Management zones from small pelagic fish species stock structure in southern Australian waters

C. Bulman, S. Condie, J. Findlay, B. Ward & J. Young

FRDC 2006/076
March 2008

Fisheries Research and Development Corporation and
Australian Fisheries Management Authority

Bulman, Cathy.
Management zones from small pelagic fish species stock structure in southern Australian waters.

Bibliography.
ISBN 9781921424007 (pdf).

1. Deep-sea fishes - Australia. 2. Marine fishes - Australia. 3. Fish stock assessment - Australia. 4. Fishery resources - Australia. 5. Fishery management - Australia. 6. Fisheries - Australia. I. CSIRO. II. Title.

333.9560994

Enquiries should be addressed to:

Dr Catherine Bulman
CSIRO Marine and Atmospheric Research
GPO Box 1538, Tasmania 7001 Australia
W 03 6232 5357
F 03 6332 5053
Cathy.Bulman@csiro.au

Distribution list

On-line approval to publish (CSIRO)	1 (pdf)
FRDC	6 (+ pdf)
AFMA	5 (+ pdf)
Authors	5
ComFRAB	1
SPFRAG scientific members (Drs Ward, Lyle & Neira)	3
State Fisheries Managers (NSW, Vic, Tas, SA, WA)	5
CMAR Library (not for circulation)	1 (pdf)

Important Notice

The Fisheries Research and Development Corporation plans, invests in and manages fisheries research and development throughout Australia. It is a statutory authority within the portfolio of the federal Minister for Agriculture, Fisheries and Forestry, jointly funded by the Australian Government and the fishing industry.

Use of this Report

GLOSSARY

AAIW	Antarctic Intermediate Water
AFMA	Australian Fisheries Management Authority
AFZ	Australian Fishing Zone
BRS	Bureau of Rural Sciences
CARS	CSIRO Atlas of Regional Seas
CSIRO	Commonwealth Scientific and Industrial Research Organization
DPIW	Department of Primary Industries and Water (Tasmania)
EAC	East Australian Current
EEZ	Exclusive Economic Zone
FL	Fork length
FRDC	Fisheries Research and Development Corporation
GAB	Great Australian Bight
ITW	Indonesian Throughflow Water
OCS	Offshore Constitutional Settlement
PIRVic	Primary Industries Research Victoria
SAMW	Subantarctic Mode Water
SARDI	South Australian Research and Development Institute
SDODE	Spatial Dynamics Ocean Data Explorer
SICW	South Indian Central Water
SLW	Subtropical Lower Water
SMP	Statutory Management Plan
SPF	Small Pelagic Fishery
SPFMAC	Small Pelagic Fisheries Management Advisory Committee
SPFRAG	Small Pelagic Fisheries Research Advisory Group
SPRAT	Small Pelagic Research and Assessment Team
SPRFMO	South Pacific Regional Fisheries Management Organisation
TAC	Total Allowable Catch
TACC	Total Allowable Commercial Catch
TAFI	Tasmanian Aquaculture and Fisheries Institute
TCL	Trigger Catch Levels

NON TECHNICAL SUMMARY

2006/076	Management zones from small pelagic fish species stock structure in southern Australian waters

PRINCIPAL INVESTIGATOR: Dr C. Bulman
ADDRESS: CSIRO Marine and Atmospheric Research

GPO Box 1538
Hobart Tas 7001
ph: 03 6232 5357

Objectives:

1. Undertake a review of the global literature on the subject of small pelagic species stock structures and delineations. The review should focus on available scientific knowledge and current understanding from similar species or general knowledge of the spatial structure of physical and biological processes in this area to suggest an appropriate spatial structure for immediate management.

2. Consolidate and review existing information on small pelagic fish species. Derive from this information, one or a range of reasonable interpretations or hypotheses for the spatial stock structuring of small pelagic species in the Commonwealth Small Pelagics Fishery off southern Australia.

3. Develop from the above interpretations/hypotheses a suite of potential and appropriate interim spatial management zones and measures, recognising the alternative hypotheses and the likely need for precaution.

4. From these hypotheses, generate recommendations regarding sampling design and appropriate analytical techniques to use in a future study to resolve the key uncertainties for future management

Non Technical Summary:

The available literature and data on the biology, habitat and catches of target species in the Commonwealth Small Pelagic Fishery was reviewed. This information suggests that, for at least 4 of the 5 species, there are likely to be two major subpopulations, one on the eastern seaboard of Australia including East Tasmania and another to the west of Tasmania across the

Great Australian Bight and the Western Australia region.

In the Eastern region, there is no evidence to suggest that jack mackerel *Trachurus declivis* is not one stock. The most recent information arising from ichthyoplankton surveys combined with the surveys of jack mackerel off eastern Tasmanian in the late 1980s are indicative of a specific association of the spawning stocks with the cool water masses of the Tasman Front. While it has been suggested that spawning is triggered by the warmer East Australian Current impinging on the shelf, there is evidence to suggest that the fish spawn in the cooler water under the surface currents. However, the eggs rise into the surface waters of the East Australian Current where development would be expected to be faster due to the warmer temperatures. While jack mackerel is caught widely throughout its distribution, catches were highest off East Tasmania in the mid 1980s for a couple of seasons, and have continued to fluctuate until redbait became the primary target in the early 2000s. While this suggests that jack mackerel are more abundant in southern regions, market forces strongly influence fishing practices and consequently the resulting catch history.

Similarly, redbait *Emmelichthys nitidus* appears to be more strongly associated with the cooler water masses in the Tasmanian region. There is some suggestion that redbait accumulate on the cooler side of the East Australian Current front. There is evidence for faunal contrast between the East Australian Current eddies and cooler Tasman Sea waters and it has been suggested that species such as tuna prefer either the cooler or warmer sides of the fronts. Simultaneous spawning of redbait throughout its range in eastern Australia also suggests one stock in the Eastern region. Historically, the largest catches of redbait have been from eastern Tasmania but again this could possibly reflect fishing practices more than abundances.

Blue mackerel *Scomber australasicus* and yellowtail scad *Trachurus novaezelandiae* are more commonly caught off New South Wales and southern Queensland. The major oceanographic influence in this region is the East Australian Current which carries warm, higher salinity water from the Coral Sea along the east coast surfacing along the Tasman Front and flowing eastwards. The position of the Tasman Front moves south in summer and north in winter and ichthyoplankton surveys off NSW and Victoria have found a mixed species composition of eggs and larvae. Blue mackerel eggs and larvae were caught exclusively in the “mixed” and East Australian Current waters. Yellowtail scad appear to prefer the warmer more northern waters although identification to species level of the *Trachurus* eggs has not yet been possible. Ongoing analyses of these data are expected to help to clarify species’ associations.

There is insufficient local data on Peruvian jack mackerel *Trachurus murphyi* to make any conclusions about stock structure in Australia. This species is widely distributed throughout the Pacific with populations in the northern and southern hemisphere considered to be two subspecies. The Southern Pacific Ocean subspecies is distributed from South America to Australia, although its extension to New Zealand and Australia is relatively recent. While it is targeted by the fishery in New Zealand, it is taken only occasionally by fisheries in Australia. It is evident from its very broad range that independent spawning stocks occur and at least four are proposed. However based on its broad oceanic range and habitat, it is probable that fish caught in Australia belong to a large south-west Pacific Ocean basin stock.

In the western region, from west of Tasmania, through the Great Australian Bight to Western Australia, there is insufficient data to determine how many stocks of any of the Small Pelagic Fishery species might occur. Only one recent study of otolith chemistry of blue mackerel suggests that stocks from WA are different from those in the Bight. However, it does seem clear

that the stocks are separate from the eastern Australian populations with the likelihood of occasional mixing via transport through Bass Strait or around southern Tasmania, particularly over winter as the Zeehan Current develops along the Tasmanian shelf-break.

We propose that the most likely stock structure is an eastern and a western stock for all species. There is uncertainty as to where the boundary might be placed, however the oceanography of southern Australia supports a separation between east and west with Tasmania and Bass Strait being a significant barrier to continuous distribution for several species, and is the suggested site for such a boundary. The barrier is not absolute and hence there is likely to be genetic flow from one population to the other, the rate of which is dependent on climatic and oceanographic conditions.

A possible stock division off south-western Australia is also supported by the oceanography of the region and bioregionalisation of demersal species. However, the exact location of that division is less clear, and more flexible, because the lack of a “rigid” barrier combined with the annual variability in the oceanography of the area would result in a less distinct separation.

KEYWORDS: Stock structure, Small Pelagic Fishery

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. NON TECHNICAL SUMMARY

The available literature and data on the biology, habitat and catches of target species in the Commonwealth Small Pelagic Fishery was reviewed. This information suggests that, for at least 4 of the 5 species, there are likely to be two major subpopulations, one on the eastern seaboard of Australia including East Tasmania and another to the west of Tasmania across the Great Australian Bight and the Western Australia region.

In the Eastern region, there is no evidence to suggest that jack mackerel *Trachurus declivis* is not one stock. The most recent information arising from ichthyoplankton surveys combined with the surveys of jack mackerel off eastern Tasmanian in the late 1980s are indicative of a specific association of the spawning stocks with the cool water masses of the Tasman Front. While it has been suggested that spawning is triggered by the warmer East Australian Current impinging on the shelf, there is evidence to suggest that the fish spawn in the cooler water under the surface currents. However, the eggs rise into the surface waters of the East Australian Current where development would be expected to be faster due to the warmer temperatures. While jack mackerel is caught widely throughout its distribution, catches were highest off East Tasmania in the mid 1980s for a couple of seasons, and have continued to fluctuate until redbait became the primary target in the early 2000s. While this suggests that jack mackerel are more abundant in southern regions, market forces strongly influence fishing practices and consequently the resulting catch history.

Similarly, redbait *Emmelichthys nitidus* appears to be more strongly associated with the cooler water masses in the Tasmanian region. There is some suggestion that redbait accumulate on the cooler side of the East Australian Current front. There is evidence for faunal contrast between the East Australian Current eddies and cooler Tasman Sea waters and it has been suggested that species such as tuna prefer either the cooler or warmer sides of the fronts. Simultaneous spawning of redbait throughout its range in eastern Australia also suggests one stock in the Eastern region. Historically, the largest catches of redbait have been from eastern Tasmania but again this could possibly reflect fishing practices more than abundances.

Blue mackerel *Scomber australasicus* and yellowtail scad *Trachurus novaezelandiae* are more commonly caught off New South Wales and southern Queensland. The major oceanographic influence in this region is the East Australian Current which carries warm, higher salinity water from the Coral Sea along the east coast surfacing along the Tasman Front and flowing eastwards. The position of the Tasman Front moves south in summer and north in winter and ichthyoplankton surveys off NSW and Victoria have found a mixed species composition of eggs and larvae. Blue mackerel eggs and larvae were caught exclusively in the “mixed” and East Australian Current waters. Yellowtail scad appear to prefer the warmer more northern waters although identification to species level of the *Trachurus* eggs has not yet been possible. Ongoing analyses of these data are expected to help to clarify species’ associations.

There is insufficient local data on Peruvian jack mackerel *Trachurus murphyi* to make any conclusions about stock structure in Australia. This species is widely distributed throughout the Pacific with populations in the northern and southern hemisphere considered to be two subspecies. The Southern Pacific Ocean subspecies is distributed from South America to Australia, although its extension to New Zealand and Australia is relatively recent. While it is targeted by the fishery in New Zealand, it is taken only occasionally by fisheries in Australia. It is evident from its very broad range that independent spawning stocks occur and at least four are proposed. However based on its broad oceanic range and habitat, it is probable that fish caught in Australia belong to a large south-west Pacific Ocean basin stock.

In the western region, from west of Tasmania, through the Great Australian Bight to Western Australia, there is insufficient data to determine how many stocks of any of the Small Pelagic Fishery species might occur. Only one recent study of otolith chemistry of blue mackerel suggests that stocks from WA are different from those in the Bight. However, it does seem clear that the stocks are separate from the eastern Australian populations with the likelihood of occasional mixing via transport through Bass Strait or around southern Tasmania, particularly over winter as the Zeehan Current develops along the Tasmanian shelf-break.

We propose that the most likely stock structure is an eastern and a western stock for all species. There is uncertainty as to where the boundary might be placed, however the oceanography of southern Australia supports a separation between east and west with Tasmania and Bass Strait being a significant barrier to continuous distribution for several species, and is the suggested site for such a boundary. The barrier is not absolute and hence there is likely to be genetic flow from one population to the other, the rate of which is dependent on climatic and oceanographic conditions.

A possible stock division off south-western Australia is also supported by the oceanography of the region and bioregionalisation of demersal species. However, the exact location of that division is less clear, and more flexible, because the lack of a "rigid" barrier combined with the annual variability in the oceanography of the area would result in a less distinct separation.

1.1 Acknowledgements

Many thanks are due to Drs Jeremy Lyle, Francisco Neira and Tim Ward and Vince Lyne for providing unpublished and draft results from current projects, and many informative and supportive discussions regarding stock structure issues. We also thank the data managers from DPIW (Tas), NSW Fisheries, PIRVIC and SARDI for providing the fishery data for our analysis. Special thanks also to Sheree Epe (BRS) for compiling some sections of this report, and to Mike Fuller, Jemery Day and Jeff Dunn (CSIRO) for extracting extensive datasets and GIS mapping. Thanks also to Louise Bell (CSIRO) for the cover design.

2. PROJECT BACKGROUND

2.1 Background

The status of the Small Pelagics Fishery (SPF) is uncertain— the fishery is currently facing a number of challenges for managing the target species. The resources are probably not over-fished in the Great Australian Bight (GAB) and western region of the Australian Fishing Zone (AFZ), but dramatic declines in jack mackerel catch in Zone A are of concern. Total Allowable Catch (TAC) limits and/or Trigger Catch Levels (TCL) apply in all four management zones (Findlay 2007). Catches from recent seasons cannot be reported for confidentiality reasons; they have fallen far below TAC levels in Zone A (eastern and southern Tasmania). While the decline of jack mackerel might have been a result of possible over-fishing in the 1980s and 1990s, changes in the regional oceanography and the subsequent impacts on prey availability, and changing market forces might also have been important, so the catch history needs careful interpretation. Nevertheless, in December 2005, the Minister for Fisheries, Forestry and Conservation directed Australian Fisheries Management Authority (AFMA) to take immediate action to prevent over-fishing in all Australian Government Fisheries through the implementation of harvest strategies. In response to that direction, a harvest strategy is being developed for the fishery by the Bureau of Rural Sciences (BRS) for consideration by the Small Pelagic Fisheries Research Advisory Group (SPFRAG) and the Small Pelagic Fisheries Management Advisory Committee (SPFMAC). Development requires caution because of the role of small pelagic fish species in the food chain and the potential for their localized depletion or overexploitation.

2.2 Need

There is an urgent need to ensure that the spatial structure of the management arrangements in the Commonwealth-managed Small Pelagics Fishery matches the ecology of the species taken. Present fishery zoning is essentially jurisdictional, whereas spatial management arrangements need to be both based on whatever biological information exists, and reflect appropriate precaution for uncertainties. Consequently, there is a need to gather the best information about the spatial structure of small pelagic fish species taken in the fishery to both inform a precautionary approach to spatial management and identify the most appropriate research for improving spatial management and reducing the reliance on precaution. In the absence of definitive scientific proof, risk-based decision-making is warranted.

2.3 Objectives

5. Undertake a review of the global literature on the subject of small pelagic species stock structures and delineations. The review should focus on available scientific knowledge and current understanding from similar species or general knowledge of the spatial

structure of physical and biological processes in this area to suggest an appropriate spatial structure for immediate management.

6. Consolidate and review existing information on small pelagic fish species. Derive from this information, one or a range of reasonable interpretations or hypotheses for the spatial stock structuring of small pelagic species in the Commonwealth Small Pelagics Fishery off southern Australia.

7. Develop from the above interpretations/hypotheses a suite of potential and appropriate interim spatial management zones and measures, recognising the alternative hypotheses and the likely need for precaution.

8. From these hypotheses, generate recommendations regarding sampling design and appropriate analytical techniques to use in a future study to resolve the key uncertainties for future management

3. OCEANOGRAPHIC ENVIRONMENT OF SOUTHERN AUSTRALIAN WATERS

Southern Australia is surrounded by subtropical surface waters that, for the most part, are low in nutrients and primary productivity. These waters are carried southward by major current systems, such as the East Australian Current (EAC) off the east coast and the Leeuwin Current off the west and south coasts (Figs 1 to 3). The oceanography of the region has been described in a number of recent reviews (Church and Craig 1998, Condie and Dunn 2006, Condie and Harris 2006). This section describes the physical, chemical and biological oceanographic characteristics of the four pelagic subregions corresponding to the waters off: NSW and eastern Victoria; Tasmania; the Great Australian Bight; and south-western Australia.

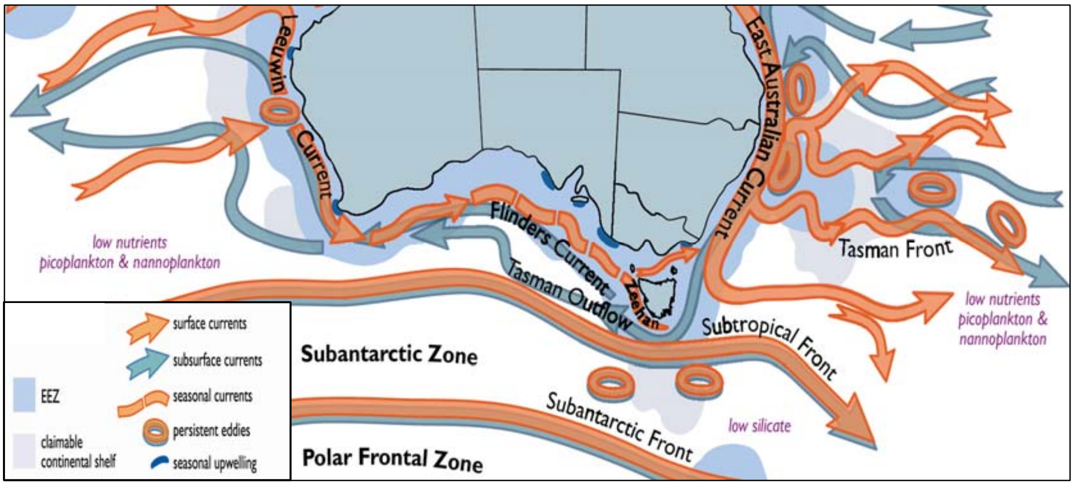


Figure 1. Schematic illustration of the larger-scale oceanographic features in the region surrounding southern Australia. Orange arrows indicate surface currents and green arrows indicate subsurface currents. Dashed arrows indicate that currents are present only on a seasonal basis and blue shading indicates regions of significant seasonal upwelling into near-surface waters.

3.1 NSW and eastern Victoria region

3.1.1 Physical Oceanographic Characteristics

The near-surface layers east of Australia and north of the Subtropical Convergence consist of relatively warm, high salinity Subtropical Lower Water (SLW) carried south by the East Australian Current and then surfacing as it moves eastward along the Tasman Front (Fig 2). At greater depth, thermocline waters are renewed by high oxygen Subantarctic Mode Water (SAMW) formed by deep winter convection between the Subtropical Convergence and the

Subantarctic Front. Below 500 m low salinity, Antarctic Intermediate Water (AIW) spreads from the Southern Ocean into the South Pacific Subtropical Gyre.

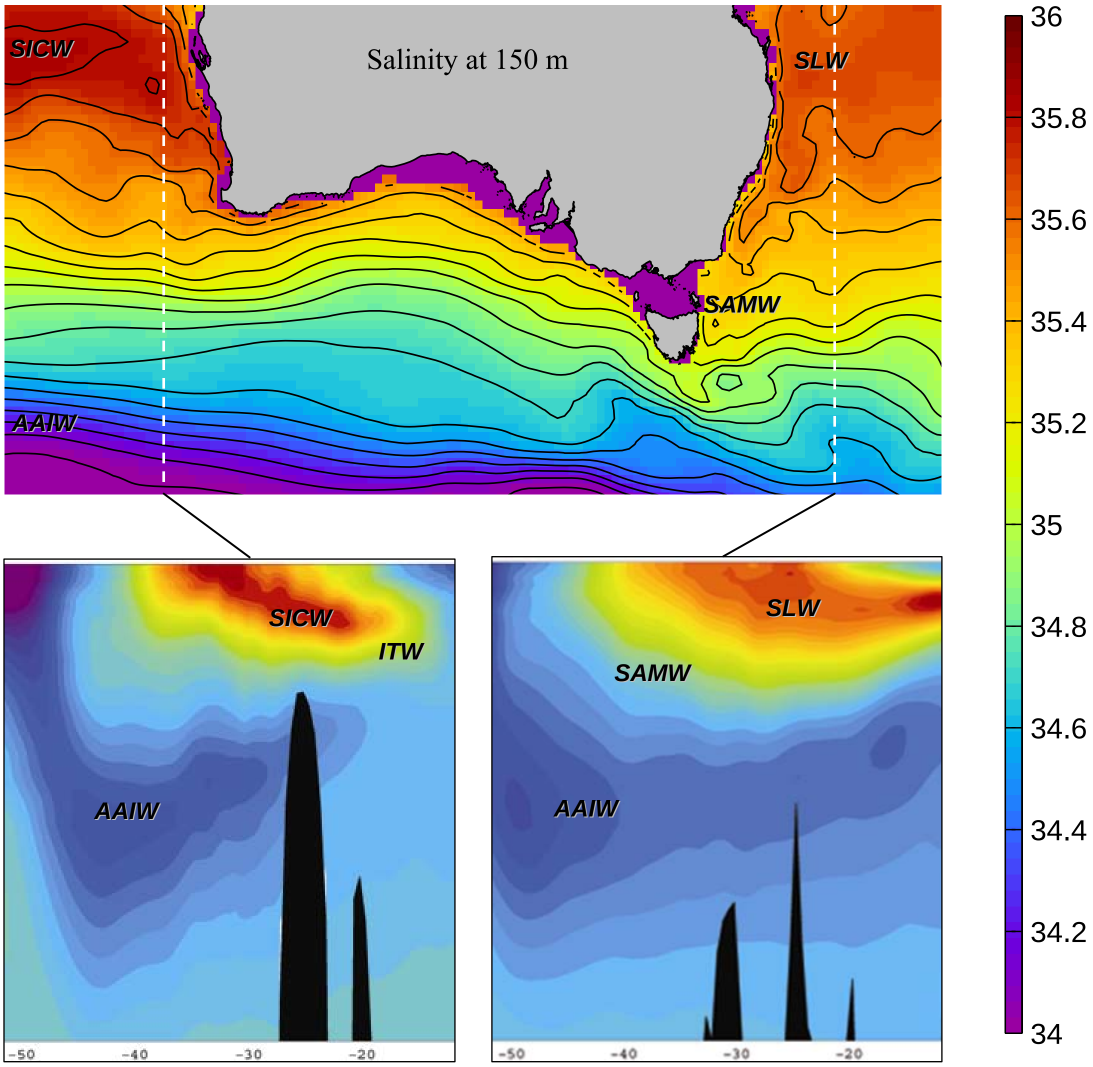


Figure 2. Salinity fields from the CSIRO Atlas of Regional Seas (CARS) at a depth of 150 m (upper), through a vertical section along 112°E (lower left) and through a vertical section along 160°E. The major water masses are Subtropical Lower Water (SLW); South Indian Central Water (SICW); Indonesian Throughflow Water (ITW); Subantarctic Mode Water (SAMW); and Antarctic Intermediate Water (AAIW).

The complex topography in the region strongly influences the circulation of the East Australian Current system. Several large ridges radiating northward from New Zealand combined with a complicated pattern of island groups, reef systems, and seamounts all influence the circulation at both large and small scales (Ridgway and Dunn 2003). In particular, the geometry of the region serves to contain the boundary current system within the region producing extensive recirculation and mixing, and hence uniform ocean properties in the southern Coral Sea and northern Tasman Sea. The southern branch of the South Equatorial Current bifurcation provides the source waters of the East Australian Current (Fig 1). This is a major western boundary current, equivalent to the Gulf Stream in the North Atlantic and the Kuroshio in the North Pacific, and it dominates the regional circulation. Over the first 500 km, it is a relatively shallow surface flow but just south of the Great Barrier Reef it intensifies and deepens, reaching its maximum strength between 25 and 30°S. Within this region, surface currents average around 1 m s^{-1} and transports average around 30 x 10^6 m^3 s^{-1}, but can reach twice these values.

The deep layers of the East Australian Current continue southward along the Australian coast as far as Tasmania. However, the upper layers separate from the coast before reaching Sydney (Fig 1). Both the strength of the East Australian Current and its separation point vary seasonally and interannually, with the largest transports occurring in summer. It also spawns two to three eddies annually with diameters of 200–300 km and lifetimes often exceeding a year. These eddies follow complicated southward trajectories, but are generally constrained within the Tasman Basin where they contribute to a mean recirculation. The remainder of the flow meanders eastward across the Tasman Sea (Fig 1). These meanders tend to form a chain of semi-permanent eddies tied to the bathymetric structure, the most prominent within the Australian region being the Norfolk Eddy.

3.1.2 Chemical Oceanographic Characteristics

The East Australian Current advects mainly oligotrophic Coral Sea water along the east coast. However, at prominent coastal features (Cape Byron, Smoky Cape) the current moves away from the coast, driving upwelling, which draws nutrient-rich water from a depth of 200 m or more (Oke and Middleton 2001). However, while the current patterns may drive nutrient-rich water onto the shelf; upwelling-favourable winds (northerly) are needed to bring that water to the surface. As the Tasman Front returns to the north over autumn and early winter, it is replaced by higher nutrient water from the south, possibly supplemented by entrainment from below as the surface mixed layer deepens (Condie and Dunn 2006).

3.1.3 Biological Oceanographic Characteristics

Chlorophyll distributions in the Southwest Pacific do not appear to be strongly associated with particular water masses. Instead, they propagate seasonally north-south across the fronts in response to nutrient availability and shallow mixed layers (Fig 3). High surface chlorophyll is concentrated in the Subtropical Convergence in March, then moves north through the Tasman Front to around 30°S by August, before retreating south again. Nitrate is most probably limiting phytoplankton biomass and primary production in the southern Coral Sea and Tasman Sea. Both the Coral and Tasman seas typically have deep chlorophyll maxima near the nutricline even when little chlorophyll can be seen in ocean colour images. These deep chlorophyll maxima are likely to be quite productive where light levels are adequate (~ 1% of surface values).

The NSW shelf experiences species successions from small diatoms to large dinoflagellates over spring and summer (Jeffrey and Hallegraeff 1990). However, when upwelling associated with the East Australia Current carries nutrient-rich water into the euphotic zone, short-lived (days to weeks) diatom blooms can result (Tranter *et al.* 1986, Hallegraeff and Jeffrey 1993). The eddies are also important for nutrient cycling and biological productivity, with primary productivity rates usually less than in surrounding waters.

There is evidence that the gemfish run and spawning are linked to the oscillations in the East Australia Current. There is also strong evidence of faunal contrasts between eddies and the surrounding Tasman Sea waters (Griffiths and Wadley 1986). Other pelagic species such as tuna appear to favour either the warm or the cooler side of the East Australian Current front.

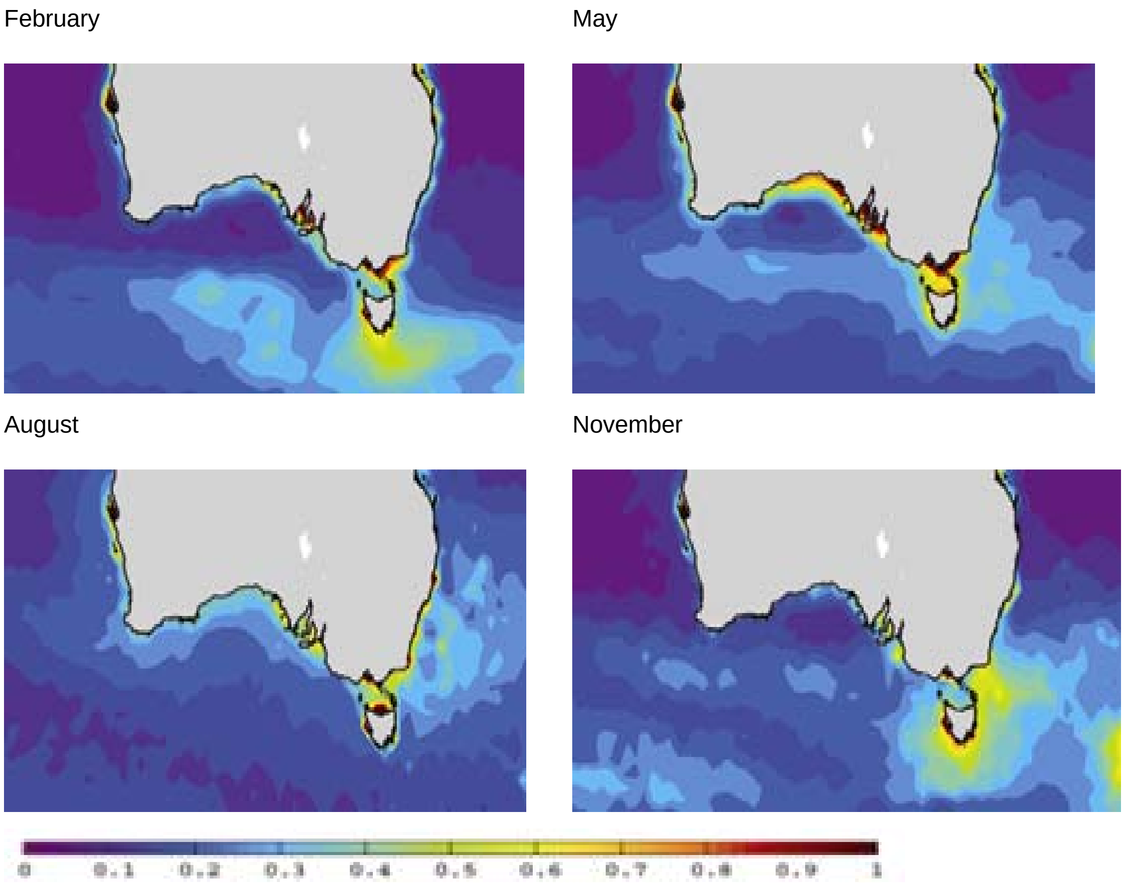


Figure 3. Seasonal chlorophylla distribution (mg m^{-3}) in the waters around southern Australia based on SeaWiFS satellite ocean-colour data (averaged across years).

The distributions of small pelagic fishes along the eastern seaboard are closely linked to the continental shelf and shelf break. In the south, nutrient enrichment along the shelf edge from eddies generated by the East Australian Current supports concentrations of jack mackerel and their predators, particularly yellowfin tuna (Young *et al.* 2001). Further north, upwelling events along the mid NSW coast provide suitable habitat for a suite of small pelagic species including blue mackerel and yellowtail scad.

3.2 Tasmanian region

3.2.1 Physical Oceanographic Characteristics

Waters off eastern Tasmania are bounded by the Tasman Front to the north and to the south by the Subtropical Convergence that skirts the southern tip of Tasmania (Fig 1). The East Australian Current pushes southward into this region over summer above Subantarctic Mode Water, which is relatively shallow in this region (Fig 2). Waters off western Tasmania are influenced by the Subtropical Convergence and seasonally by the warm Zeehan Current (Cresswell 2000), an eastward extension of the Leeuwin Current system (Ridgway and Condie 2004). At depths down to 1000 m, the Tasman Outflow carries Antarctic Intermediate Water from eastern Australia around Tasmania and into the Great Australian Bight.

The other potential link between the two sides of Tasmania is through Bass Strait. While currents tend to be dominated by tides, there is a net west to east transport driven by local winds and peaking in autumn and winter (~ 0.5×10^6 m^3 s^{-1}). During winter, the winds, tides, and surface cooling combine to produce water that is both colder and more saline than Tasman Sea surface water. The strong prevailing westerly winds drive this water eastward, where it forms a front and cascades down the slope to a depth of 500 m where it can travel more than 1000 km northward along the continental slope.

3.2.2 Chemical Oceanographic Characteristics

Nitrate is most probably limiting phytoplankton biomass and primary production in the southern Coral Sea and Tasman Sea, but silicate is also important in limiting diatom production in the Subtropical Convergence region. There is also a high level of seasonal variability, particularly on the east coast where summertime infringement of the East Australia Current and its associated eddies replace nutrient rich subantarctic water offshore and Bass Strait water over the shelf (Gibbs *et al.* 1986, 1991; Bax *et al.* 2001). Nutrient levels in central Bass Strait are low (<1 µM) throughout the year, but increase substantially (>5 µM) along the eastern edge during winter when the cold-water front is present (Gibbs *et al.* 1986, 1991).

3.2.3 Biological Oceanographic Characteristics

The waters surrounding Tasmania are characterized by a chlorophyll peak in autumn and a larger peak in spring (Fig 3). Constant tidal motions in the relative shallow environment of Bass Strait, result in increased standing stocks of chlorophyll that are exported eastwards (Gibbs *et al.* 1991). Available measurements confirm that productivity rates are also high (Harris *et al.* 1987). Interannual variability in the timing and duration of the spring phytoplankton bloom has been linked to the positioning of East Australian Current eddies and local mixed layer depths (Harris *et al.* 1987, 1988; Clementson *et al.* 1989).

The phytoplankton community is quite distinctive from those of other Australian waters (Jeffrey and Hallegraeff 1990). Upwelling produces a clear species succession from small diatoms, to large diatoms, and then to larger dinoflagellates. However, when diatom blooms are absent, nanoplankton contributes a large fraction of the chlorophyll.

The high phytoplankton productivity noted by Harris *et al.* (1987) for Tasmanian waters supports a large biomass of zooplankton and micronekton species. The zooplankton is dominated by krill *Nyctiphanes australis*, and is widespread along the Tasmanian continental shelf. Lanternfish (family Myctophidae), which occur mainly on the shelf break and offshore, dominate the micronekton. Krill are the main prey for most fish and bird species of the area. The importance of krill is underlined when we consider that they are the main prey for jack mackerel and other small pelagic species including redbait over the shelf. Krill are a swarming species but even outside of swarms, densities of up to 10 g m^{-2} have been reported (Ritz and Hosie 1982, Young *et al.*1993). The other main species group is the lanternfish. Although restricted to a thin band over the continental slope in waters of between 300 and 500 m depth, summer populations of lanternfish composed mainly of *Lampanyctodes hectoris* reach densities of 390 g m^{-2} (May and Blaber 1989). There they are preyed upon by a range of predators, including the small pelagic fishes, usually just prior to spawning (Jordan *et al.* 1995).

3.3 Great Australian Bight region

3.3.1 Physical Oceanographic Characteristics

The 2000-km extent of the zonally oriented southern shelf of Australia forms a natural northern boundary centred on a region of broad continental shelf opening onto the junction of the Indian, Pacific, and Southern Oceans. It encompasses the Subtropical Convergence for this sector, which follows a nearly zonal path along 40°S before looping poleward around the southern tip of Tasmania (Fig 1).

Surface currents along the shelf-break of the southern coast are mainly driven by seasonally reversing winds. During winter, onshore transport causes coastal sea-level to rise and the eastward extension of the Leeuwin Current to form along the shelf-break (Ridgway and Condie 2003). In summer, winds reverse, coastal sea-level drops, and the eastward extension of the Leeuwin Current is replaced by a westward flow both on the shelf (Herzfeld 1997) and offshore over the subsurface Flinders Current.

The Flinders Current is an upwelling-favourable boundary current the core of which is at depths of 500–800 m and is sourced from the Tasman Outflow (Fig 1). It reaches its maximum strength west of the Great Australian Bight, as a reconstituted zonal jet and proceeds due westward into the main Indian Ocean Gyre.

Both surface exchange and circulation patterns modify the extensive shallow shelf region within the Great Australian Bight (Herzfeld 1997). A warm pool develops in the northwest due to surface heating in summer (2–3 °C above surrounding waters) and spreads south-eastward during late summer and early autumn. The summer heating also leads to evaporation in the surface waters and a major increase in salinity. Within the Bight, the prevailing easterly winds set up an anti-clockwise gyre with westward currents near the coast (from the Eyre Peninsula) and eastward currents over the shelf break (Fig 1).

Throughout the summer period (November–March) a succession of slowly propagating, high-pressure atmospheric features move eastwards just south of the continent. Due to their orientation, certain sections of the southern shelf are subject to alongshore south-easterly winds, which are upwelling-favourable (Fig 3). Regular summer upwelling occurs off the Eyre Peninsula, Kangaroo Island, the Bonney Coast (Robe to Portland) and eastern Victoria (Fig 3). The most prominent events occur along the Bonney Coast, where classical upwelling plumes of low temperature surface water and increased chlorophyll biomass are regularly observed.

3.3.2 Chemical Oceanographic Characteristics

The few available measurements of nutrients in this region suggest that oligotrophic conditions prevail, with moderate enhancement over winter. However, nitrate levels have been observed to increase locally by factors of 30 to 70 during upwelling events on the Bonney Coast (Lewis 1981).

3.3.3 Biological Oceanographic Characteristics

The wintertime eastward extension of the Leeuwin Current is coincident with enhanced chlorophyll in the Bight (Fig 3). Summer brings a general decline in chlorophyll across the Bight, while significantly enhanced levels develop further south around the Subtropical Convergence.

While there is very little in situ data available, high chlorophyll is clearly visible around upwelling sites in ocean colour imagery. The regions of enhanced chlorophyll persist until the upwelled nutrients are exhausted and plankton is advected away from the upwelling site by surface currents.

The midwater community of the Great Australian Bight (GAB) is distinguished by the presence of a large biomass of sardines *Sardinops sagax* and anchovy *Engraulis australis* particularly in inshore waters of the eastern GAB, presumably responding to coastal upwelling in the summer and autumn (Ward *et al.* 2006). The links between these fishes and the other pelagic species including jack mackerel is not clear, although typical size-related predation is likely. However, we do know that sardines are the main prey of juvenile southern bluefin tuna in the region (see Ward *et al.* 2006). A shipboard survey of the GAB found significant biomass of micronekton on the shelf break. The species composition was similar to that in the Tasmanian shelf region and was particularly highlighted by the presence of krill and lanternfish that are prey of jack mackerel and redbait (Young *et al.* 2000). Large surface swarms of krill have been reported from the Bonney Coast and Kangaroo Island where seasonal upwelling underpins a productive local ecosystem that attracts small pelagic species through to blue whales (Gill 2002).

3.4 South-western Australian region

3.4.1 Physical Oceanographic Characteristics

The Leeuwin Current is the dominant oceanographic feature off south-western Australia, flowing southward along the shelf-edge to Cape Leeuwin, then turning to the east and continuing along the southern Australian coast (Fig 1). The Leeuwin Current is fed by relatively fresh Indonesian Throughflow Water carried by the South Equatorial Current and by salty South Indian Central Water (Fig 2). This strong connection with larger-scale influences results in significant interannual variability. Although the Leeuwin flows throughout the year, it also shows a clear seasonal variation, being strongest in autumn and winter. This variation is due to both a strengthening of the alongshore gradient and a weakening of the winds at this time. The seasonal changes in the advection of warm, low salinity water produces a distinct seasonal cycle in the water properties along the west coast. Below the poleward flow of the Leeuwin Current at depths of 300 to 400 m, the Leeuwin Undercurrent advects saline, high-oxygen South Indian Central Water equator-ward throughout the year (Fig 1).

On the west coast shelf, southerly winds peak in summer and drive northward currents against the alongshore pressure gradient. The Capes Current carries cool saline water northward from upwelling sites around Cape Leeuwin to Perth, and possibly as far north as 29°S (Pearce and Pattiaratchi 1999).

3.4.2 Chemical Oceanographic Characteristics

The Leeuwin Current is fed by nutrient poor Indonesian Throughflow Water and inflow from the west effectively suppresses any upwelling of nutrients on the continental slope (Condie and Dunn 2006, Lourey *et al.* 2006). Nutrient levels in the Leeuwin Undercurrent are somewhat higher having been derived from South Indian Central Water.

The upwelling associated with the Capes Current is a significant source of nutrients on the shelf during summer (>1 μM) and provides a strong contrast with the oligotrophic conditions in the neighbouring Leeuwin Current (Pearce and Pattiaratchi 1999).

3.4.3 Biological Oceanographic Characteristics

Surface chlorophyll levels are generally low in the Leeuwin Current, although they increase in winter due to enhanced exchange with more productive shelf waters as the current strengthens (Hanson *et al.* 2005, Fig 3). While there is a general decline in surface chlorophyll as summer approaches and the current weakens, there is evidence of persistent subsurface chlorophyll maximum near the nutricline both on the shelf and offshore. The Capes Current is likely to enhance primary production over the shelf and may play an important role in the local fisheries.

The Leeuwin Current and its associated eddy field are able to carry planktonic organisms many hundreds of kilometres. For example, it is likely to be responsible for the distribution of dinoflagellates from southwest Australia to Tasmania. It is also likely that species such as southern bluefin tuna, Australian salmon, herring, and western rock lobster utilize the current to transport eggs, larvae and juveniles along its path (Griffin *et al.* 2001). Migrating Australian salmon also benefit from the Capes Current as they head northward to west coast spawning grounds.

4. OVERVIEW OF THE SMALL PELAGICS FISHERY

The Small Pelagic Fishery (SPF) extends from southern Queensland, around southern and south-western Australia. The fishery is divided into four zones — A, B, C and D (Fig 4). Since the development of the fishery, the majority of fishing activity has occurred around eastern Tasmania in Zone A, which includes waters both inside and outside 3 nautical miles (Caton and McLoughlin, 2004).

AFMA generally manages these fisheries in waters between 3 and 200 nautical miles offshore with the States managing inside three nautical miles. However, Western Australia manages waters inside three n miles east of 125°E, with the Commonwealth having jurisdiction west of this point.

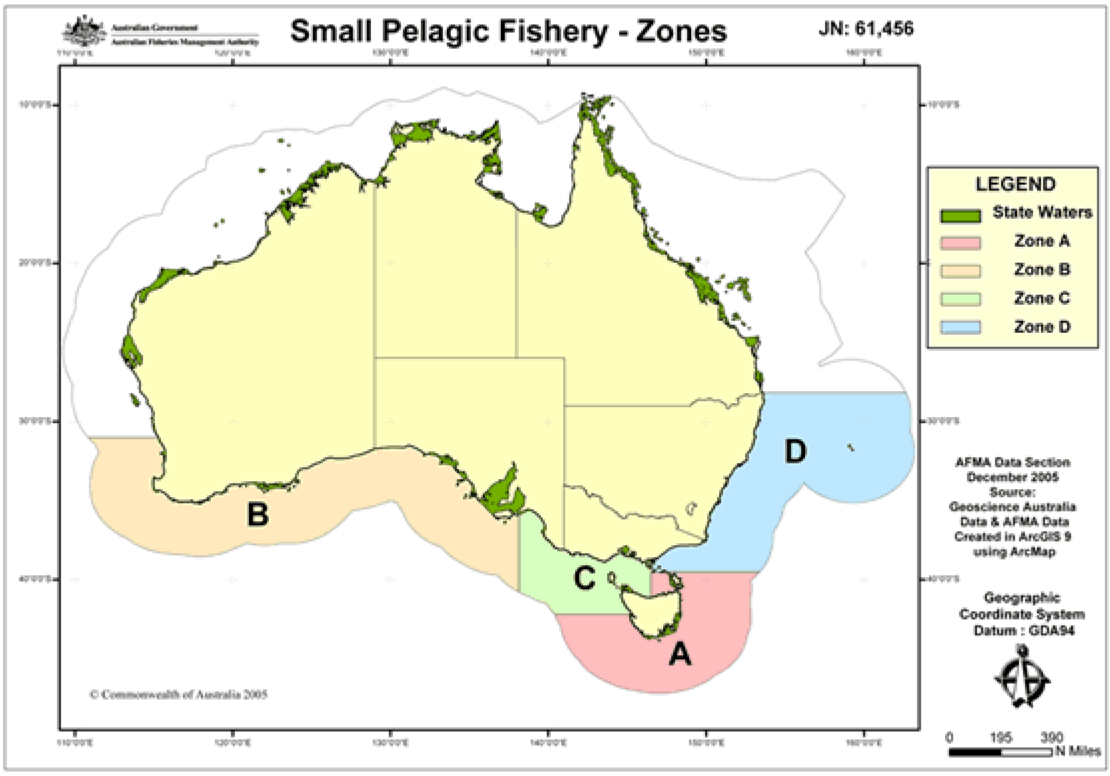


Figure 4. Management Zones of the Small Pelagics Fishery (from AFMA website 7 June 2007).

The fishery targets a number of species: jack mackerel *Trachurus declivis* and *T. murphyi*, blue mackerel *Scomber australasicus*, redbait *Emmelichthys nitidus* and yellowtail scad *Trachurus novaezelandiae*. The principal fishing methods employed include purse seine and midwater trawl. In 2001, a singe concession was granted to trial paired midwater trawl in Zone A. This method will only be broadly introduced to the fishery if it is shown to be ecologically sustainable.

4.1 History of the fishery

Historically, most small pelagic fishery catches have been jack mackerel, purse seined in Zone A within three nautical miles of eastern Tasmania. Rapid expansion of the Tasmanian jack mackerel fishery occurred in the mid 1980s. At this time, purse seine vessels began targeting jack mackerel off the east coast of Tasmania, near Maria Island (Pullen 1994). Annual catches increased from 6000 t in the 1984/85 season to a peak of almost 42 000 t in the 1986/87 season. Catches in the Commonwealth sector during the next decade were lower, generally between 8000 t and 32 000 t (Caton and McLoughlin 2004, Findlay 2007). Only a small number of fishers have been active in the fishery since 1994/95 and therefore tonnages are confidential. However, the calendar year totals over all jurisdictions are shown in Fig 5. Prior to 2000, total annual catches consisted mostly of jack mackerel (Fig 5), much of which was taken in the Tasmanian Purse Seine fishery. Since a low in 2000, total catches have increased but due mostly to redbait catches.

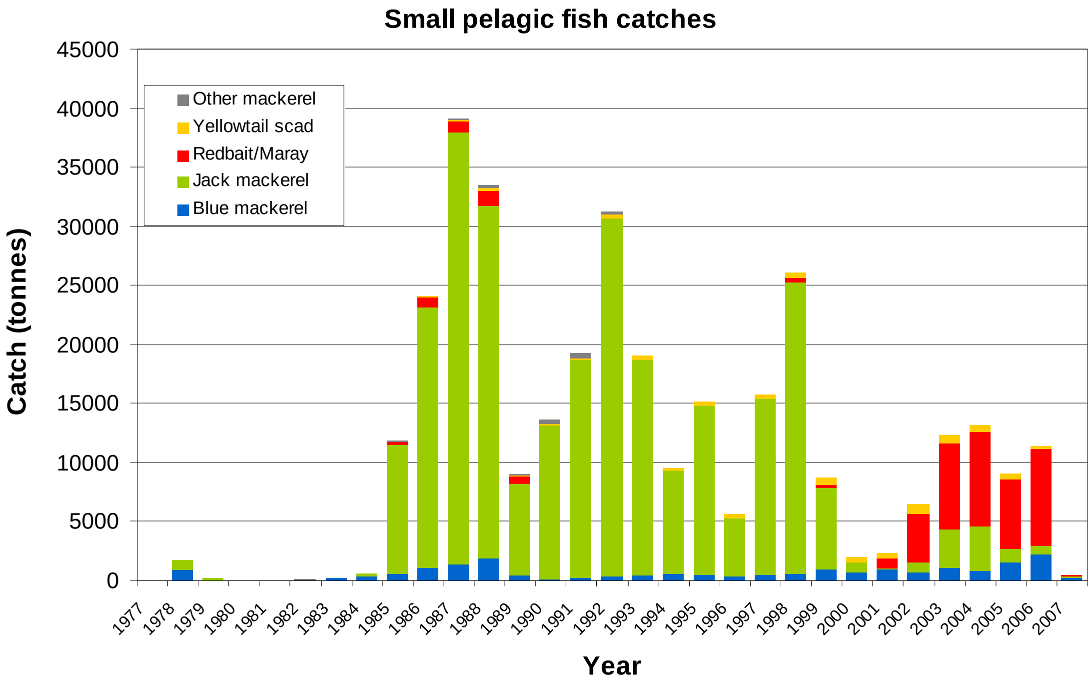


Figure 5. Total annual catches of all small pelagic fish species in the major State and Commonwealth fisheries compiled from a database held at CSIRO (not including WA and Qld). NB The data are summarised by calendar year and are incomplete for 2007.

Zone A remains the main area for effort in the fishery, although fishing operations have changed within the zone during recent years. From 2002, midwater trawling has become the predominant method and redbait has replaced jack mackerel as the main species targeted and overall catches are now mainly comprised of redbait. Until recently, the majority of catch (historically jack mackerel) from Zone A was processed into fishmeal with some of the catch frozen for use as rock lobster bait. During recent years, much of the catch has been used as feed for southern bluefin tuna *Thunnus maccoyii* aquaculture operations in Port Lincoln, South Australia (Findlay 2007).

Overall, the catches of small pelagics have fluctuated and gradually declined. However, this should be considered a reflection the market forces rather than of the resource size.

4.2 Management

The Australian and Tasmanian governments co-operatively manage Zone A. The Tasmanian Department of Primary Industries, Water and Environment set an annual Total Allowable Catch (TAC). Limited entry and gear restrictions also apply. In addition, operators must hold a Commonwealth Fishing Permit and/or a Tasmanian Fishing Licence.

Zones B, C and D are managed by Permits in accordance with the Management Policy for the Commonwealth Small Pelagic Fishery, 1 March 2002. A number of input controls are used within these zones including limited entry, gear restrictions and spatial controls. Catch levels are regulated through precautionary trigger catch limits (TCLs) followed by prescribed protocols when TCLs are reached. Midwater trawl permit holders must also hold entitlements for relevant Southern and Eastern Scalefish and Shark Fishery trawl sectors operating in the same area of water.

Generally, AFMA manages these fisheries in waters between 3 and 200 nautical miles while the States manage waters within three nautical miles. Western Australia manages waters inside three nautical miles east of longitude 125ºE, while the Australian Government has jurisdiction west of this point.

Species targeted in the SPF are also taken by a number of other Australian Government-managed and state-managed fisheries. These include the trawl sectors of the Southern and Eastern Scalefish and Shark Fishery, the Eastern and Western Tuna and Billfish Fisheries, the NSW Ocean Haul Fishery as well as a number of state-managed fisheries for Australian sardines *Sardinops sagax*.

A Statutory Management Plan (SMP) that will provide for the granting of Statutory Fishing Rights based on Individual Transferable Quotas will replace the current management policy. The SMP is expected to be finalised in 2008 (AFMA 2004).

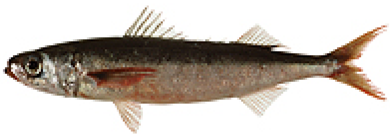
There are 75 SPF permits licences, however only six vessels have recorded catch since 1 July 2007. Substantial commercial operations have generally only occurred in Zone A. However, there is a long history of small-scale commercial operations and recreational and charter fishers targeting small pelagic species in Zones A and D. There is significant sectoral interaction/competition for bait species within and between commercial fishers (Commonwealth and State) and recreational fishers. Access to bait fish is an integral part of the tuna and billfish, skipjack and southern bluefin tuna fisheries and this is likely to continue.

Table 1. History of Small Pelagic Fishery (from the Draft Assessment Report July 2003, AFMA website)

Date	*Event*
1936	CSIRO conducts aerial surveys of pelagic fish resources off the East Coast, Tasmania and Western Australia. Large numbers of pilchard and mackerel schools were observed along the western edge of the Great Australian Bight.
1938	Government sponsors an investigation into pelagic fish resources off Victoria, Tasmania and New South Wales.
1943–50	Purse seine nets were used in pelagic fishing trials off NSW and eastern Tasmania. The first purse seine catch in Australia comprised about 4 t of jack mackerel, taken near Hobart.
1960s and 1970s	Southern bluefin tuna pole and line fleet typically take about 700 to 1000 t of live bait from east coast bait grounds (60 % yellowtail scad and blue mackerel).
mid 1970s	Purse seining was trialled near Lakes Entrance.
1973	A fishery for jack mackerel was commenced by a company operating from Triabunna in Tasmania where it located a fishmeal processing plant.
1979	The South Eastern Fisheries Committee set a TACC of 30 000 t of mackerel for Australian waters with 10,000 t reserved for waters off Tasmania
1984/85	First large catches of jack mackerel taken off Tasmania (purse seine method)
1986/87 & 1987/88	Catches of jack mackerel off Tasmania exceed 35 000 t in both fishing seasons
1993/94	Existing management arrangements agreed between the Commonwealth and the states. Zone A created.
1996	OCS signed by the Tasmanian and Commonwealth ministers but not gazetted
1991–2000	Purse seine fishery in Zone A averaged around 12 000 t per annum characterised by strong inter-annual and within season variability (linked to surface schooling behaviour).
2001/02	First significant catches of redbait taken by mid-water trawl method in Zone A
2001/02	Zone A TACC reduced proportionally between all sectors
2001/02	Commercial catches of redbait taken in Zone A using mid-water trawling
Feb 2002	First meeting of the Small Pelagic Research and Assessment Team (SPRAT)
March 2002	Management Policy for the Commonwealth Small Pelagic Fishery comes into effect (applies to zones B, C and D). Fishery formerly known as the Jack Mackerel Fishery.
Aug 2002	Zone A Small Pelagic Assessment Workshop – TACC setting and development of trigger points (included the Zone A Small Pelagic Fishery Assessment Group).
2003	The Southern and Eastern Scalefish and Shark Fishery Management Plan prohibits targeting of small pelagic species

5. SMALL PELAGIC SPECIES OF THE SPF

5.1 Redbait *Emmelichthys nitidus* Richardson, 1845



CSIRO Marine Research

5.1.1 Taxonomy

Phylum Chordata

Sub-phylum Vertebrata

Class Actinopterygii

Division Teleostei

Superorder Acanthopterygii

Order Perciformes

Family Emmelichthyidae

Species *Emmelichthys nitidus*

There are three genera and 17 species including subspecies in the family Emmelichthyidae (Froese & Pauly 2007). *Emmelichthys* has five species with probably two subspecies in *E. nitidus*: *E. nitidus nitidus* distributed from South Africa to New Zealand and *E. nitidus cyanescens* distributed from the Juan Fernandez Islands and coast of Chile (Heemstra & Randall 1977). Other species in the family occurring in Australia include *Emmelichthys strushakeri* which also occurs in the Pacific on the southern coast Japan, Malaysia, the northern part of the Kyushu-Palau Ridge, the Hawaiian Islands, and in Australia off the New South Wales coast; *Plagiogeneion rubiginosum* ruby fish, which is widely distributed throughout the Indo-West Pacific including St. Paul and Amsterdam Islands, Sri Lanka, across southern Australia from Perth to New South Wales/Queensland border, and New Zealand; and *P. macrolepis* which appears to be restricted to the GAB (Froese & Pauly 2007, CAAB, Gomon 1994).

5.1.2 Distribution

Redbait *E. nitidus* is found off the western Cape coast in South Africa, St. Paul and Amsterdam Islands, throughout southern Australia, and New Zealand. The species forms surface or midwater schools over the continental shelf (Kailola *et al.*1993). They are presumed to school by size and are structured by depth so that larger fish are over deeper water (Welsford and Lyle 2003). In Australia, they have been caught from northern New South Wales (south of 30°S), Victoria, South Australia, Tasmania and Western Australia, the type locality (Heemstra and Randall 1977) (Fig 6).

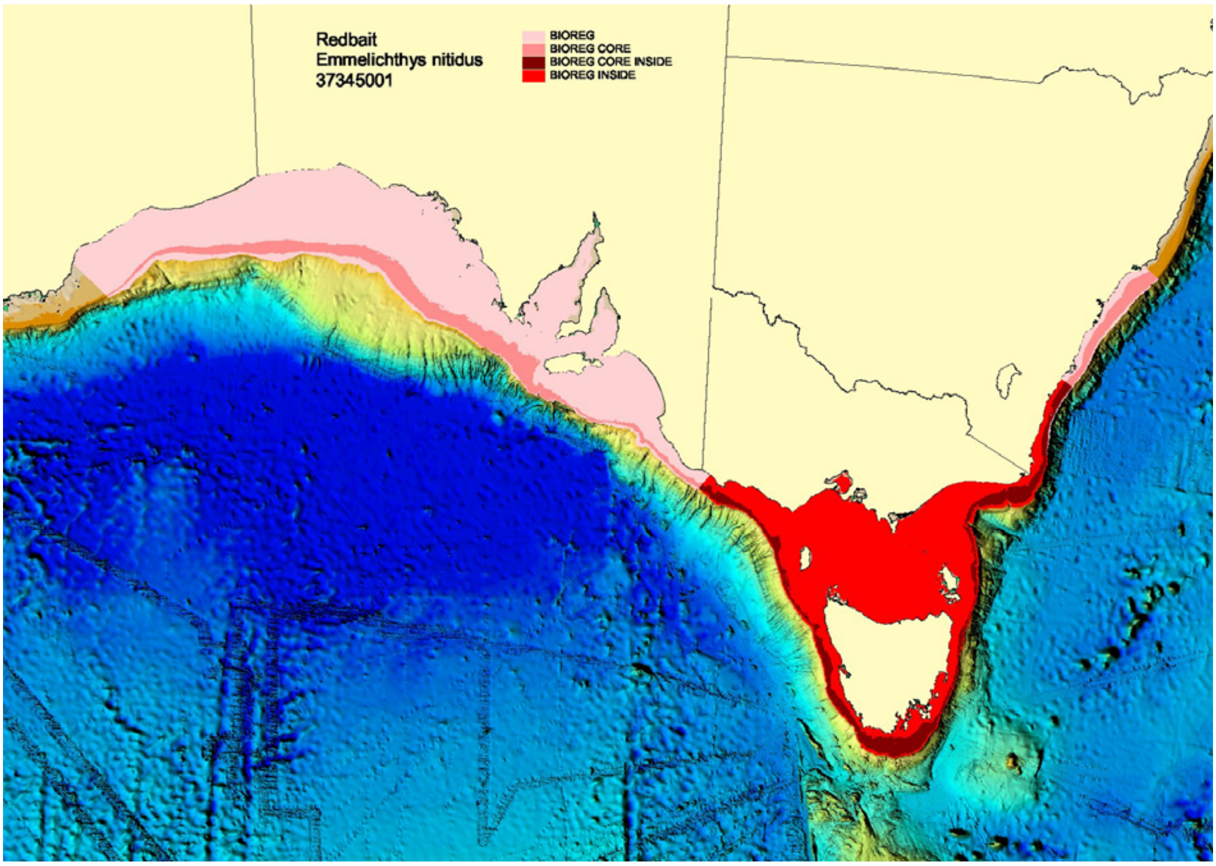


Figure 6. Distribution of redbait *Emmelichthys nitidus* in Australia. Bioreg = range determined by the Bioregionalisation project in CAAB database, CSIRO. Core= preferred depth range, Inside= unverified core distribution range (P. Last [CSIRO] 2007, pers. comm.).

5.1.3 Stock structure

There are no targeted stock structure studies on redbait in Australia.

5.1.4 Biology

Age and growth

Kailola *et al.* (1993) report that redbait in Australia grow to a maximum of 36 cm fork length (FL) and mature at about 21 cm FL. Williams *et al.* (1987) measured redbait from catches from the purse seine jack mackerel fishery off Tasmania during 1986–87. Monthly mean length decreased at the beginning of the season followed by complete disappearance in early summer and then reappearance of larger fish in January. While trends were not as clear as for jack mackerel, they deduced that mature fish spawn outside the fishing grounds during late spring and summer, leaving the smaller fish that are less vulnerable to the fishery.

Welsford and Lyle (2003) compared age and growth data of redbait caught of Tasmania during 10 years of purse seine operations from the 1984/5 season, research trawls from 1985–90 and from the 2001–02 midwater trawl fishery. The majority of fish measured from purse seine catches was between 150–300 mm FL. Distributions were generally unimodal although the 1988/9 distribution was bimodal with a mode at 120–180 mm FL and another mode at 200-280 mm FL. The research catches exhibited similar trends despite targeting fish from deeper in the water column, which suggested to Welsford and Lyle (2003) that gear selectivity effects are limited but also that schooling by size class and depth may have influenced the size structure of the catches. The fish caught in the midwater gear were slightly smaller: sampling was limited but fish were between 120–200 mm FL and another small peak at 240–250 mm FL.

Welsford and Lyle (2003) examined otoliths collected from fish from 1984–94 and from 2001–02. Otoliths were mounted in resin and transverse sections cut for examination under transmitted light. A sub-sample was measured for marginal increment analysis. Growth was modelled on the assumption that the opaque zones beyond the primordium corresponded to the age class of the fish in years. The von Bertalanffy parameters for the total data set (n = 336) were L_∞ = 287 mm, k = 0.56 yr^{-1} and t_0 = –0.36 yr. There were no significant differences between sexes. The age at 50% maturity for females was estimated to be 2–3 years. Growth appears to be rapid in the first years and the maximum unvalidated age is 8 years.

Diet

Meyer and Smale (1991) reported on the diet of redbait from South Africa. The 130 fish containing food grouped into two size classes: small (136–280 mm) and large (281–493 mm). Small redbait fed exclusively on planktonic prey such as euphausiids (63%) predominantly *E. luscens*, hyperiid amphipods *Themisto gaudichaudi* (18%), copepods (6%), unidentified crustaceans (12%) and small amount of fish *Maurolicus muelleri* (<1%). Large fish ate similar quantities of euphausiids but added the carid prawn *Pasiphae sivado* (10%) and other crustaceans, and also ate more fish such as the mesopelagic *Lampanyctodes hectoris* (23%) and squid.

From CSIRO surveys of the southeastern Australian shelf (Bax and Williams 2000), a total of 1248 redbait were measured over a range from 143 mm to 335 mm SL. Stomachs were examined from 89 of which 78 contained food (88%). Although the numbers were low for some of the seasons, diet of redbait appeared to vary seasonally (Fig 7). The fish sampled in winter ate significant proportions of pyrosomes, salps (19 and 34% respectively) although a very large proportion of the diet of winter was unidentified crustacean (Fig 7). The calanoid copepod *Temora* sp. and ascidians were significant in the diet of autumn–caught fish (24 and 27% respectively by wet weight) and unidentified fish (13%). During late spring nearly half of the diet by weight was comprised of euphausiids predominantly *Bentheuphausia ambylops* although a large part of the diet was unidentified. While data were only available for winter and spring samples, isotope analysis also reflected seasonal differences in carbon and nitrogen enrichment (Bulman *et al.* 2000). Carbon increased with fish length but nitrogen did not (as did jack mackerel), and so generally the results suggest that bigger fish feed higher in the food chain.

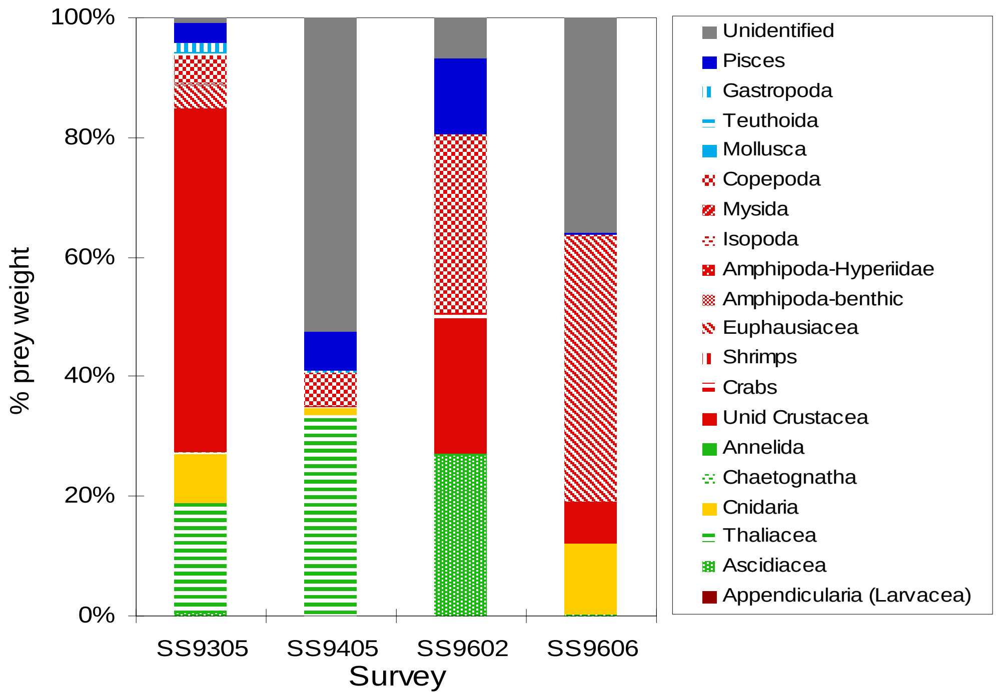


Figure 7. Seasonal diet of redbait *Emmelichthys nitidus* of southeast Australia from CSIRO surveys (taken from Bax and Williams 2000 p. 453). SS9305 = winter 1993, SS9405 = winter 1994, SS9602 = autumn 1996, SS9606 = spring 1996.

The euphausiid *Nyctiphanes australis* was the dominant prey item in the diets of redbait from the east coast of Tasmania in 2003 and 2004 (McLeod 2005). Copepods also occurred commonly although they were not as important in terms of weight overall. Of the small proportion of fish eaten, *Lampanyctodes hectoris* was identified. Ontogenetic variation in the diet was found. In fish between 100–149 mm FL euphausiids occurred in 5% of fish, while it occurred in 59% of stomachs of larger fish 250–300 mm FL.

McLeod (2005) concluded that inter-annual variations in diet were highly correlated with sea surface temperature and primary productivity in the region. In summer and autumn, EAC water which is associated with a higher abundance of copepods, moves onto the Tasmanian shelf accounting for the observed predation on copepods, while in winter, sub-Antarctic water which is related to an increase in krill (Harris *et al.* 1991) results in increased predation in krill (McLeod 2005).

Predators of redbait include Rays bream *Brama brama* (Blaber and Bulman 1986), angel shark *Squatina australis*, silver dory *Zenopsis nebulosus*, John dory *Zeus faber*, and barracouta *Thyrsites atun* (Bulman *et al.* 2000), southern bluefin tuna *Thunnus maccoyii* (Young *et al.* 1997), shy albatross *Thalassarche cauta* (Hedd and Gales 2001), Australasian gannet *Sula serrator* (Brothers *et al.* 1993), Australian fur seals *Arctocephalus pusillus* (Litnann and Mitchell unpublished data, Hume *et al.* unpublished data cited in Goldsworthy *et al*. 2002), and New Zealand fur seals *Arctocephalus forsteri* (Lake 1997, Goldsworthy unpublished data cited in Goldsworthy *et al.* 2002).

Reproduction and spawning

Welsford and Lyle (2003) examined gonad development data from the purse seine and midwater trawl fisheries. They found peaks in gonosomatic index (GSI) values in October and

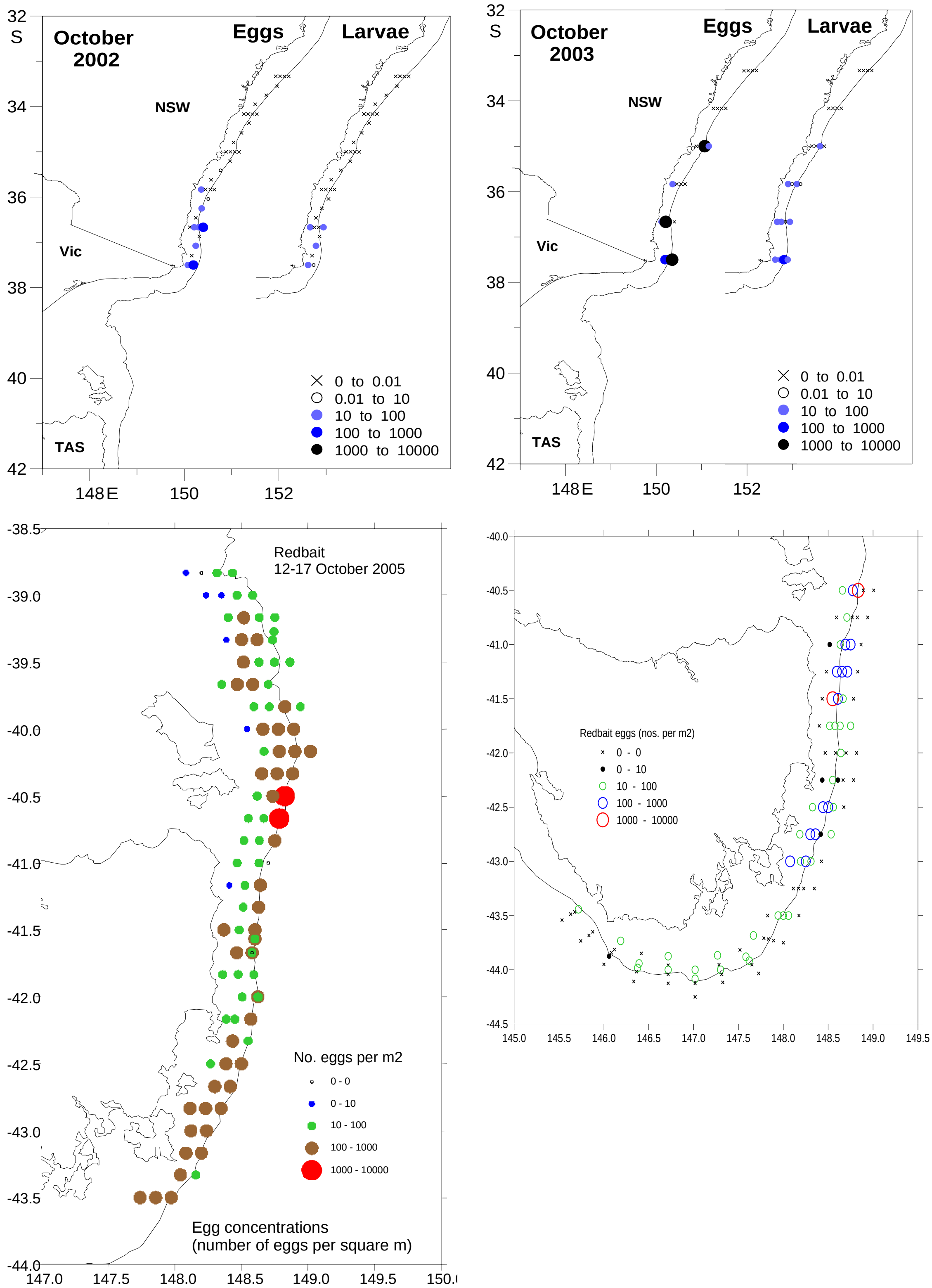


Figure 8. Egg abundances of redbait *Emmelichthys nitidus* from ichthyoplankton surveys during 2002, 2003 and 2005 (reproduced with permission from J. Lyle and F. Neira, TAFI, 2007).

November suggesting this was the peak spawning period, which was concluded by December. The macroscopic staging results also supported spawning. Distribution data from egg surveys conducted in 2003 & 2005 indicates heaviest egg abundances off north east Tasmania in 2005 and similar densities off southern NSW in 2003 (Fig 8). The egg and larval distribution results suggest that there is a single stock of redbait on the east coast (J. Lyle [TAFI] 2007, pers. comm.) however there is no indication as to the state of the stock to the west off Tasmania. Very few eggs were found there two weeks after the relatively large abundances were found on the east coast (Fig 8) but the significance of this finding is unclear. Preliminary results indicate that redbait larvae are associated with the Tasman Sea water mass (J. Keane [TAFI] 2007, pers. comm.). Estimation of spawning biomass using the daily egg production method is currently underway (FRDC 2004/039: *Evaluation of egg production as a method of estimating spawning biomass of redbait of the east coast of Tasmania*), and the results are expected to add to current knowledge.

5.1.5 Fishery

Global

Emmelichthyids are targeted throughout their distribution for human consumption, bait or fishmeal. The majority of catch was taken by the former USSR, South Africa, Australia and New Zealand. Annual redbait catches were 1800–3000 t between 1995–99 (Welsford and Lyle 2003). In New Zealand, a related species *Plagiogeneion rubiginosum* ruby fish, are trawled at the rate of about 250–600 t per year, of which about a third was a result of bycatch in other fisheries. Apart from a yield estimate for ruby fish in New Zealand based on catch records (Welsford 2003), there are no formal stock assessments or biomass estimates for any emmelichthyid species.

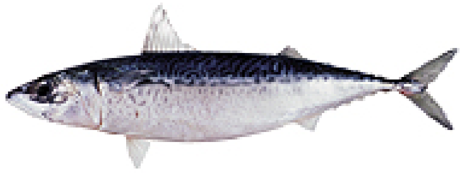
Local

Redbait was first caught as a bycatch of the jack mackerel purse seine fishery which developed during the 1980s in Tasmania. The overall catch rates in the fishery fluctuated but generally declined thereafter (Pullen 1994). Most of the jack mackerel catches including redbait and blue mackerel were processed at fishmeal plants in east Tasmania for meal and oil for aquaculture feed, pet food and human consumption (Pullen 1994).

In 2001–02, trials of midwater trawling targeted jack mackerel but redbait dominated catches and 4600 t were taken between December 2001 and April 2002 (Welsford and Lyle 2003). This initiated midwater trawling operations for redbait as whole food for the blue fin tuna feed industry.

Purse seine catches of redbait peaked at 1300 t in 1986–87 when record jack mackerel catches of about 40 000t were caught (Welsford and Lyle 2003). Redbait constituted no more than about 5% of the total catch in purse seine catches but up to 90% in midwater trawl catches. However, this apparent change was largely due to the fact that redbait were actively avoided by purse seiners targeting jack mackerel (G. Geen [Seafish Tas] 2007, pers. comm.) and therefore the bycatch rate of redbait should not be considered a reflection of true abundance. Catches in the midwater trawl fishery for redbait are now significantly greater than the first peak of the mid 1980s but this is not surprising because redbait are now the main target species in the fishery.

5.2 Blue mackerel *Scomber australasicus* Cuvier, 1832



CSIRO Marine Research

5.2.1 Taxonomy

Phylum Chordata

Sub-phylum Vertebrata

Class Actinopterygii

Division Teleostei

Superorder Acanthopterygii

Order Perciformes

Family Scombridae

Species *Scomber australasicus*

Blue mackerel *Scomber australasicus* is a member of the Scombridae family, which includes tunas and tuna-like fishes. It is a member of the tribe Scombrini that has two other species of *Scombrus*, *S. japonicus* chub mackerel and *S. scombrus* Atlantic mackerel and three species of *Rastrelliger*.

5.2.2 Distribution

Blue mackerel is found in the western Pacific Ocean including New Zealand and Australia, in the southeast Indian Ocean (off south-western Australia) through to the north Indian Ocean and Red Sea, in the northwest Pacific Ocean and East China Sea and in the northeast Pacific of Hawaii and Mexico (Collette and Nauen 1983, Scoles *et al.* 1998, Smith *et al*. 2005). In New Zealand, they are widely distributed but most abundant around the North Island and northern South Island and waters less than 250 m (Smith *et al.* 2005).

Around Australia, blue mackerel is distributed around most of the coast except in the Gulf of Carpentaria in the Northern Territory (Gomon *et al.* 1994, Yearsley *et al.* 1999) but is suspected of being distributed around the entire coast of Australia (Ward *et al.* 2001). Blue mackerel are reported from as far north as 13°S in Western Australia by Soviet vessels (Soviet data, CSIRO) however these reports are unvalidated. Larger fish are found offshore in northern waters off Fraser Island (J. Findlay [BRS] 2007, pers. comm..; D. Brown [SPFRAG] 2007, pers. comm.). Core distribution of blue mackerel is considered to be across southern Australia through the Great Australian Bight (Fig 9; P. Last [CSIRO] 2007, pers. comm.), however, is it unclear whether the distribution is continuous around Tasmania and through Bass Strait: Ward *et al.* *(*2001) attribute this uncertainty to the lack of fishing effort in Bass Strait. The earliest trawling ventures in the GAB by British United Trawlers reported catches of blue mackerel of over 1000 t, the highest catches of blue mackerel ever recorded (Walker and Clarke (1989) cited in Ward *et al.* 2001). In the GAB, Shuntov (1969) reported that blue mackerel were most abundant in mid-summer in eastern areas, but appeared to become more abundant in western and central waters by late summer corresponding to warmer water. Collins and Barron (1981, cited in Ward *et al.* 2001) reported low catches during the *Denebola* cruises in 1979–80 as did Stevens *et al.* (1984) during 1979–80. There are anecdotal reports of large schools of blue mackerel in canyons off south-western WA during autumn (T. Romaro, [SPFRAG] 2007, pers. comm.).

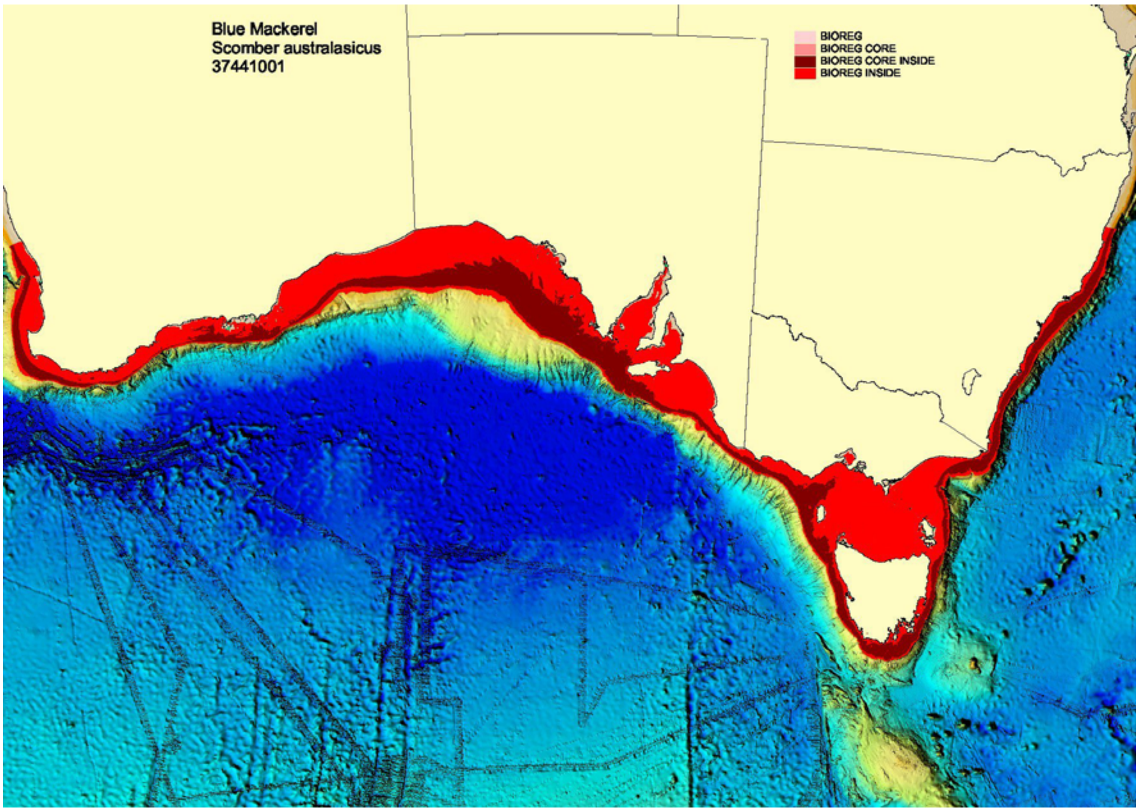


Figure 9. Distribution of blue mackerel *Scomber australasicus* data (based on CSIRO CAAB data). Bioreg = range determined by the Bioregionalisation project in CAAB database, CSIRO. Core= preferred depth range, Inside= unverified core distribution range (P. Last [CSIRO] 2007, pers. comm.).

5.2.3 Stock structure

Smith *et al.* (2005) recently evaluated three methods to assess the stock structure in New Zealand. They used meristic measurements to determine phenotypic expression due to differences in the biological and physical environment during juvenile and larval life history stages, long-lived parasite markers to determine the individual's habitat, and mtDNA to measure inherited genetic variation. Samples were collected from three management areas encompassing the northern half of New Zealand and a sample from NSW. Results of these are discussed in the following sections.

In Australia, Ward *et al.* (2001) hypothesised that there were two major stocks: a western Indian Ocean stock encompassing Western Australia, the Great Australian Bight and possibly Indonesia, and a southeastern Pacific Ocean stock encompassing southeastern Australia and New Zealand. Schmarr *et al.* (2007) assessed three methods as to their suitability to discriminate stocks of blue mackerel in southern Australia. Applying genetics (mtDNA), parasitology and otolith microchemistry to fish from three sites across Australia and one from New Zealand (details below), they concluded there were multiple stocks in Australian waters.

Phenotypic variation

Smith *et al.* (2005) used a variety of univariate ANOVAs on meristic characters to show significant differences between the management areas in New Zealand. They used counts of gillrakers, rays in the first and second dorsal, anal, pectoral and pelvic fins, and anal and dorsal finlets from 268 fish and vertebral counts of 42 fish. A MANOVA identified differences between the areas using the meristic measurements and area, and sex as independent variables and length as a surrogate for age as a co-variate. Gillraker count, first dorsal, second dorsal and pectoral fin ray fin ray counts showed significant differences between areas. Area and length also had a significant effect for first and second dorsal fin ray counts. These tests were repeated excluding samples from one NZ area where there were no age data, and then again excluding NSW, and then both areas. There were significant differences between areas for the four characters. In addition, the length significantly affected the number of second dorsal and anal fin rays and age affected the number of anal fin ray and dorsal finlets. Their results indicated that blue mackerel from the three NZ management areas were derived from separate spawning stocks. Similarly, interpretations of meristic counts coupled with different oceanographic conditions suggested the existence of two stocks of *Scomber japonicus* off southern Brazil (Perotta *et al*. 1990 cited in Smith *et al.* (2005)).

Smith *et al.* (2005) also discussed other phenotypic indicators such as morphological measurements that are often collected with meristic counts. However, they suggest that because morphological variation is determined by post-recruitment stages it reflects only local feeding conditions and spawning times whereas meristic measurements are determined by larval and juvenile conditions and therefore are indicative of specific spawning stocks. Tzeng (2004) argues that the short-term environmentally induced variation seen as morphometric variation between stocks is more applicable to fisheries management.

Around Taiwan, blue mackerel (known as spotted mackerel), is distributed along the continental shelf of the East China Sea, north to Japan and south to the South China Sea but not in the Taiwan Strait (Tzeng 2004). Stock structure in Taiwan was investigated through studies of morphometric characters, life history, isoenzyme and fishery data and tagging experiments but two different conclusions arose. Fishery data and isoenzyme data both suggested that the fish were of the same stock whereas all other studies suggested there were two stocks (Tzeng 2004). Tzeng (2004) conducted a multivariate allometric analysis and showed that there were in fact three distinct clusters corresponding to a stock located on the south of the East China Sea and coastal eastern Taiwan, another off Kaohsiung on the southwest coast, and another further southwest, in the north of the South China Sea. Tzeng (2004) justified the identification of another stock because the statistical techniques applied in previous studies were not completely appropriate. He also used the water masses in the region to support these stock hypotheses. The warm, saline Kuroshio flows northward towards Taiwan, but first breaking off through the Luzon Strait to form the north boundary of stocks in the South China Sea and then continues along the seaward coat of Taiwan veering to the east and northeast as it reaches the continental shelf break of the East China Sea. The other major current influencing northern Taiwan is the cold East China Sea coastal current that flows south. Effectively, the currents prevent the northern and southern stocks from mixing.

Geometric morphometrics is a relatively new tool to fisheries research that is showing promise as way of stock discrimination based on variations in otolith size and shape (Tracey *et al.* 2006). Tracey *et al.* (2006) using elliptical Fourier analyses and constrained ordinations to compare otolith morphology to discriminate between two populations of *Latris lineata*, a species that is distributed widely in temperate latitudes across the southern Indian, southern Pacific and southern Atlantic Oceans. While non-metric multidimensional scaling failed to differentiate between the Tasmanian and St Pauls/Amsterdam Is. populations examined, the constrained canonical analysis of principal coordinates and canonical discriminant analysis was successful. They concluded that differences in otolith form reflect that populations had reasonable phenotypic anonymity and that these statistical techniques provide a cheaper option to stock discrimination techniques. In Atlantic mackerel *Scomber scombrus*, age and year significantly affect otolith morphology; significant differences were found among northwest Atlantic and North Sea stocks but none were found between the north and south of the range of northwest Atlantic (Castonguay *et al.* 1991 cited in Smith *et al.* 2005).

Genetics

Scoles *et al.* (1998) found no significant difference in mtDNA of blue mackerel between southeastern Australia and New Zealand samples, suggesting that mixing occurs between the two areas. Samples from Japan and Mexico were distinct from the Australasian samples and the Red Sea samples were very distinct from any of the other areas suggesting that northern and southern hemisphere populations do not mix.

Smith *et al.* (2005) found little geographical differentiation from the DNA investigations of blue mackerel in New Zealand. They amplified the hypervariable left domain of the control region, from the tRNA to the central conserved region, a portion that is considered highly variable in some fishes. Haplotype diversities were high in all samples suggesting little difference between samples and nucleotide diversity was typical of marine fishes. There was no significant regional differentiation. They concluded that a low level of gene flow inhibited genetic divergence, or that there was not enough evolutionary time to allow recently isolated populations to diverge genetically.

In Australia, Schmarr *et al.* (2007) employed a more sensitive technique than Scoles (1998) using the control region of the mtDNA of fish from Qld, WA and NZ. This technique was able to discriminate the WA samples from the eastern (Qld and NZ) populations but was not able to discriminate between Qld and NZ populations. While the sample sizes were larger than the earlier study perhaps contributing to a clearer result, they were still considered too small and unequal to resolve the stock structure of blue mackerel in Australia conclusively (Schmarr *et al.* 2007).

Parasite indicators

Rohde (1987) used morphometrics of external monogenean parasites *Kuhnia* to investigate differences between Australian and New Zealand fish and found significant evidence that they were separate populations.

Smith *et al.* (2005) investigated seven parasites found in blue mackerel from New Zealand and NSW to determine their suitability as a biological marker to stock identification. Several were discounted on their low prevalence. One monogenean *Kuhnia scombri* was found to be prevalent in fish from two NZ management areas, but not in a third. However, they concluded that because the parasite is short-lived, the observed distribution might have been seasonal rather than geographical. The acanthocephalan *Rhadinorhynchus* sp., found in the gut of blue mackerel, is also very short-lived and was thought to be potentially useful to differentiate between management areas. The larval *Anisakis* sp. are widely used markers and the significant differences found between the New Zealand stocks suggested that they would be useful stock identifiers.

Schmarr *et al.* (2007) found that the parasite abundance and prevalence were able to discriminate between capture locations at a rate of 97.5% accuracy. The parasites used were similar to those found in three other studies of parasites assemblages of blue mackerel. Cluster analyses of the parasite data suggested a large amount of exchange between WA and SA populations, a small amount of exchange between Qld and SA fish, a very small exchange of fish between WA and Qld fish and no exchange between Australia and NZ (Schmarr *et al.* 2007).

Otolith microchemistry

Otoliths provide a record of the physical and chemical environment in which a fish lives. Analysis of the microchemistry of otoliths taken from fish from various locations can therefore indicate the origin of those fish and enables stock discrimination based on the history of the fish (Schmarr *et al.* 2007). Cluster and discriminant function analyses of elemental concentrations in the otolith cores suggested that most fish originated in the same location as the fish with which they were captured but a few originated in other locations (Schmarr *et al.* 2007). There was a statistically significant difference between all populations sampled (WA, SA and Qld) across Australia.

Overall, the analyses of Schmarr *et al.* (2007) suggest that otolith microchemistry and parasite indicators gave robust predictions of the origins of the fishes examined and could be used to discriminate stock structure. The genetic techniques employed might also be useful however the sample sizes were too small to give a robust evaluation.

5.2.4 Biology

Age and growth

Blue mackerel are reported to grow to at least 50cm fork length (FL) and at least 1.5 kg (commonly 20–35 cm FL and 0.2–0.7 kg) (Yearsley *et al.* 1994). Hutchins and Swainston (1986) reported angling records recording the maximum size caught as 65 cm and 2.15 kg.

In the GAB, Stevens *et al.* (1984) found that most blue mackerel were between 2 and 5 years old and the largest blue mackerel was 44 cm FL and at least 8 years old. They found that the fish grew rapidly initially and matured at around 30 cm at age 3. Similarly, Stewart and Ferrell (2001) found blue mackerel off New South Wales to grow rapidly, with mean size at age slightly higher than previous studies and a maximum age of 7 years. Estimates for length at ages 1 and 3, are 260 and 319 mm FL for NSW fish (Stewart and Ferrell 2001) compared to 209 and 294 mm for GAB fish (Stevens *et al.* 1984).

In the most recent Australian study on age and growth of blue mackerel, Rogers *et al.* (2007a) found that fish >300 mm FL were commonly collected from Tasmania, SA and Victoria but rarely from NSW, southern Qld or WA sites. Furthermore, fish >450 mm have been taken by purse seining in the GAB (SARDI Aquatic Sciences, unpublished data cited in Rogers *et al.* 2007a). Rogers *et al.* (2007a) concluded that differences in sampling method between the southern and eastern sites might account for the differences in size composition between sites. Catches from inshore waters were comprised mainly of small fish while those from offshore waters were comprised of larger fish. While the “bigger-deeper” phenomenon has been observed for jack mackerel in the GAB and off south-east Australia (Stevens *et al*. 1984, Bax and Williams 2000), it has only been observed in one blue mackerel study in the GAB (Shuntov 1969). It was not observed by Stevens *et al*. (1984) or in other Australian studies however this might be due to deficiencies of the sampling regime.

In New Zealand, the maximum length recorded is considerably larger at 53 cm at age 24 years and length at maturity is 28 cm at age 2 (NZ Ministry of Fisheries website, 7 June 2007). Growth is rapid for the first 4–5 years, slowing down thereafter and then negligible after age 12 (Morrison *et al.* 2001). Maximum age is 21 and 23 years for males and females respectively (Morrison *et al.* 2001). The fish in this study were 400–500 mm and estimated to be 4–12 years old and therefore larger than those in the Australian studies were.

Ward *et al.* (2001) compared two earlier Australian age and growth studies and one from New Zealand (Table 2) and concluded that blue mackerel grew at roughly comparable rates to other mackerel species but were possibly longer-lived. The higher New Zealand growth rate was probably due to the larger-sized fish on which the estimate was based. Morrison *et al.* (2001) suggested that different vulnerabilities of age classes to different catching methods could also be a cause for observed differences between growth rates of Australian and New Zealand fish. Stewart and Ferrell (2001) concluded that differences in length at age between fish from Australia and Taiwan could be a result of temporal or spatial differences but more likely to be from different ageing techniques employed. They suggested that due to the difficulty in interpreting the growth rings in the NSW study, their growth curves be shifted by up to 12 months. On the other hand, Rogers *et al.* (2007a) found that fish grew similarly from all regions of Australia although the absence of larger fish in eastern Australian regions resulted in a less evident asymptotic growth phase.

Table 2. Von Bertalanffy growth parameters for blue mackerel *Scomber australasicus* from Australia and New Zealand. (Adapted from Ward *et al.* 2001).

Region	L_∞	*K*	t_0	*n*	*Age range (years)*	*Authors*
South-eastern NSW	41.05	0.26	–2.8	642	0–7	Stewart and Ferrell (2001)
NSW: (combined sexes)	37.11	0.46	–1.00	4754		Rogers *et al.* (2007a)
Eastern Australia (NSW Qld)	37.89	0.43	–1.12	5705		Rogers *et al.* (2007a)
GAB	44.1	0.24	–1.79	316	1–9	Stevens *et al.* (1984)
South Australia: (combined sexes)	38.295	0.49	–0.53	1174		Rogers *et al.* (2007a)
Southern Australia (WA, SA ,Tas Vic)	39.26	0.45	–0.61	3175		Rogers *et al.* (2007a)
New Zealand: males	48.77	0.25	–0.89	177	0.2–21.9	Morrison *et al.* (2001)
New Zealand: females	51.11	0.21	–1.06	171	0.2–23.9	Morrison *et al.* (2001)
New Zealand: combined	50.02	0.23	–1.01	425	0.2–23.9	Morrison *et al.* (2001)

Diet

Diet analysis of 50 adult blue mackerel off southeast Australia found that over a third of their diet was unidentified fish (Bulman *et al.* 2000, 2001). The next largest component comprised pelagic zooplankton such as copepods, euphausiids, crustacean larvae, ascidians, siphonophores and unidentified remains, and some minor benthic components such as polychaetes and gastropods. Isotope analyses of δ13C and δ15N placed blue mackerel between jack mackerel and redbait in both values, but samples sizes were too small to show ontogenetic or seasonal changes (Bulman *et al.* 2000). Similarly, in New Zealand, blue mackerel eat zooplankton, mainly copepods, but also larval crustaceans and molluscs, fish eggs and fish larvae.

There are few records of predation on blue mackerel. However, Bunce and Norman (2000) and Bunce (2001) reported that Australasian gannet in Port Philip Bay consumed blue mackerel in small quantities (11% wet weight). Bottlenose dolphins in SA are also known to eat blue mackerel as well as jack mackerel (Kemper and Gibbs 2001 cited in Goldsworthy *et al*. 2003).

Reproduction and spawning

Blue mackerel are serial and asynchronous spawners. In the GAB, they were found to be mature at about 28 cm FL (Stevens *et al.* 1984). In South Australia, ~50% of males and females were sexually mature at 236.5 and 286.8 mm FL, respectively but in eastern Australia, samples were too small to allow calculation (Rogers *et al.* 2007b). Similarly fish in New Zealand mature at 28 cm and age 2 (NZ Ministry of Fisheries website, 7 June 2007) although Hurst *et al.* (2000) reported 36 cm FL as first maturity.

Eggs are pelagic and development is temperature dependent. Egg and larval surveys in Australia have found that blue mackerel spawn between November and April off southern Australia and between July and October off eastern Australia (Neira *et al.* 2007). Off southern Australia, the location of the spawning grounds is variable but the western GAB is suggested as an important spawning area that was not sampled intensively. The eastern Australia spawning ground is in shelf waters of southern Queensland and northern New South Wales. Most eggs were collected from shelf waters in either region, however significant numbers of eggs were found at stations located over the shelf-break during one of the east coast surveys (Neira *et al.* 2007).

Mean spawning frequencies ranged from 2 to 11 days in southern Australia; variations in this parameter were not related to fish size, month, SST or depth of sampling location and mean batch fecundity was 69 894 ± 4 361 oocytes per batch and 134 oocytes per g of weight (Neira *et al.* 2007).

In New Zealand, eggs are found from North Cape to East Cape, with the highest concentrations in the Northland, the Hauraki Gulf and the Western Bay of Plenty. In the Hauraki Gulf, eggs have been found from October to January in SST of 15–23 °C (Taylor 2002).

5.2.5 Fishery

Global

The catch of blue mackerel in the Pacific Ocean, as far as recorded by FAO is dominated by New Zealand catches (Fig 10). The 2006–07 TAC for New Zealand was11 652 t, distributed across 4 areas. In New Zealand, the status of blue mackerel stock is unknown.

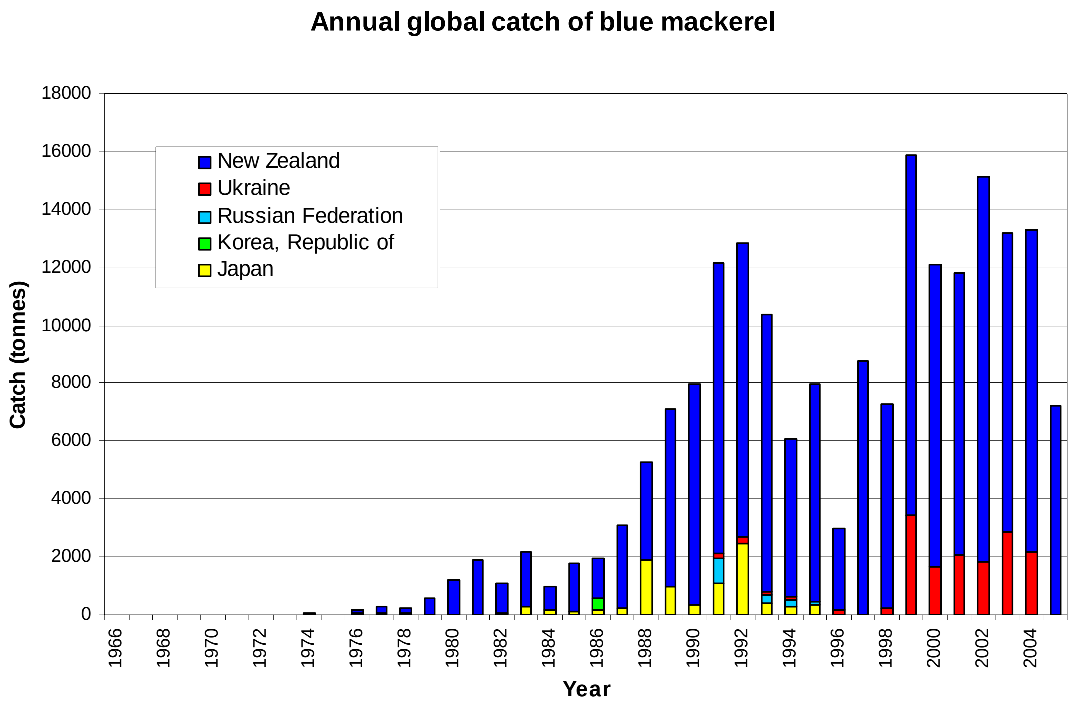


Figure 10. Global catches of blue mackerel in the Pacific Ocean (excluding Australian catch). Data for Indonesia (19 t in 2004 and 2005) and Georgia (28 t in 1974) have been excluded due to insignificant quantity (data from FAO Fisheries Dept, Fishery Information, Data and Statistical Unit, extracted using FISHSTAT Plus v.2.3, (2000)).

"Recorded catches increased from 1983–84 to peak at more than 15 000 t in 1991–92 but were reduced to about 6000 t in 1995–96. A second peak of almost 13 500 t was reported in 1998–99 and although catches dropped to 6847 t in 1999–00, an increase to 13 134 t was observed again in 2000–01, with a decrease to 11694 t in 2001–02, 11 375 t in 2002–03 and 9373 t in the

2003–04 fishing year. Purse-seine fishing effort on blue mackerel has been strongly influenced by the supply of other small pelagic species and the market value of blue mackerel relative to those species. No estimates of current and reference biomass, or yield, are available for blue mackerel. It is not known if recent catch levels are sustainable or at levels that will allow the stock to move towards a size that will support the MSY." (Extract from NZ Ministry of Fisheries website, 7 June 2007).

Local Fishery

Blue mackerel often school with other pelagic species such as jack mackerel and was caught as a bycatch in the purse seine fishery for jack mackerel but is currently the dominant species particularly in the GAB. Stevens *et al.* 1984 reported low catch rates of blue mackerel in the GAB. They were caught in only 5% of pelagic trawls with average rate of 0.03 kg^{-1} and 12% of demersal trawls, average catch rate of 0.2 k gh^{-1}. Annual catches of blue mackerel off WA and SA since the 1990s are no more than 13 t (Ward *et al.* 2001), in contrast to the fishery off Tasmania and NSW.

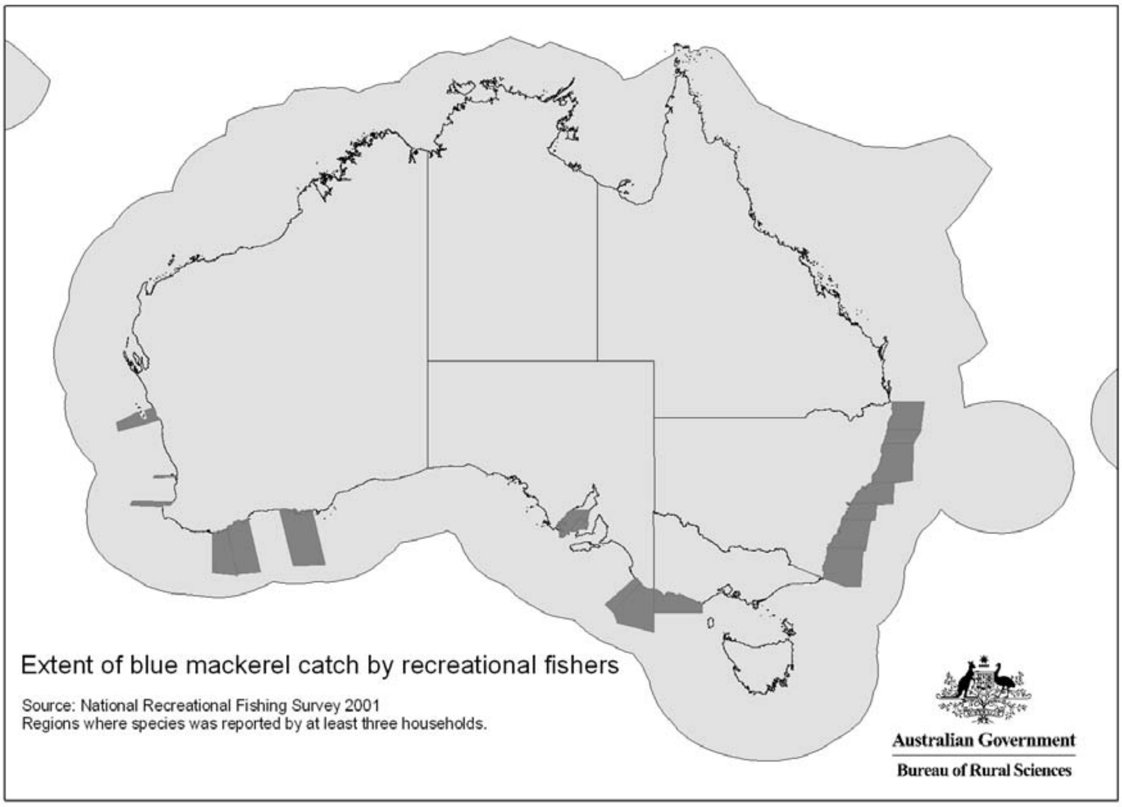


Figure 11. Statistical Local Areas where catches of blue mackerel were reported by at least three households in the National Recreational Fishing Survey 2001. Map produced by the Bureau of Rural Sciences.

Off NSW, blue mackerel are caught by both commercial and recreational fishers (Fig 11). Currently, commercial catches are mostly from the purse-seine fishery and fresh-chilled for human consumption, or frozen for bait or pet food. Most of the blue mackerel catch is from state waters with over 500 t recorded from NSW during the 90s and only small reported catches from Commonwealth waters off NSW or the GAB (Ward *et al.* 2001). A relatively small amount of the blue mackerel catch are caught for bait in game-fishing for striped marlin or in longlining for tuna along with yellowtail scad, jack mackerel and other pelagic species (Ward *et al.* 2001). Anglers will also catch them from wharves and piers especially in summer and autumn. They begin to school around December when SSTs are about 18–22 °C corresponding to the EAC formation and they migrate southwards to southeastern Tasmania. It was assumed that these aggregations were summer feeding aggregations that are targetted by fishers and then migrate northwards when the EAC and currents recede (Ward *et al.* 2001).

Blue mackerel are caught in Tasmanian waters particularly in association with the jack mackerel purse seine fishery and more recently the midwater fishery but their presence is related to seasonal oceanographic conditions. Catches in the purse seine fishery peaked in 1987/8 when the jack mackerel fishery was also at its height but usually blue mackerel represent about 1% of the annual small pelagic catches recorded in Tasmania (Small Pelagic Fish and Fisheries Workshop, TAFI, 28 Feb 2005). They are also caught in the state scalefish fishery but recent catches are less than 10 t per year (J. Lyle pers. comm. cited in Ward *et al*. 2001).

5.3 Jack mackerel *Trachurus declivis* (Jenyns, 1841)

CSIRO Marine Research

5.3.1 Taxonomy

Phylum Chordata

Sub-phylum Vertebrata

Class Actinopterygii

Division Teleostei

Superorder Acanthopterygii

Order Perciformes

Family Carangidae

Species *Trachurus declivis*

5.3.2 Distribution

Jack mackerel *Trachurus declivis* is found widely throughout southern Australia from Wide Bay, Queensland to Shark Bay, Western Australia (Fig 12) including Tasmanian waters (Williams and Pullen 1983). Jack mackerel are usually caught in less than 200m often schooling but is also found to 450 m depth (Pullen 1994). There appears to be a correlation with size and depth, with small fish found inshore and larger fish deeper. Juveniles are found inshore around Tasmania (Pullen 1994) and in the Bight (Shuntov 1969, Stevens *et al*. 1984). In the Bight only mature fish greater than 24 cm FL (age 3–7 yr) were found near the shelf break (Shuntov 1969, Stevens *et al.* 1984). Schooling fish in the Bight were also mature fish from 24–36 cm (age 4–6 years) (Shuntov 1969).

Stevens & Hausfeld (1982) found that fish larger than 30 cm were absent from samples south of 39°S (i.e. from Flinders Island and southwards) but fewer fish 10–25 cm were in samples north. However contrary to that finding, Pullen and Lyle (1994) found mean monthly sizes of jack mackerel for each season of the purse seine fishery from 1984 to 1994 of more than 30 cm usual until the 90s. Larger jack mackerel (21–37 cm) were also caught over the slope off Maria Island (east Tasmania) in depths down to 360 m (Blaber and Bulman 1987). As fish grow, they move further offshore resulting in the bigger-deeper phenomenon observed in the CSIRO southeast Australia surveys (Furlani *et al.* 2000).

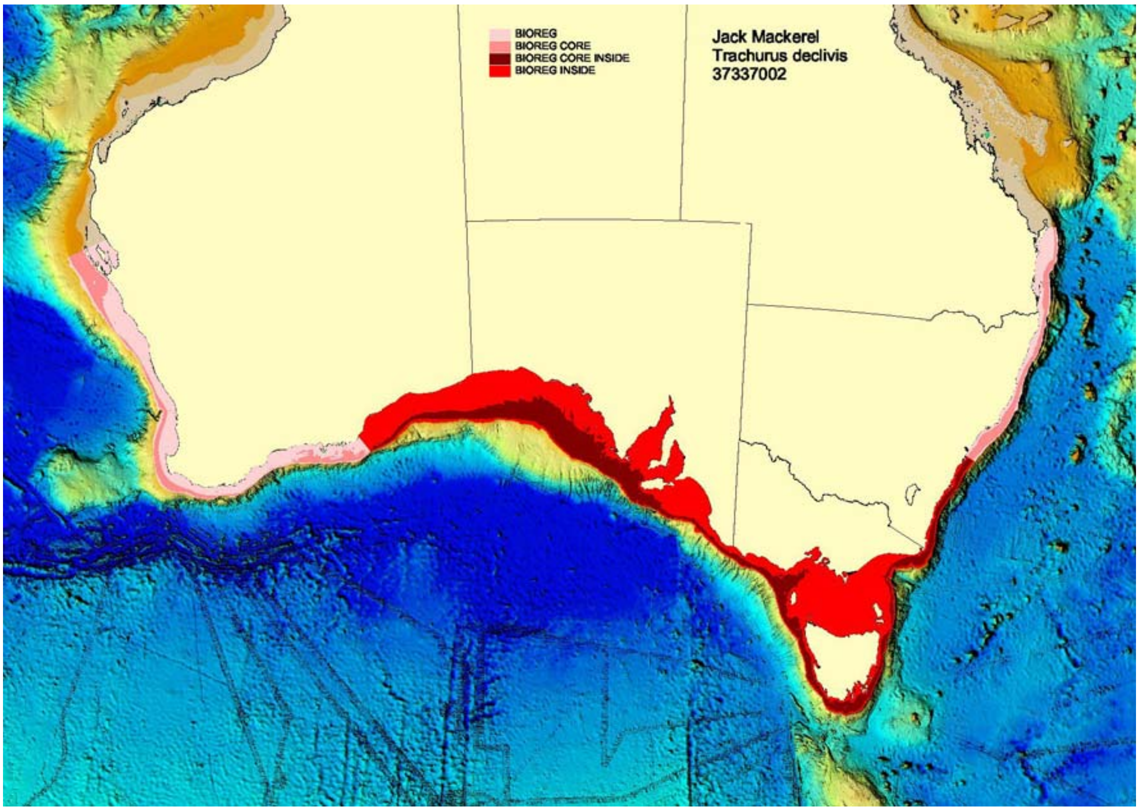


Figure 12. Distribution of jack mackerel *Trachurus declivis* in Australia (based on CSIRO CAAB data). Bioreg = range determined by the Bioregionalisation project, Core= preferred depth range, Inside= unverified core distribution range (P. Last [CSIRO] 2007, pers. comm.).

In New Zealand , jack mackerel generally occurs in deeper water than yellowtail scad (<300 m) at less than 16 °C, and north of latitude 45°S (Ministry of Fisheries, Science Group 2006).

5.3.3 Stock structure

Genetics

There are two genetics-based studies into jack mackerel in Australian waters. The first study by Richardson (1982) used allozymes to determine that the Western Australian (western GAB) jack mackerel were distinct from the New Zealand populations but the eastern populations were less clearly defined. In the south-eastern samples, five enzymes exhibited an excess of homozygotes presumed to be a result of two or more overlapping but genetically distinct populations.

The second study by Smolenksi *et al.* (1994) used 6– and 4–base restriction enzyme analyses to investigate the southeastern Australian jack mackerel populations, by comparing fish from off Eden, NSW to those of south-east Tasmania. They found that there was limited evidence using the 6–base analyses based on the occurrence of a rare haplotype in the Tasmanian samples but that overall, the analyses were not significant. The 4–base analysis also showed no separation between locations however there was evidence of genetically distinct schools off Tasmania between years, i.e. the 1990 Tasmanian sample appeared to be genetically distinct from all other samples. The results supported the assumption that jack mackerel maintain school fidelity but that in years when their major prey *Nyctiphanes australis* is low in abundance, they disperse into deeper water to find food, thus the school disintegrates. Smolenski *et al.* (1994) suggested that increased mortality from variable hydrographic conditions and greater exposure to predation on eggs and larvae during and post-spawning, could result in a reduction in effective population size and consequently in mtDNA diversity.

The two studies support the view that there are genetically distinct populations of jack mackerel; one in the GAB and one in eastern Australia.

Morphometrics

Lindholm and Maxwell (1982) used principal component analysis of morphometric measurements and meristic counts from jack mackerel from the GAB, NSW and Tasmania to determine significant separation between the GAB and the NSW samples. The Tasmanian fish overlapped with NSW fish suggesting no differences between the fish (contrary to their conclusions, and partially with GAB. The fish from GAB were generally smaller so allometric growth differences might account for the morphological differences however the sizes did overlap therefore there is not strong evidence.

Parasite indicators

There are no studies of parasite indicators in Australian fish. However, Maxwell (1982) studied cymothoid isopod *C. imbricatus* infestations in jack mackerel collected from southeastern Australia, from Eden to off Bruny Island, (southeast Tasmania). The linear relationships between size of parasite and hosts suggested that juvenile jack mackerel were infected while schooling in shallow inshore waters, and the low overall infestation rate and lack of small isopods in adult fish suggests that further infestation by adults from adults does not occur.

Size structure

Stevens & Hausfeld (1982) found that fish larger than 30 cm (FL) were absent from samples south of 39°S (i.e. from Flinders Island and southwards) but there were fewer fish between 10–25 cm in samples north of 39°S. Contrary to these findings, larger fish were caught in the Tasmanian purse seine fishery from 1984 to 1994. Pullen and Lyle (1994) found that the mean monthly size of jack mackerel for each season of the purse seine fishery from 1984 to 1994 was usually >30 cm until the 1990s. Furthermore, pelagic fish (21–37 cm) were caught up to 360 m deep over the slope off Maria Island (east Tasmania) (Blaber and Bulman 1987).

5.3.4 Biology

Age and growth

Several studies of age and growth of jack mackerel have been made since 1979: Webb and Grant (1979), Stevens and Hausfeld (1982), Jordan (1994, Lyle *et al.* (2000), Browne (2005) (Table 3). Webb and Grant (1979) examined fish from southeastern Australia and demonstrated annual rings but without validation. Stevens and Hausfeld (1982) examined fish from eastern Australia from NSW to Tasmania. Due to a difference in size composition between the areas, data were divided into northern and southern groups. Larger fish were absent from southern samples which would have resulted in a higher mortality for this area, therefore growth curve parameters were calculated for the northern data only. Validation of ages was incomplete and relied primarily on length frequency data.

In the Great Australian Bight, Shuntov (1969) characterised the age composition of jack mackerel from inshore waters as being 14–22 cm and 2–3 years old and fish from the shelf-edge as sexually mature at 30–36 cm and 5–7 years old. The sizes of fish in surface schools were between 26–36 cm, and mostly 30–34 cm and 5–6 years. However, the methods used to age the fish were undescribed and results were unvalidated. Stevens *et al.* (1984) found a lower mean length-at-age between fish from the GAB and southeast Australia but suggested the difference was a result of sampling technique. Overall, the results obtained between the earlier studies agreed well.

Larval jack mackerel from east Tasmania grew more slowly in 1991 than in the previous two years (Jordan 1994). Sea temperature was lower in that year and krill production was expected to be higher (Harris *et al*. 1991) resulting in higher abundance and availability of prey for jack mackerel (Young and Davis 1992) and therefore higher growth. The most recent studies by Lyle *et al.* (2000) and Browne (2005) re-examined the ageing of mackerel from eastern Tasmanian and validated the ages using marginal increment and radiocarbon analyses. Lyle *et al.* (2000) demonstrated that the difference in ages between southeastern Australian and New Zealand fish was likely to be real. Browne (2005) incorporated the results from Lyle *et al*. (2000) to examine the age and growth of jack mackerel caught in the commercial fishery since 1985. He found a decline in older age classes which could have been a result of factors suggested by Lyle *et al.* (2000) such as: the impact of fishing, changes in size of fish targeted by the fishery as a result of changed fishing practices, changes due to recruitment variability, changes in fish schooling behaviour as a result of a environmental influences or a combination of all factors. However, none could be differentiated with any certainty based on the available data.

Table 3. Von Bertalanffy growth parameters for jack mackerel *Trachurus declivis* derived from Australian studies from 1979–2005.

Region	L_∞	*K*	T_0	*n*	*Authors*
Southeast Aus: n of 39°S	46.4	0.2	–0.87	1000	Stevens and Hausfeld 1982
Southeast Aus: Jervis Bay to southwest Tas	46.3	0.23	–0.10	1242	Webb & Grant 1979
Southeast Aus	46.7	0.18	–0.41	306	Unpub CSIRO 1977 in Stevens and Hausfeld 1982
GAB	41.7	0.19	–2.08	652	Stevens *et al.* 1984
Southeast Aus: Tas	36.2	0.267	–1.21	2032	Lyle *et al.* (2000)
Southeast Aus: Tas 2003/4	35.52	0.28	–1.08	170	Browne (2005)

Diet

Location, size and season are factors affecting the diets of jack mackerel. Early studies in the Great Australian Bight found that jack mackerel fed during the day (Shuntov 1969, Stevens *et al.*1984) and fed on copepods more frequently inshore and euphausiids in deeper water (Shuntov 1969). The size of the fish appeared to determine the size of prey taken: fish <20 cm FL took prey between 1–18 mm and fish >25 cm FL took prey >10 mm (Stevens *et al.* 1984) which correlated with Shuntov's (1969) observations. South-eastern Australia mackerel caught on the shelf also took largely euphausiids particularly *Nyctiphanes australis* (Webb 1976, Williams and Pullen 1983, Young *et al.* 1998, Bulman *et al.* 2001, McLeod 2005). Fish from deeper water fed mainly on mesopelagic fish such as *Lampanyctodes hectoris* or other small fish (Maxwell 1979, Blaber and Bulman 1987). Mackerel also took minor quantities of gastropods, pteropods, amphipods, natantians, siphonophores and ostracods (Stevens *et al.* 1984, Blaber and Bulman 1987).

Seasonal differences were found in the Bight: euphausiids and mysids were less frequent in spring than in summer or winter, but for copepods, amphipods and pteropods the reverse was true (Stevens *et al.* 1984). Foraminiferans, zoea and megalopa larvae were more frequent in winter whereas natantians and siphonophores were more frequent in summer, and ostracods were less frequent. On the southeast Australian shelf, euphausiids were dominant in late spring and autumn, whereas fish were dominant in winter 1993 (Fig 13). Copepods appeared in the diets in winter being predominant in winter 1994. In the deeper waters over the slope off eastern Tasmania, lantern fishes were always dominant in terms of energy in jack mackerel diets however in summer, euphausiids increased to 25% of the energetic content of the diet (C. Bulman, CSIRO unpublished data).

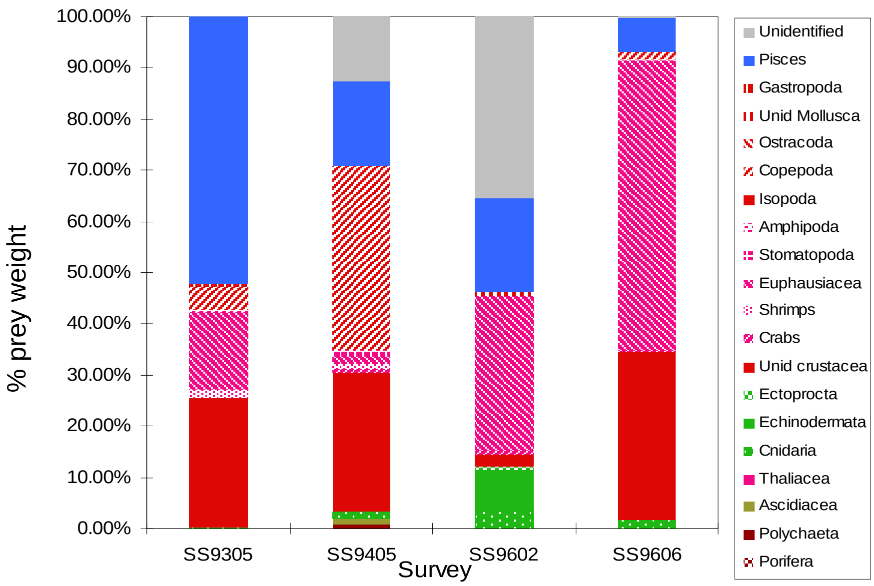


Figure 13. Seasonal diet of jack mackerel Trachurus declivis off southeast Australia from CSIRO surveys (Bax and Williams 2000). SS9305 = winter 1993; SS9405 = winter 1994, SS9602 = autumn 1996, SS9606 = spring 1996.

In Australia, jack mackerel were eaten in significant quantities by a range of commercial species: such as, silver dory *Zenopsis nebulosus*, John dory *Zeus faber* and draughtboard shark *Cephaloscyllium laticeps* (Bulman *et al.* 2001) and also barracouta *Thyrsites atun*, and to a lesser extent by gummy shark *Mustelus antarcticus,* school shark *Galeorhinus galeus*, common stargazer *Kathetostoma leave* and tiger flathead *Neoplatycephalus richardsoni* (C. Bulman unpub data). Higher predators such as Australian fur seals *Arctocephalus pusillus* (Litnann and Mitchell unpublished data, Hume *et al.* unpublished data cited in Goldsworthy *et al.*2002), New Zealand fur seals *Arctocephalus forsteri* (Lake 1997, Goldsworthy unpublished data cited in Goldsworthy *et al*. 2002), bottlenosed dolphins (Kemper and Gibbs 2001), common dolphin (Kemper and Gibbs 2001), and southern blue fin tuna *Thunnus maccoyii* (Young *et al.* 1997) all consume jack mackerel. Australasian gannets *Sula serrator* at Pedra Branca were found to eat 13% by weight of jack mackerel (Brothers *et al.* 1993). The diet of shy albatross *Thalassarche cauta* at Albatross Island was predominantly fish (89%) of which jack mackerel and redbait together comprised 57% by number of all the fish identified (Hedd and Gales 2001).

In New Zealand predators of jack mackerel are porbeagle shark *Lamna* sp. , kahawai *Arripis* sp., trumpeter *Latris* sp., larger mackerel, snapper *Chrysophrys* sp., southern bluefin tuna and albacore *Thunnus maccoyii* and barracouta *Thyrsites* sp., groper *Polyprion* sp. and gemfish *Rexea* sp. (Jones 1990).

Reproduction and spawning

Jack mackerel, like most *Trachurus* species, are serial spawners although neither the spawning frequency nor the number of batches spawned per season has been determined (Marshall *et al*. 1993). Annual fecundity has also proven indeterminable. Marshall *et al*. (1993) found that the mean age of maturity based on the more commonly accepted stage at which vitellogenesis occurs, stage 3, was 31.45 cm FL. This value is larger than the 24–24.9 cm TL of Webb and Grant (1976) who based maturity on macroscopic stage 2. Eggs are pelagic and spherical, and of between 1.1–1.3 mm diameter (Neira *et al.* 1998).

Jack mackerel are known to spawn around the whole coast of Tasmania (D. Furlani pers. comm. cited in Jordan *et al*. 1992) and in the GAB (Stevens *et al*. 1984). These separate spawning locations represent what is thought to be distinct stocks (Richardson 1982). In the GAB, jack mackerel spawn in summer (Shuntov 1969). During ichthyoplankton surveys of southeastern Australian waters in summer 1997 and winter 1998, Neira *et al.* (1999) caught jack mackerel larvae almost exclusively during the summer and most abundantly in western Bass Strait. They suggested that these larvae belonged to a South Australian–GAB population because it was highly unlikely that larvae spawned off east Tasmania could be transported against prevailing currents and winds to the region. Whether there is a distinction between NSW and Tasmanian stocks is unclear. Maxwell (1979) presumed that jack mackerel migrated south from NSW in summer following the 17 °C isotherm. However, Jordan *et al*. (1995) noted that there is resident winter population of jack mackerel on the east coast of Tasmanian and that it might only be boosted by a spring migration from the north.

Maxwell (1979) suggested that jack mackerel in NSW waters spawn earlier than in Tasmania, from October through to January. Off eastern Tasmania, jack mackerel spawn between mid-December and mid-February (Marshall *et al.* 1993, Jordan 1994, Jordan *et al.*1995, Neira *et al.* 1998). Jordan *et al*. (1995) investigated spawning over 3 years off eastern Tasmania, and found little difference in timing between years despite interannual variability in oceanographic conditions. Spawning occurred on the shelf break with some spread inshore in certain years when a strong intrusion of EAC surface waters appeared to heavily influence distribution. Larvae of jack mackerel have been caught in coastal waters of eastern Tasmania from December to April (Marshall and Jordan 1992 cited in Neira *et al*. 1998), and in eastern Bass Strait in February (Neira 2005).

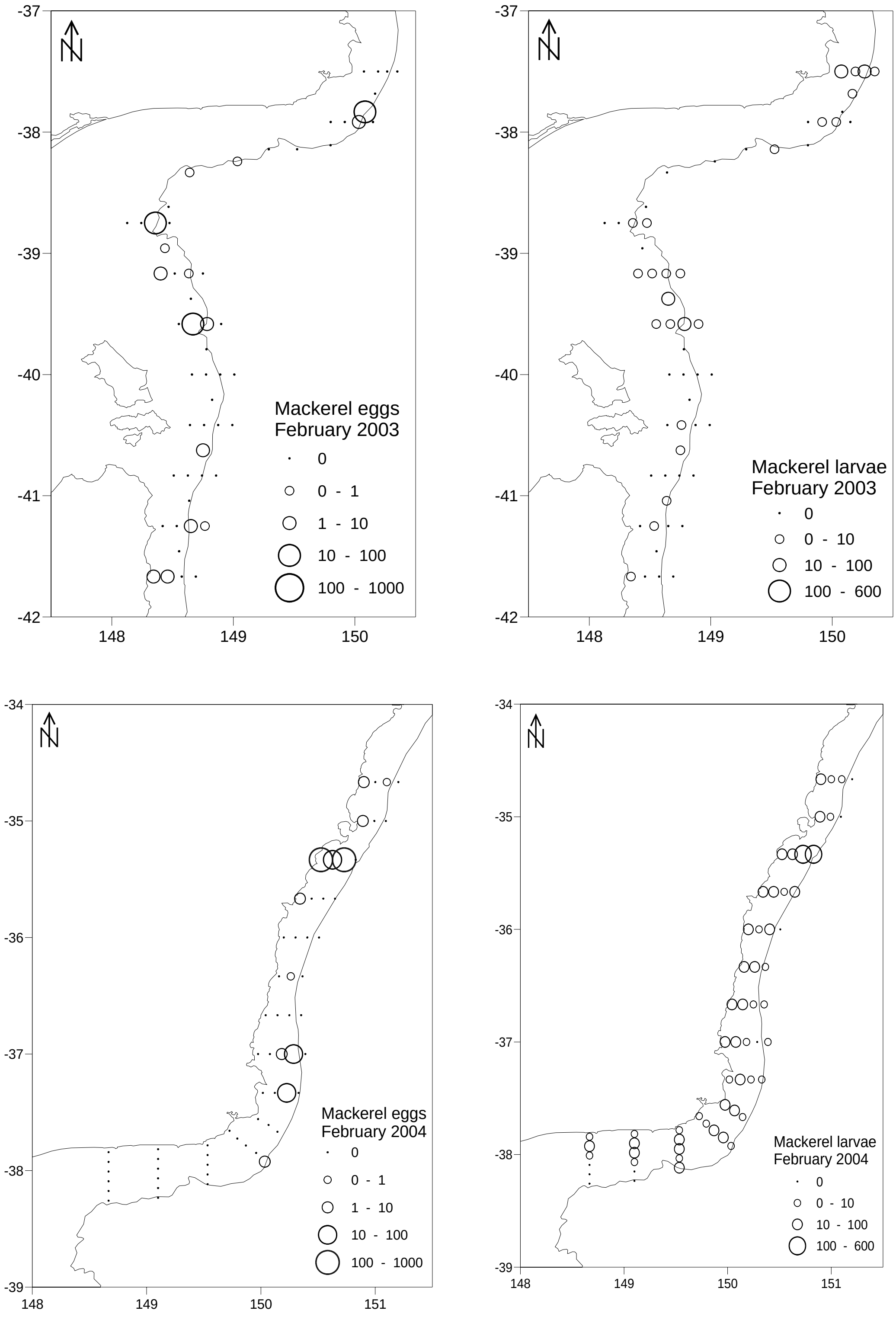


Figure 14. Distribution of mackerel Trachurus sp. eggs and larvae (numbers/m^2) in February 2004 (reproduced with permission from J. Lyle and F. Neira, TAFI, 2007 but see Neira *et al*. 2007 for complete data set).

Ichthyoplankton surveys in eastern Australia (Neira *et al.* 2007) found *Trachurus* spp. eggs and larvae distributed from southern Queensland down the east coast in October 2002 and 2003, February and July 2004, and off east Tasmania in February 2003 (Fig 14 but see Figs 9.1–9.4 in Neira *et al.* 2007 for complete data). Eggs of species of *Trachurus* are visually indistinguishable but given the known ranges of jack mackerel and yellowtail scad (Kailola *et al.* 1993), the eggs found off southeast Victoria and northeast Tasmania likely to be jack mackerel and eggs and larvae collected off southeast Queensland and NSW were presumed to be yellowtail scad (Neira *et al*. 2007). Larger larvae can be differentiated, however, and preliminary DNA analysis of the early preflexion larvae collected during these surveys indicate that jack mackerel occur in the southern region of the survey area, that they mix with yellowtail scad *e* off central NSW and only yellowtail scad occur in the northern regions (Neira *et al.* 2007). Analyses of *Trachurus* sp. egg abundances, average SST and salinities from the top 10 m indicated two groupings of high egg abundance. one group associated with an average temperature of 17 °C reflecting high jack mackerel larval abundance and another group associated with average temp of 19.5–20.5 °C reflecting high yellowtail scad larval abundance (F. Neira [TAFI] 2007, pers. comm.).

Trachurus eggs and larvae were also found off South Australia during 2003, 2004 & 2005 and a few in the western GAB in 2006 (Neira *et al.* 2007). However, the numbers were far fewer despite the fact that previous studies have found reproductively active jack mackerel. Neira *et al.* (2007) concluded that the low numbers were because the surveys did not coincide with peak spawning season, which was previously determined to be September-January by Stevens *et al.* (1984).

5.3.5 Fishery

Global

Globally, jack mackerel is an important commercial species although catches have declined since the early 1990s (Fig 15) although this figure apparently does not include the New Zealand catch. The main fishing grounds in New Zealand are off the west coast of the North Island using trawls, purse seines, traps and line gear.

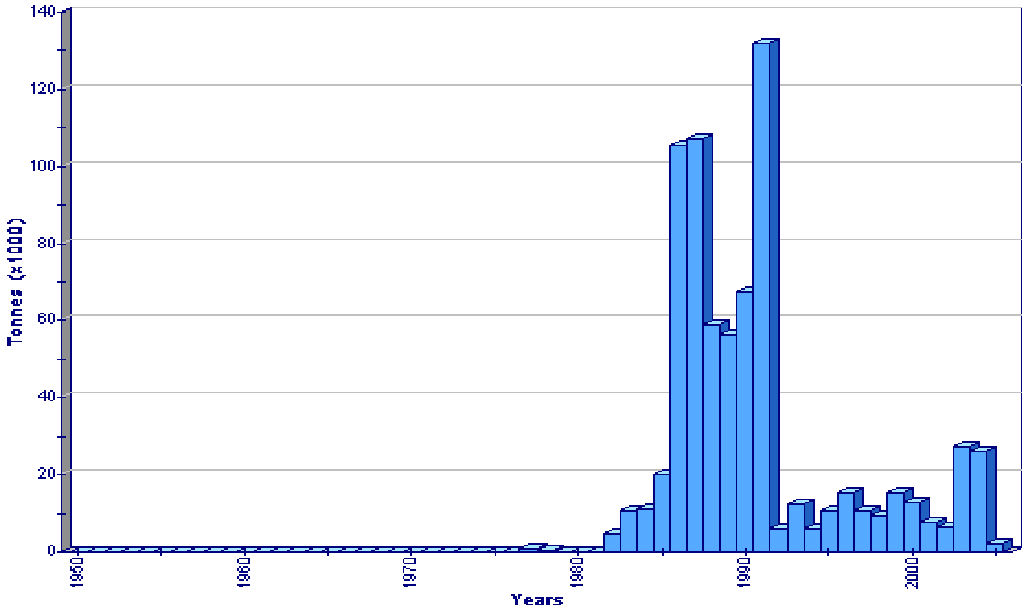


Figure 15. Annual global catches of jack mackerel *Trachurus declivis*. (Reproduced from Food and Agriculture Organization of the United Nations website: http://www.fao.org/figis/ accessed 30 May 2007.)

In New Zealand, the jack mackerel catch includes all three species of mackerel, and the proportions of *T. murphyi* increased during the first half of the 1990s but declined thereafter until 2000 because this species was considered lower value and more difficult to market and therefore was not targeted. However, jack mackerel catches have steadily risen since then from about 27 000 t in 2000–01 to 47 000 t in 2004–05.

Local

Jack mackerel have been caught mostly from Tasmanian waters (see Fig 32). The Tasmanian fishery began well before the 1970s but there was an increase of interest in catching mackerel for fishmeal processing in the mid 1970s. However, the project was unsuccessful at that time but in the mid 1980s interest increased again with a processing plant being established at Triabunna, on Tasmania's east coast. Catches peaked in 1986–87 (Fig 32) and at the time was Australia's largest fishery; however, the catches have fluctuated and declined ever since. A recent Assessment Report of the Small Pelagic Fishery found that while the downward trend might be indicative of over-fishing, "the general consensus is that the low catch and low level of effort in the fishery are more likely due to environmental fluctuations and low market demand" (Department of Environment and Heritage Assessment of the Small Pelagic Fishery February 2006).

Jack mackerel are also caught by the recreational fishers in Tasmania (Fig 16).

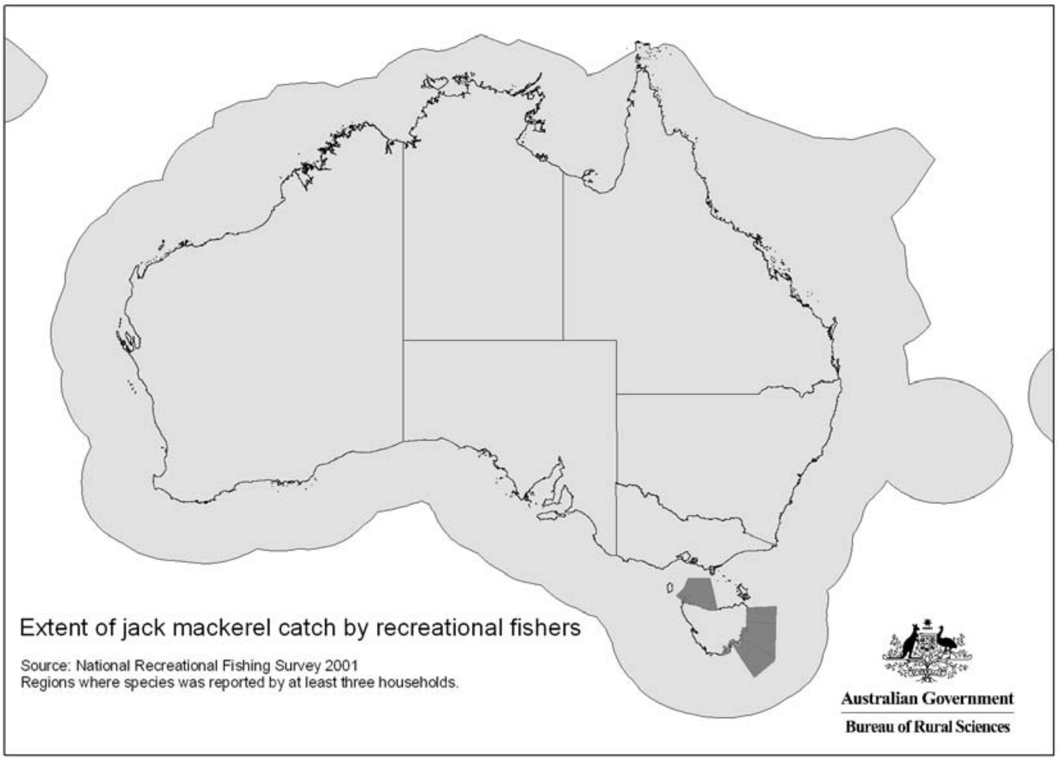


Figure 16. Statistical Local Areas where catches of jack mackerel were reported by at least three households in the National Recreational Fishing Survey 2001. Map produced by the Bureau of Rural Sciences.

Aerial spotting surveys were conducted during the mid-1970s (Williams 1981). These surveys of pelagic fish resources from 1973–77, sighted schooling jack mackerel off western Victoria in

March–May 1974, Jan–May 1975, February–March 1977 at the same time as fish were sighted off Tasmania and presumably represent different stocks (Williams 1981). Surface water temperatures in the areas where large tonnages of fish were sighted roughly coincided with SSTs of 16–17 °C in January 1974, 14–15 °C in 1975 off Victoria and east Tasmania, and 15–16 °C off east Tasmania in 1977. Fish were generally sighted in larger numbers off NSW in late winter–early spring in SSTs of 13–15 °C but up to 17 °C in some years and tended to be sighted further south in subsequent months giving rise to the hypothesis of north-south-north migrating fish stocks.

5.4 Yellowtail scad *Trachurus novaezelandiae* Richardson, 1843

CSIRO Marine Research

5.4.1 Taxonomy

Phylum Chordata

Sub-phylum Vertebrata

Class Actinopterygii

Division Teleostei

Superorder Acanthopterygii

Order Perciformes

Family Carangidae

Species *Trachurus novaezelandiae*

5.4.2 Distribution

Yellowtail scad are distributed in Australasia in southern Australia, off Lord Howe Island and New Zealand, and may be identical with a similar species in Japanese and southeast Asian waters (Fig 17; Gomon *et al*. 1994).

In Australia, they are distributed in coastal waters including estuaries along the central and southern coasts from Wide Bay, Qld to Northwest Cape, WA (May and Maxwell 1986, Gomon *et al*. 1994) but are most abundant in NSW waters (Kailola *et al*. 1993). They often form large schools in inshore in bays, estuaries, and inshore rocky reefs (Kailola *et al.*1993, Stewart *et al*. 1998 cited in Stewart and Ferrall 2001) but can be found to 500m. Juveniles are found in shallow, soft substrate areas (Kailola *et al*. 1993) and often in large schools (Neira *et al*. 1998). Recreational and commercial fishers exploit them particularly as bait for tuna fishing. The exact distribution of this species is uncertain due to the unreliability of identifications resulting from confusion with jack mackerel.

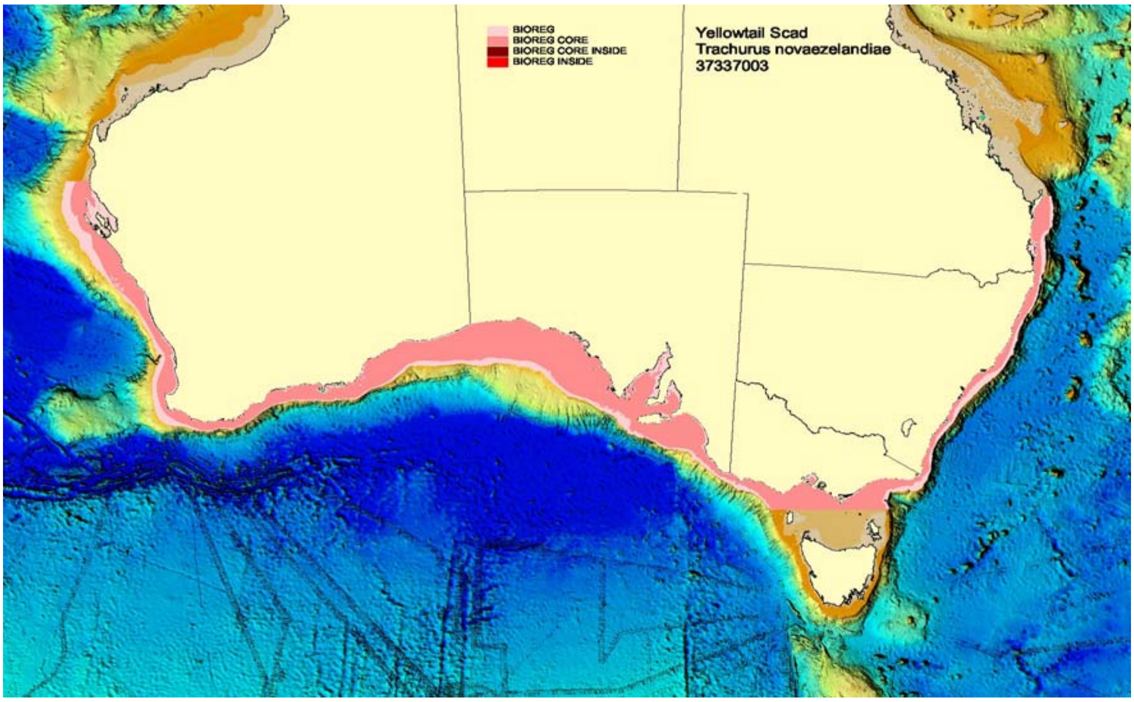


Figure 17. Distribution of yellowtail scad *Trachurus novaezelandiae* in Australia (based on CSIRO CAAB data). Bioreg = unvalidated range determined in original Bioregionalisation process. Core=preferred depth ranges.

5.4.3 Stock structure

Genetics

There are no genetic stock structure studies on this species.

Morphometrics

Lindholm and Maxwell (1982) used principal component analysis of morphometric measurements and meristic counts from yellowtail scad ranging in size form 15–25 cm FL from the GAB (n = 10), NSW (n = 20) and Tasmania (n = 21) to determine significant separation between the GAB and the southeastern Australian samples. The fish from GAB were generally smaller so allometric growth differences might account for the morphological differences however separation on the second component showed a separation within the south east even from fish caught in the same tow but could not be explained by sex, size, year, season or method of capture. They concluded that this might represent two subspecies or even separate species but further study was needed to resolve the issue.

5.4.4 Biology

Age and growth

Yellowtail scad reach a length of over 50 cm (Gomon *et al.* 1994). They first mature at about 20 cm FL for females and 22 cm FL for males and grow to 33 cm TL (Kailola *et al.* 1993). In New Zealand, yellowtail scad are presumed to mature at about 26–30 cm FL at 3–4 years (Ministry of Fisheries 2007). Von Bertalanffy growth parameters for NZ yellowtail scad were $K = 0.30$, $t_0 = -0.65$ and $L_\infty = 36$ cm (Ministry of Fisheries 2007).

Stewart and Ferrell (2001) measured and aged yellowtail scad from the inshore NSW purse seine fishery. A total of 7148 yellowtail scad was measured over 30 days in the northern regions and 11 in the southern regions. Fish from the northern regions were larger than those from the south. Half the catches were larger than 230 mm Fl whereas only 2% were from the southern samples. A total of 357 otoliths for ageing were taken from fish purchased or donated from commercial catches and supplemented by otoliths from smaller and larger fish from research catches. The fisheries were based on 2– and 3– year old fish but with a significant proportion of fish up to 11 years old in the north but only a small number of older fish up to 8 yrs old in the south. While different growth rates were apparent for the two regions, only one growth function was calculated using a Schnute growth model with parameters: $y_1 = 193.0$ (± 2.2), $y_2 = 267.9$ (± 2.6), $a = 0.24$ (± 0.05), $b = 0$, $t_0 = -3.4$ (± 1.0), $k = 0.19$ (± 0.05) and $L_\infty = 304.1$ (± 17.5). While the differences between the two populations might have been a real difference in growth rates as has been observed in New Zealand they could also have been a result of different fishing practices in the two areas. Larger fish were targeted in the north and were fished longer and resulted in a larger sample size whereas the fishers were catching yellowtail only as a bycatch of blue mackerel targeting in the south and over fewer days resulting in a smaller sample size.

Stewart and Ferrell (2001) concluded that there was insufficient evidence to suggest that there were two subpopulations of yellowtail scad off NSW. They did conclude that the fishery was very different from that of New Zealand, where the catch appears to be significantly larger (>300 mm FL) and older (>10 years old). The maximum age in NSW was 14 years old compared to 28 years old in New Zealand. They thought this difference might be related to differences in depth distribution whereby larger older fish inhabit deeper waters and were not targetted by the NSW purse seine fishery.

Diet

Yellowtail scad prey mostly on midwater prey but occasionally feed on bottom prey (Godfriaux 1970). The New Zealand study found that they ate largely crustaceans (50.4%) consisting mostly of Brachyura megalopa (14.6%) and zoea larvae (4.2%), natant decapods(7.5%) comprising carid larvae, Sergestidae, Palaemonidae, Crangonidae and unidentified carids, a mysid *Tenagomysis macropsis*, and a cumacean *Diastylis insularum*. Less common were decapoda and anomuran larvae, stomatopods, amphipoda, isopoda, and other unidentified remains. Due to rapid digestion, a large proportion of the diet was unidentifiable (26.4%). Fish comprised a further 16.8% of the diet. The only identifiable prey was *Engraulis australis*, however other fishes were suspected of comprising the digested remains. Polychaetes were also subject to rapid digestion and only “remains” were identified. In southeast Australia, the diet of yellowtail scad was analysed from a small number of fish caught in an autumn survey. The majority of the diet was unidentifiable (~90%), but the recognisable components were similar and in similarly low proportions such as reptantia and euphausiid larvae, sergestid, calanoid and cyclopoid copepods, isopods, and amphipods (Bulman *et al.* 2001, CSIRO unpub. data).

Yellowfin tuna are reported to eat yellowtail scad (Diplock (1990) cited in Glaister and Diplock 1993)

Reproduction and spawning

Yellowtail scad were believed to spawn in the open ocean (Kailola *et al*. 1993). However, ichthyoplankton surveys on the shelf for blue mackerel found *Trachurus* spp. eggs and larvae distributed from southern Queensland down the east coast in October 2002 and 2003, February and July 2004 and off east Tasmania in February 2003 (Neira *et al*. 2007). It was impossible to differentiate between the eggs of the species of *Trachurus* visually but given the known ranges of jack mackerel and yellowtail scad the eggs found off NSW and Qld, i.e. those north of the assumed jack mackerel distribution, were most likely to be yellowtail scad (F. Neira [TAFI] 2007, pers. comm.). *Trachurus* eggs and larvae were found off South Australia during 2003, 2004 & 2005 and a few were found in the western GAB in 2006 (Neira *et al.* 2007).

Larvae have been caught in Lake Macquarie, NSW and adjacent coastal waters from September to June (Miskiewicz 1987 cited in Neira *et al.* 2007), and in coastal waters off Sydney throughout the year (Gray *et al*. 1992, Gray 1993). Preliminary mtDNA testing of preflexion larvae caught during the ichthyoplankton surveys for blue mackerel indicated that yellowtail scad occurred along Qld–northern NSW, *T. declivis* further south, and the two species overlapped off central NSW (Neira *et al.* 2007).

These results are consistent with a study of biological oceanography of larval fish associations off northern NSW in Nov 1998 and January 1999 (Syahailatua 2005), which found that yellowtail scad larvae were spawned in the warmer EAC water mass and that larval transport into cooler up-welled water derived from Tasman Sea waters supported faster growth in post-flexion larval stages. Syahailatua (2005) found that the interactions of the EAC and upwellings off Diamond Head, south of Port Macquarie, NSW, greatly influenced the distribution of larval fish resulting in the uplifting of demersal species such as clupeids into the water column and the mixing of temperate and tropical fauna as reported by others (e.g. Miskiewicz 1987 *op cit.,* Gray 1993, and others cited in Syahailatua 2005).

In New Zealand, yellowtail scad have a protracted spring-summer spawning season and are known to spawn in the North and South Taranaki Bights, on the west coast of the North Island and probably elsewhere (Ministry of Fisheries 2007). Eggs have been found in the Hauraki Gulf and east Northland, and larvae were abundant in the Hauraki Gulf and the South Taranaki Bight (Jones 1990).

5.4.5 Fishery

Global

Yellowtail scad are caught in the New Zealand jack mackerel fishery but are not recorded separately. Prior to 1992, yellowtail scad dominated the jack mackerel catch taken by the purse-seine fishery in the Bay of Plenty and on the east Northland coast (JMA7) but between 1991–92 and 1995–96, the proportion of Peruvian jack mackerel in the catch increased considerably. However, by 1996–97, the low value of Peruvian jack mackerel resulted in less targeting for them and in 1999–2000 and 2000–01, the proportion of yellowtail scad in the catch had returned to approximately 95% (Ministry of Fisheries Science Group 2006). In other areas of New Zealand (JMA 1 and JMA 3), the influx of Peruvian jack mackerel resulted in increased quotas of up to 10 000 t and 18 000 t respectively for the 1994–95 year but under the proviso that the combined landings of jack mackerel and yellowtail scad did not exceed the original quotas of 5970 t and 2700 t respectively (Ministry of Fisheries Science Group 2006).

Local

The commercial fishery for yellowtail scad is primarily in NSW state waters and a minor component—no more than about 13 t—reported in the Commonwealth fishery (Fig 34). It is often caught in the recreational fishery (Fig 18). Overall, the reported catch for yellowtail scad is relatively small, <900 t, however, lack of identification to species level or misidentification might contribute to an underestimation of the catch of yellowtail. Yellowtail scad is also caught north of the SPF boundary, in the Queensland Finfish (Stout Whiting) Trawl Fishery waters with up to 44 t caught in 2002 (Annual Status Report 2006). In 2005, just over 20 t were retained and over 100 t discarded in Qld waters. In WA, 2 t of yellowtail scad were retained from the Purse Seine Managed Fishery in 2004. However, since sardines and sardinellas are the target species, yellowtail scad and blue mackerel are often discarded (Gaughan and Leary 2006).

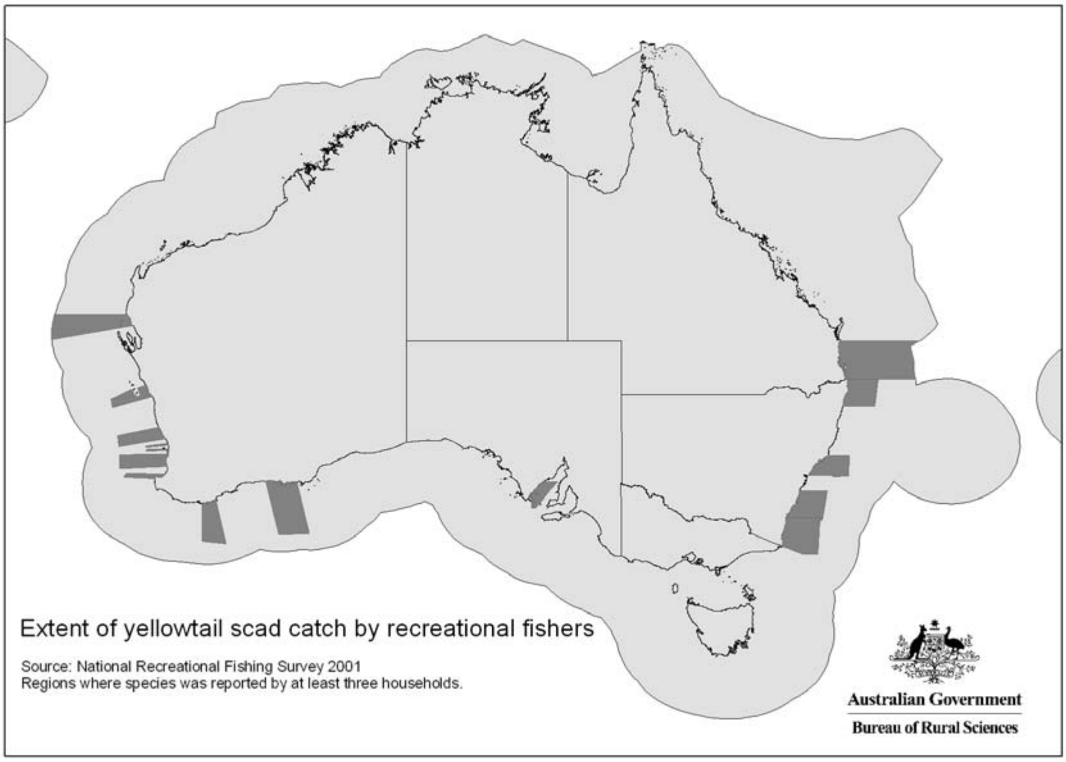


Figure 18. Statistical Local Areas where catches of yellowtail scad *Trachurus novaezelandiae* were reported by at least three households in the National Recreational Fishing Survey 2001. Map produced by the Bureau of Rural Sciences.

5.5 Peruvian jack mackerel *Trachurus murphyi* Nichols, 1920

FAO website

5.5.1 Taxonomy

Phylum Chordata

Sub-phylum Vertebrata

Class Actinopterygii

Division Teleostei

Superorder Acanthopterygii

Order Perciformes

Family Carangidae

Species *Trachurus murphyi*

Trachurus symmetricus was first described from California waters. *T. murphyi was* recognised later as a new species from Peruvian waters by Nichols (1920), however, the Chilean form was misidentified as *T. symmetricus* (Poulin 2004). At first, the morphological differences between the two forms were considered so slight as to suggest only sub-species differentiation, i.e. *T. symmetricus symmetricus* in the north and *T. symmetricus murphyi* in the south. Subsequently, morphometric and meristic analyses prompted researchers to recommend that *T. murphyi* and *T. symmetricus* should be distinct species (Poulin 2004). Stepien and Rosenblatt (1996) found little genetic divergence between the northeast Pacific and southeast Pacific populations and concluded that there is gene flow across the tropics. In contrast, Oyarzún (1998, cited in Poulin 2004) concluded that there was no basis for recognizing the sub-species status of the south-eastern Pacific population, and that the correct name for the species in this area was *T. symmetricus*. The issue was recently resolved by Poulin *et al. (*2004) by using phylogeographic reconstructions of mitochondrial DNA sequences to demonstrate that two disjunct populations could be recognized as *Trachurus murphyi* and *Trachurus symmetricus*. They suggested that the species have been isolated for at least 250 000 years. Therefore, we will refer to the species as *T. murphyi* except where source authors used otherwise.

5.5.2 Distribution

The Peruvian jack mackerel (aka Chilean jack mackerel, Inca scad) is a schooling species, distributed across 10–15° of latitude throughout the southern Pacific Ocean. It is found from the southeast from Galapagos Islands and south of Ecuador to southern Chile (Serra 1991), and southern Argentina (Nakamura *et al*. 1986), across to the southwest to Tasmania (Pullen *et al.* 1989) and New Zealand (Jones 1990). The "jack mackerel belt" was coined by Elizarov *et al.* (1993) to describe this span of the South Pacific Ocean. The species is reported to have increased significantly up to the 1990s (Serra 1991, Elizarov *et al.* 1993) resulting in the extension of its range. Elizarov *et al.* (1993) proposed the following explanation for its expansion. This region is associated with large-scale atmospheric changes that ultimately give rise to major upwellings in the equatorial regions of the Peru Current and the consequent development of El Niño in the east Pacific Ocean. Strong El Niños intensify the Peruvian counter-current that carries enriched waters farther south than usual and increases upwelling in the subantarctic divergence leading to enhanced productivity in the "jack mackerel belt" and thus favourable conditions.

A significant El Niño in the early 1970s caused a dramatic shift in the composition of the coastal communities of the southeast Pacific when the Peruvian anchovy declined and the fishery collapsed. This was followed by a rise in abundance of other pelagic planktivores such as the [Peruvian] jack mackerel, sardines and mackerel until by the end of the 1980s when the catches of these species were as high as the anchovy had once been (Elizarov *et al.* 1993).

Peruvian jack mackerel were first reported from New Zealand waters in 1984–1985. It now occurs around the Chatham Islands, Chatham Rise and Mernoo Bank, Southland/Snares Shelf and Taranaki Bight (Jones 1990). The first specimens of Peruvian jack mackerel in Australian waters were caught off Tasmania by fishermen in 1988 (Pullen *et al*. 1989)). The specimens were over 60 cm and therefore adult. In the early part of the fishery in New Zealand only large fish were caught also (range 44–63 cm), which was considered typical of fish living on the periphery of their range (Serra 1991).

The species is distributed to depths of 250–300 m off Chilean waters. In Chile, the species seasonally migrates from coastal to oceanic waters. Larger fish tend to be found in the southern range of its distribution.

From April 1993 to December 1996, CSIRO surveyed the shelf and shelf break of the southeast corner of Australia from Bermagui, NSW to Wilson's Promontory, Vic (Bax and Williams 2000). From four seasonal surveys, 15 specimens of Peruvian jack mackerel were caught, 12 of which were caught on the shelf break between Merimbula and Gabo Island in late winter. Two specimens were caught on the outer shelf edge further south of the Horseshoe in a summer survey. These records are consistent with its known range (Fig 19). It is oceanic and relatively larger than jack mackerel and is caught in small quantities as bycatch of the jack mackerel fishery (Yearsley *et al.* 1999). The protein fingerprint of Peruvian jack mackerel is very similar to the common jack mackerel both being equally dissimilar to the yellowtail scad fingerprint (Yearsley *et al*. 1999).

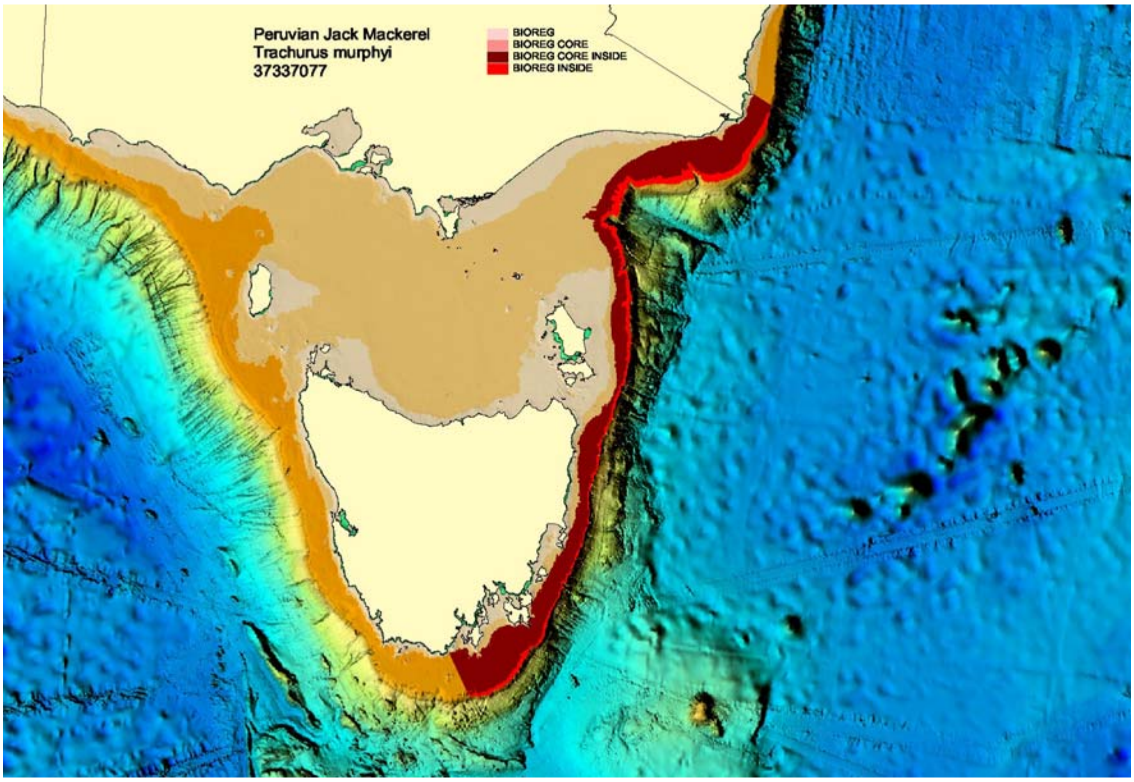


Figure 19. Distribution (presumed) of Peruvian jack mackerel *Trachurus murphyi* (based on catch data). Bioreg= range determined by the Bioregionalisation project, Core= preferred depth range, Inside= unverified core distribution range.

5.5.3 Stock structure

Across the jack mackerel belt there is a mosaic of abundance that is dependent on water mass structure and dynamics, and consequently plankton biomass, and separated by areas of low plankton biomass (Elizarov *et al.* 1993). Attempts to differentiate these populations using genetic or morphometric analyses were inconclusive and Elizarov *et al.* (1993) hypothesised that there were two populations, an oceanic and a coastal, with an unknown level of mixing. Studies off distribution and abundance suggest that there are two stocks in South America, one off Peru and one off Chile (Evseenko 1987, Serra 1991). Evseenko (1987) also proposed an oceanic stock extending to 150–160°W with which the New Zealand and Australian fish may be continuous. Originally, it was hypothesised that the New Zealand stock may be established and spawning (Taylor 2002). A few juveniles have been found in the South Taranaki Bight and of a size that strongly suggests local spawning success but they have not generally been found in the fishery although this might be due to a different habitat preference. Evidence of a change in size composition from a high frequency of large fish to a lower frequency and a broader range of sizes suggested that a local population might have established (Taylor 2002). However, current opinion is that the New Zealand (and consequently the Australian) fish are continuous with the oceanic stock spanning the South Pacific (Ministry of Fisheries 2007).

Taylor (2002) thoroughly examined the literature on stock structure of Peruvian jack mackerel *T. symmetricus murphyi* in the South Pacific and found that the results were inconclusive, as did Elizarov *et al.* (1993). The hypothesis of an oceanic and coastal stock was deemed confusing since the two subspecies *T. s. murphyi* and the Californian *T. s. symmetricus* both migrate offshore to spawn and return to the shelf to feed.

Conclusions from the Third International Meeting on the Establishment of the proposed South Pacific Regional Fisheries Management Organisation are that there are possibly four stocks: "…a Chilean stock which is a straddling stock with respect to the high seas; a Peruvian stock which is also a straddling stock with the high seas; a central Pacific stock which exists solely in the high seas; and, a southwest Pacific stock which straddles the high seas and both the New Zealand and Australian EEZs" (South Pacific Regional Fisheries Management Organisation 2007).

Genetics

Stepien and Rosenblatt (1996) found little genetic divergence between the northeast Pacific and southeast Pacific populations and concluded that there is gene flow across the tropics and that a single species *T. symmetricus* occurs throughout the Pacific Ocean from North America to South America and across to Australia. From mitochondrial DNA sequencing, *Trachurus murphyi* has since been identified as a distinct species (Poulin *et al.* 2004).

Two studies, one on esterase allele frequencies and another on allozymes markers in Chile (Koval 1996, Gonzalez *et al.*1996 cited in Taylor 2002) suggested that there were two populations in South America maintained by different migratory behaviours. Taylor (2002) also reported that an mtDNA study by Sepulveda and Galleguillos did not find significant differences between haplotype gene frequencies between samples form South America, New Zealand and Australia.

Morphometrics

Morphometrics have been used to separate jack mackerel into a Californian subpopulation and a South American subpopulation. Taylor (2002) compared twelve studies of morphometric and meristic data for Peruvian jack mackerel but found that only two were complete and comparable however one included juvenile data and the other adult. The study based on adult fish by Kotlyar (1976 cited in Taylor 2002) collected morphometric and meristic data from 50 fish from five areas off Peru and found statistical significance between most meristic comparisons but in only one morphometrics comparison between two sites. However the genetic studies by Stepien and Rosenblatt (1996) have supported this hypothesis.

Parasite indicators

Taylor (2002) reviewed nine papers containing information of parasites however the majority were descriptive only. Of three that used parasites as indicators of stock structure, two were available only as abstracts. Nine species of parasites are found to parasitise *T. s. murphyi* in the southeastern Pacific (Oliva 1994 cited in Taylor 2002): *Anisakis* sp. (Nematoda), *Scolex pleuronectis*, *Tentacularia corphaenae, Nybelinia* sp (Eucestoda), *Corynosoma australis* (Acanthocephala) and unidentified Opecoelidse (Digenea), *Caligus* sp. and *Lernathropus trachuris* (Copepoda) and *Ceratothoa gaudichaudii* (Isopoda). The last two species are absent in New Zealand fish therefore Avdeyev (1992) concluded that this might be because the life span of the parasite is not long enough to last a migration or that New Zealand fish are spawned from an intermediate mid-oceanic stock. Taylor (2002) posed two further hypotheses regarding the absence of parasites in New Zealand fish. The absence of an intermediate host was suggested but there was no evidence for either parasite to support it. He also suggested that the absence of the isopod *C. gaudichaudii* could be explained on the basis that it is at least partially cryophilic and dies because of its host fish migrations into warmer waters. This does not seem to apply to *Lernathropus* species. Taylor (2002) concluded from parasite information that there was likely a stock of *T. s. murphyi* in the south-west Pacific independent of the southeast Pacific Ocean stocks.

George-Nascimento (2000) examined the composition of the metazoan parasite composition in *T. s. murphyi* from two fishing locations along the coast of Chile to determine population structure. He examined more than 7780 parasites belonging to 15 taxa collected between 1990 and 1996 in 71 samples comprised of 3946 hosts. The same taxa were found in both areas however, fish from northern Chile had a higher abundance of *Ceratothoa* spp., whereas those from southern Chile had more *Rhadinorhynchus trachuri*, *Hysterothylacium* sp. larvae and *Anisakis* type I larvae. Interannual variability in composition with areas was suggested to be a result of heavy offshore fishing pressure. However, despite this variability, George-Nascimento (2000) concluded that the persistent differences in the composition suggest that the parasite communities could be used with more confidence for stock discrimination than previously thought and that his results support the hypothesis of two stocks in the south east Pacific Ocean.

Currently, there are no parasite indicator studies in the Southwest Pacific.

5.5.4 Biology

Age and growth

T. murphyi is described as exhibiting moderate growth and has been studied by many workers (summarised by Taylor 2002, SPRFMO–III–SWG–16). Most studies have been off Chile where maximum age is 18 years compared with 32 years in New Zealand (SPFRMO –III–SWG–18). The difference between these two estimates might partly be due to the larger size of NZ fish but more likely due to different ageing techniques.

Diet

Peruvian jack mackerel is opportunistic and able to feed on a wide variety of prey from copepods to mesopelagic fish although euphausiids such as *Nyctiphanes simplex*, *Euphausia mucronata* and other species, *Nematoscelis* sp. are most preferred (51.1 % by weight) (Konchina 1981). Mesopelagic fish were also significant proportion of the diet (20.4%) and were identified as Engraulidae, Gonsotomatidae, *Vinciguerria*, Myctophidae larvae, Scomberosocidae, Perciformes, Normanichthyidae and unidentified fish larvae. Larvae of decapoda form over 11% and copepoda about 5%. In a study off Chile, their diet was mainly euphausiids in 1997 but mesopelagic fish in 1998 and 1999 (Córdova *et al*. 1998, 1999, 2000 cited in Bertrand *et al.* 2004). Fish caught in the New Zealand fishery ate euphausiids predominantly, with most stomachs over 50% full of euphausiids (Taylor 2002). They also ate amphipods, copepods, crustaceans, *Munida gregaria*, *Pasiphae* sp., *Enoplateuthis* sp., squid, salps, Myctophidae and fish.

Juveniles are eaten by albacore (Bailey 1988) and swordfish of the Chilean coast (M. Donsoso cited in Draft Report to First International Meeting on the Establishment of the South Pacific Regional Fisheries Management Organisation). There are no known records of predation on Peruvian jack mackerel in Australia.

Bertrand *et al.* (2004) described the diel spatial distribution of jack mackerel in relation to their prey of Chile. They found that jack mackerel were at mid-depth during the day where prey was sparse due to the deeper migration of mesopelagic species beyond their reach. At night, jack mackerel foraged actively in surface waters where it overlapped with the upper depths to which one of the mesopelagic communities migrate nocturnally. However, jack mackerel appeared to aggregate at night contrary to the usual pattern of dispersal of pelagic fish (Bertrand *et al.* 2004). They noted interannual differences in scale-dependence in the predator-prey relationships, which they related to La Nina and El Nino events.

Reproduction and spawning

T. murphyi is an indeterminate batch spawner based on histology and oocyte frequency distributions of reproductive females. First spawning is reported from 21–25 cm FL by a variety of researchers based on different techniques.

The populations in South America spawn mainly north of 40°S in spring and summer mostly between October and December, and feed south of 40°S in autumn and winter. They migrate from coastal waters to oceanic waters to spawn where eggs are found in the upper 60 m (Evseenko 1987). Spawning occurs throughout the whole jack mackerel belt and does not begin and end simultaneously across its whole range (Elizarov *et al.*1993). In the north and west spawning begins 2–3 months before the southern region of the southeast Pacific. The main spawning grounds of the Chilean population are off central Chile and extend to about 93°W. Fish also spawn along the subtropical convergence between 42°S and 36°S. The larvae are oceanic (Serra 1991). Chilean larvae recruit back to the shelf at about 2 years. Fish return to coastal waters to feed. Elizarov *et al.* (1993) described migrations in oceanic waters west of 120°W where they move from cold productive southern waters to warmer northern waters where it spawns.

In New Zealand, mature fish were found off the central west coast of the South Island in July 1998 where SST was 13.8 °C (Taylor 2002). Based on the presence of small juveniles and change in length frequency distribution, Taylor (2002) concluded that there has been successful spawning.

In Australia, there is no evidence of spawning of Peruvian jack mackerel.

5.5.5 Fishery

Global

The following extract is from the Third International Meeting on the Establishment of the proposed South Pacific Regional Fisheries Management Organisation, Reñaca, Chile, 30 April – 4 May 2007.

> "Peruvian jack mackerel are predominantly caught by purse seine and midwater trawl.
>
> Since the start of the fishery in 1950, the majority (~75%) of the global catch has been taken by Chilean vessels predominantly within its EEZ. During the period 1978–1990, the fleet of the former USSR took a catch of ~10 million t

in the high seas area. Between 1994 and 2002, most of the Chilean catch of *T. murphyi* was taken within its EEZ, but in 2003 and 2004, 32% and 28% was taken outside the EEZ. In 2004 the Chilean catch was ~363 000 t from the high seas within the South Pacific region. In recent years, other flags including China, Netherlands, Republic of Korea, and Russia have taken catches on the high seas in the South Pacific region. At the western extent of the species range the high seas catch is much smaller, with New Zealand catches of <1 tonne in 2005. It is not currently possible to accurately quantify high seas catches as reporting is incomplete and those data that are reported do not separate between high seas and within EEZ catches.

Currently, with the exception of Chilean vessels, there are no management measures in place for jack mackerel fisheries on the high seas (although all New Zealand and Australian flagged vessels that may take this species as an occasional bycatch are regulated by a high seas permitting regime).

Due to the nature of the straddling Chilean stock, the same regulatory controls that apply within the Chilean EEZ also apply on the high seas. These controls include maximum catch limits per vessel owner and minimum size limits. Although jack mackerel constitute a large resource, there have been concerns at a regional (assumed stock) level. For example, the Chilean straddling stock of *T. murphyi* is currently considered to be fully exploited.

For the Chilean (straddling) stock, current stock assessment suggests that the stock is at full exploitation and, given the moderate productivity of this species, caution with respect to any increases in fishing mortality is needed.

For the other stocks given the absence of current information, it is not appropriate to provide detailed comment. However, given the moderate productivity of this species and the lack of information about current stock biomass levels, due caution is appropriate.

There has been a substantial amount of historical research on this species, particularly by Russia and Chile. However, substantially less research has been conducted over the past decade, except within the EEZs of a few coastal states.

Research is required to improve the understanding of the stock structure of *T. murphyi* to aid the development of appropriate management units, to obtain biomass estimates for stocks actively fished as inputs to stock assessment modelling, to undertake stock assessment for the fished stocks to provide robust fisheries management advice, and to evaluate bycatch levels , bycatch composition and levels of incidental catch of associated and dependent species in the active high seas fisheries to address issues associated with an ecosystem approach to fisheries management."

The global catch of Peruvian jack mackerel (Fig 20) peaked in the mid 1990s at nearly 5 million t after which it declined sharply and since stabilised at nearly 2 million t annually.

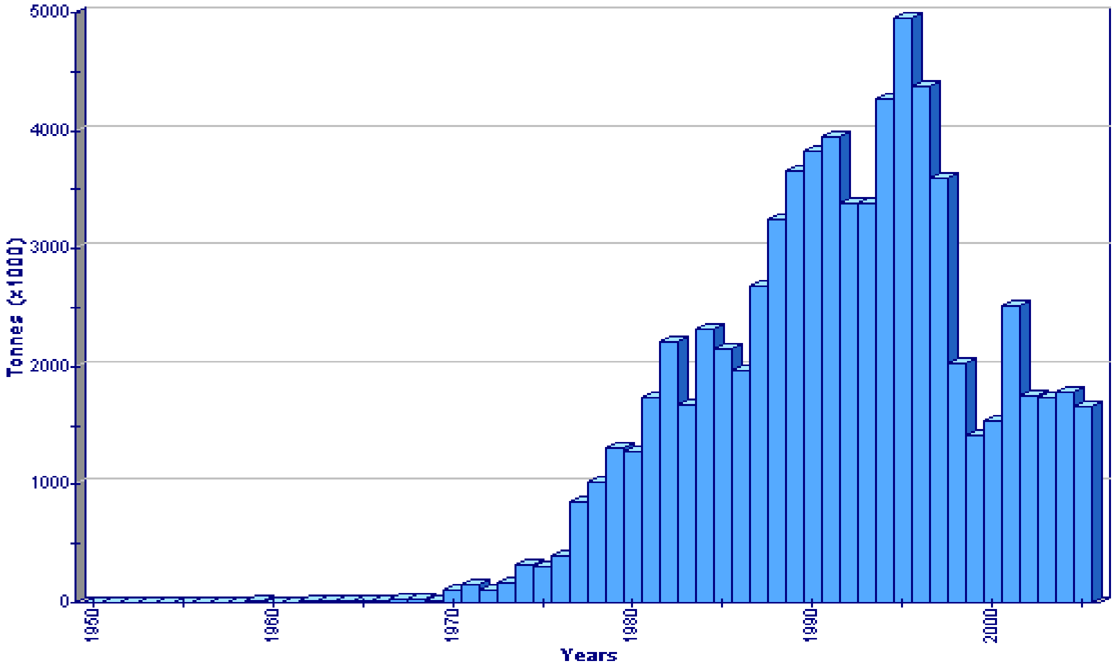


Figure 20. Annual global catch of Peruvian jack mackerel *Trachurus murphyi.* (Reproduced from Food and Agriculture Organization of the United Nations website. http://www.fao.org/figis/servlet/SQServlet?ds=Capture&k1=SPECIES&k1v=1&k1s=2309&outtype=gif&gr_props=webapps/figis/species/format/gform_large.txt . Accessed 30 May 2007.)

5.6 Stock structure of Australian sardine *Sardinops sagax* in Australia

The Australian sardine *Sardinops sagax* off eastern Australia has only recently been added to the species managed under the jurisdiction the SPF. While it was not a focus of this report, this summary of stock structure investigations was considered a useful addition. The greatest amount of research regarding stock structure of the Australian sardine has been conducted off the southern coast of Western Australia (see Edmonds and Fletcher 1997, Gaughan *et al.* 2001, Gaughan *et al.* 2002). Although there is some degree of mixing throughout the distribution of Australian sardine in WA, a number of stocks and sub-populations can be identified. The major sub-division occurs between the west coast of WA (Dunsborough and Fremantle) and the south coast (Walpole to Esperance). On the south coast of WA, three functionally distinct adult aggregations are known to occur (Gaughan *et al.* 2001). Consequently, management of WA pilchard fisheries has involved treating the western and southern stocks separately and the three major aggregations on the south coast have been treated as three separate stocks with different Total Allowable Catches (TACs) set for each (Cochrane 1999).

Larvae may mix between these WA regions, as they are transported eastwards by the Leeuwin Current. Some larvae may be transported into South Australian waters by the Leeuwin Current (Gaughan *et al.* 2001). The extent of contribution of WA recruits to the SA fishery is unclear. Eastward transportation of WA larvae also requires a westward migration of juveniles to maintain the WA functionally distinct adult aggregations. Annual catch-at-age data supports this hypothesis (Gaughan *et al.* 2002).

Information is available on the spawning patterns and fishery biology of Australian sardine in South Australia and southern Queensland (Ward and Staunton-Smith 2002). In South Australia, eggs and larvae of *S. sagax* are found throughout shelf waters during all months of the year, and are particularly abundant between January and April. The critical spawning temperature range for Australian sardine is 14–23 ºC, which coincides with the temperature range recorded across shelf waters within South Australia. Peak abundances of eggs and larvae during summer-autumn coincide with coastal upwelling events that are known to enhance productivity and increase food availability for juveniles and adults (Ward *et al.* 2006). There is no information on stock delineation or inter-mixing of South Australian sardine aggregations between regions in South Australia (Ward *et al.* 2005).

Australian sardine are also known to spawn in coastal waters between southern Queensland and southern NSW. Eggs have been reported from a small area between Noosa Heads and Caloundra in southern Queensland in winter and spring, in water temperatures <23 ºC, with highest abundances occurring during September–October (Ward and Staunton-Smith 2002). Growth and survival of larval Australian sardine is thought to be enhanced in an upwelling area of near the Tasman front, with juveniles found near Jervis Bay in southern NSW (Uehara *et al.* 2005).

Port Phillip Bay, a large, semi-enclosed marine embayment in Victoria, has been shown to be an important nursery habitat for sardines, with juveniles entering the bay in late spring–early summer and return to the sea the following winter to spawn (Neira *et al.* 1999). Usage of Port Phillip Bay as a nursery area by sardines appears to be unique to the Victorian coast, with no reports of other enclosed bays or estuaries being used as nurseries across temperate Australia.

Sardines in Victoria typically spawn in shelf waters (Hoedt and Dimmlich 1995) and not within Port Phillip Bay as initially thought (Neira and Sporcic 2002), a pattern which parallels that of sardines elsewhere in temperate Australia (Neira *et al.* 1999, and references therein).

The different spawning seasons in Australian sardine from different regions across Australia may inhibit interbreeding between the pilchards of different regions and therefore create separate breeding stocks (Blackburn 1951). For example, NSW sardines spawn in autumn–spring, Victorian sardines spawn in spring–summer, WA sardines spawn in autumn–winter and SA sardines spawn in summer–autumn. Although some overlap in spawning seasons occur between regions and may allow some mixing of spawners, Blackburn (1951) suggested that large-scale exchanges of spawners are unlikely to occur across the range of the species.

5.7 Food web interactions

Several models have been developed for the southeastern region of Australia (Goldsworthy *et al.* 1993, Fulton *et al.* 2004, Bulman *et al.* 2006), all of which include small pelagic species specifically. The most recent model for an area of the eastern Bass Strait shelf and slope (Bulman *et al.* 2006) included higher predators such as tunas and billfishes, pelagic and demersal sharks, zeid dories, seals and seabirds, and prey groups such as mesopelagic fishes, gelatinous zooplankton (pyrosomes and salps), macrobenthos and zooplankton. To focus more specifically on the small pelagic species, a food web (Fig 21) was developed from this ecosystem model of the eastern Bass Strait. Jack mackerel and redbait were single species groupings in the original models, and blue mackerel was one of two species of the original grouping, medium-sized pelagic predator, and survey information was available only for blue mackerel. Similarly, yellowtail scad was the only species of the original grouping—pelagic medium invertebrate feeder—for which information was used. Similarly, Peruvian jack mackerel was originally defined as a large pelagic invertebrate feeder, but in fact, its diet in Australia is probably very similar to jack mackerel since it is usually caught in association with jack mackerel schools. The Peruvian jack mackerel is also relatively insignificant in biomass or catches therefore the jack mackerels can probably be well represented within a single grouping.

From the proposed food web, the dependencies on the Small Pelagic Fishery species by other commercial species are obvious. Tunas and billfishes are probably the most valuable species. Bluefin tuna eats both redbait and jack mackerel in high proportions i.e. between 30–45% respectively and yellowfin tuna eats yellowtail scad, jack mackerel, blue mackerel and redbait although Engraulidae is the most important prey by volume. It is probable that Peruvian mackerel would also be eaten by tunas and billfishes as these species are known to eat them elsewhere. Both mirror dory *Zenopsis nebulosus* and John dory *Zeus faber* also eat large amounts of redbait and jack mackerel. The demersal sharks such as gummy shark *Mustelus antarcticus*, brier shark *Deania calcea*, draughtboard shark *Cephaloscyllium laticeps*, and school shark *Galeorhinus galeus* eat jack mackerel in varying degrees (8, 24, 36 and 49% respectively). Medium- or large-sized predators such as Ray's bream *Brama brama* or barracouta *Thyrsites atun* also feed on small pelagic species: they eat redbait at 2 and 4% respectively and *Thyrsites* eats 46% jack mackerel. There are also likely to be many other predators of commercial interest, particularly pelagic species, that also eat small pelagic species but for which we have no specific dietary data.

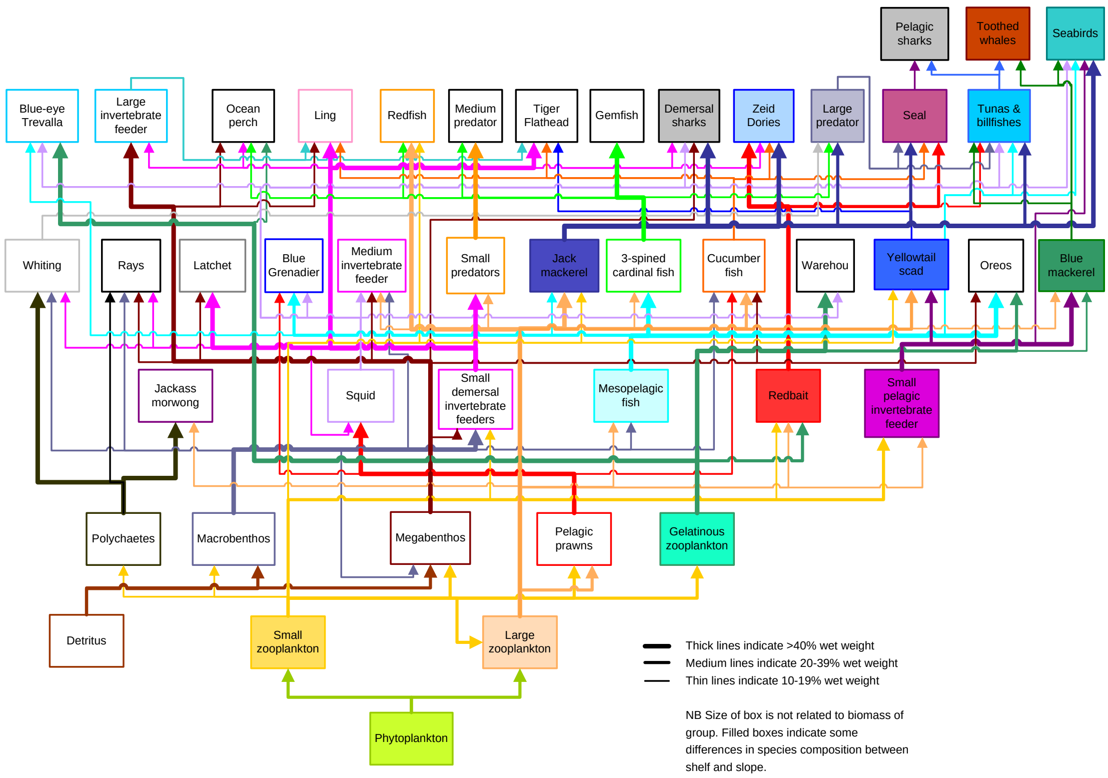


Figure 21. Food web of the southeastern Australia focussed on the Small Pelagic Fishery species. The species and direct links with their prey and dependent predators are highlighted in coloured boxes. Indirect links via competition are not highlighted but may also cause notable interactions.

The Australian fur seal *Arctocephalus pusillus pusillus* feed heavily on redbait and jack mackerel (25 and 31% respectively) and some seabirds such as shy albatross *Thalassarche cauta* and the Australasian gannet *Sula serrator* also feed predominantly on redbait and jack mackerel.

Small pelagic species eat small and large plankton including euphausiids, amphipods, copepods, and benthopelagic prawns, gelatinous plankton such as pyrosomes and salps, and mesopelagic fishes and the small pelagic invertebrate-feeding fishes including the sardines *Engraulis australis* and pilchards *Sardinops neopilchardus*.

While the direct interactions are intuitive, indirect interactions such as those arising from direct competition or release from predation, are often less intuitive. The significance of an indirect interaction is dependent on its interaction strength, which can be determined either qualitatively or quantitatively with appropriate models. The sum of these interactions determines the overall structure and functioning of an ecosystem.

Stock structure of the populations and their management play a role in ecosystem structure and function. Small pelagics have been found to be significant controlling influences within other ecosystems. For example, in the Benguela, Guinea and Humboldt upwelling systems, small pelagics exert a bottom up control on large predators whereas off South Africa, Ghana, Japan, and in the Black Sea they exert a top-down control on zooplankton (Cury *et al.* 2000). The term “wasp-waist” is often used for systems where the small pelagic functional groups exert both bottom-up and top-down control. The implications for ecosystems from fishing pressures then become significant particularly if “fishing down the food web” (Pauly *et al.* 1998) continues.

Fishing in the middle of the food web, on small pelagics, obviously has potentially large consequences for dependent fisheries such as tuna. At a more global level, Cury *et al.* (2000) found that the scale of the Peruvian jack mackerel in the South Pacific, one of the largest in the world, exemplifies the uncertainty of the effect that fishing has on carbon fluxes. Based on estimated annual zooplankton consumption by jack mackerel, the annual catches of up to 5 million t of fish during 1990–95 were estimated to have released about 2.75–5 million t of carbon per year from predation pressure, the fate of which is uncertain.

Recent model-based research into alternative management strategies has suggested that it is unlikely that large fisheries for both demersal and small pelagic fishes would be simultaneously economically viable in southern Australia (Fulton *et al.* in press). This finding was subject to model uncertainty and other relevant factors, such as the realised level of effort compared to potential effort in each fishery, but it highlighted a very real issue within Australian waters. This is the lack of definition of a system-level goal state, and consequently, the associated acceptable levels of impact on that system and subsystems and sectors to be supported in the future. An accurate understanding of the stock structures of the small pelagic species and the dynamics of the roles they play within the relevant systems is therefore of considerable importance when implementing and imposing ecosystem-based fishery management principles, and determining sustainable fishing targets.

6. COMPARISON OF ENVIRONMENTAL VARIABLES WITH CATCH & DISTRIBUTION

6.1 Introduction

One of the key areas of development in modelling population dynamics in recent years is the behaviour related to habitat selection and specifically density-dependent habitat selection, which considers the influence that population size and density has on an individuals' choice of habitat and ultimately, the species' distribution. The development of this theory has been through two avenues. One is biogeographical, largely developed by ornithologists in the 1950s and 60s, and described marginal habitat utilisation, and expansion and contraction of range according to changes in population size. A recent example is MacCall's (1990) "basin model" where species spread into more marginal habitats as populations increase and contract to core habitats as populations fall (analogous to the area and volume of a lake increasing as it fills and vice versa). The second was through development of many independent behavioural models, some of which were comprehensive treatments of socio-economic behaviour which were not recognised as significant at the time, but most were on localized geographic scales and not generally applicable.

While the data we have collated is not adequate to build such models of habitat selectivity for the small pelagic species yet, it is clear that an ecosystem-based approach to fishery management broadly encompasses such exercises. Pelagic species are highly mobile, less likely to be associated with relatively immobile ground-based habitats and more dependent on prevailing oceanography in three-dimensional space, making the task of defining preferred habitat more difficult as the boundaries or range distributions will be highly fluid. Nevertheless, we compared the catches of the small pelagic species with the physical characteristics of the water masses in which they were caught and the depth at which they were caught to determine a potential habitat range. By categorising the sizes of catch and assuming that the largest catches indicate a stronger affinity for the water in which they were caught than smaller catches, we determined a range of values of water properties that might be considered characteristic of their core distribution and therefore fundamental to developing relevant management strategies. However, the sampling is highly biased and the assumptions and uncertainties in the data mean these results should be viewed with caution.

6.2 Methods

Fisheries data were collated from NSW, South Australia, Tasmania, Victoria and Commonwealth jurisdictions and total catches per calendar year were calculated. The metadata descriptions are in Appendix C. Catch distributions were plotted monthly and overlaid on climatology maps of SST to examine visually associations of catch and environmental preferences. The monthly data are not presented in this report due to confidentiality, however the overall catch distributions are presented.

To determine environmental preferences, the catch data by shot from the Commonwealth Small Pelagic Fishery Purse seine and midwater trawl logbooks from 1985 to 2007 for which there was explicit location data and catch definition were used. For each shot, location, time and date, depth of capture (where available), and catch per species were matched with environmental variables. In instances where depth of capture was not recorded, we estimated the values. For purse seine catches, we assumed an average depth of capture of 100 m in water greater than 100m deep or otherwise, the bottom depth. Similarly, where depth of capture for the midwater trawl was missing we assumed an average value from other shots that were in a similar location. If this inferred depth was greater than the water depth, the data was discarded. The catch data were matched with modelled data retrieved from the Spatial Dynamics Ocean Data Explorer (SDODE) database (Hobday *et al.* 2006) and climatological data retrieved from the CSIRO Atlas of Regional Seas (CARS) database (Ridgway *et al.* 2002, Condie and Dunn 2006). SDODE is a system that maintains a file structure of ocean datasets routinely collected from various locations, to maintain an up-to-date metadata snapshot of ocean products. A graphical user interface enables easy viewing of ocean datasets and the extraction of ocean data information for specific points of interest. CARS is a digital atlas of seasonal ocean water properties, covering the seas around Australia. It comprises historic mean fields and average seasonal cycles, derived from all available historical subsurface ocean property measurements most of which were from research vessel instrument casts and autonomous profiling buoys.

The properties obtained from SDODE were modelled temperatures at average depth of trawl, a sea surface temperature (SST) 6 day composite, and SeaWiFS (Sea-Viewing Wide Field-of-view Sensor) chlorophyll *a*. SST was obtained from NOAA Advanced Very High Resolution Radiometer (AVHRR) data and processed in Hobart by the CMAR Remote Sensing Facility. The dataset includes Pathfinder SST daily images, and the optimal estimates (and error fields) made from them, at 10-day intervals. SeaWiFS provides quantitative data on optical properties of the global oceans and land surfaces. The concentration of phytoplankton or chlorophyll *a* can be estimated from those properties.

The six water properties retrieved from CARS were temperature, salinity, dissolved oxygen (DO_2), nitrate (NO_3), silicate (SiO_2) and phosphate (PO_4) all at depth of capture. The SDODE data retrieved for temperature and chlorophyll *a* was modelled for that specific time and date, depth and location whereas the CARS data are the climatology values (i.e. seasonal averages, for that date and location).

For each species, catches were first correlated with their corresponding environmental variables of their locations, and then regressed against selected significant variables only. We assumed that the sizes of catch were a rough proxy for abundance and habitat preference and compared the catch sizes with the environmental data. For each species (except for Peruvian jack mackerel which was not recorded), catches were grouped into size categories specific to the species and general descriptive statistics were evaluated for each variable. Minima, maxima and means of the modelled and climatology (CARS) temperatures, salinities and oxygen of locations of catches were compared with those of the major water masses in the south Australian region (Fig 22). The statistics of the water mass properties were obtained from the 2005 National Marine Bioregionalisation of Australia (NMBA) (Commonwealth of Australia 2005). The relevant water masses were Subtropical Lower Water (Water Mass P13 in the

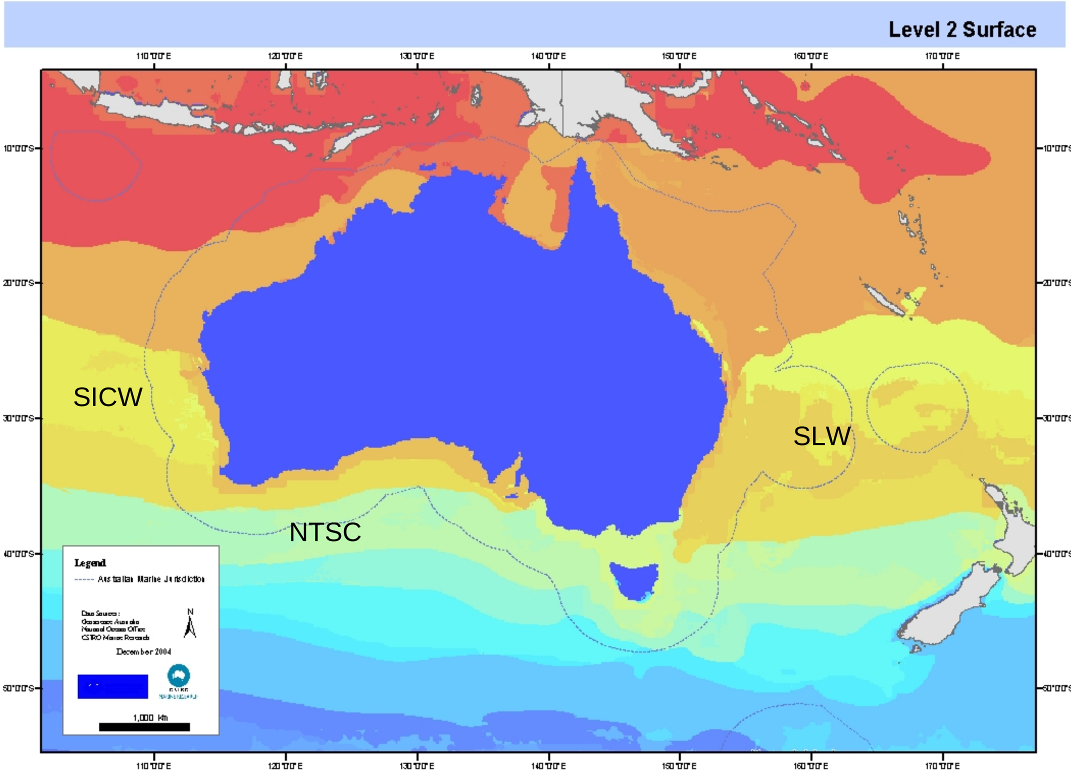


Figure 22. The National Marine Bioregionalisation Level 2 substructure of the major water masses around Australia produced by nesting substructure within the Level 1b classes. The light green band represents the Northern Sub-tropical Convergence which includes the Tasman Sea and the yellow bands represent the South Indian Central Water on the west coast and the Subtropical Lower Water on the east coast.

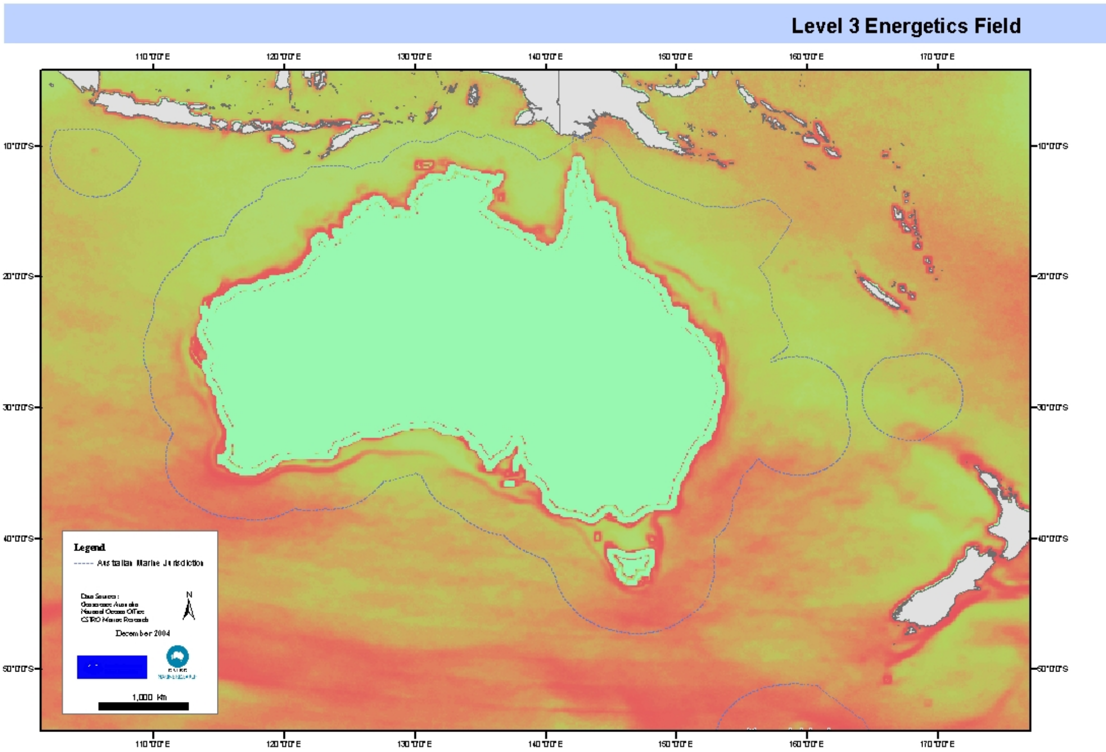


Figure 23. Energetics field of the major water masses around Australia. Brighter red regions correspond to areas of greater currents and upwellings.

NMBA), South Indian Central Water (Water Mass I13 in the NMBA), and the Northern Subtropical Convergence (Water mass 12 in the NMBA). The energetics of the regional seas indicating the currents and upwellings are shown in Fig 23. All statistical routines were performed using the Microsoft MS Excel Data Analysis routines.

6.3 Results

6.3.1 Correlations

Correlations coefficients are low but some are statistically significant (Table 4). Jack mackerel catches were the only species catches correlated (negatively) not only with the modelled temperature at depth of capture but also the climatological (average seasonal) temperature at depth (Table 4), i.e., as temperature increased catches decreased. However, redbait catches were negatively correlated with SST. As might be expected from the negative correlation with temperatures, both species were also negatively correlated with salinity. Blue mackerel was positively correlated with salinity but not with temperatures. Both redbait and jack mackerel catches were correlated positively with chlorophyll *a* values (Table 4). While the fish are unable to utilise the phytoplankton directly, their prey species might, thus enabling fish to take advantage of increased prey abundance at a suitable lag-time in the future.

Correlations between dissolved oxygen and all nutrients except phosphate occurred for jack mackerel. Blue mackerel catches were negatively correlated with silicate. These correlations are probably not particularly important to the fish specifically but reflect the water properties of the water masses in which the fish were caught.

Table 4. Correlation coefficients $r_{0.05(2)}$ of catches of small pelagic species with environmental variables. Significance values determined from Zar (1984). ** significant at 0.05, * nearly significant.

	Redbait	*n*	*Blue mackerel*	*n*	*Jack mackerel*	*n*	*Yellowtail scad*	*n*
Modelled temperature	–0.0375	911	–0.0547	403	**–0.0951	754	–0.1654	47
SST 6 day composite	**–0.0883	903	0.0434	378	–0.0271	724	0.2370	44
Chlorophyll *a*	**0.0898	823	0.0098	220	**0.1895	531	0.1073	13
T	–0.0039	920	–0.0377	419	**–0.0945	764	–0.1851	51
S	**–0.1695	920	**0.1518	419	**–0.2602	764	*–0.2615	51
DO_2	0.0119	920	–0.0221	419	**0.0816	764	–0.1478	51
SiO_2	–0.0454	920	**–0.1744	419	**–0.0897	764	0.0704	51
$P0_4$	0.0093	920	–0.0956	419	–0.0528	764	0.1438	51
NO_3	–0.0218	920	–0.0617	419	**–0.1758	764	0.1011	51

6.3.2 Comparison with water mass properties

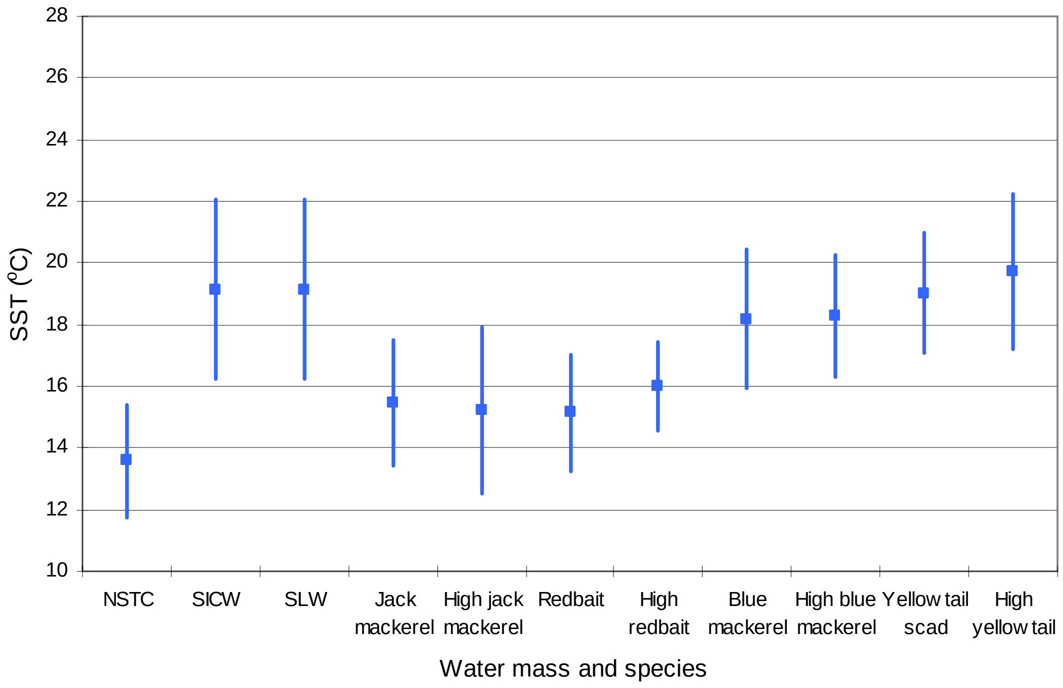
The means and ranges of SST and at-depth temperatures of jack mackerel and redbait capture locations were similar. Those of blue mackerel and yellowtail scad locations (Fig 24a & b) were also similar to each other but were higher than those of jack mackerel and redbait were. The ranges of “high catch” of both jack mackerel and redbait were much narrower than their respective overall ranges, while those of yellowtail and blue mackerel were only slightly less broad.

At-depth temperature means and ranges for jack mackerel and redbait were also similar to the mean of, and fell within the range of, the Northern Subtropical Convergence (NSTC). Means and ranges for blue mackerel and yellowtail scad were slightly higher and broader than those for the NSTC were but the means were not as high as those for the South Indian Central Water (SICW) or the Subtropical Lower Water (SLW) were. The SST values of all species capture locations were naturally higher than those of the water masses were because the values were the averages at 100m and not directly comparable. However, if a mixed layer depth of up to 80m in summer is assumed, the SST would be not much greater than 0.4 °C higher than the values at 100m that we are depicting (Condie and Dunn 2006).

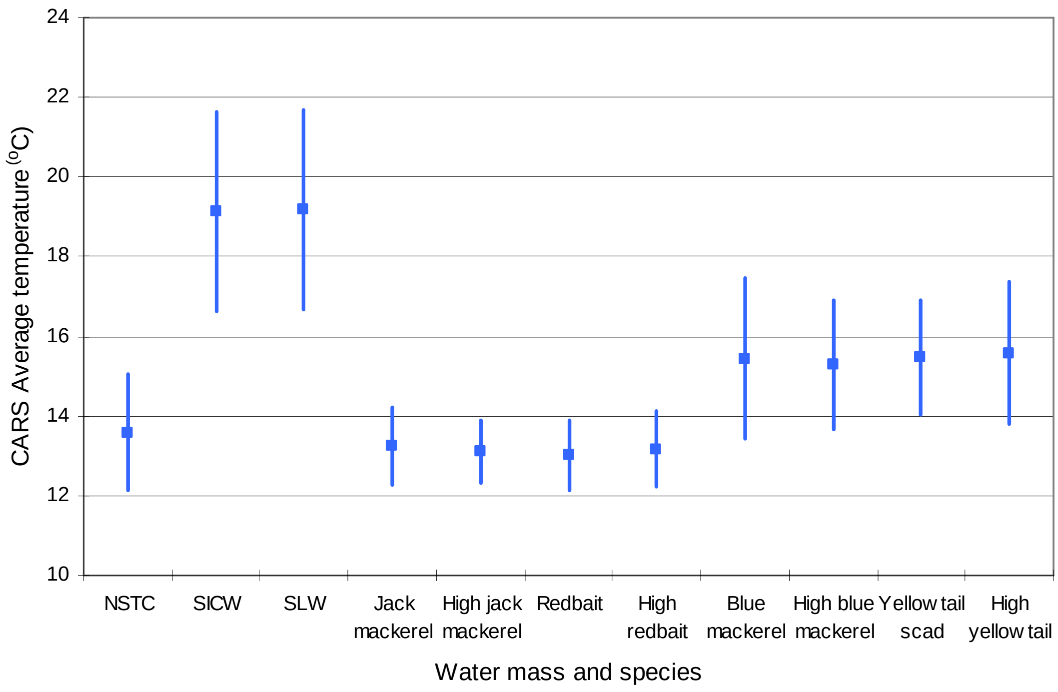
The overall ranges of SST and at-depth temperatures for blue mackerel were similar to those of jack mackerel. However, the “high catch” range was broader and the means higher for blue mackerel than those of jack mackerel. Similarly, the ranges of temperature of yellowtail scad catch locations fell within the range of the overall jack mackerel locations but the means were higher.

The mean salinity and oxygen values for jack mackerel and redbait catch locations were clearly similar to that of the NSTC water mass while those of blue mackerel and yellowtail scad were similar to those of SICW and SLW water masses (Fig 25a & b). The ranges for the high catches of redbait and jack mackerel were very narrow and barely overlapped the ranges of the warmer water masses. The range of salinities of blue mackerel catch locations was larger and overlapped those of all water masses. The range of salinities of yellowtail scad locations was narrow but still overlapped all water masses ranges.

The ranges of oxygen values at-depth of capture locations for most species were broad and overlapped those ranges of all the water masses. However, there were no significant catches of yellowtail scad in NTSC water.

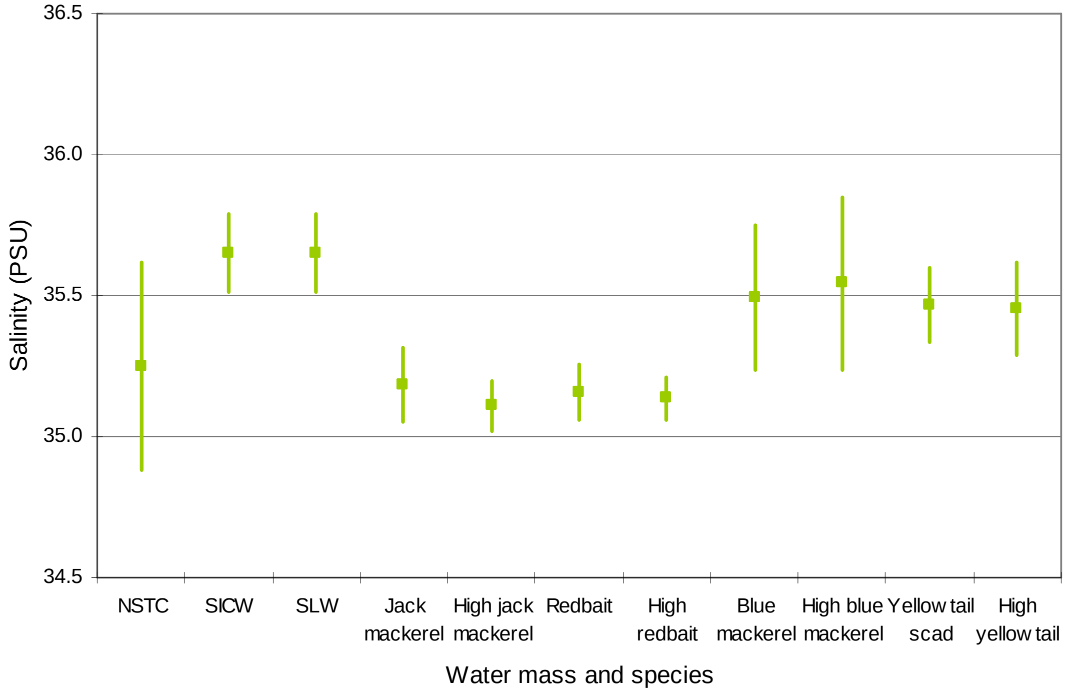


(a)

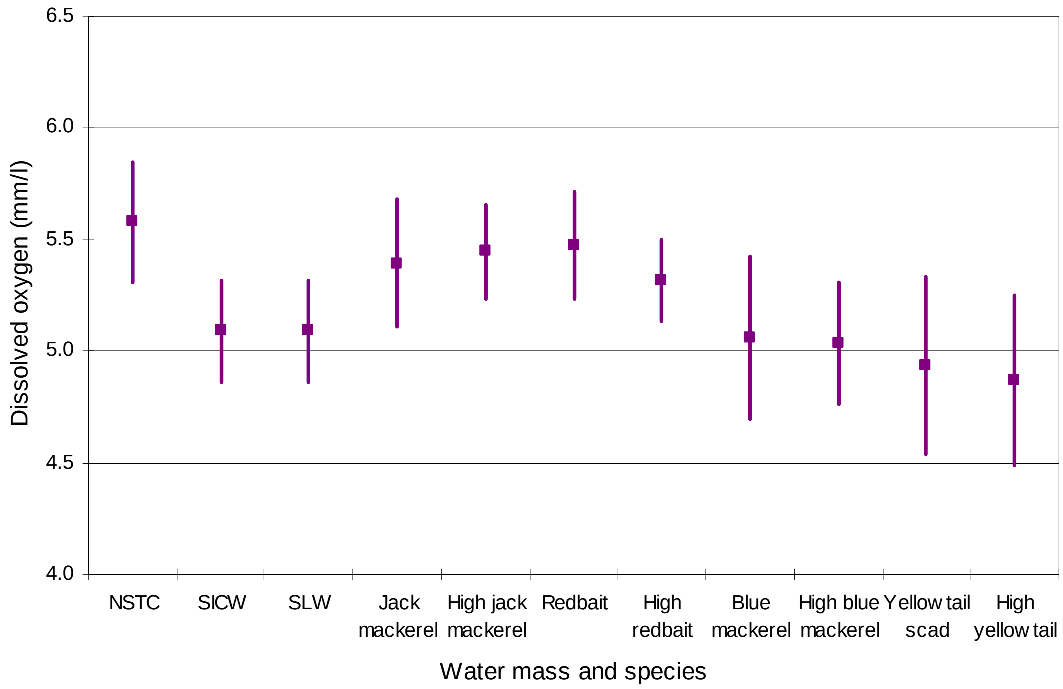


(b)

Figure 24. Mean (±SD) of (a) SST 6-day composite and (b) climatology (averaged) temperatures at capture depth for locations of all and high tonnage catches of small pelagic fishes compared to temperature means (±SD) for the major water masses in southern Australia .Surface values for water masses were estimated by adding 0.4 °C to means and SD at 100m and (b) at 100m). NSTC = Northern Subtropical Convergence, SICW = South Indian Central Water, SLW = Subtropical Lower Water.



(a)



(b)

Figure 25. Mean (±SD) of average (a) salinity and (b) oxygen values at capture depths for locations of overall and high catches of small pelagic fishes compared to salinity and oxygen means (±SD) for the major water masses in southern Australia (as at 100m). NSTC = Northern Subtropical Convergence, SICW = South Indian Central Water, SLW = Subtropical Lower Water.

In summary, the salinity preference ranges of the capture locations of redbait and jack mackerel discriminate the salinity range of the capture locations from those of the other two species and SICW and SLW water masses (Table 5). Yellowtail scad were more abundant in the SICW and SLW and the oxygen profile of the capture locations discriminated them from the NTSC water mass. Blue mackerel were also more abundant in the SICW and SLW but were also tolerant of NTSC water. No water properties discriminate capture locations of blue mackerel.

Table 5. Summary of water mass associations and most discriminant property for small pelagic species.

Species	*Water mass preference*	*Most discriminating property*
Redbait	NSTC	salinity
Blue mackerel	SICW, SLW, NSTC	
Jack mackerel	NSTC	salinity
Yellowtail scad	SICW, SLW	oxygen

6.3.3 Redbait

Catch and distribution

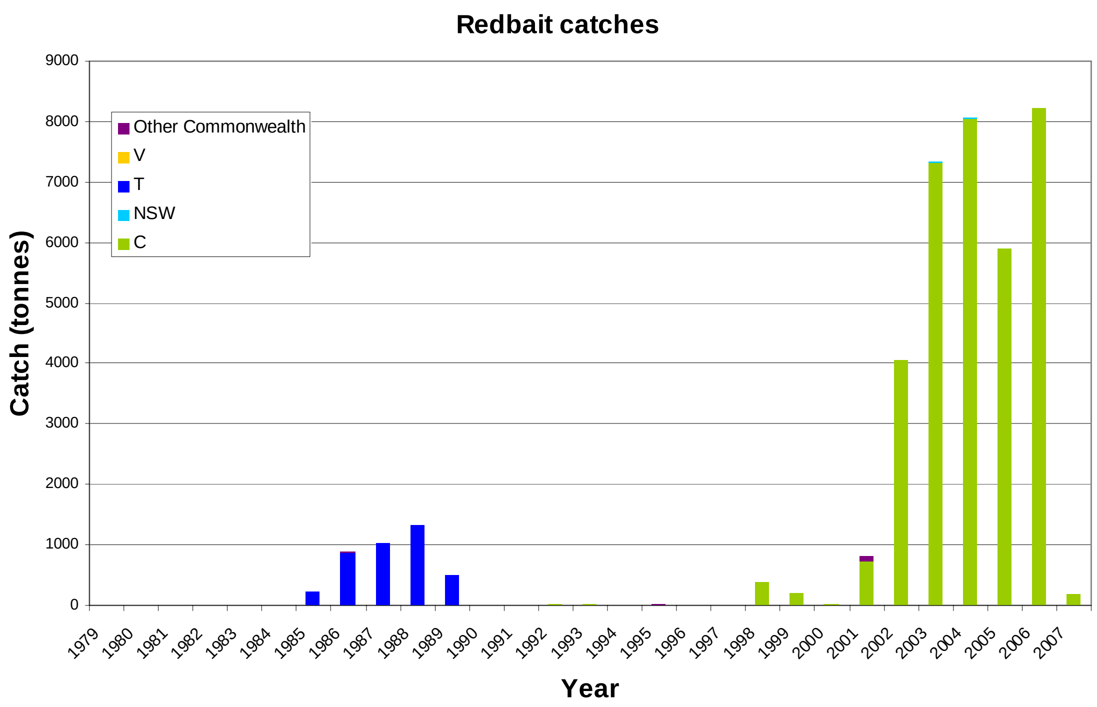


Figure 26. Annual Australian redbait catch by calendar year, including insignificant catches of maray from NSW ocean haul fishery, which were not identified separately. N.B. incomplete for 2007.

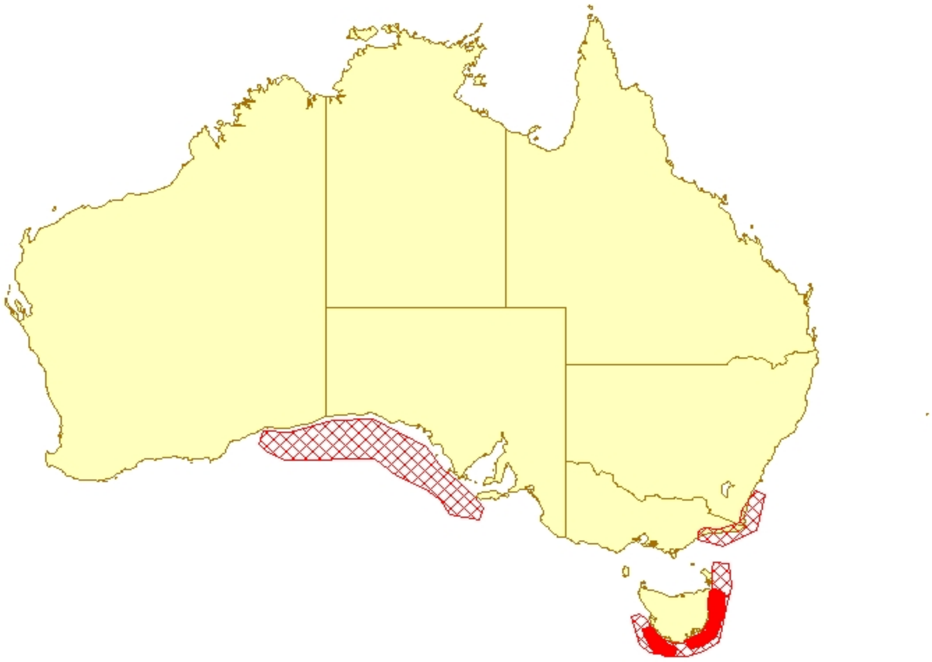


Figure 27. Catch distribution (hatched area) of redbait in the SPF across all jurisdictions (except WA). Red=areas of highest catch rates.

Environmental preferences

The second highest number of records were obtained for redbait (n = 921). The highest catches were caught around Tasmania (Figs 26 & 27). The catches were categorised into three sizes: >100 t, <11–100 t and ≤10 t. The highest catch category had a narrow range of water property values but this might be partly due to the smaller number sampled in this category. The overall means were not particularly different from the means of the high catch category (Table 6). The temperature at depth of capture and SST (Fig 28), chlorophyll *a*, silicate and phosphate were slightly higher than for other categories. Means for nitrate, oxygen, and salinity were lower. However, none of the correlations or regressions was significant.

If we consider the range of water properties as a core distribution, the properties largely corresponds with waters of the Northern Subtropical Convergence lying between Tasmania and New Zealand and is probably the core of the Tasman Sea. It is formed and subducted in the Subtropical Convergence and is cooler and fresher than the water north of the Tasman Front. In the WA/GAB region, this broad band of water meanders past southern Australia and Tasmania, which influence the energetics of the water mass. Increased energetics along the south-west coast are caused by the narrowing of the water band by Cape Leeuwin and on the east and south coast of Tasmania by Tasmania. The substructure of this water masses suggest that the band terminates in a mixed region around Tasmania, but a part of it continues into the Tasman Sea.

This strongly suggests that the core distribution of redbait lies in Tasmanian and Victorian waters but it is not limited to those waters. The range of water property values for redbait also overlap those of the adjoining water masses although only slightly for the temperature and salinity ranges perhaps suggesting this species has a slightly more restricted range of distribution than jack mackerel (Fig 24 and 25). The overall mean SST was 15.1 °C and while the regression was significant ($p = 0.007$) the fit was very poor ($R^2 = 0.007$). Higher values of chlorophyll *a* were correlated with higher catches. High catches in summer months off southeastern Tasmania correspond with high average concentrations chlorophyll (and see Fig 3, November and March).

Table 6. Descriptive statistics of redbait catches and corresponding environmental variables.

Catch category (t)	*Statistic*	*Catch (kgs)*	*Modelled temper-ature at depth of capture (°C)*	*SST 6-day composite*	*Chloro -phyll a*	*T °C*	*Salinity PSU*	*DO_2*	*SiO_2*	*$P0_4$*	*NO_3*
All	Mean	38062	13.262	15.135	0.425	13.007	35.157	5.475	2.224	0.563	5.667
	Standard Error	972	0.035	0.063	0.013	0.029	0.003	0.008	0.018	0.004	0.051
	Standard Deviation	29512	1.046	1.886	0.381	0.893	0.097	0.238	0.557	0.117	1.540
	Range	209975	6.182	10.305	6.553	5.14	0.782	1.2	2.8	0.8	10.9
	Minimum	25	10.826	10.775	0.081	10.63	34.754	5	0.7	0.2	1.5
	Maximum	210000	17.008	21.08	6.635	15.77	35.536	6.2	3.5	1	12.4
	n	921	911	903	823	920	920	920	920	920	920
>100	Mean	128476	13.490	16.001	0.477	13.160	35.136	5.314	2.395	0.586	5.362
	Standard Error	5331	0.239	0.320	0.063	0.209	0.017	0.040	0.122	0.029	0.368
	Standard Deviation	24429	1.096	1.465	0.266	0.956	0.077	0.182	0.560	0.131	1.687
	Range	102000	3.280	4.739	0.905	2.73	0.252	0.5	2	0.4	4.3
	Minimum	108000	11.573	13.303	0.257	11.44	35.004	5.1	1.4	0.4	4
	Maximum	210000	14.853	18.042	1.162	14.17	35.256	5.6	3.4	0.8	8.3
	n	21	21	21	18	21	21	21	21	21	21
11–100t	Mean	45713	13.191	14.844	0.435	12.981	35.148	5.495	2.215	0.566	5.769
	Standard Error	856	0.041	0.065	0.017	0.034	0.003	0.009	0.021	0.004	0.058
	Standard Deviation	22363	1.061	1.698	0.419	0.889	0.086	0.236	0.558	0.117	1.507
	Range	89000	6.182	8.562	6.517	4.75	0.688	1.2	2.8	0.8	10.2
	Minimum	11000	10.826	10.775	0.117	10.63	34.754	5	0.7	0.2	2.2
	Maximum	100000	17.008	19.338	6.635	15.38	35.442	6.2	3.5	1	12.4
	n	683	675	676	626	682	682	682	682	682	682
<10t	Mean	5232	13.460	16.000	0.386	13.074	35.186	5.427	2.236	0.550	5.375
	Standard Error	241	0.066	0.153	0.016	0.061	0.008	0.016	0.037	0.008	0.108
	Range	9975	5.866	10.023	1.384	4.94	0.779	1	2.8	0.8	10.9
	Minimum	25	11.122	11.057	0.081	10.83	34.757	5	0.7	0.2	1.5
	Maximum	10000	16.987	21.080	1.466	15.77	35.536	6	3.5	1	12.4
	n	217	215	206	179	217	217	217	217	217	217

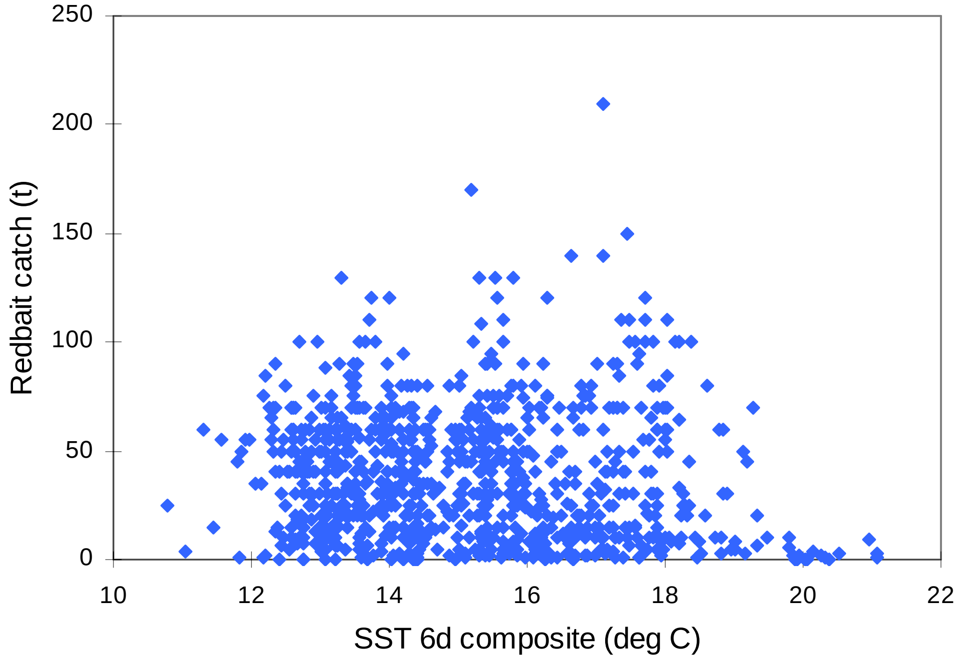


Figure 28. Sea surface temperatures (SST) at capture locations of redbait.

6.3.4 Blue mackerel

Catch and distribution

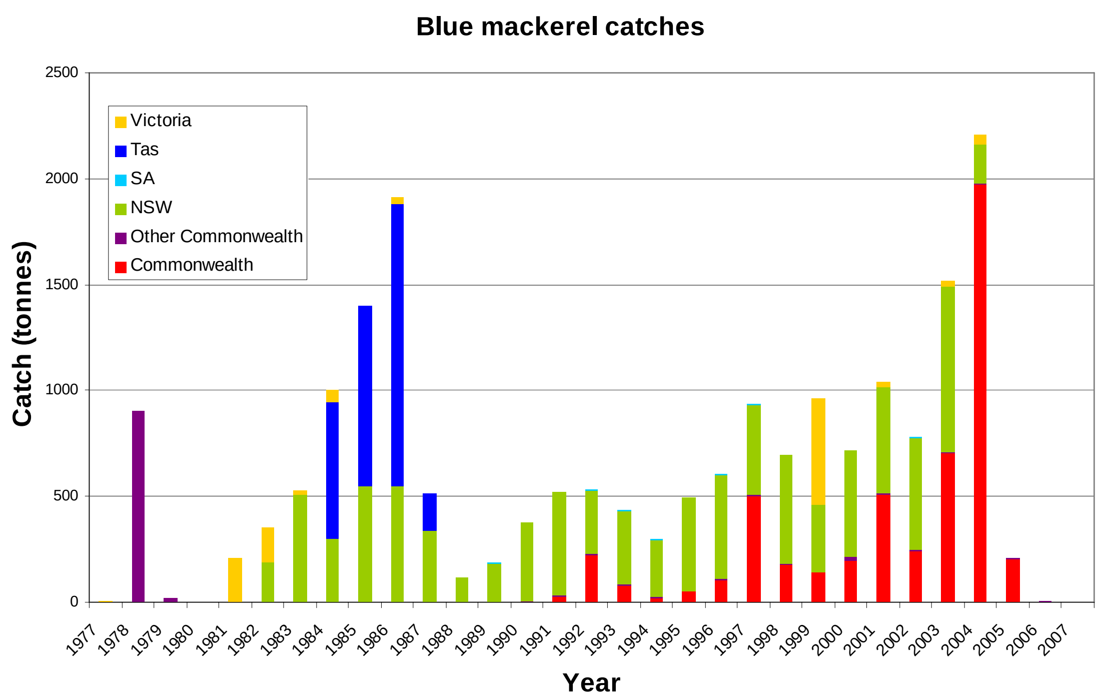


Figure 29. Annual Australian catch of blue mackerel (not including WA).

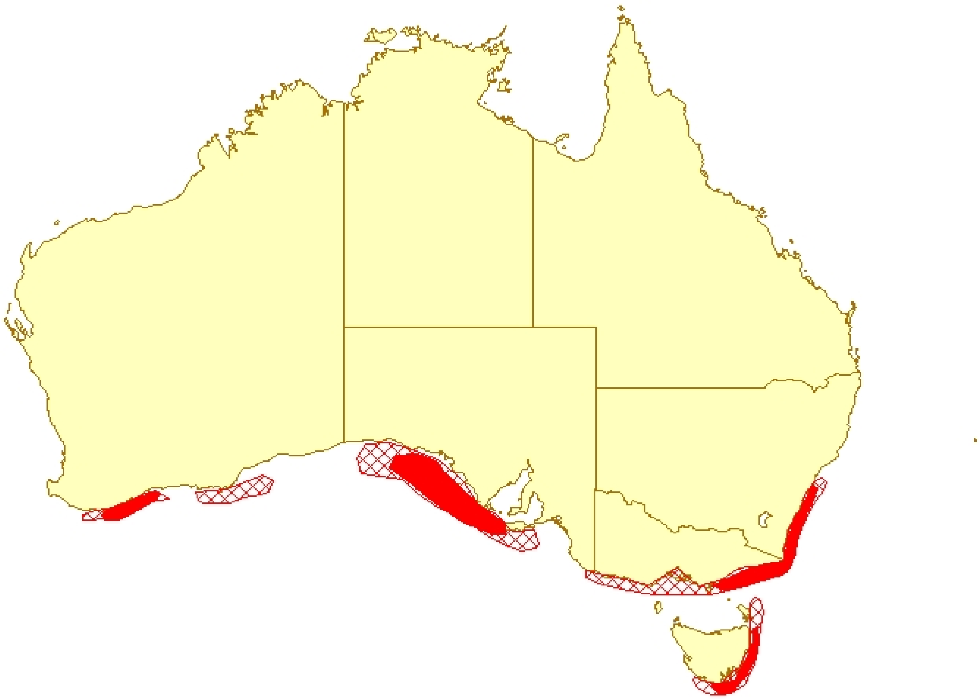


Figure 30. Catch distribution (hatched area) of blue mackerel in the SPF across all jurisdictions (except WA).

Environmental differences

A total of 410 records was obtained for blue mackerel. Highest catches are spread across southern Australia but NSW has contributed mostly to overall catches (Figs 29 & 30). The catches were categorised into three sizes: >10 t, 1–10 t and ≤1 t. The overall means were not particularly different from the means of the high catch category (Table 7). The temperature at depth of capture, SST (Fig 31), and nitrate were in fact in between the means of the lower catch categories. The areas of highest catches appear to be in areas of high chlorophyll *a* concentration seasonally although they are not significantly correlated. Means for salinity were also slightly higher and means for silicates and phosphates were lower. Not surprisingly, none of the correlations or regressions was significant.

The ranges of the water property values for blue mackerel catches suggest that the species could tolerate the water mass of the Northern Subtropical Convergence similarly to redbait and jack mackerel. However, the mean temperature-at-depth was two degrees higher and the SSTs associated with the locations of blue mackerel catches, i.e. 18.2 °C, were also 2–3 °C higher than for those of jack mackerel and redbait. Therefore, while this species has been caught in a broader range of water properties, the SSTs suggest that its core distribution is more aligned with South Indian Central Water and Subtropical Lower Water but is able to tolerate the cooler waters of Tasmania seasonally.

Table 7. Descriptive statistics of blue mackerel catches and corresponding environmental variables.

Catch category (t)	*Statistic*	*Catch (kgs)*	*Modelled temper-ature at depth of capture (°C)*	*SST 6-day composite*	*Chloro-phyll a*	*T °C*	*Salinity PSU*	*DO_2*	*SiO_2*	*$P0_4$*	*NO_3*
All	Mean	11459	15.622	18.175	0.355	15.441	35.493	5.060	2.273	0.426	3.685
	Standard Error	841	0.103	0.115	0.015	0.098	0.013	0.018	0.043	0.011	0.129
	Standard Deviation	17191	2.068	2.238	0.226	2.010	0.259	0.361	0.890	0.215	2.637
	Range	90000	10.121	15.705	1.610	9.09	1.32	1.8	4	0.9	12.2
	Minimum	0	11.258	8.273	0.114	10.8	34.754	4.2	0.7	0.1	0.2
	Maximum	90000	21.379	23.979	1.724	19.89	36.074	6	4.7	1	12.4
	n	420	403	378	220	419	419	419	419	419	419
>10	Mean	30807	15.504	18.275	0.364	15.299	35.544	5.033	2.101	0.407	3.603
	Standard Error	1619	0.137	0.174	0.026	0.141	0.026	0.024	0.066	0.017	0.195
	Standard Deviation	18738	1.583	1.964	0.260	1.631	0.305	0.274	0.762	0.194	2.255
	Range	78000	7.353	9.969	1.599	7.52	1.32	1.6	3.2	0.9	11.3
	Minimum	12000	11.258	12.711	0.125	10.8	34.754	4.4	0.9	0.1	1.1
	Maximum	90000	18.610	22.680	1.724	18.32	36.074	6	4.1	1	12.4
	n	135	134	127	100	134	134	134	134	134	134
1–10	Mean	4683	15.198	17.601	0.345	14.848	35.423	5.125	2.283	0.454	4.126
	Standard Error	251	0.171	0.228	0.025	0.162	0.024	0.031	0.070	0.017	0.216
	Standard Deviation	2814	1.917	2.388	0.197	1.823	0.270	0.351	0.789	0.190	2.430
	Range	8910	10.079	13.737	0.982	8.85	1.195	1.7	3.6	0.9	12.1
	Minimum	1090	11.300	8.273	0.114	10.83	34.757	4.3	0.7	0.1	0.3
	Maximum	10000	21.379	22.010	1.096	19.68	35.952	6	4.3	1	12.4
	n	126	125	110	61	126	126	126	126	126	126
≤1	Mean	400	16.101	18.534	0.348	16.032	35.506	5.032	2.411	0.420	3.404
	Standard Error	25	0.196	0.192	0.025	0.180	0.015	0.034	0.082	0.020	0.241
	Standard Deviation	320	2.470	2.275	0.193	2.274	0.187	0.423	1.035	0.248	3.034
	Range	1000	9.023	11.219	1.092	7.78	0.776	1.5	4	0.8	7.4
	Minimum	0	12.217	12.760	0.128	12.11	35.127	4.2	0.7	0.1	0.2
	Maximum	1000	21.240	23.979	1.220	19.89	35.903	5.7	4.7	0.9	7.6
	n	159	144	141	59	159	159	159	159	159	159

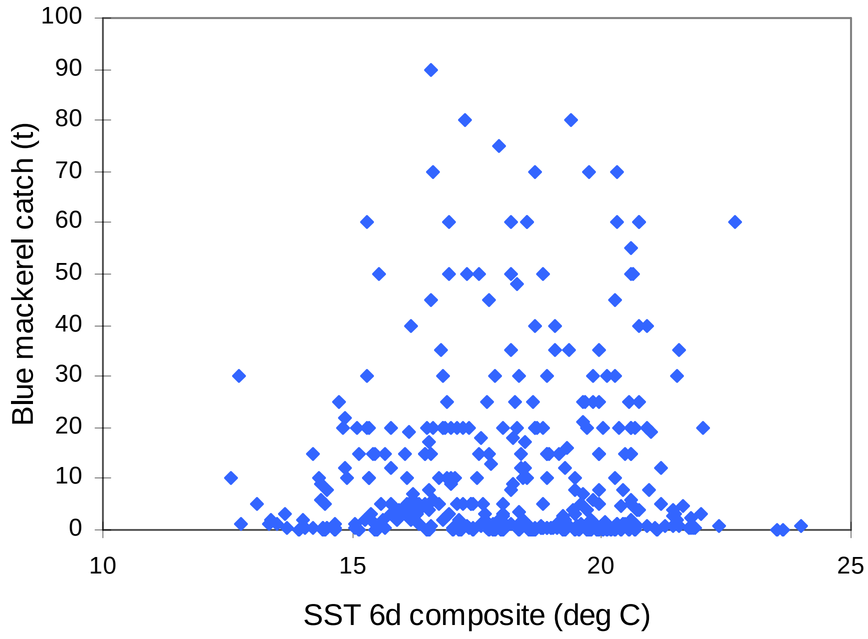


Figure 31. Sea surface temperatures (SST) at capture locations of blue mackerel.

6.3.5 Jack mackerel

Catch and distribution

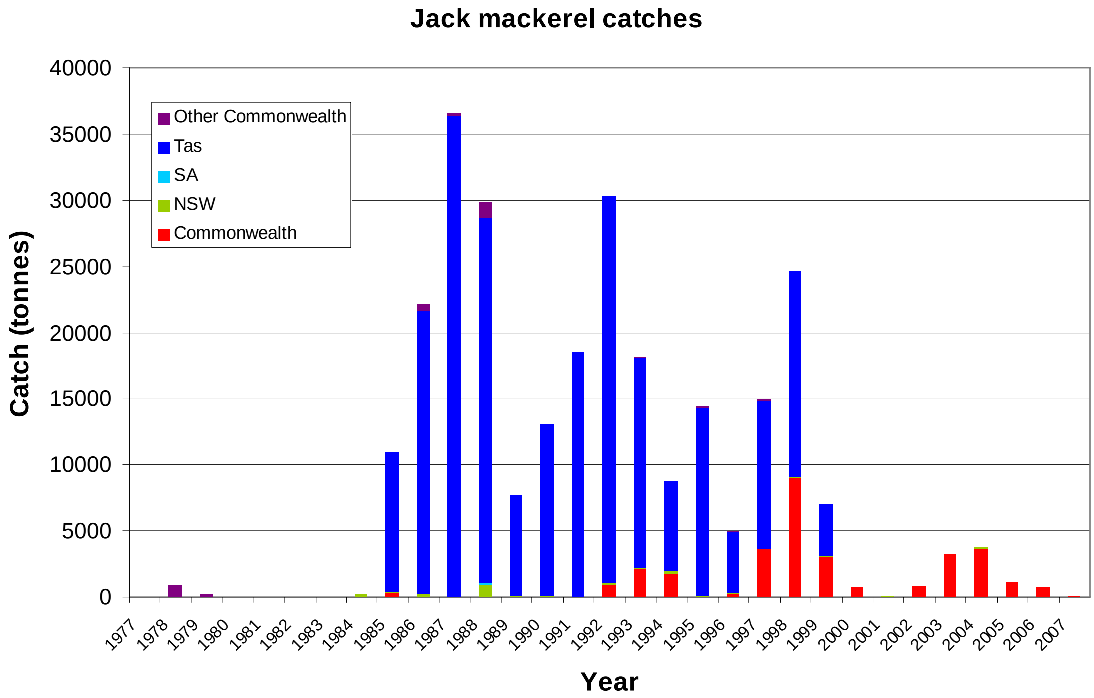


Figure 32. Annual Australian catches of jack mackerel from Commonwealth, NSW, Victorian, Tasmanian, and South Australian* data. *Maximum catch reported of 38 t in 1989 therefore SA data indistinguishable on chart.

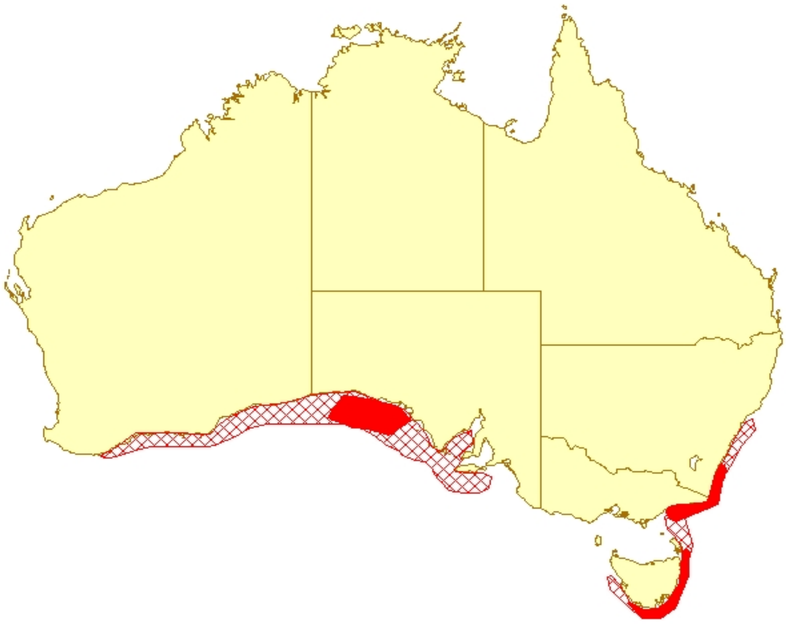


Figure 33. Catch distribution (hatched area) of jack mackerel in the SPF across all jurisdictions (except WA).Red areas are areas of highest catches.

Environmental preferences

This was the largest dataset with 765 catch records ranging in size from 0 to 250 t (Table 8). There were matching data for the majority of records. The catches were attributed by size and irrespective of time and location, into three categories: >100 t, 11–100 t, and ≤10 t. The largest size category had the lowest mean values of modelled temperature at depth value, SST (Fig 34), CARS temperature-, salinity-, silicate-, phosphate- and nitrate- at depth of capture and the highest dissolved oxygen at depth and chlorophyll *a* values. The mean values of the other categories fell within the standard deviation of the means of the “high catch” (>100 t) group. The ranges of values of the “high catch” category are narrower. While the regression of catch size against temperature at depth was significant (p = 0.008), the fit was very poor (R^2 = 0.0078).

Overall, the catch data (Figs 32 and 33) and associated environmental data strongly suggests that the core distribution of jack mackerel lies in Tasmanian and Victorian waters, but it is not limited to those areas. The overall ranges of the water properties i.e. from all catch locations and properties is quite broad and encompass at least part of the range of properties of the adjoining water masses of the Indian Central region and Subtropical Lower Water (Fig 24 and 25). As for redbait, higher values of chlorophyll *a* were correlated with higher catches. High catches in summer and autumn months off southeastern Tasmania correspond with high average concentrations chlorophyll *a*, which contract to the inshore shelf, and embayments in autumn (see Fig 3, November and February).

Table 8. Statistics of jack mackerel catches and corresponding environmental variables.

Catch category (t)	*Statistic*	*Catch (kgs)*	*Modelled temperature at depth of capture (°C)*	*SST 6-day composite*	*Chlorophyll a*	*T °C*	*Salinity (PSU)*	*DO_2*	*SiO_2*	*$P0_4$*	*NO_3*
All	Mean	34393	13.453	15.409	0.402	13.251	35.181	5.395	2.253	0.551	5.331
	Standard Error	1388	0.041	0.076	0.010	0.035	0.005	0.010	0.018	0.004	0.052
	Standard Deviation	38391	1.114	2.053	0.223	0.973	0.132	0.282	0.511	0.103	1.438
	Range	250000	10.246	21.364	1.609	8.03	1.144	1.8	3.6	0.9	12
	Minimum	0	10.933	2.286	0.115	10.8	34.754	4.2	0.7	0.1	0.4
	Maximum	250000	21.179	23.650	1.724	18.83	35.898	6	4.3	1	12.4
	Count	765	754	724	531	764	764	764	764	764	764
>100	Mean	140016	13.272	14.810	0.549	13.117	35.111	5.447	2.088	0.522	4.545
	Standard Error	4703	0.110	0.409	0.053	0.111	0.013	0.030	0.031	0.008	0.132
	Standard Deviation	32924	0.760	2.710	0.259	0.776	0.089	0.210	0.214	0.055	0.923
	Range	145000	2.899	14.967	1.000	2.87	0.413	0.9	1.1	0.2	3.8
	Minimum	105000	12.003	2.286	0.236	11.98	34.975	5	1.5	0.4	3.2
	Maximum	250000	14.902	17.253	1.236	14.85	35.388	5.9	2.6	0.6	7
	Count	49	48	44	24	49	49	49	49	49	49
11-100	Mean	41708	13.358	15.359	0.403	13.199	35.164	5.409	2.244	0.552	5.277
	Standard Error	1149	0.044	0.094	0.014	0.038	0.006	0.012	0.020	0.004	0.064
	Standard Deviation	23984	0.910	1.911	0.235	0.798	0.118	0.246	0.411	0.089	1.336
	Range	88000	6.151	17.424	1.607	5.57	1.144	1.5	2.3	0.7	11.2
	Minimum	12000	10.933	3.181	0.117	10.8	34.754	4.5	1.2	0.3	1.2
	Maximum	100000	17.083	20.604	1.724	16.37	35.898	6	3.5	1	12.4
	Count	436	427	414	295	435	435	435	435	435	435
≤10	Mean	4362	13.660	15.634	0.383	13.387	35.218	5.356	2.292	0.553	5.495
	Standard Error	221	0.084	0.128	0.013	0.073	0.009	0.020	0.038	0.007	0.096
	Standard Deviation	3761	1.421	2.118	0.194	1.236	0.149	0.335	0.655	0.127	1.630
	Range	10000	10.079	11.181	1.106	7.68	0.862	1.8	3.6	0.8	8.4
	Minimum	0	11.099	12.469	0.115	11.15	34.99	4.2	0.7	0.1	0.4
	Maximum	10000	21.179	23.650	1.220	18.83	35.852	6	4.3	0.9	8.8
	Count	290	289	275	215	290	290	290	290	290	290

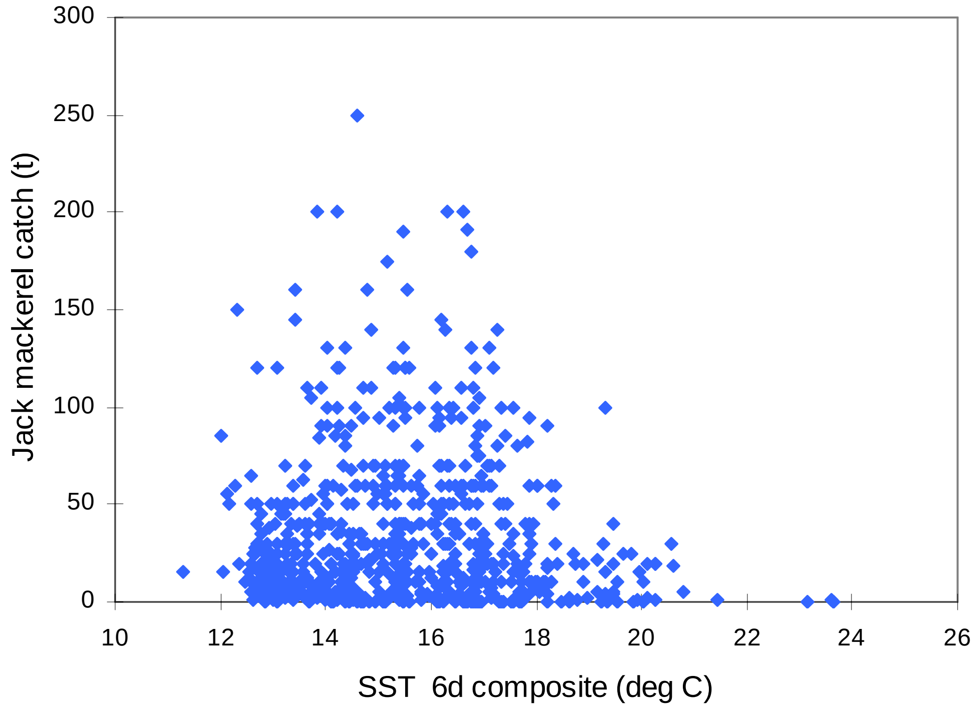


Figure 34. Sea surface temperatures (SST) at capture locations of jack mackerel.

6.3.6 Yellowtail scad

Catch and distribution

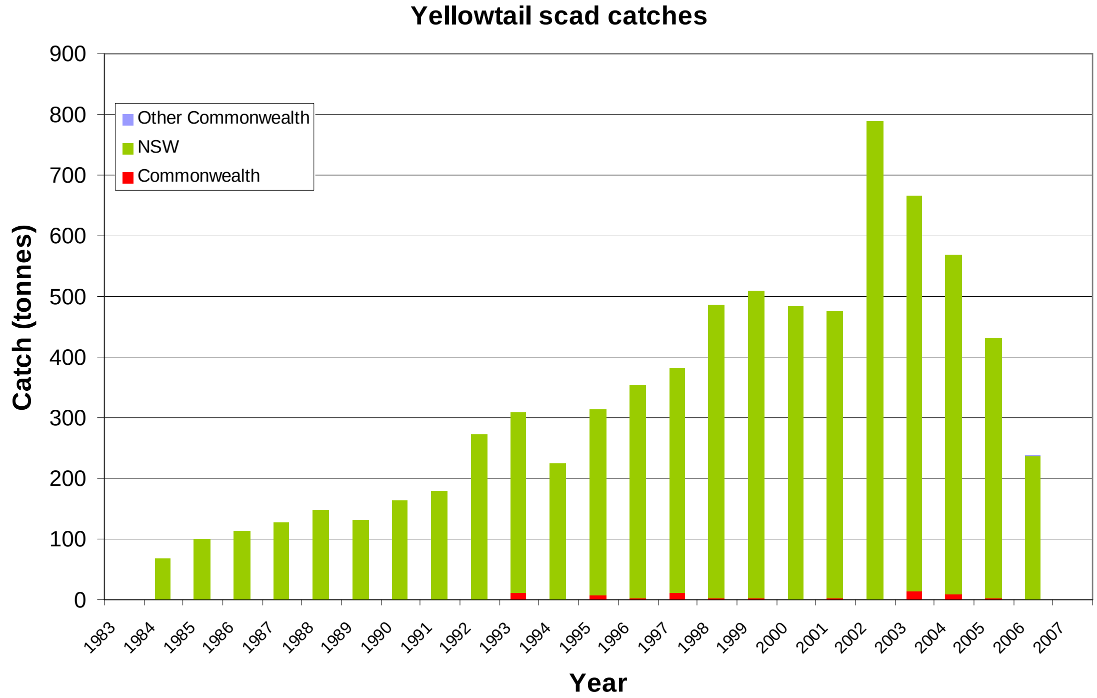


Figure 35. Annual Australian catches of yellowtail scad from Commonwealth, NSW, Victorian, Tasmanian, and South Australian* data.

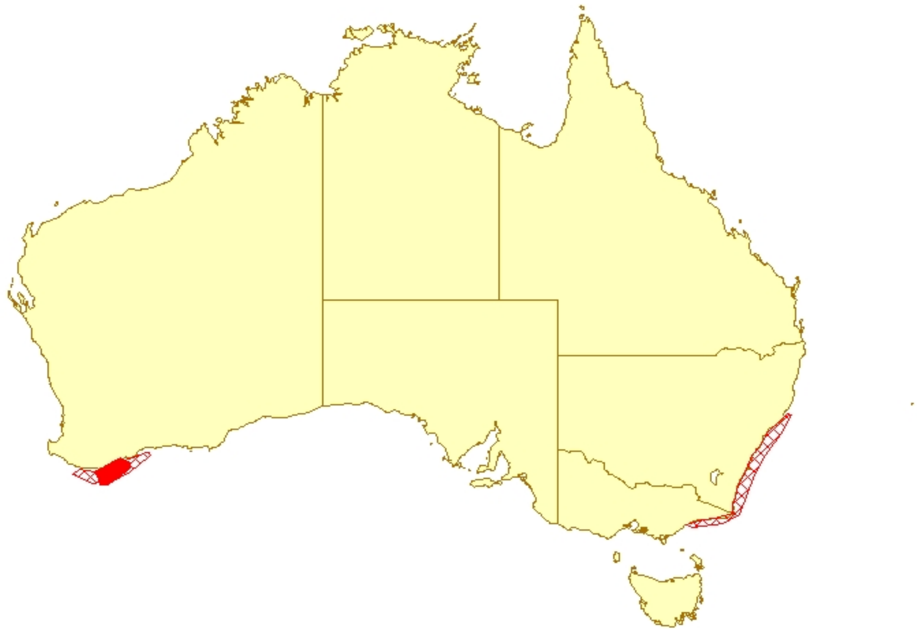


Figure 36. Catch distribution of yellowtail scad in the SPF across all jurisdictions (except WA).

Environmental preferences

There were few records for yellowtail scad (n = 51, Table 9) and the likelihood of obtaining any significant correlation much less likely. The catches were also smaller and only two size categories were used: >1 t and ≤1 t. Most of the catches were from NSW and WA (Figs 34 & 35). The means of the water properties were not very different nor were the ranges for most. The chlorophyll *a* mean was slightly higher for catches over 1 t and the range was much smaller. The regression against water temperature at depth was not significant. The mean SST (Fig 36) associated with the highest catches was the highest of all species at 19.7 °C. There were no significant correlations of catch with any environmental variable, although a correlation with salinity was almost significant.

The overall means of modelled temperatures and salinities for yellowtail scad are higher than those for jack mackerel and more analogous with the water properties of the Subtropical Lower Water region and the South Indian Central Water Mass. All water property values fall within the ranges for these water masses. Combined with the high SST mean values, this apparent preference range is consistent with the major distribution of yellowtail scad catches from NSW and the southwest of WA, and lack of sightings in Tasmania.

Table 9. Descriptive statistics of yellowtail scad catches and corresponding environmental variables.

Catch category (t)	*Statistic*	*Catch (kgs)*	*Modelled temper-ature at depth of capture (°C)*	*SST 6-day composite*	*Chloro-phyll a*	*T °C*	*Salinity PSU*	*DO_2*	*SiO_2*	*PO_4*	*NO_3*
All	Mean	873	15.946	19.018	0.396	15.466	35.465	4.937	2.982	0.500	4.635
	Standard Error	160	0.234	0.293	0.079	0.200	0.019	0.055	0.156	0.032	0.418
	Standard Deviation	1144	1.602	1.941	0.284	1.429	0.133	0.395	1.117	0.231	2.988
	Range	5990	6.617	9.010	1.069	5.5	0.491	1.5	3.6	0.7	7.1
	Minimum	10	13.581	14.881	0.151	13.25	35.236	4.2	1.1	0.2	0.4
	Maximum	6000	20.199	23.890	1.220	18.75	35.727	5.7	4.7	0.9	7.5
	Count	51	47	44	13	51	51	51	51	51	51
>1	Mean	2200	15.990	19.730	0.454	15.569	35.456	4.867	3.053	0.513	4.607
	Standard Error	349	0.484	0.696	0.088	0.460	0.042	0.098	0.259	0.062	0.680
	Standard Deviation	1351	1.810	2.509	0.177	1.781	0.164	0.379	1.001	0.242	2.634
	Range	4989	6.352	9.010	0.356	5.5	0.488	1.2	3.2	0.7	6.7
	Minimum	1011	13.847	14.881	0.282	13.25	35.239	4.2	1.5	0.2	0.5
	Maximum	6000	20.199	23.890	0.638	18.75	35.727	5.4	4.7	0.9	7.2
	Count	15	14	13	4	15	15	15	15	15	15
≤1	Mean	873	16.021	19.018	0.396	15.466	35.465	4.937	2.982	0.500	4.635
	Standard Error	160	0.220	0.293	0.079	0.200	0.019	0.055	0.156	0.032	0.418
	Standard Deviation	1144	1.572	1.941	0.284	1.429	0.133	0.395	1.117	0.231	2.988
	Range	5990	6.617	9.010	1.069	5.5	0.491	1.5	3.6	0.7	7.1
	Minimum	10	13.581	14.881	0.151	13.25	35.236	4.2	1.1	0.2	0.4
	Maximum	6000	20.199	23.890	1.220	18.75	35.727	5.7	4.7	0.9	7.5
	Count	51	51	44	13	51	51	51	51	51	51

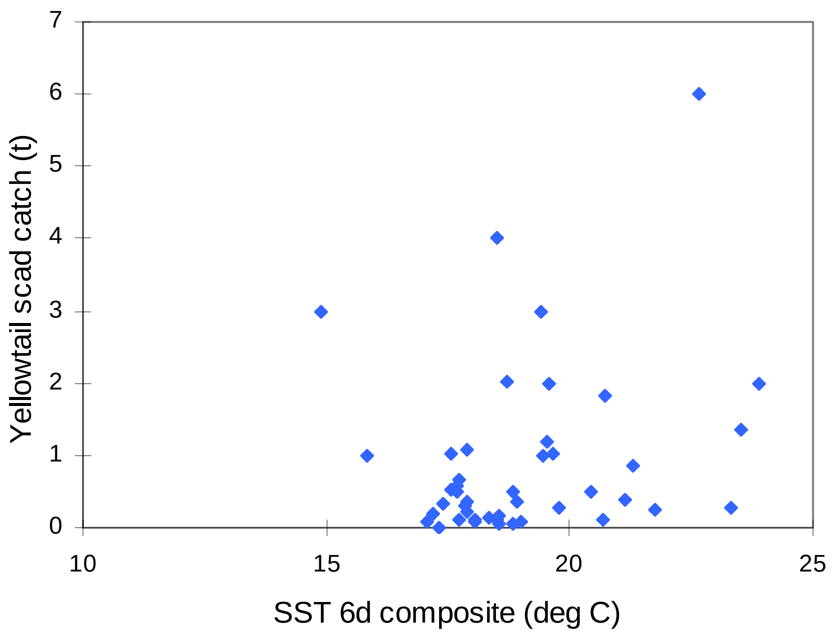


Figure 37. Sea surface temperatures (SST) at capture locations of yellowtail scad.

6.4 Conclusions

Redbait

The ichthyoplankton survey results indicate that redbait eggs and larvae are associated with the cooler water of the Northern Subtropical Convergence that is a dominant feature of eastern Tasmania and southern NSW during late winter-spring. An analysis of depth-at-capture of the egg and larvae data by TAFI is underway and should reveal spawning-related preferences. Preference for the cooler water masses around Tasmania is reflected by their catch distribution although the analysis was heavily biased by the commercial sampling.

Large redbait off Tasmania venture onto the outer shelf, shelf break and beyond to feed on mesopelagic species such as lanternfish and carid prawns. However, the majority of redbait are confined to the shelf where they are subject to incursions of the EAC water moving onto the Tasmanian shelf in summer and autumn when they feed on copepods and to the sub-Antarctic water mass in winter when they feed on krill.

There are no stock structure studies on redbait, to discriminate possible stocks however, their distribution (and catch distribution) and the implications of their apparent water property preferences suggest they are largely restricted to the Northern Subtropical Convergence water mass and possibly to a sub-region (L2–17: NMBA 2005) within that mass that more or less surrounds Tasmania. While this may limit their distribution, it does not necessarily define stock structure.

Blue mackerel

The distribution of blue mackerel in Australia suggests that it is generally associated with the warmer temperate water masses of the Subtropical Lower Water (and the EAC) and the South Indian Central Water Mass. The range of water property values e.g. temperature at depth and salinity, in locations where it has been caught is slightly broader than for the other species due to its presence in Tasmania seasonally. In Australia, blue mackerel spawn off northern NSW and southern Queensland from late winter and spring and in the GAB in summer and autumn.

Stock structure studies of blue mackerel strongly suggest that there are separate east and west stocks. The fact that there was no apparent definition between Queensland and NZ samples and the broad and seasonal distribution in southern Australia suggest that finer resolution of stocks is unlikely and a degree of mixing probably occurs.

Jack mackerel

The highest abundances of jack mackerel occur historically off eastern Tasmania, suggesting a preference for the cooler water. Aerial spotting surveys during the mid-1970s seldom found jack mackerel schooling in surface water above 17 °C (Williams 1981). Fish were generally sighted in larger numbers off NSW in late winter–early spring when SST were 13–15 °C (but up to 17 °C in some years) and tended to be sighted further south in subsequent months giving rise to the hypothesis of north-south-north migrating fish stocks. Schooling jack mackerel were sighted off western Victoria in summer-autumn at the same time as fish were sighted off Tasmania and were presumed to represent separate east and western stocks (Williams 1981). High jack mackerel larval abundances in western Bass Strait were presumed to represent the South Australian stock as opposed to an eastern Australian stock.

Jack mackerel were thought to spawn when water temperature reaches 17 °C as the EAC moves south (Neira *et al.* 2007), but Jordan (1992) found that jack mackerel spawned at consistent times irrespective of the SST, in the cooler water usually beneath the EAC thus the correlation with 17 °C SST maybe coincidental rather than causal. Larvae in western Bass Strait were found in highly stratified waters below the thermocline in 14–16 °C.

Stock structure studies have suggested that there are east and west subpopulations of jack mackerel. There was an early suggestion of a split in the eastern population, however, more recent observations, particularly those in the Tasmanian fishery, do not support this hypothesis. Without more definitive studies on jack mackerel from western Tasmania and western Victoria, at times when they occur there, we cannot be sure of stock affiliation, i.e. whether the fish belong to a GAB population or an eastern population.

Therefore, similarly to redbait, jack mackerel are attuned with the cooler waters of the Northern Subtropical Convergence water mass in the Tasman Sea that are the dominant feature of eastern Tasmania and southern NSW during late winter-spring. Their distribution (and catch distribution) and the implications of their apparent water property preferences suggest they may prefer Tasmanian and Victorian waters. While this may limit their core distribution, it does not necessarily define their overall distribution or their stock structure.

Yellowtail scad

Yellowtail scad are distributed around southern Australia but not in Tasmania. Commercial fishers report that fish disappear from the southern NSW coast during winter when the SST fall below 13 °C and reappear when the SST reaches 17 °C in summer. The egg and larval surveys indicated that yellowtail scad may be more abundant along the Qld–northern NSW coast in the warmer (19.0–20.5 °C) and less saline waters (35.40–35.50 PSU) of the EAC. In New Zealand, *T. novaezelandiae* predominates in waters <150 m and warmer than 13 °C and is uncommon south of latitude 42°S.

Their distribution (and catch distribution) and the implications of their apparent water property preferences suggest they may prefer the warmer waters of the Subtropical Lower Water (and the EAC) and the South Indian Central Water. There are no conclusive stock structure studies on this species however based on their more northerly distribution it is likely that Tasmania and Bass Strait would present a significant barrier to a continuous population. On the other hand, the shallow waters of Bass Strait might not be as significant if the water temperatures were within a tolerable range. Focussed studies on stock structure would be useful.

Peruvian jack mackerel

Peruvian jack mackerel is an oceanic species that has a broad distributional range throughout the southern Pacific Ocean from South America to Australia and New Zealand within a 10–15° band. The South American populations mainly spawn north of 40°S in spring and summer and along the subtropical convergence between 36 and 42°S. Based on records of capture from the surveys in 1994–96 off southeast Australia, and assuming the specimens were captured close to the bottom, we can deduce that the fish were experiencing water temperatures of about 12–14 °C at 200 m indicative of nutrient-rich sub-Antarctic water (Bax *et al.* in Bax and Williams

2000). This water mass was particularly extensive during August–September 1994 when most of the specimens were caught. *T. murphyi* is generally recorded in catches with *T. declivis*; therefore, we could assume that their environmental preferences at least overlap if not entirely similar.

Stock structure studies generally indicate a broad population structure for this species off South America and throughout the Pacific. There appears to be no difference between fish caught in Australia and New Zealand and are presumed to be part of a southwest Pacific stock which straddles the high seas and both the New Zealand and Australian EEZs.

7. STOCK STRUCTURE HYPOTHESES AND RECOMMENDATIONS FOR MANAGEMENT ZONES

It is generally accepted that it is desirable that discrete or semi-discrete fish stocks are managed as separate units and that spatial management arrangements appropriately reflect stock delineation. This report has collated the available information on the potential stock structure of target species in the Commonwealth Small Pelagic Fishery. While it is acknowledged that stock structure is only one consideration in the determination of management arrangements including spatial management, the available information is discussed below in response to a number of key questions.

Do the existing SPF management zones reflect the likely stock structure of SPF species?

The current management arrangements for the SPF divide the area of the fishery into four zones (Fig 4,). There is little or no evidence to support a view that the existing management zones reflect stock delineation for SPF species. Indeed, there are some boundaries that are likely to 'split' unit stocks of one or more SPF species e.g., a single subpopulation of blue mackerel is likely to straddle the latitudinal boundary between SPF Zones A and D.

Does the evidence support a 'single stock' approach for SPF species?

While there is little direct evidence for stock delineation of redbait, there is good evidence to reject a single stock hypothesis for jack mackerel, blue mackerel and yellowtail scad. However, it should be noted that nearly all studies suffer from lack of good sampling coverage particularly in the western Tasmanian/Bass Strait region and Western Australia. The oceanography of southern Australia supports a probable separation between east and west with Tasmania and Bass Strait being a significant barrier to continuous distribution for several species.

Does the evidence support east and west subpopulations for any or all species?

Stock structure information for jack mackerel, blue mackerel and yellowtail scad and ichthyoplankton surveys for all SPF species support a hypothesis of separation of stocks for these species along a longtitudinal (i.e. east-west) boundary near Tasmania. The oceanography of southern Australia also supports a probable separation between east and west stocks. Tasmania and Bass Strait form a significant barrier to continuous distribution for SPF species other than redbait.

For SPF species other than redbait it seems appropriate to consider east and west populations as separate for management purposes. However, it should be noted that this barrier would not be absolute and hence there is likely to be genetic flow from one population to the other, either through Bass Strait and/or around the southern tip of Tasmania but the extent of the flow would be dependent on climatic and oceanographic conditions.

Bioregionalisation studies of shelf demersal fish show clear patterns of separation at Wilson’s Promontory (IMCRA 1998). Studies of sub-tidal macro fauna of the southern Australia also support this strong disjunction. Waters et al. (1995) found sharp biogeographical disjunction in the distribution of a highly mobile intertidal gastropod *Nerita atramentosa* in marked contrast to the species’ high dispersal abilities, and is consistent with other studies of coastal taxa of echinoderms and crustacea. They also proposed that the EAC and Leeuwin currents were responsible for maintaining the east-west disjunction.

Further research is required to determine whether or not there is separation of redbait into east and west stocks however fishers report a narrow discontinuity in sightings of redbait off southern Tasmania between Tasman Head and Maatsuyker Island (G. Geen [Seafish Tasmania Pty Ltd] 2007, pers. comm.) and this would support a possible separation of redbait stocks between east and west.

Does the evidence support further splitting of either east or west subpopulations for any or all species?

While there is no evidence to support further splitting of eastern populations of SPF species, otolith microchemistry results for blue mackerel suggest that there may be two western populations for blue mackerel (one off southern-western WA and another in the Bight). The oceanography of the region and bioregionalisation of demersal species also support a possible stock separation of SPF species off south-western Australia.

However, the exact location of a division here is less clear since any separation here is not caused by a fixed barrier and this combined with the annual variability in the oceanography would result in far less rigid separation. The National Marine Bioregionalisation of Australia project suggested a division in this region based on a distinct change in the demersal fish fauna, which is in agreement with the shelf currents in the region. However, this does not necessarily imply that distinct boundaries will prevail in the pelagic structure.

Further research would improve our understanding of potential stock delineation in the western areas of the fishery but given the oceanography in this area and the biology of SPF species, it is unlikely that it will be resolved in the short-term. Monitoring and assessment of the fishery based on spawner abundance e.g. using the Daily Egg-Production Method (Lyle and Neira: FRDC 2004/039) as an index of abundance would provide additional information to improve understanding of stock delineation in the SPF including in the west.

8. BENEFITS AND ADOPTION

The Australian Commonwealth Small Pelagics Fishery is the major beneficiary of this research. The Fishery has been managed in four zones, however it became obvious that the species distributions were such that allocation of effort and quota did not easily match their distributions, making management unnecessarily complicated and subject to error.

On 23 August 2007, draft results of the report were presented by the Principle Investigator to MAC and RAG members. Based on the preliminary results and discussions with members at the meeting, AFMA has redrafted the Plan to include an eastern and western zone divided at 146°30′E. At the meeting of 26 October 2007, James Findlay presented an overview of the report's stock structure hypotheses and recommendations on management zones. Subsequently, SPFMAC recommended that the fishery be managed as having stocks east and west of 146°30′E noting that:

• the evidence for a stock delineation for redbait at that point is not as strong as that for the other key species but that industry experience supports a separation;

• while there is some evidence that separate stocks occur in the far west of the fishery there is no strong basis upon which to recommend a meaningful boundary to further split the western zone. The MAC noted that as the fishery expands and more information comes to hand these uncertainties may be reduced; and

• rezoning of the fishery does not preclude the use of other spatial management measures as the fishery develops.

9. PLANNED OUTCOMES

The planned outcome of the project was to provide managers with an assessment of the current evidence pertaining to stock structure of the species of the Commonwealth Small Pelagics Fishery to assist the determination of a new spatial management structure. The proposed structure had to account for the underlying ecological and biological attributes of the managed species and therefore enable the fishery to be managed in an ecologically sustainable manner. In doing so, we took into account the uncertainty of the recommended strategies and recommend suitable research to address those uncertainties and to allow further evaluation of the range of management options. The very significant role of the small pelagics in the food webs of most Australian fin-fisheries emphasizes the importance of careful and appropriate management of this fishery for the benefit of all fisheries.

10. FURTHER DEVELOPMENT

Further research in the areas of stock discrimination would improve our understanding of potential stock delineation in the western areas of the fishery but given the oceanography in this area and the biology of SPF species, it is unlikely that short-term research would definitively resolve this uncertainty.

Monitoring and assessment of the fishery based on spawner abundance (e.g. use of a Daily Egg-Production Method as an index of abundance i.e. Lyle and Neira: FRDC 2004/039) would provide additional information to improve understanding of stock delineation in the SPF particularly in the west.

Future studies will need to consider the effects of climate change on the distribution of the species resulting from changes in water mass movements and location.

REFERENCES

AFMA (2004). Future Management of the Small Pelagic Fishery (Zones B, C & D). Australian Fisheries Management Authority, Canberra, Australia.

Avdeyev, V. V. (1992).On the possible uses of parasitic isopods as bioindicators of the migratory routes of horse mackerels in the Pacific Ocean. *Journal of Ichthyology* 32: 14-21.

Bailey, K. (1988). Description and surface distribution of juvenile Peruvian jack mackerel, Trachurus murphyi, Nichols from the subtropical convergence zone of the central South Pacific. *Fishery Bulletin* 87, 273-278.

Bax, N. J. and Williams, A. (Eds) (2000). Habitat and Fisheries Production in the Southeast Fishery Ecosystem. Project No 94/040. Final Report to the FRDC. (CSIRO, Hobart, Australia.)

Bax, N., Williams, A. and Davenport, S. (2000). Physical Oceanography. Pp 19-57. *In* Bax, N. J. and Williams, A. (Eds) "Habitat and Fisheries Production in the Southeast Fishery Ecosystem." Project No 94/040. Final Report to the FRDC. (CSIRO, Hobart, Australia.)

Bertrand, A., Barbieri, M. A., Córdova, J., Hernández, C., Gómez, F., and Leiva, F. (2004). Diel vertical behaviour, predator-prey relationships, and occupation of space by jack mackerel (*Trachurus murphyi*) off Chile. *ICES Journal of Marine Science* 61, 1105-1112.

Blaber, S. J. M. and Bulman, C. M. (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. (1951). Races and populations of the Australian pilchard *Sardinops neopilchardus* (Steindachner). *Australian Journal of Marine and Freshwater Research* 2, 179-92.

Brothers, N., Gales, R. and Pemberton, D. (1993). Prey harvest of the Australasian Gannet (*Sula serrator*) in Tasmania. *Wildlife Research* 20, 777-783.

Browne, A. (2005). "Changes in the growth and age structure of jack mackerel in south-east Australian waters". B.Sc. Thesis, University of Tasmania.

Bulman, C., Davenport, S., and Althaus, F. (2000) Trophodynamics. Pp 319-367. *In* Bax, N. J. and Williams, A. (Eds) "Habitat and Fisheries Production in the Southeast Fishery Ecosystem." Project No 94/040. Final Report to the FRDC. (CSIRO, Hobart, Australia)

Bulman, C. M., Althaus, F., He, X., Bax, N. and Williams, A. (2001). Diets and trophic guilds of demersal fishes of the southeastern Australian shelf. *Marine and Freshwater Research* 52, 537-548.

Bulman, C., Condie, S., Furlani, D., Cahill, M., Klaer, N., Goldsworthy, S. and Knuckey, I., (2006). 'Trophic dynamics of the eastern shelf and slope of the south east fishery: impacts of and on the fishery.' Final Report for FRDC Project 2002/028. (FRDC and CSIRO Marine and Atmospheric Research, Hobart, Australia.)

Bunce, A. and Norman, F. I. (2000). Changes is the abundance of the Australasian gannet (*Morus serrator)* in response to the 1998 mortality of pilchards (*Sardinops sagax*). Marine and Freshwater Research 51, 349-353.

Church, J. A. and Craig, P. D. 1998. Australia's shelf seas: diversity and complexity - coastal segment (30, W-S). In *The Sea,* Vol. 11, A. R. Robinson and K. H. Brink, (Eds). New York, pp. 933-96.

Clementson, L., Harris, G. P., Griffiths, F. B. and Rimmer, D. W. (1989). Seasonal and interannual variability in chemical and biological parameters in Storm Bay, Tasmania. 1. Physics, chemistry and the biomass of components of the food chain. *Australian Journal of Marine and Freshwater Research* 40, 25-38.

Cochrane, K. L. (1999). Review of the Western Australian Pilchard Fishery 12-16 April 1999. Fisheries Management Paper 129. (Department of Fisheries, Government of Western Australia, Perth, Australia.)

Condie, S. A. and Dunn, J. R. (2006). Seasonal characteristics of the surface mixed layer in the Australasian region: Implications for primary productivity and biogeography. *Marine and Freshwater Research*, 57, 569-590.

Condie, S. A. and Harris, P. T. (2006). Interactions between physical, chemical, biological, and sedimentological processes in Australia's shelf seas. *The Sea*, 14, 1413-1449.

Cresswell, G. R., (2000). Currents of the continental shelf and upper slope of Tasmania. *Proceedings of the Royal Society of Tasmania,* 133.

Cury, P., Bakun, A., Crawford, R.J.M., Jarre, A., Quiñones, R.A., Shannon, L. J., and Verheye, H. M. (2000). Small pelagics in upwelling systems: patterns of interaction and structural changes in "wasp-waist" ecosystems. *ICES Journal of Marine Science* 57, 603-618.

Department of Primary Industries and Fisheries (2007). Annual Status Report of Queensland Finfish (Stout Whiting) Trawl Fishery. (Qld Department of Primary Industries and Fisheries, Brisbane).

Dunn, J. R. and Ridgway, K. R. (2002). Mapping ocean properties in regions of complex topography. *Deep-Sea Research I,* 49**,** 591-604.

Edmonds, J. S. and Fletcher, W. J. (1997). Stock discrimination of pilchards *Sardinops sagax* by stable isotope ratio analysis of otolith carbonate. *Marine Ecology Progress Series* 152, 241-247.

Elizarov, A. A.., Grechina, A. S., Kotenev, B. N., and Kuzetsov, A. N.(1993). Peruvian jack mackerel, *Trachurus symmetricus murphyi*, in the open water of the South Pacific. *Journal of Ichthyology* 33, 86-104.

Evseenko, S. A. (1987). Reproduction of Peruvian jack mackerel *Trachurus symmetricus murphyi* in the Southern Pacific. *Journal of Ichthyology* 27, 151-160.

Findlay, J. (2007). Small Pelagics Fishery, pp.217–220. *In* Larcombe, J. and McLoughlin, K (eds.) "Fishery Status Reports 2006: Status of fish stocks managed by the Australian Government". (Bureau of Rural Sciences, Canberra..)

Froese, R. and D. Pauly. (Editors). (2007). FishBase. World Wide Web electronic publication. www.fishbase.org, version (04/2007).

Fulton, E. A., Fuller, M., Smith, A. D. M. and Punt, A.. (2004). "Ecological indicators of the ecosystem effect of fishing". Australian Fisheries Management Authority Final Report Project R99/1546. (AFMA & CSIRO, Hobart, Tasmania.)

Fulton, E. A., Smith, A. D. M. and Smith, D. C. (in press). "Alternative Management Strategies for Southeast Australian Commonwealth Fisheries: Stage 2: Quantitative Management Strategy Evaluation." Australian Fisheries Management Authority Report.(CSIRO, Hobart, Tasmania.)

Furlani, D. Williams, A. and Bax, N. (2000) Fish Biology (length and Age). Pp 271-315. *In* Bax, N. J. and Williams, A. (Eds). "Habitat and Fisheries Production in the Southeast Fishery Ecosystem." Project No 94/040. Final Report to the FRDC.(CSIRO, Hobart, Australia.)

Gales, R. & Pemberton, D. (1994). Diet of the Australian fur seal in Tasmania. *Australian Journal of Marine and Freshwater Research* 45**,** 653-64.

Gales, R., Pemberton, D., Clarke, M. & Lu, C. C. (1992). Stomach contents of long-finned pilot whales (*Globicephala melas*) and bottlenose dolphins (*Tursiops truncatus*) in Tasmania. *Marine Mammal Science* 8, 405-13.

Gales, R., Williams, C & Ritz, D. (1990). Foraging behaviour of the little penguin, *Eudyptula minor*: Initial results and assessment of instrument effect. *Journal of Zoology* 220**,** 61-85.

Gaughan, D. J., Fletcher, W. J. and McKinlay, J. P. (2002). Functionally distinct adult assemblages within a single breeding stock of the sardine, *Sardinops sagax*: management units within a management unit. *Fisheries Research* 59, 217-31.

Gaughan, D. and Leary, T. (2006).West Coast Purse Seine Managed Fishery status report. In J.W. Penn, W.J. Fletcher and F. Head (Eds), "State of the Fisheries Report 2005/05" (Department of Fisheries, Western Australia). pp. 51-53.

Gaughan, D. J., White, K. V. and Fletcher, W. J. (2001). The links between functionally distinct adult assemblages of *Sardinops sagax*: larval advection across management boundaries. ICES *Journal of Marine Science* 58, 597-606.

George-Nascimento, M. (2000). Geographical variations in the jack mackerel *Trachurus symmetricus murphyi* populations in the southeastern pacific ocean as evidenced from the associated parasite communities. *Journal of Parasitology* 86, 929–932.

Gibbs, C. F., Arnott, G. H., Longmore, A. R. and Marchant, J. W. (1991). Nutrient and plankton distribution near a shelf break front in the region of Bass Strait Cascade. *Australian Journal of Marine and Freshwater Research*, 42, 201-217.

Gibbs, C. F., Tomczak, M. and Longmore, A. R. (1986). The nutrient regime of Bass Strait. *Australian Journal of Marine and Freshwater Research*, 37, 451-466.

Gill, P. (2002). A blue whale (*Balaenoptera musculus*) feeding ground in a southern Australian coastal upwelling zone. *The Journal of Cetacean Research and Management* 4, 179-184.

Glaister, J. P. and Diplock, J. H. (1993). "Baitfish and the East Coast Tuna and Billfish Fishery: Species, status and situation." (East Coast Tuna management Advisory Committee, Australian Fisheries Management Authority, Canberra, Australia.)

Godfriaux, B. L. (1970). Food of predatory demersal fish in Hauraki Gulf. 2. Five fish species associated with snapper. *New Zealand Journal of Marine and Freshwater Research* 4, 248-66.

Goldsworthy, S. D., Bulman, C., He, X. Larcombe, J. and Littnan, C. (2003). Trophic interactions between marine mammals and Australian fisheries: An Ecosystem Approach. Pp 62-99. *In* N. Gales, M. Hindell and R. Kirkwood (Eds). "Marine Mammals: Fisheries, Tourism and Management Issues". (CSIRO Publishing, Melbourne, Australia.)

Gomon, M., Glover, J. C. M., and Kuiter, R. H. (1994). "The Fishes of Australia's South Coast." (State Print, Adelaide, Australia.)

Gray, C. A. (1993). Horizontal and vertical trends in the distribution of larval fishes in coastal waters off central New South Wales, Australia. *Marine Biology* 116, 649-666.

Gray, C. A., Otway, N., Laurenson, F. A., Miskiewicz, A. G. and Pethebridge, R. L. (1992). Distribution and abundance of marine fish larvae in relation to effluent plumes from sewage outfalls and depth of water. *Marine Biology* 113, 549-559.

Griffin, D. A., Wilkin, J. L., Chubb, C. F., Pearce, A. F. and Caputi, N. (2001). Ocean currents and the larval phase of Australian western rock lobster, *Panulirus cygnus*. *Marine and Freshwater Research* 52, 1187-1199.

Griffiths, F. B. and Wadley, V. A. (1986). A synoptic comparison of fishes and crustaceans from a warm-core eddy, the East Australian Current, and the Tasman Sea. *Deep-Sea Research,* 33**,** 1907-1922.

Hanson, C. E., Pattiaratchi, C. B. and Waite, A. M. (2005). Seasonal production regimes off south-western Australia: influence of the Capes and Leeuwin Currents on phytoplankton dynamics. *Marine and Freshwater Research*, 56, 1011–1026. doi:10.1071/MF04288.

Harris, G. P., Davies, P., Nunez, M., and Meyers, G. (1988). Interannual variability in climate and fisheries in Tasmania. *Nature* 333, 754-757.

Harris, G. P., Griffiths, F. B., Clementson, L. A., Lyne, V., and Van der Doe, H. (1991). Seasonal and interannual variability in physical processes, nutrient cycling and the structure of the food chain in Tasmanian shelf waters. *Journal of Plankton Research* 13, 109-131.

Harris, G. P., Nilsson, C., Clementson, L., and Thomas, D. (1987). The water masses of the east coast of Tasmania: seasonal and interannual variability and the influence on phytoplankton biomass and productivity. *Australian Journal of Marine and Freshwater Research* 38, 569-90.

Hedd, A. & Gales, R. (2001). The diet of shy albatrosses (*Thalassarche cauta*) at Albatross Island, Tasmania. *Journal of Zoology* 253**,** 69-90.

Hedd, A., Gales, R. and Brothers, N. (2001). Foraging strategies of the shy albatrosses (*Thalassarche cauta*) breeding at Albatross Island, Tasmania, Australia. *Marine Ecology Progress Series* 224, 267-282.

Herzfeld, M., (1997). The annual cycle of SST in the Great Australian Bight. *Progress in Oceanography,* 39**,** 1-27.

Hobday, A. J., Hartmann, K., Hartog, J. and Bestley, S. (2006). “SDODE: Spatial dynamics ocean data explorer. User Guide.” (CSIRO Marine and Atmospheric Research, Hobart.)

Hoedt, F.E. and Dimmlich, W.F. 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.

Hurst, R. J., Bagley, N. W., Anderson, O. F, Francis, M. P, Griggs, L. H., Clark, M. R., Paul, L. J, and Taylor, P. R. (2000). Atlas of juvenile and adult fish and squid distributions from bottom and midwater trawls and tuna longlines in New Zealand waters. *NIWA Technical Report* 84. (National Institute of Water and Atmospheric Research, Wellington, New Zealand.) 162 pp.

Hutchins, B. and Swainston, R. (1986). “Sea fishes of southern Australia: complete field guide for anglers and divers.” (Swainston Publications, Perth, W.A.)

Jeffrey, S. W. and Hallegraeff, G. M. (1990). Phytoplankton ecology of Australasian waters. *In* Clayton, M. N. and King, R. J. (Eds). “Biology of Marine Plants.” pp. 311-348. (Longman Cheshire, Melbourne.)

Jones, J. B. (1990). Jack mackerels (*Trachurus* spp.) in New Zealand waters. *Fisheries Technical Report* 23. (Ministry of Agriculture and Fisheries, Wellington, New Zealand.) 28 pp.

Jordan, A., Pullen, G., and Williams, H., (1992). Jack Mackerel Resource Assessment in South Eastern Australian Waters. Project DFT2Z. Final Report to the Fishing Industry Research and Development Council. (Tasmanian Department of Primary Industry, Fisheries and Energy, Hobart.)

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

Jordan, A., Pullen, G., Marshall, J., and Williams, H., (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., Williams, M. J, Stewart, P.C., Reichelt, R. E., McNee, A., and Grieve, C. (1993). "Australian Fisheries Resources." (Bureau of Rural Sciences and Fisheries Research and Development Corporation, Canberra, Australia.) 422 pp.

Koval, L. I. (1996). Polymorphic locus frequency in Peruvian horse mackerel and females intrapopulation heterogeneity in growth rates. ICES Council Meeting Papers CM 1996/H: 35. (ICES, Copenhagen, Denmark.) 9pp.

Konchina, Y. V. (1981). The feeding of Peruvian jack mackerel *Trachurus symmetricus murphyi*. *Journal of Ichthyology* 21, 46-59.

Lake, S. (1977). Analysis of the diet of New Zealand fur seals *Arctocephalus forsteri* in Tasmania. *In* M. Hindell and C. Kemper (Eds). "Marine Mammal Research in the Southern Hemisphere, Vol 1: Status, Ecology and Medicine." pp 125-129. (Surrey Beatty & Sons, Chipping Norton, Sydney.)

Lewis, R. K., (1981). Seasonal upwelling along the south-eastern coastline of south Australia. *Australian Journal of Marine and Freshwater Research*, 32, 843-854.

Lindholm, R. and Maxwell, J. G. H. (1982). 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* 189. (CSIRO, Sydney Australia.)

Lourey, M. J., Dunn, J. R. and Waring, J. (2006). A mixed-layer nutrient climatology of Leeuwin Current and Western Australian shelf waters: seasonal nutrient dynamics and biomass. *Journal of Marine Systems* 59, 25–51. doi:10.1016/J.JMARSYS.2005.10.001

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

MacCall, A. D. (1990). "Dynamic Geography of Marine Fish Populations."(Washington Sea Grant Program, Seattle and London.)

Marshall, J., Pullen, G. and Jordan, A. (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. (1982). Infestation of the jack mackerel *Trachurus declivis* (Jenyns), with the cymothoid isopod, *Ceratothoa imbricatus* (Fabricus), in south eastern Australian waters. *Journal of Fish Biology* 20, 341-349.

May, J. and Blaber, S. J. M. (1989). Benthic and pelagic fish biomass of the upper continental slope off eastern Tasmania. *Marine Biology* 101, 11-25.

McClatchie, S., Middleton, J., Pattiaratchi, C. and Kendrick, G. (2007). “The South-west marine region: Ecosystems and Key Species Groups.” (Department of Environment and Water Resources, Canberra.)

McLeod, D. (2005). “Ecological and functional equivalence in small pelagic fishes off the east coast of Tasmania.” Hons. Thesis. (University of Tasmania, Hobart.)

Meyer, M. and Smale, M. J. (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.

Ministry of Fisheries (2006). Jack Mackerels JMA. *In* “Report from the Fishery Assessment Plenary, May 2006: stock assessment and yield estimates.” pp. 313-320. (Ministry of Fisheries, Wellington, New Zealand.) 875pp.

Ministry of Fisheries (2007) a. “Report from the Fishery Assessment Plenary, May 2007: stock assessments and yield estimates.” (Ministry of Fisheries, Wellington, New Zealand.) 1015 p.

Ministry of Fisheries (2007)b. www.fish.govt.nz/en-nz/SOF/Species.htm?code=JMA&list=scientific, 15 March 2007.

Morrison, M., Taylor, P., Marriott, P. and Sutton, C. (2001). An assessment of information on blue mackerel (*Scomber australasicus*) stocks. *Fisheries Assessment Report* 2001/44. (Ministry of Fisheries, Wellington, New Zealand.) 26 pp.

Nakamura, I., Inada, T., Takeda, M., and Hatanaka, H. (1986). “Important fishes trawled off Patagonia.” (Japan Marine Fishery Resource Research Centre, Tokyo.) 369 pp.

Neira, F. J. (2005). Summer and winter plankton fish assemblages around offshore oil and gas platforms in south-eastern Australia. *Estuarine, Coastal and Shelf Science* 63, 589-604.

Neira, F. J., Jenkins, G.P., Longmore, A. R. and Black, K. R. (2000). Spawning and larval recruitment processes of commercially important species in coastal waters of Victoria 1997-1998. Final Report FRDC Project No 96/116. (MAFRI, Queenscliff, Australia)

Neira, F.J., Miskiewicz, A.G., and Trnski, T. (1998). “Larvae of Temperate Australian Fishes. Laboratory Guide for Larval Fish Identification. (University of Western Australia Press, Nedlands, Australia.) 474 pp.

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

Neira, F.J. and Sporcic, M.I. 2002. Use of ichthyoplankton ecology to evaluate ecosystem changes: a case study in a large, semi-enclosed Australian bay. *Marine and Freshwater Research* **53**: 2: 339-354.

Neira, F. J., Ward, T. M., Rogers, P. J., McLeay, L. J. and Keane, J. (2007). Distribution and abundance of eggs and larvae of four taxa of pelagic species in eastern and southern Australia. *In* Ward, L. J. and Rogers, P. J.(Eds) “Development and evaluation of egg-based stock assessment methods for blue mackerel *Scomber australasicus* in southern Australia.” Report to the Fisheries Research and Development Corporation, Project No. 2002/061. (FRDC, Canberra; SARDI, Adelaide.)

Nunes-Vaz, R. A., Lennon, G. W. and Bowers, D. G. (1990). Physical behaviour of a large, negative or inverse estuary. *Continental Shelf Research*, 10, 277-304.

Oke, P. R. and Middleton, J. H. (2001). Nutrient enrichment off Port Stephens: the role of the East Australian Current. *Continental Shelf Research*, 21, 587-606.

Pauly, D., Christensen, V., Dalsgaard, J., Froese, R., and Torres, F. (1998). Fishing down marine food webs. *Science* 279, 860-863.

Pearce, A. F. and Pattiaratchi, C. B.(1999). The Capes Current: a summer countercurrent flowing past Cape Leeuwin and Cape Naturaliste, Western Australia. *Continental Shelf Research,* 19**,** 401-420.

Poulin, E., Cárdenas, L., Hernández, C. E., Kornfield, I., and Ojeda,F. P. (2004). Resolution of the taxonomic status of Chilean and Californian jack mackerels using mitochondrial DNA sequence. *Journal of Fish Biology* 65, 1160–1164.

Pullen, G., Williams, H. and Last, P. (1989). South American fish found of Tasmania. *Australian Fisheries* 48, 35.

Pullen, G. (1994). Jack mackerel (*Trachurus declivis*). *In* Finfish Assessment Section. “Species Status Report: Key Scalefish Species.” Pp 31-41. *Internal Report* No 14. (Marine Resources Division, Department of Primary Industry and Fisheries, Hobart, Tasmania.)

Pullen, G., Jordan, A. and Williams, H. (1997). “Summary Report Mackerel Research 1985-1996.” (Marine Resources Division, Department of Primary Industry and Fisheries, Hobart, Tasmania.)

Pullen, G. and Lyle, J. (1994). “Jack mackerel Research Review.” (Sea Fisheries Division, Department. of Primary Industry and Fisheries, Taroona, Tasmania). 66 pp.

Richardson, B. J. (1982). Geographical distribution of electrophoretically detected protein variation in Australian commercial fishes . I. Jack mackerel, *Trachurus declivis* Jenyns. *Australian Journal of Marine and Freshwater Research* 33, 917-27.

Ridgway, K. R. and Condie, S. A. (2004). The 5500-km long boundary flow off western and southern Australia. *Journal of Geophysical Research* 109:C04017, doi:10.1029/2003JC001921.

Ridgway, K. R. and Dunn, J. R. (2002). Mesoscale structure of the mean East Australian Current System and its relationship with topography. *Progress in Oceanography,* 56**,** 189-222.

Ridgway, K. R., Dunn, J. R. and Wilkin, J. L. (2002). Ocean interpolation by four-dimensional least squares - Application to the waters around Australia. *Journal of Atmospheric and Oceanic Technology* 19**,** 1357-1375.

Rogers, P. J., Ward, T. M. and Lowry, M.(2007)a. Spatial and temporal patterns in the size, age and growth of blue mackerel *Scomber australasicus* in southern and eastern Australia. *In* Ward, T. M. and Rogers, P. J. (Eds). "Development and evaluation of egg-based stock assessment methods for blue mackerel *Scomber australasicus* in southern Australia." Report to the Fisheries Research and Development Corporation, Project No. 2002/061. (Fisheries Research and Development Corporation, Canberra and South Australian Research and Development Institute, Adelaide.)

Rogers, P. J., Ward, T. M., McLeay, L. J., Lowry, M., and Williams, D.(2007)b. Reproductive biology and spawning dynamics of blue mackerel *Scomber australasicus* off southern and eastern Australia. *In* Ward, T. M. and Rogers, P. J. (Eds). "Development and evaluation of egg-based stock assessment methods for blue mackerel *Scomber australasicus* in southern Australia." Report to the Fisheries Research and Development Corporation, Project No. 2002/061. (Fisheries Research and Development Corporation, Canberra and South Australian Research and Development Institute Adelaide.)

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.

Ritz, D. A. and Hosie, G. W. (1992) Production of the euphausiid *Nyctiphanes australis* in Storm Bay, south-eastern Tasmania. *Marine Biology* 68,103-108

Schmarr, D. W., Whittington, I. D., Ovenden, J. R., and. Ward, T. M. (2007). Techniques for discriminating stocks of blue mackerel Scomber australasicus. *In* Ward, L.J. and Rogers, P.J. (Eds). "Development and evaluation of egg-based stock assessment methods for blue mackerel *Scomber australasicus* in southern Australia." Report to the Fisheries Research and Development Corporation, Project No. 2002/061. (Fisheries Research and Development Corporation, Canberra and South Australian Research and Development Institute, Adelaide.)

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

Serra, R. (1991). Important life history aspects of the Chilean jack mackerel *Trachurus symmetricus murphyi*. *Investigacion Pesquera* 36, 67-83.

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

Smith , P. J., Diggles, B. and Kim, S. (2005). Stock structure of blue mackerel *Scomber australasicus*. Fisheries Assessment Report 2005/43. (Ministry of Fisheries, Wellington, New Zealand.) 38pp.

Smith, R. L., Huyer, A., Godfrey, J. S. and Church, J. A. (1991). The Leeuwin Current off Western Australia. *Journal of Physical Oceanography,* 21**,** 323-345.

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

Stepien, C. A. and Rosenblatt, R. H. (1996). Genetic divergence in antitropical pelagic marine fishes (*Trachurus*, *Merluccius*, and *Scomber*) between North and South America. *Copeia* 3, 586-598.

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

Stevens, J. D., Hausfeld, H. F. and Davenport, S.(1984). Observations on the biology, distribution and abundance of *Trachurus declivis*, *Sardinops neopilchardus* and *Scomber australasicus* in the Great Australian Bight. *Marine Laboratories Report* 164, (CSIRO, Hobart, Australia.)

Stewart, J. and Ferrell, D. J. (2001). Age, growth, and commercial landings of yellowtail scad (*Trachurus novaezelandiae*) and blue mackerel (*Scomber australasicus*) of the coast of New South Wales, Australia. *New Zealand Journal of Marine and Freshwater Research* 35, 54-551.

Syahailatua, A. (2005). Biological oceanography of larval fish diversity and growth off eastern Australia. Ph.D. thesis. (University of New South Wales, Australia.)

Taylor, P. R. (2002). Stock structure and population biology of the Peruvian jack mackerel *Trachurus symmetricus murphyi*. *Fisheries Assessment Report* 2002/21. (Ministry of Fisheries, Wellington, New Zealand.) 78 pp.

Tracey, S. R., Lyle, J. M., and Duhamel, G. (2006) Application of elliptical Fourier analysis of otolith form as a tool for stock identification. *Fisheries Research* 77, 138-147.

Tranter, D. J., (1962). Zooplankton abundance in Australasian waters. *Australian Journal of Marine and Freshwater Research,* 13**,** 106-142.

Tzeng, T.-D. (2004). Morphological variation between populations of spotted mackerel (*Scomber australasicus*) off Taiwan. *Fisheries Research* 68, 45-55.

Uehara, S., Syahailatua, A. and Suthers, I. M. (2005). Recent growth rate of larval pilchards *Sardinops sagax* in relation to their stable isotope composition, in an upwelling zone of the East Australian Current. *Marine and Freshwater Research* 56, 549-60.

Ward, P., Timmiss, T. and Wise, B. (2001). “A review of biology and fisheries for mackerel.” (Bureau of Rural Resources, Canberra, Australia.)

Ward, T. M., McLeay, L. J., Dimmlich, W. F., Rogers, P. J., McClatchie, S., Matthews, R., Kaempf, J., and Van Ruth, P. D. (2006). Pelagic ecology of a northern boundary current system: effects of upwelling on the production and distribution of sardine (*Sardinops sagax)*, anchovy (*Engraulis australis*) and southern bluefin tuna (*Thunnus maccoyii*) in the Great Australian Bight. *Fisheries Oceanography* 15, 191-207.

Ward, T., McLeay, L. J. & Rogers, P. J. (2005). Spawning biomass of sardine (pilchard, Sardinops sagax) in South Australian waters. Final Report prepared for PIRSA Fisheries. RD05/0019-1. (South Australian Research and Development Institute (Aquatic Sciences), Adelaide.)

Ward, T. M. and Rogers, P. J. (Eds) (2007). "Development and evaluation of egg-based stock assessment methods for blue mackerel *Scomber australasicus* in southern Australia." Report to the Fisheries Research and Development Corporation, Project No. 2002/061. (FRDC, Canberra; SARDI, Adelaide.)

Ward, T., Staunton-Smith, J. (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., Staunton-Smith, J., Hoyle, S. and Halliday, I. A. (2003). Spawning patterns of four species of predominantly temperate pelagic fishes in the sub-tropical waters of southern Queensland. *Estuarine, Coastal and Shelf Science* 56, 1125-40.

Waters, J. M., King, T.M., O'Loughlin, P.M., and Spencer, H.G. (1995). Phylogeographical disjunction in abundant high-dispersal littoral gastropods. *Molecular Ecology*14, 2789–2802.

Webb, B. F. and Grant, C. J. (1979). Age and growth of jack mackerel *Trachurus declivis* (Jenyns) from south-eastern Australian waters. *Australian Journal of Marine and Freshwater Research* 30, 1-9.

Welsford, D. C. and Lyle, J. M. (2003). Redbait (*Emmelichthys nitidus*): a synopsis of fishery and biological data. *Technical Report* 20. (Tasmanian Aquaculture and Fisheries Institute, University of Tasmania, Hobart, Australia.) 32 pp.

Williams, K. (1981). Aerial survey of pelagic fish resources off south east Australia 1973-1977. *Division of Fisheries and Oceanography Report* 130. (CSIRO, Cronulla, Australia.)

Williams, H. and Pullen, G. (1993). Schooling behaviour of jack mackerel, *Trachurus declivis* (Jenyns), observed in the Tasmanian Purse Seine Fishery. *Australian Journal of Marine and Freshwater Research* 44, 577-587.

Yearsley, G. K., Last, P. R. and Ward, R. D. (Eds) (1999). "Australian Seafood Handbook." (CSIRO Marine Research, Hobart, Australia.) 461 pp.

Young, J. W. and Davis, T. L. O. (1992). Feeding ecology and interannual variations in diet of larval jack mackerel, *Trachurus declivis* (Pisces: Carangidae), from coastal waters off eastern Tasmania. *Marine Biology* 113, 11-20.

Young, J. W., Jordan, A. R., Bobbi, C., Johannes, R. E., Haskard, K. and Pullen, G. (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.

Young, J. W., Lamb, T. D., Bradford , R., Clementson, L., Kloser, R. and Galea, H. (2001). Yellowfin tuna (*Thunnus albacares*) aggregations along the shelf break of southeastern

Australia: links between inshore and offshore processes. *Marine and Freshwater Research* 52, 463 – 474.

Young, J. W., Nishida, T. and Stanley, C. (2000) A preliminary survey of the summer hydrography and plankton biomass of the eastern Great Australian Bight, Australia. *In* Report of the R/V Shoyo-Maru Cruise for study on the spawning and nursery ground of southern bluefin tuna in the Indian ocean, during December 8, 1998 - March 6, 1999. December, 2000 Fisheries Agency of Japan

Zar, J. H. (1984). “Biostatistical Analysis.” (Prentice Hall, New Jersey, USA.)

APPENDIX A

INTELLECTUAL PROPERTY

The intellectual property arising from this research is the property of CSIRO and FRDC.

APPENDIX B

STAFF

Staff		% funded by FRDC	Approx % on project
Dr Catherine Bulman	CSIRO	70	40
Dr Scott Condie	CSIRO	70	5
Dr James Findlay	BRS	100	-
Mr Brendon Ward	CSIRO	70	10
Dr Jock Young	CSIRO	70	10

Contributions were made by Ms Sheree Epe (BRS) and Mr Jay Hender (BRS).

APPENIDIX C

FISHERY METADATA

Commonwealth SPF Catch Data

Custodian	AFMA Australian Fisheries Management Authority
Date Supplied	8/05/2007
Contact	Small Pelagics – Manager Melissa Brown (02) 6225 5465 melissa.brown@afma.gov.au
Temporal Range	1/01/1979 to 1/12/2006
Geographic Range	Top: -25 Left: 115.50 Bottom: -48.50 Right: 160.50

Data Fields

Name	Data type	Comment
id	integer	Unique identifier
year	integer	Year part of catch date
Afz_in	text	Return type code
Zone_1	text	Relates to a defined geographical area
Operation_date	text	Date of fishing operation
latitude	double precision	Latitude – decimal degrees
longitude	double precision	Longitude – decimal degrees
species	text	Species common name of catch
Caab_code	double precision	Species CAAB code
catch_wt	double precision	Weight in kilograms of catch
month	number	Month part of operation date

Description

The Commonwealth Small Pelagic Fishery catch data extracted from the AFMA Genlog database (Microsoft Access).

The Commonwealth Small Pelagic Catch dataset records the catch details of four species:

Jack Mackerel (includes Peruvian jack mackerel)
Blue Mackerel
Redbait
Yellowtail Scad.

NSW SPF Catch Data

Custodian	NSW DPI
Date Supplied	8/05/2007
Contact	David Makin DPI - Fisheries Manager (02) 9527 8556
Temporal Range	1950 to 2006
Geographic Range	Top: -28 Left: 149.00 Bottom: -38.50 Right: 155.00

Data Fields

Name	Data type	Comment
id	integer	Unique identifier
year	integer	Year part of catch date
code category	text	Fishing zone/type code
Codes category.name	text	Fishing zone/type code descriptor
Code hregion	text	Code for geographic regions
Codes hregions.name	text	Descriptor of geographic region
Class water	text	Ocean/Estuary
Codes species.name	text	Species common name of catch
Species class	text	Finfish
catch_wt	double precision	Weight in kilograms of catch

Description

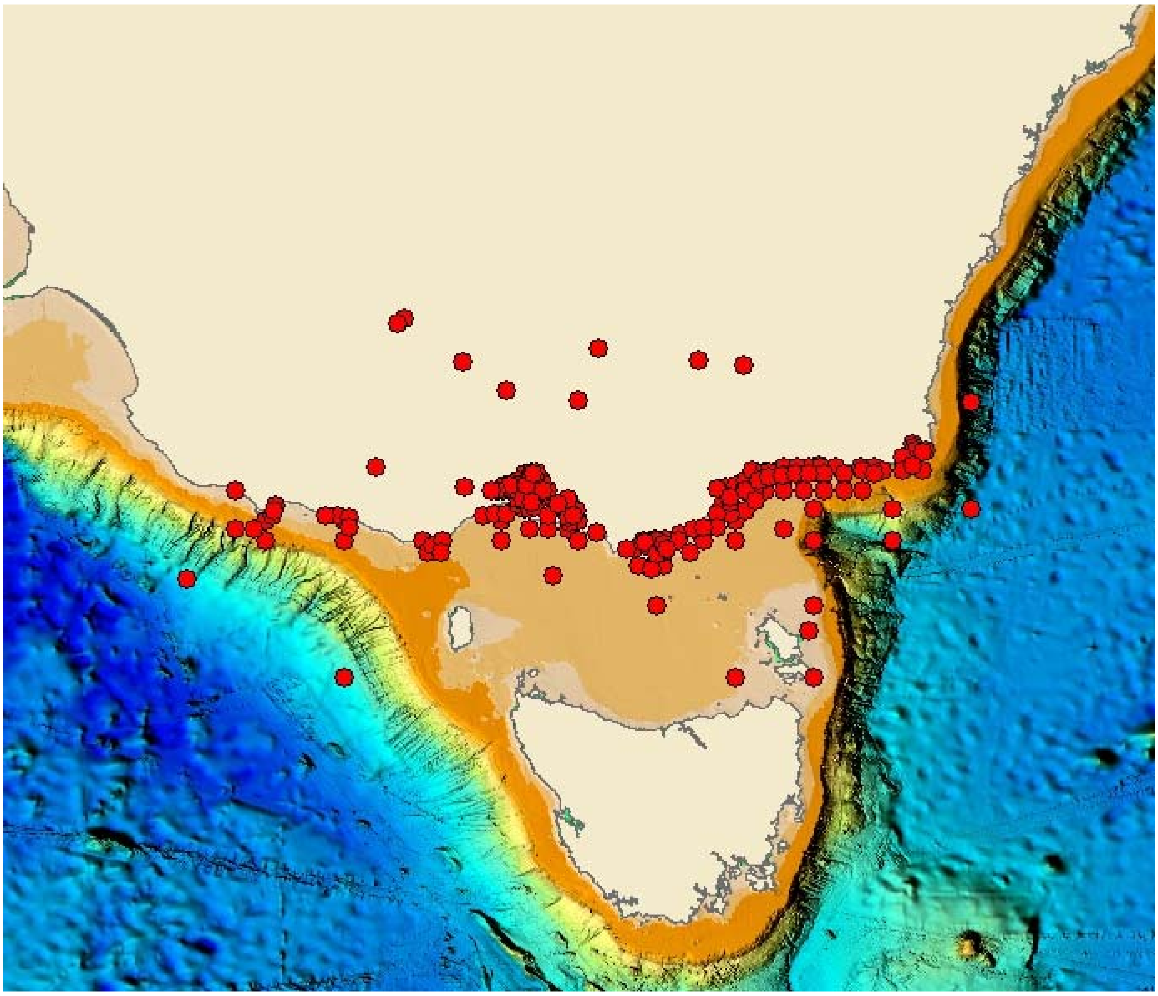
The NSW Small Pelagic Fishery catch data extracted from the NSW DPI Fisheries catch database was supplied as an excel workbook
The NSW Small Pelagic Catch dataset records the catch details of four species:

Jack Mackerel

Blue Mackerel
Redbait
Yellowtail Scad.

PIRVic SPF Catch Data

Custodian	PIRVic (Primary Industries Research Victoria) - Queenscliff Centre
Date Supplied	8/05/2007
Contact	Paula Baker Manager, Catch & Effort Unit PIRVic (Primary Industries Research Victoria) - Queenscliff Centre Ph: 03 5258 0243 Fax: 03 5258 4553 Email: paula.baker@dpi.vic.gov.au
Temporal Range	1/01/1979 to 1/12/2006
Geographic Range	Top: -35.93 Left: 140.50 Bottom: -40.50 Right: 150.50



Data Fields

Name	Data type	Comment
pirvic_id	double precision	PIRVIC unique identifier
month	text	Month part of catch date
pirvic_return_type	text	Return type code
pirvic_area	text	Relates to a defined geographical area
gear_code	text	Code for fishing gear used
gear	text	Text description of fishing gear
days	double precision	Fishing effort days per month
c_e_species_code	double precision	Catch and Effort species code used by PIRVIC
species	text	Species common name of catch
caab	double precision	Species CAAB code
catch_kg	double precision	Weight in kilograms of catch
value	double precision	Estimated market value

Name	Data type	Comment
number_of_fishers	double precision	Number of fishers on vessel
pirvic_areas_id	double precision	ID code for the PIRVIC area
area_description	text	Description of geographic area
lat_deg	double precision	Degree component of latitude of area centroid
lat_min	double precision	Minute component of latitude of area centroid
long_deg	double precision	Degree component of longitude of area centroid
long_min	double precision	Minute component of longitude of area centroid
effective	text	Effective date
expired	text	Expiration date
lat	double precision	Latitude of area centroid in decimal degrees
long	double precision	Longitude of area centroid in decimal degrees
year	double precision	Year part of fishing date

Description

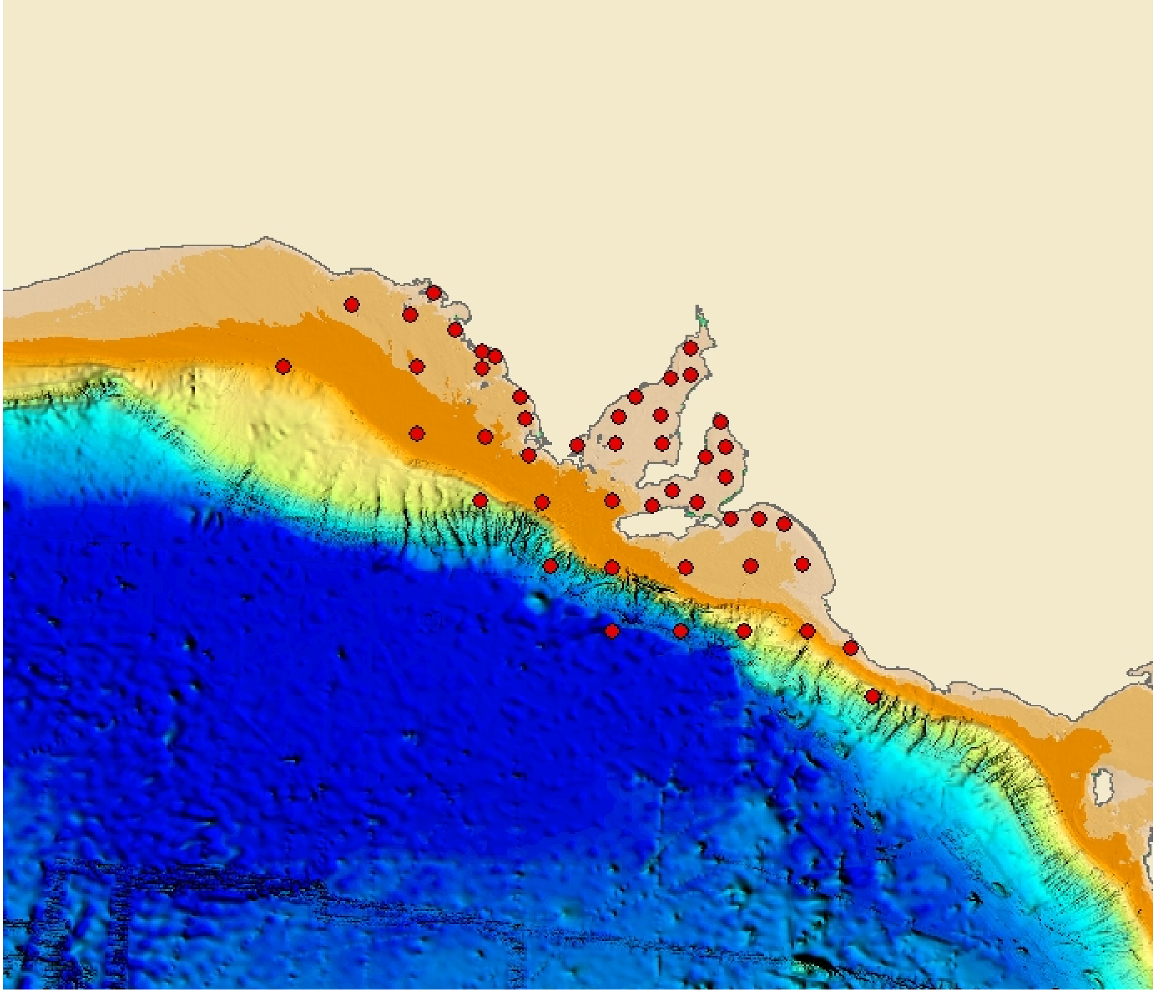
The PIRVIC Small Pelagic Fishery catch data was supplied to CMAR as an Excel spreadsheet. The spreadsheet was imported into an Access database for storage and manipulation of the data. PIRVIC supplied the centroids of the geographic areas referenced by the catch data as a separate Excel spreadsheet. These two files were joined and the lat and long fields as described above were derived from this join. The year field as described above was derived by extracting the year part from the month field as supplied by PIRVIC.

The PIRVIC Small Pelagic Catch dataset records the catch details of nine species:

Anchovy, Southern
Mackerel, Blue
Mackerel, Scaly
Mackerel, Unspecified
Pilchard
Redbait
Sprat
Sprat, Blue
Sprat, Sandy

SARDI SPF Catch Data

Custodian	South Australian Research and Development Institute
Date Supplied	16/05/2007
Contact	Angelo Tsolos Manager - Information Services SARDI - Aquatic Sciences 2 Hamra Avenue, West Beach SA 5024 PO Box 120, Henley Beach SA 5022 ph: +61 8 8207 5414 fax: +61 8 8207 5415 mailto:tsolos.angelo@saugov.sa.gov.au www.sardi.sa.gov.au
Temporal Range	1/01/1979 to 1/12/2006
Geographic Range	Top: -32.33 Left: 131.44 Bottom: -38.48 Right: 140.45



Data Fields

Name	Data type	Comment
id	integer	Unique identifier
financial_year	text	Financial year
year	double precision	Year part of catch date
month	double precision	Month part of catch date
area	double precision	SARDI defined geographic area grid
gear_descr	text	Description of gear used
target_species_name	text	Common name of targeted species
catch_species_name	text	Common name of catch species
wholewt_kg	double precision	Weight in kilograms of catch
boat_days	double precision	Effort recorded as boat days
man_days	double precision	Effort recorded as man days
licence_count	double precision	Licence count
x_coord	double precision	Longitude in decimal degrees
y_coord	double precision	Latitude in decimal degrees

Description

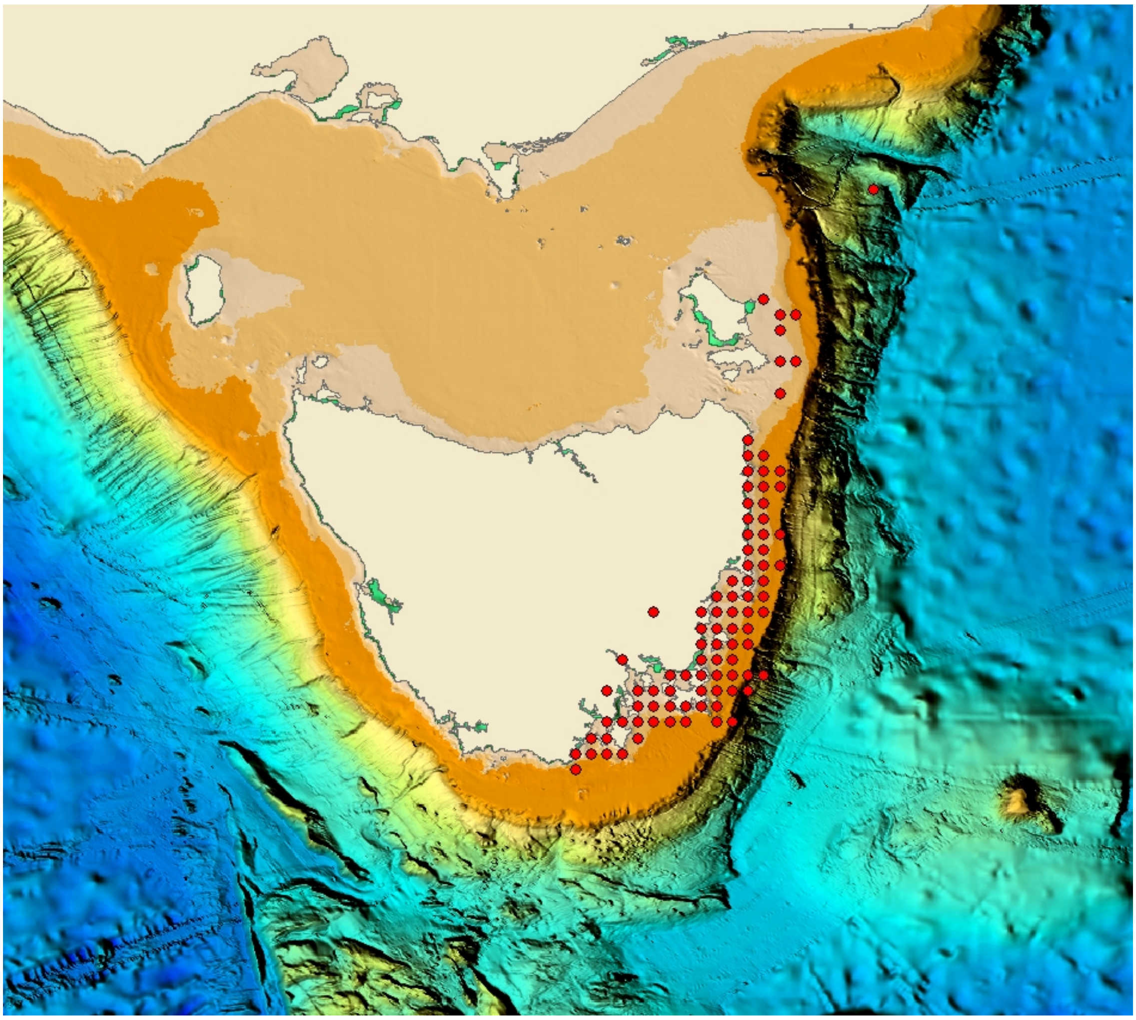
The SARDI Small Pelagic Fishery catch data was supplied to CMAR as an Excel spreadsheet. The spreadsheet was imported into an Access database for storage and manipulation of the data. SARDI supplied a hard copy map showing the numbered grid system they use to define geographic areas for their catch data. The centroids for the grids were derived from this map and they were joined to the dataset.

The SARDI Small Pelagic Fishery catch data records the catch details of 4 species:

Jack Mackerel
Blue Mackerel
Other Mackerel
Trevally

TAFI 1985 SPF Catch Data

Custodian	TAFI – Tasmanian Aquaculture and Fisheries Institute
Date Supplied	27/4/2007
Contact	Dr Jeremy Lyle Senior Research Scientist Tasmanian Aquaculture and Fisheries Institute Phone: (03) 6227 7255 Nubeena Cres TAROONA TAS 7053 Mob: 0407 277426 Fax: (03) 6227 8035 e-mail: Jeremy.Lyle@utas.edu.au
Temporal Range	27/02/1985 to 22/06/1989
Geographic Range	Top: -39.00 Left: 146.93 Bottom: -43.68 Right: 149.31



Data Fields

Name	Data type	Comment
id	integer	Unique identifier
trip_id	double precision	TAFI identifier
trip_status	text	Code for trip status e.g. C for completed
vessel_mark	text	Vessel marking
trip_start_date	text	Date of trip start
month	double precision	Month part of trip
year	double precision	Year part of trip
season	text	Fishing season in which trip occurred
trip_total_volume_h	double precision	Trip volume
trip_total_weight_k	double precision	Total catch weight in kilograms
st_hr	double precision	Trip start time hour
st_min	double precision	Trip start time minutes
fin_hr	text	Trip finish time hour
fin_min	text	Trip finish time minutes

Name	Data type	Comment
portime_status	double precision	
station_id	double precision	TAFI station identifier
station_no	double precision	TAFI station number
loc_method	double precision	Location method
start_date	text	Date of trip start
search_minutes	double precision	Minutes spent searching for catch
st_hr_2	double precision	Start time of catch hour
st_min_2	double precision	Start time of catch minutes
duration_min	double precision	Duration of catch effort
block	text	TAFI grid block, for geographic location
temp_surface	text	Surface temperature in degrees Celsius
surface_school_yn	text	Was the catch from a surface school
percent_school_caug	double precision	Estimate of the percentage of the school taken
shot_total	double precision	Total weight of shot catch
catch_unit_id	double precision	TAFI catch unit id
valid_yn	text	Validation flag
catch_id	double precision	TAFI identifier for each catch
identification_code	double precision	CAAB code for the species caught
common_name	text	Common name of catch species
catch_total_weight_	double precision	Catch weight in kilograms of identified species
flag	text	Record level flags
flag_notes	text	Notes referring to flag i.e. reason or action
lat	double precision	Latitude in decimal degrees
long	double precision	Longitude in decimal degrees

Description

The TAFI 1985-1989 Small Pelagic Fishery catch data was supplied to CMAR as an Excel spreadsheet. The spreadsheet was imported into an Access database for storage and manipulation of the data.

The location of the catch data had to be derived using an algorithm written in Java. The algorithm deduced the centroid of the supplied TAFI block code. Hardcopy maps showing the TAFI blocks were supplied and deriving the geographic extent for each block was done after assessing these hardcopy maps.

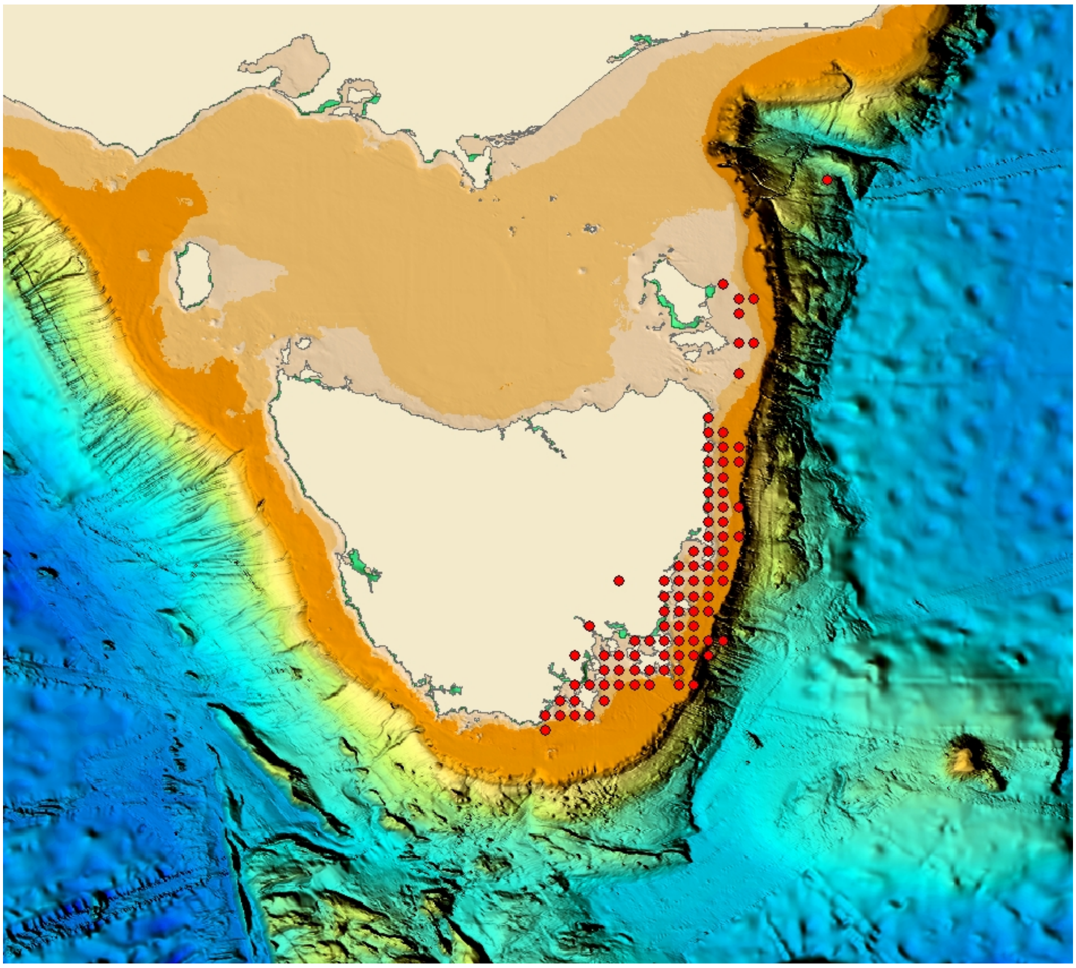
The TAFI 1985-1989 Small Pelagic Fishery catch data supplied details on the catch records of nine species:

Jack Mackerel
Redbait
Blue Mackerel
Australian Anchovy

Barracouta
Trash Fish
Other Commercial
Pilchard
Slender Tuna

TAFI 1989–99 SPF Catch Data

Custodian	TAFI – Tasmanian Aquaculture and Fisheries Institute
Date Supplied	27/4/2007
Contact	Dr Jeremy Lyle Senior Research Scientist Tasmanian Aquaculture and Fisheries Institute Phone: (03) 6227 7255 Nubeena Cres TAROONA TAS 7053 Mob: 0407 277426 Fax: (03) 6227 8035 e-mail: Jeremy.Lyle@utas.edu.au
Temporal Range	14/12/1990 to 21/05/1999
Geographic Range	Top: -39.00 Left: 146.93 Bottom: -43.68 Right: 149.31



Data Fields

Name	Data type	Comment
id	double precision	Unique identifier
logbook	text	Logbook used
method	text	Fishing method
trip_id	double precision	TAFI trip identifier
duration	double precision	Duration of trip in days
vessel	text	Vessel name
date_out_new	text	Date trip began
set	double precision	
shot_date_5	text	Date of the shot
season	text	Season in which shot occurred
total_catch	double precision	Total catch weight in kilograms
block	text	TAFI grid block system for recording geographic extent
advice	text	Was the shot in response to outside advice
surf	text	Was the catch surface schooling
perc_caught	double precision	Percentage of identified species
flag	text	Flag for record level checking
flag_notes	text	Notes referring to the flag/ and or action
lat	text	Latitude of shot in decimal degrees

Name	Data type	Comment
long	text	Longitude of shot in decimal degrees
year_part	double precision	Year part extracted from the shot data

Description

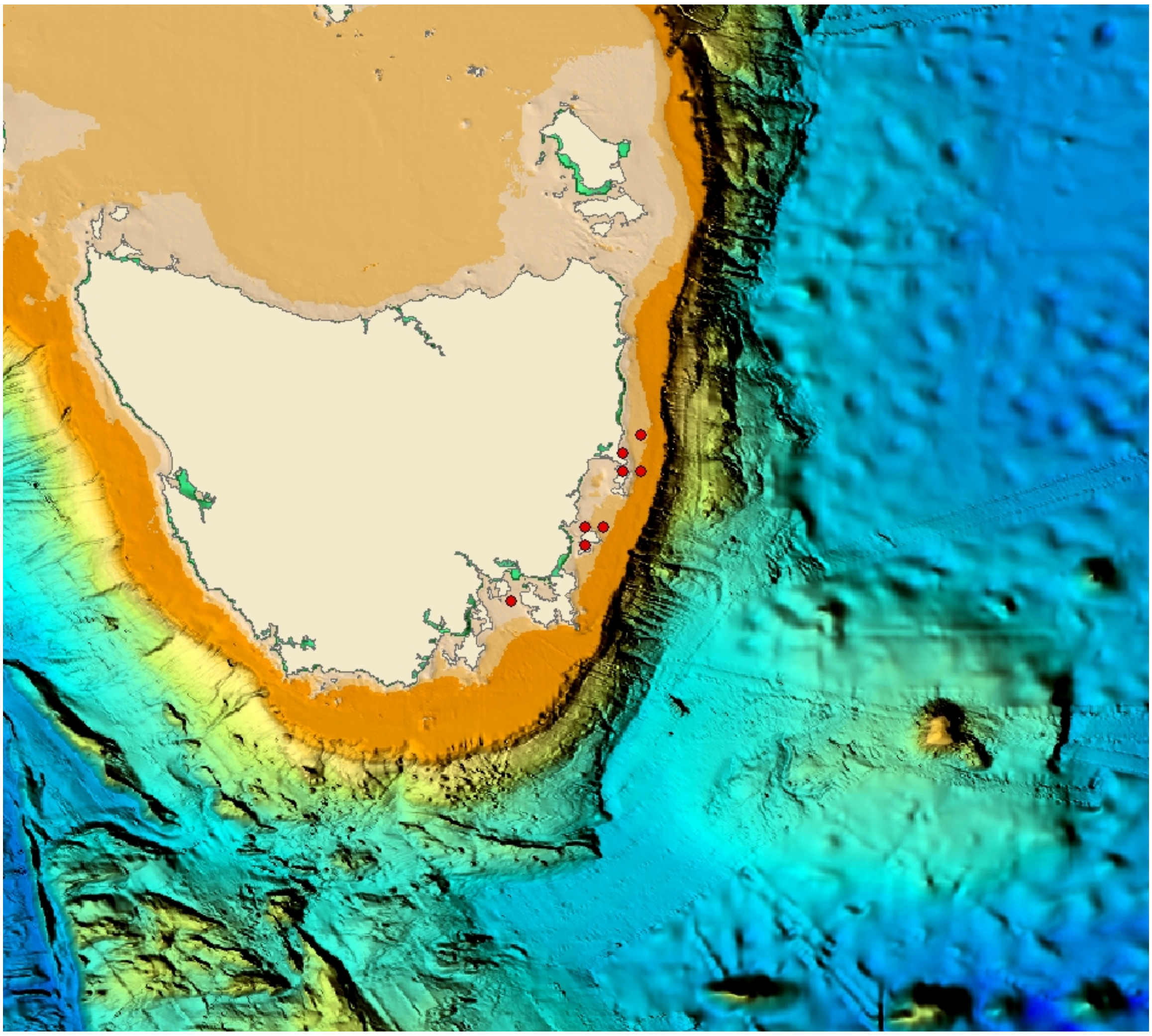
The TAFI 1989-1999 Small Pelagic Fishery catch data was supplied to CMAR as an Excel spreadsheet. The spreadsheet was imported into an Access database for storage and manipulation of the data.

The location of the catch data had to be derived using an algorithm written in Java. The algorithm deduced the centroid of the supplied TAFI block code. Hardcopy maps showing the TAFI blocks were supplied and deriving the geographic extent for each block was done after assessing these hardcopy maps.

The TAFI 1989-1999 Small Pelagic Fishery catch data supplied no species information so all catch were assigned to Jack Mackerel.

TAFI 1999 SPF CATCH DATA

Custodian	TAFI – Tasmanian Aquaculture and Fisheries Institute
Date Supplied	27/4/2007
Contact	Dr Jeremy Lyle Senior Research Scientist Tasmanian Aquaculture and Fisheries Institute Phone: (03) 6227 7255 Nubeena Cres TAROONA TAS 7053 Mob: 0407 277426 Fax: (03) 6227 8035 e-mail: Jeremy.Lyle@utas.edu.au
Temporal Range	25/11/1999 to 23/04/2000
Geographic Range	Top: -41.93 Left: 147.56 Bottom: -43.06 Right: 149.31



Data Fields

Name	Data type	Comment
id	integer	Unique identifier
vessel	text	Vessel identifier
dkt_no	double precision	Docket Number
date_out	text	Date out
date_in	text	Date in
day_out	double precision	Day part of the date out
month_out	double precision	Month part of the date out
year_out	double precision	Year part of the date out
day_in	double precision	Day part of the date in
month_in	double precision	Month part of the date in
year_in	double precision	Year part of the date in
season	text	Fishing season
block	text	TAFI grid block for geographic extent
advice	text	Was the fishing effort in response to outside advice

Name	Data type	Comment
set	double precision	Shot number for the day
day	double precision	Day of the month shot was taken
tonnes	double precision	Catch weight in tonnes
perc_caught	double precision	Percentage of school caught
surf	text	Was it a surface school
lat	double precision	Latitude in decimal degrees
long	double precision	Longitude in decimal degrees

Description

The TAFI 1999 Small Pelagic Fishery catch data was supplied to CMAR as an Excel spreadsheet. The spreadsheet was imported into an Access database for storage and manipulation of the data.

The location of the catch data had to be derived using an algorithm written in Java.The algorithm deduced the centroid of the supplied TAFI block code. Hardcopy maps showing the TAFI blocks were supplied and deriving the geographic extent for each block was done after assessing these hardcopy maps.

The TAFI 1999 Small Pelagic Fishery catch data supplied no species information so all catch were assigned to Jack Mackerel.