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Commonwealth Small Pelagic Fishery: Fishery Assessment Report 2015

T.M. Ward and G.L. Grammer

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Commonwealth Small Pelagic Fishery: Fishery Assessment Report 2015

Report to the Australian Fisheries Management Authority

T. M. Ward and G. L. Grammer

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EXECUTIVE SUMMARY

This report presents fishery data and synthesises stock status information for key species in each sub-area (i.e. East and West) of the Commonwealth Small Pelagic Fishery (SPF). This report is required at Tiers 1 and 2 of the SPF Harvest Strategy 2008 (last revised April 2015).

The spawning biomass of Jack Mackerel off the east coast in 2014 was estimated to be 157,805 t (95% CI = 59,570–358,731), which is within the range of preliminary estimates (114,900–169,000t) obtained from surveys undertaken in 2002–2004. The total catch in 2014/15 was 317 t. During 2014/15, the modal size of Jack Mackerel East taken in mid-water trawls was below the mean size at 50% maturity. Recent low catches of Jack Mackerel East reflect low fishing effort rather than low abundance. Current catches of Jack Mackerel East are assessed as sustainable, as they were <1% of the estimated spawning biomass and well below the sustainable exploitation rate of 12% suggested for this species.

The Daily Egg Production Method (DEPM) has not been applied to Jack Mackerel West due to the current lack of data, and an empirical estimate of spawning biomass is not available for this stock. Annual catches of Jack Mackerel West have not exceeded 400 t since 1997/98. The total catch in 2014/15 was <1 t. Catches have mainly contained fish above the mean size at 50% maturity. Low catches of Jack Mackerel West appear to reflect low fishing effort rather than low abundance. Jack Mackerel West is likely to be sustainable, because catches are small compared to the large size of the sub-area. However, an estimate of spawning biomass is needed confirm this assessment, especially if effort/catches increase significantly.

The spawning biomass of Blue Mackerel East during 2014 was estimated to be ~83,300 t (95% CI = 35,100–165,000 t), which is higher than the preliminary estimate for 2004 of 23,009 t. The total catch in 2014/15 was 442 t. Catches have mainly contained fish at or above the mean size at 50% maturity. During 2014/15, the modal size of Blue Mackerel East from mid-water trawl catches was well above the mean size at 50% maturity. Recent low catches of Blue Mackerel East reflect reductions in fishing effort rather than a decline in abundance. Current catches of Blue Mackerel East are assessed as sustainable, as they have been <1% of the estimated spawning biomass for 2014, and well below the sustainable exploitation rate of 23% suggested for this stock.

The spawning biomass of Blue Mackerel West estimated during 2005 was 56,228 t. Total annual catches of Blue Mackerel West increased to ~2,200 t in both 2006/07 and 2008/09 and have decreased since then, with <1 t taken in 2014/15 t. Catches have mainly contained fish well above the mean size at 50% maturity. Low annual catches in recent years reflect low fishing effort rather than low abundance. Recent catches of Blue Mackerel West are assessed as sustainable, as they

have been <1% of the estimated spawning biomass for 2005, which is well below the sustainable exploitation rate of 23% suggested for this stock.

The spawning biomass of Redbait East was estimated to be ~70,000 t from surveys in 2005 and 2006. Total annual catches peaked at 7,446 t in 2003/04 and declined to 75 t in 2010/11. The total catch of Redbait East in 2014/15 was 2.1 t. Catches have mainly contained fish above the mean size at 50% maturity. During 2014/15, the modal size of Redbait East taken from mid-water trawl catches was well above the mean size at 50% maturity. Low annual catches in recent years appear to reflect low fishing effort rather than low abundance. Recent catches of Redbait East are assessed as sustainable, as they have been <1% of the estimated spawning biomass and well below the sustainable exploitation rate of 9% suggested for this stock. However, the existing estimate of spawning biomass for Redbait East is 10 years old and should be updated.

The DEPM has not been applied to Redbait West due to the current lack of data, and an empirical estimate of spawning biomass is not available for this stock. Total annual catches of Redbait West peaked at 3228 t in 2006/07 and progressively declined to 298 t in 2009/10; there have been no reported catches of Redbait West since 2009/10. Catches have mainly contained fish below the mean size at 50% maturity for the western stock. Recent low catches of Redbait West are due to low fishing effort rather than low abundance. Redbait West is likely sustainable, because no catches have been taken in recent years. An estimate of spawning biomass is needed confirm this assessment, especially if effort/catches increase significantly.

The spawning biomass of Australian Sardine East during the main spawning winter/spring spawning period in 2014 was estimated to be ~49,600 t (95% CI = 24,200–213,300 t). Total annual catches of Australian Sardine East peaked at 4,619 t in 2007/08 and declined to 893 t in 2014/15. Catches have mainly contained fish at or above the mean size at 50% maturity. During 2014/15, the modal size of Australian Sardine East was at the mean size of 50% maturity. Current catches of Australian Sardine East are assessed as sustainable, because since 2012/13 they have been <7% of the 2014 spawning biomass estimate and well below the sustainable exploitation rate of 33% suggested for this species.

All SPF species are assessed as sustainable given the recent low levels of fishing effort/catches. However, estimates of spawning biomass are not available for Jack Mackerel West and Redbait West, and those for Blue Mackerel West and Redbait East are ≥10 years old. DEPM surveys of these species should be undertaken if fishing effort increases.

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). 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*) and summarises data available for Yellowtail Scad (*Trachurus novaezelandiae*; a permitted by-product species). The assessment is based on commercial catch and effort data up to 30 April 2015 and available biological information (size and age structures, reproduction, maturity). Biomass estimates from fishery-independent surveys and outputs from several Management Strategy Evaluations (MSEs) are also considered. This report satisfies the requirements of the SPF Harvest Strategy for assessment of stocks at Tiers 1 and 2 (AFMA 2008, revised in 2015).

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 (i.e. East and West) by a line through longitude 146°30'E (Figure 1.1, AFMA 2009).

The three main target species of the SPF are Jack Mackerel, Blue Mackerel and Redbait. Australian Sardine is a target species in the 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. Yellowtail Scad is one of several permitted by-product species.

The SPF has changed dramatically since the commencement of large scale fishing operations in the mid-1980s. Between the late 1980s and prior to the implementation of the SPF Management Plan 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 fish 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 at which time the SPF was split into East and West sub-areas and, under the SPF Harvest Strategy (AFMA 2008), species and sub-area specific TACs were established. A more 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.

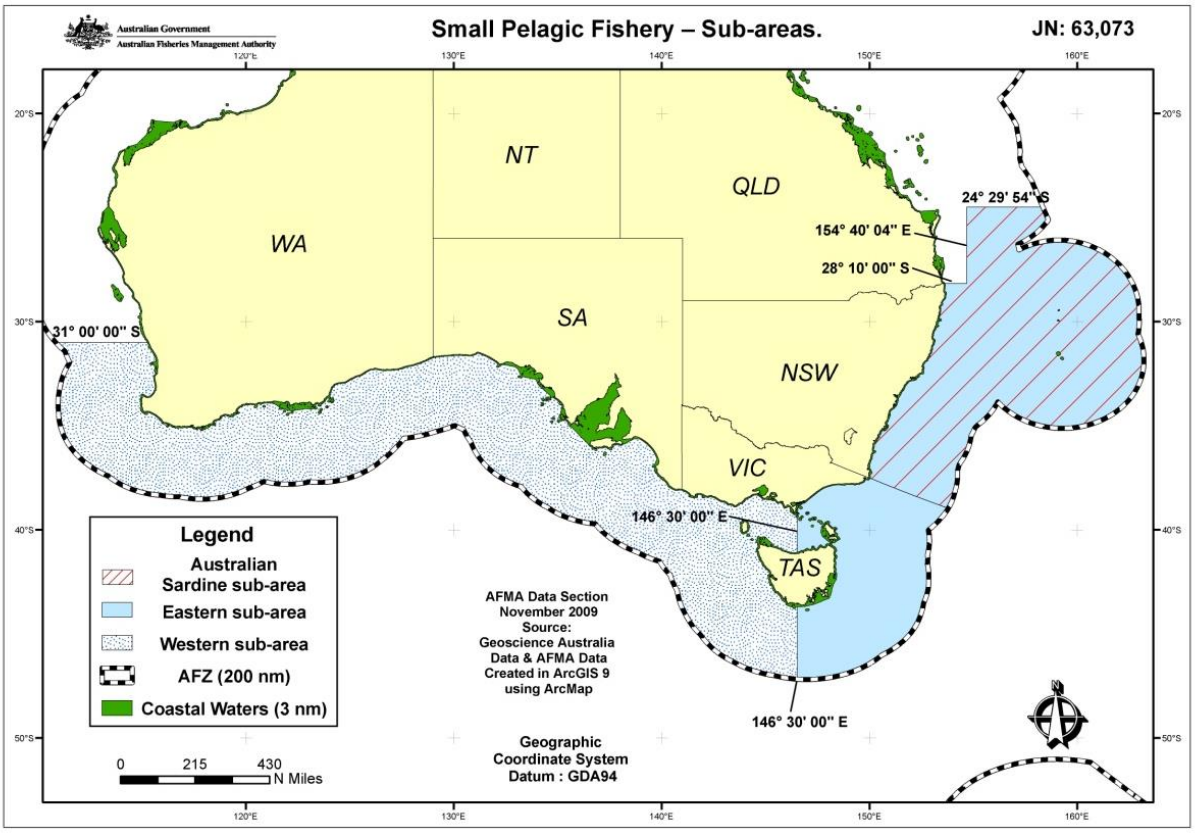

Figure 1.1 Management sub-areas of the Small Pelagic Fishery.

1.3.1 Harvest Strategy

In 2008, AFMA established a harvest strategy (HS) for the SPF; it was last updated in 2015 (AFMA 2008, reviewed in April 2015). 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.

Tier 1: 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 to 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 years. Blue Mackerel and Australian Sardine can remain at Tier 2 for up to 5 years.

Tier 3: Maximum RBCs for Tier 3 species in each sub-area will be set based on available information including biology, historical catch and the spatial area of a zone but may not exceed 500 t.

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

(Neira and Lyle 2011), Jack Mackerel East (Neira 2011, Ward et al. 2015a) and Yellowtail Scad East (Neira 2009).

In 2014, two DEPM surveys were completed for three quota species in the East sub-area. In January 2014, the first dedicated application of the DEPM to Jack Mackerel was undertaken (Ward et al. 2015a, 2016). This survey also provided new information on the spawning area of Australian Sardine off eastern Australia during summer. The survey in August/September 2014 quantified the spawning biomass of Blue Mackerel and Australian Sardine off Australia's east coast during late winter and early spring (Ward et al. 2015b).

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.

<u>Giannini et al. (2010)</u>

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 levels (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.

<u>Smith et al. (2015)</u>

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 SPFHS) 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) 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 (Blue Mackerel and Australian Sardine) or 10 years (Jack Mackerel and Redbait).

1.5 Aims and Objectives

This report collates and presents fishery data for the SPF and available biological information for each of the quota species: Blue Mackerel, Jack Mackerel, Redbait and Australian Sardine, as well as Yellowtail Scad (a by-product species). Biomass estimates and MSEs are also included where available. This report satisfies the requirements of the SPF Harvest Strategy (AFMA 2008, reviewed in April 2015).

2 JACK MACKEREL (*Trachurus declivis*)

2.1 Introduction

2.1.1 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 consisted of 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, large inter-annual fluctuations in catches and an overall downward trend in fishery production caused purse-seine operations to cease in 2000.

Mid-water trawling to target subsurface 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. A decline of trawl effort in the late 2000s saw the resumption of small-scale purse seine operations that continued into the early 2010s (Emery et al. 2015).

The long term trend in production levels throughout the history of the fishery for Jack Mackerel is likely 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 Australia current (e.g. Harris et al. 1992, Young et al. 1993, McLeod et al. 2012), which may contribute to changes in relative abundance of surface schools of small pelagic species such as Jack Mackerel and their availability to the fishery. It has been suggested that the apparent shift from Jack Mackerel to Redbait as the dominant small pelagic fish in this region during the 1990s, was a result of a decline in the abundance of Jack Mackerel due to environmentally-mediated changes in the composition of the plankton assemblage (i.e. food availability; Harris et al. 1992, Young et al. 1993, McLeod et al. 2012).

2.1.2 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*.

2.1.3 Distribution

Jack Mackerel is widely distributed throughout coastal waters of southern Australia and New Zealand. In Australia, the 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 down to depths of 500 m, but is more abundant over the continental shelf to 200 m (Pullen 1994).

2.1.4 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 fish (Smolenski et al. 1994), but distinct differences between GAB and New Zealand fish (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 fish from west of Tasmania, including the GAB and Western Australia.

2.1.5 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.

2.1.6 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 a variety of other prey items in minor quantities including ostracods, gastropods, amphipods, isopods, polychaetes and echinoderms (Stevens et al. 1984, Blaber and Bulman 1987, McLeod et al. 2012). Dietary composition has also been shown to vary 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).

2.1.7 Age, Growth and Size

Jack Mackerel reach a maximum of 470 mm fork length (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 the time they reach 10 years, with no significant difference in growth between males and females (Lyle et al. 2000).

2.1.8 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), and 50% of females are undergoing vitellogenesis at 315 mm FL (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). 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).

2.1.9 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). Jack Mackerel eggs are morphologically similar to Yellowtail Scad eggs but slightly larger (Yellowtail Scad egg diameter: 0.78–0.88 mm; Neira 2009).

2.1.10 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 the Jack Mackerel stocks; (2) describe factors contributing to inter-annual variability in the availability of Jack Mackerel; and (3) collect information on early life history and reproductive biology of the species (Jordan et al. 1992, 1995). Research outputs included greater understanding of interactions between local oceanography and availability of surface schools of Jack Mackerel (Harris et al. 1992, Williams and Pullen 1993), and data on the reproductive biology and early life history of Jack Mackerel (Harris et al. 1992, Marshall et al. 1993, Williams and Pullen 1993, Jordan 1994, Jordan et al. 1995). The abundance of surface schools of Jack Mackerel off eastern Tasmania was found to have a close relationship with 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 this, a preliminary DEPM was applied to Jack Mackerel 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).

2.1.11 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 by fishers in New South Wales, 26% in Western Australia and 19% in Queensland. Catches from the other States comprised the remaining 8% of the total recreational catch (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.

2.1.12 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 locally collected species-specific 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 has not been applied to Jack Mackerel in the West sub-area of the SPF.

2.1.13 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 should not be applied for more than 10 years. The study results also indicated it is not safe to apply Tier 2 harvest rates unchecked for long periods of time (i.e. >10 years; Smith et al. 2015).

2.1.14 Management

Jack Mackerel in both the East and West sub-areas are currently managed at the Tier 2 level under the SPF HS. A preliminary DEPM assessment of Jack Mackerel East was performed in 2011 (data from 2002–2004) and a dedicated DEPM assessment occurred in 2014.

2.2 Methods

2.2.1 Fishery Statistics

Fishery statistics from 1997/98 to 2014/15 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 Jack Mackerel East include data from the NSW Ocean Fisheries (Hauling and Trawl), 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.

2.2.2 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. Following the commencement of mid-water trawl operations 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 of mid-water trawl and purse-seine operations adjacent to Tasmania was implemented in 2009/10 as part of the SPF monitoring program under the SPF Harvest Strategy (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 during 2014/15. Samples of Jack Mackerel were collected (n = 50 randomly selected fish per shot) and supplied to SARDI Aquatic Sciences for processing to provide current size and age composition estimates 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 Marshall et al. 1993) and gonad weight (to the nearest 0.1 g). Otoliths were removed from random sub-samples of fish for age estimation. The age structure of Jack Mackerel East 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. Ages for Jack Mackerel East in 2014/15 were based on annual growth increment counts in thin-sectioned otoliths (sub-sample n = 10 fish per sample). Gonad stages were designated as: I) immature; II) maturing virgins or recovering spent; III) maturing; IV) ripe; and V) spent.

Commercial logbook information, length-frequency and biological data collected between 1984 and 2015 are included in this assessment. In addition to current catch samples, age, growth and reproductive data for Jack Mackerel were available from previous studies (Jordan et al. 1992, Lyle et al. 2000, Browne 2005, Ward et al. 2011). Length-frequency data were also available for Jack Mackerel from research (demersal trawl net) sampling undertaken between St. Helens (Tasmania) and Eden (New South Wales) in January 2014 (Ward et al. 2015a). Summarised biological data prior to 2014/15 are presented in financial years; all current SPF catch sampling data are presented in the current fishing season from 1 May 2014 to 30 April 2015.

2.3 Results

2.3.1 Jack Mackerel East

2.3.1.1 Fishery Statistics

Number of vessels

The number of vessels reporting catches of Jack Mackerel East declined from 95 vessels in 1997/98 to a low of 7 vessels in 2012/13. In 2014/15, 14 vessels landed Jack Mackerel East, most of which were based in Tasmania (64%). One Commonwealth vessel reported catches of Jack Mackerel East in 2014/15.

Annual patterns: Total catch

Total catches of Jack Mackerel East declined from 9,873 t in 1997/98 to 381 t in 2000/01 (Figure 2.1). Catches increased to 3,363 t in 2003/04, before decreasing to 63 t in 2011/12. In 2012/13 and 2013/14, annual catches were <3 t. Total catch increased to 317 t in 2014/15 (Figure 2.1). The main fishery taking Jack Mackerel East is the SPF (purse-seine and mid-water trawl).

Annual patterns: Catch and Effort

Within the SPF, purse-seining has historically been used to target Jack Mackerel East (Figure 2.2). Since the early 2000s, mid-water trawls have replaced purse-seines (Figure 2.3). There has been a general long-term decline in purse-seine effort on Jack Mackerel East from a peak of 86 boat days in 1997/98 to zero boat days in 2012/13 (Figure 2.2). Annual purse-seine catch mirrors effort with a high of 9,873 t in 1997/98 to no reported catch in 2012/13. There has been no purse-seine effort and catch reported in the SPF since 2011/12 (Figure 2.2). Trends of mid-water trawl effort over time are also similar to annual catch in the SPF for Jack Mackerel East, i.e. trawl effort peaked in 2003/04 (69 boat days, 3,265 t), decreased to zero effort from 2011/12 to 2013/14 and increased to 6 boat days in 2014/15 (311 t, Figure 2.3).

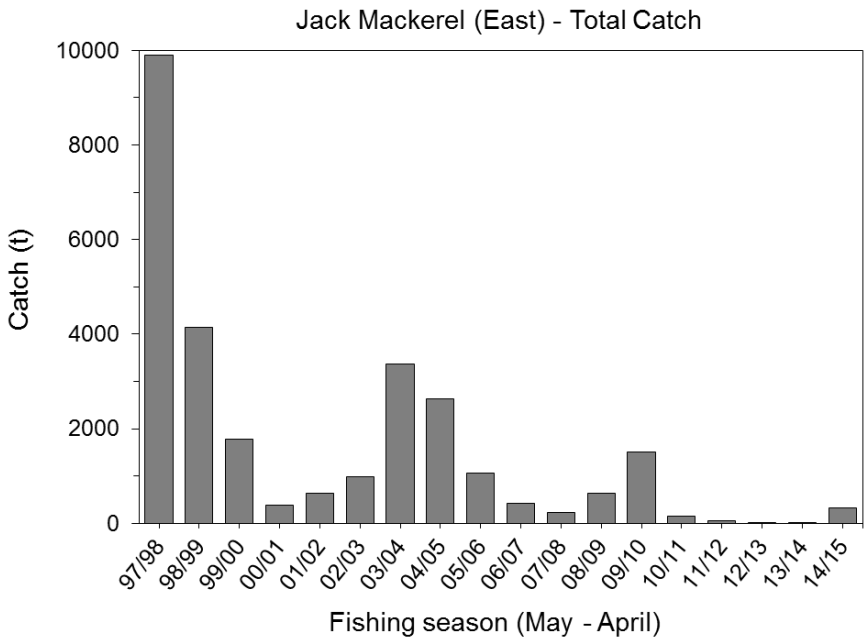

Figure 2.1. Total annual landed catch (tonnes) of Jack Mackerel East for each fishing season from 1997/98 to 2014/15.

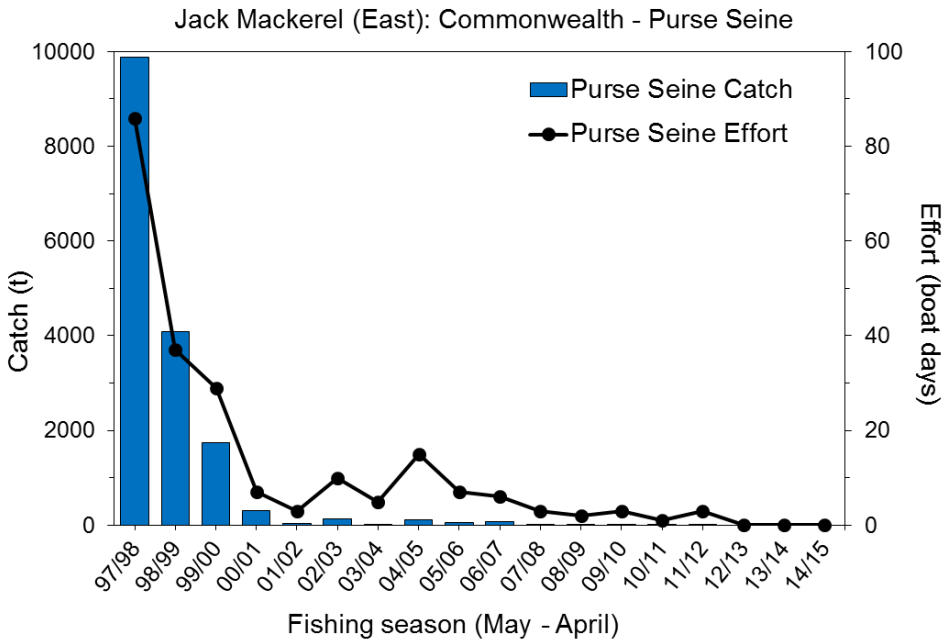

Figure 2.2. Annual landed catch (tonnes) and effort (boat days) of Jack Mackerel East by purse-seine in the SPF for each fishing season from 1997/98 to 2014/15.

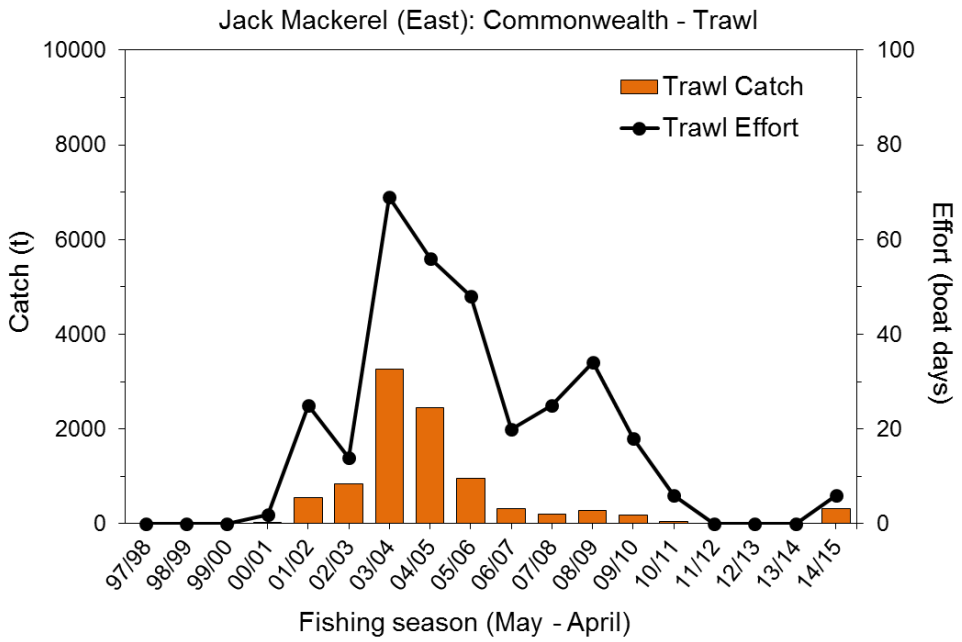

Figure 2.3. Annual landed catch (tonnes) and effort (boat days) of Jack Mackerel East by mid-water trawl in the SPF for each fishing season from 1997/98 to 2014/15.

2.3.1.2 Biological Information

Catch sampling of Jack Mackerel East adjacent to Tasmania during 2009/10 resulted in the collection of 1,412 fish from purse-seines and 318 fish from mid-water trawls (Table 2.1). Due to limited commercial fishing for Jack Mackerel, catch samples were not obtained during 2010/11 to 2013/14 in the SPF. In January 2014, 10 samples (n = 1,759) of Jack Mackerel were collected from catches taken as part of the 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 the north-eastern coast of Tasmania (Ward et al. 2015a). No age information was collected from these samples. In 2014/15, length-frequency data were collected from 325 Jack Mackerel sampled from commercial mid-water trawl catches taken in southern New South Wales during April 2015; age-frequency data were collected from 102 of those fish (Table 2.1).

Table 2.1. Summary of Jack Mackerel East catch samples collected from commercial SPF landings.

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

Size structure

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

Purse-seine catches of Jack Mackerel East between 1984/85 and 1995/96 off eastern Tasmania mainly comprised fish between 210 and 350 mm FL, and included individuals up to 440 mm FL (Figure 2.4). The size structure for catches taken in 1984/85 was bimodal and contained fish between 240 and 360 mm FL. From 1985/86 to 1988/89, catches were dominated by a single mode, with most fish in the 250–350 mm FL size range and evidence for a slight shift in size structure toward larger fish. A second cohort of small fish (<250 mm FL) was evident in 1988/89, and in 1989/90 the size distribution was bimodal with peaks at 240 mm FL and 320–330 mm FL. A bimodal size structure was evident in the following three years with the position and relative heights of the modes varying among years. The size structures from 1993/94–1995/96 were unimodal and showed evidence of a general shift to larger fish. In 2009/10, the size structure was unimodal and dominated by smaller fish (190–220 mm FL size range; Figure 2.4).

Mid-water trawl fishery: 2001/02–2014/15

Jack Mackerel caught by mid-water trawl operations off eastern Tasmania from 2002/03 to 2004/05 were considerably smaller than those caught by the earlier purse-seine operations, with specimens mostly between 200 and 300 mm FL (Figure 2.5). 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 2.4–2.5).

Mid-water trawl catches in the East were characterised by an increase in modal length, from 240 to 270 mm FL between 2002/03 and 2004/05, and only a small proportion of the catch comprised fish >300 mm FL (Figure 2.5). Catch sampling of Jack Mackerel East from mid-water trawling in 2014/15 off southern New South Wales revealed an increase in size structure compared to 2009/10. The modal length increased to 230 mm FL, and more fish were in the 250 to 300 mm FL size classes (Figure 2.5). The modal length of the 2014/15 commercial mid-water trawl catch is

slightly smaller (230–240 mm FL) than the commercial trawl catches of the early 2000s (240–270 mm FL; Figure 2.5).

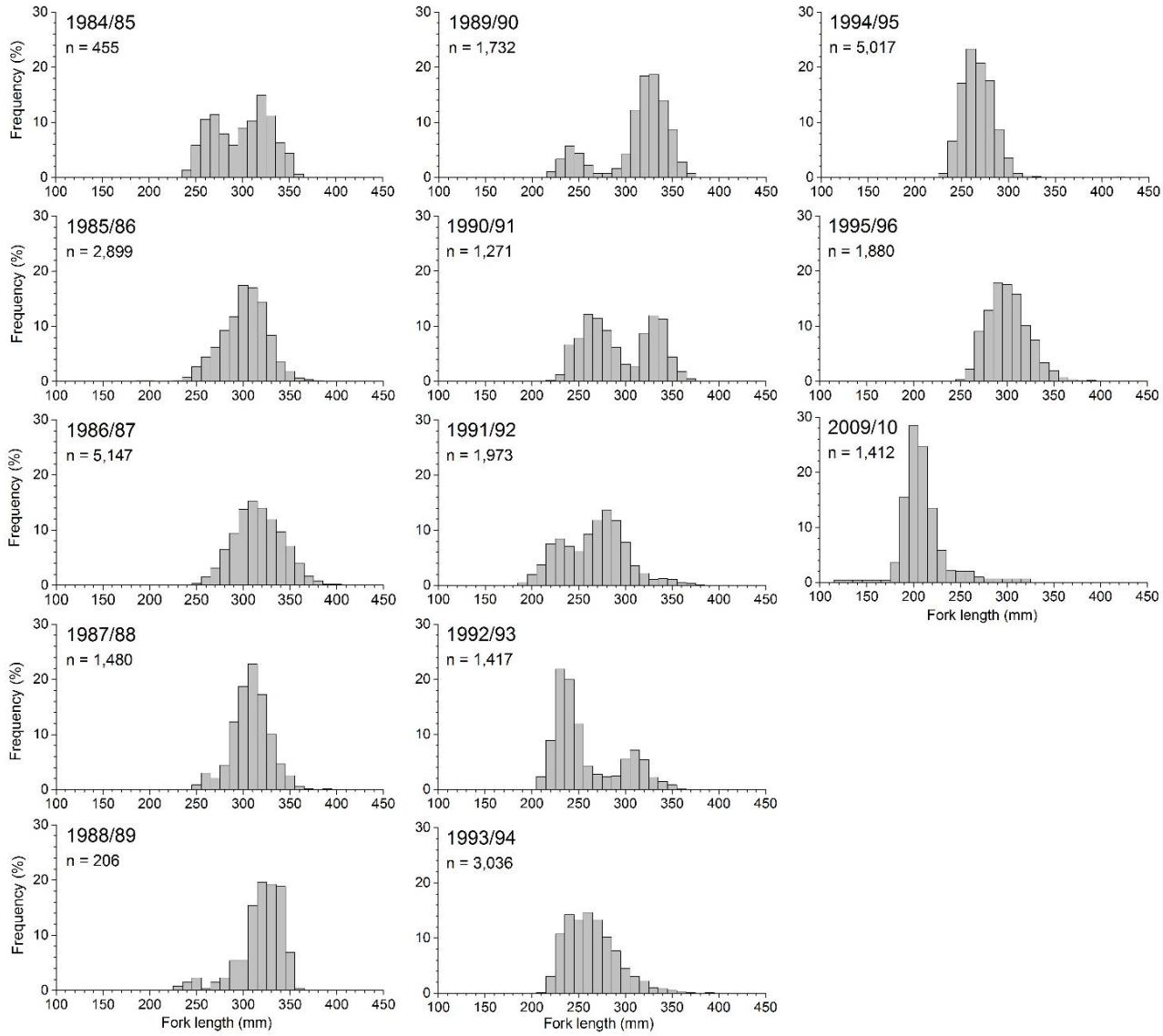

Figure 2.4. Length-frequency distributions of Jack Mackerel East caught in the SPF by purse-seine from 1984/85 to 1995/96 and in 2009/10; n = sample size.

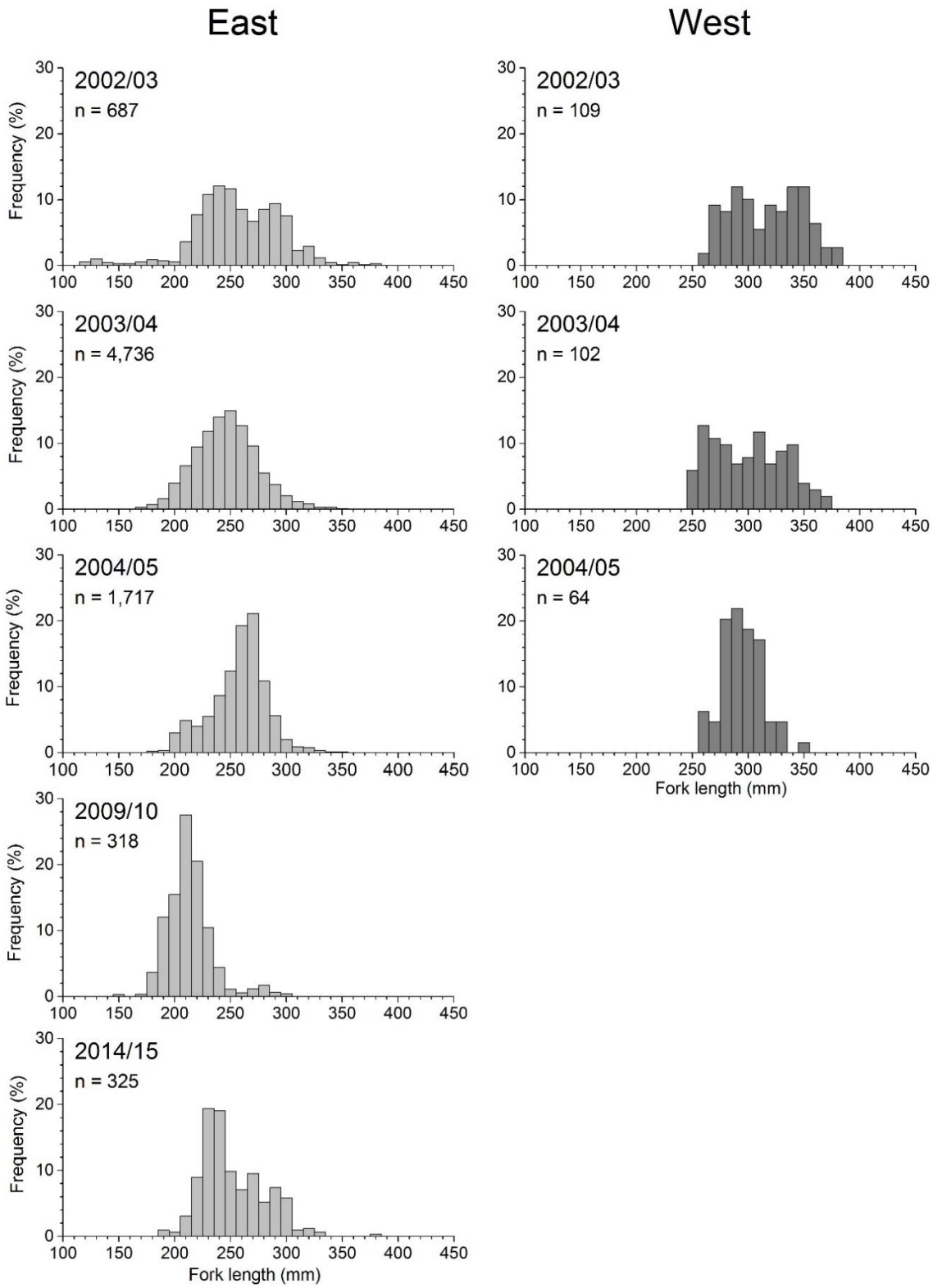

Figure 2.5. Length-frequency distributions of Jack Mackerel East and West caught by mid-water trawl in the SPF; n = sample size.

Research (demersal trawl net) surveys: 2014

The research samples of Jack Mackerel collected off eastern Victoria/southern New South Wales (above 39°S) mainly comprised fish between 240–310 mm FL, with a mode at 250 mm FL (Figure 2.6). 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 mode at 280 mm FL (Figure 2.6). The modal length of the Jack Mackerel in research catches from eastern Victoria/southern New South Wales were larger compared to those from the 2014/15 commercial trawl catches taken in the same vicinity (Figures 2.5–2.6).

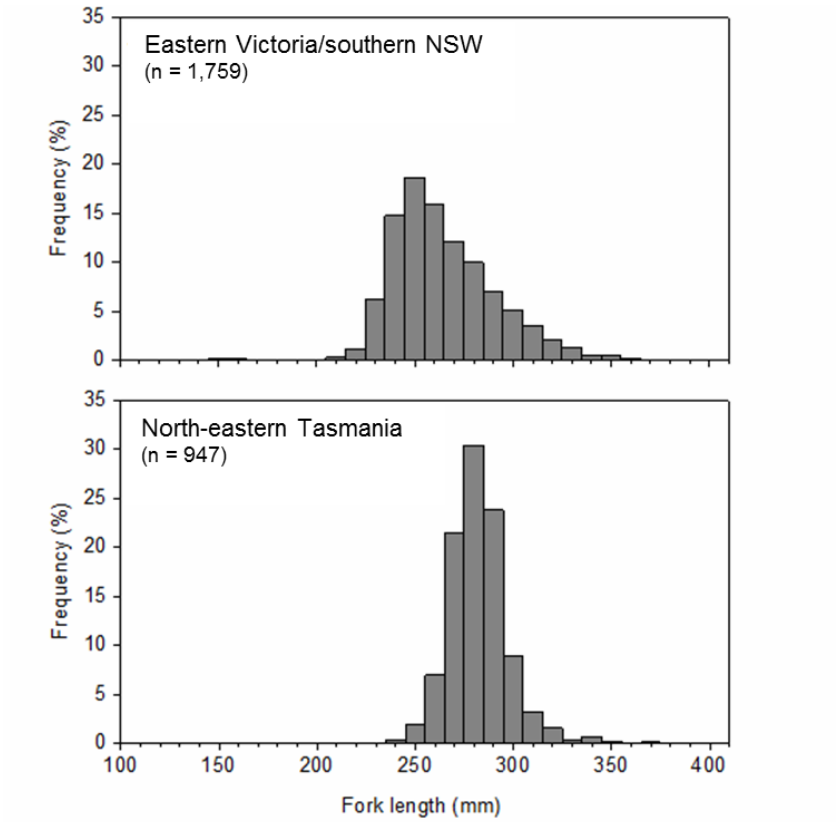

Figure 2.6. Length-frequency distributions (mm FL) for Jack Mackerel from research sampling off south-eastern Australia in January 2014.

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 2.7). 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 evident in the intervening years may not have been solely due to impact of fishing on population age structure. However, it should be noted that the application of 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 again dominated by younger fish in the 2–3 year age groups (Figure 2.7).

Mid-water trawl fishery: 2001/02–2014/15

Mid-water trawl catches of Jack Mackerel East off eastern Tasmania between 2001/02 and 2004/05 consisted of mainly fish aged 2–5 years old, with a modal age of 4 years (Figure 2.8). During 2009/10, mid-water trawl catches from eastern Tasmania were dominated by 2–3 year old fish. In mid-water trawl catches off southern New South Wales during 2014/15, 68% of the fish were between 4 and 7 years old (age mode: 7 years) (Figure 2.8). The maximum estimated age of Jack Mackerel East from mid-water trawl catch samples was 16 years (Figure 2.8).

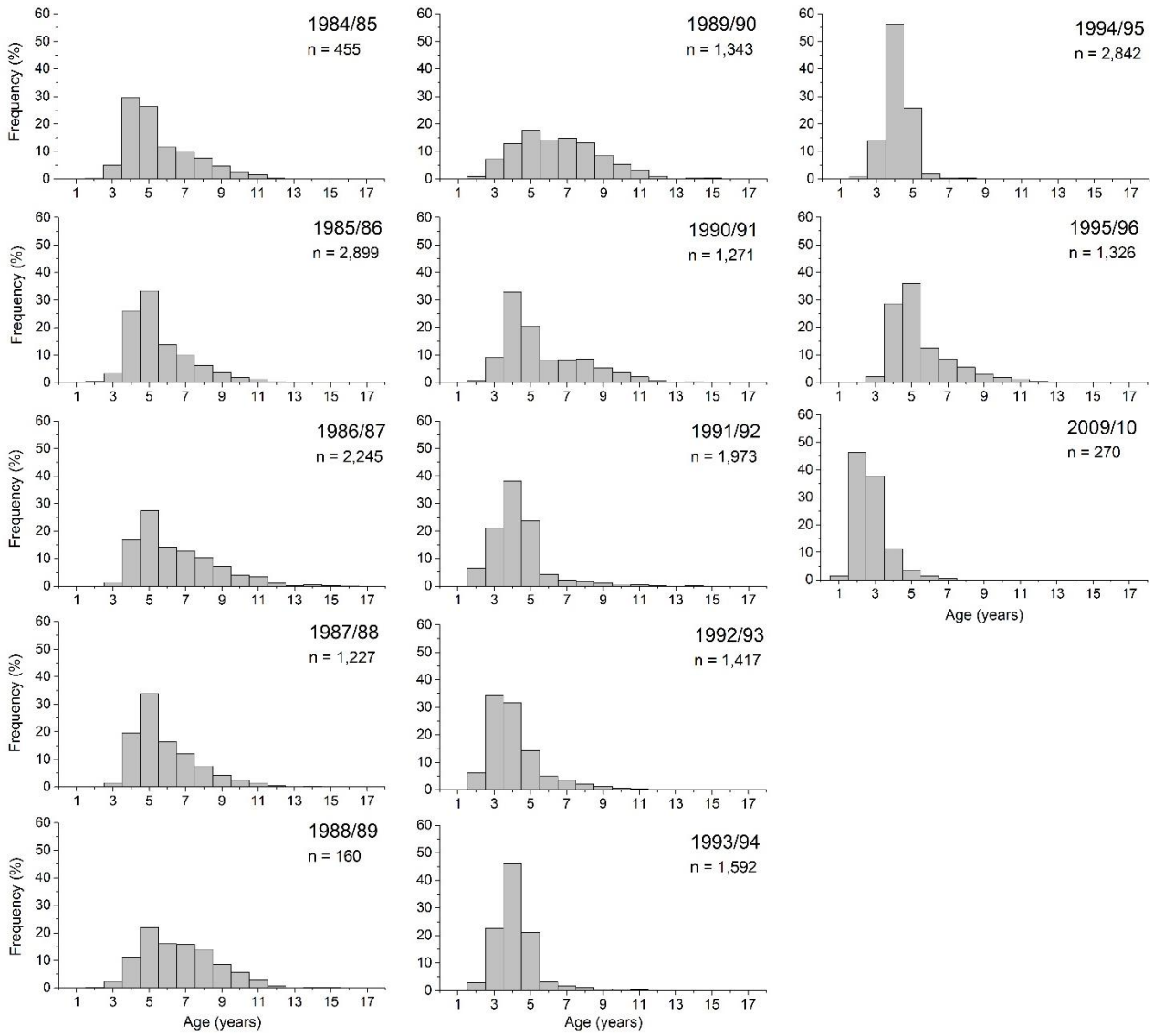

Figure 2.7. Age-frequency distributions of Jack Mackerel East caught in the SPF by purse-seine from 1984/85 to 1995/96 and in 2009/10; n = sample size.

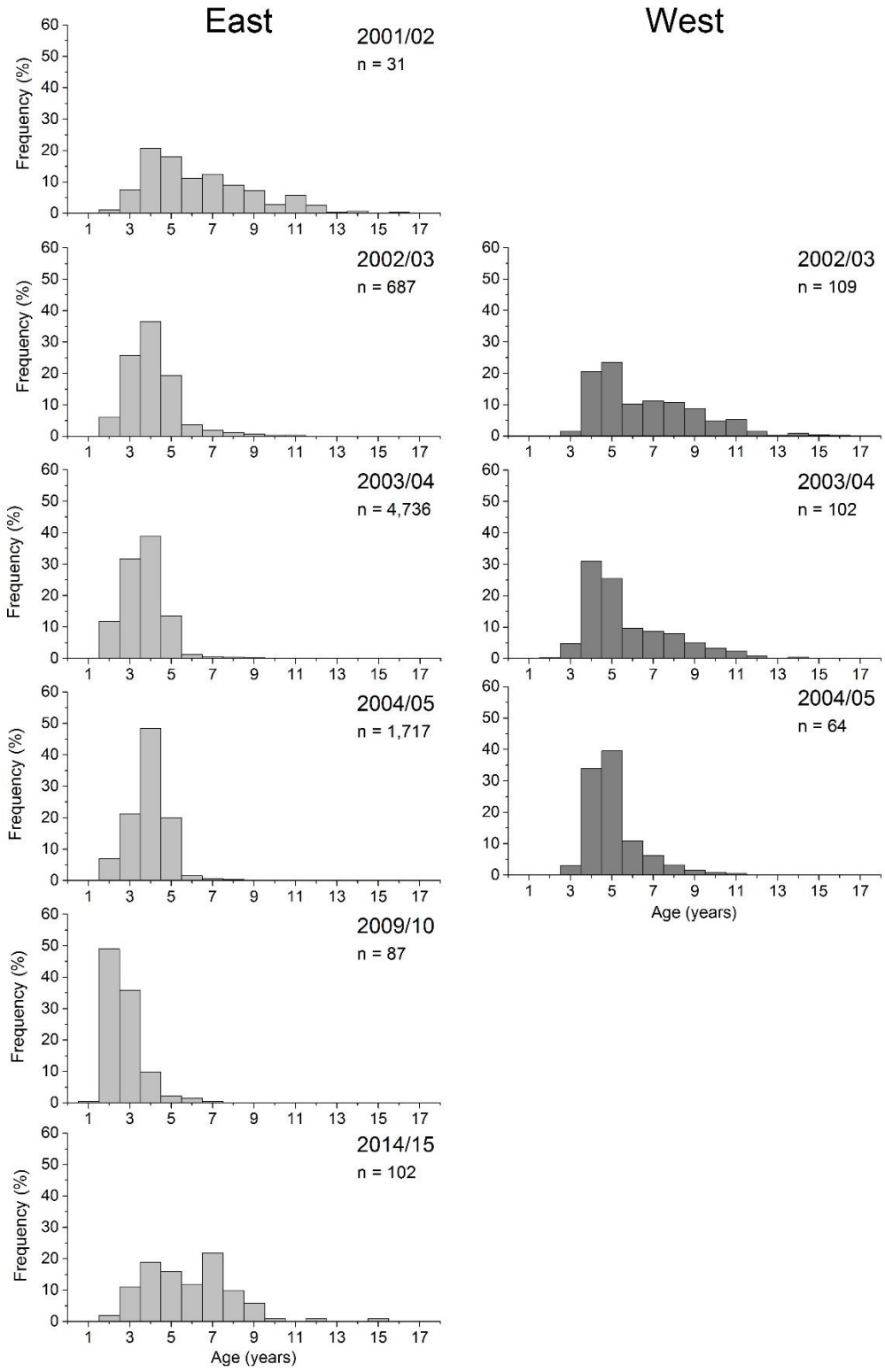

Figure 2.8. Age-frequency distributions of Jack Mackerel East and West caught by mid-water trawl in the SPF; n = sample size.

Growth

Growth of male and female Jack Mackerel from eastern Tasmania was described using the von Bertalanffy growth function (VBGF) (Table 2.2, Figure 2.9). Growth was rapid within the first few years of life, with individuals reaching a mean length in excess of 230 mm FL, i.e. approximately 64% of L_∞ in the first three years, slowing thereafter. Maximum assigned ages were 15 years for females and 16 years for males.

Table 2.2. Summary of von Bertalanffy growth function parameters for Jack Mackerel. Pooled data includes males, females and unsexed/unknown individuals. Based on Ward et al.(2011).

		VBGF parameters		
Sex	n	L_∞	K	t_0
Male	534	364.0	0.27	-0.92
Female	763	360.3	0.29	-0.63
Pooled	2,143	362.8	0.29	-0.81

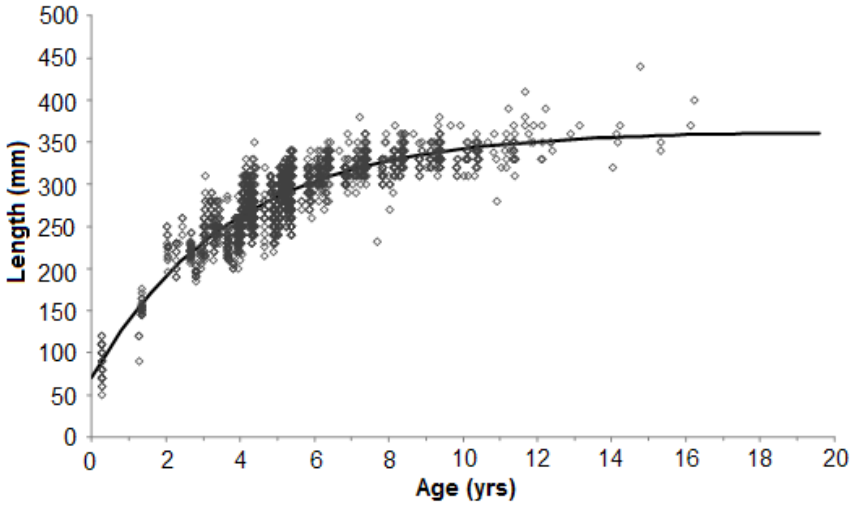

Figure 2.9. Length (mm FL) at age (years) data for Jack Mackerel. The black line represents the von Bertalanffy growth function. Based on Ward et al. (2011).

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 a three month period from late spring to mid-summer

(Figures 2.10–2.11). 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 2.10).

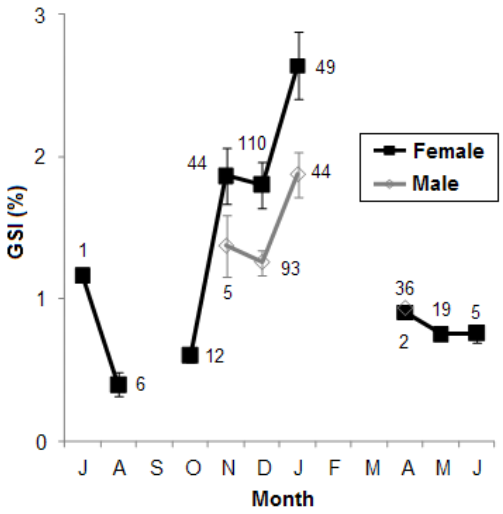

Figure 2.10. Monthly mean GSI values of Jack Mackerel by sex. Numbers associated with data points represent sample size (±SE). Based on Ward et al. (2011).

Gonad stages

Macroscopic staging of female gonad indicated Jack Mackerel off eastern Tasmania began actively spawning (gonads in Stages IV–VI) in November and spawning activity increased during December–January (Figure 2.11).

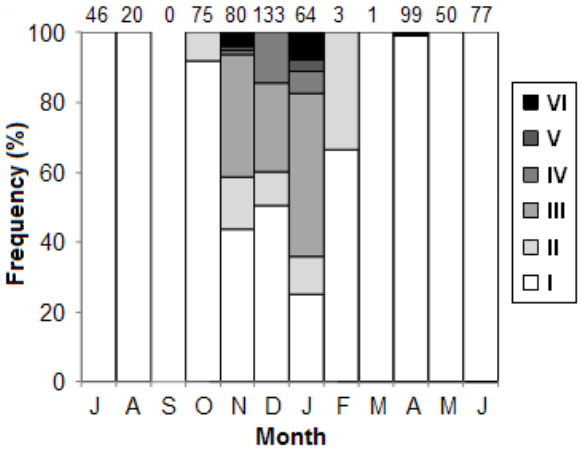

Figure 2.11. Monthly distribution of macroscopic gonad stages (Stages I–VI) from female Jack Mackerel; top numbers represent sample sizes. Based on Ward et al. (2011).

Size at maturity

Fifty percent maturity was estimated to be 268 mm FL for female Jack Mackerel in eastern Tasmania and 291 mm FL for males (Table 2.3, Figure 2.12). All fish larger than 360 mm FL were mature.

Table 2.3. Size at sexual maturity logistic parameters and 50% maturity (L_{50}) values of Jack Mackerel by sex. Based on Ward et al. 2011.

			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

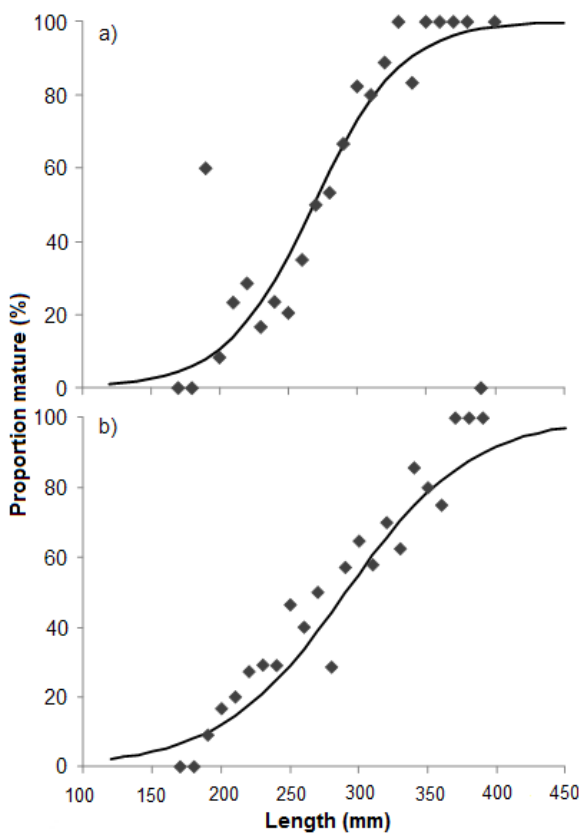

Figure 2.12. Proportion of mature female (a) and male (b) Jack Mackerel by length class (mm FL) fitted with logistic ogives; based on Ward et al. (2011).

2.3.2 Jack Mackerel West

2.3.2.1 Fishery Statistics

Number of vessels

The number of vessels reporting catches of Jack Mackerel West declined from 14 vessels in 1998/99 to a low of one vessel in 2012/13. Vessel numbers have remained at ≤5 since 2010/11. During 2014/15, a total of 5 vessels reported catches of Jack Mackerel.

Annual patterns: Total catch

Historically, Jack Mackerel catches in the West sub-area have been lower than those in the East (Figure 2.13). Annual catches peaked at 366 t in 2006/07. All other catches have been <250 t (Figure 2.13). In 2014/15, <1 t of Jack Mackerel West was taken. Generally, the SPF has been the main fishery landing Jack Mackerel West (purse-seine and mid-water trawl).

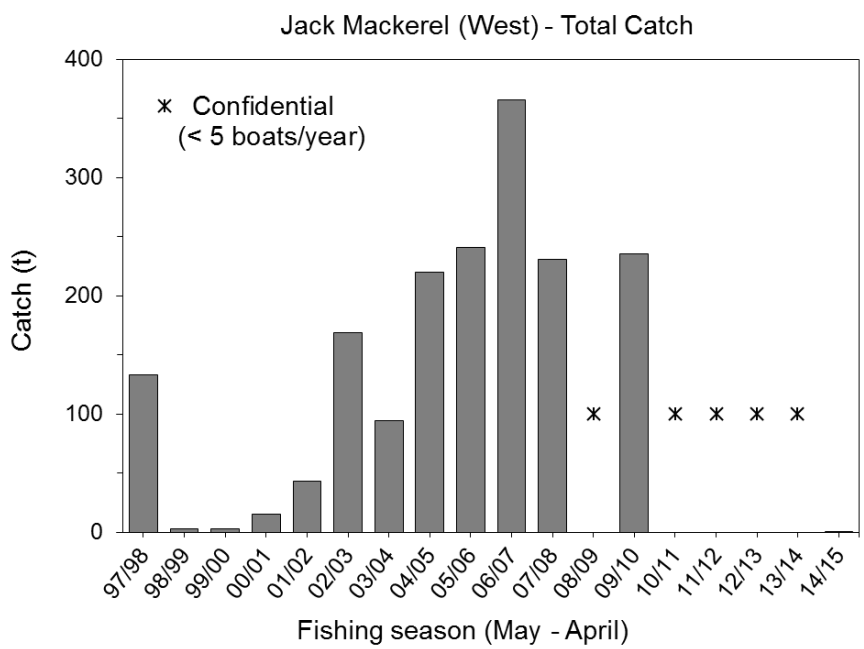

Figure 2.13. Total annual landed catch (tonnes) of Jack Mackerel in the West for each fishing season from 1997/98 to 2014/15. (⁎) indicates data confidentiality where <5 license holders reported landings.

Annual patterns: Catch and Effort

There has been very limited use of purse-seines by the SPF for Jack Mackerel West; mid-water trawls have historically been the dominant gear type (Figures 2.14–2.15). Purse-seine effort has not exceeded 16 boat days (1997/98), and the maximum catch was 142 t in 2006/07 (Figure 2.14). There has been no reported purse-seine effort and catch of Jack Mackerel West in the SPF since 2010/11 (Figure 2.14). Catch and effort of Jack Mackerel West taken by mid-water trawling during the mid-2000s peaked at 232 t and 19 boat days (Figure 2.15). There has been no reported effort and catch by mid-waters to land Jack Mackerel in the West by the SPF since 2010/11 (Figure 2.15).

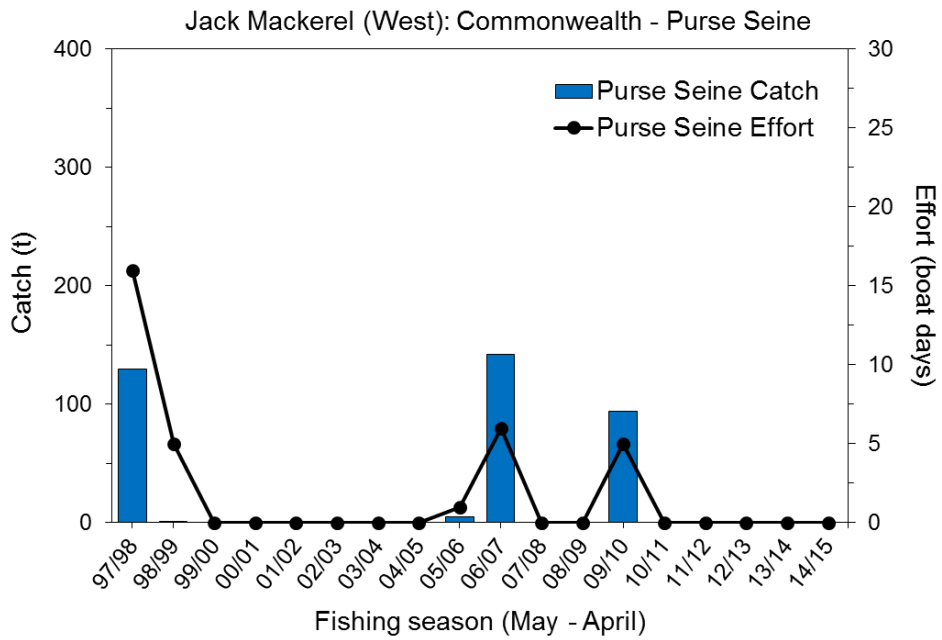

Figure 2.14. Annual landed catch (tonnes) and effort (boat days) of Jack Mackerel West by purse-seine in the SPF for each fishing season from 1997/98 to 2014/15.

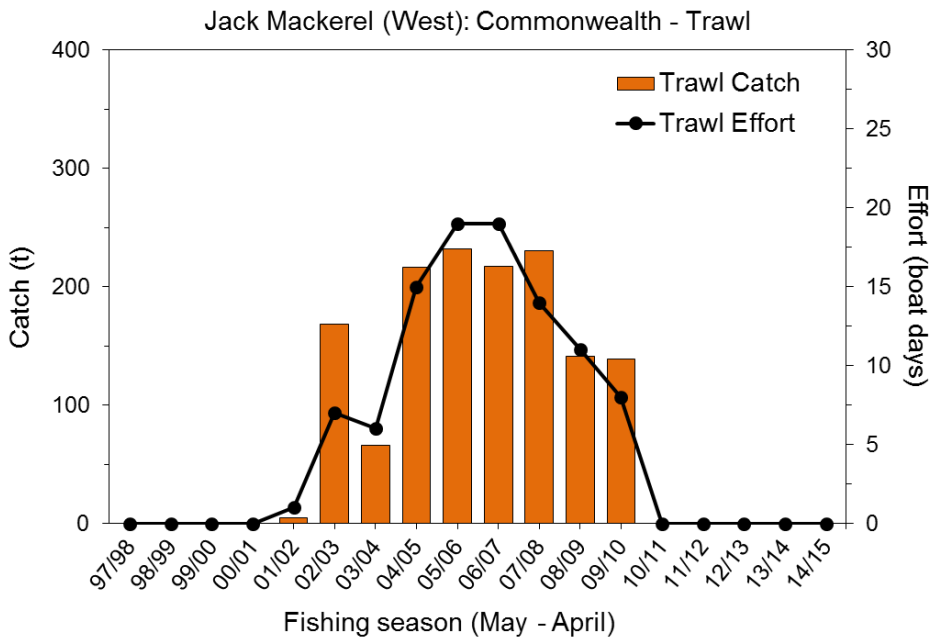

Figure 2.15. Annual landed catch (tonnes) and effort (boat days) of Jack Mackerel West by mid-water trawl in the SPF for each fishing season from 1997/98 to 2014/15.

2.3.2.2 Biological Information

A total of 132 Jack Mackerel were collected from mid-water trawls in the West sub-area adjacent to south-western Tasmania during 2009/10; age data were collected from 20 of those fish (Table 2.4).

Table 2.4. Summary of Jack Mackerel West catch samples collected from commercial SPF landings.

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

<u>Size structure</u>

The purse-seine fishery

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

Mid-water trawl fishery: 2001/02–2014/15

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 2.5). Jack Mackerel taken in the West sub-area over this period were larger than those from the East (overall modal length: 260 mm FL) (Figure 2.5).

In 2009/10, a sample from a single mid-water trawl catch from the West (south-western Tasmania) contained fish 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 2.5). Jack Mackerel West caught in 2009/10 (Table 2.4) were substantially smaller than fish taken by mid-water trawl in the West during the early 2000s (modal length: 260–350 mm FL; Figure 2.5).

Age structure

The purse-seine fishery

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

Mid-water trawl fishery: 2001/02–2014/15

Annual age structures of Jack Mackerel West catches from south-western Tasmania between 2001/02 and 2004/05 were characterised by a higher proportion of fish older than 5 years, and a mode of 4–5 years in each of the years sampled (Figure 2.8). The age structure of the single catch from south-west Tasmania in 2009/10 (Table 2.4) showed a high proportion of 2 year old fish, representing about 70% of the distribution, which is similar to the age structure from the East during the same period (Figure 2.8). The maximum estimated age of Jack Mackerel West from mid-water trawl catches was 16 years (Figure 2.8).

2.4 Summary and Conclusions

2.4.1 Jack Mackerel East

The spawning biomass of Jack Mackerel East during 2014 was estimated to be 157,805 t (95% CI = 59,570–358,731) (Ward et al. 2015a), which is within the range of estimates derived from surveys targeting Blue Mackerel in 2002–04 by Neira (2011) of ~114,900–169,000 t and plausible estimates for the ecosystem obtained from simulation studies by Fulton (2013). Ward et al. (2015a) suggested that the estimate of spawning biomass for 2014 was robust because it was based on reliable estimates of critical DEPM parameters (e.g. egg production, spawning area and spawning fraction).

Total annual catches of Jack Mackerel East declined from 9,873 t in 1997/98 to 381 t in 2000/01 and have not exceeded ~3,000 t since 2003/04. Catches were mainly taken by purse-seining from 1997/98 to 2000/01 and by mid-water trawling from 2001/02 onwards. Minimal fishing was conducted between 2010/11 and 2013/14. The total catch in 2014/15 was 317 t. Recent low catches of Jack Mackerel East reflect low fishing effort rather than low abundance.

Age and length structures since 2002/03 have varied among years, but are difficult to interpret due to the limited fishing effort, small sample sizes and changes in fishing locations over time. The modal size of samples obtained from mid-water trawl catches in 2014/15 (230–240 mm) was below the size at 50% maturity (268 mm FL for female; 291 mm FL for males). However, samples used to estimate size at 50% maturity were obtained off eastern Tasmania in 2009/10 (e.g. Ward et al. 2011) and may not be relevant to the catch samples for 2014/15 that were obtained off New South Wales.

Recent catches of Jack Mackerel East are assessed as sustainable, as they have been <1% of the estimated spawning biomass (Ward et al. 2015a), and well below the sustainable exploitation rate of 12% suggested for this species (Smith et al. 2015). Flood et al. (2014) also found that the biological stock of Jack Mackerel East is sustainable. Patterson et al. (2015) classified Jack Mackerel East as ‘not overfished’ and ‘not subject to overfishing’.

2.4.2 Jack Mackerel West

The DEPM has not been applied to Jack Mackerel West, and an empirical estimate of spawning biomass is not available for this stock. Annual catches of Jack Mackerel West have not exceeded 400 t since 1997/98. The total catch in 2014/15 was <1 t. Low catches of Jack Mackerel West appear to reflect low fishing effort rather than low abundance.

Age and length structures of Jack Mackerel West between 2002/03 and 2004/05 were consistent among years, with dominant age classes of 4–5 years and an overall modal length of 290 mm FL. This was above the mean size at 50% maturity of ~280 mm FL (Ward et al. 2011). Jack Mackerel taken in the West sub-area at this time were larger than those from the East. Biological data for Jack Mackerel West has not been obtained since 2009/10 due to limited fishing activity.

Jack Mackerel West is likely to be sustainable, because catches are small compared to the large size of the sub-area. Flood et al. (2014) also classified the stock status of Jack Mackerel West as sustainable. Patterson et al. (2015) classified Jack Mackerel West as ‘not overfished’ and ‘not subject to overfishing’.

An estimate of the spawning biomass is needed to confirm the status of Jack Mackerel West, especially if effort/catches increase significantly.

3 BLUE MACKEREL (*Scomber australasicus*)

3.1 Introduction

3.1.1 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 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, 2015c).

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 shot-by-shot record of fishing operations and species taken. 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 (Pullen 1994). Species-specific information was not available for other years.

3.1.2 Taxonomy

The genus *Scomber* (family *Scombridae*) traditionally included three Mackerel species: Blue Mackerel (*S. australasicus*), Chub Mackerel (*Scomber japonicus*), and Atlantic Mackerel (*Scomber scombrus*). However, *S. australasicu*s 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*.

3.1.3 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 their genus to occur there (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).

3.1.4 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).

3.1.5 Movement

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

3.1.6 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).

3.1.7 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).

3.1.8 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 (SSTs) of 18-22°C (Ward and Rogers 2007, Ward et al. 2015b). The location of spawning off southern Australia appears to vary substantially between 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).

3.1.9 Early Life History and Recruitment

Blue Mackerel eggs are transparent and spherical, measuring 1.05 to 1.35 mm in diameter. The eggs possess 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).

3.1.10 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 amenable to assessment using the DEPM (Ward and Rogers 2007, Ward et al. 2009). A dedicated DEPM survey for Blue Mackerel East occurred 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).

3.1.11 Recreational fishing

Recreational fishers harvest Blue Mackerel using rod and line, hand line and troll lines (Ward and Rogers 2007) throughout the southern waters of 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 those Blue Mackerel retained, 75% were taken in New South Wales, and 14% and 8% taken in Western Australia and South Australia, respectively. Catches from Victoria, Tasmania and Queensland comprised the remaining 3% of the total recreational catch (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).

3.1.12 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 of 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 (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 $eggs{\cdot}female^{-1}$) and the higher estimate of daily egg production (69.5 $eggs{\cdot}day^{-1}{\cdot}m^{-2}$). These variations 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).

3.1.13 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" quantities and represent 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 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, particularly on shorter lived species such as Blue Mackerel (Smith et al. 2015).

3.1.14 Management

DEPM assessments of Blue Mackerel have been conducted for the both the East and West Zones of the SPF: Blue Mackerel East in 2004 and 2014, and Blue Mackerel West in 2005. Blue Mackerel in both the East and West sub-areas are managed at the Tier 2 level.

3.2 Methods

3.2.1 Fishery Statistics

Fishery statistics from 1997/98 to 2014/15 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 and 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, South Australian Marine Scalefish Fishery and Commonwealth SPF.

3.2.2 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. Hence, catch sampling from the as required under the SPF Harvest Strategy (AFMA 2008) also recommenced. AFMA observers collected samples of Blue Mackerel East from mid-water trawl catches (n = 50 randomly selected fish per shot), which were supplied to SARDI Aquatic Sciences for processing.

Samples of Blue Mackerel from the West 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). Otoliths were removed from random sub-samples of fish for age estimation. Ages for Blue Mackerel East in 2014/15 were based on annual growth

increment counts in whole otoliths (sub-sample n = 10 fish per sample). An otolith weight-age algorithm developed by Ward and Rogers (2007) was used to estimate ages of Blue Mackerel collected in the West. Gonad stages were designated as: Stage 1: immature; Stage 2: maturing virgins or recovering spent; Stage 3: maturing; Stage 4: ripe; and Stage 5: spent (full descriptions in Ward and Rogers 2007). Biological data prior to 2014/15 are presented in financial years; all current SPF catch sampling data are presented in the current fishing season from 1 May 2014 to 30 April 2015.

3.3 Results

3.3.1 Blue Mackerel East

3.3.1.1 Fishery statistics

Number of vessels

The number of vessels reporting catches of Blue Mackerel East ranged from 236 to 349 between 1997/98 and 2008/09. Since then, vessel numbers have ranged between 28 and 64, with 39 vessel reporting catches of Blue Mackerel East in 2014/15. On average, 91% of the vessels reporting catch in each year are from New South Wales; about 2% of vessels reporting Blue Mackerel catches per year are Commonwealth vessels.

Annual patterns: Total catch

Total annual catches of Blue Mackerel East decreased from a high of 1036 t in 2003/04 to a low of 290 t in 2011/12 (Figure 3.1). The annual catch increased to 513 t in 2012/13 and declined to 442 t in 2014/15. The main fisheries that take Blue Mackerel East have been the NSW Ocean Hauling Fishery (purse-seine) and the SPF (purse-seine and mid-water trawl). Since 1997/98, New South Wales Ocean Fisheries and the SPF have taken an average of 65% and 22% of the total annual catch for the East, respectively.

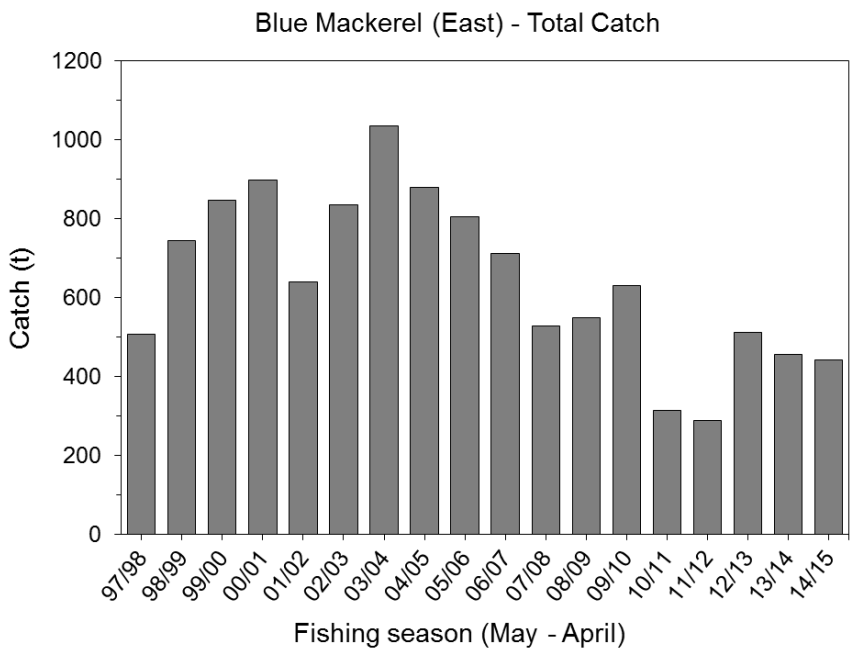

Figure 3.1. Total annual landed catch (tonnes) of Blue Mackerel East for each fishing season from 1997/98 to 2014/15.

Annual patterns: Catch and Effort

Purse-seining has historically been used to take Blue Mackerel East. This remains the case for the NSW Ocean Hauling Fishery (Figure 3.2), but in the SPF, mid-water trawling has replaced purse-seining (Figures 3.3–3.4). There has been a general long-term decline in purse-seine effort of Blue Mackerel East with increased effort using mid-water trawls in 2014/15 (Figures 3.2–3.4).

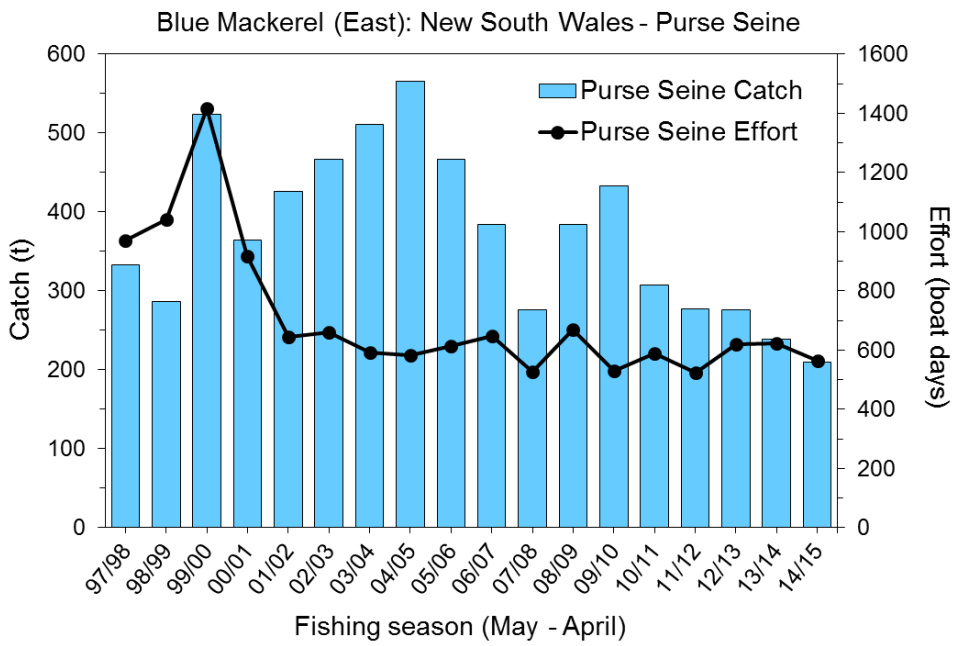

Figure 3.2. Annual landed catch (tonnes) and effort (boat days) of Blue Mackerel East by purse-seine in the NSW Ocean Hauling Fishery for each fishing season from 1997/98 to 2014/15.

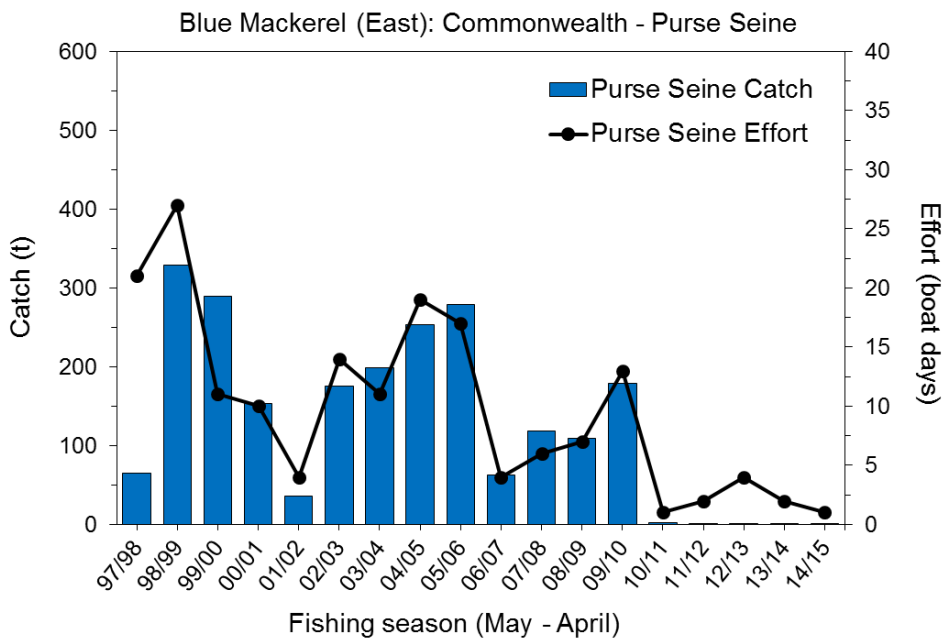

Figure 3.3. Annual landed catch (tonnes) and effort (boat days) of Blue Mackerel East by purse-seine in the SPF for each fishing season from 1997/98 to 2014/15.

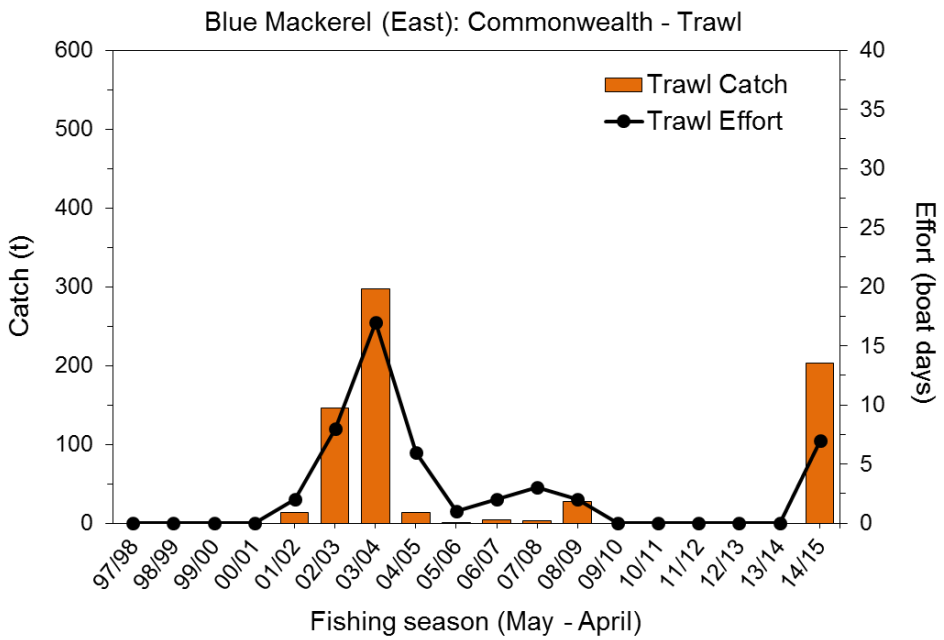

Figure 3.4. Annual landed catch (tonnes) and effort (boat days) of Blue Mackerel East by mid-water trawl in the SPF for each fishing season from 1997/98 to 2014/15.

Trends in annual purse-seine effort in the SPF for Blue Mackerel East are similar to annual catch, i.e. effort was >20 boat days in the late 1990s and has been <5 boat days since 2010/11 (Figure 3.3). In 2014/15, there was 1 boat day of purse-seining effort (Figure 3.3). Trends in SPF mid-water trawl effort for Blue Mackerel East are also similar to the annual catch, peaking at 17 boat days in 2003/04, decreasing to zero from 2009/10 to 2013/14 and increasing to 7 boat days in 2014/15 (Figure 3.4).

3.3.1.2 Biological Information

Length-frequency data were collected from 6,632 Blue Mackerel East sampled from commercial purse-seine catches off New South Wales between 2006/07 and 2014/15 (Table 3.1). 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 obtained from 264 Blue Mackerel sampled from catches taken in the East sub-area during April 2015. Age-frequency data were obtained from 105 fish (Table 3.2). No biological data were available from Victoria, which has accounted for ~15% of the annual catch in the East over the last 10 years. Biological samples from New South Wales may not be representative of Blue Mackerel harvested throughout the East sub-area.

Table 3.1. Summary of Blue Mackerel samples collected from commercial New South Wales State catches between 2006/07 and 2014/15 (data supplied by New South Wales DPI).

Season	SPF sub-area	Gear type	No. of samples	Length-frequency n	Size range (mm FL)
2006/07	East	purse-seine	23	1869	220–400
2007/08	East	purse-seine	13	1286	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	1177	170–360
2014/15	East	purse-seine	12	1382	180–370

Table 3.2. Summary of Blue Mackerel East catch samples collected from commercial SPF landings during 2014/15.

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

Size structure

There were substantial differences in the size distributions among years of Blue Mackerel East sampled from purse-seine catches (Figure 3.5). Fish ranged from 160 to 400 mm FL (Table 3.1). From 2006/07 to 2012/13, size distributions generally consisted of a single mode between 280 and 320 mm FL, with the exception of the bimodal distribution for 2007/08 that involved 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 3.5).

The modal length of Blue Mackerel East from mid-water trawl catch samples during 2014/15 was 290 mm FL, with fish sizes ranging from 242 to 342 mm FL (Figure 3.6). This length-frequency distribution is similar to purse-seine catches in the East prior to 2014/15 (Figures 3.5–3.6). In 2014/15, the mid-water trawl modal length was larger than the purse-seine modal length (290 versus 250 mm FL; Figures 3.5–3.6).

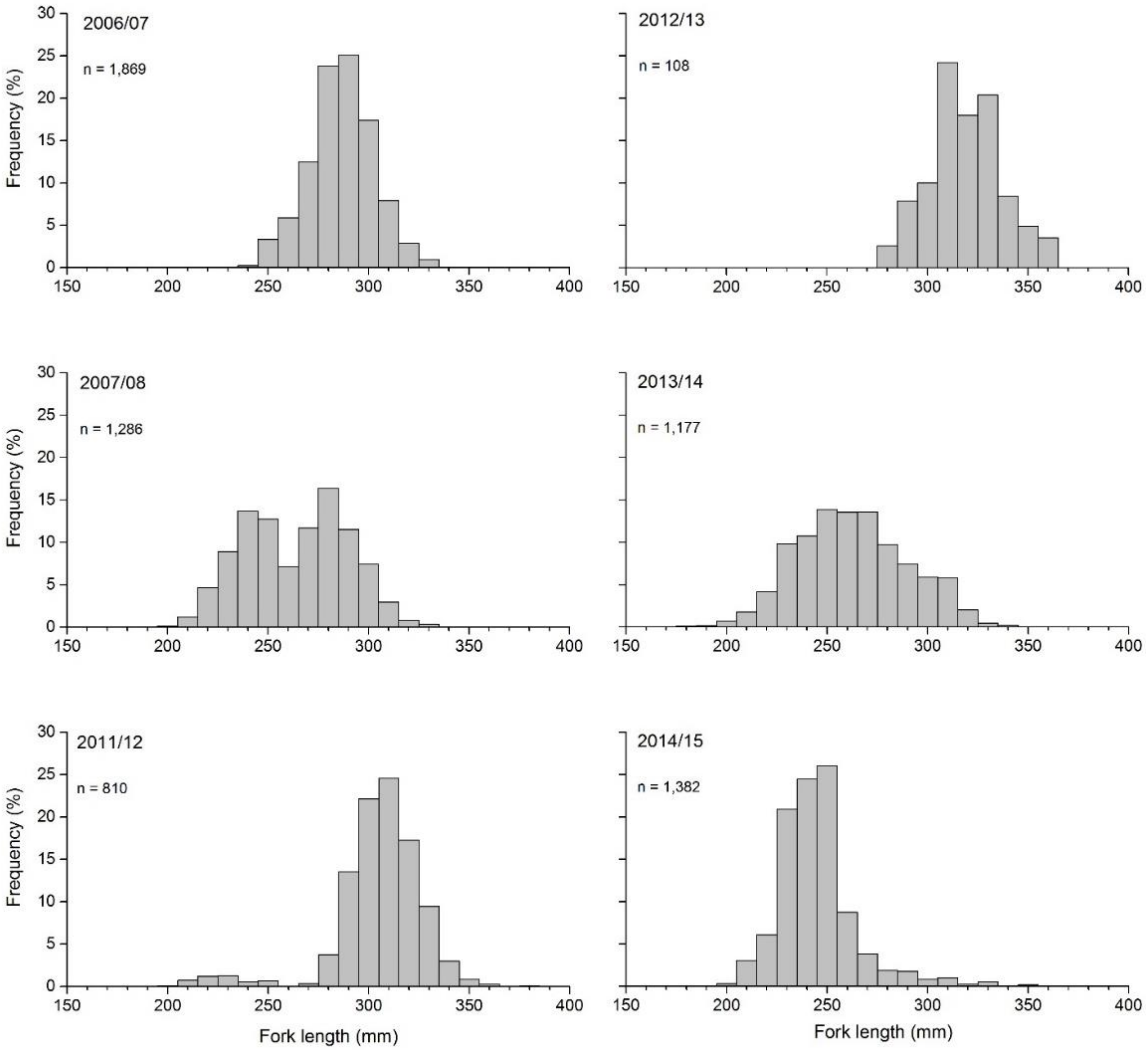

Figure 3.5. Length-frequency distributions (mm FL) of Blue Mackerel East collected from purse-seine shots in New South Wales between 2006/07 and 2014/15 (data supplied by New South Wales DPI).

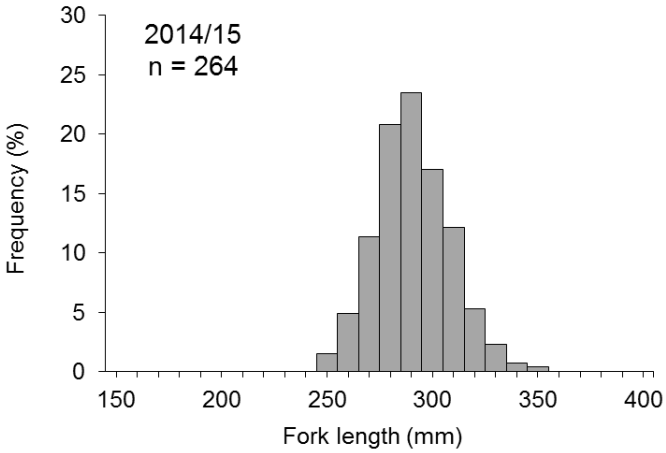

Figure 3.6. Length-frequency distribution of Blue Mackerel East caught by mid-water trawl in the SPF during 2014/15. n = sample size. Data supplied by SARDI Aquatic Sciences.

Age structure

The age structure of Blue Mackerel East caught in mid-water trawls was dominated by 3 to 5 year old fish in 2014/15 (72%) with ages ranging from 1 to 8 years (age mode: 3 years; Figure 3.7).

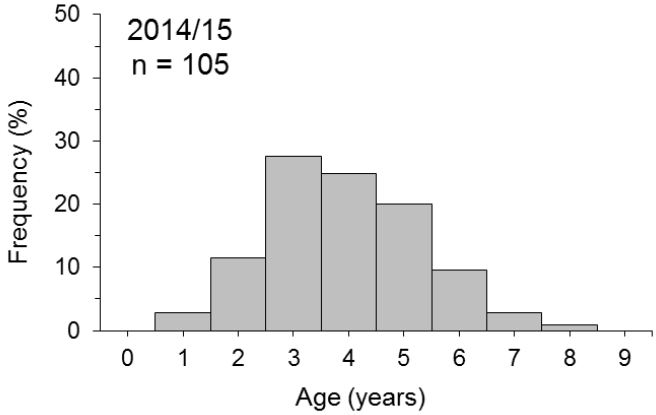

Figure 3.7. Age-frequency distribution of Blue Mackerel East caught by mid-water trawl in the SPF during 2014/15. n = sample size. Data supplied by SARDI Aquatic Sciences.

3.3.2 Blue Mackerel West

3.3.2.1 Fishery statistics

Number of vessels

The number of vessels reporting catches of Blue Mackerel West declined from a high of 23 vessels in 2008/09 to a low of 5 vessels in 2013/14. During 2014/15, 6 vessels reported catches of Blue Mackerel West; vessel numbers have ranged from 5 to 11 since 2010/11.

Annual patterns: Total catch

Total annual catches of Blue Mackerel West were low in the late 1990s and early 2000s (<55 t) and increased to >2000 t in both 2006/07 and 2008/09 (Figure 3.8). Since then, annual catches have decreased to <2 t in 2012/13 and have stayed low with 0.4 t being taken in 2014/15 (Figure 3.8). Historically, the SPF has been the main fishery taking Blue Mackerel West.

Annual patterns: Catch and Effort

Purse-seines have historically been the dominant gear type used in the SPF to land Blue Mackerel West (Figure 3.9). During the early to mid-2000s, there was also limited use of mid-water trawls (<45 t per year taken, Figure 3.9).

Since 1997/98, SPF purse-seining effort for Blue Mackerel West has been variable (Figure 3.10). Purse-seine effort was high (26 boat days) with a low catch (27 t) in 1997/98. Effort and catch peaked in the mid- to late-2000s with effort ranging from 13 to 60 boat days (Figure 3.10). Purse-seine effort and catch in the SPF has decreased since 2008/09, with zero catch and effort since 2012/13.

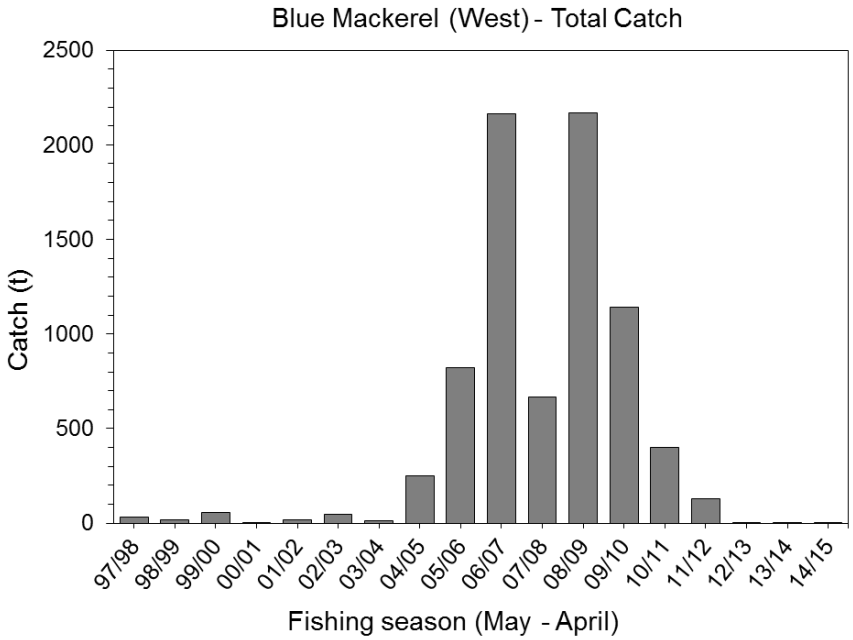

Figure 3.8. Total annual landed catch (tonnes) of Blue Mackerel West for each fishing season from 1997/98 to 2014/15.

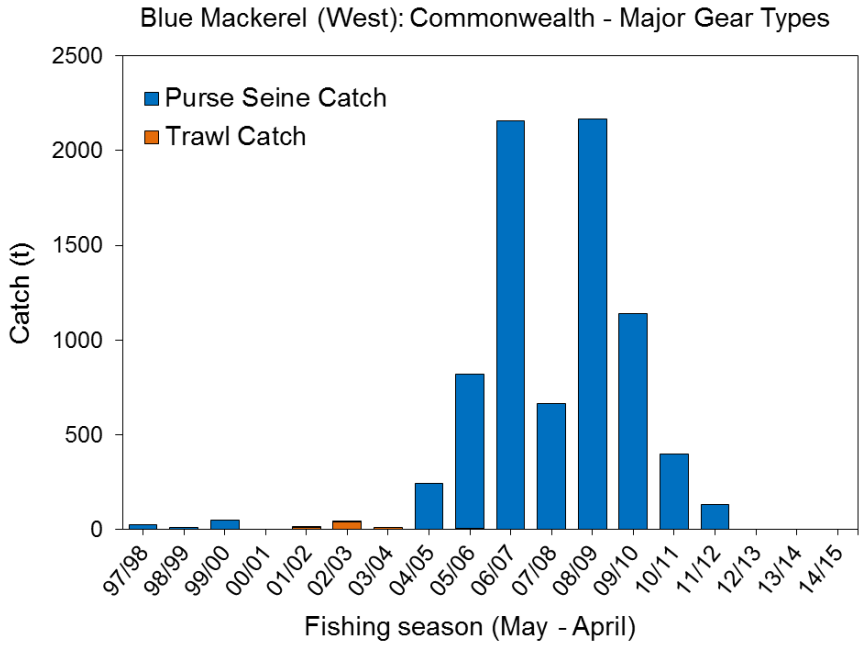

Figure 3.9. Annual landed catch (tonnes) of Blue Mackerel West taken by purse-seine and mid-water trawl in the SPF for each fishing season from 1997/98 to 2014/15.

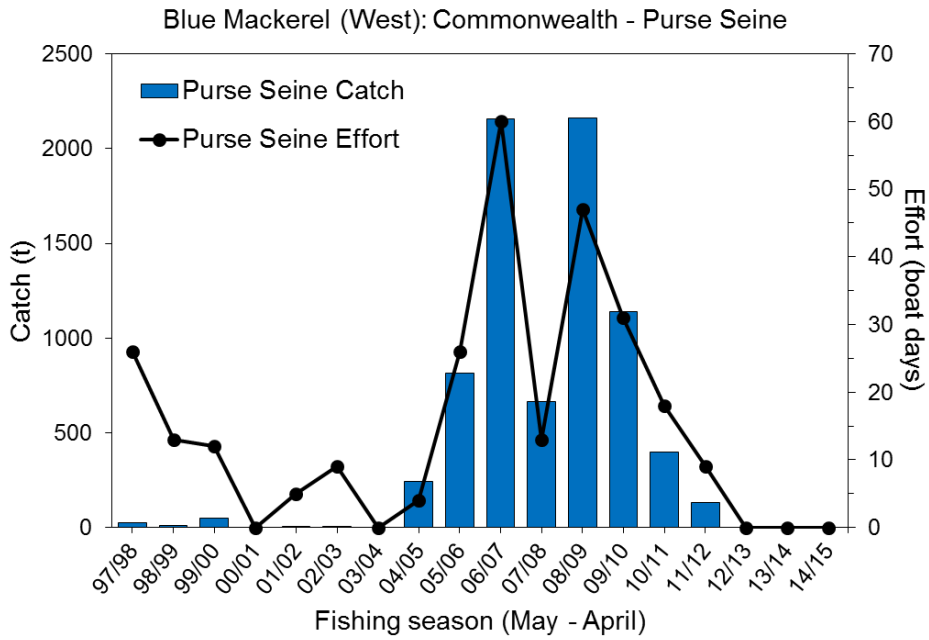

Figure 3.10. Annual landed catch (tonnes) and effort (boat days) of Blue Mackerel West by purse-seine in the SPF for each fishing season from 1997/98 to 2014/15.

3.3.2.2 Biological Information

Sample Summary

Samples of Blue Mackerel West for biological analysis were collected from purse-seine catches taken off South Australia (Table 3.3). A total of 1,257 fish were sampled over the three years; sex ratios were close to 1:1 but slightly biased towards females (Table 3.3). Blue Mackerel West catches from 2008/09 to 2010/11 were limited to the summer/early autumn period, and biological samples from these catches may not be representative of the Blue Mackerel population in that sub-area. No samples were collected from 2011/12 to 2014/15, which reflects the recent low levels of fishing activity in the West.

Table 3.3. Summary of Blue Mackerel West samples collected from commercial purse-seine catches 2008/09 and 2010/11.

Season	No. of samples	Length-frequency n	Age-frequency n	Size range (mm FL)	Sex ratio M:F
2008/09	1	79	74	316–390	1:1
2009/10	28	933	396	245–400	0.9:1
2010/11	8	245	180	293–395	0.9:1

Size structure

Blue Mackerel West sampled during 2008/09 off South Australia ranged from 320 to 390 mm FL (Figure 3.11), and >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 3.11) were larger than those of fish caught in the East (250–310 mm FL; Figures 3.5–3.6).

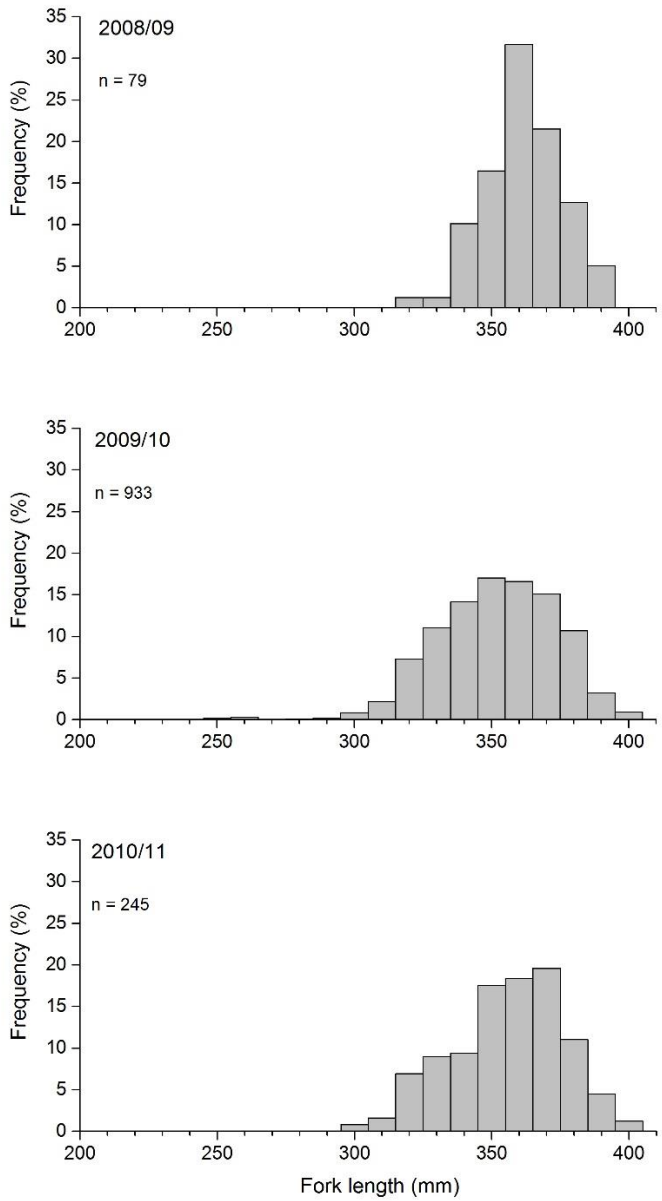

Figure 3.11. Length-frequency distributions of Blue Mackerel West caught by purse-seine in the SPF from 2008/09 to 2010/11; n = sample size.

Age structure

In 2008/09, ages ranged from 3 to 6 years (Figure 3.12) and 82% of fish were 4 and 5 years old. A similar age structure was identified in 2009/10 and 2010/11, however a greater range of ages were observed, with fish aged up to 8 years. In all years, the majority of fish were older than three years.

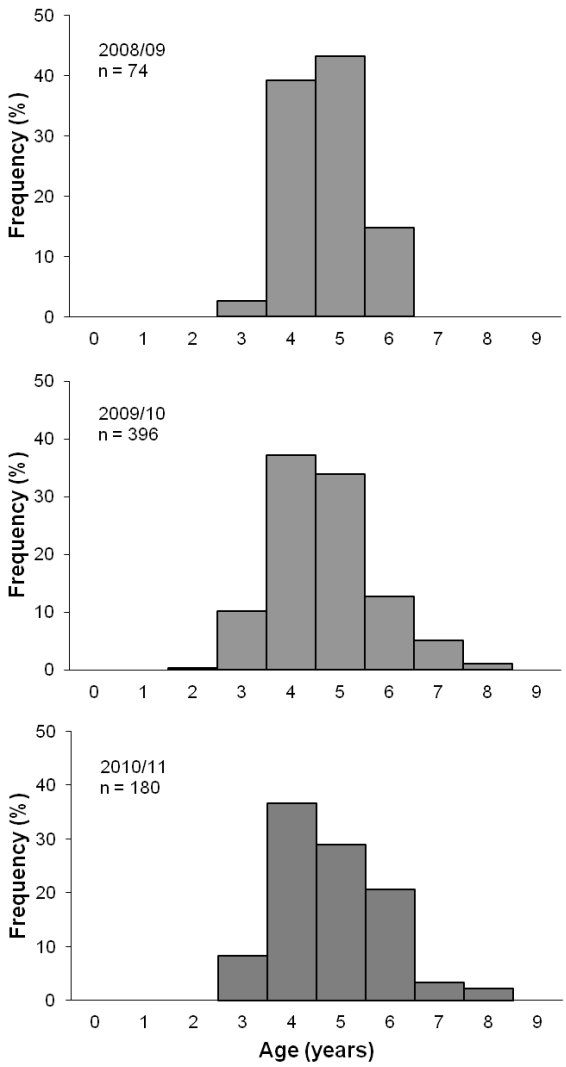

Figure 3.12. Age-frequency distribution for Blue Mackerel West from 2008/09 to 2010/11; n = sample size.

3.4 Summary and Conclusions

3.4.1 Blue Mackerel East

The spawning biomass of Blue Mackerel East during 2014 was estimated to be ~83,300 t (95% CI = 35,100–165,000 t; Ward et al. 2015b), which is higher than the preliminary estimate obtained for Blue Mackerel East in 2004 of 23,009 t (Ward and Rogers 2007; Ward et al. 2009). Ward et al. (2015b) recommended that the estimate of spawning biomass for 2014 should be used with caution due to uncertainty in the estimates of adult parameters, especially spawning fraction.

The total annual catch of Blue Mackerel East peaked at 1,036 t in 2003/04 and decreased to a low of 290 t in 2011/12. In the SPF, there has been a general long-term decline in purse-seine effort for Blue Mackerel East with increased effort using mid-water trawls in 2014/15. The total catch in 2014/15 was 442 t. This decline in total catch reflects reductions in fishing effort rather than a decline in abundance.

The size structure from commercial mid-water trawl catch samples in 2014/15 (modal length: 290 mm FL) was larger compared to the 2014/15 purse seine structure (modal length: 250 mm FL). Size structures of Blue Mackerel East in purse seine catches since 2006/07 have varied among years, and the modal length has reduced since 2012/13. Blue Mackerel East from mid-water trawl catches have been well above the mean size at 50% maturity of ~260 mm FL (Ward and Rogers 2007) with age classes mainly 3–5 years.

Recent catches of Blue Mackerel East are assessed as sustainable, as they have been <1% of the estimated spawning biomass for 2014 (Ward et al. 2015b), and well below the sustainable exploitation rate of 23% suggested for this stock (Smith et al. 2015). Using the definitions of Flood et al. (2014), the stock of Blue Mackerel East is also classified as sustainable.The Blue Mackerel stock in the East was classified as ‘not overfished’ and ‘not subject to overfishing’ by Patterson et al. (2015).

3.4.2 Blue Mackerel West

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).

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. Total annual catches decreased to <2 t in 2012/13 and have stayed low, with just 0.4 t being taken in 2014/15 t. Low annual catches in recent years reflect low levels of fishing effort.

Blue Mackerel from commercial catch samples in the West have been well above the mean size at 50% maturity of ~260 mm FL (Ward and Rogers 2007) and are generally larger and older than those from the East. During 2014/15, no catch samples were collected for Blue Mackerel West due to the limited fishing activity.

The Blue Mackerel stock in the West was classified as ‘not overfished’ and ‘not subject to overfishing’ by Patterson et al. (2015). Fishery-dependent and -independent data presented in this report suggest that the current level of fishing pressure on Blue Mackerel West is unlikely to cause the stock to become recruitment overfished. The stock of Blue Mackerel East is classified as sustainable using the definitions of Flood et al. (2014). Recent catches of Blue Mackerel West have been <1% of the estimated spawning biomass for 2005 (Ward and Roger 2007), which is well below the sustainable exploitation rate of 23% suggested for this stock (Smith et al. 2015). However, it is noted that the current estimate of spawning biomass for Blue Mackerel West is more than 10 years old and should be updated.

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 shot-by-shot record of fishing operations and species taken. Landings of Redbait rarely exceeded 5% of the total catch, but the high volume of production meant that 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 use in 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). Emmelichthyids are widespread and found throughout tropical and temperate waters around the globe. 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 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

Redbait is 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, its 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, Bulman et al. (2008) concluded that Redbait from eastern Australia were likely to be a single stock based on spawning dynamics. The situation for western Tasmania and the GAB is less clear. Neira et al. (2008) observed Redbait from eastern and south-western Tasmania exhibit biological differences, which provides some evidence for separation into eastern and western stocks around Tasmania.

4.1.5 Movement

No studies have investigated Redbait movement.

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 individuals (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 of unspecified size, captured on the shelf off eastern Victoria 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 these species also feed on similar prey items.

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); this is considerably smaller than reported for the species 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, derived from otoliths, suggest rapid growth in the first years of life (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 varies greatly by region. Age validation of Rubyfish in New Zealand, using otolith 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 very 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 compared to Redbait from eastern Tasmania (Ewing and Lyle 2009). However, Ewing and Lyle (2009) suggested this difference could have resulted from sampling bias due to slightly 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 (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

An application of the DEPM to Redbait East occurred during 2005 and 2006 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 conservative and considered negatively biased, since they were derived from an area likely be less than half the actual spawning area of Redbait in south-eastern Australia (Neira and Lyle 2011).

West

The DEPM has not been applied to Redbait in the West sub-area of the SPF.

4.1.13 Management Strategy Evaluation

2010

For Redbait East, the DEPM estimate of spawning biomass was 23% of the model calculated estimate of spawning biomass (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 these harvest quantities are “absolute” quantities and represent a much smaller proportion of the model calculated biomass than the DEPM estimate of biomass.

The results for Redbait West are similar to those of Redbait East. 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 should not be applied for more than 10 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).

4.1.14 Management

A DEPM assessment of Redbait East was conducted during 2005–2006. The fishery in both the East and West sub-areas is currently managed at the Tier 2 level.

4.2 Methods

4.2.1 Fishery Statistics

Fishery statistics from 1997/98 to 2014/15 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 supplied for Redbait East include data from the NSW Ocean Fisheries (Hauling and 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.

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. 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. Following the commencement of mid-water trawl

operations 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 was implemented in 2009/10 as part of the SPF monitoring program under the SPF Harvest Strategy (AFMA 2008). Catch samples were not obtained 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 shot) and supplied to SARDI Aquatic Sciences for processing to provide current size and age composition estimates 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 (to the nearest 0.1 g). Otoliths were removed from random sub-samples of the fish for age estimation. 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. Ages for Redbait East in 2014/15 were based on annual growth increment counts in thin-sectioned otoliths (sub-sample n = 10 fish per sample). Gonad stages were designated as: I) immature; II) maturing virgins or recovering spent; III) maturing; IV) ripe; and V) spent.

Commercial logbook information, length-frequency and biological data collected between 1984 and 2015 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; all current SPF catch sampling data are presented in the current fishing season from 1 May 2014 to 30 April 2015.

4.3 Results

4.3.1 Redbait East

4.3.1.1 Fishery Statistics

Number of vessels

Since 1997/98, a limited number of vessels have reported catches of Redbait East; annual vessels numbers have ranged from zero (2013/14) to 10 (2010/11). On average, over the last 18 years, four boats per year have reported catches of Redbait East. The SPF has generally accounted for >50% of the annual catch. In 2014/15, only 1 vessel landed Redbait East.

Annual patterns: Total catch

Due the confidentiality of data from State jurisdictions (i.e. <5 license holders reporting catch per year), only SPF catches will be discussed in this section. From 1997/98 to 2000/01, Redbait East catches did not exceed 315 t, and purse-seining was prevalent (Figure 4.1). Mid-water trawls replaced purse-seines beginning in the early 2000s (Figure 4.1). With the change to mid-water trawling, catches increased substantially to 3,610 t in 2001/02 and peaked at 7,446 t in 2003/04. From then, annual catches declined to 75 t in 2010/11. No catches of Redbait East were reported from 2011/12 to 2013/14; a total of 2.1 t was reported in 2014/15.

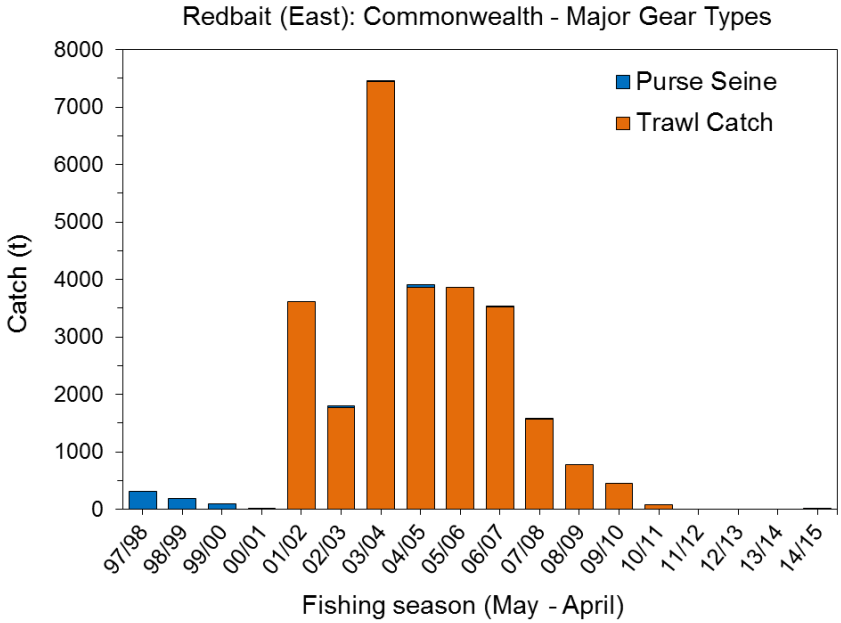

Figure 4.1. Annual landed catch (tonnes) in the SPF of Redbait East taken by purse-seine and mid-water trawl for each fishing season from 1997/98 to 2014/15.

Annual patterns: Catch and Effort

Purse-seining catch and effort for Redbait East in the SPF was highest in the late 1990s with catches ranging from 98 to 315 t and effort ranging from 7 to 18 boat days (Figure 4.2). From there, the use of purse-seines declined, and there have been no reported catches since 2007/08 (Figure 4.2).

Trends of mid-water trawl effort over time have been similar to annual catch for Redbait East, i.e. trawl effort peaked in 2003/04 (126 boat days; 7,439 t), decreased to zero effort from 2011/12 to 2013/14, and increased to 2 boat days in 2014/15 (2.1 t, Figure 4.3).

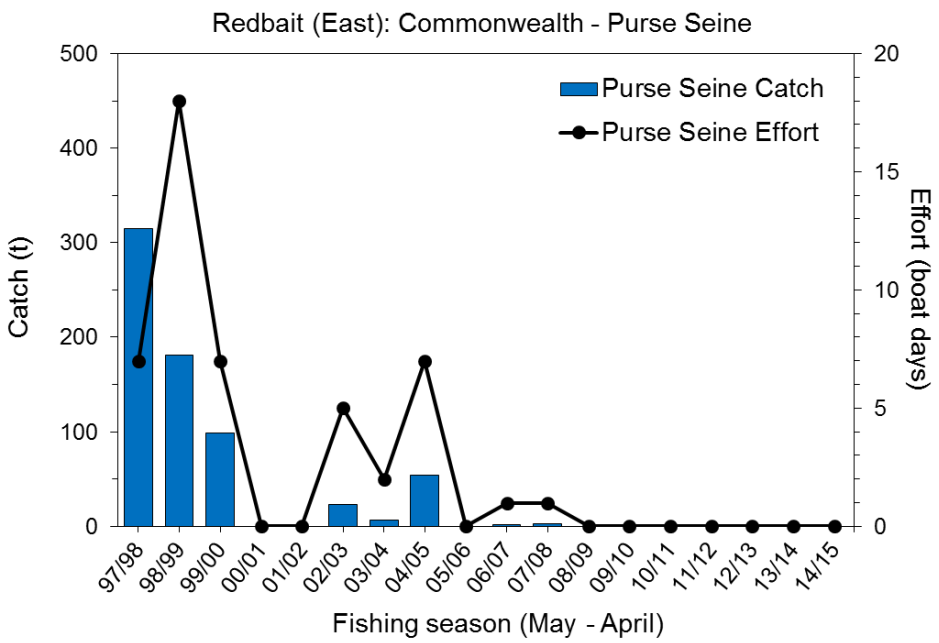

Figure 4.2. Annual landed catch (tonnes) and effort (boat days) of Redbait East by purse-seine in the SPF for each fishing season from 1997/98 to 2014/15.

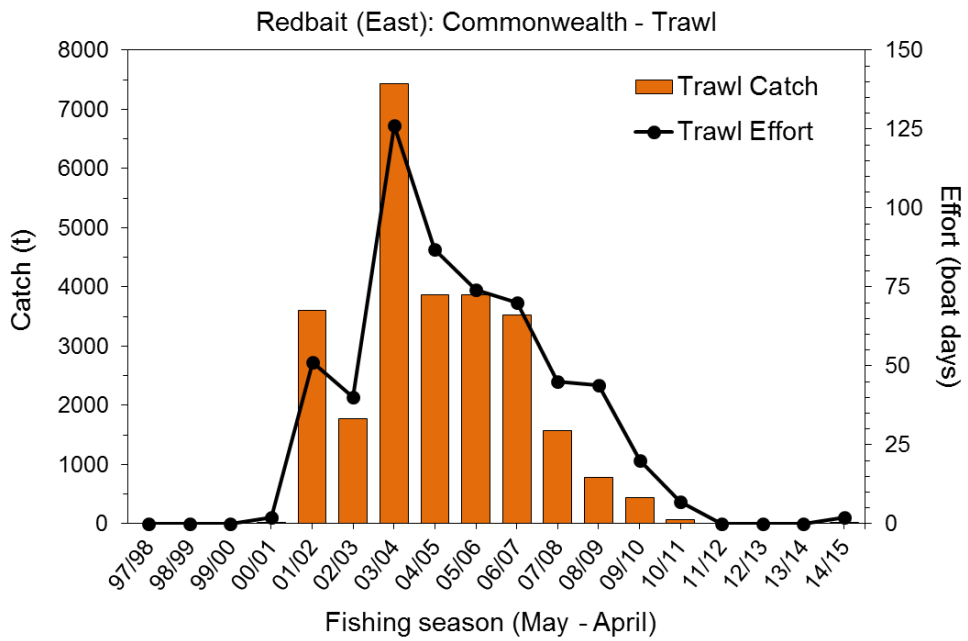

Figure 4.3. Annual landed catch (tonnes) and effort (boat days) of Redbait East by mid-water trawl in the SPF for each fishing season from 1997/98 to 2014/15.

4.3.1.2 Biological Information

Catch sampling of Redbait East off Tasmania during 2009/10 resulted in the collection of 494 fish from purse-seines and 393 fish from mid-water trawls (Table 4.1). Due to limited commercial fishing for Redbait in the SPF, catch samples were not obtained between 2010/11 and 2013/14. In 2014/15, length-frequency data were collected from 62 Redbait sampled from commercial mid-water trawl catches taken off southern New South Wales during April 2015; age-frequency data were collected from 42 of those fish (Table 4.1).

Table 4.1. Summary of Redbait catch samples collected during 2009/10 and 2014/15 from commercial SPF landings in the East sub-area of the SPF.

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	3	62	42	200–275	2–14

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 were mainly between 140 and 290 mm FL, with individuals recorded up to 320 mm FL (Figure 4.4). 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 (<200 mm FL) dominated the catch (Figure 4.4). No data were collected between 2010/11 and 2014/15.

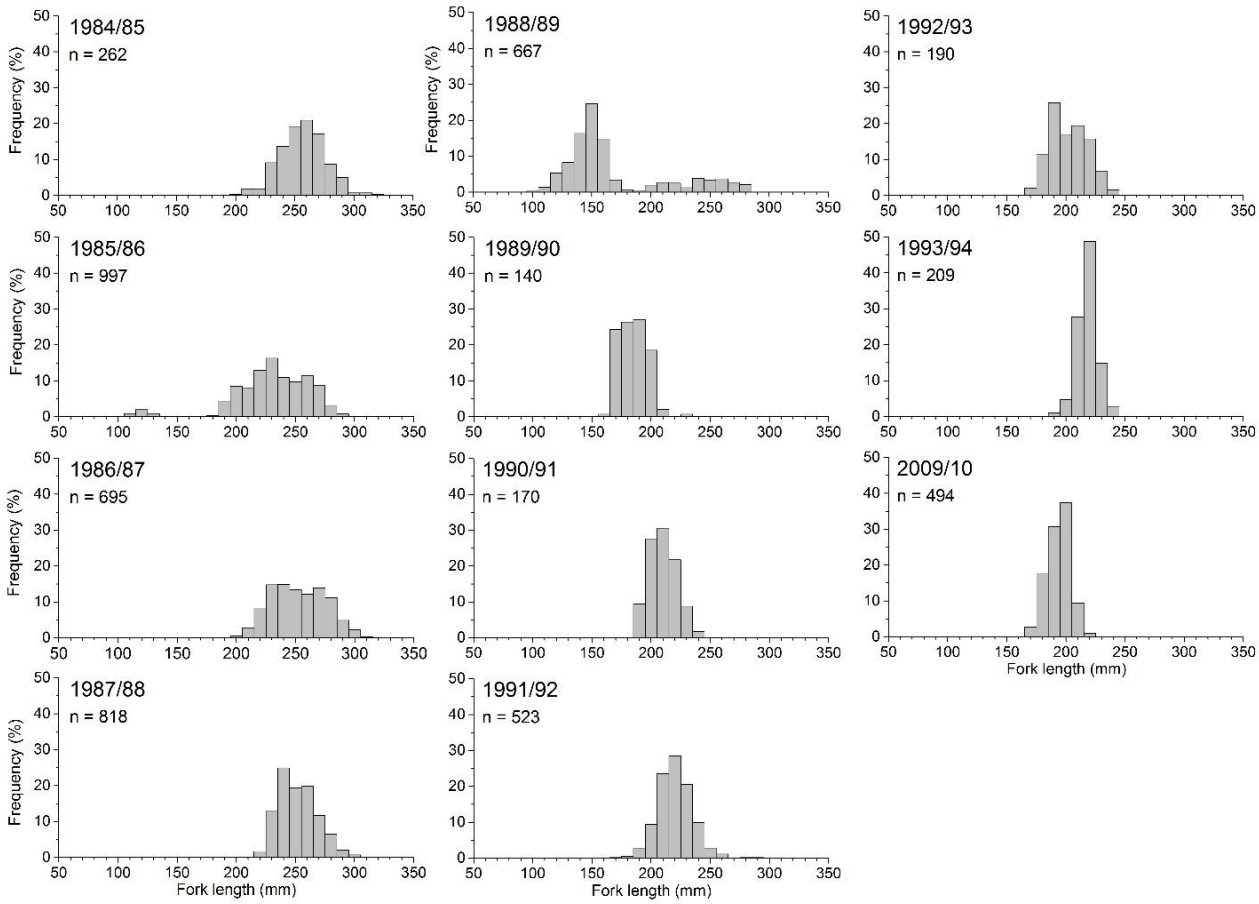

Figure 4.4. Length-frequency distributions (mm FL) of Redbait caught in the SPF by purse-seine from 1984/85 to 1993/94 and 2009/10. n = sample size.

Mid-water trawl fishery: 2001/02–2014/15

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 210 mm FL (Figures 4.4–4.5). East sub-area catches comprised a high proportion of small fish with modes varying between 140 and 210 mm FL (Figure 4.5). Only a small proportion of the catch was made up of fish larger than 200 mm FL.

The size structure of Redbait East increased in mid-water trawl catches off eastern Tasmania during 2009/10; fish were primarily 190–240 mm FL (modal length: 190 mm FL; Figure 4.5). The size structure in the East sub-area continued to increase in 2014/15 (modal length: 230 mm FL; range: 200–280 mm FL; Figure 4.5). The size structures of mid-water trawl catches since 2009/10 were generally larger than that of purse-seine catches in 2009/10 (Figures 4.4–4.5).

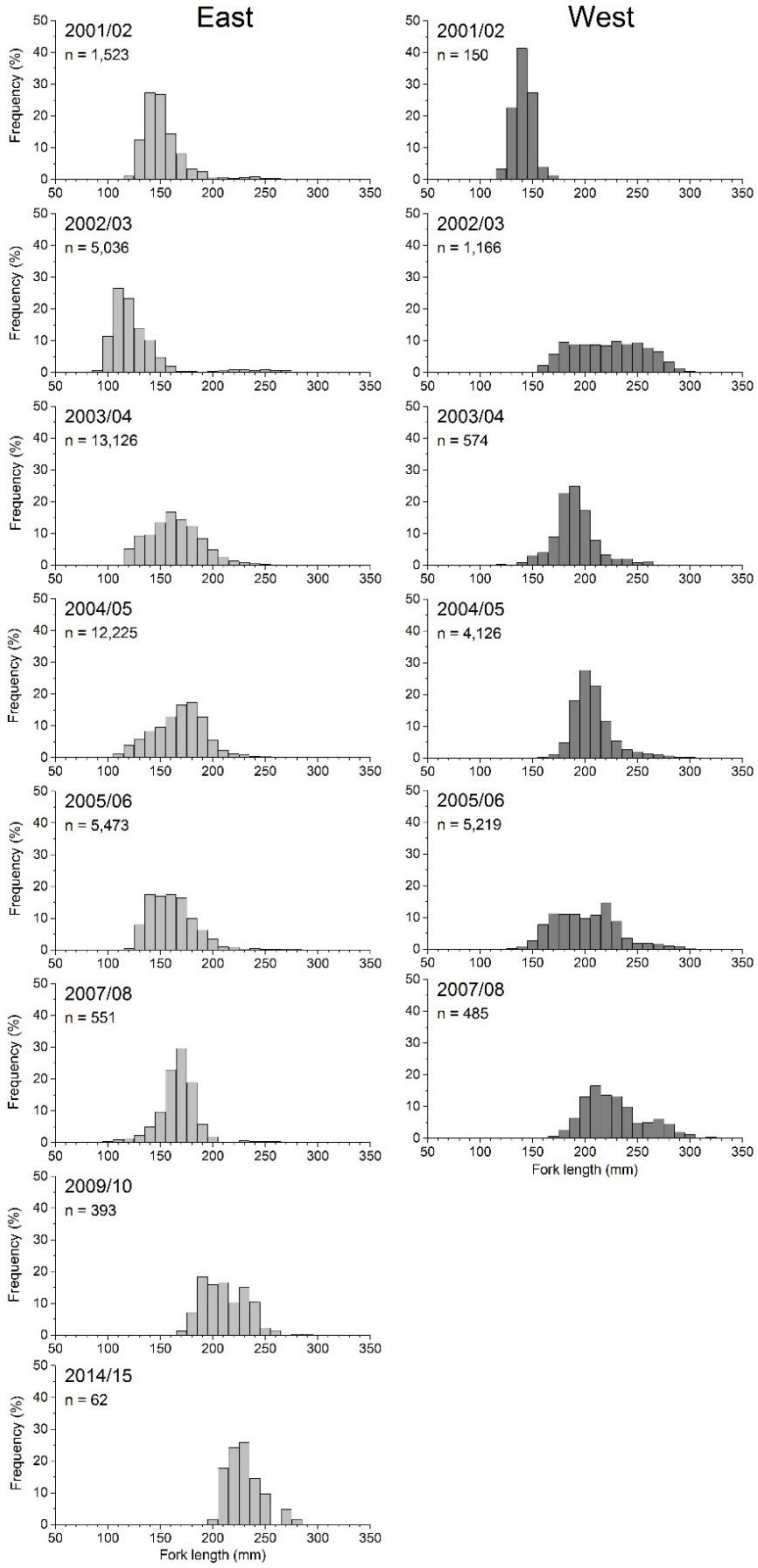

Figure 4.5. Length-frequency distributions of Redbait caught by mid-water trawl in the East and West sub-areas of the SPF. n = sample size.

Age structure

The purse-seine fishery: 2009/10

Purse-seine catches off eastern Tasmania were mainly composed of 2 and 3 year old fish in 2009/10, with 2 year olds constituting greater than half of the catch (Figure 4.6). Age data for Redbait East caught by purse-seine in the SPF were not available for other years.

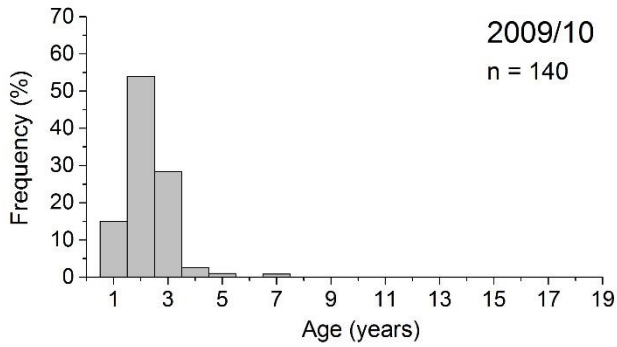

Figure 4.6. Age-frequency distribution of Redbait East caught by purse-seine in the SPF during 2009/10; n = sample size.

Mid-water trawl fishery: 2001/02–2014/15

Mid-water trawl catches of Redbait East mainly contained fish between 1 and 5 years with maximum ages of 14 years (Figure 4.7). 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 4.7). Mid-water trawl catches of 2009/10 had a slightly older age structure than purse-seine catches in the same year (Table 4.1; Figures 4.6–4.7). In 2014/15, the age structure continued to become older: 51% of the fish were 3 to 4 years old (Figure 4.7). However, it should be noted that the 2014/15 age structure is only based on a small sample size of 42 fish.

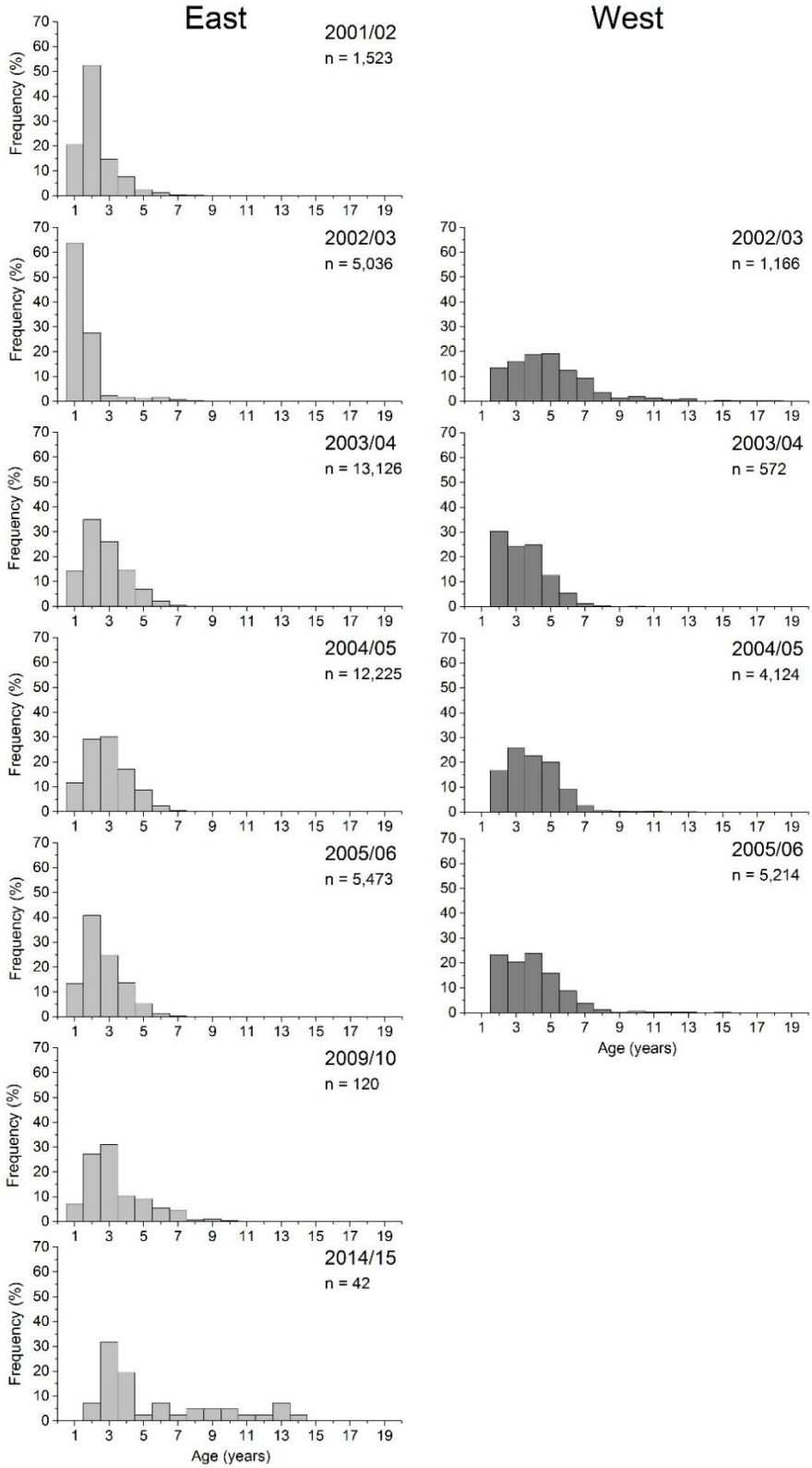

Figure 4.7. Age-frequency distributions of Redbait caught by mid-water trawl in the East and West sub-areas of the SPF; n = sample size.

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 1997/98 were even lower than those in the East: the annual average was 1 boat per year. The SPF is the principal fishery reporting catches of Redbait West. In 2014/15, zero vessels reported catches of Redbait West.

Annual patterns: Total catch

Due the confidentiality of data originating from State jurisdictions (i.e. <5 license holders reporting catch per year), only SPF catches will be discussed in this section. Historically, Redbait catches in the West sub-area have been lower than those in the East, but follow a similar temporal trend (Figure 4.8). Mid-water trawling has been the primary method used to target Redbait West. From 1997/98 to 2000/01, there were no reported catches of Redbait West; annual catches began increasing in 2001/02 and peaked at 3,228 t in 2006/07 (Figure 4.8). From then, annual catches progressively declined to 298 t in 2009/10. There has been no reported catch of Redbait West since then.

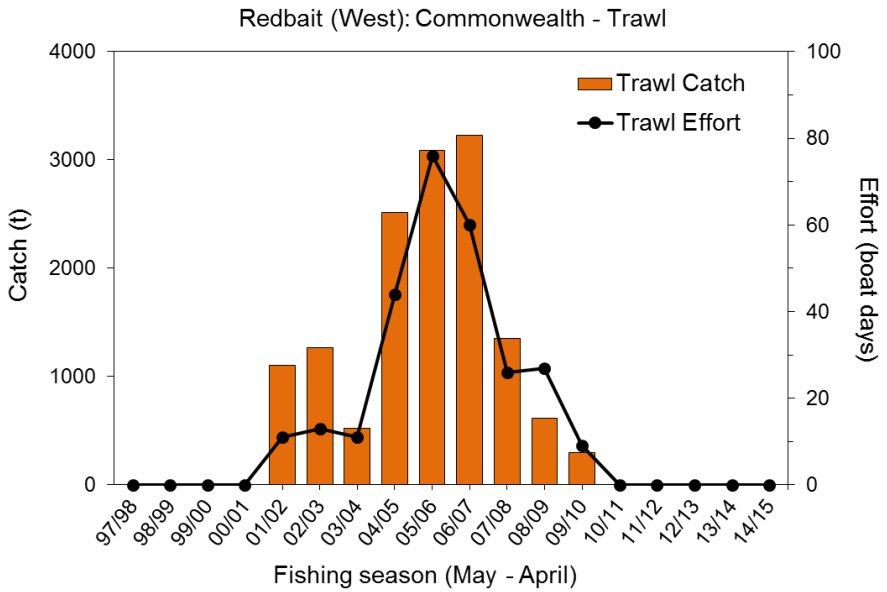

Figure 4.8. Annual landed catch (tonnes) and effort (boat days) of Redbait West by mid-water trawl in the SPF for each fishing season from 1997/98 to 2014/15.

Annual patterns: Catch and Effort

In the SPF, peak catches of Redbait West by mid-water trawling during the mid-2000s (ranging from 2,511 to 3,228 t) coincided with years when effort was the highest (44 to 76 boat days, Figure 4.8). There has been no reported fishing effort for Redbait West by the SPF since 2009/01 (Figure 4.8).

4.3.2.2 Biological Information

Catch sampling of Redbait West off south-western Tasmania during 2009/10 resulted in the collection of 77 fish from mid-water trawls; age-frequency data were collected from 20 of those fish (Table 4.2). Due to limited commercial fishing for Redbait West in the SPF, catch samples have not been obtained since then.

Table 4.2. Summary of Redbait catch samples collected during 2009/10 from SPF landings in the West sub-area.

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

Size structure

Mid-water trawl fishery: 2001/02–2014/15

Redbait West from mid-water trawl catches off south-western Tasmania during 2001/02 to 2007/08 ranged mainly from 130 to 280 mm FL, with an overall modal length of 200 mm FL (Figure 4.5). Redbait West taken over this time period were larger than those from the East sub-area (overall modal length: 160 mm FL; Figure 4.5).

A single catch of Redbait West (taken from south-western Tasmania) contained fish between 210 and 310 mm FL (mode 240 mm) (Table 4.2). This was consistent with the size range from previous years in that region and is similar to mid-water trawl catches since 2009/10 in the East (Figure 4.5).

Age structure

Mid-water trawl fishery: 2001/02–2014/15

From 2001/02 to 2007/08, the age structure of Redbait West in catches off south-west Tasmania had a higher proportion of older fish than the East sub-area; ages ranged from 2 to 18 years (Figure 4.7). A strong cohort of 2 year old fish was evident in catches during 2003/04; this cohort subsequently dominated catches as 3 year olds in 2004/05 and 4 year olds in 2005/06. A single sample of Redbait West from south-western Tasmania in 2009/10 contained individuals that were substantially older than those sampled from 2009/10 catches in the East (up to 13 years; Table 4.1), with 90% of fish estimated to be over 4 years of age. Due to limited commercial fishing for Redbait West in the SPF, catch samples have not been obtained since 2009/10.

4.4 Summary and Conclusions

4.4.1 Redbait East

The most recent application of the DEPM for Redbait East in 2005 and 2006 estimated a spawning biomass of ~70,000 t (surveys combined; Neira et al. 2008). Neira and Lyle (2011) suggested these estimates were conservative and potentially negatively biased, since the survey area likely excluded more than half of the actual spawning area of Redbait in south-eastern Australia.

Since 1997/98, annual catches of Redbait East in the SPF peaked at 7,446 t in 2003/04 and declined to 75 t in 2010/11. Catches were mainly taken by purse-seining from 1997/98 to 1999/00 and by mid-water trawling from 2001/02 onwards. Minimal fishing has been conducted since 2010/11. The total catch in 2014/15 was 2.1 t. Current low catches of Redbait East appear to reflect low fishing effort rather than low abundance.

Age and length structures of Redbait East since 2001/02 have varied among years, but are difficult to interpret due to the limited fishing effort, small sample sizes and changes in fishing locations over time. The modal size (age) of samples obtained from mid-water trawl catches in 2014/15 of 230 mm FL (3 years) was above the size (age) at 50% maturity of ~150 mm FL (2 years).

Recent catches of Redbait East are assessed as sustainable, as they have been <1% of the estimated spawning biomass for 2005 and 2006 (Neira et al. 2008), and well below the sustainable exploitation rate of 9% suggested for this stock (Smith et al. 2015). Using the definitions of Flood et al. (2014), the stock of Blue Mackerel East is also classified as sustainable. Patterson et al. (2015) classified the Redbait East stock as ‘not overfished’ and ‘not subject to overfishing’.

However, the current estimate of spawning biomass for Redbait East is 10 years old and should be updated.

4.4.2 Redbait West

The DEPM has not been applied to Redbait West, and an empirical estimate of spawning biomass is not available for this stock. Total annual catches of Redbait West peaked at 3228 t in 2006/07 and progressively declined to 298 t in 2009/10. Catches have been mainly taken by mid-water trawling since 1997/98. There have been no reported catches of Redbait West since 2009/10; this is due to low fishing effort rather than low abundance.

Age and length structures of Redbait West from 2001/02–2009/10 have varied among years, but are difficult to interpret due to the limited fishing effort, small sample sizes and changes in fishing locations over time. The modal size (age) of samples obtained from mid-water trawl catches has ranged from 140–240 mm FL (2–5 years), and have generally been below the size and age at 50% maturity of ~250 mm FL and 4 years. However, reported size and age at 50% maturity should be reviewed for Redbait West as differences between East and West population may have resulted from depth-based sampling bias (Ewing and Lyle 2009).

Redbait West is likely to be sustainable, because catches have been small in recent years. The stock of Redbait East is also classified as sustainable using the definitions of Flood et al. (2014). Patterson et al. (2015) classified Redbait West as ‘uncertain’, due to the lack of estimates of spawning biomass for the stock. However, given the absence of catches in recent years, Redbait West is classified as ‘not subject to overfishing’ (Patterson et al. 2015).

An estimate of the spawning biomass is needed to confirm the status of Redbait West, especially if effort/catches were to increase significantly.

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 (Stratoudakis et al. 2006). Australian Sardine (*Sardinops sagax*) support several commercial fisheries in temperate 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, when several purse-seine fisheries were developed in south-western Western Australia. From then, annual catch in Western Australia increased steadily to ~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). Between 1994 and 2001, catches in this fishery ranged between 3,000 and 6,000 t.

In 1995 and 1998, two mass mortality events affected all Australian Sardine populations and reduced the biomass in South Australia by 75% and 70%, respectively (Ward et al. 2001b). Catches in the Western Australian Sardine fishery have remained low since these mortality events (<3,000 t since 1999), but current catch rates are greater than pre-mortality levels (Fletcher and Santoro 2015). In 2014, ~1,500 t of Australian Sardine were taken in Western Australia (Fletcher and Santoro 2015). The South Australian fishery recovered relatively quickly after the mortality events with a catch of ~14,000 t in 2002 and annual catches above 27,000 t since 2007 (Ward et al. 2015d). In 2014, the total catch by the South Australian fishery was 33,972 t (Ward et al. 2015d).

In 1996, a 3-year developmental fishery permit was issued for a single purse-seine vessel to take 600 t of four small pelagic fish species, including Sardine (Ward and Staunton-Smith 2002). Sardine catches from southern Queensland prior to 1996 were minimal as only small quantities were taken by beach seine nets for bait purposes (Ward and Staunton-Smith 2002). In 2000, purse-seine fishing was prohibited in Queensland. In New South Wales, the annual catch of Sardines has increased rapidly in recent years from historical averages of 30–40 t to almost 5,000 t in 2008/09, but declined to 352 t in 2013 as a result of a reduction in fishing effort (Ward et al. 2014a).

5.1.2 Taxonomy

Australian Sardine (*Sardinops sagax*, Jenyns 1842) belong to the order Clupeiformes which is primarily composed of small, stream-lined schooling fishes. This order contains about 400 species in seven families, including *Clupeidae* (sardines, shads, menhadens, herrings) and *Engraulidae* (anchovies) (Eschmeyer and Fricke 2016). *Clupeidae*, of which the Australian Sardine is a member, are mostly marine forage fishes that are characterised by a compressed, silvery body with no obvious lateral line and weakly attached cycloid scales (Gomon et al. 2008). Worldwide, there are more than 50 genera and about 200 species of clupeids (Eschmeyer and Fricke 2016). Of these genera, six occur in waters off southern Australia with each represented by one species (Gomon et al. 2008). The Australian Sardine is the single representative of the genus *Sardinops*.

5.1.3 Distribution

Australian 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

There is a high level of genetic heterogeneity within the Australian stock of Sardine, but no evidence of spatially consistent stock structure (Okazaki et al. 1996, Ward et al. 1998). The existence of separate eastern and western stocks has been proposed for the species, with the Bass Strait suggested as a significant barrier to gene flow (Izzo et al. 2012). However, no studies have been undertaken across the distribution of Australian Sardine to confirm this.

Information on the movement rates of Australian Sardine across their distribution would assist future management. An Australia-wide study that concurrently uses genetic, parasitic and otolith-based lines of evidence is a practical approach to address questions of stock structure and movement rates; similar methodology has been successfully applied to several species of mackerel (e.g. Buckworth et al. 2006, Ward and Rogers 2007).

5.1.5 Movement

Sardines are known to 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 Sardine 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). Despite this, the use of sectioned sagittal otoliths for ageing sardine from southern Australia has been problematic 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, yet 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 showed 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 Sardines. 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), while Sardines off Fremantle reached maximum GSI values during June (Murhling et al. 2008). Along the east coast of Australia, Sardine reach peak GSI values in winter to early spring (Ward and Staunton-Smith 2002, Ward et al. 2015c), while in southern New South Wales peak GSI values 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). Between 1989 and 1991, Sardine larvae were collected off Sydney in all months, except March (Gray and Miskiewicz 2000).

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 the preferred fishery-independent method of assessing spawning-stock biomass of sardine, worldwide (see review in Barangé et al. 2009), i.e. Atlanto-Iberian Sardine (*Sardina pilchardus*) (Bernal et al. 2011a, Bernal et al. 2011b). This approach is advantageous since it 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. 2014b).

During 2014, two DEPM surveys were applied to Sardine off eastern Australia (Ward et al. 2015a). The first survey identified a significant summer spawning area for Australian Sardine off northern Tasmania and in the Bass Strait, while the second survey quantified the spawning biomass of Australian Sardine East during the peak spawning period in late winter and early spring (Ward et al. 2015b). 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 National Stock Status Report indicated that recreational and indigenous catches of Australian Sardine are likely to be negligible (Ward et al. 2014a).

5.1.12 Biomass Estimates

<u>East</u>

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 in 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 not an estimate of the total adult biomass of Australian Sardine off eastern Australia, it is only an estimate of the portion of the population that was spawning in this part of the range during that period. 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 in south-eastern Australia, 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 ~49,600 t (95% CI = 24,200–213,300 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. 49,600 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).

5.1.14 Management

Australian Sardine East in the SPF are currently managed at the Tier 2 level based on the DEPM assessment that was conducted for the East sub-area in 2004.

5.2 Methods

5.2.1 Fishery Statistics

Fishery statistics from 1997/98 to 2014/15 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 supplied for Australian Sardine East include data from the NSW Ocean Fisheries (Hauling and Trawl), Victorian Ocean Purse Seine Fishery and the Commonwealth SPF.

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 2014/15. 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 South Australian commercial catch relationship (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

In 1998/99, 111 vessels reported catches of Australian Sardine East; 96% were from New South Wales. Since then, the number has gradually declined to 8 vessels in 2013/14. In 2014/15, only 13 commercial vessels reported catches of Australian Sardine East (77% from New South Wales).

Annual patterns: Total catch

From 1997/98 to 2001/02, total catches of Australian Sardine East were relatively low and ranged from 42 t to 733 t (Figure 5.1). From then, catch increased to a peak of 4,619 t in 2007/08, before declining to 893 t in 2014/15. The principal fisheries taking Australian Sardine East have been the New South Wales Ocean Hauling Fishery, the SPF and the Victorian Ocean Purse Seine Fishery.

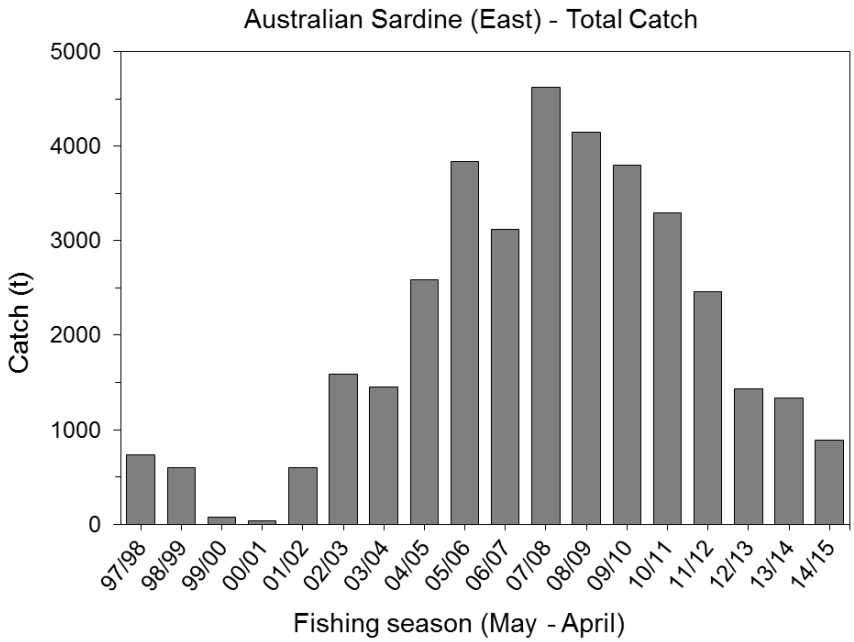

Figure 5.1. Total annual landed catch (tonnes) of Australian Sardine East for each fishing season from 1997/98 to 2014/15.

Annual patterns: Catch and Effort

Purse-seining has been the main method used to take Australian Sardine East. In the New South Wales fishery, purse-seining effort for Australian Sardine has been highly variable among years; in 1999/00, effort was 344 boat days with a catch of only 28 t (Figure 5.2). Fishing effort declined to <125 boat days in the early 2000s and increased to a peak of >350 boat days in the late 2000s. Catches also peaked at ~1950 t during that time (Figure 5.2). Annual catch and effort data are confidential in the New South Wales fishery from 2011/12 to present due to the low number (<5) of license holders reporting catch.

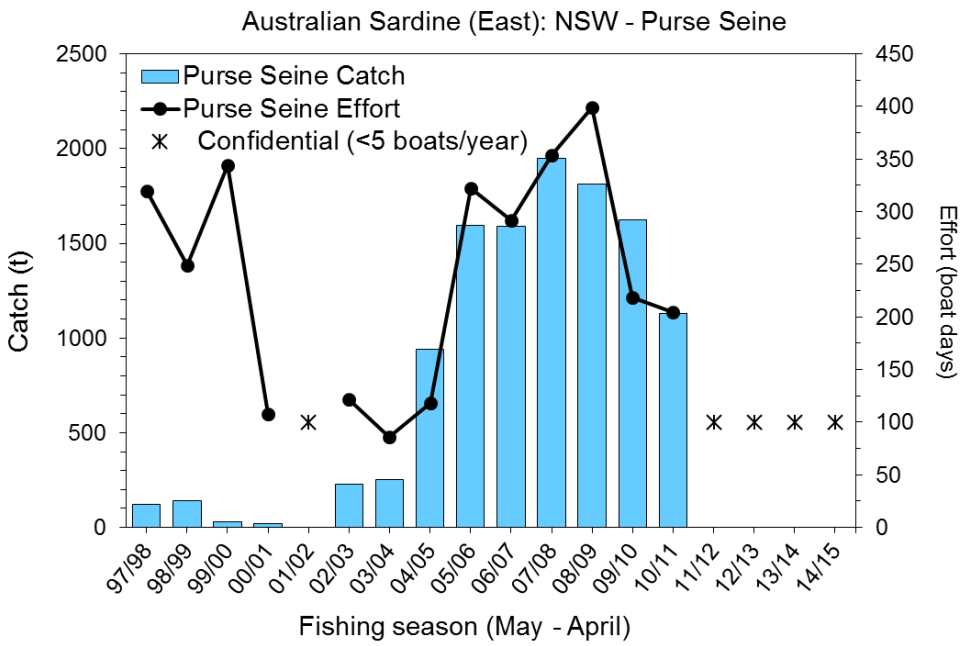

Figure 5.2. Annual landed catch (tonnes) and effort (boat days) of Australian Sardine East by purse-seine in the New South Wales Ocean Hauling Fishery for each fishing season from 1997/98 to 2014/15.

In the SPF, catches of Australian Sardine East have been solely taken by purse-seine. Historically, trends in annual purse-seining effort in the SPF have been substantially less than that in the New South Wales fishery but with only slightly less tonnages of catch. For example, in 2007/08, effort and catch in the New South Wales fishery was 1948 t with 354 boat days compared to 1759 t and 49 boat days in the SPF (Figure 5.3). Catch trends in the SPF are similar to those in the New South Wales fishery, with the highest catches landed in the mid to late 2000s (Figure 5.3). Temporal effort was relatively consistent, averaging 47 boat days from 2004/05 to 2010/11. Both effort and catch of Australian Sardine East in the SPF decreased to low levels between 2011/12 and 2013/14 (Figure 5.3). Fishing effort and catch increased in 2014/15: 152 t of Australian Sardine East were taken in the SPF with 57 boat days of effort (Figure 5.3).

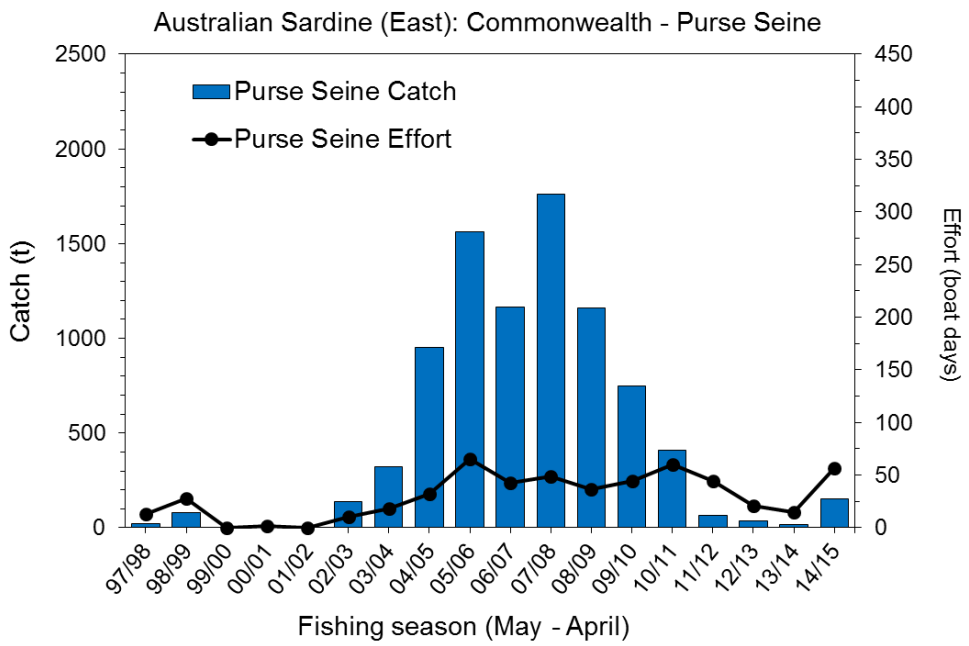

Figure 5.3. Annual landed catch (tonnes) and effort (boat days) of Australian Sardine East by purse-seine in the SPF for each fishing season from 1997/98 to 2014/15.

5.3.1.2 Biological Information

Length-frequency data were collected from 16,587 Australian Sardine East sampled from purse-seine catches in the New South Wales Ocean Hauling Fishery between 2004/05 and 2014/15 (Table 5.1). The number of samples collected in each year ranged between 2 (2004/05) and 54 (2009/10). In 2014/15, 1,223 fish were collected from 12 sampling events.

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).

Table 5.1. Summary of Australian Sardine East samples collected from commercial New South Wales State purse-seine catches between 2004/05 and 2014/15 (data supplied by New South Wales DPI).

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

Table 5.2. Summary of Australian Sardine East catch samples collected from commercial SPF landings off New South Wales from 2009/10 to 2014/15.

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

Size Structure

Annual size distributions for Australian Sardines sampled between 2004/05 and 2014/15 from the New South Wales Ocean Hauling Fishery were mainly between 100 and 200 mm FL, although the modal length varied among years (Figure 5.4). 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. However, the size structures for all other years comprised a single dominant mode between 130 and 170 mm FL. For 2012/13 and 2013/14, the lengths of fish sampled were narrowly distributed around dominant modes at 140–150 mm FL. In 2014/15, the size mode increased to 160 mm SL (Figure 5.4).

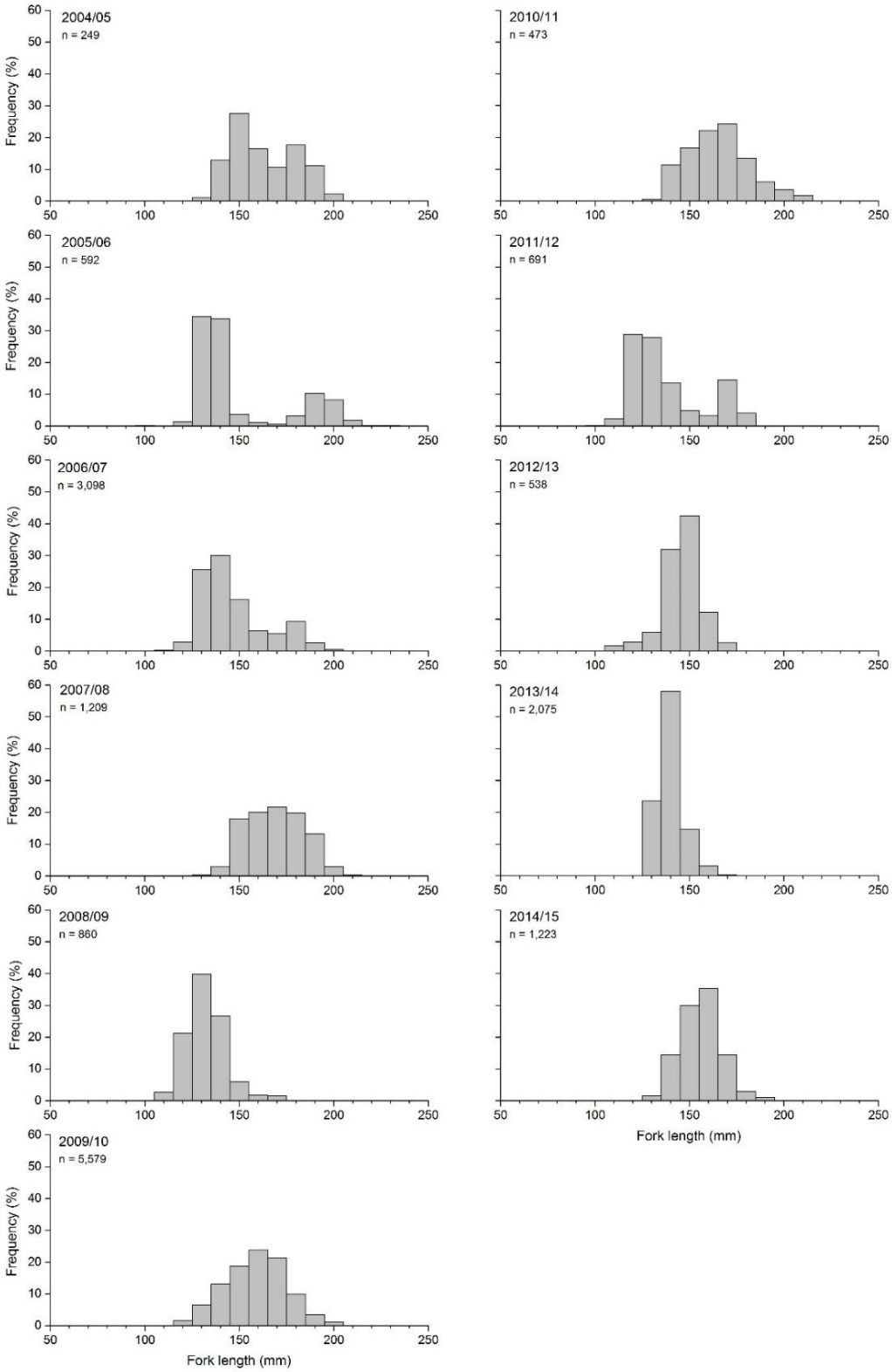

Figure 5.4. Annual length-frequencies (mm FL) of Australian Sardine East sampled from purse-seine catches taken in New South Wales from 2004/05 to 2014/15. Data supplied by New South Wales DPI.

Size structures compared between the north and south coasts of New South Wales in 2009/10 showed Australian Sardine East in the south were, on average, slightly larger than those in the north (Figure 5.5). Purse-seine catch samples taken in the SPF between 2012/13 and 2014/15 indicated a slight increase in the size structure over time but a consistent modal length at 150 mm FL (Figure 5.5).

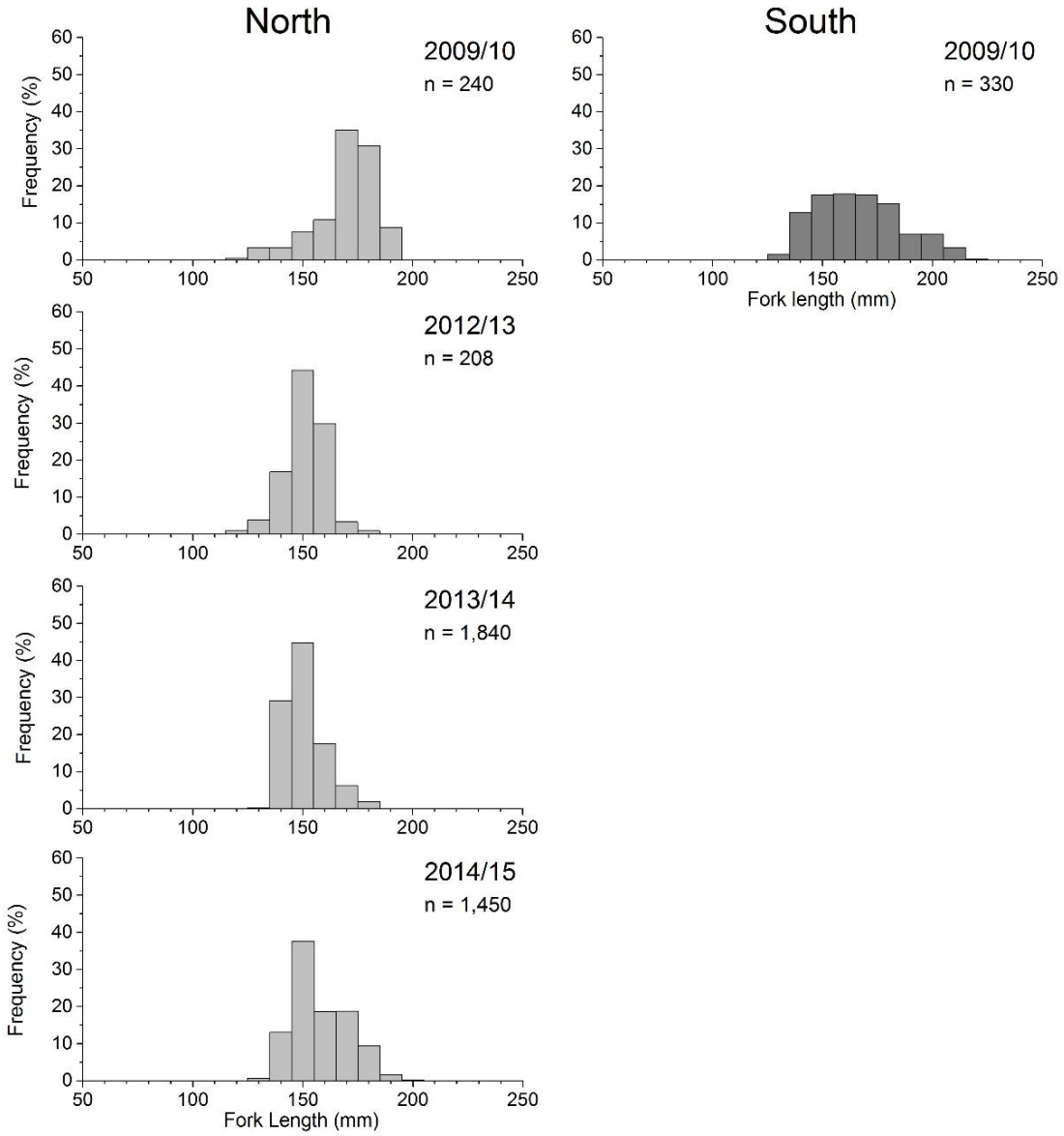

Figure 5.5. Length-frequency distributions of Australian Sardine East caught in the SPF by purse-seining along the northern and southern New South Wales coastline; n = sample size.

Age structure

Ages of Australian Sardine East collected from purse-seine catches in the SPF from the south coast of New South Wales in 2009/10 ranged from 0+ to 5 years, whereas catches from the northern region consisted of individuals from 0+ to 3 years (Figure 5.6). Commercial catch samples from the north in 2012/13 contained mostly 2 year old fish. In 2013/14 and 2014/15, the age structure in the northern region continued to increase, with more fish evident in the 3 and 4 year old age classes. Fish reached a maximum age of 6 years in 2014/15 (Figure 5.6).

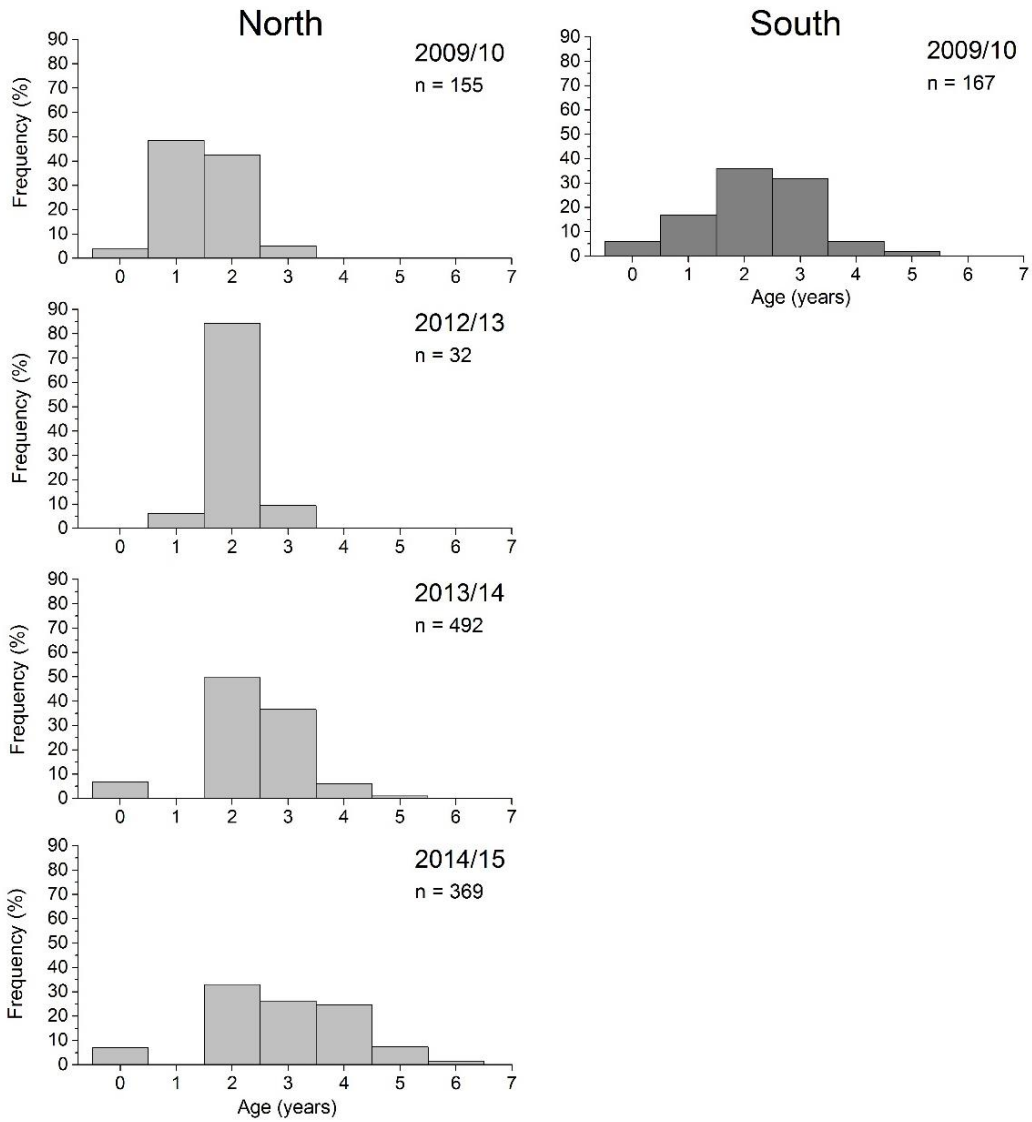

Figure 5.6. Age-frequency distributions of Australian Sardine East caught by purse-seine in the SPF along the northern and southern New South Wales coastline; n = sample size.

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 ~49,600 t (95% CI = 24,200–213,300 t) (Ward et al. 2015b). This estimate is larger than the 2004 estimate of 28,809 t for Australian Sardine off eastern Australia (Ward et al. 2007). Ward et al. (2015b) suggested the main 2014 estimate of spawning biomass was robust, as it was based on reliable estimates of all DEPM parameters but likely negatively-biased due to a portion of the adult population possibly occurring outside the survey area.

Total annual catches of Australian Sardine East peaked at 4,619 t in 2007/08 and declined to 893 t in 2014/15. Catches were mainly taken by purse-seining, and since 1997/98, annual fishing effort in the SPF has been substantially less than that in the New South Wales Ocean Hauling Fishery but with only slightly less tonnages of catch. Both effort and catch of Australian Sardine East in the SPF decreased to low levels between 2011/12 and 2013/14, but increased slightly in 2014/15. There has been a general reduction in total catch since 2008/09, which reflects a significant reduction in the size of the fishing fleet. Only 13 commercial vessels reported catch in 2014/15 compared to >80 vessels in some years of the 2000s. Other factors that may have also contributed to the reduction in catch and effort include a fire in a major fish processing factory in Eden (southern New South Wales) and movement of Sardines from inshore to offshore waters (AFMA 2014).

Size structures of Australian Sardine East since 2004/05 in purse seine catches have varied among years, with the modal length ranging from 130–170 mm FL. The size structure of commercial purse seine catch samples in 2014/15 was slightly larger than or consistent with previous years (modal length: 150–160 mm FL). Australian Sardine East 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.

Current catches of Australian Sardine East are assessed as sustainable, as they have been <7% of the estimated spawning biomass (Ward et al. 2015b) since 2012/13, and well below the sustainable exploitation rate of 33% suggested for this species (Smith et al. 2015). Flood et al. (2014) also 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. (2015).

6 YELLOWTAIL SCAD (*Trachurus novaezelandiae*): PERMITTED BY-PRODUCT SPECIES

6.1 Introduction

6.1.1 Background to Fishery

Yellowtail Scad are mainly caught by commercial purse-seine in state waters of New South Wales, with a much smaller portion of catch reported in the SPF (Stewart et al. 1998, Bulman et al. 2008, Ward et al. 2015c). Yellowtail Scad and Blue Mackerel are important baitfish and are targets of a purse-seine fishery in New South Wales that has been expanding since the 1980s (Stewart et al. 1998, Stewart and Ferrell 2001). The fish are targeted along the coast in inshore waters and destined for human consumption (Stewart et al. 1998, Stewart and Ferrell 2001). Catches steadily increased to a peak in 1999/00, decreased to a low in 2009/10 and have since increased to historical highs in the 2010s (Ward et al. 2015c). Yellowtail Scad are also an important component of the recreational fishery (Stewart et al. 1998, Henry and Lyle 2003, Bulman et al. 2008)

6.1.2 Taxonomy

Yellowtail Scad (*Trachurus novaezelandiae*) belong to the family *Carangidae*, which includes 140 species representing 32 genera (Nelson 2006). Carangids are found worldwide; 65 species are found around Australia (Gomon et al. 2008). The genus *Trachurus* contains 13 species with three inhabiting Australian waters: *T. declivis, T. murphyi* and *T. novaezelandiae*.

6.1.3 Distribution

Yellowtail Scad are widely distributed throughout coastal waters of southern Australia and New Zealand. In Australia, they occur in subtropical and temperate waters from Wide Bay, Queensland, along the southern coast to Northwest Cape, Western Australia, but are rare around Tasmania (Gomon et al. 2008). Yellowtail Scad form large schools in bays and estuaries; adults are generally found offshore over rocky reefs, while juveniles occur inshore over soft substrate (Kailola et al. 1993).

6.1.4 Stock Structure

Limited information is available about the stock structure of Yellowtail Scad in Australian waters, but there is evidence supporting the separation of at least two populations of Yellowtail Scad: one in south-eastern Australian waters and one in the GAB. Analysis of morphometric measurements and meristic counts differentiated east Australian fish from those in the GAB (Lindholm and Maxwell 1988).

6.1.5 Movement

No specific studies have examined the movement of Yellowtail Scad. However, a correlation between size and depth is evident, with smaller fish generally found inshore and larger fish offshore (Kailola et al. 1993). Such size-dependent distribution suggests offshore movement with increasing size.

6.1.6 Food and Feeding

Yellowtail Scad are pelagic omnivores that primarily devour krill, carid shrimp, fish (myctophids and anchovies) and the early life stages of crab and shrimp (Bulman et al. 2001, Bulman et al. 2008, Bulman et al. 2011). They also feed on minor quantities of other prey items such as copepods, amphipods, isopods, mysids, cumaceans, tunicate larvae and polychaetes (Bulman et al. 2008).

6.1.7 Age, Growth and Size

Growth of Yellowtail Scad is variable; fish grow to ~200 mm between 2 and 4 years of age (Stewart and Ferrell 2001). In Australia, the maximum reported size of Yellowtail Scad is 330 mm TL (Kailola et al. 1993), and individuals may reach 14 years of age (Stewart and Ferrell 2001). Horn (1993) reported a maximum age and size of 28 years and 440 mm FL for Yellowtail Scad in New Zealand. Along the New South Wales coast, Yellowtail Scad sampled from purse-seine catches were larger from the northern region than those from the south (Stewart and Ferrell 2001). However, this size difference could also be related to differing regional fishing practices as opposed to populations specific growth rates (Stewart and Ferrell 2001).

6.1.8 Reproduction

The reproductive biology of Yellowtail Scad is not fully understood for the Australian population (Neira 2009). Yellowtail Scad reach 50% sexual maturity at 200 mm FL for females and 220 mm FL for males (Kailola et al. 1993). Mean batch fecundity has been estimated to be ~39,000 eggs based on published values (as $eggs.g^{-1}$) applied to mean female weight from commercial catch data (Neira 2009). Eggs have been collected in shelf waters off southern Queensland and southern New South Wales during spring, with the majority found in northern New South Wales and southern Queensland (Neira et al. 2015).

6.1.9 Early Life History and Recruitment

Yellowtail Scad eggs are positively buoyant and morphologically similar to Jack Mackerel eggs but slightly smaller in diameter (0.70–0.99 mm; Neira et al. 2015). Larvae have been described in Neira et al. (1998). Significant concentrations of Yellowtail Scad larvae have been found long the mid-

New South Wales coast and shelf in association with the East Australian Current during spring/summer (Smith 2003, Syahailatua et al. 2011)

6.1.10 Stock Assessment

There have been limited stock assessments of Yellowtail Scad in Australia. A provisional DEPM assessment was applied to Yellowtail Scad in 2009 using samples collected off south-eastern Australia in 2002 during a survey of Blue Mackerel (Neira 2009).

6.1.11 Recreational fishing

In Australia, recreational fishers target multiple species of scad (including Yellowtail Scad and 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 by fishers in New South Wales, 26% in Western Australia and 19% in Queensland. Catches from the other States made up the remaining 8% of the total recreational catch (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.

6.1.12 Biomass Estimates

A provisional DEPM analysis by Neira (2009) estimated the spawning biomass of Yellowtail Scad along the east coast of Australian to be between 2,900 t and 5,900 t (mean ~4,400 t). This estimate was based on samples collected during a survey in October 2002 directed at Blue Mackerel and was dependant on the model used to estimate daily egg production. There is uncertainty around both egg identification and some adult parameters, so this estimate of spawning biomass must be viewed with caution.

6.1.13 Management

Yellowtail Scad is classed as a permitted by-product species in the SPF.

6.2 Methods

6.2.1 Fishery Statistics

Fishery statistics from 1997/98 to 2014/15 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 supplied for Yellowtail Scad East include data from the NSW Ocean Fisheries (Hauling and Trawl), Victorian Ocean Fishery and the Commonwealth SPF.

6.2.2 Biological Information

Annual length-frequency data for Yellowtail Scad, sampled from commercial purse-seine catches taken in New South Wales were supplied by New South Wales DPI for the period from 2000/01 to 2014/15. Samples collected in 2011/12 and 2012/13 were sub-sampled, and otoliths were extracted for age estimation. Ages were based on annual growth increment counts in thin-sectioned otoliths. All biological data are presented in financial years.

6.3 Results

6.3.1 Yellowtail Scad East

6.3.1.1 Fishery Statistics

Number of vessels

The number of vessels that reported catches of Yellowtail Scad East ranged from 394 to 574 between 1997/98 and 2008/09. Since then, vessel numbers have ranged between 46 and 92, with 46 vessel reporting catches of Yellowtail Scad East in 2014/15. On average, 98% of the vessels reporting catch in each year are from New South Wales.

Annual patterns: Total catch

Total catches of Yellowtail Scad East have gradually declined from ~450 t in the late 1990s and early 2000s to a low of 271 t in 2009/10 (Figure 6.1). Catches increased to 548 t in 2013/14 and have declined slightly to 524 t in 2014/15 (Figure 6.1). The main fisheries that take Yellowtail Scad East have been the New South Wales Ocean Hauling and Trawl Fisheries (purse-seine and trawl).

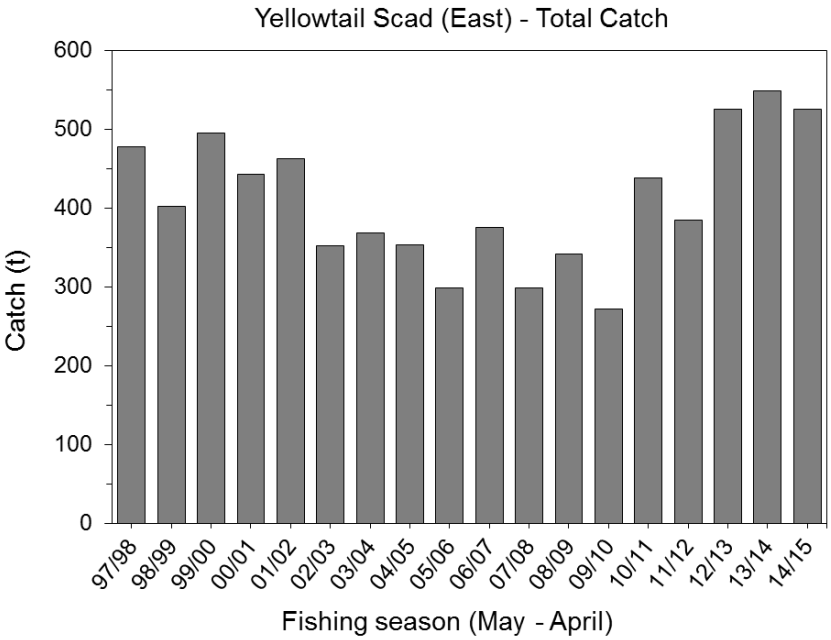

Figure 6.1. Total annual landed catch (tonnes) of Yellowtail Scad East for each fishing season from 1997/98 to 2014/15.

Annual patterns: Catch and Effort

Purse-seines have been the primary gear used to take Yellowtail Scad East; there has also been a lower but consistent use of trawls in the New South Wales fishery (Figure 6.2). Catches of Yellowtail Scad by the SPF have been solely taken by purse-seine.

Trends in annual purse-seining effort in the New South Wales Ocean Hauling Fishery for Yellowtail Scad East are similar to annual catch, i.e. purse-seine effort was relatively high in the late 1990s and early 2000s (>900 boat days), decreased to a lower level, averaging ~600 boat days per year from 2002/03 to 2009/10, and increased to 978 boat days in 2013/14 (Figure 6.3). In 2014/15, 827 boat days of effort were reported in the New South Wales Ocean Hauling Fishery with 474 t of catch (Figure 6.3).

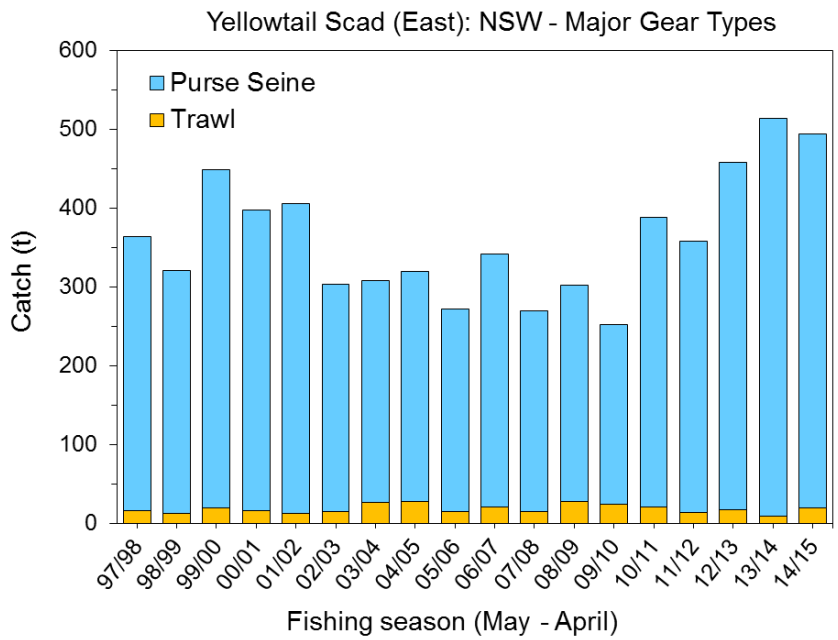

Figure 6.2. Annual landed catch (tonnes) of Yellowtail Scad East taken by purse-seine and trawl in the New South Wales Ocean Hauling and Trawl Fisheries for each fishing season from 1997/98 to 2014/15.

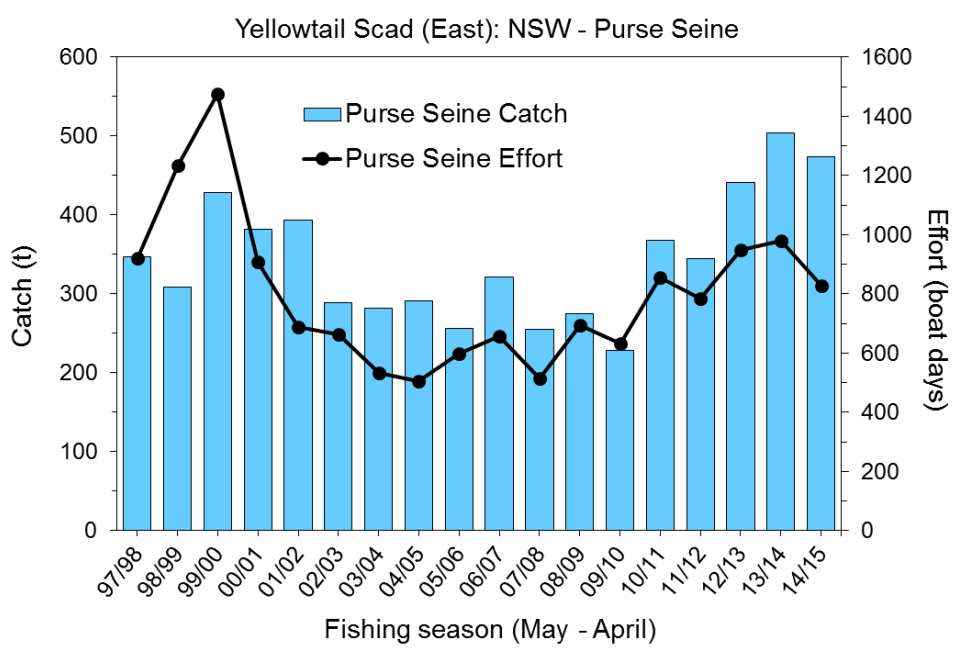

Figure 6.3. Annual landed catch (tonnes) and effort (boat days) of Yellowtail Scad East by purse-seine in the New South Wales Ocean Hauling Fishery for each fishing season from 1997/98 to 2014/15.

Trends of purse-seine effort are also similar to annual catch in the SPF for Yellowtail Scad East (Figure 6.4). However, purse-seine effort has never increased beyond 18 boat days (1997/98) and catches have remained below a peak of 15 t in 2003/04 (Figure 6.4). Since 2005/06, SPF catch and effort of Yellowtail Scad East has been low with catches <1 t per year and effort ≤ 5 boat days per year (Figure 6.4). In 2014/15, there was 0.6 t of Yellowtail Scad East taken in the SPF with 1 boat day of effort (Figure 6.4).

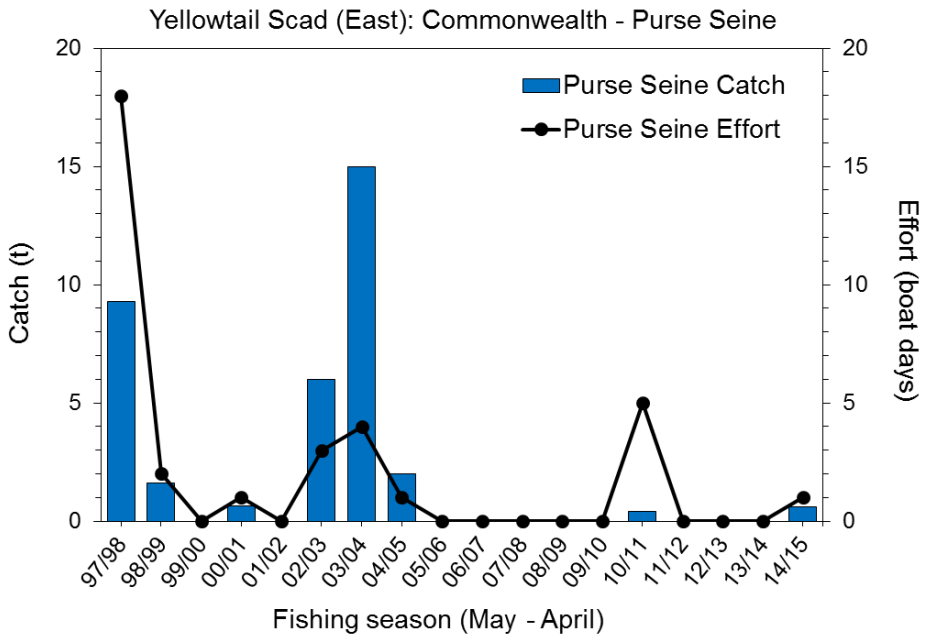

Figure 6.4. Annual landed catch (tonnes) and effort (boat days) of Yellowtail Scad East by purse-seine in the SPF for each fishing season from 1997/98 to 2014/15.

6.3.1.2 Biological Information

Length data were collected for Yellowtail Scad East from a total of 30,775 fish sampled from commercial catches taken in New South Wales between 2000/01 and 2014/15 (Table 6.1). Information on the spatial and temporal coverage of these samples relative to fishery production in New South Wales was not available, although between 8 and 47 catch samples of Yellowtail Scad were taken in each year. Yellowtail Scad otoliths were collected for ageing in 2011/12 (n = 119) and 2012/13 (n = 69).

Table 6.1. Summary of Yellowtail Scad East samples of collected from commercial State catches taken in New South Wales between 2000/01 and 2014/15 (data supplied by New South Wales DPI).

Season	SPF sub-area	Gear type	No. of samples	Length-frequency n	Size range (mm FL)
2000/01	East	purse-seine	41	5,078	80–330
2001/02	East	purse-seine	47	4,996	80–330
2003/04	East	purse-seine	7	1,400	220–325
2004/05	East	purse-seine	20	1,499	100–320
2005/06	East	purse-seine	31	2,661	110–320
2006/07	East	purse-seine	25	3,048	190–310
2007/08	East	purse-seine	18	2,429	80–310
2008/09	East	purse-seine	8	1,328	100–310
2011/12	East	purse-seine	17	2,040	120–290
2012/13	East	purse-seine	8	916	180–290
2013/14	East	purse-seine	19	2,137	170–300
2014/15	East	purse-seine	27	3,243	160–320

Size Structure

Commercial purse-seine fishing operations: New South Wales only

Annual size structures for Yellowtail Scad East taken by commercial purse-seine between 2000/01 and 2014/15 mainly contained fish between 200 and 280 mm FL (Figure 3.17). The size structures were relatively stable among years, with each containing a narrow dominant mode and varying between 220 and 270 mm FL (excepting 2014/15). For some years, the size structure also included a secondary mode at ~150 mm FL. The modal length of 200 mm FL in 2014/15 is the smallest primary mode recorded in the last 15 years.

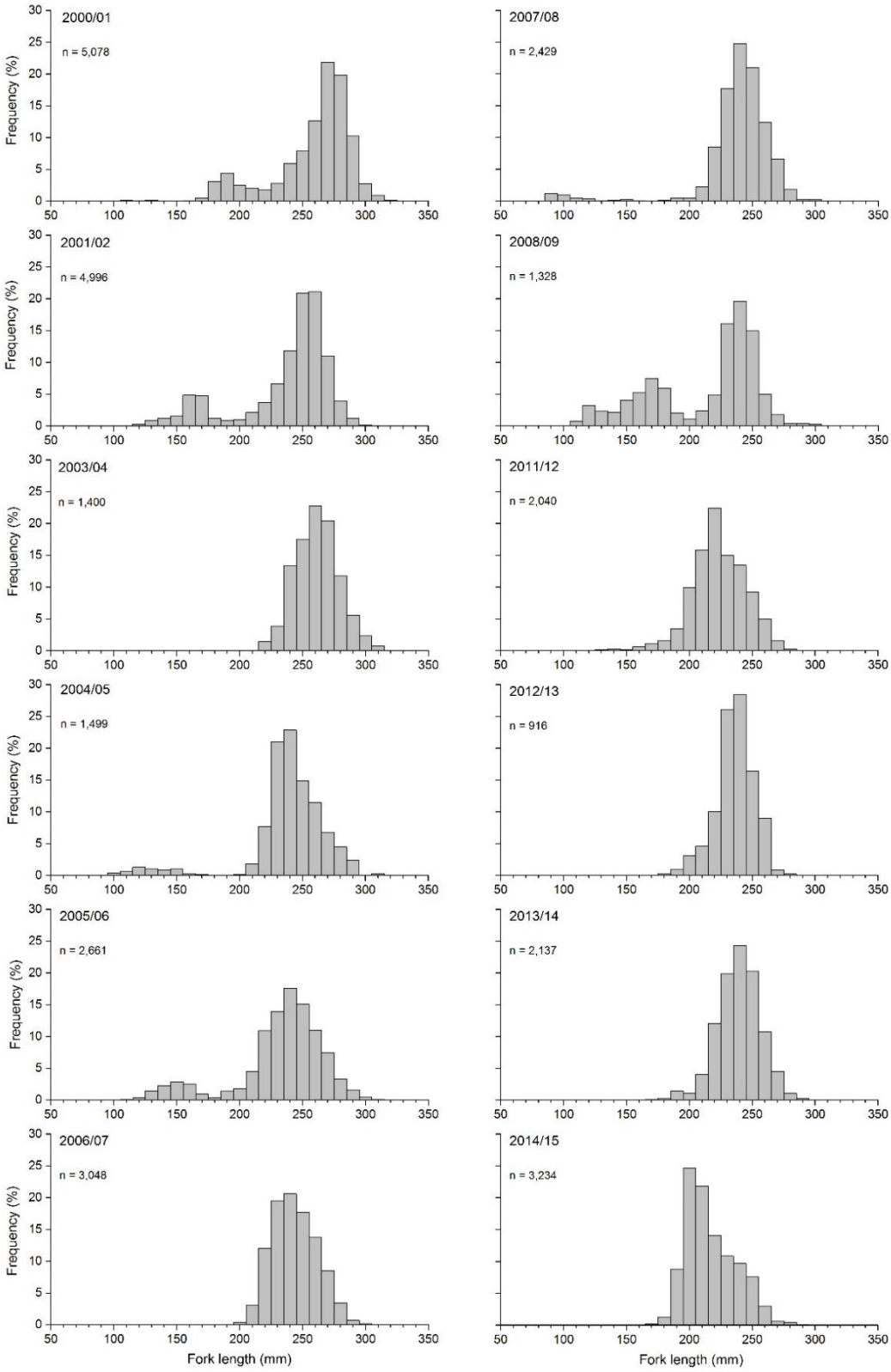

Figure 6.5. Length-frequency distributions (mm FL) of Yellowtail Scad East collected from purse-seine shots in New South Wales from 2000/01 to 2014/15 (data supplied by New South Wales DPI).

Age Structure

Purse-seine operations: 2011/12–2012/13

The ages of Yellowtail Scad collected from purse-seine catches along the New South Wales coast in 2011/12 and 2012/13 ranged from 2 to 14 years; >59% of the annual samples were between 4 and 5 years (Figure 6.6).

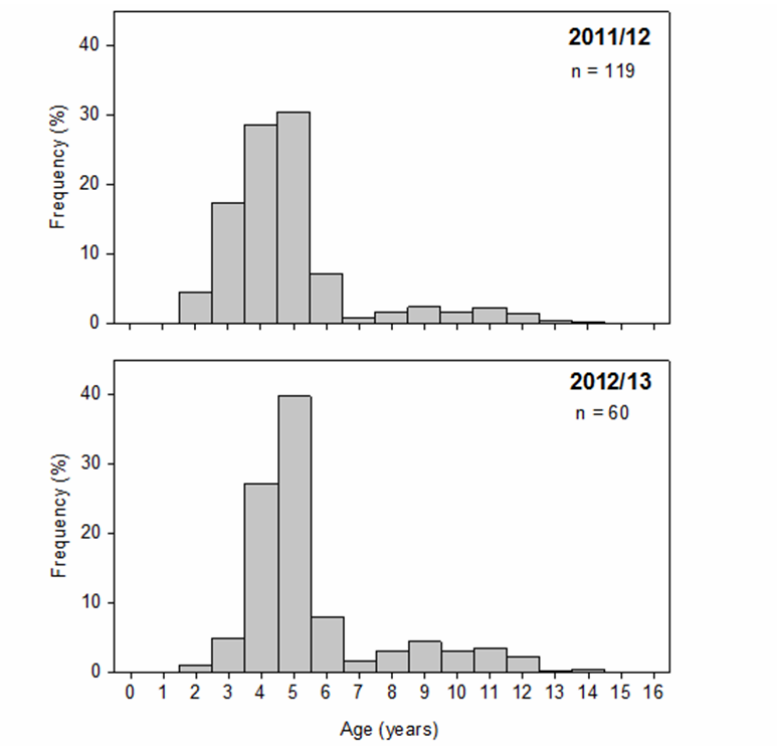

Figure 6.6. Age-frequency distribution of Yellowtail Scad East from purse-seine catches taken in 2011/12 and 2012/13 along the New South Wales coast (data supplied by New South Wales DPI).

6.4 Summary and Conclusions

6.4.1 Yellowtail Scad East

Total catches of Yellowtail Scad East declined from ~450 t in the late 1990s and early 2000s to a low of 271 t in 2009/10. Catches peaked at 548 t in 2013/14 and declined to 524 t in 2014/15. The main fisheries taking Yellowtail Scad East have been the New South Wales Ocean Hauling and Trawl Fisheries; the SPF reports very small amounts taken by purse-seining. In 2014/15, 0.6 t of Yellowtail Scad East was taken in the SPF. Current total catches of Yellowtail Scad East have been ~13% of the provisional estimated spawning biomass (Neira 2009).

Size structures of Yellowtail Scad East in purse seine catches have been relatively stable since 2000/01, with a narrow dominant mode varying between 220 and 270 mm FL (except in 2014/15). The modal length of 200 mm FL in 2014/15 is the smallest primary mode recorded in the last 15 years. Limited temporal data is available for age structures; >59% of fish sampled annually have been 4 and 5 years (age range: 2–14 years). Yellowtail Scad East have been above the mean size at 50% maturity of ~210 mm FL (Kailola et al. 1993), excepting 2014/15.

Recent total annual catches of Yellowtail Scad East are among the highest recorded for SPF species, being second only to Australian Sardine. Current, assessment of the stock status for this species is limited by the lack of biological and demographic data.

7 GENERAL SUMMARY AND CONCLUSIONS

Available evidence suggests that recent catch levels of all SPF quota species are sustainable. In 2014/15, catches of Blue Mackerel, Jack Mackerel, Redbait and Australian Sardine were relatively low and well below the Tier 2 maximum RBCs of each species for both the West and East sub-areas of the SPF. There is no evidence to suggest that the recent low catches for these species relate to a depleted stock biomass. Rather, reductions in fishing effort and catch appear to be driven by economic constraints. In 2014/15, catches increased following the entrance of a factory-trawler into the SPF.

The most recent classification of stock status for Jack Mackerel East and West and Australian Sardine East suggested that the biological stocks are sustainable (Flood et al. 2014). Blue Mackerel and Jack Mackerel in both sub-areas and Redbait and Australian Sardine East were classified as ‘not over-fished’ and ‘not subject to over fishing’ (Patterson et al. 2015). Redbait West was classified as ‘uncertain’ (Patterson et al. 2015). The evidence presented in this report suggests that the current catch levels of Blue Mackerel, Jack Mackerel and Redbait in the East and West sub-areas and Australian Sardine in the East sub-area are sustainable.

Knowledge of the status of SPF species in the East sub-area was enhanced in 2014 with DEPM surveys being completed on Blue Mackerel, Jack Mackerel and Australian Sardine. However, DEPM surveys have not been completed on Jack Mackerel and Redbait in the West sub-area. Surveys of Blue Mackerel West and Redbait East were also completed about a decade ago and need to be updated.

REFERENCES

AFMA. 2008. Small Pelagic Fishery Harvest Strategy (last revised April 2015). Australian Fisheries Management Authority, Canberra. 9 pp.

AFMA. 2009. Small Pelagic Fishery Management Plan 2009. Australian Fisheries Management Authority, Canberra, Federal Register of Legislative Instruments F2010L00081. 51 pp.

AFMA. 2014. Small Pelagic Fishery Management Arrangements Booklet 2014, Australian Fisheries Management Authority. Canberra, Australia. 32 pp.

AFMA. 2015. Geelong Star meets AFMA requirements on arrival into Australia. Australian Fisheries Management Authority. Media release. Available: http://www.afma.gov.au/geelong-star-meets-afma-requirements-arrival-australia/. (April 2015).

Arneri, E., P. Carpi, F. Donatato, and A. Santojanni. 2011. Growth in small pelagic fishes and its implications in their population dynamics. Biologia Marina Mediterranea 18: 106-113

Barangé, M., M. Bernal, M. C. Cercole, L. Cubillos, C. L. Cunningham, G. M. Daskalov, J. A. A. De Oliveira, and e. al. 2009. Current trends in the assessment and management of small pelagic fish stocks.*in* D. M. Checkley, C. Roy, J. Alheit, and Y. Oozek, editors. Climate Change and Small Pelagic Fish. Cambridge University Press, Cambridge, UK.

Barnes, J. T., A. D. Maccall, L. D. Jacobson, and P. Wolf. 1992. Recent Population Trends and Abundance Estimates for the Pacific Sardine (*Sardinops-Sagax*). California Cooperative Oceanic Fisheries Investigations Reports 33:60-75.

Bernal, M., Y. Stratoudakis, S. Wood, L. Ibaibarriaga, A. Uriarte, L. Valdés, and D. Borchers. 2011a. A revision of daily egg production estimation methods, with application to Atlanto-Iberian sardine. 1. Daily spawning synchronicity and estimates of egg mortality. ICES Journal of Marine Science: Journal du Conseil 68:519-527.

Bernal, M., Y. Stratoudakis, S. Wood, L. Ibaibarriaga, L. Valdés, and D. Borchers. 2011b. A revision of daily egg production estimation methods, with application to Atlanto-Iberian sardine. 2. Spatially and environmentally explicit estimates of egg production. ICES Journal of Marine Science: Journal du Conseil 68:528-536.

Blaber, S. J. M., and C. M. Bulman. 1987. Diets of fishes of the upper continental slope of eastern Tasmania: content, calorific values, dietary overlap and trophic relationships. Marine Biology 95:345-356.

Blackburn, M. 1950. Studies on the age, growth, and life history of the sardine *Sardinops neopilchardus* (Steindachner), in Southern and Western Australia. Australian Journal of Marine and Freshwater Research 1:221-258.

Browne, A. 2005. Changes in the growth and age structure of jack mackerel in south-east Australian waters. Honours Thesis, University of Tasmania, School of Zoology. 58 pp.

Bruce, B. D., and D. A. Short. 1990. Observations on the distribution of larval fish in relation to a frontal system at the mouth of Spencer Gulf, South Australia. Bureau of Rural Resources Proceedings 15:124-137.

Buckworth, R., S. Newman, J. Ovenden, R. Lester, and G. McPherson, editors. 2006. The stock structure of Northern and Western Australian Spanish mackerel. Final Report, Fisheries Research & Development Corporation Project 1998/159. Fisheries Group, Department of Business Industry and Resource Development, Northern Territory Government, Darwin, Australia.

Bulman, C., F. Althaus, X. He, N. J. Bax, and A. Williams. 2001. Diets and trophic guilds of demersal fishes of the south-eastern Australian shelf. Marine and Freshwater Research 52:537-548.

Bulman, C., S. Condie, J. Findlay, B. Ward, and J. Young. 2008. Management zones from small pelagic fish species stock structure in southern Australian waters. Final Report for FRDC Project 2006/076. CSIRO Marine and Atmospheric Research: Hobart, Tasmania. .

Bulman, C., S. Davenport, and F. Althaus. 2000. Trophodynamics. In: Habitat and fisheries production in the South East Fishery ecosystem. Final report to the Fisheries Research and Development Corporation, Project No. 94/040, (eds N.J. Bax and A. Williams). Division of Marine Research, CSIRO Marine Laboratories, Hobart.

Bulman, C. M., S. A. Condie, F. J. Neira, S. D. Goldsworthy, and E. A. Fulton. 2011. The trophodynamics of small pelagic fishes in the southern Australian ecosystem and the implications for ecosystem modelling of southern temperate fisheries. Final report for FRDC project 2008/023., CSIRO Marine and Atmospheric Research. Hobart. 101 pp.

Burke, M. T. 2012a. Gillard Labor Government acts to stop super trawler. Press release. Available: www.environment.gov.au/minister/burke/2012/mr20120911.html. (September 2012).

Burke, M. T. 2012b. Tough new environmental conditions imposed on super trawler. Press release. Available: www.environment.gov.au/minister/burke/2012/mr20120904.html. (September 2012).

Butler, J. L., M. L. Granados, J. T. Barnes, M. Yaremko, and B. J. Macewicz. 1996. Age composition, growth, and maturation of the Pacific sardine (*Sardinops sagax*) during 1994. California Cooperative Oceanic Fisheries Investigations Reports 37:152-159.

Catanese, G., M. Manchado, and C. Infante. 2010. Evolutionary relatedness of mackerels of the genus Scomber based on complete mitochondrial genomes: Strong support to the recognition of Atlantic Scomber colias and Pacific Scomber japonicus as distinct species. Gene 452:35-43.

Curtis, K. A. 2004. Fine scale spatial pattern of Pacific sardine (*Sardinops sagax*) and northern anchovy (*Engraulis mordax*) eggs. Fisheries Oceanography 13:239-254.

Daly, K. 2007. The diet and guild structure of the small pelagic fish community in the eastern Great Australian Bight, South Australia. Honours thesis, University of Adelaide.

Emery, T., J. Bell, J. Lyle, and K. Hartmann. 2015. Tasmanian Scalefish Fishery Assessment 2013/14. Institute for Marine and Antarctic Studies, University of Tasmania. 102pp.

Eschmeyer, W. N., and R. Fricke. 2016. Catalog of Fishes: Genera, Species, References. (http://researcharchive.calacademy.org/research/ichthyology/catalog/fishcatmain.asp). Electronic version accessed 28 January 2016.

Ewing, G. P., and J. M. Lyle. 2009. Reproductive dynamics of redbait, Emmelichthys nitidus (Emmelichthyidae), from south-eastern Australia. Fisheries Research 97:206-215.

Fletcher, W., and R. Tregonning. 1992. Distribution and timing of spawning by the Australian pilchard (<I>Sardinops sagax neopilchardus</I>) off Albany, Western Australia. Marine and Freshwater Research 43:1437-1449.

Fletcher, W. J. 1990. A synopsis of the biology and exploitation of the Australian sardine, *Sardinops neoplichardus* (Steindachner). I: Biology. Western Australian Department of Fisheries. *Fisheries Research Report*.

Fletcher, W. J., and S. J. Blight. 1996. Validity of using translucent zones of otoliths to age the pilchard *Sardinops sagax neopilchardus* from Albany, western Australia. Marine and Freshwater Research 47:617-624.

Fletcher, W. J., and K. Santoro. 2015. Status Reports of the Fisheries and Aquatic Resources of Western Australia 2014/15: The State of the Fisheries. Department of Fisheries, Western Australia. 353 pp.

Fletcher, W. J., R. J. Tregonning, and G. J. Sant. 1994. Interseasonal variation in the transport of pilchard eggs and larvae off southern Western Australia. Marine Ecology Progress Series 111:209-224.

Flood, M., I. Stobutzki, J. Andrews, C. Ashby, G. Begg, R. Fletcher, C. Gardner, L. Georgeson, S. Hansen, K. Hartmann, P. Hone, P. Horvat, L. Maloney, B. McDonald, A. Moore, A. Roelofs, K. Sainsbury, T. Saunders, T. Smith, C. Stewardson, J. Stewart, and B. e. Wise. 2014. Status of key Australian fish stocks reports 2014. Fisheries Research and Development Corporation, Canberra.

Fu, D. 2013. Characterisation analyses for blue mackerel (Scomber australasicus) in EMA 1, 2, 3, and 7, 1989–90 to 2009–10. New Zealand Fisheries Assessment Report 2013/16:54.

Fulton, E. A. 2013. Simulation analysis of jack mackerel stock size: Ecosystem model based plausibility study. CSIRO, Australia. 24 pp.

Furlani, D., A. Williams, and N. Bax. 2000. Fish biology (length and age). In: Habitat and fisheries production in the South East Fishery ecosystem. Final report to the Fisheries Research and Development Corporation, Project No. 94/040, (eds N.J. Bax and A. Williams). Division of Marine Research, CSIRO Marine Laboratories, Hobart.

Galindo-Cortes, G., J. A. De Anda-Montañez, F. Arreguín-Sánchez, S. Salas, and E. F. Balart. 2010. How do environmental factors affect the stock–recruitment relationship? The case of the Pacific sardine (Sardinops sagax) of the northeastern Pacific Ocean. Fisheries Research 102:173-183.

Garrido, S., A. Marcalo, J. Zwolinski, and C. D. Van Der Lingen. 2007. Laboratory Investigations on the Effect of Prey size and Concentration on the Feeding Behaviour of *Sardina pilchardus*. Marine Ecology Progress Series 330:189-199.

Gaughan, D. J., W. J. Fletcher, and J. P. McKinlay. 2002. Functionally distinct adult assemblages within a single breeding stock of the sardine, *Sardinops sagax*: management units within a management unit. Fisheries Research 59:217-231.

Gaughan, D. J., and R. W. D. Mitchell. 2000. The biology and stock assessment of the tropical sardine, Sardinells lemura, off the mid-west coast of Western Australia., Fisheries Western Australia. No. 119, North Beach.

Giannini, F., P. I. Hobsbawn, G. A. Begg, and M. Chambers. 2010. Management strategy evaluation (MSE) for the harvest strategy for the Small Pelagic Fishery. FRDC Project 2008/064, Final Report. Fisheries Research and Development Corporation and Bureau of Rural Sciences, Canberra. 157 pp.

Gomon, M., D. Bray, and R. H. Kuiter. 2008. Fishes of the Australia's South Coast. Museum of Victoria. New Holland Publishers (Australia).

Gonçalves, P., A. M. Costa, and A. G. Murta. 2009. Estimates of batch fecundity and spawning fraction for the southern stock of horse mackerel (*Trachurus trachurus*) in ICES Division IXa. ICES Journal of Marine Science: Journal du Conseil 66:617-622.

Gray, C. A., and A. G. Miskiewicz. 2000. Larval fish assemblages in south-east Australian coastal waters: seasonal and spatial structure. Estuarine Coastal and Shelf Science 50:549-570.

Harris, G. P., F. B. Griffiths, and L. A. Clementson. 1992. Climate and the fisheries off Tasmania — interactions of physics, food chains and fish. South African Journal of Marine Science 12:585-597.

Hartmann, K., and J. M. Lyle. 2011. Tasmanian scalefish fishery – 2009/10. Fisheries Assessment Report., Institute for Marine and Antarctic Studies, University of Tasmania. 102 pp.

Heemstra, P. C., and J. E. Randall. 1977. A revision of the Emmelichthyidae (Pisces : Perciformes). Marine and Freshwater Research 28:361-396.

Henry, G. W., and J. M. Lyle. 2003. The National Recreational and Indigenous Fishing Survey. Final Report of FRDC Project No. 99/158. Final Report to FRDC 1999/158., New South Wales Fisheries Research Centre. 188 pp.

Hoedt, F. E., and W. F. Dimmlich. 1995. Egg and Larval Abundance and Spawning Localities of the Anchovy (*Engraulis australis*) and Pilchard (*Sardinops neopilchardus*) near Phillip Island, Victoria. Marine and Freshwater Research 46:735-743.

Horn, P. L. 1993. Growth, age structure, and productivity of jack mackerels (Trachurus spp.) in New Zealand waters. New Zealand Journal of Marine and Freshwater Research 27:145-155.

Horn, P. L., H. L. Neil, L. J. Paul, and P. J. McMillan. 2012. Age verification, growth and life history of rubyfish *Plagiogeneion rubiginosum*. New Zealand Journal of Marine and Freshwater Research 46:353-368.

Infante, C., E. Blanco, E. Zuasti, A. Crespo, and M. Manchado. 2006. Phylogenetic differentiation between Atlantic *Scomber colias* and Pacific *Scomber japonicus* based on nuclear DNA sequences. Genetica:1-8.

Izzo, C., B. M. Gillanders, and T. M. Ward. 2012. Movement patterns and stock structure of sardine (*Sardinops sagax*) off South Australia and the East Coast: implications for future stock assessment and management. South Australian Research and Development Institute (Aquatic Sciences), Adelaide.

Jordan, A., G. Pullen, and H. Williams. 1992. Jack mackerel resource assessment in south eastern Australian waters: Final Report to FRDC, Project DFT2Z. Tasmanian Department of Primary Industry, Fisheries and Energy, Sea Fisheries Research Laboratories. Taroona, Tasmania.

Jordan, A. R. 1994. Age, growth and back-calculated birthdate distributions of larval jack mackerel *Trachurus declivis* (Pisces: Carangidae), from eastern Tasmanian coastal waters. Journal of Marine and Freshwater Research 45:19-33.

Jordan, A. R., G. Pullen, J. Marshall, and H. Williams. 1995. Temporal and spatial patterns of spawning in jack mackerel, *Trachurus declivis* (Pisces: Carangidae), during 1988-91 in eastern Tasmanian waters. Marine and Freshwater Research 46:831-842.

Kailola, P. J., M. J. Williams, P. C. Stewart, A. M. Reichelt, and C. Grieve. 1993. Australian Fisheries Resourses. Bureau of Resource Sciences, Department of Primary Industries and Energy and the Fisheries Research and Development Corporation, Canberra.

Karlou-Riga, C., and P. S. Economidis. 1997. Spawning frequency and batch fecundity of horse mackerel, Trachurus trachurus (L.), in the Saronikos Gulf (Greece). Journal of Applied Ichthyology 13:97-104.

Keane, J. P. 2009. Mesoscale Characterisation of the Pelagic Shelf Ecosystem of South-Eastern Australia: Integrated Approach Using Larval Fish Assemblages and Oceanography. PhD Thesis, University of Tasmania. 269 pp.

Kerstan, M. 2000. Estimation of precise ages from the marginal increment widths of differently growing sardine (*Sardinops sagax*) otoliths. Fisheries Research 46:207-225.

Lasker, R. 1985. An egg production method for estimating spawning biomass of pelagic fish: Application to the Northern Anchovy, *Engraulis mordax*. National Marine Fisheries Services. National Oceanic and Atmospheric Administration Technical Report.

Last, P. R., E. O. G. Scott, and F. H. Talbot. 1983. Fishes of Tasmania. Tasmanian Fisheries Development Authority. 563 pp.

Lindholm, R., and J. G. H. Maxwell. 1988. Stock separation of jack mackerel *Trachurus declivis* (Jenyns, 1841), and yellowtail *T. novaezealandiae* (Richardson, 1843) in southern Australian waters using principal component analysis. CSIRO Marine Laboratories Report No. 189. Hobart, Tasmania. 7 pp.

Logerwell, E. A., B. Lavaniegos, and P. E. Smith. 2001. Spatially-explicit bioenergetics of Pacific sardine in the Southern California Bight: are mesoscale eddies areas of exceptional prerecruit production? Progress In Oceanography 49:391-406.

Louw, G. G., C. D. Van der Lingen, and M. J. Gibbons. 1998. Differential feeding by sardine *Sardinops sagax* and anchovy *Engraulis capensis* recruits in mixed shoals. South African Journal of Marine Science 19:227-232.

Lyle, J. M., K. Krusic-Golub, and A. K. Morison. 2000. Age and growth of jack mackerel and the age structure of the jack mackerel purse-seine catch. Final Report for FRDC Project 1995/034. Tasmanian Aquaculture and Fisheries Institute, University of Tasmania. Hobart, Tasmania. 49 pp.

Markina, N. P., and V. Z. Boldyrev. 1980. Feeding of the redbait on underwater elevations of the southwest Pacific. Biologiya Morya (Vladivostok) 4:40-45.

Marriott, P. M., and M. J. Manning. 2011. Reviewing and refining the method for estimating blue mackerel (*Scomber australasicus*) ages. New Zealand Fisheries Assessment Report 2011:25.

Marshall, J. M., G. Pullen, and A. R. Jordan. 1993. Reproductive biology and sexual maturity of female jack mackerel, *Trachurus declivis* (Jenyns), in eastern Tasmanian waters. Australian Journal of Marine and Freshwater Research 44:799-809.

Maxwell, J. G. H. 1979. Jack mackerel. Fishery Situation Report, no. 2. Division of Fisheries and Oceanography. CSIRO Australia, 18 pp.

May, J. L., and J. G. H. Maxwell. 1986. Field guide to trawl fish from temperate waters of Australia. CSIRO Division of Fisheries Research.

McGarvey, R., and M. A. Kinloch. 2001. An analysis of the sensitivity of stock biomass estimates derived from the daily egg production method (DEPM) to uncertainty in egg mortality rates. Fisheries Research 49:303-307.

McLeod, D. J., A. J. Hobday, J. M. Lyle, and D. C. Welsford. 2012. A prey-related shift in the abundance of small pelagic fish in eastern Tasmania? ICES Journal of Marine Science: Journal du Conseil.

Mel'nikov, Y., and N. A. Ivanin. 1995. Age-size composition and mortality of the rubyfish *Plagiogeneion rubiginosum* (Emmelichthyidae) in West Indian Submarine Ridge. Journal of Ichthyology 35:20-27.

Meléndez, C. R., and M. R. Céspedes. 1986. *Emmelichthys nitidus cyanescens* (Guichenot, 1848) in the Chilean Southern fisheries (Perciformes, *Emmelichthyidae*). Investigacion Pesquera 33:111-114.

Meyer, M., and M. J. Smale. 1991. Predation patterns of demersal teleosts from the Cape south and west coasts of South Africa. 1. Pelagic predators. South African Journal of Marine Science 10:173-191.

Moore, A., and M. Skirtun. 2012. The Small Pelagic Fishery. In J. Woodhams, S. Vieira and J. Stobutzki (Eds), Fishery Status Reports 2011, Australian Bureau of Agricultural and Resources Economics and Sciences, Canberra, 2012, 93 pp.

Murhling, B. A., L. E. Beckley, D. J. Gaughan, C. M. Jones, A. G. Miskiewicz, and S. A. Hesp. 2008. Spawning, larval abundance and growth rate of *Sardinops sagax* off south western Australia: influence of an anomalous eastern boundary current. Marine Ecology Progress Series 364:157-167.

Neira, F. J. 2009. Provisional spawning biomass estimates of yellowtail scad (*Trachurus novaezelandiae*) off south-eastern Australia. Report to New South Wales Department of Primary Industries (NSW DPI). 31 pp.

Neira, F. J. 2011. Application of daily egg production to estimate biomass of jack mackerel, *Trachurus declivis* - a key fish species in the pelagic ecosystem of south-eastern Australia. Final Report to the Winifred Violet Scott Charitable Trust. Fisheries, Aquaculture and

Coasts Centre, Institute for Marine and Antarctic Studies (IMAS), University of Tasmania. 42 pp.

Neira, F. J., and J. P. Keane. 2008. Ichthyoplankton-based spawning dynamics of blue mackerel (*Scomber australasicus*) in south-eastern Australia: links to the East Australian Current. Fisheries Oceanography 17:281-298.

Neira, F. J., and J. M. Lyle. 2011. DEPM-based spawning biomass of *Emmelichthys nitidus* (Emmelichthyidae) to underpin a developing mid-water trawl fishery in south-eastern Australia. Fisheries Research 110:236-243.

Neira, F. J., J. M. Lyle, G. P. Ewing, J. P. Keane, and S. R. Tracey. 2008. Evaluation of egg production as a method of estimating spawning biomass of redbait off the east coast of Tasmania. Final report, FRDC project no. 2004/039. Tasmanian Aquaculture and Fisheries Institute, Hobart.

Neira, F. J., A. Miskiewicz, and T. Trnski. 1998. Larvae of temperate Australian fishes: laboratory guide for larval fish identification. University of Western Australia Press, Nedlands, W.A.

Neira, F. J., R. A. Perry, C. P. Burridge, J. M. Lyle, and J. P. Keane. 2015. Molecular discrimination of shelf-spawned eggs of two co-occurring Trachurus spp. (Carangidae) in southeastern Australia: a key step to future egg-based biomass estimates. ICES Journal of Marine Science: Journal du Conseil 72:614-624.

Neira, F. J., M. I. Sporcic, and A. R. Longmore. 1999. Biology and fishery of pilchard, *Sardinops sagax* (Clupeidae), within a large south-eastern Australian bay. Marine and Freshwater Research 50:43-55.

Nelson, J. S. 2006. Fishes of the World. Fourth Edition. John Wiley and Sons, Inc. Hoboken, New Jersey. 601 pp.

Okazaki, T., T. Kobayashi, and Y. Uozumi. 1996. Genetic relationships of pilchards (genus: *Sardinops*) with anti-tropical distributions. Marine Biology 126:585-590.

Parin, N. V., A. N. Mironov, and K. N. Nesis. 1997. Biology of the Nazca and Sala y Gomez submarine ridges, an outpost of the Indo-West Pacific Fauna in the Eastern Pacific Ocean: composition and distribution of the fauna, its communities and history. Advances in Marine Biology 32:145-242.

Parker, K. 1980. A direct method for estimating northern anchovy, *Engraulis mordax*, spawning biomass. Fisheries Bulletin 84:541-544.

Patterson, H. M., L. Georgeson, I. Stobutzki, and R. Curtotti. 2015. Fishery status reports 2015. Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra. CC BY 3.0. 509 pp.

Paul, L. J., P. L. Horn, and M. P. Francis. 2000. Development of an ageing methodology, and first estimates of growth parameters and natural mortality for rubyfish (*Plagiogeneion rubiginosum*) off the east coast of the North Island (QMA 2). Fisheries Assessment Report 2000/22. Ministry of Fisheries, New Zealand.

Prokopchuk, I., and E. Sentyabov. 2006. Diets of herring, mackerel, and blue whiting in the Norwegian Sea in relation to *Calanus finmarchicus* distribution and temperature conditions. ICES Journal of Marine Science 63:117-127.

Pullen, G. 1994. Fishery status report: Purse-seine (The Tasmanian jack mackerel fishery). Department of Primary Industry and Fisheries, Tasmania. Internal Report 13. 49pp.

Richardson, B. 1982. Geographical distribution of electrophoretically detected protein variation in Australian commercial fishes. I. Jack mackeral, *Trachurus declivis* Jenyns. Marine and Freshwater Research 33:917-926.

Rogers, P. J., and T. M. Ward. 2007. Application of a 'case-building approach' to investigate the age distributions and growth dynamics of Australian sardine (*Sardinops sagax*) off South Australia. Marine and Freshwater Research 58:461-474.

Rogers, P. J., T. M. Ward, L. J. McLeay, M. Lowry, and D. Williams. 2009. Reproductive biology of blue mackerel, *Scomber australasicus*, off southern and eastern Australia: suitability of the Daily Egg Production Method for stock assessment. Marine and Freshwater Research 60:187-202.

Rohde, K. 1987. Different populations of *Scomber australasicus* in New Zealand and south-eastern Australia, demonstrated by a simple method using monogenean sclerites. Journal of Fish Biology 30:651-657.

Schmarr, D. W., I. D. Whittington, J. R. Ovenden, and T. M. Ward. 2011. Discriminating stocks of *Scomber australasicus* using a holistic approach: a pilot study. American Fisheries Society Symposium 76:1-21.

Schwartzlose, R. A., J. Alheit, A. Bakun, T. R. Baumgartner, R. Cloete, R. J. M. Crawford, W. J. Fletcher, Y. Green-Ruiz, E. Hagen, T. Kawasaki, D. Lluch-Belda, S. E. Lluch-Cota, A. D. MacCall, Y. Matsuura, M. O. Nevárez-Martínez, R. H. Parrish, C. Roy, R. Serra, K. V. Shust, M. N. Ward, and J. Z. Zuzunaga. 1999. Worldwide large-scale fluctuations of sardine and anchovy populations. South African Journal of Marine Science 21:289-347.

Scoles, D. R., B. B. Collette, and J. E. Graves. 1998. Global phylogeography of mackerels of the genus *Scomber*. Fishery Bulletin 96:823-842.

Shuntov, V. P. 1969. Some features of the ecology of pelagic fishes in the Great Australian Bight. Problems of Ichthyology 9:801-809.

Smith, A. D. M., T. M. Ward, F. Hurtado, N. Klaer, E. Fulton, and A. E. Punt. 2015. Review and update of harvest strategy settings for the Commonwealth Small Pelagic Fishery: Single species and ecosystem considerations. Final Report of FRDC Project No. 2013/028. CSIRO Oceans and Atmosphere Flagship, Hobart. 74 pp.

Smith, K. A. 2003. Larval distributions of some commercially valuable fish species over the Sydney continental shelf Proceedings of the Linnean Society of New South Wales 124:1-11.

Smith, M. M., and P. C. Heemstra. 1986. Smith's Sea Fishes. MacMillan, Johannesburg. 1047 pp.

Smolenski, A. J., J. R. Ovenden, and R. W. G. White. 1994. Preliminary investigation of mitochondrial DNA variation in jack mackerel (*Trachurus declivis*, Carangidae) from south-eastern Australian waters. Marine and Freshwater Research 45:495-505.

Staunton-Smith, J., and T. M. Ward. 2000. Stock assessment of pelagic bait fishes in southern Queensland with special reference to pilchards (*Sardinops sagax*). FRDC Project 95/043, Department of primary Industries, Queensland, Brisbane.

Stevens, J. D., and H. F. Hausfeld. 1982. Age determination and mortality estimates of an unexploited population of Jack mackerel *Trachurus declivis* (Jenyns, 1841) from south-east Australia. CSIRO Marine Laboratories Report. Hobart, Tasmania. 148 pp.

Stevens, J. D., H. F. Hausfeld, and S. R. Davenport. 1984. Observations on the biology, distribution and abundance of *Trachurus declivis*, *Sardinops neopilchardus* and *Scomber australasicus* in the Great Australian Bight. CSIRO Marine Laboratories, Cronulla.

Stewart, J., G. Ballinger, and D. J. Ferrell. 2010. Review of the biology and fishery for Australian sardines (*Sardinops sagax*) in New South Wales - 2010. Industry and Investment NSW, Cronulla.

Stewart, J., and D. J. Ferrell. 2001. Age, growth, and commercial landings of yellowtail scad (*Trachurus novaezelandiae*) and blue mackerel (*Scomber australasicus*) off the coast of New South Wales, Australia. New Zealand Journal of Marine and Freshwater Research 35:541-551.

Stewart, J., D. J. Ferrell, and N. L. Andrew. 1998. Ageing yellowtail (*Trachurus novaezelandiae*) and blue mackerel (*Scomber australasicus*) in New South Wales. FRDC Project No. 95/151. NSW Fishereis Final Report Series No. 3. 3., NSW Fisheries Research Institute. Cronulla, NSW. 59 p.

Stewart, J., D. J. Ferrell, and N. L. Andrew. 1999. Validation of the formation and appearance of annual marks in the otoliths of yellowtail (*Trachurus novaezelandiae*) and blue mackerel (*Scomber australasicus*) in New South Wales. Marine and Freshwater Research 50:389-395.

Stratoudakis, Y., M. Bernal, K. Ganias, and A. Uriarte. 2006. The daily egg production method: recent advances, current applications and future challenges. Fish and Fisheries 7:35-57.

Syahailatua, A., M. Roughan, and I. M. Suthers. 2011. Characteristic ichthyoplankton taxa in the separation zone of the East Australian Current: Larval assemblages as tracers of coastal mixing. Deep Sea Research Part II: Topical Studies in Oceanography 58:678-690.

Tracey, S., C. Buxton, C. Gardner, B. Green, K. Hartmann, M. Haward, J. Jabour, J. Lyle, and J. McDonald. 2013. Super Trawler Scuppered in Australian Fisheries Management Reform. Fisheries 38:345-350.

van der Lingen, C. D. 1994. Effect of Particle-Size and Concentration on the Feeding-Behavior of Adult Pilchard *Sardinops sagax*. Marine Ecology-Progress Series 109:1-13.

van der Lingen, C. D., and J. A. Huggett. 2003. The role of ichthyoplankton surveys in recruitment research and management of South African anchovy and sardine.*in* H. I. Browman and A. B. Skiftesvic, editors. The Big Fish Bang. Proceedings of the 26th Annual Larval Fish Conference. Institute of Marine Research, Norway.

Waldron, M. 1998. Annual ring validation of the South African sardine *Sardinops sagax* using daily growth increments. South African Journal of Marine Science 19:425-430.

Ward, P. J., T. Timmiss, and B. Wise. 2001a. A review of biology and fisheries for mackerel. Bureau of Rural Sciences, Canberra.

Ward, T., B. Molony, J. Stewart , J. Andrews, and A. Moore. 2014a. Australian Sardine *Sardinops sagax,* in M. Flood, I. Stobutzki, J. Andrews, C. Ashby, G. Begg, R. Fletcher, C. Gardner,

L. Georgeson, S. Hansen, K. Hartmann, P. Hone, P. Horvat, L. Maloney, B. McDonald, A. Moore, A. Roelofs, K. Sainsbury, T. Saunders, T. Smith, C. Stewardson, .J Stewart & B. Wise (eds) 2014, *Status of key Australian fish stocks reports 2014*, Fisheries Research and Development Corporation, Canberra.

Ward, T. M., O. Burnell, A. Ivey, J. Carroll, J. Keane, J. Lyle, and S. Sexton. 2015a. Summer spawning patterns and preliminary daily egg production method survey of Jack Mackerel and Australian Sardine off the East Coast. South Australian Research and Development Institute (Aquatic Sciences), Adelaide.

Ward, T. M., O. W. Burnell, A. Ivey, S. C. Sexton, J. Carroll, J. Keane, and J. M. Lyle. 2016. Spawning biomass of Jack Mackerel (Trachurus declivis) off eastern Australia: Critical knowledge for managing a controversial fishery. Fisheries Research 179:10-22.

Ward, T. M., G. L. Grammer, A. R. Ivey, J. R. Carroll, J. P. Keane, J. Stewart, and L. Litherland. 2015b. Egg distribution, reproductive parameters and spawning biomass of Blue Mackerel, Australian Sardine and Tailor off the East Coast during late winter and early spring. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. FRDC Project No. 2014/033. 77 p.

Ward, T. M., F. Hoedt, L. McLeay, W. F. Dimmlich, M. Kinloch, G. Jackson, R. McGarvey, P. J. Rogers, and K. Jones. 2001b. Effects of the 1995 and 1998 mass mortality events on the spawning biomass of *Sardinops sagax* in South Australian waters. ICES Journal of Marine Science 58:830-841.

Ward, T. M., A. R. Ivey, and J. D. Carroll. 2014b. Spawning biomass of sardine, *Sardinops sagax*, in waters off South Australia in 2014. Report to PIRSA Fisheries and Aquaculture. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2007/000566-6. SARDI Research Report Series No. 807. 33 pp.

Ward, T. M., A. R. Ivey, and J. Earl. 2014c. Commonwealth Small Pelagic Fishery: Fishery Assessment Report 2013. Report to the Australian Fisheries Management Authority., South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2010/000270-5. SARDI Research Report Series No. 778. 105 pp.

Ward, T. M., A. R. Ivey, and J. Earl. 2015c. Commonwealth Small Pelagic Fishery: Fishery Assessment Report 2014. Report to the Australian Fisheries Management Authority. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2010/000270-6. SARDI Research Report Series No. 847. 113 pp.

Ward, T. M., A. R. Ivey, and D. Gorman. 2013. Commonwealth Small Pelagic Fishery: Fishery Assessment Report 2012. Report to the Australian Fisheries Management Authority. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2010/000270-4. SARDI Research Report Series No. 696. 100 pp.

Ward, T. M., M. Kinloch, J. G.K., and F. J. Neira. 1998. A Collaborative Investigation of the Usage and Stock Assessment of Baitfish in Southern and Eastern Australian Waters, with Special Reference to Pilchards (*Sardinops sagax*). South Australian Research and Development Institute (Aquatic Sciences). Final Report to Fisheries Research and Development Corporation.

Ward, T. M., J. Lyle, J. P. Keane, G. A. Begg, P. Hobsbawn, A. R. Ivey, R. Sakabe, and M. A. Steer. 2011. Commonwealth Small Pelagic Fishery: Status Report 2010. Report to the

Australian Fisheries Management Authority. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2010/000270-2. SARDI Research Report Series No. 524. 84 pp.

Ward, T. M., J. Lyle, J. P. Keane, G. A. Begg, P. Hobsbawn, A. R. Ivey, R. Sakabe, and M. A. Steer. 2012. Commonwealth Small Pelagic Fishery: Fishery Assessment Report 2011. Report to the Australian Fisheries Management Authority. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2010/000270-3. SARDI Research Report Series No. 614. 98 pp.

Ward, T. M., L. J. McLeay, P. J. Rogers, and W. F. Dimmlich. 2001c. Spawning Biomass of Pilchard (*Sardinops sagax*) in South Australia in 2001. Report to Primary Industries and Resourses South Australia Fisheries. South Australian Research and Development Institute (Aquatic Sciences).

Ward, T. M., and P. J. Rogers, editors. 2007. Development and evaluation of egg-based stock assessment methods for blue mackerel *Scomber australasicus* in southern Australia. Final report to the Fisheries Research and Development Corporation Project 2002/061. SARDI Aquatic Science, Adelaide.

Ward, T. M., P. J. Rogers, L. J. McLeay, and R. McGarvey. 2009. Evaluating the use of the daily egg production method for stock assessment of blue mackerel, *Scomber australasicus*. Journal of Marine and Freshwater Research 62:112-128.

Ward, T. M., D. W. Schmarr, L. J. McLeay, P. J. Rogers, and A. Ivey. 2007. A preliminary investigation of the spawning biomass of sardine (pilchard, *Sardinops sagax*) off eastern Australia. Final report for the New South Wales Department of Primary Industry. South Australian Research and Development Institute (Aquatic Sciences), Adelaide.

Ward, T. M., and J. Staunton-Smith. 2002. Comparison of the spawning patterns and fisheries biology of the sardine, *Sardinops sagax*, in temperate South Australia and sub-tropical southern Queensland. Fisheries Research 56:37-49.

Ward, T. M., A. R. Whitten, and A. R. Ivey. 2015d. South Australian Sardine (*Sardinops sagax*) Fishery: Stock Assessment Report 2015. Report to PIRSA Fisheries and Aquaculture. South Australian Research and Development Institute (Aquatic Sciences), Adelaide.

Watanabe, Y., H. Zenitani, and R. Kimura. 1996. Offshore expansion of spawning of the Japanese sardine, *Sardinops melanostictus*, and its implication for egg and larval survival. Canadian Journal of Fisheries and Aquatic Sciences 53:55-61.

Webb, B. F. 1976. Aspects of the biology of jack mackerel, *Trachurus declivis* (Jenyns) from south-east Australian waters. Tasmanian Fisheries Research 10:1-14.

Welsford, D. C., and J. M. Lyle. 2003. Redbait (*Emmelichthys nitidus*): A synopsis of fishery and biological data. TAFI Technical Report Series, no. 20 20

Williams, H., and G. Pullen. 1986. A synopsis of biological data on the jack mackerel *Trachurus declivis* Jenyns. Technical Report No. 10. Department of Sea Fisheries, Tasmania, Marine Laboratories: Taroona. 34 pp.

Williams, H., and G. Pullen. 1993. Schooling behaviour of jack mackerel, *Trachurus declivis* (Jenyns), observed in the Tasmanian purse-seine fishery. Marine and Freshwater Research 44:577-587.

Williams, H., G. Pullen, G. Kucerans, and C. Waterworth. 1987. The jack mackerel purse-seine fishery in Tasmania, 1986-87. Technical report No. 19. . Department of Sea Fisheries, Tasmania, Marine Laboratories. Taroona, Tasmania. 32 pp.

Young, J. W., A. R. Jordan, C. Bobbi, R. E. Johannes, K. Haskard, and G. Pullen. 1993. Seasonal and interannual variability in krill (*Nyctiphanes australis*) stocks and their relationship to the fishery for jack mackerel (*Trachurus declivis*) off eastern Tasmania, Australia. Marine Biology 116:9-18.