Sardine
(Pilchard)

Sardinops sagax

Fishery Assessment Report

2004

P.J. Rogers, P. Stephenson, L.J. McLeay, W.F. Dimmlich and T.M. Ward

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This is the fifth fishery assessment report on sardine *Sardinops sagax* in South Australia. The goals of this report are to synthesise and assess scientific information available for the fishery, assess the status of the South Australian sardine resource, comment on the performance indicators, reference points and decision rules in the management plan and identify future research needs. The report complements the annual spawning biomass report that assesses the status of the South Australia sardine stock.

Fishery Assessment Report: Sardine 2004

Report to PIRSA Fisheries

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

PREFACE

The objectives of this fishery assessment report are to synthesise information relevant to the South Australian Sardine Fishery, to assess the biological suitability of the current management arrangements and to identify future research needs. Since 1998 SARDI Aquatic Sciences has been contracted by PIRSA Fisheries to monitor and assess the status of the South Australian Sardine Fishery. Under the service level agreement with PIRSA Fisheries, SARDI Aquatic Sciences are required to provide an annual stock assessment report. This report includes a synthesis of fishery dependent and independent data that complements the annual spawning biomass report (Ward *et al.* 2003a). This is the fifth fishery assessment report on sardine *Sardinops sagax* in South Australia.

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EXECUTIVE SUMMARY

1. The goals of this report are to synthesise and assess scientific information available for the fishery, assess the status of the South Australian sardine resource, comment on the performance indicators, reference points and decision rules in the management plan and identify future research needs. The report complements the annual spawning biomass report for the fishery (Ward *et al.* 2004a).

2. Prior to the 1990s, sardines were mostly used as live bait in the pole-and-line fishery for southern bluefin tuna (SBT, *Thunnus maccoyii*). A purse-seine fishery was established in the early 1990s to provide fodder for the SBT mariculture industry and to supply markets for human consumption and recreational fishing bait. Recently several companies have built processing factories to supply the increasing demand for high quality sardine. Larger vessels with greater onboard storage capacity have entered the fishery in response to increase in the Total Allowable Commercial Catch (TACC).

3. The development of the South Australian Sardine Fishery has been affected by mass mortality events in 1995 and 1998. Each event killed approximately 70% of the spawning stock. Annual catches increased during the early and mid 1990s to reach 6,431 tonnes in 1998. Since the last mass mortality event in 1998, catches and effort increased from 3,548 tonnes and 415 boat days in 1999 to 24,248 tonnes and 658 boat days in 2003. Catch per unit effort (CPUE) has increased from 6.7 tonnes per boat day in 1995 to 36.9 tonnes per boat day in 2003, which reflects the increases in efficiency by the fleet.

4. Sardines otoliths are difficult to read. Between reader estimates of average percent error (APE) and mean coefficient of variation (CV) for sardine otoliths (~1 to 5 years old) were high (APE = 15.6%, CV = 22.1%) compared to other marine fishes. Most sardine taken in the South Australian fishery are >125 mm caudal fork length (CFL) and 1 to 5 years old. Size and age structures in Spencer Gulf varied between years in response to the two mass mortality events. During the recovery from the second mass mortality event, the modal size in Spencer Gulf gradually increased to 170 mm, CFL. The 2 and 3-year-old age classes dominated catch samples obtained during 2003.

5. Between 1998 and 2003, sardines were also collected from offshore waters using fishery independent methods. Sardine obtained off Kangaroo Island and in the eastern Great Australian Bight are generally larger (up to 220 mm, CFL) and older (up to 7

years) than those obtained from commercial catches in southern Spencer Gulf. These data suggest that age information obtained from catches may not reflect the age structure of the population.

6. Female and male sardine collected from the catch between 1995 and 2003 reached L_{50} at approximately 152 and 147 mm, CFL, respectively, which coincides with ages of approximately 1-2 years old. Approximately 28.9% of females and 26.8% males collected from catches between March 1995 and December 2003 were smaller than the estimated L_{50}.

7. Spawning mostly occurs between early January and late April off Eyre Peninsula, the north-west coast of Kangaroo Island, the southern parts of the two gulfs and Investigator Strait.

8. Estimates obtained using the DEPM suggest that the spawning biomass decreased from ~165,000 to ~37,000 tonnes following the 1995 mass mortality event. The population recovered quickly and the spawning biomass reached ~146,000 tonnes (95% C.I. = 70,000 to 234,000) in 1998. After the 1998 mortality event, the spawning biomass decreased to ~36,000 tonnes (95% C.I. = 19,000 to 67,000) in 1999 before recovering rapidly to ~292,000 tonnes (95% C.I. = 179,325 to 463,651) in 2004.

9. Since 1996, spawning biomass estimates have provided the scientific basis for establishing the Total Allowable Commercial Catch (TACC) for the following year. Up to 2001, the exploitation rate was set at 10% of the conservative estimate of spawning biomass. The TACC for 2005 was set at 17.5% of the spawning biomass estimate for 2004 based on performance indicators and reference points outlined in the interim management plan for fishery.

10. An age-structured stock assessment model was implemented recently for the South Australian Sardine Fishery. Problems with the reliability of data on the age structure of the population and inter-annual levels of recruitment, limited the use of the model as a predictive stock assessment tool. Hence, the DEPM should remain the primary tool for stock assessment in the medium term. However, the model should be used to conduct a management strategy evaluation of the decision rules, performance indicators and reference points that have been established for the fishery.

1. GENERAL INTRODUCTION

1.1 Overview

This is the fifth fishery assessment report on sardine *Sardinops sagax* in South Australia. Sardine is known as 'pilchard' in South Australia. However, *S. sagax* belongs to a mono-specific genus that is known throughout the world by fishers, fisheries managers, scientists and the general public by the common name, sardine.

The four goals of this report are to synthesise and assess scientific information available for the fishery, assess the status of the South Australian sardine resource, comment on the performance indicators, reference points and decision rules in the management plan and identify future research needs. The report complements the annual spawning biomass report for the fishery (Ward *et al.* 2004a).

This report is divided into six main sections. The first section is the general introduction, which provides an overview of scientific literature on sardine and other clupeoids occurring in South Australia and describes the history and development of the South Australian Sardine Fishery. Section two provides an updated summary of catch, effort and catch-per-unit-effort (CPUE) data between 1991 and 2003. The third section presents fishery dependent data on length frequency and age structure of commercial catch samples between 1995 and 2003. The fourth and fifth sections summarise fishery-independent length frequency and age structure information and describe the reproductive patterns and inter-annual fluctuations in spawning biomass of sardine in South Australia between 1995 and 2003. The general discussion specifically addresses the four goals of the report.

1.2 Review of Recent Literature

1.2.1 South Australian Clupeoid Assemblage

The clupeoid assemblage in South Australia includes sardine (*S. sagax*), Australian anchovy (*Engraulis australis*), round herring (*Etrumeus teres*), sandy sprat (*Hyperlophus vittatus*) and blue sprat (*Spratelloides robustus*).

Sardine (*S. sagax*) is found throughout southern temperate waters of Australia from Rockhampton in Queensland to Shark Bay in Western Australia and throughout shelf and southern gulf waters of South Australia (Gomon *et al.* 1994). Studies of clupeoid egg and larval abundance in South Australia suggest sardine is the dominant member of the small pelagic fish assemblage (Ward *et al.* 2001a, b; Rogers *et al.* 2003; Rogers and Ward in review;

Dimmlich *et al.* 2004). Therefore the size of the sardine population is likely to have significant implications for the trophic structure of the broader pelagic ecosystem.

Australian anchovy (*E. australis*) is found throughout South Australian gulf and offshore shelf waters. Anchovy eggs are less abundant in the regions where sardine prefer to spawn and this may be related to temperature tolerances, egg predation by sardine and competition for resources (Ward *et al.* 2001a; Alheit and Niquen 2004; Dimmlich *et al.* 2004). The highest abundances of anchovy eggs have been found in northern Spencer Gulf, which is characterised by high sea surface temperatures (SST) (26ºC) in summer (Dimmlich *et al.* 2004).

Round herring or maray (*E. teres*) is usually only a minor bycatch of the South Australian Sardine Fishery, but occasionally form large schools that dominate a single catch. This species grows larger than sardine (300 mm, TL), particularly in offshore shelf waters. Unpublished egg and larval information suggests spawning occurs in southern gulf and shelf waters.

Blue sprat (blue bait) (*S. robustus*) and sandy sprat (whitebait) (*H. vittatus*) are mostly found in the gulfs, sheltered embayments and near river mouths. These small (100 mm, CFL), relatively short-lived (8 months - 4 years) species support small-scale fisheries in Western Australia, Victoria and New South Wales and are food sources for little penguins (*Eudyptula minor*) and inshore pelagic fishes, including Australian salmon (*Arripis trutataceus*) (Klomp and Wooler 1988; Kailola *et al.* 1993; Hoedt and Dimmlich 1994; Gaughan *et al.* 1996; Rogers *et al.* 2003).

1.2.2 Distribution and Movement

Little is known about the movement patterns of sardine aggregations in southern Australia. DEPM surveys in South Australia suggest adult sardine are distributed throughout southern gulf and shelf waters out to the shelf break (Ward *et al.* 2001a, b). During summer and autumn larvae are widespread throughout shelf and southern gulf waters and aggregations occur in the mouth of Spencer Gulf, where seasonal SST and salinity fronts form (Bruce and Short 1990). Juveniles were found near small inshore islands in southern Spencer Gulf and in upper Gulf St Vincent near the entrance to the Port River during a recent FRDC funded study (2000/125).

In the Benguela Current system off western Africa, larval retention near suitable nursery areas is lowest when upwelling intensity is high, due to offshore movement of surface water (Stenevik *et al.* 2003). Larvae transported offshore away from suitable food supplies (small phytoplankton and zooplankton) are expected to have lower survival rates than those remaining near the coastline.

Several factors influence the schooling behaviour of sardine. Giannoulaki *et al.* (2003) used geo-statistical techniques to determine that spatial heterogeneity of habitat influenced schooling behaviour more than the total area available in which small pelagic fish could aggregate. Misund *et al.* (2003) found sardine schools in South Africa moved at rates of up to 1.59 $m.s^{-1}$, were most dense in the afternoon and changed shape approximately every 2 minutes.

1.2.3 Food and Feeding

Clupeoids feed on an array of planktonic prey items including phytoplankton, zooplankton and the pelagic egg and larval stages of fishes. Anchovies (*Engraulis* spp.) consume larger zooplankton than sardine, which mostly feed on smaller zooplankton and phytoplankton taxa (Van der Lingen 2002). Fluctuations in sardine and anchovy biomass may be related to oceanographic conditions that favour production in certain zooplankton and phytoplankton taxa. Higher anchovy abundance was correlated with periods of higher calanoid copepod biomass (Louw *et al*. 1998; Alheit and Niquen 2004).

1.2.4 Age, Growth and Size

Sardine are relatively fast growing and short-lived. Larval and juvenile sardine in South Australian waters have maximum growth rates of approximately 0.76 and 0.59 $mm.day^{-1}$, respectively (Ward *et al.* 2005). Larvae in upwelling areas off western Eyre Peninsula grow faster than those in less productive regions in the western GAB (Ward *et al.* 2005). Sardine that inhabit productive upwelling regions, such as those off the coast of Baja California, grow rapidly and attain lengths of 280 to 300 mm CFL in 4 to 5 years, whereas in southern Australian coastal waters they rarely exceed 220 mm CFL in 7 years (Baird 1970; Butler *et al.* 1996; Ward *et al.* 2005).

1.2.5 Reproduction

In South Australia female sardine spawn 10,000 to 30,000 eggs approximately every 5 to 7 days during a peak spawning period of 3-4 months during late summer and autumn. The spatial distribution of eggs across shelf waters off South Australia varies considerably between years (Ward *et al*. 2001b; Ward *et al.* 2003a, 2004a). Decreases in the inshore extent of spawning by sardine off California, has been associated with decreases in SST due to coastal upwelling (Lynn 2003). Similar processes may drive the distribution of spawning sardine in South Australia. In Western Australia sardine have two spawning seasons (summer and early winter), which may be due to the oceanographic influence of the Leeuwin Current in the southern region near Albany (Fletcher 1990; Pearce and Walker 1991). In Victoria, sardine spawn during late summer and autumn (Blackburn 1950; Hoedt and Dimmlich 1995) and in southern Queensland spawning occurs from July to October (Winter-Spring) (Ward *et al.* 2003b).

1.2.6 Early Life History

Sardine spawn below the upper mixed layer and their buoyant eggs float into the surface layer (Stenevik *et al.* 2001). Lynn (2003) found the abundance of sardine eggs off California was positively correlated with high zooplankton biomass measured acoustically (mean volume backscatter). Eggs hatch approximately two days after fertilisation and the newly hatched transparent larvae are approximately 2.2 to 2.5 mm in total length (TL) (Neira *et al.* 1998).

Sardine larvae undertake vertical migrations, which may reduce passive transport by currents to other areas (Stenevik *et al.* 2001). Larvae metamorphose into juveniles after approximately 1 to 2 months, at lengths of 35 to 40 mm, TL before moving into nursery areas that are closely linked to areas where adults aggregate. These include the embayments in the southern parts of South Australia's gulfs and near inshore islands. Recruitment from these juvenile nursery areas to the fishery in southern Spencer Gulf is poorly understood.

1.2.7 Recruitment

Recruitment information can act to reduce uncertainty surrounding DEPM biomass estimates and provide management agencies with additional biological reference points on which to base decisions. Annual pre-recruitment surveys are undertaken in South Africa and California to monitor the abundance of late-stage larvae using small Methot trawls. This information augments the annual estimates of spawning biomass determined from DEPM egg surveys (Van der Lingen and Huggett 2003). Acoustic procedures have been used extensively to provide recruitment estimates of juvenile sardine and anchovy in South Africa (Beckley and Van der Lingen 1999; Van der Lingen and Huggett 2003).

Variability in oceanographic processes has been implicated in influencing sardine recruitment in the upwelling systems off southern Africa (Beckley and Van der Lingen 1999; Hardman-Mountford *et al.* 2003). Oceanographic processes influence recruitment by driving nutrient enrichment, concentrating food for larvae and retaining larvae in and or near neighbouring nursery areas (Hardman-Mountford *et al.* 2003). Eddies that form on the continental shelf provide suitable habitats and environmental conditions for survival of pre-recruit stage sardine (Logerwell *et al.* 2001). The importance of annual variation in upwelling strength, predation of eggs and larvae and cannibalism to sardine recruitment success is poorly understood in South Australian waters.

1.2.8 Stock Assessment

The DEPM was initially developed for northern anchovy *E. mordax* (Lasker 1985). This method has been used as the integral tool for assessment of South Australian sardine spawning biomass over the last decade. The disadvantages of the method, which include the high running costs of research vessels during egg sampling cruises and the extensive laboratory time required to process the plankton and fish samples are outweighed by the advantages of having a direct, annual estimate of spawning stock biomass as a biological indicator on which to base management decisions.

Continuous Underway Fish Egg Samplers (CUFES) are used by research agencies in South Africa, California and Europe during DEPM surveys. The CUFES consists of a pump and series of sieves that constantly collects sardine eggs at the surface while the research vessel is steaming between stations during DEPM surveys (Lo *et al.* 2001). These instruments have the potential to save vessel time during research cruises and increase the precision of spawning area and egg production estimates used to calculate the spawning biomass.

An age-structured stock assessment model was implemented for the South Australian Sardine Fishery in 2003 as part of a recently completed FRDC (2000/125) funded study. This was based on models developed by Dr Norm Hall for the Western Australian sardine fishery. Application of this model for fisheries management purposes requires reliable estimates of recruitment and robust data on population age structure. Currently there is no information on recruitment to the South Australian Sardine Fishery and age structure data is limited to samples collected from the commercial catch and during annual DEPM surveys.

Acoustic techniques have been used widely for stock assessment of small pelagic fish (Beckley and Van der Lingen 1999). Uncertainty regarding individual species identification during acoustic surveys requires that stringent target strength validation is completed before these techniques are used for stock assessment purposes. *S. sagax* and *E. mordax* have significantly different total target strengths, making it possible to differentiate between these species (Conti and Demer 2003). *E. mordax* is a morphologically similar species to *E. australis*, therefore these techniques could be used to distinguish between sardine and anchovy schools in southern Australian waters. Acoustic studies contribute 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 (Barange *et al.* 1999).

1.2.9 Bycatch Issues

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 commercial purse seine nets (Mitchell *et al.* 2002). Levels of shark and marine mammal bycatch during sardine purse-seining operations are reported to be "infrequent", however data relating to these interactions are limited (Shanks 2004).

1.2.10 Ecological Issues

Changes in the abundance of small pelagic fish species have serious implications for the functioning of temperate ecosystems (Barker and Vestjens 1990; Bax 1991; Blaber *et al*. 1995; Ward *et al*. 1998; Goldsworthy *et al*. 2003). PIRSA Fisheries Policy Group identified the need to acquire information on the ecological importance of sardine to ensure the fishery is managed according to the principles of Ecologically Sustainable Development (Fletcher *et al.* 2003). This information is required to assess the need for an ecological allocation when determining the annual Total Allowable Catch (TACC) for the sardine fishery. Assessment of the role of sardine in the eastern Great Australian Bight (GAB) ecosystem has required the development of a trophodynamic model. These models require information on levels of primary and secondary productivity, the abundance of planktivorous fishes, including sardines, and the diets of key predators, including juvenile southern bluefin tuna (SBT) (*Thunnus maccoyii*), Australian salmon (*Arripis truttacea*), little penguins (*Eudyptula minor*), shearwaters (*Puffinis* spp.), Australasian gannets (*Morus serrator*), terns (*Sterna* spp.), Australian sea lions (*Neophoca cinerea*), fur seals (*Arctocephalus forsteri*) and sharks.

Preliminary information suggests clupeoids are important components of little penguin diets in southern Spencer Gulf (A. Weibken pers. com.). Chiaradia *et al.* (2003) showed little penguins (*Eudyptula minor*) adjust their feeding regimes in response to reductions in sardine abundance. Sardine from the GAB comprised >50% of the identified prey species of juvenile SBT collected by SARDI between 1999 and 2001 (Ward *et al.* in press).

1.3 Description of the South Australian Fishery

Since the early 1960s, sardine has been caught in the bays along the southern and western coasts of the Eyre Peninsula for use as live bait and feed for tuna (Fig. 1). Small quantities of sardine have been taken by marine-scale fishers using haul and dab nets for recreational bait and human consumption. Historically, the three main fishing areas for sardine were Boston Bay, Coffin Bay and Streaky Bay. The fishing method employed by SBT fishers involved the use of lights to attract schools to the vessel and a dinghy to surround the school with a small purse seine net. Live bait catches declined as the SBT pole and line fishery developed into a purse-seine fishery in the early 1990s. The total quantity of sardine taken from South Australian waters prior to 1990 is not well known, but may have been in the order of several hundred tonnes per annum. A dedicated sardine purse-seine fishery was established in 1991 and the catch is mostly utilised as fodder for the SBT mariculture industry (Mackie 1995).

The fishery is managed by PIRSA according to guidelines and objectives outlined in the *Interim Management Plan for the South Australian Pilchard Fishery*. The fishery comprises 14 licence holders, yet licences are amalgamated and used by only 7 or 8 vessels. Input and output controls include entry limitations, gear restrictions and individual transferable quotas (ITQs). Purse seine nets cannot exceed 1000 m in length or a depth of 200 m and there are mesh size restrictions of 14 to 22 mm.

In addition to the interim management plan, the *Ecological Assessment of the South Australian Pilchard Fishery* report was prepared for Environment Australia in 2004 (Shanks 2004). This report provides a summary of the management arrangements for the fishery and contains a series of objectives relating to the conservation, equitable sharing and best utilisation of the sardine resource in South Australia (Shanks 2004). The *Ecological Assessment of the South Australian Pilchard Fishery* aims to ensure that the fishery operates in a way that avoids negative impacts on the ecosystem including endangered, threatened and protected marine mammal and shark species.

Biological performance indicators, including spawning biomass and age structure are monitored annually via collection of fishery dependent and fishery independent data. These indicators trigger management decisions outlined in the *Interim Management Plan* for the fishery and TACCs are set according to conservative exploitation rates that range from 10 to 17% of the annual spawning biomass estimates (Shanks 2004). Conservative estimates of the spawning biomass are used to account for uncertainties involved in these annual measures of stock size.

Prior to 2001 vessels in the South Australian Sardine Fishery typically ranged from 10 to 23 metres in length. The introduction of larger, more efficient vessels occurred in 2000 and 2001 in response to recovery of the spawning biomass from the 1998/9 mass mortality event and corresponding increases in the TACC. The new vessel designs and the introduction of fish pumps greatly improved efficiency when handling the catch (Professional Fisherman 2001-2002, 2002a, b). Fish-finding technology has improved rapidly in recent years with introduction of multibeam sonars capable of locating sardine schools up to 6 km away. Some vessels use radars specifically to locate seabirds, including Australasian gannets (*Morus serrator*) and terns (*Sterna spp.*) that may be feeding on sardine schools at the surface. On most vessels, schools of sardine are located and the net is run around the school. Once encircled the catch is pumped directly on board where it is held or processed by individually quick frozen (IQF) facilities before transfer to hopper bins on arrival at the Port Lincoln Marina. The newer vessels have onboard processing capabilities of up to 185 tonnes of frozen and 70 to 80 tonnes of IQF sardine. The increased size of the TACC has also led to the development of better on-shore processing facilities.

Sardine processing factories operate in Port Lincoln, and an increasing proportion of the catch is used for recreational fishing bait. Fishers receive between 40 and 80 cents per kg as tuna fodder and $2.50 per kg for recreational bait. This difference between market values is part of the impetus behind the current FRDC-funded investigation (2002/236) of methods to improve at-sea, post-harvest handling procedures. There is also considerable potential for expansion of South Australian sardine products to export markets aimed at human consumption.

The TACC for the South Australian purse-seine fishery was set at 1,200 tonnes in 1991 and 1992, but was increased to 3,500 tonnes for the period of 1993 to 1996 (Mackie 1995). Since 1997, the TACC has been established on the basis of annual estimates of spawning biomass provided by SARDI Aquatic Sciences. The TACC for 1999 was initially set at 11,500 tonnes, but was reduced to 3,500 tonnes after the second mass mortality event in October-November 1998. The TACC for 2000 was set at 3,800 tonnes to allow the stock to recover. The TACCs for 2001, 2002 and 2003 were set at 9,100 tonnes, 17,700 tonnes, and 36,050 tonnes, respectively. In 2004 and 2005 the TACCs were set at 40,350 and 51,100 tonnes, respectively.

2. FISHERY STATISTICS

2.1 Catch and Effort Data

This chapter summarises catch, effort and catch-per-unit-effort (CPUE) data for the South Australian sardine purse-seine fishery between January 1, 1991 and December 31, 2003. Data were collated from fishery research logbooks, which are sent to SARDI Aquatic Sciences Statistical Department by the fishers. Since 2001, fishery research logbooks have been improved to provide researchers with detailed spatial information, time spent searching for sardine schools, the time of shot, water temperature, estimated catch, catch lost and bycatch of other clupeoids, sharks and marine mammals. Figures and text referring to "Coffin Bay" represent information on fishing in the area adjacent to Coffin Bay Peninsula (CBP). Key locations mentioned in the text are shown in Fig 1.

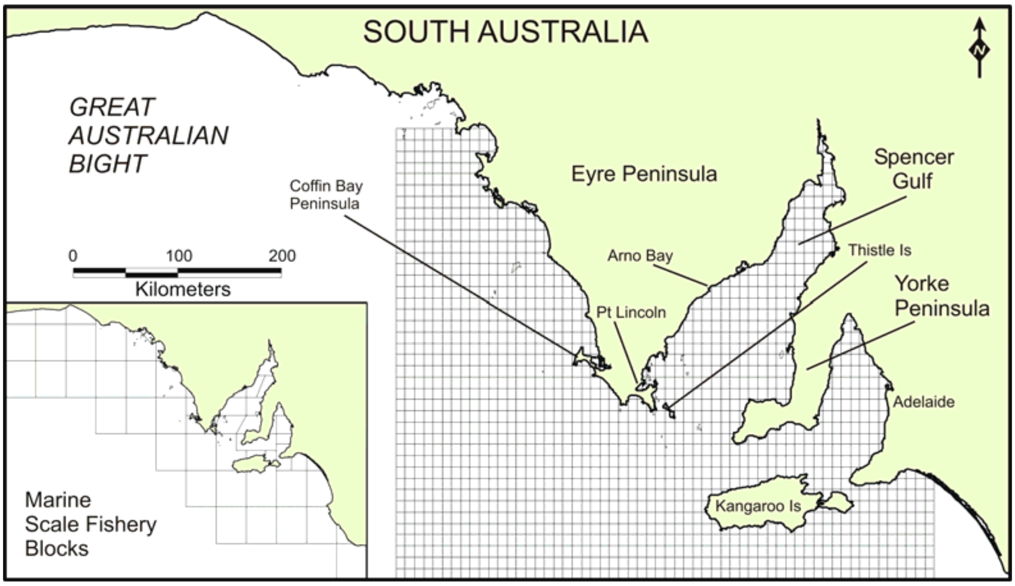

Figure 1. Location of sardine fishery in South Australia and 6 x 6 minute grid used for spatial analysis of the fishery catch between 2001 and 2003. Inset shows marine scale fishery blocks used for spatial analysis of catch and effort between 1991 and 2000.

2.1.1 Inter-annual Pattern

Effort and catches increased from 37 boat days and ~ 9 tonnes during 1991 to 803 boat days and 3,241 tonnes in 1994 (Fig. 2). A mass mortality event in April-May 1995 killed over 70% of the spawning stock, which led to a decrease in effort and catch to 370 boat days and 2,459 tonnes in 1995 (Ward *et al*. 1999a; 2001a, b). Following the first mortality the stock recovered quickly and effort increased to 831 boat days and catches increased to 6,431 tonnes in 1998. In October-November 1998 another mass mortality event killed over 70% of the spawning stock (Ward *et al*. 1999a, 2000, 2001a, b). In 1999, effort and catches decreased to 415 boat days and 3,548 tonnes respectively in response to the second mortality event. In 2000, effort increased to 482 boat days and catches decreased slightly to 3,502 tonnes. During 2001 effort decreased to 417 boat days and catches increased to 4,548 tonnes. In 2002, both fishing effort and catches increased significantly to 560 boat days and 13,324 tonnes respectively. Fishing effort increased to 658 boat days and total catch increased a further 45% from the previous year to 24,248 tonnes during 2003.

Although catch-per-unit-effort is an unreliable and inappropriate measure of abundance for highly mobile small pelagic species, this index continues to be monitored for historical purposes. CPUE increased from 1.1 tonnes per boat day in 1991 to 23.8 tonnes per boat day in 2002 (Fig 2). In 2003, CPUE continued to increase to 36.9 tonnes per boat day. This reflects the increasing efficiency of the fleet and the close proximity of sardine aggregations to Port Lincoln. Further increases in CPUE also reflect the ongoing improvement of fishing techniques and technological advances onboard the vessels, including better sonars, use of radars to locate seabirds and increased storage capacities.

2.1.2 Intra-annual Patterns

Figures 3 and 4 show the intra-annual patterns of catch, effort and CPUE between January 1991 and December 2003. Since the mid 1990's peak catches have mostly occurred from March to June. Monthly CPUE shows peaks occurring between May and September and also in December. CPUE ranged from 11.1 tonnes per boat day in December to 14.1 tonnes per boat day in September (Fig. 3). During 2003, 64% of the annual catch and 66% of annual effort occurred between March and July (Fig. 4) and peak catches of 3,533.5 tonnes and 4,069.2 tonnes were taken in March and May. August was the other notable month with a total catch of 2,479 tonnes.

2.1.3 Spatial Patterns

Prior to 2001, approximate geographical positions of sardine catches were recorded using the marine scale fishery (MSF) blocks. Boundaries of these blocks were based on whole degrees of latitude and longitude (Fig. 1, inset). Post 2000, positions of sardine catches were accurately recorded using onboard Global Positioning Systems (GPS). Spatial positions and summed catches were grouped into 6 x 6 minute (Degrees minutes seconds, DMS) grid squares using Geographical Information System (GIS) software for the 2001-2003 seasons. Between 1992 and 1995 most purse-seining occurred in Spencer Gulf near Port Lincoln. From 1996 until 1999, the fishing grounds around the Coffin Bay Peninsula became increasingly important (Figs 5 and 6). During 1999 after the second mass mortality, fishing retracted from Coffin Bay and mostly occurred in southern Spencer Gulf between 1999 and 2001 (Figs. 5, 6 and 7). High mean regional CPUE off Kangaroo Island and in Spencer Gulf reflects increases in the size of daily catches between 2001 and 2003 and the close proximity of Port Lincoln to large aggregations of sardine (Fig. 5). Figure 7 shows the finer scale, spatial expansion of the fishery from southern Spencer Gulf in 2001 to central Spencer Gulf and the northern coast of Kangaroo Island during 2003. In 2002, most of the catch (~90%) came from the area east and north east of Thistle Island and ~9.5% came from Coffin Bay Peninsula. In 2003, the catch was taken over a broader area, extending from around Thistle and Wedge Islands to east of Arno Bay. A small proportion of the catch (<5%) was taken off the northern coast of Kangaroo Island (Fig. 7).

2.1.4 Estimated Lost Catch

The estimated amount of catch lost per shot has been recorded on logbook returns by fishers since 2001. There is an unquantified degree of uncertainty regarding the accuracy of these estimates. The species composition and mortality rates of the estimated lost catch are also unknown. During 2001 and 2002 it was estimated that 2,050 and 4,740 tonnes of sardine, respectively were lost (Fig. 8). During the 2003 fishing season an estimated 3,660 tonnes were lost. These estimates are not considered when setting the annual TACC (Fig 9).

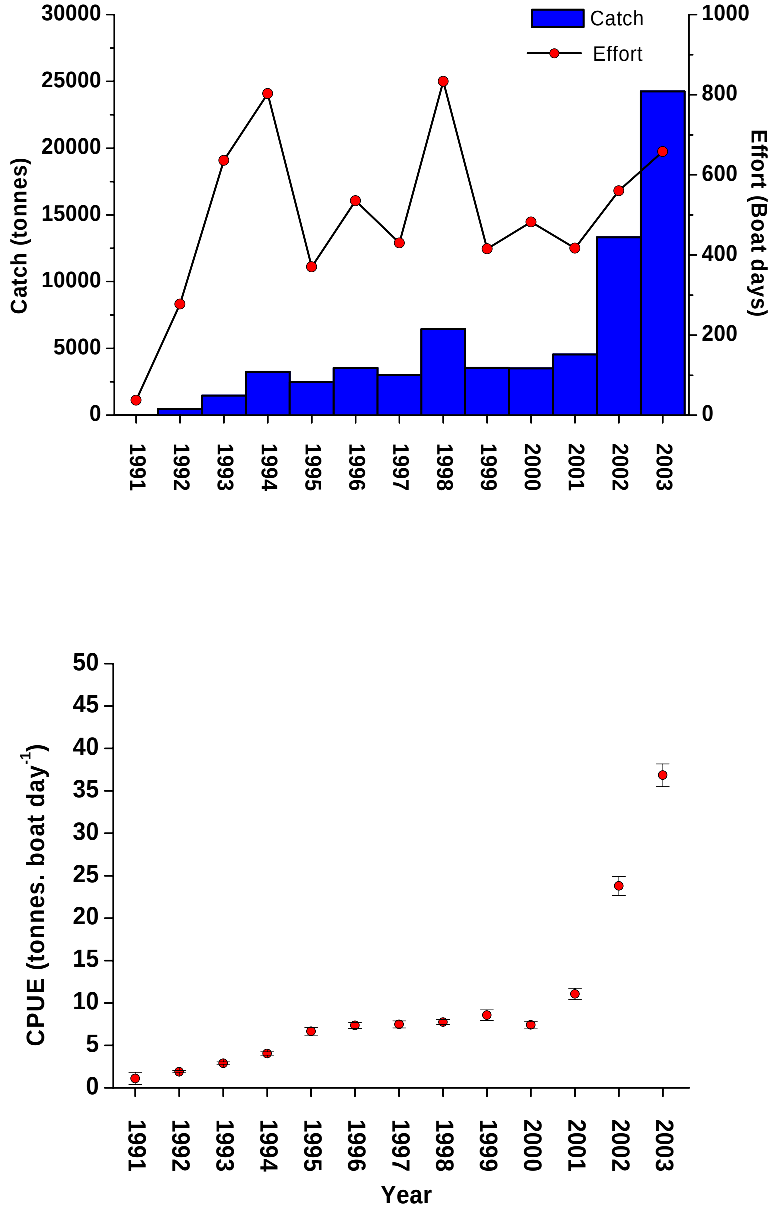

Figure 2. Trends in annual catch, effort and CPUE between 1991 and 2003.

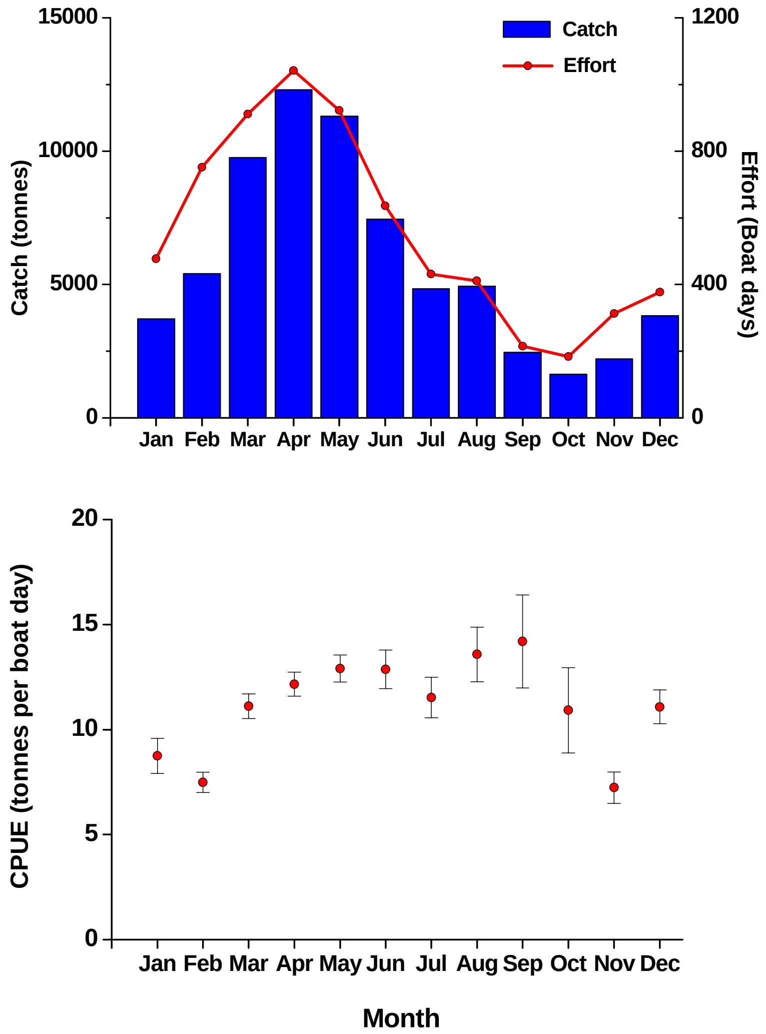

Figure 3. (A). Cumulative monthly catch and effort and (B). Mean monthly CPUE between 1991 and 2003.

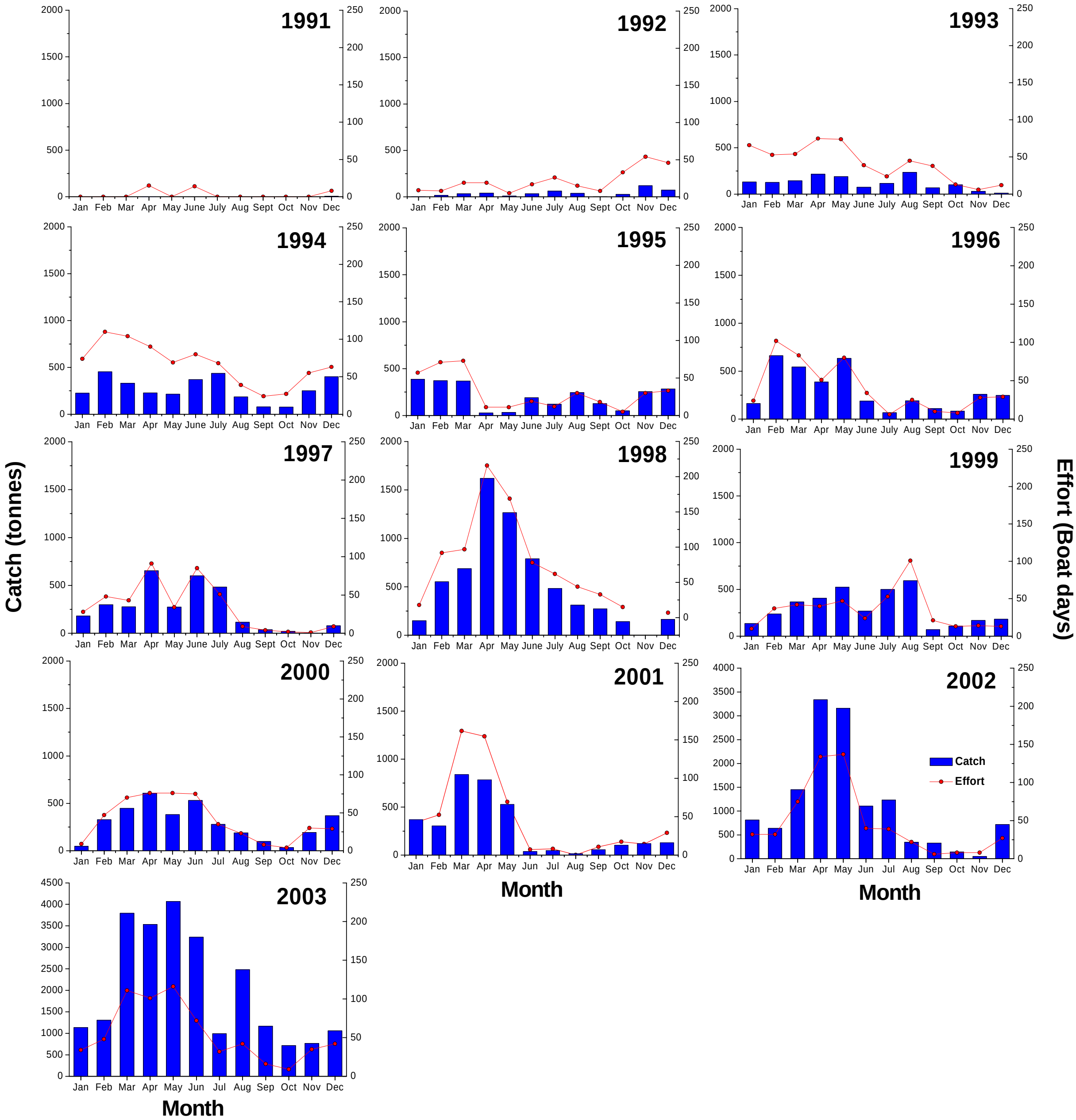

Figure 4. Monthly trends in catch and effort for each year between 1991 and 2003

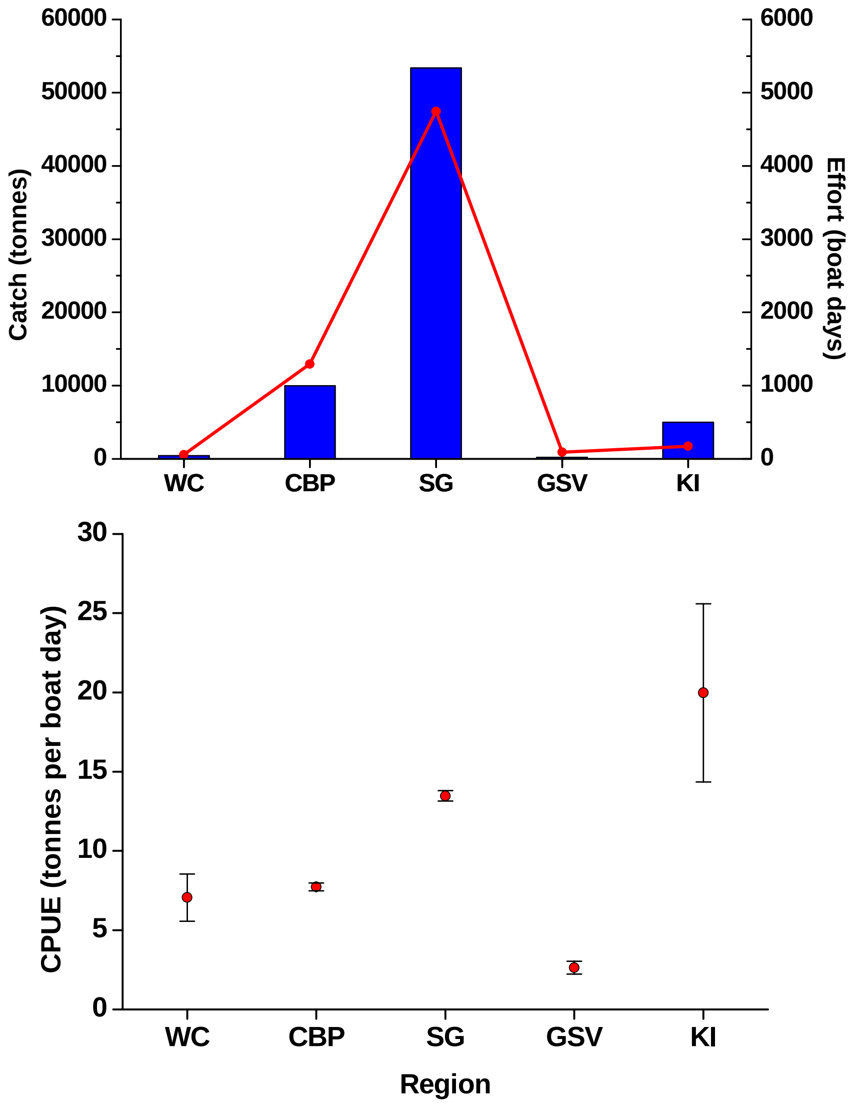

Figure 5. Spatial trends in cumulative catch and effort (top) and mean regional CPUE between 1991 and 2003 (bottom) (WC=West Coast (GAB); CB= Coffin Bay Peninsula; SG=Spencer Gulf; GSV=Gulf St Vincent; KI=Kangaroo Island).

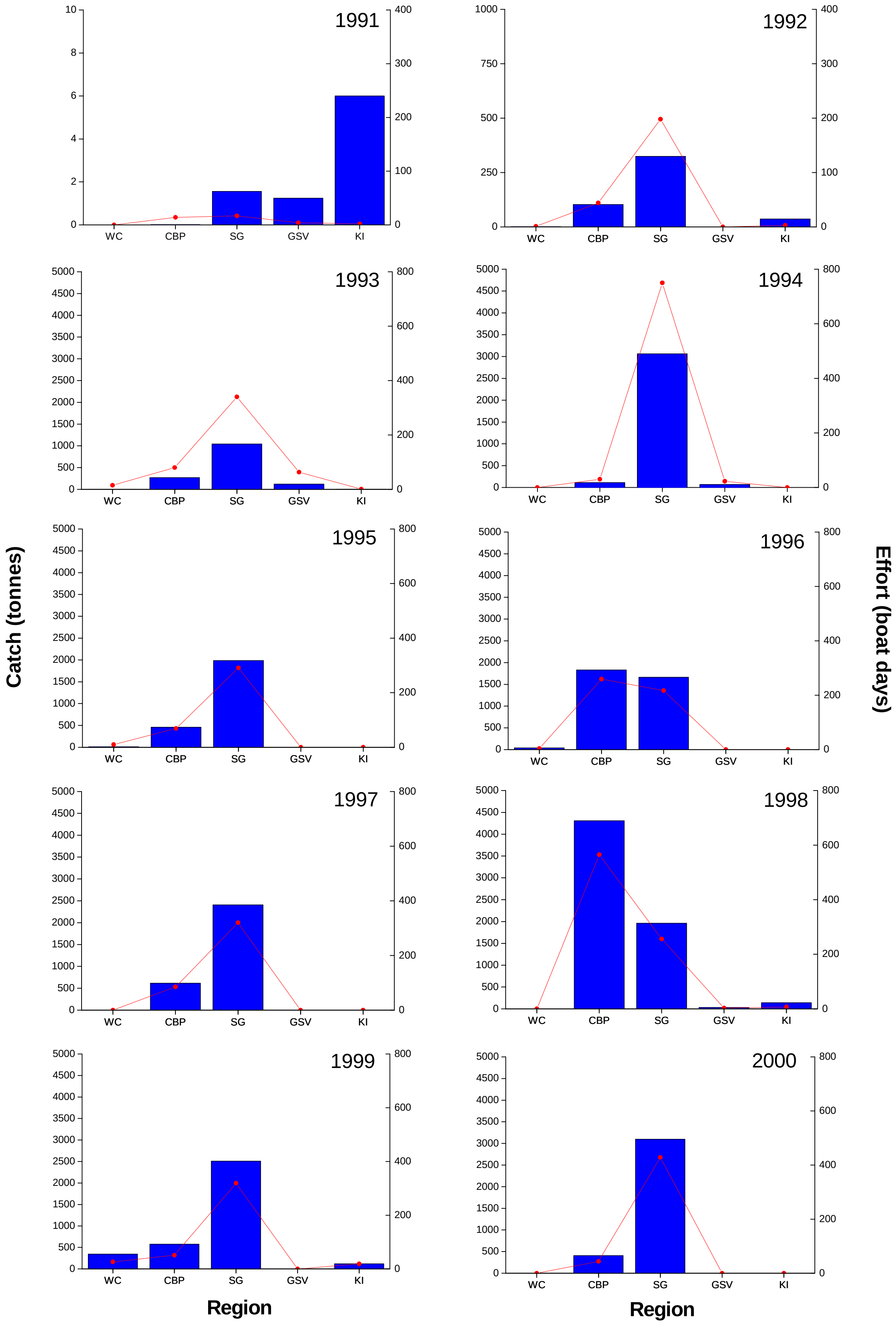

Figure 6. Spatial trends in catch and effort between 1991 and 2000.

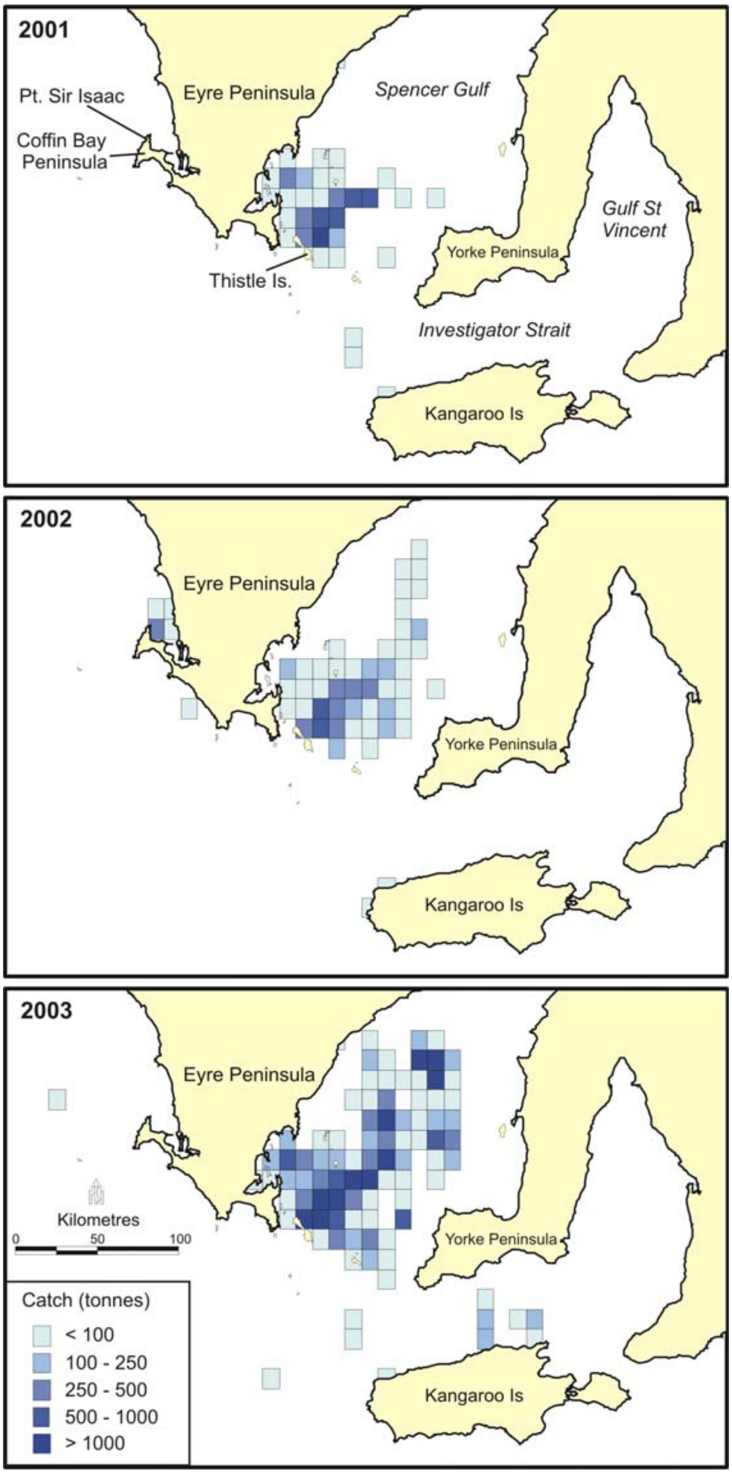

Figure 7. Spatial patterns of aggregated sardine catches (by 6x 6 minute grid squares) in southern Spencer Gulf and off Coffin Bay between 2001 and 2003.

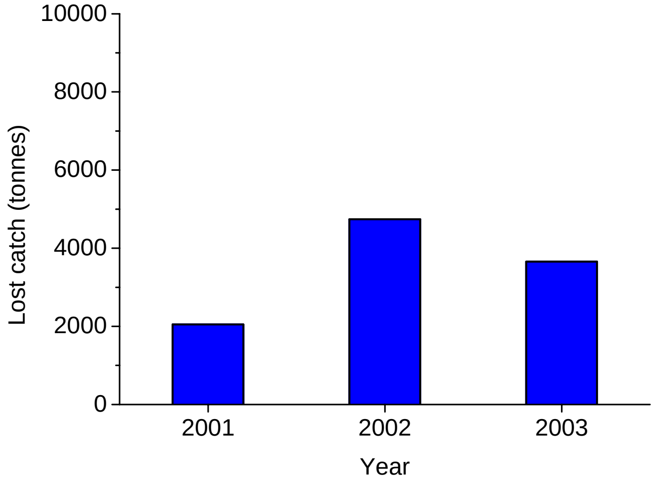

Figure. 8. Estimated lost catch in the South Australian Sardine Fishery between 2001 and 2003.

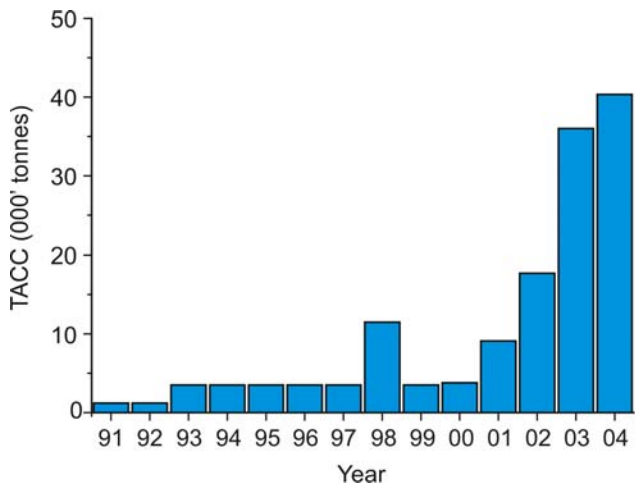

Figure 9. Total Allowable Commercial Catch (TACC) for the South Australian Sardine Fishery between 1991 and 2004.

3. RESEARCH - COMMERCIAL

3.1. Methods

3.1.1. Sampling

This section is based on monthly samples collected from the commercial catch between 1995 and 2003. Frozen samples were supplied by fish processors in Port Lincoln.

3.1.2. Size Structure

The size structures of the commercial catch samples were monitored by length frequency analysis. Fish were grouped into either 5 or 10 mm length classes.

3.1.3. Readability Indices (RI)

Sardine otoliths were classified as 1 = excellent, 2 = good, 3 = average, 4 = poor and 5 = unreadable based on their interpretability by one otolith reader.

3.1.4. Precision of Age Estimates

To estimate the levels of uncertainty in our age estimates (for otoliths assigned RI scores of 1 to 3 by both readers), two methods of determining ageing precision were employed. The ageing precision index that calculates average percent error (APE) (Beamish and Fournier 1981) was applied to determine the level of between reader variability in annuli counts where:

$$APE = \frac{100}{N}\sum_{i=1}^{R}\left[\frac{1}{R}\sum_{i=1}^{R}\frac{\left|X_{ij}-X_{j}\right|}{X_{j}}\right]$$

and N is the number of sardine aged, R is the number of times each otolith is aged by different readers, Xij is the ith age estimation for the jth individual, and Xj is the mean age for the jth individual.

The second measure of ageing precision, the coefficient of variation (CV_j) was estimated using the following equation (Campana 2001):

$$CV_j = 100\text{x}\,\frac{\sqrt{\sum_{i=1}^{R}\frac{\left(X_{ij}-X_{j}\right)^2}{X_j}}}{X_j}$$

where CV_j is the precision of the age estimate for the *j*th fish. The mean *CV* was calculated from estimates of all fish aged by the two independent readers (n = 966).

3.1.5. Relationship between Age and Otolith Weight

The relationship between otolith weight and age was determined for otoliths with the highest readabilities (1 to 3) where the two independent readers agreed on the age. Linear regression analysis was used to describe this relationship. The regression was used to calculate the ages of fish with difficult otoliths (4s and 5s) and to determine the age structures of commercial catch samples.

3.1.6. Age Structure

Age structures were constructed from the percentages of sardine in each age class, rounded to the nearest whole year.

3.1.7. Growth Patterns

In this report we analysed the age and growth for sardine collected from the commercial catch in 2002 and 2003. Previous stock assessments (Ward *et al.* 2001c, 2003c) have reported on the age and growth patterns for sardine in South Australian between 1995 and 2001. A comprehensive analysis of the growth patterns of sardine in South Australia between 1995 and 2001 is available in FRDC Report 2000/125.

Otoliths with the highest readabilities (1 to 3) were used for the growth analysis. Von Bertalanffy (*VB*) growth model fits to length at age data were estimated via 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 *S. sagax* 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.

3.1.8. Length and Age at 50% Sexual Maturity (L_{50} and A_{50})

Lengths at 50% sexual maturity (L_{50}) were estimated for sardine collected from the commercial catch between 1995 and 2003. The L_{50} was determined by fitting a logistic curve to the percentages of maturing and mature (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 $L_{50} = - a/b$.

3.1.9. Sex Ratio

Sex ratio (*SR*) was calculated for commercial catch samples collected from Spencer Gulf and Coffin Bay between 1995 and 2003 using the equation:

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

where nF is the number of females and nM is the number of males in samples.

3.1.10 Maturity Stages

Ovaries were staged macroscopically, 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 staged where stage 1= immature, stage 2 = mature and stage 3 = mature (running ripe).

3.1.11. Gonosomatic Index (GSI)

Mean monthly gonosomatic indices were calculated using the equation:

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

where *Gwt* is gonad weight and *Fwt* gonad-free is gonad free fish weight for fish with gonads of macroscopic stages ≥2.

3.2 Results

3.2.1. Size Structure

Analysis of annual trends in length frequencies between 1995 and 2003 showed sardine taken by the South Australian purse seine fishery ranged between 80 and 200 mm, CFL (Fig. 10). Prior to 2000, size modes for sardine taken in Spencer Gulf were less than 150 mm, CFL. The strong 160 mm size class present in catch samples in 2001 may have progressed to become the dominant size class in 2002. In 2003, juvenile sardine (<100 mm, CFL) comprised 5% of catch samples and adults (>150 mm, CFL) continued to dominate catch samples. Modes were present at 120 and 170 mm, CFL (Fig. 10). Monthly analysis of length frequencies in Spencer Gulf (Fig. 11) showed the length frequencies were either uni or bimodally distributed between January and December 2003. Two strong size classes were present in commercial catch samples during April, May, July and November. Most small juvenile fish (<100 mm, CFL) were taken in July and November.

Between 1995 and 1998 samples from around Coffin Bay Peninsula mostly consisted of fish ranging in sizes between 150 and 180 mm, CFL (Fig. 10). Following the second mass mortality event in 1998/9 there was a substantial decrease in the modal size to the 150 mm, CFL size class. Fishing effort decreased in this region following the second mass mortality event and fewer samples were collected between 2000 and 2003. Samples off Coffin Bay were mostly comprised of 150 to 180 mm, CFL sardine in 2002 and 2003, however few individuals (n = 312) were measured during this period.

3.2.2. Readability Indices (RI)

A total of 2,678 otoliths were assigned RI scores and were aged (IF RI = 1-4) by the first reader (Fig. 12). No otoliths were assigned the RI score of 1, 1.3% were assigned scores of 2, >50.6% were 3s, >30.2% were 4s and ~17.8% were completely unreadable (RI = 5). A second independent reader re-aged 1366 (33%) otoliths from sardine sampled in 2003 which had previously been assigned RI scores of 1 to 3 by the first reader. The second reader also assigned readability scores to those otoliths previously classified by the first reader. Otoliths assigned RI scores of 1 to 3 by both readers that were agreed to be the same age were used to determine calibration relationships between estimated age and otolith weight.

3.2.3. Precision of Age Estimates

Estimated APE and mean CVs were high (APE = 15.6%, CV = 22.1%) for sardine (~1 to 5 years old) especially when compared to other ageing studies (Campana 2001). These APE estimates were of similar magnitude to those found during sardine ageing studies in California (Butler *et al.* 1996).

3.2.4. Relationship between Age and Otolith Weight

The relationship between otolith weight and age was determined from otoliths with the highest readabilities (1 to 3) where the two independent readers agreed on the age. The linear regression equation, otolith wt = 0.2375.age + 0.5474, (R^2 = 0.68) (n = 572) predicted approximately 0.78 mg of otolith weight would be deposited during the first year of growth in southern Spencer Gulf (Fig. 13).

3.2.5. Age Structure

Commercial catches from Coffin Bay mainly consisted of 2 to 4 year olds, whereas catches from Spencer Gulf generally included a larger proportion of 1 to 3 year old sardine (Figs. 14 and 15). Catch samples from Spencer Gulf during1995, were dominated by 2 to 4 year olds (Fig. 14). After the first mortality event 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 old fish comprising >60% of the catch. Strong 2 year old age classes dominated catches during 1999 and progressed to support the fishery as strong 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 be strong 3 and 4 year old age classes in 2002. During 2003 the fishery expanded operations further north and east in Spencer Gulf. The age structure of the catch samples changed, with the 0 and 1 year old age classes reappearing (Fig. 14). Monthly analysis of age structures in Spencer Gulf during 2003 shows that catches during most months were dominated by 2 and 3 year old fish (Fig. 15). The 0 and 1 year old age classes were most common in July and November.

Off Coffin Bay, strong year classes of 2 to 4 year old fish dominated the age structure of catch samples between 1995 and 1999. Between 1999 and 2003, few samples of sardine from the commercial catch were collected from Coffin Bay due to the significant contraction of fishing effort away from this region. During 2001, no commercial catch samples were collected from Coffin Bay, as the fishery retracted into southern Spencer Gulf. In 2002, catch samples collected off Coffin Bay were mostly comprised of sardine in the 2 and 3 year old age classes. The strong 3 year old age class present in 2002 was present in samples as a strong 4 year old age class in 2003. However, due to the small sample sizes interpretation of these data should be viewed cautiously. During 2003, the 5 year old age class, which had not been present in the age distributions since 1997/8, reappeared in samples collected off Coffin Bay.

3.2.6 Growth Patterns

In 2002 and 2003 sardine collected from the commercial samples in Spencer Gulf and Coffin Bay ranged from approximately 4 months to 7 years of age. The von Bertalanffy curve (Fig. 16) shows there is considerable variation in length at age in sardine from South Australia. Von Bertalanffy growth parameter estimates are shown in Table 1. This is likely to reflect a combination of the following factors (a) natural variation in size at age in response to environmental factors including food availability and water temperature (b) low levels of precision in age estimates, (c) the protracted spawning season and resultant broad spread in birth dates and (d) varying degrees of competition for food in response to broad fluctuations in biomass. The magnitude of the von Bertalanffy growth parameters (K and L_{∞}), reflect the moderate to fast growth rates for sardine before sexual maturity is attained and slower growth during adulthood.

3.2.7. Length and Age at 50% Maturity

Female and male sardine collected from the commercial catch between 1995 and 2003 reached L_{50} at approximately 152 and 147 mm, CFL, respectively (Fig. 17). These lengths coincide with ages of approximately 1-2 years old (See *VB* growth curves in previous section). All males below the 120 mm size class and all females below the 125 mm size class had immature gonads. Of females (n = 10,090) collected from the commercial catch between March 1995 and December 2003, approximately 2,919 (28.9%) were below the estimated L_{50}. Of males (n = 7,575) collected during the same period, 2,030 (26.8%) were smaller than the estimated L_{50}.

During 2003, samples collected from the commercial catch were analysed to determine the proportion of sardine by region that were < L_{50} (Fig. 18). This analysis showed >20% of female sardine in commercial catch samples from Reevesby Island, Corny Point and Port Neill were smaller than the estimated L_{50}. Most female sardine in samples collected off Thistle Island and Dangerous Reef were larger than the estimated L_{50}. Greater than 20% of male sardine samples collected from Reevesby Island and Port Neill were smaller than the estimated L_{50}. Of the samples collected off Thistle Island, Corny Point and Dangerous Reef, <10% of male sardine from commercial samples were smaller than L_{50} (Fig. 18).

3.2.8. Sex Ratio

Sex ratio data from sardine collected from the commercial catch were combined between 1995 and 2003. Sex ratios were dominated (*ANOVA* $P<0.05$) by females (>50%) in Spencer Gulf and off Coffin Bay (Fig. 19). Males were more common than females in samples collected off Coffin Bay during September and October.

3.2.9. Maturity Stages

Male and female sardine from commercial catch samples in Spencer Gulf (1995-2003) mostly had immature stage 1 and stage 2 gonads (>75%). Mature females (>10%) (stage 3) were present in samples between January and April (Fig. 20). Actively spawning females (stage 4) comprised a very low proportion (<1%) of catch samples from the commercial purse seine fishery. Small proportions (<20%) of mature stage 3 males and females were taken throughout the year.

Sardine with stage 3 gonads comprised >50% of commercial catch samples taken out from Coffin Bay between January and March (Fig. 20). There was a marked decrease in the occurrence of mature stages in both sexes during April. Small quantities of spawning females were present in samples from Coffin Bay (<5%) between November and April. Immature and maturing fish (stages 1 and 2) comprised >80% of samples between April and December.

3.2.10. Gonosomatic Index (GSI)

Mean GSIs indicate the spawning season for female sardine in Spencer Gulf extends from December through until April with males and females showing a similar seasonal pattern (Fig. 21). Mean GSIs were highest (>3.5) between December and February. Mean GSIs for males were higher than for females during the spawning season. Mean GSIs for females sampled from the commercial catch off Coffin Bay indicated the spawning season mostly occurred between January and April. Males were mostly in spawning condition between January and March, with highest mean GSIs occurring in March.

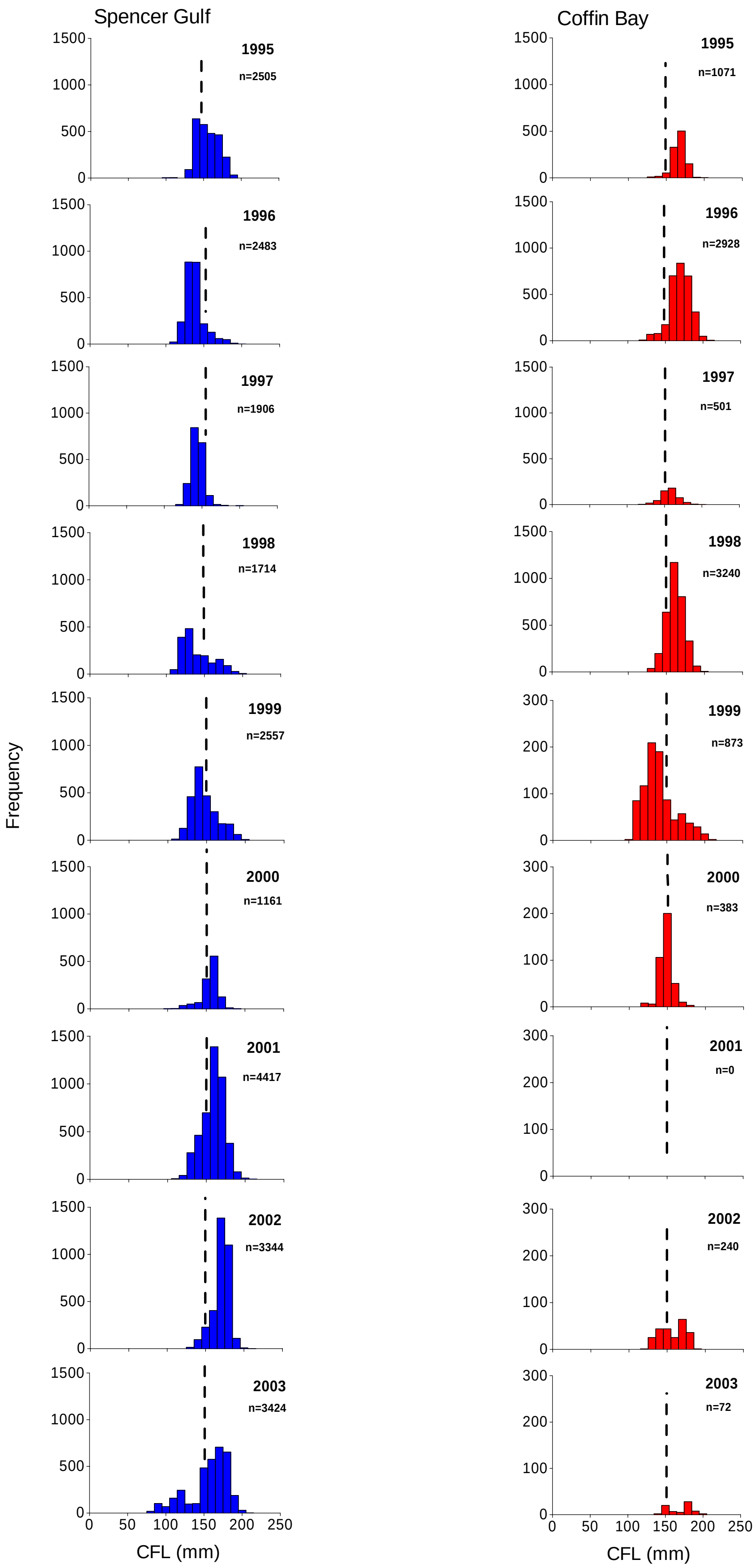

Figure 10. Length frequency distributions by year for catch samples from Spencer Gulf and Coffin Bay between 1995 and 2003.

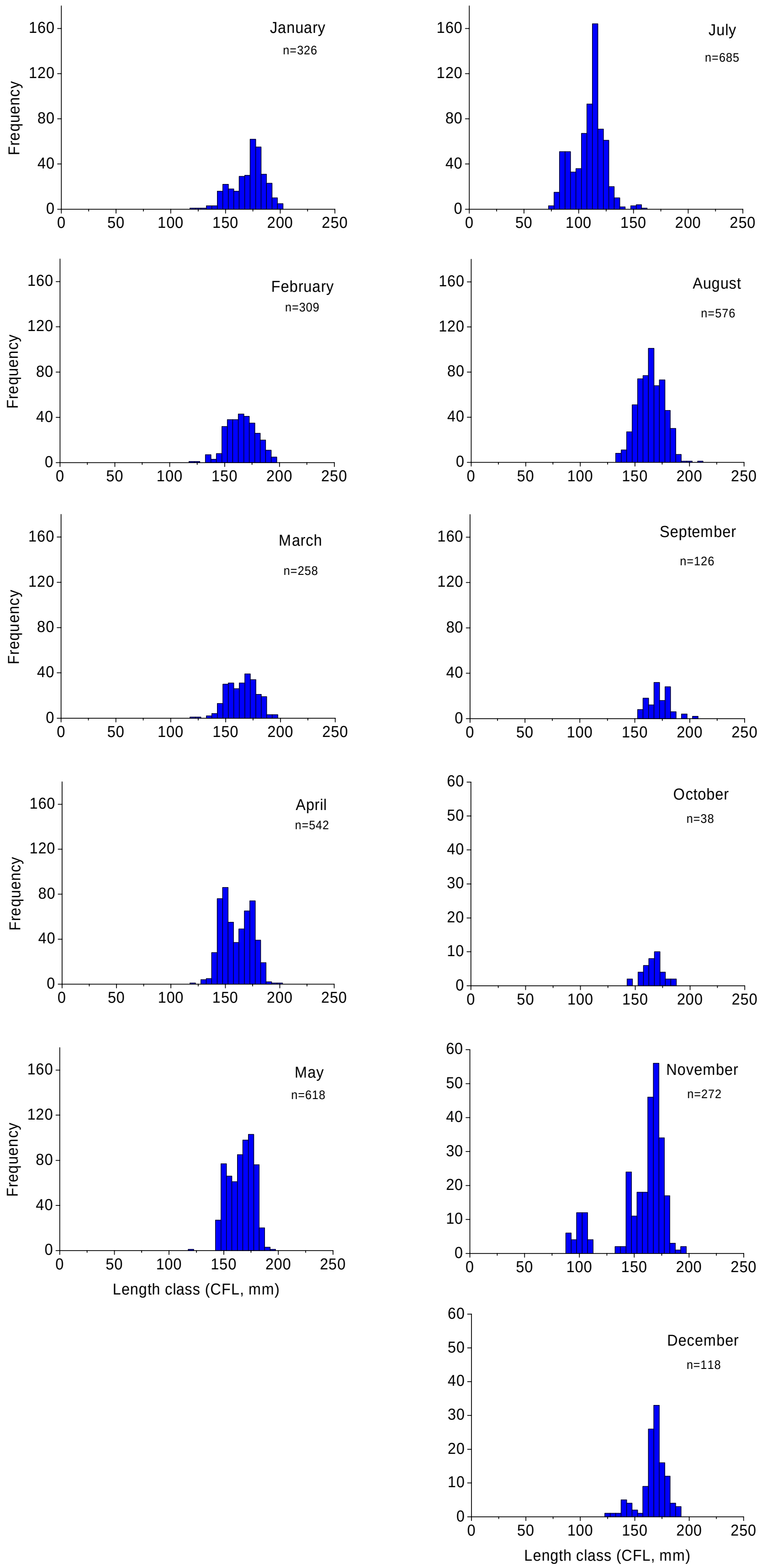

Figure 11. Length frequency distributions by month for catch samples from Spencer Gulf in 2003.

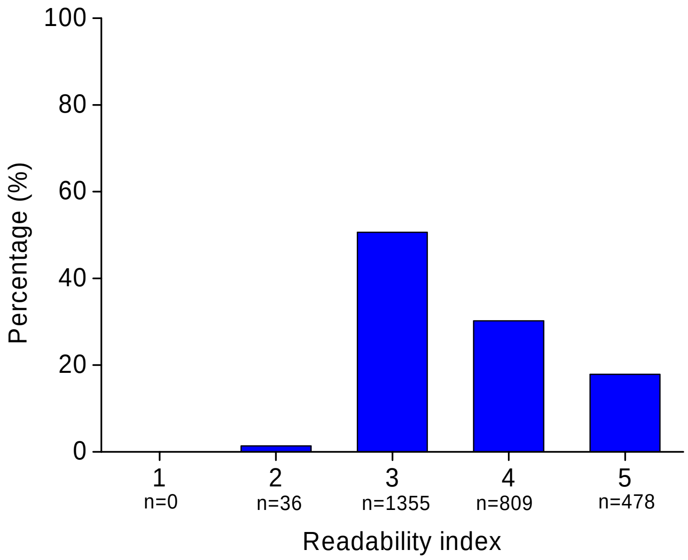

Figure 12. Subjective readability index (RI) scores assigned to sardine otoliths from the commercial catch samples in 2003.

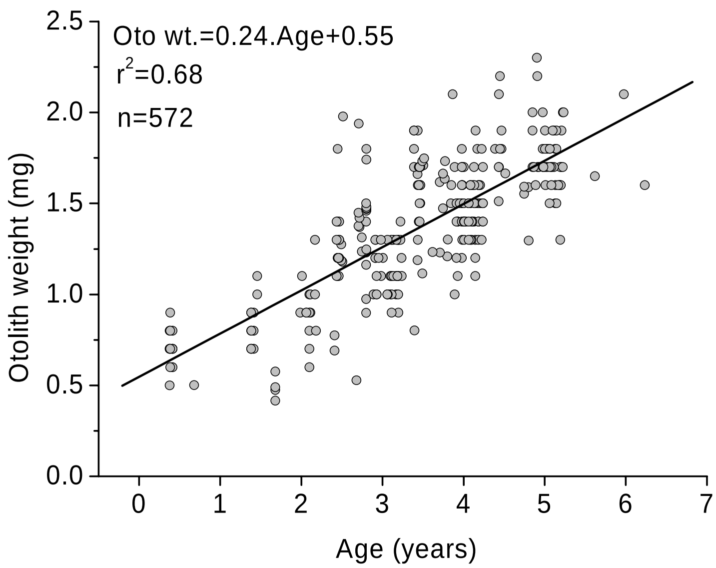

Figure 13. Relationship between age and otolith weight for otoliths (RI scores≤ 3) collected from commercial catch samples during 2003.

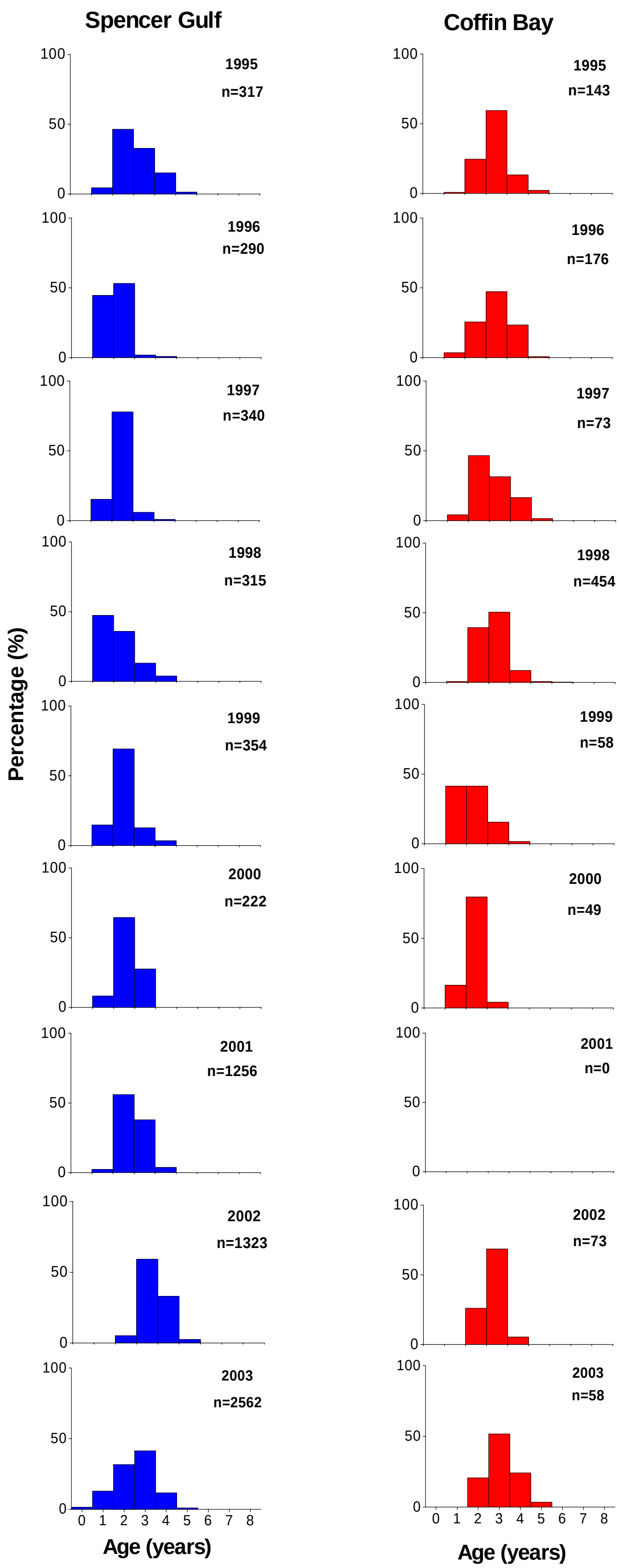

Figure 14 Age structure of the commercial catch in Spencer Gulf and Coffin Bay between 1995 and 2003.

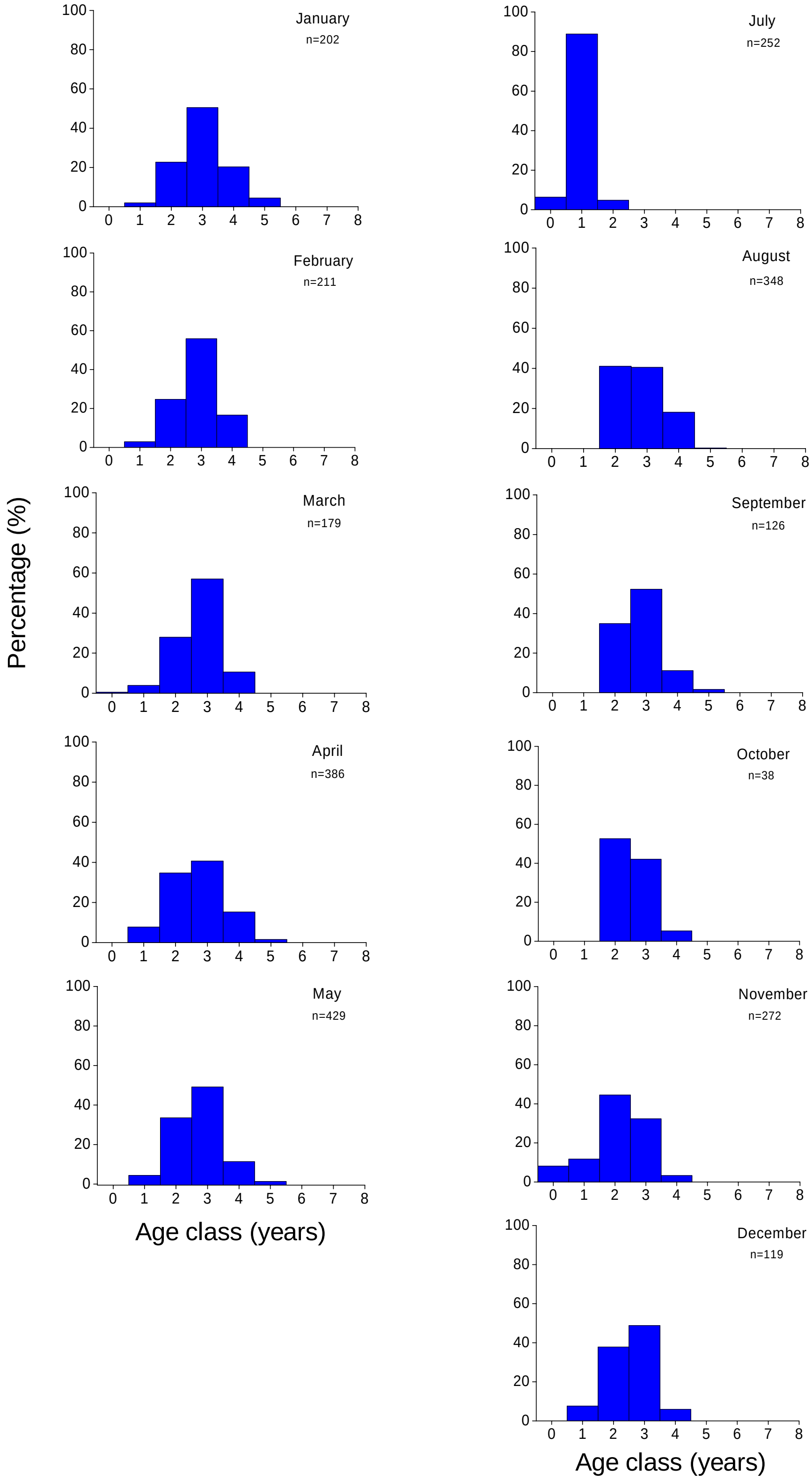

Figure 15. Age structure by month in samples collected from the commercial catch in Spencer Gulf during 2003.

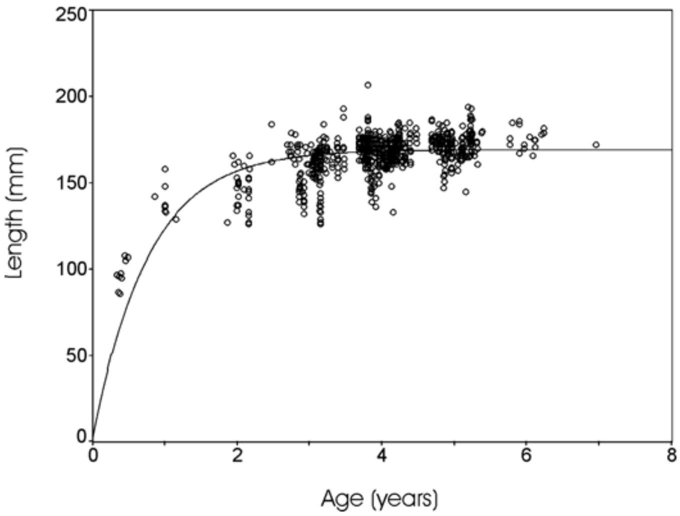

Figure 16. Von Bertalanffy growth curve for sardine collected from commercial catch samples collected in Spencer Gulf and Coffin Bay in 2002 and 2003.

Table 1. Von Bertalanffy growth parameters for sardine sampled from the commercial catch in 2002 and 2003. 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)	*Brody growth coefficient K* (yr^{-1})	r^2	*n*
All Commercial	169.19 (168.55 & 169.82)	1.29 (1.22 & 1.36)	0.32	1489
Spencer Gulf	168.88 (168.34 & 169.43)	1.47 (1.39 & 1.56)	0.35	1411

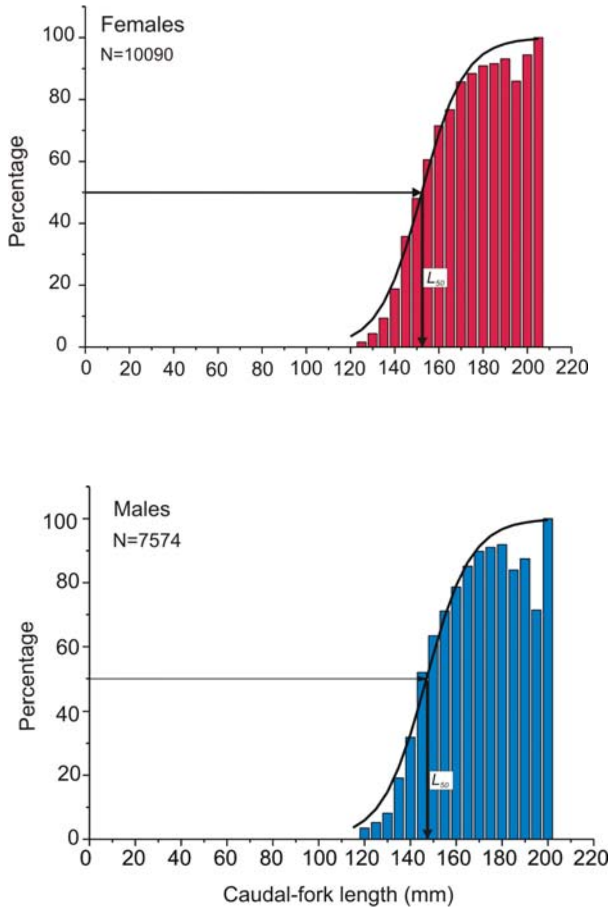

Figure. 17. Relationship between length and the percentage of male and female sardine from South Australian waters at 50% sexual maturity. Arrows show lengths at which 50% of males and females were sexually mature.

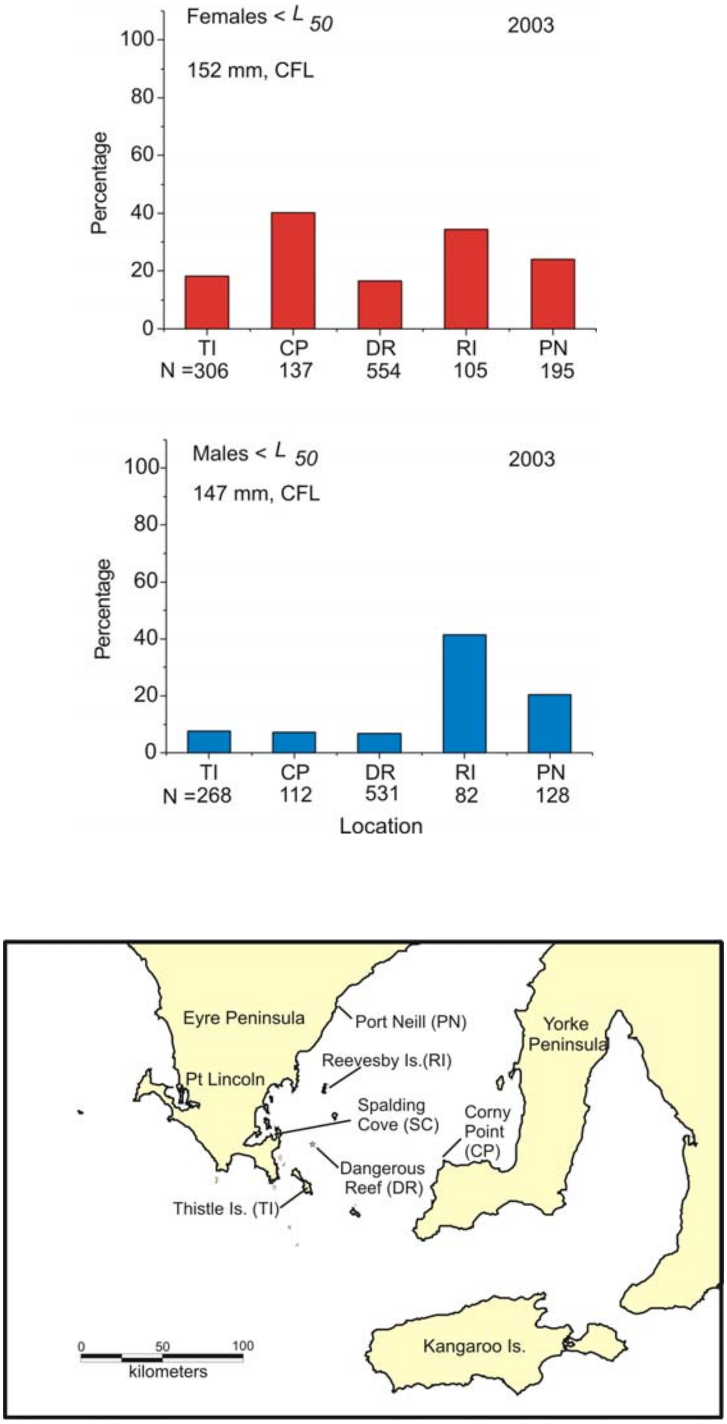

Figure 18. Percentage of commercial catch samples below lengths at 50% maturity taken from locations in the map of the fishing area.

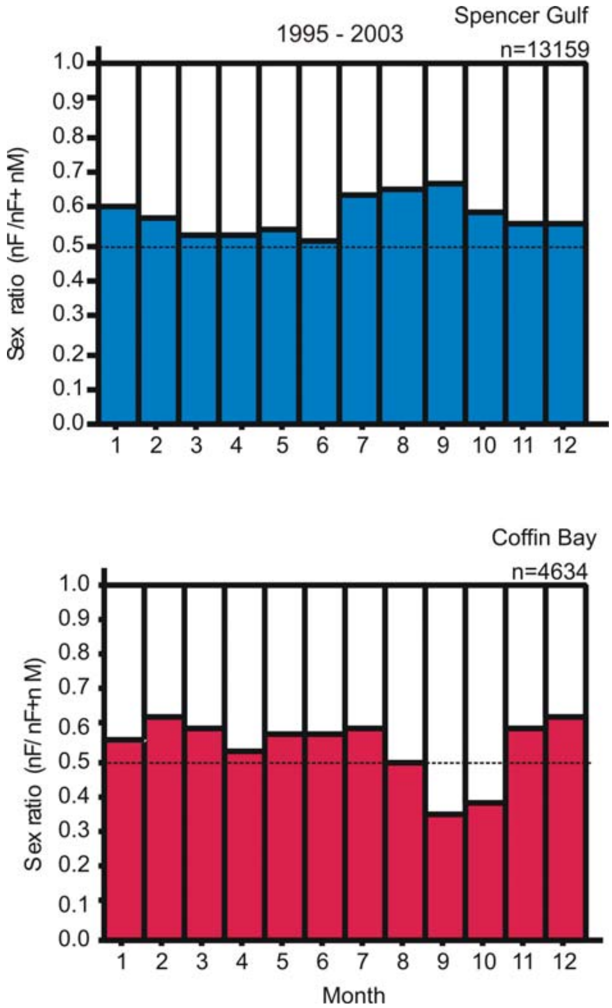

Figure 19. Sex ratio by month for samples collected from the commercial catch in Spencer Gulf and off Coffin Bay between 1995 and 2003.

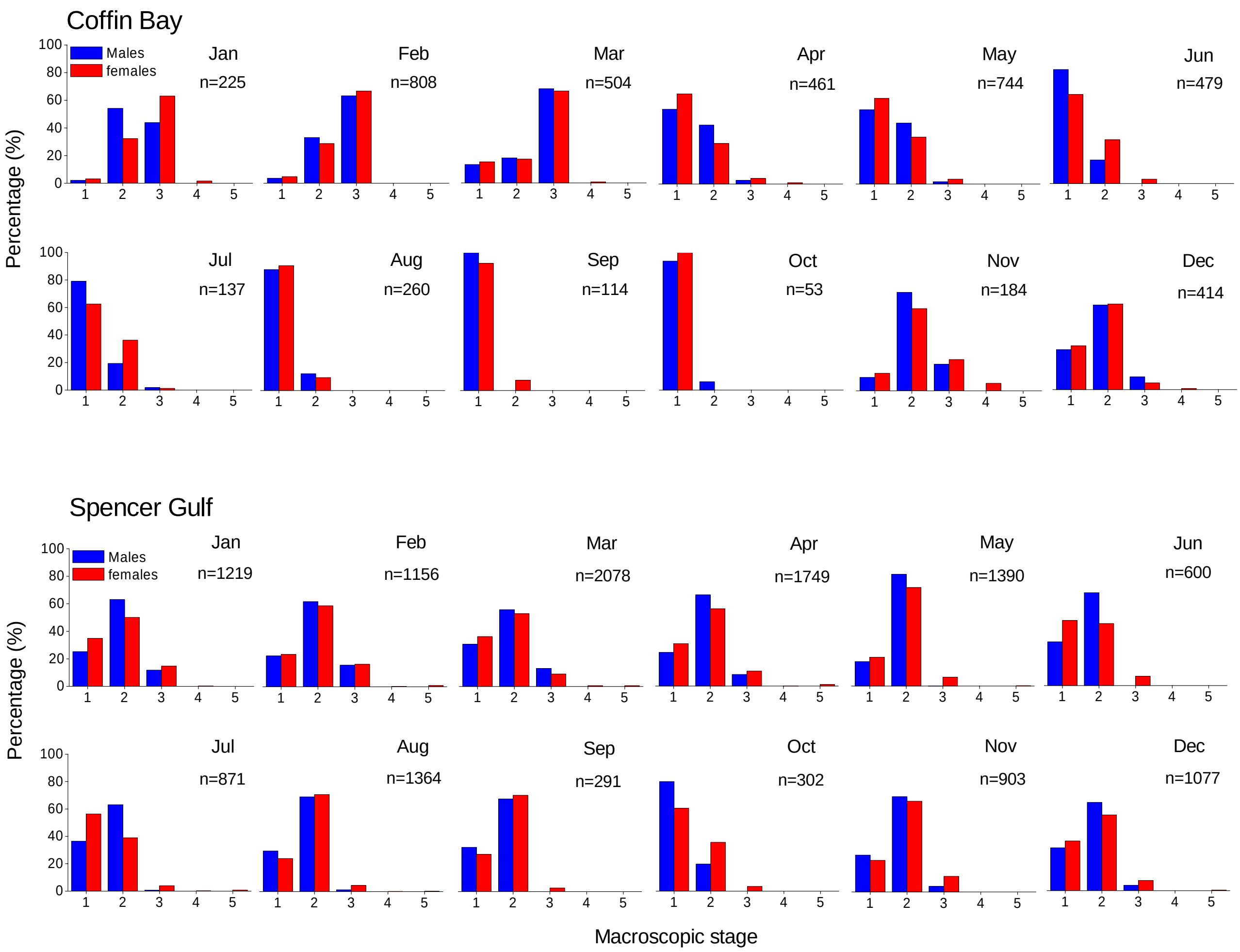

Figure 20. Proportion of each gonad stage for sardine collected from the commercial catch in Spencer Gulf and off Coffin Bay Peninsula between 1995 and 2003.

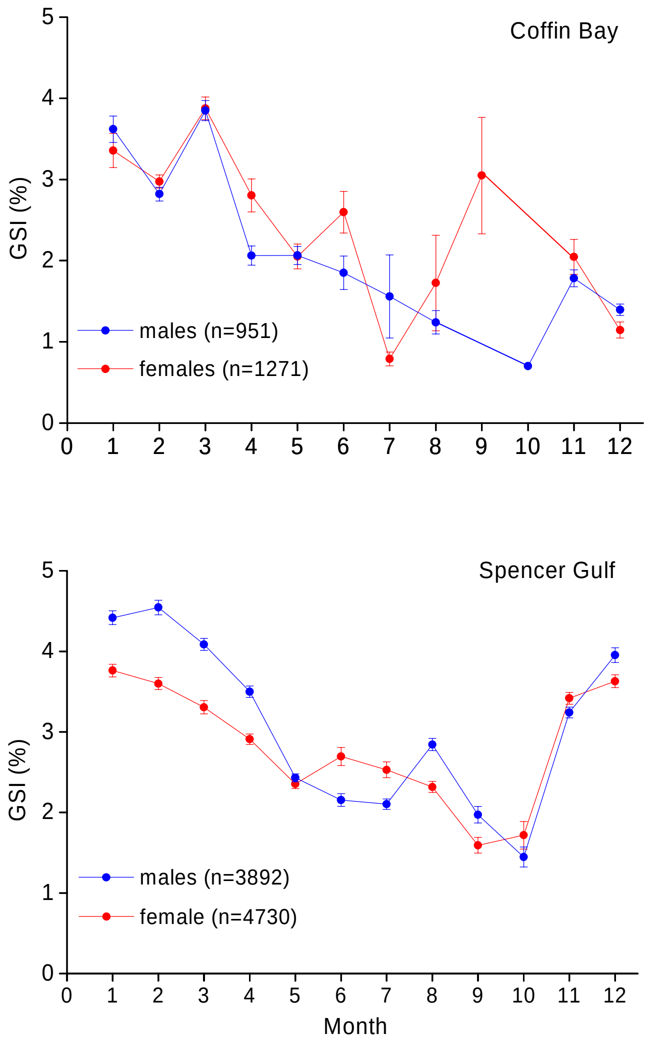

Figure 21. Mean monthly gonosomatic index (GSI) (pooled for all years) for males and females in Spencer Gulf and Coffin Bay Peninsula between 1995 and 2003.

4. RESEARCH - FISHERY INDEPENDENT

4.1. Methods

4.1.1. Sampling

Fishery independent samples of sardine were collected during annual research cruises on *RV Ngerin* between February and April 1998 to 2003. Sardine schools were located on dusk using a Furuno CH-240 (60-180 KHz), sonar and by following aggregations of feeding sea birds. Multi-panelled, multifilament gill-nets and underwater lights were used to collect samples of sardine. This sampling method is discussed in detail in Ward *et al.* (2001b). Table 2 shows the locations and years in which fishery independent samples were collected.

Table 2. Locations and years in which fishery independent samples were collected between 1998 and 2003. CB = Coffin Bay, FI = Flinders Is, FRI = Franklin Is, GI = Greenly Island, SFI = St Francis Island, SC = Scotts Cove, COB = Corvisart Bay, GOI = Goat Island, WI = Waldegrave Island, TI = Thistle Island, FI = Flinders Island, SB = Streaky Bay.

Year	Location sampled
1998	CB, FI, SC, SFI
1999	CB, FI, FRI, GI, SC, SFI
2000	FI, GI, SC, SFI
2001	FI, GI, SC
2002	COB, FI, GOI, GI, SC, SFI, WI
2003	CB, FI, GI, SC, SB, TI

4.1.2. Size and Age Structure

Size and age structures were analysed as per the samples collected from the commercial catch (Section 3).

4.1.3. Age Structured Stock Assessment Model

The age structured stock assessment model used in this study was written by Dr Peter Stephenson and based on a model written by Dr Norm Hall for Western Australian sardine. This section represents a summarised version of findings in the FRDC report titled, "Implementation of the age structured stock assessment model for sardine (*Sardinops sagax*) in South Australia". The parameters in the age structured stock assessment model were as follows:

Commercial catch and age composition

Monthly commercial catch data from the South Australian Sardine Fishery were available from 1992 to 2002. Age-composition data from commercial catches were available from 1995 to 2002 and from fishery independent research surveys from 1998 to 2002.

Fishery independent spawning biomass estimation

Estimates of spawning biomass were obtained from the daily egg production method during research surveys conducted in March each year from 1995 to 2002 (Fig. 22).

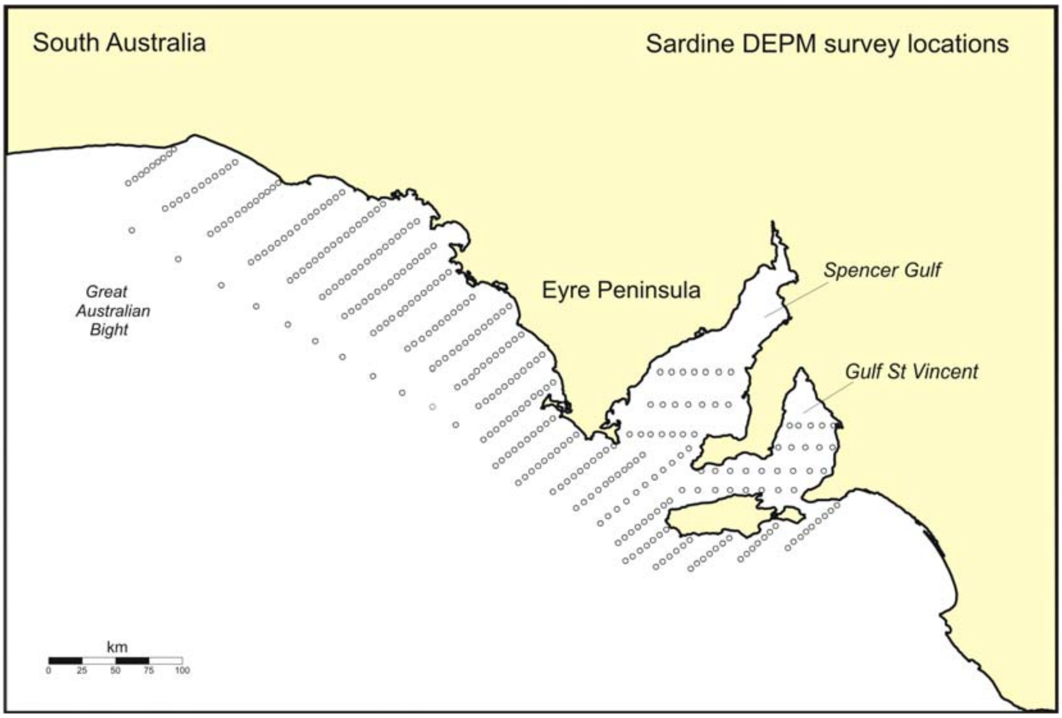

Figure. 22. The DEPM survey conducted annually between February and April in South Australian gulf and shelf waters. The black circles show the location of each station sampled for sardine eggs.

Change in abundance over time

The fishery model was driven by the catches in monthly time steps with ages a = 0 to a = 96 months and instantaneous rate of natural mortality, M , assumed to be constant for all ages and estimated in the model. The sardine population was assumed to be in state of unfished equilibrium in 1992. As sardine spawn in March in South Australia, the initial recruitment θ_{Init} was estimated in the model for March 1992. The number of sardine (millions), $N^s_{a,t}$, of age a (a = 0 to a = 96 months) and sex s (s = f and s = m) at the beginning of time-step $t=0$ (March 1992) was calculated from Equation 1.

$$N^s_{a,0} = \begin{cases} 0 & \text{if } \mathrm{mod(a,12)} \neq 0 \\ \rho_s \theta_{Init} & \text{if } a = 0 \\ N^s_{a-12,0} \exp(-M) & \text{if } \mathrm{mod(a,12)} = 0 \text{ and } 0 < a < 96 \\ N^s_{a-12,0} \exp(-M)/[1-\exp(-M)] & \text{if } a = 96 \end{cases} \quad (1)$$

where ρ_s is the proportion of each sex with $\rho_f = 0.59$ and $\rho_m = 1 - \rho_f$ .and $\mathrm{mod}(a,12) = a - 12\,\mathrm{int}(a/12)$.

Recruitment

Sardine recruitment is highly variable and depends on environmental conditions and to a lesser extent stock size. In the assessment model, yearly recruitment was determined firstly from the Beverton and Holt stock-recruitment relationship with the parameters determined from the biomass in the initial state using a steepness parameter (Hilborn *et al.* 1994) fixed at $h = 0.7$. Low steepness factor values were assigned based on the assumption that recruitment is not highly reliant on stock size. To account for environmental variation, for the years 1992 to 2000 the Beverton and Holt recruitment was multiplied by a log-normally distributed recruitment deviation factor, which is estimated in the model. After 2000, there was no information in the age-composition data to calculate recruitment deviations and therefore environmental variation in years after 2000 were modelled by a log-normally random sample with standard deviations equal to that estimated for years 1992 to 2000. The recruits into the age 0 fish were represented by R_t , Equation 2:

$$R_t = \begin{cases} 0 & \text{if } m' \neq 3 \\ R_t & \text{if } m' = 3 \text{ and } y = 1992 \\ R_t \ \ e^{d_t} & \text{if } m' = 3 \text{ and } 1993 \leq y < 2000 \\ R_t \ \ e^{\varepsilon_t} & \text{if } m' = 3 \text{ and } y \geq 2000 \end{cases} \tag{2}$$

where m' is the month, R_t the recruitment in the fishery from the stock recruitment relationship, d_t is the recruitment deviation parameter, and ε_t is a random selection from $N(0, \sigma_t^2)$ where σ_t is the standard deviation of d_t .

Abundance in successive time steps

Sardine numbers in successive time-steps after recruitment were reduced due to losses from natural mortality and fishing according to Equation 3:

$$N_{a,t}^s = \begin{cases} R_t & \text{if } a = 0 \text{ and } m' = 7 \\ N_{a-1,t-1}^s \left(1 - H_{t-1} V_{a-1}\right) \exp\left(-M/12\right) & \text{if } a > 0 \text{ and } a \neq 96 \\ \left[\begin{array}{l} N_{a-1,t-1}^s \left(1 - H_{t-1} V_{a-1}\right) \\ \qquad + N_{a+11,t-1}^s \left(1 - H_{t-1} V_{a+11}\right) \end{array}\right] \exp\left(-M/12\right) & \text{if } a = 96 \\ N_{a-1,t-1}^s \left(1 - H_{t-1} V_{a-1}\right)\left(1 - D_{1995}\right) \exp\left(-M/12\right) & \text{if } y = 1995 \text{ and } m' = 4 \\ N_{a-1,t-1}^s \left(1 - H_{t-1} V_{a-1}\right)\left(1 - D_{1999}\right) \exp\left(-M/12\right) & \text{if } y = 1998 \text{ and } m' = 8 \end{cases} \tag{3}$$

where R_t is the recruitment in each region, H_t is the harvest rate (proportion of the vulnerable sardines caught) for time-step t , V_a is the proportion of sardines of age a that are vulnerable. $D_{1995} = 0.7$ is the estimated proportion of fish age ≥ 3 that died as a result of the first mass mortality event in 1995 and $D_{1998} = 0.7$ is the estimated proportion of fish aged ≥ 1 that died as a result of the second mass mortality event in 1998 (Ward *et al.* 2001a).

Vulnerable biomass

Sardine in South Australia mostly first become vulnerable to fishery exploitation at the age of two years old. The vulnerability of sardine aged 2, 3, and 4 years is estimated in the model with 5-year-old fish being fully recruited. Vulnerability at age *a* (months) was assumed constant throughout the year while they remained within the same age-class.

Vulnerable biomass, $\hat{B}_t$ in tonnes, at the beginning of time-step *t* for sardine of sex *s* was calculated as:

$$\hat{B}_t = 1000 \sum_{s=m,f} \sum_{a=0}^{A} N_{a,t}^{s} V_a W_a^{s} \qquad (4)$$

where W_a^s is the weight (kg) at age *a* and sex *s* and $W_a^s = 0.0000039939 \times (L_a^s)^{3.20}$.

Harvest rate

The monthly harvest rate, H_t^r, at each time step was calculated from the observed catch and the current estimate of vulnerable biomass, Equation 5.

$$H_t^r = \begin{cases} \dfrac{C_t}{\hat{B}_t} & \text{if } C_t^r < \hat{B}_t^r \\ 1.0 & \text{otherwise} \end{cases} \qquad (5)$$

where C_t is the monthly catch and $\hat{B}_t$ is the current estimate of vulnerable biomass.

Penalty function

To ensure the model parameters produced estimates of vulnerable biomass sufficiently large to allow the removal of the observed catch, a penalty function, P_1 (Equation 6), was included in the objective function if the catch exceeded 95% of the vulnerable biomass in the region. These factors are necessary with catch conditioned models.

$$P_1 = 100 \sum_{\substack{t=0 \\ C_t > 0.95 B_t}}^{T} \left(C_t - 0.95 \hat{B}_t \right)^2 \qquad (6)$$

Growth

The growth of sardines is represented by the von Bertalanffy growth curve:

$$L_a^s = L_\infty^s \left\{1 - \exp\left[-K^s\left(\frac{a}{12} - t_0^s\right)\right]\right\} \tag{7}$$

where L_a^s is the fork length (mm) of a fish of age *a* months ($0 \le a \le A$) and sex s ($s = m$ for males, $s = f$ for females), and the values of the growth parameters are $L_\infty^f = 191.9$, $L_\infty^m = 183.4$ $K^f = 0.62$, $K^m = 0.57$ and $t_0^s = 1.0$.

Age at sexual maturity

The proportion of sardine sexually mature at age *a* (months) is given by:

$$p_a = \frac{1}{1 + \exp\left[-\ln(19)\left(\frac{\text{int}(a/12) - 3.02}{5.5 - 3.02}\right)\right]} \tag{8}$$

where the age at which 50% are mature is 3.02 years and the age at which 95% are mature is 5.5 years (based on preliminary analysis of 1995-2001 growth patterns).

Log-likelihood associated with DEPM biomass estimates

Observations of spawning biomass, D_t, and their estimated coefficients of variation, CV_t, determined from the daily egg production surveys. The estimated mature biomass, $\hat{D}_t^s$, in tonnes, at the beginning of time-step *t* for sardine of sex *s*, was calculated as:

$$\hat{D}_t^s = 1000 \sum_{s=m,f} \sum_{a=0}^{A} N_{a,t}^s \, p_a \, W_a^s \tag{9}$$

Errors were assumed to be normally distributed, and an estimate of the log-likelihood associated with these DEPM derived biomass observations (ignoring constant terms) was obtained using Equation 10:

$$\lambda_2 = -\frac{\sum_{\substack{t \\ D_t \text{ exists}}} \left(D_t - \hat{D}_t\right)^2}{2\left(CV_t \; D_t\right)^2} \tag{10}$$

Log-likelihood associated with age

The estimated proportion, $\hat{p}_{a,t}$, of vulnerable sardine within each age-class a, combining sexes, were calculated for the 2+ to 8+ age classes recruitment in May each year. It was assumed that the observed ages represented samples from a multinomial distribution, and thus the log-likelihood associated with age samples (ignoring constant terms) was determined using Equation 11:

$$\lambda_3 = \sum_{\substack{t \\ m'=5 \\ \text{Sample exists}}} N_t \left\{ \sum_{a=24}^{96} \left\{ p_{a,t} \log(\hat{p}_{a,t}) \right\} \right\} \tag{11}$$

where $p_{j,t}$ is the observed proportion at age and $\hat{p}_{j,t}$ is the model estimated proportion at age and N_t is the sample size.

Overall log-likelihood

The overall log-likelihood was the sum log-likelihoods for the observed biomass estimates, age-composition data, recruitment deviations, as well as the penalty function associated with harvest rates (Equation 12).

$$\lambda = \lambda_2 + \lambda_3 + \lambda_4 - P_1 \tag{12}$$

The objective function was maximised using the software package, AD Model Builder (Otter Research Ltd 1994). The population was projected forward from 2003 to 2006 using harvest rates based on the DEPM estimate of the stock size the previous year and the decision rules for determining the Total Allowable Commercial Catch (TACC) aimed to keep the mature biomass greater than 40% of the mature biomass in 1992. A Bayesian procedure was used to determine estimates of uncertainty of the mature biomass, D. A joint posterior probability distribution was generated using the Markov Chain Monte Carlo (MCMC) procedure in AD model Builder.

4.2. Results

4.2.1. Size Structure

Comparison of size structures of fishery independent samples with samples from the commercial catch shows commercial samples do not accurately represent the size structure of the wider population. Samples of larger fish with length frequency modes ≥170 mm, CFL have consistently been collected from around offshore islands, including Flinders Island, St Francis Island and Greenly Island in the eastern Great Australian Bight (GAB). Samples of adult sardine were difficult to obtain at these locations during 2002 and 2003. This coincided with strong south-easterly winds during summer/autumn, which led to cool (14.5-16°C) upwelled water at the surface that spread across the inner continental shelf. Size frequency distributions for samples (n = 8404) collected between 1998 and 2003 showed sardine ranged in size between 110 and 220 mm, CFL, and most were 150 to 170 mm (Fig. 23). During 1998, size classes ranged from 120 to 190 mm and dual modes were present at 130 and 170 mm. In 1999 after the first mortality event, the modal size remained at 170 and 180 mm, which represented ~51% of samples. During 2000, adults between 150 and 180 mm dominated samples with a single mode at 160 mm. There was a clear modal progression from the 160 mm size class in 2000 to the 170 mm size class in 2001. The robust 150 to 180 mm size classes present during 2000 continued to represent ~97% of adults sampled in 2001.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, CFL with a single mode at 180 mm, CFL. During 2003 sardine mostly ranged in size between 140 and 180 mm and dual size modes were present at 140 and 170 mm.

4.2 .2. Age Structure

Adult sardine (n = 3067) sampled by fishery independent methods between 1998 and 2003 ranged in age between 2 and 7 years old (Fig. 24). In 1998, the 3, 4 and 5 year old age classes were dominant and comprised 36.7%, 20.3% and 30.4% of samples respectively. Minimal negative effects were evident in the age structure of samples after the second mass mortality event in 1999. The main change occurred in the 6 year old age class, which comprised >10% of samples in 1998 and declined to ~4% in 1999. During 2000, the 3 to 5 year old age classes continued to dominate. This pattern continued in 2001 as the 3 and 4 year old age classes from the previous year progressed to 4 (43.3%) and 5 (35.8%) year old age classes and the 6 year old age class recovered slightly to comprise ~1.7% of samples. Similarly during 2002, the 3 to 5 year old age classes remained prominent and the 6 year old age class continued to recover. During 2003 a negative shift in the modal age occurred. The 4 year old age class from the previous year was less dominant and the 1 and 2 year old age classes became more common.

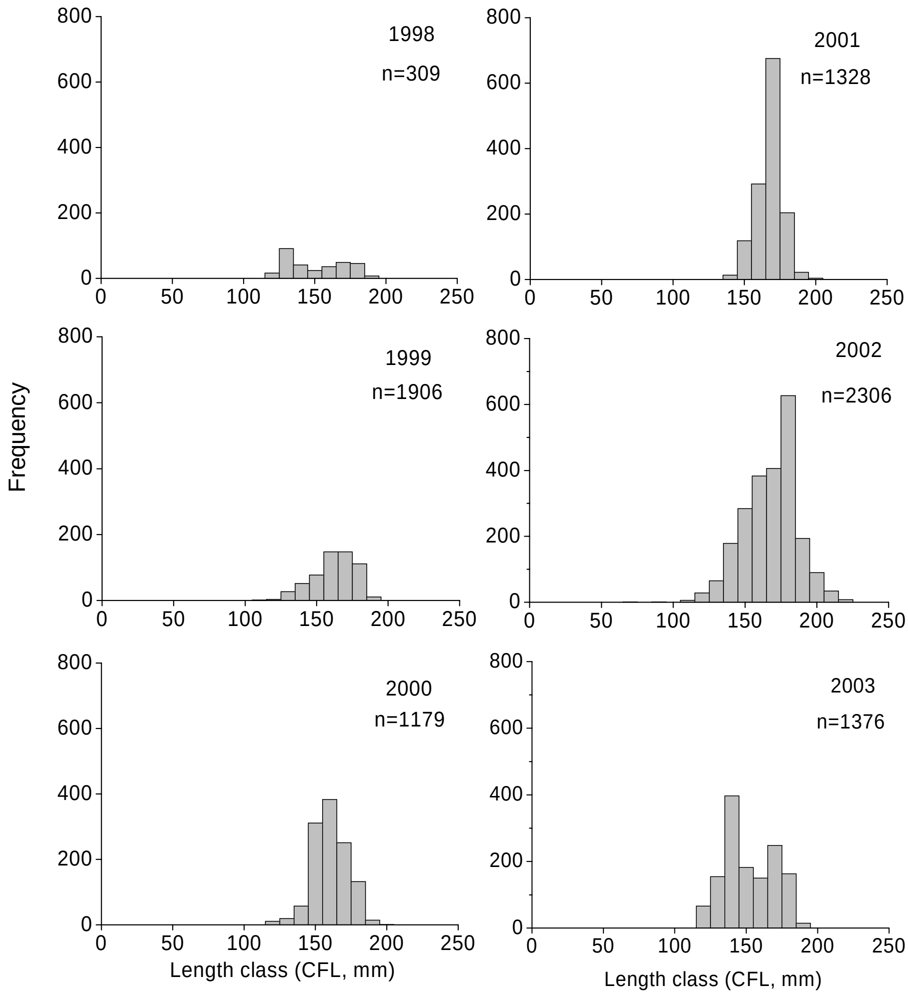

Figure 23. Length frequency distributions for sardine collected using fishery independent methods between 1998 and 2003.

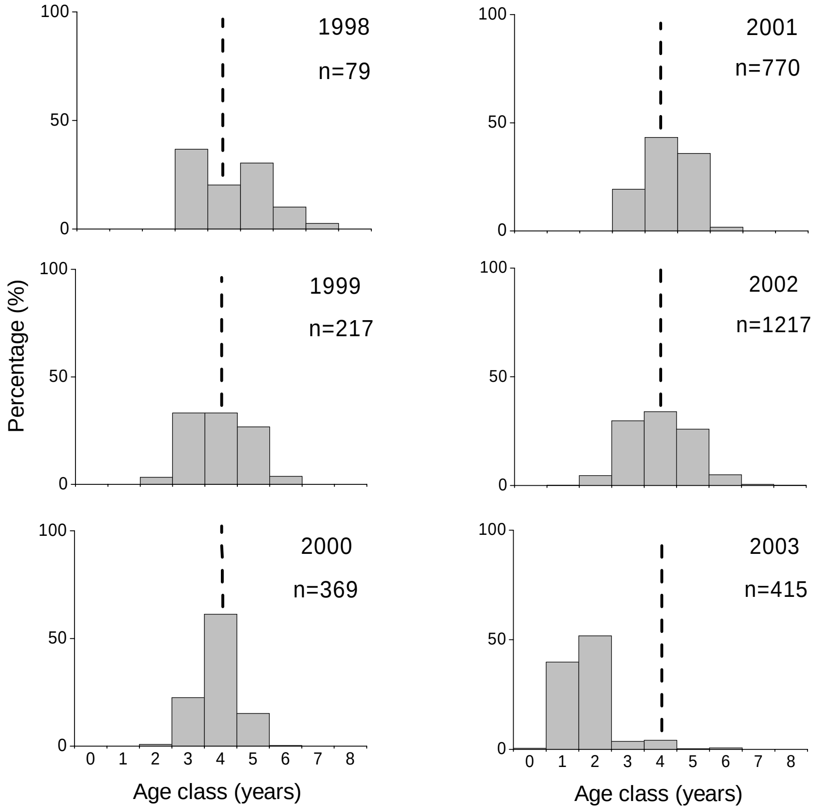

Figure 24. Age structures of sardine collected using fishery independent methods between 1998 and 2003.

4.2.3. Age Structured Stock Assessment Model

Average and high recruitment scenarios were used as starting parameters during preliminary runs of the age-structured stock assessment model. Estimates of annual recruitment indicated strong recruitment events between 1996 and 1998 followed by weaker recruitment in 1999 and 2000, although the later estimate is only based on the abundance of 2 year old fish in 2002. After 2000, there was no information in the age structure data to estimate deviation from recruitment determined from the stock-recruitment relationship. At medium recruitment levels between 2001 and 2003 (Fig. 25), the model predicted the biomass would diverge from the DEPM biomass estimate after 2001 and decline to approximately 150,000 tonnes by 2004 (Fig. 26). Model estimates of initial recruitment, natural mortality and vulnerability and the standard deviations are presented in Table 3.

Under the high recruitment scenario (Fig. 27), the age structured model biomass estimates followed a similar upward trajectory to the DEPM estimates between 2001 and 2003, and predicted biomass would recover to >200,000 tonnes by 2004 (Fig. 28). Model estimates were slightly higher than the DEPM estimates between 1996 and 2000 and lower in 2002. The DEPM biomass estimates in 2002 and 2003 (240,600 to 269,063 tonnes) suggested a stronger than average recruitment event occurred in one or more of the years between 2000 and 2002. The rapid recovery of the stock in South Australia was supported by strong 2 and 3 year old age classes that persisted in fishery catch samples even after the second mortality event killed ~70% of the spawning stock.

In its current form, the age structured stock assessment model does not allow simulation of biomass trajectories for different inputs of annual recruitment strength (2 year olds). Modification of the model to allow these simulations is easily achieved, however in the absence of reliable recruitment and age structure information this issue is currently a low priority. Currently the age structured model is not a reliable tool for predicting the magnitude of the sardine biomass for management of the fishery.

Table 3. Estimates of initial recruitment, natural mortality and vulnerability and their standard deviations

Model parameter	Estimate	Standard deviation
θ_{Init}	44, 479	5, 087
V_2	0.038	0.006
V_3	0.209	0.025
V_4	0.621	0.051

Comparison of model estimated recruitment and recruitment age class strength

Between 1995 and 2001 only 13% of the variability in recruitment estimated by the model was explained by differences in the strength of the 1 year old recruitment age classes (*Pearson's Correlation coefficient,* $r^2 = 0.13$, $P = 0.43$, $n = 7$), with a 1 year lag. Similarly, only 14% of the change in recruitment estimated by the model was explained by variation in the strength of the 2 year old recruitment age classes (*Pearson's Correlation coefficient,* $r^2 = 0.14$, $P = 0.40$, $n = 6$), with a 2 year lag.

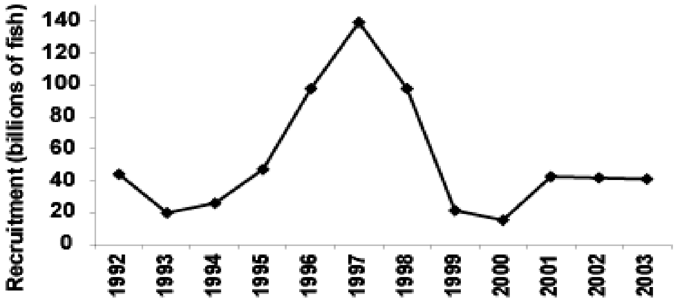

Figure 25. Sardine recruitment estimated by the age-structured model from 1992 to 2000 with average levels of recruitment in 2001 to 2003.

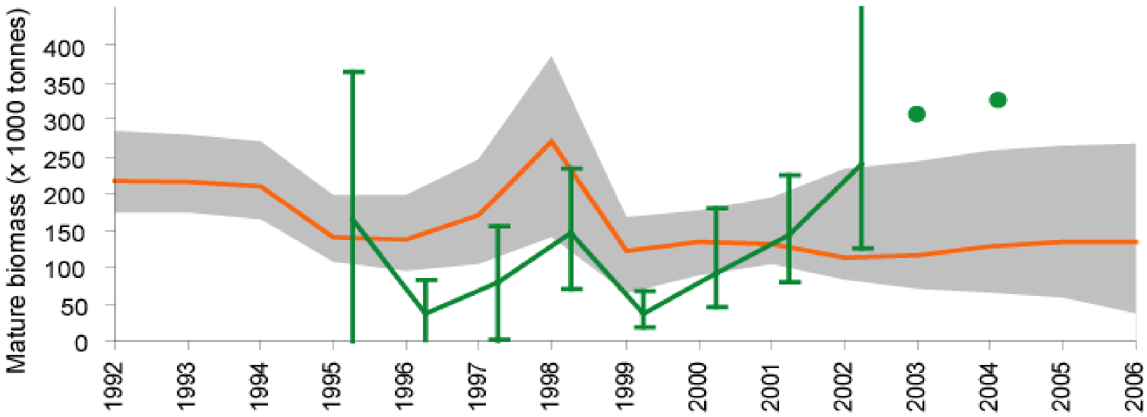

Figure 26. The mature biomass in orange (95% C.I.s in grey) and the DEPM survey estimates (95% C.I.s) in green. Recruitment is estimated from 1992 to 2000 and average levels of recruitment allocated from 2001 to 2003.

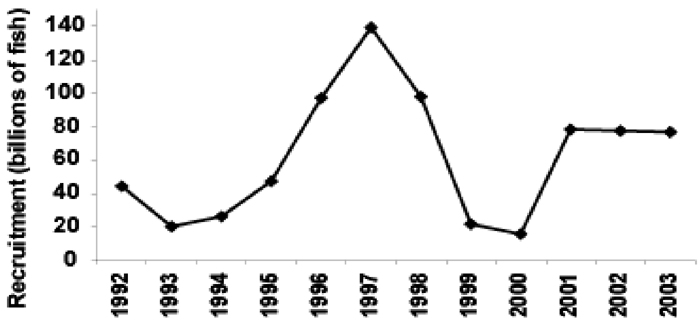

Figure 27. Sardine recruitment estimated by the age-structured model from 1992 to 2000 with high recruitment allocated from 2001 to 2003.

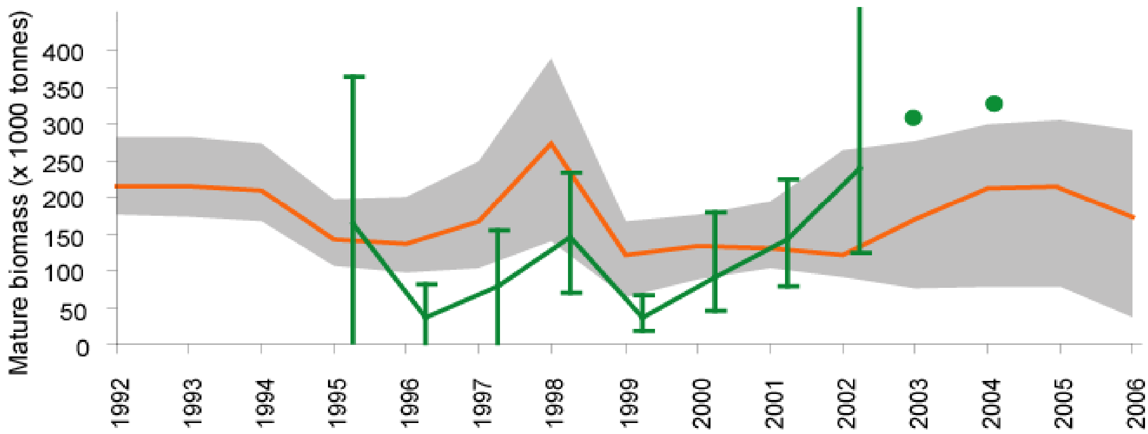

Figure 28. The mature biomass (95% C.I.s in grey) in orange and the DEPM survey estimates (with 95% C.I.s) in green. Recruitment is estimated from 1992 to 2000 and high recruitment allocated from 2001 to 2003.

5. SUMMARY OF ESTIMATES OF SPAWNING BIOMASS BETWEEN 1995 AND 2003

Between 1995 and 2004 the spawning biomass in shelf waters of South Australia has been estimated using the daily egg production method (DEPM). This method relies on the premise that spawning stock 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 the equation:

$$B = \frac{P \cdot A \cdot W}{R \cdot F \cdot S}$$

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

5.1 Sampling Area

Between 1995 and 2004, 2-3 plankton surveys of 10-15 days duration have been conducted annually from the *RV Ngerin* during the spawning season. The number of stations sampled and orientation of transects (lines) has varied between years. In 1995 and 1996, the primary goal was to identify the main spawning areas and transects were orientated north-south. Between 1997 and 2004 transects were orientated northeast-southwest to improve sampling efficiency (Fig. 21, 29 and 30).

In 1995, the sampling area covered approximately 112,000 km^2, but only 97 sites were sampled. In years following, the sampling area generally decreased as our knowledge of the location of the spawning area improved. In 2004 a total of 284 plankton samples were collected along 28 NE-SW facing transects encompassing an area of 93,846 km^2. Figures 29 and 30 show the spatial and temporal patterns of sardine egg distribution and abundance between 1995 and 2004.

5.2. Spawning Area

The estimates of spawning area varied among years and reflected both the size of the sampling area and the status of the biomass (and thus the effects of the two mortality events) (Table 4).

Table 4. Estimates of sardine spawning area in South Australian waters between 1995 and 2004.

Year	**Spawning area (km^2)**
1995	85,000
1996	18,000
1997	33,000
1998	32,000
1999	13,500
2000	31,000
2001	35,000
2002	33,000
2003	32,000
2004	34,000

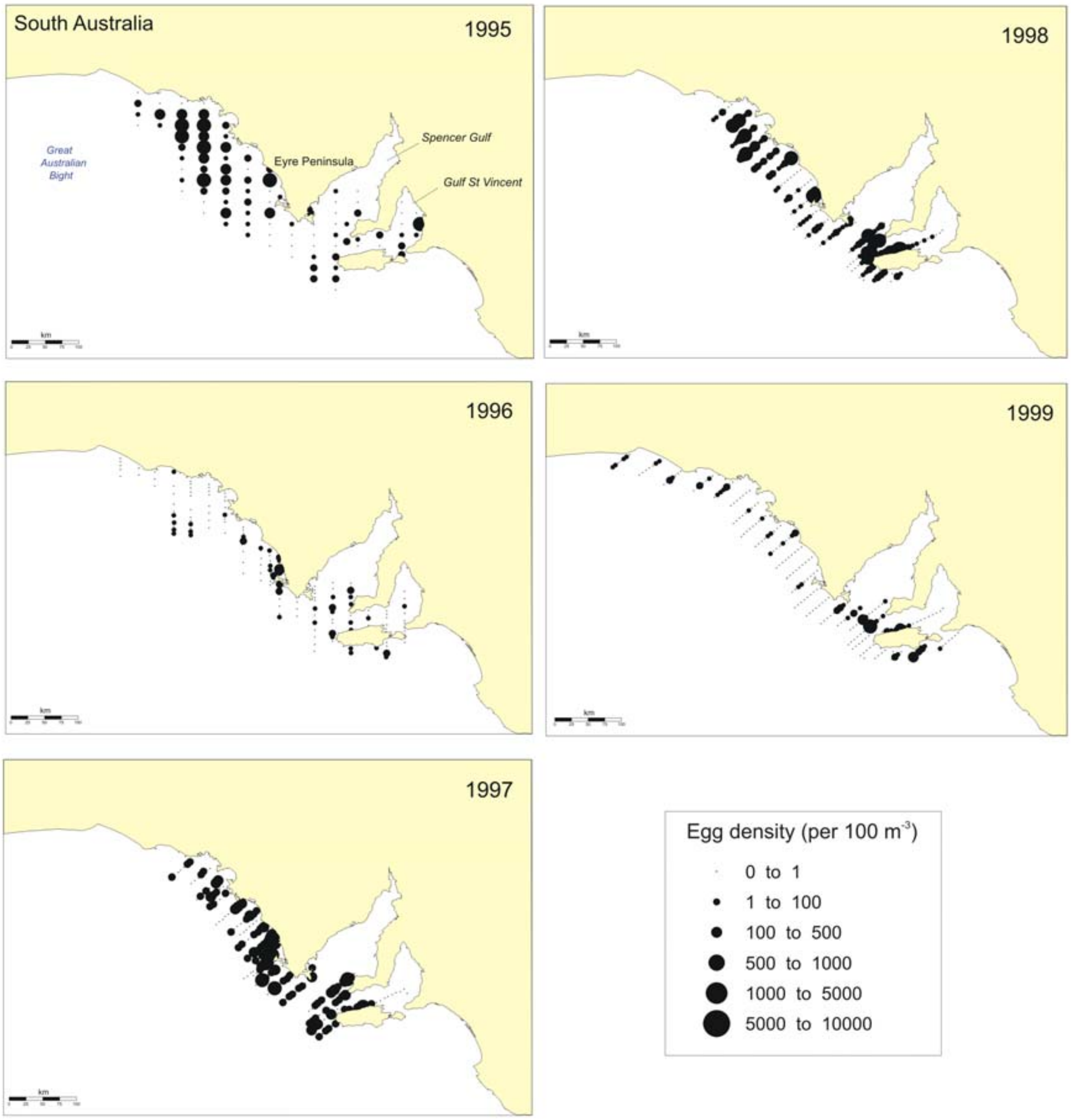

Figure 29. Distribution and abundance of sardine eggs collected during the annual DEPM surveys in South Australian waters between 1995 and 1999.

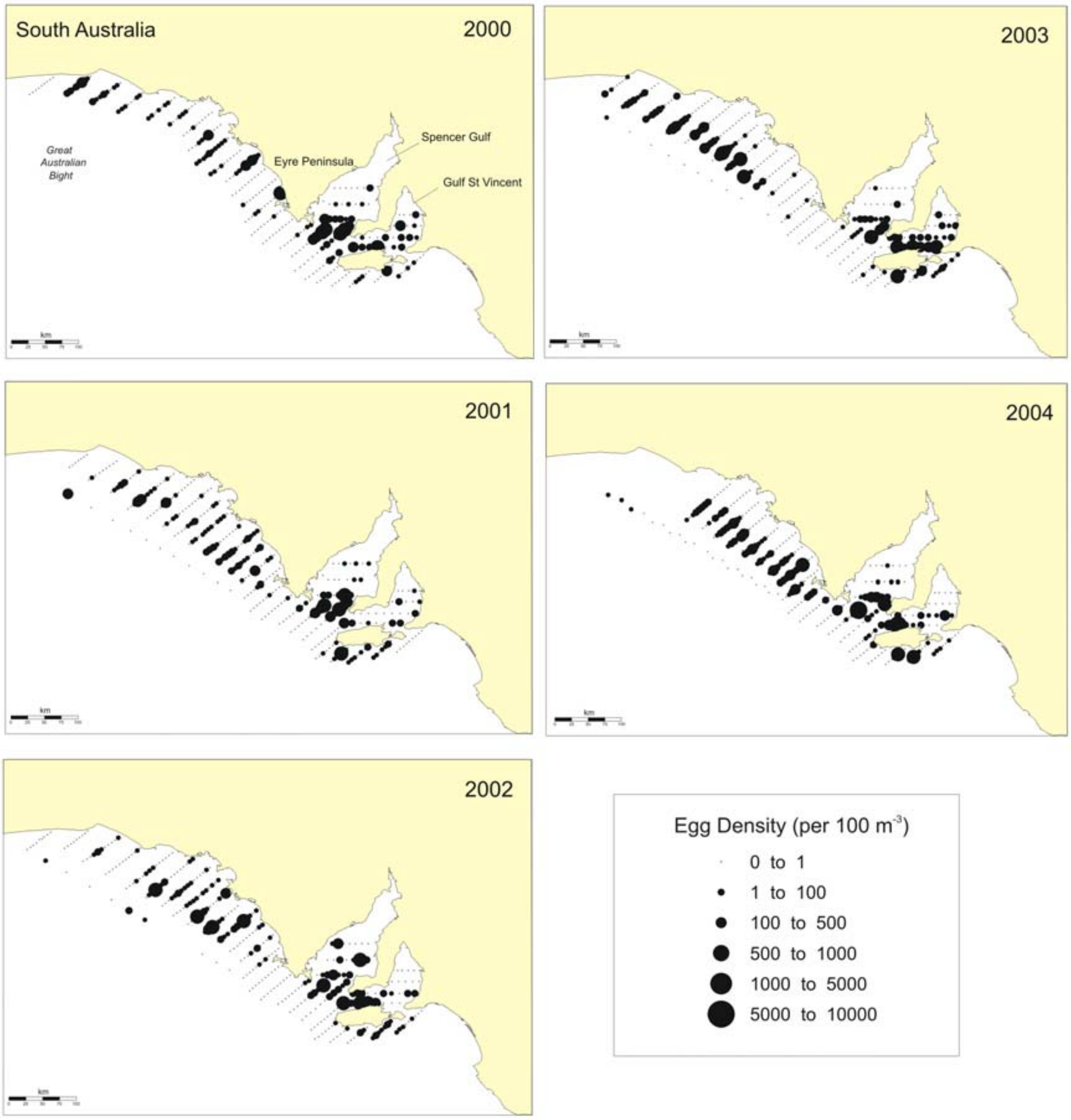

Figure 30. Distribution and abundance of sardine eggs collected during the annual DEPM surveys in South Australian waters between 2000 and 2004.

5.3 Egg Production

Changes in mean egg production provide an indicator of the status of the spawning stock. In 1995, mean egg production was low (~26 eggs per m^{-2}), presumably because the biomass surveys were conducted outside the main spawning season. In contrast, the low egg productions in 1996 and 1997 (~22 and 47 eggs per m^2 respectively) reflect the reduction in the spawning stock size by the first mass mortality event in 1995. In 1998/99 a second mortality event caused egg production to decrease from ~100 eggs per m^{-2} in 1998 to around 54 and 62 eggs per m^{-2} in 1999 and 2000 respectively. Egg production then increased to 138 eggs per m^{-2} in 2002. In the absence of further mortality events egg production increased further to 185 and 197 eggs per m^{-2} in 2003 and 2004 respectively.

5.4 Adult Reproductive Parameters

Between 1998 and 2004, multiple samples of spawning sardine were collected in the eastern Great Australian Bight, southern Spencer Gulf and the Investigator Strait using surface and sub-surface lights and a multi-panelled gillnet. Estimates of adult reproductive parameters including sex ratio, female weight, batch fecundity and spawning fraction are shown in Table 5.

Table 5. Estimates of adult reproductive parameters used to calculate spawning biomass between 1995 and 2004.

Parameter	**95**	**96**	**97**	**98**	**99**	**00**	**01**	**02**	**03**	**04**
Sex Ratio	0.51	0.58	0.54	0.51	0.47	0.48	0.56	0.59	0.44	0.51
Female Wt	42.9	46.30	43.0	45.20	52.28	48.83	51.90	62.40	52.69	56.37
Batch Fecundity	N/A	N/A	13,947	13,615	15,252	13,650	17,359	18,393	10,907	24,796
Spawning Fraction	N/A	0.16	0.16	0.14	0.18	0.16	0.18	0.11	0.11	0.17

5.5 Spawning Biomass

Between 1995 and 1997, the lack of data on adult reproductive parameters impeded estimation of the spawning biomass of sardine in waters of western and central South Australia. Estimates of adult parameters obtained in other studies were used to calculate estimates of spawning biomass in these years (Ward *et al.* 2001b). These estimates suggest that the spawning biomass was approximately 165,000 tonnes in 1995, 37,000 tonnes in 1996 and 59,000 tonnes in 1997 (Fig. 31). The spawning biomass estimate for 1995 based on the first DEPM survey was particularly low, which is likely to be due to under-sampling of the total spawning area.

The estimates of spawning biomass between 1998 and 2004 were based on conservative and robust estimates of egg production, spawning area and sardine reproduction. Analyses of these data suggest that the spawning biomass was approximately 146,000 tonnes (95% C.I. = 70,000 to 234,000) in 1998, but fell to 36,000 tonnes (95% C.I. = 19,000 to 67,000) in 1999, after the second mortality event (Ward *et al.* 2000a, 2001a). The spawning biomass increased to 91,000 tonnes in 2000 and reached approximately 240,600 in 2002. Estimates of spawning biomass increased further to 269,000 tonnes in 2003 and 292,000 tonnes in 2004 (Ward *et al.* 2003a; 2004a).

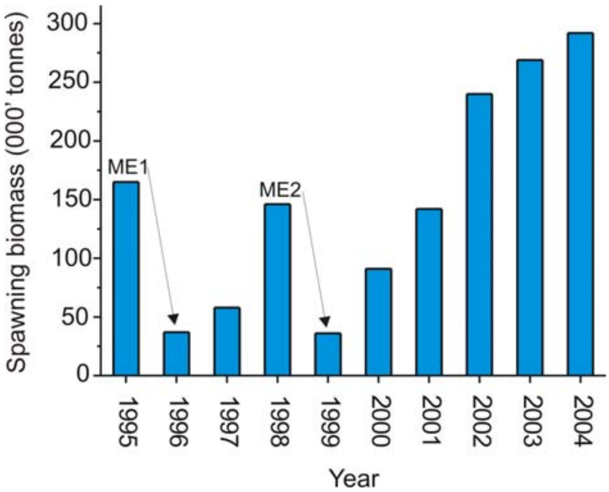

Figure 31. Annual spawning biomass estimates for sardine in South Australian waters between 1995 and 2004 (ME1 = first mass mortality event and ME2 = second mass mortality event).

6. GENERAL DISCUSSION

6.1 Synthesis and Assessment of Scientific Information for the Fishery

Catch, effort and CPUE for the South Australian Sardine Fishery has been monitored using a logbook system since 1991. Reporting was improved significantly in 2001, when the GPS locations of individual catches were included, allowing spatially explicit analysis of the annual patterns of catch and effort. Total catches and effort increased significantly between 2002 and 2003 from 560 days and 13,324 tonnes to 658 days and 24,248 tonnes, in response to increases in spawning biomass estimates in the preceding years and corresponding increases in TACCs. Despite growth in the total catch since 1999, the fishery has concentrated most of its effort near the entrance to Spencer Gulf with effort in Coffin Bay and Investigator Strait varying between years. However, during 2002 and 2003 the fishery expanded further toward Arno Bay, Corny Point and along the northern coast of Kangaroo Island.

Fishery-dependent information is not used for stock assessment of the South Australian Sardine Fishery. CPUE is an inappropriate indicator of relative abundance and an unsuitable performance indicator for the fishery, as it does not account for technological advances, fishing efficiency and changes in the areas fished in response to the movement patterns of fish aggregations. This weakness was evident in 1996 and 1999, when CPUE increased twice despite loss of approximately 70% of the spawning population due to mass mortality events in the preceding years (Ward *et al.* 2001b).

Uncertainty in sardine age estimates is relatively high (APE = 15.6%, CV = 22.1%) compared to other fish species due to the difficulties in interpreting annual zones in otoliths (Campana 2001). This issue has been largely overcome by using age-otolith weight relationships based on a subset of the best otoliths to determine age structures of samples from the commercial catch (Ward *et al.* 2005).

The size and age structures of fishery independent samples showed fish >160 mm and 3-6 years old were dominant in the eastern Great Australian Bight, whereas samples from the commercial catch in Spencer Gulf mostly ranged from 120-160 mm and were 1-4 year old. This suggests these mid-sized fish may move out of southern Spencer Gulf at approximately 4-5 years of age. Age-specific movement has also been documented for sardine off southern Queensland and South Africa where populations undertake conspicuous annual migrations (Hutchings *et al.* 2002; Ward and Staunton Smith 2002).

An age-structured model was recently established to integrate information currently available for the South Australian Sardine Fishery. Application of this model identified significant limitations in the age structure data, which is clearly not representative of the age structure of the South Australian sardine population (Ward *et al.* 2005). Data on interannual variations in recruitment levels were also shown to be unreliable. Outputs from the age structured model were driven almost entirely by DEPM estimates of spawning biomass and the model is not suitable for predicting changes in sardine biomass in the future. Hence, estimates of spawning biomass obtained using the DEPM should continue to be used for management of the fishery, at least until issues surrounding the reliability of age structure and recruitment data can be resolved.

6.2 Status of the South Australian Sardine Resource

Since 1995, the DEPM has been used to obtain annual estimates of the spawning biomass of sardine in South Australian waters. This approach has provided the scientific basis for management of the South Australian Sardine Fishery. This method has proven to be suitable for stock assessment of the fishery (Ward *et al.* 2005), however spawning biomass estimates are considered to be relatively imprecise as large confidence intervals are associated with the estimates (Gaughan *et al.* 2004). This lack of precision is mostly due to the difficulties involved in estimating spawning area and egg production, which have a significant effect on the magnitude of the spawning biomass estimates (Ward *et al.* 2004a). The precision of these parameter estimates could be increased by incorporating a Continuous Underway Egg Sampler into annual DEPM egg surveys (Lo *et al.* 2001; Ward *et al.* 2004a).

The South Australian sardine stock was affected by mass mortality events in 1995 and 1998, which each killed over 70% of the spawning stock. Following these mortalities the spawning stock recovered rapidly, with conservative estimates of spawning biomass increasing from 36,000 in 1999 to 292,000 tonnes in 2004 (Ward *et al.* 2001b). This recovery of the stock may be attributable to the biological characteristics of sardine, including short lifespan, low age at first reproduction high growth rates, extended spawning seasons, high spawning frequencies and high batch fecundities. The recovery may also reflect the occurrence of environmental and/or climatic conditions that were suitable for successful recruitment in the one or several years following each of the mass mortality events.

6.3 Current Management Arrangements

Between 1998 and 2004, DEPM estimates have been used for setting TACCs in the following year. A framework of decision rules, performance indicators and reference points has also been established in the interim management plan for the fishery. The simultaneous rapid recovery of the stock and the development of the South Australian Sardine Fishery following the mortality events, suggests these decision rules have been effective during this critical period. However, a quantitative management strategy evaluation should now be conducted using the age-structured model once the robustness of the input data is improved.

An '*Ecological Assessment of the South Australian Pilchard Fishery*' was completed for the Department of Environment and Heritage during 2004 (Shanks 2004). This report outlines the objectives and strategies that have been established to ensure that the South Australian Sardine Fishery is managed according to the "world's best practice". In reply to this report, the Department of Environment and Heritage identified several issues that should be addressed over the next 3 years. These include the development of performance indicators for bycatch, mitigation of interactions with protected and listed marine species and maintenance of a suitable level of accuracy when reporting these interactions. The development and implementation of these measures and actions will be assisted by a pilot study and independent observer program that will be completed in October 2005.

6.4 Future Research Needs

There have been ongoing concerns communicated by the industry, managers and scientists regarding localised depletion of the sardine stock in southern Spencer Gulf (Ward *et al.* 2001c; 2003c). In response to these concerns, the 2006 DEPM egg survey will include additional plankton tows in this area to improve the resolution of egg distribution and abundance information. In addition, detailed analysis of the spatial patterns of catch and effort will be provided in the 2005 sardine stock assessment report.

Continuous Underway Egg Samplers collect eggs continuously at 3 metres depth, as the research vessel steams along transects between CalVET egg tows. These instruments are used successfully during sardine and anchovy DEPM surveys in California and South Africa. They are relatively inexpensive and have the potential to improve the design of DEPM surveys, save vessel time and increase the precision of estimates of spawning area and egg production (Lo *et al.* 2001). A Continuous Underway Egg Sampler could possibly be used over finer spatial scales for assessing levels of localised depletion.

The absence of indicators of inter-annual variability in the abundance of sardine pre-recruits (large larvae, early juveniles) in South Australian waters has impeded application of the age-structured model. Pre-recruitment surveys are undertaken following annual DEPM surveys in South Africa and California where significant sardine and anchovy fisheries exist (Van Der Lingen and Huggett 2003). Similar long-term surveys would provide useful information on the relationships between the abundance and mortality of pre-recruits and the spawning biomass of adults in subsequent years and the linkages between nursery and fishing areas.

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