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Commonwealth Small Pelagic Fishery: Fishery Assessment Report 2018

Report to the Australian Fisheries Management Authority

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Contents

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Executive Summary

This report uses fishery-dependent and fishery-independent data to assess the status of target species in the East and West sub-areas of the Commonwealth Small Pelagic Fishery (SPF). The target species are Jack Mackerel (*Trachurus declivis*), Blue Mackerel (*Scomber australasicus*), Redbait (*Emmelichthys nitidus*) and, in the Australian Sardine sub-area of the East sub-area, Australian Sardine (*Sardinops sagax*). The primary fishing methods are purse-seining and mid-water trawling. The SPF Harvest Strategy 2008 (last revised April 2017) specifies that the primary technique for assessing the status of SPF species is the Daily Egg Production Method (DEPM). To retain a species in a sub-area at Tier 1, where exploitation rates are highest, the DEPM must be applied every 5 years. Between applications of the DEPM, fishery-dependant data are analysed to identify variations in fishing patterns or catches that may be indicative of changes in stock status.

Between 2010/11 and 2014/15, catches in the SPF of all species in both sub-areas were low (<200 t per annum). Effort and catch in the SPF increased during 2015/16 and 2016/17, when a mid-water factory trawler operated in offshore waters of both sub-areas. In 2017/18, a smaller mid-water trawler without onboard processing facilities began operating in inshore waters of the East sub-area. No fishing was undertaken by SPF vessels in the west-sub area in 2017/18.

East sub-area

The total catch of target species by SPF vessels in the East sub-area during 2017/18 was 5,714 t. The majority of the catch was Blue Mackerel (50%) and Jack Mackerel (48%) taken off southern NSW, with a small incidental catch of Redbait (0.2%). Australian Sardine comprised 2% of the SPF catch from East sub-area and was taken mainly off northern NSW.

Blue Mackerel East

The main fisheries for Blue Mackerel East are the NSW Ocean Hauling Fishery (purse seine) and the SPF. From 1995/96 to 2014/15, NSW Ocean Fisheries and the SPF took an average of 69% and 20% of the total annual catch in the East sub-area, respectively. Total annual catches from 2010/11 to 2014/15 were less than 550 t. The SPF has taken >80% of the total catch since 2015/16.

The total catch of Blue Mackerel East in the SPF in 2017/18 was 2,858 t, which is the highest on record, eclipsing the total catches of 2,022 t in 2015/16 and 1,248 t in 2016/17. The increase in catch reflects the recent establishment of the new fishing operation off southern NSW, which targeted Blue Mackerel. The catch-per-unit-effort (CPUE) of Blue Mackerel East in 2017/18 of 4 $t \cdot trawl\ hour^{-1}$ was similar to that recorded by the factory trawler in 2015/16 (3 $t \cdot trawl\ hour^{-1}$) and 2016/17 (4 $t \cdot trawl\ hour^{-1}$). The increase in catch of Blue Mackerel East in 2017/18 reflects the increased trawl effort (799 trawl hours) compared to 638 trawl hours in 2015/16 and 349 trawl hours in 2016/17.

In 2017/18, the distribution of fish lengths of Blue Mackerel East in mid-water trawl catches was bimodal, with a mode at 170 mm FL and 270 mm FL. During 2014/15 to 2016/17, the modal length of Blue Mackerel East varied between 260 and 280 mm FL, similar to the mean size of 50% maturity (~260 mm FL). The modal age of Blue Mackerel East in 2017/18 was 2 years, down from 3 years during 2014/15 to 2016/17. The decrease in the size and age of Blue Mackerel East taken in 2017/18 may reflect the transition of effort into inshore waters.

The average total catch of Blue Mackerel East over the last 3 fishing seasons has been ~2,350 t. The spawning biomass of Blue Mackerel East in 2014 was ~83,300 t (95% CI = 35,100–165,000 t). The recent average exploitation rate has been <3%, and below the maximum exploitation rate at Tier 1 for Blue Mackerel East of 12%. The total catch in 2017/18 was <30% of the available TAC. On the basis of the information provided above, Blue Mackerel East is classified as **sustainable**.

Jack Mackerel East

The main fishery for Jack Mackerel East is the SPF; recent catches in other fisheries in this sub-area have been negligible (<10 t per annum). The total annual catch of Jack Mackerel East from 2010/11 to 2014/15 was <320 t. The vessel that operated in inshore waters off southern NSW in 2017/18 took 2,748 t. The factory trawler that fished offshore caught 6,316 t in 2015/16 and 3,966 t of Jack Mackerel in 2016/17. CPUE of Jack Mackerel East in 2017/18 was 3 t·trawl $hour^{-1}$, about one third that of the factory trawler (10 t·trawl $hour^{-1}$ in 2015/16 and 11 t·trawl $hour^{-1}$ in 2016/17). The reduced catches of Jack Mackerel East in 2017/18 compared to the previous two years reflects the reduced CPUE compared to 2015/16 and 2016/17.

The modal length of Jack Mackerel taken in 2017/18 was 200 mm FL, below the size at 50% maturity of ~270 mm FL, and down from ~230 mm FL in both 2015/16 and 2016/17. In 2017/18 the modal age was 4 years, lower than the modal ages of 5 years and 5-6 years in 2015/16 and 2016/17, respectively. The smaller size and younger age of Jack Mackerel taken from East sub-area in 2017/18 reflects the transition of fishing activity to inshore waters.

The average total annual catch of Jack Mackerel East over the last three fishing seasons has been approximately 4,350 t. The spawning biomass of Jack Mackerel East in 2014 was estimated to be 157,805 t (95% CI = 59,570–358,731). The recent annual average catch of Jack Mackerel East have been <3% of this estimate of spawning biomass and below the Tier 1 exploitation rate for this stock of 12%. The total catch in 2017/18 was <30% of the available TAC. On the basis of the information provided above, Jack Mackerel East is classified as **sustainable**.

Redbait East

The main fishery for Redbait East is the SPF. The highest annual catch of Redbait East in the SPF between 2010/11 and 2017/18 was 217 t in 2015/16. The annual catch in the SPF in 2017/18 was 9.5 t. Catches of Redbait East in mid-water trawls have mainly comprised fish above the mean size at 50% maturity of ~150 mm FL.

The total annual catch of Redbait East in 2017/18 was 9.5 t. The spawning biomass of Redbait East was estimated to be ~70,000 t in 2005 and 2006. Recent catches of Redbait East have been <1% of this estimate spawning biomass and below the Tier 2 exploitation rate for this stock of 5%. The total catch in 2017/18 was <1% of the available TAC. On the basis of the information provided above, Redbait East is classified as **sustainable**.

Australian Sardine East

The main fisheries taking Australian Sardine in the Sardine sub-area are the NSW Ocean Hauling Fishery and the SPF. Catches from the Sardine sub-area have mainly contained fish at or above the mean size at 50% maturity of ~150 mm FL. The maximum total catch for the Sardine sub-area of the East sub-area did not exceed 601 t between 2015/16 and 2017/18. The spawning biomass of Australian Sardine East in this region in 2014 was estimated to be ~49,600 t (95% CI = 24,200–213,300 t). Current catches from the Sardine sub-area of Australian Sardine East are <2% of the 2014 estimate of spawning biomass and below the Tier 1 exploitation rate for this species of 20%.

West sub-area

Blue Mackerel West

The largest fishery for Blue Mackerel West has been the SPF. There was no catch of Blue Mackerel West in the SPF in 2017/18; this was down from 766 t in 2016/17 and 980 t in 2015/16. Catches were mainly comprised of fish >300 mm FL, above the mean size at 50% maturity of ~260 mm FL. The modal age of Blue Mackerel West caught in mid-water trawls in 2015/16 and 2016/17 was 5 years.

Recent total annual catches of Blue Mackerel West have been <1000 t. The spawning biomass for Blue Mackerel West in 2005 was estimated to be 56,228 t. Recent catches of Blue Mackerel West have been <2% of the estimated spawning biomass for 2005 and below the Tier 3 exploitation rate for this stock of 3.75%. The total annual catch in 2017/18 (<1 t) was <50% of the available TAC. On the basis of the information provided above, Blue Mackerel West is classified as **sustainable**.

Jack Mackerel West

The main fishery for Jack Mackerel West is the SPF. Annual catches did not exceed 360 t prior to 2015/16. There was no catch of Jack Mackerel West in the SPF in 2017/18; this was down from 686 t in 2016/17 and 634 t in 2015/16. The modal length in 2016/17 was 270 mm FL, similar to the mean size at 50% maturity of ~270 mm FL, and larger than the modal length of 240–250 mm FL in 2015/16. The modal age in 2016/17 was 7 years, up from 4 years in 2015/16.

Recent annual catches of Jack Mackerel West have not exceeded 700 t. The spawning biomass of Jack Mackerel West in 2016/17 was estimated to be at least 31,000 t. Recent catches of Jack Mackerel West have been <3% of this estimate of spawning biomass and below the Tier 2 exploitation rate for this stock of 12%. The total annual catch in 2017/18 was <1% of the available TAC. On the basis of the information provided above, Jack Mackerel West is classified as **sustainable**.

Redbait West

The main fishery for Redbait West is the SPF. The total SPF catch in 2017/18 was 0 t, down from 1,140 t in 2016/17 and 1,157 t in 2015/16. In 2016/17, the modal length was 240 mm FL, whereas in 2015/16 the catch was bimodal, with modes at 130 and 220 mm FL. Catches have mainly contained fish below the mean size at 50% maturity of ~250 mm FL.

Recent annual catches of Redbait West have not exceeded 1,160 t. The spawning biomass for Redbait West in 2017 was estimated to be 66,767 t. Recent catches of Redbait West have been <2% of this estimate of spawning biomass and below the Tier 1 exploitation rate for this stock of 9%. The total catch in 2017/18 was 0% of the available TAC. On the basis of the information provided above, Redbait West is classified as **sustainable**.

Summary

All SPF stocks are classified as sustainable. DEPM surveys have now been conducted for all stocks. Resulting estimates of spawning biomass could be used to inform the establishment of target (e.g. B_{50}) and limit reference points (e.g. B_{20}) for each stock.

Keywords: Commonwealth SPF, Jack Mackerel, Blue Mackerel, Redbait, Sardine, purse seine, mid-water trawl, AFMA

1 General Introduction

1.1 Overview

This assessment of the Commonwealth Small Pelagic Fishery (SPF) builds on annual reports published since 2010 (Ward et al. 2011, 2012, 2013, 2014c, 2015c, Ward and Grammer 2016, 2017, 2018). This report provides a synopsis of information available and current status of SPF quota species, namely Jack Mackerel (*Trachurus declivis*), Blue Mackerel (*Scomber australasicus*), Redbait (*Emmelichthys nitidus*) and Australian Sardine (*Sardinops sagax*). The assessment uses commercial catch and effort data up to 30 April 2018 and available biological information (size and age structures, reproduction, maturity). The assessments are underpinned by outputs from several Management Strategy Evaluations (MSEs) and estimates of spawning biomass obtained from fishery-independent surveys. This report satisfies the requirements of the SPF Harvest Strategy (HS) for assessment of stocks at Tiers 1 and 2 (see Section 1.3.1; AFMA 2008, revised in 2017).

1.2 Description of the Commonwealth Small Pelagic Fishery

The SPF is a purse seine and mid-water trawl fishery that operates in Commonwealth waters (3 to 200 nm) from southern Queensland to south-western Western Australia, including Tasmania (Figure 1-1). The fishery is divided into two sub-areas (East and West) by a line through longitude 146°30'E (Figure 1-1, AFMA 2009). There is also a designated Australian Sardine sub-area within the East sub-area that extends from southern Queensland to southern New South Wales (Figure 1-1; referred to here as the 'Sardine East sub-area'). The East and West sub-areas are further divided into seven sub-zones and catch grids (Figure 1-2).

The three main target species of the SPF are Jack Mackerel, Blue Mackerel and Redbait. Australian Sardine is a target species in the Sardine East sub-area. These species are targeted by recreational fishers in some States (Henry and Lyle 2003) and by State-managed commercial fisheries. Small quantities of SPF species are caught in other Commonwealth fisheries, primarily the Southern and Eastern Scalefish and Shark Fishery, Western Tuna and Billfish Fishery and the Eastern Tuna and Billfish Fishery (Moore and Skirtun 2012). Combined catches of SPF quota species in these fisheries have not exceed 40 t per year since their inception in 2002 and are not included in this assessment.

The fishery has changed dramatically since large scale fishing operations targeting Jack Mackerel began in the mid-1980s. Between the late 1980s and prior to the SPF Management Plan being implemented in 2009 (AFMA 2009), the Tasmanian component of the fishery (north-eastern Tasmania to central western Tasmania) was managed using a combination of input and output controls, including a total allowable catch (TAC). A combined species TAC for the Tasmanian component of the fishery was set at 42,000 t in

1988/89 and based on the highest annual catch from the purse seine fishery (Jordan et al. 1992; Pullen 1994). The TAC was decreased to 34,000 t in 2002/03 with the renewed interest in small pelagic species and the commencement of mid-water trawl operations. Despite catches not approaching this level, the TAC was applied in subsequent fishing seasons up until 2008/09 when the SPF was split into East and West sub-areas. Under the SPF Harvest Strategy (SPF HS; AFMA 2008), species and sub-area specific TACs were established. From 2014/15 to 2106/17, effort has increased in the SPF with the introduction of a factory trawler. A detailed history of the SPF is described in Moore and Skirtun (2012).

1.3 Management of the Fishery

The SPF is managed by the Australian Fisheries Management Authority (AFMA) under the SPF Management Plan (AFMA 2009) using a combination of input and output controls that include limited entry, zoning, mesh size restrictions and TAC limits for target species (hereafter referred to as quota species) within each sub-area.

Figure 1-1 Management sub-areas of the Small Pelagic Fishery.

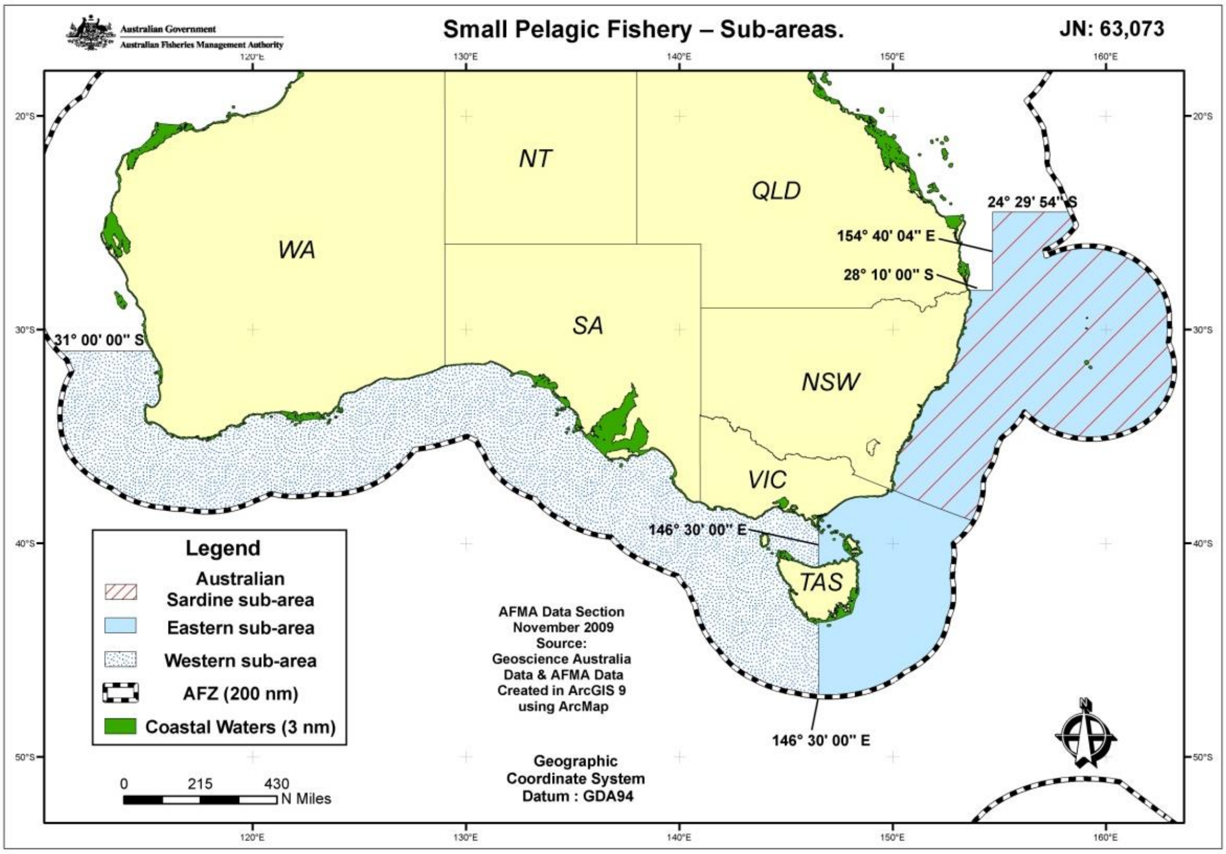
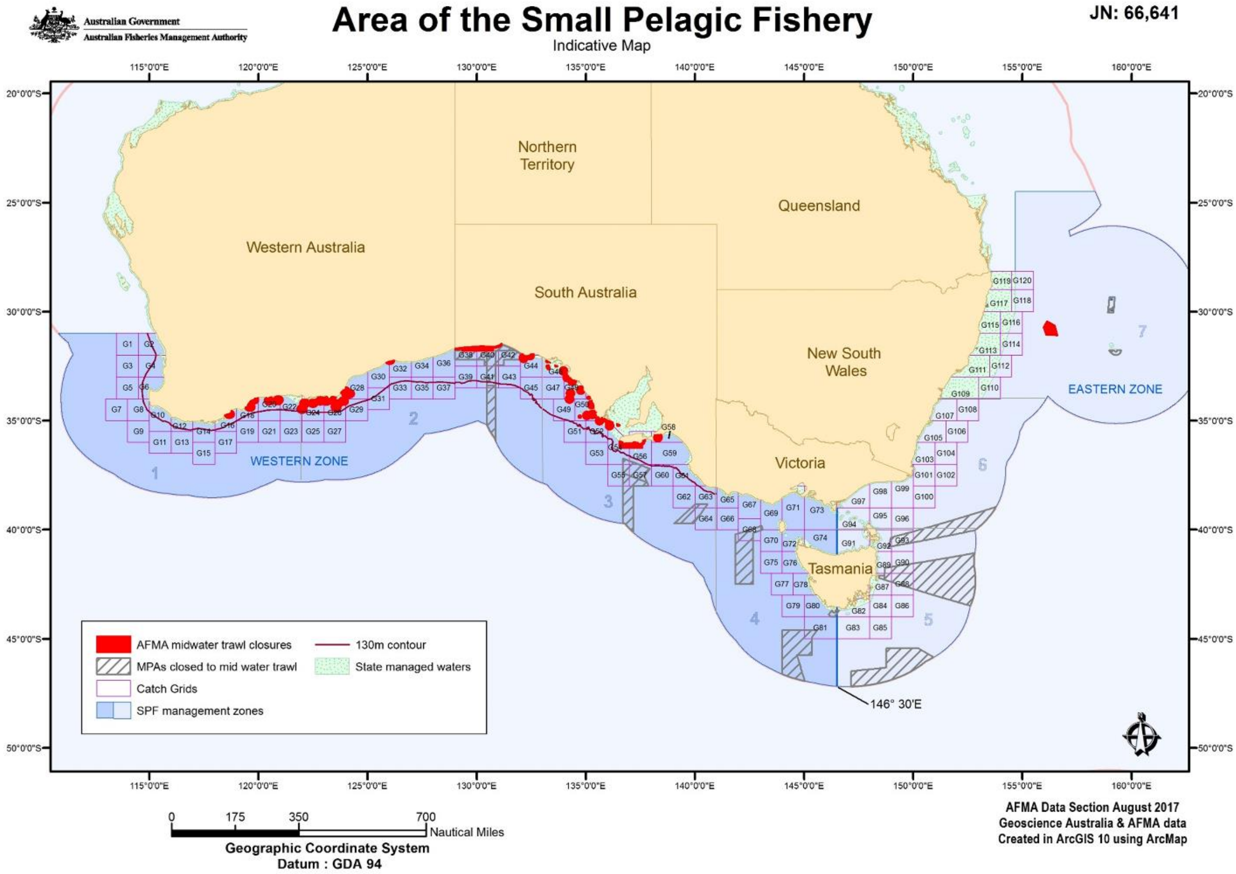


Figure 1-2. Sub-zones, catch grids and areas closed to mid-water trawling within management sub-areas of the Small Pelagic Fishery.



1.3.1 Harvest Strategy

The HS for the SPF established in 2008 was last revised in 2017 (AFMA 2008, revised April 2017). The HS is a three-tiered system used by the SPF Scientific Panel (SPFSP, previously the SPF Resource Assessment Group, SPFRAG) to develop advice on the Recommended Biological Catches (RBCs) for stocks (East and West) for each quota species. Stocks are allocated to a tier based upon the level of knowledge about stock size (spawning biomass), with Tier 1 representing the highest level of available information and Tier 3 the lowest (Moore and Skirtun 2012). Corresponding individual transferable quotas (ITQs) are established; Tier 1 stocks have the largest quota (by weight), and Tier 3 the smallest (Tracey et al. 2013). The tiered system was introduced to ensure that heavy exploitation only occurs in stocks where there is a high level of confidence that such exploitation can be sustained (Moore and Skirtun 2012). TACs for each quota species are determined by subtracting other sources of mortality (i.e. catches taken in other Commonwealth and State fisheries) from the corresponding RBCs.

A brief description of each tier is provided below.

<u>Tier 1:</u> The maximum exploitation rates for Tier 1 species in each sub-area are 10% for Redbait, 12% for Jack Mackerel, 15% for Blue Mackerel and 20% Australian Sardine (East

sub-area only). RBCs are set by applying exploitation rates up to these levels based on the median spawning biomass estimated using the Daily Egg Production Method (DEPM). Species remain at Tier 1 for five seasons after a DEPM survey is completed.

Tier 2: The maximum exploitation rates for Tier 2 species are half the level specified at Tier 1. Redbait and Jack Mackerel can remain at Tier 2 for up to 10 seasons. Blue Mackerel and Australian Sardine can remain at Tier 2 for up to 5 seasons.

Tier 3: The maximum exploitation rates for Tier 3 species are half the level specified at Tier 2 when a biomass estimate has been previously based on a DEPM survey, i.e. 2.5% for Redbait, 3% for Jack Mackerel, 3.75% for Blue Mackerel and 5% Australian Sardine (East sub-area only). For stocks with no previous DEPM survey, the exploitation rates may not exceed a quarter of the Atlantis–SPF derived, mean spawning biomass estimate, i.e. West sub-area: 1.25% Redbait and 1.5% Jack Mackerel. A stock can remain at Tier 3 indefinitely. The Atlantis-SPF model is a variant of the Atlantis-SE ecosystem model (see section 1.4.2; Smith et al. 2015).

1.4 Previous Assessments

1.4.1 DEPM

DEPM surveys have been conducted for Blue Mackerel East and West (Ward and Rogers 2007, Ward et al. 2009, 2015b), Australian Sardine East (Ward et al. 2007, 2015a, 2015b), Redbait East and West (Neira and Lyle 2011, Ward et al 2018d), and Jack Mackerel East and West (Neira 2011, Ward et al. 2015a, Ward et al. 2016, Ward et al. 2018).

1.4.2 Management Strategy Evaluations (MSEs)

Management Strategy Evaluations (MSEs) have been conducted by the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) (Giannini et al. 2010) and Commonwealth Scientific and Industrial Research Organisation (CSIRO) (Smith et al. 2015). The 2015 MSE included a formal review of the HS for the SPF; these results are discussed in this assessment report.

Giannini et al. (2010)

In 2010, an MSE model was used to test the settings (i.e. exploitation rates) in the SPF HS for each stock (Giannini et al. 2010). In most scenarios, the 30 year simulation period used in the MSE was sufficient for each stock to reach equilibrium, and generally this was well above 20% of virgin biomass (B_{20}). Sensitivities of the model to the various input parameters were also tested. The model was most sensitive to the assumed stock-recruitment relationship and natural mortality. The model was re-examined in 2011 to address concerns about values used for number of recruits.

Smith et al. (2015)

In 2015, an MSE was undertaken using ecosystem and population models to evaluate and provide advice on the reference points (e.g. biomass depletion levels) and settings (e.g. exploitation rates) for the SPF target species (Smith et al. 2015). A new variant of the Atlantis ecosystem model (Atlantis-SPF) indicated that SPF species are not keystone species within the ecosystem, and population modelling suggested that conventional single species targets and limits (e.g. the defaults under the SPF HS) are appropriate (Smith et al. 2015). Based on results from the ecosystem model and default settings in the Commonwealth Harvest Strategy Policy, Smith et al. (2015) evaluated constant Tier 1 exploitation rates for each species that achieved a median depletion to 50% of unfished levels (B_{50}) while maintaining a <10% chance of falling below 20% of unfished levels (B_{20}). The base case model assumed DEPM surveys every 5 years. Evaluation of the Tier 2 exploitation rate (50% of Tier 1) assumed that it would only be applied after 5 years of exploitation at Tier 1 and no further DEPM surveys would occur. Smith et al. (2015) also produced Atlantis-SPF biomass estimates that have been used in Tier 3 of the SPF HS when DEPM spawning biomass estimates were not available.

Smith et al. (2015) suggested the previous Tier 1 harvest rate of 15% was too high for Jack Mackerel and Redbait and too low for Blue Mackerel and Australian Sardine. Smith et al. (2015) recommended: 1) Tier 1 harvest rates be applied for not more than 5 years after a DEPM survey; 2) Tier 2 harvest rates be 50% of Tier 1 rates; and 3) not be applied for more than 5 years for Blue Mackerel and Australian Sardine or 10 years for Jack Mackerel and Redbait.

1.5 Aims and Objectives

This report uses fishery-dependent and fishery-independent data to assess the status of target species of the Commonwealth Small Pelagic Fishery (SPF) and presents information needed to optimise the design of future catch sampling programs in the SPF. The status of Jack Mackerel, Blue Mackerel, Redbait are assessed in the West and West sub-areas. Australian Sardine is assessed in the Sardine sub-area of the East sub-area.

2 Blue Mackerel (*Scomber australasicus*)

2.1 Introduction

2.1.1 Background to Fishery

Large fisheries for *Scomber* spp. (i.e. ~50,000 to 500,000 t per annum) are located off Japan, Peru, China, Korea, Russia, and the Ukraine (Ward et al. 2001a). The largest fishery for Blue Mackerel in the southern hemisphere is based in New Zealand where annual catches have ranged between ~6,000 t and 15,000 t per annum since the early 1990s (Fu 2013). In Australia, Blue Mackerel is taken in several fisheries with annual catches typically <3,000 t (Ward et al. 2001a, Ward and Grammer 2017).

The New South Wales commercial purse seine fishery has targeted Yellowtail Scad and Blue Mackerel since the early 1980s (Stewart and Ferrell 2001). During that time, Blue Mackerel typically comprised ~38% of the total annual catches. The average annual catch of Blue Mackerel in Victorian waters between 1978/79 and 2004/05 was 49 t (±22.9 t) with catches ranging between 0.2 and 370.6 t per annum (Ward and Rogers 2007). Blue Mackerel are also an important target species for recreational fisheries in Australia (Henry and Lyle 2003).

The Tasmanian Purse Seine Fishery has recorded catch and effort data since its inception in 1984. Logbooks contain a record of fishing operations and species taken for each net-set. Landings of Blue Mackerel were first reported in 1985/86 with a catch of 587 t (1984/85: 0 t; Pullen 1994). From 1984/85 to 1989/90, Blue Mackerel represented <4% of the total annual catch of small pelagic fishes in Tasmania (Pullen 1994). Species-specific information was not available for other years.

2.1.2 Taxonomy

The genus *Scomber* (family *Scombridae*) historically included three Mackerel species: Blue Mackerel (*S. australasicus*), Chub Mackerel (*Scomber japonicus*), and Atlantic Mackerel (*Scomber scombrus*). However, *S. australasicus* and *S. japonicus* have proved to be more closely related to each other than to *S. scombrus*, and morphological and genetic differences in Atlantic and Indo-Pacific populations of *S. japonicus* warranted recognition of two separate species (Scoles et al. 1998). Atlantic Chub Mackerel (*Scomber colias*) was identified through further genetic analyses and replaces *S. japonicus* in the Atlantic Ocean (Infante et al. 2006, Catanese et al. 2010). Thus, two closely related species occur in the Indian and Pacific Oceans: *S. japonicus* and *S. australasicus,* and two closely related species are found in the Atlantic Ocean: *S. scombrus* and *S. colias*.

2.1.3 Distribution

Blue Mackerel occur throughout the Pacific Ocean, including South East Asia, Australia and New Zealand, and in coastal and continental shelf waters of the northern Indian Ocean and Red Sea (depths up to 200m). In Australia, Blue Mackerel are found in subtropical and temperate waters from Queensland to Western Australia and are the only member of the genus present (Ward et al. 2001a, Gomon et al. 2008). Juveniles and small adults usually live in inshore waters, while larger adults form schools in depths of 40–200 m across the continental shelf (Kailola et al. 1993).

2.1.4 Stock Structure

The stock structure of Blue Mackerel in Australasian waters is uncertain. Significant differences in the morphology of monogenean parasites distinguished fish from Australia and New Zealand (Rohde 1987). However, genetic differences have not been found between Blue Mackerel from Australia and New Zealand using mtDNA RFLP analysis and cytochrome *b* sequencing (Scoles et al. 1998). The Australian east coast and west coast Blue Mackerel populations are thought to be genetically separate stocks (Ward and Rogers 2007, Schmarr et al. 2011). An additional stock in southern Australia has tentatively been identified through differentiation with otolith microchemistry and parasite analyses (Ward and Rogers 2007, Schmarr et al. 2011).

2.1.5 Movement

No studies have specifically examined the movement of Blue Mackerel in Australasia.

2.1.6 Food and Feeding

Blue Mackerel are pelagic omnivores, feeding mainly on krill, fish and gelatinous nekton (Bulman et al. 2001, Daly 2007, Bulman et al. 2011). Mackerel (*Scomber* spp.) alter their feeding behaviour and ingestion rates depending on prey size and density (Prokopchuk and Sentyabov 2006, Garrido et al. 2007).

2.1.7 Age, Growth and Size

Age estimation in small pelagic fish can be problematic (Gaughan and Mitchell 2000, Arneri et al. 2011), and Blue Mackerel are no exception (Stewart et al. 1999, Ward and Rogers 2007, Marriott and Manning 2011). Although the otoliths of Blue Mackerel have complex inner microstructures, they have been successfully used to estimate annual ages in both Australia (Stewart and Ferrell 2001, Ward and Rogers 2007) and New Zealand (Marriott and Manning 2011). Juveniles of both sexes grow rapidly and reach ~250 mm fork length (FL) after ~2 years of life (Ward and Rogers 2007). Blue Mackerel reach sizes of up to 440 mm FL in the GAB and are estimated to attain ~8 years (Stevens et al. 1984). Growth rates and trajectories of males and females from waters off South Australia are similar (Ward and Rogers 2007). Off eastern Australia, an opaque zone forms in the otoliths of one-year old fish during winter and is complete by early summer (Stewart et al. 1999). Commercial catches of Blue Mackerel taken off southern New South Wales contained mostly 1 to 3 year old fish and included individuals up to 7 years old (Stewart and Ferrell 2001).

2.1.8 Reproduction

Blue Mackerel are serial spawners, and spawn multiple times over a prolonged spawning season with 50% sexual maturity occurring around 237 mm FL for males and 287 mm FL for females (Ward and Rogers 2007, Rogers et al. 2009). Spawning in southern Australia takes place from summer to early autumn and late winter to spring in New South Wales (Ward and Rogers 2007, Ward et al. 2015b). Mean spawning frequencies range from 2 to 11 days in southern Australia. Mean batch fecundity is ~70,000 oocytes per batch and 134 oocytes per gram of weight (Rogers et al. 2009). Fecundity increases exponentially with fish length and weight. Most of the eggs collected off southern and eastern Australia have been obtained from the mid-shelf. High egg and larval densities are recorded at depths >50 m with sea surface temperatures (SST) of 18-22°C (Ward and Rogers 2007, Ward et al. 2015b). The location of spawning off southern Australia appears to vary substantially among years. Results of an exploratory survey suggest that the western GAB is an important spawning area. However, this region has not yet been sampled intensively (Ward and Rogers 2007).

2.1.9 Early Life History and Recruitment

Blue Mackerel eggs are transparent and spherical, measuring 1.05 to 1.35 mm in diameter. The eggs have a smooth chorion, a prominent unsegmented yolk, and a single oil globule 0.22 to 0.38 mm in diameter (Ward and Rogers 2007, Neira and Keane 2008). Blue Mackerel yolk-sack larvae are <3.2 mm total length (TL) at hatching and metamorphose at lengths of ~23.3 mm TL (Neira et al. 1998).

2.1.10 Stock Assessment

An extensive study that included both the East and West sub-areas of the SPF investigated the application of a range of egg-based stock assessment methods for Blue Mackerel and concluded that the species was suitable for assessment using the DEPM (Ward and Rogers 2007, Ward et al. 2009). A dedicated DEPM survey for Blue Mackerel East was conducted in 2014 (Ward et al. 2015b). Both the annual and daily egg production methods have been used to estimate the spawning biomass of Atlantic Mackerel (*Scomber scombrus*) in the north-eastern Atlantic Ocean (Gonçalves et al. 2009).

2.1.11 Recreational fishing

Recreational fishers harvest Blue Mackerel using rod and line, hand line and troll lines (Ward and Rogers 2007) throughout the waters of southern Australia, including southern Queensland. The Australian National Survey of Recreational and Indigenous Fishing estimated that boat-based recreational fishers harvested 720,814 Blue Mackerel annually, with 21% of these being released back into the water (Henry and Lyle 2003). Of the Blue Mackerel retained, 75% were taken in New South Wales, and 14% and 8% taken in Western Australia and South Australia, respectively (Henry and Lyle 2003). Based on the length/weight key developed by Stewart and Ferrell (2001), the estimated weight of Blue Mackerel harvested annually by the recreational sector in Australia is 228 t (Ward and Rogers 2007).

2.1.12 Biomass Estimates

East

A preliminary estimate of spawning biomass for Blue Mackerel East in 2004, calculated from the 'best' estimate of each parameter, was 23,009 t (Ward and Rogers 2007). 'Minimum' and 'maximum' estimates ranged from 7,565 to 116,395 t. The 'best' estimate of spawning biomass was considered to be conservative due to both the approach used to estimate egg production (i.e. McGarvey and Kinloch 2001) and because the survey most likely occurred outside the peak spawning season in that region (Ward and Rogers 2007).

A DEPM survey, undertaken in August/September 2014 off eastern Australia by Ward et al. (2015b), estimated spawning biomass of Blue Mackerel East to be ~83,300 (95% CI = 35,100–165,000 t). The estimated spawning area for Blue Mackerel off eastern Australia was 17,911 km^2, comprising 27.3% of the total area sampled (65,528 km^2) (Ward et al. 2015b). Live Blue Mackerel eggs (n = 2,330) were collected from 70 of the 262 (26.7%) stations between Sandy Cape, Queensland to just south of Newcastle, NSW. Mean daily egg production (P_0) was 35.1 eggs·day^{-1}·m^{-2}. The highest densities of Blue Mackerel eggs were recorded in waters just north of Coffs Harbour and off Port Stephens where SSTs ranged between 18 and 20°C.

The estimate of spawning biomass of 83,300 t was based on estimates of adult parameters from South Australia and should be treated with caution. Sensitivity analyses showed that realistic variations of each parameter produced estimates of spawning biomass for Blue Mackerel that were between about 50,000 t and 100,000 t. The exceptions were the lower estimates of spawning fraction (0.05) and batch fecundity (22,085 eggs·female^{-1}) and the higher estimate of daily egg production (69.5 eggs·day^{-1}·m^{-2}), which produced estimates of spawning biomass between about 150,000 t to 250,000 t. Sampling intensity for estimates of egg production in the region was higher than in the preliminary surveys conducted in 2003 and 2004. Current estimates of egg production and spawning area are likely to be more robust than those previously reported.

West

The preliminary estimate of spawning biomass for Blue Mackerel West in 2005, calculated from the 'best' estimate of each parameter, was 56,228 t (Ward and Rogers 2007). 'Minimum' and 'maximum' estimates ranged from 10,993 t to 293,456 t. The 'best' estimate of spawning biomass was considered to be conservative due to both the approach used to estimate of egg production (i.e. McGarvey and Kinloch 2001) and because there was evidence to suggest that spawning occurred outside the area surveyed in the West (i.e. in the western Great Australian Bight) (Ward and Rogers 2007).

2.1.13 Management Strategy Evaluation

2010

For Blue Mackerel East, the “best” 2004 DEPM estimate of spawning biomass was 13% of the model calculated estimate of virgin biomass (Giannini et al. 2010). All Tier 1 scenarios reached equilibrium around B_{60} by the end of the 30 year simulation period. The Tier 2 and Tier 3 results suggest that these harvest levels were conservative and sustainable. However, these outputs should be treated with caution as these harvest quantities are “absolute” values and represented a much smaller proportion of the model calculated biomass than the DEPM estimate of biomass.

The outputs for Blue Mackerel West were similar to those for Blue Mackerel East (Giannini et al. 2010). In this case, the 2005 DEPM estimate of spawning biomass was 31% of the model calculated estimate of spawning biomass.

2015

Smith et al. (2015) concluded the harvest rate of 15% may be too low for Blue Mackerel and suggested a Tier 1 harvest rate of 23% for Blue Mackerel East and West, with the Tier 1 rate being applied for not more than 5 years. Tier 2 harvest rates for Blue Mackerel East and West were recommended to be 50% of Tier 1 rates and not to be applied for more than 5 years. The study results also indicated it is not safe to apply Tier 2 harvest rates unchecked for long periods of time, particularly on shorter lived species such as Blue Mackerel (Smith et al. 2015). The Atlantis-SPF biomass estimate for Blue Mackerel East is 52,600 t (typical range: 44,000–60,000 t) and 42,500 t (typical range: 34,000–46,000 t) for Blue Mackerel West (Smith et al. 2015).

2.1.14 Management

Currently, Blue Mackerel East is managed at the Tier 1 level, and Blue Mackerel West is managed at the Tier 3 level. DEPM assessments of Blue Mackerel have been conducted for both the East and West sub-areas of the SPF: Blue Mackerel East in 2004 and 2014, and Blue Mackerel West in 2005.

2.2 Methods

2.2.1 Fishery Statistics

Fishery statistics from 1984/85 to 2017/18 have been supplied by relevant jurisdictions and collated by SARDI Aquatic Sciences. Annual data are reported in fishing seasons (May 1 to April 30) rather than financial years as was done in previous assessments (e.g. Ward et al. 2013, 2014c, 2015c).

Estimates of total annual catch for Blue Mackerel East include data from the NSW Ocean Fisheries (Hauling, Trap and Line, Trawl), NSW Estuary Fisheries (General and Prawn Trawl), Tasmanian Scalefish Fishery, Victorian Ocean Purse Seine Fishery and the Commonwealth SPF. In the West, total annual catch estimates include data from the Tasmanian Scalefish Fishery, Victorian Ocean Purse Seine Fishery, South Australian Marine Scalefish Fishery and Commonwealth SPF. Due to data confidentiality (<5 license holders annually reporting catch since 2015/16), fishery data from Victoria were not provided and have not been included in total annual catch statistics since 2015/16.

Mean annual CPUE of Blue Mackerel East and West in the Commonwealth SPF is calculated for the gear types of mid-water trawl (tonnes·trawl hour^{-1} ±SE) and purse-seine (tonnes·net-set^{-1} ±SE) from 2000/01 to 2016/17. Zero catch of Blue Mackerel in a trawl was assumed when effort but not catch was reported in the logbook record.

2.2.2 Biological Information

Length-frequency data for Blue Mackerel East were collected from commercial purse seine catches taken off New South Wales between 2006/07 and 2014/15. These data were supplied by the New South Wales Department of Primary Industries (DPI) and are presented in financial years.

Mid-water trawl operations resumed in the SPF during 2014/15; catch sampling required under the SPF HS (AFMA 2008) also recommenced. Samples of Blue Mackerel from mid-water trawl catches (n = 50 randomly selected fish per trawl), and supplied to SARDI Aquatic Sciences to estimate the size and age composition of the catch.

Samples of Blue Mackerel West prior to 2014/15 were obtained from catches taken in summer/early autumn by the commercial purse seine fishery operating from Port Lincoln, South Australia between 2008/09 and 2010/11.

Biological data collected from each fish included body length (mm FL), total weight (±1 g), sex, gonad developmental stage (following the macroscopic staging criteria described in Ward and Rogers 2007) and gonad weight (±0.1 g). Gonad stages were designated as: I) immature; II) maturing virgins or recovering spent; III) maturing; IV) ripe; and V) spent (full descriptions in Ward and Rogers 2007). Otoliths were removed from random sub-samples of fish for age estimation. An otolith weight-age algorithm developed by Ward and Rogers (2007) was used to estimate ages of Blue Mackerel West prior to 2015/16. Since 2014/15, all Blue Mackerel ages are based on annual growth increment counts in thin-sectioned otoliths (sub-samples of 5 to 10 fish per sample).

Blue mackerel otoliths were aged following the protocol of Marriott and Manning (2011) after thin-sectioning and mounting on microscope slides. Edges of each annual opaque zone were counted (edges of opaque zones are more easily delineated than edges of translucent zones). The edge of the opaque core was designated as the first opaque zone. The period of age represented by the opaque core differed based on the region where the fish were collected. All fish collected in southern Australia (Commonwealth subzones 3-4) were assigned a birthdate of Jan 1 based on the spawning times for southern Australia (Rogers et al. 2009). In eastern Australia (SPF sub-zones 5 and 6), Blue Mackerel were assigned a birthdate of Sept 1 based on spawning times for eastern Australia (Rogers et al. 2009, Ward et al. 2015b). Blue mackerel form an opaque zone in the winter, but it does not become discernible until spring-summer, i.e. until sufficient translucent material is deposited (Stewart et al. 1999). Therefore, we designated a standardised completion date of Oct 31 for the opaque zone for all regions. The completion of annual opaque zones in otoliths during spring/summer in temperate marine waters is common (e.g. Choat and Axe 1996, Fowler and Short 1998, Smith and Deguara 2003, Ewing et al. 2007). The opaque core (first year of growth) in fish caught in southern AUS represents growth from 1 Jan to 31 Oct (10 months), while the opaque core in fish caught in eastern AUS represent growth from 1 Sept to Oct 31 (14 months). Each otolith was aged by two different readers and the counts compared. Where the counts differed, the otolith was re-read and an age consensus reach, or the otolith was removed from further analyses.

Catch weighting was applied to length- and age-frequency data collected since 2014/15 in each sub-area. Length- and age-frequencies were weighted by the number of fish sampled per trawl to account for uneven sample sizes and then were catch weighted by the total amount of Blue Mackerel taken in the same trawl.

Biological data prior to 2014/15 are presented in financial years. From 2014/15 to present, all SPF catch sampling data are presented in fishing seasons from 1 May to 30 April.

2.3 Results

2.3.1 Blue Mackerel East

2.3.1.1 Fishery statistics

Number of vessels

The number of vessels reporting catches of Blue Mackerel East ranged from 233 to 462 between 1984/85 and 2008/09. Since then, vessel numbers decreased and have ranged between 122 and 162 (122 vessel in 2017/18). On average, 96% of the vessels reporting catch in each year since 2000/01 are from New South Wales and about 1% are Commonwealth vessels.

Annual patterns: Total catch

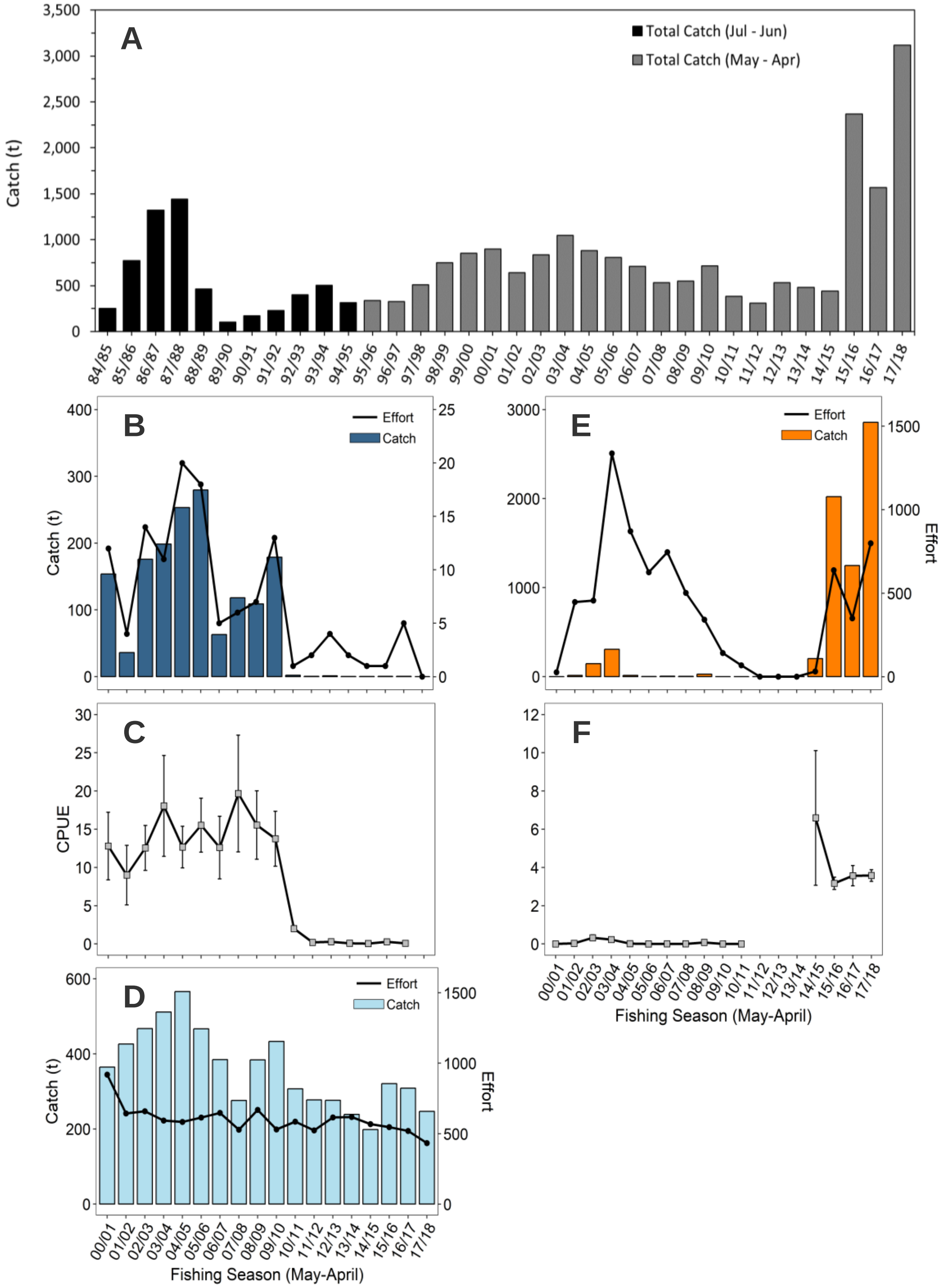
Total catches of Blue Mackerel East declined from ~1,400 t in 1986/87 to ~100 t in 1989/90 (Figure 2-1). Between 2003/04 and 2011/12, catches ranged from 309 to 1,045 t. From 2012/13 to 2014/15, catches averaged 486 t. Total catch increased to 2,368 t in 2015/16 and reached a historical high of 3,119 t in 2017/18 (Figure 2-1a). The main fisheries that take Blue Mackerel East are the NSW Ocean Hauling Fishery (purse seine) and the SPF (purse seine and mid-water trawl). From 1995/96 to 2014/15, NSW Ocean Fisheries and the SPF took on average 69% and 20% of the total annual catch for the East, respectively. The SPF has taken >80% of the total catch since 2015/16.

Annual patterns: Catch, Effort and CPUE

Purse seining has historically been used to take Blue Mackerel East. In the SPF mid-water trawling has replaced purse seining (Figure 2-1b, c, e, f), but in the NSW Ocean Hauling Fishery, purse seining is still the primary method used for Blue Mackerel (Figure 2-1d). There has been a long-term decline in purse seine effort in SPF for Blue Mackerel East from a peak of 20 net-sets in 2004/05 to a mean of 2 net-sets annually from 2010/11 to 2015/16 (Figure 2-1b). Effort increased to 5 net-sets in 2016/17 and decreased to zero in 2017/18. Annual purse seine catch is similar to effort with a high of 280 t in 2005/06, and ≤1 t taken since 2011/12 (0 t in 2017/18; Figure 2-1b). Mean annual CPUE of purse seines in the SPF decreased from a long term mean of 14 $t{\cdot}net\text{-}set^{-1}$ between 2000/01 and 2009/10 to ≤2 $t{\cdot}net\text{-}set^{-1}$ from 2010/11 to 2016/17 (Figure 2-1c).

Trends in fishing effort and catch by mid-water trawling in the SPF for Blue Mackerel East are similar (Figure 2-1e). Effort decreased from a peak of 1,338 trawl hours in 2003/04 (catch: 307 t) to 0 trawl hours (2011/12–2013/14) and increased to 638 trawl hours in 2015/16 (catch: 2,022 t). Trawl effort in the SPF increased to 799 trawl hours in 2017/18 with a catch of 2,858 t (Figure 2-1e). Mean annual CPUE of Blue Mackerel in mid-water trawls in the SPF was <0.4 $t{\cdot}trawl\ hour^{-1}$ prior to 2014/15 (Figure 2-1f). CPUE increased to 7 $t{\cdot}trawl\ hour^{-1}$ in 2014/15 and was 4 $t{\cdot}trawl\ hour^{-1}$ in 2017/18 (Figure 2-1f).

Figure 2-1. Fishery statistics for Blue Mackerel East. (A) Total annual landed catch (tonnes) for all jurisdictions from 1984/85 to 2017/18; black bars: catch per financial year; grey bars: catch per fishing season. Long-term purse seining trends in the SPF by fishing season from 2000/01 to 2017/18: (B) annual landed catch (tonnes) and effort (net-sets); (C) mean annual CPUE (t·net-set^{-1}; ±SE). (D) Annual landed catch (tonnes) and effort (net-sets) by purse seining in the New South Wales Ocean Hauling Fishery. Long-term mid-water trawling trends in the SPF: (E) annual landed catch (tonnes) and effort (trawl hours); (F) mean annual CPUE (t·trawl hour^{-1}; ±SE).



2.3.1.2 Biological Information

Length-frequency data were collected from 8,887 Blue Mackerel sampled from commercial purse seine catches off New South Wales between 2006/07 and 2017/18 (Table 2-1). Information on the spatial and temporal coverage of these samples relative to fishery production in New South Wales was not available. In 2014/15, length-frequency data for the SPF were collected from 264 Blue Mackerel sampled from midwater trawl catches in the East sub-area during April 2015. Age-frequency data were obtained from 105 of those fish (Table 2-2). During 2015/16, length-frequency data were collected from 61 catch samples (2,977 fish) with age-frequencies collected from 364 fish. In 2017/18, length- and age-frequency data were collected from 26 samples (length n = 1,202; age n = 170; Table 2-2). Biological samples from New South Wales may not be representative of Blue Mackerel harvested throughout the East sub-area.

Season	SPF sub-area	Gear type	No. of samples	Length-frequency n	Size range (mm FL)
2006/07	East	purse seine	23	1,869	220–400
2007/08	East	purse seine	13	1,286	160–340
2011/12	East	purse seine	13	810	180–390
2012/13	East	purse seine	2	108	280–370
2013/14	East	purse seine	11	1,177	170–360
2014/15	East	purse seine	12	1,382	180–370
2017/18	East	purse seine	31	2,255	210–390

Table 2-1. Summary of Blue Mackerel samples collected from commercial New South Wales State catches between 2006/07 and 2017/18 (data supplied by New South Wales DPI).

Season	SPF sub-area	Gear type	No. of samples	Length-frequency n	Age-frequency n	Size range (mm FL)	Age range (years)
2014/15	East	mid-water trawl	7	264	105	242–342	2–8
2015/16	East	mid-water trawl	61	2,977	364	187–398	0–11
2016/17	East	mid-water trawl	22	1,090	110	173-351	1–5
2017/18	East	mid-water trawl	26	1,202	170	157-340	0–6

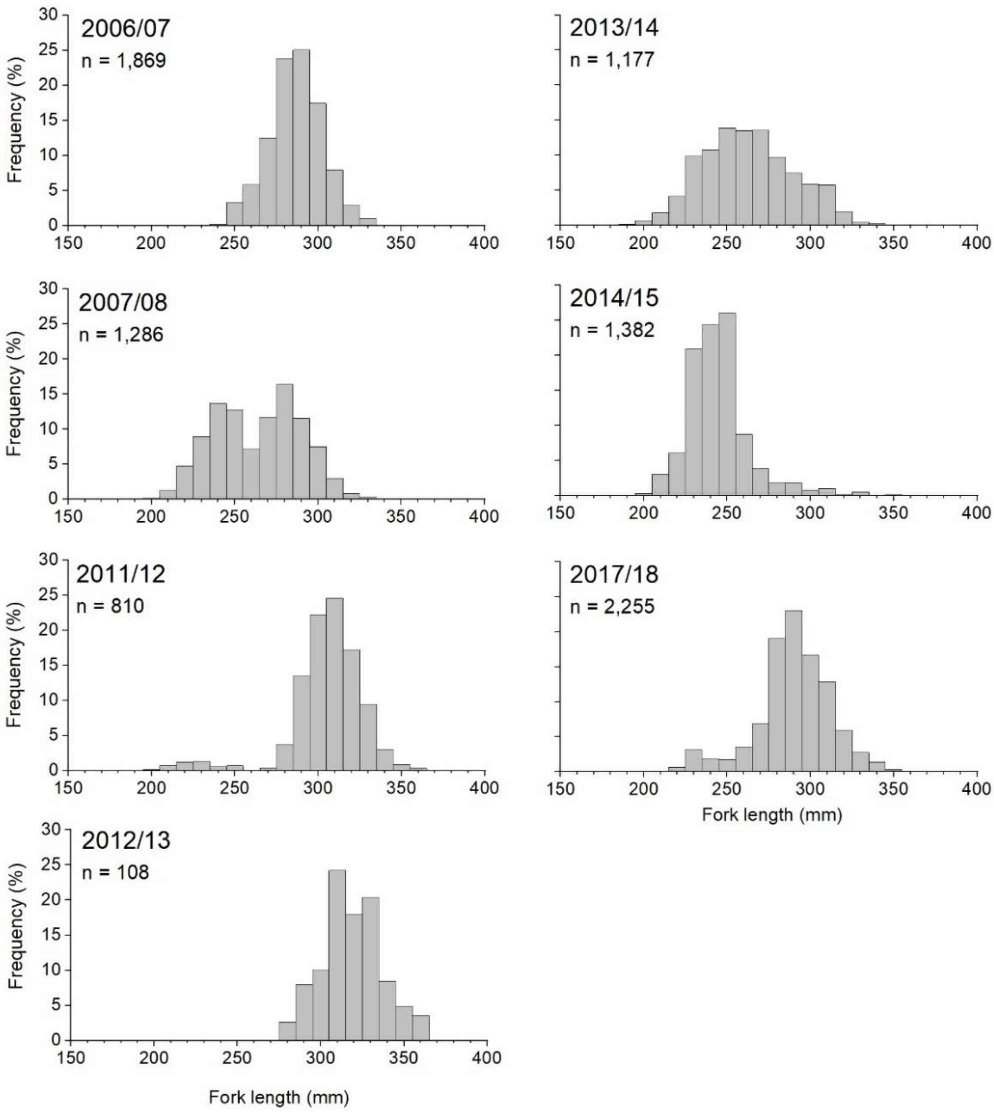
Table 2-2. Summary of Blue Mackerel East catch samples collected from commercial SPF landings. Note: number of samples in brackets is number for age frequency if different from length frequency.

Size structure

Purse seine fishery (NSW): 2006/07–2014/15

There were substantial differences in the size distributions among years of Blue Mackerel East sampled from purse seine catches (Figure 2-2). Fish ranged from 160 to 400 mm FL (Table 2-1). From 2006/07 to 2012/13 (excepting 2007/08), size distributions contained a single mode between 290 and 310 mm FL; the bimodal distribution of 2007/08 had modes at 240 mm FL and 280 mm FL. In 2013/14 and 2014/15, the size distribution included fish from 170 to 370 mm FL, with a single mode at 250 mm FL in each year (Figure 2-2). The length mode increased to 290 mm FL in 2017/18.

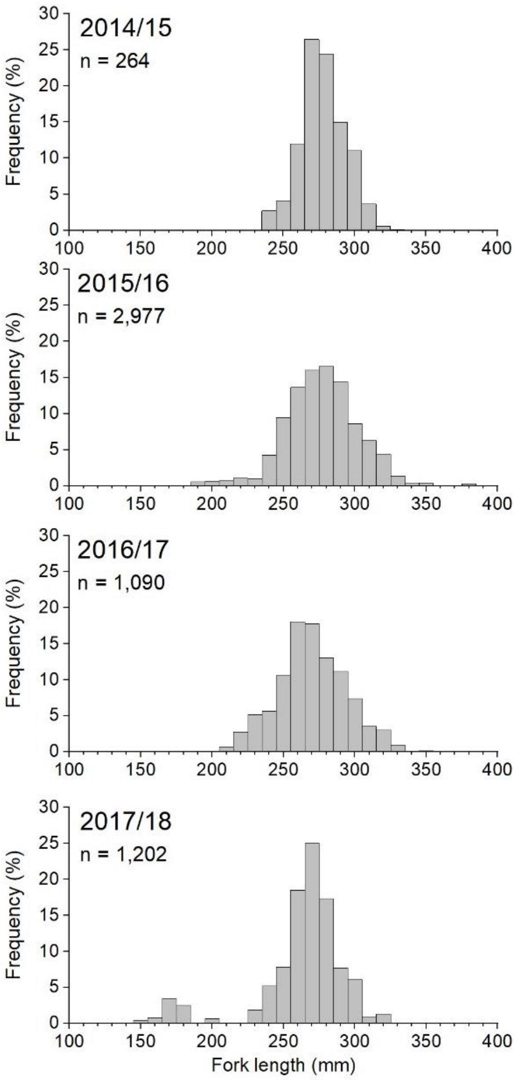
Figure 2-2. Length-frequency distributions of Blue Mackerel East collected from purse seine net-sets in New South Wales between 2006/07 and 2017/18. Data supplied by New South Wales DPI; n = number of fish. See Table 2-1 for sample N.



Mid-water trawl fishery: 2014/15–2017/18

The modal length of Blue Mackerel East from mid-water trawl catch samples from 2014/15 to 2016/17 varied between 260 and 280 mm FL, with fish sizes ranging from 187 to 398 mm FL (Figure 2-3; Table 2-2). There was a bimodal distribution of fish lengths in 2017/18 with a small mode at 170 mm FL and larger one at 270 mm FL; 61% of the fish were 260–280 mm FL (Figure 2-3). These length-frequency distributions from mid-water trawling are similar to those from purse seine catches taken in the East (Figures 3.2–3.3).

Figure 2-3. Length-frequency distribution of Blue Mackerel East caught by mid-water trawl in the SPF from 2014/15 to 2017/18. n = number of fish. See Table 2-2 for sample N.

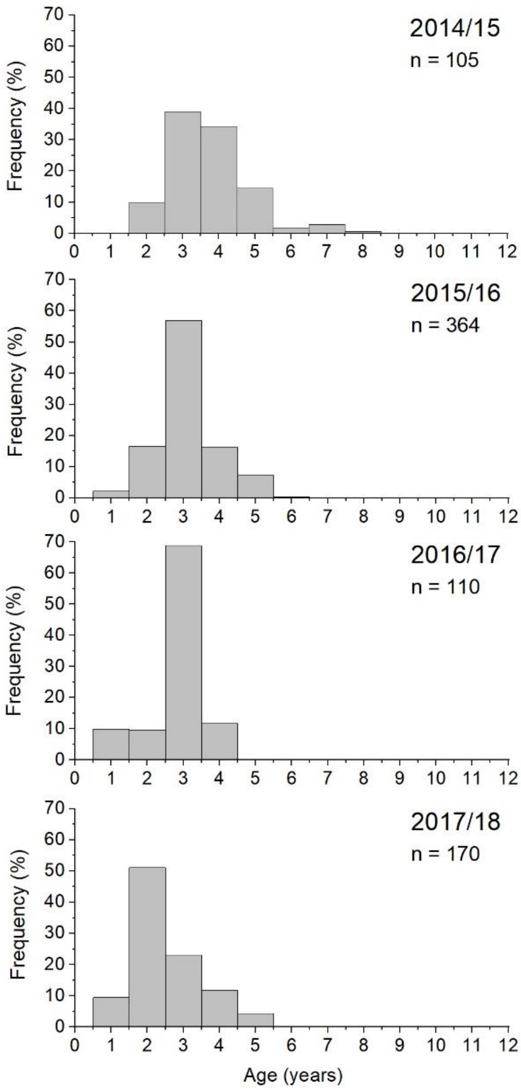


Age structure

Mid-water trawl fishery: 2014/15–2017/18

The age structure of Blue Mackerel East caught in mid-water trawls was dominated by 3 to 4 year old fish in 2014/15 (73%) and ages ranged from 2 to 8 years (age mode: 3 years; Figure 2-4). The modal age was also 3 years in 2015/16 and 2016/17. In 2017/18, the age mode decreased to 2 years (51%), and ages ranged from 1 to 6 years. The maximum estimated age of Blue Mackerel East from mid-water trawl catch samples was 11 years (Figure 2-4, Table 2-2).

Figure 2-4. Age-frequency distributions of Blue Mackerel East caught by mid-water trawl in the SPF from 2014/15 to 2017/18; n = number of fish. See Table 2-2 for sample N.



2.3.2 Blue Mackerel West

2.3.2.1 Fishery statistics

Number of vessels

The number of vessels reporting catches of Blue Mackerel West declined from a high of 27 vessels in 2008/09 to 5 vessels in 2013/14. During 2017/18, 6 vessels reported catches of Blue Mackerel West; vessel numbers have ranged from 5 to 13 since 2009/10.

Annual patterns: Total catch

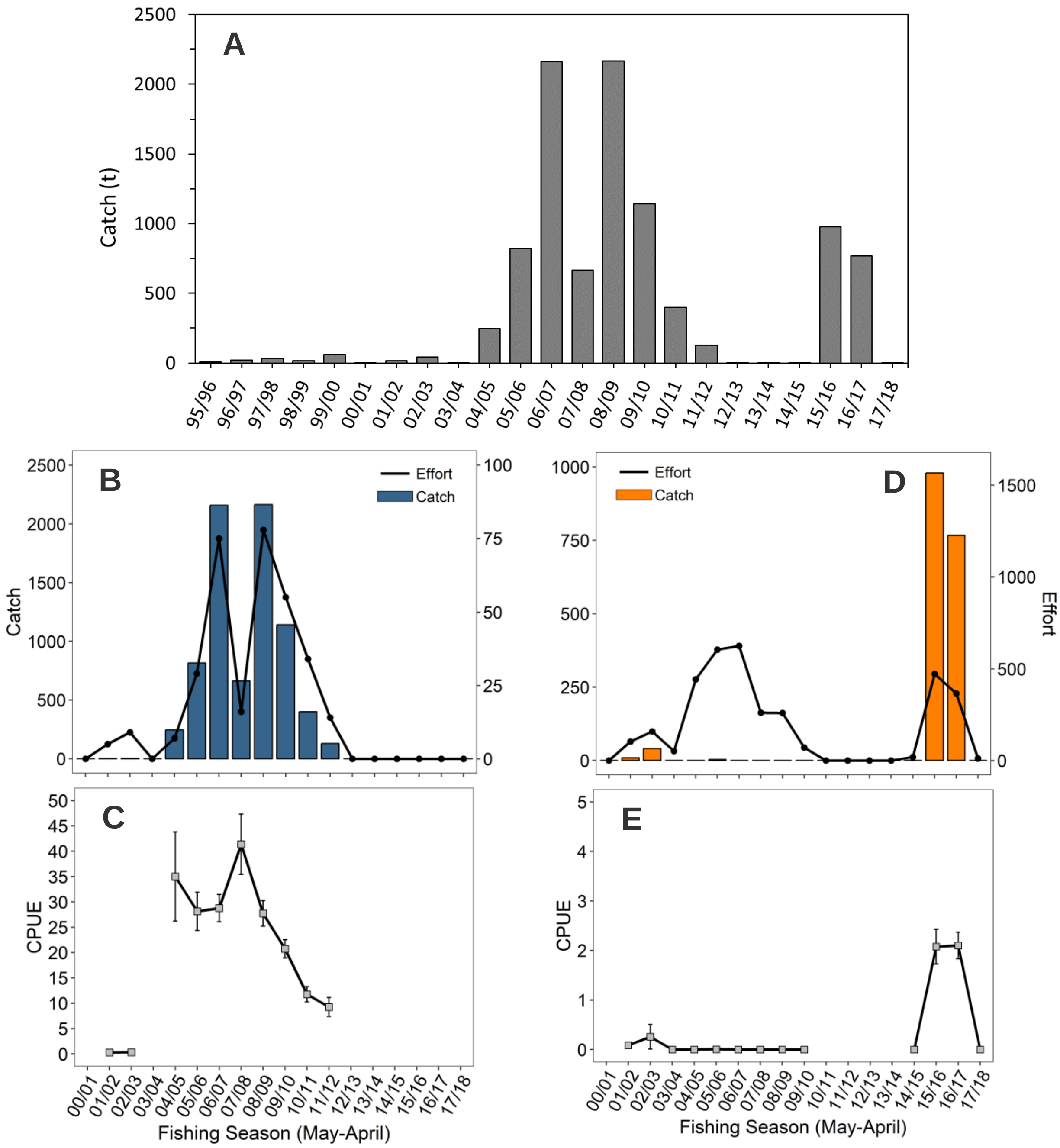
Total annual catches of Blue Mackerel West were low in the mid/late 1990s and early 2000s (<65 t) and increased to >2000 t in both 2006/07 and 2008/09 (Figure 2-5a). Since then, annual catches decreased to <2 t in 2012/13, remained low through 2014/15 and increased to 980 t in 2015/16 (Figure 2-5a). Total catch decreased from 767 t in 2016/17 to <1 t in 2017/18. Historically, the SPF has been the main fishery taking Blue Mackerel West.

Annual patterns: Catch, Effort and CPUE

Purse seines have historically been the main gear type used in the SPF for Blue Mackerel West, and purse seining effort has been variable since 2000/01 (Figure 2-5b). Catch and effort peaked in the mid- to late-2000s with effort ranging from 16 to 75 net-sets annually (Figure 2-5b). Purse seine effort and catch in the SPF has decreased since 2007/08, with zero effort reported since 2011/12. Mean annual CPUE of purse seines in the SPF decreased from a peak of 41 $t{\cdot}net\text{-}set^{-1}$ in 2006/07 to 9 $t{\cdot}net\text{-}set^{-1}$ in 2010/11 (Figure 2-5c).

Prior to 2015/16, mid-water trawl catches of Blue Mackerel West in the SPF were low (Figure 2-5d). Trawl effort increased in the mid-2000s (range: 260–625 trawl hours) when a multi-purpose 50 m mid-water trawler began targeting small pelagic species, particularly Redbait and Jack Mackerel, off Tasmania. In 2015/16, mid-water trawl effort in the SPF increased to 472 trawl hours with a Blue Mackerel catch of 979 t (Figure 2-5d). Effort decreased to 365 trawl hours in 2016/17 (catch: 766 t) and has further decreased to 11.5 trawl hours in 2017/18 with 0 t of catch. Mean annual CPUE of mid-water trawls in the SPF was <1 $t{\cdot}trawl\ hour^{-1}$ prior to 2015/16 and was 2 $t{\cdot}trawl\ hour^{-1}$ in both 2015/16 and 2016/17 (0 $t{\cdot}trawl\ hour^{-1}$ in 2017/18; Figure 2-5e).

Figure 2-5. Fishery statistics for Blue Mackerel West. (A) Total annual landed catch (tonnes) for all jurisdictions by fishing season from 1984/85 to 2017/18. Long-term trends in the SPF by fishing season from 2000/01 to 2017/18: (B) annual landed catch (tonnes) and effort (net-sets) by purse seine; (C) mean annual CPUE (t·net-set^{-1}; ±SE) by purse seine; (D) annual landed catch (tonnes) and effort (trawl hours) by mid-water trawl; (E) mean annual CPUE (t·trawl hour^{-1}; ±SE) by mid-water trawl.



2.3.2.2 Biological Information

Samples of Blue Mackerel West for biological analysis were collected from purse seine catches taken off South Australia (Table 2-3). A total of 1,257 fish were sampled over the three years; sex ratios were close to 1:1 but with slightly more females than males (Table 2-3). Blue Mackerel West catches from 2008/09 to 2010/11 were limited to the summer/early autumn period; biological samples from these catches may not be representative of the population. No samples were collected from 2011/12 to 2014/15, due to low levels of fishing activity. In 2015/16, length-frequency data were collected from 9 catch samples (142 fish), and age-frequencies were collected from 102 of those fish (Table 2-3). In 2016/17, length- and age-frequency data were collected from 21 samples (length n = 1,020; age n = 193; Table 2-3). Catch sampling did not occur in 2017/18 due to the lack of fishing.

Season	SPF sub-area	Gear type	No. of samples	Length-frequency n	Age-frequency n	Size range (mm FL)	Age range (years)	Sex ratio M:F
2008/09	West	purse seine	1	79	74	316–390	3–6	1:1
2009/10	West	purse seine	28	933	396	245–400	2–8	0.9:1
2010/11	West	purse seine	8	245	180	293–395	3–8	0.9:1
2015/16	West	mid-water trawl	9	142	102	239–403	0–11	na
2016/17	West	mid-water trawl	21	1,020	193	229–425	3–12	na

Table 2-3. Summary of Blue Mackerel West catch samples collected from commercial SPF landings. Note: number of samples in brackets is number for age frequency if different from length frequency.

Size structure

Purse seine fishery: 2008/09–2010/11

Blue Mackerel West sampled during 2008/09 off South Australia ranged from 320 to 390 mm FL (Figure 2-6); >50% of fish were between 340 and 370 mm FL. In 2009/10 and 2010/11, most fish ranged between 300 and 400 mm FL. Annual modal lengths of Blue

Mackerel from purse seine catches in the West (350–370 mm FL; Figure 2-6) were larger than those of fish caught in the East (250–310 mm FL; Figures 3.2–3.3).

Mid-water trawl fishery: 2015/16–2016/17

The modal length of Blue Mackerel West from mid-water trawl catch samples in 2015/16 was 350 mm FL (range: 239–403 mm FL) and increased to 370 mm FL (range: 229–425 mm FL) in 2016/17 (Figure 2-7; Table 2-3). The length-frequency distributions are similar to purse seine catches in the West, and the modal length is larger than in the East (250–310 mm FL; Figures 3.2–3.3).

Figure 2-6. Length-frequency distributions of Blue Mackerel West caught by purse seine in the SPF from 2008/09 to 2010/11; n = number of fish. See Table 2-3 for sample N.

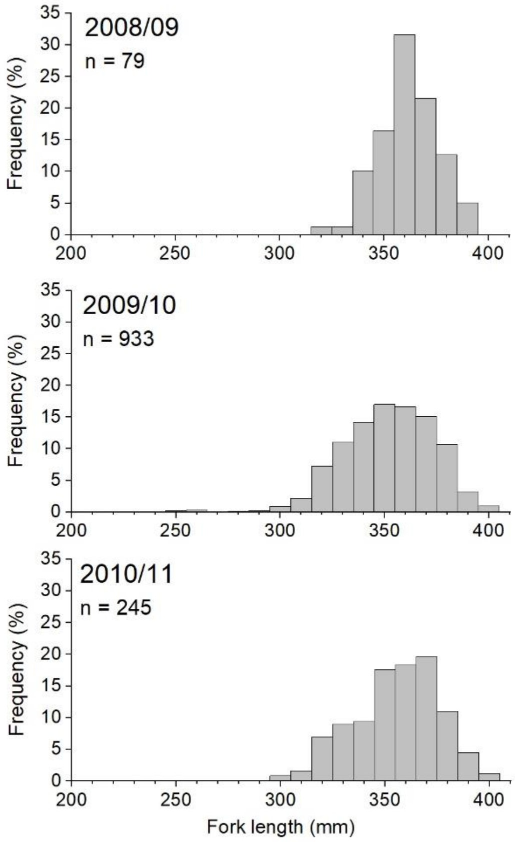
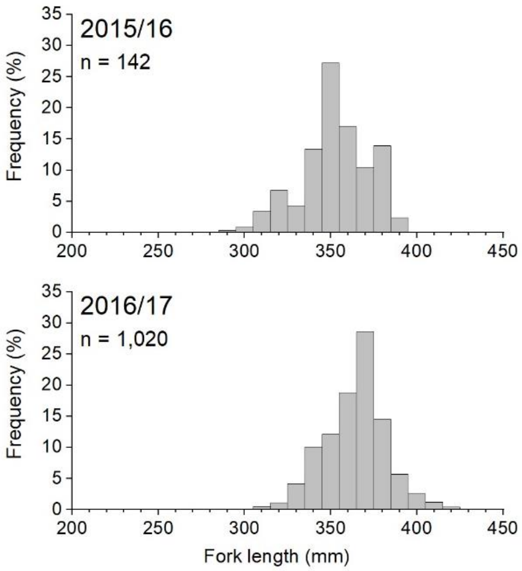


Figure 2-7. Length-frequency distributions of Blue Mackerel West caught by mid-water trawl in the SPF during 2016/17; n = number of fish. See Table 2-3 for sample N.



Age structure

Purse seine fishery: 2008/09–2010/11

In 2008/09, the age of fish in purse seine catches ranged from 3 to 6 years (Figure 2-8); 82% of fish were 4–5 years old. A similar age structure was found in 2009/10 and 2010/11, but some fish were up to 8 years old. In all years, most fish were older than 3 years.

Mid-water trawl fishery: 2015/16–2016/17

The modal age of Blue Mackerel West caught in mid-water trawls in both 2015/16 and 2016/17 was 5 years (Figure 2-9). Fish ages ranged from 0 to 12 years. The age structure shifted towards older fish in 2016/17 compared to 2015/16 (2015/16: 81% were 3 to 7 years; 2016/17: 65% were 3–7 years and 34% were 8–10 years (Figure 2-9).

Figure 2-8. Age-frequency distribution for Blue Mackerel West caught by purse seine in the SPF from 2008/09 to 2010/11; n = number of fish. See Table 2-3 for sample N.

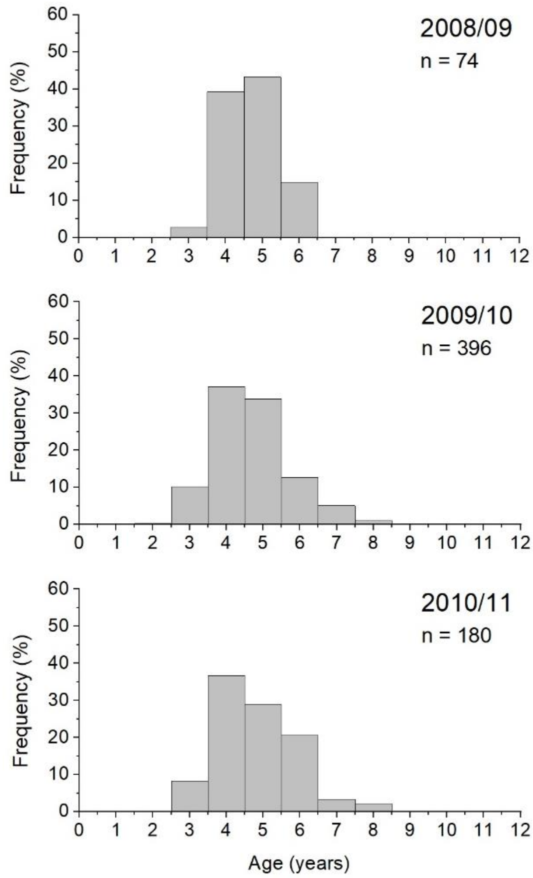
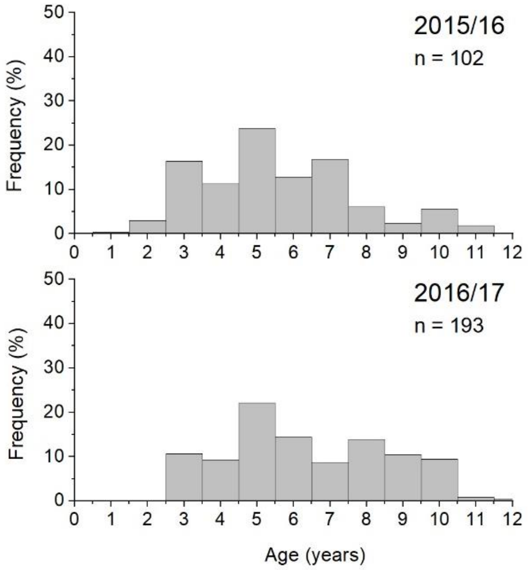


Figure 2-9. Age-frequency distribution for Blue Mackerel West caught by mid-water trawl in the SPF from 2015/16 to 2016/17; n = number of fish. See Table 2-3 for sample N.



2.4 Summary and Conclusions

2.4.1 Blue Mackerel East

The main fisheries for Blue Mackerel East are the NSW Ocean Hauling Fishery (purse seine) and the SPF. From 1995/96 to 2014/15, NSW Ocean Fisheries and the SPF took an average of 69% and 20% of the total annual catch in the East sub-area, respectively. Total annual catches from 2010/11 to 2014/15 were <550 t. The SPF has taken >80% of the total catch since 2015/16.

The total catch of Blue Mackerel East in the SPF in 2017/18 was 2,858 t, which is the highest on record, eclipsing the total catches of 2,022 t in 2015/16 and 1,248 t in 2016/17. The increase in catch reflects the recent establishment of the new fishing operation off southern NSW targeting Blue Mackerel. The catch-per-unit-effort (CPUE) of Blue Mackerel East in 2017/18 of 4 t·trawl hour^{-1} was similar to that recorded by the factory trawler in 2015/16 (3 t·trawl hour^{-1}) and 2016/17 (4 t·trawl hour^{-1}). The increase in catch of Blue Mackerel East in 2017/18 reflects the increased trawl effort (799 trawl hours) compared to 638 trawl hours in 2015/16 and 349 trawl hours in 2016/17.

In 2017/18, the distribution of fish lengths of Blue Mackerel East in mid-water trawl catches was bimodal, with a mode at 170 mm FL and 270 mm FL. During 2014/15 to 2016/17, the modal length of Blue Mackerel East varied between 260 and 280 mm FL, similar to the mean size of 50% maturity (~260 mm FL). The modal age of Blue Mackerel East in 2017/18 was 2 years, down from 3 years during 2014/15 to 2016/17. The decrease in the size and age of Blue Mackerel East taken in 2017/18 may reflect the transition of effort into inshore waters.

The average total catch of Blue Mackerel East over the last 3 fishing seasons has been ~2350 t. The spawning biomass of Blue Mackerel East in 2014 was ~83,300 t (95% CI = 35,100–165,000 t, Ward et al. 2015b). The recent average exploitation rate has been <3%, well below the maximum exploitation rate at Tier 1 for Blue Mackerel East of 12% (Smith et al. 2015). The total catch in 2017/18 was <30% of the available TAC. On the basis of the information provided above, Blue Mackerel East is classified as sustainable. Stewardson et al. (2018) also found the biological stock of Blue Mackerel East to be sustainable. Patterson et al. (2018) classified Blue Mackerel East as 'not overfished' and 'not subject to overfishing'.

2.4.2 Blue Mackerel West

Total annual catches of Blue Mackerel West were low in the late 1990s and early 2000s (<55 t) and increased to >2000 t in 2006/07 and 2008/09. In the SPF, catches have been mainly taken by purse seining prior to 2015/16. Total annual catches decreased to <2 t from 2012/13–2014/15, increased to 980 t in 2015/16, and decreased to 766 t in 2016/17. There was negligible catch of Blue Mackerel West in 2017/18. Mean annual CPUE of purse seines in the SPF peaked at 41 t·net-set^{-1} in 2006/07; CPUE of mid-water trawls rose to 2 t·trawl hour^{-1} in 2015/16 and 2016/17. Low annual catch in recent years reflects low fishing effort in areas where Blue Mackerel are known to be abundant (e.g. Great Australian Bight).

Blue Mackerel from commercial catch samples from both purse seines and mid-water trawls in the West have been well above the mean size at 50% maturity of ~260 mm FL (Ward and Rogers 2007) and tend to be larger and older than those from the East. In 2015/16, the modal length of Blue Mackerel West from mid-water trawls was 350 mm FL and increased to 3702 mm FL in 2016/17. The modal age class in both years was 5 years (age range: 0–12 years). Age and length structures are difficult to interpret due to the limited fishing effort, small sample sizes, differing ageing methods and changes in fishing locations over time.

A preliminary application of the DEPM to Blue Mackerel West off South Australia during 2005 provided a 'best' estimate spawning biomass of 56,228 t (Ward and Rogers 2007). This estimate of spawning biomass was considered to be conservative because the survey only covered a limited part of the West sub-area, and there was clear evidence of significant spawning activity outside the survey area in the western Great Australian Bight (Ward and Rogers 2007).

Recent catches of Blue Mackerel West have been <2% of the estimated spawning biomass for 2005 and below the Tier 3 exploitation rate for this stock of 3.75%. The total annual catch in 2017/18 (<1 t) was <50% of the available TAC. On the basis of the information provided above, Blue Mackerel West is classified as sustainable. Stewardson et al. (2018) classified the biological stock of Blue Mackerel West as sustainable. Patterson et al. (2018) Blue Mackerel West as 'not overfished' and 'not subject to overfishing' by Patterson et al. (2018).

3 Jack mackerel (*Trachurus declivis*)

3.1 Introduction

3.1.1 Background to Fishery

A large purse seine fishery for small pelagic fishes was developed off Tasmania in the mid-1980s. The majority of the catch was Jack Mackerel (*Trachurus declivis*), with relatively small quantities of Redbait (*Emmelichthys nitidus*) and Blue Mackerel (*Scomber australasicus*) taken as by-product. The fishery became the largest in Australia by weight, with catches of Jack Mackerel peaking at 39,747 t in 1986/87 (Kailola et al. 1993, Pullen 1994). In 1988/89, the Jack Mackerel catch fell to 8,150 t (Kailola et al. 1993, Pullen 1994). Large-scale purse seine operations for Jack Mackerel continued through the 1990s. However, purse seine operations ceased in 2000 due to large inter-annual fluctuations in catches and an overall downward trend in fishery production.

Mid-water trawling to target sub-surface schools of Jack Mackerel off Tasmania was trialled in 2001/02. Between December 2001 and April 2002, a total catch of over 5,000 t of small pelagic fishes was taken, with 90% being Redbait. A multi-purpose 50 m mid-water trawler was used to target small pelagic fishes from late 2002 onwards. By mid-2003, more than 7,000 t of small pelagic fishes had been taken, with Redbait dominating the catch. Trawl effort declined in the late 2000s, whereas small-scale purse seine operations continued into the early 2010s (Emery et al. 2015).

The long-term patterns of production in the fishery for Jack Mackerel off eastern Australia is likely to be the result of a combination of changes in fish availability/abundance and market/economic factors. However, the potential effects of fishing on abundance and population structure are poorly understood. Several authors have documented large inter-annual variability in oceanographic conditions in the southern part of the East Australian Current (e.g. Harris et al. 1992, Young et al. 1993, McLeod et al. 2012), which may have contributed to changes in relative abundance of surface schools of small pelagic species such as Jack Mackerel and their availability to the fishery. The apparent shift from Jack Mackerel to Redbait as the dominant small pelagic fish in this region during the 1990s may have resulted from changes in food availability cause by environmentally-driven changes in the plankton assemblage (Harris et al. 1992, Young et al. 1993, McLeod et al. 2012).

3.1.2 Taxonomy

Jack Mackerel belong to the family *Carangidae*, which includes 140 species representing 32 genera (Nelson 2006). Carangids are found worldwide with most species occurring in tropical waters. There are 65 species in Australian waters; eight species from four genera inhabit temperate waters (Gomon et al. 2008). The genus *Trachurus* contains 13 species; three of these species are found in Australia: *T. declivis, T. murphyi* and *T. novaezelandiae*.

3.1.3 Distribution

Jack Mackerel are widely distributed throughout coastal waters of southern Australia and New Zealand. In Australia, this species occurs along the southern coast from Shark Bay in Western Australia to Wide Bay in Queensland, including the waters around Tasmania (Gomon et al. 2008). Jack Mackerel is found to depths of 500 m, but is most abundant over the continental shelf to 200 m (Pullen 1994).

3.1.4 Stock Structure

There is some evidence to suggest that at least two populations of Jack Mackerel occur within Australian waters, whilst a third occurs in New Zealand. Analysis of morphometric measurements and meristic counts showed a significant difference between east Australian fish and those from the Great Australian Bight (GAB) (Lindholm and Maxwell 1988). Genetic studies have found no significant differences between southern New South Wales and eastern Tasmanian populations (Smolenski et al. 1994), but distinct differences between those from the GAB and New Zealand (Richardson 1982). In an extensive review of available biological, environmental and fishery data, Bulman et al. (2008) concluded that Jack Mackerel from eastern Australia, including eastern Tasmania, were likely to be a separate sub-population to those from west of Tasmania, which includes the GAB and Western Australia.

3.1.5 Movement

No specific studies have examined the movement of Jack Mackerel. However, a correlation between size and depth is evident, with smaller fish generally found inshore and larger fish offshore (Shuntov 1969, Stevens et al. 1984, Kailola et al. 1993, Pullen 1994). Such size-dependent distribution suggests offshore movement with increasing size.

3.1.6 Food and Feeding

Jack Mackerel feed primarily on aquatic crustaceans (Shuntov 1969, Stevens et al. 1984, Bulman et al. 2008, McLeod et al. 2012), and krill (*Nyctiphanes australis*) are the most common dietary item throughout the fish's distribution. Krill accounts for ~44% of the diet in Jack Mackerel from eastern Tasmania (Webb 1976, Williams and Pullen 1986, McLeod et al. 2012). Jack Mackerel living in deeper waters also feed on mesopelagic fish (Maxwell 1979, Blaber and Bulman 1987). In addition, Jack Mackerel eat minor quantities of other prey items, including ostracods, gastropods, amphipods, isopods, polychaetes and echinoderms (Stevens et al. 1984, Blaber and Bulman 1987, McLeod et al. 2012). Dietary composition varies seasonally (Bulman et al. 2008).

In the GAB, Jack Mackerel generally feed during the day with fish in offshore waters feeding mostly on krill and fish in inshore waters consuming mainly copepods (Shuntov 1969, Stevens et al. 1984). Prey size is dependent on fish size, with larger prey items taken by larger fish (Stevens et al. 1984).

3.1.7 Age, Growth and Size

Jack Mackerel reach a maximum of 470 mm FL, 1 kg in weight and 17 years of age (Last et al. 1983, Williams and Pullen 1986, Lyle et al. 2000, Browne 2005). Multiple studies have investigated the age and growth of Jack Mackerel (whole otoliths: Stevens and Hausfeld 1982, Jordan 1994; sectioned otoliths: Lyle et al. 2000, Browne 2005). The annual formation of increments in otoliths has been validated using bomb radiocarbon analysis (Lyle et al. 2000). In Tasmania, Jack Mackerel grow quickly at a young age, reaching 270 mm TL within their first 4 years and 335 mm TL by 10 years, with no significant difference in growth between males and females (Lyle et al. 2000).

3.1.8 Reproduction

Jack Mackerel are serial spawners (Marshall et al. 1993, Neira 2011), and mean spawning fraction (proportion of mature females spawning per day/night) is estimated at 0.056 (range: 0.0 to 0.134) in Australian waters (Ward et al. 2015a, 2016). Estimates of spawning fraction equate to a mean spawning frequency of 17.9 days (range: 7.5-142.9 days). Mean batch fecundity has been estimated at ~63,000 eggs for fish from eastern Tasmania (Neira 2011) and ~34,000 eggs for fish along the eastern Bass Strait (Ward et al. 2015a, 2016). Both male and female Jack Mackerel off south-eastern Australia are reported to be sexually mature at ~270 mm (Webb 1976), with 50% of females ≥315 mm FL undergoing vitellogenesis during the spawning season (Marshall et al. 1993).

Spawning occurs in spring along most of the New South Wales coastline (Maxwell 1979, Keane 2009), and during summer in south-eastern Australia (Eden, New South Wales to St. Helens, Tasmania) and in the GAB (Stevens et al. 1984, Marshall et al. 1993, Jordan et al. 1995, Ward et al. 2015a, SARDI unpublished data). Mean gonadosomatic index (GSI) values for females off eastern Tasmania increase substantially in November and remain high until January, before declining in February (Williams and Pullen 1986; Ward et al. 2011). Back-calculation of birthdates based on otolith microstructure of larval fish otoliths indicates that spawning occurs between mid-December and mid-February and follows a semi-lunar cycle, where peak activity is associated with both full and new moons (Jordan 1994).

3.1.9 Early Life History and Recruitment

Jack Mackerel eggs are positively buoyant and 0.97–1.03 mm in diameter (Neira 2011). Larvae have been described in Neira et al. (1998). Larvae have been collected off southern New South Wales during spring, and off eastern Tasmania, in Bass Strait and the GAB during summer (Stevens et al. 1984, Keane 2009, Ward et al. 2015a, SARDI unpublished data). Jack Mackerel eggs are morphologically similar to Yellowtail Scad eggs but slightly larger (Yellowtail Scad egg diameter: 0.78–0.88 mm; Neira 2009).

3.1.10 Stock Assessment

During the late 1980s and early 1990s, considerable research effort was directed at describing the fisheries biology of Jack Mackerel. Projects were initiated to (1) evaluate tools for assessment of stocks; (2) describe factors contributing to inter-annual variability in abundance; and (3) collect information on early life history and reproductive biology (Jordan et al. 1992, 1995). Research outputs included greater understanding of interactions between local oceanography and presence of surface schools of Jack Mackerel (Harris et al. 1992, Williams and Pullen 1993), and data on their reproductive biology and early life history (Harris et al. 1992, Marshall et al. 1993, Williams and Pullen 1993, Jordan 1994, Jordan et al. 1995). The abundance of surface schools off eastern Tasmania was closely related to oceanographic changes (Young et al. 1993). However, no successful method of assessing the size of the Jack Mackerel resource was developed, despite attempts to use a combination of aerial surveys of surface-schooling fish and hydro-acoustic surveys of surface and sub-surface schools on the shelf break (Jordan et al. 1992).

The first dedicated application of the DEPM to Jack Mackerel off the south-east coast of Australia (i.e. the key spawning area off eastern Australia) occurred in 2014 (Ward et al. 2015a). Prior to that study, a preliminary DEPM was done in 2011 using samples collected off south-eastern Australia in 2002–2004 during a survey of Blue Mackerel (Neira 2011). Ecosystem modelling of south-east Australian waters has also been used to estimate the spawning biomass of Jack Mackerel (Fulton 2013). The first dedicated DEPM survey for Jack Mackerel along the southern Australian coast (Kangaroo Island to western Tasmania) occurred during December 2016 and January 2017 (Ward et al.2018).

3.1.11 Recreational fishing

In Australia, recreational fishers target Jack Mackerel using rod and line, and troll lines in New South Wales, Queensland, South Australia, Western Australia and Tasmania. The Australian National Survey of Recreational and Indigenous Fishing (Henry and Lyle 2003) estimated that boat-based recreational fishers harvested 740,260 Jack Mackerel and Scads (combined) in 2000/01, with 37% of these being released back into the water. Of those fish retained, 46% were taken in New South Wales, 26% in Western Australia and 19% in Queensland (Henry and Lyle 2003). Based on the mean length/weight key developed by Stewart and Ferrell (2001), the estimated weight of Jack Mackerel/Yellowtail Scad harvested by the recreational sector annually in Australia was ~94 t (Ward and Rogers 2007). This catch information is not presented in this report, as estimates of catch for individual species were not available.

3.1.12 Biomass Estimates

East

Preliminary application of the DEPM estimated the spawning biomass of Jack Mackerel East between Sugarloaf Point and Cape Howe, New South Wales during October 2002 to be 114,000–169,000 t (Neira 2011). This estimate was considered imprecise due to a lack of samples to estimates of adult reproductive parameters.

The first dedicated application of the DEPM to Jack Mackerel East was undertaken in January 2014 between Eden, New South Wales and Triabunna, Tasmania and involved concurrent sampling of eggs and adults (Ward et al. 2015a). The estimate of spawning biomass of 157,805 t (95% CI = 59,570–358,731) was considered to be robust, because it was based on reliable estimates of key adult parameters. The 2014 estimate is also within the range of estimates provided by Neira (2011) and within the range of plausible estimates of biomass suggested for the ecosystem (130,000 to 170,000 t) by Fulton (2013).

West

The DEPM survey conducted during December 2016 and January 2017 between Kangaroo Island, South Australia and western Tasmania was the first dedicated application of the method to Jack Mackerel in the West sub-area (Ward et al. 2018). Two major areas of spawning activity—split by the Bonny Coast—were identified: an area south of Kangaroo Island and an area between King Island and the western Victorian coast. In addition to egg samples collected in the main survey area, opportunistic samples were also taken in Bass Strait where a large amount of spawning activity was detected. The estimate of spawning biomass derived from all samples (main survey + Bass Strait) was approximately 31,000 t, which is considered suitable for setting recommended biological catches as outlined by the SPF HS. This estimate is conservative as Bass Strait was not sampled extensively, and the western Jack Mackerel stock is known to extend west of Kangaroo Island (e.g. Stevens et al. 1984, Bulman et al. 2015).

3.1.13 Management Strategy Evaluation

2010

In the 2010 MSE, only one stock of Jack Mackerel was modelled (Giannini et al. 2010). As there were no DEPM survey estimates for spawning biomass to differentiate the East and West stocks at the time of assessment, model conditions were the same for both stocks. All Tier 1 scenarios investigated reached equilibrium around B_{40} by the end of the 30 year simulation period. The Tier 2 and Tier 3 results suggest that these harvest levels were conservative and sustainable. However, it was noted that these findings should be treated with caution as harvest quantities are “absolute” values and done without a DEPM estimate of spawning biomass to provide a benchmark.

2015

Smith et al. (2015) concluded the harvest rate of 15% may be too high for Jack Mackerel and suggested a Tier 1 harvest rate of 12% for Jack Mackerel East and West, with the Tier 1 rate being applied for not more than 5 years. Tier 2 harvest rates for Jack Mackerel East and West were recommended to be 50% of Tier 1 rates and not to be applied for more than 10 years. The study indicated that it is not safe to apply Tier 2 harvest rates unchecked for long periods of time (i.e. >10 years; Smith et al. 2015). The Atlantis-SPF biomass estimate for Jack Mackerel East used by Smith et al. (2015) was 137,000 t (typical range: 91,000–208,000 t) and 62,000 t (typical range: 60,000–110,000 t) for Jack Mackerel West (Smith et al. 2015).

3.1.14 Management

Currently, the Jack Mackerel East and West sub-areas are managed at the Tier 1 level under the SPF HS.

3.2 Methods

3.2.1 Fishery Statistics

Fishery statistics from 1984/85 to 2017/18 were supplied by relevant jurisdictions and collated by SARDI Aquatic Sciences. Unless indicated, annual data are reported in fishing seasons (May 1 to April 30) rather than financial years.

Estimates of total annual catch for Jack Mackerel East include data from the NSW Ocean Fisheries (Hauling, Trap and Line, Trawl), NSW Estuary General Fishery, Victorian Ocean Purse Seine Fishery, Tasmanian Scalefish Fishery and the Commonwealth SPF. For Jack Mackerel West, total annual catch estimates include data from the Tasmanian Scalefish Fishery, Victorian Ocean Purse Seine Fishery, South Australian Marine Scalefish Fishery and Commonwealth SPF. Due to data confidentiality (<5 license holders annually reporting catch since 2015/16), fishery data from Victoria were not provided and so are not included in total annual catch statistics since 2015/16.

Mean annual catch per unit effort (CPUE) of Jack Mackerel East and West in the Commonwealth SPF is calculated for the gear types of mid-water trawl (tonnes·trawl hour^{-1} ±SE) and purse-seine (tonnes·net-set^{-1} ±SE) from 2000/01 to 2017/18. Zero catch of Jack Mackerel in a trawl was assumed when fishing occurred but catch of Jack Mackerel was not reported in the logbook record.

3.2.2 Biological Information

Fishery-dependent length frequency and biological data were collected between 1984 and 1993 as part of a monitoring program of the Jack Mackerel Purse Seine Fishery off

Tasmania. Samples collected between 1985 and 1990 during demersal research trawling, conducted by CSIRO and the Tasmanian fisheries agency, supplied some biological information. Between 1994 and 2001, the level of catch sampling of the purse seine fishery was limited.

Biological data were collected by AFMA observers on a small proportion of trips during the 2001/02 pair-trawl fishing trials undertaken off Tasmania. When mid-water trawl operations started in 2002, the Tasmanian Aquaculture and Fisheries Institute (TAFI) began an intensive biological monitoring program that continued to 2006. AFMA also provided observer coverage of mid-water trawl operations, with additional length-frequency data collected from 2002 to 2008.

Purse seine operations for small pelagic fish resumed in Tasmanian State waters in 2008/09, mainly targeting Redbait and Jack Mackerel. Catch sampling was implemented in 2009/10 as part of the SPF monitoring program under the SPF HS (AFMA 2008). No catch samples were obtained for Jack Mackerel from 2010/11 to 2013/14 due to limited fishing activity. Catch sampling by AFMA observers resumed in the SPF in 2014/15. Samples of Jack Mackerel were collected (n = 50 randomly selected fish per trawl) and supplied to SARDI Aquatic Sciences to estimate the current size and age composition of the catch.

Biological data collected from each fish include: body length (mm FL), total weight (g), sex, gonad developmental stage (following the macroscopic staging criteria described in Marshall et al. 1993) and gonad weight (to the nearest 0.1 g). Gonad stages were designated as: I) immature; II) maturing virgins or recovering spent; III) maturing; IV) ripe; and V) spent. Otoliths were removed from random sub-samples of fish for age estimation. The age structure of Jack Mackerel prior to 2014/15 was estimated using age-length keys based on age data pooled from 1985/86, 1989/90, 1993/94 and 1994/95. Since 2014/15, ages for Jack Mackerel have been based on annual growth increment counts in thin-sectioned otoliths (sub-samples of 5 to 10 fish per sample).

Jack mackerel otoliths were aged following the protocol of Lyle et al. (2000) after thin-sectioning and mounting on microscope slides. Edges of each annual opaque zone were counted because they are more easily delineated than edges of translucent zones. The edge of the first annual opaque zone was identified using guidelines described of Lyle et al. (2000), where a sub-annual inner increment was sometimes present and was disregarded. The period of age represented by the first annual increment was assumed to be similar across all regions where the fish were collected, based on spawning stock, spawning time and time of opaque increment formation (Lyle et al. 2000, Ward et al. 2015a, Ward et al. 2016). All fish were assigned a birthdate of 1 January based on the known spawning of southern Australia (Ward et al. 2016). Jack mackerel deposit the opaque regions of their otoliths during winter (Lyle et al. 2000). The completion of annual opaque zones in otoliths during spring/summer in temperate marine waters is common (e.g. Choat and Axe 1996, Fowler and Short 1998, Smith and Deguara 2003, Ewing et al. 2007). A standardised completion date of 31 October was designated for the opaque zone for all regions. The first year of growth of Jack mackerel in southern Australia represents growth from 1 January to 31 October (10 months). Each otolith was aged by two different readers and the counts compared. Where the counts differed, the otolith was re-read and an age consensus reached, or the otolith was removed from further analyses. Prior to ageing otoliths, the readers used a species-specific reference collection to calibrate their ageing technique (see Appendix 1 for details).

Catch weighting was applied to length/age-frequency data collected since 2014/15. Length- and age-frequencies were weighted by the number of fish sampled per trawl to account for uneven sample sizes and then catch weighted by the total amount of Jack Mackerel taken in the trawl.

Commercial logbook information, length-frequency and biological data collected between 1984 and 2018 are included in this assessment. In addition to current catch samples, age, growth and reproductive data from previous studies are included (Jordan et al. 1992, Lyle et al. 2000, Browne 2005, Ward et al. 2011). Length-frequency data from research sampling undertaken in January 2014 (Ward et al. 2015a). Summarised biological data prior to 2014/15 are presented in financial years. From 2014/15 to present, all SPF catch sampling data are presented in fishing seasons from 1 May to 30 April.

3.3 Results

3.3.1 Jack Mackerel East

3.3.1.1 Fishery Statistics

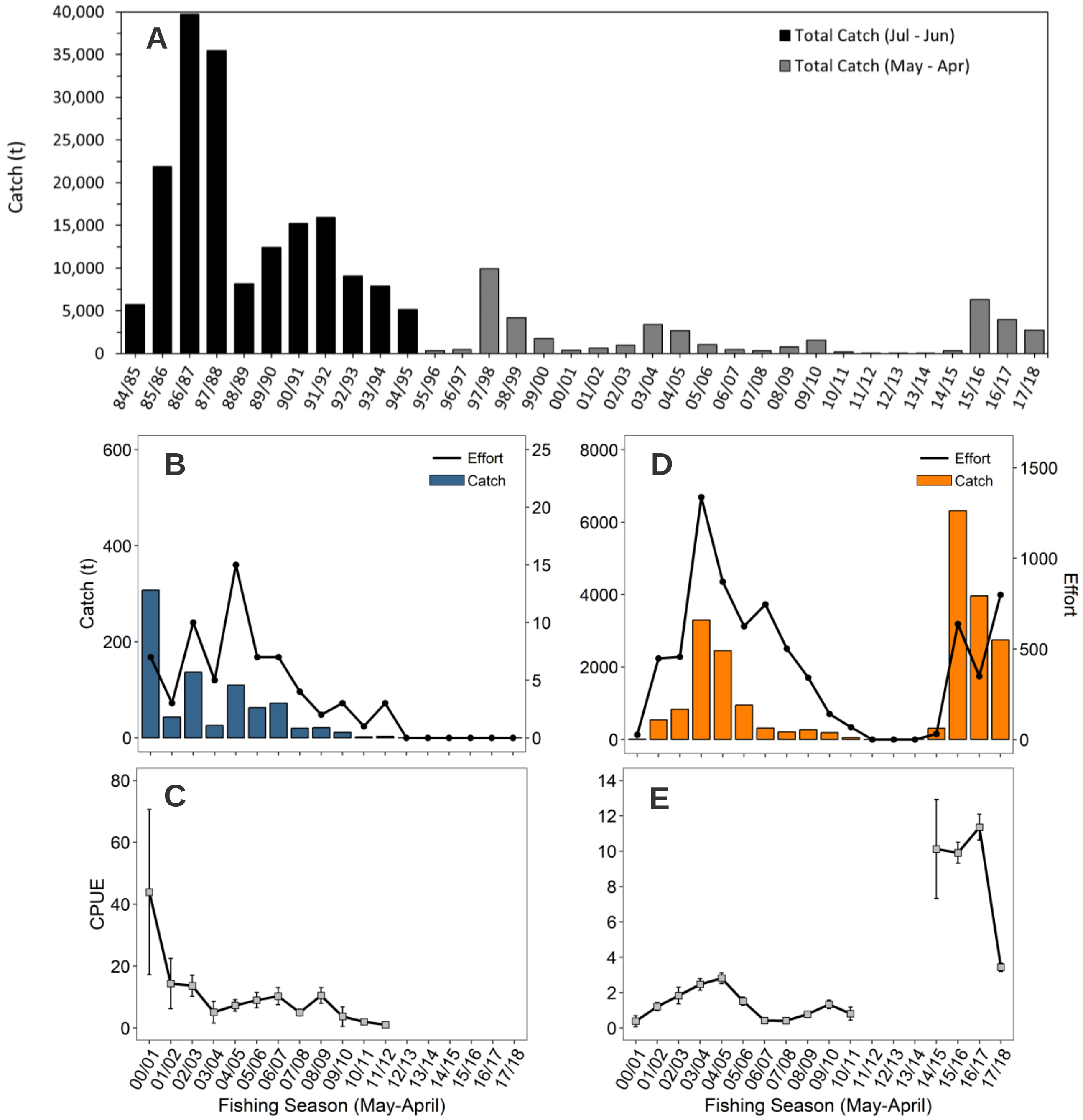
Number of vessels

The number of vessels reporting catches of Jack Mackerel East declined from >100 vessels prior to 1998/99 to 12 vessels in 2012/13 and increased to 18 vessels in 2013/14. In 2017/18, 8 vessels landed Jack Mackerel East. One Commonwealth vessel reported catches of Jack Mackerel East in 2017/18.

Annual patterns: Total catch

Total catches of Jack Mackerel East declined from ~40,000 t in 1986/87 to 310 t in 1995/96 (Figure 3-1a). Catches increased to 9,916 t in 1997/98 and decreased through the 2000s with catches of <100 t from 2011/12 to 2013/14. Total catch increased to 6,321 t in 2015/16 and dropped to 3,966 t in 2016/17 and 2,751 t in 2017/18 (Figure 3-1a). The main fishery for Jack Mackerel East is the SPF (purse seine and mid-water trawl).

Figure 3-1. Fishery statistics for Jack Mackerel East. (A) Total annual landed catch (tonnes) for all jurisdictions from 1984/85 to 2017/18; black bars: catch per financial year; grey bars: catch per fishing season. Long-term trends in the SPF by fishing season from 2000/01 to 2017/18: (B) annual landed catch (tonnes) and effort (net-sets) by purse seine; (C) mean annual CPUE (t·net-set^{-1}; ±SE) by purse seine; (D) annual landed catch (tonnes) and effort (trawl hours) by mid-water trawl; (E) mean annual CPUE (t·trawl hour^{-1}; ±SE) by mid-water trawl.



Annual patterns: Catch, Effort and CPUE

Within the SPF, purse seining has historically been used to target Jack Mackerel East (Figure 3-1b). Purse seine effort for Jack Mackerel East declined from 15 net-sets in 2004/05 to zero net-sets from 2012/13 to 2017/18 (Figure 3-1b). Annual purse seine catch follows effort with 307 t taken in 2000/01 and no reported catch since 2012/13 (Figure 3-

1b). Mean annual CPUE for purse seining in the SPF has declined from 44 t·net-set^{-1} in 2000/01 to 1 t·net-set^{-1} in 2011/12 (Figure 3-1c).

Mid-water trawling replaced purse seining in the SPF for Jack Mackerel East after the early 2000s (Figure 3-1d). Annual trends of mid-water trawl effort and catch are similar since 2000/01: both increased in 2003/04 (1,338 trawl hours; 3,300 t), decreased to zero effort and catch from 2011/12 to 2013/14 and increased to 638 trawl hours in 2015/16, with 6,316 t of catch. Effort increased in 2017/18 to 799 trawl hours while catch declined to 2,748 t (Figure 3-1d). Mean annual CPUE of mid-water trawls increased from zero in 2011/12 to 11 t·trawl hour^{-1} in 2016/17 and declined to 3 t·trawl hour^{-1} in 2017/18 (Figure 3-1e).

3.3.1.2 Biological Information

Catch sampling of Jack Mackerel East has varied since 2009/10 due to limited commercial fishing in the SPF. During 2009/10, 1,412 fish were collected from purse seines and 318 fish from mid-water trawls off Tasmania (Table 3-1). Catch samples were not collected from 2010/11 to 2013/14, but in January 2014, 10 samples (n = 1,759) of Jack Mackerel were collected during DEPM research surveys (demersal trawl net) off eastern Victoria and southern New South Wales (Ward et al. 2015a). An additional seven samples (n = 947) were collected from waters off north-eastern Tasmania (no age data taken; Ward et al. 2015a). Catch sampling in the SPF resumed in 2014/15. During 2015/16, length-frequency data were collected from 94 samples (4,532 fish) with age-frequencies collected from 92 samples (510 fish). In 2017/18, length- and age-frequency data were collected from 29 samples (length n = 1,438; age n = 144; Table 3-1).

Season	SPF sub-area	Gear type	No. of samples	Length-frequency (n)	Age-frequency (n)	Size range (mm FL)	Age range (years)
2009/10	East	purse seine	15	1,412	270	120–320	1–7
2009/10	East	mid-water trawl	5	318	87	150–290	2–7
2014/15	East	mid-water trawl	7	325	102	185–380	2–15
2015/16	East	mid-water trawl	94 (92)	4,532	510	82–425	1–11
2016/17	East	mid-water trawl	30	1,478	144	144–306	2–10
2017/18	East	mid-water trawl	29	1,438	144	178–291	1–10

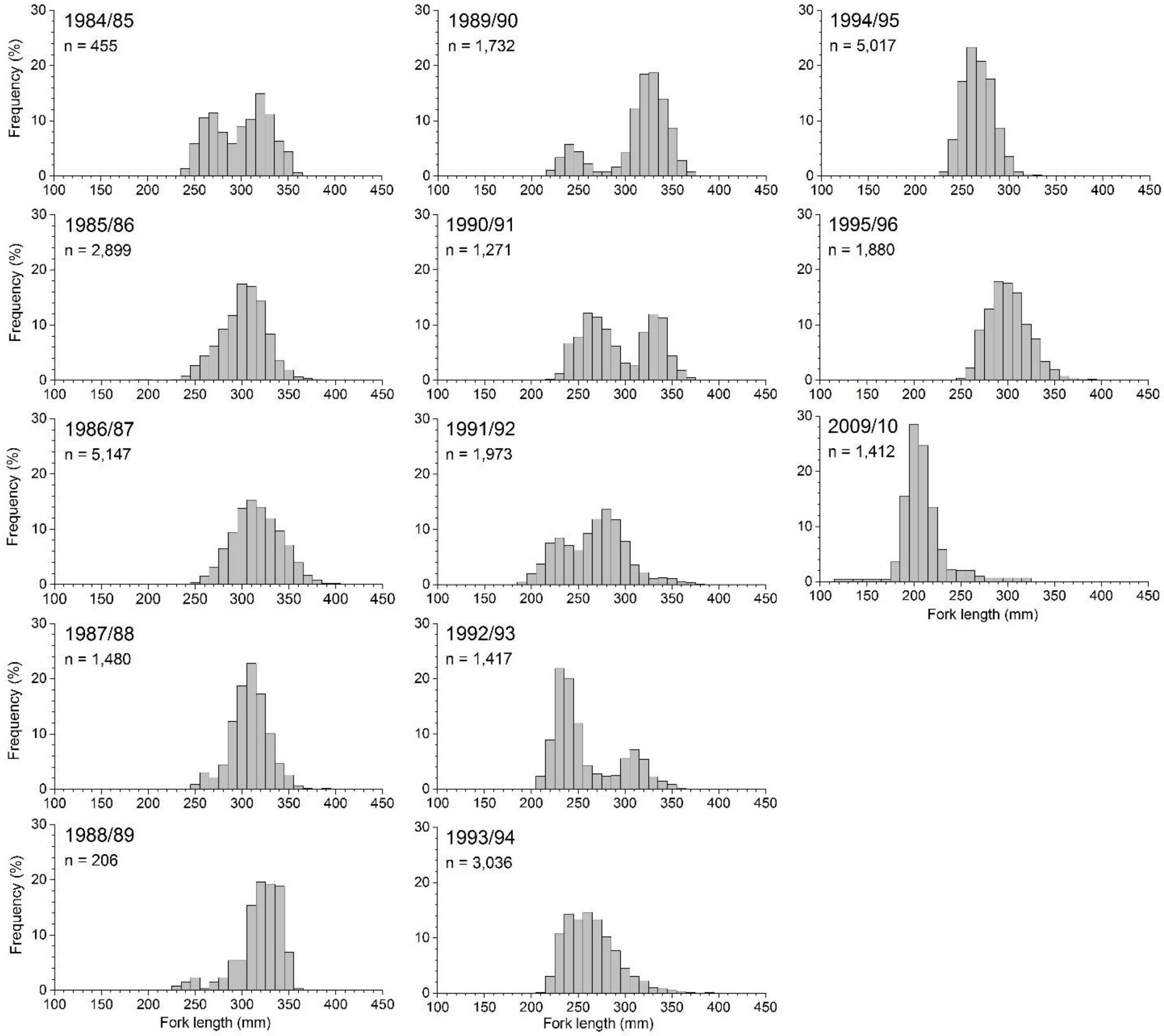
Table 3-1. Summary of Jack Mackerel East catch samples collected from commercial SPF landings. Note: number of samples in brackets is number for age frequency if different from length frequency.

Size structure

The purse seine fishery: 1984/85–2009/10

Purse seine catches of Jack Mackerel East off eastern Tasmania between 1984/85 and 1995/96 mainly contained fish between 210 and 350 mm FL, and included individuals up to 440 mm FL (Figure 3-2). The size structure in 1984/85 was bimodal, and fish ranged from 240 to 360 mm FL. From 1985/86 to 1988/89, catches were unimodal with most fish in the 250–350 mm FL size range, shifting towards larger fish. A cohort of small fish (<250 mm FL) was present in 1988/89, and in 1989/90 the size distribution was bimodal with peaks at 240 mm FL and 320–330 mm FL. The size structure was bimodal during the following three years with the position and relative heights of the modes varying among years. From 1993/94–1995/96, size structures were unimodal with a shift to larger fish. In 2009/10, the size structure was unimodal and dominated by smaller fish (190–220 mm FL size range; Figure 3-2).

Figure 3-2. Length-frequency distributions of Jack Mackerel East caught in the SPF by purse seine from 1984/85 to 1995/96 and in 2009/10; n = number of fish.

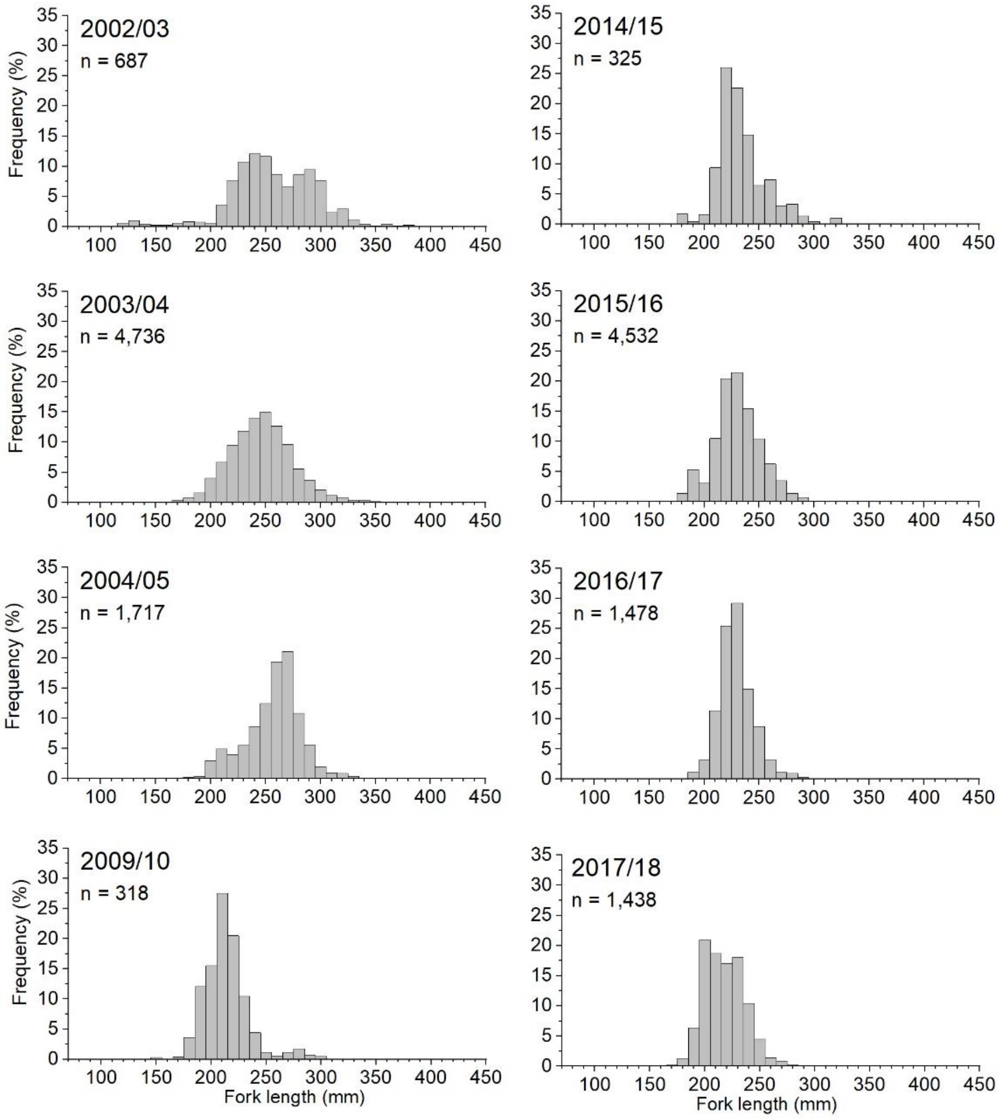


Mid-water trawl fishery: 2002/03–2017/18

Jack Mackerel caught by mid-water trawl off eastern Tasmania from 2002/03 to 2004/05 were mostly between 200 and 300 mm FL (Figure 3-3), and considerably smaller than those caught in earlier purse seine operations. The size composition of mid-water trawl and purse seine catches in the East during 2009/10 were similar, with each dominated by fish between 180 and 240 mm FL (Figures 2.2–2.3).

Modal length of Jack Mackerel increased from 240 to 270 mm FL between 2002/03 and 2004/05 in mid-water trawl catches taken in the East, but only a small proportion of the catch contained fish >300 mm FL (Figure 3-3). In 2014/15, the size structure of catch samples from mid-water trawling off southern New South Wales increased compared to 2009/10. The modal length increased to 220 mm FL, and more fish were in the 250 to 300 mm FL size classes (Figure 3-3). The modal length of the 2014/15 commercial mid-water trawl catch was smaller (220 mm FL) than the commercial trawl catches of the early 2000s (240–270 mm FL; Figure 3-3). The model length increased to 230 mm FL in 2015/16, was the same in 2016/17, and decreased to 200 mm FL in 2017/18 (Figure 3-3).

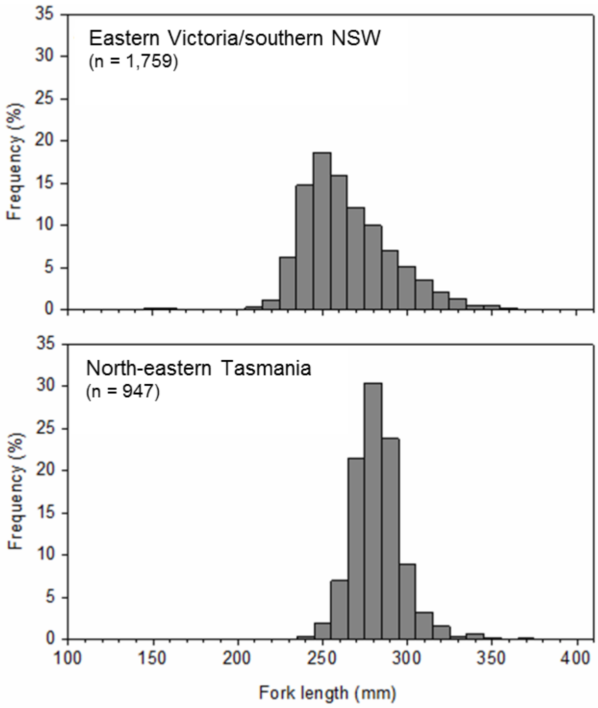
Figure 3-3. Length-frequency distributions of Jack Mackerel East caught by mid-water trawl in the SPF from 2002/03 to 2017/18; n = number of fish.



Research (demersal trawl net) surveys: 2014

The research samples of Jack Mackerel collected off eastern Victoria/southern New South Wales (above 39°S) mainly consisted of fish between 240–310 mm FL, with a mode at 250 mm FL (Figure 3-4). Similarly, the size structure for research samples off north-eastern Tasmania (below 39°S) mainly contained fish between 250–310 mm FL, although with a narrower range and stronger mode (280 mm FL; Figure 3-4). The modal length of the Jack Mackerel in research catches from eastern Victoria/southern New South Wales were larger compared to those from commercial trawl catches taken in the same area in 2014/15 (Figures 2.3–2.4).

Figure 3-4. Length-frequency distributions for Jack Mackerel from research sampling off south-eastern Australia in January 2014.

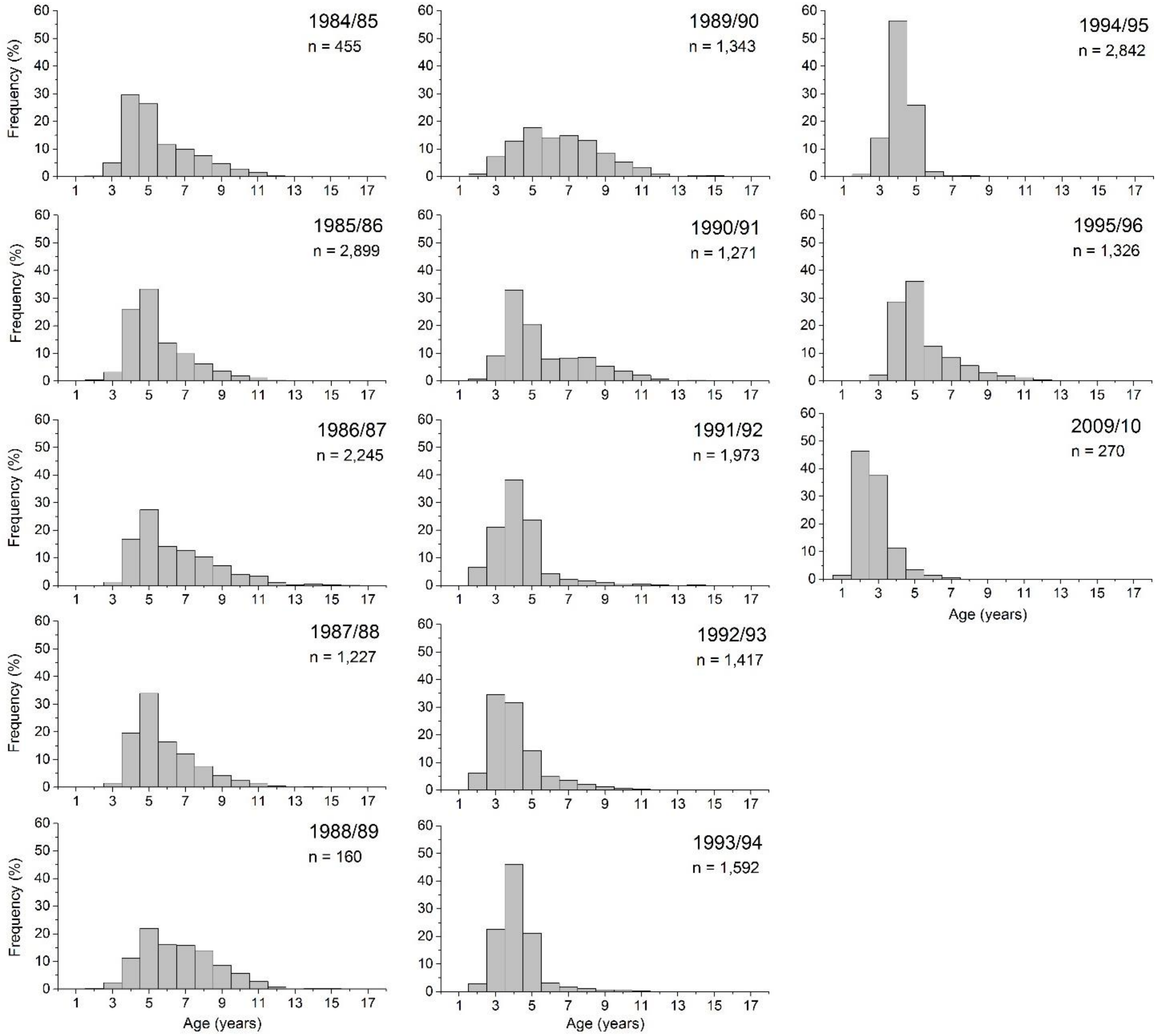


Age structure

The purse seine fishery: 1984/85–2009/10

Jack Mackerel East taken by purse seine off eastern Tasmania were generally 3–10 years old (Figure 3-5). Catches between 1984/85 and 1990/91 were dominated by 4–5 year olds with fish up to 9 years also well represented. Between 1991/92 and 1994/95, few fish older than 6 years were taken, with 3 to 5 year olds the dominant age classes. The 1995/96 age structure was similar to that of the mid 1980s suggesting the relative scarcity of older fish in the intervening years may not have been solely due to the impact of fishing on population age structure. However, it should be noted that using a pooled age-length key rather than annual age data may have had a smoothing effect on age composition, in particular when representing the older age groups. In 2009/10, purse seine catches from eastern Tasmania were dominated by fish in the 2–3 year age groups (Figure 3-5).

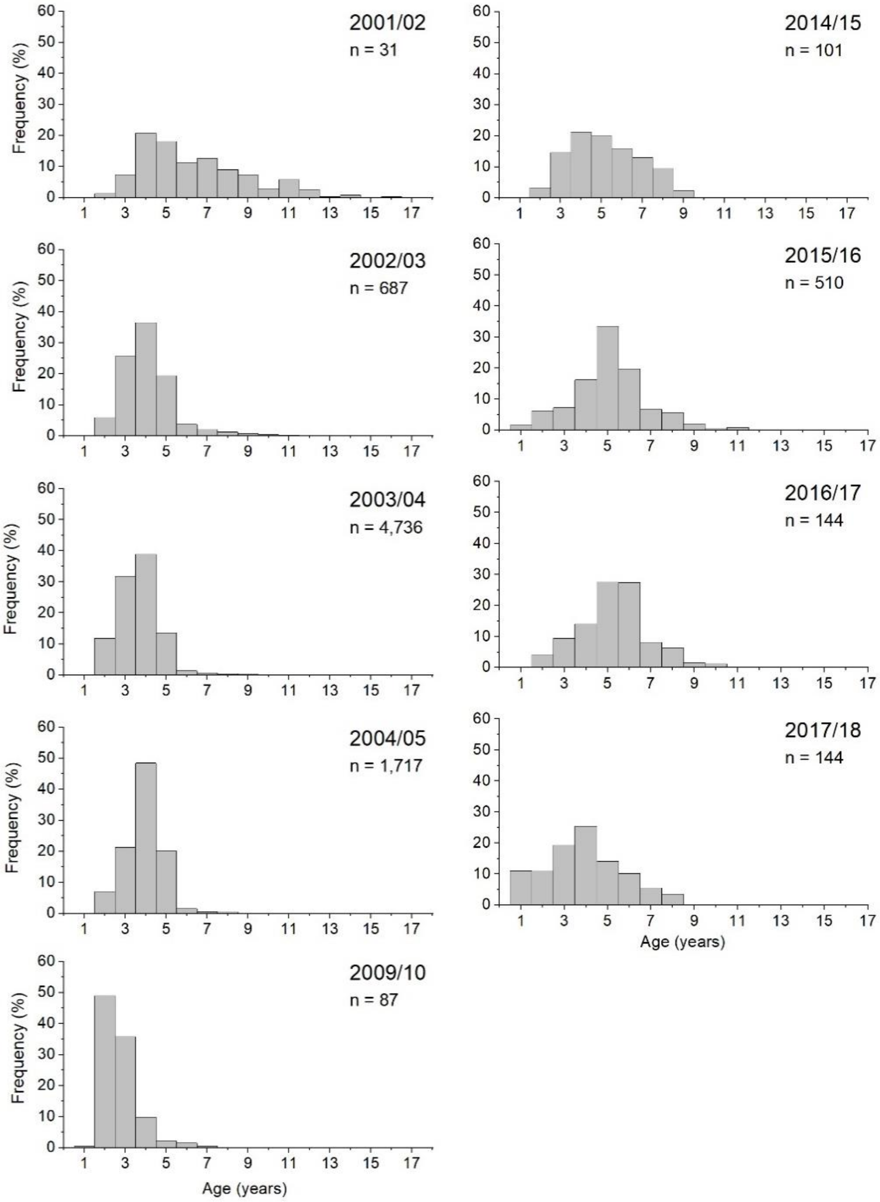
Figure 3-5. Age-frequency distributions of Jack Mackerel East caught in the SPF by purse seine from 1984/85 to 1995/96 and in 2009/10; n = number of fish in distribution.



Mid-water trawl fishery: 2001/02–2017/18

Mid-water trawl catches of Jack Mackerel East off eastern Tasmania between 2001/02 and 2004/05 mainly consisted of fish aged 2–5 years old, with a modal age of 4 years (Figure 3-6). During 2009/10, mid-water trawl catches from eastern Tasmania mostly contained 2–3 year old fish. In mid-water trawl catches off southern New South Wales during 2014/15, 72% of the fish were between 3 and 6 years old (age mode: 4 years) (Figure 3-6). In 2015/16, the modal age was 5 years with 70% of fish between 4 and 6 years. In 2016/17, 5–6 year olds made up 55% of the age structure. In 2017/18, the modal age was 4 years with 60% of the fish between 3 and 5 years (Figure 3-6). The maximum estimated age of Jack Mackerel East from mid-water trawl catch samples was 16 years (Figure 3-6).

Figure 3-6. Age-frequency distributions of Jack Mackerel East caught by mid-water trawl in the SPF from 2001/02 to 2017/18; n = number of fish in distribution.

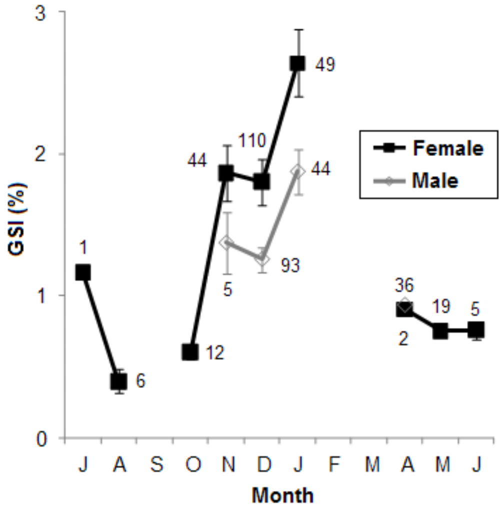


Reproduction

Gonadosomatic Index (GSI)

Trends in male and female GSI indicated that Jack Mackerel from eastern Tasmania have a discrete spawning season that extends over about a three month period from late spring to mid-summer (Figures 2.8–2.9). From October, female GSI rose sharply to 2.6% in January. Male GSI also increased in January. After this, female GSI values declined rapidly and remained low through June (Figure 3-8).

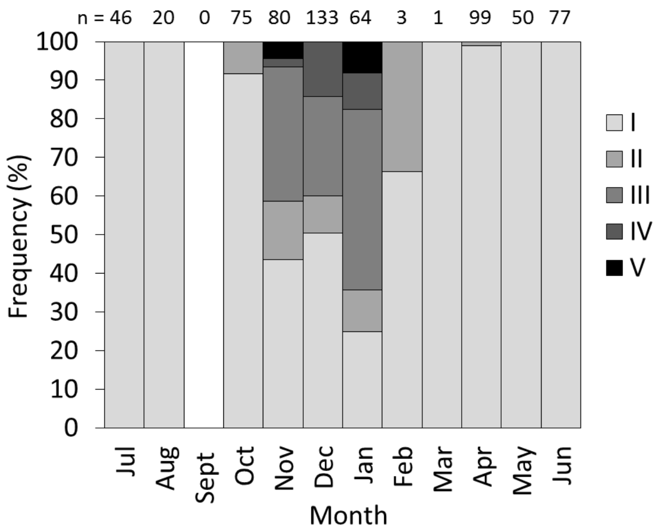
Figure 3-7. Monthly mean GSI values of Jack Mackerel by sex. Numbers associated with data points represent sample size (±SE). Based on data collected by Ward et al. (2011).



Gonad stages

Macroscopic staging of ovaries indicated Jack Mackerel off eastern Tasmania began actively spawning (gonads in Stages IV–V) in November and spawning activity increased during December–January (Figure 3-9).

Figure 3-9. Monthly macroscopic ovary stages (Stages I–V) from Jack Mackerel; top numbers represent sample sizes. Based on data collected by Ward et al. (2011).



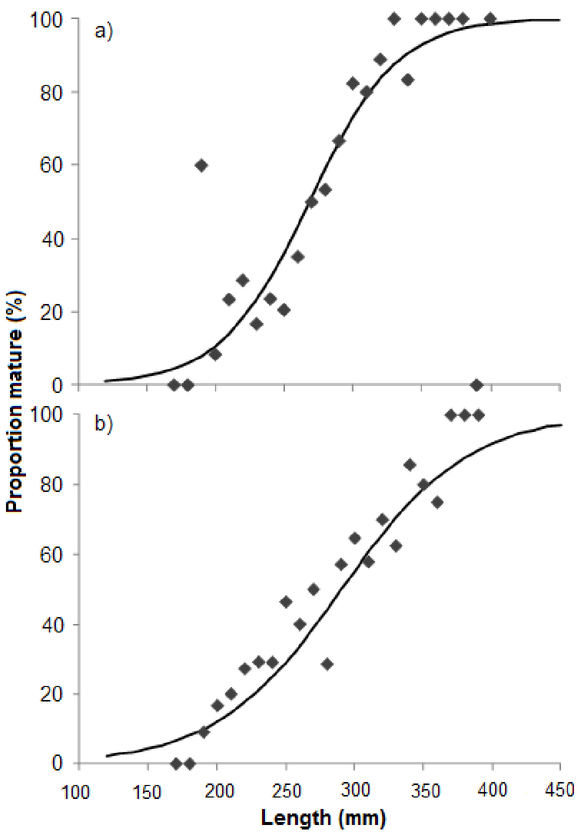
Size at maturity

Fifty percent maturity was estimated to be 268 mm FL for female Jack Mackerel from eastern Tasmania and 291 mm FL for males (Table 3-3, Figure 3-10). All fish larger than 360 mm FL were mature.

			Size at maturity		
Region	Sex	N	a	b	L_{50} (mm)
Eastern Tasmania	female	333	-8.40	0.031	268
	male	309	-6.40	0.022	291

Table 3-2. Size at sexual maturity logistic parameters and 50% maturity (L_{50}) values of Jack Mackerel by sex. Based on data collected by Ward et al. 2011.

Figure 3-10. Proportion of mature female (a) and male (b) Jack Mackerel by length class (mm FL) fitted with logistic ogives; based on data collected by Ward et al. (2011).



3.3.2 Jack Mackerel West

3.3.2.1 Fishery Statistics

Number of vessels

The total number of vessels reporting catches of Jack Mackerel West declined from 17 in 1998/99 to 1 in 2012/13. Total vessel numbers increased to 6 in 2014/15; 5 vessels were fishing in 2017/18.

Annual patterns: Total catch

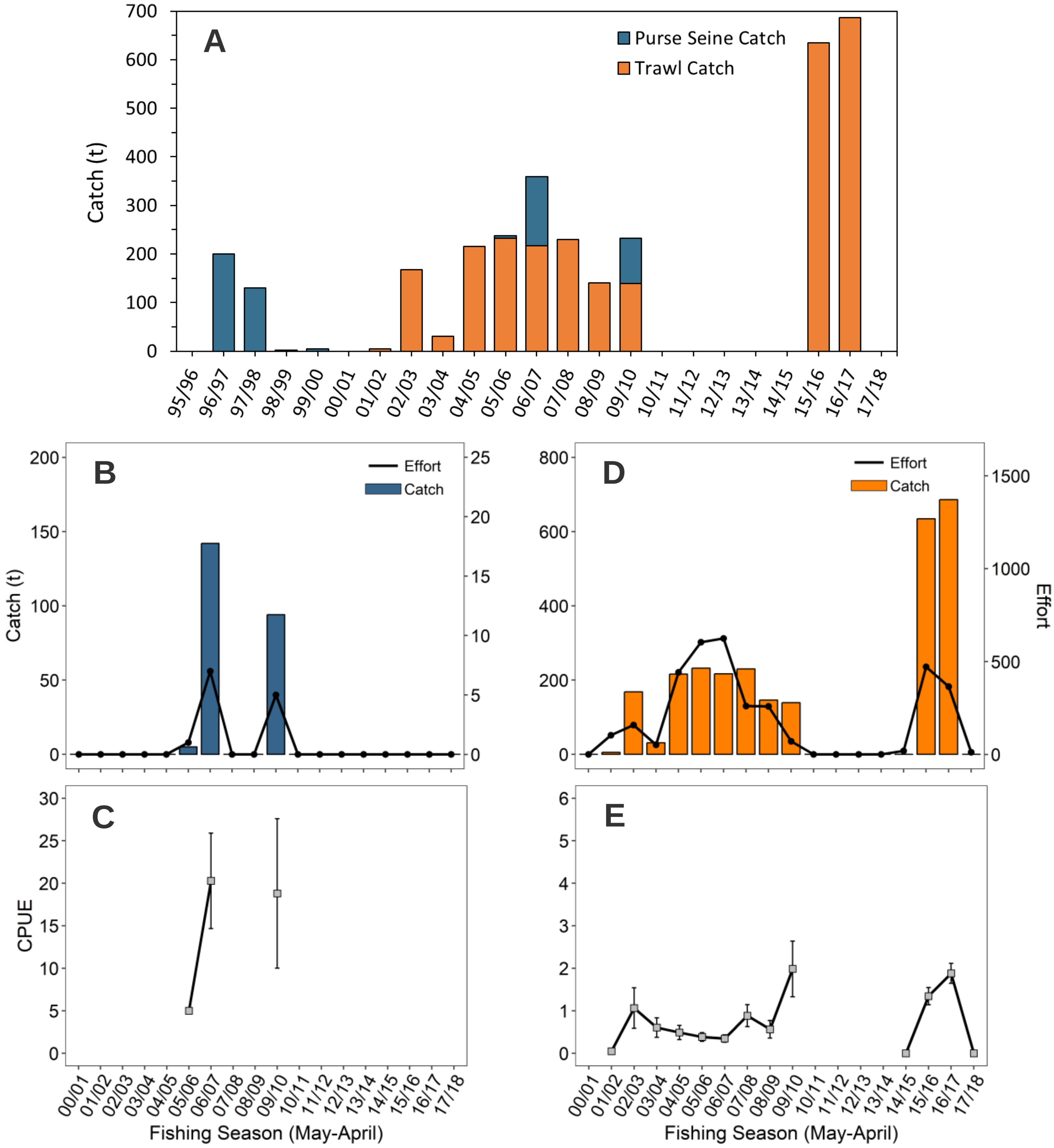
Historically, Jack Mackerel catches in the West sub-area have been lower than in the East, with the SPF taking 93% of the total annual catch since 1995/96. Due to data confidentiality (<5 license holders reporting catch per year) only SPF catches are discussed in this section (Figure 3-11a). Annual catches of Jack Mackerel West (purse seine and mid-water trawl) did not exceed 360 t prior to 2015/16 (Figure 3-11a). Catches in the SPF peaked at 359 t in 2006/07 and declined from there onwards, with no catches reported from 2010/11 to 2014/15. Catches increased to 686 t in 2016/17. In 2017/18, 0 t of Jack Mackerel West was taken in the SPF (Figure 3-11a).

Annual patterns: Catch, Effort and CPUE

Mid-water trawls have historically been the main gear type used by the SPF for Jack Mackerel West; purse seines have had limited use (Figure 3-11a). Since 2000/01, annual purse seine effort has not exceeded 7 net-sets (2006/07), and the maximum annual catch was 142 t in 2006/07 (Figure 3-11b). There has been no reported purse seine effort and catch of Jack Mackerel West in the SPF since 2010/11 (Figure 3-11b). Mean annual CPUE of purse seining is similar to effort and catch: peaks in 2006/07 (20 t·net-set^{-1}) and 2009/10 (19 t·net-set^{-1}), with minimal fishing in other years (Figure 3-11c).

Mid-water trawl effort and catch of Jack Mackerel West peaked at 625 trawl hours and 232 t during the mid-2000s and decreased to zero effort and catch from 2010/11 to 2013/14 (Figure 3-11d). Fishing effort resumed in 2014/15 (19 trawl hours; zero catch) and 686 t were taken during 2016/17 in 365 trawl hours (Figure 3-11d). In 2017/18, fishing effort decreased to 12 trawl hours with zero catch. Mean annual CPUE of mid-water trawls in the SPF decreased from 1 t·trawl hour^{-1} in 2001/02 to <1 t·trawl hour^{-1} in 2006/07, peaked in 2009/10 (2 t·trawl hour^{-1}) with no further activity until 2015/16 (1 t·trawl hour^{-1}) (Figure 3-11e). CPUE increased to 2 t·trawl hour^{-1} in 2016/17 and decreased to 0 t·trawl hour^{-1} in 2017/18.

Figure 3-11. Fishery statistics for Jack Mackerel West. (A) Total annual landed catch (tonnes) in the SPF taken by purse seining and mid-water trawling from 1995/96 to 2017/18. Long-term trends in the SPF by fishing season from 2000/01 to 2017/18: (B) annual landed catch (tonnes) and effort (net-sets) by purse seine; (C) mean annual CPUE (t·net-set^{-1}; ±SE) by purse seine; (D) annual landed catch (tonnes) and effort (trawl hours) by mid-water trawl; (E) mean annual CPUE (t·trawl hour^{-1}; ±SE) by mid-water trawl.



3.3.2.2 Biological Information

Catch sampling of Jack Mackerel West has varied since 2009/10 due to limited commercial fishing in the SPF. During 2009/10, 132 fish were collected from mid-water trawls off south-western Tasmania (Table 3-4). Catch samples were not collected from 2010/11 to 2014/15. Catch sampling in the SPF resumed in 2015/16, and length-frequency data were collected from 14 catch samples (670 fish); age-frequencies were taken from 11 samples (119 fish) (Table 3-4). In 2016/17, length-frequency data were collected from 24 samples (length n = 1,197; age n = 113; Table 3-4). Catch sampling did not occur in 2017/18 due to the lack of fishing.

Table 3-3. Summary of Jack Mackerel West catch samples collected from commercial SPF landings. Note: number of samples in brackets is number for age frequency if different from length frequency.

Season	SPF sub-area	Gear type	No. of samples	Length-frequency n	Age-frequency n	Size range (mm FL)	Age range (years)
2009/10	West	mid-water trawl	1	132	20	160–220	1–3
2015/16	West	mid-water trawl	14 (13)	670	129	211–355	2–10
2016/17	West	mid-water trawl	24	1,197	113	228–395	4–13

Size structure

The purse seine fishery

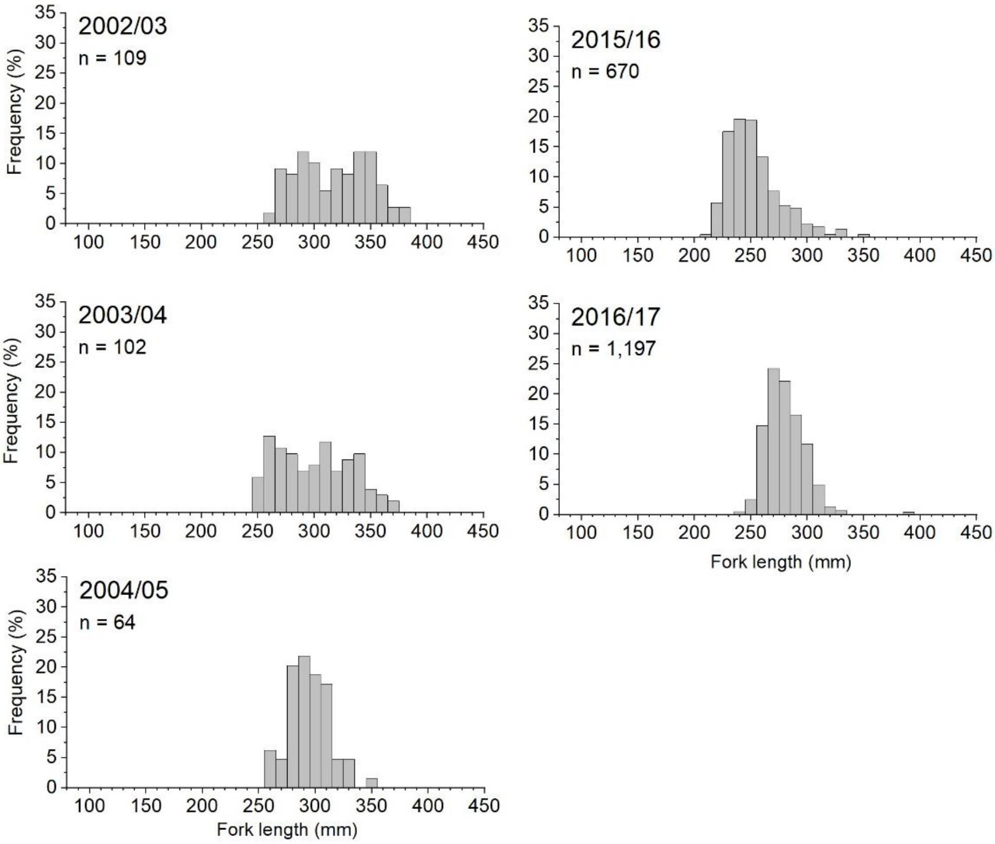
Size structure data are not available for purse seine catches of Jack Mackerel West.

Mid-water trawl fishery: 2002/03–2016/17

Jack Mackerel caught by mid-water trawl operations off south-western Tasmania from 2002/03 to 2004/05 were mainly between 250 and 370 mm FL, with an overall modal length of 290 mm FL (Figure 3-12). Jack Mackerel taken in the West sub-area over this period were larger than those from the East (East overall modal length: 260 mm FL) (Figure 3-12).

In 2009/10, a sample from a single mid-water trawl catch from the West (south-western Tasmania) contained Jack Mackerel of similar sizes (modal length: 190 mm FL) to catches from eastern Tasmania (modal length: 210 mm FL) (Tables 2.1 and 2.4; Figure 3-3). The modal length ranged between 240–250 mm FL in 2015/16 and increased to 270 mm FL in 2016/17. The current mode is slightly smaller than that from the commercial trawl catches of the early 2000s (Figure 3-12).

Figure 3-12. Length-frequency distributions of Jack Mackerel West caught by mid-water trawl in the SPF from 2002/03 to 2016/17; n = number of fish in distribution.



Age structure

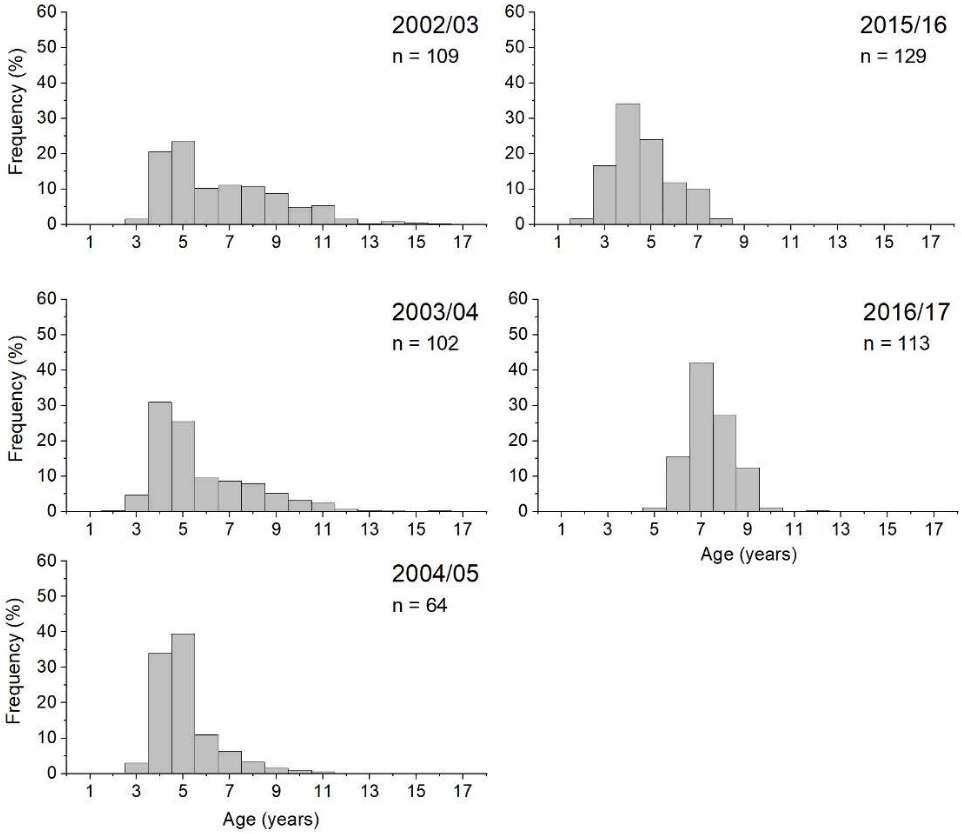
The purse seine fishery

Age structure data are not available for purse seine catches of Jack Mackerel West.

Mid-water trawl fishery: 2002I03–2016/17

Annual age structures of Jack Mackerel West sampled from catches taken off south-western Tasmania from 2002/03 to 2004/05 had a high proportion of fish >5 years, and a mode of 4–5 years (Figure 3-13). The age structure of the single catch in 2009/10 (Table 3-4) contained a high proportion of 2 year old fish, representing about 70% of the distribution (similar to the 2009/10 age structure in the East; Figure 3-3). In 2015/16, the modal age was 4 years with 75% of fish between 3 and 5 years (Figure 3-13). The modal age increased to 7 years in 2016/17, and 70% of fish were 7–8 years of age. The maximum estimated age of Jack Mackerel West from mid-water trawl catches was 13 years (Figure 3-13).

Figure 3-13. Age-frequency distributions of Jack Mackerel West caught by mid-water trawl in the SPF from 2002/03 to 2016/17; n = number of fish in distribution.



3.4 Summary and Conclusions

3.4.1 Jack Mackerel East

The main fishery for Jack Mackerel East is the SPF; recent catches in other fisheries in this sub-area have been negligible (<10 t per annum). The total annual catch of Jack Mackerel East from 2010/11 to 2014/15 was <320 t. The factory trawler operating in offshore waters from 2014/15 to 2016/17 was replaced in 2017/18 by a mid-water trawler operating in inshore waters off southern NSW. The SPF catch in 2017/18 (2,748 t) was about one third of the catch landed by the factory trawler in 2015/16 and about two thirds of that landed in 2015/16. CPUE of Jack Mackerel East in 2017/18 was 3 t·trawl hour^{-1}, about one third that of the factory trawler (10 t·trawl hour^{-1} in 2015/16 and 11 t·trawl hour^{-1} in 2016/17). The reduced catches of Jack Mackerel East in 2017/18 reflect the reduced CPUE compared to 2015/16 and 2016/17.

The modal length of Jack Mackerel taken in 2017/18 was 200 mm FL, below the size at 50% maturity of ~270 mm FL, and down from ~230 mm FL in both 2015/16 and 2016/17. In 2017/18 the modal age was 4 years, lower than the modal ages of 5 years and 5-6 years in 2015/16 and 2016/17, respectively. The smaller size and younger age of Jack

Mackerel taken from East sub-area in 2017/18 reflects the transition of fishing activity to inshore waters.

The average total catch annual catch Jack Mackerel East over the last three fishing seasons has been approximately 4,350 t. The spawning biomass of Jack Mackerel East in 2014 was estimated to be 157,805 t (95% CI = 59,570–358,731, Ward et al. 2015). The recent annual average catch of Jack Mackerel East have been <3% of this estimate of spawning biomass and below the Tier 1 exploitation rate for this stock of 12% (Smith et al. 2015). The total catch in 2017/18 was <30% of the available TAC. On the basis of the information provided above, Jack Mackerel East is c as being sustainable. Stewardson et al. (2018) also found the biological stock of Jack Mackerel East to be sustainable. Patterson et al. (2018) classified Jack Mackerel East as ‘not overfished’ and ‘not subject to overfishing’.

3.4.2 Jack Mackerel West

The main fishery for Jack Mackerel West is the SPF. Annual catches did not exceed 360 t prior to 2015/16. There was no catch of Jack Mackerel West by the SPF in 2017/18; this was down from 686 t in 2016/17 and 634 t in 2015/16. The modal length in 2016/17 was 270 mm FL, similar to the mean size at 50% maturity of ~270 mm FL, and larger than the modal length of 240–250 mm FL in 2015/16. The modal age in 2016/17 was 7 years, up from 4 years in 2015/16.

Recent annual catches of Jack Mackerel West have not exceeded 700 t. The spawning biomass of Jack Mackerel West in 2016/17 was estimated to be at least 31,000 t (Ward et al. 2018). Recent catches of Jack Mackerel Wes have been <3% of this estimate of spawning biomass and below the Tier 2 exploitation rate for this stock of 12% (Smith et al. 2015). The total catch in 2017/18 was 0% of the available TAC. On the basis of the information provided above, Jack Mackerel West is assessed as being sustainable. Stewardson et al. (2018) also found the biological stock of Jack Mackerel West to be sustainable. Patterson et al. (2018) classified Jack Mackerel West as ‘not overfished’ and ‘not subject to overfishing’.

4 Redbait (*Emmelichthys nitidus*)

4.1 Introduction

4.1.1 Background to Fishery

Redbait was a key by-product species in the Tasmanian Purse Seine Fishery for Jack Mackerel (Trachurus declivis) that developed off Tasmania in the mid-1980s. This fishery has recorded catch and effort data since its inception in 1984. Logbooks contain a record of fishing operations and species taken by net-set. Although landings of Redbait rarely exceeded 5% of the total catch in a net-set, annual catches averaged ~700 t from 1984/85 to 1989/90 (Pullen 1994).

Mid-water trawling to target subsurface schools of Jack Mackerel off Tasmania was trialled in 2001/02 (Welsford and Lyle 2003). Between December 2001 and April 2002, a total catch of over 5,000 t of small pelagic fishes was taken; 90% was Redbait. In late 2002, a multi-purpose 50 m mid-water trawler began targeting small pelagic species off Tasmania, particularly Redbait. By mid-2003, more than 7,000 t of small pelagic fishes had been taken, with Redbait dominating the catch. Small-scale purse seine operations were temporarily resumed in response to declining trawl effort in the late 2000s (Emery et al. 2015).

Redbait have primarily been frozen whole for use as feed for farmed Southern Bluefin Tuna (*Thunnus maccoyii*) and have also been used to produce fish meal for the aquaculture industry.

4.1.2 Taxonomy

Redbait (*Emmelichthys nitidus,* Richardson 1845) belong to the family *Emmelichthyidae*, which contains three genera and 15 species (Nelson 2006). Redbait are one of two species of emmelichthyid found off southern Australia, the other being the Rubyfish (*Plagiogeneion rubiginosum*) (Last et al. 1983, May and Maxwell 1986, Gomon et al. 2008).

4.1.3 Distribution

Emmelichthyids are found throughout tropical and temperate waters world-wide. Generally, they are found in schools over continental shelf breaks, seamounts and submarine ridges. They inhabit depths from the surface to >800 m, though are mostly recorded from mid-water trawls in 100–400 m water (Heemstra and Randall 1977, Smith and Heemstra 1986, Mel'nikov and Ivanin 1995). Redbait are widely distributed throughout the southern hemisphere, with the species reported from Tristan da Cunha in the southern Atlantic, the south-western coast of South Africa, St Paul and Amsterdam Islands, mid-oceanic ridges and seamounts through the Indian Ocean, Australia, New Zealand, submarine ridges in the south-eastern Pacific, and the southern coast of Chile (Markina and Boldyrev 1980, Meléndez and Céspedes 1986, Parin et al. 1997). Within Australian waters, their range extends from mid New South Wales to south-west Western Australia, including Tasmania (Gomon et al. 2008).

4.1.4 Stock Structure

There have been no studies on the stock structure of Redbait in Australia. However, Redbait from eastern Australia are thought to be a single stock based on spawning dynamics (Bulman et al. 2008). The situation for western Tasmania and the GAB is less clear. Neira et al. (2008) observed that Redbait from eastern and south-western Tasmania exhibit biological differences, which provides some evidence for separation into eastern and western stocks off Tasmania.

4.1.5 Movement

No studies have investigated movement of Redbait.

4.1.6 Food and Feeding

In South African coastal waters, smaller size classes of Redbait (136-280 mm) feed exclusively on small planktonic crustaceans, with euphausiids (*Nyctiphanes* and *Euphausia* spp.), hyperiid amphipods (primarily *Themisto gaudichaudi*), mysids and large copepods comprising the entire diet (Meyer and Smale 1991). Larger Redbait (281–493 mm) also fed primarily on small planktonic crustaceans, but nekton, such as cephalopods, carid shrimp, and small fishes including myctophids, were part of the diet (Meyer and Smale 1991). Redbait captured on the shelf off eastern Victoria (unspecified size) had a varied diet that was dominated by pelagic crustaceans and other invertebrates, including gelatinous zooplankton (Bulman et al. 2000, Bulman et al. 2001). Similarly, Redbait captured off eastern Tasmania consumed mainly pelagic crustaceans, with krill and copepods comprising 66% and 33% of the diet, respectively (McLeod et al. 2012).

The diet of Redbait is similar to that of Jack Mackerel from Tasmania, with krill representing the dominant prey item on the continental shelf (Young et al. 1993, McLeod et al. 2012). Since Redbait and Jack Mackerel form mixed species schools in Tasmanian waters (Williams and Pullen 1993), it is not surprising the two species feed on similar prey.

4.1.7 Age, Growth and Size

The maximum reported size for female and male Redbait from Tasmania is 317 and 304 mm FL, respectively (Neira et al. 2008), which is considerably smaller than reported in other areas. Redbait grow to 335 mm FL off eastern Victoria (Furlani et al. 2000), 344 mm standard length (SL) off the coast of Chile (Meléndez and Céspedes 1986) and to 493 mm TL in South African waters (Heemstra and Randall 1977, Meyer and Smale 1991). Redbait are observed to school by size and stratify by water depth, with larger (>200 mm FL) individuals found deeper and closer to the seafloor (Markina and Boldyrev 1980).

Growth estimates for Redbait (otolith-based) suggest rapid growth during the first few years (Williams et al. 1987, Neira et al. 2008). On average, Redbait off Tasmania reached >200 mm FL in the first three years, with growth slowing thereafter (Neira et al. 2008). The maximum estimated age for Redbait is 21 years for females and 18 years for males (Neira et al. 2008). The larger Redbait reported from Africa (e.g. Meyer and Smale 1991) suggest that maximum age may be higher than reported for Tasmanian fish or that growth rates vary between regions. Age validation of Rubyfish in New Zealand, using otoliths and the bomb radiocarbon chronometer, has shown fish over 400 mm can be up to 100 years old (Paul et al. 2000, Horn et al. 2012), indicating some emmelichthyids are long-lived.

4.1.8 Reproduction

Redbait is an asynchronous batch spawner with indeterminate fecundity. Annual trends in GSI and macroscopic gonad stages indicated that Redbait from eastern Tasmania spawn between September and November, with a peak in activity during September and October (Ewing and Lyle 2009). A similar pattern was evident for south-western Tasmania, although the peak occurred one month later between October and November (Ewing and Lyle 2009). Spawning occurs along a 2.5 nautical mile (nm) corridor either side of the continental shelf break when mid-water temperatures are 12 to 15.2°C (Neira et al. 2008).

There are regional differences in size and age at sexual maturity for Redbait. Males and females from south-western Tasmania matured ~100 mm larger and two years older than Redbait from eastern Tasmania (Ewing and Lyle 2009). However, Ewing and Lyle (2009) suggested this difference could have resulted from sampling bias due to the different depths fished in each region. The size (age) at 50% sexual maturity for Redbait in eastern Tasmania was 147 mm FL (2 years) for males and 157 mm FL (2 years) for females. In south-western Tasmania, the size (age) at 50% sexual maturity was 244 mm FL (4.8 years) for males and 261 mm FL (4.1 years) for females (Ewing and Lyle 2009).

4.1.9 Early Life History and Recruitment

Redbait eggs are positively buoyant and hatch about 2–4 days after fertilisation depending on temperature (Neira et al. 2008). Newly hatched yolk sac larvae range from 1.9–3.3 mm TL. Little is known about the early life history of Redbait post-hatching, although spawning areas (eggs and larvae) have been described by Neira et al. (2008).

4.1.10 Stock Assessment

Spawning habitat of Redbait was described from egg, larval and environmental data collected over shelf waters between north-eastern Bass Strait and lower south-western Tasmania in 2005 and 2006 (Neira et al. 2008). The DEPM was subsequently applied to estimate the spawning biomass of Redbait East in these years (Neira et al. 2008, Neira and Lyle 2011).

4.1.11 Recreational fishing

There is no known recreational fishery for Redbait in Australia.

4.1.12 Biomass Estimates

East

The DEPM was applied to Redbait East during 2005 and 2006. The survey extended from the north-eastern Bass Strait (38.8°S) to south of the Tasman Peninsula (43.5°S) and involved concurrent sampling of eggs and adults (Neira *et al.* 2008). Estimates of Redbait spawning biomass were 86,994 t (CV: 3.7) in 2005 and 50,782 t (CV: 2.1) in 2006 (Neira and Lyle 2011). These estimates are considered to be negatively biased, as the surveys covered less than half the known spawning area of Redbait in south-eastern Australia (Neira and Lyle 2011).

West

The first dedicated application of the DEPM to Redbait West occurred during October 2017 between Kangaroo Island, South Australia and western Tasmania. It involved concurrent sampling of eggs and adults (Ward et al. 2019). Redbait eggs were widely distributed between western Kangaroo Island and south-western Tasmania in outer shelf and upper slope waters, with the highest egg densities occurring off western Victoria and the west coast of Tasmania. The estimate of spawning biomass of 66,767 t (CI = 28,797–190,392) is considered suitable for setting RBCs for Redbait in West sub-area of the SPF, because it is based on robust and/or conservative estimate of key DEPM parameters. This estimate is also similar to the Atlantis-SPF biomass estimate for Redbait West of 66,000 t (typical range: 59,000–70,000 t; Smith et al. 2015).

4.1.13 Management Strategy Evaluation

2010

For Redbait East, the DEPM estimate of spawning biomass was 23% of the estimate calculated from the model (Giannini et al. 2010). All Tier 1 scenarios investigated reached equilibrium around B_{40} by the end of the 30 year simulation period. The Tier 2 and Tier 3 results suggest that these harvest levels are conservative and sustainable. However, these outputs should be treated with caution as the harvest levels are “absolute” quantities and represent a much smaller proportion of the model biomass than the DEPM estimate of biomass.

The results for Redbait West are similar to those of Redbait East. However, in this case there was no DEPM estimate of spawning biomass.

2015

Smith et al. (2015) concluded the harvest rate of 15% may be too high for Redbait and suggested a Tier 1 harvest rate of 9% for Redbait East and 10% for Redbait West, with the Tier 1 rate being applied for not more than 5 years. Tier 2 harvest rates for Redbait East and West were recommended to be 50% of Tier 1 rates and not to be applied for more than 10 years. The study also indicated that it is not safe to apply Tier 2 harvest rates unchecked for long periods of time (Smith et al. 2015). The Atlantis-SPF biomass estimate for Redbait East is 82,000 t (typical range: 75,000–105,000 t) and 66,000 t (typical range: 59,000–70,000 t) for Redbait West (Smith et al. 2015).

4.1.14 Management

Currently, Redbait East is managed at the Tier 2 level and Redbait West is managed at the Tier 1 level under the SPF HS. A dedicated DEPM assessment occurred for Redbait East in 2005–2006 and Redbait West in 2017.

4.2 Methods

4.2.1 Fishery Statistics

Fishery statistics from 1995/96 to 2017/18 were provided by relevant jurisdictions and collated by SARDI Aquatic Sciences. Annual data are reported in fishing seasons (May 1 to April 30) rather than financial years as was done in previous assessments (e.g. Ward et al. 2013, 2014c, 2015c).

Estimates of total annual catch supplied for Redbait East include data from the NSW Ocean Fisheries (Hauling, Trap and Line, Trawl), Victorian Ocean Purse Seine Fishery, Tasmanian Scalefish Fishery and the Commonwealth SPF. In the West, total annual catch estimates include data from the Tasmanian Scalefish Fishery and Commonwealth SPF. Due to data confidentiality (<5 license holders annually reporting catch since 2015/16), fishery data from Victoria were not provided and have not been included in total annual catch statistics since 2015/16.

Mean annual CPUE of Redbait in the Commonwealth SPF by sub-area is calculated for the gear types of mid-water trawl (tonnes·trawl hour^{-1} ±SE) and purse-seine (tonnes·net-set^{-1} ±SE) from 2000/01 to 2016/17. Zero catch of Redbait in a trawl was assumed when effort but not catch was reported in the logbook record.

4.2.2 Biological Information

Fishery-dependent length frequency and biological data were collected for Redbait between 1984 and 1993 as part of a monitoring program of the Jack Mackerel Purse seine Fishery off Tasmania. Some biological information was obtained from samples collected between 1985 and 1990 from demersal research trawls conducted by CSIRO and the

Tasmanian fisheries agency. Between 1994 and 2001, there was limited catch sampling of the purse seine fishery.

Biological data were collected by AFMA observers from a small proportion of trips during the 2001/02 pair-trawl fishing trials undertaken off Tasmania. When mid-water trawl operations started in 2002, TAFI began an intensive biological monitoring program that continued to 2006. AFMA also provided observer coverage of mid-water trawl operations, with additional length-frequency data collected from 2002 to 2008.

Purse seine operations for small pelagic fish resumed in Tasmanian State waters in 2008/09, mainly targeting Redbait and Jack Mackerel. Catch sampling of mid-water trawl and purse seine operations adjacent to Tasmania began in 2009/10 as part of the SPF monitoring program under the SPF HS (AFMA 2008). Catch samples were not collected for Redbait from 2010/11 to 2013/14 due to limited fishing activity. Catch sampling by AFMA observers resumed in the SPF during 2014/15. Samples of Redbait were collected (n = 50 randomly selected fish per trawl) and supplied to SARDI Aquatic Sciences to estimate the size and age composition of the catch.

Biological data collected from each fish include: body length (mm FL), total weight (±1 g), sex, gonad developmental stage (following the macroscopic staging criteria described in Neira et al. 2008) and gonad weight (±0.1 g). Gonad stages were designated as: I) immature; II) maturing virgins or recovering spent; III) maturing; IV) ripe; and V) spent. Otoliths were removed from random sub-samples of the fish for age determination. The age structure of Redbait prior to 2014/15 was estimated using age-length keys based on age data pooled between 2001/02 to 2005/06. From 2014/15 to present, ages for Redbait have been based on annual growth increment counts in thin-sectioned otoliths (sub-samples of 5 to 10 fish per sample).

Redbait otoliths were aged following the protocol of Ewing and Lyle (2009) after thin-sectioning and mounting on microscope slides. Edges of each annual opaque zone were counted (edges of opaque zones are more easily delineated than edges of translucent zones). Identifying the edge of the first annual opaque zone followed guidelines described in (Ewing and Lyle 2009), where it followed a distinctive wide translucent area just exterior to the inner opaque region. The period of age represented by the opaque core was assumed to be similar across all regions where the fish were collected based on spawning stock, spawning time and time of opaque increment formation (Neira et al. 2008, Ewing and Lyle 2009). All fish were assigned a birthdate of Oct 1 based on the spawning times for the spawning stocks in southern Australia (Ewing and Lyle 2009). Redbait form an opaque zone during winter with the completion becoming discernible from November to February (Ewing and Lyle 2009). The completion of annual opaque zones in otoliths during spring/summer in temperate marine waters is common (e.g. Choat and Axe 1996, Fowler and Short 1998, Smith and Deguara 2003, Ewing et al. 2007). Therefore, we designated a standardised completion date of Oct 31 for the opaque zone for all regions. The first year of growth of Redbait in southern AUS represents growth from 1 Oct of the birth year to 31 Oct of the next year (13 months). Each otolith was aged by two different readers and the counts compared. Where the counts differed, the otolith was re-read and an age consensus reach, or the otolith was removed from further analyses. Prior to ageing otoliths, the reader used a species specific reference collection to calibrate their ageing technique (see Appendix 1 for details).

Catch weighting was applied to length- and age-frequency data collected since 2014/15 in each sub-area. Length- and age-frequencies were weighted by the number of fish sampled per trawl to account for uneven sample sizes and then were catch weighted by the total amount of Redbait taken in the same trawl.

Commercial logbook information, length-frequency and biological data collected between 1984 and 2017 are included in this assessment. In addition to current catch samples, age, growth and reproductive data for Redbait were available from previous studies (i.e. Welsford and Lyle 2003 and Neira et al. 2008). Summarised biological data prior to 2014/15 are presented in financial years. From 2014/15 to present, all SPF catch sampling data are presented in fishing seasons from 1 May to 30 April.

4.3 Results

4.3.1 Redbait East

4.3.1.1 Fishery Statistics

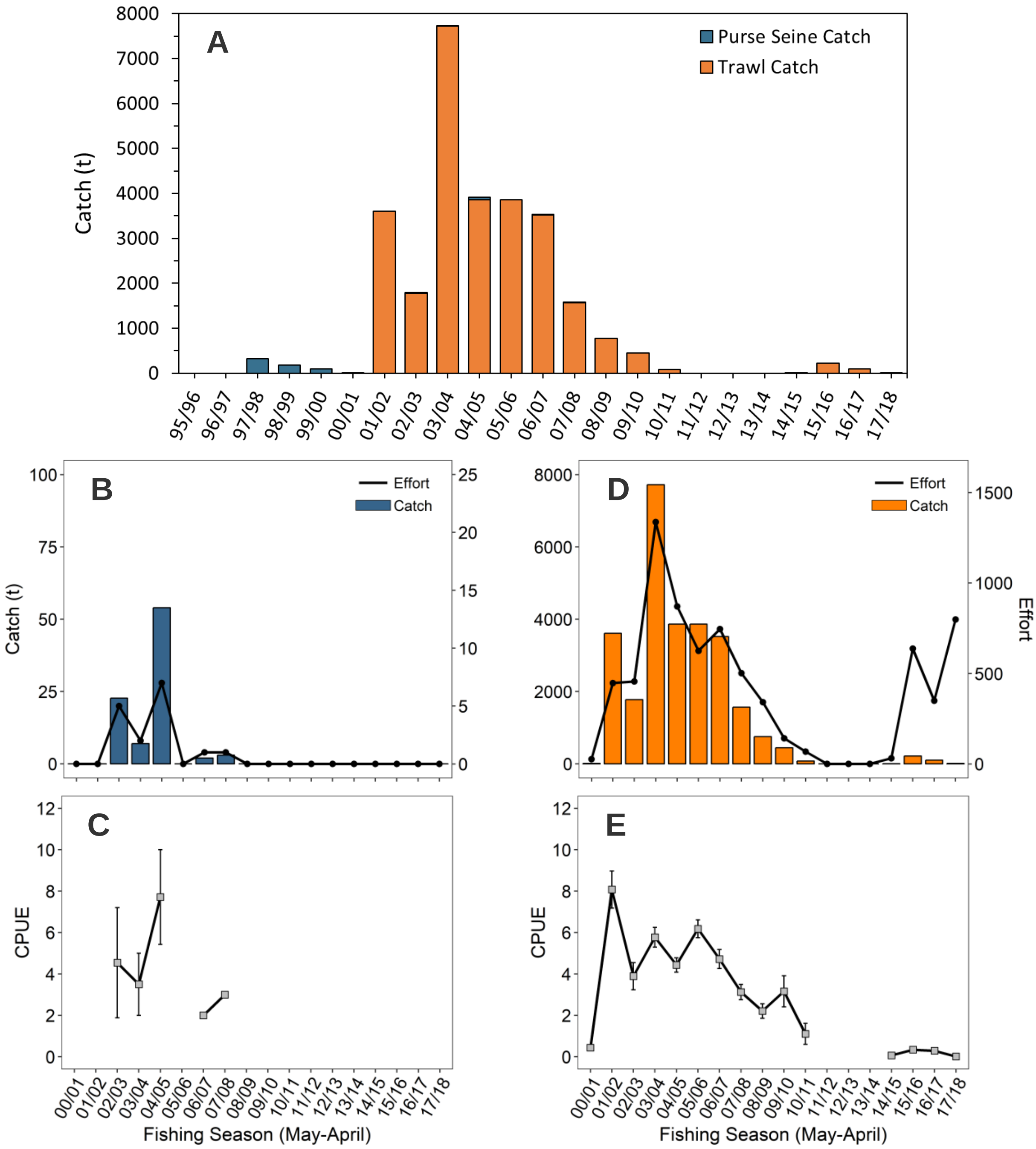
Number of vessels

Since 1995/96, a limited number of vessels have reported catches of Redbait East; annual vessels numbers have ranged from zero to seven. On average, over the last 23 years, three boats per year have reported catches of Redbait East, and ~50% of the vessels reporting catch in each year are Commonwealth vessels. Since 2013/14, only 1 vessel annually has landed Redbait East.

Annual patterns: Total catch

Due to data confidentiality (<5 license holders reporting catch per year), only SPF catches are reported. From 1995/96 to 2000/01, Redbait East catches did not exceed 315 t, and purse seining was the prevailing method (Figure 4-1a). Mid-water trawling began to replace purse seining in the early 2000s (Figure 4-1a). With the change to mid-water trawling, catches increased to 3,610 t in 2001/02 and peaked at 7,728 t in 2003/04. From then onwards, annual catches declined to 75 t in 2010/11. No catches of Redbait East were reported from 2011/12 to 2013/14; 217 t were taken in 2015/16 and catches declined to 9.5 t in 2017/18.

Figure 4-1. Fishery statistics for Redbait East. (A) Total annual landed catch (tonnes) in the SPF taken by purse seining and mid-water trawling from 1995/96 to 2017/18. Long-term trends in the SPF by fishing season from 2000/01 to 2017/18: (B) annual landed catch (tonnes) and effort (net-sets) by purse seine; (C) mean annual CPUE (t·net-set^{-1}; ±SE) by purse seine; (D) annual landed catch (tonnes) and effort (trawl hours) by mid-water trawl; (E) mean annual CPUE (t·trawl hour^{-1}; ±SE) by mid-water trawl.



Annual patterns: Catch, Effort and CPUE

There has been limited use of purse seines in the SPF for Redbait East; mid-water trawls have historically been the main gear type (Figures 4.1a). Since 2000/01, purse seine effort has not exceeded 7 net-sets with a maximum catch of 54 t in 2004/05 (Figure 4-1b). There has been no reported purse seine effort and catch of Redbait East in the SPF since

2007/08 (Figure 4-1b). Mean annual CPUE of purse seining in the East peaked in 2004/05 (8 t·net-set^{-1}) and decreased to ≤3 t·net-set^{-1} in 2005/06–2007/08, with minimal to no fishing in other years (Figure 4-1c).

Mid-water trawl effort in the SPF for Redbait East peaked at 1,338 trawl hours (catch: 7,721 t) in 2003/04, decreased to 0 trawl hours (2011/12 to 2013/14) and increased to 638 trawl hours (catch: 217 t) in 2015/16 (Figure 4-1d). In 2017/18, trawl effort increased to 799 trawl hours (catch: 9.5 t). Mean annual CPUE of Redbait in mid-water trawls in the SPF declined from 8 t·trawl hour^{-1} in 2001/02 to 1 t·trawl hour^{-1} in 2010/11, with no further activity until 2014/15 (Figure 4-1e). Mean annual CPUE was <1 t·trawl hour^{-1} in 2017/18 (Figure 4-1e).

4.3.1.2 Biological Information

Catch sampling of Redbait East has varied since 2009/10 due to limited commercial fishing in the SPF. During 2009/10, 494 fish were collected from purse seines and 393 fish from mid-water trawls (Table 4-1). Catch samples were not collected from 2010/11 to 2013/14. Catch sampling in the SPF resumed in 2014/15, and length-frequency data were collected from 61 Redbait (age-frequency n: 40) sampled from mid-water trawl catches off southern New South Wales (Table 4-1). During 2015/16, length-frequency data were collected from 35 catch samples (2,091 fish) with age-frequencies collected from 31 samples (191 fish). In 2017/18, length- and age-frequency data were collected from three samples (length n = 86; age n = 13; Table 4-1).

Season	SPF sub-area	Gear type	No. of samples	Length-frequency n	Age-frequency n	Size range (mm FL)	Age range (years)
2009/10	East	purse seine	6	494	140	170–230	1–5
2009/10	East	mid-water trawl	6	393	120	170–300	1–9
2014/15	East	mid-water trawl	2	61	40	200–275	2–14
2015/16	East	mid-water trawl	35 (31)	2,091	191	87–277	0–15
2016/17	East	mid-water trawl	5 (4)	242	20	119–278	2–14
2017/18	East	mid-water trawl	3	86	13	210–261	2–15

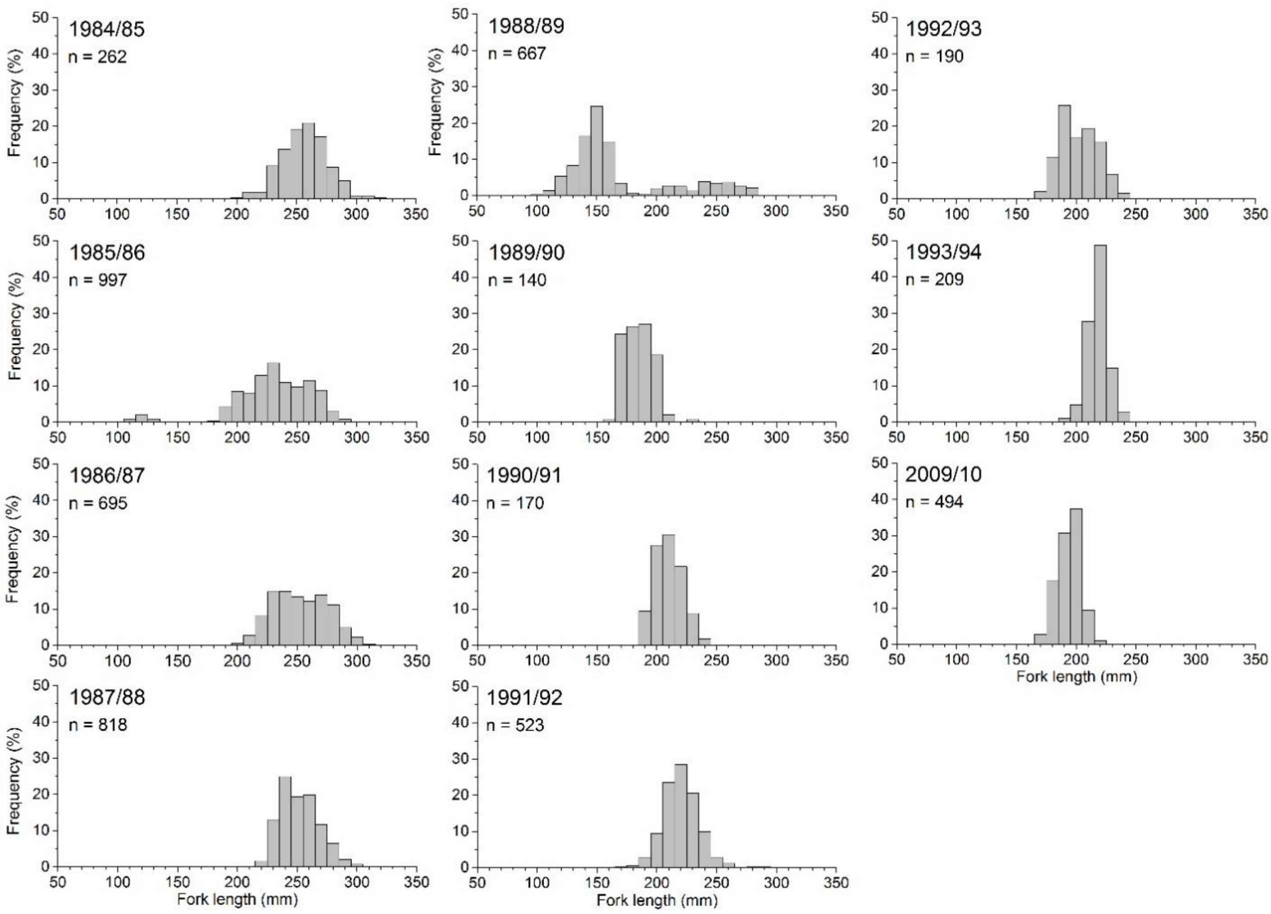
Table 0-4. Summary of Redbait East catch samples collected from commercial SPF landings. Note: number of samples in brackets is number for age frequency if different from length frequency.

Size structure

The purse seine fishery: 1984/85 to 1993/94 and 2009/10

Purse seine catches of Redbait between 1984/85 and 1994/95 off eastern Tasmania mainly contained fish between 140 and 290 mm FL (max length: 320 mm FL; Figure 4-2). Catches between 1984/85 and 1987/88 were dominated by fish from 200–300 mm FL, with only a few small fish (100–140 mm FL) caught in 1985/86. A strong cohort of smaller fish (120–170 mm FL) was present in the size structure for 1988/89 and accounted for most of the catch in the following year. Between 1989/90 and 2009/10, smaller fish (160–240 mm FL) were prevalent (Figure 4-2). No catch samples have been collected from purse seines since 2009/10.

Figure 4-2. Length-frequency distributions (mm FL) of Redbait caught in the SPF by purse seine from 1984/85 to 1993/94 and in 2009/10. n = number of fish.

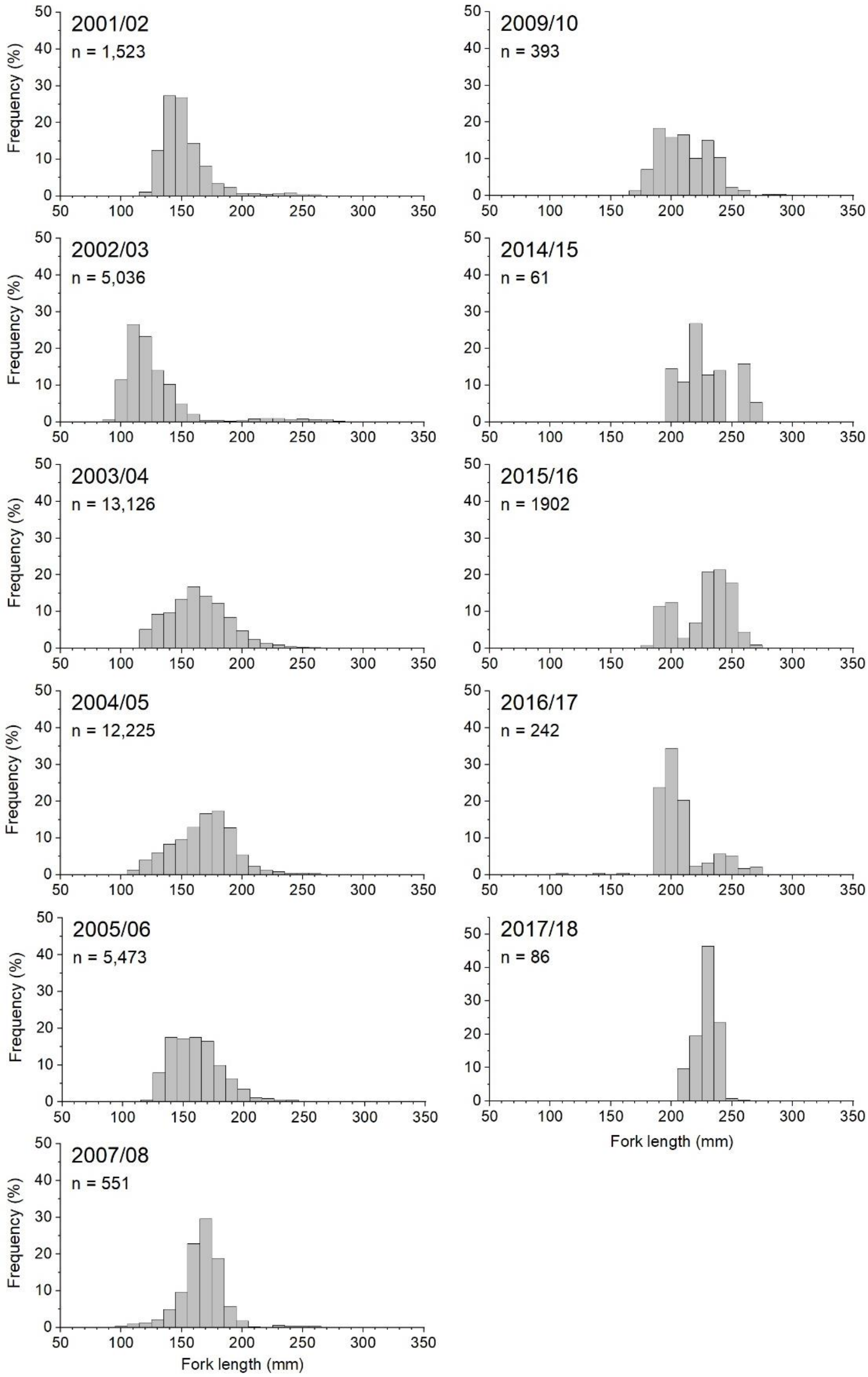


Mid-water trawl fishery: 2001/02–2016/17

Redbait East caught by mid-water trawl operations between 2001/02 and 2007/08 off eastern Tasmania were considerably smaller than those caught by the earlier purse seine operations, with individuals mainly between 100 and 200 mm FL (Figures 4.2–4.3). Redbait East catches contained a high proportion of small fish with modes varying between 110 and 180 mm FL (Figure 4-3). Only a small proportion of the catch was made up of fish larger than 200 mm FL.

The size structure of Redbait East in mid-water trawl catches increased during 2009/10; fish were primarily 190–240 mm FL (modal length: 190 mm FL; Figure 4-3). The size structure continued to increase through 2015/16 (modal length: 240 mm FL), decreased in 2016/17 (modal length: 200 mm FL), and increased again in 2017/18 (modal length: 230 mm FL; Figure 4-3). The size structures of recent mid-water trawl catches have been larger than those of purse seine catches in 2009/10 (Figures 4.2–4.3; Table 4-1).

Figure 4-3. Length-frequency distributions of Redbait East caught by mid-water trawl in the SPF from 2001/02 to 2017/18. n = number of fish. See Table 4-1 for sample N since 2009/10.

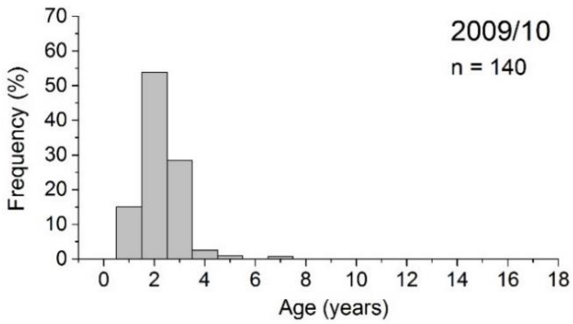


Age structure

The purse seine fishery: 2009/10

Purse seine catches off eastern Tasmania mainly contained 2–3 year old fish in 2009/10, with 2 year olds making up >50% of the catch (Figure 4-4). Age data for Redbait East caught by purse seine in the SPF were not available for other years.

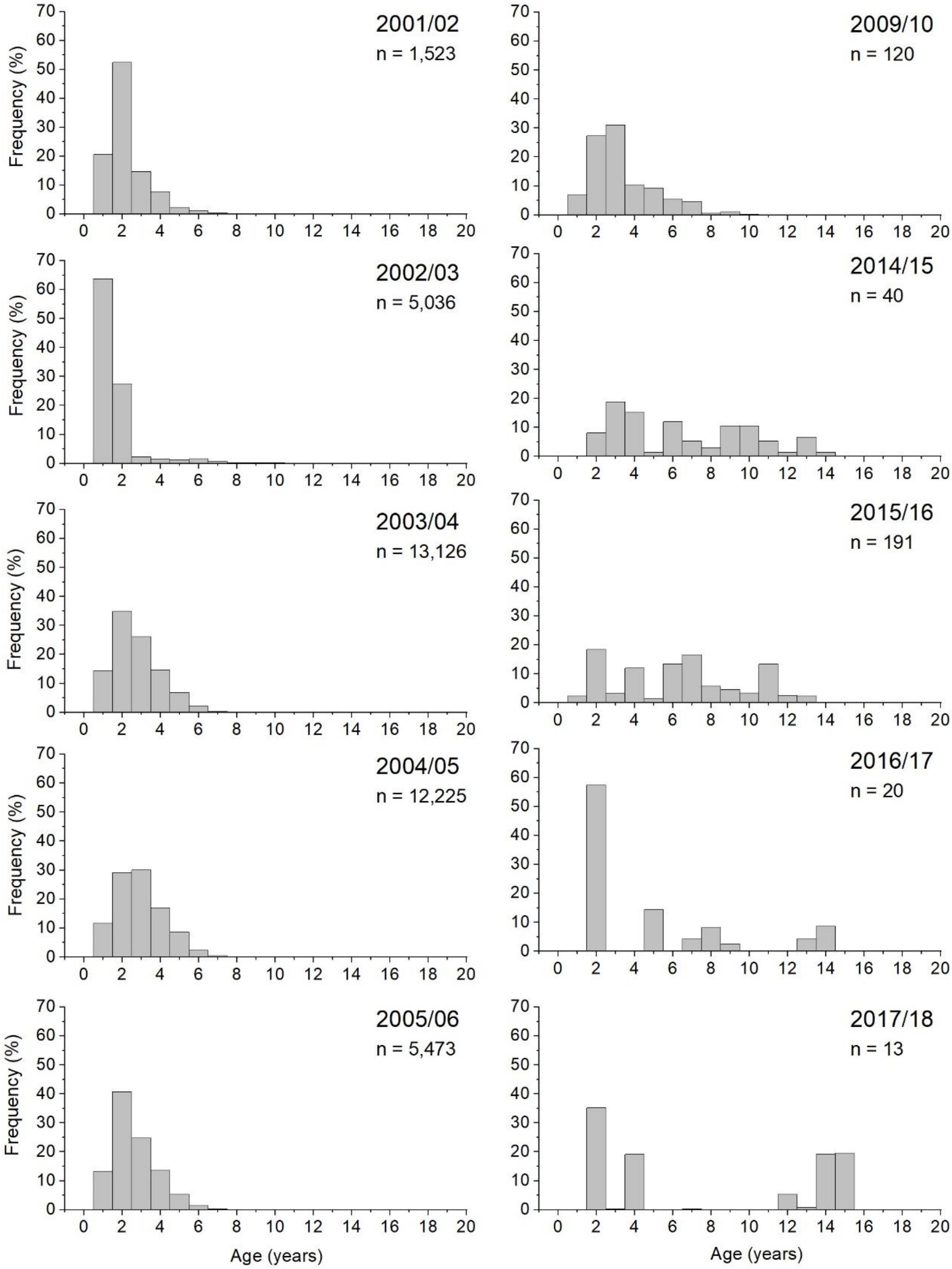
Figure 4-4. Age-frequency distribution of Redbait East caught by purse seine in the SPF during 2009/10; n = number of fish. See Table 4-1 for sample N.



Mid-water trawl fishery: 2001/02–2017/18

Mid-water trawl catches of Redbait East prior to 2015/15 mainly comprised fish between 1 and 5 years with maximum ages of 19 years (Figure 4-5). Catches off eastern Tasmania were dominated by 1 and 2 year olds from 2001/02 to 2002/03; during 2003/04 to 2009/10, the age structure shifted to 2 and 3 year olds (Figure 4-5). Mid-water trawl catches of 2009/10 had slightly older age structures than purse seine catches in the same year (Table 4-1; Figures 4.4–4.5). In 2014/15, the age structure comprised an increasing proportion of older fish: 57% of the fish were >4 years old (Figure 4-5). Two modes are present in the age structure during 2015/16: one at 2 years and one at 7 years. Older ages are present in 2016/17, but 2 year old fish dominate the catch. The age structure in 2017/18 is based on a small number of fish (n = 13) and shows both young and old fish are prevalent (Figure 4-5). Since 2014/15, the maximum age found in mid-water trawl catches has been 15 years.

Figure 4-5. Age-frequency distributions of Redbait East caught by mid-water trawl in the SPF from 2001/02 to 2017/18; n = number of fish. See Table 4-1 for sample N since 2009/10.



4.3.2 Redbait West

4.3.2.1 Fishery Statistics

Number of vessels

In the West sub-area of the SPF, the number of vessels reporting catches of Redbait since 1995/96 were lower than those in the East: the annual average has been 1 boat per year. The SPF is the principal fishery reporting catches of Redbait West. From 2011/12 to 2013/14, no vessels reported catches of Redbait West; since 2014/15, 1 vessel annually has fished for Redbait in the West sub-area.

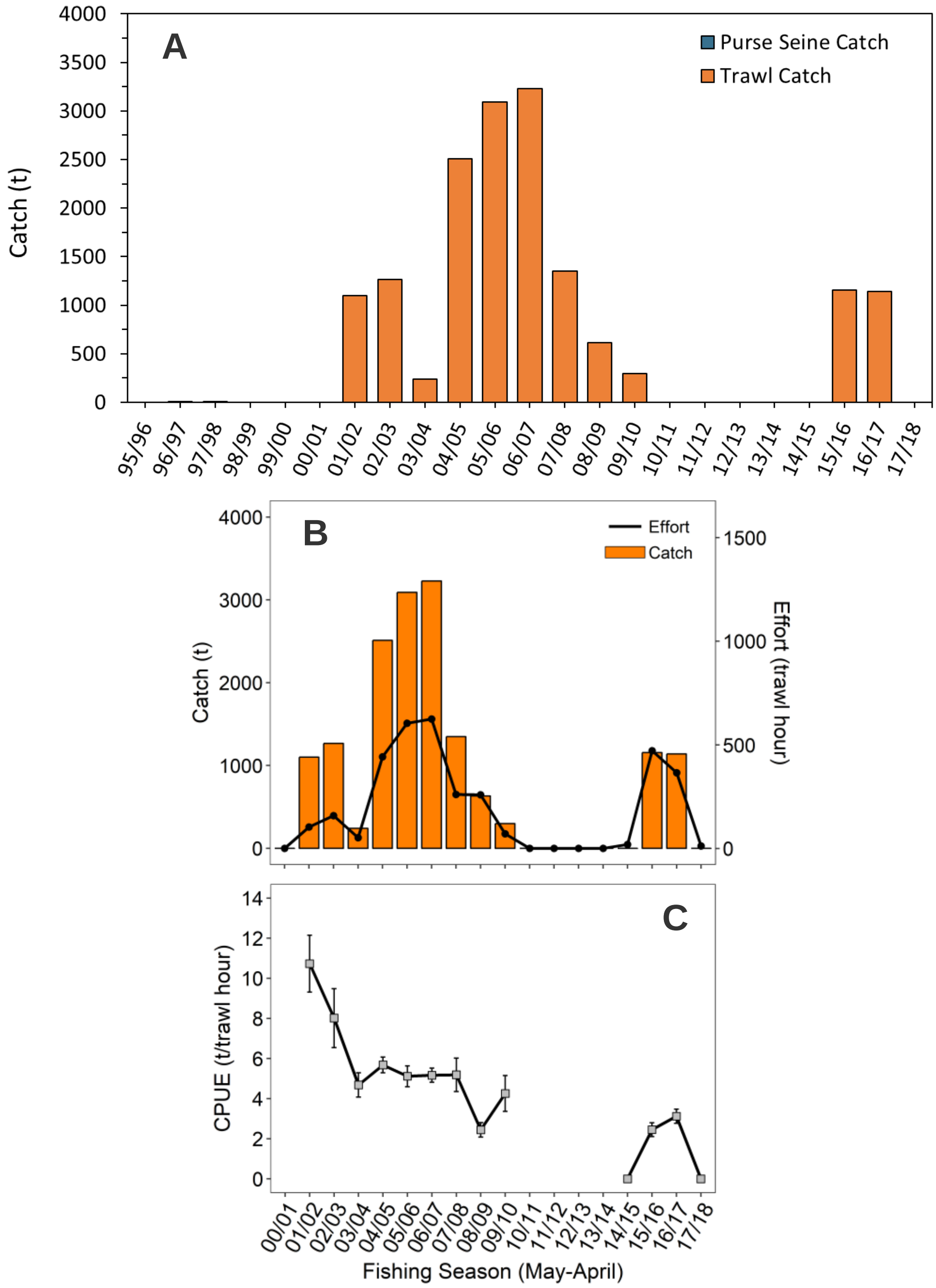
Annual patterns: Total catch

Due to data confidentiality (<5 license holders reporting catch per year), only SPF catches are reported. Historically, Redbait catches in the West sub-area have been lower than those in the East, but follow a similar temporal trend (Figure 4-6a). Mid-water trawling has been the primary method used to target Redbait West. From 1995/96 to 2000/01, there were minimal catches of Redbait West; annual catches began increasing in 2001/02, peaked at 3,228 t in 2006/07 and declined to 298 t in 2009/10 (Figure 4-6a). Redbait was not caught again in the West sub-area until 2015/16 (1,157 t). In 2017/18, zero catch was reported for Redbait West (Figure 4-6a).

Annual patterns: Catch, Effort and CPUE

In the SPF during the mid-2000s, mid-water trawling effort for Redbait West (442–625 trawl hours) peaked in years when the catch was highest (2,511–3,228 t; Figure 4-6b). No fishing effort was reported for Redbait West from 2010/11 to 2013/14 (Figure 4-6b). Effort began increasing in 2014/15, peaked at 472 trawl hours (catch: 1,157 t) in 2015/16, and decreased to 11.5 trawl hours (catch: 0 t) in 2017/18 (Figure 4-6b). Mean annual CPUE of mid-water trawls for Redbait West decreased from 11 t·trawl hour^{-1} in 2001/02 to 4 t·trawl hour^{-1} in 2009/10, with no effort reported until 2014/15 (Figure 4-6c). Mean annual CPUE increased to 3 t·trawl hour^{-1} in 2016/17 and dropped to 0 t·trawl hour^{-1} in 2017/18 (Figure 4-6c).

Figure 4-6. Fishery statistics for Redbait West. (A) Total annual landed catch (tonnes) in the SPF taken by purse seining and mid-water trawling from 1995/96 to 2017/18. Long-term trends of mid-water trawling in the SPF by fishing season from 2000/01 to 2017/18: (B) annual landed catch (tonnes) and effort (trawl hours); (C) mean annual CPUE (t·trawl hour^{-1}; ±SE).



4.3.2.2 Biological Information

Catch sampling of Redbait West has varied since 2009/10 due to limited commercial fishing in the SPF. During 2009/10, 77 fish were collected from mid-water trawls (Table 4-2). Catch samples were not collected from 2010/11 to 2014/15. Catch sampling in the SPF for Redbait West resumed in 2015/16; length-frequency data were collected from 19 catch samples (1,526 fish) and age-frequencies from 9 samples (130 fish). In 2016/17, length- and age-frequency data were collected from 25 catch samples (length n = 1,190; age n = 112; Table 4-2). Catch sampling did not occur in 2017/18 due to the lack of fishing.

Season	SPF sub-area	Gear type	No. of samples	Length-frequency n	Age-frequency n	Size range (mm FL)	Age range (years)
2009/10	West	mid-water trawl	1	77	20	210–310	2–13
2015/16	West	mid-water trawl	19 (9)	1,526	130	94–291	0–10
2016/17	West	mid-water trawl	25	1,190	112	148–304	1–14

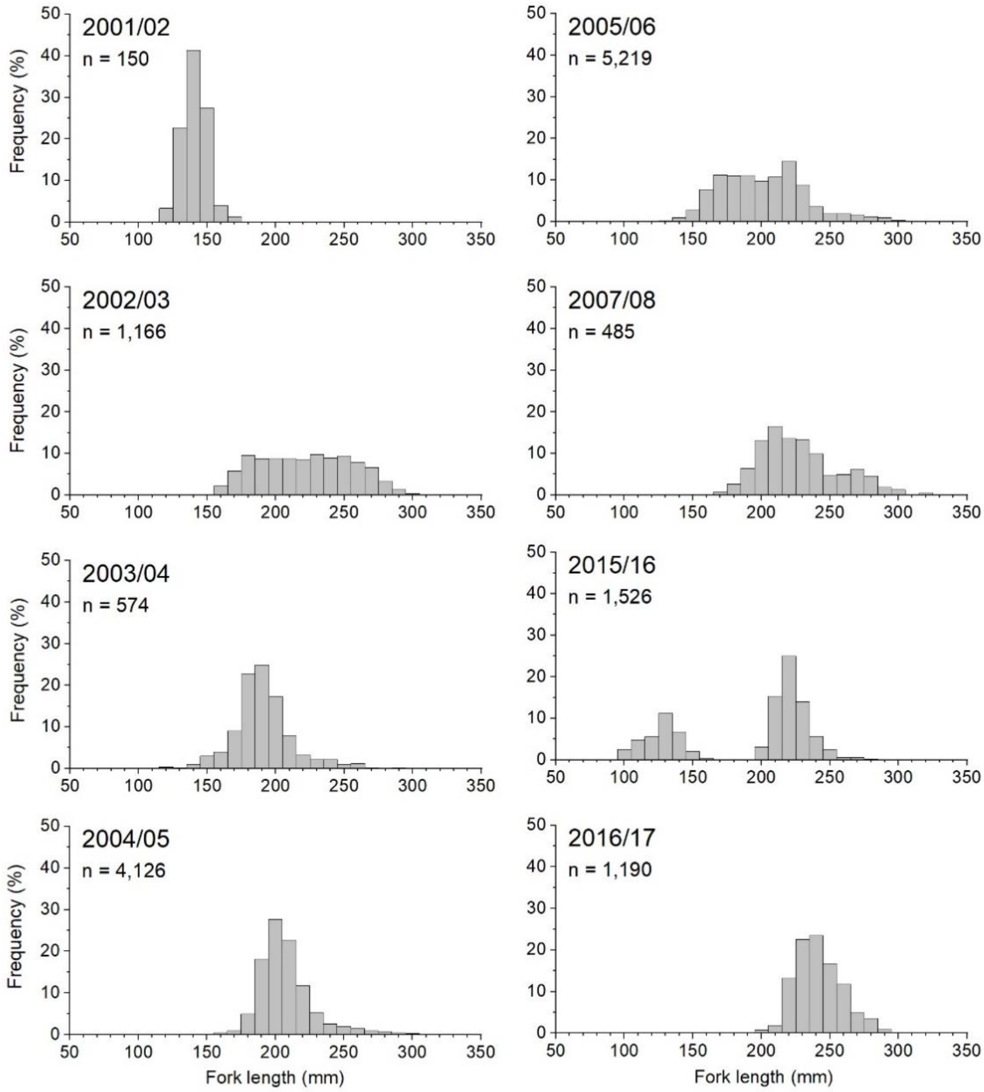
Table 0-5. Summary of Redbait West catch samples collected from commercial SPF landings. Note: number of samples in brackets is number for age frequency if different from length frequency.

Size structure

Mid-water trawl fishery: 2001/02–2016/17

Redbait West from mid-water trawl catches off south-western Tasmania during 2001/02 to 2007/08 ranged mainly from 130–280 mm FL (overall modal length: 200 mm FL; Figure 4-7). Redbait West taken over this time period were larger than those from the East (overall modal length: 160 mm FL; Figure 4-3). A single catch of Redbait West in 2009/10 (from south-western Tasmania) contained fish between 210–310 mm FL (mode 240 mm) (Table 4-2). The size structure was bimodal in 2015/16 with modes at 130 and 220 mm FL. In 2016/17, the modal length increased to 240 mm FL. The size structure of Redbait West in 2016/17 is similar to those of the purse seine catches in the mid-1980s off eastern Tasmania (Figures 4.2 and 4.7).

Figure 4-7. Length-frequency distributions of Redbait West caught by mid-water trawl in the SPF from 2001/02 to 2016/17. n = number of fish. See Table 4-2 for sample N.

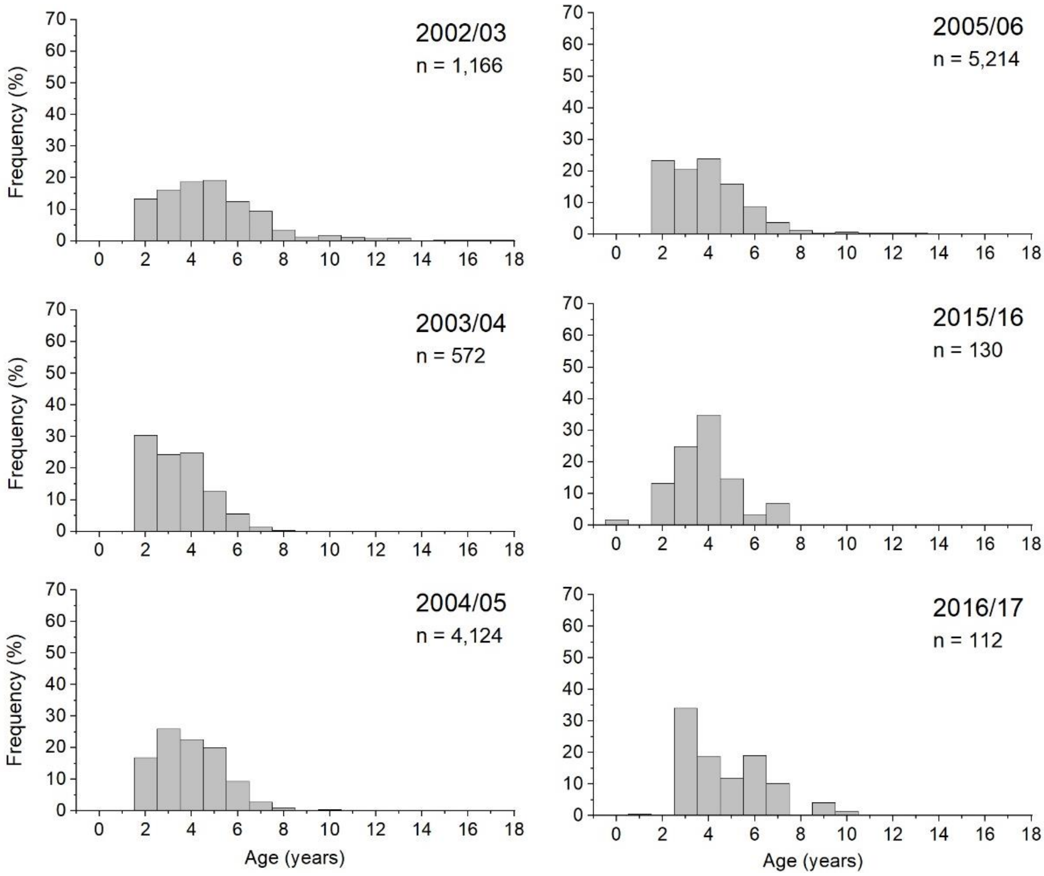


Age structure

Mid-water trawl fishery: 2002/03–2016/17

From 2002/03 to 2007/08, catches of Redbait West off south-west Tasmania had a higher proportion of older fish than in the East; Redbait West ages ranged from 2–18 years (Figure 4-8). There was a strong cohort of 2 year old fish in 2003/04 catches that was prevalent in 2004/05 catches as 3 year olds and as 4 year olds in 2005/06 (Figure 4-8). One sample of Redbait West from south-western Tasmania in 2009/10 had fish that were older than those from 2009/10 catches in the East (up to 13 years; Table 4-2), with 90% of fish estimated to be over 4 years of age (East: 76% ≤4 years). In 2015/16, the age structure ranged from 0–10 years, with 88% 2–5 year olds and a modal age of 4 years (Figure 4-14). The modal age decreased to 3 years in 2016/17, but with an age range of 1–14 years.

Figure 4-8. Age-frequency distributions of Redbait West caught by mid-water trawl in the SPF from 2002/03 to 2016/17; n = number of fish. See Table 4-2 for sample N.



4.4 Summary and Conclusions

4.4.1 Redbait East

The main fishery for Redbait East is the SPF. The highest annual catch of Redbait East in the SPF between 2010/11 and 2017/18 was 217 t in 2015/16. The annual catch in the SPF in 2017/18 was 9.5 t. Catches of Redbait East in mid-water trawls have mainly comprised fish above the mean size at 50% maturity of ~150 mm FL.

The total annual catch of Redbait East in 2017/18 was 9.5 t. The spawning biomass of Redbait East was estimated to be ~70,000 t in 2005 and 2006. Recent catches of Redbait East have been <1% of this estimate spawning biomass and below the Tier 2 exploitation rate for this stock of 5%. The total catch in 2017/18 was <1% of the available TAC. On the basis of the information provided above, Redbait East is classified as sustainable. Patterson et al. (2018) also classified the Redbait East stock as ‘not overfished’ and ‘not subject to overfishing’.

4.4.2 Redbait West

The main fishery for Redbait West is the SPF The total SPF catch in 2017/18 was 0 t, down from 1,140 t in 2016/17 and 1,157 t in 2015/16. In 2016/17, the modal length was 240 mm FL, whereas in 2015/16 the catch was bimodal, with modes at 130 and 220 mm FL. Catches have mainly contained fish below the mean size at 50% maturity of ~250 mm FL.

Recent annual catches of Redbait West have not exceeded 1,160 t. The spawning biomass for Redbait West in 2017 was estimated to be 66,767 t (CI= 33,574–140,126; Ward et al. 2019). Recent catches of Redbait West have been <2% of this estimate of spawning biomass and below the Tier 1 exploitation rate for this stock of 9% (Smith et al. 2015). The total catch in 2017/18 was 0% of the available TAC. On the basis of the information provided above, Redbait West is classified as sustainable. Patterson et al. (2018) also classified the Redbait West stock as ‘not overfished’ and ‘not subject to overfishing’.

5 Australian Sardine (*Sardinops sagax*)

5.1 Introduction

5.1.1 Background to Fishery

Sardines (*Sardinops* spp.) form the basis of some of the world's largest fisheries (Schwartzlose et al. 1999) and have been the focus of extensive research (e.g. Stratoudakis et al. 2006). In Australia, Sardine (*Sardinops sagax*) support several commercial fisheries in waters from southern Queensland to Western Australia (Ward and Staunton-Smith 2002).

Exploitation of Sardine in Australia has occurred since the 1800s (Kailola et al. 1993), but combined national catches did not exceed 1,000 t until the 1970s. Several purse seine fisheries developed in south-western Western Australia, and the annual catch in the west reached ~8,000 t in 1990 (Kailola et al. 1993). In 1991, a Sardine fishery was established in South Australia to provide fodder for the tuna mariculture industry (Ward and Staunton-Smith 2002).

In 1995 and 1998, two mass mortality events caused by Pilchard herpesvirus (Whittington et al. 2008) reduced the adult biomass of Australian Sardine populations by ~70% (Ward et al. 2001b). Catches in Western Australia have remained low since the mortality events (<3,000 t since 1999). In 2014, ~1,500 t of Australian Sardine were taken off Western Australia (Fletcher and Santoro 2015). The South Australian fishery grew quickly after the mortality events; in 2016, the total catch by the South Australian fishery was 37,940 t (Ward et al. 2017).

Off eastern Australia, the annual catch of Sardine increased rapidly from historical averages of 30–40 t to almost 5,000 t in 2008/09, but declined since then as a result of a reduction in fishing effort (Ward et al. 2014a, Izzo et al. 2017).

5.1.2 Taxonomy

Australian Sardine (*Sardinops sagax*, Jenyns 1842) belong to the order Clupeiformes, which contains about 400 species in seven families, including *Clupeidae* (sardines, shads, menhadens, herrings) and *Engraulidae* (anchovies) (Eschmeyer and Fricke 2016).

The genus *Sardinops* has historically included five species: *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* off the Japanese coast (Whitehead 1985). Parrish et al. (1989) proposed the genus *Sardinops* is mono-specific 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*). Currently, the accepted taxonomic classification for Sardine in the Indo-Pacific region is as one species, *Sardinops sagax*, with three confirmed linages within the genus.

The common name for Sardine off Australia has also varied through the years. It has been referred to as either the Australian Sardine or Pilchard. Since May 2006, Australian Sardine and *Sardinops sagax* (Jenyns 1842) have been listed in the Standard Fish Names List for Australia. *Sardinops sagax* is also the name used in the Australian Faunal Directory, Eschmeyer's Catalogue of Fishes Fishes of Australia, and FishBase. In this report, we use Sardine to refer to *S. sagax* in Australia and elsewhere.

5.1.3 Distribution

Sardine are found in waters off Australia, Japan, North and South America, Africa and New Zealand. In Australia, they occur throughout temperate waters between Rockhampton (Queensland) and Shark Bay (Western Australia), including northern Tasmania (Gomon et al. 2008).

5.1.4 Stock Structure

The Australian Sardine population has a complex stock structure. It is a meta-population with extensive mixing among adjacent sub-groups, illustrated by the rapid spread of Pilchard herpesvirus through the population in the late 1990s (Ward et al. 2001b, Whittington et al. 2008, Izzo et al. 2017). An integrated analysis that of genetic, morphological, otolith, growth, reproductive and fishery data by Izzo et al. (2017) suggested the existence of least four stocks: 1) south-western Australia (Western Australia); 2) Great Australian Bight and Spencer Gulf (South Australia); 3) Victoria, Tasmania and southern NSW); and 4) eastern Australia (southern Queensland and northern New South Wales). The stock off south-western Australia appears to comprise two sub-stocks: west and south.

5.1.5 Movement

Sardines undergo extensive migrations. For example, schools of Sardine migrate north into waters off southern Queensland during winter-spring to spawn (Ward and Staunton-Smith 2002). Similarly, off Africa, Sardine migrate north and south along the coast to access conditions that are favourable for spawning and the survival of recruits (van der Lingen and Huggett 2003). The movement patterns of Sardines in Australian waters are poorly understood, although there is evidence of an ontogenetic shift in distribution in South Australia with larger, older fish most commonly found in shelf waters, and small, younger fish mainly found in embayments, including Spencer Gulf (Rogers and Ward 2007).

5.1.6 Food and Feeding

Sardines have two feeding modes: filter-feeding on micro-zooplankton and phytoplankton, and particulate-feeding on macro-zooplankton. Sardines switch between the two modes depending on relative prey density (van der Lingen 1994, Louw et al. 1998). In South Australian waters, Sardines consume at least 12 different prey taxa; krill (29.6% biomass) and other unidentified crustaceans (22.2% biomass) are the major prey items (Daly 2007). Krill were found in greater numbers (65.3%) than other crustaceans (27%). Crab zoea, other decapods, copepods, polychaetes, fish eggs and larvae, and gelatinous zooplankton were also dietary components (Daly 2007).

5.1.7 Age, Growth and Size

Sardines have been aged using growth increments in scales (Blackburn 1950) and otoliths (Butler et al. 1996, Fletcher and Blight 1996) and by modelling marginal increment formation in otoliths (Kerstan 2000). Several methods show that translucent zones form annually in otoliths of 1 year old fish off South Africa (Waldron 1998), 2 year olds off North America (Barnes et al. 1992) and 4 year olds off Western Australia (Fletcher and Blight 1996). Ageing sardine from southern Australia has been challenging due to difficulties associated with interpreting and counting growth zones (Rogers and Ward 2007).

Growth rates and maximum size of Australian Sardine vary in accordance with localised variation of food resources and environmental conditions (Ward and Staunton-Smith 2002). In southern Australia, Australian Sardines rarely exceed 250 mm FL after 6 to 8 years (Rogers and Ward 2007). Larval and juvenile Sardines in southern Australian waters have growth rates of approximately 1.2 and 0.4 $mm.day^{-1}$, respectively (Rogers and Ward 2007). Growth rates of Sardines were higher in South Australian waters than along other parts of the Australian coastline and lower than those in more productive boundary current ecosystems, such as the Benguela, Agulhas and Californian systems (Rogers and Ward 2007). A notable finding of the study was that fish in commercial catches were younger (and smaller) than those from fishery-independent samples.

5.1.8 Reproduction

In Australia, Sardines usually spawn in open waters between the coast and shelf break (Blackburn 1950, Fletcher and Tregonning 1992, Fletcher et al. 1994). They are serial (batch) spawners with asynchronous oocyte development and indeterminate fecundity. The number of eggs released in a batch (batch fecundity) is correlated with female size and varies among locations and years (Lasker 1985). In South Australia, females spawn batches of 4,000 to 35,000 pelagic eggs about once per week during the extended spawning season (Ward et al. 2014b). In most locations, there is one spawning season per year, but off Albany in Western Australia, there are two (Fletcher 1990).

The peak spawning season is variable across the Australian distribution of Sardine. For example, in South Australia, spawning occurs during the summer-autumn upwelling from

January to April (Ward et al. 2001c, Ward and Staunton-Smith 2002). Similarly, along the south coast of Western Australia spawning peaks between January and June (Gaughan et al. 2002), whereas Sardines off Fremantle have maximum GSI values during June (Murhling et al. 2008). Off southern Qld and northern NSW, Sardine GSI values peak in winter to early spring (Ward and Staunton-Smith 2002, Ward et al. 2015c), whereas off southern New South Wales the peak occur between July and December (Stewart et al. 2010, Ward et al. 2011). In Victoria, GSI values of Sardine are greatest from spring to early summer (Hoedt and Dimmlich 1995, Neira et al. 1999).

The size and age at of sexual maturity in Sardine varies between locations, and ranges from 100 to 180 mm FL and 1.8 to 2.8 years (Blackburn 1950, Fletcher 1990, Staunton-Smith and Ward 2000). In South Australia, 50% of males are sexually mature at 146 mm FL and females at 150 mm FL (Ward and Staunton-Smith 2002).

5.1.9 Early Life History and Recruitment

Sardines have a relatively long larval phase: eggs hatch approximately two days after fertilization and yolk-sac larvae are 2.2–2.5 mm TL (Neira et al. 1998). Larvae metamorphose at 1–2 months of age and at lengths of 35–40 mm TL. Larvae are known to undertake vertical migrations to prevent passive transport away from regions with favourable environmental conditions for survival (Watanabe et al. 1996, Logerwell et al. 2001, Curtis 2004). Survival rates of sardine eggs and larvae strongly affect recruitment success (Louw et al. 1998). Large variations in abundance that characterise sardine populations worldwide are attributed to fluctuations in recruitment, which can be influenced by environmental factors, regime shifts and over-fishing (Galindo-Cortes et al. 2010). Larval survival is a key determinant of recruitment success, but factors affecting survivorship may vary spatially and temporally. The effects of food availability on larval survival have been discussed at length (Galindo-Cortes et al. 2010), but there has been less consideration about how predation on eggs and larvae may affect recruitment success.

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 of the eastern and central Great Australian Bight (Ward et al. 2014b). Juvenile sardine occupy nursery areas that include shallow embayments and semi-protected waters. The factors affecting recruitment success of Sardines are poorly understood.

5.1.10 Stock Assessment

The DEPM was developed to assess the status of northern anchovy (*Engraulis mordax*) stocks off the coast of California (Parker 1980, Lasker 1985) and is widely used for assessing spawning-stock biomass of sardine worldwide (see review in Barangé et al. 2009), e.g. Atlanto-Iberian Sardine (*Sardina pilchardus*) (Bernal et al. 2011a, Bernal et al. 2011b). This approach provides direct estimates of spawning biomass for the basis of management decisions. The DEPM has been used extensively to estimate the spawning biomass of Australian Sardine in South Australia since 1995 (Ward et al. 2017). During 2014, two DEPM surveys were undertaken for to Sardine off eastern Australia (Ward et al. 2015a). Prior to 2014, a preliminary DEPM was applied to Australian Sardine in 2004 using samples collected along the southern Queensland and northern New South Wales coast during a survey of Blue Mackerel (Ward et al. 2007).

5.1.11 Recreational fishing

Information on the magnitude of recreational catches of Sardine is not available. The most recent report on the Status of Australian Fish Stocks indicated that recreational and indigenous catches of Australian Sardine are likely to be negligible (Stewardson et al 2018).

5.1.12 Biomass Estimates

East

An early application of the DEPM to Australian Sardines off eastern Australia in 2004 produced a spawning biomass estimate of 28,809 t (Ward et al. 2007). This estimate was calculated from the ‘best’ estimate of each parameter, and ‘minimum’ and ‘maximum’ estimates ranged from 7,565 to 116,395 t. The ‘best’ estimate was considered conservative and likely negatively biased as spawning season and area varies temporally and spatially on the east coast of Australia (Ward and Staunton-Smith 2002); it was unlikely that the entire spawning area was sampled during peak spawning season (Ward et al. 2007).

During 2014, two DEPM surveys were applied to Sardine off eastern Australia: a summer survey and a winter/spring survey (Ward et al. 2015a, 2015b). The summer DEPM survey, undertaken in January 2014 between Eden, New South Wales and Triabunna, Tasmania, estimated the spawning biomass for Australian Sardine off south-eastern Australia to be 10,962 t over a spawning area of 11,906 km^2 (Ward et al. 2015a). It is important to note that this was not considered an estimate of the total adult biomass off eastern Australia, only an estimate of the portion of the population that was spawning in the southern part of the range during summer. The main spawning area for Australian Sardine East occurs off northern New South Wales and southern Queensland during late winter and early spring (Ward and Staunton-Smith 2002). The study by Ward et al. (2015a) provides unequivocal evidence that Sardine occur off eastern Tasmania and in Bass Strait, at least in some years, and provides insights into the quantum of catches that may be suitable for any developmental fishery established in the region.

The second DEPM survey, undertaken in August/September 2014 off eastern Australia by Ward et al. (2015b), estimated spawning biomass of Australian Sardine East to be 49,575 t (95% CI = 24,179–213,323 t). The estimated spawning area was 22,400 km^2, comprising 34.2% of the total area sampled (65,528 km^2). Most Sardine eggs were collected between

Sandy Cape, Queensland and just south of Newcastle, New South Wales where sea surface temperatures were 17– 22°C. The highest densities of eggs were collected from sites with SSTs of 18–21°C. All DEPM parameters were estimated from a large number of samples and were considered robust. These parameters included: mean daily egg production (P_0): 52.6 eggs·day^{-1}·m^{-2}; mean sex ratio: 0.54; mean female weight: 38.8 g; mean batch fecundity: 11,942 eggs; and mean spawning fraction: 0.14.

The 2014 winter/spring estimate of spawning biomass for Australian Sardine East, i.e. 49,575 t, is considered suitable for setting recommended biological catches as outlined by the SPF HS. Most of the estimates of spawning biomass obtained in the sensitivity analyses were between approximately 30,000 and 110,000 t. Credible values for only one parameter (spawning fraction, 0.04) provided estimates outside that range (i.e. ~175,000 t). The proportion of total adult biomass of Australian Sardine East that occurred outside the survey area during the winter/spring survey period is unknown.

5.1.13 Management Strategy Evaluation

2010

For Australian Sardine East, the DEPM estimate of spawning biomass based on surveys in 2004, was 96% of the model calculated estimate of spawning biomass. All Tier 1 scenarios reached equilibrium around B_{60} by the end of the 30 year simulation period. The Tier 2 and Tier 3 results suggest that these harvest levels were sustainable. Given that the DEPM survey estimate of spawning biomass is close to the model calculated estimate, these conclusions can be considered with greater certainty.

2015

Smith et al. (2015) concluded the harvest rate of 15% may be too low for Australian Sardine East and suggested a Tier 1 harvest rate of 33%, with the Tier 1 rate being applied for not more than 5 years. Tier 2 harvest rates for Australian Sardine East were recommended to be 50% of Tier 1 rates and should not be applied for more than 5 years. The study results also indicated it is not safe to apply Tier 2 harvest rates unchecked for long periods of time (Smith et al. 2015). The Atlantis-SPF biomass estimate for Australian Sardine East is 147,000 t (typical range: 32,000–184,000 t) (Smith et al. 2015).

5.1.14 Management

Sardine in the Australian Sardine sub-area of the East sub-area in the SPF are currently managed at the Tier 1 level based on the 2014 DEPM assessments.

5.2 Methods

5.2.1 Fishery Statistics

Fishery statistics from 1984/85 to 2017/18 have been supplied by relevant jurisdictions and collated by SARDI Aquatic Sciences. Annual data are reported in fishing seasons (May 1 to April 30) rather than financial years as was done in previous assessments (e.g. Ward et al. 2013, 2014c, 2015c). Data reported for Australian Sardine East include the Australian Sardine sub-area and not the entire East sub-area, due to the eastern and south-eastern Sardine stock separations that occur in southern NSW/eastern VIC (Figure 1-1; see Izzo et al. 2017).

Estimates of total annual catch supplied for Australian Sardine East include data from the NSW Ocean Fisheries (Hauling, Trap and Line, Trawl), NSW Estuary Fisheries (General and Prawn Trawl) and the Commonwealth SPF.

Mean annual CPUE of Australian Sardine East in the Commonwealth SPF is calculated for purse-seine (tonnes·net-set^{-1} ±SE) from 2000/01 to 2017/18.

5.2.2 Biological Information

Length-frequency data for Australian Sardine sampled from commercial catches taken in New South Wales were supplied by New South Wales DPI from 2004/05 to 2016/17. Additional samples were collected from commercial catches taken from the north (Iluka) and south-central (Eden) coast of New South Wales between March 2009 and January 2010 for biological analysis. These fish were dissected and morphometric data collected by New South Wales DPI, while otoliths were interpreted for age by SARDI Aquatic Sciences using the methods of Rogers and Ward (2007).

AFMA observers collected biological samples of Sardine during trips in September 2012 and August 2013 which were supplied to SARDI Aquatic Sciences for processing. The fish were measured (mm FL), and a random sub-sample were retained for ageing. Australian Sardines were also sampled from commercial catches taken in New South Wales between July 2013 and August 2014 to determine population size and age structures and monitor reproductive activity.

Ages were derived from the otolith weights in 2012/13 using the relationship calculated from South Australian commercial catches (Rogers and Ward 2007). In all other years, ages were based annual growth increment counts in whole otoliths.

Summarised biological data from New South Wales DPI are presented in financial years and all other biological data are presented in fishing seasons (1 May to 30 April).

The number and spatio-temporal coverage of the biological samples of Australian Sardine East are limited in comparison to the magnitude of catches since the mid-1990s, and may not provide a good representation of the catch.

5.3 Results

5.3.1 Australian Sardine East

5.3.1.1 Fishery Statistics

Number of vessels

Prior to 1999/00, >85 vessels annually reported catches of Australian Sardine East; 99% were from New South Wales. Since then, vessel numbers taking Australian Sardine East declined to 15 vessels in 2012/13 and have averaged 24 per year over the last 3 years (87% from New South Wales).

Annual patterns: Total catch

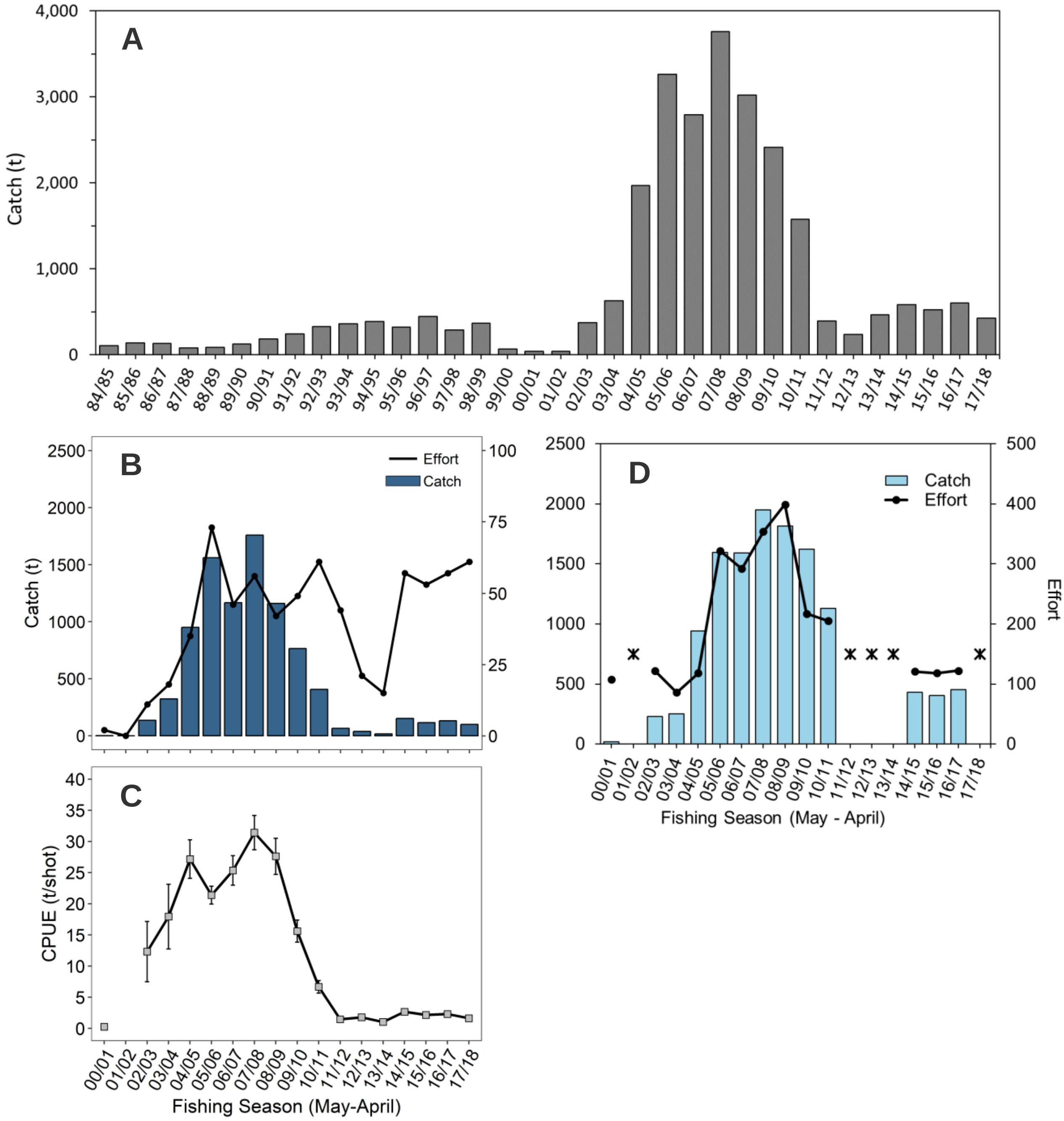
Total catches of Australian Sardine have varied over the last 34 years (Figure 5-1a). Catches were low in the mid- to late-1980s (<200 t), increased to ~450 t in 1996/97 and fell to low levels in the early 2000s. The low catches of the late 1990s and early 2000s resulted from the widespread die-off of Sardine from the Pilchard herpesvirus that spread through the Australian population in 1995 and 1998 (Ward et al. 2001b, Whittington et al. 2008). The stocks recovered and catches increased to 3,761 t in 2007/08 (Figure 5-1a). Total catches declined to 234 t in 2012/13 and have remained below 650 t since then. Total catch was 429 t in 2017/18. The main fisheries taking Australian Sardine in the Sardine sub-area are the NSW Ocean Hauling Fishery and the SPF.

Annual patterns: Catch, Effort and CPUE

Purse seining has been the main method used to take Australian Sardine East. In the SPF, catches of Australian Sardine East have been solely taken by purse seine (Figure 5-1b, c). Historically, annual purse seining effort in the SPF has been substantially less than in the NSW fishery but with only slightly lower catch. For example, in 2007/08, effort and catch in the NSW fishery was 1,948 t with 354 boat days compared to 1,759 t and 56 net-sets (49 boat days) in the SPF (Figure 5-1b, d). Catch trends in the SPF are similar to those in the NSW fishery, with the highest catches in the mid to late 2000s (Figure 5-1 b, d). Temporal effort in the SPF was relatively stable, averaging 53 net-sets annually from 2005/06 to 2011/12. Both effort and catch of Australian Sardine East in the SPF decreased to low levels between 2011/12 and 2013/14 (Figure 5-1b). Fishing effort and catch increased in 2014/15 (57 net-sets, catch: 152 t) and remained steady through 2016/17 (effort: 57 net-sets, catch: 131 t) (Figure 5-1b). In 2017/18, effort was 61 net-sets with 99 t of catch. Mean annual CPUE of purse seining in the SPF for Sardine declined from 31 $t \cdot net\text{-}set^{-1}$ in 2007/08 to 7 $t \cdot net\text{-}set^{-1}$ in 2010/11 (Figure 5-1c). Mean annual CPUE has been <3 $t \cdot net\text{-}set^{-1}$ from 2011/12 to the present.

In the NSW fishery, purse seining effort for Australian Sardine has been highly variable among years; in 2000/01, effort was 108 boat days with a catch of only 18 t (Figure 5-1d). Fishing effort remained low in the early 2000s and increased to a peak of >350 boat days in the late 2000s. Catches also peaked at ~1,950 t during that time (Figure 5-1d). From 2014/15 to 2016/17, effort averaged 121 boat days per year with 429 t of catch. Annual catch and effort data are confidential in the NSW fishery from 2011/12–2013/14 and in 2017/18 due to the low number (<5) of license holders reporting catch.

Figure 5-1. Fishery statistics for Australian Sardine East (Sardine Sub-area only). (A) Total annual catch (tonnes) for all jurisdictions by fishing season from 1984/85 to 2017/18. Long-term purse seining trends in the SPF from 2000/01 to 2017/18: (B) annual landed catch (tonnes) and effort (net-sets); (C) mean annual CPUE (t·net-set^{-1}; ±SE). Long term purse seining trends in the NSW Ocean Hauling Fishery: (D) annual landed catch (tonnes) and effort (boat days). (⁎) indicates data confidentiality where ≤5 license holders reported landings.



5.3.1.2 Biological Information

Length-frequency data were collected from 18,610 Australian Sardine East sampled from purse seine catches in the NSW Ocean Hauling Fishery between 2004/05 and 2016/17 (Table 5-1). The number of samples collected in each year ranged between 2 (2004/05) and 54 (2009/10). In 2016/17, 8 catch samples were collected (733 fish). Catch sample data are not available for 2017/18.

In the SPF, length-frequency data were collected from 4,068 Australian Sardine East taken by purse seining off New South Wales between 2009/10 and 2014/15 (Table 5-2). Of these samples, age-frequency data were collected from 1,215 individuals (Table 5-2).

Season	No. of samples	No. of fish	Size range (mm FL)
2004/05	2	249	90–210
2005/06	7	592	80–240
2006/07	31	3,098	70–230
2007/08	12	1,209	90–230
2008/09	8	860	110–210
2009/10	54	5,579	50–230
2010/11	5	473	100–220
2011/12	6	691	100–200
2012/13	4	538	100–180
2013/14	30	2,075	120–190
2014/15	12	1,223	120–200
2015/16	12	1,186	90–200
2016/17	8	733	120–210

Table 0-6. Summary of Australian Sardine East samples collected from commercial New South Wales State purse seine catches between 2004/05 and 2016/17 (data supplied by New South Wales DPI).

Season	NSW Region	No. of samples	Length-frequency n	Age-frequency n	Size range (mm FL)	Age range (years)
2009/10	North	15	240	155	120–190	0–3
2009/10	South	6	330	167	127–213	0–5
2012/13	North	3	208	32	120–175	1–3
2013/14	North	40	1,840	492	68–175	0–5
2014/15	North	32	1,450	369	124–195	0–6

Table 0-7. Summary of Australian Sardine East catch samples collected from commercial SPF landings off New South Wales from 2009/10 to 2014/15.

Size Structure

Annual size distributions for Australian Sardines sampled between 2004/05 and 2016/17 from the NSW Ocean Hauling Fishery were mainly between 100 and 200 mm FL, although the modal length varied among years (Figure 5-2). For some years (i.e. 2004/05 to 2006/07, 2011/12), the size structure was bimodal with a dominant mode at ~130 to 140 mm FL (i.e. the approximate size at sexual maturity for Australian Sardine) and a smaller mode at ~170 to 190 mm FL. In all other years, the size structures contained a single dominant mode between 130 and 180 mm FL. The length mode has increase since 2012/13 from 140–150 mm FL to 180 mm FL in 2016/17 (Figure 5-2).

Size structures of catches off New South Wales in 2009/10 Australian Sardine East were larger on average in the south than in the north (Figure 5-3). Purse seine catch samples taken in the SPF between 2012/13 and 2014/15 indicated an increase in the size structure over time but a consistent modal length at 150 mm FL (Figure 5-3).

Age structure

Ages of Australian Sardine East collected from purse seine catches in the SPF along the south coast of New South Wales in 2009/10 ranged from 0+ to 5 years, whereas catches from the northern region contained fish aged 0+ to 3 years (Figure 5-4). Commercial catch samples from the north in 2012/13 mostly consisted of 2 year old fish. In 2013/14 and 2014/15, the range of ages in age structures in the northern region continued to increase, with more fish in the 3 and 4 year old age classes. Fish reached a maximum age of 6 years in 2014/15 (Figure 5-4).

Figure 5-2. Length-frequency distributions of Australian Sardine East sampled from purse seine catches taken in New South Wales from 2004/05 to 2016/17. Data supplied by New South Wales DPI; n = number of fish. See Table 5-1 for sample N.

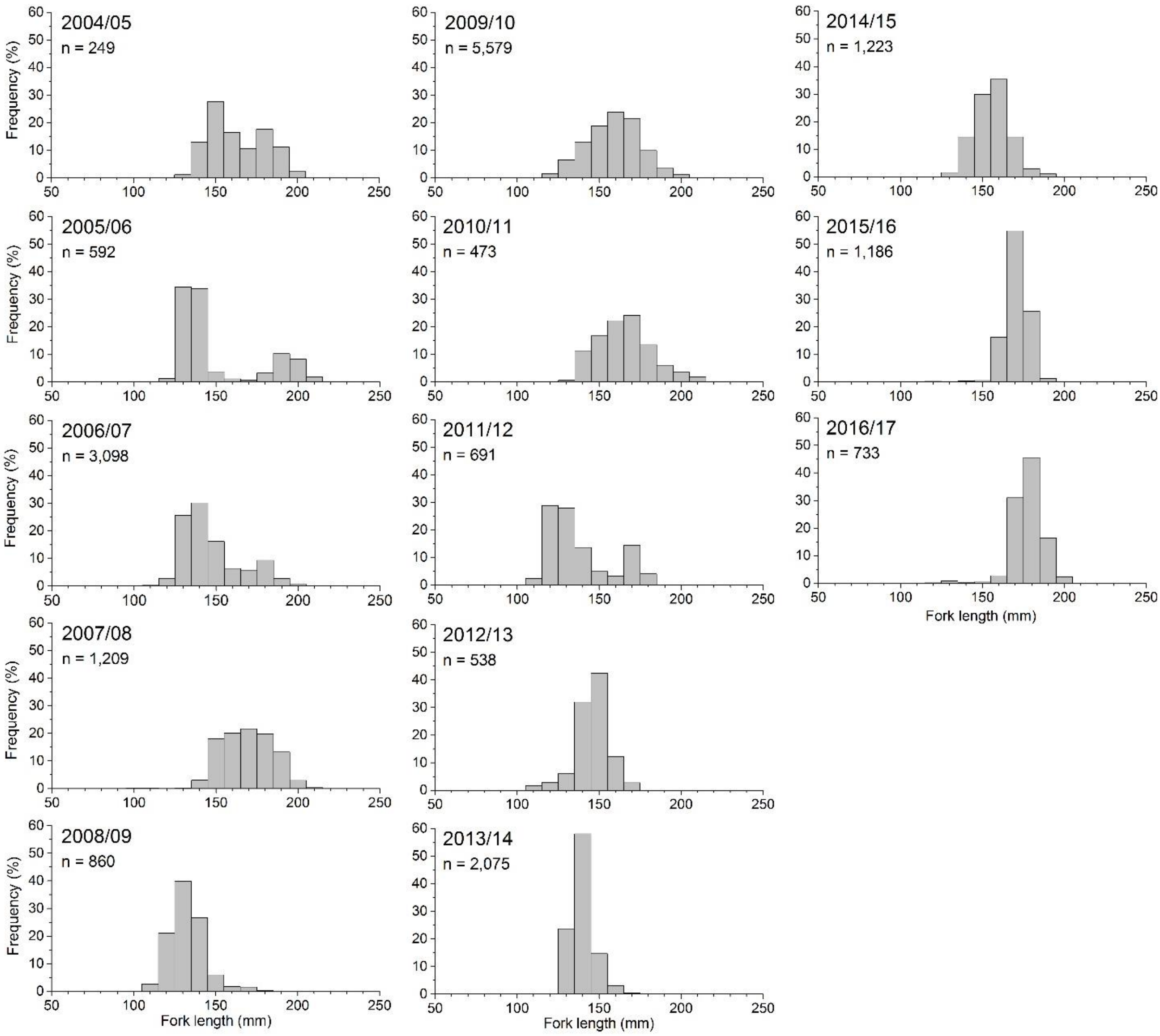


Figure 5-3. Length-frequency distributions of Australian Sardine East caught in the SPF by purse seine along the northern and southern New South Wales coastline; n = number of fish. See Table 5-2 for sample N.

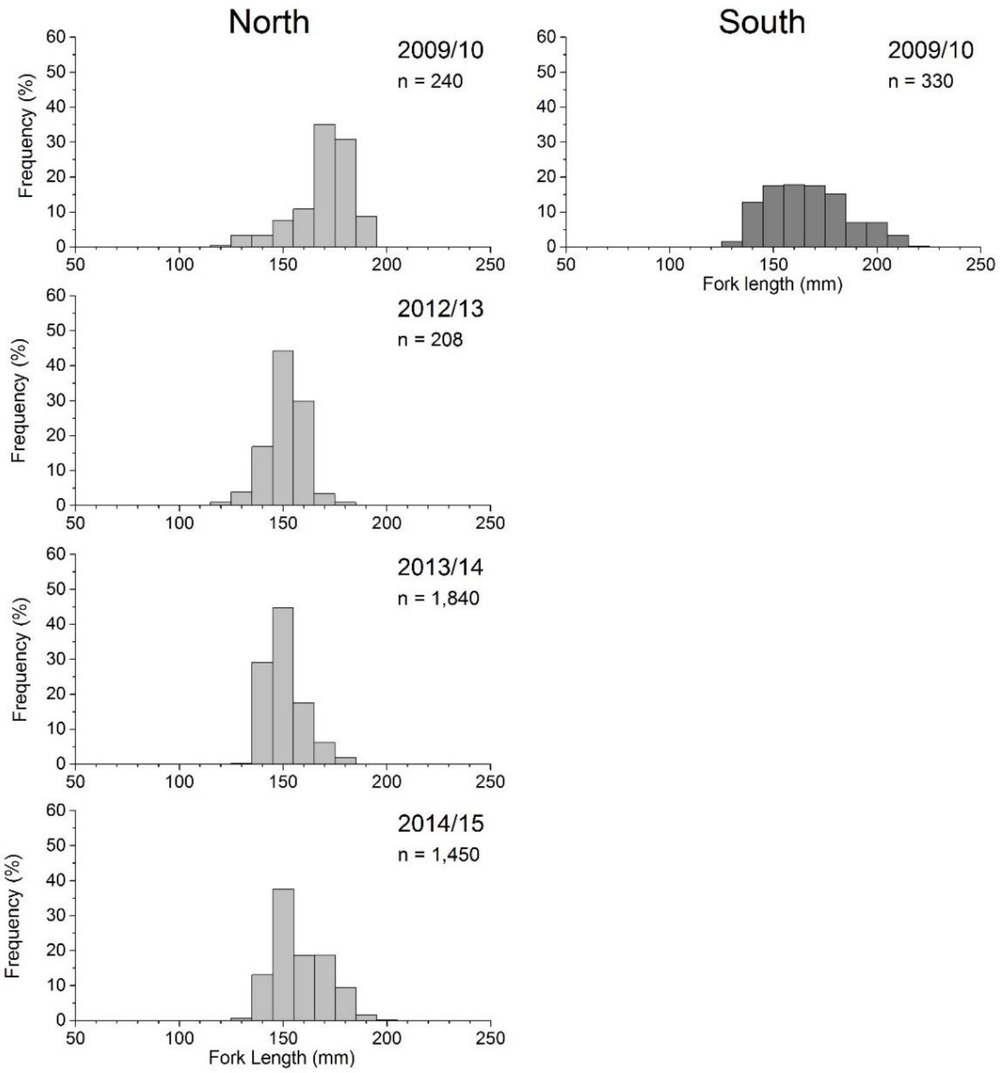
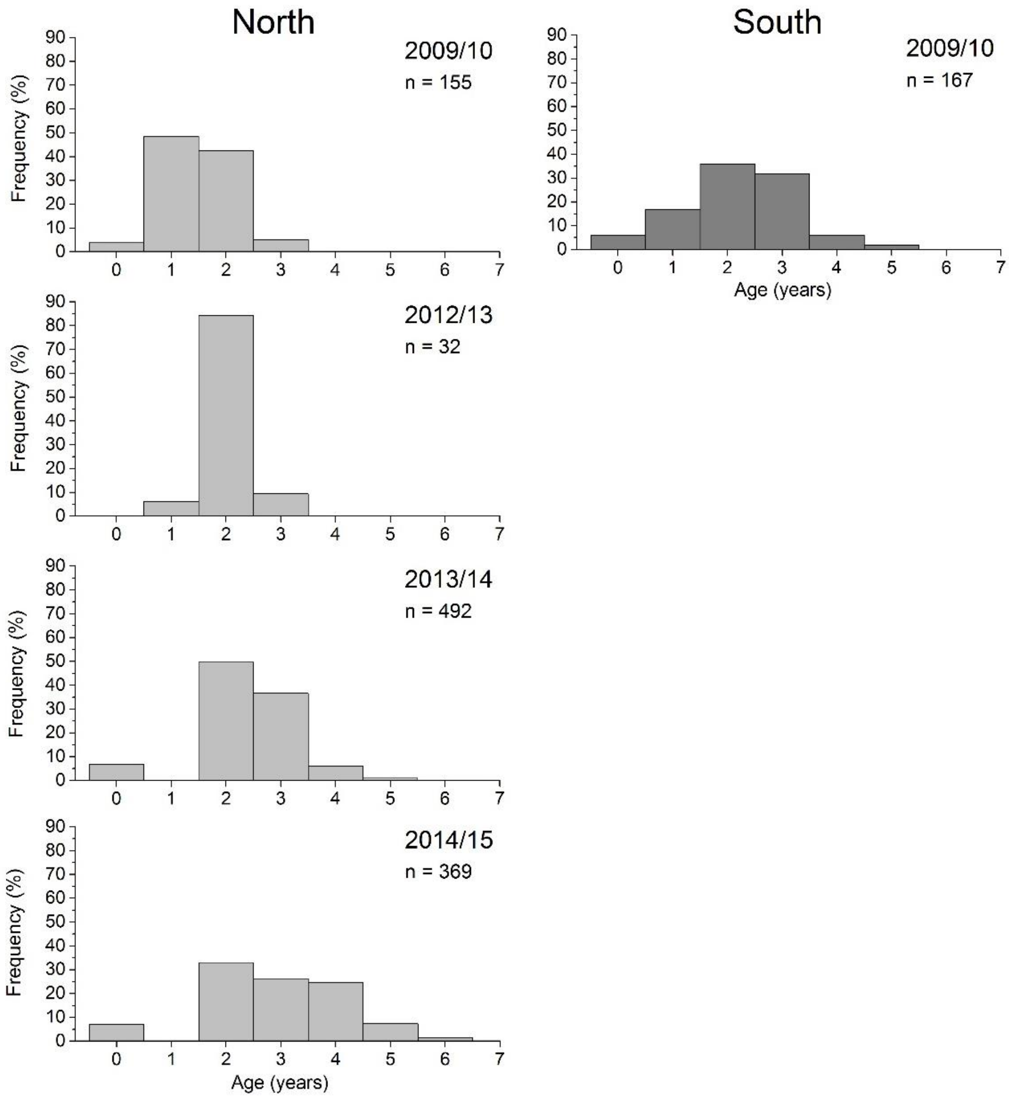


Figure 5-4. Age-frequency distributions of Australian Sardine East caught by purse seine in the SPF along the northern and southern New South Wales coastline; n = number of fish. See Table 5-2 for sample N.



5.4 Summary and Conclusions

5.4.1 Australian Sardine East

The spawning biomass of Australian Sardine East during the main spawning winter/spring spawning period in 2014 was estimated to be 49,575 t (95% CI = 24,179–213,323 t) (Ward et al. 2015b). This estimate is larger than the 2004 estimate of 28,809 t for Australian Sardine off eastern Australia, which did not cover the entire spawning area (Ward et al. 2007). Ward et al. (2015b) suggested the 2014 estimate of spawning biomass during winter/spring was robust, as it was based on reliable estimates of all DEPM parameters.

Total annual catches of Australian Sardine East in the Sardine sub-area peaked at 3,761 t in 2007/08 and declined to 239 t in 2012/13; total catches increased to 601 t in 2016/17 and were 429 t in 2017/18. Catches were mainly taken by purse seine, and since 2000/01, annual fishing effort in the SPF has been substantially less than in the NSW Ocean Hauling Fishery but with only slightly lower catch. Both effort and catch of Australian Sardine East in the SPF decreased to low levels between 2011/12 and 2013/14, but have increased since then. There has been a general reduction in total catch since 2008/09 that reflects a significant reduction in the size of the fishing fleet. Less than 30 vessels annually have reported catch since 2011/12, compared to >90 vessels prior to 1999. Other factors that may have contributed to the reduction in catch and effort include a fire in a major fish processing factory in Eden (southern New South Wales) and apparent movement of Sardines from inshore to offshore waters (AFMA 2014).

Size structures of Australian Sardine East in purse seine catches since 2004/05 have varied among years, with the modal length ranging from 130–180 mm FL. The length mode of commercial purse seine catch samples increased from 150 mm FL in 2012/13 to 180 mm FL in 2016/17. Australian Sardine East in catches have been at or above the mean size at 50% maturity of ~150 mm FL (Ward and Rogers 2007) with age classes of mainly 2–4 years. Age and length structures are difficult to interpret due to changes in fishing effort over time, differing ageing methods and regional stock differences (i.e. north and south coasts of New South Wales).

Current catches of Australian Sardine East in the Sardine sub-area are assessed as sustainable, as they are <2% of the estimated spawning biomass for 2014 (Ward et al. 2015b), and below the Tier 1 exploitation rate for this stock of 20% (Smith et al. 2015). Stewardson et al. (2018) classified the biological stock of Australian Sardine East as sustainable. The Australian Sardine stock in the East is classified as ‘not overfished’ and ‘not subject to overfishing’ by Patterson et al. (2018).

6 Optimise Catch Monitoring Program

6.1 Introduction

Recent catch sampling in the SPF has occurred on an *ad hoc* basis. The level of sampling effort has been determined largely by the level of observer coverage, which has varied between ~20 and 100%. Observers have been requested to collect ~50 fish of each SPF species caught from every observed fishing operation. The trade-off between scientific precision and logistical costs associated with different levels of sampling effort and different sample sizes (i.e. fish measured and otoliths read) has not been evaluated.

The aim of this chapter is to present information needed to optimise the design of future catch sampling programs in the SPF. To evaluate the trade-offs between the costs of processing and the precision of estimates of mean age/length, catch samples obtained from the SPF were analysed to address the following questions.

How do: 1) the precision of estimates of the mean length/age of a species in a sub-area of the SPF and 2) the cost of the sampling program (for a species in a sub-area), vary in relation to:

i) the number of catch samples taken;
ii) the number of fish measured (to estimate length);
iii) the number of otoliths sectioned and read (to estimate age)?

Findings from these analyses provided the basis for the SPF Scientific Panel to evaluate, on balance, i) how many catch samples should be taken; ii) how many fish should be measured and iii) how many otoliths should be read to monitor the mean length/age of a species taken in a sub-area of the SPF.

6.2 Methods

Precision

Catch sampling data collected from the SPF between 2015/16 and 2017/18 were used to evaluate how the precision of estimates of mean length/age for a species in sub-area vary in relation to the number of samples taken, number of fish measured and number of otoliths read.

The datasets used for these analyses were those obtained for species in sub-areas where significant catches were taken during a fishing season and relatively large numbers of catch samples were available (Table 6-1). Suitable datasets were obtained from 1) the factory trawler that operated in the East sub-area off southern NSW in 2015/16 (Blue Mackerel, Jack Mackerel, Redbait) and the West sub-area south of Kangaroo Island in 2016/17 (Blue Mackerel, Jack Mackerel, Redbait) and 2) a smaller vessel without onboard processing facilities that operated in inshore waters of the East sub-area off southern NSW in 2017/18 (Blue Mackerel, Jack Mackerel). The effects of the number of fish measured on the precision of estimates of mean length and numbers of otoliths read on the precision of mean age were evaluated separately. All analyses were conducted in the R programming environment (R Core Team, 2018).

A two-stage random resampling procedure was used for the analyses. In the first stage, *n* catch samples were randomly sampled from a dataset without replacement, and the mean length or age was calculated along with the standard deviation. 100 replicates were run for each *n* catch samples.

In the second stage, *n* catch samples were randomly selected; then *m* fish/otoliths were randomly sampled from each of those catch samples without replacement. The mean length and age were calculated for *m* fish/otoliths per *n* catch samples along with the standard deviation. 100 replicates were run for each *m* fish/otolith per *n* catch samples combination. Catch samples with less than 20 fish measured for length (age: <5 otoliths) were dropped from the analyses. In the second stage, *m* was not allowed to be larger than the smallest number of fish/otoliths actually collected for a catch sample (Table 6-1).

Relative mean standard errors (%; RSE) of length and age were calculated after the resampling procedures were completed. The overall mean RSEs for each analysis were plotted with 95%CIs (2.5% and 97.5% quantiles of the mean RSEs). These plots were used to investigate how the number of samples and sample sizes (i.e. fish measured, otoliths read) influenced the precision of estimates of mean length and age.

Costs

The costs of processing a fish from a catch sample to estimate length and age data were calculated in November 2018 (Table 6-2). These costs included all fish processing and data entry, as well as laboratory consumables, and shipping costs from Ulladulla, NSW to Adelaide, South Australia.

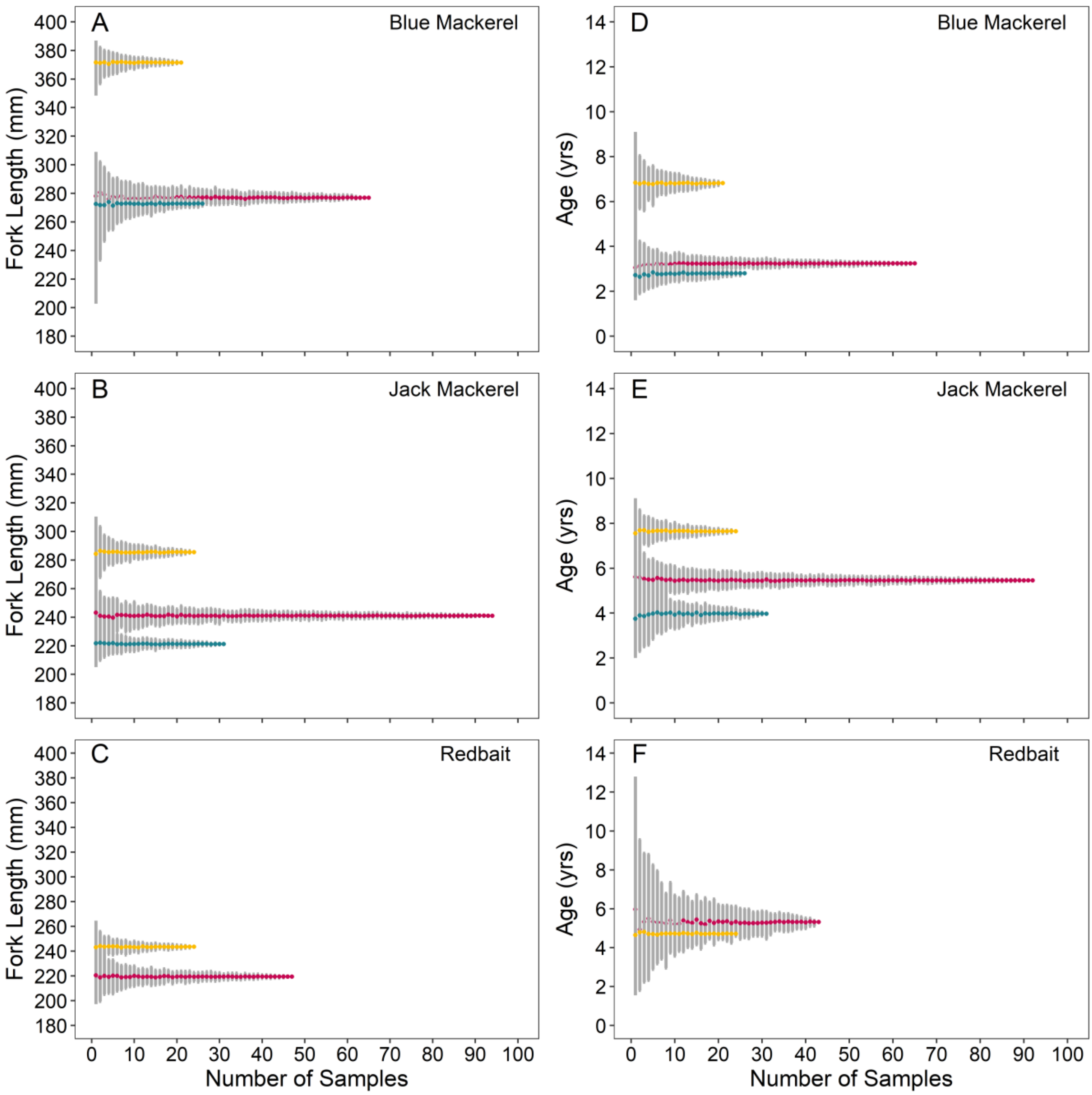
Table 6-1. Maximum number of catch samples and fish used in the various datasets to examine precision when estimating the mean fork length or age of an SPF species for a region and fishing season. Regions: NSW: southern New South Wales; SA: south of Kangaroo Island.

SPF Species	NSW 2015/16 (factory trawler)		NSW 2017/18 (non-factory trawler)		SA 2016/17 (factory trawler)	
	n Samples Length (Age)	n Fish Length (Age)	n Samples Length (Age)	n Fish Length (Age)	n Samples Length (Age)	n Fish Length (Age)
Analysis: Varying the number of catch samples collected						
Blue Mackerel	65 (65)	-	26 (26)	-	21 (21)	-
Jack Mackerel	94 (92)	-	31 (31)	-	24 (24)	-
Redbait	47 (43)	-	-	-	24 (24)	-
Analysis: Varying the number of fish per sample and number of catch samples collected						
Blue Mackerel	64 (65)	29 (5)	24 (26)	25 (5)	21 (21)	25 (5)
Jack Mackerel	94 (77)	38 (5)	30 (29)	40 (5)	24 (21)	48 (5)
Redbait	46 (36)	38 (5)	-	-	24 (16)	45 (5)

6.3 Results

Results show that as the number of catch samples taken was increased, the uncertainty around the estimates of the mean length and mean age of the sample populations were reduced (Figure 6-1). Mean lengths and mean ages varied among species, sub-area and fishing season. The total number of catch samples in each dataset reflected the level of fishing effort and the number of trawls in which each species was present in the catch (Table 6-1; Figure 6-1).

Figure 6-1. Overall mean fork length (mm) and mean age (years) of SPF species from randomly generated replicates of *n* catch samples by sub-area/fishing season. A & D: Blue Mackerel, B & E: Jack Mackerel; C & F: Redbait. Colours designate sub-area/fishing season: yellow: south of Kangaroo Island (2016/17 fishing season); fuchsia: southern NSW (2015/16 fishing season); teal: southern NSW (2017/18 fishing season). Grey bars: 95% CI of overall mean fork length or age.



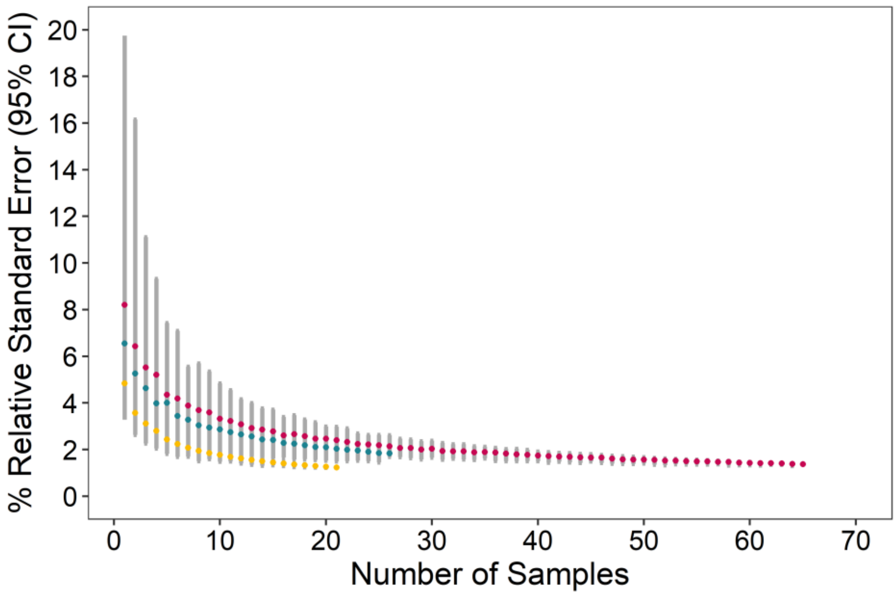
6.3.1 Blue Mackerel

6.3.1.1 Length

Varying the number (n) of catch samples

Increasing the number of catch samples used to estimate the mean length of Blue Mackerel catches reduced the relative standard errors (%) in all three datasets (Figure 6-2). Minimal improvement in precision was achieved by taking more than 30 catch samples.

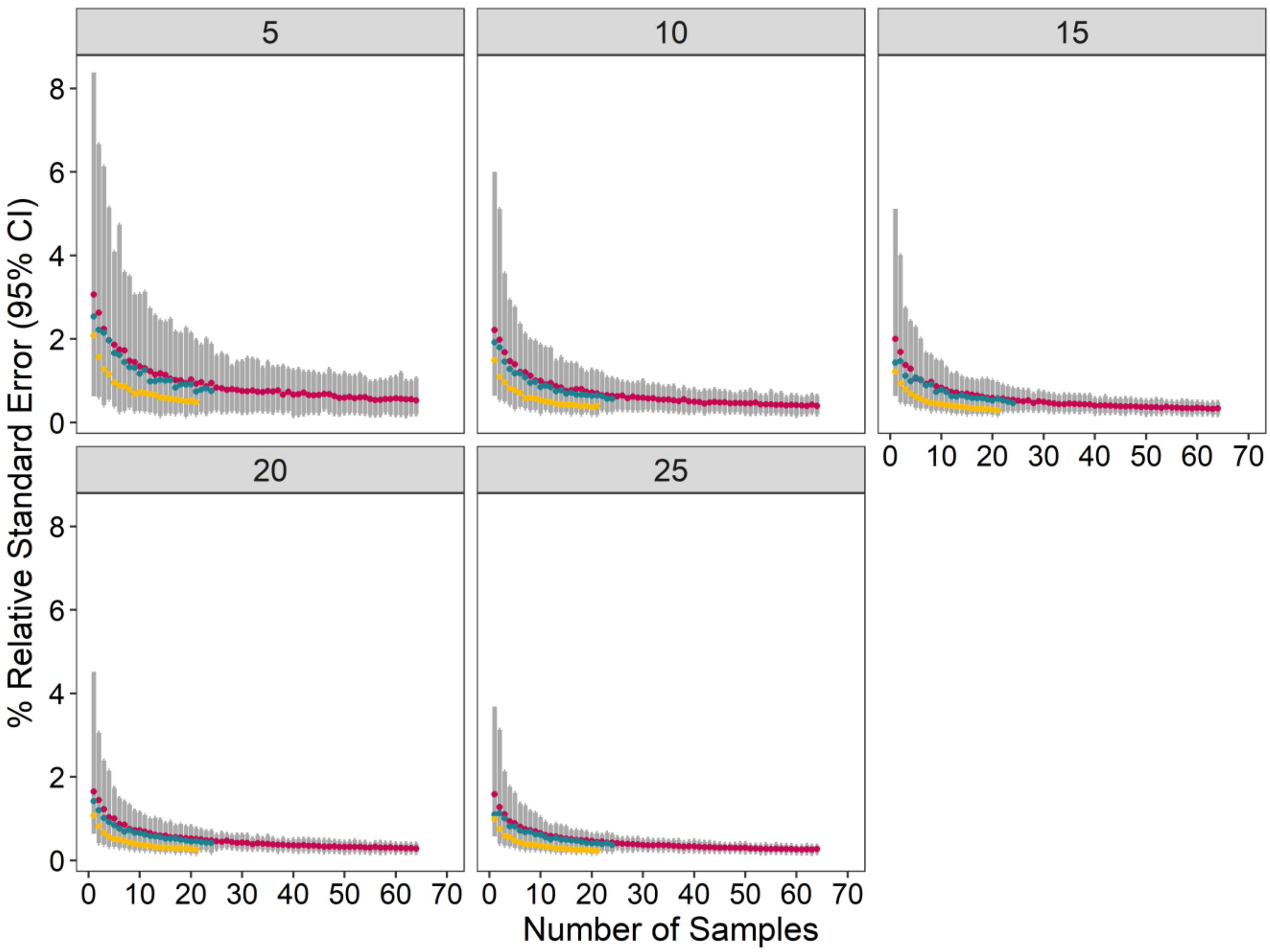
Figure 6-2. Overall mean relative standard error (%; RSE) of the estimates of mean fork length of Blue Mackerel obtained by systematically increasing the number of catch samples taken (100 replicates per *n* catch samples randomly selected from data pooled by sub-area and fishing season). Sub-area/fishing season: yellow: south of Kangaroo Island (2016/17 fishing season); fuchsia: southern NSW (2015/16 fishing season); teal: southern NSW (2017/18 fishing season). Grey bars: 95% CI of overall mean RSE.



Varying the number (n) *of catch samples and number of fish measured per sample* (m)

As the number of catch samples and fish measured were increased, the relative standard errors (%) estimates of mean length of Blue Mackerel catches decreased for all three datasets (Figure 6-3). Uncertainty in the estimates of mean length reduced as the number of fish increased, with limited improvement in precision after about 20 fish. The number of catch samples taken had a greater influence on uncertainty than the number of fish measured. Little improvement in precision was achieved by taking more than 30 catch samples (Figure 6-3).

Figure 6-3. Overall mean relative standard error (%; RSE) of the estimates of mean fork length of Blue Mackerel obtained by systematically increasing the number of fish in a sample and the number of catch samples collected (100 replicates per *n* catch sample–*m* fish combination randomly selected from data pooled by region and fishing season). Numbers above each plot are *m* fish per sample when varying *n* catch samples. Sub-area/fishing season: yellow: south of Kangaroo Island (2016/17 fishing season); fuchsia: southern NSW (2015/16 fishing season); teal: southern NSW (2017/18 fishing season). Grey bars: 95% CI of overall mean RSE.

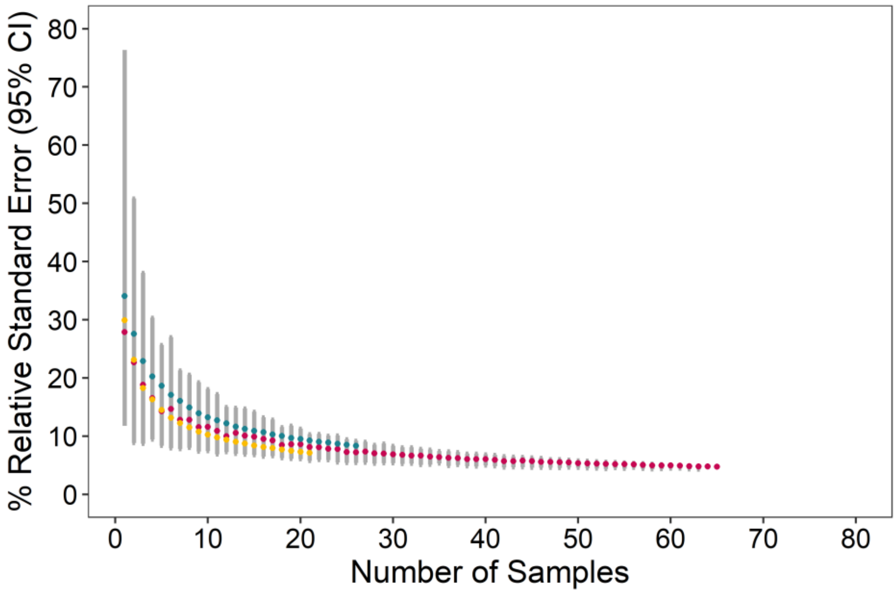


6.3.1.2 Age

Varying the number (n) of catch samples

Increasing the number of catch samples used to estimate the mean age of Blue Mackerel decreased the relative standard errors (%) in all three datasets (Figure 6-4). Minimal improvement in precision was achieved by taking more than 30 catch samples.

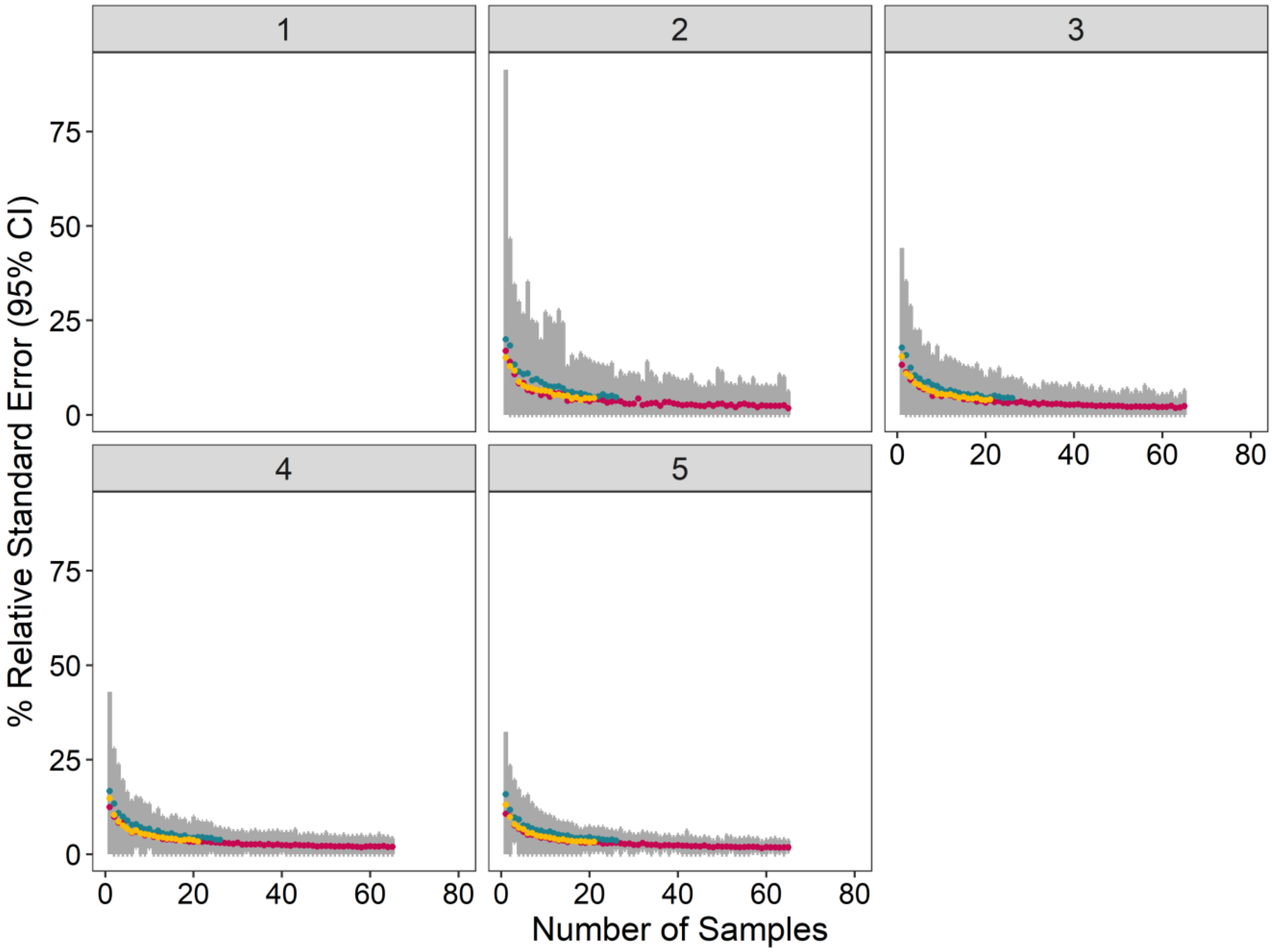
Figure 6-4. Overall mean relative standard error (%; RSE) of the estimates of mean age of Blue Mackerel obtained by systematically increasing the number of catch samples taken (100 replicates per *n* catch samples randomly selected from data pooled by sub-area and fishing season). Sub-area/fishing season: yellow: south of Kangaroo Island (2016/17 fishing season); fuchsia: southern NSW (2015/16 fishing season); teal: southern NSW (2017/18 fishing season). Grey bars: 95% CI of overall mean RSE.



Varying the number (n) of catch samples and number of otoliths read (m)

As the number of catch samples and otoliths read were increased, the relative standard errors (%) of the estimates of mean age of Blue Mackerel decreased for all three datasets (Figure 6-5). Uncertainty in the estimate of mean age reduced as the number of otoliths read was increased, up to the maximum m of 5 otoliths. The number of catch samples taken had a greater influence on uncertainty than did the number of otoliths read. Little improvement in precision was achieved by taking more than 30 catch samples (Figure 6-5).

Figure 6-5. Overall mean relative standard error (%; RSE) of the estimates of mean age of Blue Mackerel obtained by systematically increasing the number of fish in a sample and the number of catch samples collected (100 replicates per *n* catch sample–*m* fish combination randomly selected from data pooled by region and fishing season). Numbers above each plot are *m* fish per sample when varying *n* catch samples. Sub-area/fishing season: yellow: south of Kangaroo Island (2016/17 fishing season); fuchsia: southern NSW (2015/16 fishing season); teal: southern NSW (2017/18 fishing season). Grey bars: 95% CI of overall mean RSE.



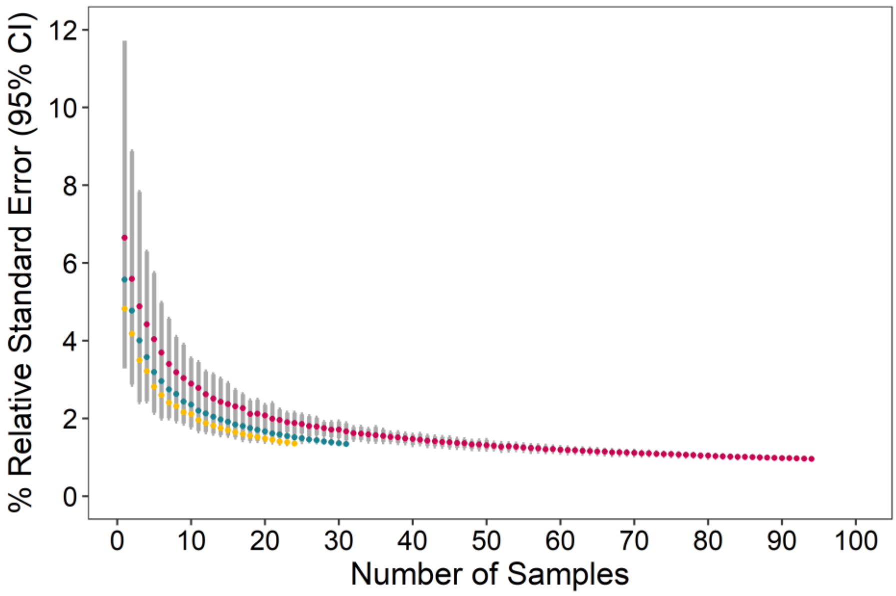
6.3.2 Jack Mackerel

6.3.2.1 Length

Varying the number (n) of catch samples

Increasing the number of catch samples used to estimate the mean length of Jack Mackerel catches reduced the relative standard errors (%) in all three datasets (Figure 6-6). Minimal improvement in precision was achieved by taking more than 30 catch samples.

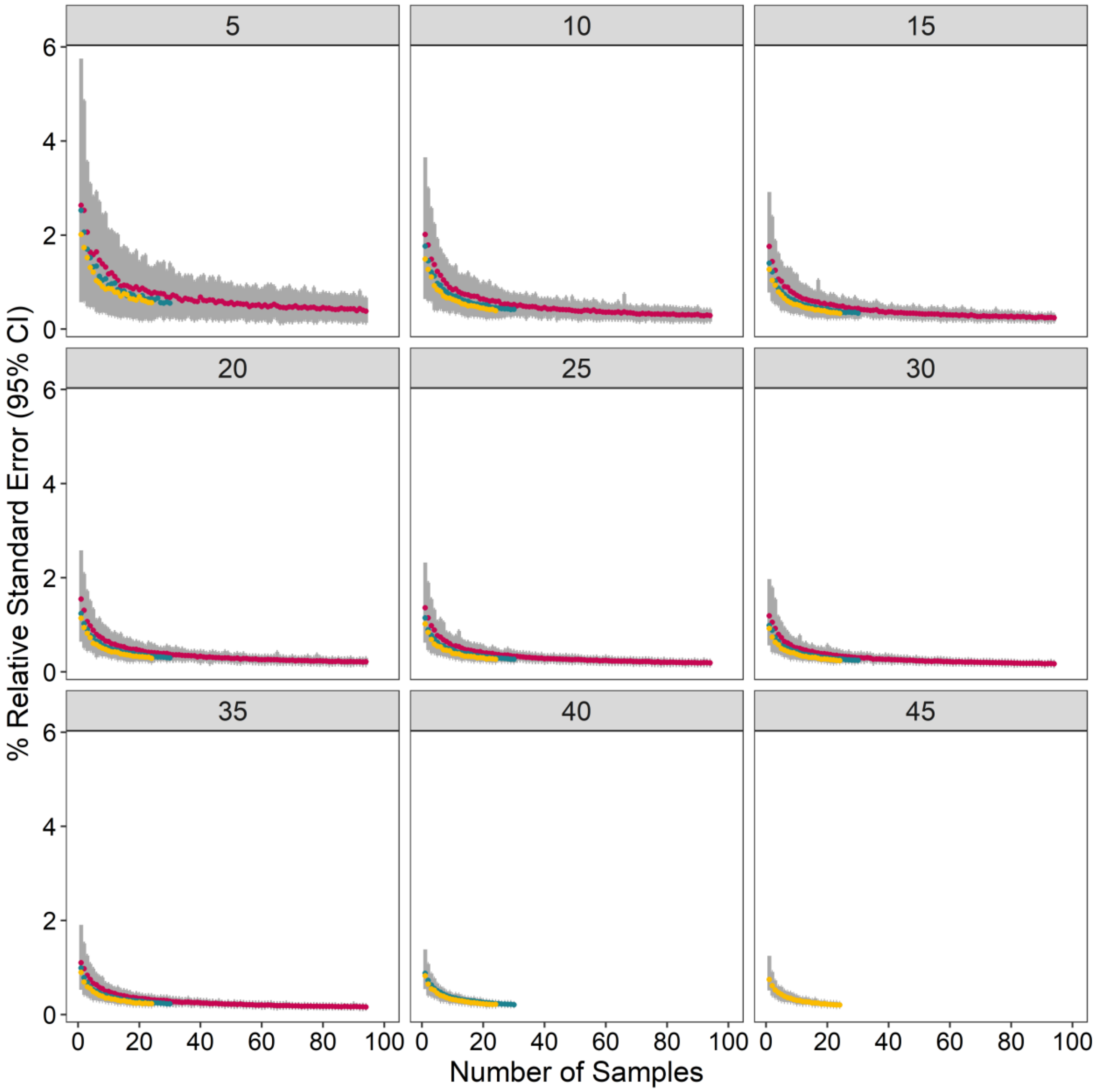
Figure 6-6. Overall mean relative standard error (%; RSE) of the estimates of mean fork length of Jack Mackerel obtained by systematically increasing the number of catch samples taken (100 replicates per *n* catch samples randomly selected from data pooled by sub-area and fishing season). Sub-area/fishing season: yellow: south of Kangaroo Island (2016/17 fishing season); fuchsia: southern NSW (2015/16 fishing season); teal: southern NSW (2017/18 fishing season). Grey bars: 95% CI of overall mean RSE.



Varying the number (n) of catch samples and number of fish measured per sample (m)

As the number of catch samples and fish measured were increased, the relative standard errors (%) estimates of mean length of Jack Mackerel catches decreased for all three datasets (Figure 6-7). Uncertainty in the estimates of mean length reduced as the number of fish increased, with limited improvement in precision after about 20 fish. The number of catch samples taken had a greater influence on uncertainty than the number of fish measured. Little improvement in precision was achieved by taking more than 30 catch samples (Figure 6-7).

Figure 6-7. Overall mean relative standard error (%; RSE) of the estimates of mean fork length of Jack Mackerel obtained by systematically increasing the number of fish in a sample and the number of catch samples collected (100 replicates per *n* catch sample–*m* fish combination randomly selected from data pooled by region and fishing season). Numbers above each plot are *m* fish per sample when varying *n* catch samples. Sub-area/fishing season: yellow: south of Kangaroo Island (2016/17 fishing season); fuchsia: southern NSW (2015/16 fishing season); teal: southern NSW (2017/18 fishing season). Grey bars: 95% CI of overall mean RSE.

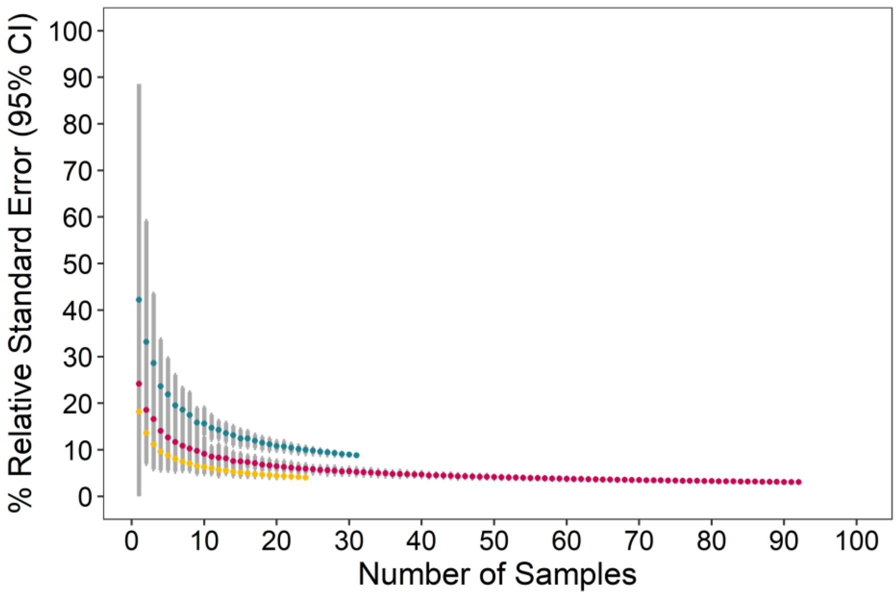


6.3.2.2 Age

Varying the number (n) of catch samples

Increasing the number of catch samples used to estimate mean age of Jack Mackerel decreased relative standard errors (%) in all three datasets (Figure 6-8). Minimal improvement in precision was achieved by taking more than 30 catch samples.

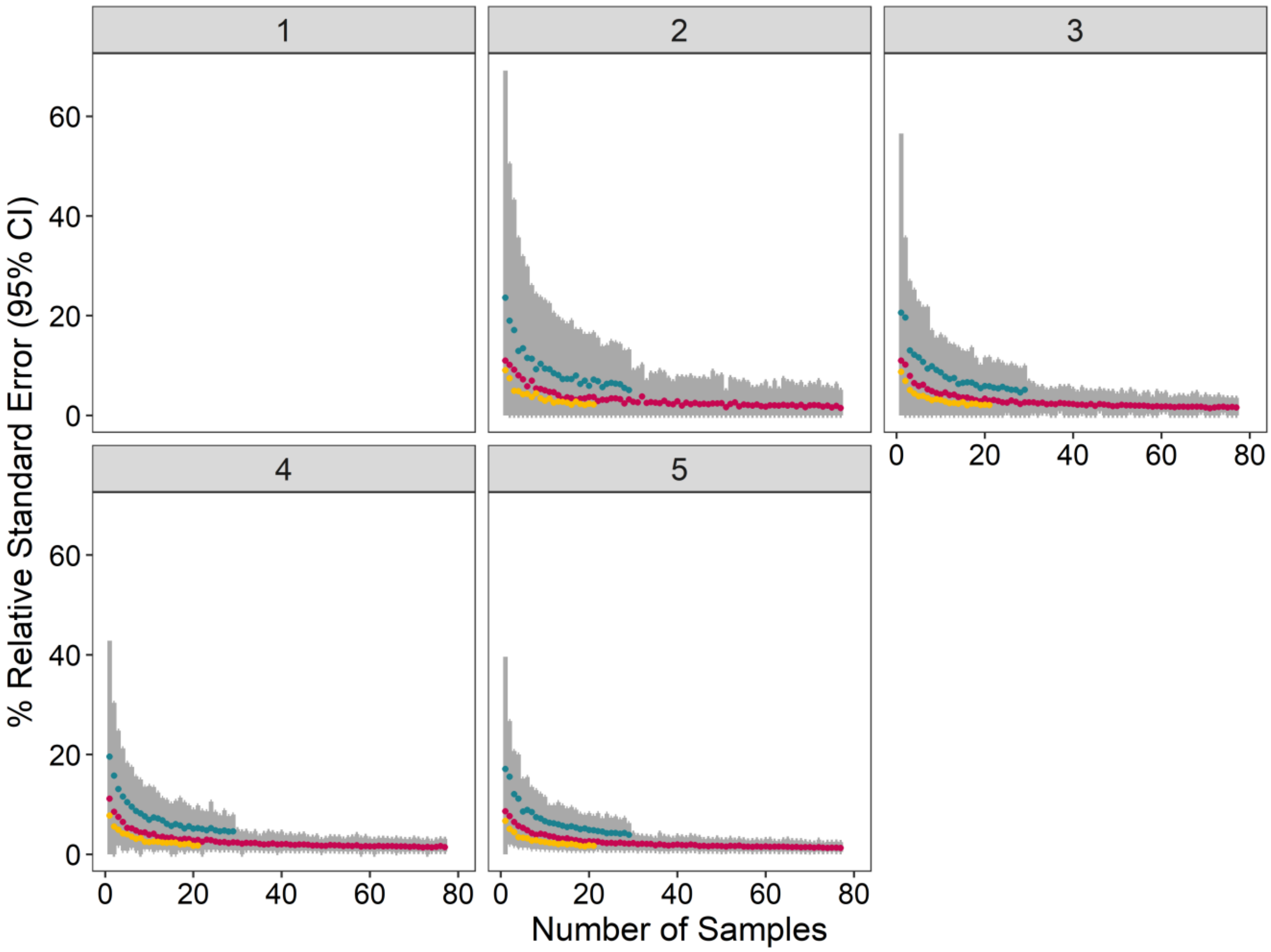
Figure 6-8. Overall mean relative standard error (%; RSE) of the estimates of mean age of Jack Mackerel obtained by systematically increasing the number of catch samples taken (100 replicates per *n* catch samples randomly selected from data pooled by sub-area and fishing season). Sub-area/fishing season: yellow: south of Kangaroo Island (2016/17 fishing season); fuchsia: southern NSW (2015/16 fishing season); teal: southern NSW (2017/18 fishing season). Grey bars: 95% CI of overall mean RSE.



Varying the number (n) *of catch samples and number of otoliths read* (m)

As the number of catch samples and otoliths read were increased, the relative standard errors (%) of the estimates of mean age of Jack Mackerel decreased for all three datasets (Figure 6-9). Uncertainty in the estimate of mean age reduced as the number of otoliths read was increased, up to the maximum m of 5 otoliths. The number of catch samples taken had a greater influence on uncertainty than did the number of otoliths read. Little improvement in precision was achieved by taking more than 30 catch samples (Figure 6-9).

Figure 6-9. Overall mean relative standard error (%; RSE) of the estimates of mean age of Jack Mackerel obtained by systematically increasing the number of fish in a sample and the number of catch samples collected (100 replicates per *n* catch sample–*m* fish combination randomly selected from data pooled by region and fishing season). Numbers above each plot are *m* fish per sample when varying *n* catch samples. Sub-area/fishing season: yellow: south of Kangaroo Island (2016/17 fishing season); fuchsia: southern NSW (2015/16 fishing season); teal: southern NSW (2017/18 fishing season). Grey bars: 95% CI of overall mean RSE.



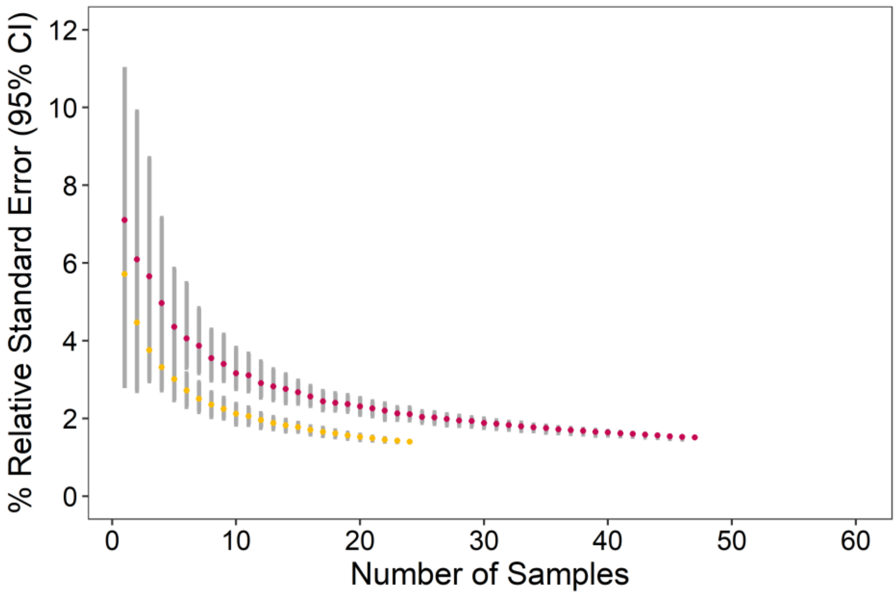
6.3.3 Redbait

6.3.3.1 Length

Varying the number (n) of catch samples

Increasing the number of catch samples used to estimate the mean length of Redbait catches reduced the relative standard errors (%) in both datasets (Figure 6-10). Minimal improvement in precision was achieved by taking more than 30 catch samples.

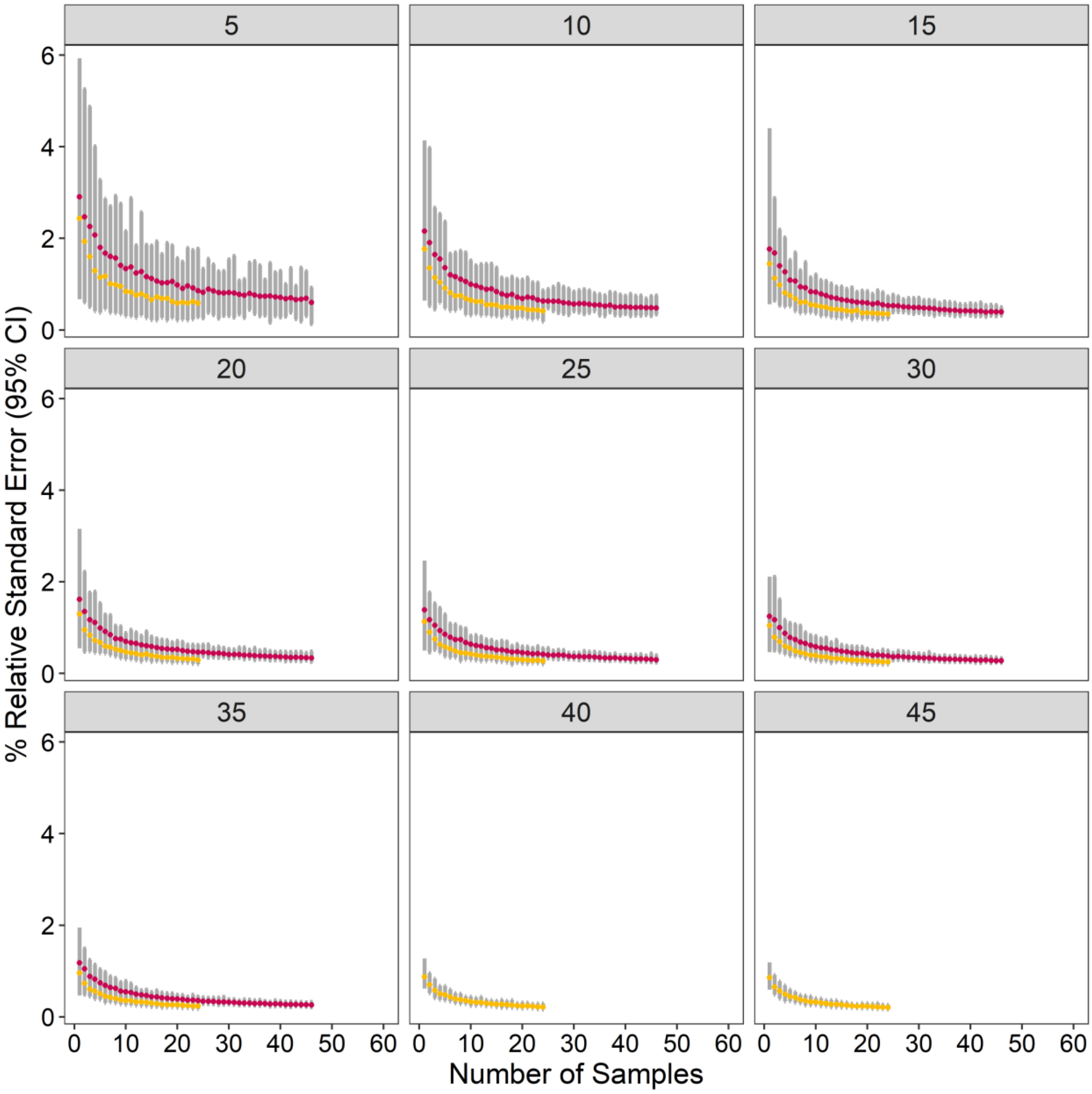
Figure 6-10. Overall mean relative standard error (%; RSE) of the estimates of mean fork length of Redbait obtained by systematically increasing the number of catch samples taken (100 replicates per *n* catch samples randomly selected from data pooled by sub-area and fishing season). Sub-area/fishing season: yellow: south of Kangaroo Island (2016/17 fishing season); fuchsia: southern NSW (2015/16 fishing season). Grey bars: 95% CI of overall mean RSE.



Varying the number (n) of catch samples and number of fish measured per sample (m)

As the number of catch samples and fish measured were increased, the relative standard errors (%) estimates of mean length of Redbait catches decreased for both datasets (Figure 6-11). Uncertainty in the estimates of mean length reduced as the number of fish increased, with limited improvement in precision after about 20 fish. The number of catch samples taken had a greater influence on uncertainty than the number of fish measured. Little improvement in precision was achieved by taking more than 30 catch samples (Figure 6-11).

Figure 6-11. Overall mean relative standard error (%; RSE) of the estimates of mean fork length of Redbait obtained by systematically increasing the number of fish in a sample and the number of catch samples collected (100 replicates per *n* catch sample–*m* fish combination randomly selected from data pooled by region and fishing season). Numbers above each plot are *m* fish per sample when varying *n* catch samples. Sub-area/fishing season: yellow: south of Kangaroo Island (2016/17 fishing season); fuchsia: southern NSW (2015/16 fishing season). Grey bars: 95% CI of overall mean RSE.

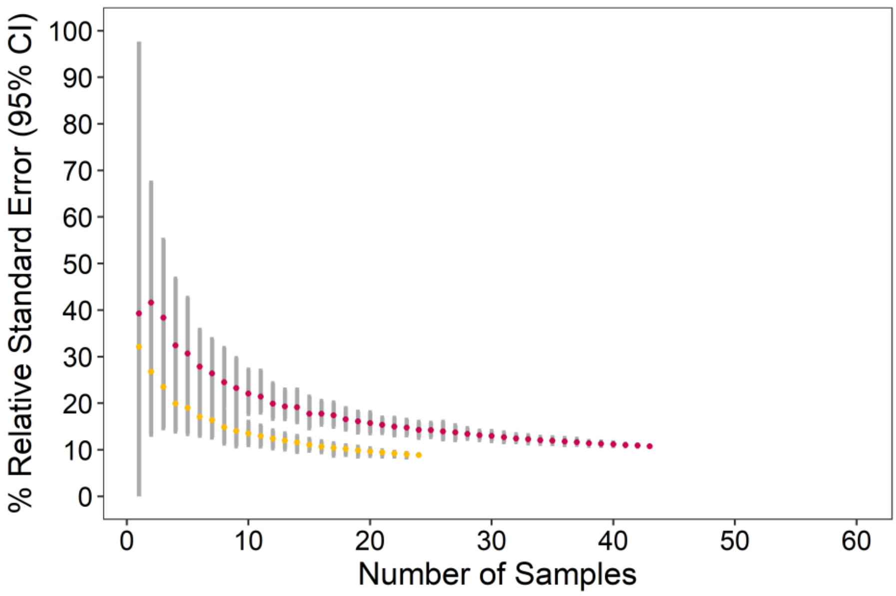


6.3.3.2 Age

Varying the number (n) of catch samples

Increasing the number of catch samples used to estimate the mean age of Redbait decreased the relative standard errors (%) in all three datasets (Figure 6-12). Minimal improvement in precision was achieved by taking more than 30 catch samples.

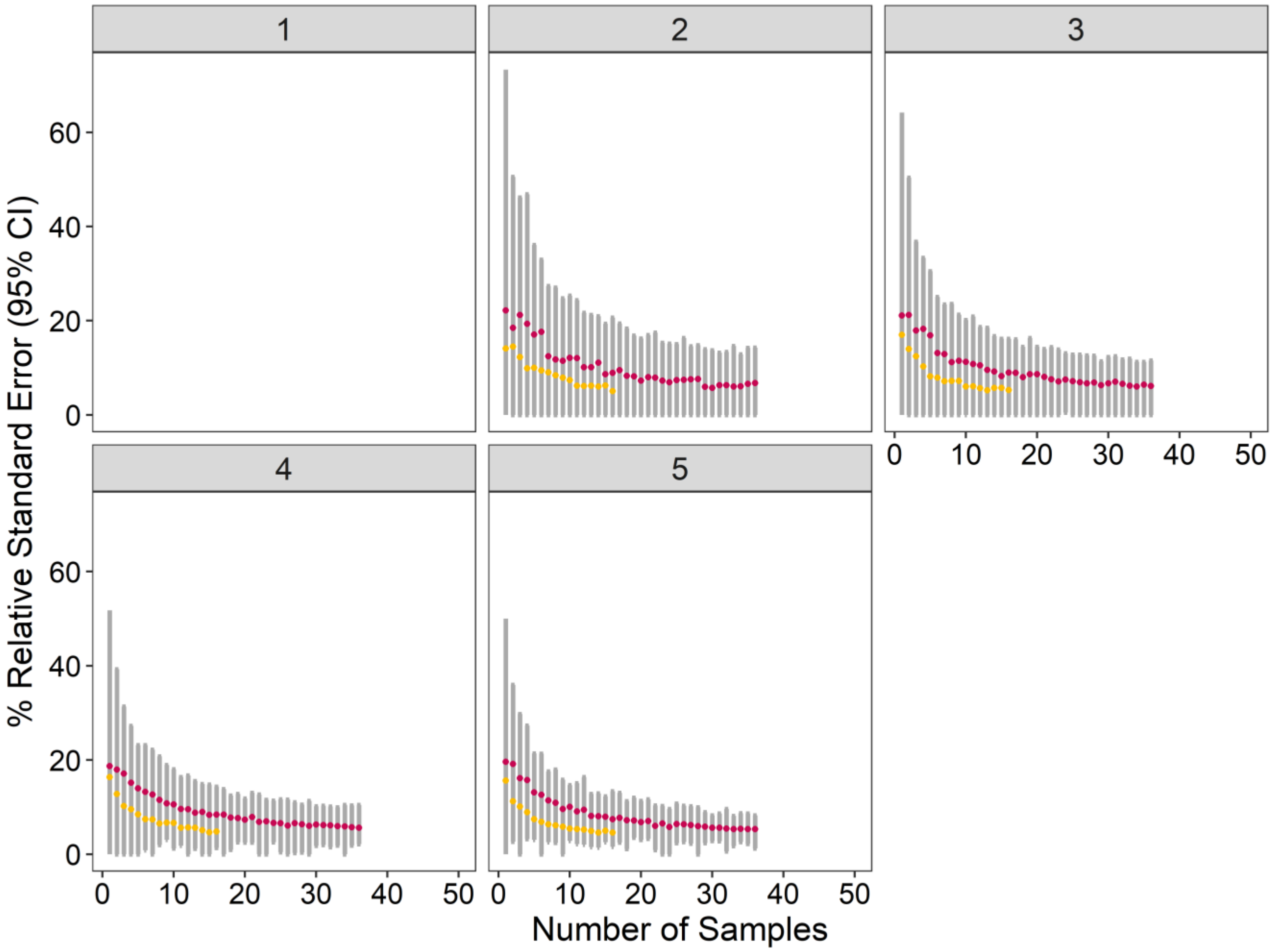
Figure 6-12. Overall mean relative standard error (%; RSE) of the estimates of mean age of Redbait obtained by systematically increasing the number of catch samples taken (100 replicates per *n* catch samples randomly selected from data pooled by sub-area and fishing season). Sub-area/fishing season: yellow: south of Kangaroo Island (2016/17 fishing season); fuchsia: southern NSW (2015/16 fishing season). Grey bars: 95% CI of overall mean RSE.



Varying the number (n) of catch samples and number of otoliths read (m)

As the number of catch samples and otoliths read were increased the relative standard errors (%) of the estimates of mean age of Redbait decreased for both datasets (Figure 6-13). Uncertainty in the estimate of mean age reduced as the number of otoliths read was increased, up to the maximum m of 5 otoliths. The number of catch samples taken had a greater influence on uncertainty than did the number of otoliths read. Little improvement in precision was achieved by taking more than 30 catch samples (Figure 6-13).

Figure 6-13. Overall mean relative standard error (%; RSE) of the estimates of mean age of Redbait obtained by systematically increasing the number of fish in a sample and the number of catch samples collected (100 replicates per *n* catch sample–*m* fish combination randomly selected from data pooled by region and fishing season). Numbers above each plot are *m* fish per sample when varying *n* catch samples. Sub-area/fishing season: yellow: south of Kangaroo Island (2016/17 fishing season); fuchsia: southern NSW (2015/16 fishing season). Grey bars: 95% CI of overall mean RSE.



6.4 Cost of Catch Sampling and Processing

The cost per fish of obtaining length-weight data was AU$11.12 and the cost per fish for obtaining age data from otoliths was AU$41.43 per fish. Processing costs for estimating the mean length of one species in a sub-area during the fishing season based on 100 catch samples with 50 fish measured per sample would be ~$50,000 (Figure 6-14). The cost of estimating the mean age of one species in a sub-area based on 100 samples and 10 otoliths read per sample would be approximately $40,000 (Figure 6-15).

Table 6-2. Cost per fish of processing catch samples for length-weight and otolith ageing as of November 2018.

Catch Sample Processing	Cost per fish	Services/costs included per fish
Length-Weight	$11.12	• Weight & length • Reproductive biology: sex, stage gonads, weigh gonads • Otolith removal • Data entry • Freight from Ulladulla to Adelaide • Laboratory consumables
Ageing	$41.43	• Weigh otoliths, • embed in resin & thin section (batch processing) • cut with low speed saw • Mount on slide, polish & clean • Calibrating otolith agers with reference collection • 2 separate reads of otolith ages & a consensus read • Otolith processing consumables

Figure 6-14. Processing cost to obtain length-weight data for *n* catch samples and measuring *m* fish. Black line is the total processing cost for length-weight data based on $11.12 per fish. Reference mark is provided at 30 samples (dashed line).

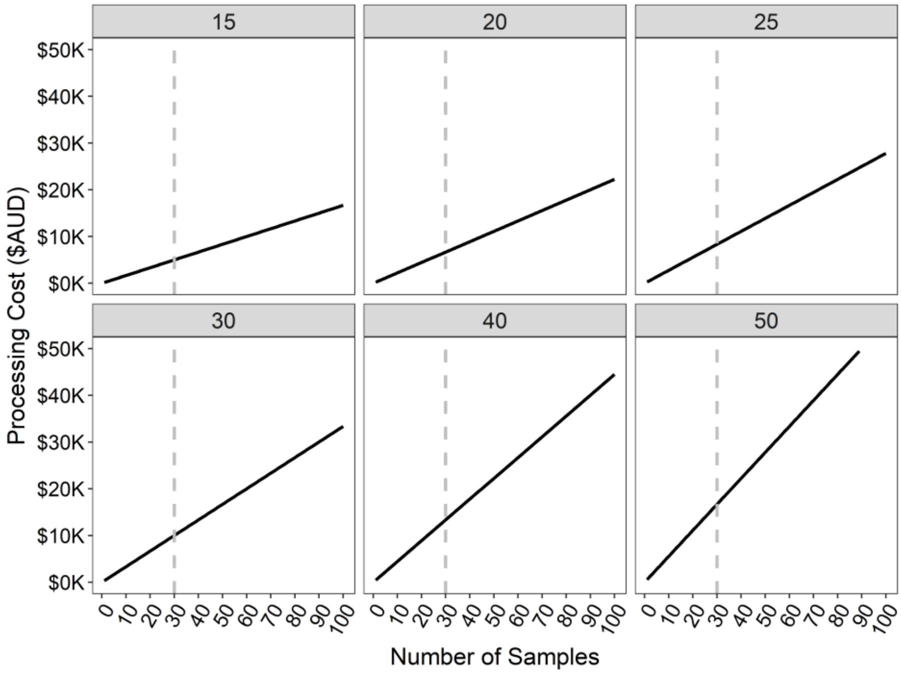
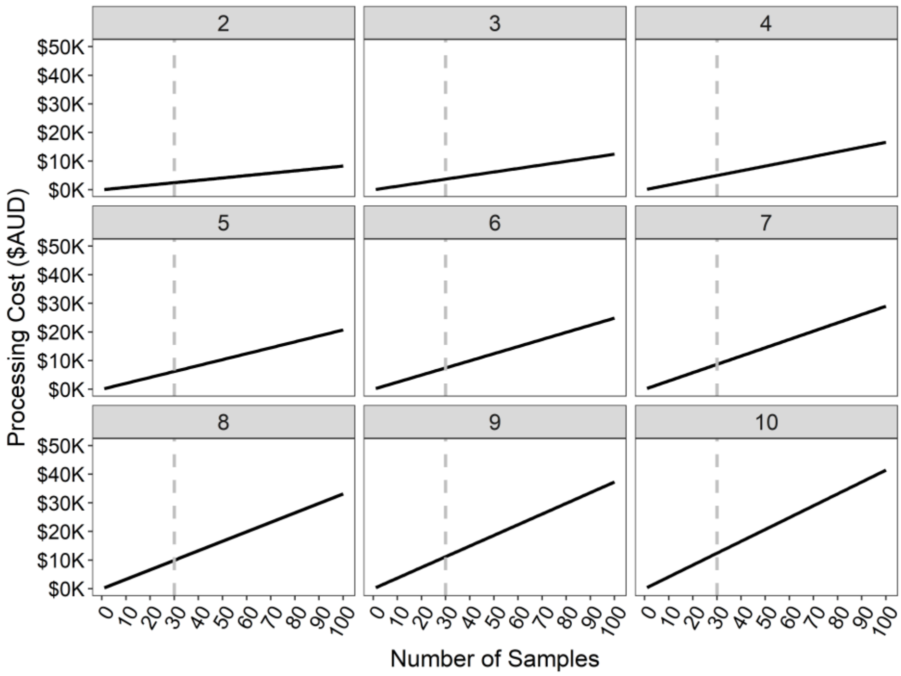


Figure 6-15. Processing cost to obtain otolith-based age data for *n* catch samples and reading *m* otoliths. Black line is the total processing cost for otolith ageing based on $41.43 per fish. Reference mark is provided at 30 samples (dashed line).



6.5 Summary

For all three species, minimal improvement in the precision of estimates of mean length were obtained by taking more than 30 samples or measuring more than 20 fish. Similarly, the precision of the estimates of mean age was not improved markedly by reading more than 5 otoliths from each sample. The total cost of estimating the mean size and mean age of a species in a sub-zone, based on 30 samples, 20 fish measured and five otoliths read from each sample, would have been approximately $12,900 (Table 6-3; costs calculated in November 2018).

Table 6-3. Recommended total number of catch samples to be collected and the number of fish measured and otoliths read per sample to optimise the cost of catch sampling in the SPF.

Optimised Total Cost:	
30 catch samples	
20 fish (length)	$6,700
5 fish (age)	$6,200
Per species	$12,900

7 General Summary and Conclusions

The most recent classifications of the stock status of Jack Mackerel East and West, Blue Mackerel East and West, and Australian Sardine East concluded that the biological stocks are sustainable (Stewardson et al. 2018). Jack Mackerel, Blue Mackerel and Redbait in both sub-areas, and Australian Sardine in the Sardine Sub-area were classified as 'not over-fished' and 'not subject to over fishing' by Patterson et al. (2018). The evidence presented in this report confirms that recent catches of Blue Mackerel, Jack Mackerel and Redbait in the East and West sub-areas and Australian Sardine in the Sardine sub-area have been sustainable.

Initial DEPM surveys have now been conducted for all SPF stocks. However, surveys conducted in the West sub-area have only covered a limited portion of that region. As a result, the distribution and abundance of SPF species in the West sub-area in the region west of Kangaroo Island is poorly understood. Despite the limitations of some estimates of spawning biomass, the estimates now available could be used to inform the establishment of preliminary target (e.g. B_{50}) and limit reference points (e.g. B_{20}) for each stock in the SPF. These reference points could be revised when new information becomes available.

Fishery-dependent data have been monitored to evaluate the potential for changes in stock status between DEPM surveys. The spatial and temporal distribution of catches have varied over time, driven mainly by changes in the fishing operations. Differences observed in age and length structures among years and sub-areas, have been difficult to interpret due to these changes in the fishery. Ideally, performance indicators (e.g. mean age) and reference points would be developed for fishery-dependent data. However, until the fishery operation stabilises and time-series of data become available, this goal will be difficult to achieve.

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Appendix 1: Ageing SPF Species

Precision of Otolith Age Estimates

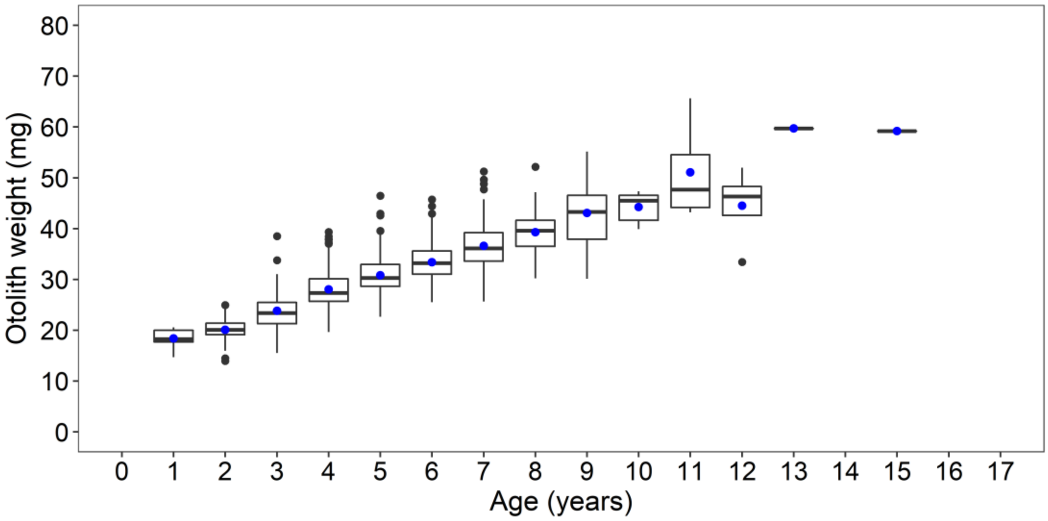
Otolith reference collections were used to calibrate ageing techniques prior to ageing Jack Mackerel and Redbait. The reference collections for Jack Mackerel and Redbait were developed by researchers at the Institute for Marine and Antarctic Studies, University of Tasmania. A known-age otolith reference collection for Blue Mackerel was not available, and a SARDI researcher experienced otolith ageing guided the process. Ages of Blue Mackerel were based on the ageing protocol for sectioned otoliths described by Marriott and Manning (2011) for Blue Mackerel in New Zealand and took into account ageing protocols from whole otoliths of Blue Mackerel in Australia (Ward and Rogers 2007, Stewart et al. 1999). A sub-set of Blue Mackerel otoliths (aged as described above) were used to calibrate the agers for this species.

After calibration with the reference collection or ageing sub-set for each species, the agers both read the otoliths once and scored each on a scale of readability from 1 (very good) to 5 (unreadable; readability scale from Marriott and Manning 2011). When the agers disagreed on an age, the otolith was re-aged; if a consensus could not be reached, the otolith was removed from the dataset. The agreed ages were used as the final dataset for any further age-based analyses. Age bias plots, average percent error (APE, Beamish and Fournier, 1981), and average coefficient of variation (ACV, Chang 1982) were used to examine the precision of repeated age estimates of the otoliths. These metrics were based on otoliths with readability scores of 1 to 4. Campana (2001) suggested that many ageing studies could be done with ACVs of <7.6% (= APE 5.5%), and an ACV of 5.0% could serve as a reference point for many fishes of moderate longevity and reading complexity. Small pelagic fish species are known have otoliths with complex increment structures—potentially due to the fishes' migratory behaviour—that can be challenging to age (e.g. Lyle et al. 2000, Stewart and Ferrell 2001, Ward and Rogers 2007, Neira et al. 2008, Marriott and Manning 2011). Therefore, ACVs nearing 7.6% were acceptable for ageing precision in this study. All analyses were done in the R programming environment (R Core Team, 2018); age bias plots and estimates of ACV and APE were produced using the 'FSA' package (Ogle 2016).

Jack Mackerel

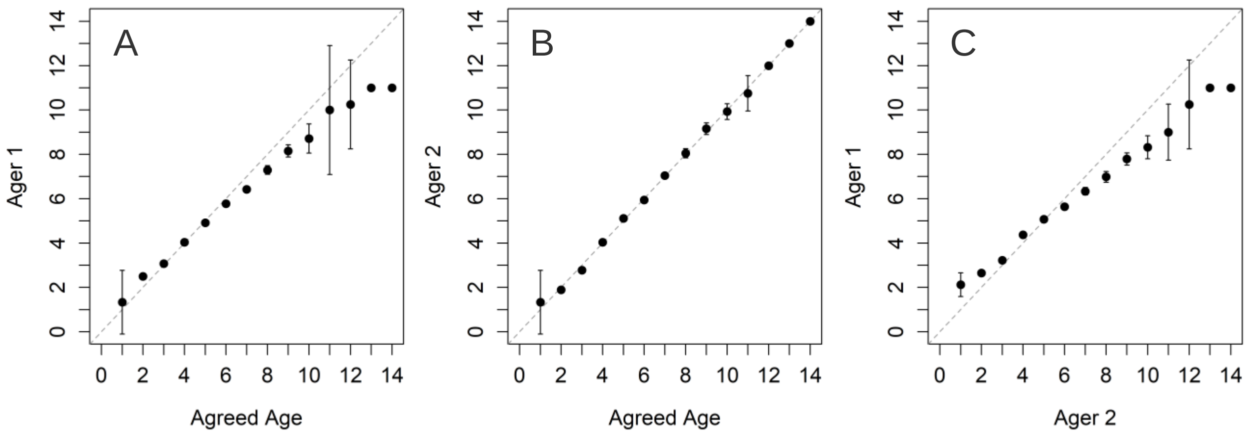
During the ageing process, fish were not separated by sub-area and a total of 1,142 Jack Mackerel otoliths were aged. As expected, when otolith weight was plotted by age, otolith weight increased as the fish grew older (Figure A-1). Ages of Jack Mackerel ranged from 1 to 15 years.

Figure A-1. Box-plot of otolith weight (mg) by age (years) of Jack Mackerel (n = 1,142) from catch samples collected in the SPF from 2014/15 to 2017/18. Blue: mean otolith weight by age.



Estimates of precision from the repeat readings indicated that Ager 2 (ACV: 4.9%) was more the more precise ager of Jack Mackerel otoliths (Figure A-2, Table A-1). Both agers achieved ACVs of ≤5.0% and APEs of 3.5% compared to the final agreed age (Table A-1). These ACV and APE values are within those recommended by Campana (2001).

Figure A-2. Age bias plots: mean estimated ages (95% CI) from Agers 1 (A) and 2 (B) to the Agreed ages of Jack Mackerel. A comparison between Ager 1 and 2 (C) shows ageing bias between the two Agers prior to the final read for the Agreed Age. Dashed line: 1:1 agreement line.



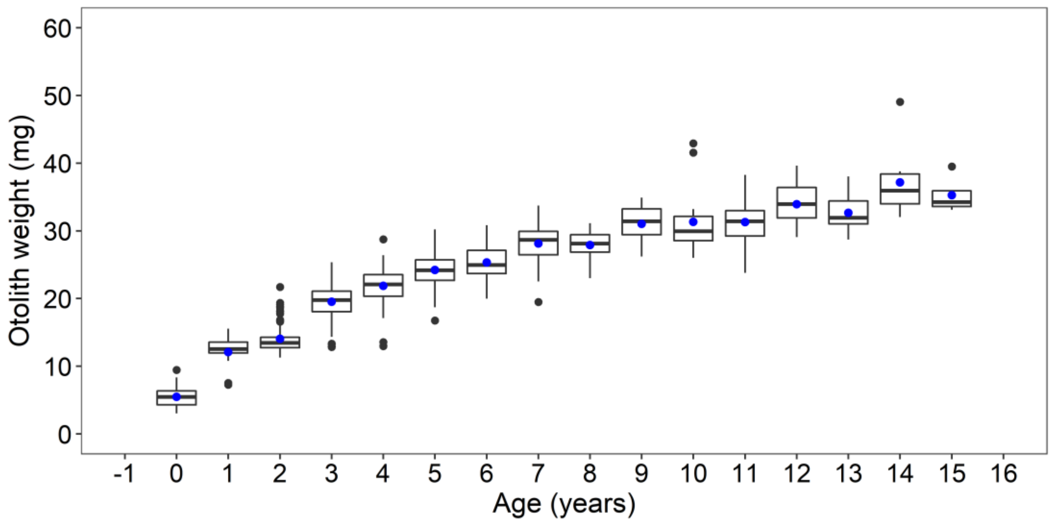
JACK MACKEREL (n = 818)	ACV (%)	APE (%)	% Agree
Ager 1 vs Ager 2	9.6	6.8	43.8
Ager 1 vs Agreed Age	5.0	3.5	68.3
Ager 2 vs Agreed Age	4.9	3.5	68.6

Table A-1. Precision of repeated age estimates of Jack Mackerel otoliths. Average coefficient of variation (ACV), average percent error (APE) and percent agreement on otoliths ages of Jack Mackerel for Ager 1 versus Ager 2 versus Agreed Age. Metrics were based on otoliths with readability scores of 1 to 4.

Redbait

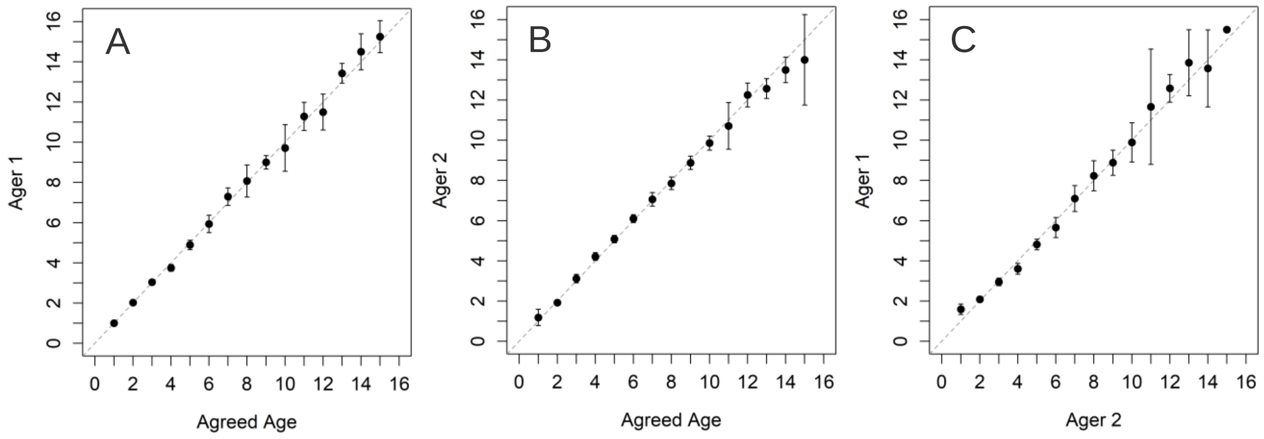
During the ageing process, fish were not separated by sub-area and a total of 506 Redbait otoliths were aged. As expected, when otolith weight was plotted by age, otolith weight increased as the fish grew older (Figure A-3). Ages of Rebait ranged from 0 to 15 years.

Figure A-3. Box-plot of otolith weight (mg) by age (years) of Redbait (n = 506) from catch samples collected in the SPF from 2014/15 to 2017/18. Blue: mean otolith weight by age.



Estimates of precision from the repeat readings indicated that Ager 2 (ACV: 5.2%) was more the more precise ager of Redbait otoliths (Figure A-4, Table A-2). Both agers achieved ACVs of ≤6.4% and APEs of ≤4.5% compared to the final agreed age (Table A-2). These ACV and APE values are within those recommended by Campana (2001).

Figure A-4. Age bias plots: mean estimated ages (95% CI) from Agers 1 (A) and 2 (B) to the Agreed ages of Redbait. A comparison between Ager 1 and 2 (C) shows ageing bias between the two Agers prior to the final read for the Agreed Age. Dashed line: 1:1 agreement line.



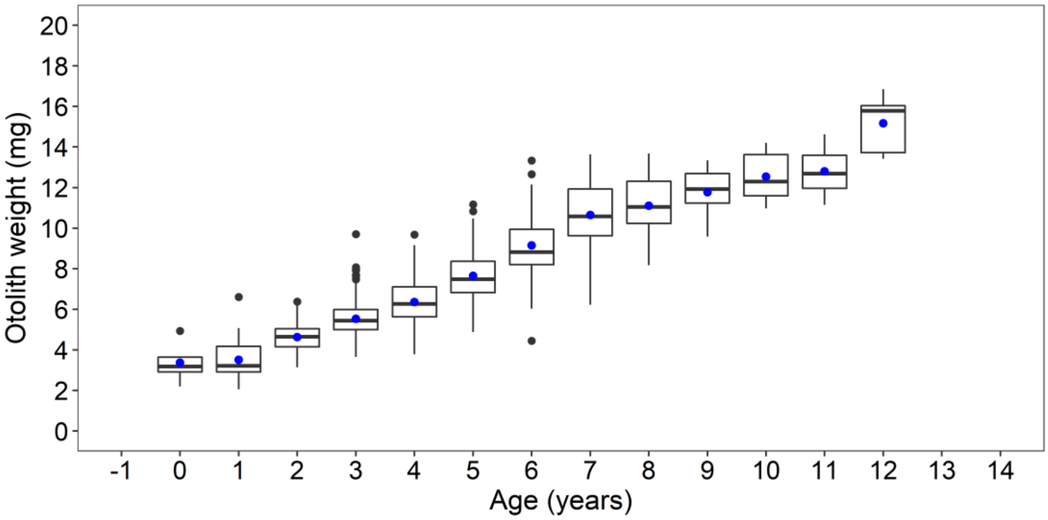
Rebait (n = 336)	ACV (%)	APE (%)	% Agree
Ager 1 vs Ager 2	11.3	8.0	51.3
Ager 1 vs Agreed Age	6.4	4.5	69.6
Ager 2 vs Agreed Age	5.2	3.6	76.7

Table A-2. Precision of repeated age estimates of Redbait otoliths. Average coefficient of variation (ACV), average percent error (APE) and percent agreement on otoliths ages of Redbait for Ager 1 versus Ager 2 versus Agreed Age. Metrics were based on otoliths with readability scores of 1 to 4.

Blue Mackerel

During the ageing process, fish were not separated by sub-area and a total of 1044 Blue Mackerel otoliths were aged. As expected, when otolith weight was plotted by age, otolith weight increased as the fish grew older (Figure A-5). Ages of Blue Mackerel ranged from 0 to 12 years.

Figure A-5. Box-plot of otolith weight (mg) by age (years) of Blue Mackerel (n = 1044) from catch samples collected in the SPF from 2014/15 to 2017/18. Blue: mean otolith weight by age.



The ages of Ager 3 were used as the 'agreed' ages for Blue Mackerel as Ager 3 was the most experienced with ageing Blue Mackerel otoliths. Estimates of precision between Agers 2 and 3 were 9.0% ACV and 6.4% APE (Figure A-6, Table A-3). These values are marginally higher than those recommended by Campana (2001) but within the range reported when ageing other small pelagic fishes (Ward and Rogers 2007).

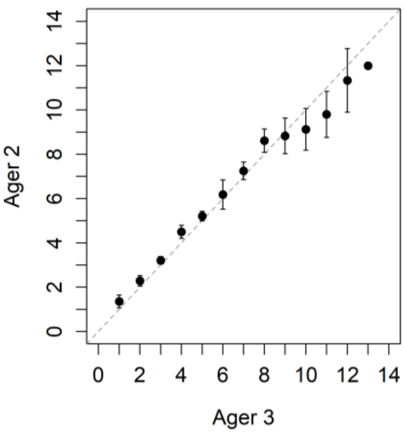


Figure A-6. Age bias plots: mean estimated ages (95% CI) between Ager 2 and Ager 3. Dashed line: 1:1 agreement line.

Blue Mackerel (n = 202)	ACV (%)	APE (%)	% Agree
Ager 2 vs Ager 3	9.0	6.4	50.5

Table A-3. Precision of repeated age estimates of Redbait otoliths. Average coefficient of variation (ACV), average percent error (APE) and percent agreement on otoliths ages of Redbait for Ager 1 versus Ager 2 versus Agreed Age. Metrics were based on otoliths with readability scores of 1 to 4.

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