	31.1	52	16	30.8
2002	1,475	1,117	236	204	18.3	53	11	20.8
2003	1,718	1,260	223	185	14.7	53	17	32.1
2004	3,186	2,576	906	735	28.5	53	18	34.0
2005	1,808	1,303	86	68	5.2	54	9	16.7
2006	3,083	2,866	369	347	12.1	45	18	40
2007	3,909	3,450	739	690	19.2	45	27	55.5

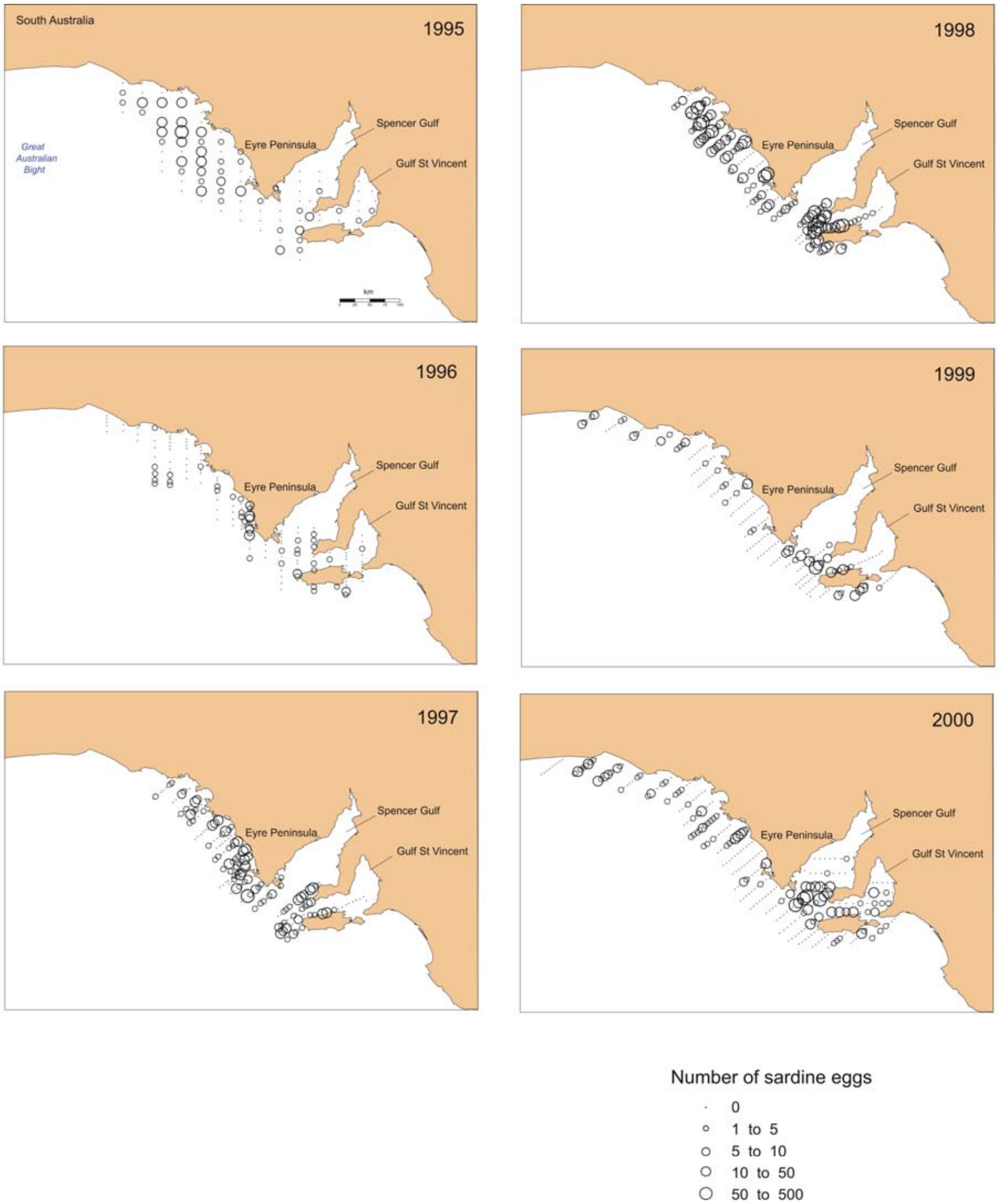

Figure 4-3. Distribution and abundance of *S. sagax* eggs collected during surveys between 1995 and 2000.

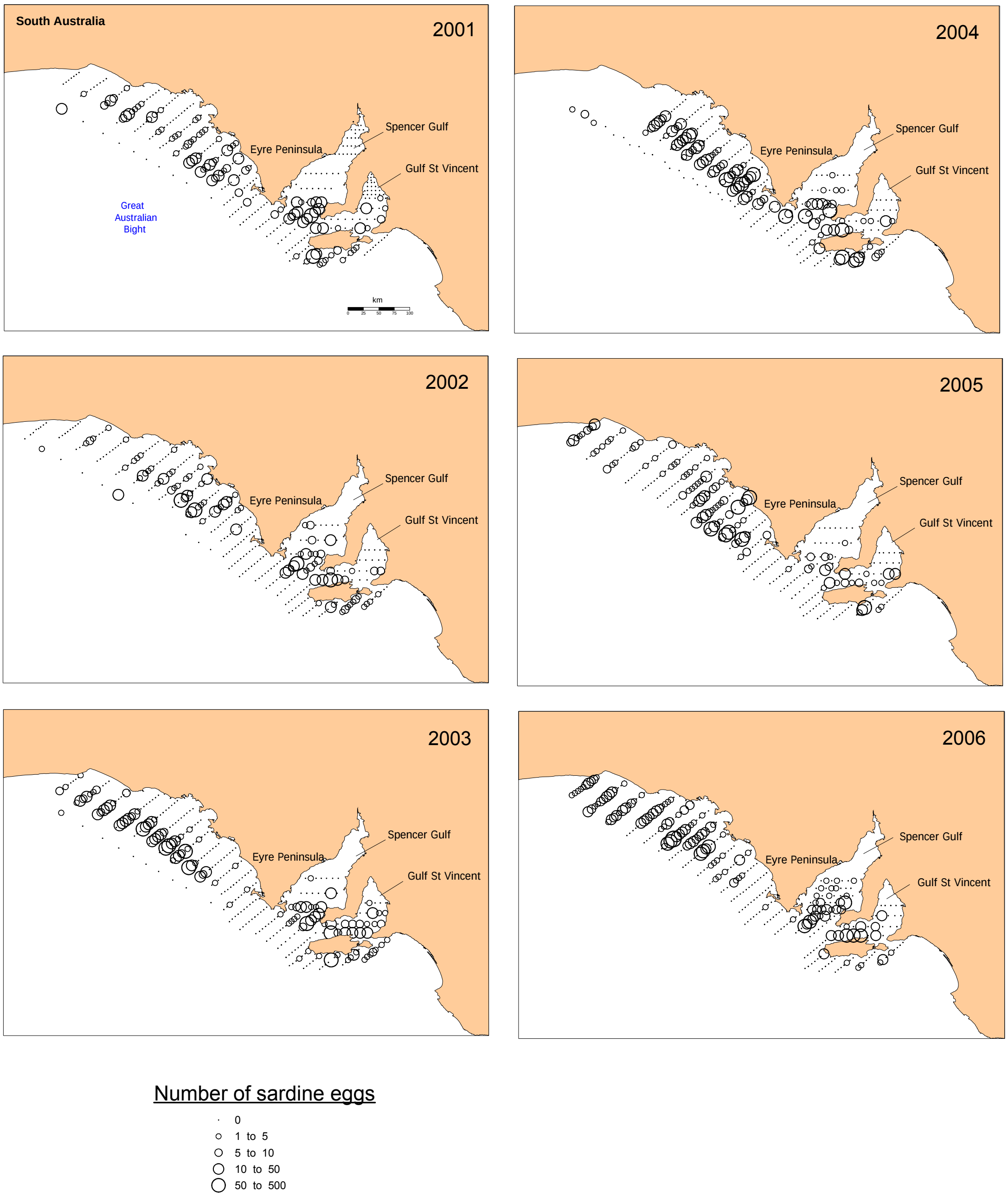

Figure 4-4. Distribution and abundance of *S. sagax* eggs collected during surveys between 2001 and 2006.

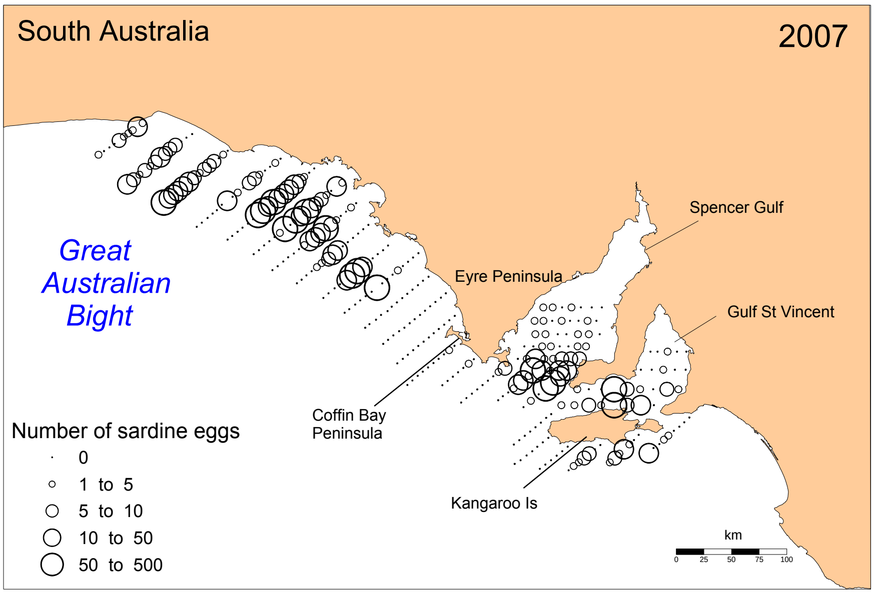

Figure 4-5. Distribution and abundance of *S. sagax* eggs collected in 2007.

4.3.3 Spawning Time

The peak daily 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. The 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 4-2). 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). The spawning area was 44,891 and 43,946 km^2 in 2006 and 2007 respectively. 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 4-2. Spawning area estimates for *S. sagax* in South Australia between 1995 and 2007.

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
2006	44,891
2007	43,946

4.3.4 Egg Production

Table 4-3 shows estimates of egg production and 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}. Egg production was 104.7 and 116.6 eggs per m^2, in 2006 and 2007 respectively.

Table 4-3. Egg production estimates and associated confidence intervals between 1995 and 2007. Note that no 95% C.I.s were calculated in 1997 and a range of estimates were provided in 2005.

Year	Egg production ($eggs.day^{-1}.m^{-2}$)	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	
2006	104.70	*67.95–158.44*
2007	116.6	*74.2 - 182.4*

4.3.5 Adult Reproductive Parameters

Estimates of adult reproductive parameters between 1995 and 2007 including sex ratio, female weight, batch fecundity and spawning fraction are shown in Table 4-4.

Table 4-4. Adult reproductive (R.P.) parameter estimates used to calculate spawning biomass between 1995 and 2007. (*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).

RP	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
R	0.51	0.58	0.54	0.51	0.47	0.48	0.56	0.59	0.44	0.51	0.50	0.64	0.52
W	42.9	46.30	43.0	45.20	52.28	48.83	51.90	62.40	52.69	56.37	73.5	57.2	71.0
F	N/A	N/A	13,947	13,615	15,252	13,650	17,359	18,393	10,907	24,796	22,271	14,289	20,518
S	N/A	0.16	0.16	0.14	0.18	0.16	0.18	0.11	0.11	0.17	0.10	0.13	13.01

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 4-5). 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 4-5) for a range of egg mortality (*Z*) and egg production (P_0) values. The spawning biomass estimate in 2006 was 226,088 t (136,060 – 417,612) and in 2007 was 264,557 t (95% CI = 147,947 - 489,520).

Table 4-5. Spawning biomass estimates between 1995 and 2007. 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	
2006	225,389	136,060 – 417,612
2007	263,747	147,947 - 489,520

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% (Figure 4-6). The actual and expected exploitation rates in 2006 were 15%.

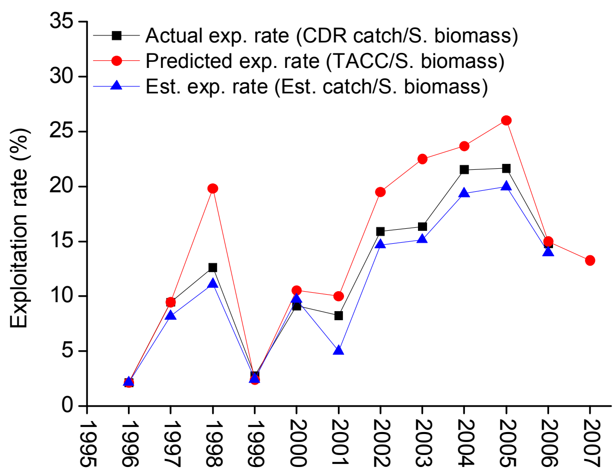

Figure 4-6. Actual, predicted and estimated exploitation rates of spawning biomass between 1996 and 2006.

4.4 Discussion

The DEPM has been integral to the rapid and sustainable development of the SASF. The main weakness of the method is that 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, variances 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). Spawning biomass is also highly correlated with spawning area.

To address this uncertainty, the management framework for the SASF was recently amended to address a key industry priority, i.e. stability in catches. Rather that setting the TACC as a percentage of the estimate of spawning biomass, as was done previously, a baseline TACC of 30,000 t has now been set for the fishery. This baseline TACC will be established as the effective TACC while the latest annual/biannual estimate of spawning biomass remains between 150,000 t and 300,000 which corresponds to exploitation rates of 20% and 10%, respectively.

Numerous reports have also identified the need to continue to refine the approach taken to applying the DEPM in SA. In particular, SARDI has frequently identified the need to refine methods for estimating egg production and spawning area. To address this need, SARDI recently purchased a Continuous Underway Fish Egg Sampler (CUFES) to support estimation of spawning area and providing a basis for enhancing current knowledge of egg patchiness and mortality to refine methods used to estimate egg production (Lo *et al.* 2001; ICES 2002; Lo and Macewicz 2004). In addition, a research proposal was submitted to FRDC in 2007 to examine the development of improved approaches to estimating egg production and spawning area.

5 GENERAL DISCUSSION

5.1 Status of the Resource

The steady rise of the estimates of spawning biomass of sardine off South Australia from ~36,000 t (95% C.I. = 19,000–67,000 t) in 1999, following the second mortality event in 1998/99, to reach 264,557 t (95%CI, 147,947–489,520 t) in 2007 provides clear evidence that SASF is being managed within sustainable limits (Ward *et al.* 2007). The estimate of spawning biomass obtained in February-March 2007 is the highest recorded for the sardine stock off South Australia and lies within the upper third of the target range 150,000–300,000 t, which corresponds to exploitation rates of 20% and 10%, respectively. The baseline TACC of 30,000 t is ~11.3% of the 2007 spawning biomass. There is no evidence of localized depletion of the spawning stock within the main fishing area. Hence, all available evidence suggests that the sardine stock on which the SASF is based is in a strong position.

Size and age structure information suggests there is demographic structure in the South Australian sardine population. For example, sardine from commercial catches in southern Spencer Gulf usually had a modal size of 150 mm and were mostly 2 and 3 year olds. In comparison, fishery independent samples taken mostly near offshore islands and in deep water adjacent to Kangaroo Island, were often larger (modal sizes ≥170 mm) and older (3–5 year old) with a broader age distribution (1–8 yrs, Roger and Ward 2007). Fishery independent samples collected in 2005 were dominated by 3 and 4 year olds, which were ~1 year older than the commercial samples for that year. However, in 2006, fishery-independent samples were mostly 2 and 3 year olds, like the commercial samples. The smaller, younger fish in fishery-independent samples in 2006 were mostly from around Thistle Island where the fishery mainly operates (Figure 3-4). In 2007, large fish (modes 170–190 mm) were again dominant in fishery independent samples from the eastern GAB. Inshore-offshore movement may play a role in demographic variability of sardine in South Australia. Difficulties obtaining representative samples complicate the use of an age structured assessment model for stock assessment (Rogers and Ward 2007). There is a need to investigate the stock structure and movement patterns of sardine in South Australia and other jurisdictions where significant fishing occurs.

5.2 Management Framework

The new framework of decision rules for the SASF resolves the major negative aspect of the previous management system, namely the high potential for large inter-annual variations in the TACC resulting from both fluctuations in estimates of spawning biomass and the application of different exploitation rates at different biomass levels (Shanks 2005). Whilst the previous system ensured sustainability and supported the growth of the new fishery, the current system was specifically established to provide greater stability in catches over the next 3–5 years. The reference range reflects the knowledge of the potential spawning biomass that has been developed through the application of the DEPM over the last decade. All of the estimates of spawning biomass since 2002 lie within the reference range (i.e. 150,000–300,000 t).

Currently, the key issues for the SASF do not relate to stock assessment and management but to the potential effects of the fishery on other components of the ecosystem. The two major issues are (i) operational interactions of the fishery with protected, endangered and threatened species and (ii) potential trophic implications for populations of key predators. The first issue has been addressed in another report (e.g. Hamer and Ward 2007). The potential for establishing ecological performance indicators to address the potential trophic effects on key predators will be assessed in an FRDC report to be completed in 2008 (Goldsworthy *et al.* in prep.).

5.3 Future research priorities

Numerous sensitivity analyses have shown that the DEPM parameters that have the largest overall effects on estimates of spawning biomass are spawning area and egg production. In 2006/07, SARDI Aquatic Sciences will establish approaches for using data from a Continuous Underway Fish Egg Sampler (CUFES) to estimate spawning area and assess the options for including data on yolk-sac larvae in calculations of egg production. A research proposal was submitted to FRDC in 2007 seeking funds to develop improved methods and technologies for estimating spawning area and egg production. A proposal aiming to investigate the stock structure and movement patterns of sardine in Australian waters will be submitted to FRDC in 2008.

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