

Stock assessment of Australian Sardine (*Sardinops sagax*) off South Australia 2017



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

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SARDI Aquatics Sciences
PO Box 120 Henley Beach SA 5022

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EXECUTIVE SUMMARY

This is the eleventh stock (fishery) assessment report by SARDI Aquatic Sciences on the South Australian Sardine Fishery (SASF).

The SASF was established in 1991 to provide feed for the ranching of Southern Bluefin Tuna (*Thunnus maccoyii*) in southern Spencer Gulf.

The Total Allowable Commercial Catch (TACC) has increased over the last decade from 30,000 t in 2007–09 to 34,000 t in 2010–14 and 38,000 t in 2015–16. The TACC for 2017 is 42,750 t.

The SASF is divided into two zones: Gulfs Zone and Outside Zone. The catch that can be taken from the Gulfs Zone is determined from the mean length of Sardine taken in catches in the previous year. Since 2010, catch from the Gulfs Zone has been capped at 27,000 t or 30,000 t.

Total annual catches over the last decade have increased in line with changes in the TACC, ranging from ~30,000 t in 2007 to ~38,000 t in 2016. Catches from the Outside Zone since 2014 have ranged between approximately 6,500 t and 8,000 t.

Effort has been relatively stable since 2007, ranging from ~760 to 1100 net-sets per year. Mean annual catch-per-unit-effort (CPUE) has risen from ~30 t.net-set⁻¹ in 2007 to over 40 t.net-set⁻¹ in 2015 and 2016.

Prior to 2009, the mean length of Sardine taken from the Gulfs Zone was consistently >142 mm Fork Length (FL), but in 2010–12 and 2014 was <142 mm FL. In 2015 and 2016 it was >142 mm FL. Over the last decade, Sardine from the Outside Zone have been consistently >150 mm FL.

Up to 2009 and after 2013, 3+ year old Sardine usually dominated catches from the Gulfs Zone. During 2010–2012, 2+ year olds were more abundant than 3+ year olds. Recent catches from the Outside Zone have been dominated by 3+, 4+ and 5+ year old Sardines.

Changes in management arrangements and fishing patterns over the history of the fishery have driven changes in the size and age composition of catches. Catch samples are unlikely to be representative of the population; size/age selectivity is likely to have changed over time.

The estimate of spawning biomass for 2017 obtained using the Daily Egg Production Method (DEPM) of 305,000 t (95% CI = 177,000–521,000 t) is the largest obtained for the southern stock of Sardine.

The age structure model (Stock Synthesis) suggests that the spawning stock biomass in 2017 is approximately 236,000 t, which is above the estimated pre-fishing level of 200,000 t in 1992.

The southern stock of Sardine is classified as **Sustainable**, as the spawning biomass for 2017 is above the target reference point of 150,000 t in the harvest strategy for the SASF. The spawning biomass for 2017 is also above the upper reference point of 190,000 t.

Estimates of spawning biomass obtained using both the DEPM and Stock Synthesis are uncertain. This uncertainty is due to the inherent imprecision of the DEPM, limitations of fishery data (e.g. catch-at-age) and assumptions of the stock assessment model.

Ongoing efforts to improve the precision of estimates of key DEPM parameters should continue. The population model should be refined as a multi-area fishery, with varying age-structures and size/age selectivity.

Consideration should also be given to establishing a more precise measure of stock status as the key performance indicator in the harvest strategy for the SASF. In particular, the suitability of establishing the size of the spawning area, which can be measured robustly and is strongly correlated with adult abundance, as the key performance indicator should be evaluated.

Statistic	2017	2016	2015	2014
TACC	42,750 t	38,000 t	38,000 t	34,000 t
DEPM Spawning Biomass	305,000 t	140,000 t		291,000 t
Spawning Area	68,408 km ²	50,105 km ²		71,859 km ²
Model Biomass	236,000 t	160,000 t	182,000 t	217,000 t
Status	Sustainable	Sustainable	Sustainable	Sustainable

Keywords: Daily Egg Production Method, spawning biomass, pelagic fishes, spawning fraction, egg production.

1. INTRODUCTION

1.1. Rationale and Objectives

This is the eleventh stock (fishery) assessment report by SARDI Aquatic Sciences on the South Australian Sardine Fishery (SASF). The objectives of the report are to:

- review scientific literature on the biology, ecology and fisheries for small pelagic species, especially the Australian Sardine, *Sardinops sagax* (Jenyns 1842, Clupeidae), and describe the development and management of the SASF (Chapter 1);
- present catch, effort, catch-per-unit-effort (CPUE) and size composition data for the fishery from 1991 to 2016 (Chapter 2);
- describe the age-composition of the commercial catch and key elements of the reproductive biology of Australian Sardine (Chapter 3);
- provide estimates of spawning biomass obtained using the Daily Egg Production Method (DEPM) during 1995–2016 (Chapter 4);
- use an age-structured stock assessment model to integrate fishery-independent and dependent data (Chapter 5);
- assess the current status of the Sardine stock, discuss management implications and identify future research needs (Chapter 6).

1.2. Biology and assessment of Sardines

1.2.1. Taxonomy

Historically, five species have been recognised in the genus *Sardinops*: *S. ocellatus* off southern Africa; *S. neopilchardus* off southern Australia and New Zealand; *S. sagax* off the west coast of South America; *S. caeruleus* off the west coast of North America; and *S. melanostictus*, around Japan (Whitehead 1985). However, most fisheries scientists now follow the taxonomy for the genus proposed by Parrish *et al.* (1989), who suggested that the genus *Sardinops* is monospecific with no valid sub-species and that the name *Sardinops sagax* (Jenyns 1842) has taxonomic priority. This finding was confirmed by Grant and Leslie (1996). Grant *et al.* (1998) suggested that cluster and parsimony analyses of haplotypic divergences supported the hypothesis that there were three lineages within the genus: southern Africa (*ocellatus*) and Australia (*neopilchardus*); Chile (*sagax*) and California (*caeruleus*); and Japan (*melanostictus*). Polymorphic micro-satellites that have been isolated have the potential to help resolve some of the minor taxonomic questions that remain for this species (Pereyra *et al.* 2004).

The common and scientific names of the Australian Sardine or Pilchard have been debated for many years. The names pilchard and *Sardinops neopilchardus* (Steindachner 1879) were used in many Australian publications prior to 2000. However, the terms Australian Sardine and *Sardinops sagax* (Jenyns 1842) have been listed in the Standard Fish Names List for Australia since May 2006. *Sardinops sagax* is also the name used in the Australian Faunal Directory and Eschmeyer's Catalogue of Fishes. In this report we use the term Sardine to refer to *S. sagax* in Australia and elsewhere.

1.2.2. Distribution

Sardine occur in cool temperate to sub-tropical waters of the Northern and Southern Hemispheres where, along with different local species of anchovy (*Engraulis* spp.), they commonly dominate the fish biomass in upwelling regions. Sardine support important fisheries in the eastern boundary current systems off the west coasts of northern and southern Africa and North and South America. These globally important upwelling regions are known as the Canary, Benguela, California and Humbolt current systems, respectively. The Sardine is also found in the rich coastal waters surrounding Japan, and the generally less productive waters off southern Australia and around New Zealand.

In Australia, Sardine are found throughout temperate and sub-tropical waters between Rockhampton (Queensland) and Shark Bay (Western Australia), including northern Tasmania (Gomon *et al.* 1994). Waters off South Australia are the centre of the Sardine's Australian distribution and support the largest component of the Australian population (Ward *et al.* 2006). Shelf waters off South Australia also include Australia's largest upwelling system, the Flinders Current system (Middleton and Cirano 2002). Sardine is the dominant clupeoid off South Australia, occurring in the southern portions of Gulf St Vincent and Spencer Gulf and over the continental shelf (Ward *et al.* 2001a, 2001b). As in other upwelling systems worldwide, one species of engraulid, the Australian anchovy (*Engraulis australis*) is also abundant off South Australia (Dimmlich *et al.* 2009). When Sardine biomass is high, the Australian anchovy occurs mainly in the northern gulfs, but when Sardine biomass is low this species has the capacity to increase in abundance and expand its distribution into shelf waters (Ward *et al.* 2001a, Dimmlich *et al.* 2004, Dimmlich and Ward 2006).

1.2.3. Movement patterns and stock structure

Sardine are known to undergo extensive migrations. For example, off Africa, Sardine migrate along the coast to access conditions that are favourable for spawning and the survival of recruits

(van der Lingen and Huggett 2003). Similarly, it has been hypothesised that schools of Sardine migrate into waters off northern New South Wales and southern Queensland during winter-spring to spawn (Ward and Staunton-Smith 2002). The movement patterns of Sardine in waters of South Australia are largely unknown although there is evidence of an ontogenetic shift in distribution with larger, older fish most commonly found in shelf waters and smaller, younger fish mainly found in embayments including Spencer Gulf (Rogers and Ward 2007).

Fishing effort in the SASF is concentrated in southern Spencer Gulf but a substantial proportion of the spawning biomass is located in the Great Australian Bight; hence, understanding the rate of movement between shelf and gulf waters has been identified as a high priority for the fishery. A collaborative project funded by the Fisheries Research and Development Corporation (FRDC) (Izzo *et al.* 2012) provided some evidence of separation between the southern Australian and east coast populations using otolith shape and elemental composition. This study suggested inter-annual variations in the population sub-structuring off South Australia (Izzo *et al.* 2012), possibly driven by environmental factors. This finding led to the establishment of spatial management rules in the harvest strategy established for the SASF in 2014.

The existence of separate eastern and western stocks has been proposed for species, including Sardine, that are targeted in the Commonwealth Small Pelagic Fishery (Bulman *et al.* 2008), with Bass Strait suggested as a significant barrier to genetic flow. The possibility of a stock division for small pelagic species, such as Sardine, off southern Australia (between western Tasmania and southern west coast of Western Australia) was also proposed by Bulman *et al.* (2008), but the level of separation was considered less distinct than for the east coast because of the lack of a clearly defined barrier to movement (like Bass Strait). Several studies suggest that there are distinct breeding stocks off the west and south coasts of Western Australia (Edmonds and Fletcher 1997, Gaughan *et al.* 2001, 2002). Recently, Izzo *et al.* (2017) confirmed that the Australian Sardine is a meta-population by using a Stock Differentiation Index (SDI) that integrated genetic, morphological, otolith reproductive and fishery data from a 60-year period. This meta-population comprises four stocks: i.e. the Eastern Australian; Southern Australian (western Victoria and South Australia); Western Australian South Coast; and Western Australian West Coast stocks (Izzo *et al.* 2017).

1.2.4. Schooling behaviour

The schooling behaviour of Sardine is complex and varies at both 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. Similarly, in some parts of the California Current system (e.g. Oregon, USA), schools of Sardine have also been observed displaying patterns consistent with anti-predator behaviour, dispersing at night, reforming rapidly at sunrise and remaining in schools throughout the day (Kaltenberg and Benoit-Bird 2009). However, at other locations in the California Current system (e.g. Monterey Bay, USA) transitions between day and night behaviour occur more gradually (Kaltenberg and Benoit-Bird 2009). Factors such as habitat heterogeneity, food availability, predation levels and vessel noise can influence schooling behaviour (Freon *et al.* 1993, Giannoulaki *et al.* 2003). Schooling behaviour of Sardine in Australian waters varies within and among locations, days, months and years and complicates the application of acoustic techniques for stock assessment. There is evidence that spawning also influences schooling behaviour, with spawning females under-represented in commercial catches (Ward *et al.* 2011b).

1.2.5. Food and feeding

Sardine have two feeding modes: filter-feeding on micro-zooplankton and phytoplankton and particulate-feeding on macro-zooplankton. Sardine switch between these two modes depending on relative prey density (van der Lingen 1994, 2002; Louw *et al.* 1998). Sardine tend to feed on smaller zooplankton than anchovies (e.g. Espinoza *et al.* 2009). The prey composition of Sardine varies among regions. For example, in the northern Humboldt Current system, Sardine tend to feed on larger prey and consume more euphausiids than in the northern Canary and southern Benguela systems.

In South Australian waters, Sardine have been found to consume at least 12 prey taxa with krill (29.6% biomass) and unidentified crustacea (22.2% biomass) contributing the highest biomass (Daly 2007). However, krill occurred in greater numbers (65.3%) in the diet than other crustaceans (27.0 %). Crab zoea, other decapods, copepods, polychaetes, fish eggs and larvae and gelatinous zooplankton were also present in the diet of Sardine in waters off South Australia (Daly 2007).

1.2.6. Reproduction

Sardine are serial spawners with asynchronous oocyte development and indeterminate fecundity. Serial or batch spawning fishes release numerous batches of pelagic eggs throughout an extended spawning season. The number of eggs in a batch, or batch fecundity, is correlated with female size and varies among locations and years (Lasker 1985).

In Australia, Sardine usually spawn in open waters between the coast and shelf break (Blackburn 1950, Fletcher and Tregonning 1992, Fletcher *et al.* 1994). In most locations there is one

spawning season per year, but off Albany in Western Australia there are two (Fletcher 1990). The size and age at which Sardine reach sexual maturity vary between locations, and range from 100 to 180 mm Fork Length (FL), and 1.8 to 2.8 years, respectively (Blackburn 1950, Joseph 1981, Stevens *et al.* 1984, Fletcher 1990, Butler *et al.* 1996).

The reproductive biology of Sardine in South Australian waters is relatively well known. Ward and Staunton-Smith (2002) found approximately 50% of males and females reach sexual maturity (L_{50}) at 146 and 150 mm, respectively. Spawning occurs during the summer-autumn upwelling period of January-April (Ward *et al.* 2001a, 2001b, 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 shelf waters (Ward *et al.* 2006).

1.2.7. Early life history and recruitment

Sardine have a relatively long larval phase: eggs hatch approximately two days after fertilisation and larvae metamorphose at 1–2 months of age (Neira *et al.* 1998). Survival rates of Sardine eggs and larvae strongly affect recruitment success (Lo *et al.* 2005). The large variations in abundance that characterise Sardine populations worldwide have been attributed to fluctuations in recruitment, which can be influenced by environmental factors, regime shifts and over-fishing (e.g. Galindo-Cortes *et al.* 2010). Larval survival is a key determinant of recruitment success, but the factors affecting survivorship may vary spatially and temporally. The effects of food availability on larval survival have been discussed at length (Lasker 1975), but there has been less consideration of the effects of egg and larval predation on recruitment success (e.g. Agostini *et al.* 2007).

In the Californian Current system, recruitment success and large population sizes have coincided with warm periods characterised by reduced primary productivity; during this time the centre of spawning shifts northward (e.g. Lluch-Belda *et al.* 1992). Surprisingly, a recent study linked high zooplankton abundance to poor recruitment of Sardine, suggesting that lower predation pressure on eggs and larvae may be a key factor contributing to strong recruitment in the Californian Current system (Agostini *et al.* 2007). Similarly, a reduction in zooplankton abundance was followed by an increase in Sardine recruitment in Peru (Carrasco and Lozano 1989) and the Sardine population off South Africa collapsed when zooplankton abundance increased (Verheye 2000).

In South Australia, Sardine larvae are highly abundant at temperature and salinity fronts that form near the mouths of the two gulfs during summer and autumn (Bruce and Short 1990) and in mid-

shelf waters off the Eyre Peninsula (e.g. Ward et al. 2014). Spawning coincides with the summer-autumn upwelling period in South Australia (Ward et al. 2006). It is predicted that the intensity and duration of upwelling events could increase under future climate change scenarios (Hobday et al. 2009). The effects of such changes on the future recruitment success of Sardine in South Australia are poorly understood.

1.2.8. Age, growth and size

Age determination studies of Sardine have involved counting growth increments in scales (Blackburn 1950) and sagittal otoliths (ear bones) (Butler et al. 1996, Fletcher and Blight 1996), and modelling the formation of marginal increments in otoliths (Kerstan 2000). Daily deposition of growth increments in the otoliths of larvae and juveniles has been validated in laboratory trials (Hayashi et al. 1989). Age validation studies involving the capture and maintenance of Sardine and other clupeoids have proven to be problematic owing to logistical difficulties (Fletcher 1995) and sensitivity to handling (Rogers et al. 2003). Other methodological approaches have been used to show that translucent zones form annually in the sagittae of 1+ year old Sardine off South Africa (Waldron 1998), $\leq 2+$ year olds off North America (Barnes et al. 1992) and $\geq 4+$ year olds off Western Australia (Fletcher and Blight 1996). Despite this theoretical basis for using increment-based age-determination methods, the application of these standard approaches has proven to be problematic in Western Australia, South Australia and California due to difficulties associated with interpreting and counting opaque and translucent zones (Butler et al. 1996, Fletcher and Blight 1996, Rogers and Ward 2007).

Studies of growth dynamics of Sardine in the Benguela and California Current systems suggest that growth rates of larvae (up to $0.85 \text{ mm}\cdot\text{day}^{-1}$) and juveniles ($0.48\text{--}0.63 \text{ mm}\cdot\text{day}^{-1}$) are high (Butler et al. 1996, Quinonez-Velazquez et al. 2000). In South Africa, Sardine were found to reach larger asymptotic sizes ($L_{\infty} = 221 \text{ mm}$) and have lower growth constants ($k = 1.09 \text{ year}^{-1}$) than those off southern California ($L_{\infty} = 205 \text{ mm}$, $k = 1.19 \text{ year}^{-1}$, Thomas 1984, Butler et al. 1996). Parameter estimates for Sardine in Western Australia (Fletcher and Blight 1996) suggest that growth in this area is slower and that fish reach smaller asymptotic sizes than those in the more productive eastern boundary current systems.

A detailed study by Rogers and Ward (2007) showed that the growth rates of Sardine are higher in South Australian waters than off other parts of the Australian coastline, but lower than those in more productive boundary current ecosystems (Ward et al. 2006). 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 implications for the use of age structured models (based on fishery samples) for stock assessment of the SASF (see Chapter 5).

1.2.9. Mass mortality events

Mass mortality events in 1995 and 1998/99, spread throughout the entire Australian range of Sardine and are thought to have killed more fish over a larger area than any other single-species fish-kill recorded (Jones *et al.* 1997). Characteristics of the 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 Sardine were naïve (Jones *et al.* 1997, Gaughan *et al.* 2000, Whittington *et al.* 2008).

Each event was estimated to have killed over 70% of the spawning biomass in South Australian waters (Ward *et al.* 2001b). Recovery of the South Australian population following these events has been monitored using the DEPM (Lasker 1985, Ward *et al.* 2001c). Assessment of the impacts of the mortality events on the age structure of the South Australian population of Sardine 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 (Ward *et al.* 2005).

1.2.10. Role in the ecosystem

Small pelagic fishes such as Sardine 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. Sardine are an important food source for many predatory fishes (Hoedt and Dimmlich 1995, Alheit and Niquen 2004, Ward *et al.* 2006), squid (O'Sullivan and Cullen 1983), seabirds (Montevecchi and Myers 1995, Dann *et al.* 2000, Crawford 2003) and marine mammals (Ohizumi *et al.* 2000, Page *et al.* 2005). Populations of predators fluctuate in response to changes in productivity in the regions where they feed. Therefore, aspects of the reproductive and feeding ecology of predators have been used to monitor the health of marine ecosystems, assess changes in environmental conditions, and monitor effectiveness of fishery management regimes (Rindorf *et al.* 2000, Boyd *et al.* 2006). A study assessing the importance of Sardine in the diet of marine predators in waters of the eastern Great Australia Bight (Goldsworthy *et al.* 2011) found no evidence of ecological impacts from the SASF.

The effect of the Sardine mortality events on marine predators provides evidence of the important role in the pelagic ecosystems off southern Australia. In Victoria, negative impacts of the Sardine mortality events on apex predators were documented for little penguins (*Eudyptula minor*) and little terns (*Sterna albifrons*) in 1995/1996 (Dann *et al.* 2000), and Australasian gannets (*Morus*

serrator) in 1998/1999 (Bunce and Norman 2000, Bunce et al. 2005). In South Australia, McLeay et al. (2008) investigated the diet, age structure, and morphology of a population of crested tern (*Sterna bergii*) to determine whether survival and growth were reduced for cohorts reared in years immediately following Sardine mortality events. Age-specific information collected from banded adults indicated that the cohort reared after the first Sardine mortality event in 1995 exhibited significantly lower rates of recruitment than predicted by life-table analyses. This suggested that survival was reduced in response to the absence of Sardine. Females from cohorts reared one year after the end of each Sardine mortality event (in 1996 and 1999) were smaller than other age classes, suggesting that chick growth was reduced during periods of low Sardine abundance.

1.2.11. Biomass estimates

Daily Egg Production Method

The Daily Egg Production Method (DEPM, Parker 1980, Lasker 1985) has been used to estimate the spawning biomass of Sardine in South Australia since 1995. The DEPM was originally developed for direct stock assessment of the northern anchovy, *Engraulis mordax*, off the west coast of North America (Parker 1980). The method relies on the premise that the biomass of spawning adults can be calculated by dividing the mean number of pelagic eggs produced per day throughout the spawning area, i.e. total daily egg production, by the mean number of eggs produced per unit mass of adult fish, i.e. mean daily fecundity (Lasker 1985).

The DEPM can be applied to fishes that spawn multiple batches of pelagic eggs over an extended spawning season (e.g. Parker 1980). Data used to estimate DEPM parameters are typically obtained during fishery-independent surveys. The key assumptions of the method are that: 1) surveys are conducted during the main (preferably peak) spawning season; 2) the entire spawning area is sampled; 3) eggs are sampled without loss and identified without error; 4) levels of egg production and mortality are consistent across the spawning area; and 5) representative samples of spawning adults are collected during the survey period (Parker 1980, Alheit 1993, Hunter and Lo 1997, Stratoudakis et al. 2006). The method does not account for non-spawning adults that are distributed outside the spawning area (see Hill et al. 2017).

The DEPM has been used for stock assessment of more than 15 species of small pelagic fishes, mostly clupeoids (e.g. Stratoudakis et al. 2006). Although the method is used widely, a range of problems have been encountered and estimates of spawning biomass are generally considered to be accurate (unbiased) but relatively imprecise (e.g. Alheit 1993, Hunter and Lo 1997, Stratoudakis et al. 2006). The imprecision that characterises the DEPM is mainly due to

uncertainties associated with the estimation of mean daily egg production (P_0) and spawning fraction (A) (Fletcher et al. 1996, McGarvey and Kinloch 2001, Gaughan et al. 2004, Stratoudakis et al. 2006). Difficulties associated with estimating mean daily egg production primarily relate to statistical problems associated with fitting regression models to over dispersed egg density data. Difficulties associated with obtaining representative adult samples to estimate spawning fraction (S) have also impeded many applications (see Stratoudakis et al. 2006).

At least two reviews (Alheit 1993, Stratoudakis et al. 2006) have concluded that the DEPM is better tailored to species with high spawning fractions (>50%), such as anchovies (*Engraulis* spp.), than species such as Sardine that have low spawning fractions (e.g. 10%). This is because spawning biomass is inversely proportional to spawning fraction, i.e. low estimates of spawning fraction produce high estimates of spawning biomass (e.g. Alheit 1993, Stratoudakis et al. 2006). As a result, relatively small variations in estimates of low spawning fractions (5–15%) have strong effects on spawning biomass (i.e. 300%) whereas comparable variations for species with high spawning fractions (45–60%) have relatively less impact (i.e. 25%).

It is widely recognised that the DEPM parameter most strongly correlated with estimates of spawning biomass is spawning area (e.g. Gaughan et al. 2004). In situations, when P_0 and/or S cannot be estimated reliably, spawning area can be used as an indicator of spawning biomass and is less prone bias/uncertainty than P_0 and/or S (e.g. Gaughan et al. 2004, Ward et al. 2014). Accounting for non-spawning adults occurring outside the spawning area is a major challenge to application of the method in some locations, especially north-south coastlines with strong latitudinal temperature gradients (Ward et al. 2015, Hill et al. 2017). However, extending adult sampling beyond the spawning area has been identified as a way to quantify the proportion of the biomass not undertaking spawning during the survey (Ward et al. 2015).

Acoustic Techniques

Acoustic techniques have been widely used for the stock assessment of small pelagic fishes (Beckley and van der Lingen 1999, van der Lingen and Huggett 2003), and have also contributed significantly to understanding Sardine movement (Barange et al. 1999), stock structure (Barange and Hampton 1997), relationships with oceanographic features (Tameishi et al. 1996, Lynn 2003), predator-prey interactions and inter-annual variability in abundance (Barange et al. 1999). Sources of error in acoustic estimation of biomass include: variations in target strength due to spatial or temporal differences in fish behaviour (Freon et al. 1993), difficulties associated with discrimination of species and size classes, and spatial sampling error. An acoustic survey supported by mid-water trawling (conducted over 80 days) has replaced the DEPM as primary

source of fishery-independent information about coastal pelagic species, including Pacific sardine (*Sardinops sagax*) off the west coast of the USA (Hill et al. 2017). Acoustic surveys require relatively large vessels with sophisticated electronic equipment and capacity to tow large mid-water trawl nets at approximately seven knots.

1.2.12. Management procedures in small pelagic fisheries

Modern fisheries management aims to constrain exploitation rates within ecologically sustainable limits while maximising potential yields. This is done by establishing harvest strategies with performance indicators and reference points (Gabriel and Mace 1999). Harvest strategies that include agreed operational targets and decision rules have been successfully incorporated into the management systems of several commercial small pelagic fisheries, including the South African Pelagic Fishery, Western Australian Pilchard Fishery, Pacific Sardine Fishery and SASF (Cochrane et al. 1998, De Oliveira et al. 1998, Cochrane 1999, Gaughan et al. 2004, Hill et al. 2005).

Smith et al. (2015) suggested that target and limit reference points for spawning biomass of small pelagic species in Australian waters, including Sardine, of 50% (B_{50}) and 20% (B_{20}) of the unfished level, respectively, are “safe from an ecosystem perspective and provide reasonable levels of yield”. Smith et al. (2015) also suggest that exploitation rates below 33% are likely to maintain the median spawning biomass of Sardine above B_{50} and the chance of falling below B_{20} at less than 10%. Cury et al. (2011) suggest a maximum rate of approximately one-third of the maximum observed prey abundance could be applied as a principal in low trophic level fisheries. Smith et al. (2011) showed that broader ecosystem impacts from fishing low trophic level species could be reduced by halving exploitation rates from typical maximum sustainable yield levels (i.e. ~60%).

1.3. The South Australian Sardine Fishery

The SASF is managed by the *Fisheries Management (Marine Scalefish Fisheries) Regulations 2006* and *Fisheries Management Act 2007*. Management goals for the SASF are consistent with the objectives of the *Fisheries Management Act 2007* and are outlined in the current Management Plan (PIRSA 2014). 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. There are 14 license holders with several companies operating multiple licenses. The costs of the policy, compliance and research programs that are needed to manage the SASF are recovered through license fees collected by PIRSA Fisheries and Aquaculture.

The Total Allowable Commercial Catch (TACC) was set at 1,000 t in 1992 (calendar year) , and increased to 3,500 t during 1993–1997 (Figure 1–1). In 1998, the TACC was set at 12,500 t, but this was reduced to 3,500 t and 3,800 t in 1999 and 2000, respectively, after the mass mortality event in late 1998. The stock recovered rapidly and the TACC increased to 51,100 t in 2005 and was reduced to 25,500 t in 2006. From 2007 to 2009, the TACC was set at 30,000 t. During 2010 to 2014, the TACC was set at 34,000 t (PIRSA 2014). In 2015 and 2016, the TACC was 38,000 t. The TACC for 2017 is 42,750 t.

From 2010, onwards, there has been a cap on the catch taken from Spencer Gulf (Figure 1–1, Figure 1–2). The SASF is now divided into two zones: Gulfs Zone and Outside Zone (Figure 1–2). The TACC for 2017 is 42,750 t, including up to 30,000 t from the Gulfs Zone and 12,750 t from the Outside Zone (Figure 1–1).

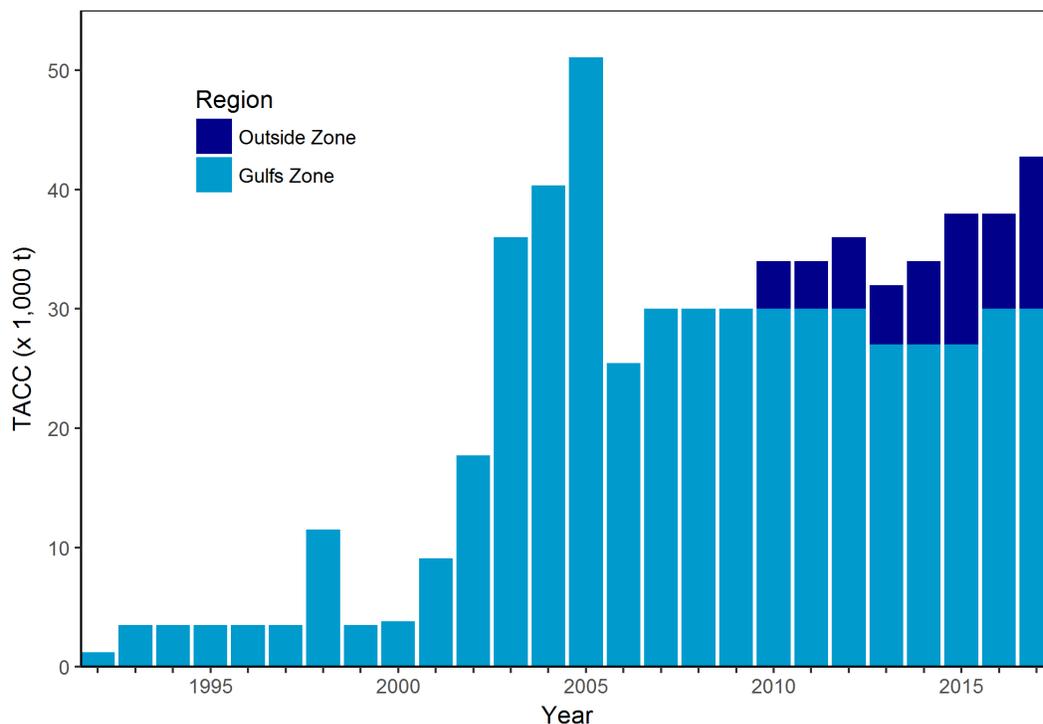


Figure 1–1. Total Allowable Commercial Catch (TACC) for the South Australian Sardine Fishery (SASF) between 1992 and 2017 for Gulfs Zone and Outside Zone (see Figure 1–2).

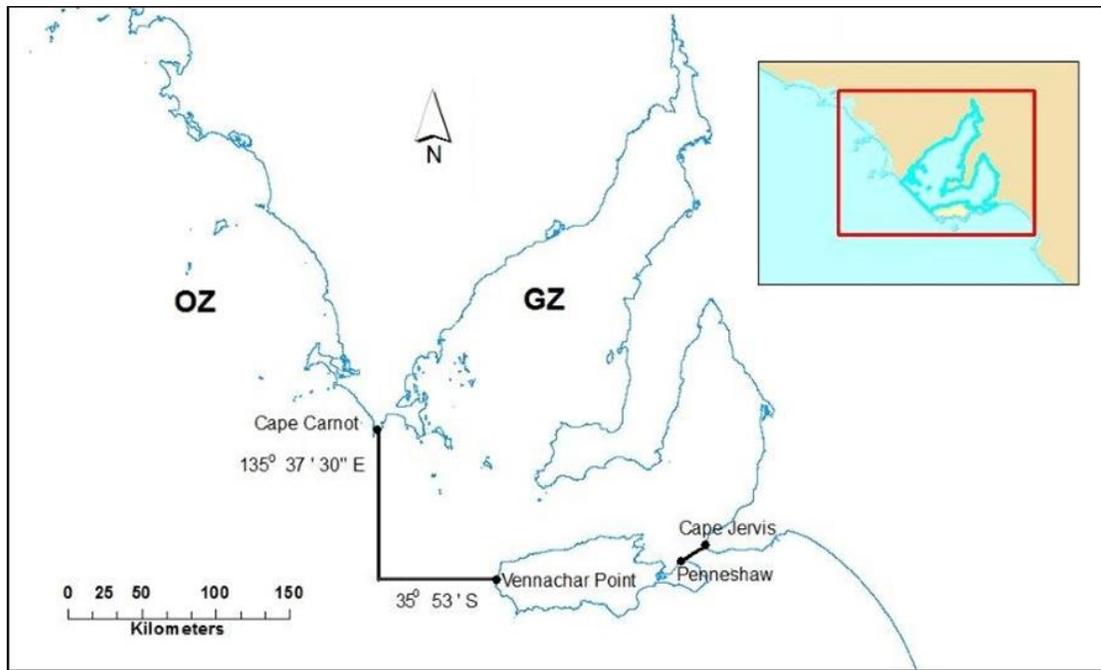


Figure 1–2. The two spatial management zones defined in the harvest strategy for the SASF. Abbreviations: OZ, Outside Zone; GZ, Gulfs Zone (source PIRSA 2014).

1.4. Harvest Strategy

Since 1998, the key biological performance indicator for the SASF has been the estimate of spawning biomass obtained using the DEPM. From 1997 to 2006, the 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). From 2007 to 2009, the indicative TACC was set at 30,000 t (PIRSA 2007), while the estimate of spawning biomass obtained using the DEPM remained between 150,000 and 300,000 t.

In 2014, a tiered Harvest Strategy (Figure 1–3) was established that sets the TACC based on the size of the spawning biomass and level of monitoring and assessment (Table 1–1). At Tier 3, DEPM and fishery assessments are done in alternate years and the maximum TACC is 38,000 t. At Tier 1, DEPM and fishery assessments are both undertaken annually and the maximum TACC is 47,500 t. At Tier 2, either DEPMs or assessments are done annually (with the other done biennially) and the maximum TACC is 42,750 t. Lower TACCs are set at each Tier if the spawning biomass is below 190,000 t. The SASF was managed at Tier 1 up to 2016 and at Tier 2 in 2017.

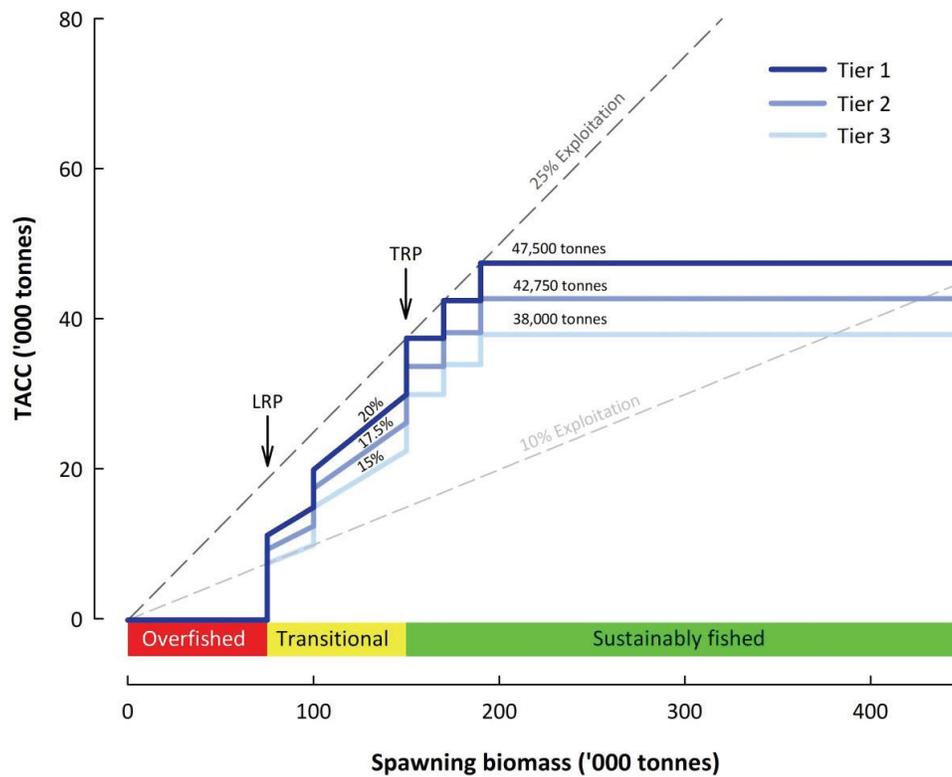


Figure 1–3. The relationship between spawning biomass, stock status and level of exploitation (or TACC) of the Sardine harvest strategy for each tier (LRP = limit reference point; TRP = target reference point).

Table 1–1. Decision making rules for the tiered Harvest Strategy.

Spawning Biomass			Tier 1		Tier 2		Tier 3	
			TACC (t)	Maximum Exploitation	TACC (t)	Maximum Exploitation	TACC (t)	Maximum Exploitation
190000 t <	SpB		47,500 t	25%	42,750 t	22.5%	38,000 t	20%
170000 t <	SpB	≤ 190000 t	42,500 t	25%	38,250 t	22.5%	34,000 t	20%
150000 t <	SpB	≤ 170000 t	37,500 t	25%	33,750 t	22.5%	30,000 t	20%
100000 t <	SpB	≤ 150000 t	20% of SpB	20%	17.5% of SpB	17.5%	15% of SpB	15%
75,000 t <	SpB	≤ 100000 t	15% of SpB	15%	12.5% of SpB	12.5%	10% of SpB	10%
	SpB	≤ 75000 t	Closed	0%	Closed	0%	Closed	0%

Spatial management was established in the SASF in 2010 and formalised in 2014 (Figure 1–2). The catch that can be taken from the Gulfs Zone is determined from the mean size (Fork Length, FL) of Sardine taken in catches from Gulfs Zone in the previous year (Table 1–2; Figure 1–2). If the mean size is above 142 mm FL, up to 30,000 t can be taken from Spencer Gulf whereas if it is below 135 mm FL, the maximum catch from Spencer Gulf is 24,000 t. If the mean size is between 135 and 142 mm, the maximum catch from Spencer Gulf is 27,000 t.

Table 1–2. Catch allocation decision table for the harvest strategy for the SASF to guide the maximum TACC allowed from the Gulfs Zone (GZ) (PIRSA 2014).

Mean size of Sardines (MSS, mm Fork Length) in GZ	Maximum catch limits for GZ
142 mm < MSS	30,000 t
135 mm < MSS ≤ 142 mm	27,000 t
MSS ≤ 135 mm	24,000 t

1.5. Stock Status Classification

A national stock status classification system has been developed to assess key Australian fish stocks (Table 1-3; Flood *et al.* 2014). The classification system combines information on current stock size and the level of fishing pressure to assess 'stock status' (Flood *et al.* 2014). Each stock is classified as: 'sustainable', 'transitional-recovering', 'transitional-depleting', 'overfished', 'environmentally limited', or 'undefined' as outlined in Table 1–3.

As outlined in Section 1.2.3 of the current report, for the purposes of fisheries management the Australian Sardine population is considered to be comprised of four separate stocks (Whittington *et al.* 2008, Izzo *et al.* 2012, Izzo *et al.* 2017). The SASF targets the Southern Australian stock, which occurs off South Australia and western Victoria (Izzo *et al.* 2012). The Southern Australian stock was assessed as being sustainable in the most recent Status of Key Australian Fish Stocks (Flood *et al.* 2014).

Table 1–3. Stock status terminology (Flood *et al.* 2014).

	Stock Status	Description	Potential implications for management of the stock
	Sustainable	Stock for which biomass (or biomass proxy) is at a level sufficient to ensure that, on average, future levels of recruitment are adequate (i.e. not recruitment overfished) and for which fishing pressure is adequately controlled to avoid the stock becoming recruitment overfished	Appropriate management is in place
↑	Transitional-recovering	Recovering stock—biomass is recruitment overfished, but management measures are in place to promote stock recovery, and recovery is occurring	Appropriate management is in place, and the stock biomass is recovering
↓	Transitional-depleting	Deteriorating stock—biomass is not yet recruitment overfished, but fishing pressure is too high and moving the stock in the direction of becoming recruitment overfished	Management is needed to reduce fishing pressure and ensure that the biomass does not deplete to an overfished state
	Overfished	Spawning stock biomass has been reduced through catch, so that average recruitment levels are significantly reduced (i.e. recruitment overfished). Current management is not adequate to recover the stock; or adequate management measures have been put in place but have not yet resulted in measurable improvements	Management is needed to recover this stock; if adequate management measures are already in place, more time may be required for them to take effect
	Environmentally limited	Spawning stock biomass has been reduced to the point where average recruitment levels are significantly reduced, primarily as a result of substantial environmental changes / impacts or disease outbreaks (i.e. the stock is not recruitment overfished). Fisheries management has responded appropriately to the environmental change in productivity	Appropriate management is in place
	Undefined	Not enough information exists to determine stock status	Data required to assess stock status are needed

2. FISHERY INFORMATION

2.1. Introduction

This chapter presents catch, effort, size composition data and catch-per-unit-effort (CPUE) for the SASF from 1 January 1991 to 31 December 2016. This information is used to describe the main spatial and temporal patterns in the fishery and forms the key inputs to the stock assessment model (Chapter 5).

2.2. Methods

2.2.1. Data Collection

Catch and effort data were collated from commercial fishing logbooks. Prior to 2001, catch and effort were reported according to the pre-existing South Australian Marine Fishing Areas (MFAs). Following the implementation of SASF logbooks in 1998, catch and effort were reported by latitude and longitude. Estimated catches (presented in monthly and annual time steps in these results) are aggregates of daily catches recorded in logbooks. CPUE estimates are based on these aggregated catches and corresponding effort data. Actual total annual catches were estimated from the Catch Disposal Records (CDRs) collated from landings by PIRSA Fisheries and Aquaculture.

2.2.2. Commercial catch sampling

Between 1995 and 2016, samples of the commercial catch were collected from vessels under a range of sampling protocols. Recently independent observers present on about 10% of fishing trips have taken a sample of approximately 50 fish from each observed shot. Size frequencies were constructed from caudal fork lengths (FLs), aggregated into 10 mm length classes for all samples. Age determination methods are described in Chapter 3.

Sex ratio (R)

The proportion of females in commercial catch samples was calculated using the equation:

$$R = \frac{nF}{(nF + nM)}$$

where nF was the number of females and nM was the number of males in the samples. Sex was not recorded for commercial samples obtained in 2007.

2.3. Results

2.3.1. Effort, catch and CPUE

Annual patterns

The SASF expanded quickly after its inception in 1991 with total effort and catches recorded in logbooks increasing from 5 boat-nights and approximately 7 t during 1991 to 736 boat-nights and 3,241 t in 1994 (Figure 2–1). However, total effort and catch were reduced significantly in 1995 as a result of the first mass mortality event (Ward *et al.* 2001b), but increased rapidly to reach 530 boat-nights and 5,973 t in 1998. In 1999, after the second mass mortality event in late 1998 (Ward *et al.* 2001b), effort and catch declined to 345 boat-nights and 3,081 t, respectively.

Since the second mortality event, the fishery has expanded rapidly, with total effort reaching 1,274 net-sets across 1,233 boat-nights in 2005, with an estimated total catch of 39,831 t (Figure 2–1). Between 2007 and 2014, total effort was relatively stable at approximately 760–1100 net-sets over 680–900 boat-nights with an estimated catch of 27,500–32,500 t. Catches in 2015 and 2016 (36,110 and 34,561, respectively) are the highest they have been since the peak in catch in 2005. These high catches have resulted from the fishery's highest annual CPUE (51 t.net-set⁻¹ and 55 t.net-set⁻¹ for 2015 and 2016, respectively). In 2015 there were 714 boat nights resulting in 846 net sets while in 2016 there were 632 boat nights resulting in 819 net sets. The number of boat nights in 2016 was the lowest number since 2002 (Figure 2–1).

Total annual catches recorded in CDRs have exceeded catches estimated in logbooks in most years. Actual catches increased from 2,597 t in 1995 to 42,475 t in 2005, and fell to 25,137 t in 2006 (Figure 2–1). Since 2007, catches in CDRs have ranged from 29,854 t to 37,956 t.

Mean CPUE was calculated as the tonnage per boat-night between 1991 and 1998. Commencing in 1999, mean CPUE was also calculated as the tonnage per net-set, as well as per boat-night (Figure 2–1). Mean CPUE_(boat-night) increased from 1.3 t.boat-night⁻¹ in 1991 to 11.3 t.boat-night⁻¹ in 1998 and reached 36.5 t.boat-night⁻¹ in 2004. Between 2004 and 2011, CPUE_(boat-night) ranged between 32.5 and 38.7 t.boat-night⁻¹. CPUE_(boat-night) then increased to 50.6 and 54.7 t.boat-night⁻¹ for 2015 and 2016, respectively. Mean CPUE_(net-set) increased from 7.8 t.net-set⁻¹ in 2001 to 32.6 t.net-set⁻¹ in 2004. CPUE_(net-set) remained between 28.2 and 33.5 t.net-set⁻¹ between 2004 and 2012, before increasing to 42.7 and 42.2 t.net-set⁻¹ in 2015 and 2016, respectively.

Intra-annual patterns

Between 1991 and 2016, there has been a reasonably consistent intra-annual pattern in fishing effort (Figure 2–2). Relatively little fishing is usually conducted during August to October. Effort and catches often begin to increase in November/December, prior to the start of the southern bluefin tuna farming season. Catches continue to increase during January-February and usually peak in March-June. The peak fishing season reflects the extended periods of calm weather between April and June and the high demand for Sardine to feed southern bluefin tuna following their capture during summer. The months in which significant catches have been taken from the Outside and Gulfs Zone have varied among years.

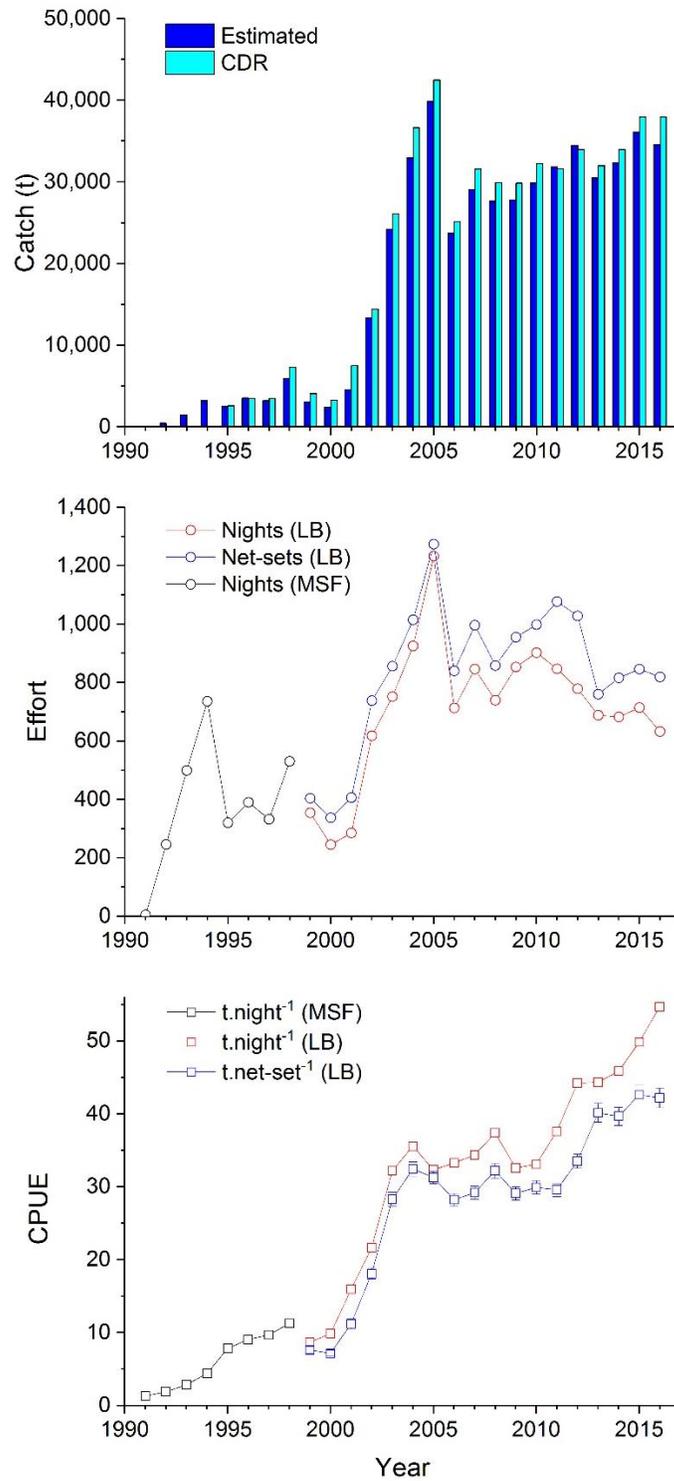


Figure 2–1. Total catches (estimated from logbooks, CDR), fishing effort (nights, net-sets) and mean annual CPUE (t.night⁻¹, t.net-set⁻¹, ± SE). Data prior to 1999 is derived from Marine Scalefish Fishery (MSF) records, specific SASF logbooks (LB) were introduced in 1999.

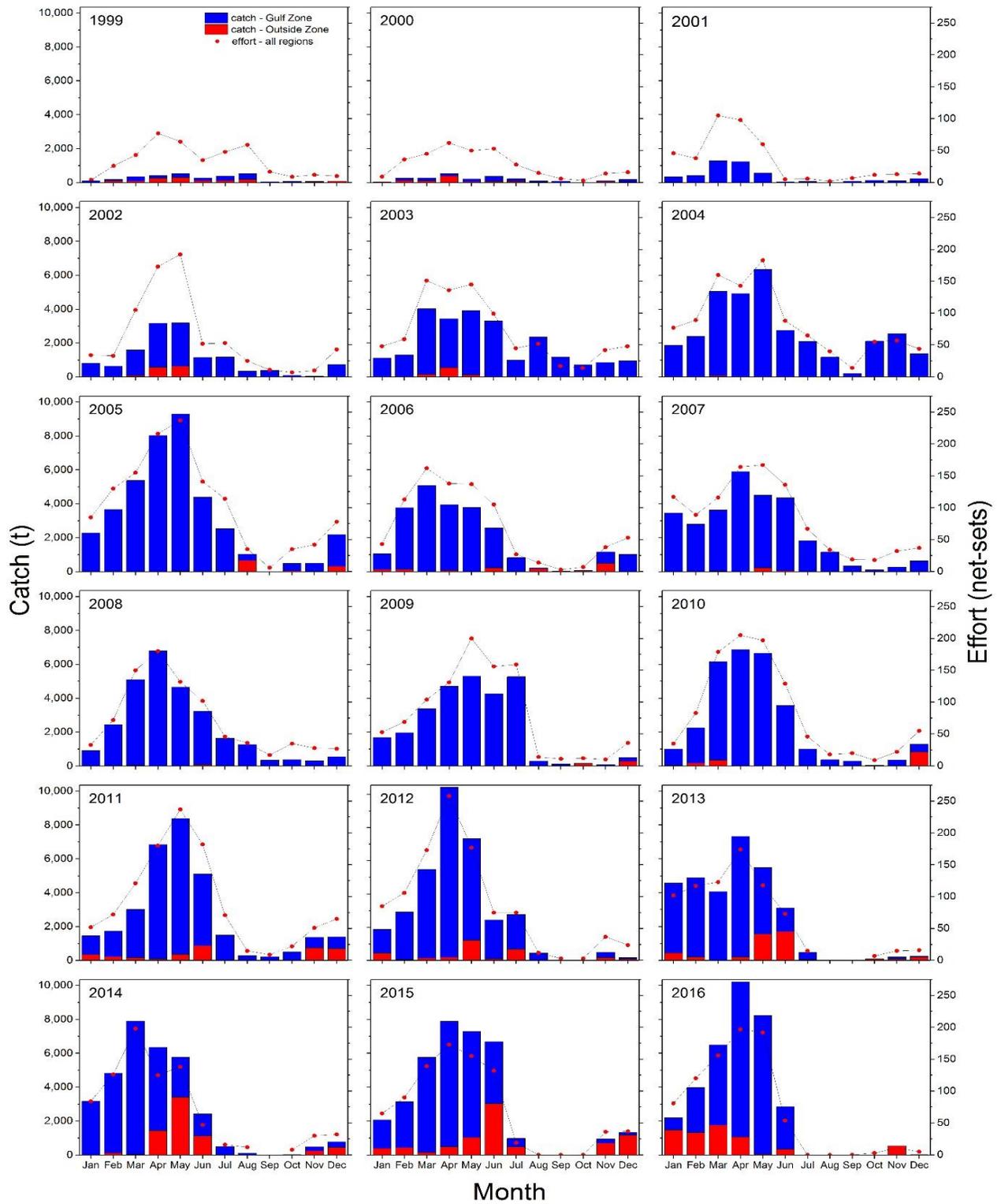


Figure 2–2. Intra-annual patterns in Sardine catch (tonnes, bars) by region and effort (net-sets, red points with black lines, all regions) in SASF between 1999 and 2016

Spatial patterns

From 1992, up until the first mortality event in 1995, most Sardines were taken from Spencer Gulf (Figure 2–3). A small proportion of the catch was taken from the Outside Zone in 1999 and 2000 (Figure 2–3, 2–4). In 2002, ~90% of the catch was taken north-east of Thistle Island and ~9.5% was taken off Coffin Bay (Figure 2–4). In 2003, as the TACC increased the fishery expanded northwards in Spencer Gulf and an increasing proportion of the catch was 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. Significant catches were also taken along the northern coast of Kangaroo Island, between Cape Borda and Marsden Point. In 2005, when the TACC was set at 51,100 t, the spatial extent of the SASF expanded further. 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 heavily than in previous years. The TACC was reduced to 26,000 t in 2006 and the area fished contracted, 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. Between 2007 and 2009, the area fished remained relatively consistent with the majority of fishing occurring in southern Spencer Gulf (Figure 2–5). Since 2010, when additional quota was allocated outside of the Spencer Gulf, a significant amount of catch has been taken from Investigator Strait, Gulf St Vincent and waters between Anxious Bay and Flinders Island. Catches from the outside Zone in 2014, 2015 and 2016 have been the largest in the fishery’s history (6,870 t, 7,893 t and 6,593 t, respectively) (Figure 2–3). This resulted from an expansion of fishing effort along the Western Eyre Peninsula (Figure 2–5). Historically, fishing effort and catches have been low in the Gulf St Vincent which continued in 2015 and 2016 with small catches coming from North Kangaroo Island.

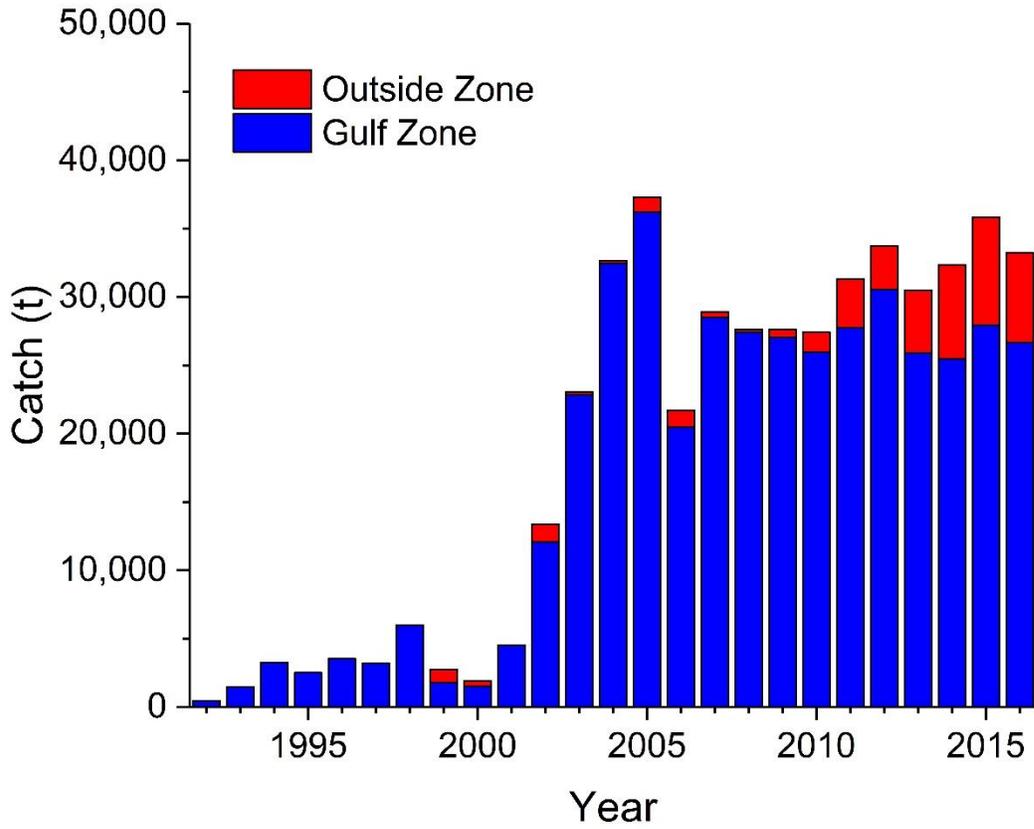


Figure 2–3. Annual Sardine catch (tonnes) by zone between 1992 and 2016.

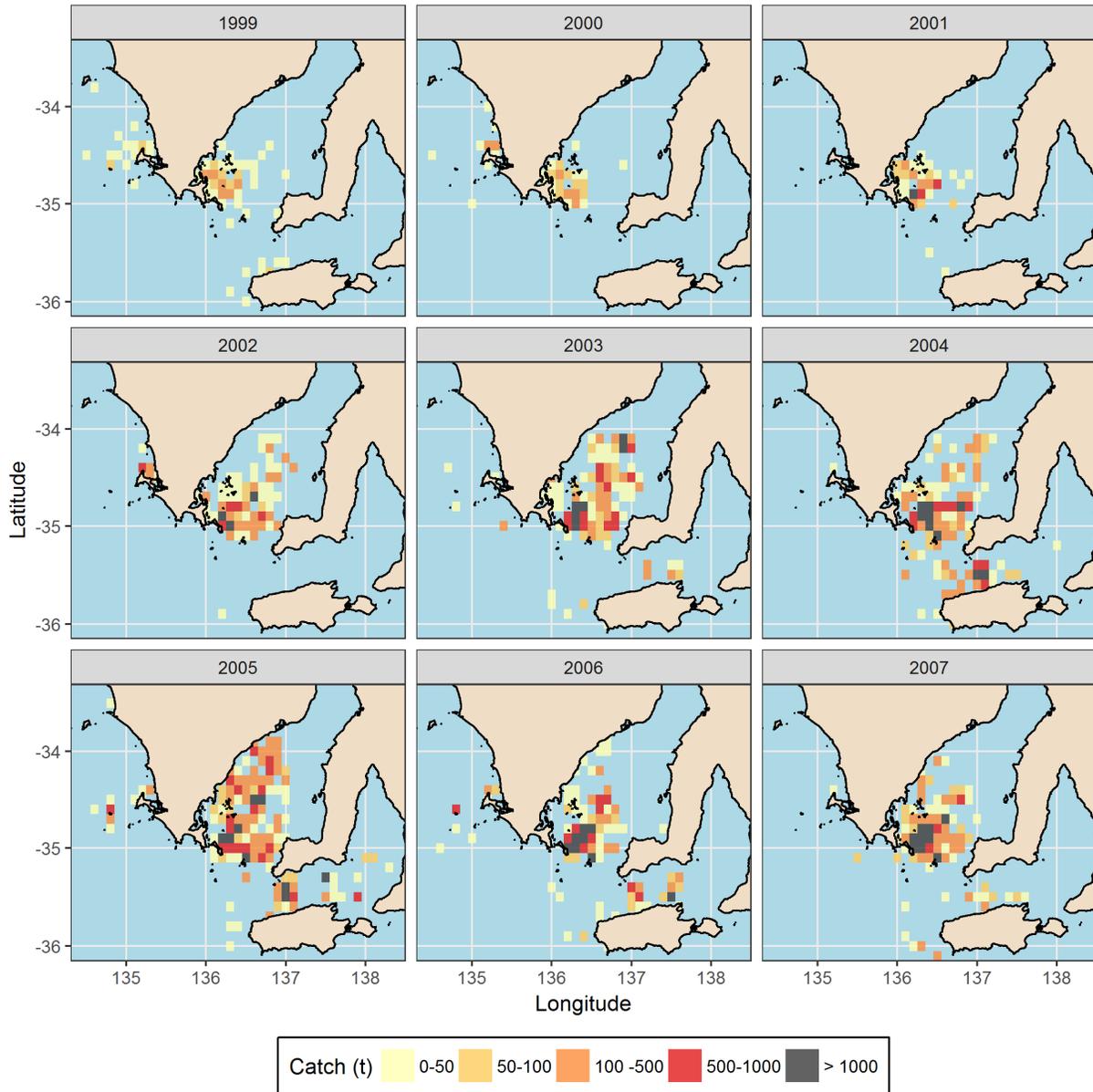


Figure 2-4. Spatial trends in Sardine catches (tonnes) between 1999 and 2007

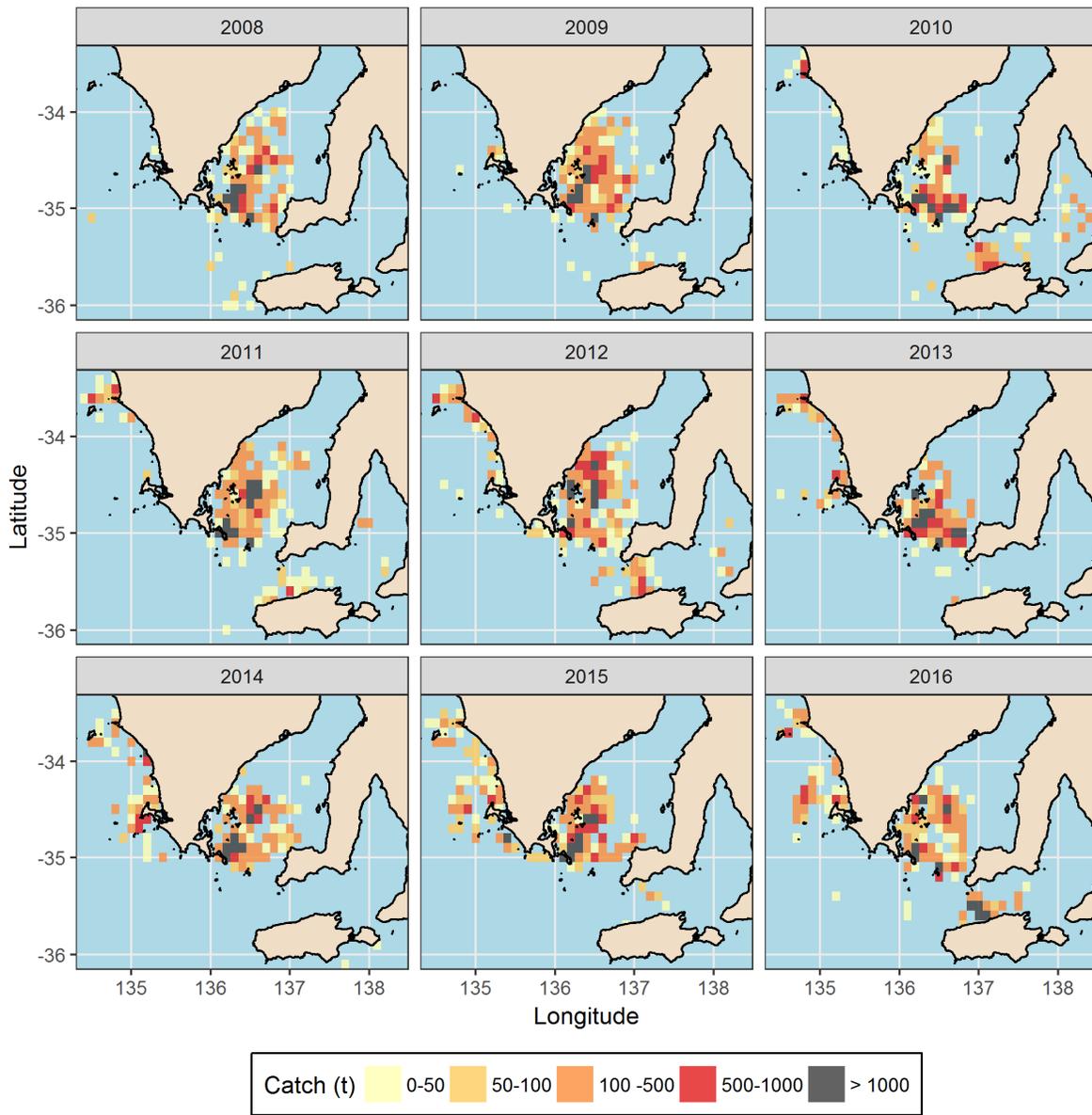


Figure 2-5. Spatial trends in Sardine catches (tonnes) between 2008 and 2016

2.3.2. Catch composition

Size frequency

In 1995, the modal size for Sardine caught in the Gulfs Zone was 140 mm FL with fish mostly ranging from 130 to 170 mm FL (Figure 2–6). The modal size of Sardine in the Gulfs Zone declined to 130 mm FL in 1996 and was 120 mm FL in 1998. Between 1999 and 2002, Sardine from the Gulfs Zone were mostly >140 mm FL with modes between 150 and 170 mm FL. In 2003 and 2004, catch samples were bimodal as significant quantities of juveniles (80–120 mm FL) were caught in addition to adults (150–180 mm FL). Prior to 2003, few catch samples from the Gulfs Zone included Sardine ≤ 100 mm FL. Between 2005 and 2010, size distributions from the Gulfs Zone remained stable with a mode at 140–150 mm FL and fish ranging from 120 to 190 mm FL. The mode declined to 130 mm FL in 2011 and 2012. In 2013–2016, the mode increased to ~140 mm FL (Figure 2–6).

Larger size ranges have been caught in the Outside Zone throughout the history of the fishery. In the Outside Zone Sardine of 150–180 mm FL dominated catches between 1995 and 1998 (Figure 2–7). In 1999, after the second mortality event the modal length fell to 130 mm FL, but increased to 140 mm FL in 2000. In 2004, the modal size was 140 mm FL and this increased to 170–190 mm FL in 2005–06. Few fish were taken in the Outside Zone in 2007–09 (none sampled in 2009). Between 2010 and 2013, the modal size for fish from the Outside Zone remained at 160 mm FL. In 2014 catches were bimodal, with modes at 130 and 170 mm FL. The modal size was 160 mm FL in 2015 and 2016 with no fish smaller than 100 mm FL included in the samples.

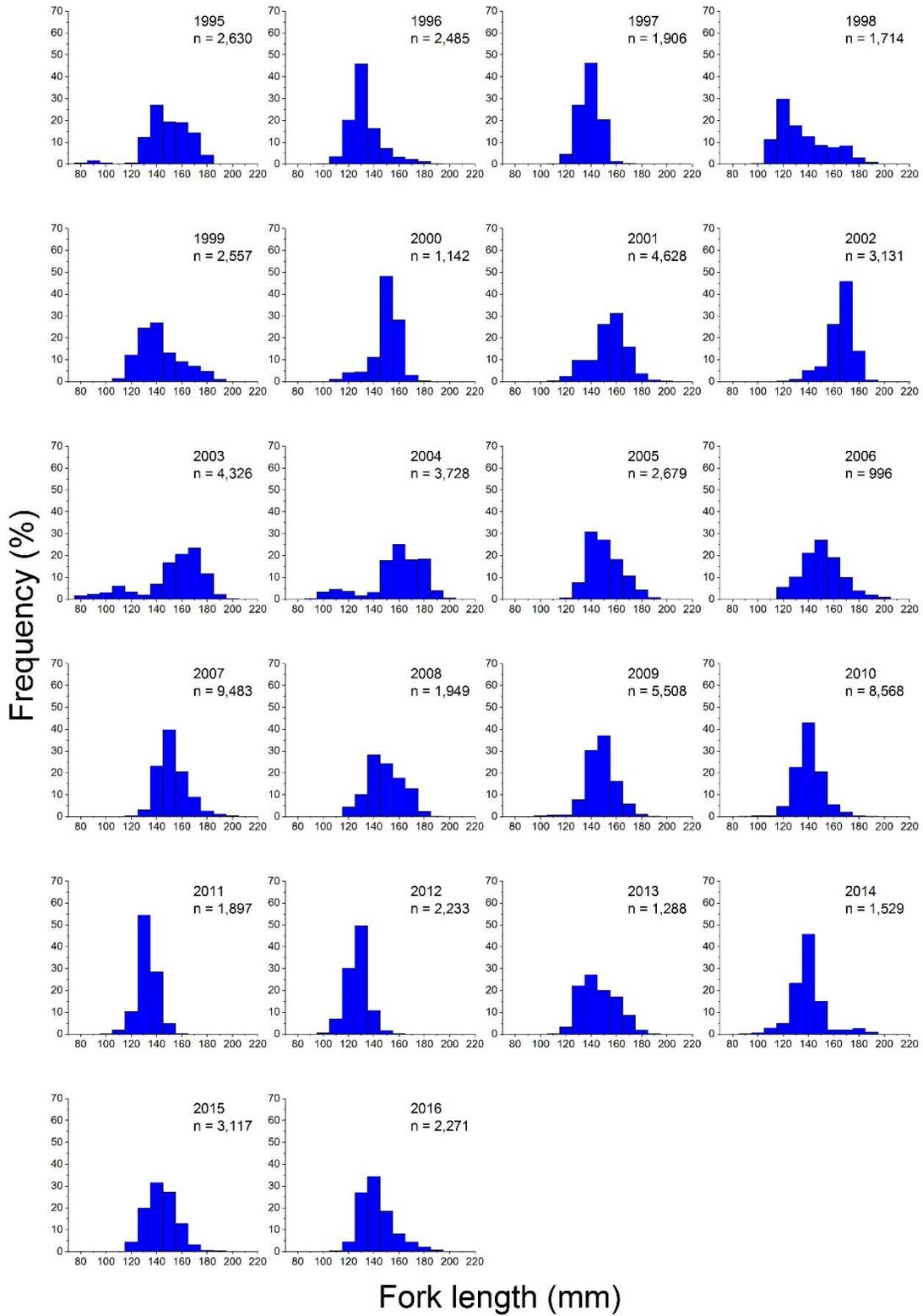


Figure 2–6. Length frequency distributions of Sardine from commercial catch samples for the Gulfs Zone between 1995 and 2016.

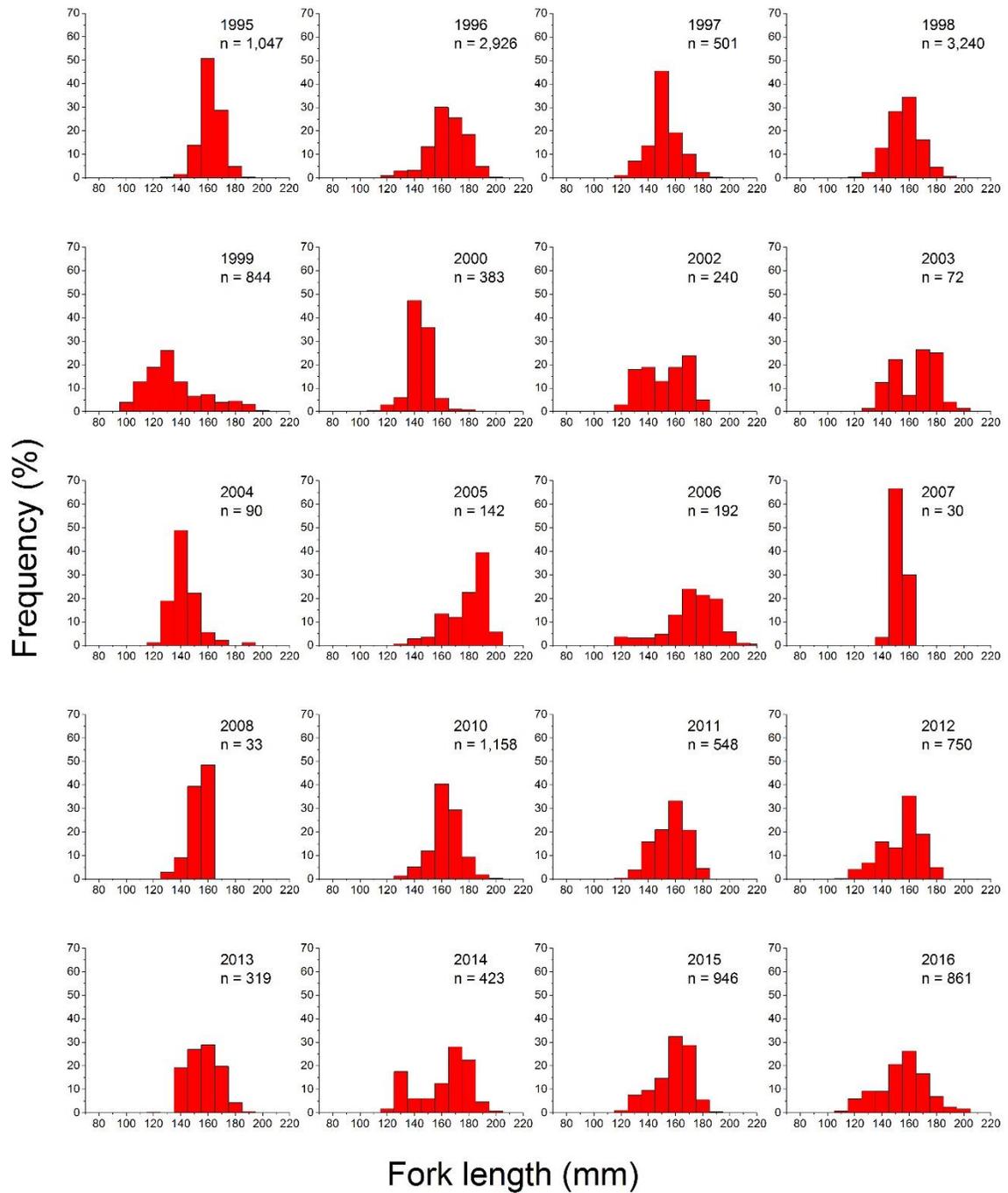


Figure 2–7. Length frequency distributions of Sardine from commercial catch samples for the Outside Zone between 1995 and 2016.

Mean size

The mean size of Sardine from Spencer Gulf ranged from 133 to 149 mm FL between 1995 and 1998 and rose to 166 mm FL in 2002 (Figure 2–9). Between 2003 and 2009, mean fish length in Spencer Gulf was relatively stable between 148 and 159 mm FL and declined to 128 mm FL in 2012. The mean length in Spencer Gulf between 2013 and 2016 was stable and ranged from 139 to 146 mm FL, respectively.

The mean size of Sardine from the Outside Zone was generally higher than Spencer Gulf (Figure 2–9), particularly in 2005 and 2006. Between 2010 and 2016, the mean size remained stable and ranged between 155–163 mm FL.

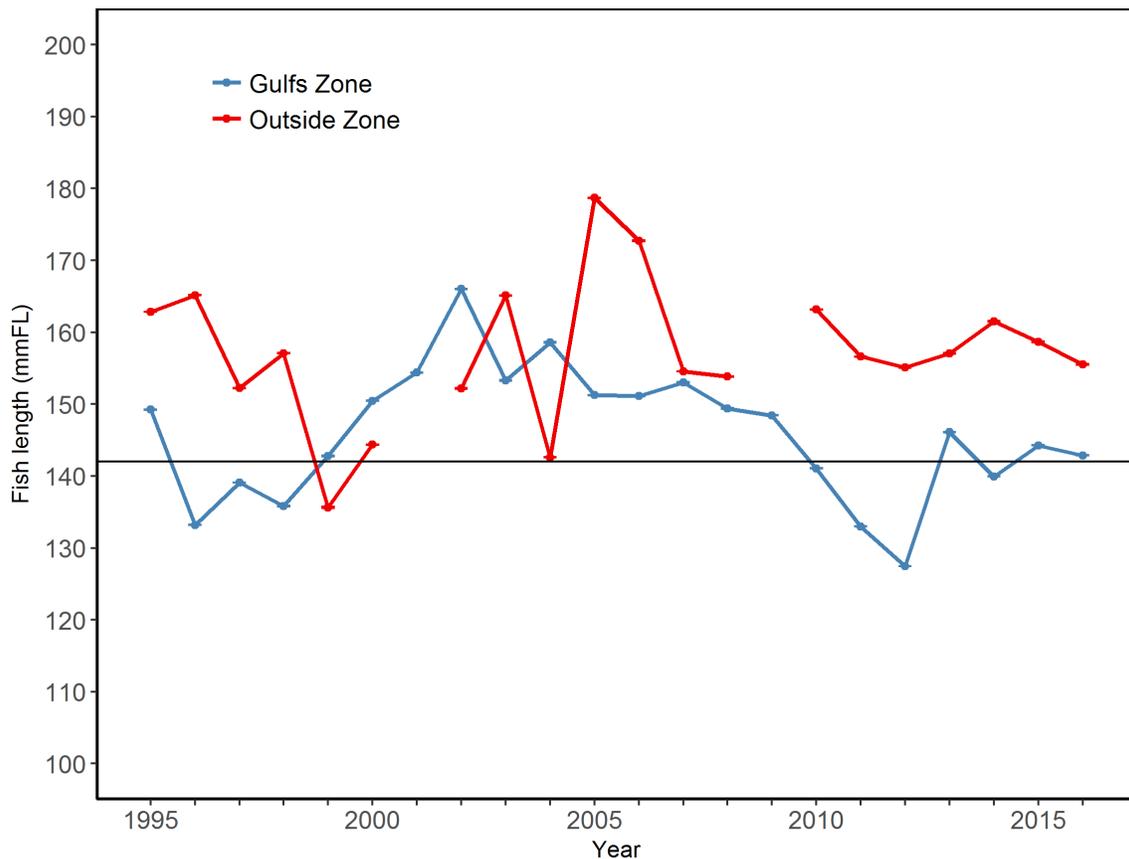


Figure 2–8. Average fork length (mm FL) by year for commercial samples from the three regions of the SASF, error bars are standard error. Horizontal line indicates the reference point for maximum catch limit for the Gulfs Zone of 142 mm FL (Table 1–2).

Sex ratio

The mean sex ratio (by number) in commercial catches has varied over the history of the fishery. Exact ratio tests indicated significant differences between the sexes caught in several years (Table 2–1) which always resulted in a higher proportion of females (Figure 2–9). The highest proportion of females occurred in 1995 and 2005 at 63% while the lowest proportion of females was 47% which occurred in 2000 and 2013 (Figure 2–9).

Table 2–1. Mean annual sex ratios for commercial catch samples from all regions between 1995 and 2016. Data were unavailable for 2007.

Year	Females	Males	$nf/(nm+nf)$
1995	1248	728	0.63
1996	1501	1049	0.59
1997	317	251	0.56
1998	1088	928	0.54
1999	1117	779	0.59
2000	358	398	0.47
2001	1461	929	0.61
2002	1662	1412	0.54
2003	2020	1715	0.54
2004	1827	1477	0.55
2005	1601	959	0.63
2006	608	585	0.51
2008	1168	797	0.59
2009	3088	2317	0.57
2010	4078	4152	0.50
2011	923	929	0.50
2012	1003	1063	0.49
2013	682	760	0.47
2014	828	843	0.50
2015	1445	1540	0.48
2016	1793	1515	0.54

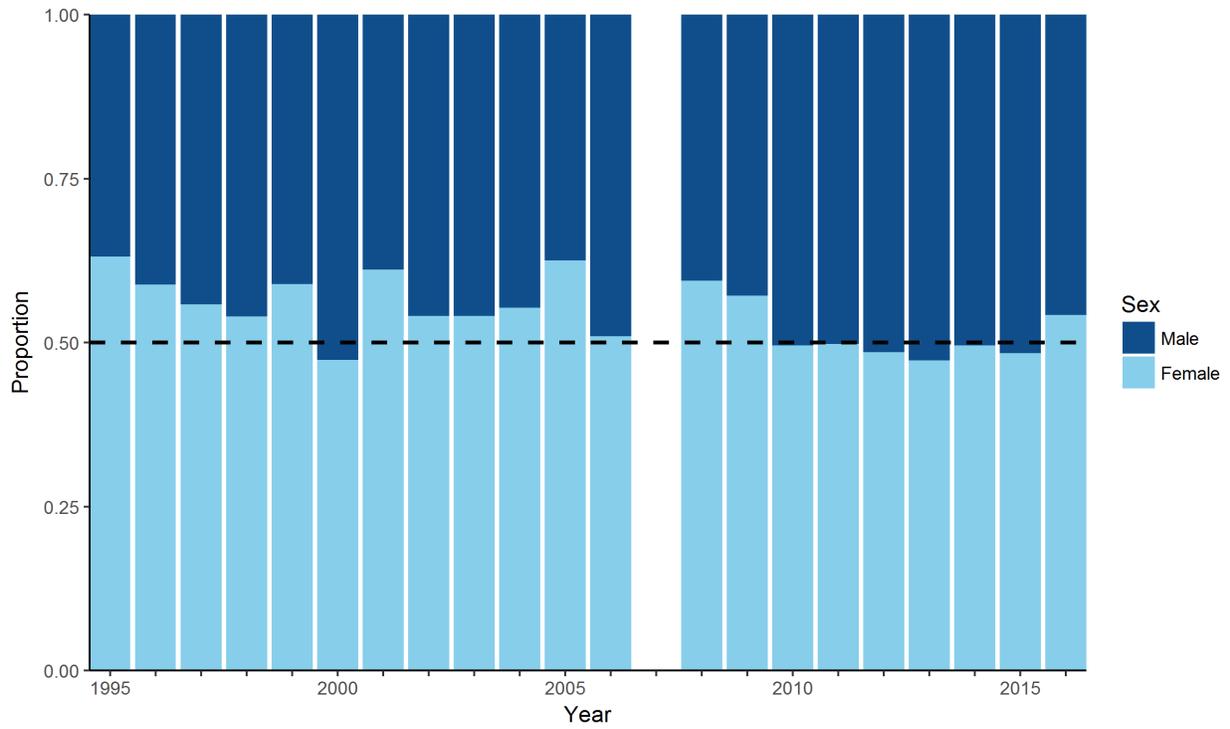


Figure 2–9. Sex ratio of commercial catch samples from all regions between 1995 and 2016. Data are unavailable for 2007. Dashed line represents a 1:1 sex ratio.

2.4. Discussion

One of the most notable features of the SASF has been its rapid growth. The TACC for 2016 (38,000 t) was 38 times the TACC in 1992 (1,000 t) and more than ten times the TACC in 2000 (3,500 t). The TACC for 2017 is 42,750 t. This rapid growth has occurred despite the impacts of two mass mortality events, each of which is thought to have killed more fish than any other single-species mortality event recorded (Jones *et al.* 1997, Ward *et al.* 2001b).

Another notable feature of the SASF is the stability in catches over recent years. This stability has been achieved by establishing a harvest strategy that addresses the imprecision in estimates of spawning biomass obtained using the DEPM. Under the previous harvest strategies for the SASF, and the management arrangements for many other Sardine fisheries (e.g. US Pacific Sardine Fishery, Hill *et al.* 2005), TACCs can vary significantly among years in response to changes in estimates of spawning biomass that may be more reflective of the imprecision in stock assessment methods rather than changes in stock size.

The concentration of fishing effort in a relatively small proportion of the total area over which the managed population is distributed has been a notable feature of the SASF. Since 2010, a range of management arrangements have been implemented to: reduce the capture of small fish; limit the catch from Spencer Gulf; and increase the catch from the Outside Zone. This has culminated in explicit rules for limiting the total catch that can be taken from the Gulfs Zone, based on the mean size of fish taken from that Zone in the previous year. This approach appears to have been successful in increasing the mean size of fish taken from the Gulfs Zone. The spatial management arrangements have also resulted in a shift in effort. The percentage of the catch taken in the Outside Zone increased between 2010 and 2016. The maximum catch recorded from the Outside Zone was 7,893 t in 2015, which represented 22% of the total catch that year.

Changes in management arrangements and fishing patterns over the history of the SASF have influenced the size composition of fish taken in catches. In particular, size-based decision rules implemented in 2010 have resulted in fishers selectively targeting large fish in the Gulfs Zone (Marcus Turner, *pers. comm.*). Recent catches from the Outside Zone have also contained larger fish than samples from the Gulfs Zone. Size composition data from the commercial catch are unlikely to be representative of the population; size selectivity is likely to have changed over time.

The increase in CPUE over the history of the SASF reflects increased catch capacity of the fleet and reaffirms the unsuitability of this parameter for monitoring the abundance of pelagic fishes.

3. AGE COMPOSITION AND REPRODUCTIVE BIOLOGY

3.1. Introduction

This chapter describes the methods used to determine age compositions from the commercial catch of Sardine in South Australian waters. Catch-at-age information presented in this chapter is key input to the population model presented in Chapter 5.

3.2. Methods

3.2.1. Age-determination

Otolith preparation and interpretation

Sagittal otoliths were collected from sub-samples ($n = 10\text{--}20$) of the commercial catch samples and fishery-independent samples (Chapter 2). 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, immersed in water against a flat black background (Butler *et al.* 1996).

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).

Decimal age estimates from annuli counts

To estimate decimal age for adults with a translucent zone count of one or more an arbitrary birth-date of March 1 was assigned, which represents the time of peak spawning. The midpoint of translucent zone formation was assumed to be mid-winter (Rogers and Ward 2007). Decimal age (A) was calculated as:

$$A = \begin{cases} (\alpha - \beta_p)/365 + TZC + 0.334 & \alpha \leq \beta_s \\ (\alpha - \beta_s)/365 + TZC + 0.334 & \alpha > \beta_s, \end{cases}$$

where α is the date of capture, β_s is the assumed translucent zone formation date from the same year as α , β_p is the assumed translucent zone formation date from the previous year, TZC is

the translucent zone count and 0.334 (4 decimal months) adjusts for the difference between the assigned birth-date and the approximate timing of the first translucent zone.

Age estimations from otolith weight

The relationship between age and otolith weight was determined using a linear model fitted to decimal age and otolith weight data from those otoliths with readability scores of 1 and 2. Aged otoliths from commercial catch samples between 1995 and 2016 and fishery-independent samples between 1998 and 2016 were pooled for the analysis. The resulting model was used to derive an age estimate for all otoliths based on otolith weight. Due to the change in the spatial patterns of fishing over time it is not possible to separate annual effects from regional effects on the relationship (i.e. region and season were confounded), so data from all regions were used in the analysis

3.2.2. 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). Only fish sampled during the spawning season (1 December to 31 March) were included as outside of this period stages 2 and 5 are difficult to macroscopically differentiate.

The length at which 50% of the population was mature (L_{50}) was estimated using Binomial GLM's with a logit link function (logistic regression). The model was fitted to separately for males and females using binary maturity assignments where immature = 0 (stage 1) and 1 = mature (stages ≥ 2). The proportion of the mature population at length 'L' calculated as:

$$P(L) = P_{max} \left(1 + e^{-\ln(19) \left(\frac{L-L_{50}}{L_{95}-L_{50}} \right)} \right)^{-1}$$

where $P(L)$ is the proportion of the population mature at fork length 'L' and P_{max} is the maximum proportion of mature individuals. Size-at-maturity models were fit to each sampling year to determine if L_{50} has changed over the history of the fishery. Some years were omitted as insufficient data were collected within the spawning season to accurately fit the model.

A size-at-maturity ogive was produced using the data pooled across all years and fishery dependent and independent sampling. These data were also restricted to within the spawning season and Gulfs Zone.

3.2.3. Growth

Length-at-age was estimated using the standard von Bertalanffy growth function (VBGF) fitted to individuals that were aged with a readability score of 1 or 2. Discrete ages were converted to decimal ages using the methods outlined previously. Preliminary analyses indicated that growth was not sex dependent and therefore the sexes were pooled. This allowed the inclusion of juvenile fish that were aged using daily ring counts and had been too young to accurately determine sex (Rogers and Ward 2007). The VBGF was represented by the equation:

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

Where L_t was the length at time ' t ', L_∞ was the asymptotic length, k was the growth completion parameter (yr^{-1}) and t_0 was the theoretical time when length was zero. Two parameterisations of the VBGF were fit to the data: the standard VBGF with a t_0 fixed at zero and the standard VBGF model with a freely estimated t_0 . Akaike's information criterion (AIC) was also applied to both models where $AIC = n\log(\sigma^2) + 2K$, K is the total number of parameters +1 for variance (σ^2) and n is the sample size. The model with the lowest AIC value is the most appropriate for the data. Length-at-age 95% confidence intervals were computed using 1000 bootstrap iterations.

3.2.4. Gonosomatic index (GSI)

Mean monthly gonosomatic indices (GSI) were calculated from both fishery independent and commercial samples using the equation:

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

where Gwt is gonad weight and Fwt is gonad-free fish weight for fish with gonads of macroscopic stages ≥ 2 . The mean estimate of GSI of all fish above size-at-maturity was used for both males and females to determine spawning season. It is important to note that it is sometimes difficult to macroscopically distinguish between Stage 2 and Stage 5 gonads in frozen samples.

3.3. Results

3.3.1. Age-determination

Between 1995 and 2016, a total of 20,541 otoliths from commercial and fishery-independent samples were read (Table 3–1). Less than 0.1% were assigned a Readability Index (RI) score of 1, while 6.0%, 50.0% and 27.6% were assigned scores of 2, 3 and 4, respectively. Approximately 16.4% were assigned an RI of 5 (Figure 3–1, Table 3–1 and 3–2).

Table 3–1. Summary of otolith Readability Index scores for otoliths collected between 1995 and 2016.

Year	Readability					Total
	1	2	3	4	5	
1995	0	87	411	159	2	659
1996	1	145	367	109	10	632
1997	0	154	275	54	3	486
1998	18	200	800	262	11	1,291
1999	0	50	546	389	18	1,003
2000	2	82	490	65	2	641
2001	0	59	1,431	689	113	2,292
2002	0	53	1,527	895	133	2,608
2003	0	39	1,057	229	18	1,343
2004	10	121	690	465	265	1,551
2005	1	13	301	235	368	918
2006	0	9	180	135	469	793
2008	0	9	144	183	303	639
2009	0	27	314	370	784	1,495
2010	4	64	469	577	74	1,188
2011	1	7	111	138	91	348
2012	0	0	9	14	13	36
2013	0	15	222	146	143	526
2014	0	9	253	150	110	522
2015	0	6	297	184	310	797
2016	0	33	389	224	127	773
All Years	37	1182	10283	5672	3367	20,541

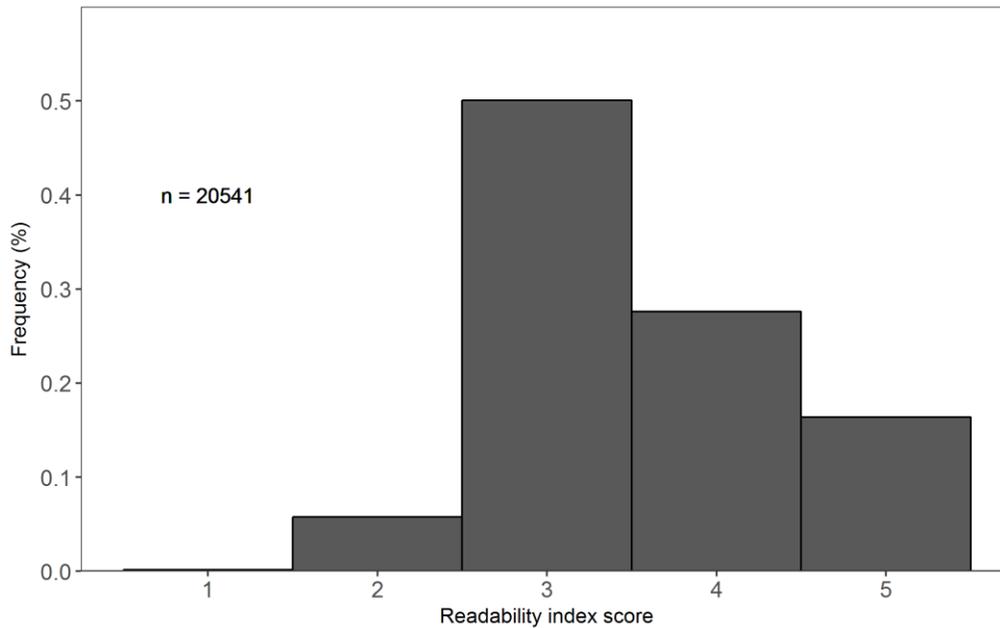


Figure 3–1. Readability Index scores assigned to otoliths from all samples between 1995 and 2016.

Otolith weight relationship

The modelled relationship between decimal age and otolith weight provided a reasonable fit to the data ($R^2 = 0.77$; Figure 3–2). However, while the 95% confidence intervals were narrow, the variation around the linear relationship was large. Therefore, while age can be inferred from otolith weight, the lack of precision resulting from this method means that these age estimates must be used with caution.

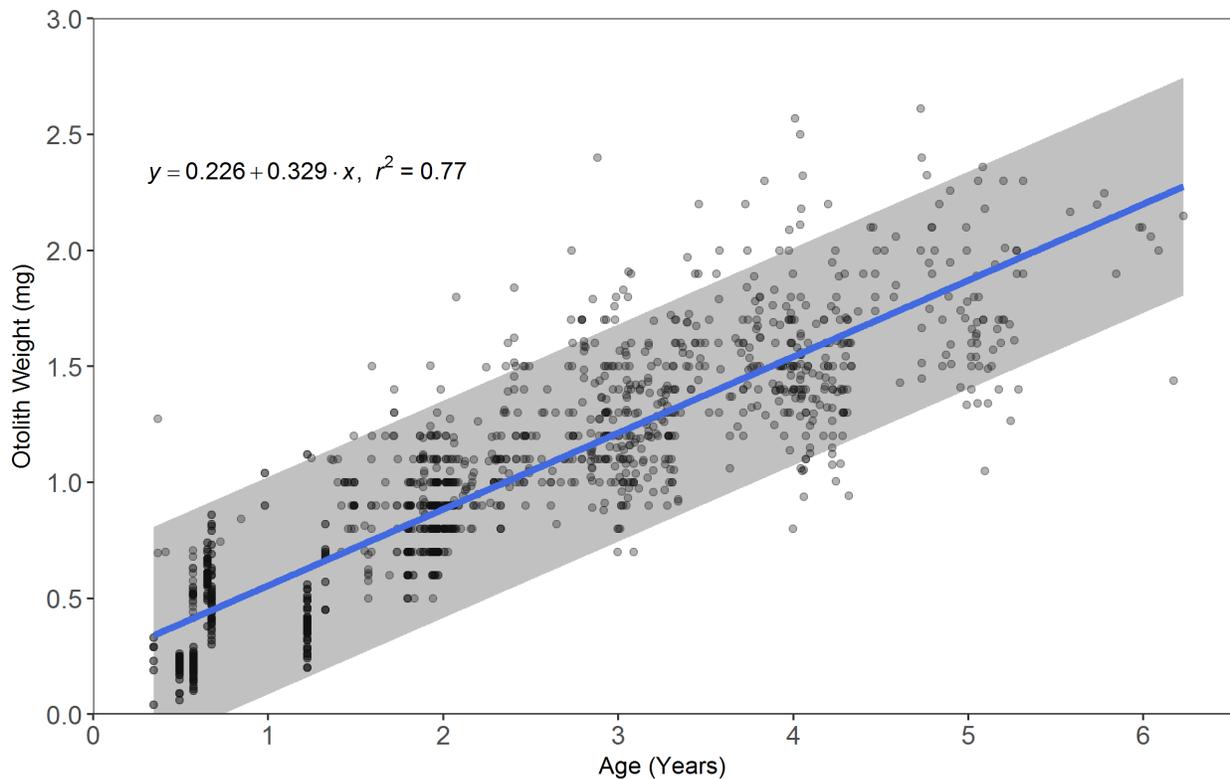


Figure 3–2. Regression of decimal age and otolith weight for Sardine otoliths of readability 1 and 2 from commercial and fishery-independent samples collected between 1995 and 2016. The light grey area represents 95% confidence intervals.

3.3.2. Age composition

Age composition data from commercial catches were available from 1995 to 2016, with the exception of 2007 when no otoliths were collected. Ages ranged from 0+ to 8+ years. In 1995, fish aged 2+, 3+, and 4+ years dominated catches from the Gulfs Zone, but in 1996–1998, catches were mostly dominated by age 1+ and 2+ fish, with a noticeable reduction in older fish in 1997 (Figure 3–3). These trends reflect the 1995 mass mortality event which mainly affected adult fish. In 1999, 2+ year olds (fish that were juveniles in 1998 and largely unaffected by the 1998 mass mortality event) dominated the catch. Fish that were spawned during 1997 and 1998 continued to dominate catches from the Gulfs Zone as 2+ and 3+ year olds in 2000. From 2001 to 2009, 3+ year olds dominated the catch from the Gulfs Zone in all years, except 2006 and 2008, when 2+ year olds were most abundant in catch samples (Figure 3–3). From 2010 to 2012, 2+ year olds dominated catches from the Gulfs Zone whereas from 2013 to 2016, 3+ year old fish were most abundant.

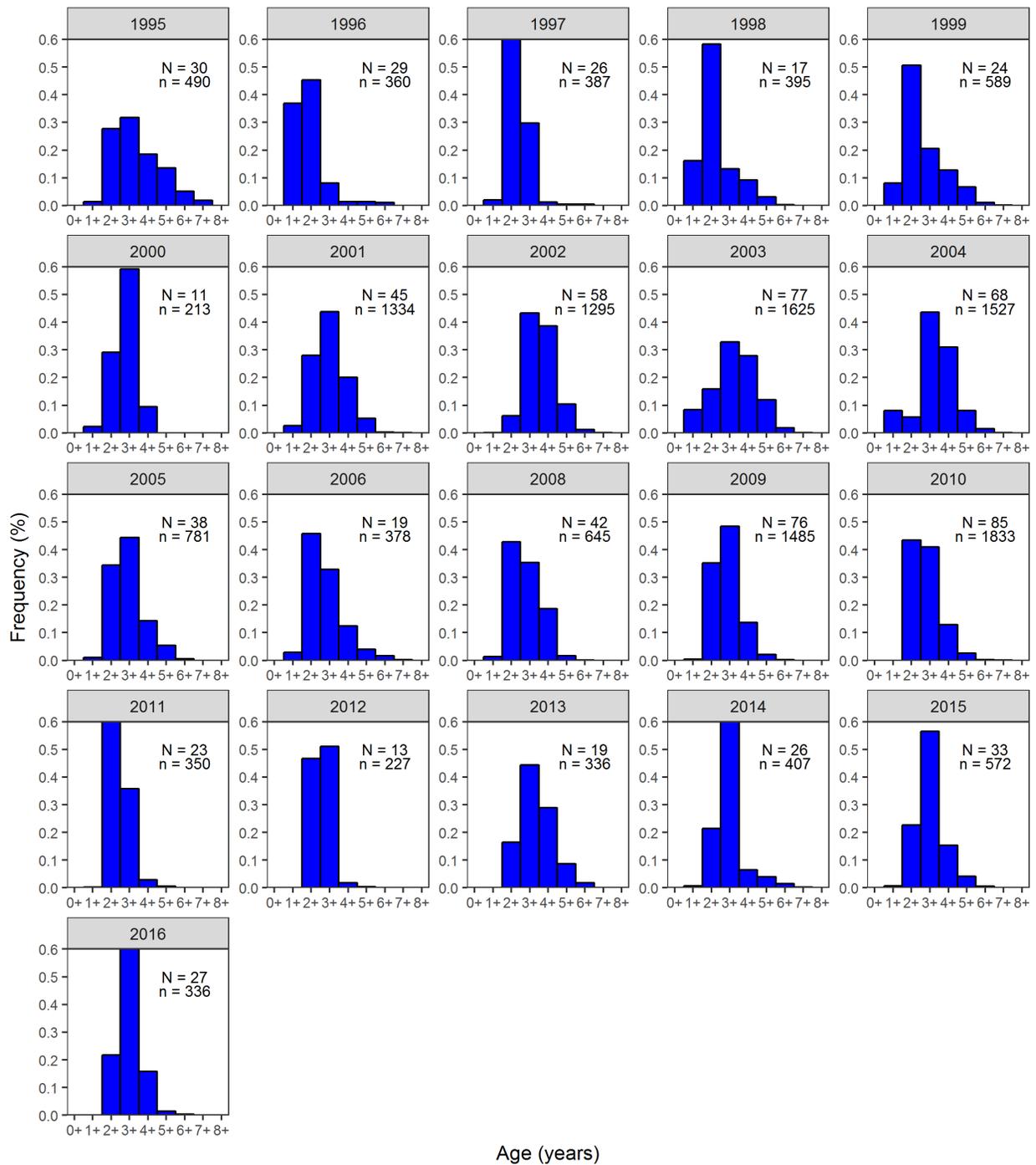


Figure 3-3. Age distributions for commercial catch samples of Sardine from the Gulfs Zone between 1995 and 2016. Note that no data were available for 2007. Ages are derived from an otolith-weight-age relationship calculated for all years from readability 1 and 2 otoliths and applied to all weighed otoliths for each year.

Catches from the Outside Zone have generally been comprised of older fish than those from the Gulfs Zone (Figure 3–4). In most years, fish aged 3+, 4+ and 5+ years dominated catches from the Outside Zone. However, fish aged 2+ years dominated catches in 1999, immediately after the 1998 mortality event, as well as in 2000 and in 2004.

3.3.3. Growth

The VBGF model with a free t_0 was the best performing model as its AIC value was 226.86 lower than the model with a fixed t_0 . Fixing t_0 is a common approach for species whose life history includes a larval phase. However, this approach provided a poor model fit for Sardines as L_∞ was underestimated and k was overestimated due to parameter covariation. Therefore, the VBGF with a freely estimated t_0 provided more plausible parameter estimates (Figure 3–5).

3.3.4. Size-at-maturity

Size-at-maturity (SAM, L_{50}) estimated for Sardine from the commercial catch samples from Gulfs Zone between 1995 and 2016 varied slightly among seasons (Figure 3–6). SAM could not be estimated in 1998, 2007, 2012, 2013 and 2014 due to a lack of commercial samples collected during the spawning season. The inter-annual variation that occurred was due to differing sample sizes between years. All males below 116 mm FL and females below 118 mm FL had immature gonads. The estimate of L_{50} using data from all years combined was 139.8 mm FL (95%CI = 139.43–140.16) and 144.18 mm FL (143.79–144.56) for males and females, respectively (Figure 3–7).

3.3.5. Gonosomatic index (GSI)

There was a large amount of seasonal variability in GSI. However, sample size was variable, with sufficient samples obtained only from the Gulfs Zone in most years. GSI peaked between November and March (Figure 3–8). Very high values occurred in February which resulted from fishery-independent surveys in this period targeting spawning fish. Higher mean GSI values were observed for males than females, which may be caused by male gonads not decreasing in size as much as females after each spawning event. Higher mean GSI values were also observed from larger fish.

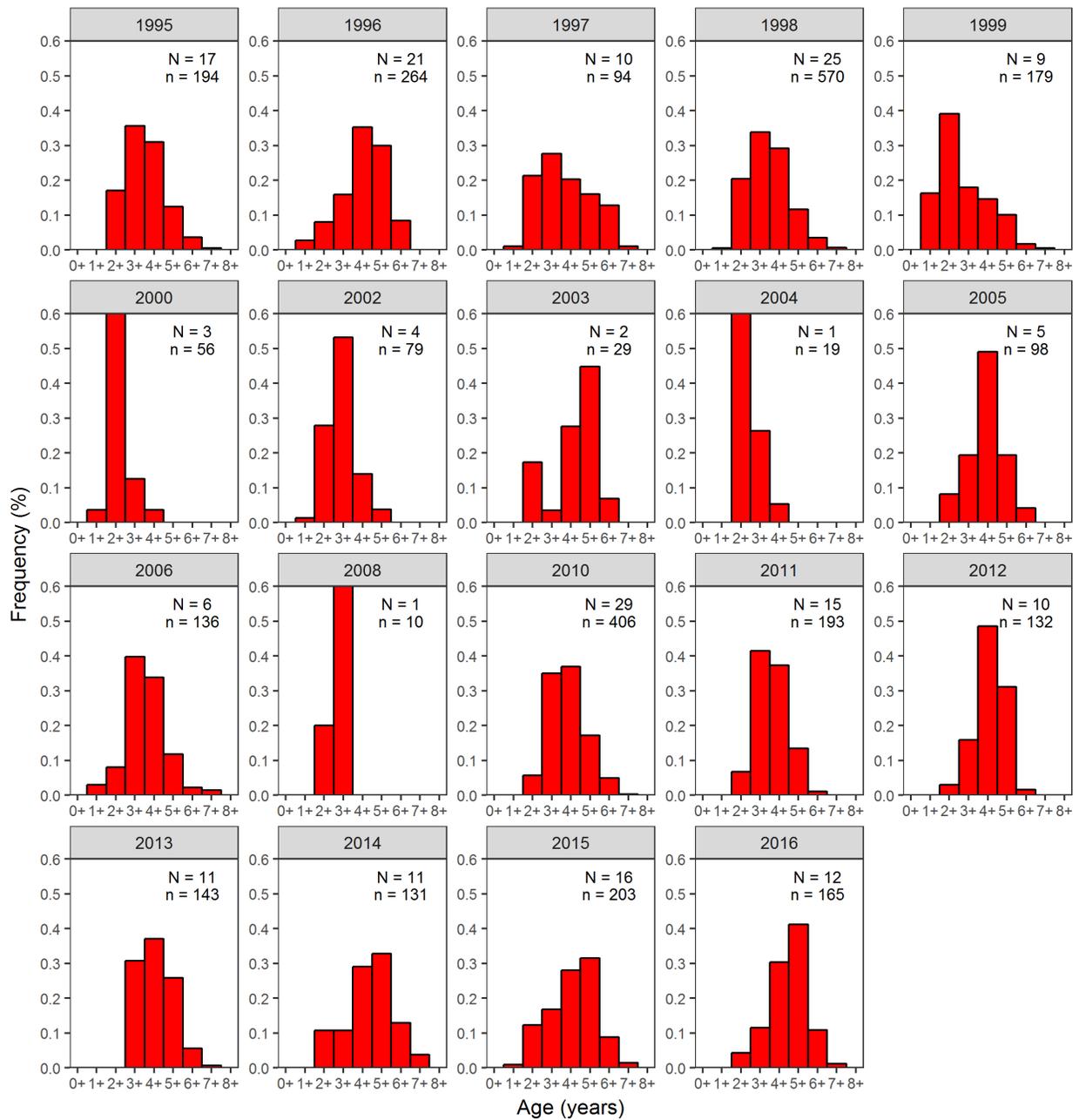


Figure 3–4. Age distributions for commercial catch samples of Sardine from the Outside Zone between 1995 and 2016. Note that no data were available for 2007. Ages are derived from an otolith-weight-age relationship calculated for all years from readability 1 and 2 otoliths and applied to all weighed otoliths for each year.

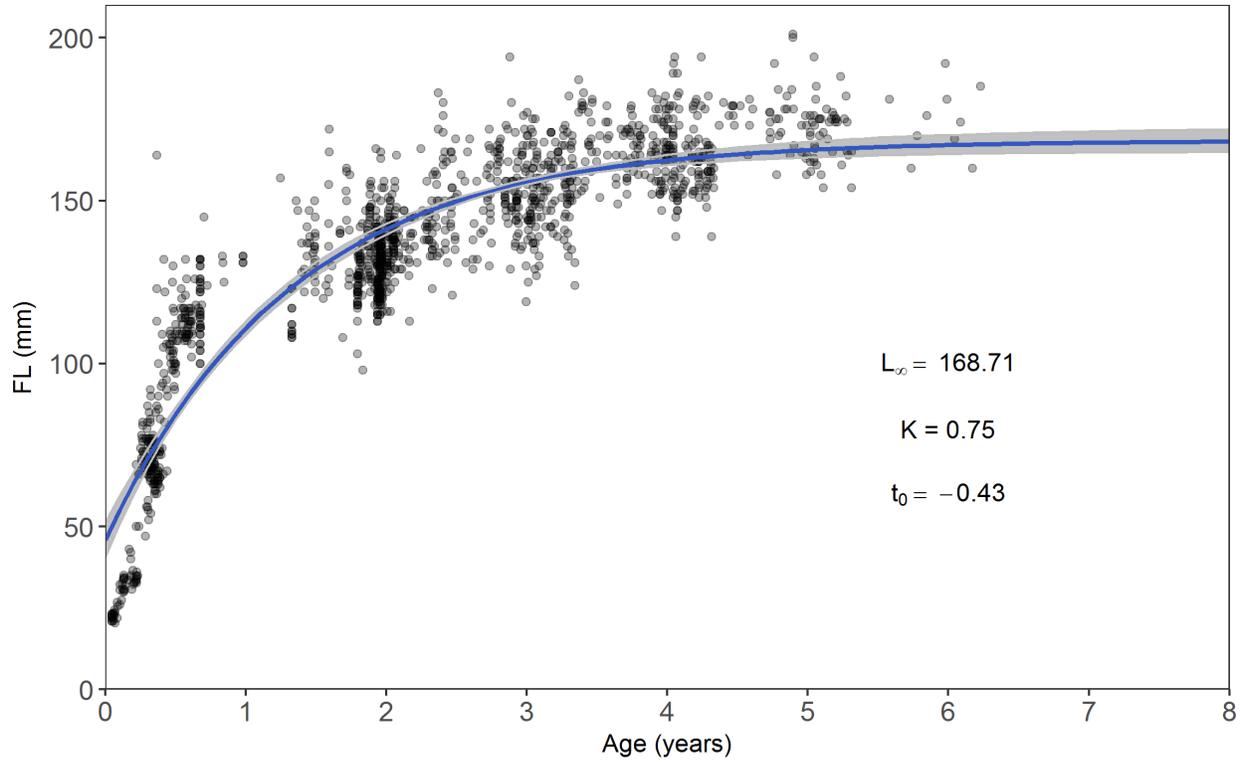


Figure 3–5. von Bertalanffy growth model fitted to length-at-age data (grey points) of individuals with readability scores of 1 or 2 collected between 1995 and 2016. The grey shaded area represents 95% confidence intervals

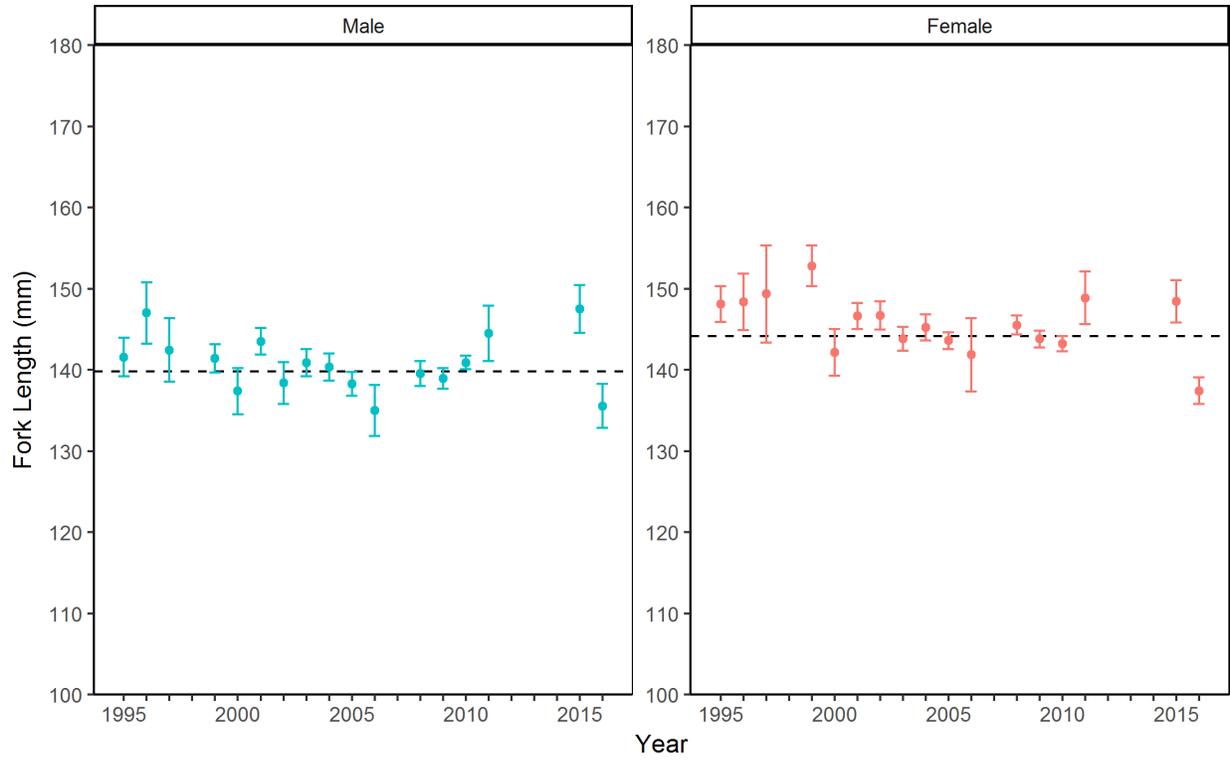


Figure 3–6. Size-at-maturity (L_{50}) for male and female Sardine collected in Gulfs Zone by year, between 1995 and 2014. Some years were omitted due to low sample size. Error bars are 95% confidence intervals. Dashed lines represent the mean L_{50} across all years calculated in Figure 3–6.

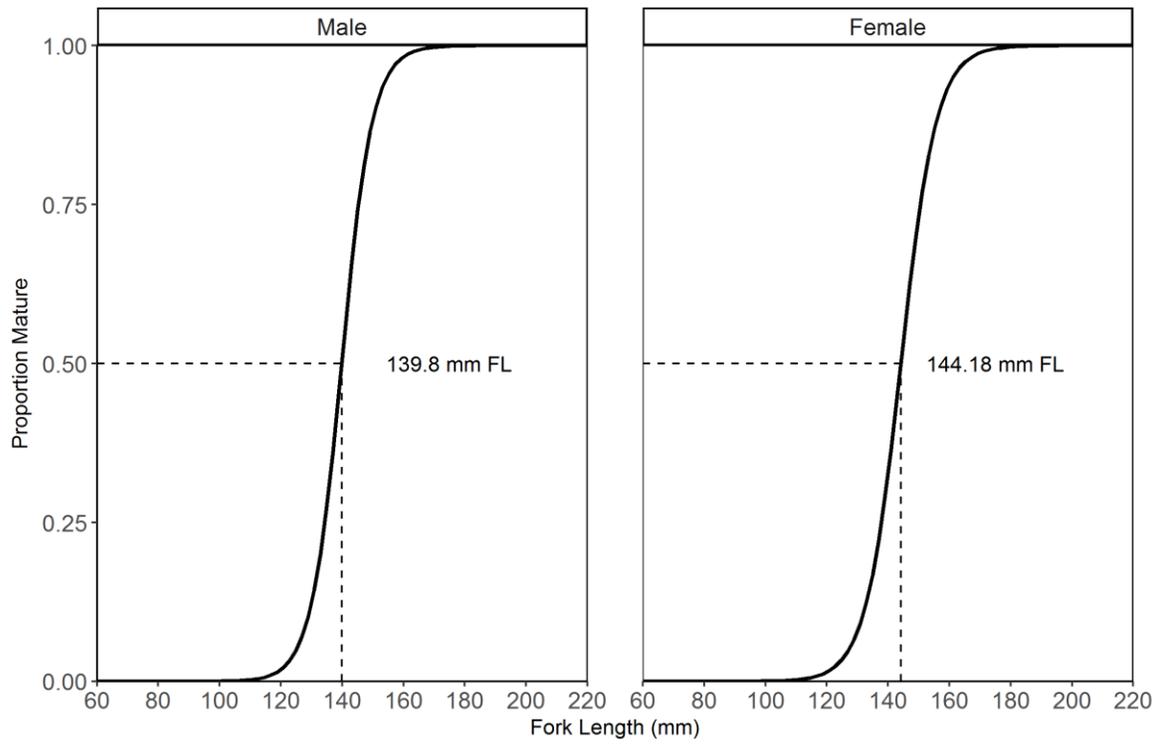


Figure 3–7. Size-at-maturity (L_{50}) for male and female Sardine collected from the Gulfs Zone for all years combined.

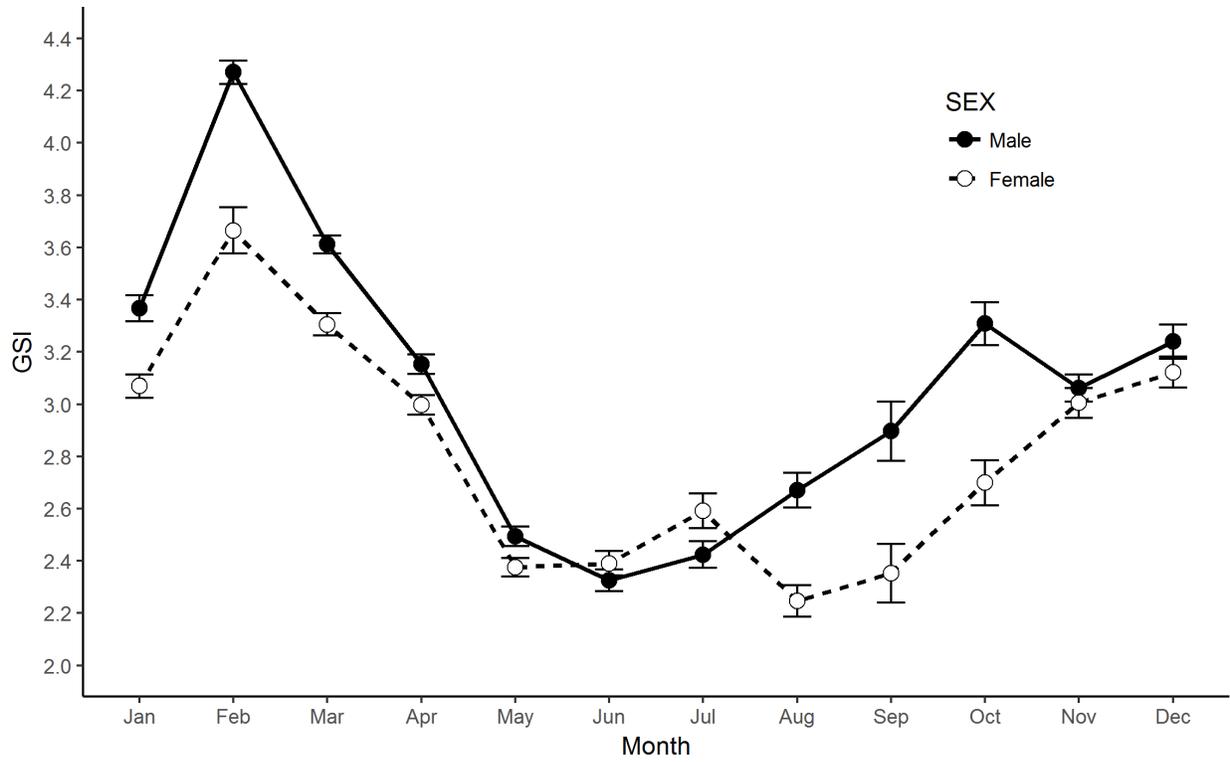


Figure 3–8. Mean monthly gonosomatic index of male and female Sardine from the Gulfs Zone commercial samples from 1995 to 2016 combined. Error bars are standard error. Fish below the size-at-maturity have been excluded.

3.4. Discussion

The relatively high level of uncertainty associated with estimating the age of Sardine from annual growth increments in otoliths has been noted elsewhere (Fletcher 1994, Rogers and Ward 2007). This issue can be partly overcome by using an age-otolith weight relationship developed from otoliths with high readabilities to estimate the age of Sardine with otoliths that are more difficult to read. This approach requires a relatively large number of otoliths to be read each year to provide adequate numbers of otoliths with high readability. This approach should be applied with caution as the relationship between otolith weight and fish age is relatively imprecise. The use of alternative approaches to assigning ages warrants consideration.

The growth rates of individuals vary with age (Rogers and Ward 2007), with moderate to high growth rates occurring prior to sexual maturity, with slower growth rates as adults. Several studies have found that fish length display limited modal progression through samples, whereas cohorts could be tracked using otolith weight (Fletcher 1994, Rogers et al. 2004). This variability in growth rates limits the use of age-length keys for estimating the age of Sardine.

As discussed in the previous chapter (with respect to fish size), changes in management arrangements and fishing practices over the history of the fishery have driven changes in the age composition of catches. As a result, catch samples are unlikely to be representative of the population and size/age selectivity is likely to have changed over time. The effects of these limitations of the age structure data need to be considered when interpreting the outputs of the population model (Chapter 5).

Although the most important fishing months are between March and June (i.e. partially overlapping with the spawning season), actively spawning females (Stage 4) have comprised only a small proportion (<1%) of the catch. This finding suggests that spawning Sardine may be poorly sampled using purse-seine gear (Hewitt 1985) or that spawning rates in Spencer Gulf, where most samples have been collected, are low. Studies of the reproductive status of Sardine collected from vessels operating outside the Gulfs Zone are needed to help resolve this uncertainty. A dedicated program to obtain reproductive data from samples collected from commercial vessels is scheduled for 2018.

4. ESTIMATES OF SPAWNING BIOMASS

4.1. Introduction

This chapter presents the time series of estimates of Sardine spawning biomass for South Australia that have been obtained using the DEPM between 1995 and 2017. This information is used to make inferences about the recent status of the South Australian Sardine resource and is a key input to the population model in Chapter 5

4.2. Methods

4.2.1. Daily Egg Production Method

The DEPM has been used to estimate the spawning biomass of Sardine in waters off South Australia 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 the equation:

$$B = \frac{P_0 * A * W}{R * F * S}$$

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, Alheit 1993).

Sampling area

Between 1995 and 2007, annual ichthyoplankton and adult Sardine sampling surveys of ~28 days' duration were conducted during each spawning season (January-March) from the *RV Ngerin*. Between 2009 and 2014, surveys were biennial with annual surveys recommencing in 2016. The location of plankton sampling stations used in 2017 is shown in Figure 4–1. The number of stations and orientation of transects have varied among years as the survey design has been 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 favour of additional stations in Spencer Gulf.

In 2014, after the 2013 survey failed to cover the entire survey area due to increased spawning occurring offshore, an adaptive approach has been taken to egg sampling. Under this adaptive protocol additional sites beyond pre-determined sites (i.e. red dots shown in Figure 4–1) are sampled based on the presence/absence of eggs in the sample obtained from Continuous Underway Fish Egg Sampler (CUFES) at the outermost site on each transect.

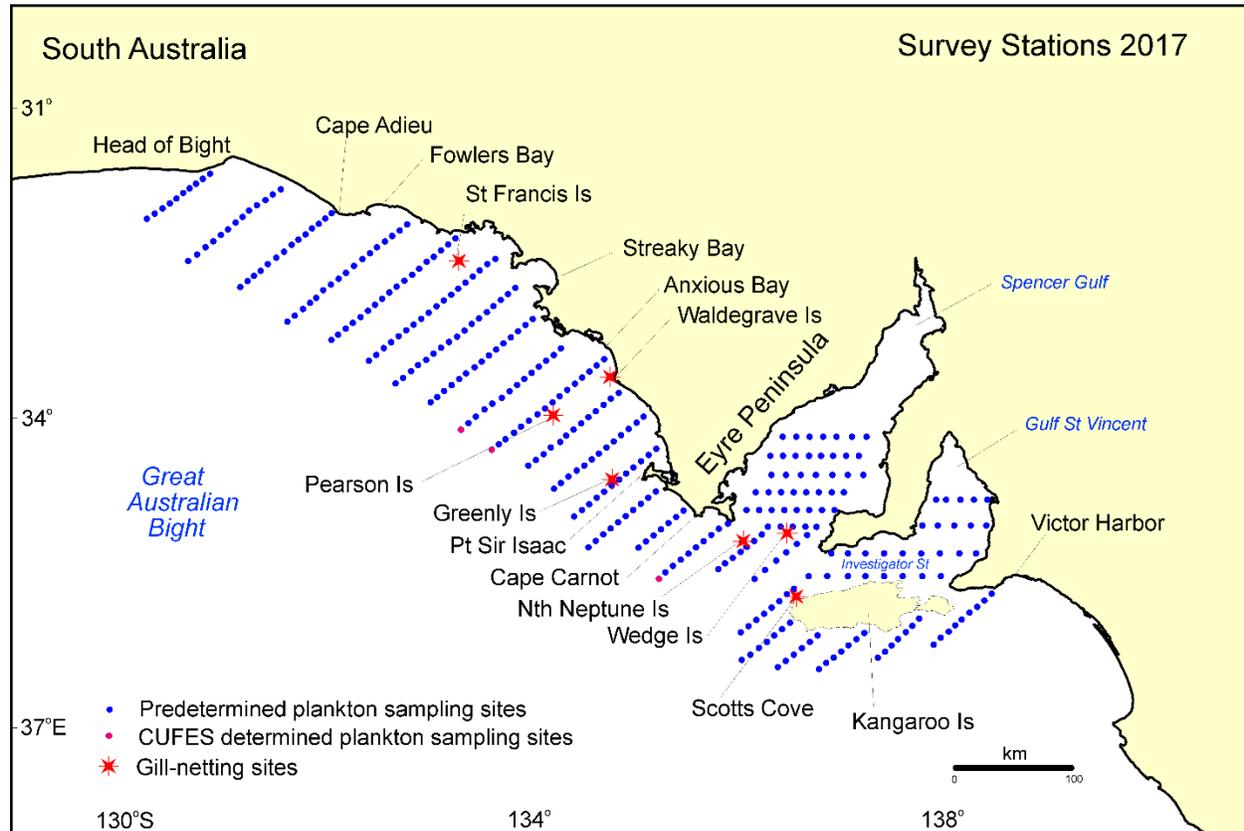


Figure 4–1. Typical design of a Sardine DEPM survey (2017), showing locations where plankton and adult samples are collected.

Plankton sampling

Plankton samples were collected at each station using Californian Vertical Egg Tow (CaVET) plankton nets. CaVET 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 $\text{m}\cdot\text{s}^{-1}$. General Oceanics™ flowmeters were used to estimate the distance travelled by each net. Samples from the two cod-ends were combined and stored in 5% buffered formaldehyde and seawater.

Egg distribution and abundance

Sardine eggs were identified, counted, staged and assigned ages according to descriptions and temperature-development keys in White and Fletcher (1998). The number of eggs of each stage under one square metre of water (P_i) is estimated at each station according to the equation:

$$P_i = \frac{C.D}{V}$$

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

Spawning time

Sardine eggs in each sample were counted and staged according to criteria in White and Fletcher (1998). The age of each developmental stage was estimated using a temperature dependent egg development model that incorporated time of sampling, sea surface temperature and egg stage (Ward *et al.* 2011b).

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.

Spawning area

A key premise of using the DEPM is to accurately estimate the entire spawning area (Lasker 1985, Somarakis *et al.* 2004). After the surveys were completed, the survey area was divided into a series of contiguous grids approximately centred on each station using the Voronoi natural neighbour method in the statistical program 'R' using the 'deldir' package (Badderly and Turner 2005, R Development Core Team 2017, Turner (2016); Figure 4–2). Then the area represented by each station (km^2) was calculated. The spawning area (A) was defined as the total area of grids where live Sardine eggs were found in CalVet samples (see Fletcher *et al.* 1996).

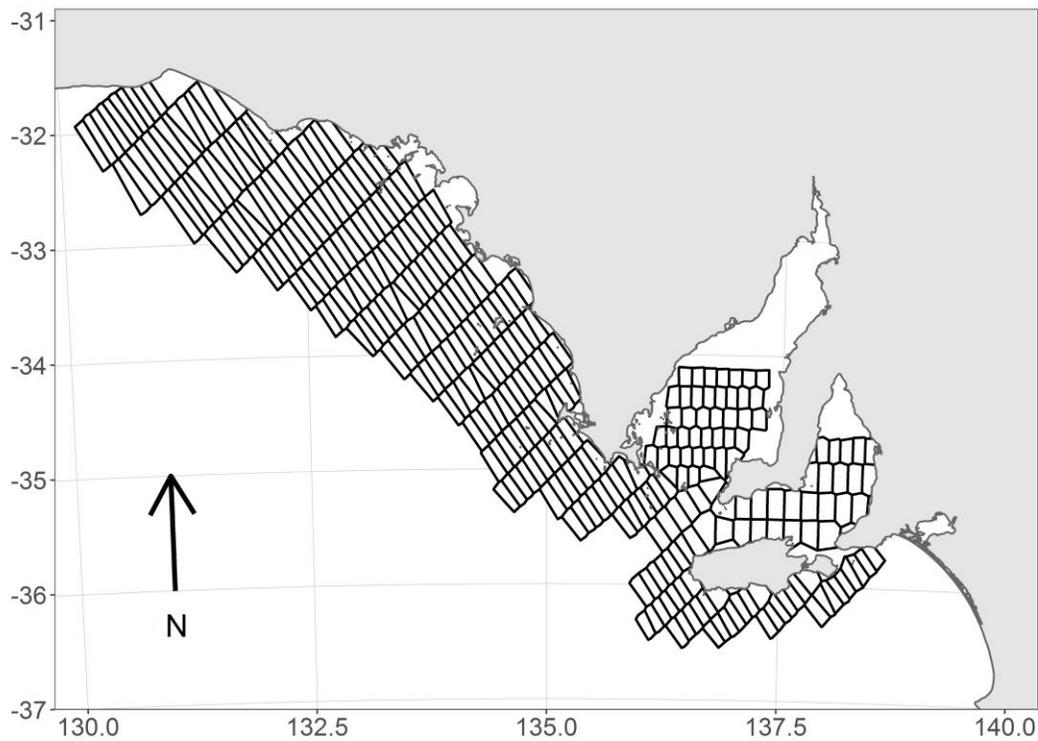


Figure 4–2. Spatial grids generated using the Voronoi natural neighbour method, used to estimate the spawning area of Sardine in 2017.

Egg production P_0

Biased mean daily egg production (P_b) was calculated by fitting the linear version of the exponential egg mortality model to estimates of egg age and density for each daily cohort at each station (Picquelle and Stauffer 1985). To allow the inclusion of data from stations where either day 1 or day 2 eggs were absent, one egg was added to the counts of both day 1 and day 2 eggs at every positive station. The linear version of the exponential egg mortality model is:

$$\ln P_b = \ln(P_i) - Zt$$

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

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

$$P_0 = e^{(\ln P_b + \sigma^2/2)}$$

where, σ^2 is the variance of the estimate of biased mean daily egg production (P_b). This bias correction assumes that the true distribution of sample densities is lognormal. Because the true (observed) distribution is more highly skewed than lognormal, this correction is an approximation.

A recent review by Ward *et al.* (2017) addressed the process by which P_i was estimated—providing more precise estimates of egg age for inclusion in the P_0 calculation. This methodology has been applied retrospectively over the history of the fishery to re-calculate annual estimates of P_0 and update the time-series biomass estimates using these new statistics.

Adult reproductive parameters

Between 1995 and 1997, there were difficulties collecting samples of mature Sardine. Mid-water trawling and sampling from commercial catches during the spawning season were 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).

From 1998 to 2017, samples of mature Sardine were collected during research surveys in the eastern Great Australian Bight, 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 based on these samples.

Mean female weight (W)

Mature females from each research sample were removed from formalin and weighed (± 0.01 g). W was calculated from the average of sample means weighted by proportional sample size:

$$W = \left[\overline{W}_i * \frac{n_i}{N} \right]$$

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

Sex ratio (R)

For fishery-independent samples, R was calculated from the average of sample means weighted by proportional sample size:

$$R = \left[\bar{R}_i * \frac{n_i}{N} \right],$$

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

$$\bar{R}_i = \frac{nF}{(nF+nM)}$$

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 ($d0$) (assumed to be 0–23 hrs old), day-1 POFs ($d1$) (assumed to be 24–48 hrs old) and day-2 POFs ($d2$) (assumed to be 48+ hrs old). Then the mean spawning fraction of the population was calculated from the average of sample means weighted by proportional sample size from:

$$S = \left[\bar{S}_i * \frac{n_i}{N} \right]$$

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

$$\bar{S}_i = \frac{[(d0 + d1 + d2POFs)/3]}{n_i},$$

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.

Confidence intervals

Confidence intervals were obtained from a two stage bootstrap process with 100,000 iterations (Efron and Tibshirani 1993). The two-stage bootstrap method accounts for any covariance of adult parameters within individual samples, which improved the accuracy of confidence interval estimates (Ward *et al.* 2011a).

4.3. Results

Sampling area

The total area sampled during the DEPM surveys varied from 46,525 to 122,567 km² between 1998 and 2017 (Figure 4–2, 4–4). The survey area was relatively consistent between 2006 and 2013 at ~115,000 km². Since 2014, when Sardine eggs were present in samples collected with the Continuous Underway Fish Egg Sampler (CUFES), additional stations were sampled (e.g. 2017, Figure 4–1), increasing the total survey area in these years (e.g. 2017, Figure 4–1).

Egg distribution and abundance

The distribution and abundance of Sardine eggs has varied considerably among years. Important spawning areas include shelf waters of the eastern Great Australian Bight, between Coffin Bay and the Head of Bight, southern Spencer Gulf, and the western end of Investigator Strait (Figures 4–3). Mass mortality events in 1995 and 1998 had substantial effects on both the abundance of eggs and their spatial distribution (Ward *et al.* 2001a).

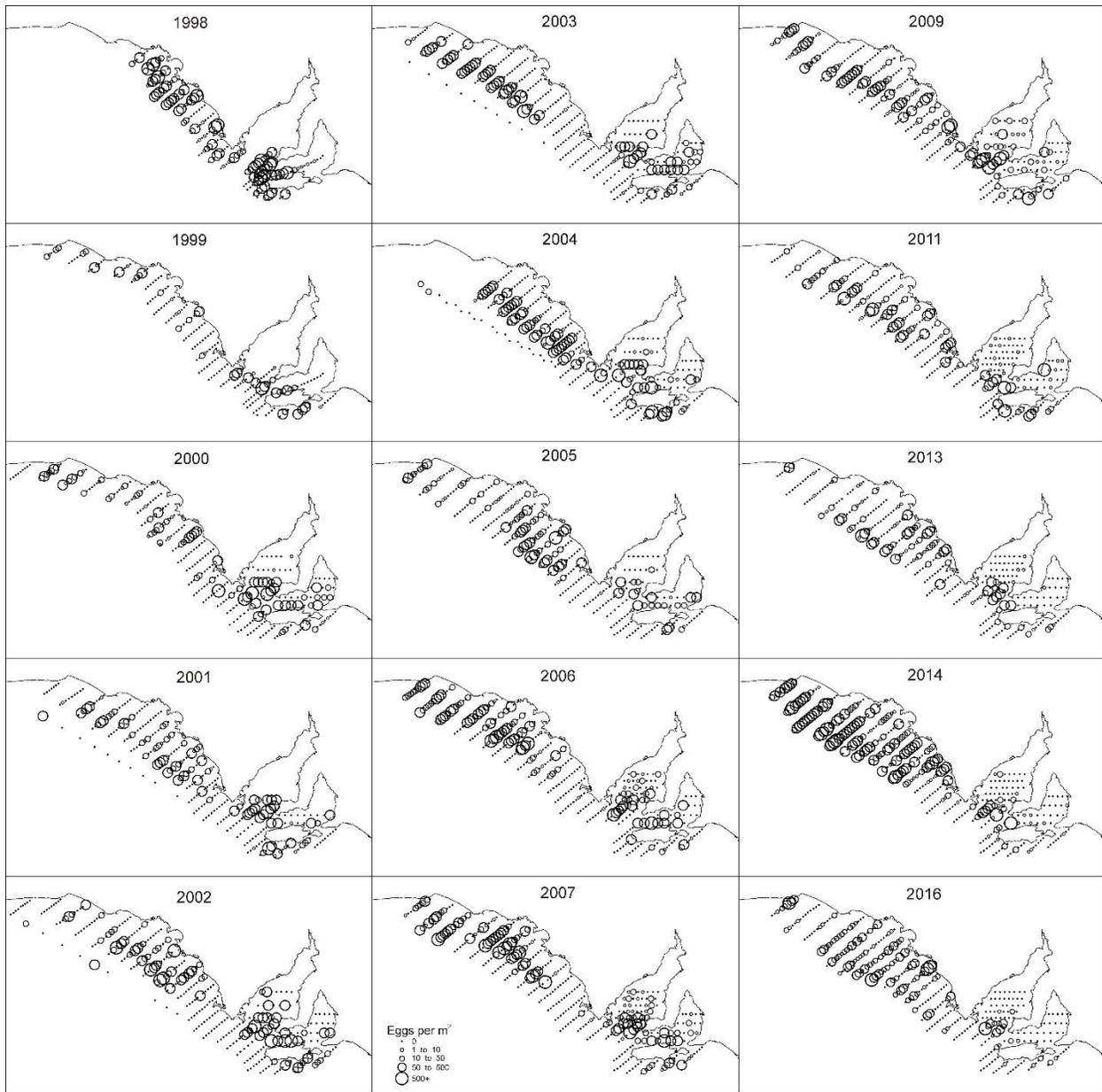


Figure 4–3. Distribution and abundance of Sardine eggs collected during surveys between 1998 and 2016

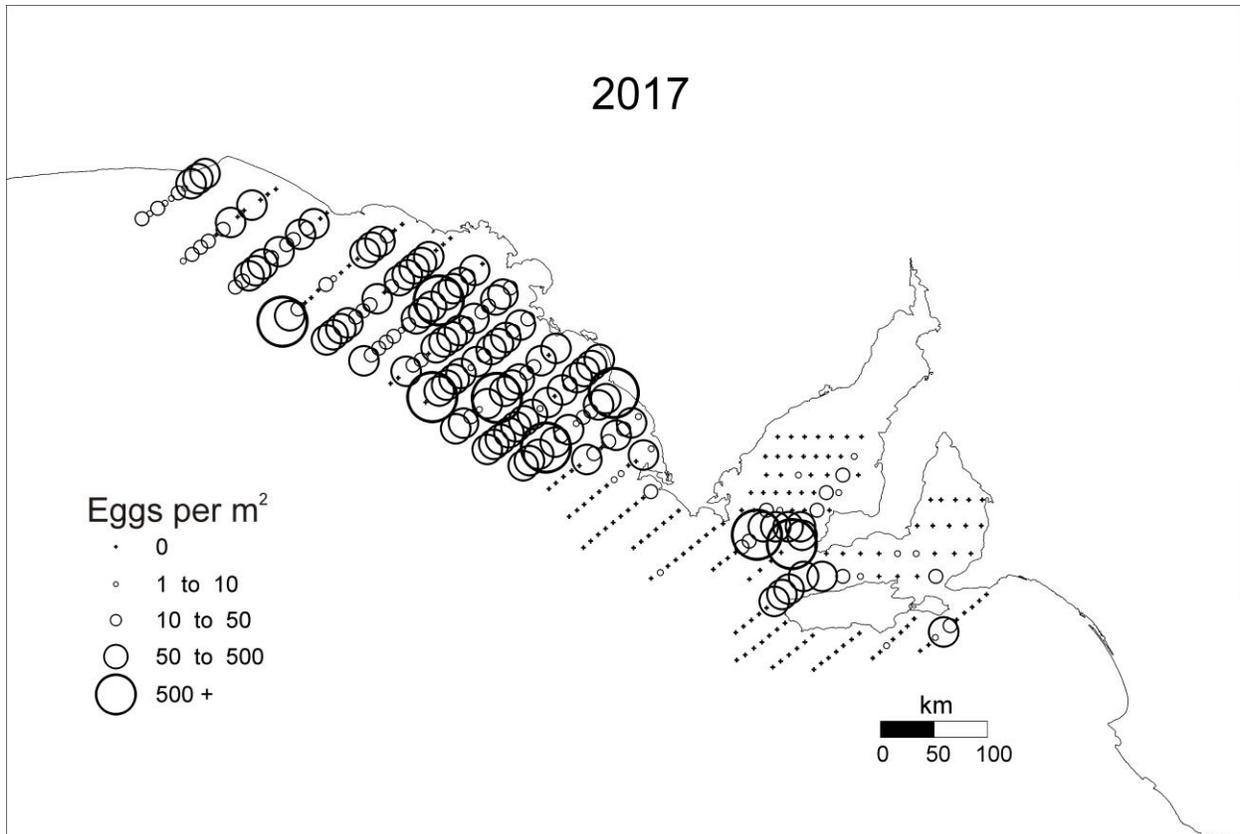


Figure 4–4. Distribution and abundance of Sardine eggs collected during surveys in 2017

Spawning area (A)

Estimates of spawning area varied among years and reflected both the size of the survey area and the status of the spawning biomass. The spawning area declined substantially following the two mass mortality events in 1995/96 and 1998/99, from 68,260 km² in 1995 to 17,990 km² in 1996 and from 31,510 km² in 1998 to 14,876 km² in 1999 (Figure 4–5). The spawning area increased to 37,893 km² in 2000 and remained between 34,182 and 40,817 km² until 2005, then rose to ~50,000 km² in 2006 and 2007. The 2013 survey did not cover the entire spawning area. This result led to the adoption of the adaptive sampling from 2014 onwards to ensure coverage of the entire spawning area. Spawning area increased to 71,859 km² in 2014, and remained relatively high in 2016 and 2017 (50,105 km² and 68,408 km², respectively).

Egg production (P_0)

Figure 4–5 shows estimates of egg production and their associated 95% CI between 1995 and 2017. Following the second mass mortality event, egg production declined from 87.51 eggs.day⁻¹.m⁻² in 1998 to 35.42 eggs.day⁻¹.m⁻² in 1999. Between 2000 and 2014, egg production was highly variable and ranged between 38.00 and 120.75 eggs.day⁻¹.m⁻². In 2017, egg production was estimated at 108.63 eggs.day⁻¹.m⁻².

Sex ratio (R)

Estimates of sex ratio from fishery-independent samples ranged between 0.44 in 2003 and 0.68 in 2013 (Figure 4–5). The variability reflects the challenges of sampling Sardine representatively.

Mean female weight (W)

Estimates of W ranged from 45.2 g in 1998 to 78.7 g in 2004 (Figure 4–5). In 2017 W was estimated to be 59.51 g. Fishery-independent samples were mainly taken from shelf waters and typically larger than commercial catch samples that were mainly taken from the Gulfs Zone.

Batch fecundity (F)

Batch fecundity was not estimated in 1995 and 1996 because no hydrated females were caught in adult sampling. Between 1997 and 2017, estimates of F from fishery-independent samples ranged between 13,600 and 23,736 hydrated oocytes (Figure 4–5). Variations in F between years mainly reflected variations in gonad-free female weight (and W).

Spawning fraction (S)

Estimates of S varied between 0.04 in 2017 and 0.18 in both 1999 and 2001 (Figure 4–5). Estimates of S for 2003 and 2004 were based on less than 500 females.

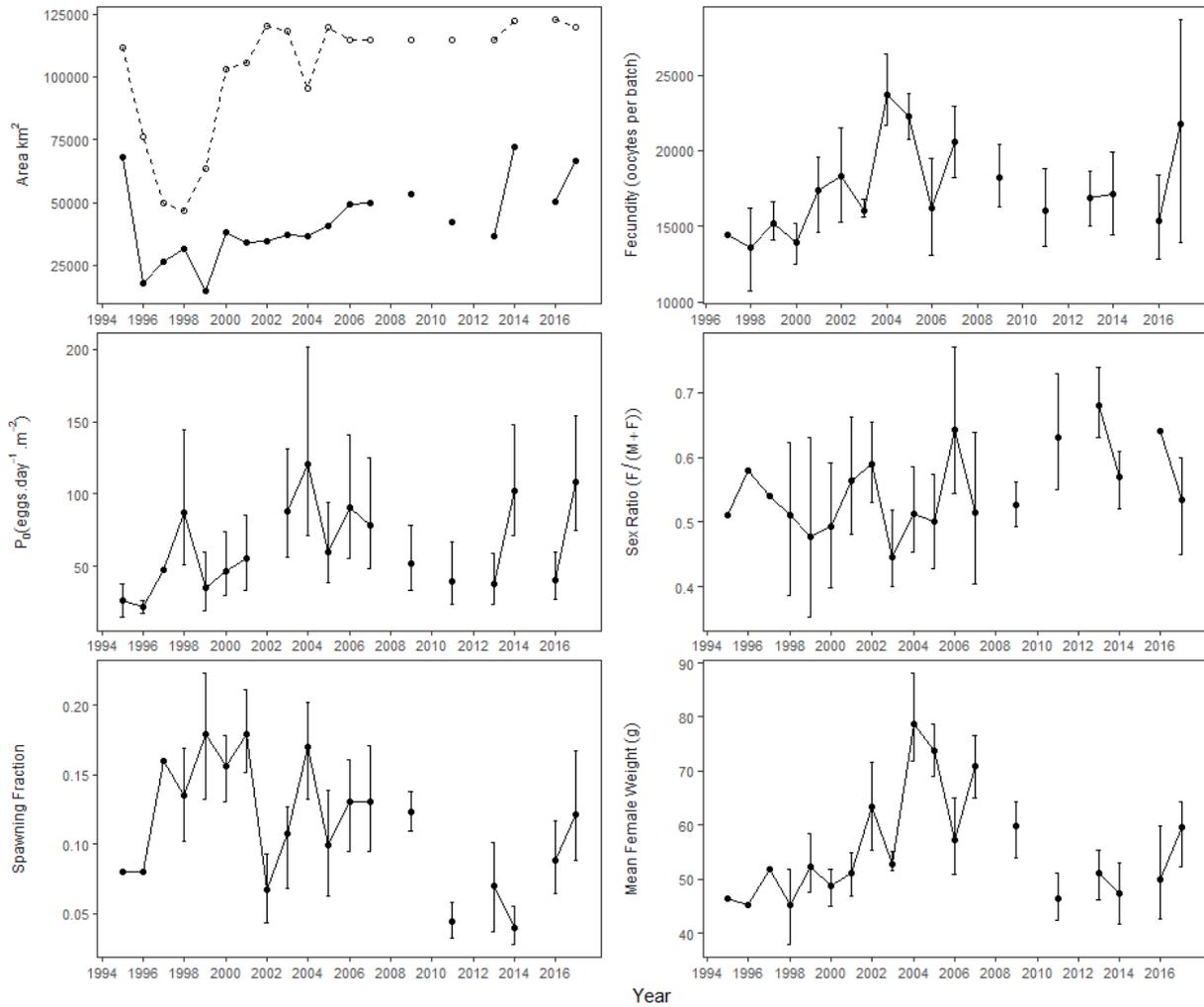


Figure 4–5. Spawning biomass parameters ($\pm 95\%$ CI) used for Sardine from 1995–2017.

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. Hence, there is no reliable estimate of the spawning biomass prior to the first mass mortality event in late 1995. The estimate of spawning biomass declined to 37,000 t in 1996 following this mass mortality event but increased to 59,000 t in 1997 (Ward *et al.* 2001a).

Estimates of Stock biomass between 1998 and 2009 (Figure 4–6) have been recalculated after a review by Ward *et al.* (in review) that investigated opportunities for improving the precision of estimates of mean daily egg production (P_b). Spawning biomass estimates increased from 21,285 t (95% CI = 12,000–38,000) in 1999 to 180,000 t (103,000–337,000) in 2002. Estimates of spawning biomass remained between 161,000 and 231,000 t for 2003 to 2005, and then increased to 223,000 t (141,000–380,000) in 2006 and 199,000 t (102,000–360,000) in 2007. The estimates of spawning biomass between 2009 and 2016 ranged from 115,000t (58,000–267,000) in 2013 to 290,000t (218,000–396,000) in 2014. In 2017, the stock biomass was estimated as 305,068 t (176,000–521,000), which is the largest estimate of spawning biomass obtained for the SASF.

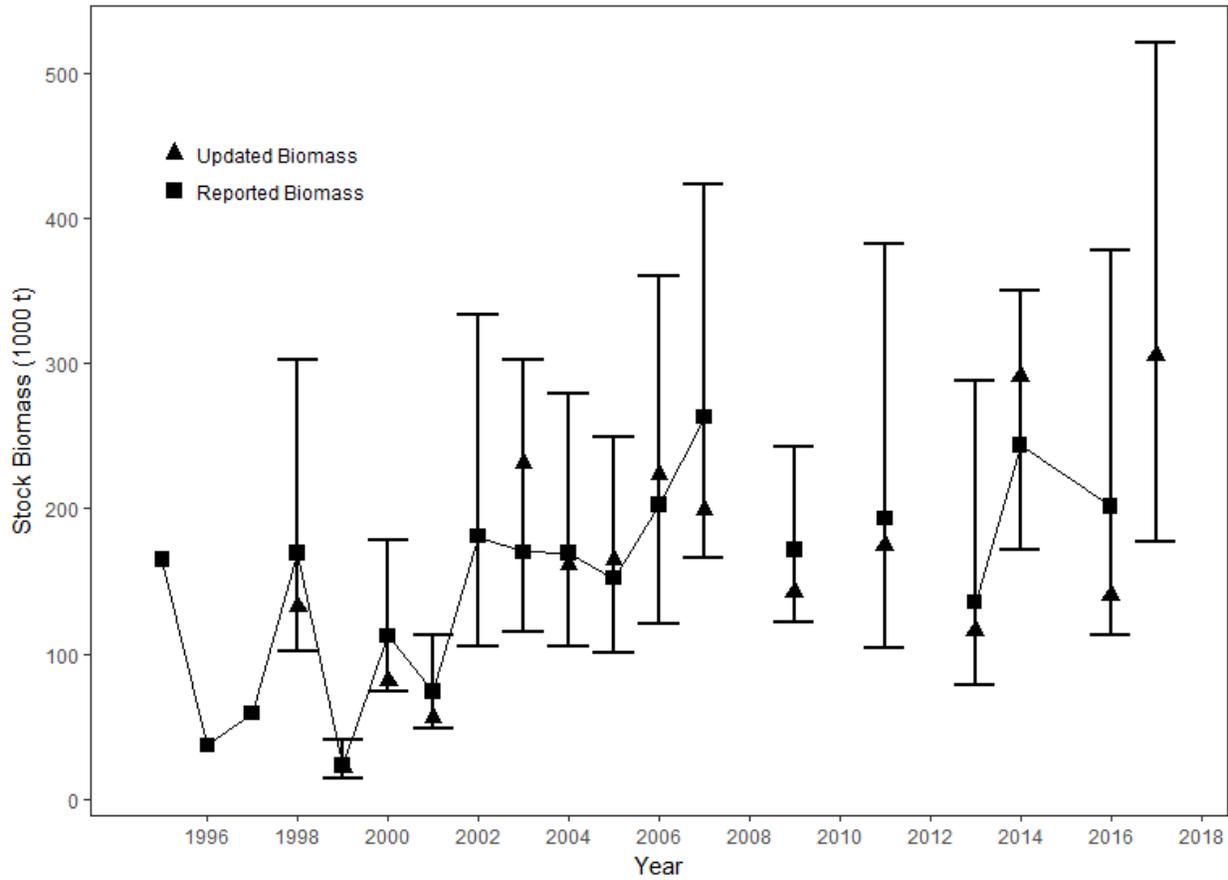


Figure 4–6. Daily Egg Production Method (DEPM) estimates of spawning biomass ($\pm 95\%$ CI) for Sardine in South Australian waters from 1995–2017. Updated biomass estimates are represented by black triangles. These were calculated using the updated methods for calculating P_0 presented in Ward *et al.* (2017) using universal egg stages.

4.4. Discussion

The DEPM has been integral to the sustainable development of the SASF. It has provided information about the size of spawning stock of Sardine in waters off South Australia that has underpinned the growth of the fishery. The estimate of spawning biomass for 2017 provides strong evidence that the southern stock of Sardine is sustainable. However, the time series presented here also demonstrates the main limitation of the DEPM, i.e. that estimates of spawning biomass are imprecise (Cochrane 1999).

Interannual variations in estimates of spawning biomass are mainly driven by three parameters: egg production, spawning fraction and spawning area. The low estimate of spawning biomass for 2013 demonstrates the effects that errors in estimating one or more of these parameters can have on findings. The failure of the 2013 egg survey to cover the entire spawning area was a key driver of the low estimate of spawning biomass for that year. From 2014 onwards, an adaptive approach to egg sampling has been adopted which uses the CUFES to ensure that egg surveys cover the entire spawning area (within predefined spatial limits). Similarly, the absence of a method for sampling adults in offshore waters, and the resulting limitations of the estimate of spawning fraction, reduced the reliability of the estimate of spawning biomass obtained in 2014.

The high variances of estimates of mean daily egg production contribute significantly to the high levels of uncertainty in estimates of spawning biomass observed in this and other studies (Fletcher *et al.* 1996, Ward *et al.* 2001a, Gaughan *et al.* 2004, Stratoudakis *et al.* 2006; Bernal *et al.* 2012; Dickey-Collas *et al.* 2012). For Sardine off South Australia, uncertainties associated with estimates of egg production have been addressed by using the log linear-model to estimate this parameter. This approach was recommended by Ward *et al.* (2011b) because the log-linear model provides more conservative and precise estimates of egg production than other methods (i.e. exponential model, various GLMs). Unlike other models, the log-linear model does not provide unrealistically high estimates of egg production in years when a few samples contain very large numbers of young eggs (Ward *et al.* 2011b). A recent re-analysis of data available for Sardine off South Australia confirmed the suitability of this approach (Ward *et al.* in review).

The other key parameter driving uncertainty in estimates of spawning biomass of Sardine off South Australia is spawning fraction. It is widely recognised (e.g. Stratoudakis *et al.* 2006) that the effects of uncertainty in this parameter are greatest for species with low spawning fractions (e.g. Sardine, ~10%) and lowest for species with high spawning fraction (e.g. Snapper, ~85%, Steer *et al.* 2017). For Sardine off South Australia, the potential impacts of uncertainty of

estimates of spawning fraction on estimates of spawning biomass have been mitigated by adopting an approach which is likely to produce high (i.e. conservative) estimates of spawning fraction and thus low estimates of spawning biomass. This approach involves using fish with day–0, day–1 and day–2 post-ovulatory follicles and hydrated oocytes to estimate spawning fraction (see Ward *et al.* 2011b). Adopting a conservative approach to estimating spawning fraction that minimises the chance of over-estimating the spawning biomass has been important for the SASF. This is because despite extensive efforts (e.g. conducting a fishery-independent trawl survey), a method for sampling adult Sardines that can be used throughout the spawning area has not yet been established. As a result of this limitation, the spawning fraction of Sardine in offshore waters of South Australia, where many eggs have been collected over the last decade, remains poorly understood.

The other approach that has been used in the SASF to address uncertainties associated with estimates of spawning biomass obtained using DEPM has been to establish a harvest strategy which is based around conservative exploitation rates and which is relatively robust to year to year fluctuations in spawning biomass (i.e. keeps TACCs stable unless there are large changes in spawning biomass). For example, the maximum TACC is capped at the level set when the spawning biomass is greater than 190,000 t; higher estimates of spawning biomass do not result in higher TACCs. This approach has proven to be highly effective in developing the SASF. However, adopting a more precise indicator of the size of the spawning stock biomass using knowledge gained over the last two decades also warrants consideration.

The DEPM parameter with the strongest influence on estimates of spawning biomass is spawning area (Mangel and Smith 1990, Gaughan *et al.* 2004). Establishing spawning area as the key performance indicator for the SASF may address uncertainty in estimates of spawning biomass resulting from the combined imprecision and potential biases associated with estimating egg production and spawning fraction. For example, in 2016, spawning area was used as a proxy for spawning biomass due to uncertainties in estimates of both these parameters. Establishing spawning area as the key performance indicator for the SASF would require ongoing application and formalisation of the adaptive sampling protocols established in 2014 to ensure that the entire spawning area is sampled each year (within pre-determined spatial limits). Spawning biomass could still be estimated for use in population modelling and to provide context for estimates of spawning area. However, spawning area could potentially be established as the key performance indicator in the harvest strategy. The historical relationship between spawning area and spawning biomass could be used to set reference points to underpin decision rules for setting TACCs.

5. STOCK ASSESSMENT MODEL

5.1. Introduction

This chapter describes the application of an integrated stock assessment model for the SASF. This assessment model was a statistical catch-at-age model that was developed using Stock Synthesis (Methot and Wetzel 2013; Version 3.24S) and describes the fishery as a single stock, fleet and area. This model fits to commercial catch data (Chapter 2), fishery-dependent age-composition data (Chapter 3) and fishery-independent estimates of spawning biomass obtained using the DEPM (Chapter 4). Biological parameters (e.g. growth and maturity) are estimated from fishery-dependent and fishery-independent data (Chapter 3)

The Stock Synthesis model was used to estimate numbers-at-age for all years in the fishery (1992–2017) and calculate quantities used in fisheries management, particularly spawning stock biomass (i.e. female adult biomass). The SASF was previously assessed using a simpler age-structured stock assessment model developed as part of an FRDC funded project (Ward *et al.* 2005). This model was used in stock assessments until 2012 (Ward *et al.* 2010, 2012) before transitioning to the current assessment model for 2015 (Ward *et al.* 2015). The previous model (Pre–2015) had known limitations that included large uncertainties and wide confidence bounds on estimates of spawning biomass, difficulties in estimating natural mortality (especially time varying mortality), difficulty fitting to age-composition data and a reliance on subjective model likelihood weightings. The current Stock Synthesis assessment model addressed these issues and has permitted a number of innovations and improvements for the assessment of the SASF that include:

1. Estimations of stock recruitment deviations from an assumed underlying stock recruitment relationship using penalised likelihoods and bias adjustments (Methot and Taylor 2011).
2. Adjustments of time varying and age-specific natural mortality that can be altered to represent the mass mortality events of the SASF in 1995 and 1998 (Ward *et al.* 2001b).
3. Improved fits to age-composition data.
4. Estimation of dome-shaped selectivity (as a ‘double-normal’ curve) that better represents the reduced availability of older fish in the main fishing areas (i.e. Spencer Gulf).
5. A more robust data-weighting approach consistent with Francis (2011, 2017).

5.2. Methods

5.2.1. Base-case model

The 2017 stock assessment model (see Appendix) was developed using the software Stock Synthesis (Methot and Wetzel 2013), which was developed using the open-source model development software ADMB (Fournier *et al.* 2012). Model diagnostics, including model selection, and plots of outputs, were done using the open-source R package 'r4ss' (Version 1.24.0, Taylor *et al.* (2015)). The model specifications are given in the Appendix.

Model structure

The 2017 stock assessment model is age-structured, sex-dependent and assumes a single area, fleet and stock for the SASF. All available data from 1992–2016 as well as spawning biomass estimates from 2017 have been integrated into the model. Fish recruit to the model at age 0+ years and experience both natural (M) and fishing (F) mortality annually. Each year surviving fish progress to the next age class until they reach the final age class (9+) where they remain until they are fished or die from natural causes.

Prior to 1992, the population was assumed to have been in a state of unfished equilibrium (see Chapter 2). Unfished equilibrium recruitment (R_0) was estimated in relation to an assumed Beverton-Holt stock-recruitment relationship parameterised to include a steepness term (h) that was fixed at 0.9.

Annual recruitments deviations were estimated with the standard deviation of variation of the stock-recruitment relationship (σ_R) fixed at 0.8. Recruitment, associated standard errors and bias adjustment were estimated following Methot and Taylor (2011) between 1992–2017. Forecast recruitments (2017 onwards) were assumed to follow the underlying stock-recruitment relationship. In previous assessments (Ward *et al.* 2015), recruitment deviations were fixed from 2011 onwards due to difficulties in estimating these parameters for recent years. Given the additional years of data are available in the current assessment, there was no need to adjust the recruitment deviations in these years.

Biological parameters

The biological parameters (i.e. growth and maturity) used in the models were based on information presented in previous chapters. Previous analyses have found no significant temporal changes to these parameters of the history of the fishery, or that there has been insufficient

sampling to detect such changes (Ward *et al.* 2010, 2012, 2015). Each parameter was fixed at historical values and held constant in the stock assessment model.

Growth was assumed to follow the von Bertalanffy growth function with sex-independent parameters (Table 5–1). Sex specific weight-length relationships were derived from both commercial and fishery independent samples. An allometric relationship of the form $W = A * FL^B$ was applied, where W is weight in kg, FL is caudal fork length in mm and A and B are the scaling and power coefficients respectively. These parameters were estimated via non-linear regression using the 'nls' function in 'R' (Table 5–1).

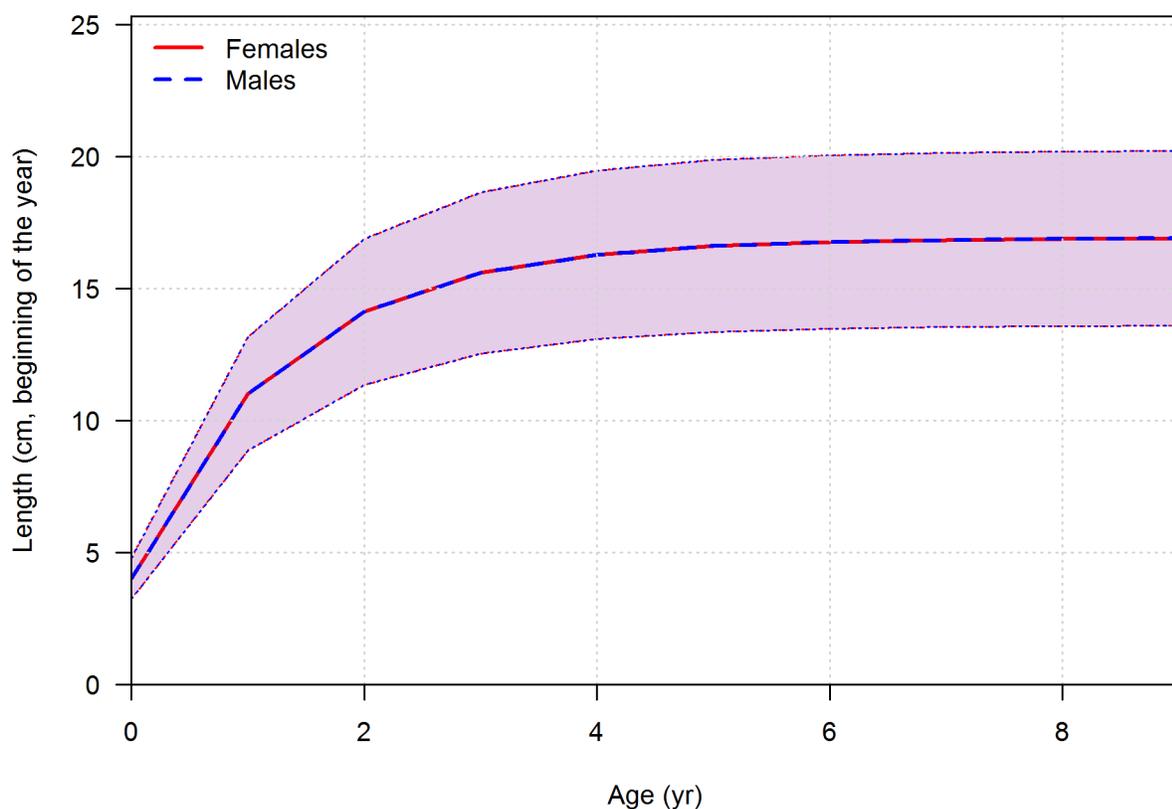


Figure 5–1. Model input relationship between age (years) and length (mm) for female and male Sardine (expected growth) with assumed CV = 0.1 for young and old ages.

Natural mortality (M) was assumed to be constant for all ages, across all years with the exception of 1995 and 1998. In those years, two mass mortality events each killed an estimated 70% of the adult population (Ward *et al.* 2001b). Accordingly, natural mortality was configured in the model

to vary for adult fish (≥ 3 years) in those years. This was achieved by estimating a baseline M in those years and applying an additional deviation from that estimate to that portion of the population. Maturity was configured as a logistic ogive as a function of age, with an age at 50% maturity (A_{50}) of 2.5 years with a slope of 5 (Figure 5-2). These values were determined using a conversion from growth and length-at-maturity parameters presented in Chapter 3. The female sex ratio was set at 0.54 as this is the mean sex ratio over the history of the fishery (Chapter 3).

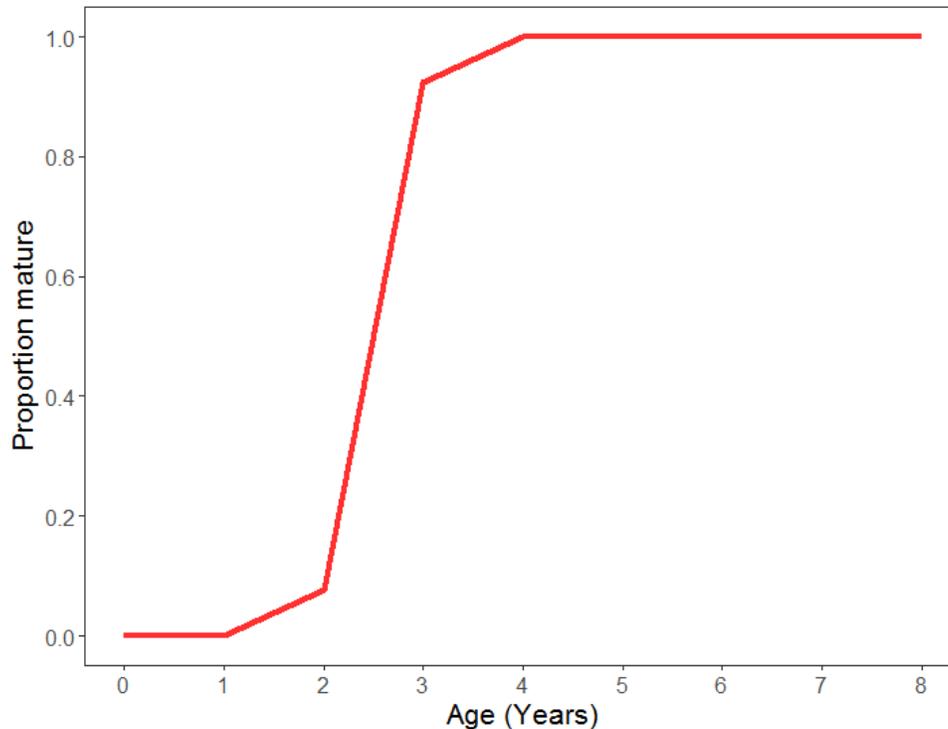


Figure 5–2. Model input relationship between age (years) and maturity (proportion) for female Sardine (expected age-at-maturity), represented by a logistic function with $A_{50} = 2.5$ (inflection point) and slope parameter =-5.

Fishery parameters

The base-case assessment model assumes that fishing occurs across a single stock and single area, and that selectivity for the commercial fishing fleet is a time-invariant, dome-shaped function of age. This was implemented by estimating the parameters of a ‘double-normal’ function. This results in a selectivity curve with a descending right-side limb that mimics the expected reduced availability of older fish to the main components of the fishery, where younger (and smaller) fish dominate (Figure 5–5). The selectivity-at-age for the DEPM survey assumes all fish aged one and

greater are fully available to the survey, with the fully realised availability being proportional to the assumed maturity curve (Figure 5–2; 5–3). Table 5–1 lists the full specifications for the base-case assessment model.

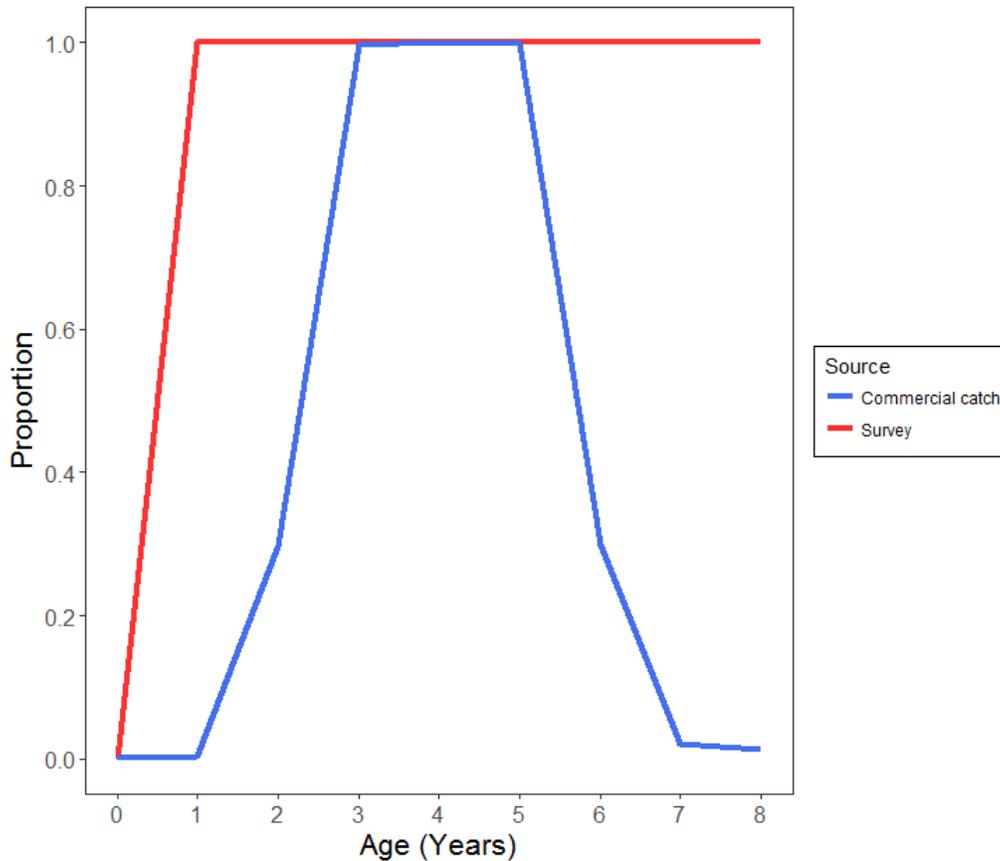


Figure 5–3. Age-based selectivity (expected proportion available to fishing/survey by age). Model estimated dome-shaped selectivity for the commercial purse seine fishery (blue line) and assumed selectivity-at-age for the spawning (DEPM) survey (red line).

Model selection and weighting

The model fit to the DEPM estimates of spawning biomass is based on the assumption that the expected value of the estimate is equal to the expected value of spawning biomass in any particular year. That is, the survey expected value is related to the spawning biomass by a survey catchability coefficient, $Q = 1$.

Data weighting can have a substantial impact on the outcomes of integrated stock assessment modelling (Francis 2011, 2017). The weighting approach of Francis (2011) was applied in this assessment. This approach can be summarised as: (a) the model should fit the trends in the abundance indices as well as possible; and (b) the yearly effective sample sizes and CVs assigned to the data should match the variation implied by the residuals.

During the 2015 SASF assessment, likelihood components were re-weighted during model fitting by adjusting additional multiplicative weighting values for the age composition data and the additive variance of the spawning biomass data (Ward et al. 2015). These methods resulted in the age composition data being down-weighted, such that the final multiplicative down-weighting value was set to 0.056 while a final value of 0.145 was added to variance term in the spawning biomass likelihood function.

In the current SASF assessment model, likelihood component weightings were re-visited. A range of options were examined including the re-weighting approach used in 2015 and the subjective likelihood component weightings used in 2012 (0.01 for age-composition data and 1 for spawning biomass and recruitment deviations) (Ward et al. 2012, 2015). Additionally, likelihood components were iteratively adjusted to determine the best model specification for the current assessment model.

Table 5–1. Model specifications for the base-case assessment model, developed using Stock Synthesis, Version 3.24S.

Specification	Base-case Model
Time-step	Yearly
Model years	1992–2017
Catch data	1992–2016
Spawning Abundance (DEPM)	1995–2007; 2009; 2011; 2013–14, 2016–17
CPUE index	Not included
Model age classes	Ages 0–9+
Age composition data	Ages 0–8+, 1995–2016 (excluding 2007)
Natural mortality (M)	
1992–94; 96,97; 1999+	M = 0.60
1995, 1998	Fixed Relative to base M, M = 1.47, Ages 3+ (~0.75 mortality rate)
Growth parameters	Fixed, time-invariant SS-von-Bertalanffy
K	0.75
L_{∞}	16.9
L_{Amin}	11 cm (est. size at age 1)
CV_{Young}, CV_{Old}	0.1
Length-weight relationship	Fixed power function (approx. cubic)
<i>A</i> (Scalar parameter)	5.03×10^{-6} (Female), 4.94×10^{-6} (Male)
<i>B</i> (Power parameter)	3.26 (Female), 3.27 (Male)
Maturity	Fixed logistic function of age
Inflection point (A_{50})	2.50 years
Slope parameter	-5
Fraction female	0.54
Stock-recruitment	Beverton-Holt function
Steepness, <i>h</i>	0.9
Recruitment variance, σ_R	0.8
Bias-adjustment years	1982–1994
Maximum bias-adjustment	0.91
Selectivity	
Commercial Fishery	Estimated, domed-shaped function of age (SS 'double-normal' function)

5.2.2. Input data

Data from multiple sources were integrated for the purposes of the assessment, including age-composition data, spawning stock biomass estimates from DEPM surveys (Ward et al. 2016), and

catch data from the commercial fishery. Table 5–1 shows the data used in the model by type, year, and data source.

Commercial catch data

Commercial catch data were available for all years between 1992 and 2016. Data based on catch disposal records (CDRs) were used as they are considered most accurate. Full details on the collection and analyses of commercial catch data are presented in Chapter 2. As no catch data was available for 2017, an assumption was made that the 2017 catch would match the quota; as has been the case for the last 10 years.

Fishery-independent spawning biomass estimates

Spawning biomass estimates obtained from annual DEPM surveys between 1995 and 2007, and 2009, 2011, 2013, 2014, 2016 and 2017 were used as a measure of absolute abundance in the model. The methodology for estimating daily egg production has recently been revisited and updated (Ward *et al.* 2017). This new methodology was applied retrospectively in the previous chapter over the history of the fishery to update estimates of annual spawning biomass. Estimates of spawning biomass for 2013 and 2014 are particularly uncertain due to difficulties estimating spawning area and spawning fraction, respectively. Accordingly, estimates of spawning biomass in those years were adjusted using average values of spawning area (2013 estimate), and of spawning fraction (2014 estimate) from all previous years (Ward *et al.* 2013, 2014). The adjusted values were used as inputs to the stock assessment model, with assumed CVs equal to the average CV across all previous years.

Age data

Age composition data from commercial catches were available for all years between 1995 and 2016, except for 2007. Ages were determined from an estimated otolith-weight-age relationship and applied to fish in commercial catch samples for which an otolith weight was available. Details on the collection of age-composition data and determination of age from otolith weights are presented in Chapter 3.

5.2.3. Sensitivity analyses and model diagnostics

The sensitivity of the base-case assessment model to changes in key parameters was tested in relation to important model outputs, such as the estimated time-series of spawning biomass. Sensitivity to the value chosen for steepness of the stock-recruitment relationship (h) was tested

for values of $h = 0.8$ and 0.95 . Sensitivity to the estimated value of the ‘base’ natural mortality (M) value was tested for fixed values of $M = 0.5$ and 0.7 .

Likelihood profile analyses were performed for natural mortality (M), steepness of the stock-recruitment relationship (h), and unfished equilibrium stock recruitment (R_0) for the base-case model. These analyses indicate the degree to which various data sources (and all data sources integrated together) provide information on estimates of these key parameters.

5.2.4. Stock Projections

The forecast feature of Stock Synthesis was implemented to project the biomass for 2018 given the quota set in 2017. Forecasts beyond 2018 are not presented as recent management measures designed to reduce catches of young fish (<2 years) have limited information available on recruitment and prevent accurate projections beyond 1–2 years.

5.3. Results

5.3.1. Analytical assessment

The base-case model fits well to commercial catch-at-age data aggregated across all years (Figure 5–4). Model fits are particularly good for 2005 and 2014. In 1996 and 1998, the model fits are quite poor, potentially due to difficulties in modelling the effects of and recovery from the mass mortality events. Good fits to the commercial catch-at-age data were observed despite the low weighting on these data in the base-case model.

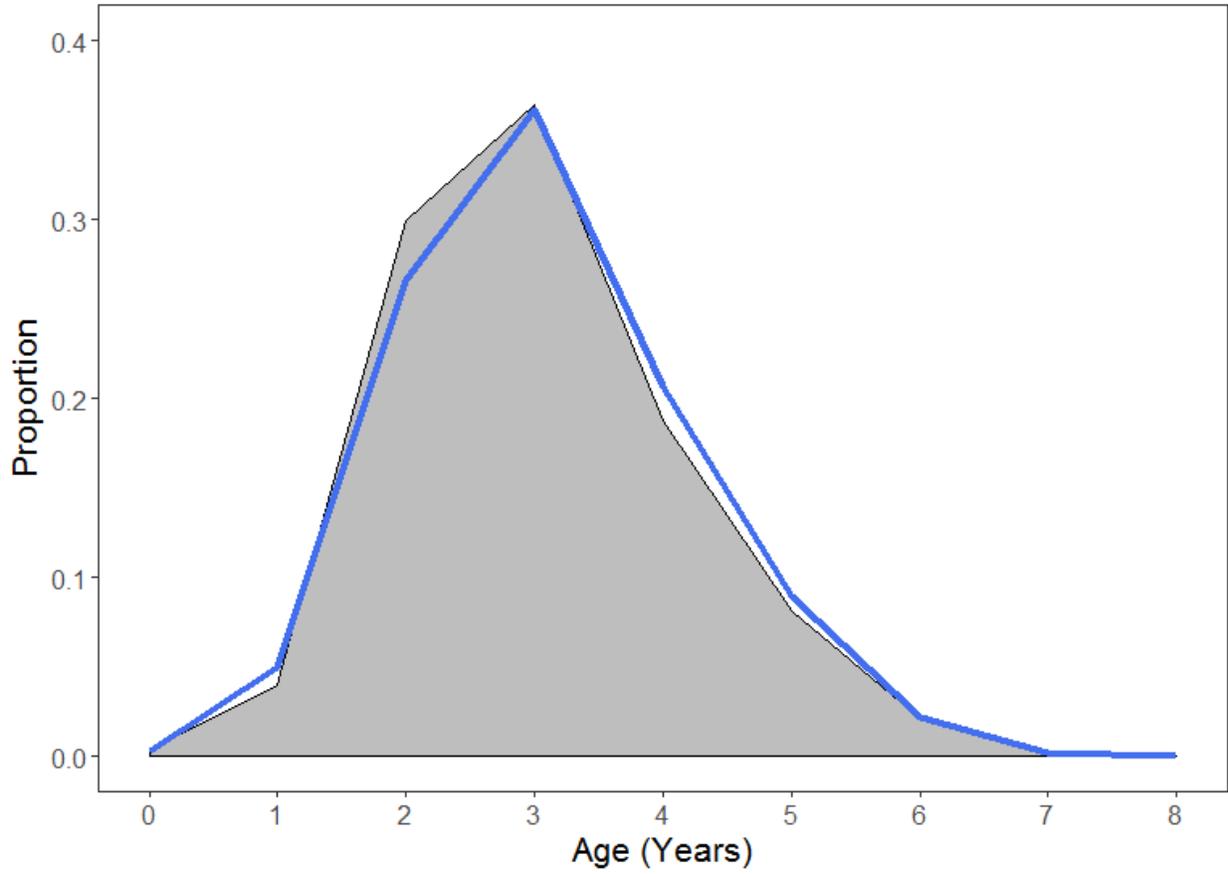


Figure 5–4. Base-case model fit (Blue line) to the aggregated age composition data (black lines and grey fill) across 1995–2016 for the commercial purse seine fishery of the SASF.

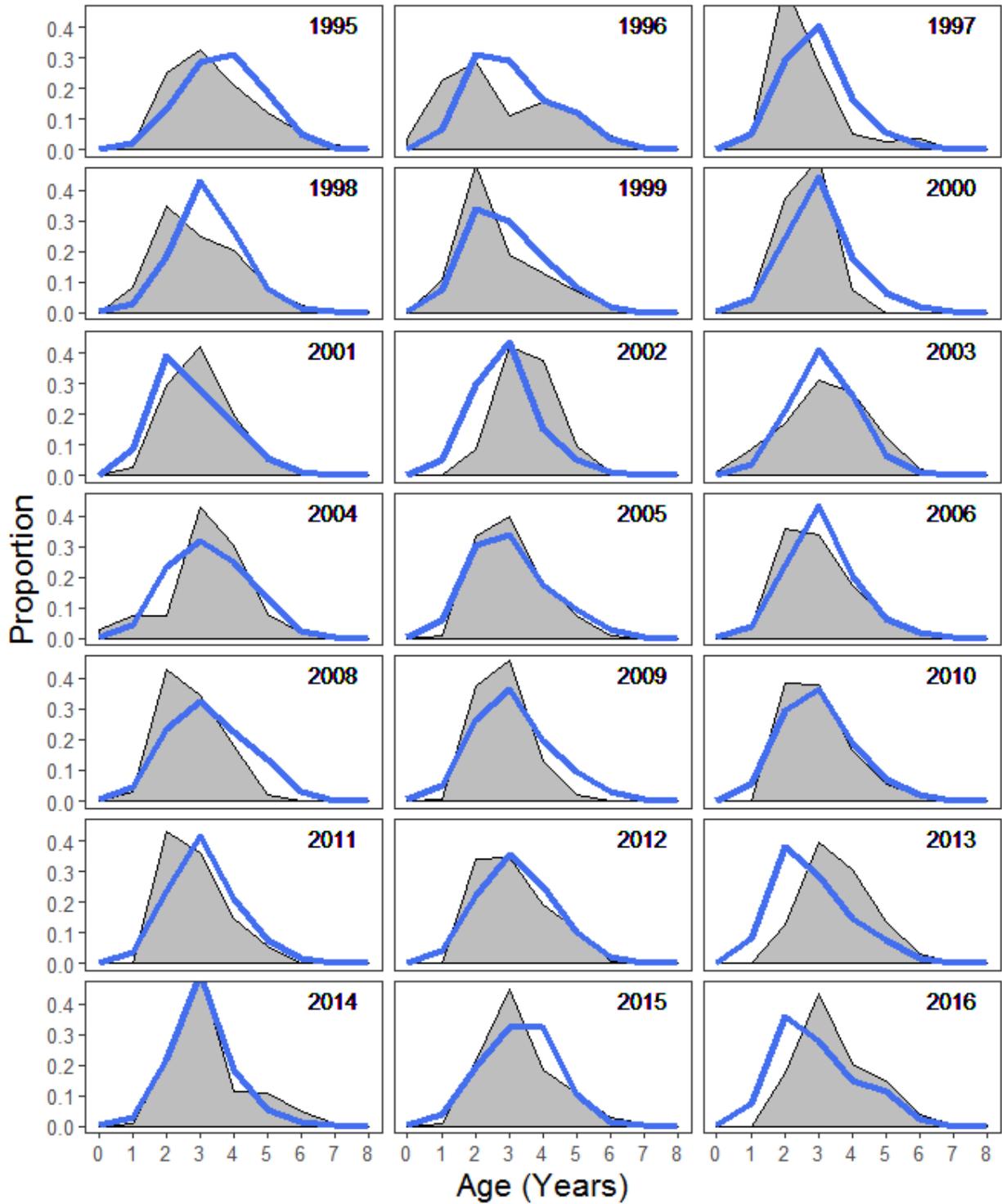


Figure 5–5. Base-case model fit (Blue line) to the annual age composition data (black lines and grey fill) across 1995–2016 for the commercial purse seine fishery of the SASF.

The base-case model fits more closely to the estimates of spawning biomass than models used in previous assessments (Ward *et al.* 2010, 2012, 2015), reflecting the lower weighting on commercial catch-at-age data in 2017. All model estimates lie within the 95% confidence intervals of the DEPM estimates (Figure 5–6). The assessment model acts to dampen the year-to-year variation observed in the DEPM estimates.

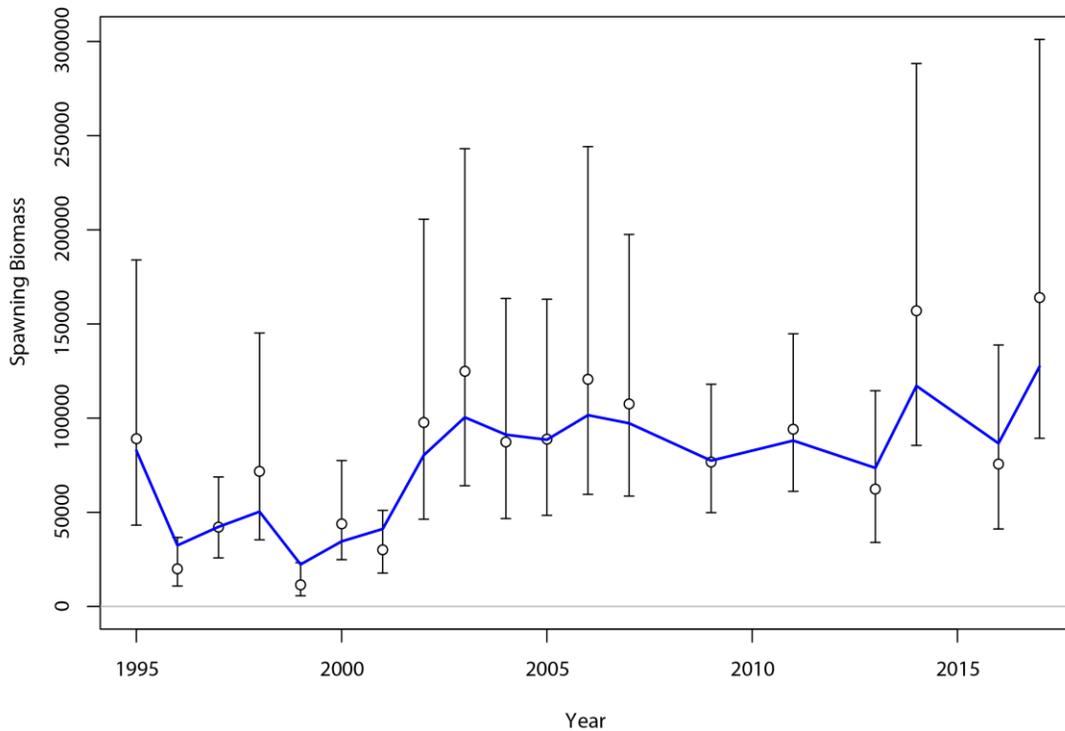


Figure 5–6. Base-case model fit (blue line) to the index of spawning biomass (females only) (black circles, \pm final input CVs) derived from Daily Egg Production Method (DEPM) surveys for the SASF.

The exploitation rate has increased over the history of the fishery (1992–2017); it is currently estimated to be approximately 22%. Annual estimates reveal an increase in exploitation rate in 1998, when spawning biomass was estimated to be low and recovering from the second mass mortality event (Ward *et al.* 2001b). This was followed by a significant increase in exploitation rate between 2000 and 2005, when catches peaked. Since that time (2006–2017) the exploitation rate of spawning biomass is estimated to have fluctuated between 15–30%.

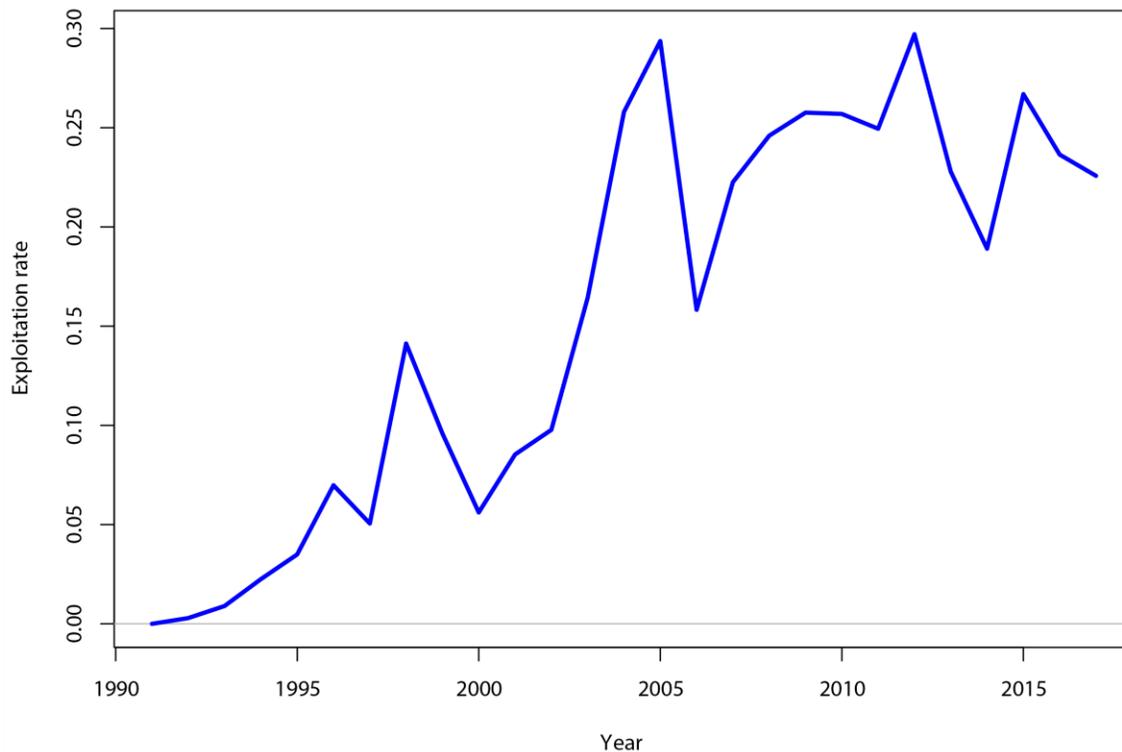


Figure 5–7. Model-derived estimates of spawning biomass exploitation rate between 1992–2017 for the commercial purse-seine fishery.

The estimated time-series of recruitment shows an increasing trend that was punctuated with large recruitment in some years (Figure 5–8). A high period of recruitment occurred in 1999 following the second mass mortality event in 1998 and two high periods of recruitment occurred in 2011 and 2014. The 2011 and 2014 peaks are linked to high biomass estimates in 2014 and 2017, respectively. As most fish are in the 3+ year age class (Figure 5–4), the assessment model

estimates high recruitments 3 years prior to each of these biomass peaks. Following these years of strong recruitment, the numbers of recruits have been lower and more stable.

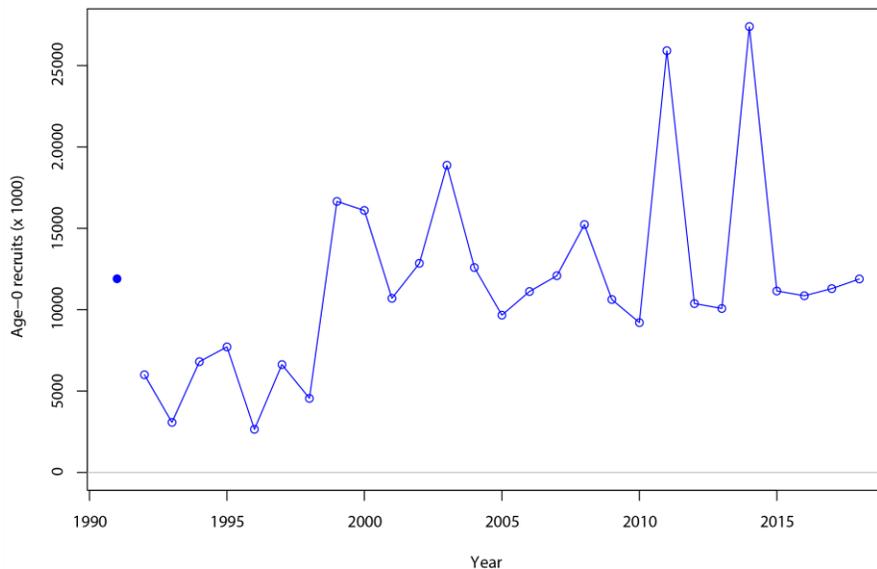


Figure 5–8. Model estimated recruitment series from 1992 until 2017, including the forecast recruitment (assumed to follow the underlying stock recruitment curve) for 2018.

5.3.2. Spawning Biomass

Under the base-case assessment model, unfished equilibrium total biomass (B_0) was estimated at approximately 200,000 t in 1992 (Figure 5–9). Estimates of total spawning biomass fell beneath the limit reference point (75,000 t) to approximately 60,000 t and 41,000 t in 1996 and 1999, respectively, following mass mortality events of 1995 and 1998 (Ward et al. 2001b). Following those declines, the spawning stock is estimated to have recovered and remained mostly above the target reference point (150,000 t) between 2003 and 2013. This was followed by the two peaks in stock biomass which reached 217,000 t in 2014 before decreasing in 2015–2016 and then peaking again at approximately 236,000 t in 2017. Currently the stock is estimated to be above pre-fishing levels (200,000 t in 1992) and is forecast (based on the Beverton-Holt stock recruitment relationship) to decrease to ~190,000 t in 2018 under the 2017 quota of 42,750 t.

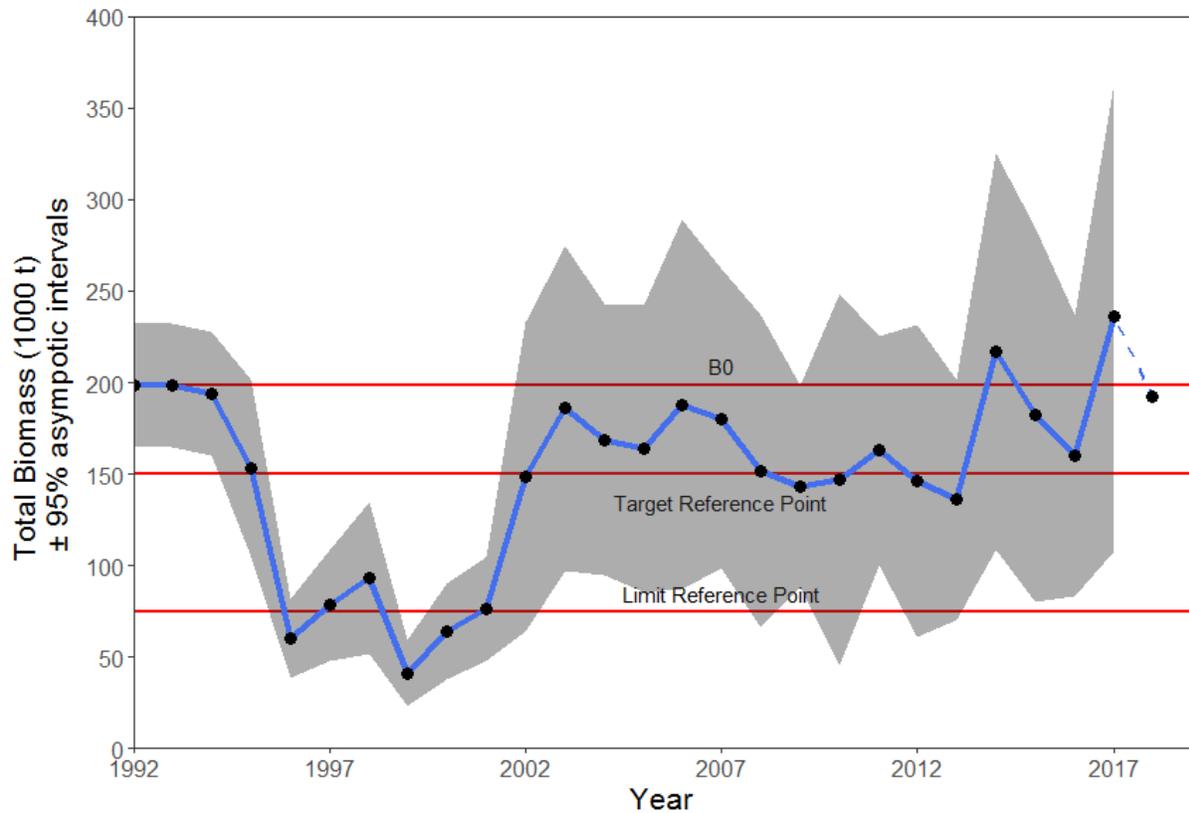


Figure 5–9. Time-series of base-case model estimates of total biomass (tonnes, solid blue line and black circles) with 95% confidence intervals (grey shading), including current (2017) estimated biomass and 2018 forecast biomass (dashed line). Three points of reference are included (red lines) which are the unfished equilibrium biomass (B_0) and the target and limit reference points from the SASF management strategy (PIRSA 2007, 2014)

5.3.3. Sensivity Analysis

5.3.3.1. Data weighting

Down weighting age composition data resulted in the best likelihood specifications for the current assessment model. This was achieved by reducing the multiplicative scalar of the variance term in the age composition likelihood component. Down weighting age composition data was also considered the best approach in previous assessments (Ward *et al.* 2012, 2015). The likelihood weightings used in the current assessment were many orders of magnitude lower (i.e. better) than simulations tested using the alternative likelihood specifications used in previous assessments

(Table 5–2). The likelihood weightings used in the 2017 base-case improved model performance compared to previous assessments.

Table 5–2. Various likelihood weightings applied to the current assessment model. Base-case are the final weightings used in this assessment model. Variance adjustment was where multiple variance components were adjusted. Individual likelihood component weighting are subjective likelihood weights applied directly to likelihood components.

Likelihood component	Base-case	Variance adjustment	Individual likelihood component weighting
Total Likelihood function	-9.50	80.86	9.21
Spawning Biomass	-16.39	-3.75	-13.45
Age Composition	2.92	80.43	19.29
Recruitment Deviations	3.17	2.29	2.30
Annual Fishing Mortality (F)	0.81	1.90	1.07

When the age composition data were not strongly down-weighted, low numbers of recruits were estimated beyond 2009 (Figure 5–10) and annual biomasses estimated by the model did not correspond well to the DEPM estimates (Chapter 4). This finding suggests that DEPM and age composition data provide conflicting inferences about the stock. When the age data were not down weighted, the model suggested that biomass peaked in 2012 and declined continuously through to 2017 (Figure 5–11). Down-weighting the age composition data using the base-case likelihood weights and the subjective weighting used in previous years provided improved model fits (Table 5–2). These approaches resulted in the estimated annual number of recruits being less influenced by the age composition data (Figure 5–10) and produced biomass estimates that were more reflective of DEPM estimates than when age composition data were not strongly down-weighted (Figure 5–11; Chapter 4).

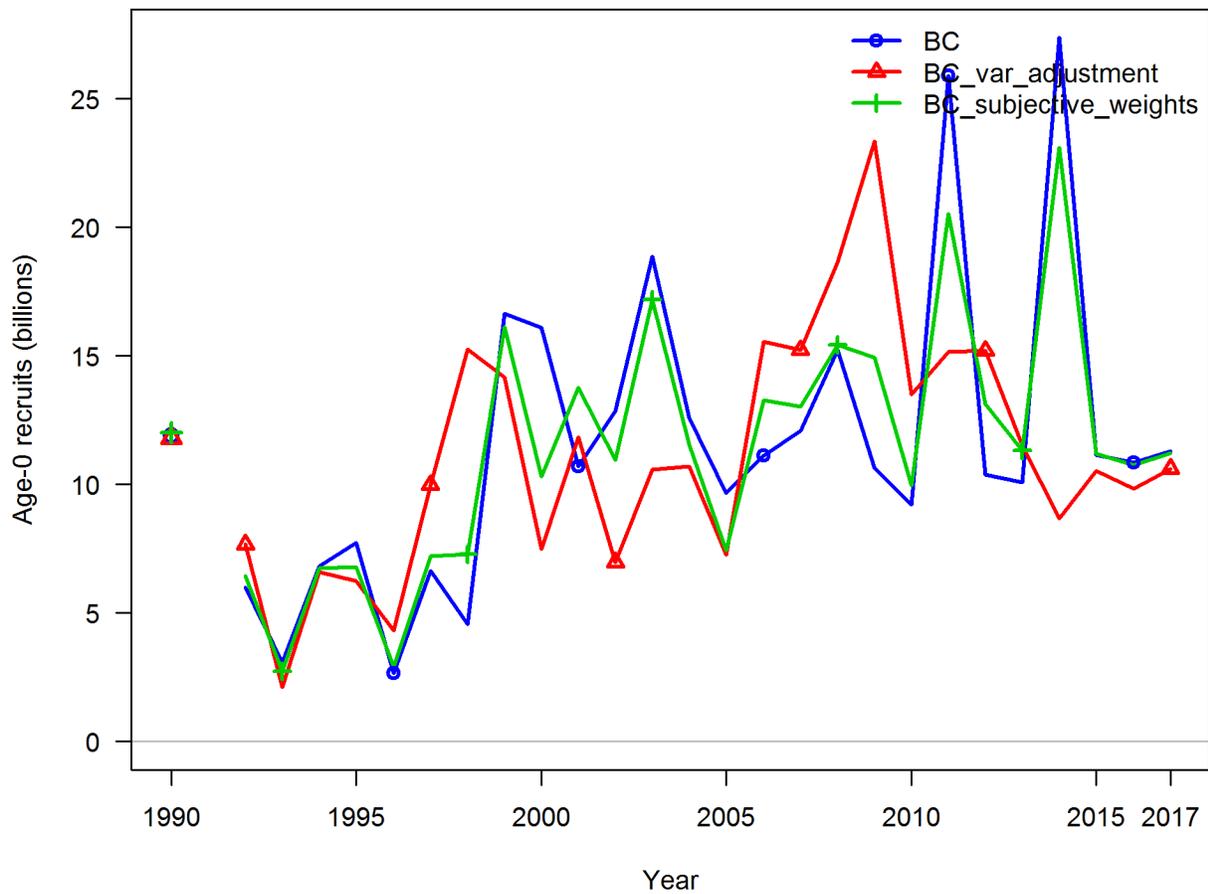


Figure 5–10. Time-series of estimated annual recruits from assessment models configured with different likelihood weightings. The blue line is the base-case model, the green line is the subjective likelihood weights that weight age-composition at 0.1 and the red line is the variance adjustments of 0.056 to the age composition data and 0.145 to the survey data CV.

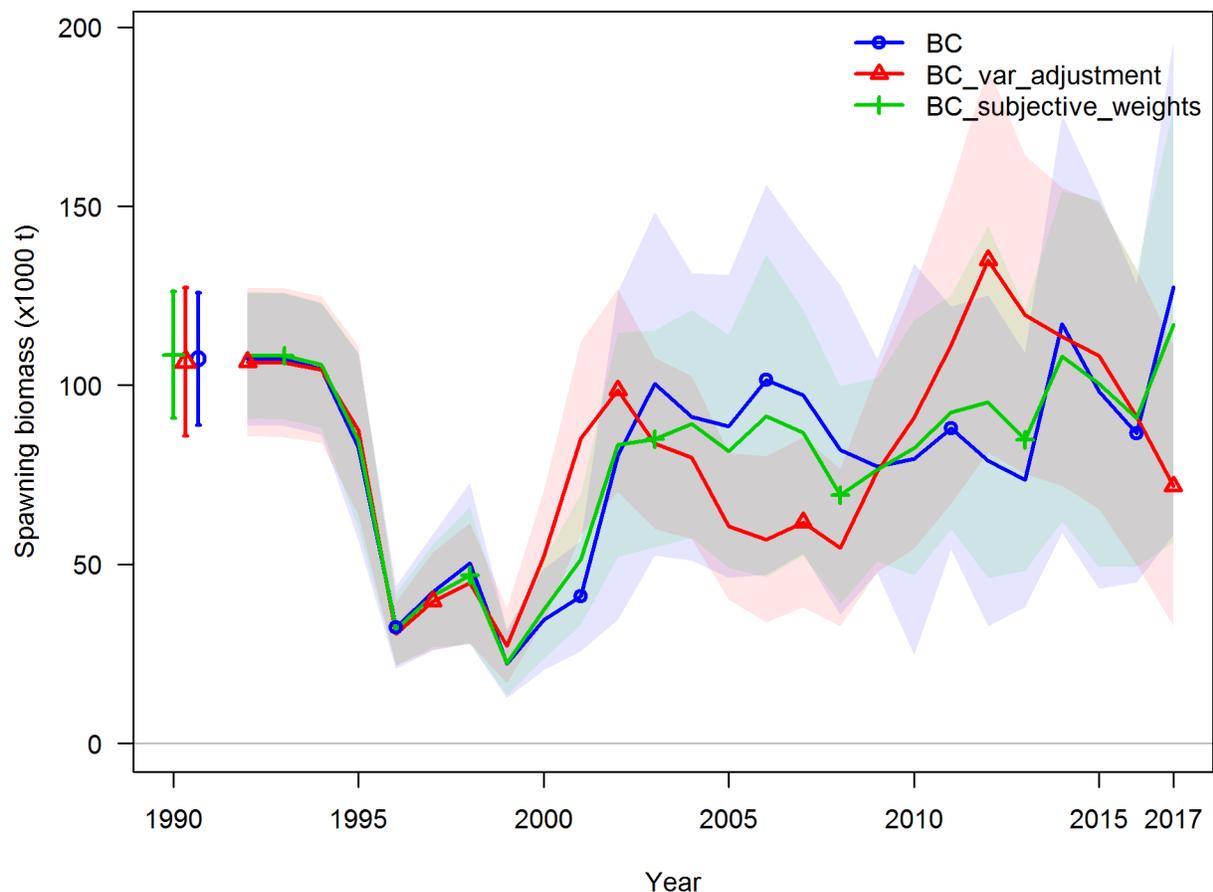


Figure 5–11. Time-series of estimated spawning biomass and 95% confidence intervals from models configured with different likelihood weightings. The blue line is the base-case model, the green line is the subjective likelihood weights that weight age-composition at 0.1 and the red line is the variance adjustments of 0.056 to the age composition data and 0.145 to the survey data CV.

5.3.3.2. Model diagnostics

Sensitivity analyses that included alternative values of the natural mortality (M ; Figure 5–12) and the stock recruitment steepness parameter (h ; Figure 5–13) did not influence the model estimates of spawning stock biomass. In most years, the biomass estimates remained identical with some minor variation occurring from 1992–1994 in both analyses.

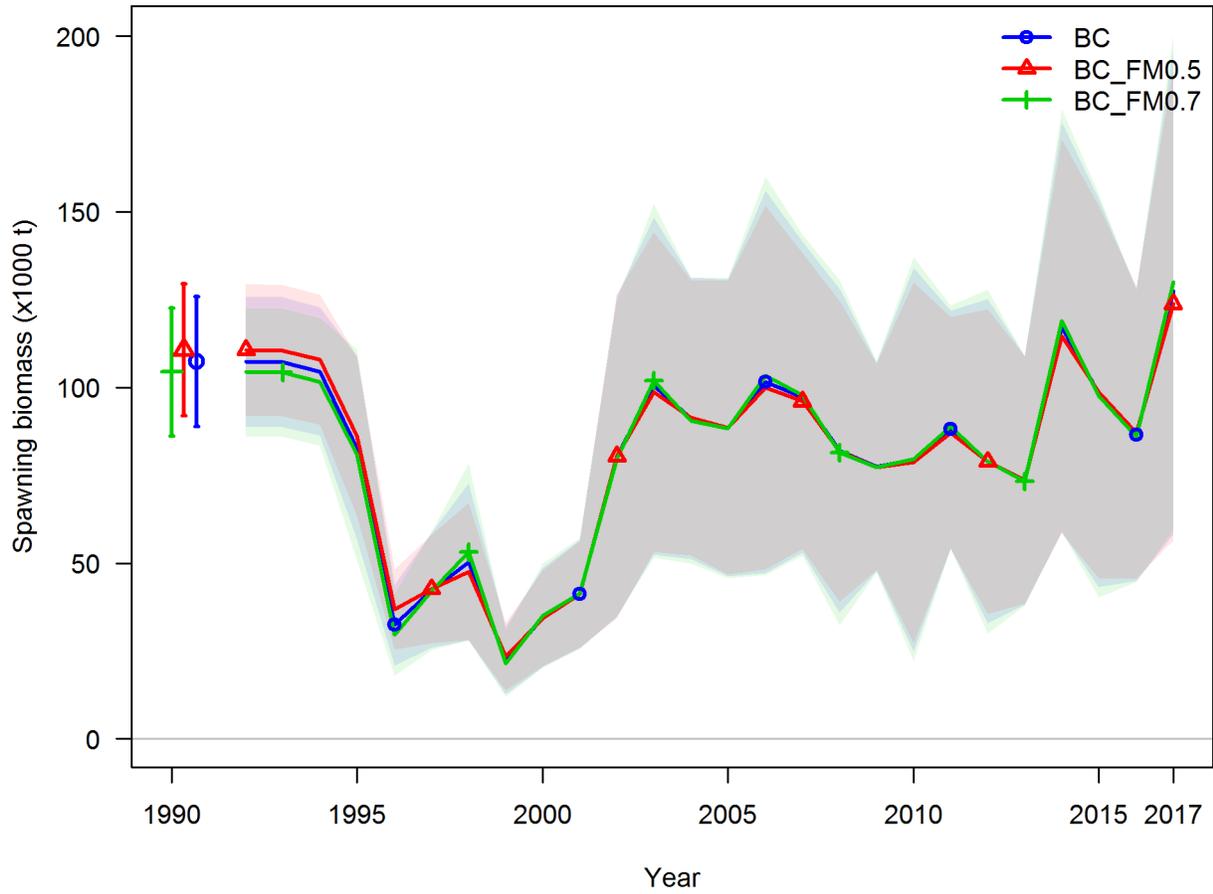


Figure 5–12. Time-series of estimated spawning biomass and 95% confidence intervals for the base-case model with estimated natural mortality, $M=0.6$ (blue line and points), compared to sensitivity tests with fixed natural mortality, $M = 0.5$ (red line and points), and $M = 0.7$ (green line and points).

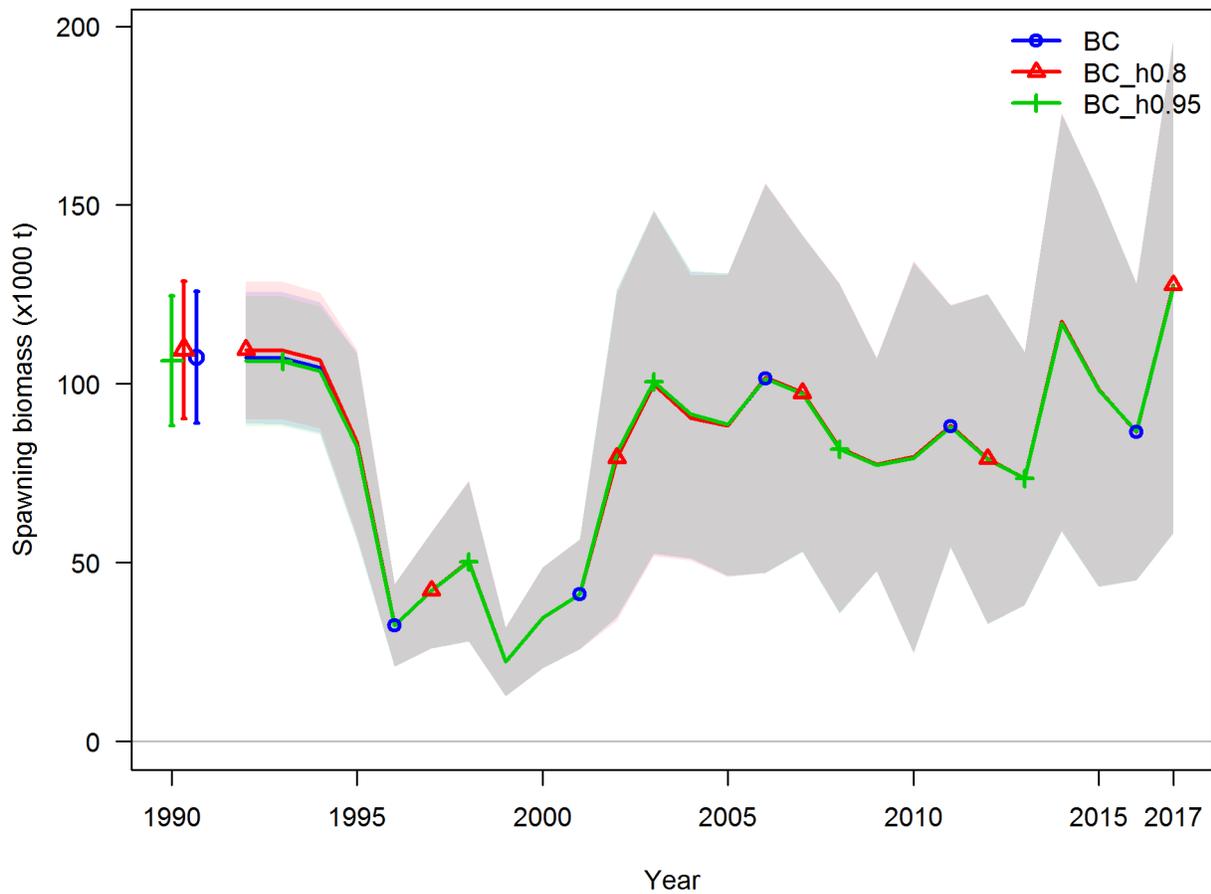


Figure 5–13. Time-series of estimated spawning biomass and 95% confidence intervals for the base-case model with fixed steepness ($h = 0.9$) of the stock-recruitment curve (blue line and points), compared to sensitivity tests with fixed $h = 0.8$ (red line and points), and $h = 0.95$ (green line and points).

5.4. Discussion

The age-structured model implemented in Stock Synthesis in 2017 is a significant improvement on models presented in previous stock assessment reports for the SASF (Ward *et al.* 2005; 2010, 2012; 2015). This improvement was achieved through configuring the assessment model with more appropriate data weightings. These configurations were needed to address changes in the fishery since 2012, including increased fishing effort in the Outside Zone (Chapter 2). As much of the adult stock resides offshore, the catch from the Outside Zone has an older age composition than the Gulfs Zone (Chapter 3). As the model does not take into account spatial patterns of fishing, this change in age composition is interpreted as low recruitment in the preceding years. Not down-weighting the age composition resulted in a high biomass estimate for 2012, which then declined steeply due to the apparent low recruitment. Down-weighting the age composition data in this assessment resulted in the number of recruits being estimated predominately from the estimates of spawning biomass (Chapter 4) rather than the age compositions. These changes resulted in estimates of recruitment and biomass that reflect estimates of stock biomass obtained using the DEPM. The strong effect that data weighting has on the model estimates of recruitment and biomass demonstrate the uncertainties inherent in the model. Model outputs need to be interpreted with caution due to uncertainties in both the DEPM estimates of spawning biomass and the catch-at-age data, that are reflected in the broad confidence intervals around model estimates of stock biomass.

The base-case model demonstrates the **Sustainable** status of the Southern Stock of Australian Sardine. It estimates that the stock size in 2017 is the largest in the history of the fishery (consistent with the high DEPM estimate of spawning biomass, Chapter 4) with a total stock size of 236,000 t. This estimate of biomass is higher than the estimated unfished equilibrium of 200,000 t (prior to 1992), although confidence intervals around both estimates are large. As the current year's biomass is larger than the estimated virgin level, it is expected to decrease in 2018 as the stock currently fluctuates around the theoretical carrying capacity. However, there is some evidence to suggest that the size of the spawning stock off South Australia may have increased over time (Chapter 4 of this report, Goldsworthy *et al.* 2013), despite the relatively high levels of fishing effort over the last two decades. For this reason, the 2018 biomass forecast should be interpreted with caution. The apparent large decline in the spawning biomass in 2018 under the current TACC of 42,750 t may reflect the assumption that the biomass will return to the theoretical carrying capacity.

The current assessment model suggests that the management targets that have been in place for the past several years for the SASF are appropriate (PIRSA 2007, 2014). Reviews of Australia's small pelagic fisheries have recommended that stocks remain at 50% of pre-fishing levels (B_{50}), with a less than 10% chance of the stock decreasing below 20% of unfished levels (B_{20}) during a 50 year period (Smith *et al.* 2015). International studies have recommended that stocks should be maintained above 75% of pre-fishing levels (B_{75}) in order to maintain ecosystem integrity (Smith *et al.* 2011). The target reference point for the SASF was set at 150,000 t as it was considered to be a conservative estimate of B_{75} (PIRSA 2007, 2014). Modelling conducted in this report supports this assessment as virgin biomass (B_0) was estimated as 200,000 t (i.e. 150,000 t equals B_{75}).

Currently, the assessment model is structured as a single stock, fleet and area. As much of the spawning biomass is offshore, modelling the SASF as a multi-area fishery with different age-structures and size/age selectivity warrants consideration. The successful implementation of the 2017 model is a substantial step forward for assessment of the fishery, despite the uncertainty surrounding key outputs. Importantly, the assessment model could be adapted to conduct management strategy evaluations to inform the development of future harvest strategies for the SASF.

6. DISCUSSION

6.1 Stock status and uncertainty

Under the criteria outlined in the decision rules of the harvest strategy for the SASF (PIRSA 2014), the Southern Stock of Australian Sardine is classified as **Sustainable**. The DEPM estimate of spawning biomass for 2017 of 305,068 t is above the target reference point of 150,000 t and above the upper reference point of 190,000 t. The model estimate of spawning biomass for 2017 of 236,000 t is also above the target reference point and above the estimated pre-fishing level of 200,000 t in 1992. The spawning biomass in 2018 (i.e. after the 2017 TACC of 42,750 t has been taken) is forecast to remain at or above the upper reference point of ~190,000 t.

Although estimates of spawning biomass obtained using the DEPM are recognised as being imprecise (e.g. Stratoudakis *et al.* 2006, Bernal *et al.* 2012, Dickey-Collas *et al.* 2012), the large estimate of spawning biomass for 2017 provides strong evidence that the Southern Stock of Sardine is above the upper target reference point of 190,000 t. The strongest single piece of empirical evidence indicating that the Southern Stock of Sardine is in a **Sustainable** is that the spawning area recorded during the 2017 survey (68,408 km²) was the second largest on record. It is widely recognised that spawning area is a reliable indicator of the size of the spawning stock of pelagic fish such as Sardine (e.g. Mangel and Smith 1990, Gaughan *et al.* 2004).

The population modelling undertaken in this report addresses some of the uncertainty in estimates of spawning biomass obtained using the DEPM and smooths out inter-annual fluctuations. However, model outputs need to be interpreted with caution due to uncertainties in data sources (i.e. DEPM estimates of spawning biomass and catch-at-age data) that are reflected in the broad confidence intervals around the model estimates of stock biomass. In particular, the potential for smoothing of inter-annual fluctuations to mask real increases or decreases in spawning biomass needs to be taken into account when interpreting the results. Uncertainties surrounding the catch-at-age data are particularly important because recent changes in management arrangements and fishing patterns have meant that catch samples are not representative of the population. This problem is not resolved by current assumptions about size/age selectivity. It is important to note the catch-at-age data and DEPM surveys provide different inferences about the historical trends in stock size. In this assessment, this conflict was addressed by down-weighting the influence of the catch-at-age data. However, the large differences in the biomass trends resulting from the different weightings on the catch-at-age data demonstrate the high levels of uncertainty associated with the model outputs.

6.2 Management implications

Recent studies (e.g. Ward et al. 2011; in review) and data presented in this report suggest that significant increases in the precision of estimates of the spawning biomass of Sardine off South Australia will be difficult to achieve due to the combined challenges of estimating mean daily egg production and spawning fraction. However, improving estimates of these two parameters remains a high priority for the SASF, because currently there is no viable alternative to the DEPM for estimating the size of spawning stock of Sardine off South Australia. An FRDC project has recently commenced to assess whether the precision of estimates of mean daily egg production can be improved by collecting samples using oblique rather than vertical plankton tows. An industry-based program will be undertaken in 2018 to assess the potential for using samples obtained from commercial vessels to estimate spawning fraction in the Outside Zone of the SASF.

Results presented in this report suggest that as well as trying to improve the precision of estimates of spawning biomass consideration should be given to establishing an alternative key performance indicator in the harvest strategy for the SASF. One option for tracking the future status of the Sardine population off South Australia is to use spawning area as an indicator of stock status, as suggested by Mangel and Smith (1990) and Gaughan et al. (2004). It is notable that spawning area has been used as an informal proxy for spawning biomass in the SASF when estimates of one or more parameters have produced uncertain estimates of spawning biomass (e.g. Ward et al. 2014, 2016). Establishing spawning area as an indicator of stock status may address current difficulties associated with estimating both egg production and spawning fraction reliably, and may provide the most precise option for tracking year to year fluctuations in stock size. Reference points could potentially be established on the basis of the historical relationship between spawning area and spawning biomass (SARDI unpublished data). Sampling protocols for using the CUFES to underpin adaptive sampling would need to be established to ensure that surveys cover the entire spawning area (within predefined limits of recent surveys).

An alternative approach to addressing uncertainties in the DEPM estimates of spawning biomass would be to use model outputs of spawning biomass as the key performance indicator for the SASF. However, this approach is problematic because the two main sources of information used in the model (i.e. DEPM estimates of spawning biomass and catch-at-age data) provide conflicting inferences about the stock size. As is the case with many population models, it is likely that some of the key model assumptions do not match the characteristics of the stock. For example, there is some evidence to suggest that the Sardine stock off South Australia may have increased over time (Goldsworthy et al. 2013, Chapter 4 of this report), whereas the model assumes that the

stock will fluctuate around the theoretical environmental carrying capacity (equal to B_0). The fact that the spawning biomass estimate for 2017 exceeded B_0 may explain the large decline in spawning biomass in 2018 forecast by the model under the current TACC of 42,750 t.

6.3 Future directions

Using estimates of spawning biomass obtained with the DEPM as the key performance indicator has facilitated the rapid and sustainable development of the SASF. The application of methods for estimating egg production and spawning fraction that produce conservative estimates of spawning biomass has been critical to this success. Establishing a harvest strategy that accounts for this uncertainty has also been important. Consideration should be given to assessing the suitability of establishing spawning area as the key performance indicator in the harvest strategy for the SASF. This option should be evaluated because spawning area is a good indicator of stock size and can be estimated more reliably than spawning biomass. Historical data would need to be re-analysed to confirm that this parameter is a suitable proxy for spawning biomass and to identify suitable reference points for inclusion in the harvest strategy. Adaptive sampling protocols and analytical procedures would also need to be established to ensure that spawning area is estimated as robustly as possible.

Establishing spawning area as the key performance indicator in the management plan for the SASF would not reduce the need to continue to improve the precision of estimates of spawning biomass obtained using the DEPM. Efforts to improve the precision of estimates of egg production and spawning fractions should continue because estimates of spawning biomass is the key source of information driving the population model. Estimates of spawning biomass would also be needed to provide context for the estimates of spawning area. Consideration should also be given to further developing the population model as a multi-area fishery with varying age-structures and size/age selectivity.

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APPENDIX: SS3 INPUT FILES FOR THE BASE-CASE MODEL**STARTER.SS**

```

# SSV3.24S
# Starter File
# South Australian Sardine Fishery, 2017
# Jonathan Smart, SARDI, jonathan.smart@sa.gov.au

sardine.dat
sardine.ctf
0 # 0=use init values in control file; 1=use ss3.par
2 # run display detail (0,1,2)
1 # detailed age-structured reports in REPORT.SSO (0,1)
0 # write detailed checkup.sso file (0,1)
0 # write parm values to ParmTrace.sso (0=no,1=good,active; 2=good,all; 3=every_iter,all_parms;4=every,active)
0 # write to cumreport.sso (0=no,1=like&timeseries; 2=add survey fits)
0 # Include prior_like for non-estimated parameters (0,1)
1 # Use Soft Boundaries to aid convergence (0,1) (recommended)
0 # Number of bootstrap datafiles to produce
5 # Turn off estimation for parameters entering after this phase
0 # MCMC burn interval
0 # MCMC thin interval
0 # jitter initial parm value by this fraction
-1 # min yr for sdreport outputs (-1 for styr)
-1 # max yr for sdreport outputs (-1 for endyr;-2 for endyr+Nforecastyrs)
0 # N individual STD years
0.0001 # final convergence criteria (e.g. 1.0e-04)
0 # retrospective year relative to end year (e.g.-4)
0 # min age for calc of summary biomass
1 # Depletion basis: denom is: 0=skip; 1=rel X*B0; 2=rel X*Bmsy; 3=rel X*B_styr
1 # Fraction (X) for Depletion denominator (e.g. 0.4)
4 # (1-SPR)_reporting: 0=skip; 1=rel(1-SPR); 2=rel(1-SPR_MSY); 3=rel(1-SPR_Btarget); 4=notrel
1 # F_std reporting: 0=skip; 1=exploit(Bio); 2=exploit(Num); 3=sum(frates)
0 # F_report_basis: 0=raw; 1=rel Fspr; 2=rel Fmsy ; 3=rel Fbtgt
999 # check value for end of file

```

CONTROL FILE 'SARDINE.CTL'

```

# SSV3.24S
# Control File
# South Australian Sardine Fishery, 2017
# Jonathan Smart, SARДИ, Jonathan.Smart@sa.gov.au

1 #_N_Growth_Patterns
1 #_N_Morphs_Within_GrowthPattern

1 #_Nblock_Designs
2 # Number of blocks per design
# Beginning and ending years of blocks:
1995 1995 1998 1998

# Biological specifications
0.54 #_Fracfemale
1 #_NatM_type:_0=1Parm; 1=N_breakpoints;_2=Lorenzen;_3=agespecific;_4=agespec_withseasinterpolate
2 #_Number of breakpoints
# Age at each breakpoint
2.5 3.0

1 #_GrowthModel: 1=vonBert with L1&L2; 2=Richards with L1&L2; 3=age_speciific_K; 4=not implemented
1 #_Growth_Age_for_L1
999 #_Growth_Age_for_L2 (999 to use as Linf)
0 #_SD_add_to_LAA (set to 0.1 for SS2 V1.x compatibility)
0 #_CV_Growth_Pattern: 0 CV=f(LAA); 1 CV=F(A); 2 SD=F(LAA); 3 SD=F(A); 4 logSD=F(A)
2 #_maturity_option: 1=length logistic;2=age logistic;3=read age-maturity matrix by growth_pattern; 4=read age-
fecundity; 5=read fec and wt from wtatage.ss
1 #_First_Mature_Age
1 #_Fecundity option:(1)eggs=wt*(a+b*wt);(2)eggs=a*L^b;(3)eggs=a*wt^b; (4)eggs=a+b*L; (5)eggs=a+b*W
0 #_Hermaphroditism option: 0=none; 1=age-specific fxn
3 #_Parameter_offset_approach (1=none, 2= M, G, CV_G as offset from female-GP1, 3= M and CV old offset to young
same sex (as per SS2 V1.x)
1 #_Env/block/dev_adjust_method (1=standard; 2=logistic transform keeps in base parm bounds; 3=standard w/ no bound
check)

# Mortality and growth parameters
# Lo Hi Init Prior Prior Prior Param Env Use Dev Dev Dev Block Block
# bnd bnd value mean type SD phase var dev minyr maxyr SD design func
0.40 0.80 0.60 0 -1 0.8 -2 0 0 0 0 0.5 0 0 # M at age <=2.5
0.00 1.00 0.00 0 -1 0.8 -2 0 0 0 0 0.5 1 2 # M at age >=3.0 (exp offset)
10.8 11.2 11 0 -1 0.8 -3 0 0 0 0 0.5 0 0 # Lmin
16.5 17.2 16.9 0 -1 0.8 -2 0 0 0 0 0.5 0 0 # Lmax
0.66 0.86 0.75 0 -1 0.8 -3 0 0 0 0 0.5 0 0 # VBK
0.01 0.20 0.1 0 -1 0.8 -3 0 0 0 0 0.5 0 0 # CV young
-3 3 0 0 -1 0.8 -3 0 0 0 0 0.5 0 0 # CV old: exp offset to CV young

```

```

# Males (Offset to females)
-3 3 0 0 -1 0.8 -3 0 0 0 0 0.5 0 0 # M at age <=2.5: exp offset to GP 1
(female)
-3 3 0 0 -1 0.8 -3 0 0 0 0 0.5 1 2 # M at age >=3.0: exp offset to GP 1
(female)
-3 3 0 0 -1 0.8 -3 0 0 0 0 0.5 0 0 # Lmin: exp offset to GP 1 (female)
-3 3 0 0 -1 0.8 -2 0 0 0 0 0.5 0 0 # Lmax: exp offset to GP 1 (female)
-3 3 0 0 -1 0.8 -3 0 0 0 0 0.5 0 0 # VBK: exp offset to GP 1 (female)
-3 3 0 0 -1 0.8 -4 0 0 0 0 0.5 0 0 # CV young: exp offset to GP 1 (female)
-3 3 0 0 -1 0.8 -4 0 0 0 0 0.5 0 0 # CV old: exp offset to CV young (male)

# Weight-length and maturity parameters (L in cm, w in kg)
# Females
# Lo Hi Init Prior Prior Prior Param Env Use Dev Dev Dev Block Block
# bnd bnd value mean type SD phase var dev minyr maxyr SD design function
-3 3 5.03e-6 0 -1 0.8 -3 0 0 0 0 0.5 0 0 # W-L scale (Female) (Parameter A in
W=A*L^AB, weight in kg)
3 4 3.26 0 -1 0.8 -3 0 0 0 0 0.5 0 0 # W-L power (Female) (Parameter B in
W=A*L^AB, weight in kg)
0 3 2.5 0 -1 0.8 -3 0 0 0 0 0.5 0 0 # Age at 50% maturity (Logistic curve
inflection point)
-6 3 -5 0 -1 0.8 -3 0 0 0 0 0.5 0 0 # Maturity slope (Logistic curve slope,
must have a negative value)
-3 3 1 0 -1 0.8 -3 0 0 0 0 0.5 0 0 # Fecundity: Intercept eggs/gm
-3 3 0 0 -1 0.8 -3 0 0 0 0 0.5 0 0 # Fecundity: Slope eggs/gm

-3 3 4.94e-6 0 -1 0.8 -3 0 0 0 0 0.5 0 0 # W-L scale (Male) (Parameter A in
W=A*L^AB, weight in kg)
1 4 3.27 0 -1 0.8 -3 0 0 0 0 0.5 0 0 # W-L power (Male) (Parameter B in
W=A*L^AB, weight in kg)

# Distribute recruitment among growth pattern x area x season
-4 4 0 0 -1 99 -3 0 0 0 0 0.5 0 0 # RecrDist_GP_1
-4 4 0 0 -1 99 -3 0 0 0 0 0.5 0 0 # RecrDist_Area_1
-4 4 0 0 -1 99 -3 0 0 0 0 0.5 0 0 # RecrDist_Seas_1

# Cohort growth (K) deviation parameter
1 1 1 1 -1 99 -5 0 0 0 0 0.5 0 0 # CohortGrowDev

# Cond: MG time-block setup:
1 # (0=Read one line apply all, 1=read one line each parameter)
# Block parameters for M:
0.0 2.00 0.90 0 -1 99 -3 #Nat_M_Breakpoint Block 1, 1995 Mass Mortality (Females)
0.0 2.00 0.90 0 -1 99 -3 #Nat_M_Breakpoint Block 1, 1998 Mass Mortality (Females)
0.0 2.00 0.90 0 -1 99 -3 #Nat_M_Breakpoint Block 1, 1995 Mass Mortality (Males)
0.0 2.00 0.90 0 -1 99 -3 #Nat_M_Breakpoint Block 1, 1998 Mass Mortality (Males)

```

```

# Seasonal_effects_on_biology_parms
#_femwtlen1, femwtlen2, mat1, mat2, fec1, fec2, Malewtlen1, malewtlen2, L1, K
0 0 0 0 0 0 0 0 0 0

# MG_Deviations Parm Phase (CONDITIONAL, if any MG parameters use annual-devs, then estimation for the deviations will
begin in this phase)
#4

# Spawner-recruit parameters
3 #_SR_function: 2=Ricker; 3=std_B-H; 4=SCAA; 5=Hockey; 6=B-H_flattop; 7=survival_3Parm
# Lo Hi Init Prior Prior Prior Param
# bnd bnd value mean type SD phase
10 20 15 0 -1 10 1 # Ln(R0) # SR_R0
0.2 1 0.9 0 -1 0.5 -2 # Steepness # SR_steep
0 2 0.8 0 -1 0.8 -3 # Sigma R # SR_sigmaR
-5 5 0.0 0 -1 1 -3 # Environmental link coefficient # SR_envlink
-5 5 0.0 0 -1 1 -4 # Initial equilibrium offset to virgin # SR_R1_offset
0.0 0.5 0.0 0 -1 99 -2 #_Reserve for future autocorrelation # SR_autocorr

# Spawner-recruit set-up
0 #_SR_env_link
0 #_SR_env_target_0=none;1=devs;_2=R0;_3=steepness

1 # do_recr_dev: 0=none; 1=devvector; 2=simple deviations
1992 # first year of main recr_devs; early devs can precede this era
2017 # last year of main recr_devs; forecast devs start in following year
2 #_recdev phase
1 # (0/1) to read 13 advanced options
0 #_recdev_early_start (0=none; neg value makes relative to recdev_start)
-1 #_recdev_early_phase
0 #_forecast_recruitment phase (incl. late recr) (0 value resets to maxphase+1)
1000 #_lambda for prior_fore_recr occurring before endyr+1
1982 #_last_early_yr_nobias_adj_in_MPD
1994 #_first_yr_fullbias_adj_in_MPD
2011 #_last_yr_fullbias_adj_in_MPD
2017 #_first_recent_yr_nobias_adj_in_MPD
0.533 #_max_bias_adj_in_MPD
0.0 # period for recruitment cycles-use only if modelling seasons as years
-5 # min rec_dev
5 # max rec_dev
0 #_read_recdevs
# End of advanced SR options

#Fishing Mortality info
0.2 # F ballpark for tuning early phases
2000 # F ballpark year (neg value to disable)
3 # F_Method: 1=Pope; 2=instan. F; 3=hybrid (hybrid is recommended)
4 # max F or harvest rate, depends on F_Method

```

```

4      # N iterations for tuning F in hybrid method (recommend 3 to 7)

# Initial_F_parms
# Lo  Hi  Init  Prior Prior Prior Param
# bnd bnd  value mean  type  SD   phase
0.00  1   0.00  0    -1   99  -1   # Commercial_PS

# Catchability Q_setup
# Q_type options: <0=mirror, 0=float_nobiasadj, 1=float_biasadj, 2=parm_nobiasadj, 3=parm_w_random_dev,
4=parm_w_randwalk, 5=mean_unbiased_float_assign_to_parm
0  0  0  0  # 1 Commercial_PS
0  0  0  2  # 2 Spawn_Survey

# Q parameters
# Lo  Hi  Init  Prior Prior  Prior  Param
# bnd bnd  value mean  type  SD   phase
-2   2   0   0   -1   99  -2   # Fix Q=1, such that index is assumed to be absolute abundance.

# Size_selex_types
# Discard_options:_0=none;_1=define_retention;_2=retention&mortality;_3=all_discarded_dead
# Pattern, Discard, Male, Special
0  0  0  0  # 1 Commercial_PS # Set commercial size selectivity = 1.0 for all sizes (and use age-based
selectivity)
30 0  0  0  # 2 Spawn_Survey # Set special selectivity 30, expected survey abundance equal to spawning biomass

# Age_selex_types
# Pattern, Discard, Male, Special
20 0  0  0  # 1 Commercial_PS # Double normal
10 0  0  0  # 2 Spawn_Survey # Age selectivity = 1.0 for all ages, (special selex defined in size-selex section)

# Age_selex_parms
# Lo  Hi  Init  Prior Prior  Prior  Param Env Use Dev  Dev  Dev  Block  Block
# bnd bnd  value mean  type  SD   phase var dev minyr maxyr SD  design function

# Age_Selex_Parms 1: Commercial_PS (Double normal)
0.0  9.9  3.0  0  -1   99  2  0  0  0  0  0.5  0  0  # 1 Peak3
-10.0  3.0 -5.0  0  -1   99  3  0  0  0  0  0.5  0  0  # 2 Top
-4.0  12.0  2.5  0  -1   99  3  0  0  0  0  0.5  0  0  # 3 Asc-width
-2.0  6.0  2.0  0  -1   99  3  0  0  0  0  0.5  0  0  # 4 Desc-width
-15.0  5.0 -10.0  0  -1   99  4  0  0  0  0  0.5  0  0  # 5 Init
-15.0  5.0 -10.0  0  -1   99  4  0  0  0  0  0.5  0  0  # 6 Final

# Cond: Custom_sel-env_setup
# Cond: 2 2 0 0-1 99-2 #_placeholder when no enviro fxns

# Cond: selex time-block setup:
# 1 # (0=Read one line apply all, 1=read one line each parameter)

```

```
# Tag loss and tag reporting
0 # 0=no read; 1=read if tags exist

### Likelihood related quantities ###
# Variance adjustments to input values
1 #_variance_adjustments_to_input_values (1/0 on/off)
# One column for each fleet/survey
0.000 0.000 # constant added to survey CV
0.000 0.000 # constant added to discard SD
0.000 0.000 # constant added to body weight SD
1.000 1.000 # multiplicative scalar for length comps
0.000 1.000 # multiplicative scalar for agecomps
1.000 1.000 # multiplicative scalar for length at age obs

5 # Max number of lambda phases: read this number of values for each component below
1 # SD offset (CPUE, discard, mean body weight, recruitment devs): 0=omit log(s) term, 1=include

2 # number of changes to make to default Lambdas (default value is 1.0)
# Like_comp codes: 1=surv; 2=disc; 3=mnwt; 4=length; 5=age; 6=SizeFreq; 7=sizeage; 8=catch;
# 9=init_equ_catch; 10=recrdev; 11=parm_prior; 12=parm_dev; 13=CrashPen; 14=Morphcomp; 15=Tag-comp; 16=Tag-negbin

#like_comp fleet/survey phase value sizefreq_method
# Lamba value for survey index:
1 2 1 1 1

# Lambda value for age data:
5 1 1 1 1

0 # (0/1) read specs for more stddev reporting
999 # EOF
```

DATA FILE 'SARDINE.DAT'

```
# SSV3.24S
# Data File
# South Australian Sardine Fishery, 2017
# Jonathan Smart, SARDI, Jonathan.Smart@sa.gov.au
```

```
1992 #_styr
2017 #_endyr
1 #_nseas
12 #_months/season
1 #_spawn_seas
1 #_Nfleet
1 #_Nsurvey
1 #_N_areas
```

Commercial_PS%Spawn_Survey

```
#1 2
0.35 0.20 # Timing_in_season (sardine fishing peaks Mar-Jun, spawning and survey occur Feb-Mar)
1 1 # Area_assignments_for_each_fishery_and_survey
1 # Units of catch: 1=bio; 2=number
0.05 # SE of log(catch) only used for init_eq_catch and for Fmethod 2 and 3

2 # Nsexes (females (1), then males (2))
9 # Accumulator age (+group, must be older than oldest age data)
0 # Init_equil_catch_for_each_fishery
```

26 # Number of years of catch data

# value	Year	Season
464.883	1992	1
1435.404	1993	1
3241.230	1994	1
2597.000	1995	1
3531.000	1996	1
3500.000	1997	1
7312.000	1998	1
4080.000	1999	1
3290.000	2000	1
7507.000	2001	1
14450.000	2002	1
26137.000	2003	1
36631.000	2004	1
42475.000	2005	1
25137.000	2006	1
31577.110	2007	1
29922.050	2008	1
29854.605	2009	1
32253.646	2010	1

```

32969.512  2011  1
33990.205  2012  1
31981.276  2013  1
33972.196  2014  1
37956.260  2015  1
37939.760  2016  1
42750      2017  1 #Assumed catch based on that years quota

```

```

19 # Number of Abundance indices
# Fleet Unit ErrType (-1=Norm, 0=Lognorm)
1     1     0     #Commercial_PS (no data)
2     1     0     #Spawn_Survey

```

```

# Observations: (NOTE THESE OBSERVATIONS FOR ESTIMATES OF FEMALE-ONLY SPAWNING BIOMASS)

```

```

# Year Seas Survey Value SE of Log(Value)
1995 1 2 89100 0.37
1996 1 2 19980 0.31
1997 1 2 42120 0.25
1998 1 2 71716 0.36
1999 1 2 11494 0.36
2000 1 2 43896 0.29
2001 1 2 30063 0.27
2002 1 2 97625 0.38
2003 1 2 124835 0.34
2004 1 2 87343 0.32
2005 1 2 88873 0.31
2006 1 2 120578 0.36
2007 1 2 107584 0.31
2009 1 2 76679 0.22
2011 1 2 94065 0.22
2013 1 2 62376 0.31
2014 1 2 157033 0.31
2016 1 2 75611 0.31
2017 1 2 164000 0.31

```

```

# Discard biomass
0 # Number fleets with discard
0 # Number of discard observations

```

```

# Mean body weight
0 # No. Mean-body weight observations
0 # Degree of freedom for mean body weight T-distribution likelihood

```

```

# Population length bins:
# These define the resolution at which the mean weight-at-length, maturity-at-length and size-selectivity are based.
# Calculations use the mid-length of the population bins.
2     # Length bin method: 1=use databins; 2=generate from binwidth, min, max below; 3=read vector
2     # Binwidth for population size comp

```

```

4.0 # Minimum size in the population (lower edge of first bin and size at age 0.00)
22.0 # Maximum size in the population (lower edge of last bin)

# Length composition
-1 # Comp_tail_compression
1e-007 # Add_to_comp
0 # Combine males into females at or below this bin number
2 # N_LengthBins

# Lower edge of each length data bin (in cm)
8 16 # (Need at least two length bins and some numbers here for model to run, but these values are inconsequential to
model when length data not used)

0 # Number of length observations
# Yr Seas Flt Sex Part Nsamp datavector(female-male)

# Age composition
9 # No. Age Bins

# Age Bin Vector-Lower age of each bin (first and last are accumulator bins)
0 1 2 3 4 5 6 7 8

1 # Number of ageing error matrices
-1-1-1-1-1-1-1-1-1-1
#0.001 0.001 0.001 0.001 0.001 0.001 0.001 0.001 0.001 0.001 0.001
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
#0.59 1.46 2.45 3.65 4.56 5.13 6.10 7.10 8.10 9.10
#0.63 0.85 0.73 0.99 1.11 1.06 1.06 1.06 1.06 1.06 1.06

21 # Number of age observations
1 # Length (at age) bin range method: 2 means value refers to length data bin index
0 # Combine males and females below this age bin number

# Age Composition Data
#YEAR SEASON FLEET SEX PARTITION AGE_ERR LBIN_LO LBIN_HI N_SAMPLES 0 1 2 3 4
5 6 7 8 V1 V2 V3 V4 V5 V6 V7 V8 V9
1995 1 1 0 2 1 -1 -1 684 0.0000 0.0146 0.2515 0.3289 0.2120 0.1199
0.0570 0.0146 0.0015 0 0 0 0 0 0 0 0 0 0
1996 1 1 0 2 1 -1 -1 624 0.0353 0.2292 0.2885 0.1138 0.1554 0.1314
0.0465 0.0000 0.0000 0 0 0 0 0 0 0 0 0 0
1997 1 1 0 2 1 -1 -1 481 0.0000 0.0561 0.5468 0.2807 0.0499 0.0270
0.0374 0.0021 0.0000 0 0 0 0 0 0 0 0 0 0
1998 1 1 0 2 1 -1 -1 965 0.0000 0.0839 0.3482 0.2497 0.2052 0.0829
0.0218 0.0062 0.0021 0 0 0 0 0 0 0 0 0 0
1999 1 1 0 2 1 -1 -1 768 0.0013 0.1068 0.4844 0.1875 0.1276 0.0703
0.0195 0.0026 0.0000 0 0 0 0 0 0 0 0 0 0
2000 1 1 0 2 1 -1 -1 269 0.0000 0.0483 0.3755 0.5019 0.0743 0.0000
0.0000 0.0000 0.0000 0 0 0 0 0 0 0 0 0 0

```

2001	1	1	0	0	2	1	-1	-1	1334	0.0000	0.0270	0.2961	0.4220	0.1949	0.0562
0.0030	0.0007	0.0000	0	0	0	0	0	0							
2002	1	1	0	0	2	1	-1	-1	1374	0.0000	0.0022	0.0852	0.4214	0.3777	0.0983
0.0131	0.0022	0.0000	0	0	0	0	0	0							
2003	1	1	0	0	2	1	-1	-1	1654	0.0133	0.0840	0.1693	0.3096	0.2727	0.1282
0.0206	0.0024	0.0000	0	0	0	0	0	0							
2004	1	1	0	0	2	1	-1	-1	1546	0.0272	0.0737	0.0705	0.4282	0.3014	0.0796
0.0181	0.0013	0.0000	0	0	0	0	0	0							
2005	1	1	0	0	2	1	-1	-1	879	0.0000	0.0102	0.3322	0.3959	0.1797	0.0717
0.0102	0.0000	0.0000	0	0	0	0	0	0							
2006	1	1	0	0	2	1	-1	-1	514	0.0019	0.0389	0.3560	0.3385	0.1751	0.0623
0.0214	0.0058	0.0000	0	0	0	0	0	0							
2008	1	1	0	0	2	1	-1	-1	655	0.0000	0.0275	0.4275	0.3450	0.1802	0.0183
0.0015	0.0000	0.0000	0	0	0	0	0	0							
2009	1	1	0	0	2	1	-1	-1	1485	0.0007	0.0054	0.3771	0.4620	0.1313	0.0215
0.0020	0.0000	0.0000	0	0	0	0	0	0							
2010	1	1	0	0	2	1	-1	-1	2239	0.0000	0.0004	0.3859	0.3810	0.1653	0.0531
0.0130	0.0013	0.0000	0	0	0	0	0	0							
2011	1	1	0	0	2	1	-1	-1	543	0.0000	0.0018	0.4291	0.3628	0.1473	0.0552
0.0037	0.0000	0.0000	0	0	0	0	0	0							
2012	1	1	0	0	2	1	-1	-1	359	0.0000	0.0000	0.3426	0.3454	0.1894	0.1142
0.0084	0.0000	0.0000	0	0	0	0	0	0							
2013	1	1	0	0	2	1	-1	-1	479	0.0000	0.0000	0.1253	0.3946	0.3069	0.1378
0.0334	0.0021	0.0000	0	0	0	0	0	0							
2014	1	1	0	0	2	1	-1	-1	538	0.0000	0.0093	0.2119	0.4963	0.1134	0.1097
0.0483	0.0112	0.0000	0	0	0	0	0	0							
2015	1	1	0	0	2	1	-1	-1	775	0.0000	0.0103	0.2116	0.4490	0.1832	0.1097
0.0284	0.0077	0.0000	0	0	0	0	0	0							
2016	1	1	0	0	2	1	-1	-1	501	0.0000	0.0000	0.1717	0.4331	0.2016	0.1477
0.0379	0.0060	0.0020	0	0	0	0	0	0							

```

0 #_N_MeanSize-at-Age_obs
1 #_N_envirom_variables
0 #_N_envirom_obs
0 # N sizefreq methods to read
0 # no tag data
0 # no morphcomp data

```

```
999 # EOF
```

FORCAST.SS

```

# SSV3.24S
# Forecast File
# South Australian Sardine Fishery, 2017
# Jonathan Smart, SARDI, Jonathan.Smart@sa.gov.au

# For all year entries except rebuilders; enter either: actual year, -999 for styr, 0 for endyr, neg number for rel.
endyr
1 # Benchmarks: 0=skip; 1=calc F_spr,F_btgt,F_msy
2 # MSY: 1= set to F(SPR); 2=calc F(MSY); 3=set to F(Btgt); 4=set to F(endyr)
0.40 # SPR target (e.g. 0.40)
0.40 # Biomass target (e.g. 0.40)

#_Bmark_years: beg_bio, end_bio, beg_selex, end_selex, beg_reIF, end_reIF (enter actual year, or values of 0 or -integer
to be rel. endyr)
0 0 0 0 0 0
1 # Bmark_reIF_Basis: 1 = use year range; 2 = set reIF same as forecast below

1 # Forecast: 0=none; 1=F(SPR); 2=F(MSY) 3=F(Btgt); 4=Ave F (uses first-last reIF yrs); 5=input annual F scalar
2 # N forecast years
0 # F scalar (only used for Do_Forecast==5)

#_Fcast_years: beg_selex, end_selex, beg_reIF, end_reIF (enter actual year, or values of 0 or -integer to be rel.
endyr)
0 0 0 0
1 # Control rule method (1=catch=f(SSB) west coast; 2=F=f(SSB) )
0.40 # Control rule Biomass level for constant F (as frac of Bzero, e.g. 0.40); (Must be > the no F level below)
0.1 # Control rule Biomass level for no F (as frac of Bzero, e.g. 0.10)
1 # Control rule target as fraction of Flimit (e.g. 0.75)
3 #_N forecast loops (1=OFL only; 2=ABC; 3=get F from forecast ABC catch with allocations applied)
3 #_First forecast loop with stochastic recruitment
0 #_Forecast loop control #3 (reserved for future bells&whistles)
0 #_Forecast loop control #4 (reserved for future bells&whistles)
0 #_Forecast loop control #5 (reserved for future bells&whistles)
2020 # FirstYear for caps and allocations (should be after years with fixed inputs)
0 # stddev of log(realized catch/target catch) in forecast (set value>0.0 to cause active impl_error)
0 # Do West Coast gfish rebuilders output (0/1)
0 # Rebuilder: first year catch could have been set to zero (Ydecl)(-1 to set to 1999)
0 # Rebuilder: year for current age structure (Yinit) (-1 to set to endyear+1)
1 # Fleet relative F: 1=use first-last alloc year; 2=read seas(row) x fleet(col) below
# Note that fleet allocation is used directly as average F if Do_Forecast=4
2 # Basis for fcast catch tuning and for fcast catch caps and allocation (2=deadbio; 3=retainbio; 5=deadnum;
6=retainnum)
# Max totalcatch by fleet (-1 to have no max) must enter value for each fleet
-1
# Max totalcatch by area (-1 to have no max); must enter value for each fleet

```

```
-1
# Fleet assignment to allocation group (enter group ID# for each fleet, 0 for not included in an alloc group)
0
# Conditional on >1 allocation group
# Allocation fraction for each of: 0 allocation groups
# No allocation groups
2 # Number of forecast catch levels to input (else calc catch from forecast F)
2 # basis for input Fcast catch: 2=dead catch; 3=retained catch; 99=input Hrate(F) (units are from fleetunits; note
new codes in SSV3.20)
# Input fixed catch values
#Year Seas Fleet Catch(or_F)
2018 1 1 42750

#
999 # End of file.
```